Dark Matter Phenomenology

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UNIVERSITA' DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

Physics Torino Department of Excellence

INFN Istituto Nazionale di Fisica Nucleare

SOUP 2022: INFN School on Underground Physics

Outline of the lectures

Principles of particle cosmology and astrophysics

- Evidences of dark matter
- Production mechanisms in the early Universe
- Connection to particle physics beyond the Standard Model
- Identification of non-gravitational DM signals

Direct detection

Charged cosmic-rays signals

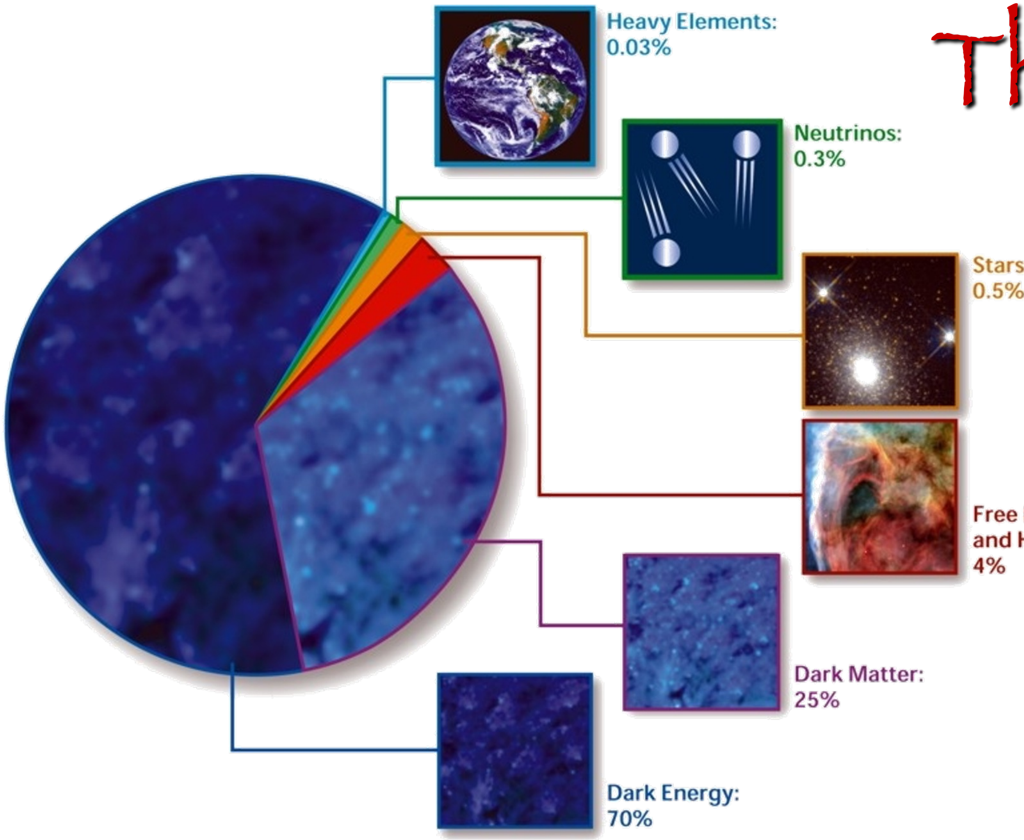
- Electrons and positrons
- Antiprotons
- Antideuterons

Electromagnetic signals (multi-wavelength)

- Radio
- Gamma-rays
- Anisotropies

Neutrino signals

The Dark Universe



$1 - \Omega_{\rm TOT}$	-0.0105 ± 0.061	[95% C.L.]
Ω_Λ	0.693 ± 0.019	[68% C.L.]
$\Omega_{\rm M}$	0.307 ± 0.019	[68% C.L.]
H_0	67.9 ± 1.5	[95% C.L.]
(km s^{-1} Mpc^{-1})	73.8 ± 2.4	[*]
	74.3 ± 2.6	[+]
$\Omega_{\rm M} h^2$	0.1414 ± 0.0029	[68% C.L.]
$\Omega_{\rm b} h^2$	0.02217 ± 0.00033	[68% C.L.]
$\Omega_{\rm DM} h^2$	0.1186 ± 0.0031	[68% C.L.]

Ade et al. (Planck Collab.), arXiv: 1303.5076
[*] Riess et al., Ap. J. 730 (2011) 119
[+] Freedmann et al., Ap. J. 758 (2012) 24

Geometry: the Universe is Flat
Dynamics: the Universe is expanding

- Decelerate for most of its history
- Accelerate since "recent" time and at very "old" times (inflation)

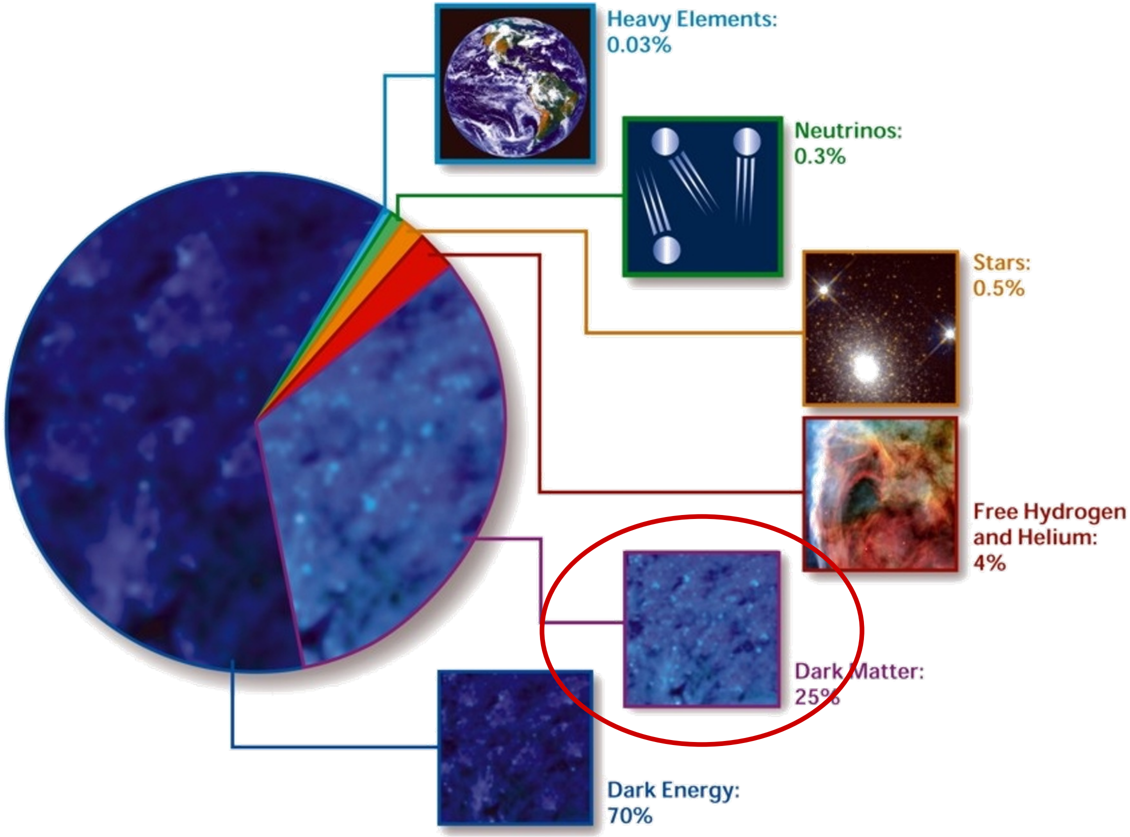
$\Omega_{\rm T}$ CMB temperature anisotropies

Ω_Λ Luminosity distance of high-z SNIa

$\Omega_{\rm M}$ Clustered mass abundance

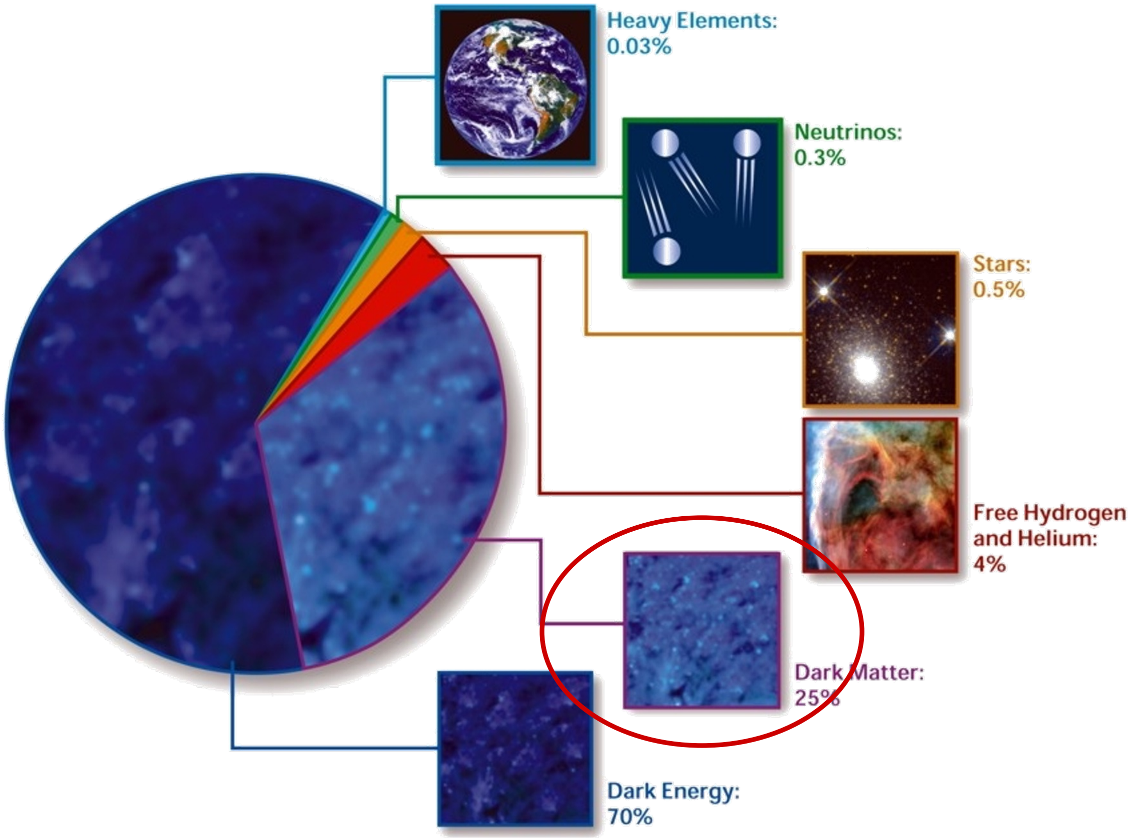
$\Omega_{\rm B}$ Primordial Nucleosynthesis
Amplitude of CMB temperature anisotropies

Dark Matter



- Dynamics of galaxy clusters
- Rotational curves of galaxies
- Weak lensing
- Structure formation from primordial density fluctuations
- Energy density budget

Dark Matter



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

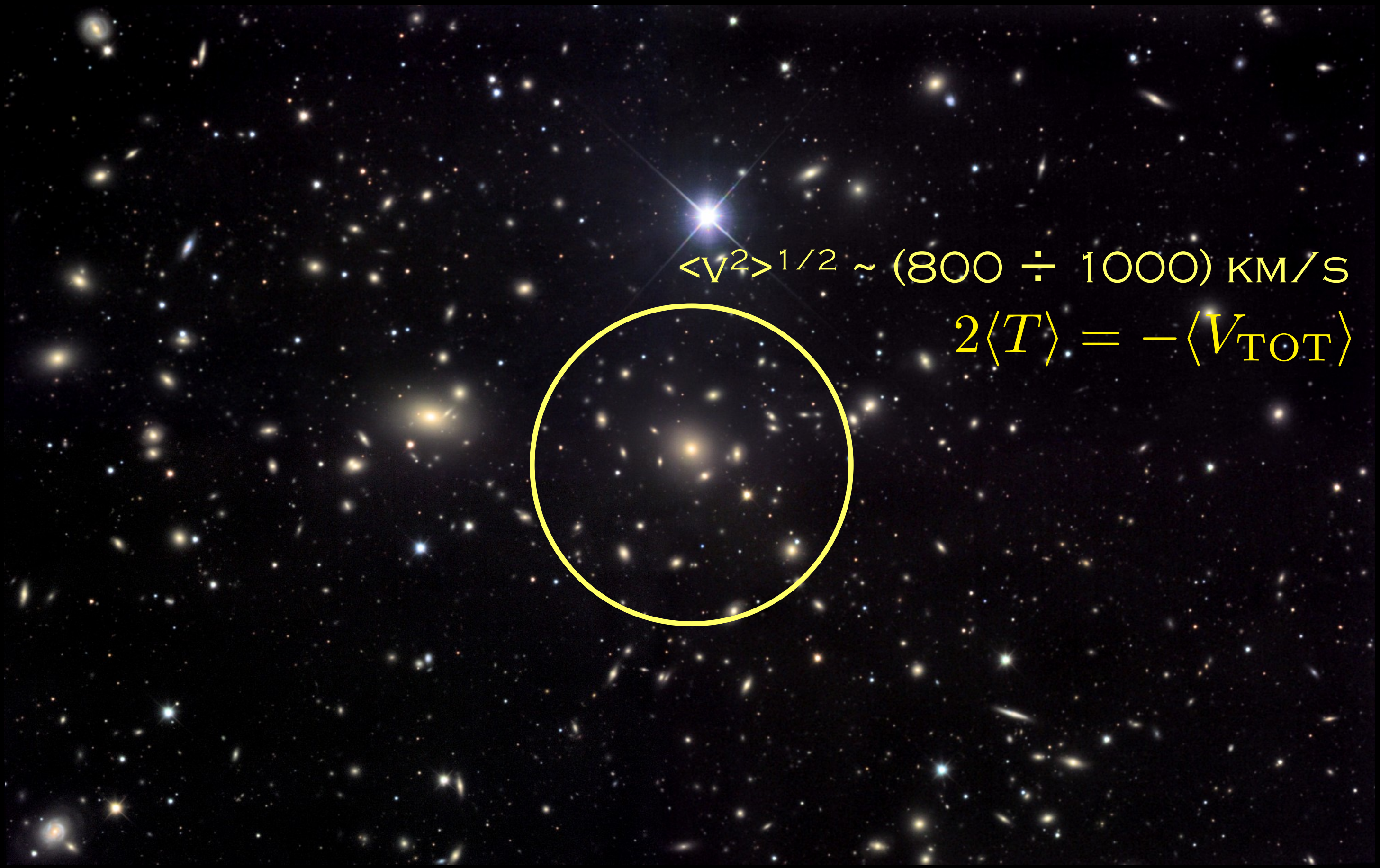
Zwicky, 1933 →

Virial theorem

$$2\langle T\rangle = -\langle V_{\mathrm{TOT}}\rangle$$

Galaxy cluster

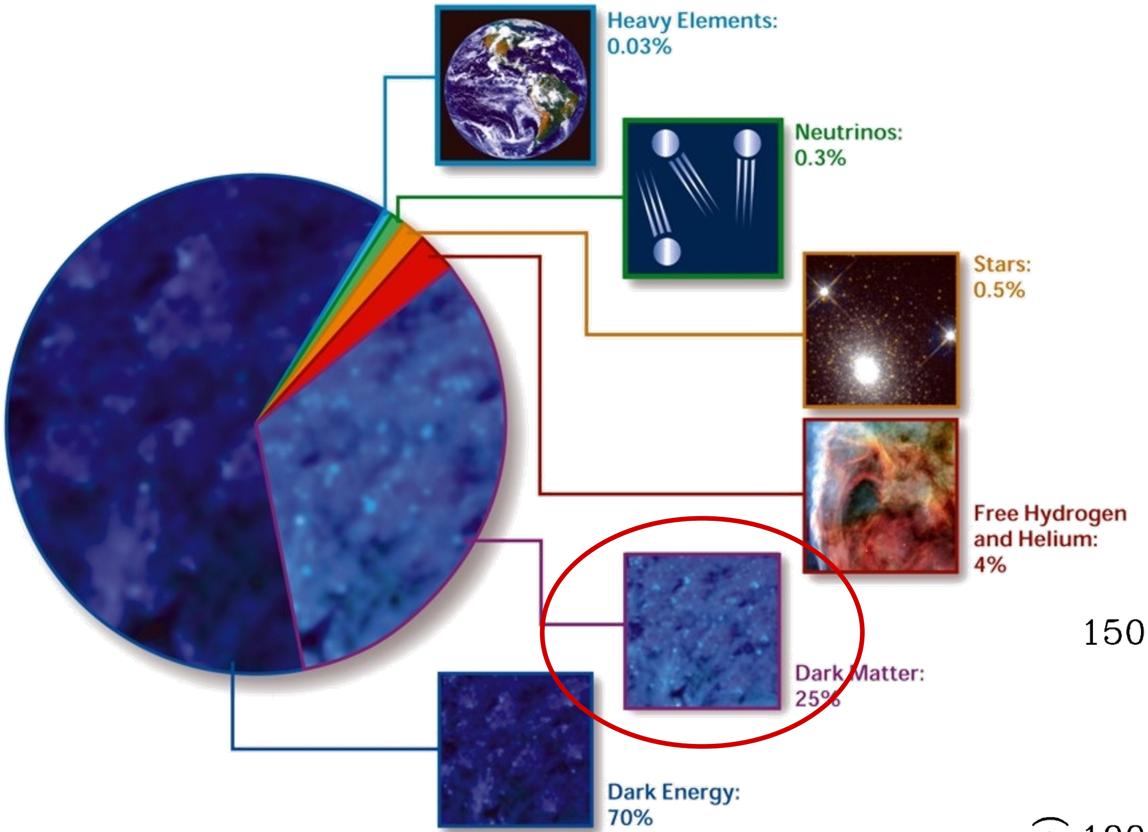
Zwicky (1933)



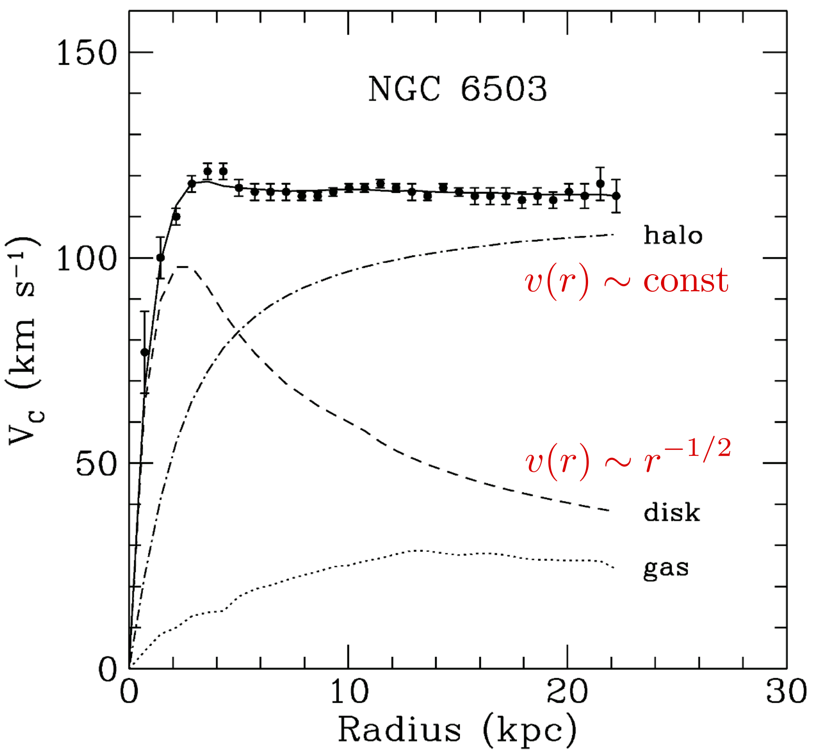
Velocity dispersion of galaxies in the cluster is too large: the cluster should "evaporate"

Galaxies : Gas : DM = 1: 9 :90

Dark Matter



$$v(r) \propto \sqrt{M(r)/r}$$



Dynamics of galaxy clusters

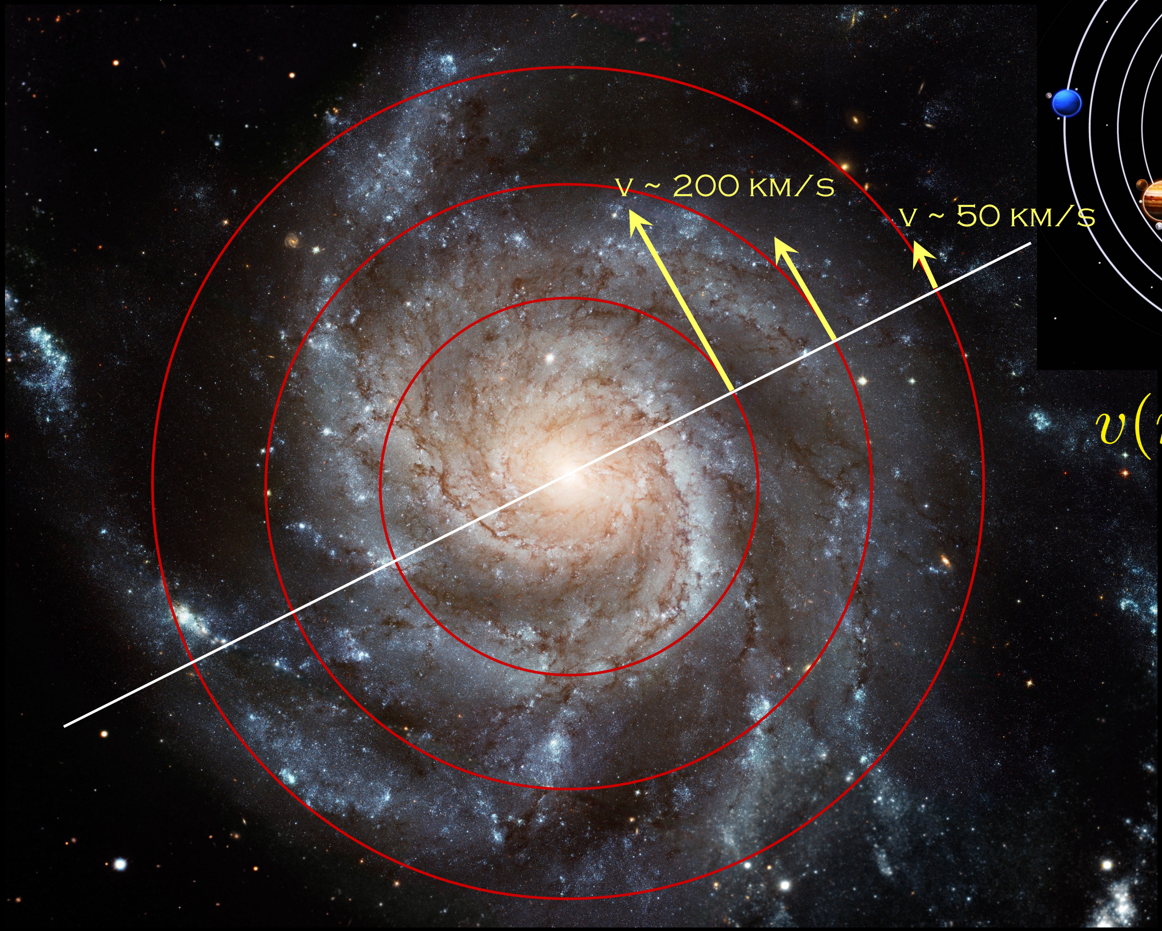
Rotational curves of galaxies — Rubin, early '70s →

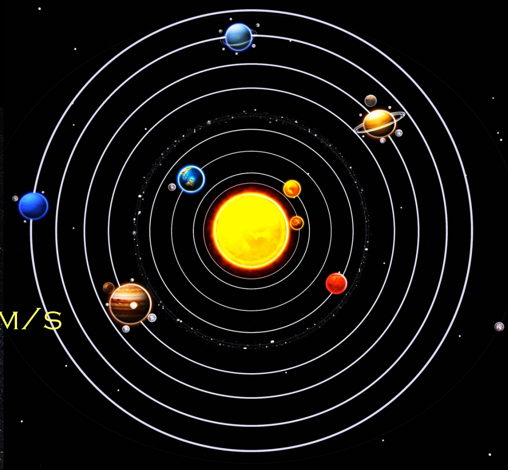
Weak lensing

Structure formation from primordial density fluctuations

Energy density budget

Spiral Galaxy

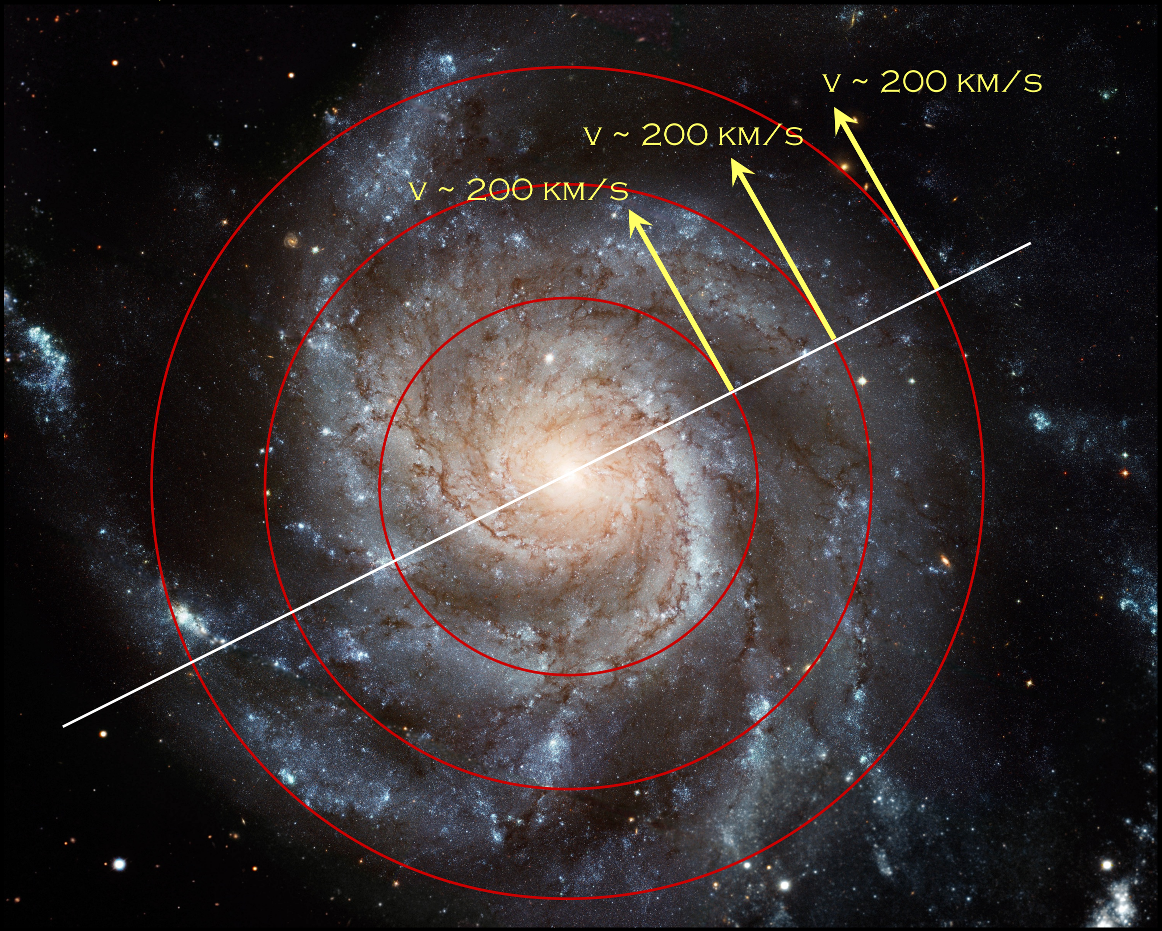




$$v(r) \propto r^{-1/2}$$

Spiral Galaxy

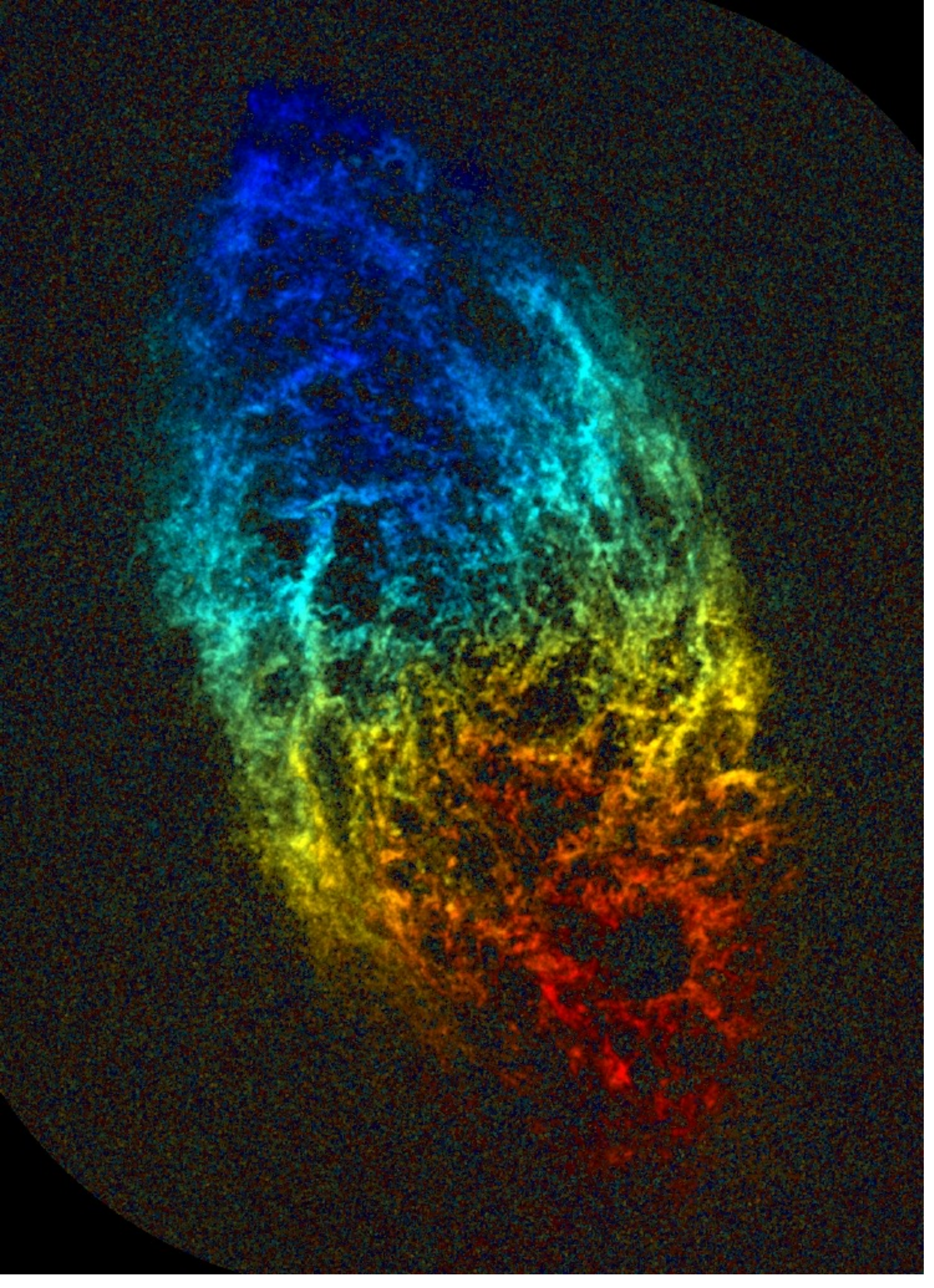
Rubin (1970)



Periferic stars are faster than expected
Faster = More mass

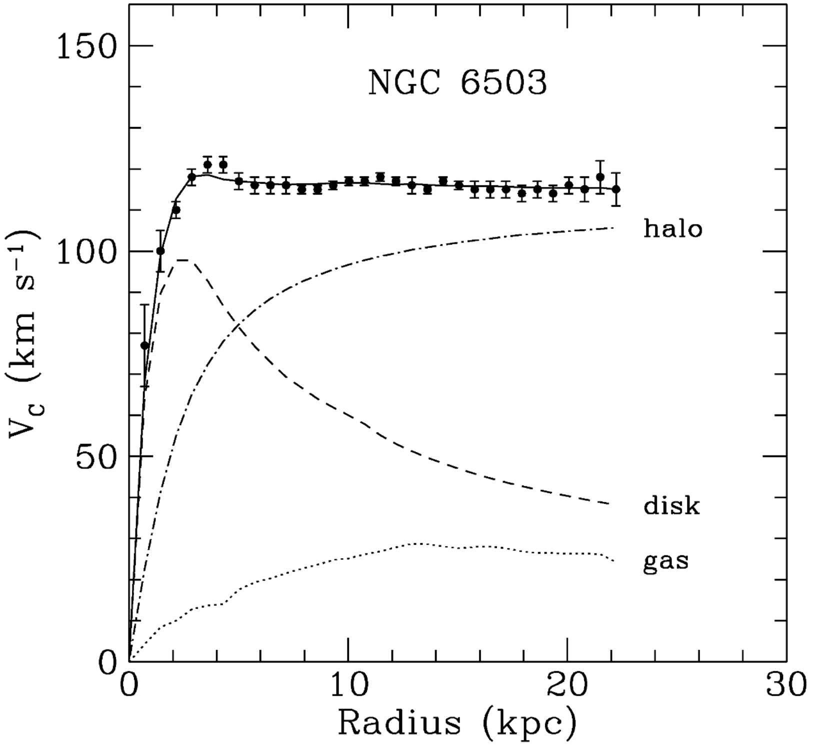
Much more mass than luminous mass

Dark Matter

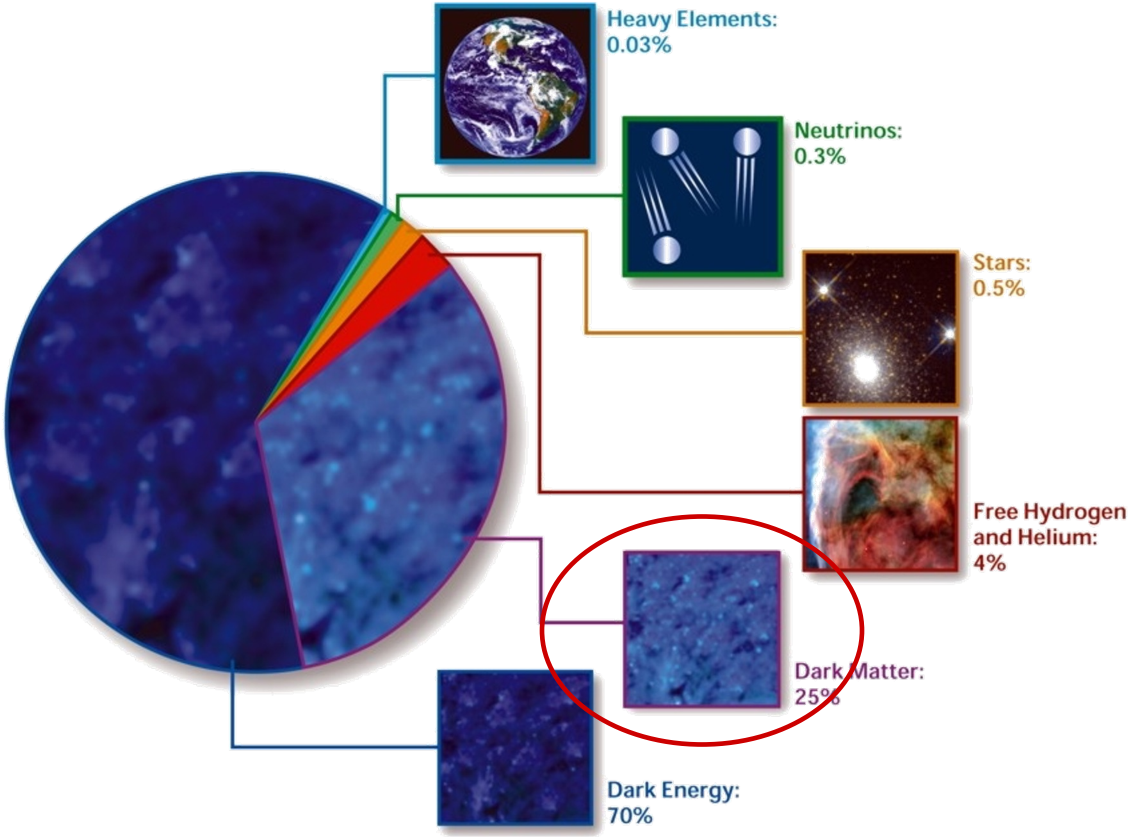


M33
Hydrogen gas
Doppler image

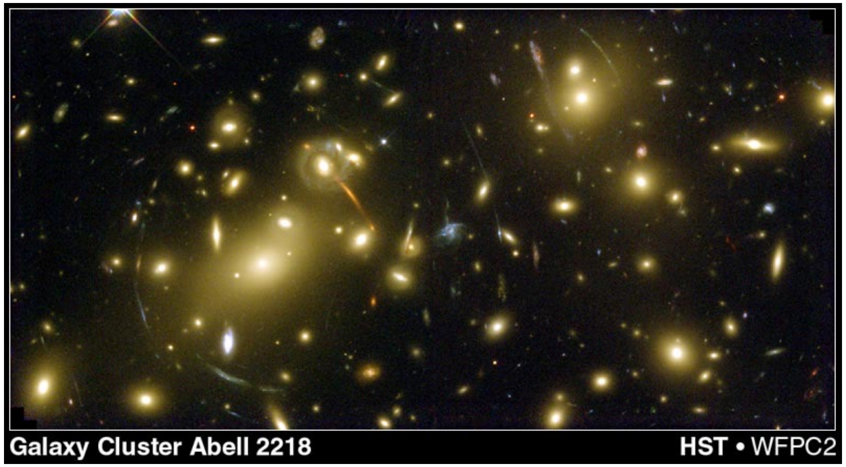
$$v(r) \propto \sqrt{M(r)/r}$$

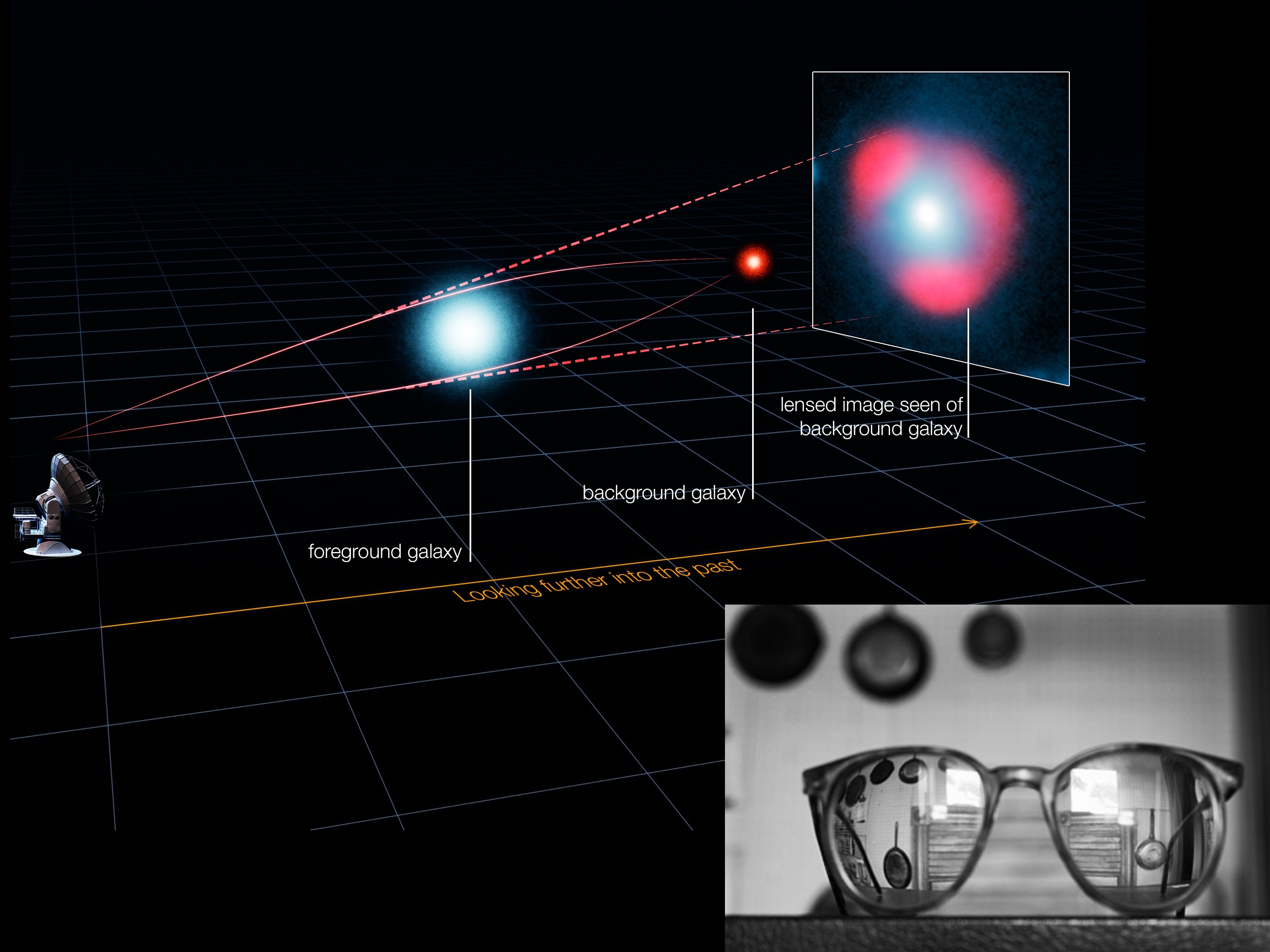


Dark Matter



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing →
Structure formation from primordial density fluctuations
Energy density budget




lensed image seen of
background galaxy
background galaxy
foreground galaxy
Looking further into the past

Lens equation

Thin lens: distances involved are much larger than the size of the lens

Lens equation (can have multiple solutions)

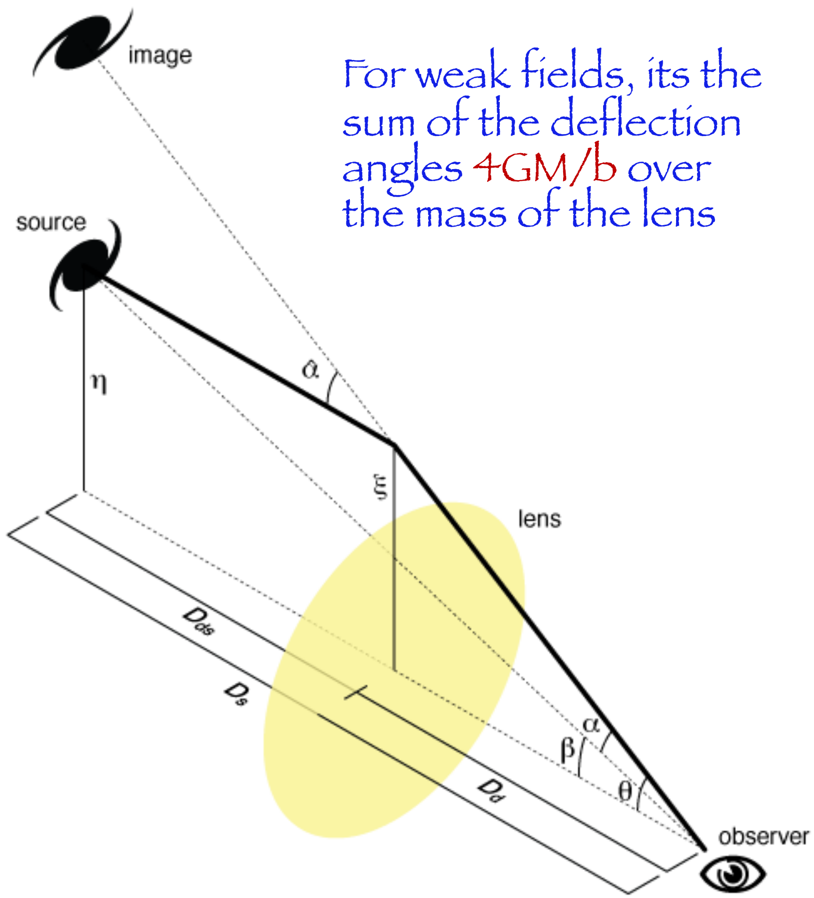
$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

Deflection angle

$$\alpha(\vec{\theta}) = 4G\int \frac{(\vec{\xi} - \vec{\xi'})\Sigma(\vec{\xi'})}{|\vec{\xi} - \vec{\xi'}|^2}\, d^2\xi'$$

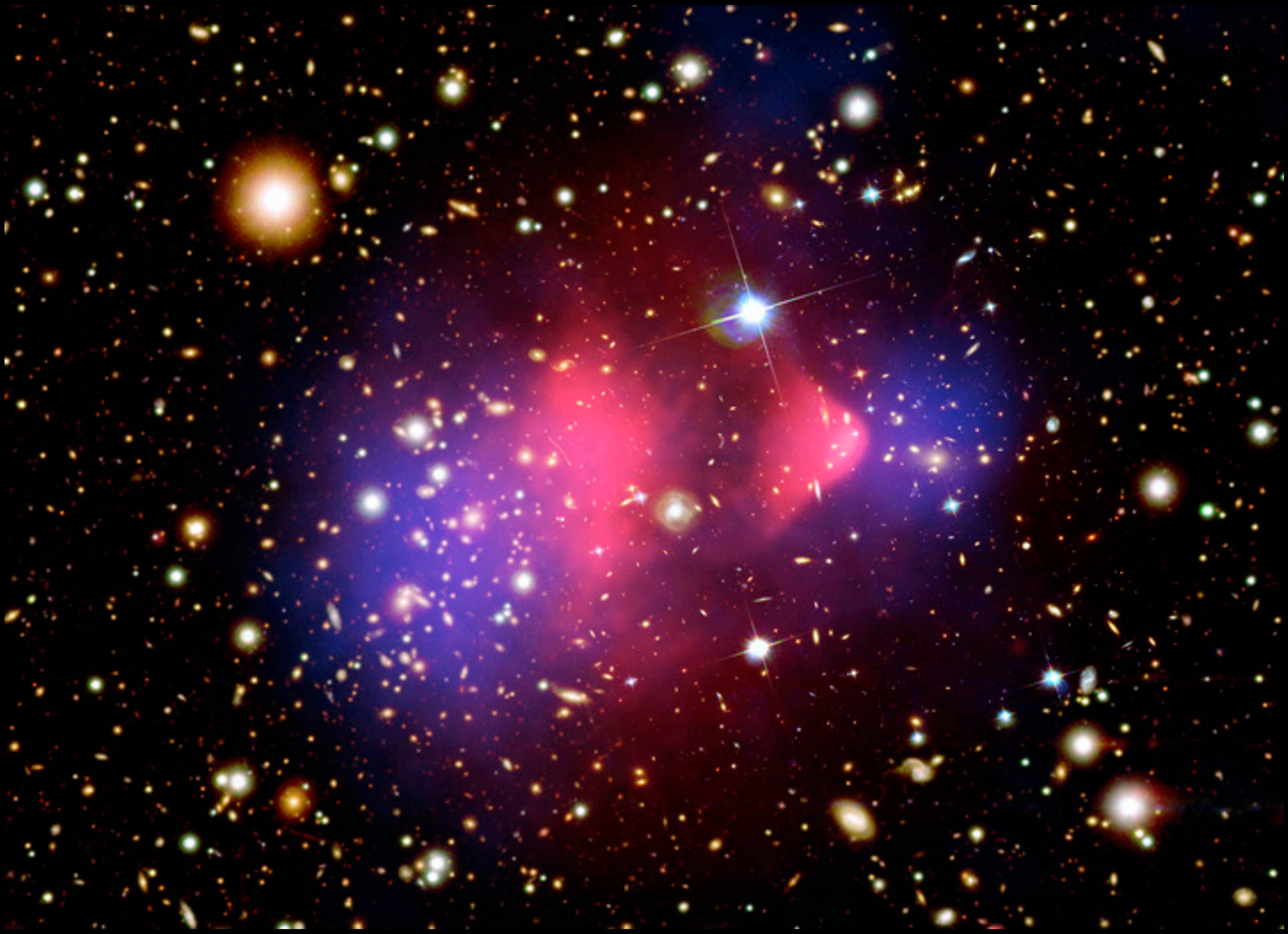
Projected mass density

$$\Sigma(\vec{\xi'}) = \int \rho(\vec{\xi}, z)\, dz$$



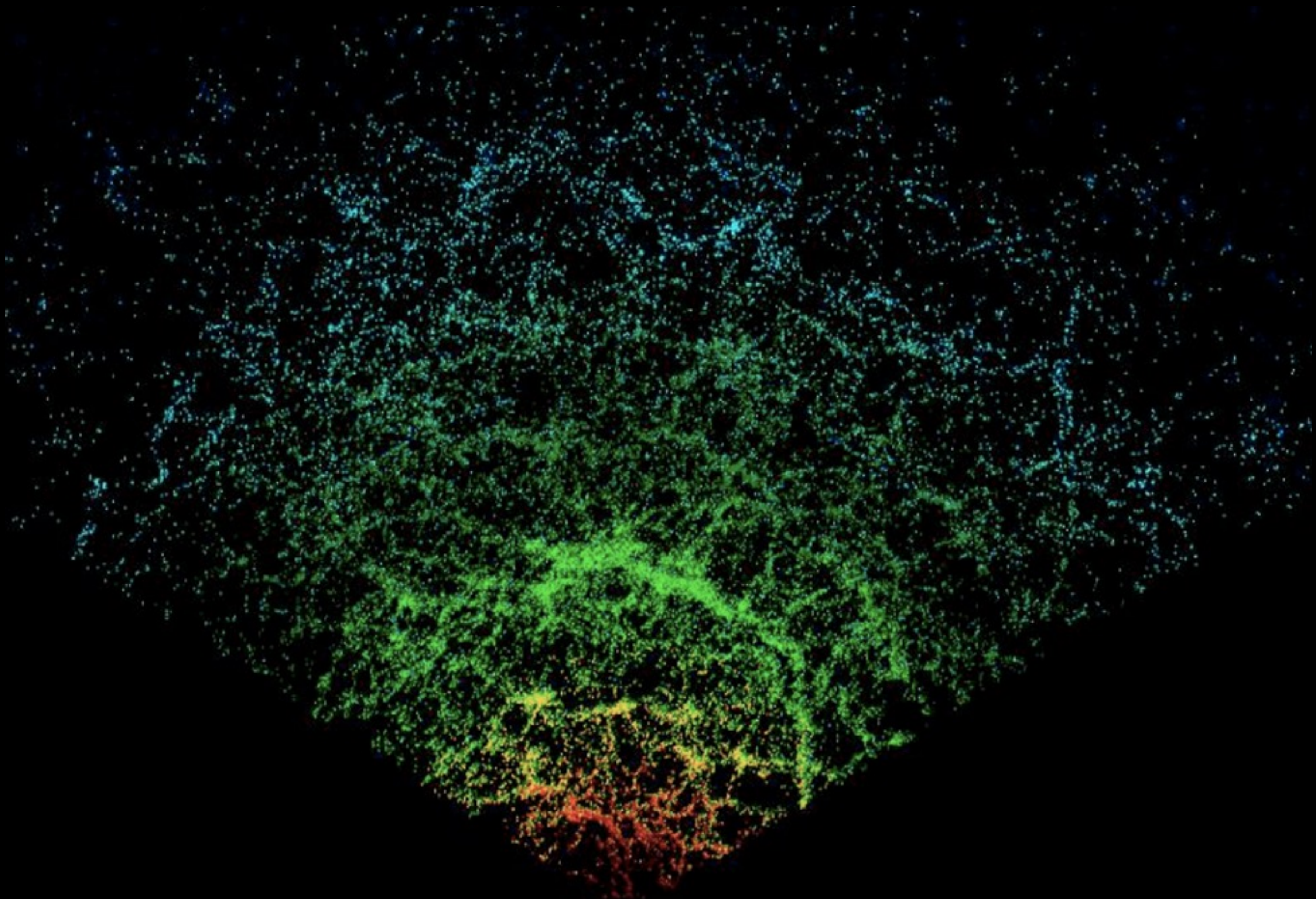
For weak fields, its the sum of the deflection angles 4GM/b over the mass of the lens

The “Bullet cluster” (1E 0657-558)

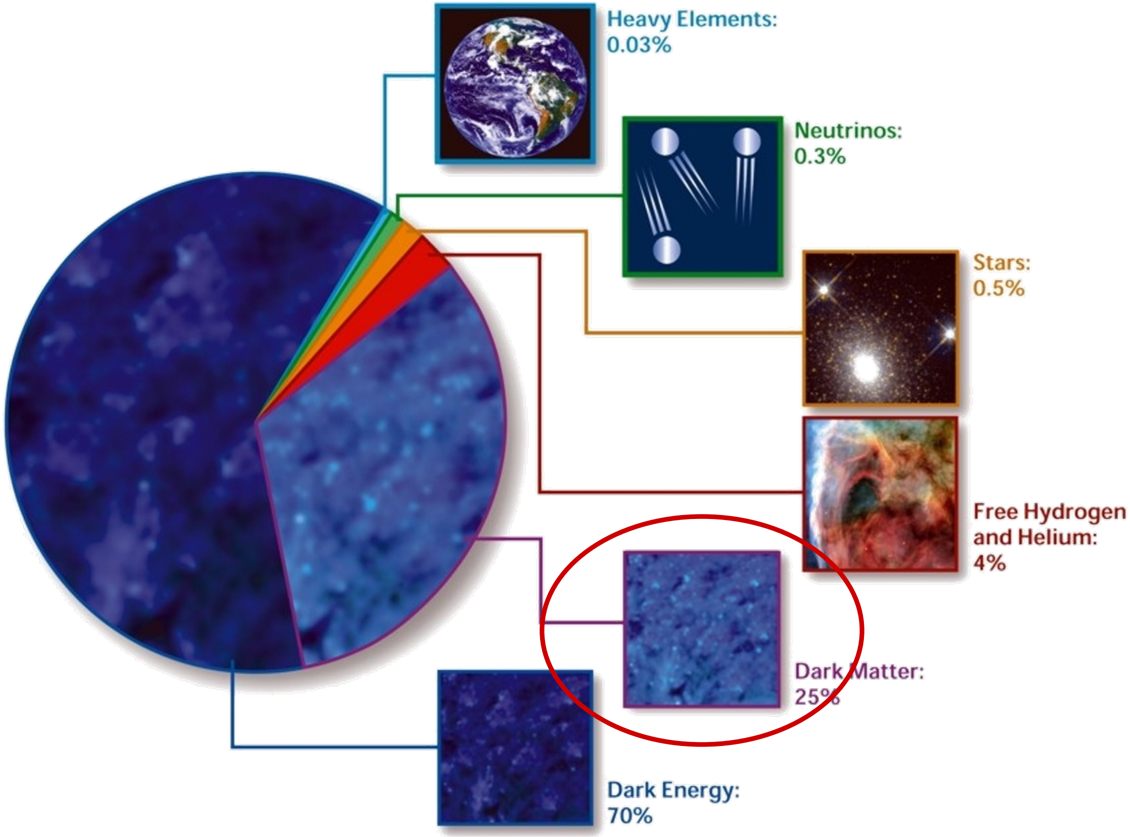


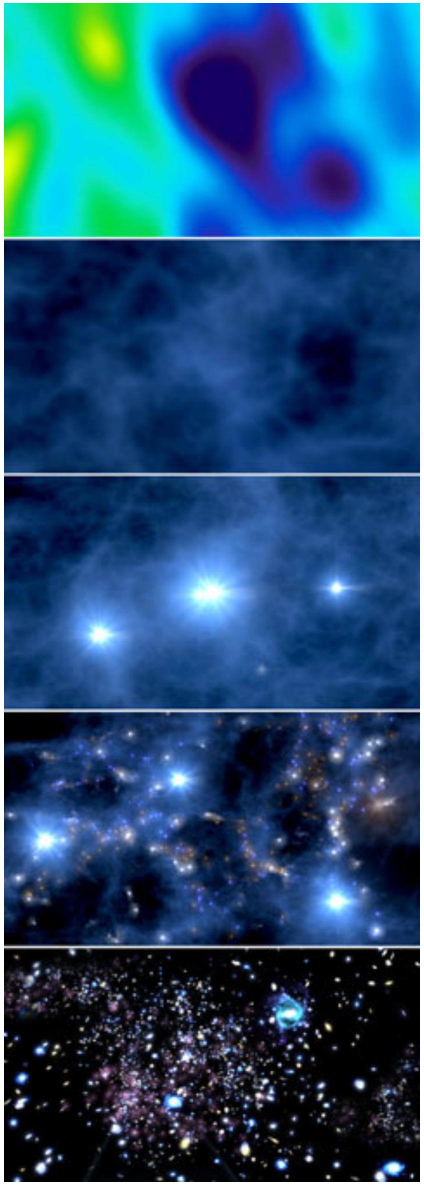
Colliding galaxy clusters

Universe at large scales



Dark Matter

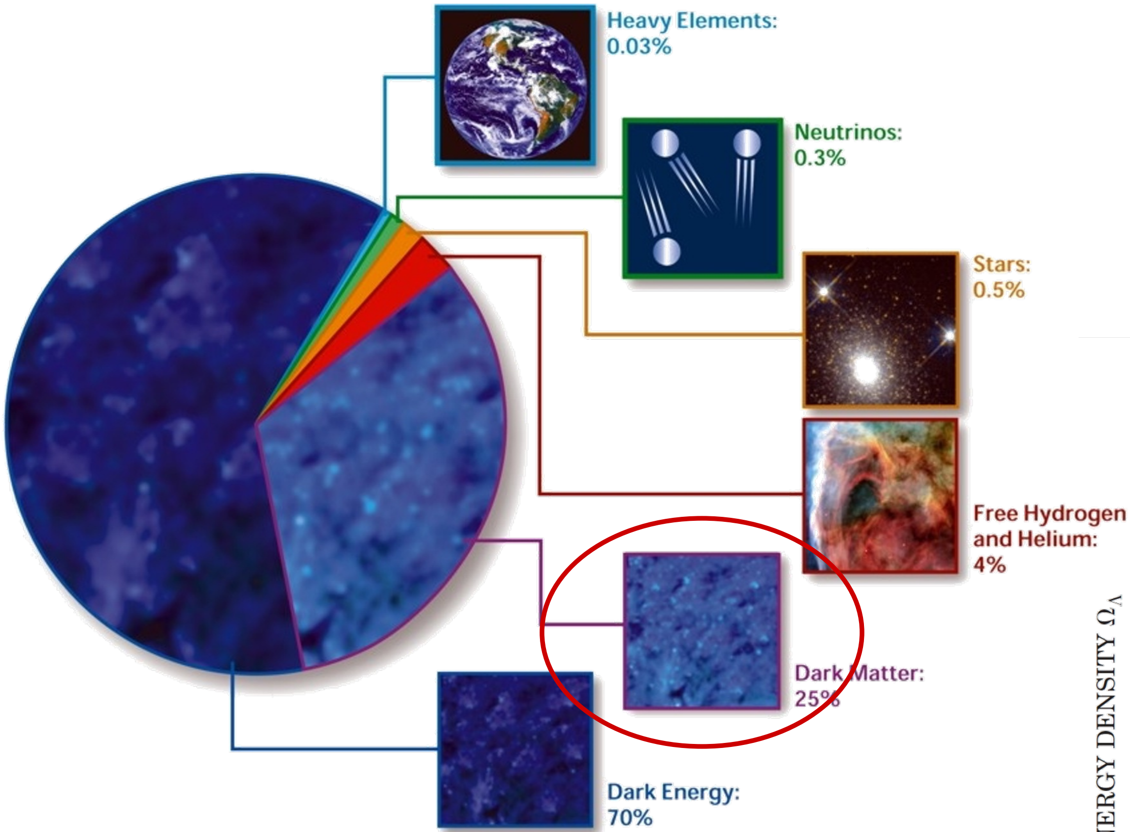




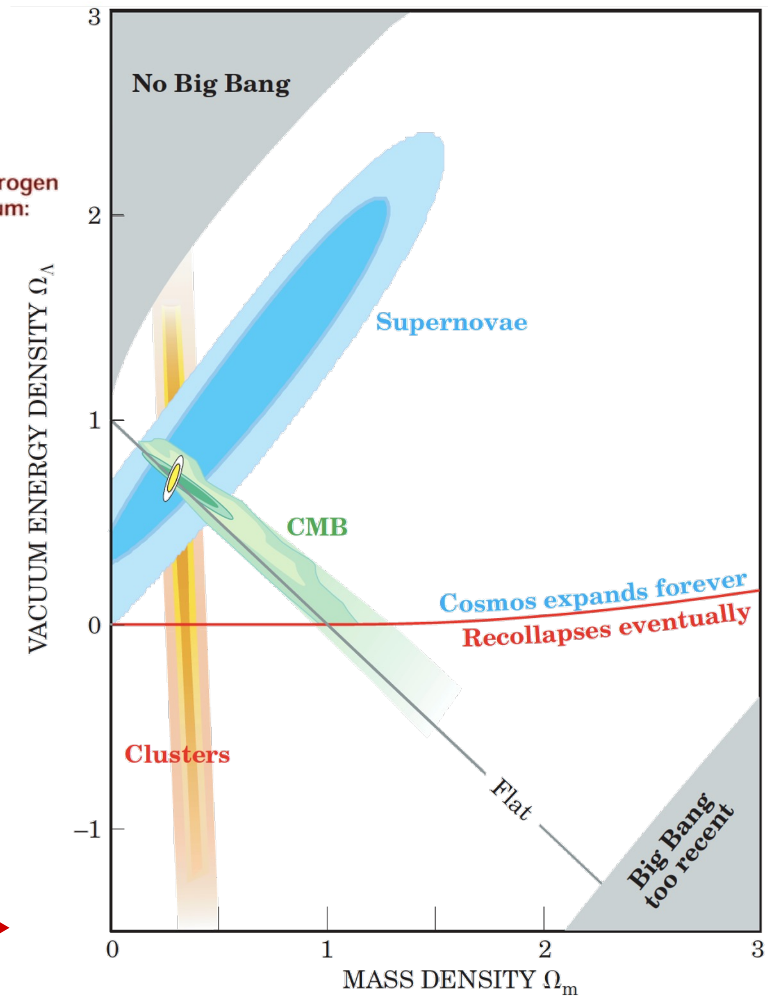
Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

DM needs to be (mainly) cold and (mainly) non-collisional

Dark Matter



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget → Concordance model



Dark Matter: what's going on?

- Generaly Relativity needs to be modified ?
  - The 'anomaly' we call DM is due to a behaviour of gravity on large scales different from what predicted by GR (and its Newtonian limit)

- Relic from the early Universe ?
  - GR works just fine, DM is some new 'stuff'
    - A new elementary particle
    - Primordial Black Holes

Primordial Black Holes

PBHs are thought to originate from gravitational collapse of large density fluctuations in the early universe (produced by various mechanisms)

Density perturbations δ_H entering the cosmological horizon can form a BH if:

$$w = \delta_c < \delta_H < \delta_{\max} = 1$$

The mass grows with the time at which they are produced

$$M \sim \frac{c^3\,t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)\mathrm{g}$$

Planck time (10^{-43} s): 10^{-5} g
BBN time (1 s): $10^5 M_{Sun}$ ($M_{sun} \approx 2\,10^{33}$ g)

Hawing evaporation: temperature and lifetime

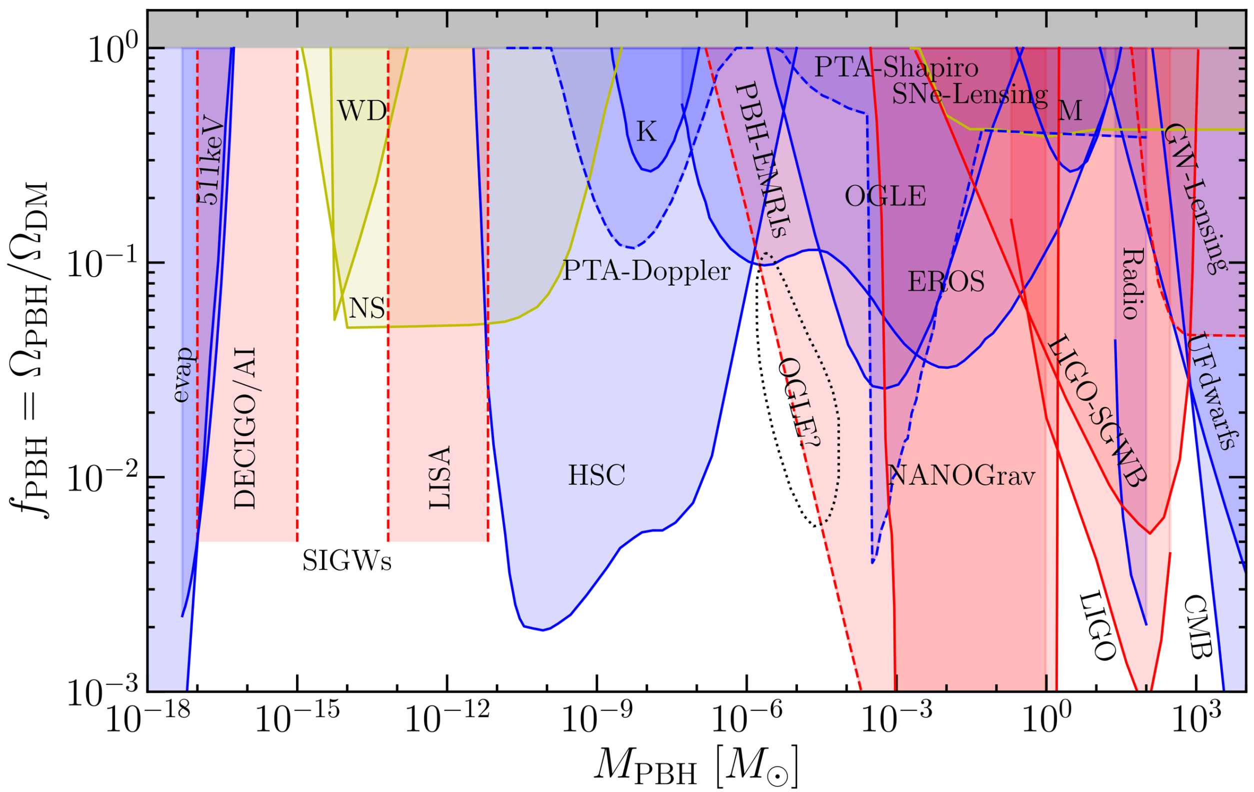
$$T_{\rm BH} = \frac{\hbar c^3}{8\pi k_B G M} \sim 10^{-7}\ \mathrm{K}\ \frac{M_\odot}{M}$$

$$\tau(M) \sim 10^{64}\ \mathrm{yr}\left(\frac{M}{M_\odot}\right)^3$$

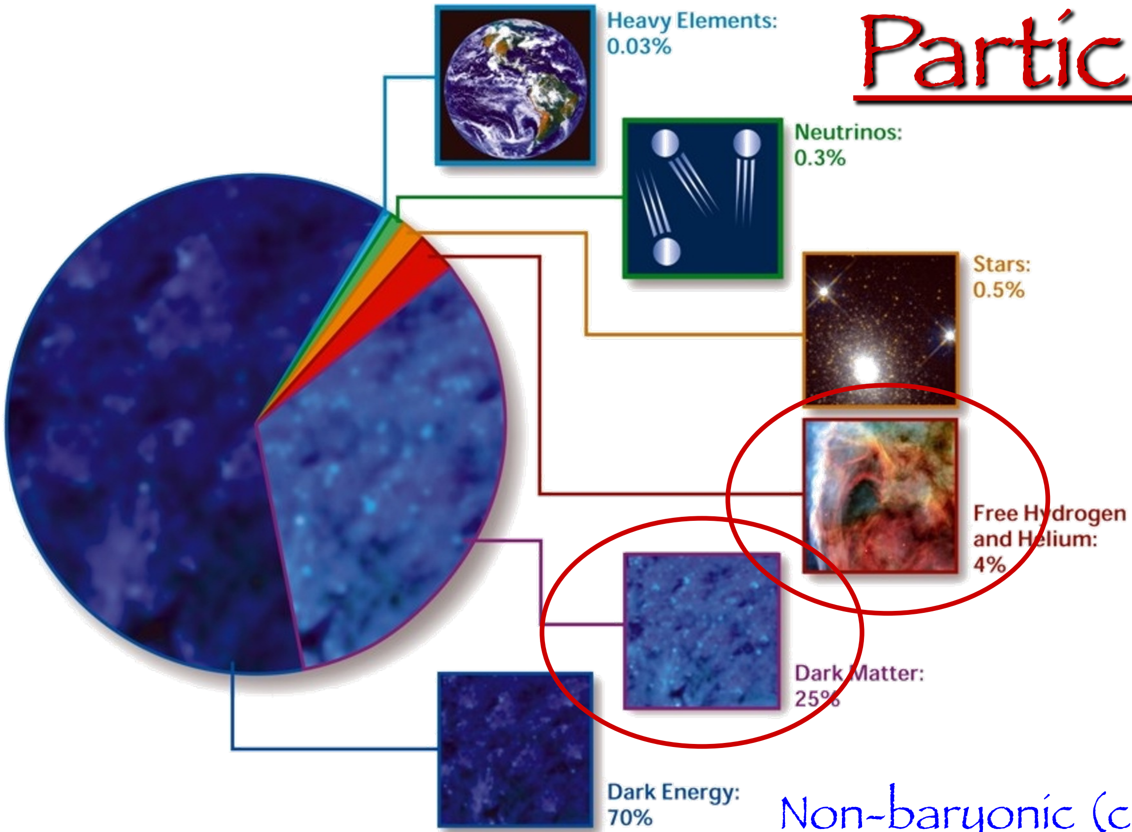
PBH with masses below 10^{15} g have already evaporated

Primordial Black Holes

Evaporation
Microlensing
Gravitational waves
Dynamical constraints (heat star clusters by the presence of PBH)
CMB distortions or anisotopies
Ly-alpha
21cm cosmology (PBH can change termal state of IGM)



Particle Dark Matter



Non-baryonic (cold-ish) dark matter is needed

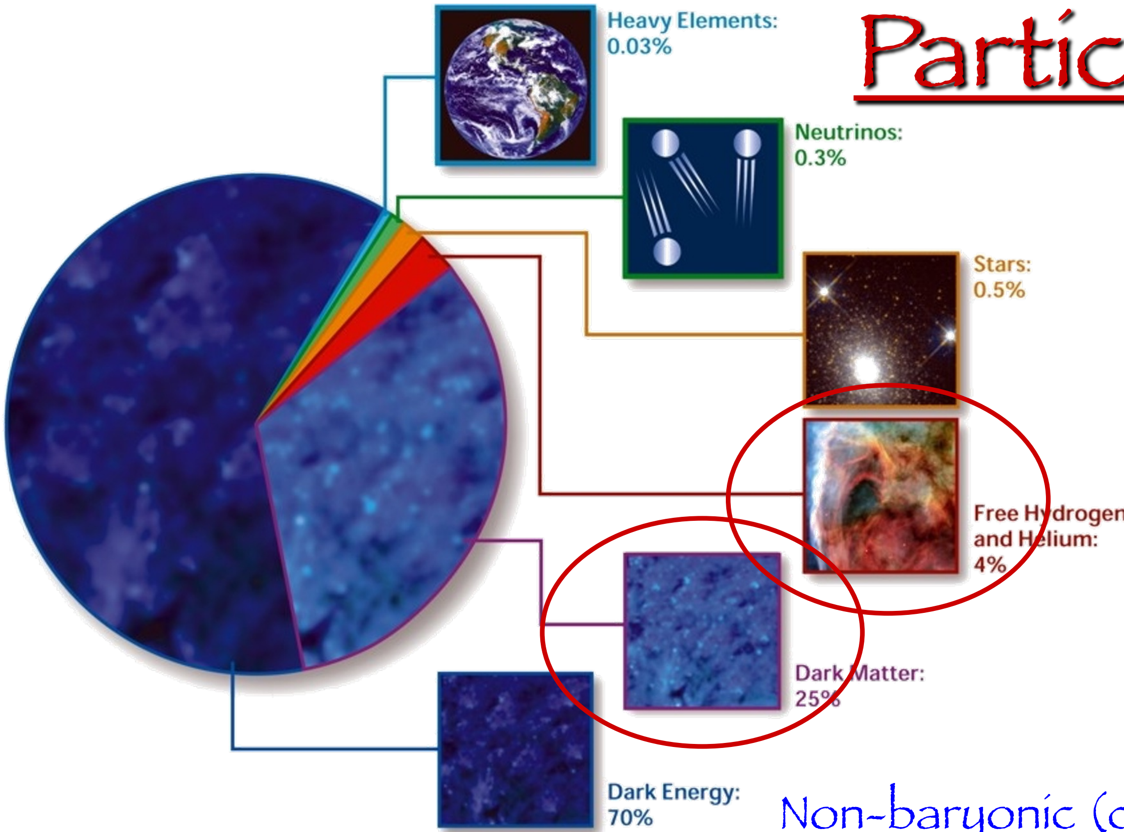
No candidate in the Standard Model (*)

New fundamental Physics

(*) Standard neutrino:

Too light: acts as H(-ish)DM, not C(-ish)DM)

Particle Dark Matter



Non-baryonic (cold-ish) dark matter is needed

No candidate in the Standard Model (*)

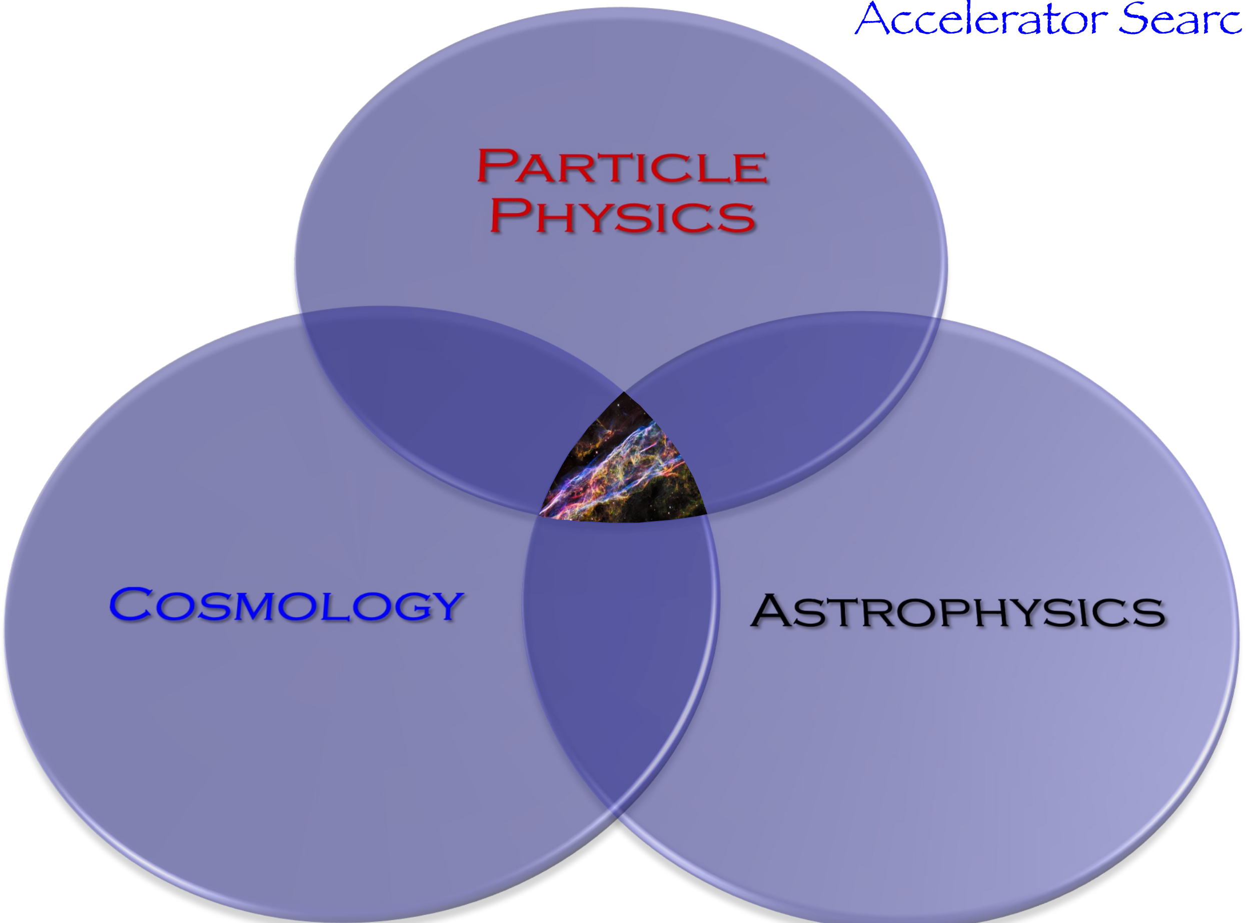
New fundamental Physics

Two fundamental questions

- Identify the particle candidate
- Identify a non-gravitational signal

The Particle Dark Matter Crossroad

Particle Candidate: Models of New Physics
(Superymmetry, Extra-dimensions, ...)
Accelerator Searches



Cosmology of the
Dark Matter Particle

Astrophysical Signals of the
Dark Matter Particle

Cosmology
of the DM particle

Standard cosmological model

- Dynamical description — U. expansion
  - General Relativity: Einstein equation (gravity)
  - Cosmological principle: the U. is spatially homogeneus and isotropic

- Statistical description — Thermal equilibrium and U. temperature T
  - The Universe can be described as a self-gravitating, perfect fluid
  - The fluid is multicomponent (radiation, "matter", ...)
  - Conditions of thermal equilibrium may/may not be met

- Microhpysical description — Particle cosmology
  - The components of the fluid are elementary d.o.f. (particles)
  - Their physical properties (masses and interactions) determine their behaviour
  - Boltzmann equation

Einstein equations

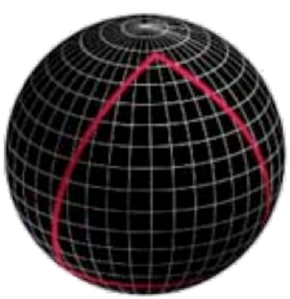
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{3} T_{\mu\nu}$$

gravity (geometry) matter/energy

The Cosmological Principle determines:

- space-time geometry is determined by a single function a(t) [the scale factor] and by a curvature parameter k
- the U. can be described by a perfect fluid, which posseses an energy density ρ(t) and pressure p(t)

Einstein eq. take the form of the Friedmann eq.:



$$\left(\frac{\dot a}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad [\rho = \sum_i \rho_i]$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad [p = \sum_i p_i]$$

Geometry is connected to energy content

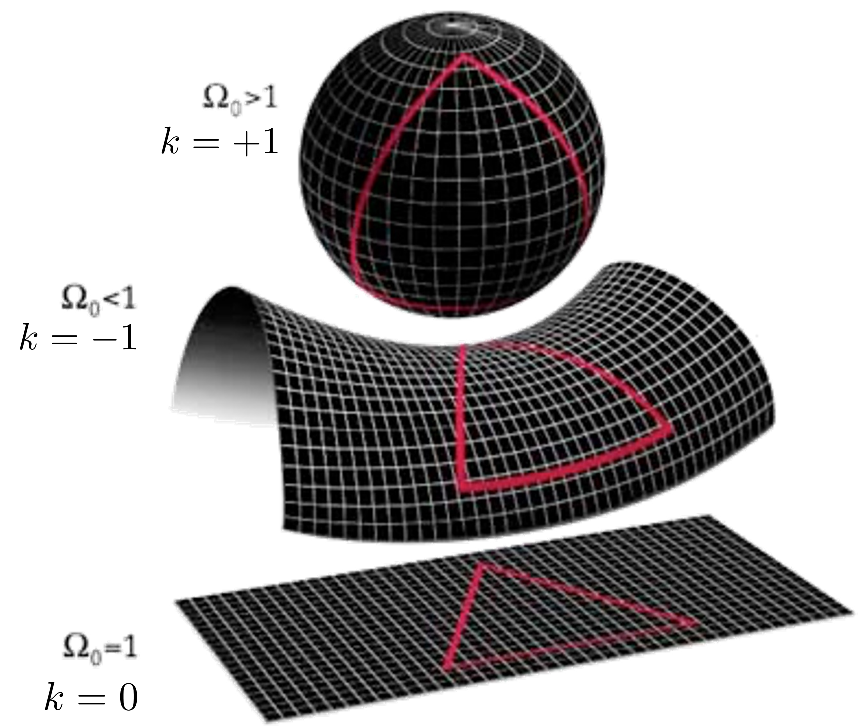
Density parameter $\Omega_i = \rho_i / \rho_c$

$$\Omega = \sum_i \Omega_i = 1$$

Critical density $\rho_c = \frac{3H_0^2}{8\pi G}$

Hubble parameter $H(t) = \frac{\dot{a}}{a}$

Hubble constant $H_0 = H(t_0)$



Types of fluid and dynamical evolution

Radiation (relativistic component) $p = \rho/3$

"Matter" (non-relativistic component) $p = 0$

Cosmological constant $p = -\rho$

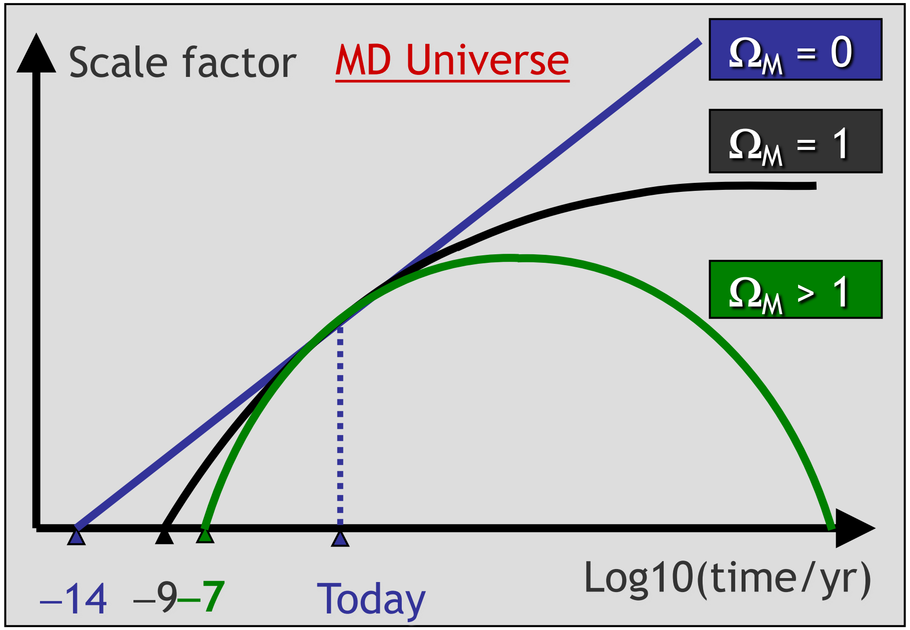
The evolution of the U. (i.e. of the scale factor in time) depends on its content (and on its geometry), ad dictated by the Einstein equations

Flat Universe

RD U. $a(t) = a_0\, t^{1/2}$

MD U. $a(t) = a_0\, t^{2/3}$

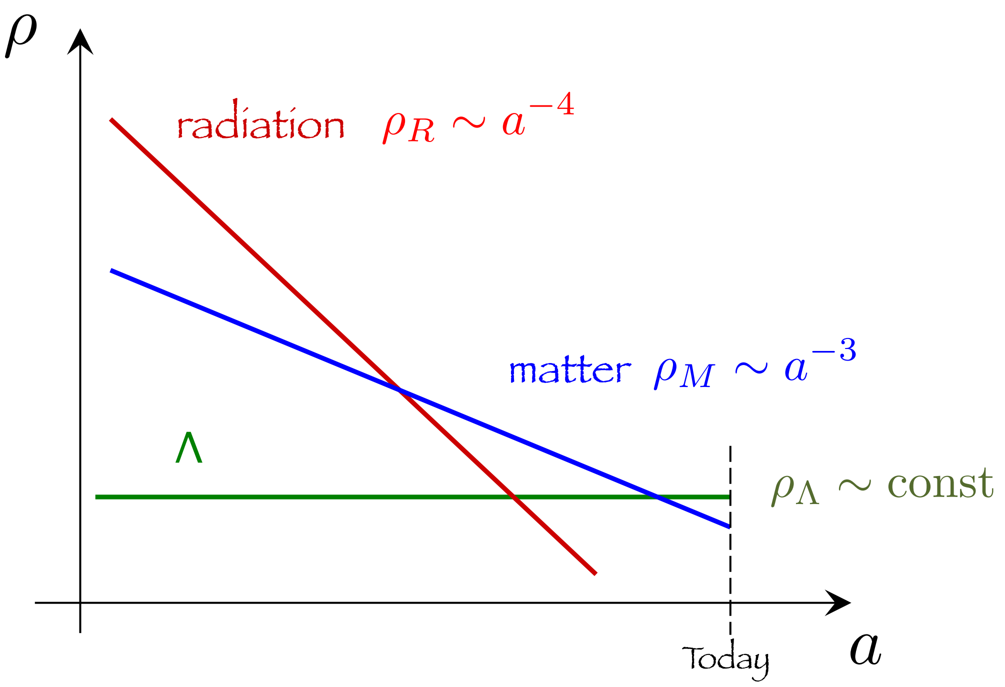
ΛD U. $a(t) = a_0\, \exp H_0(t - t_0)$



Evolution of the fluid

Conservation of the stress-energy tensor (i.e. of energy/momentum) determines the evolution of the fluid with the U. evolution (i.e. with a(t))

$$T_{\mu\nu} \longleftarrow \rho \; , \; p$$



Statistical properties of the fluid

The fluid is assumed to be in thermal/statistical equilibrium

Each species *i* has a phase-space distribution $f_i(p)$

If equilibrium is met, a temperature T can be defined and $f_i(p)$ depend on T

i = fermion: Fermi-Dirac

i = boson: Bose-Einstein

Number density
$$n_i(T) = \int d^3p \; f_i(p,T)$$

Energy density
$$\rho_i(T) = \int d^3p \; E \; f_i(p,T)$$

Pressure
$$p_i(T) = \int d^3p \; \frac{p^2}{3E} f_i(p,T)$$

Temperature dependence

	Relativistic Bosons	Relativistic Fermions	Non-relativistic (Either)
n_i	$\frac{\zeta(3)}{\pi^2} g_i T^3$	$\left(\frac{3}{4}\right) \frac{\zeta(3)}{\pi^2} g_i T^3$	$g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$
ρ_i	$\frac{\pi^2}{30} g_i T^4$	$\left(\frac{7}{8}\right) \frac{\pi^2}{30} g_i T^4$	$m_i n_i$
p_i	$\frac{1}{3}\rho_i$	$\frac{1}{3}\rho_i$	$n_i T \ll \rho_i$
Entropy density s_i	$\frac{2\pi^2}{45} g_i T^3$	$\left(\frac{7}{8}\right) \frac{2\pi^2}{45} g_i T^3$	

$$\rho(T) = \frac{\pi^2}{30}\, g_*(T) T^4$$

$$s(T) = \frac{2\pi^2}{54}\, g_{*S}(T) T^3$$

$$S = s a^3 = \text{const}$$

Microphysical properties of the fluid

The fluid, at the microphysical level, is composed by elementary d.o.f. (particles)

The various components of the fluid may (or may not) be in thermal equilibrium

Equilibrium is determined by the occurrence of mutual interactions

(for 2-to-2 processes)

elastic scattering	$\chi A \longleftrightarrow \chi A$	kinetic equilibrium
inelastic scattering	$\chi \bar{\chi} \longleftrightarrow \bar{A} A$	chemical equilibrium

Particle thermalization in the early Universe

Thermalization processes

$$\chi A \longleftrightarrow \chi A$$
$$\chi\bar{\chi} \longleftrightarrow \bar{A}A$$

	Relativistic Bosons	Relativistic Fermions	Non-relativistic (Either)
n_i	$\frac{\zeta(3)}{\pi^2} g_i T^3$	$\left(\frac{3}{4}\right) \frac{\zeta(3)}{\pi^2} g_i T^3$	$g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$
ρ_i	$\frac{\pi^2}{30} g_i T^4$	$\left(\frac{7}{8}\right) \frac{\pi^2}{30} g_i T^4$	$m_i n_i$
p_i	$\frac{1}{3}\rho_i$	$\frac{1}{3}\rho_i$	$n_i T \ll \rho_i$

$\Gamma = n\langle\sigma v\rangle$: interaction rate

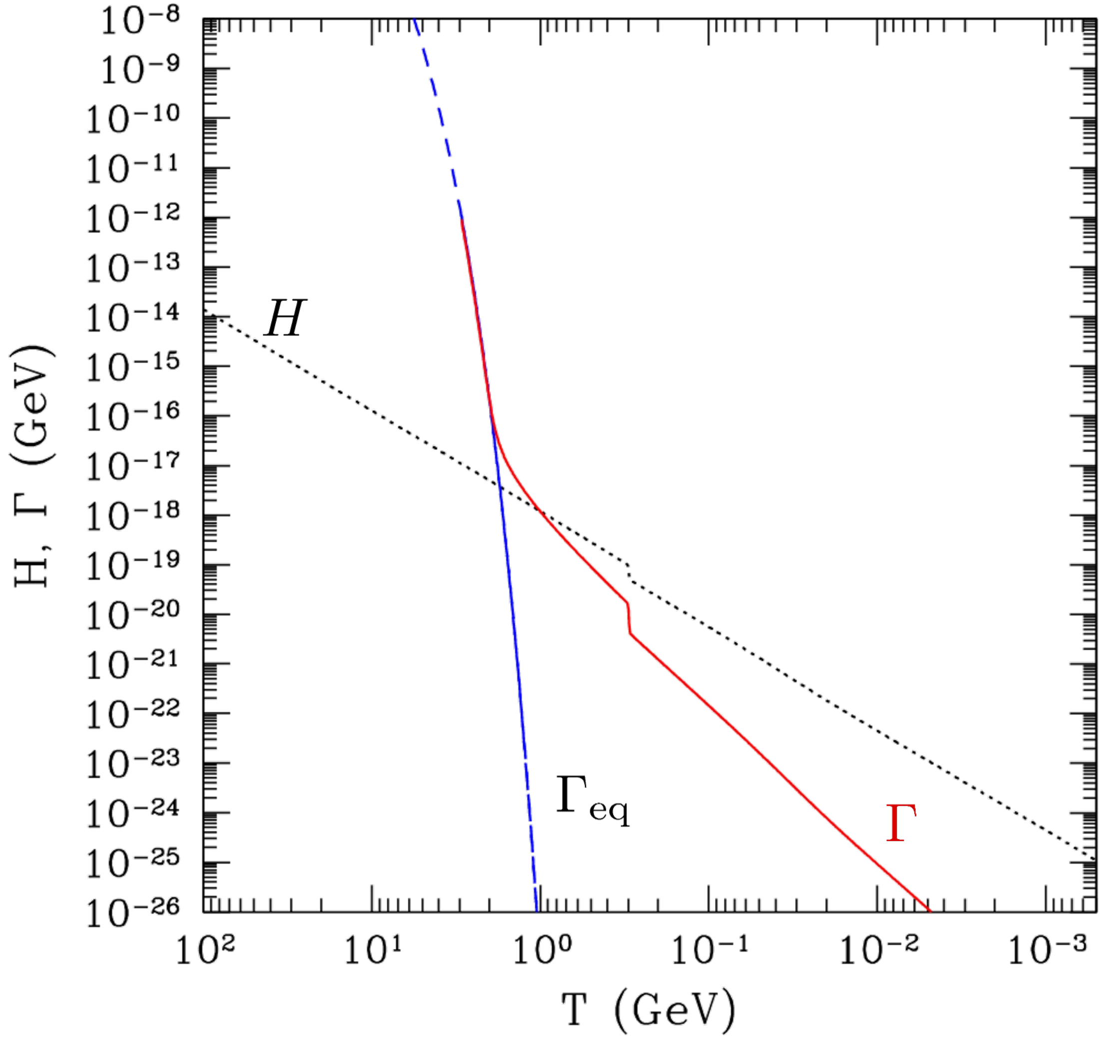
$H = \dot{a}/a$: expansion rate

$$\langle\sigma v\rangle = \frac{\int d^3p_i \, d^3p_j \, f_i(E) \, f_j(E) \, \sigma_{ij} v_{ij}}{\int d^3p_i \, d^3p_j \, f_i(E) \, f_j(E)}$$

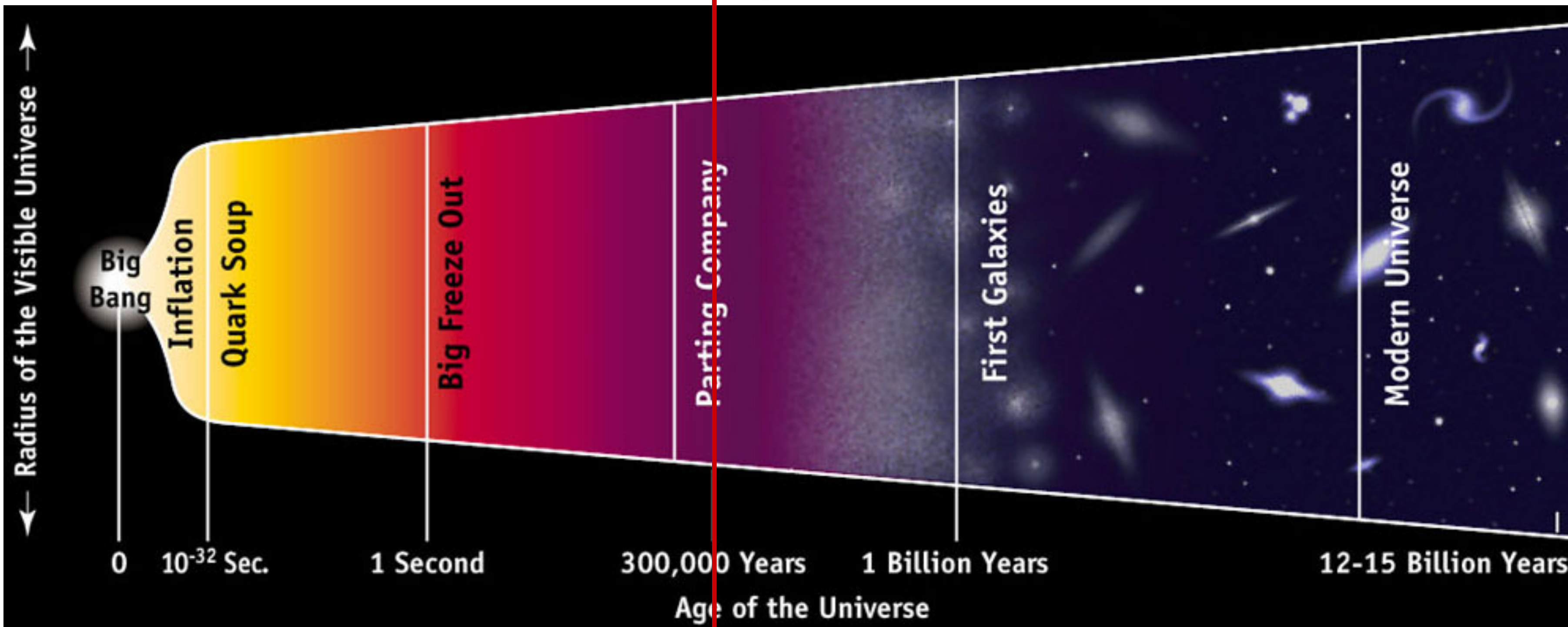
Particle thermalization in the early Universe

$\Gamma > H$ equilibium

$\Gamma \leq H$ out of equilibium



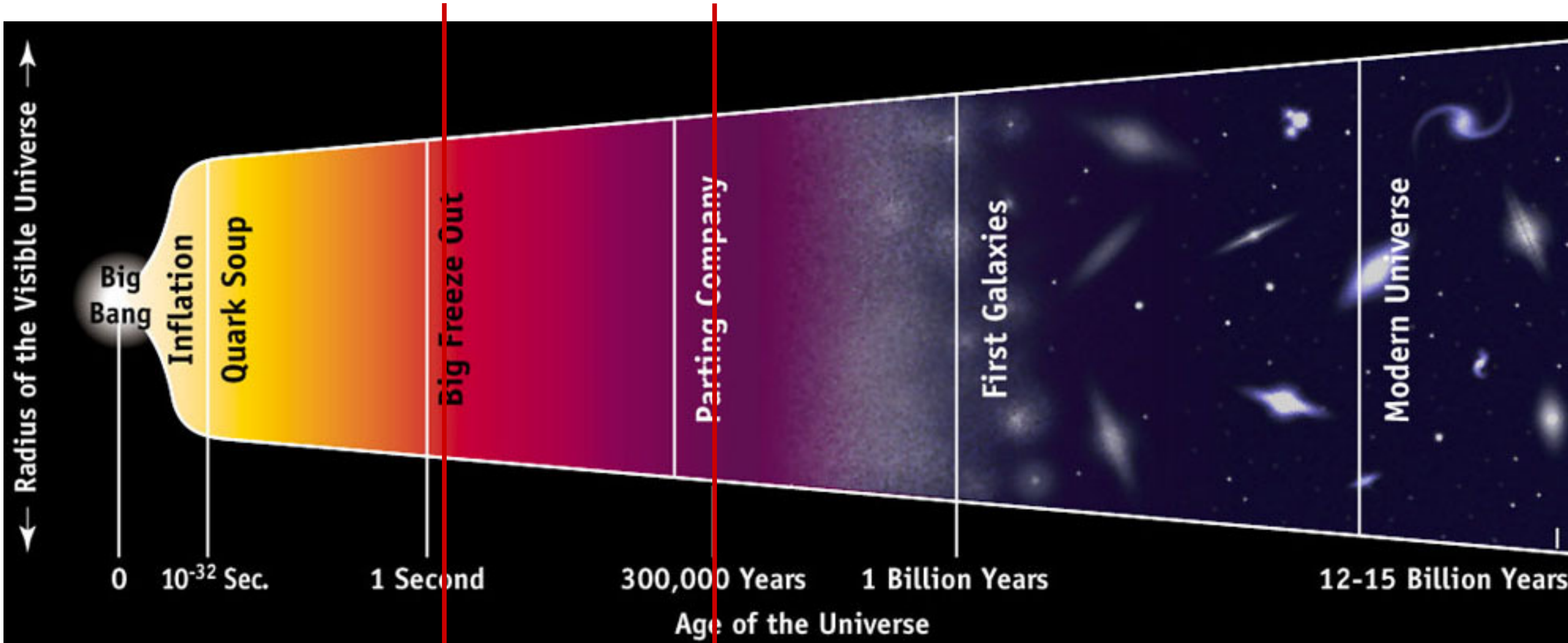
Thermal history of the Universe



Plasma phase

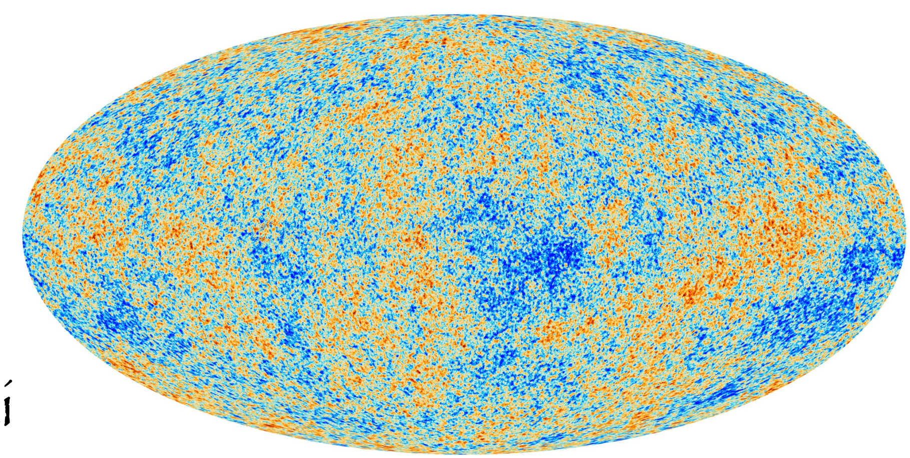
In this primordial phase, U. evolution is determined by particle interactions

In this phase, U. evolution is determined only by gravity



T 10^{16} GeV 1 MeV 0.23 eV

BBN CMBR



primordial H, D, ^{4}He, ^{7}Li

Detailed evolution of the particle

The detailed evolution of each species in the fluid is governed by the Boltzmann equation:

$$L[f_i] = C[f_i; f_j, f_k, ...]$$

Liouville operator   Collision operator

For the Friedmann U.

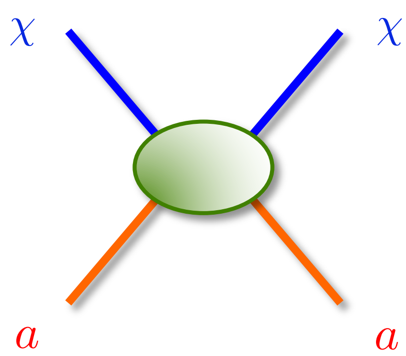
$$L[f_i] = E\frac{\partial f_i}{\partial t} - \frac{\dot{a}}{a}|\vec{p}|^2\frac{\partial f_i}{\partial E}$$

The collision operator contains the detailed information on all possible interactions of the *i* species with all other species in the plasma

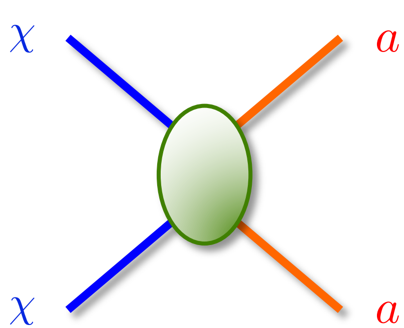
$$C[f_i; f_j, f_k, ...] = C_{\text{elastic}}[f_i; f_j, f_k, ...] + C_{\text{inelastic}}[f_i; f_j, f_k, ...]$$

Collision operator

$$C[f_i; f_j, f_k, ...] = C_{\text{elastic}}[f_i; f_j, f_k, ...] + C_{\text{inelastic}}[f_i; f_j, f_k, ...]$$



Elastic process — kinetic equilibrium



Inelastic process — chemical equilibrium

Both processes are able to modify the phase-space distribution $f_i(p,T)$

Elastic processes: do not modify the number density $n_i(T)$

Inelastic processe: do modify the number density $n_i(T)$

Boltzmann eq. for the number density

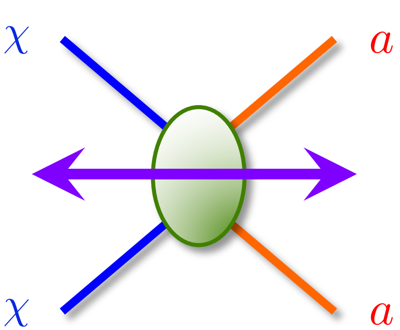
After integration over momenta (and some mathematical manipulation) a Boltzmann eq. for the number density can be cast in the form:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{\text{eq}}^2)$$

dilution due to expansion

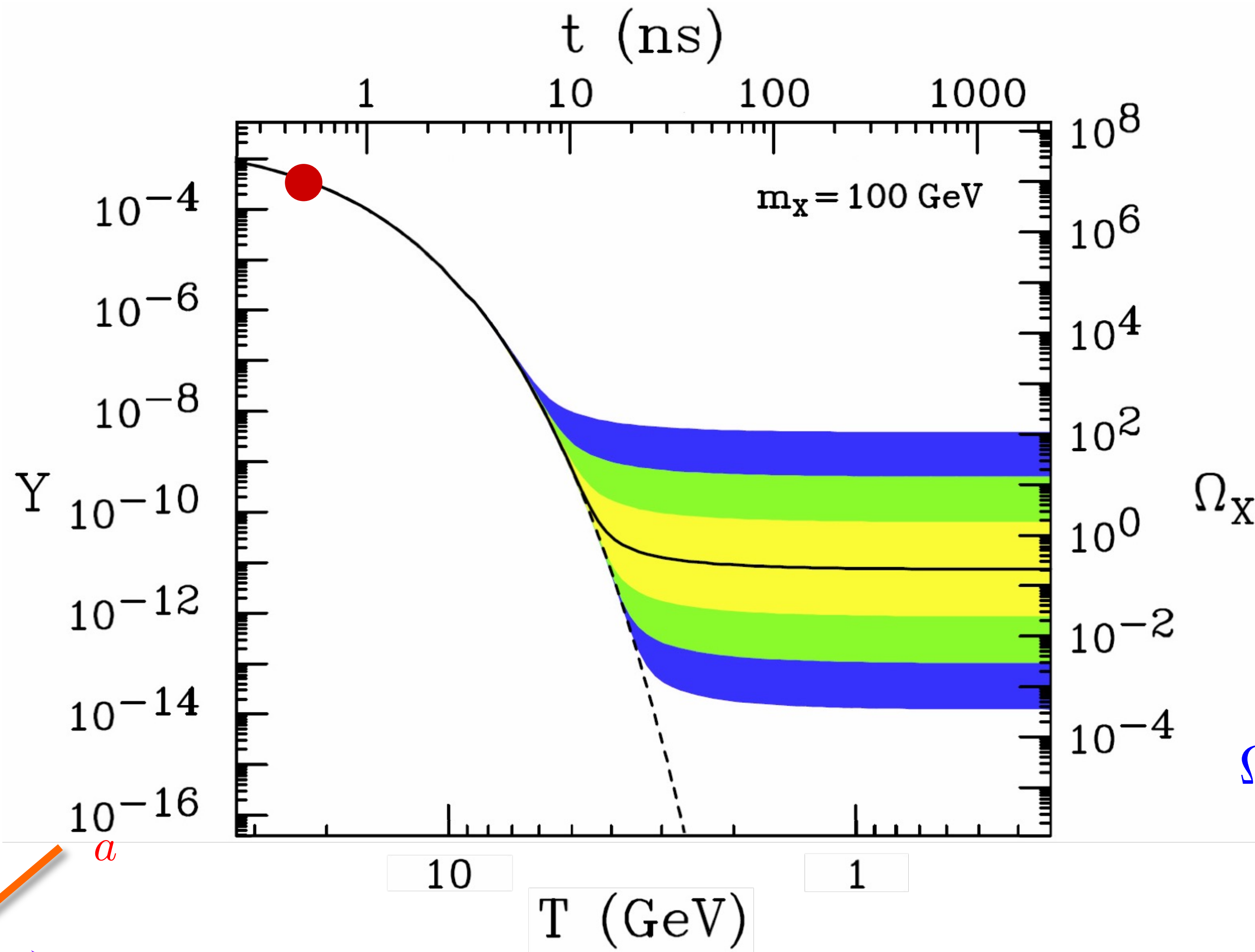
dilution due to annihilation

production due to inverse annihilation

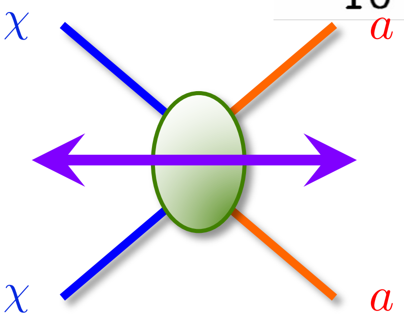


Abundance evolution

$Y = n/s$



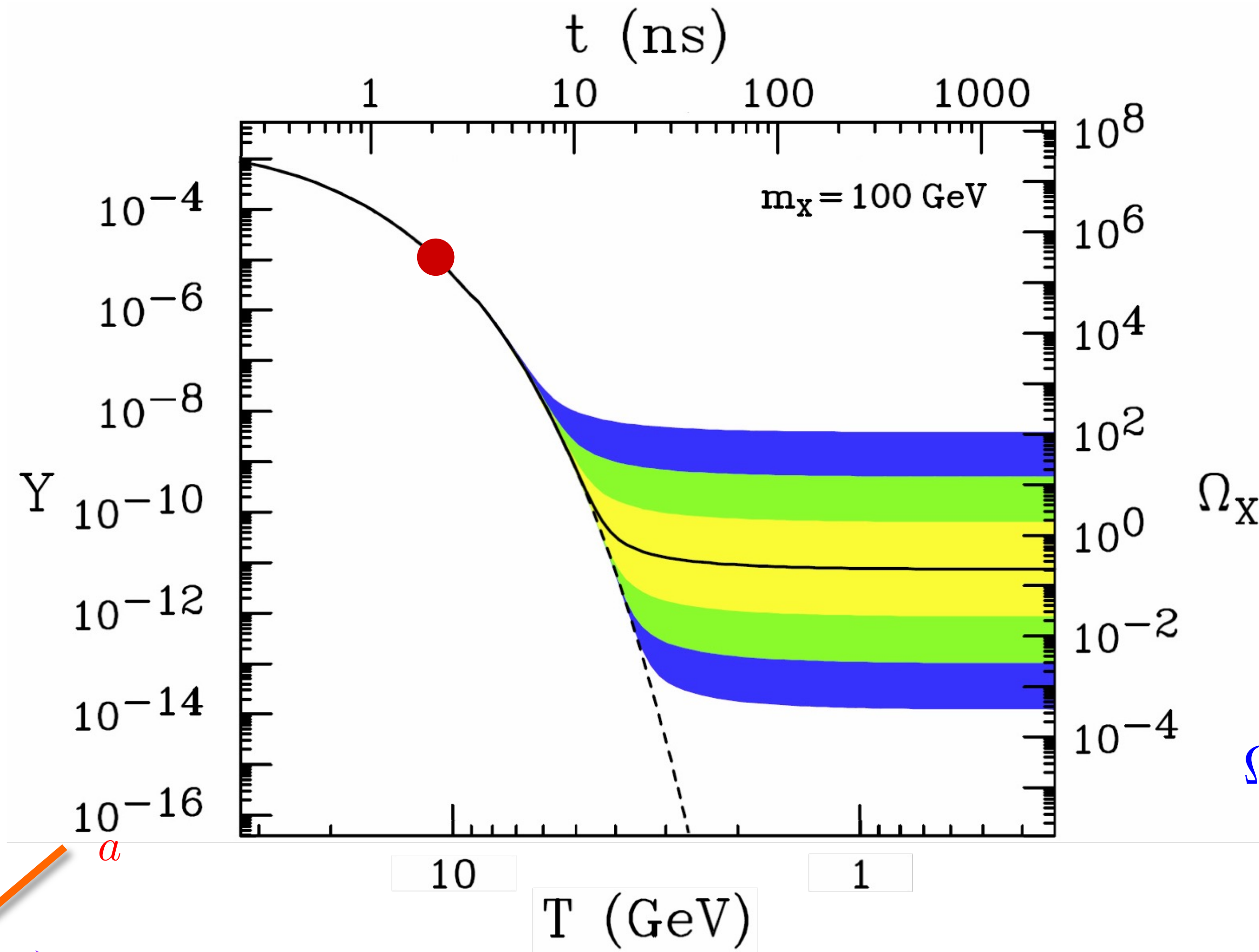
$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$



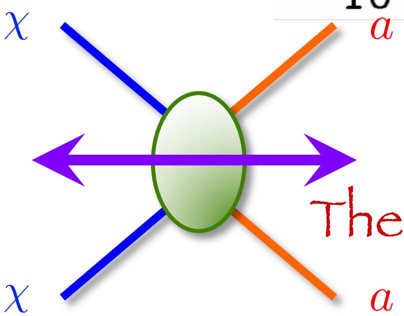
particle in equilibium

Abundance evolution

$Y = n/s$



$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

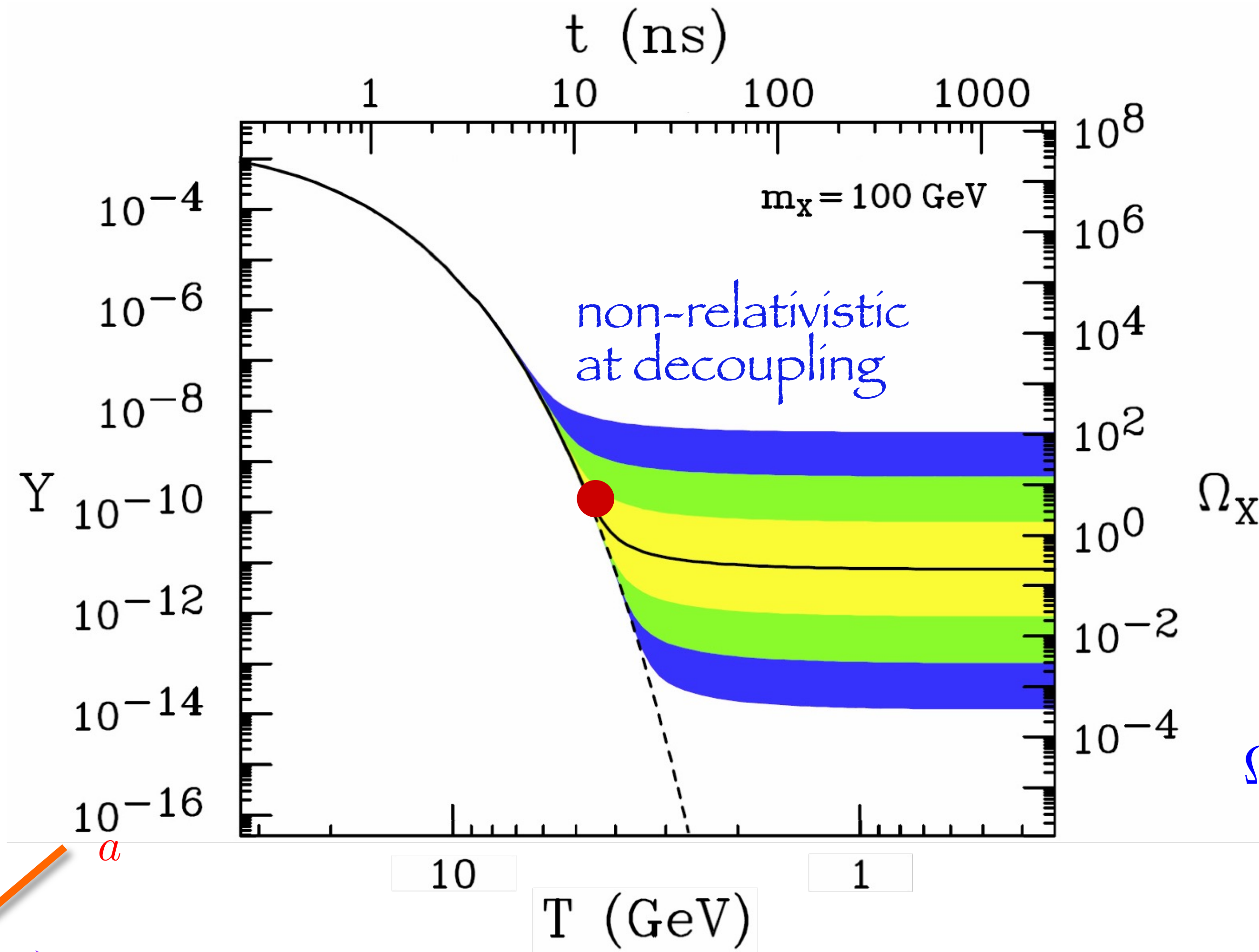


The universe cools down

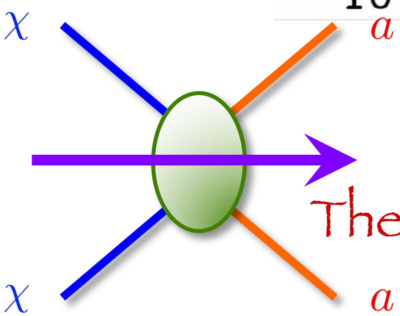
particle in equilibium

Abundance evolution

$Y = n/s$



$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

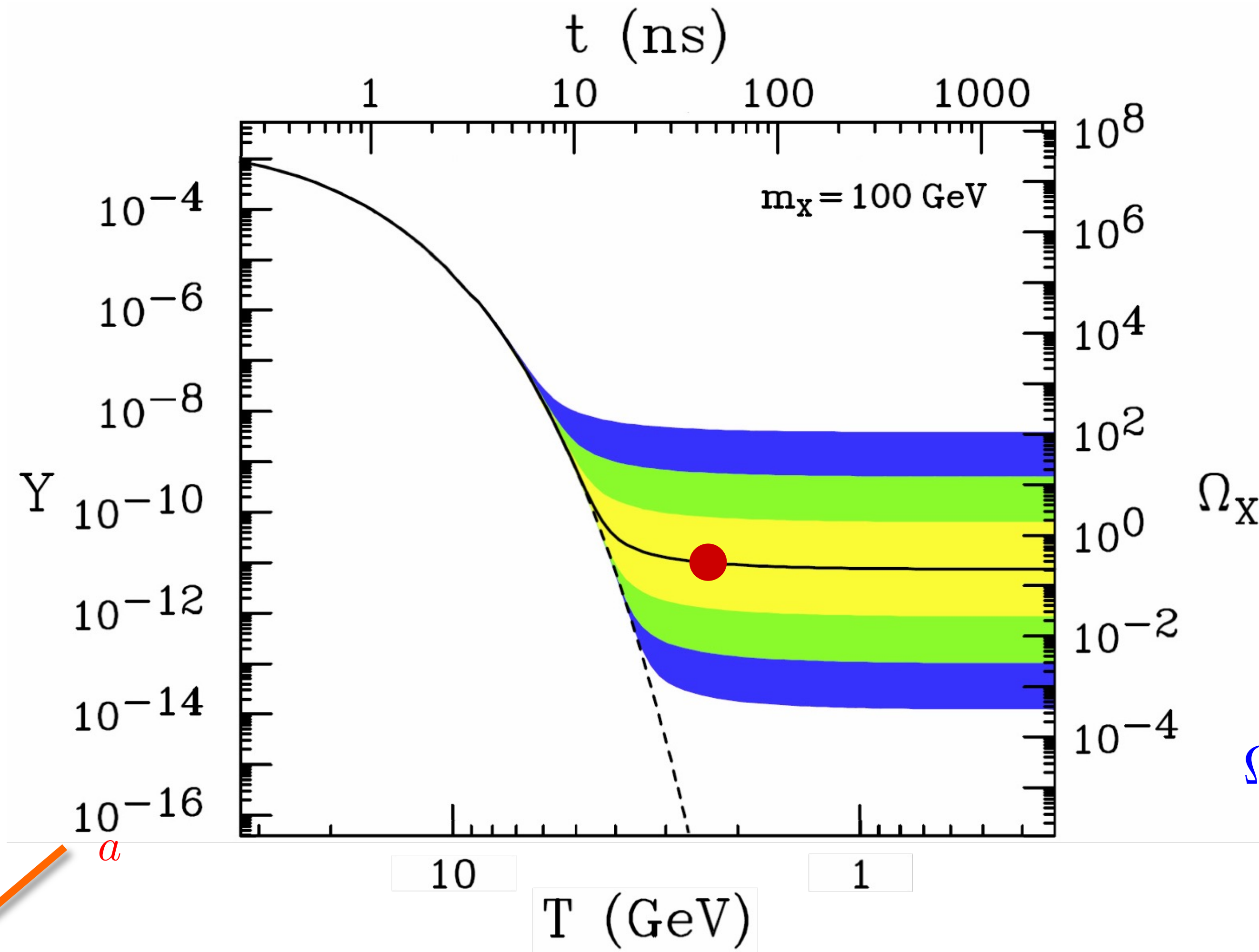


The universe cools down

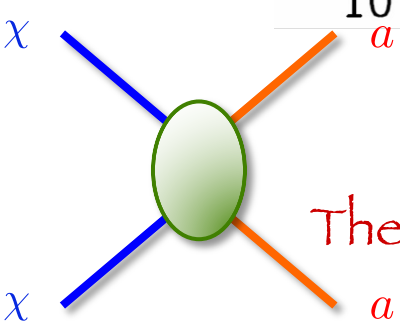
particle detaches from the plasma
“freeze-out” of its abundance

Abundance evolution

$Y = n/s$



$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

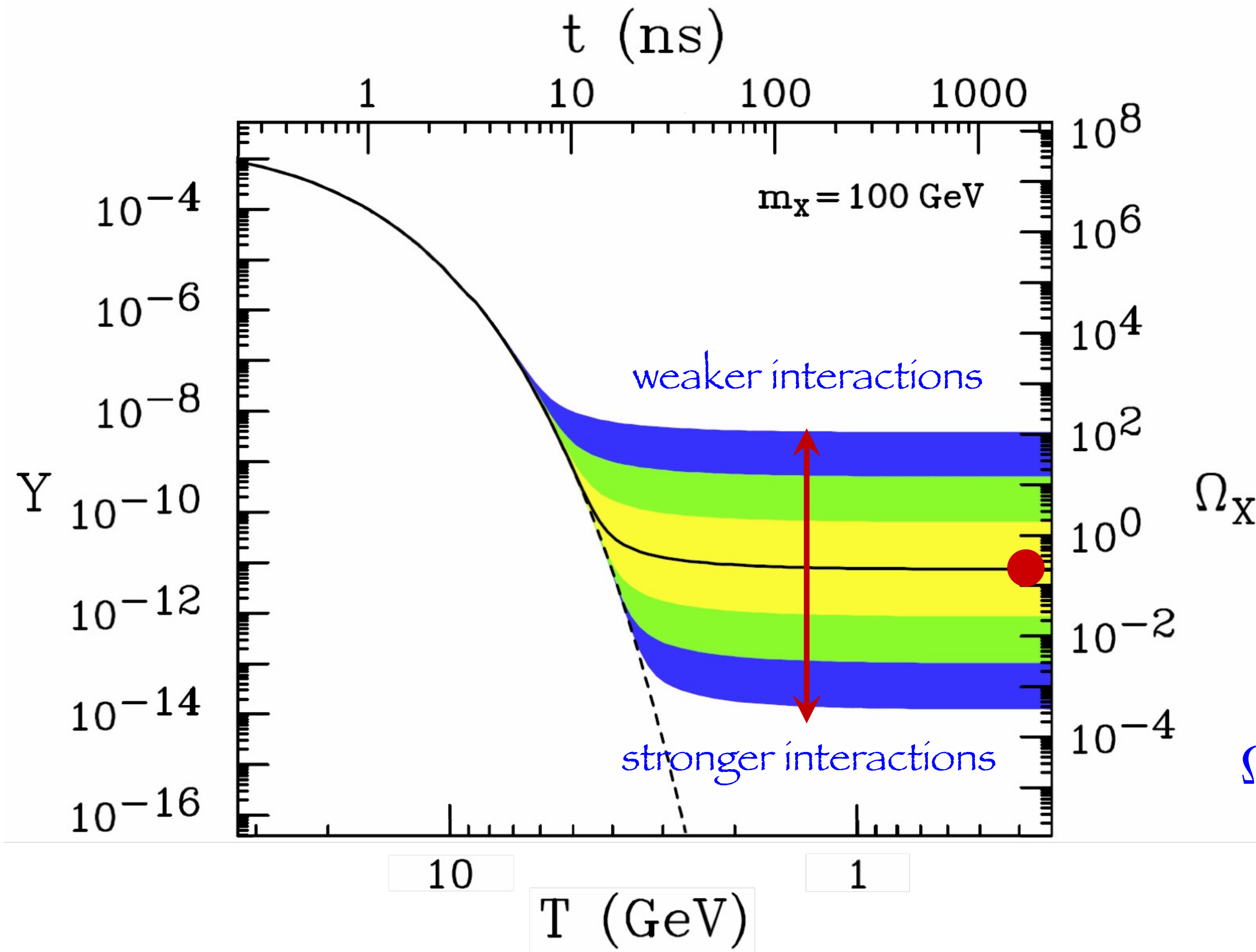


The universe cools down

particle detaches from the plasma
"freeze-out" of its abundance

Abundance evolution

$Y = n/s$



$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

The universe cools down

abundance today (relic)

Freeze-out mechanism

Freeze-out temperature

$$x_f = \ln[(0.246)(0.145)\, m_{DM}\, M_P\, g\, g_\star^{-1/2}(x_f) \langle \sigma_{\rm ann} v \rangle_{(x_f)}\, x_f^{-1/2}]$$

$$(x_f = m_{\rm DM}/T_f)$$

Relic abundance today

$$\Omega h^2 = 8.5 \cdot 10^{-11}\, \frac{g_\star^{1/2}(x_f)}{g_{\star S}(x_f)} \left(\frac{\rm GeV^{-2}}{\langle \sigma_{\rm ann} v \rangle_{\rm int}} \right)$$

The WIMP "miracle"

WIMP: Weakly Interacting Massive Particle

$$m_\chi \sim (\mathrm{GeV} \div \mathrm{TeV})$$

$$\langle \sigma_{\mathrm{ann}} v \rangle \sim (\xi G_F)^2 \, m_{\mathrm{DM}}^2 \qquad \sim 10^{-10} \xi^2 \left(\frac{m}{\mathrm{GeV}} \right)^2 \ \mathrm{GeV}^{-2}$$

weak type

$$\langle \sigma_{\mathrm{ann}} v \rangle \ \sim \ \frac{10^{-10}}{(\Omega h^2)_{\mathrm{CDM}}} \ \sim \ 10^{-9} \ \ \mathrm{GeV}^{-2}$$

naturally $\Omega_\chi h^2 \sim 0.1$

$x_f \sim (10 \div 30)$ cold relic

In more details

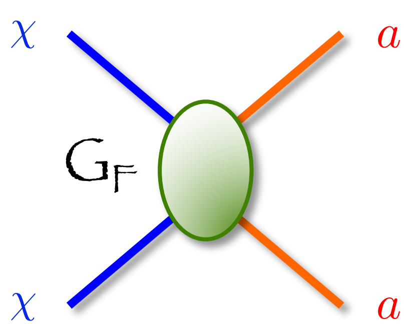
$m \ll m_Z$

$\langle \sigma_{\rm ann} v \rangle \sim G_F^2 m_{\rm DM}^2$

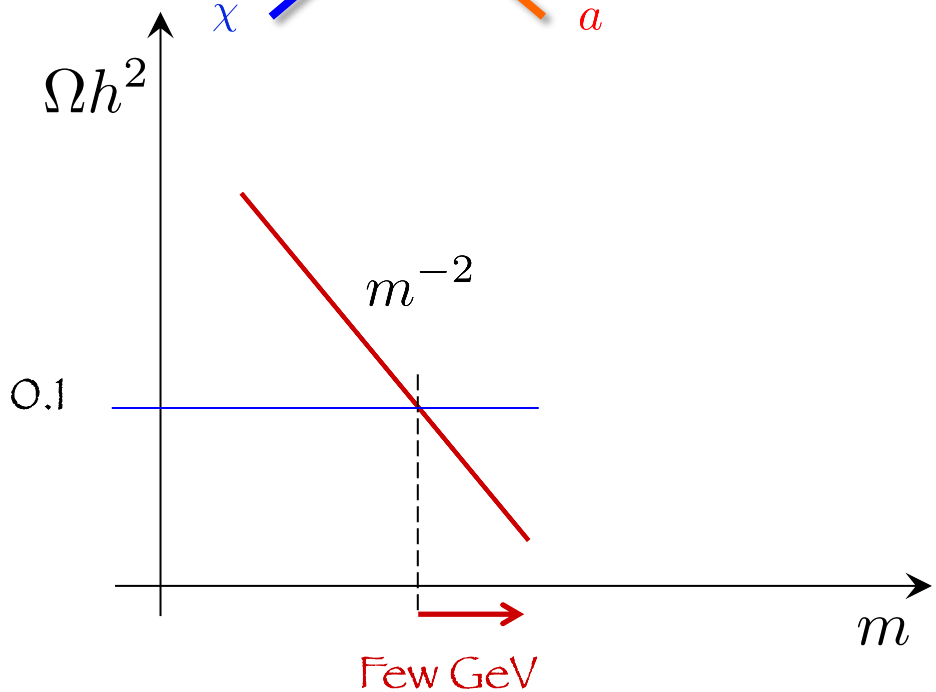
$s = q^2 \sim (2\, m_{\rm DM})^2$

non-relativistic

$\langle E \rangle \sim m_{\rm DM}$



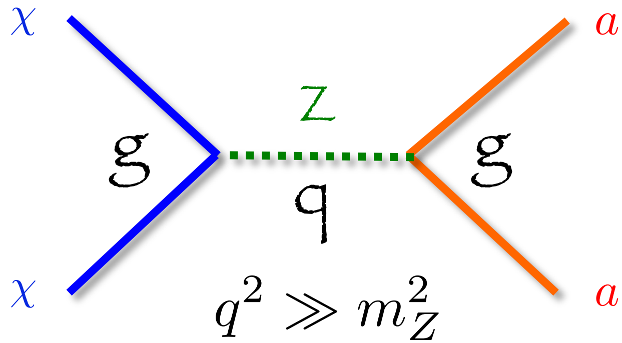
Fermi limit



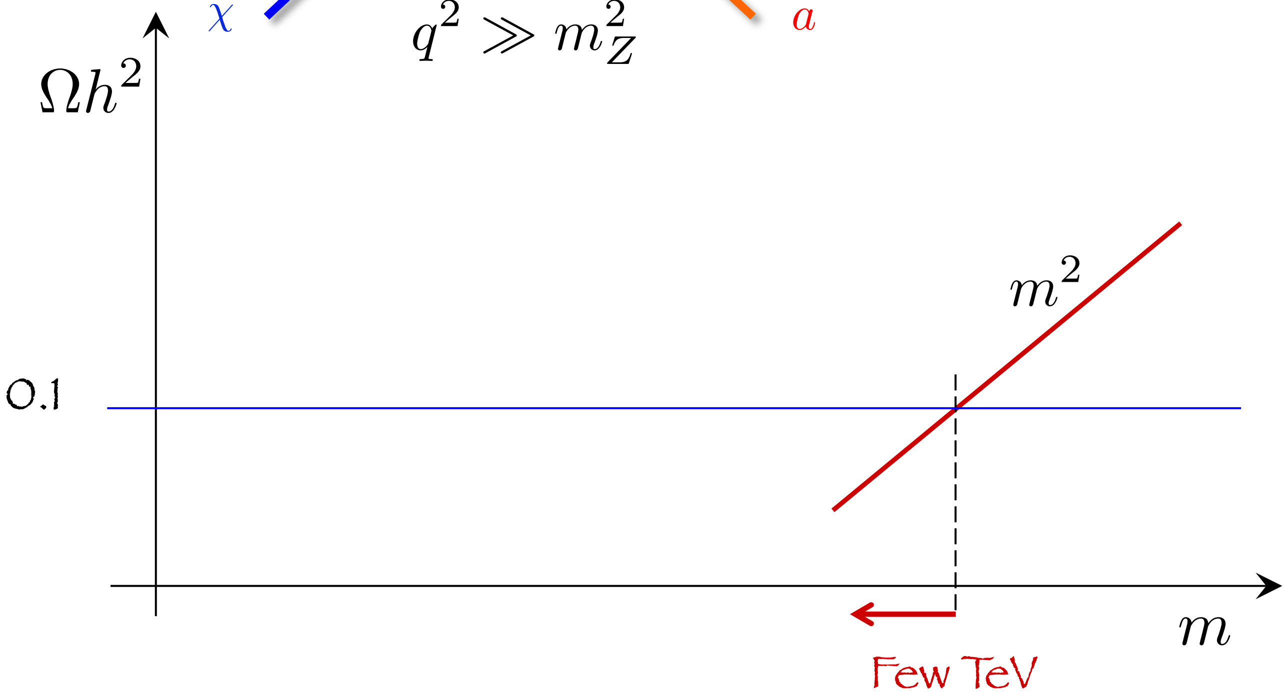
Lee-Weinberg bound

In more details

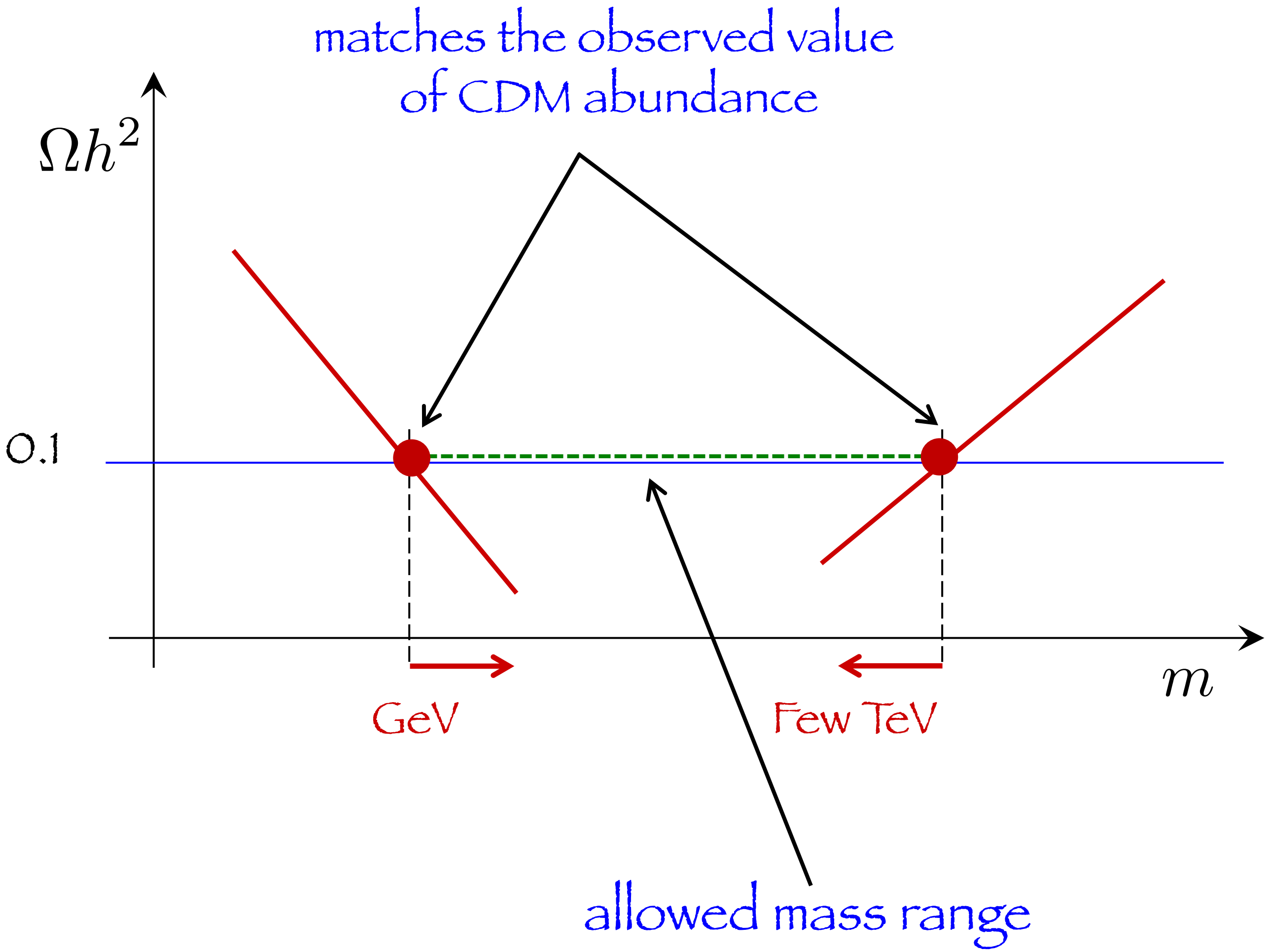
$$m \gg m_Z \qquad \langle \sigma_{\rm ann} v \rangle \sim \frac{g^4}{m_{\rm DM}^2} \qquad s = q^2 \sim (2\, m_{\rm DM})^2$$



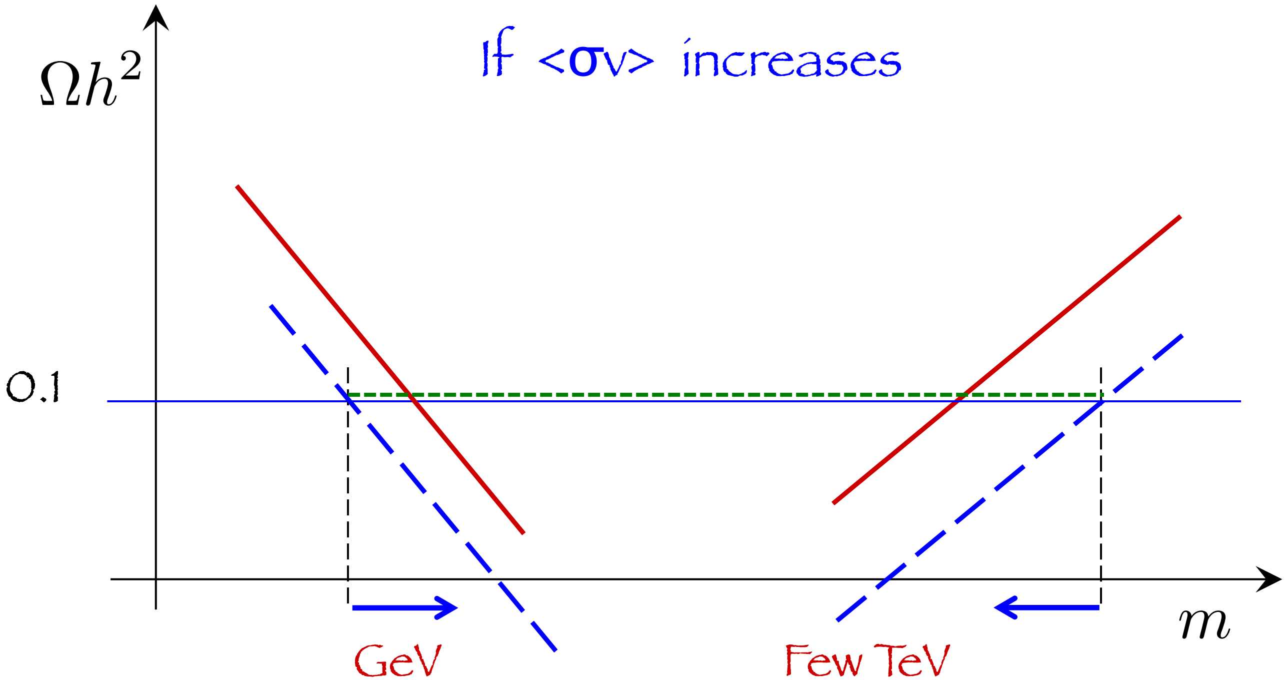
Effectively massless Z



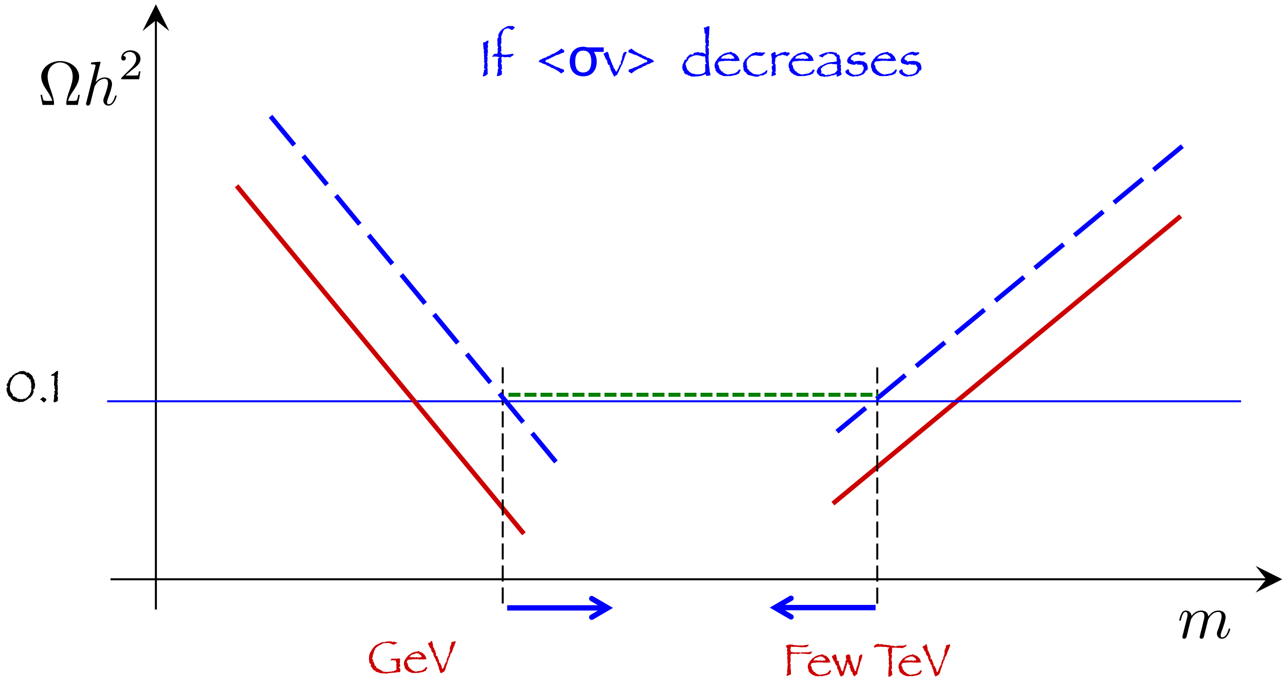
Summarizing



Dependencies



Dependencies



Additional features

Poles (Z, H, others) $m_{\rm DM} \sim m_Z/2\,,\, m_H/2$

Coannihilations $m_{\rm DM} \sim m_{\rm sligthly\ heavier\ state}$

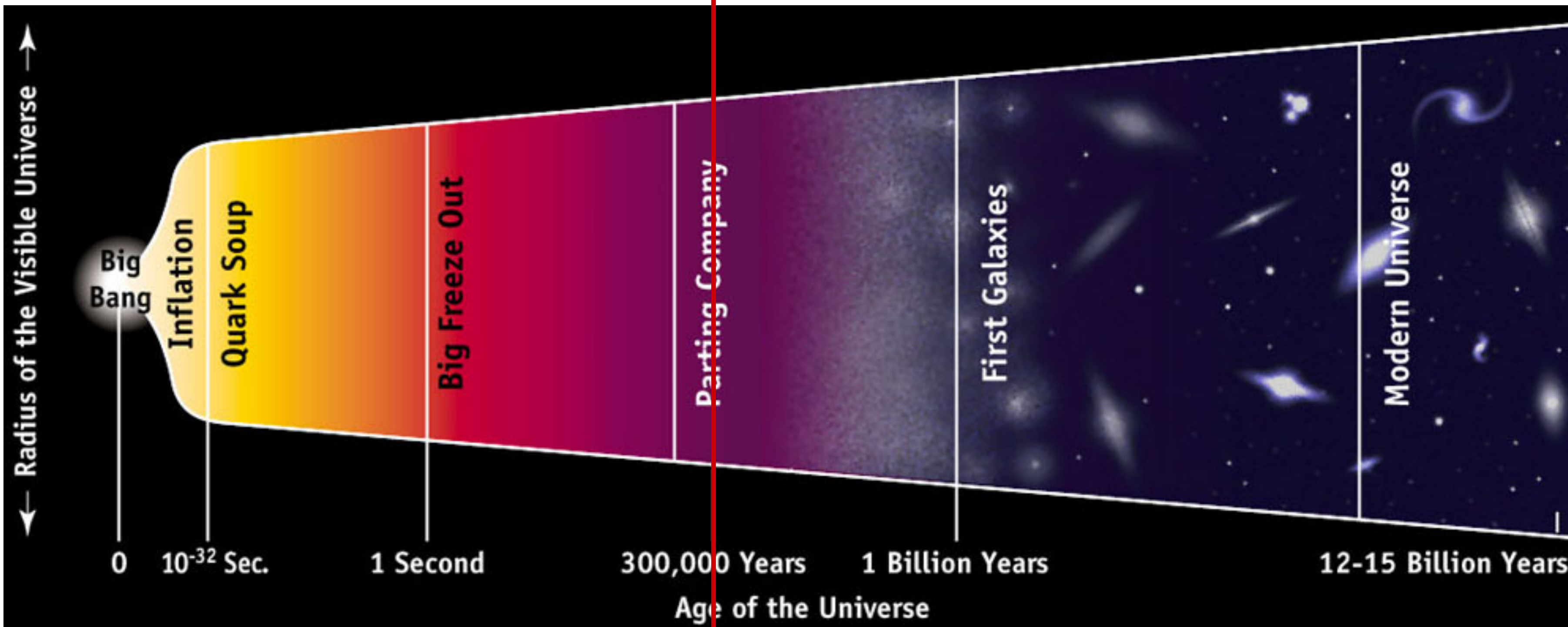
Sommerfeld enhancements light mediator

The WIMP "miracle"

Loosely speaking a WIMP with:

- Mass: sligthely sub-GeV to multi-TeV
- Interactions: weak type

can succesfully explain the observed abundance (and structure) of dark matter in the Universe



T | 10^{16} GeV | 1 MeV | 0.23 eV

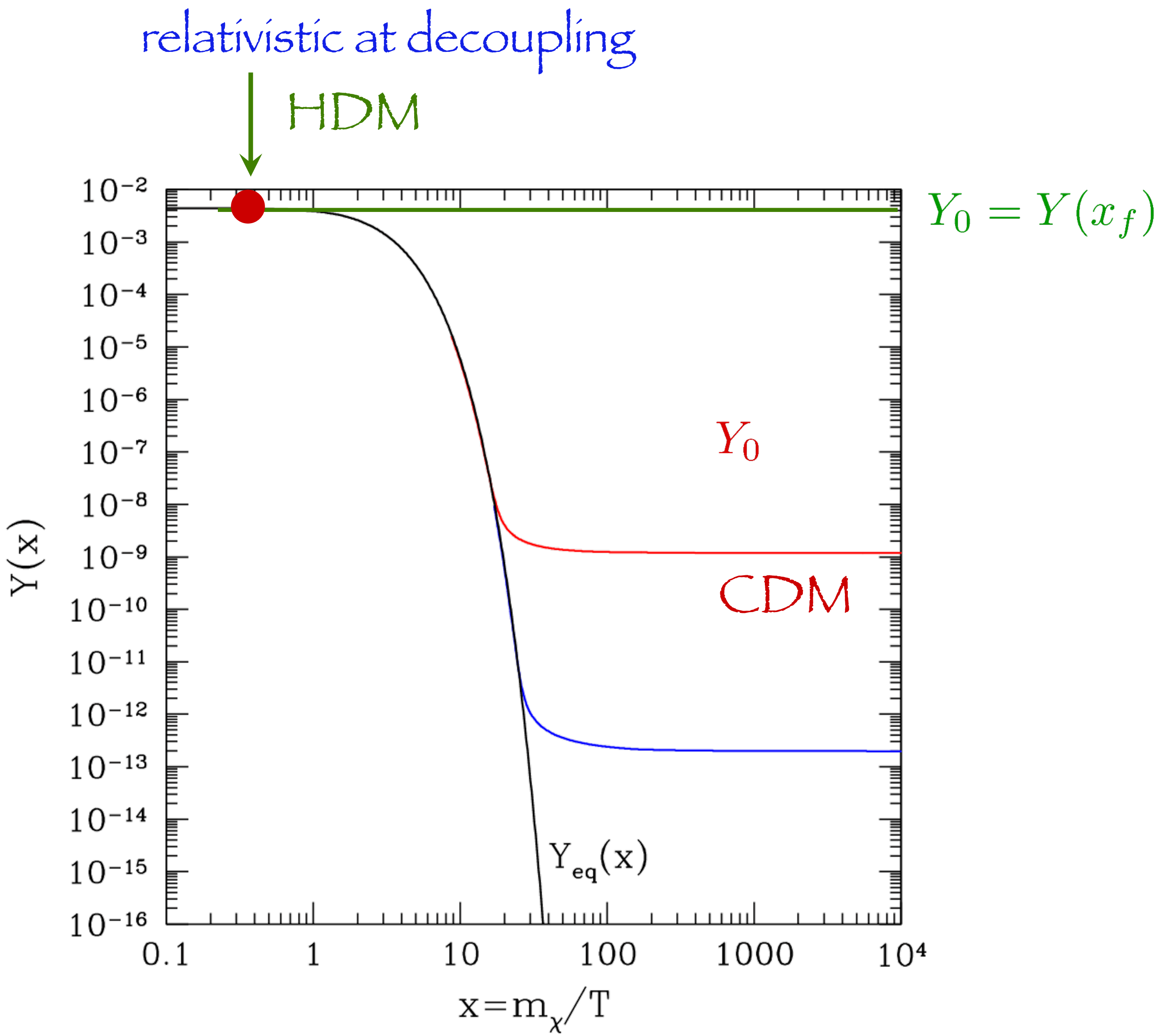
BBN

CMBR

CDM

T_{dec} of the order of 100 MeV – 100 GeV

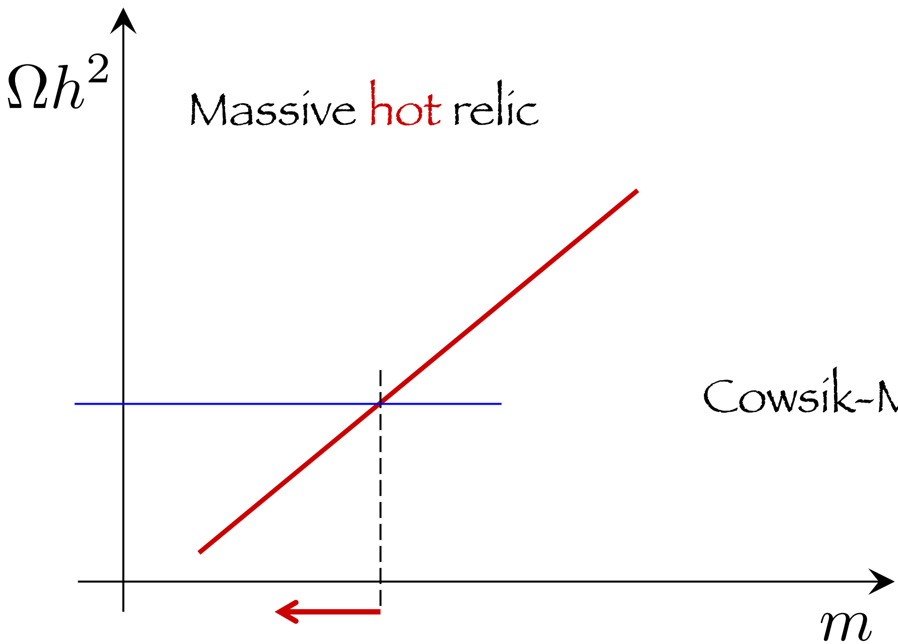
Light thermal relics



Light relics as HDM (e.g. neutrinos)

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93 \text{ eV}}$$

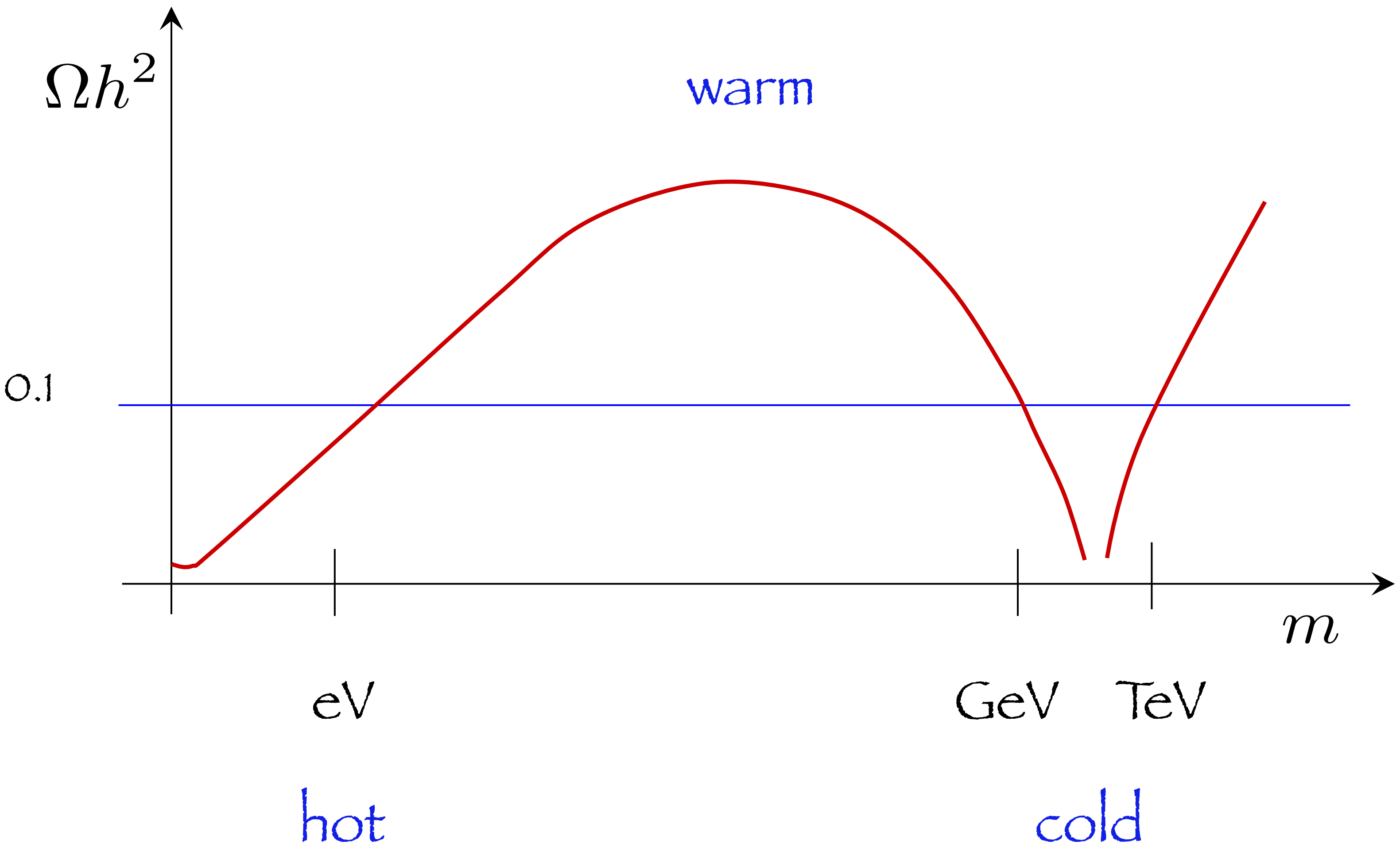
$$\Omega_\nu h^2 \leq (\Omega_{\rm DM} h^2) = 0.13 \longrightarrow \sum_i m_i \leq 12 \text{ eV}$$



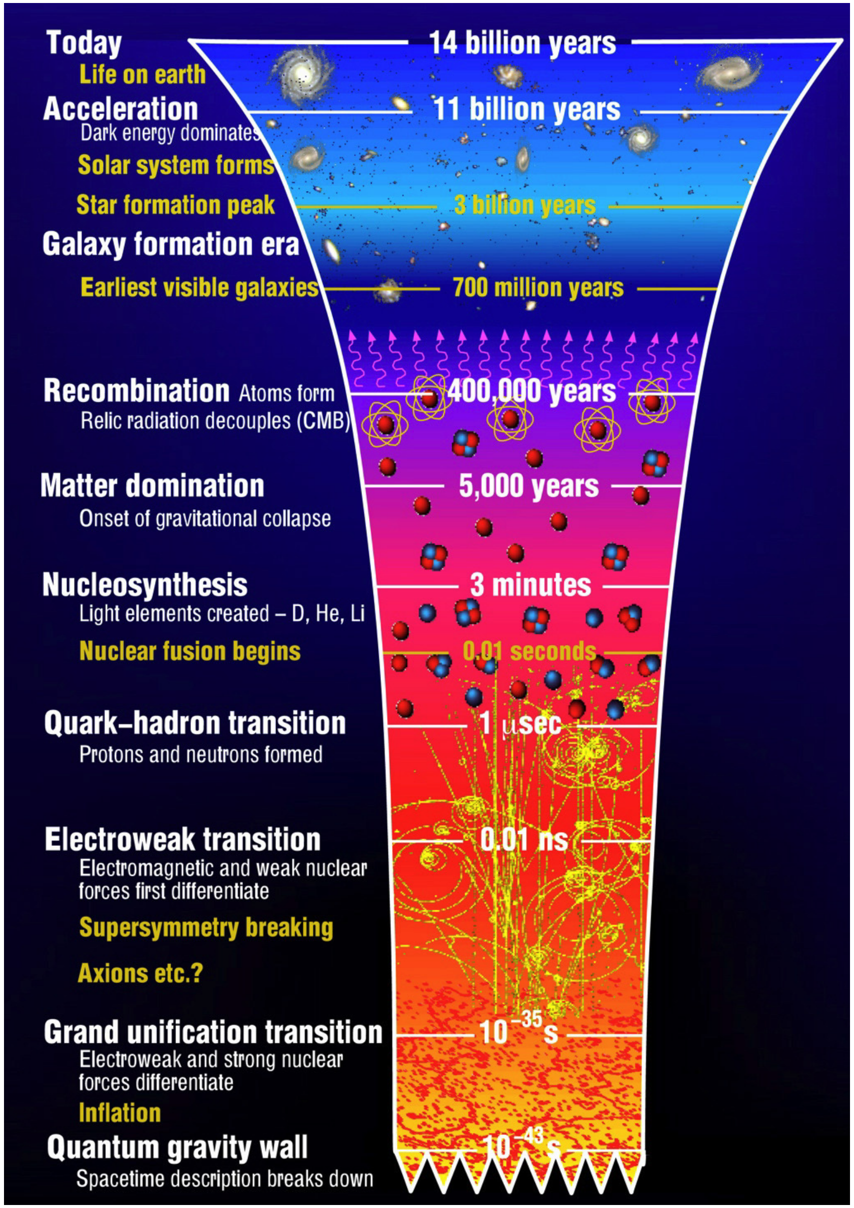
Cowsik-McClellan bound

Summary for a thermal relic

(with weak type interactions)



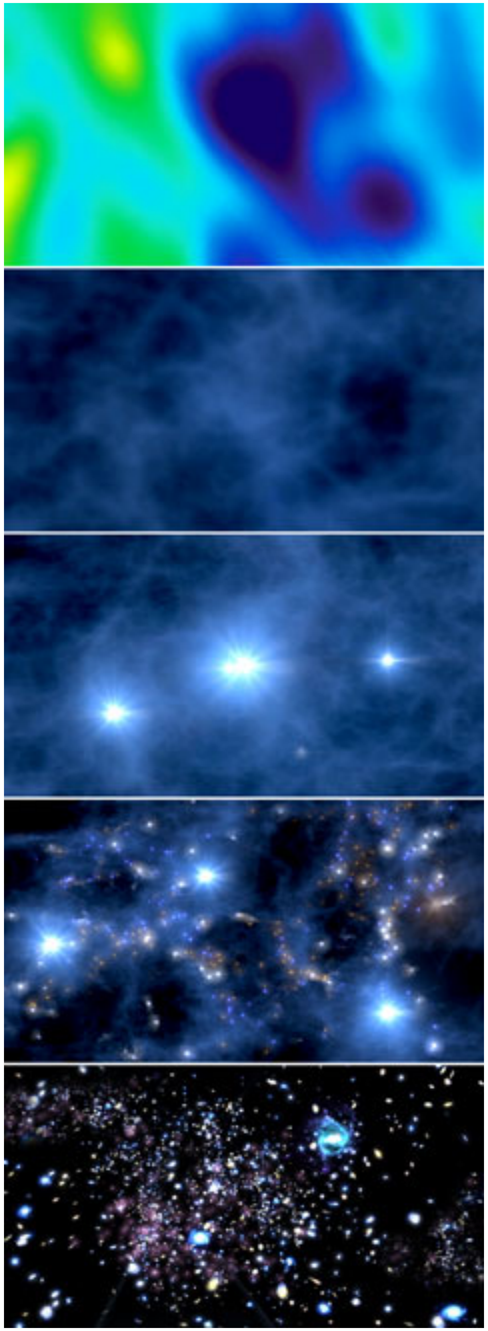
Early Universe



Gravity Phase

Plasma phase

Particle can be thermally excited

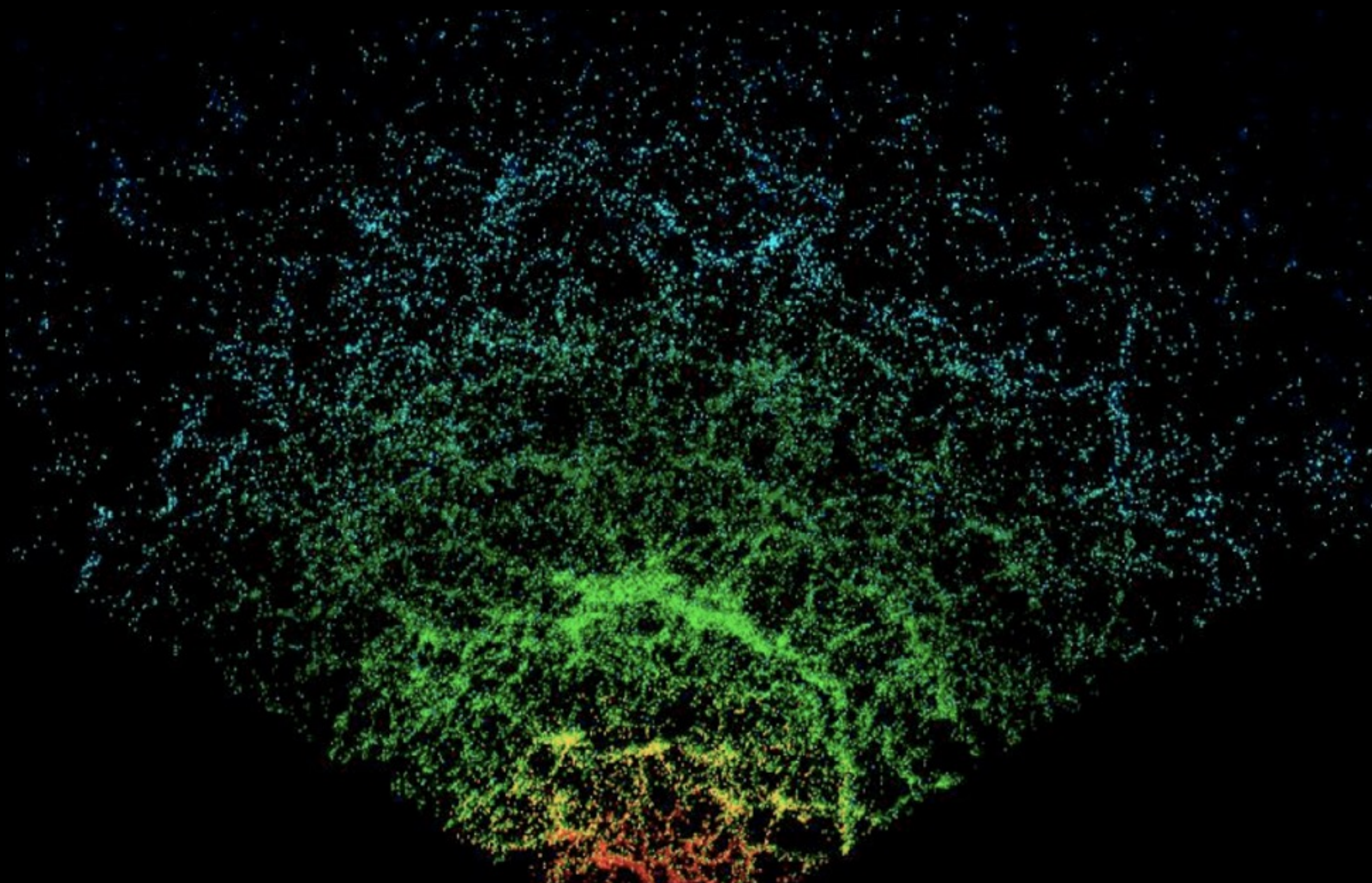


Primordial fluctutaion at CMB

Growth of perturbation by Gravitational instabilities

Dark matter acts as Key element (and is required to be effectively cold)

Structure formation (galaxies, clusters, filaments, voids)



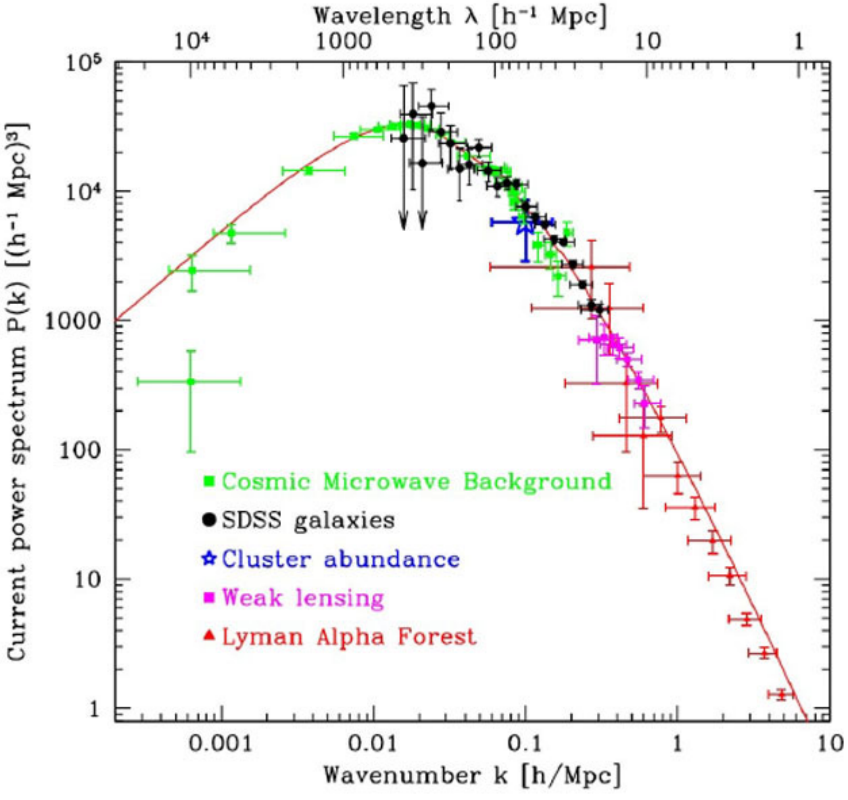
Why cold? Power Spectrum

Describes the density contrast of the Universe as a function of scale

large scales: linear

small scales: non-linear

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$



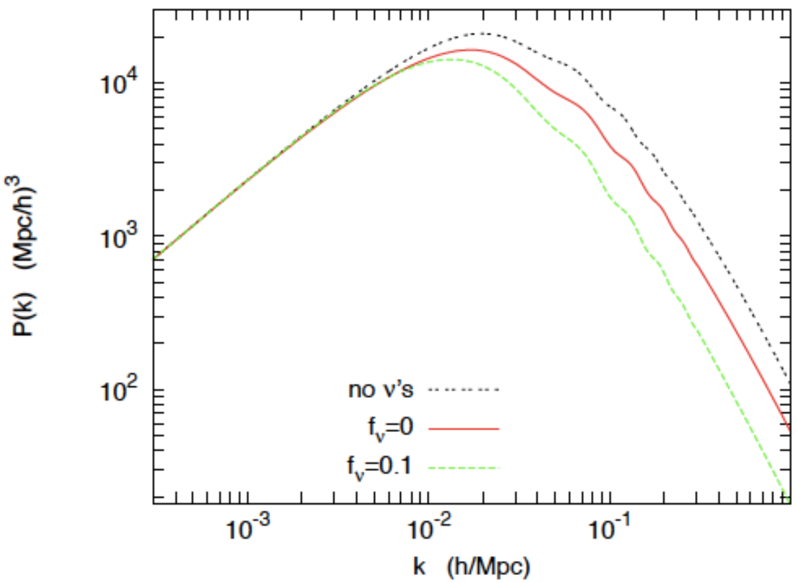
Fourier Transform

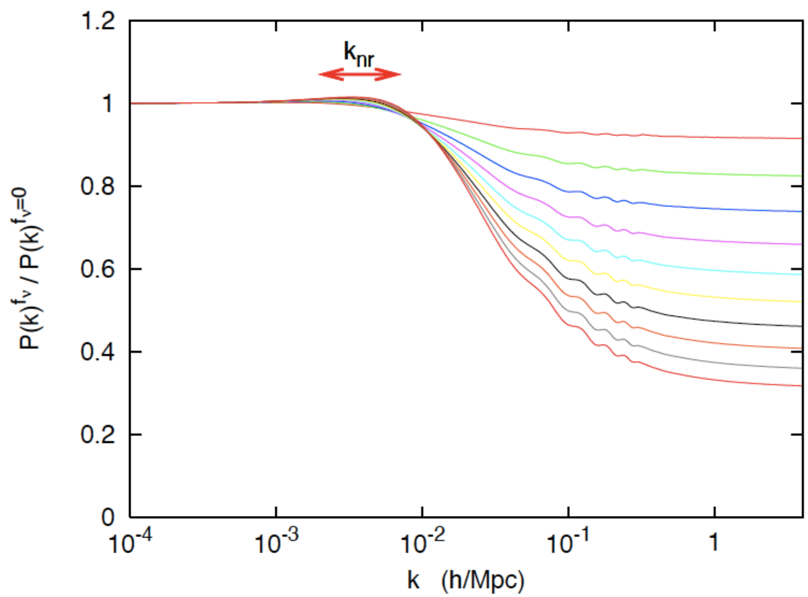
$$\langle \delta(\vec{k})\delta(\vec{k}') \rangle = (2\pi)^3 \delta^3(\vec{k} - \vec{k}')\, P(k)$$

Measures the variance of the density contrast

Neutrinos as HDM

HDM: erases density contrast (structure) on scales smaller than the free-streming cale





Dominat HDM is in contradiction with observations (SDSS, 2dF)
Neutrinos may contribute, but only subdominantly

CMB+SDSS+2dF	$\sum_i m_i \leq (0.9 \div 1.7)$ eV	$\Omega h^2 \leq (0.0097 \div 0.018)$
Atm. neutrinos	$\sqrt{\Delta m_{13}^2} = 0.047$ eV	$\Omega h^2 \geq 0.0005$

Succesfull DM candidate - Recap

- Needs to be produced in the early Universe
- Needs to be "cold" (or, at least, "warm" enough)
  - For thermal production: weakly interacting and massive (WIMP)

$$\Omega h^2 \sim \langle \sigma v \rangle_{\rm ann}^{-1} \longrightarrow \langle \sigma v \rangle_{\rm ann} = 3 \cdot 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

unless coannihilation occurs

  - If light, it nevertheless needs to act as "cold"
- Needs to be neutral
- Needs to be stable (or, if it decays, it needs a lifetime larger than the age of the Universe)

Alternative mechanisms

The standard paradigm for WIMP CDM is a thermal symmetric relic (i.e. particle and antiparticles have the same number density)

Partial thermaliztion

- Freeze-in, E-WIMP, FIMPs

Asymmetry between particle/antiparticle

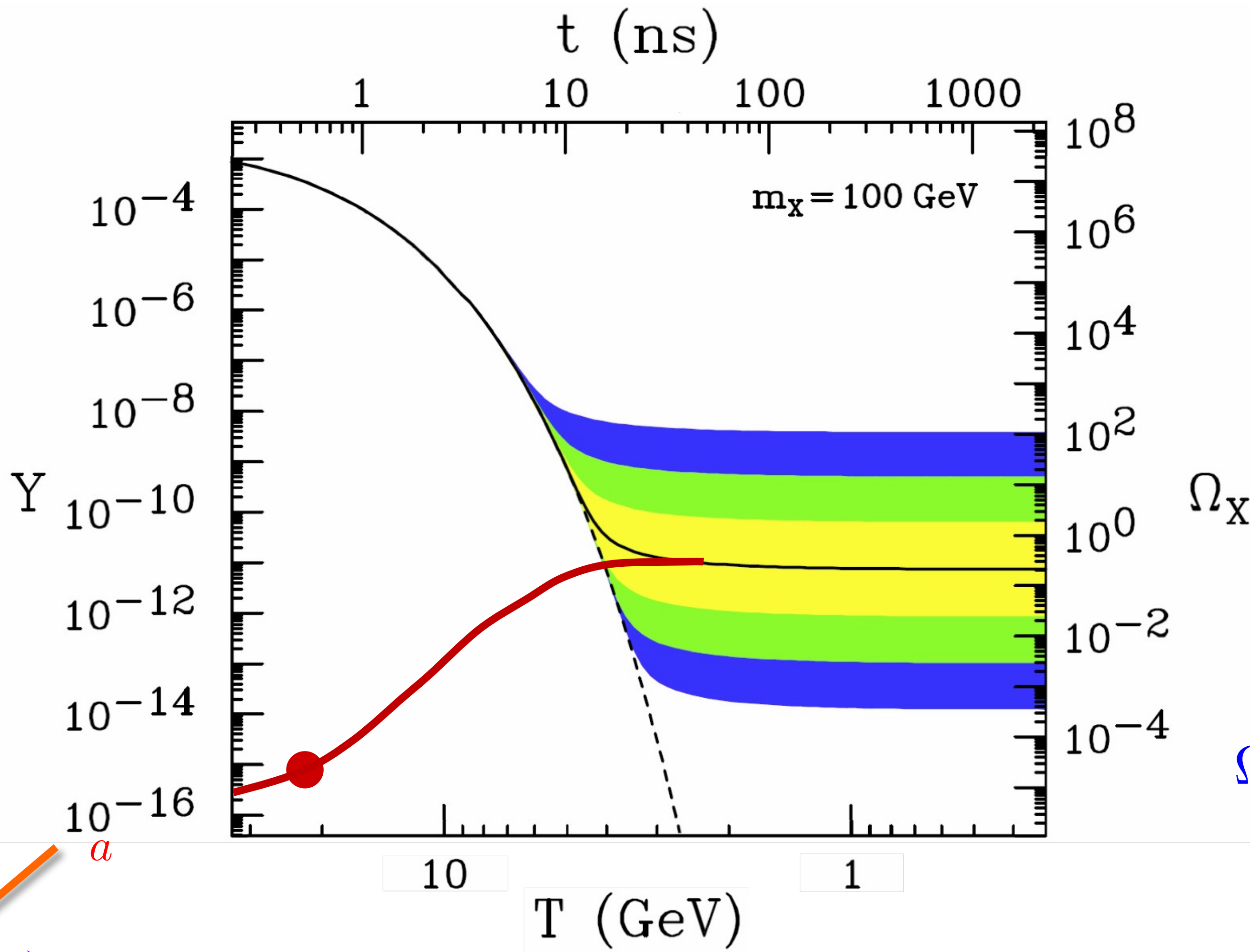
- The relic abundance is set by the asymmetry, not thermal freeze-out
- This may link DM abundance to baryon asymmetry

Non-thermal production

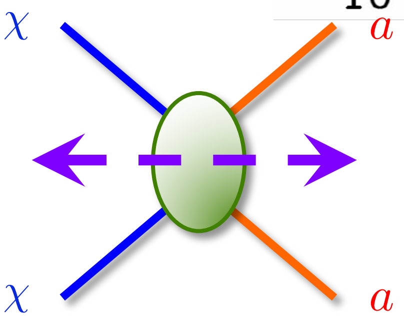
- DM produced by the decay of a heavier particle
- Peculiar cosmological dynamics (e.g.: misalignment for axions)
- Oscillations from "friendly" states (e.g. sterile neutrinos)

Freeze-in mechanism

$Y = n/s$



$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$

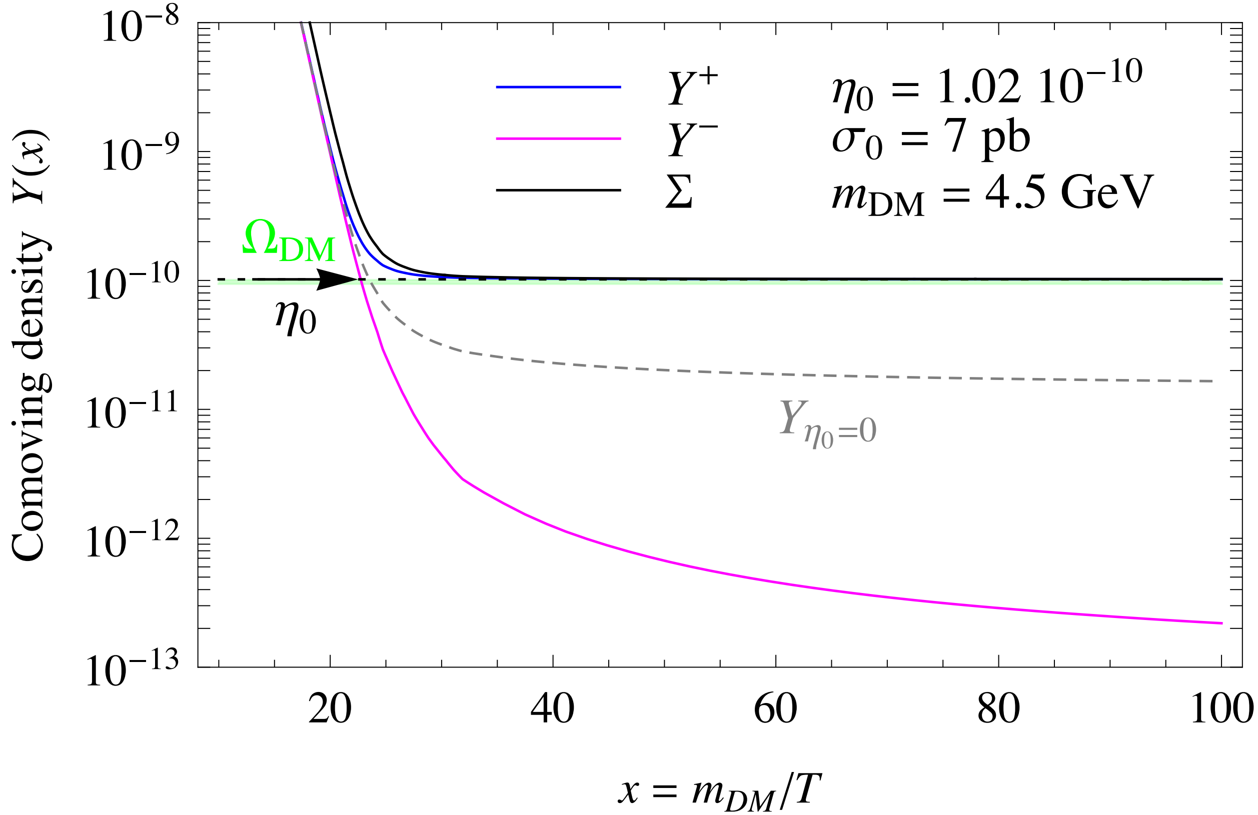


particle never in full equilibium

Asymmetric DM

Asymmetry can arise because of:

- Initial conditions (quite fine tuned)
- Sakharov conditions (like for baryo/lepto genesis; maybe related to them ?)



Asymmetric DM

$n_\chi \neq n_{\bar\chi}$ $\Omega h^2 \sim |n_\chi - n_{\bar\chi}|\, m_\chi$

Example: $\frac{\Omega_\chi}{\Omega_b} \sim 5$

$|n_\chi - n_{\bar\chi}| \sim (n_b - n_{\bar b}) \sim n_b$ (baryon asymmetry)

$\frac{\Omega_\chi}{\Omega_b} = \frac{|n_\chi - n_{\bar\chi}| m_\chi}{n_b m_N} \sim k \frac{m_\chi}{m_N}$ model dependen link (DM,B) needed

If $k \sim 1$: $m_\chi \sim 5\, m_N \sim 5$ GeV

Asymmetry may occur also without a link between DM and B

From decay

N $\rightarrow$ X + (...)   N heavier that X

Example: N can reach thermal equilibrium
Then freezes-out an abundance
Then decays out of equilibrium

$$n_N \longrightarrow n_\chi$$

$$\rho_\chi = m_\chi n_\chi = m_\chi \frac{\rho_N}{m_N}$$

$$\Omega_\chi = \frac{m_\chi}{m_N} \Omega_N$$

(depends on $\langle\sigma_N v\rangle$)

From oscillations

ν_S sterile neutrino

Needs to be very weakly mixed

$\sin^2(2\theta) \sim 10^{-11} - 10^{-12}$

$m_{\nu S} \sim 10$ KeV

Particle DM and Physics beyond the Standard Model

Standard Model

Normal particles/fields	
Symbol	Name
$q = d, c, b, u, s, t$	quark
$l = e, \mu, \tau$	lepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino
g	gluon
$W^\pm$	W-boson
B	B-field
W^3	W^3-field
H^0	Higgs boson

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

No viable DM candidate present !

DM strength of interactions

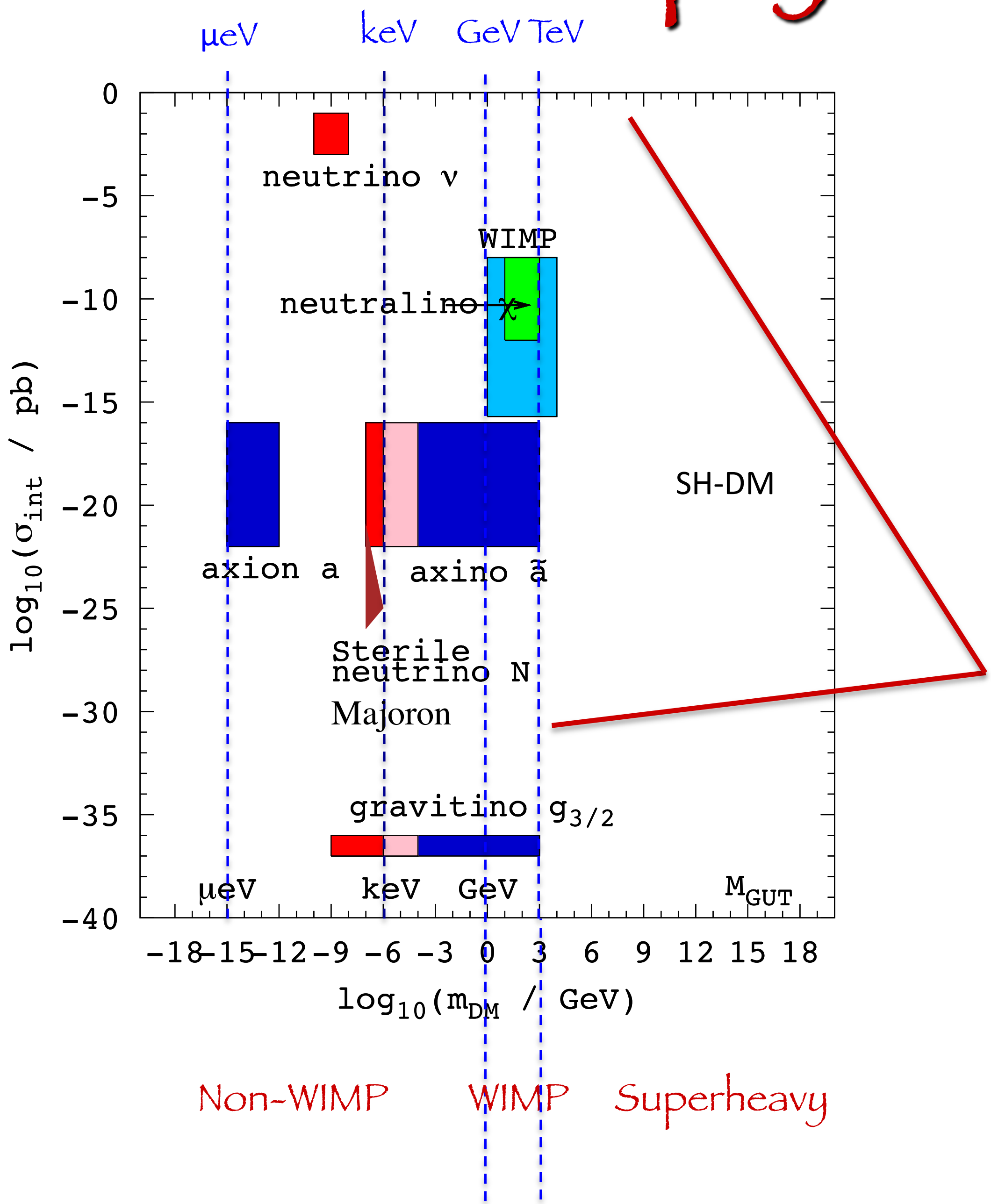
- Weak
  - Light (standard) neutrinos, (heavier) RH neutrinos (…)
  - Weakly Interacting Massive Particles (WIMPs) paradigm for thermal CDM
  - (…)
- Strong-type
  - Mirror DM
  - Technicolor DM
  - (…)
- Gravitational-type
  - Gravitino
  - (…)
- Electromagnetic
  - Open window if $100(q_X/e)^2 < m_X < 10^8(q_X/e)$ TeV ?

DM stability (or significantly long-lived)

- Accidental/automatic/just-so stability
  - Neutrino
  - Minimal DM
  - Axion
  - (…)

- Discrete symmetry imposed
  - R- parity: supersymmetric models
  - KK-parity: extra-dimensional models
  - T-parity: "little-higgs" models
  - Z_2-simmetry: inert doublet models, (…)
  - (…)

Particle physics scales



"Strong (-ish)"

- Self-interacting
- Technicolor DM
- …

"EM (-ish)"

- Millicharged DM
- Electric/magnetic dipole
- …

Weak

- WIMP

Gravitational

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Standard Model

Normal particles/fields	
Symbol	Name
$q = d, c, b, u, s, t$	quark
$l = e, \mu, \tau$	lepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino
g	gluon
$W^\pm$	W-boson
B	B-field
W^3	W^3-field
H^0	Higgs boson

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

No viable DM candidate present !

SUSY extension of the Standard Model

SUPERSYMMETRY: FERMION $\longleftrightarrow$ BOSON

Normal particles/fields			Supersymmetric partners			
			Interaction eigenstates		Mass eigenstates	
Symbol		Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$		quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$		lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$		neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g		gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$		W-boson	$\tilde{W}^\pm$	wino		
H^-		Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^+		Higgs boson	$\tilde{H}_2^+$	higgsino		
B		B-field	$\tilde{B}$	bino		
W^3		W^3-field	$\tilde{W}^3$	wino		
h: H_1^0	scalar	Higgs boson			$\tilde{\chi}^0_{1,2,3,4}$	neutralino
H: H_2^0	scalar	Higgs boson	$\tilde{H}_1^0$	higgsino		
A: H_3^0	pseudoscalar	Higgs boson	$\tilde{H}_2^0$	higgsino		

2 Higgs doublets

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

SUSY extension of the Standard Model

Normal particles/fields			Supersymmetric partners			
			Interaction eigenstates		Mass eigenstates	
Symbol		Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$		quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$		lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$		neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g		gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$		W-boson	$\tilde{W}^\pm$	wino		
H^-		Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}_{1,2}^\pm$	chargino
H^+		Higgs boson	$\tilde{H}_2^+$	higgsino		
B		B-field	$\tilde{B}$	bino		
W^3		W^3-field	$\tilde{W}^3$	wino		
h H_1^0	scalar	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H H_2^0	scalar	Higgs boson	$\tilde{H}_1^0$	higgsino		
A H_3^0	pseudoscalar	Higgs boson	$\tilde{H}_2^0$	higgsino		

Neutral particles: sneutrinos, neutralinos [gravitinos]

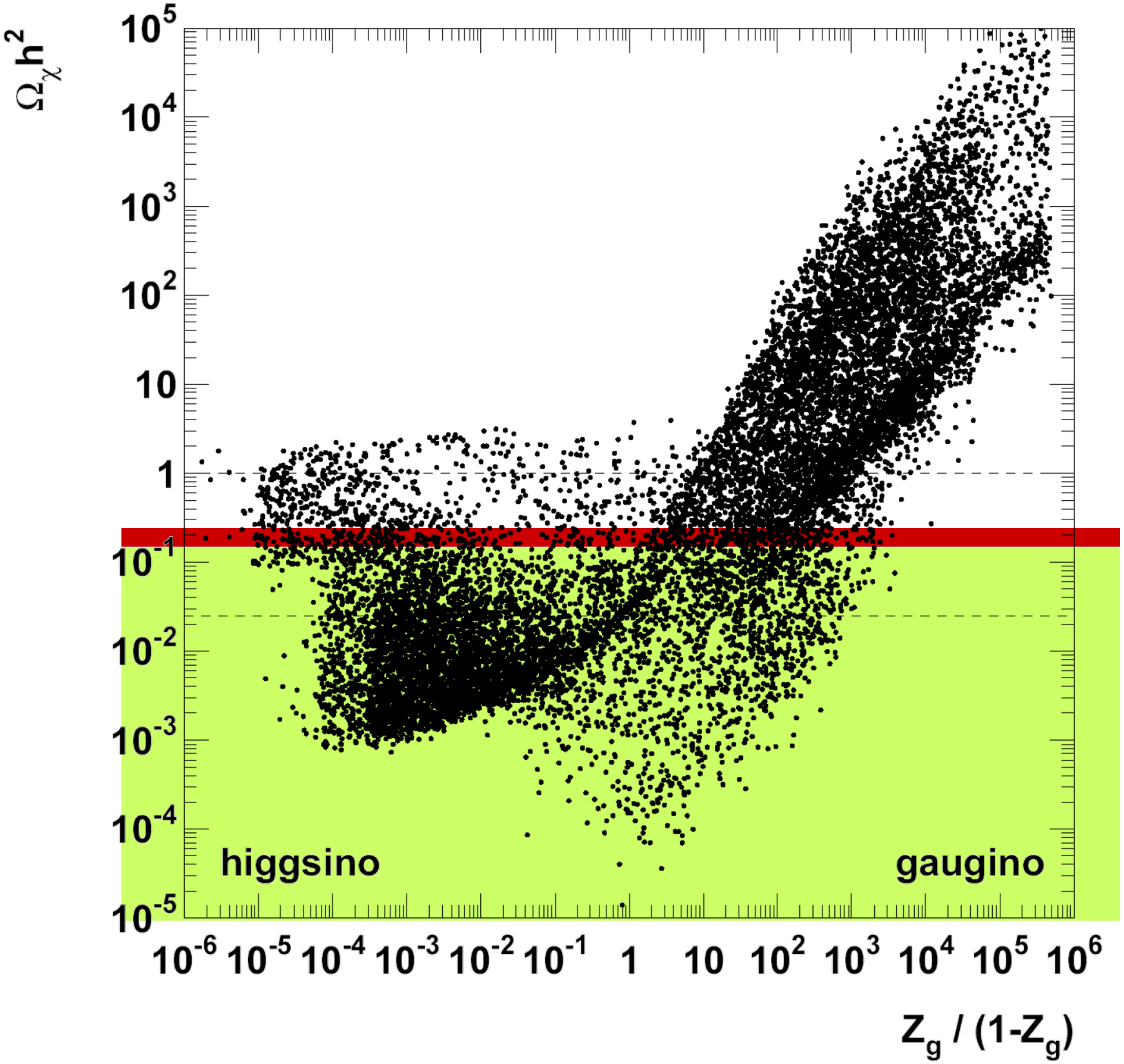
SUSY breaking $\longrightarrow$ massive SUSY partners

R PARITY $\longrightarrow$ LSP: stable

$$P_R = (-1)^{3(B-L)+2s}$$

$$A + B \longrightarrow \tilde{X} + \tilde{Y}$$
$$\tilde{X} \longrightarrow \tilde{Y} + A + B$$

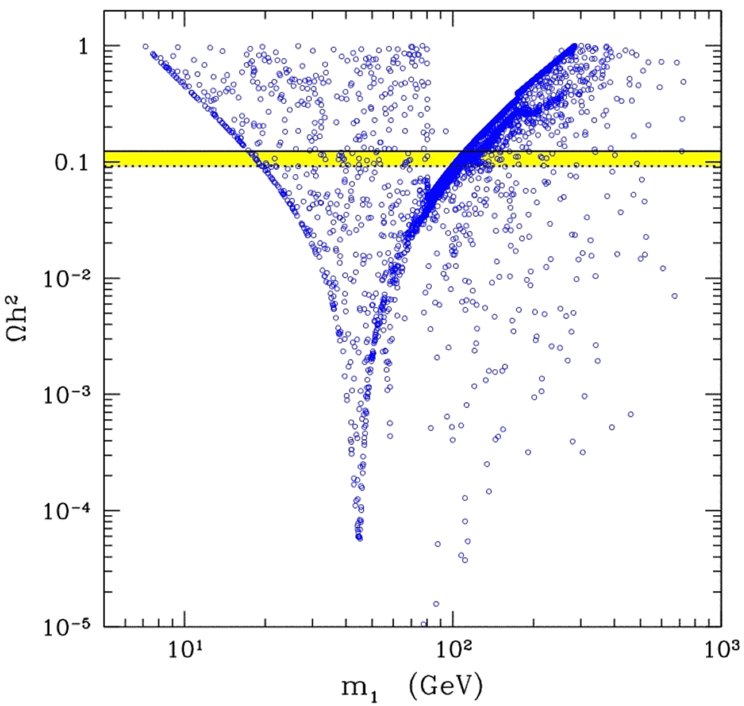
Neutralino in a generic MSSM



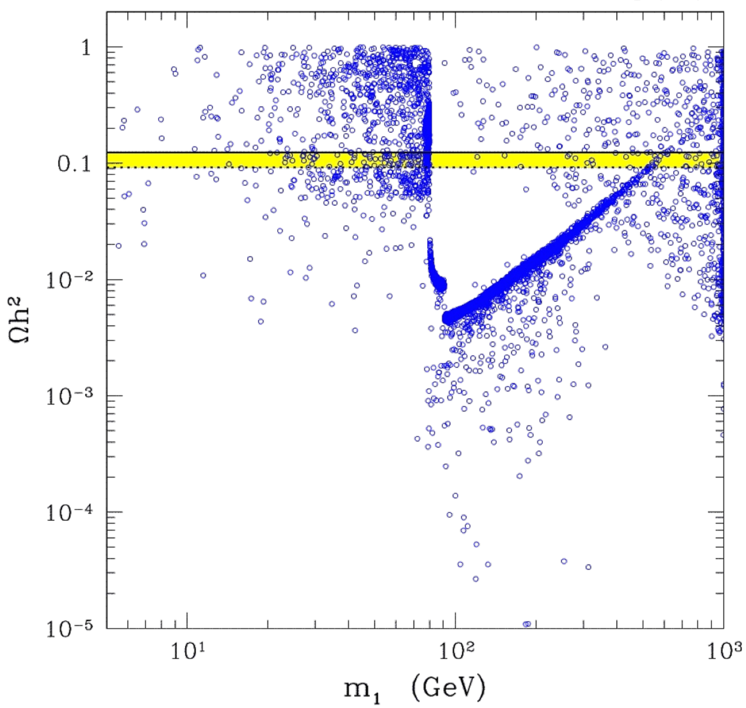
Sneutrino dark matter

MSSM at the EW scale with terms that induce neutrino masses

(May) Address DM + neutrino mass in the same sector



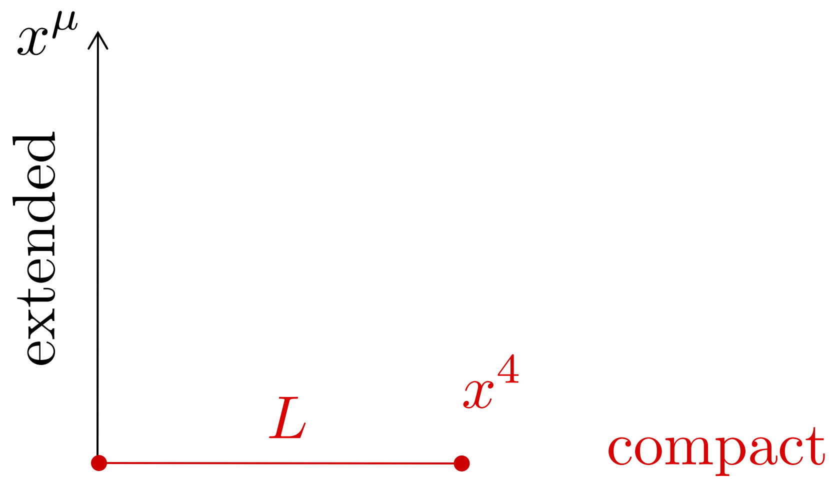
Left+Right models



"Majorana" models

Extra dimensions (Kaluza Klein theories)

5D spacetime : $x^M = (x^0, x^1, x^2, x^3, x^4)$



$$m_n^2 = m_0^2 + \frac{n^2}{L^2}$$

$n = 0$ SM

$n = 1, 2, \ldots$ KK states

KK parity → LKP: stable

Minimal models

$$\mathscr{L} = \mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{Fermion multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{Scalar multiplet} \end{cases}$$

Quantum numbers			DM can	DM mass	$m_{\rm DM^\pm} - m_{\rm DM}$	Events at LHC	$\sigma_{\rm SI}$ in
$SU(2)_L$	$U(1)_Y$	Spin	decay into	in TeV	in MeV	$\int \mathcal{L}\, dt = 100/\text{fb}$	$10^{-45}\ \text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

Renormalizable decay modes absent:

Fermions: $n \geq 5$

Scalars: $n \geq 7$

Further models and candidates

- Models with additional scalars
  - Singlet
  - Doublet (e.g.: 2 higgs doublet model)
  - Triplet

- Models based on extended symmetries
  - GUT inspired
  - Discrete symmetries

- Mirror dark matter
- Sterile neutrinos [keV, non WIMP, warm]
- Axion [μeV, non WIMP, cold]
- ALP (axion-like-particles, light scalars)

Axion

- Axions arise as a dynamical way to solve the strong-CP problem
- Being particles, they can have a cosmological role
- They can be DM:
  - Thermally produced: HDM
  - Non-thermally produced: CDM

The CP Problem of Strong Interactions

$$\mathcal{L}_{QCD} = \sum_q \bar{q}(i\not{D} - m_q e^{i\theta_q})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

CP-odd
No effect in perturbative QCD

Remove phase of mass term by chiral transformation of quark fields

$$q \to e^{i\gamma_5\alpha}q$$

$$\mathcal{L}_{QCD} = \sum_q \bar{q}(i\not{D} - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - [\theta - \theta_q]\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\bar{\theta} = [\theta - \theta_q] \ \to \ [\theta - \arg\det M_q]$$

QCD Flavor

The CP Problem of Strong Interactions

This term can induce a neutron electric dipole moment (T-violating quantity)

$$d_n \sim \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \sim 10^{-16}|\bar{\theta}|\, e\,\mathrm{cm}$$

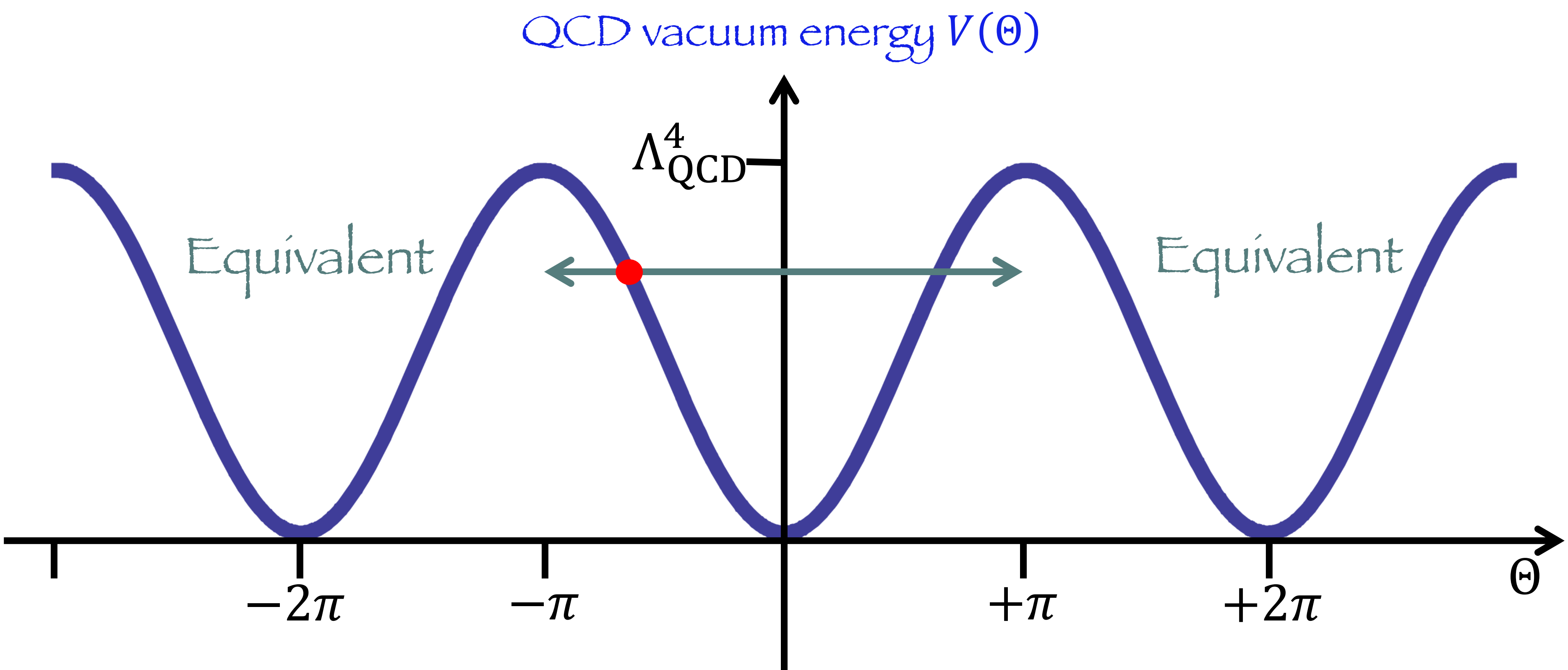
Experimental bound

$$d_n \lesssim 2 \cdot 10^{-26}\, e\,\mathrm{cm}$$

The theta-parameter has to be extremely small – Why?

$$|\bar{\theta}| \lesssim 10^{-10}$$

Strong CP Problem



CP conserving vacuum has $\Theta = 0$ (Vafa and Witten 1984)

QCD could have any $-\pi \leq \Theta \leq +\pi$, is "constant of nature"

Energy can not be minimized: Θ not dynamical

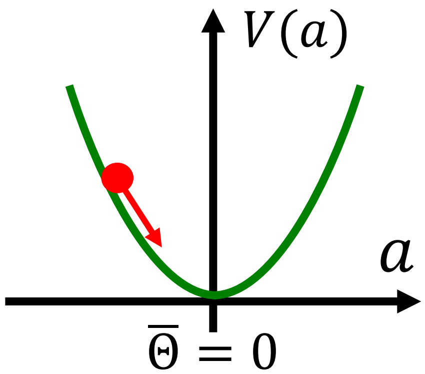
Peccei-Quinn solution:

Make Θ dynamical, let system relax to lowest energy

Dynamical Solution

Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978

Solution: re-interpret $\bar{\Theta}$ as a dynamical variable, which is driven to zero by dynamics



Assume a global $U(1)_{PQ}$ symmetry which is sponstaneously broken

axion a(x) pseudo scalar field

pseudo Nambu-Goldstone boson of the symmetry breaking

$\theta_{\rm eff}$ Set to zero by QCD dynamics

$$\mathcal{L}_{\rm eff} = \left(\bar{\theta} + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2}\partial^\mu a \partial_\mu a + (\ldots)$$

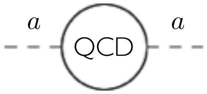
$$a(x) \rightarrow \langle a \rangle + a(x) \qquad \langle a \rangle = -\bar{\theta} f_a$$

$$\frac{a}{f_a} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

This is induces axion properties

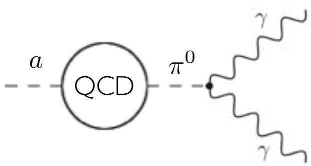
Axion properties

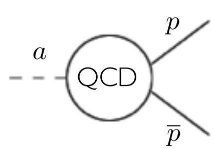
Axion mass

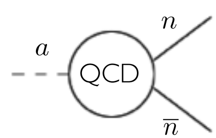


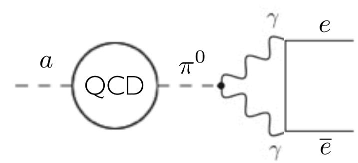
$$\sim \frac{\Lambda_{\rm QCD}^4}{f_a^2} \qquad \longrightarrow \qquad m_a \sim \Lambda_{\rm QCD}^2/f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a}\right)$$

Axion coupling to photons, protons, neutrons and electrons







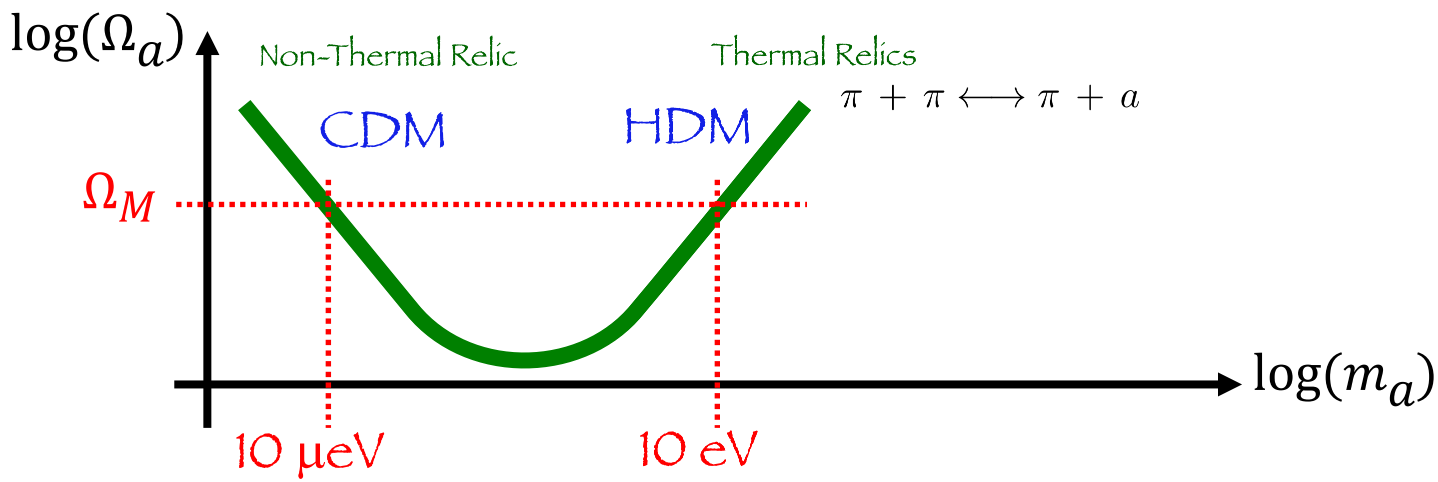


$C_\gamma = -1.92(4)$ $\qquad$ $C_p = -0.47(3)$ $\qquad$ $C_n = -0.02(3)$ $\qquad$ $C_e \simeq 0$

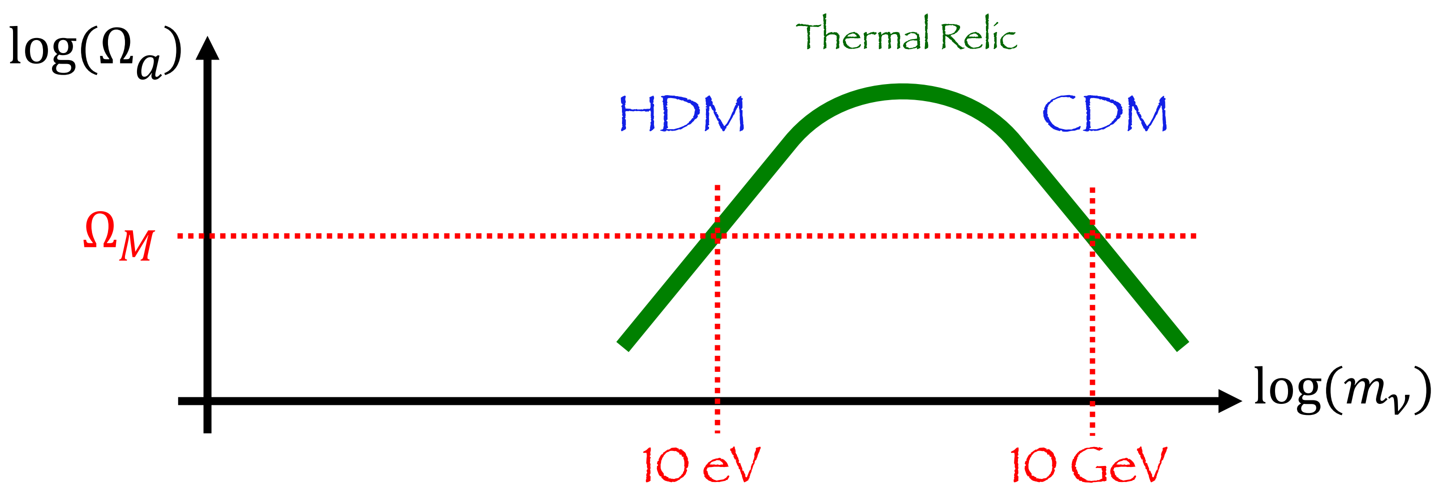
$$\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad\qquad C_\Psi m_\Psi \frac{a}{f_a}[i\overline{\Psi}\gamma_5\Psi] \qquad (\Psi = p, n, e\,)$$

Cosmological abundance

Axions



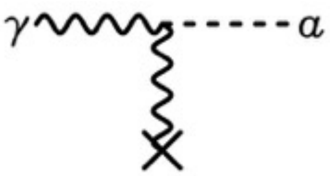
Neutrinos
WIMPs



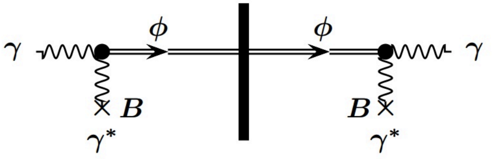
Axions/ALP search strategies

Serches typically rely on the axion-photon coupling, which can produce axion-photon conversion in a magnetic field (Primakoff effect):

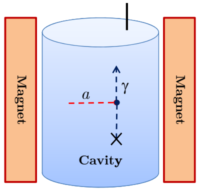
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F \cdot \tilde{F} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



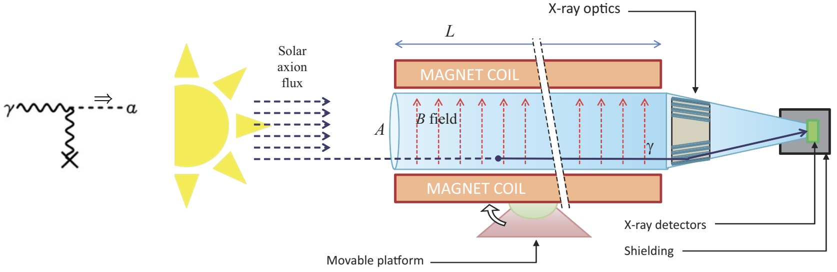
Light shining through walls



Haloscopes (axion DM)



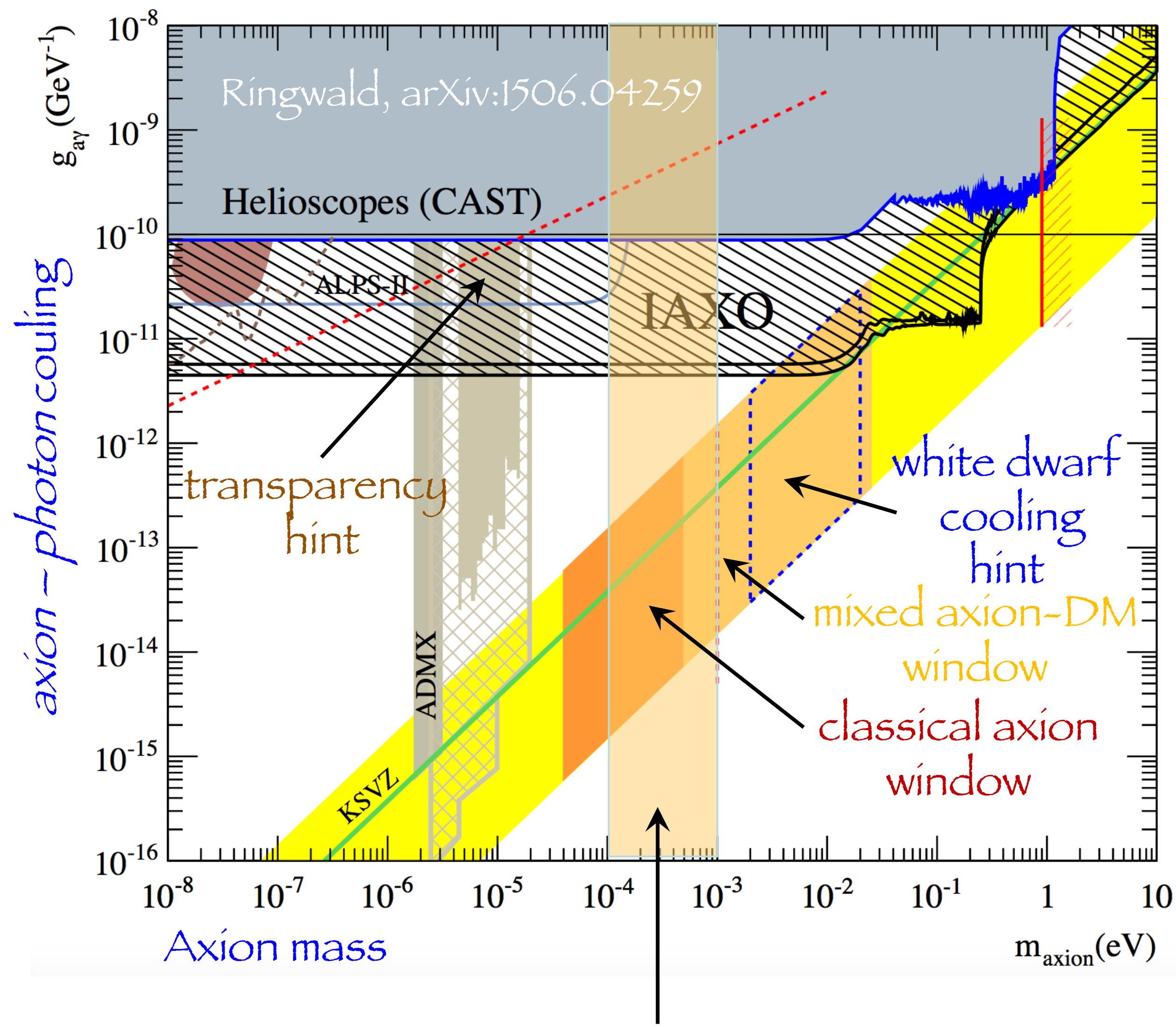
Helioscopes (axions from the Sun)



Cooling of stars

(...)

Axions and ALPs



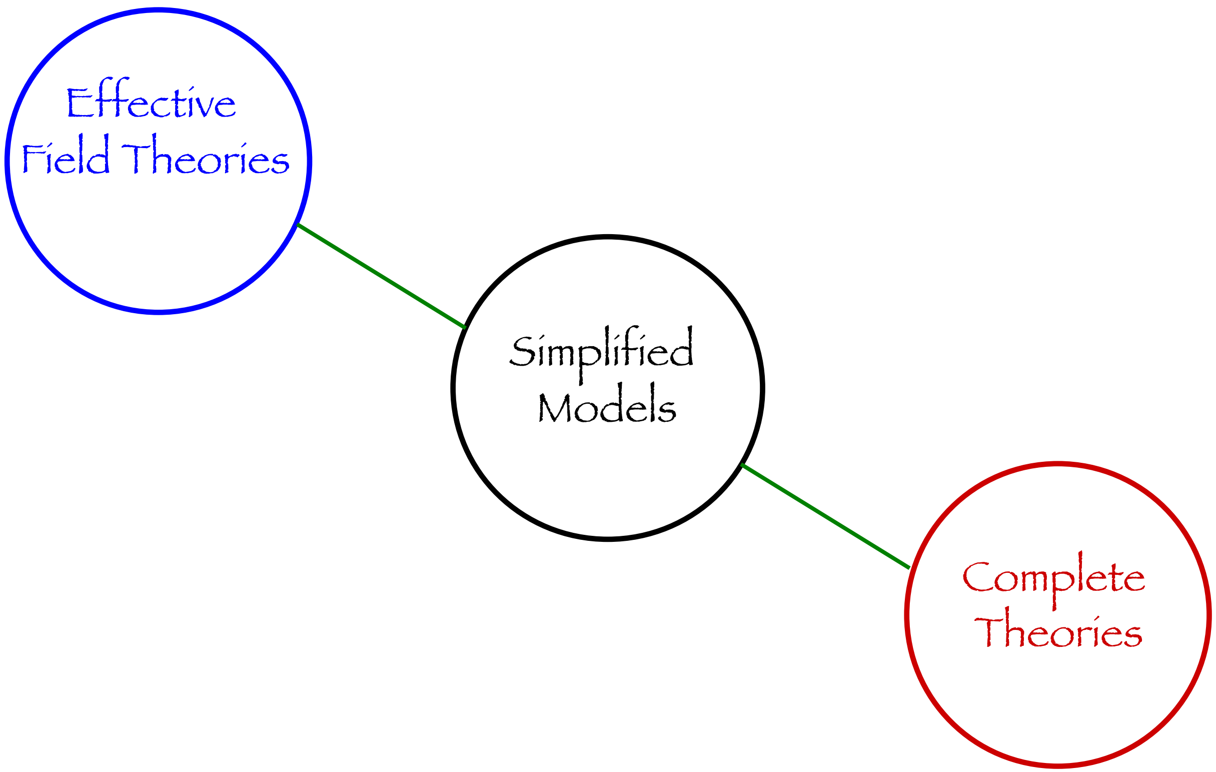
Techniques:

- Shine through wall (ALPS, OSQAR)
- Helioscopes (CAST, IAXO)
- Haloscopes (ADMX)
- Magnetic resonance (CASPEr)

QUAX: high-frequency magnetometer
axion-electron coupling

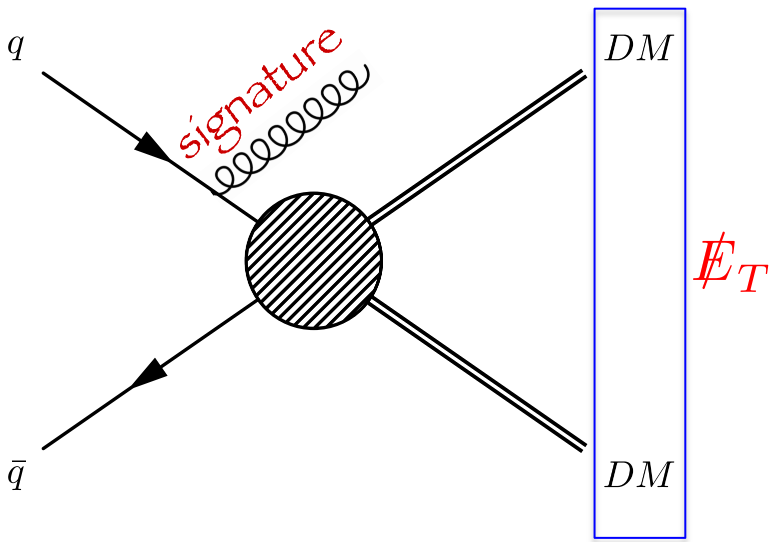
LAboratory searches

WIMPs at accelerators



Effetive Field Theory

- Sistematic study of the Effective Field Theory approach
- Mono-X + missing ET   where X = photon, Z, higgs, top, ...



DM type: S, F, V (...)

$g_{(DM,q)}$ m_{DM}

coupling structure (s, v, t)

Λ : EFT scale and validity

Set of operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

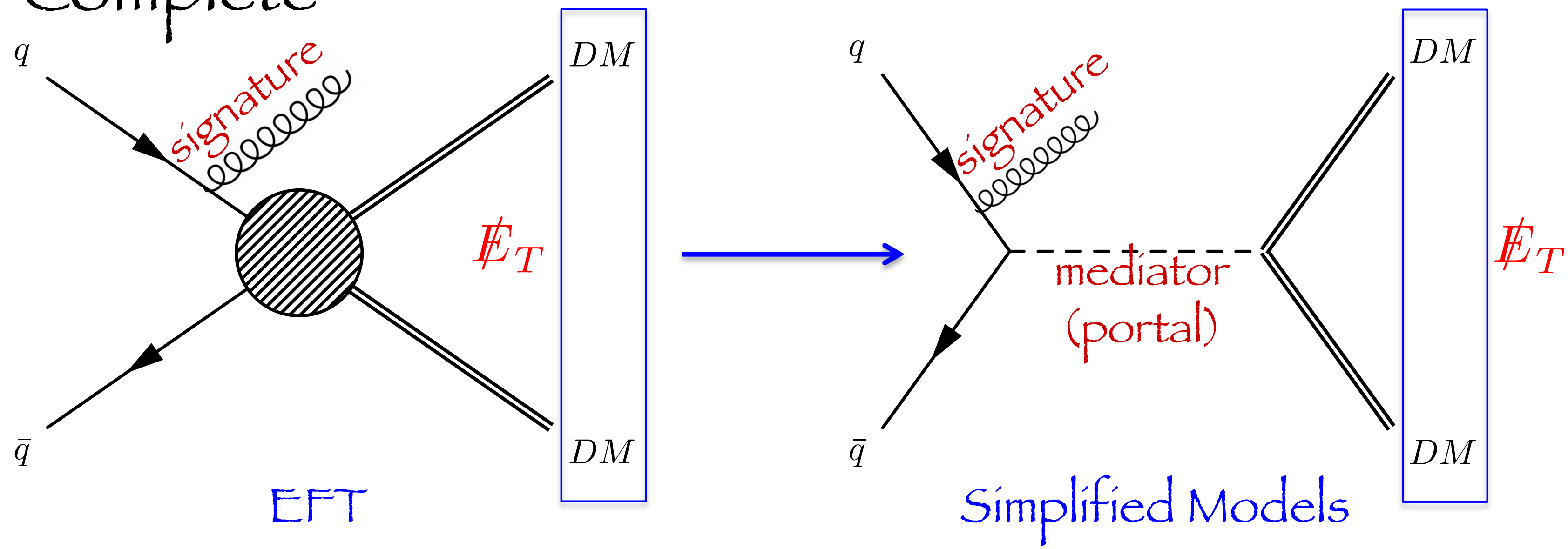
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

D: Dirac fermions
C: Complex scalars
R: Real scalars

Simplified models

- EFT → Simplified Models - - - → UV

Complete



DM type: S, F, V (...)

Portal: S, F, V, T

$g_{(DM,med)}$ m_{DM}

$g_{(med,\,q)}$ Γ_{med} m_{med} channel

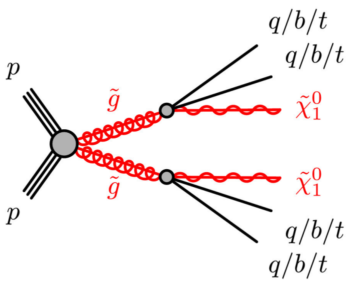
Complete models: e.g. SUSY

mSUGRA	4 parameters	High-energy related	Very constrained
Non-Universal SUGRA	4+2, 4+5, 4+N parameters	High-energy related	Somehow less contrained
MSSM	115 parameters	Low energy	Maximal freedom
pMSSM	20 parameters	Low energy	Very free
(...)	(...)	(...)	(...)

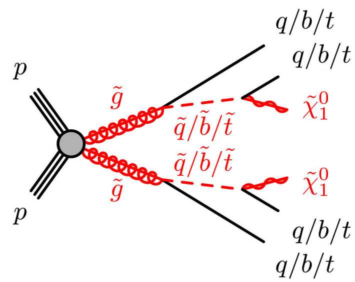
To have DM:

- Neutralino or sneutrino need to be the LSP
- R-parity needed to ensure the LSP is stable
- LSP relic abundance need to match (or be smaller) than observed value

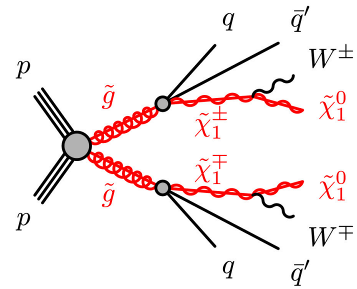
Complete models: e.g. SUSY



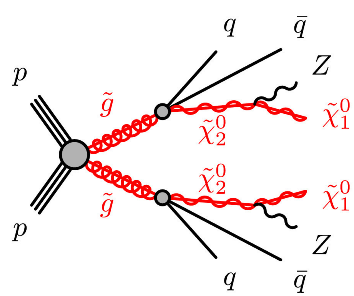
(a)



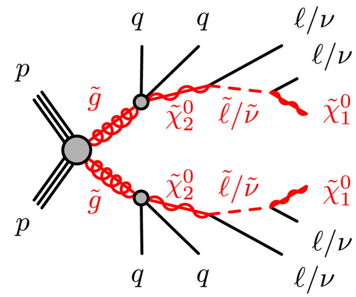
(b)



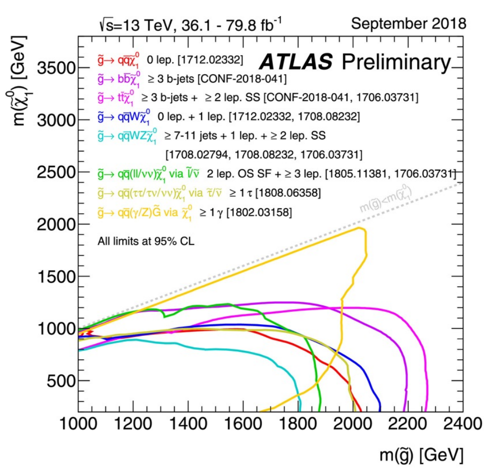
(c)

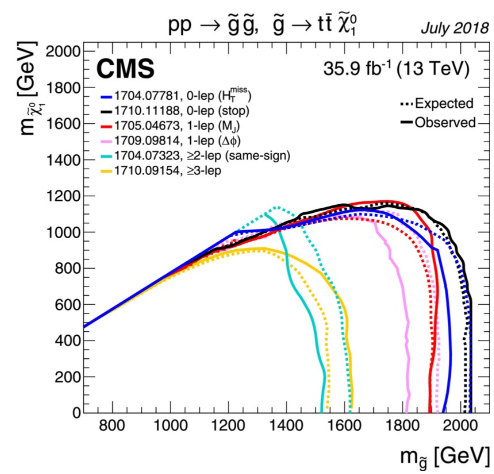


(d)

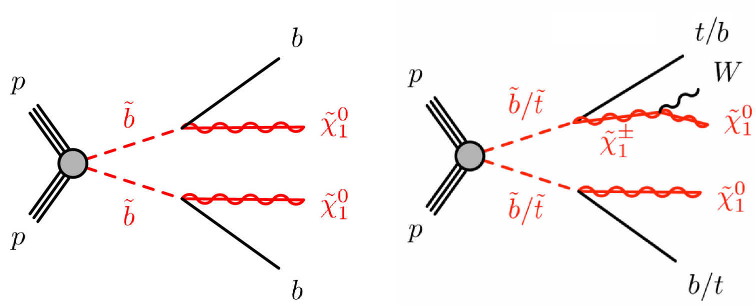


(e)

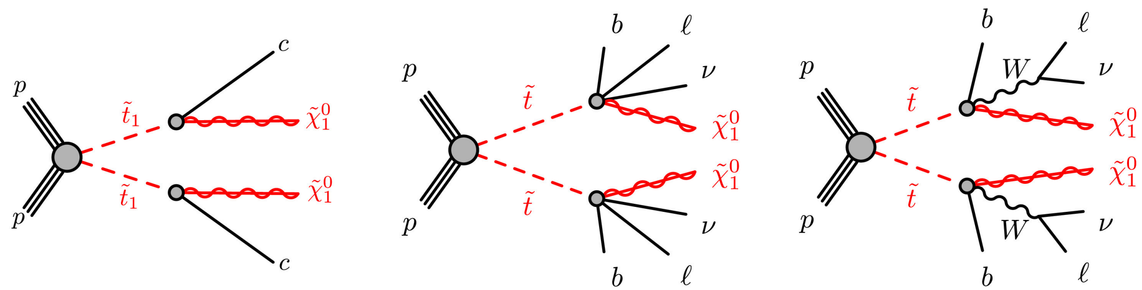




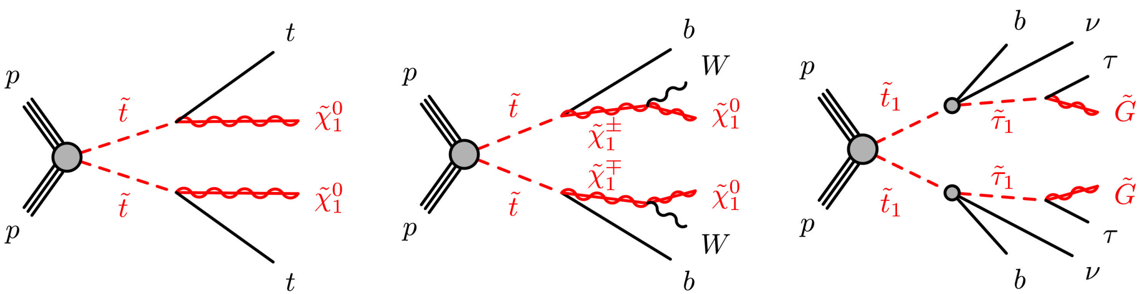
Complete models: e.g. SUSY



(a) (b)

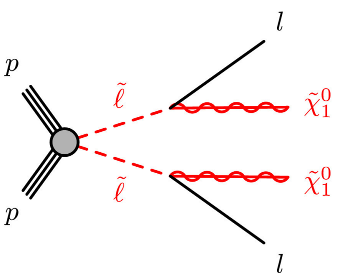


(a) (b) (c)

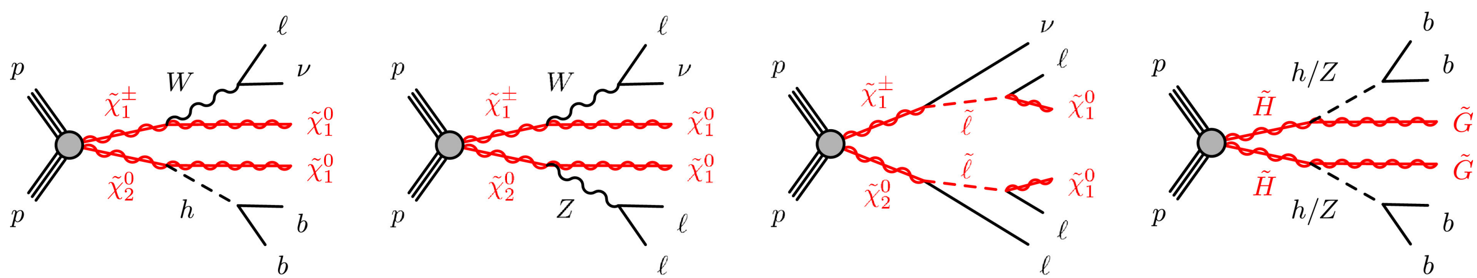


(d) (e) (f)

Complete models: e.g. SUSY



(a)



(a) (b) (c) (d)

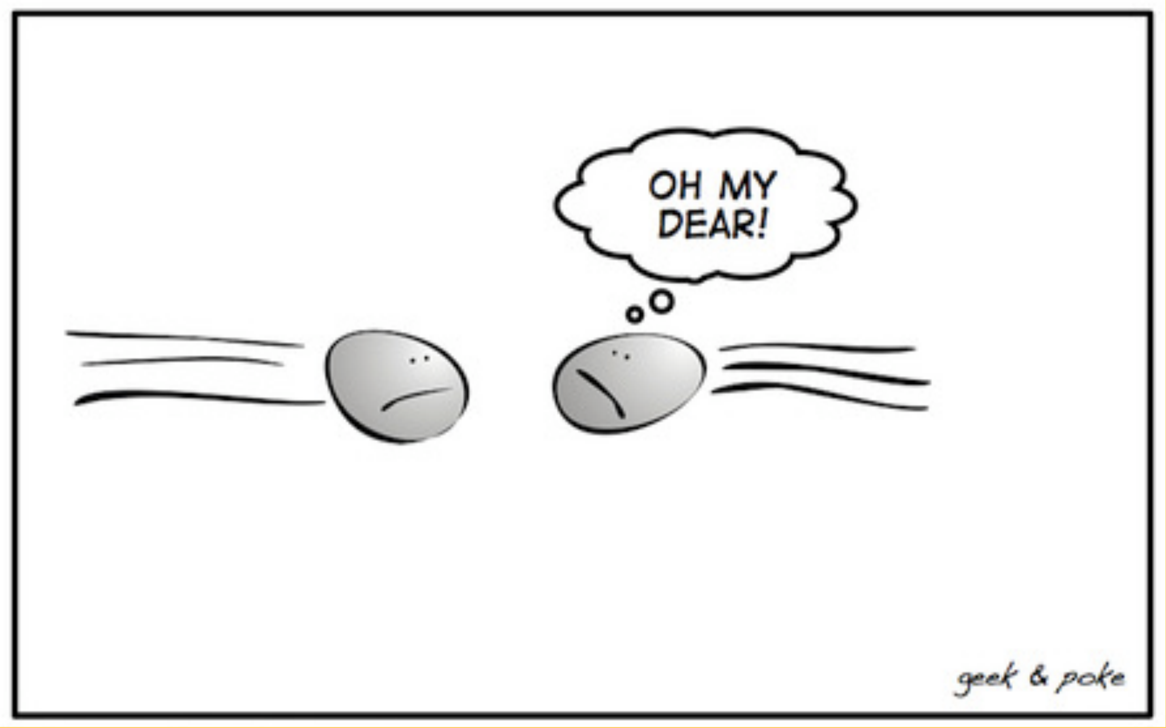
Non-WIMPs at accelerators

- Light DM at the MeV-GeV scale:
  - Dirac or Majorana fermions
  - Scalars o pseudoscalars
  - Asymmetric LDM
  - Dark photons
- Mediators:
  - Vector portal
  - Higgs portal
  - Neutrino portal
  - Axion portal
- Search of visible decays (e^+e^-) and invisible decays
- Rich experimental program:
  - Hadronic beams
  - Electron beams
  - Meson decays

Electron beams

- LNF: PADME + BDX (Beam Dump eXperiment)
  - Linac at 1-1.2 GeV, up to 10^{20} EOT/year
- JLab: BDX (HPS, APEX, DarkLight)
  - Beam: 12 GeV, 10^{22} EOT/year
- MAINZ (MESA): BDX
  - Beam: 150 MeV, 10^{22} EOT/year
- Cornell: PADME-like
  - Beam: 5 GeV
- Belle:
  - Trigger mono-jet to search for "heavy photons"

Non – gravitational signals of particle DM

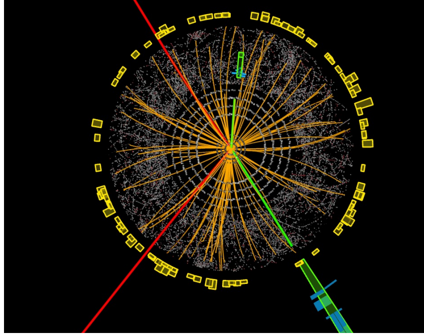


Dark Matter

- DM evidence is purely gravitational
  - Galaxy clusters dynamics
  - Rotational curves of spiral galaxies
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Energy budget of the Universe
  - The same theory of structure formation

- This evidence can be ascribed either to:
  - Modification of the theory of Gravity (difficult to explain all observations)
  - Elementary particle, relic from the early Universe
    - No viable candidate in the SM: New Physics BSM
    - However, to demonstrate that DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is needed

A multiple approach

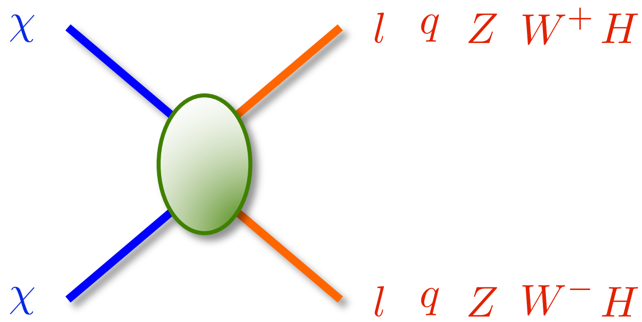


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy

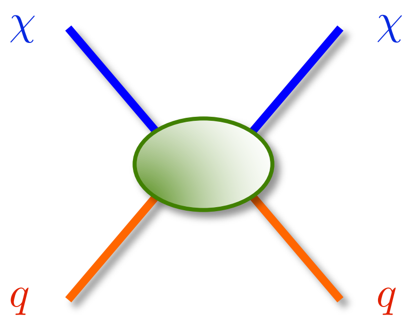
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all … profit of all opportunities

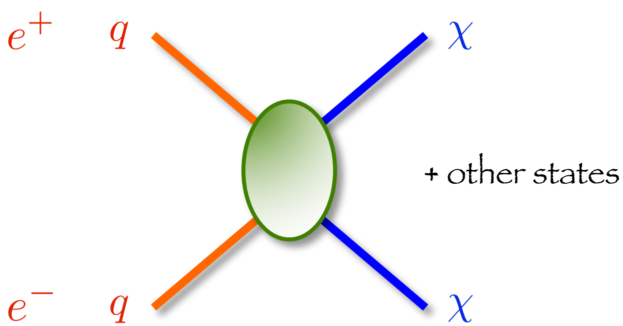
Mechanisms of DM signal production



Annihilation (or decay)

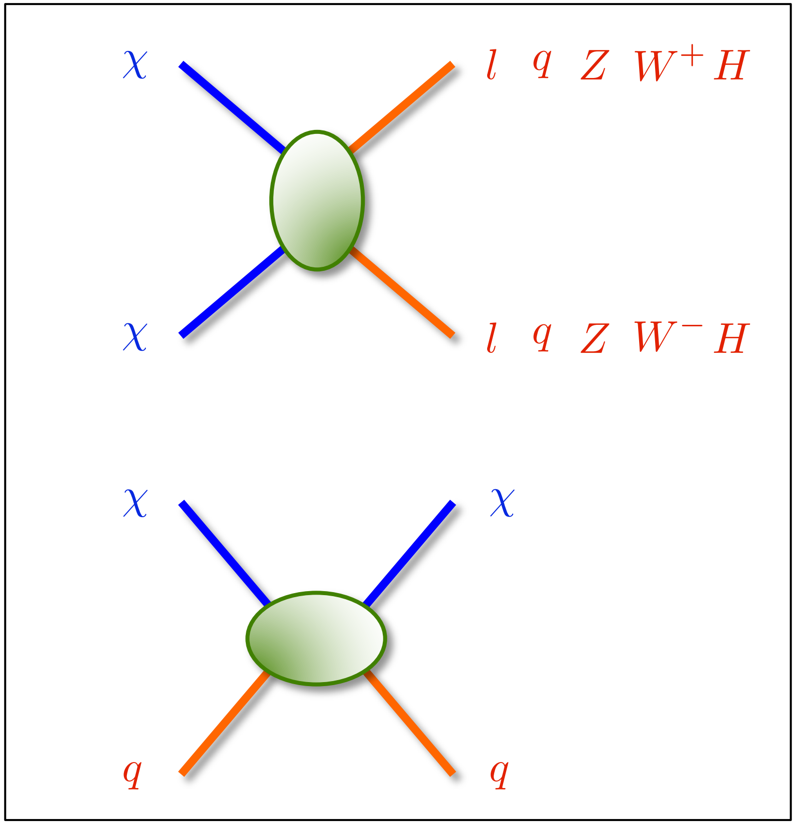


Scattering with ordinary matter



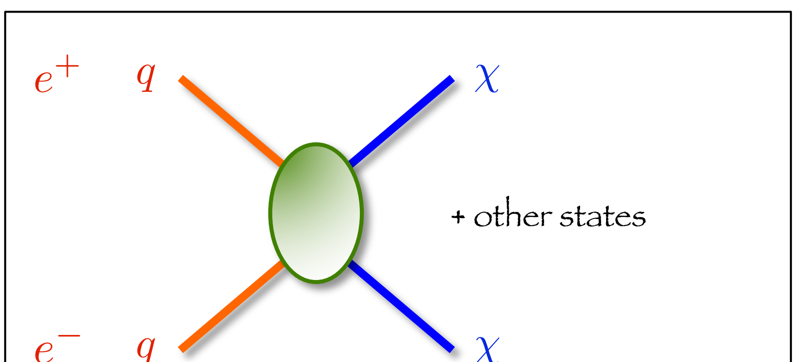
Production at accelerators

Mechanisms of DM signal production



Signals occur in astrophysical context

Directly test DM the particle-physics nature of DM



Signal produced in accelerators

Directly tests New Physics: compatibility with DM needs to be cross-checked with cosmology adn astrophysics

DM as a particle might ...

Interact with ordinary matter

Inside our detector
Direct detection

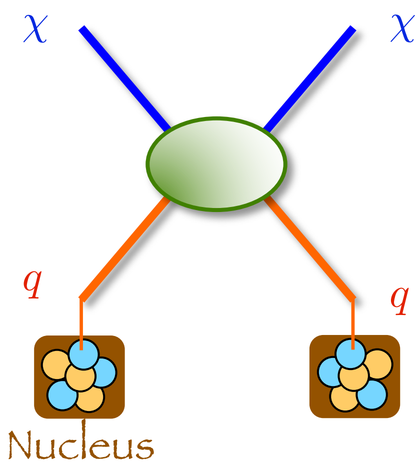
Produce effects in astrophysical environments, like in stars

Self annihilate or decay

Send us messengers
Indirect detection

Exotic injections that can alter properties of messengers (e.g. CMB: SZ, reionization; gamma-rays absorption)

Direct detection signal



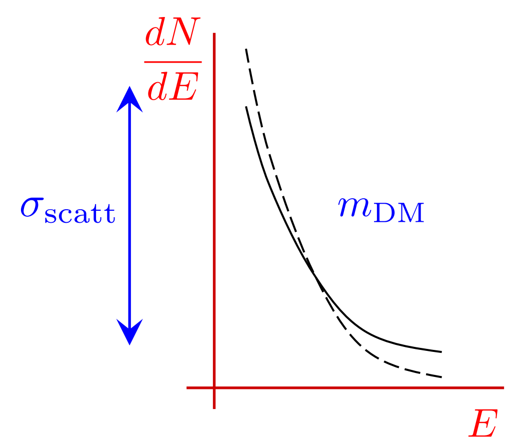
Scattering with ordinary matter

Relevant particle physics properties:

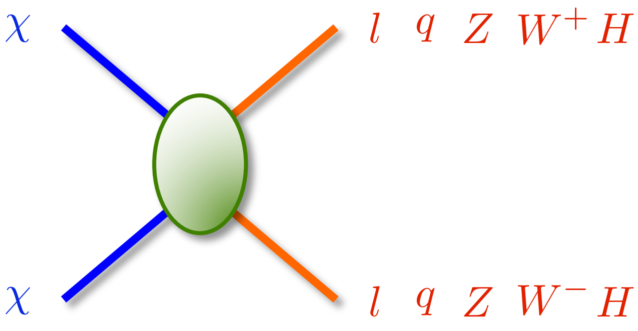
1. Scattering cross section
2. Mass of the DM particle

1 + 2 : Size of the signal

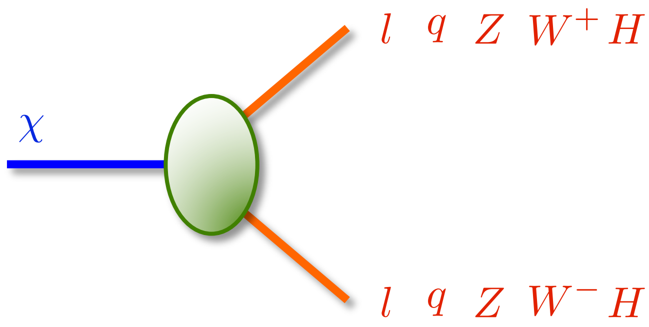
2 : Spectral features of nuclear recoil



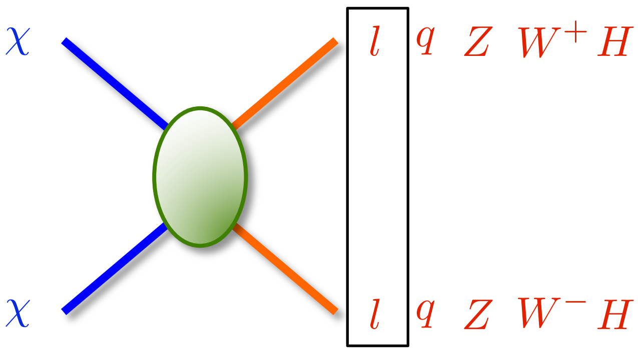
Indirect astrophysical signals



Annihilation or decay



Indirect astrophysical signals



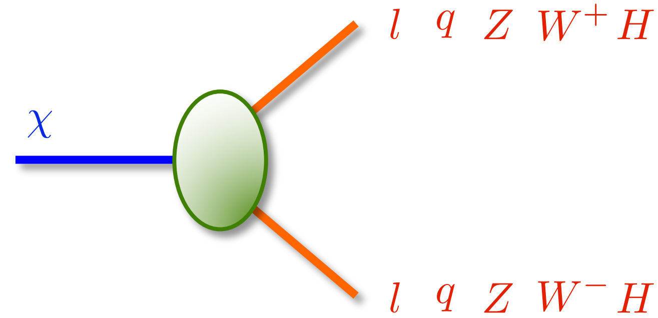
$\downarrow$ e, μ, τ

$e^{\pm}$

ν_e, ν_μ, ν_τ

$\gamma_{\rm FSR}$

Annihilation or decay



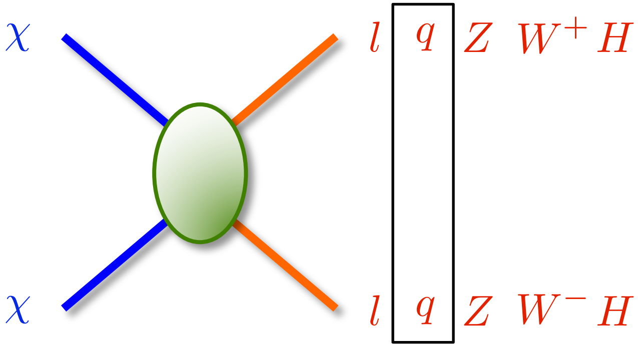
Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\rm DM}$	ann
$m_i < m_{\rm DM}/2$	decay

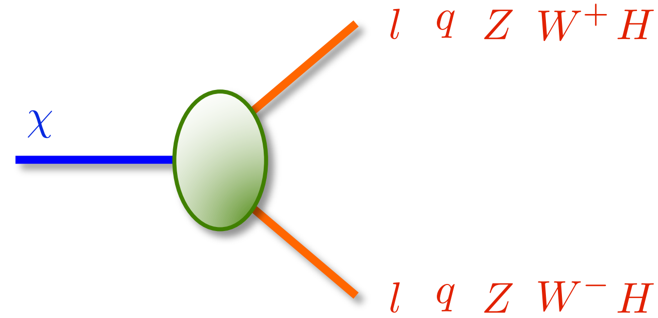
The maximal energy of the final product also depends on the mass of the DM particle

$E < m_{\rm DM}$	ann
$E < m_{\rm DM}/2$	decay

Indirect astrophysical signals



Annihilation or decay



hadronizazion

$p, n,$ heavier Barions

$\pi^0, \pi^\pm,$ heavier Mesons

$\overline{p}, \overline{D}, \overline{He}$

γ

$e^\pm$

ν_e, ν_μ, ν_τ

γ_{FSR}

Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\mathrm{DM}}$	ann
$m_i < m_{\mathrm{DM}}/2$	decay

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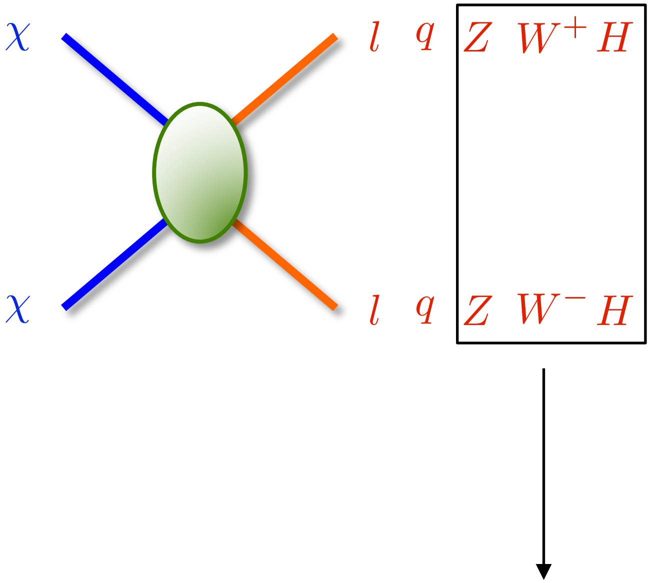
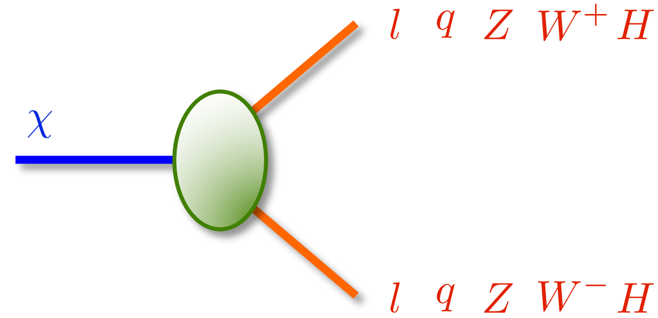
Indirect astrophysical signals



Annihilation or decay



$\overline{p}, \overline{D}, \overline{He}$

γ

$e^{\pm}$

ν_e, ν_μ, ν_τ

$\gamma_{\rm FSR}$

Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\rm DM}$ ann

$m_i < m_{\rm DM}/2$ decay

The maximal energy of the final product also depends on the mass of the DM particle

$E < m_{\rm DM}$ ann

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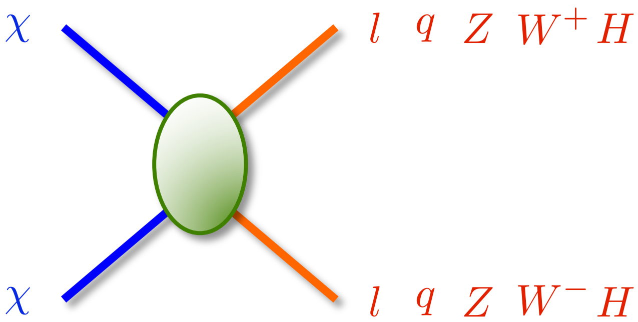
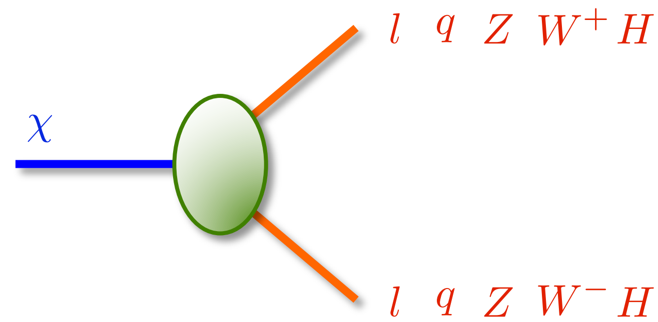
Indirect astrophysical signals

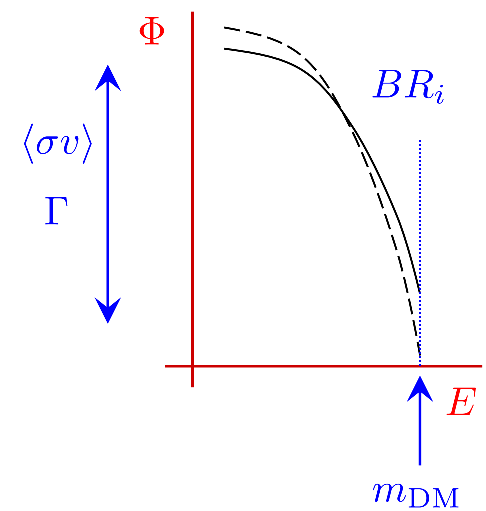


Annihilation or decay



Relevant particle physics properties:

1. Annihilation cross section (*) (or decay rate)
2. Mass of the DM particle
3. BR in the different final states

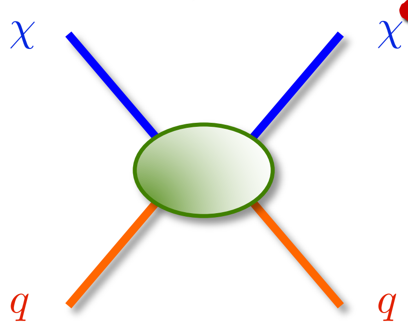


1 + 2 : Size of the signal
2 + 3 : Spectral features

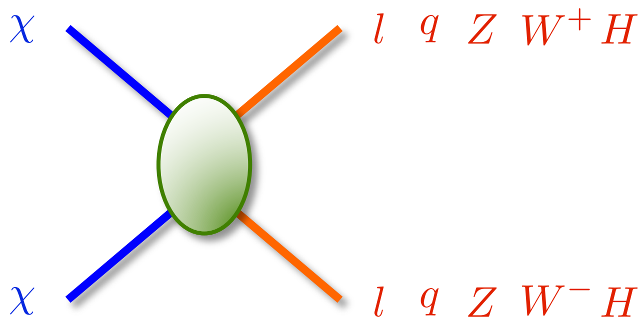
(*) Determines also the cosmological relic abundance (for a thermal DM)

$$\Omega h^2 = 0.11 \quad \longleftrightarrow \quad \langle \sigma_{\rm ann} v \rangle = 2.3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$$

Neutrino signals from Earth and Sun



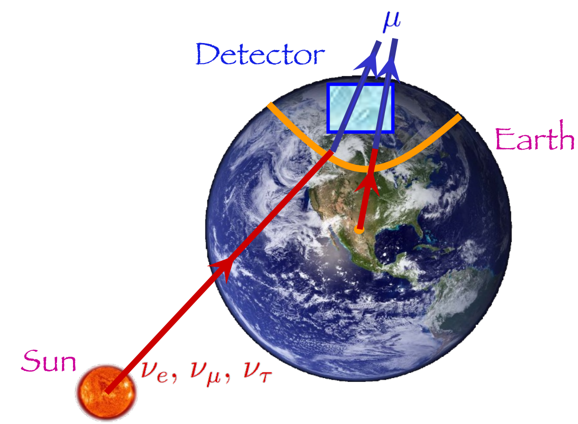
Scattering with ordinary matter
Capture



Annihilation (or decay)
Generation of the neutrino signal

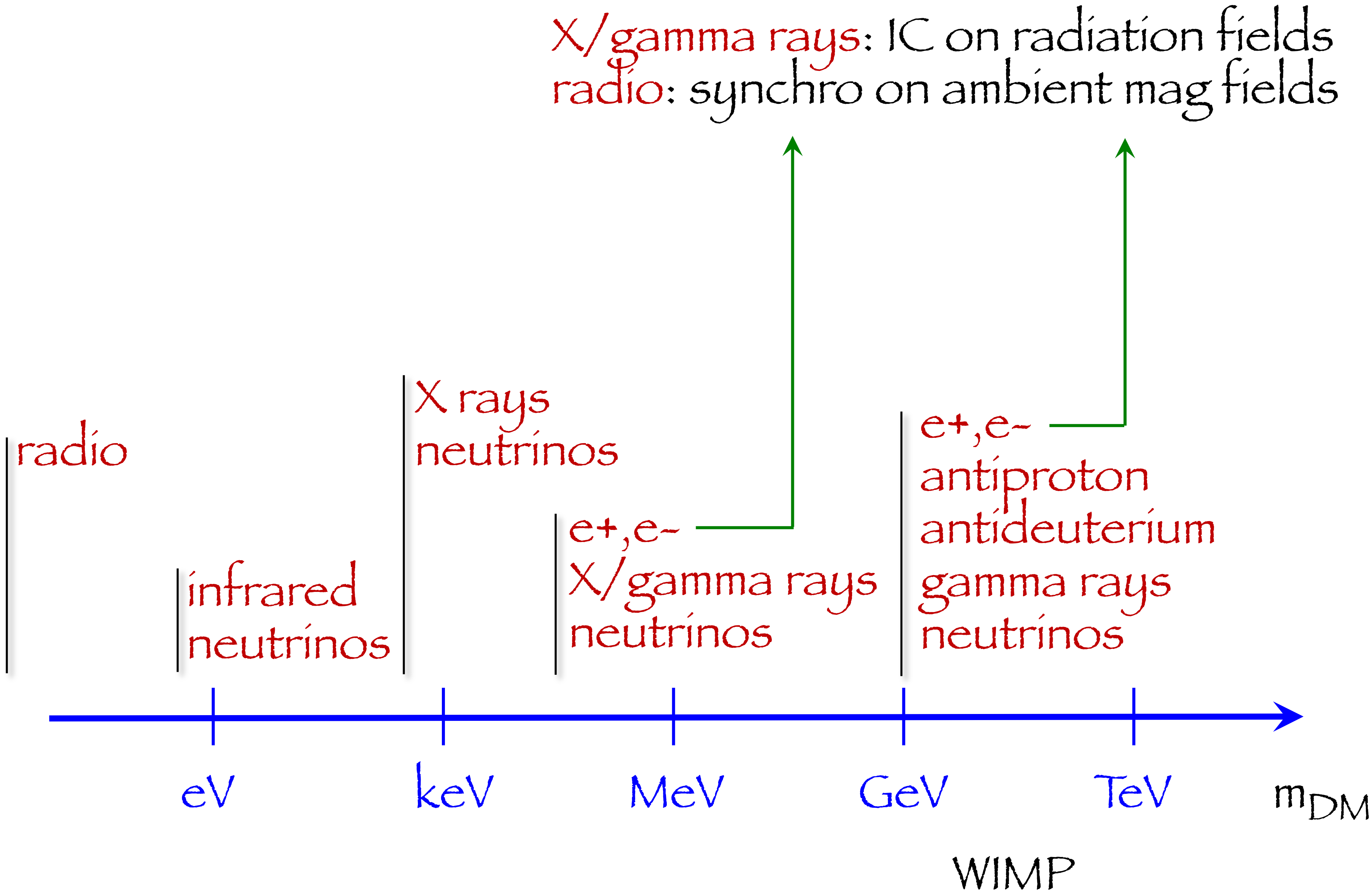
Relevant particle physics properties:

1. Scattering cross section
2. (Annihilation cross section)
3. Mass of the DM particle
4. BR in the different final states



1 + 2 : Size of the signal
3+4 : Spectral features

The Multimessenger Landscape



Multi: messenger/wavelength/technique

	radio	IR	X	gamma
	WIMP non WIMP		WIMP non WIMP	WIMP
Photons	radio	IR	X	gamma

Cosmic rays
- electrons/positrons — WIMP, non WIMP
- antiprotons, antideuterium, antinuclei — WIMP

Neutrinos — WIMP, non WIMP

Gravitational waves — non WIMP (DM = primordial BH)

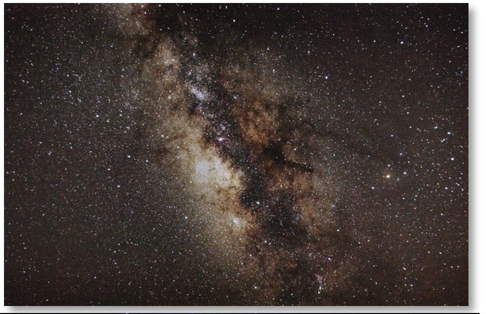
Direct detection — WIMP, non WIMP

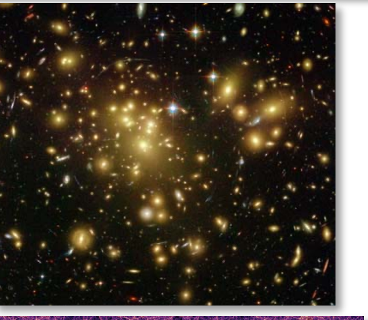
Accelerator searches for New Physics — WIMP, non WIMP

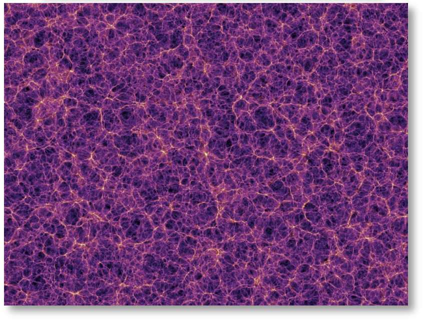
Where to search for a signal

DM is present in:

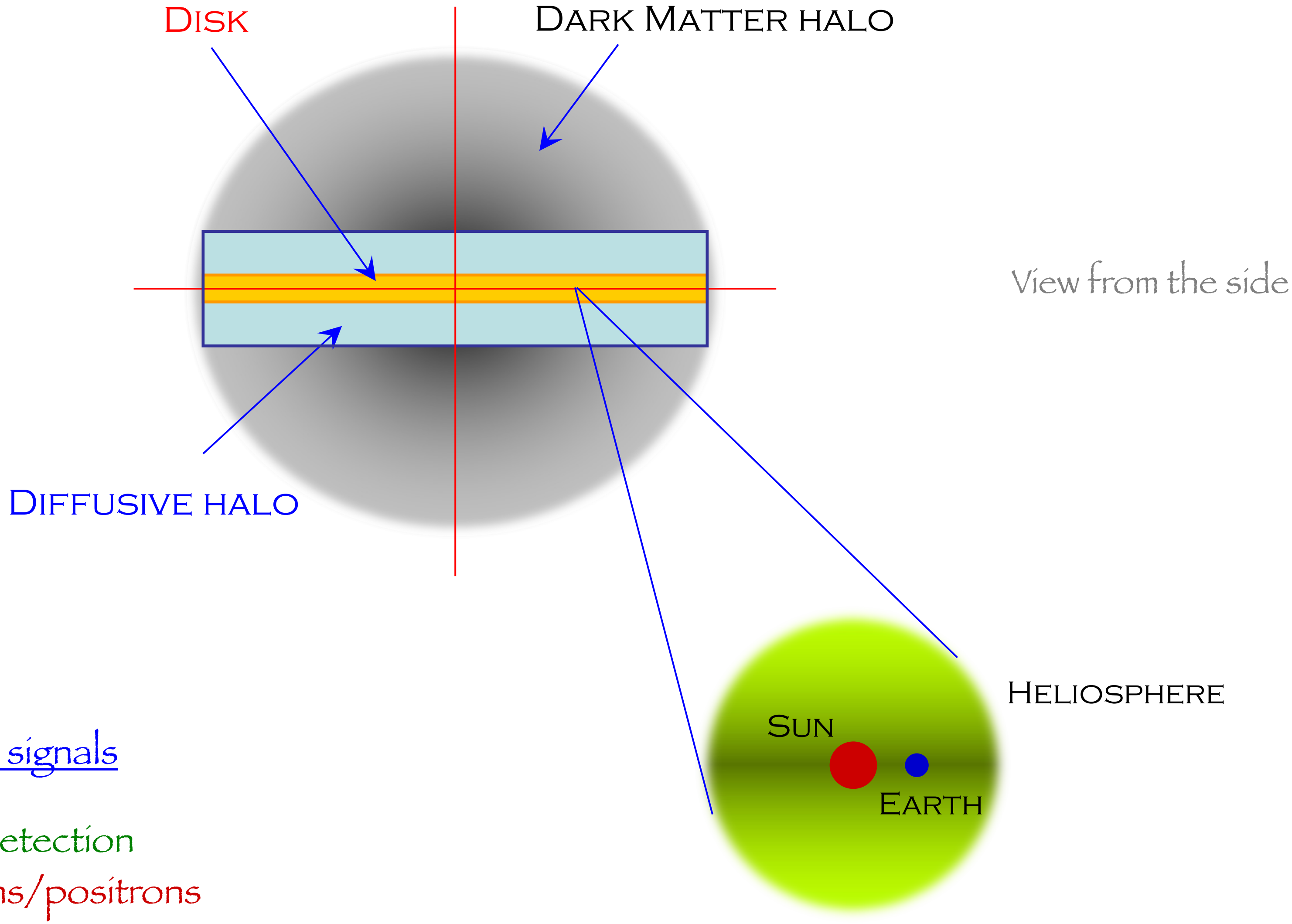
- Our Galaxy
  - ➢ smooth component
  - ➢ subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - ➢ smooth component
  - ➢ individual galaxies
  - ➢ galaxies subhalos
- "Cosmic web"







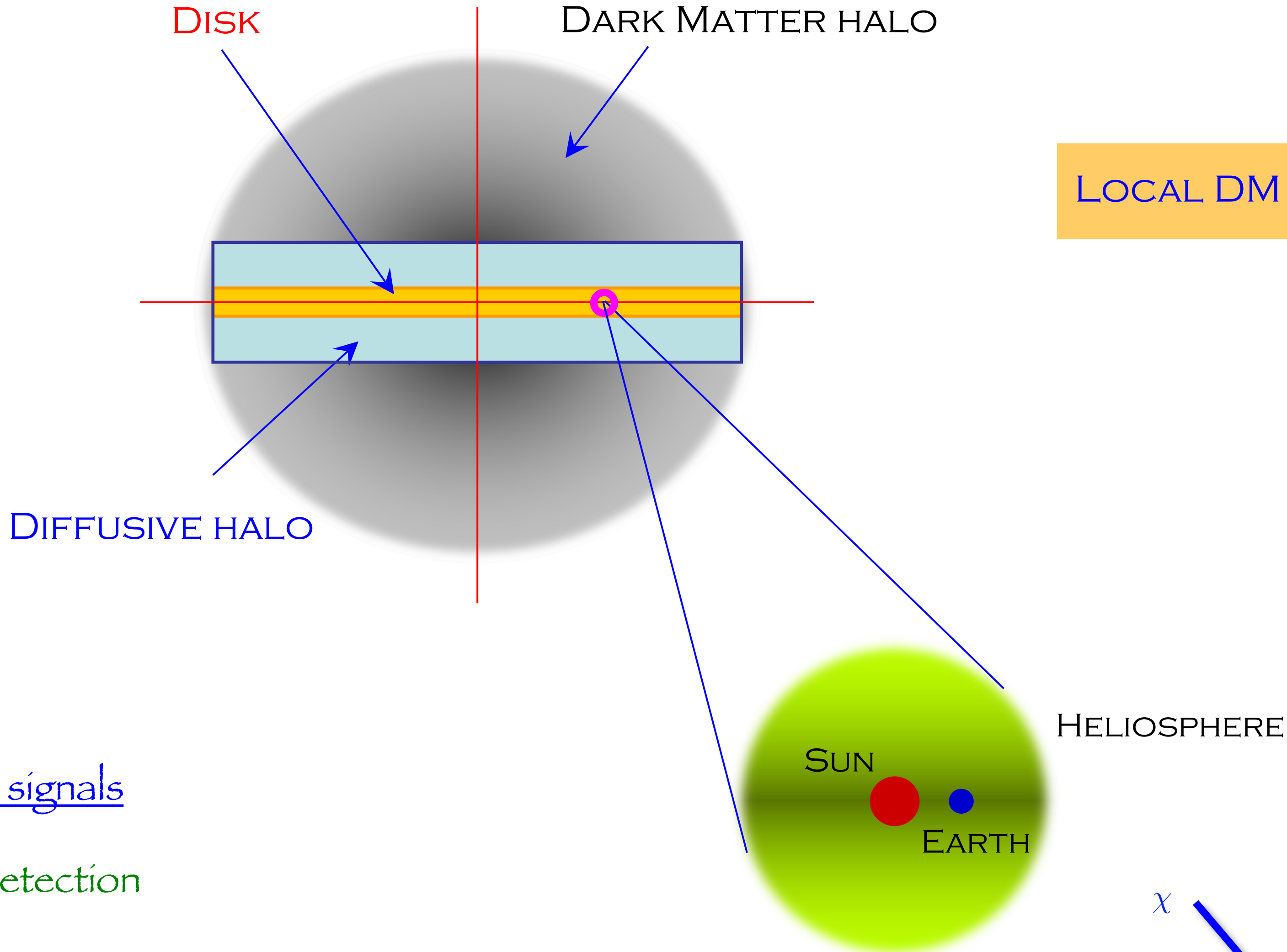
Galactic environment



Galactic signals

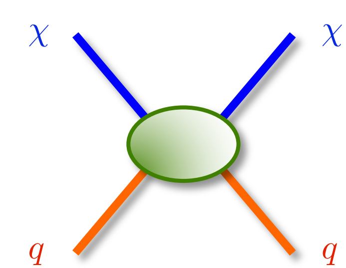
Direct detection
Electrons/positrons
Antiprotons
Antideuterons
Photons (from radio to gamma rays)
Neutrinos

Local DM halo



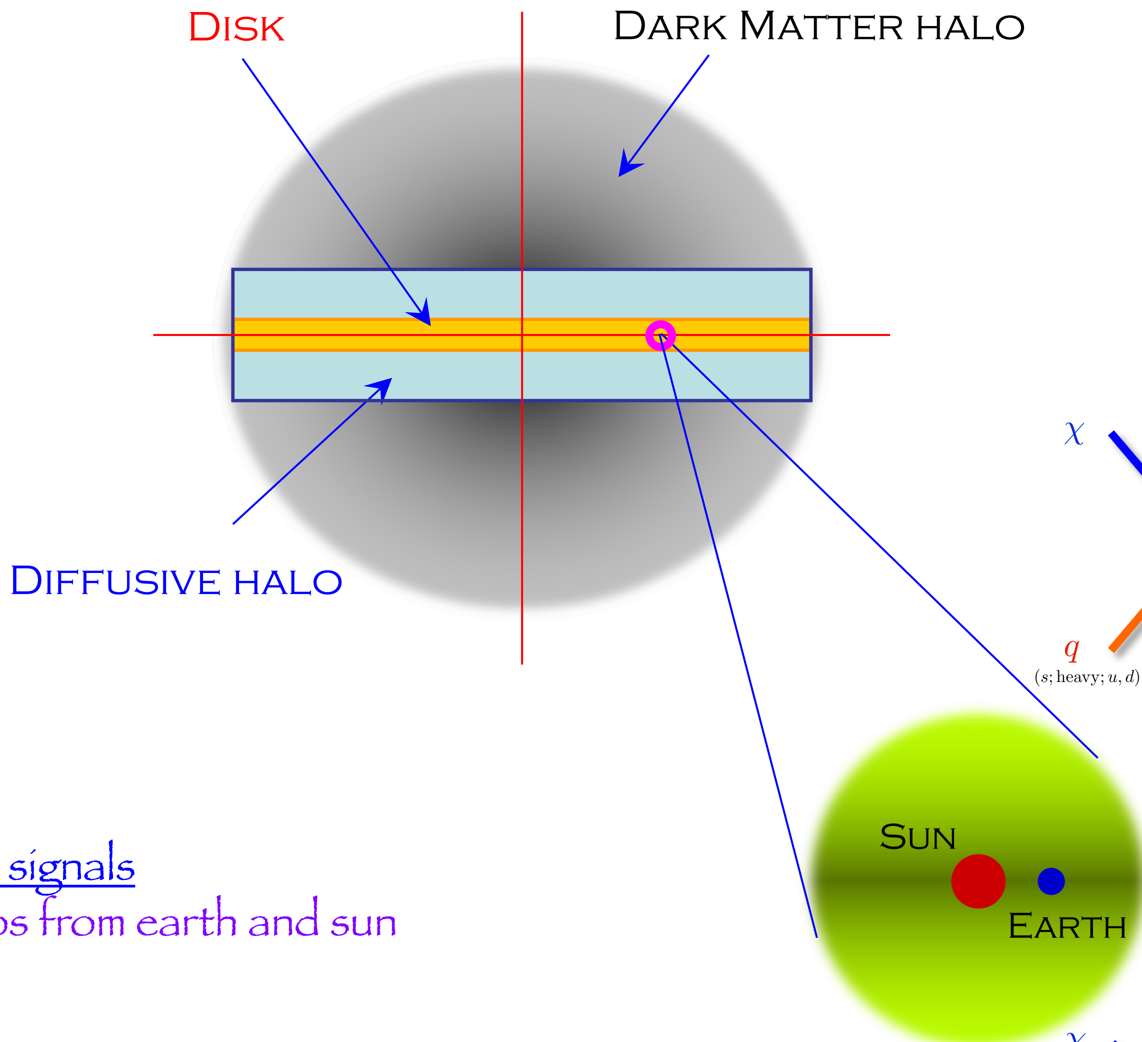
[Galactic signals]

Direct detection

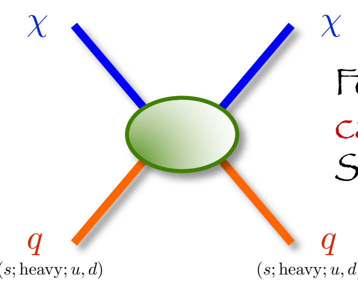


Feels ony the local DM density
Feels how DM is locally distributed in velocity space

$$S \sim \rho(r_{\rm local}) \times f_{\rm local}(v) \times \sigma_{\rm DM-matter}$$



Local DM halo



For gravitational capture in the Sun and Earth

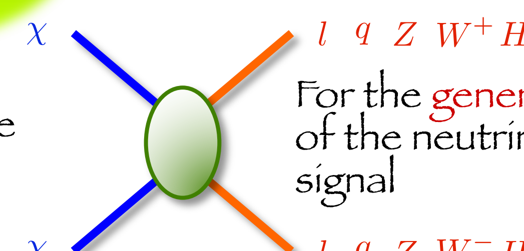
Galactic signals

Neutrinos from earth and sun

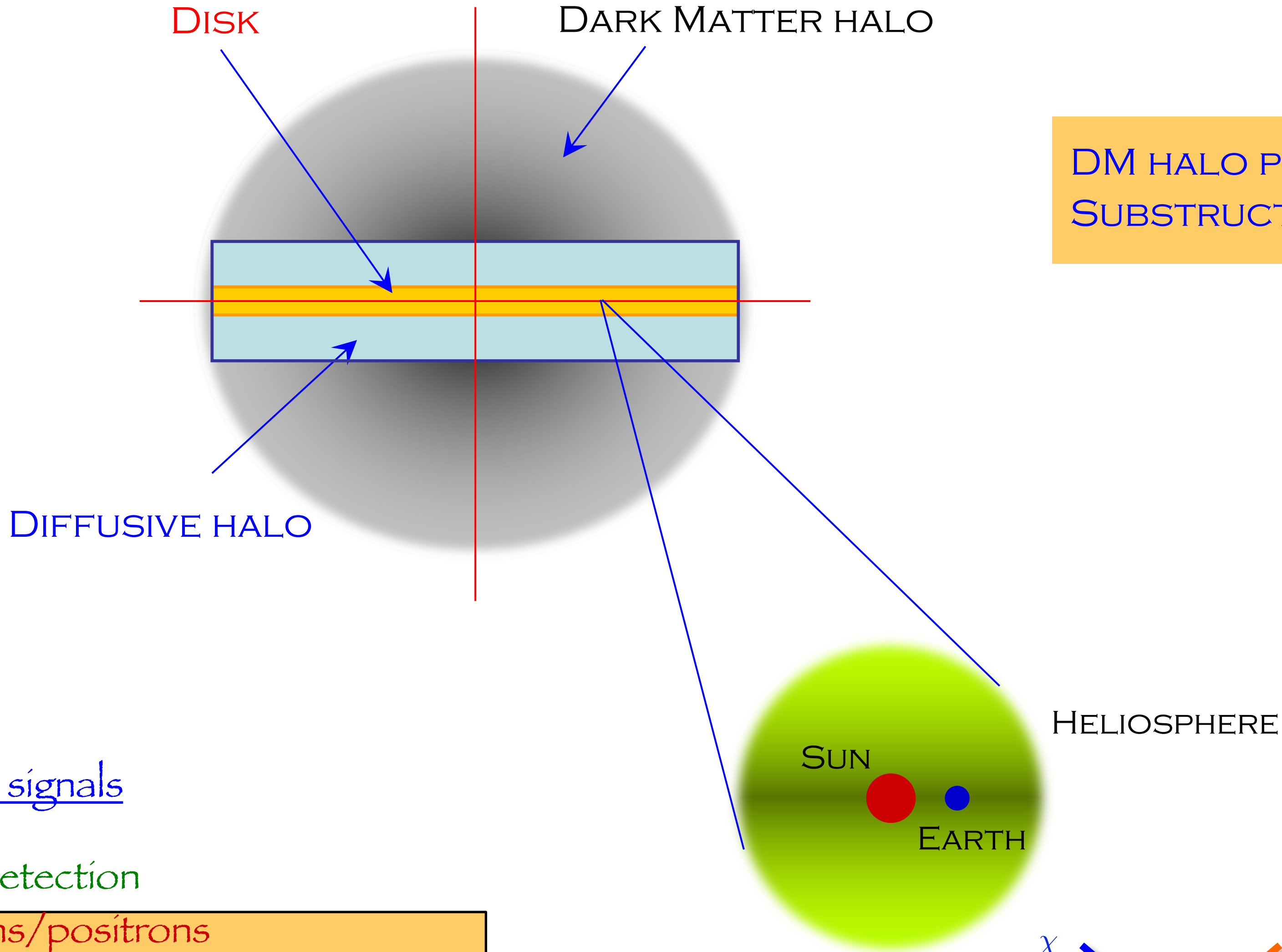
Feels ony the local DM density

Feels (somehow) how DM is locally distributed in velocity space

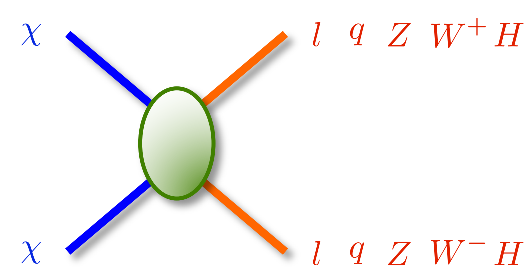
$$S \sim \rho(r_{\text{local}}) \times F[\sigma_{\text{DM-matter}}, \sigma \text{ann}]$$



For the generation of the neutrino signal



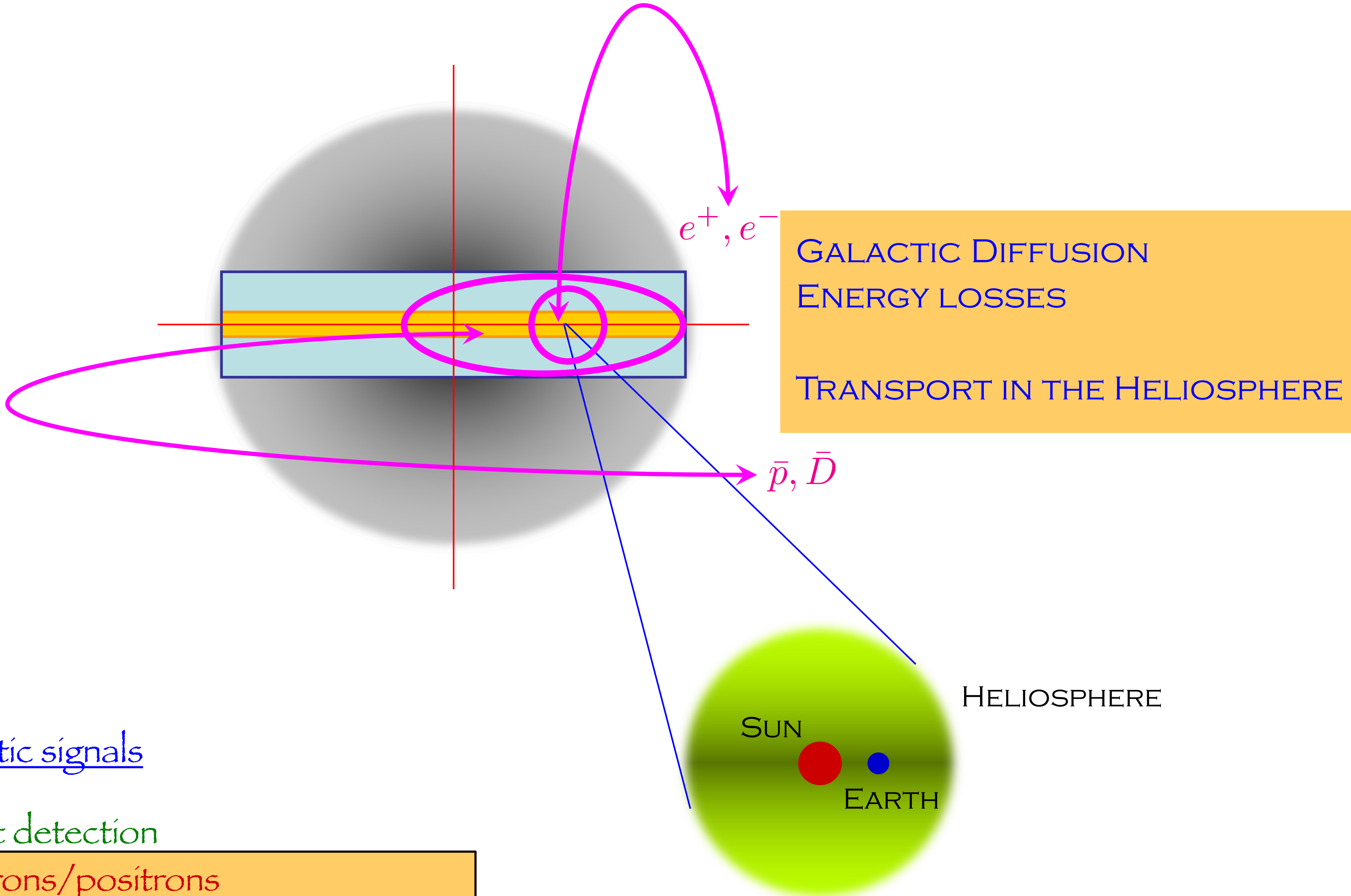
DM halo profile
Substructures



Galactic signals

Direct detection

- Electrons/positrons
- Antiprotons
- Antideuterons
- Photons (from radio to gamma rays)
- Neutrinos from the Galaxy

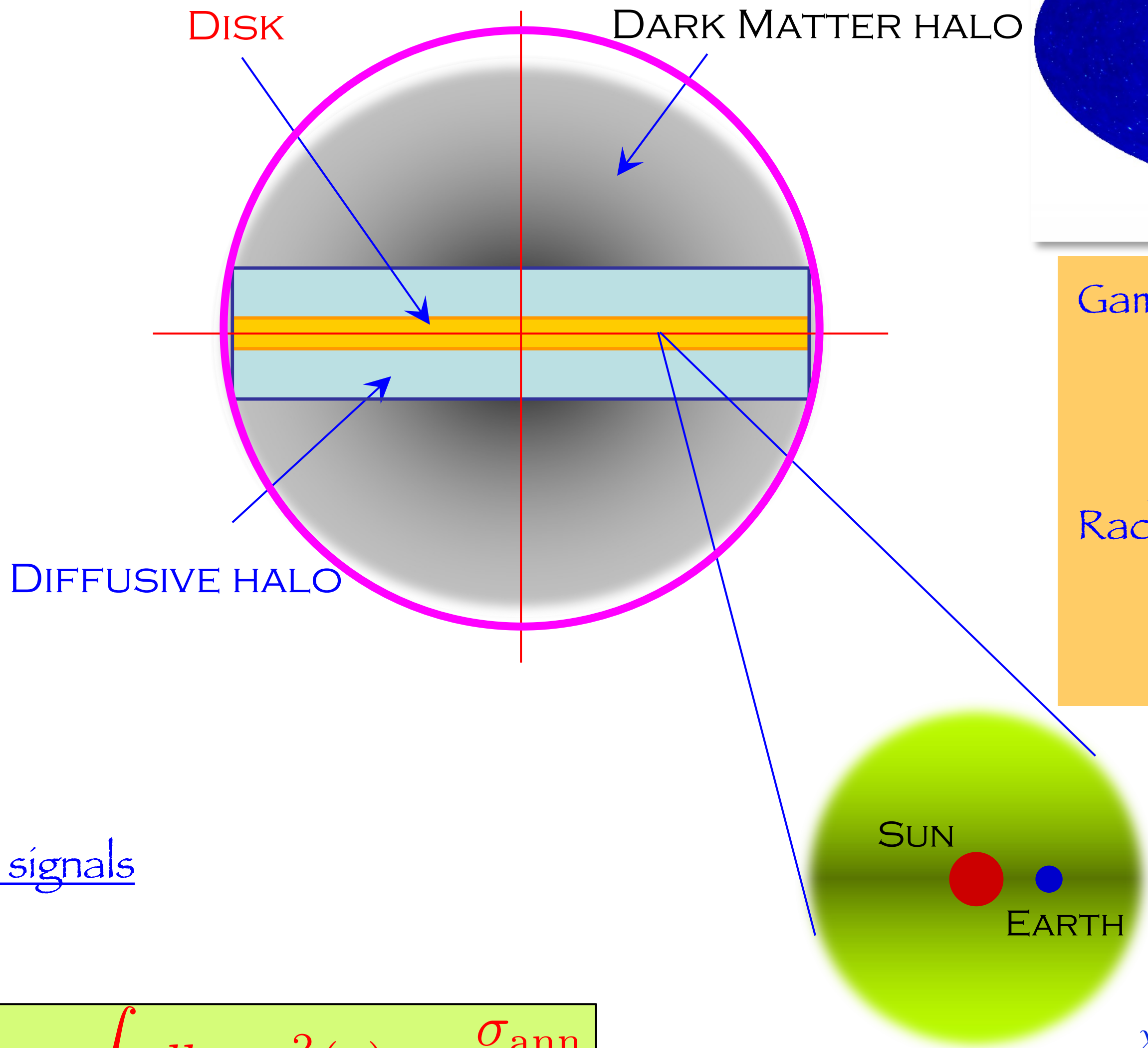


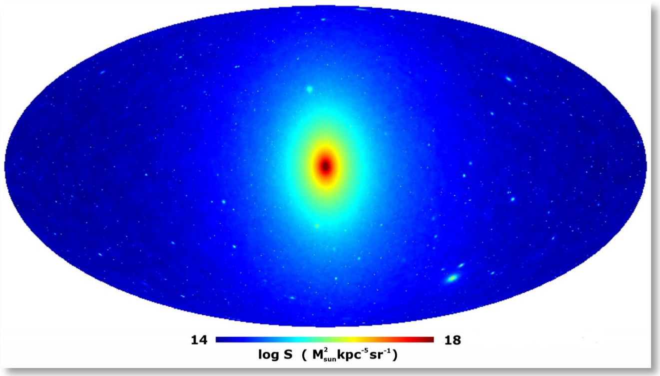
Galactic signals

Direct detection

Electrons/positrons
Antiprotons
Antideuterons

$$S \sim F[\rho^2(r), \text{diffusion, energy losses}] \times \frac{\sigma_{\text{ann}}}{m_{\text{DM}}^2}$$





Gamma rays

prompt (π^0 decay)

IC from e+/e- on ISRF

Radio

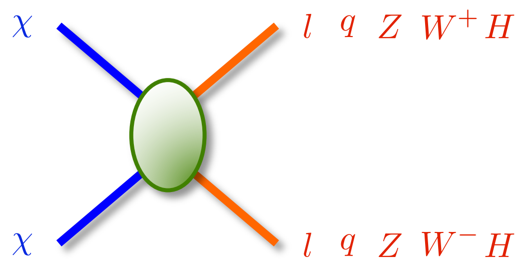
synchrotron emission from e+/e- on galactic B

Galactic signals

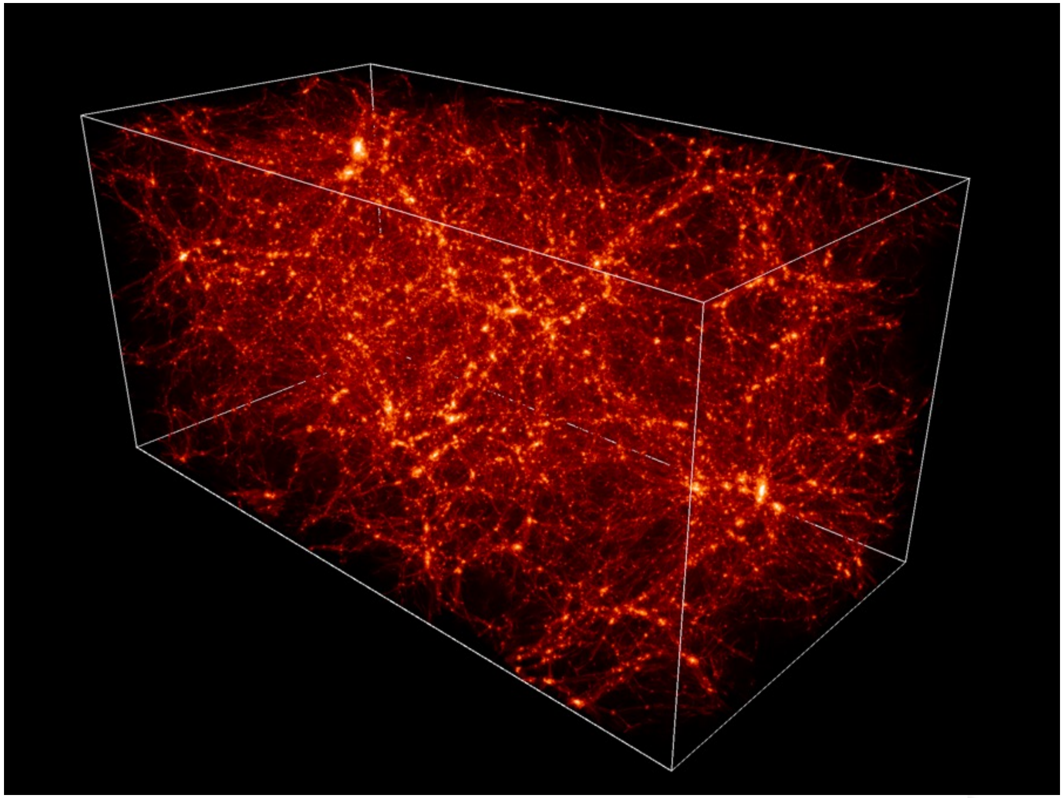
$$S_{\rm prompt} \sim \int dl_{\rm los}\, \rho^2(r) \times \frac{\sigma_{\rm ann}}{m_{\rm DM}^2}$$

Photons (from radio to gamma rays)

Neutrinos from the Galaxy



Extra-galactic environment



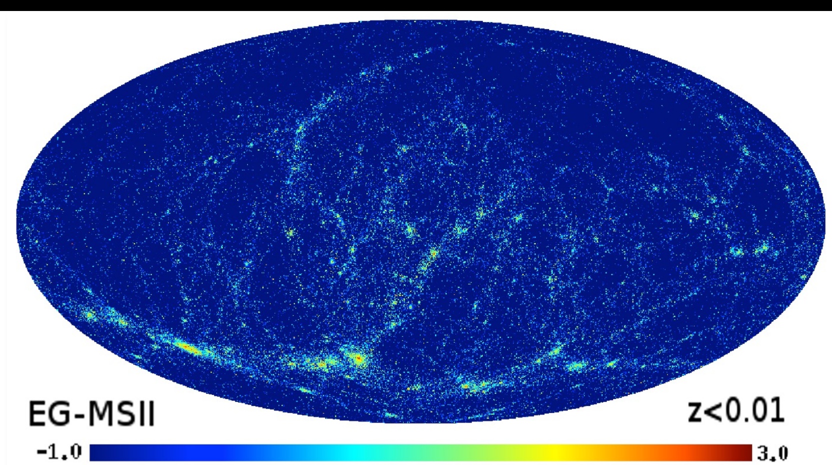
Extragalactic signals

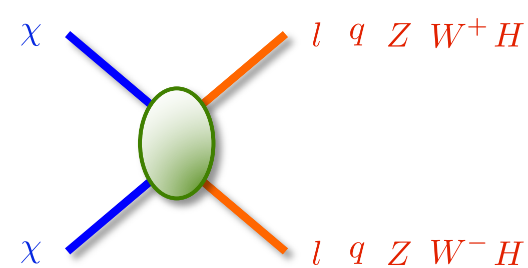
Photons: gamma, X, radio

Neutrinos

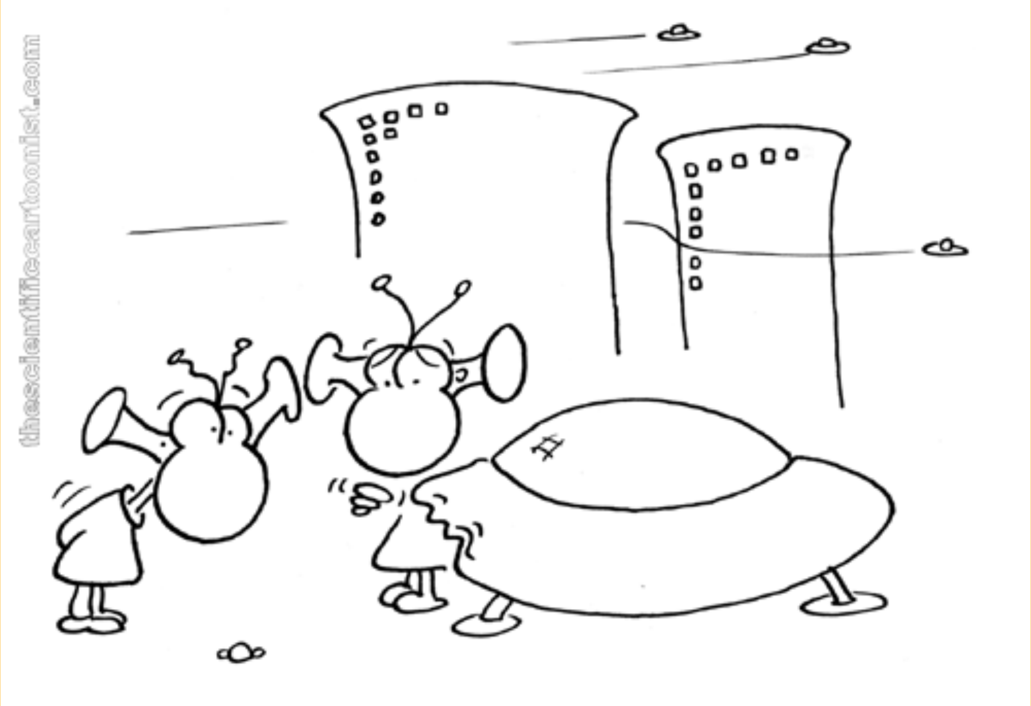
Sunyaev-Zeldovich effect on CMB

Optical depth of the Universe

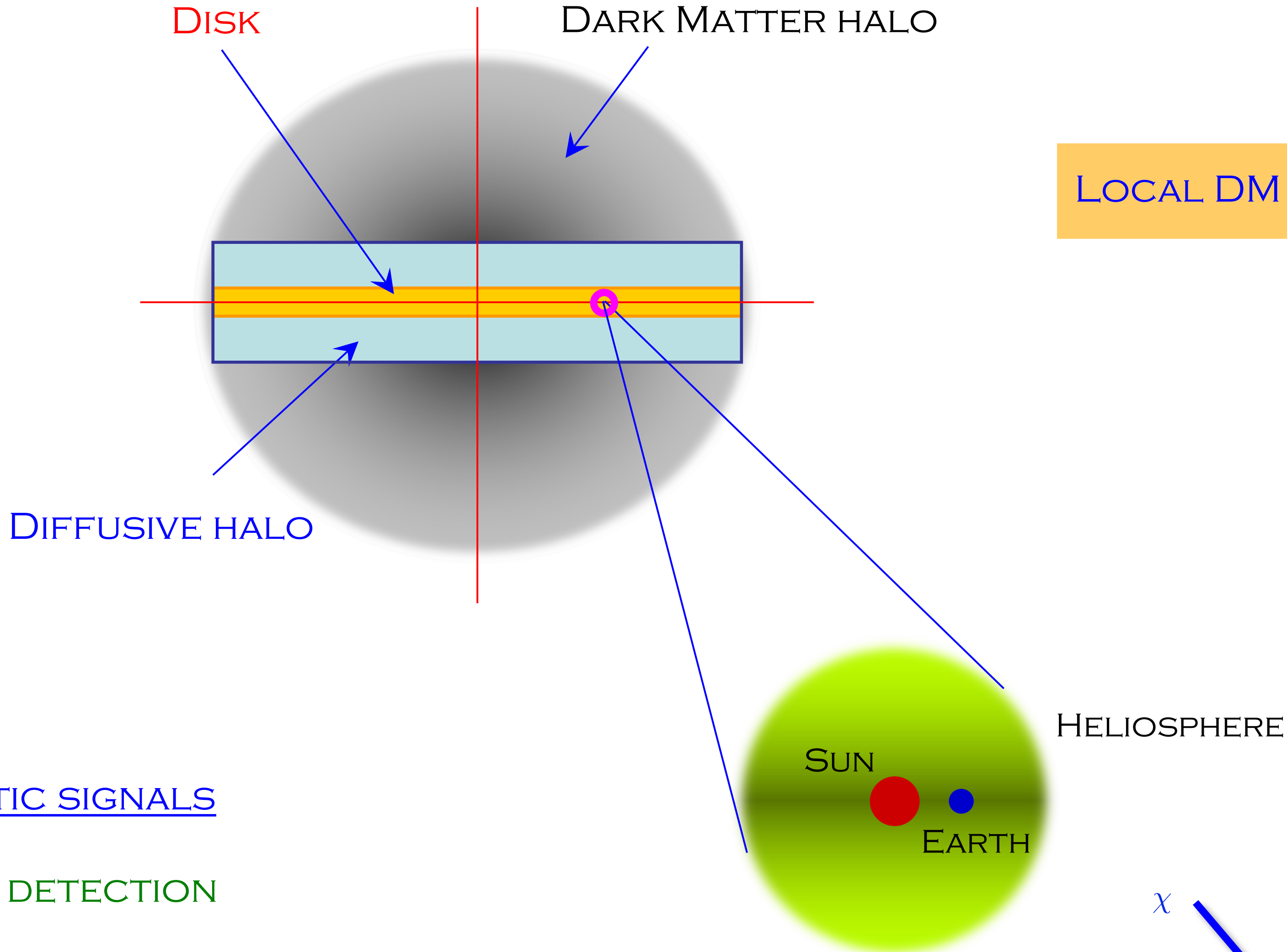




Direct detection of DM



"A piece of dark matter appeared from nowhere and... you know."

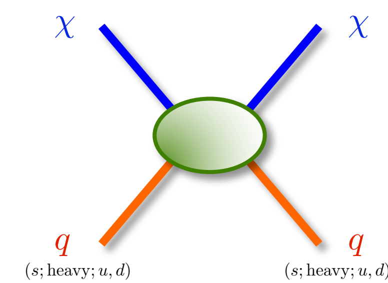


Local DM halo

Galactic signals

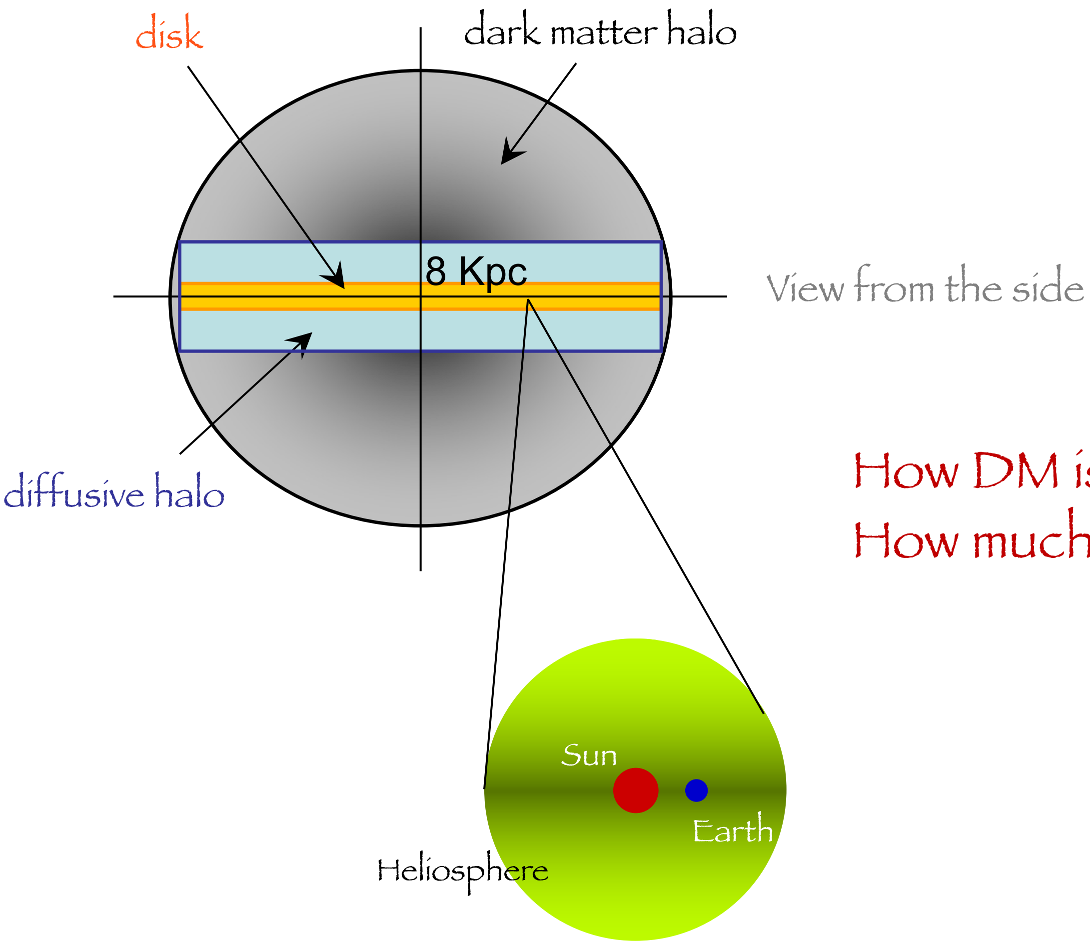
Direct detection

Feels ony the local DM density
Feels how DM is locally distributed in velocity space



DM distribution in Galaxies

Galactic environment



How DM is distributed in the Galaxy?
How much DM is there?

1 pc = 3.26 ly

The vanilla model: isothermal sphere

$$v_0^2 \equiv v_{\rm rot}^2(R_\odot) \; = \; \frac{G}{R_\odot}[M_{\rm vis} + M_{\rm DM}]$$

$$\rho_{\rm DM}(r) = \frac{v_0}{4\pi G}\,\frac{1}{r^2} \longrightarrow \frac{v_0}{4\pi G}\,\frac{r^2 + 3R_c^2}{(r^2 + R_c^2)^2}$$

unphysical at small r

$$f(v) = N \exp\left(-v^2/v_0^2\right)$$

Numerical simulations

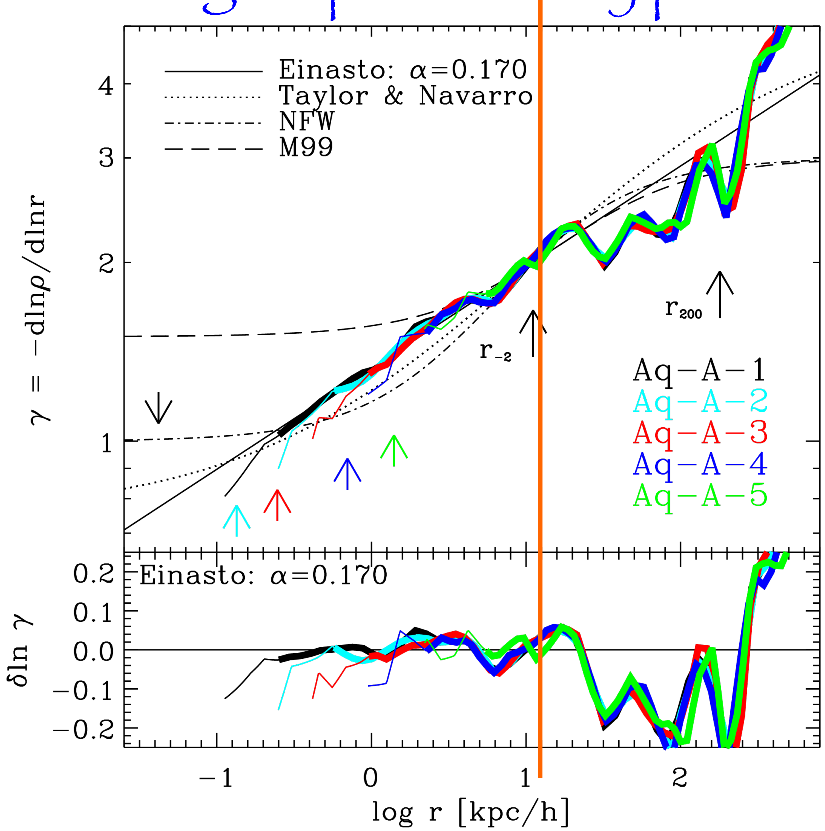
Cold Dark Matter — N-body

Gas coolings, photo-ionization
Star formation, ISM model
Stellar evolution — Hydrodinamical
Stellar feedback (winds)
Black holes and SMBH feedback

Volume: $(100\ \mathrm{Mpc})^3$
DM particles/cells: 10^9 - 10^{10}

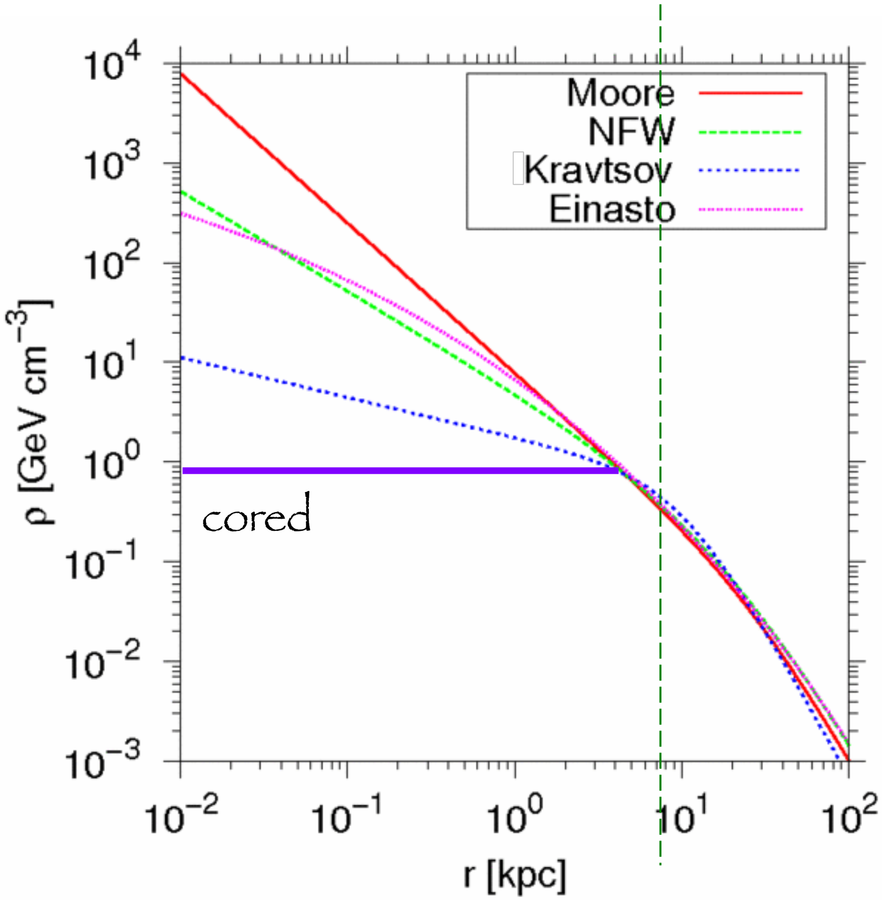
Density profile: smooth component

Log-slope of density profile

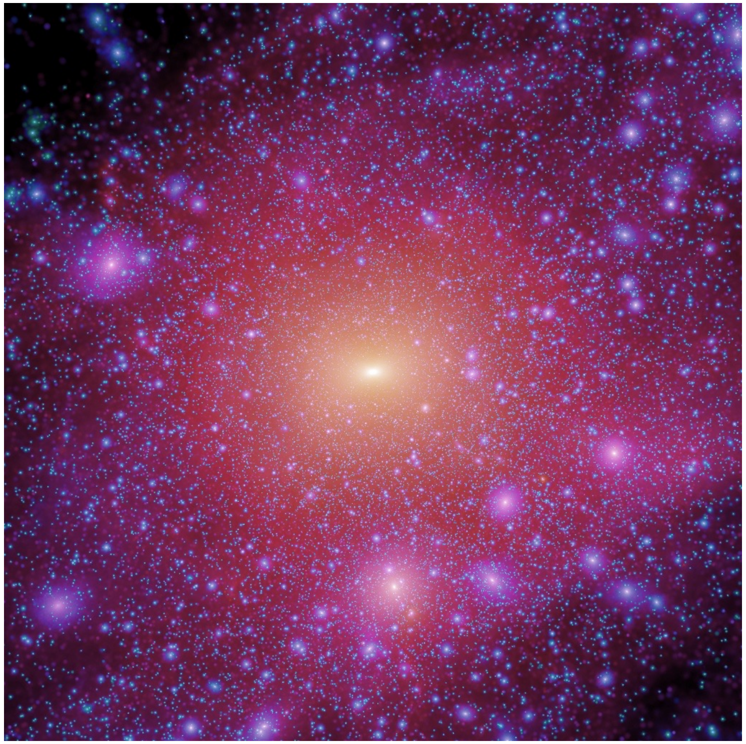


From numerical simulations

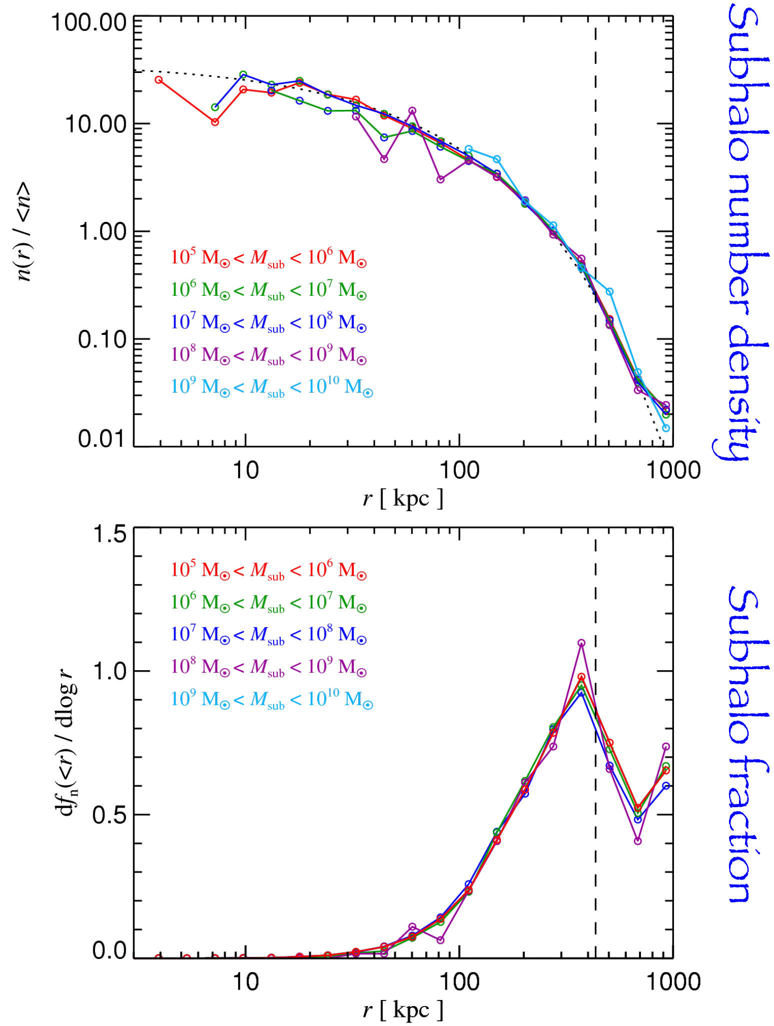
Navarro et al., arXiv:0810.1522



CDM: Subhalos



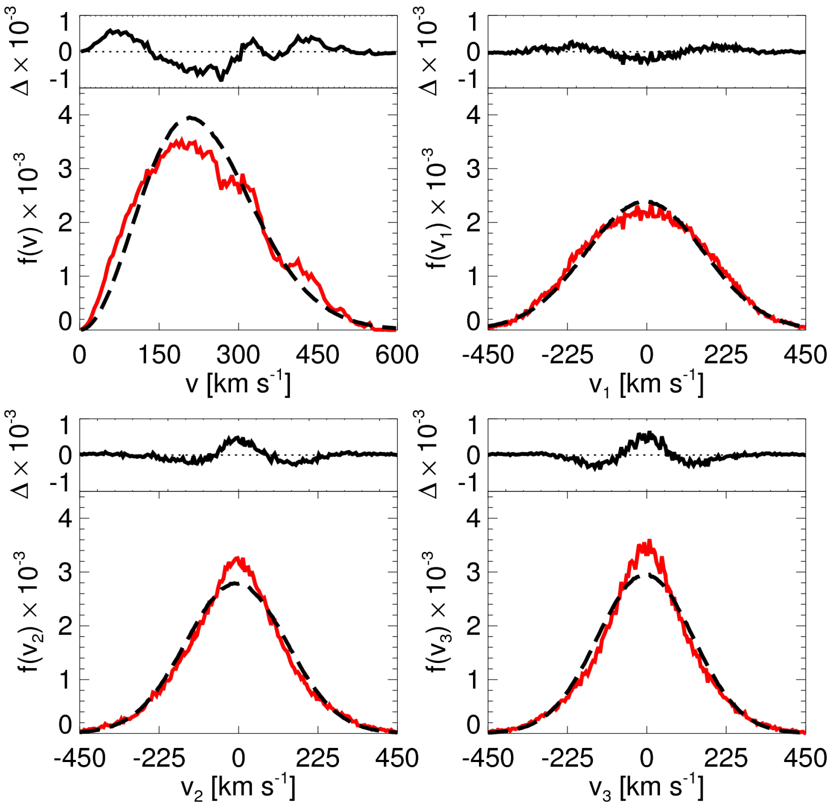
The Aquarius Project



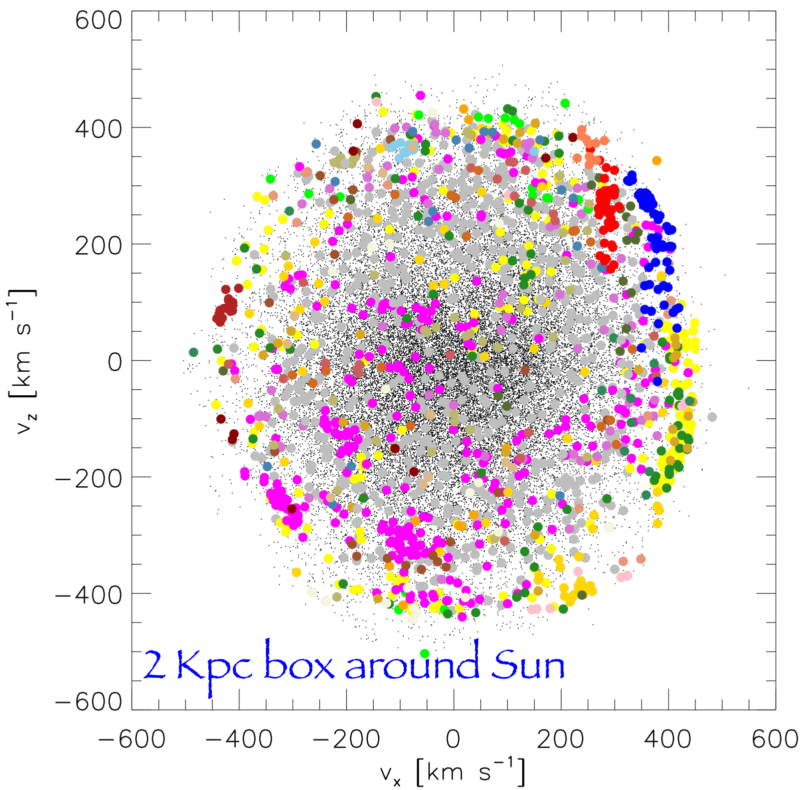
Most subhalos are in the outer halo

Springel et al., MNRAS 391 (2008) 1685

Velocity distribution (at Sun's position)



Velocity streams



From numerical simulations

Vogelsberger et al., arXiv:0812.0362

Vogelsberger et al., arXiv:0812.0362

“Canonical” halo

$\rho(r) \longrightarrow \rho_0 = 0.3\ \mathrm{GeV\ cm^{-3}}$

$\rho(r) \longrightarrow r^{-1}\ [r \to 0]$

Some determinations [1-3]

[1] $\rho_0 = 0.385 \pm 0.027\ \mathrm{GeV\ cm^{-3}}$ (Einasto)
$\rho_0 = 0.389 \pm 0.025\ \mathrm{GeV\ cm^{-3}}$ (NFW)

[2] $\rho_0 = 0.43(11)(10)\ \mathrm{GeV\ cm^{-3}}$

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm\ 50)\mathrm{km\ s^{-1}}$$

$$v_{\rm esc} = (450 \div 650)\ \mathrm{km\ s^{-1}}$$

[1] Catena, Ullio, arXiv:0907.0018
[2] Salucci et al. arXiv:1003.3101
[3] Pato et al., arXiv:1006.1322

“Canonical” halo

$$\rho(r) \longrightarrow \rho_0 = 0.3 \text{ GeV cm}^{-3}$$

Debated whether cuspy or cored

Effect of baryons unclear

$$\rho(r) \longrightarrow r^{-1} \; [r \to 0]$$

Substructures likely are present (although sparsely distributed, mostly in the outer parts (anti-biased)

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm \; 50)\text{km s}^{-1}$$

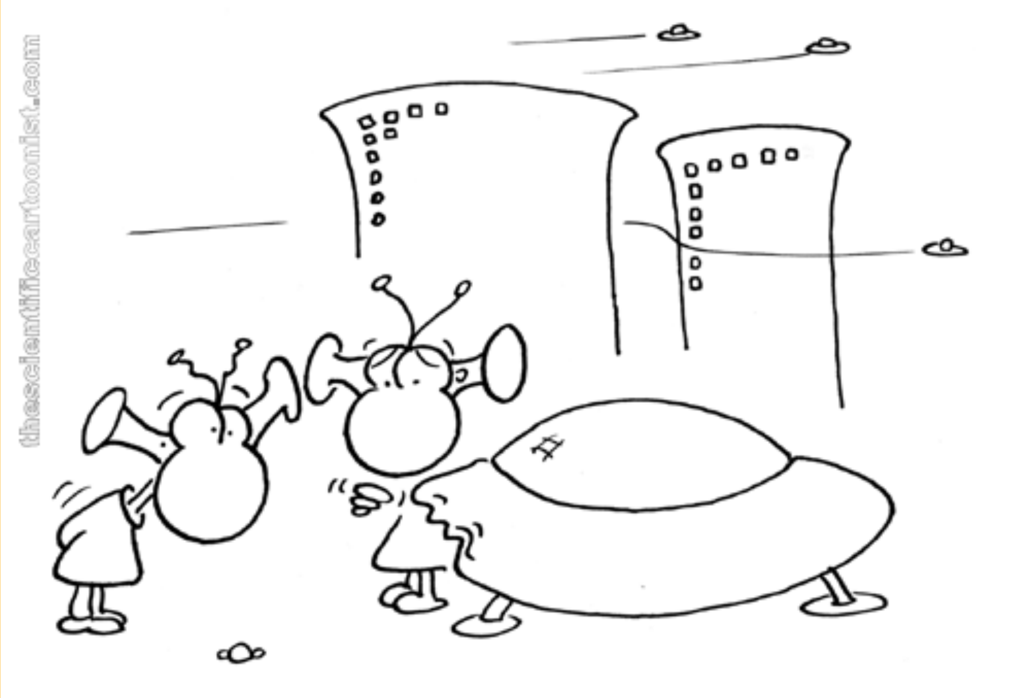
$$v_{\rm esc} = (450 \div 650) \text{ km s}^{-1}$$

Anisotropies may be present

The high-v tail may not be fully “thermal”

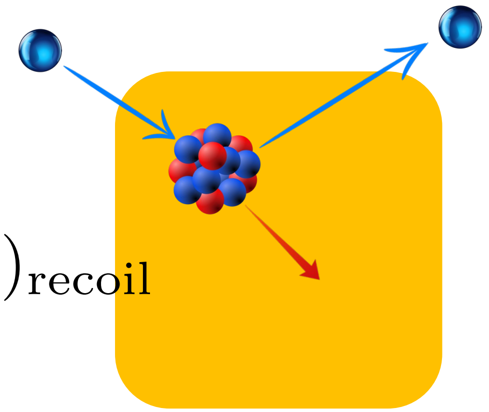
Streams may have impact

Direct detection of DM



"A piece of dark matter appeared from nowhere and... you know."

Direct detection signal



Typical process for WIMP DM

$$\chi + \mathcal{N}(A_{\mathcal{N}}, Z_{\mathcal{N}})_{\text{at rest}} \to \chi + \mathcal{N}(A_{\mathcal{N}}, Z_{\mathcal{N}})_{\text{recoil}}$$

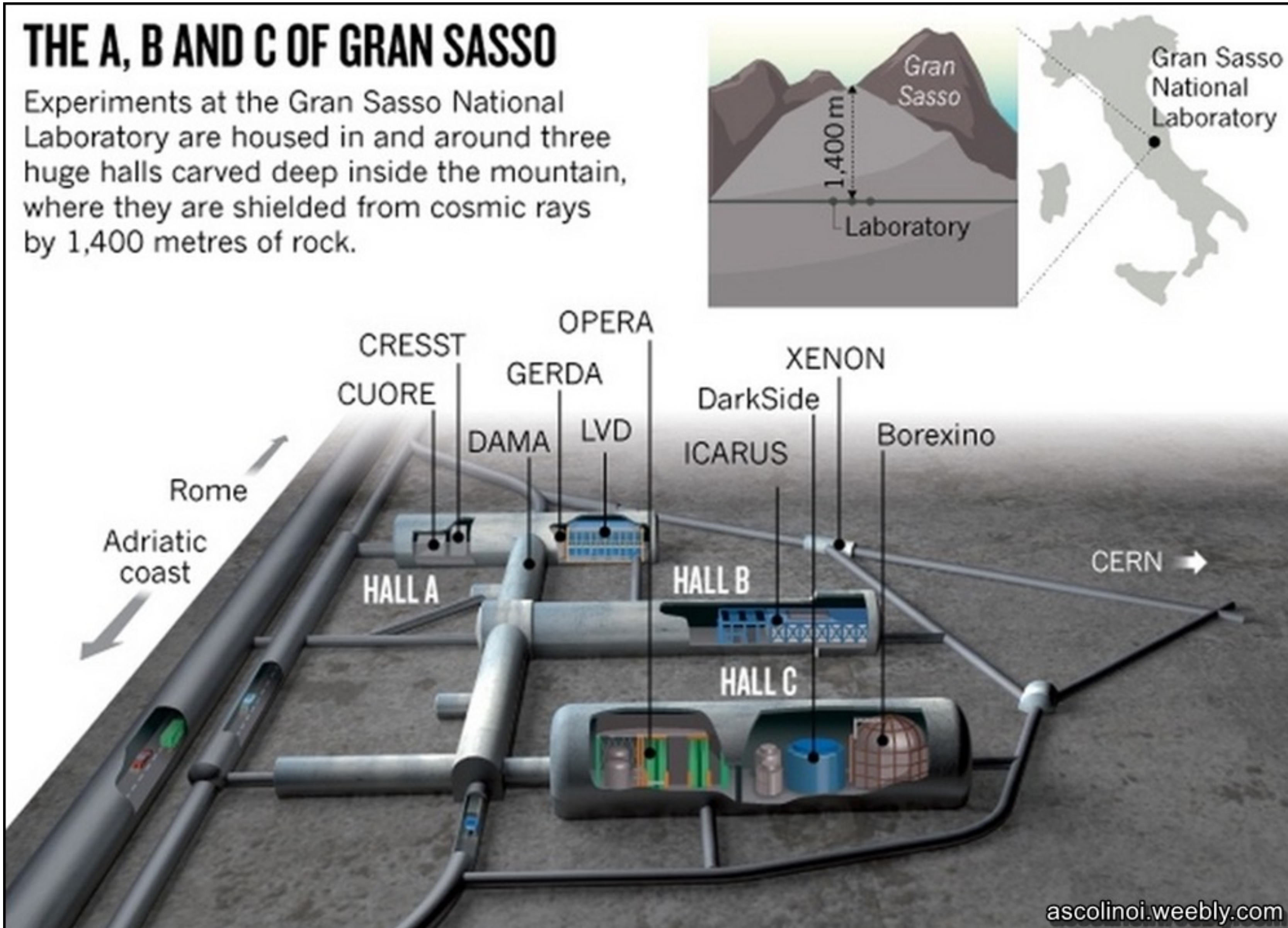
Recoil rate

$$\frac{dR}{dE_R} = \frac{\xi_{\mathcal{N}}}{m_{\mathcal{N}}} \frac{\rho_{\odot}}{m_{\chi}} \int_{v_{\min}(E_R)}^{v_{\text{esc}}} d^3v \, v \, f_E(\vec{v}) \frac{d\sigma_{\mathcal{N}}}{dE_R}(v, E_R)$$

For non-WIMP (kev, MeV) DM: interaction on electrons

Underground Labs

LNGS – Gran Sasso Lab (INFN)



Interaction mechanisms

- Elastic scattering with nuclei $\chi\,\mathcal{N} \longrightarrow \chi\,\mathcal{N}$
  - Coherent coupling to nucleons
  - Coupling the nucleus spin
  - Long-range mediators
  - Electric/magnetic dipole-moment interactions
  - ...
- Inelastic scattering with nuclei $\chi\,\mathcal{N} \longrightarrow \chi'\,\mathcal{N}$
  - Scatter requires a mass difference between X and X' of the order of 1-100 keV
- Scattering on electrons

Interaction mechanisms

- Elastic scattering with nuclei — WIMP DM (GeV-TeV^{+})

$$E_R = \mu_{\mathcal{N}}^2 v^2 (1-\cos\theta)/m_{\mathcal{N}}$$

$$\langle E_{\mathrm{R}} \rangle \sim \mathrm{KeV} \left(\frac{m_{\mathcal{N}}}{\mathrm{GeV}}\right) \left(\frac{m_\chi}{m_\chi + m_{\mathcal{N}}}\right)^2$$

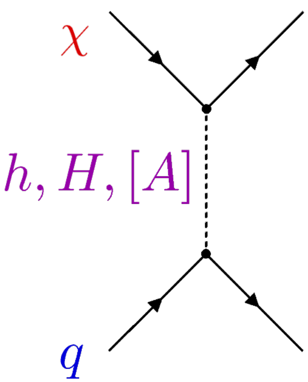
E_R > few KeV

- Inelastic scattering with nuclei — WIMP DM (GeV-TeV^{+})

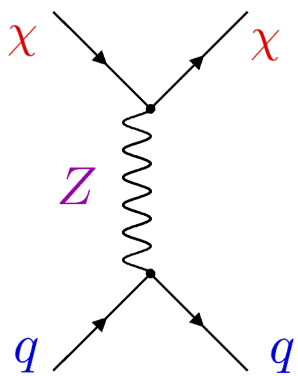
- Scattering on electrons — Light (keV) [pseudo]scalars

Example: Neutralino-quark scattering

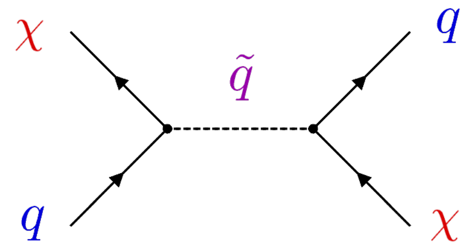
$\chi q \to \chi q$	$\tilde{q}_L, \tilde{q}_R$	s channel
	Z, h, H, A	t channel
	$\tilde{q}_L, \tilde{q}_L$	u channel



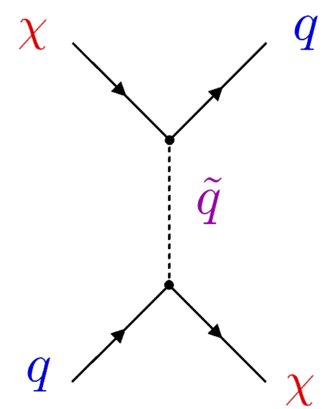
coherent



spin



coherent
spin



coherent
spin

Cross section

$$\mathcal{L}_{\rm eff} = \sum_i \bar{\alpha}_i (\bar{q} O q) \, (\bar{\chi} O' \chi)_i$$

$$\mathcal{L}_{\rm eff} \longrightarrow < N|\bar{q}Oq|N > \propto \bar{\psi}_{\rm N} O \psi_{\rm N} \longrightarrow < \mathcal{N} \left| \bar{\psi}_{\rm N} O \psi_{\rm N} \right| \mathcal{N} \rangle$$

$$\begin{aligned} \mathcal{M} &= \langle \mathcal{N}, \chi \left| \mathcal{L}_{\rm eff} \right| \mathcal{N}, \chi \rangle \\ &= \sum_i \langle \mathcal{N} \left| \bar{\psi}_{\rm N} O \psi_{\rm N} \right| \mathcal{N} \rangle \langle \chi \left| \bar{\chi} O' \chi \right| \chi \rangle_i \end{aligned}$$

Cross section

Scattering amplitude on nucleon n

$$\mathcal{M}_n = \sum_{i=1}^{16} c_i^n(\lambda, m_\chi)\, \mathcal{O}_i^{\mathrm{NR}}$$

Basis of 16 non-relativistic operators

λ: parameters of the underlying non-relativistic theory (mediator masses, couplings, ...)

Fitzpatrick et al, JCAP 1302 (2013) 004
Fitzpatrick et al, arXiv:1211.2818
Anand et al, PRC 89 (2014) 065501
Dent et al, PRD 92 (2015) 063515

Set of operators

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$ scalar

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$ spin

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

$$\hat{\mathcal{O}}_{17} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp\right)$$

$$\hat{\mathcal{O}}_{18} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N\right)$$

Catena, JCAP 1407 (2014) 055
Arina, Del Nobile, Panci, PRL 114 (2015) 011301
Scopel, Yoon, JCAP 1507 (2015) 041
Catena, Gondolo, JCAP 08 (2015) 022
Gluscevic et al, JCAP 12 (2015) 057
Catena, Ibarra, Wild JCAP 05 (2016) 039
Kalhofer, Wild, arXiv:1607.04418
(...)

Fitzpatrick et al, JCAP 1302 (2013) 004
Fitzpatrick et al, arXiv:1211.2818
Anand et al, PRC 89 (2014) 065501
Dent et al, PRD 92 (2015) 063515

Cross section

Scattering amplitude on nucleon n

$$\mathcal{M}_n = \sum_{i=1}^{16} c_i^n(\lambda, m_\chi)\, \mathcal{O}_i^{\rm NR}$$

Basis of 16 non-relativistic operators

λ: parameters of the underlying non-relat. theory
(mediator masses, couplings, ...)

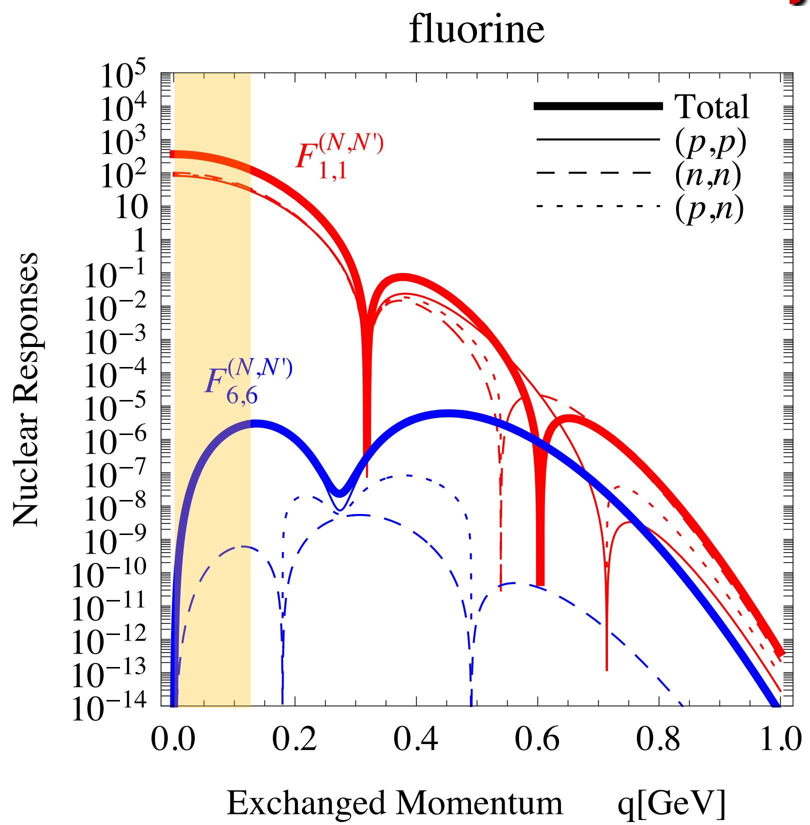
Transition probability on nucleus $\mathcal{N}$

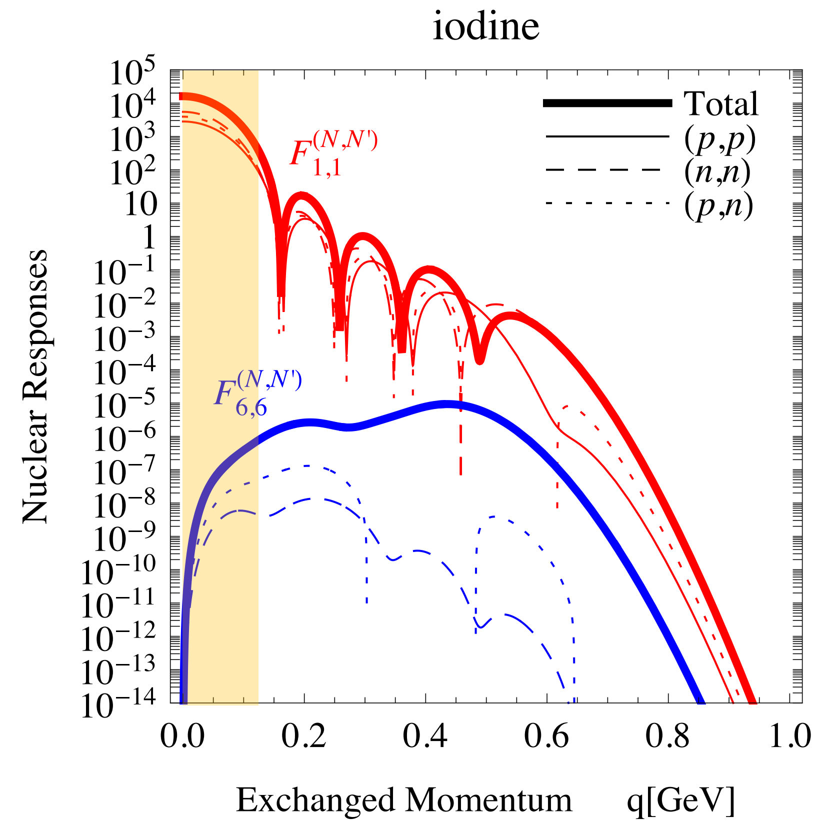
$$\overline{|\mathcal{M}_\mathcal{N}|^2} = \frac{m_\mathcal{N}^2}{m_n^2} \sum_{i,j=1}^{16} \sum_{n,n'=p,n} c_i^n c_j^{n'} F_{i,j}^{(n,n')}(v, E_R|\mathcal{N})$$

nuclear response functions

Fitzpatrick et al, JCAP 1302 (2013) 004

Nuclear response functions





(1,1): $\mathcal{O}_1^{\rm NR} = \mathbb{1}$ "Vanilla" coherent scattering
A^2 enhanced

(6,6): $\mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})\,(\vec{s}_n \cdot \vec{q})$ e.g., pseudo-scalar mediator
scattering on p dominant (no unpaired n on F and I)

Cross section

Cross section on nucleus $\mathcal{N}$

$$\frac{d\sigma_{\mathcal{N}}}{dE_R}(v, E_R) = \frac{1}{32\pi}\frac{1}{m_\chi^2 m_{\mathcal{N}}}\frac{1}{v^2}\overline{|\mathcal{M}_{\mathcal{N}}|^2}$$

Non-relativistic scattering on nucleons -> nucleus

Relevant quantities:

$\vec{v}$	DM velocity	m_χ	DM mass
$\vec{q}$	Exchanged momentum	m_n	nucleon mass
$\vec{s}_n$	Nucleon spin	$m_{\mathcal{N}}$	nucleus mass
$\vec{s}_\chi$	DM spin		

Summarizing

$$\frac{dR_{\mathcal{N}}}{dE_R} = K \rho_{\odot}\, \xi_{\mathcal{N}} \sum_{i,j=1}^{16} \sum_{n,n'=p,n} c_i^n(\lambda, m_\chi)\, c_j^{n'}(\lambda, m_\chi)\, \mathcal{F}_{i,j}^{(n,n')}(E_R, \mathcal{N})$$

$$\mathcal{F}_{i,j}^{(n,n')}(E_R, \mathcal{N}) = \int_{v_{\min}(E_R)}^{v_{\rm esc}} d^3v\, \frac{1}{v}\, f_{\rm G}(\vec{v} + \vec{v}_{\rm E}(t))\, F_{i,j}^{(n,n')}(v, E_R, \mathcal{N})$$

Structure of the interaction
Nuclear response
Galactic modeling
Local motions

Sun/Earth revolution in the Galaxy	stationary boost
Earth revolution around the Sun	annual periodicity
Earth rotation around its axis	diurnal periodicity

Interaction rate (WIMP ; scalar interaction)

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\text{scalar}}^{(\text{nucleon }\,)}\right] F^2\left(E_R\right) \mathcal{I}\left(v_{\min}\right)$$

$$\mathcal{I}(v_{\min}) = \int_{w \geq v_{\min}} d^3 w \;\; \frac{f_{\text{ES}}(\vec{w})}{w}$$

$$f_{\text{ES}}(\vec{w}) = f(\vec{w} + \vec{v}_{\oplus})\big|_{[v_{\text{rot}};v_{\text{esc}}]}$$

$$v_{\min} = [m_N E_R/(2\mu_A^2)]^{1/2}$$

Interaction rates

Spin-independent (scalar)

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\text{scalar}}^{(\text{nucleon})}\right] F^2(E_R)\, \mathcal{I}(v_{\min})$$

Spin-dependent

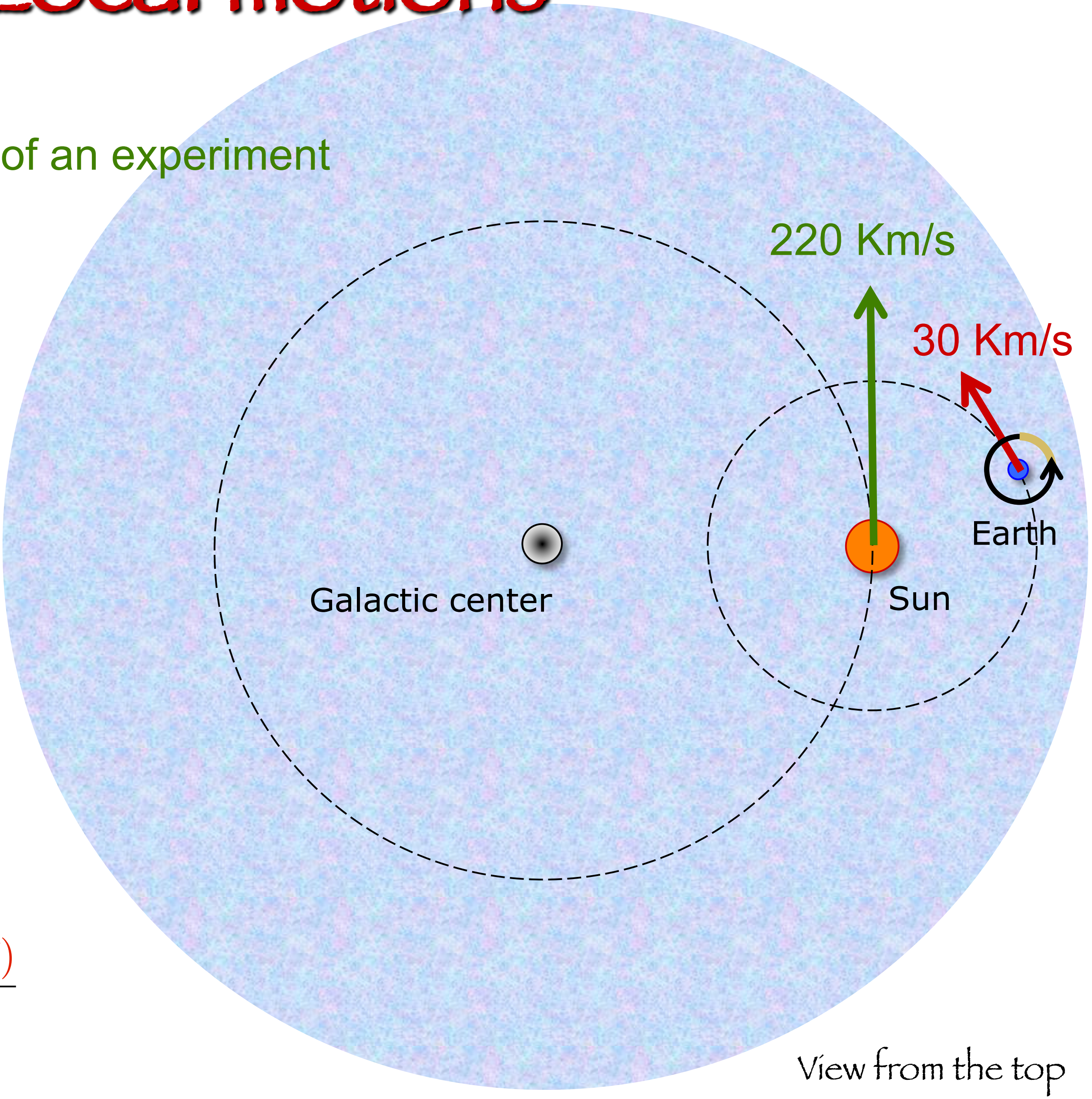
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{2m_N}{\mu_1^2} \lambda J(J+1) \left[\sigma_{\text{spin}}^{(\text{nucleon})}\right] F^2(E_R)\, \mathcal{I}(v_{\min})$$

Local motions

Stationary over the lifetime of an experiment

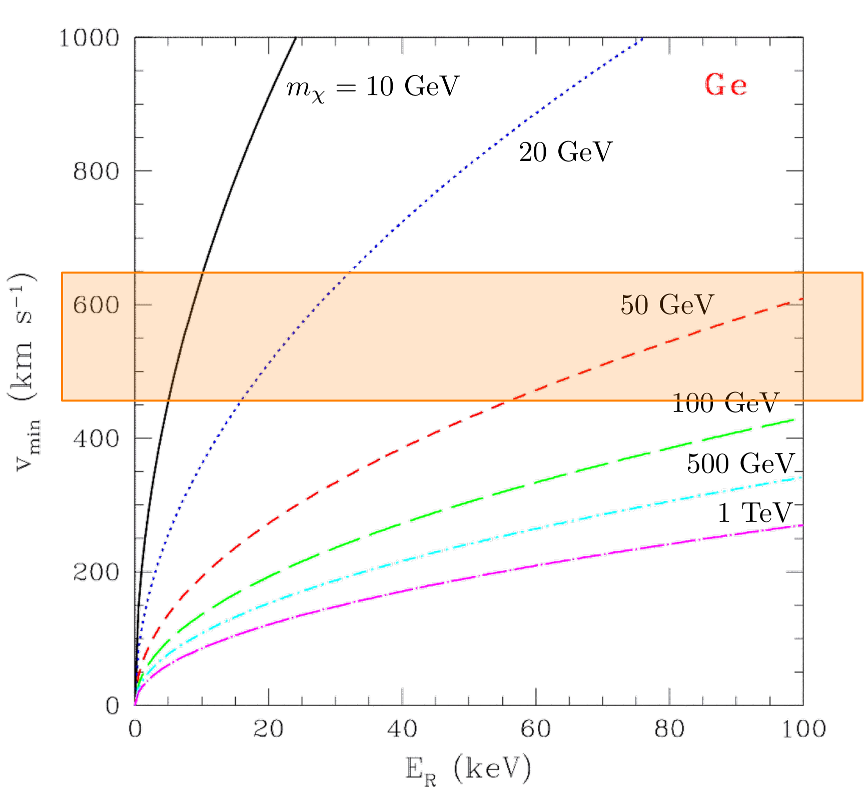
Directional boost

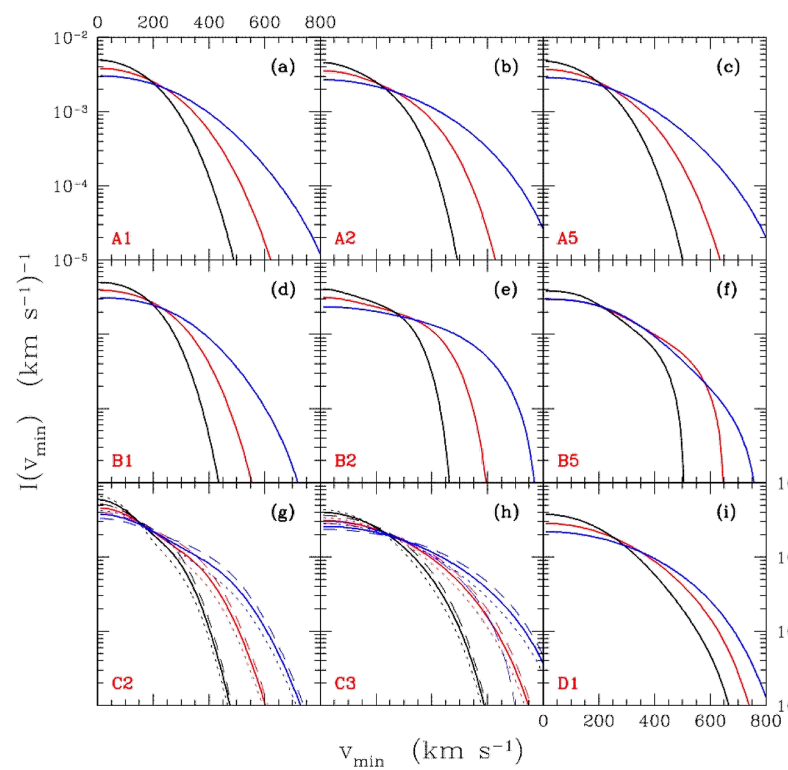


$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \ \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot};v_{\rm esc}]}$$

Response function

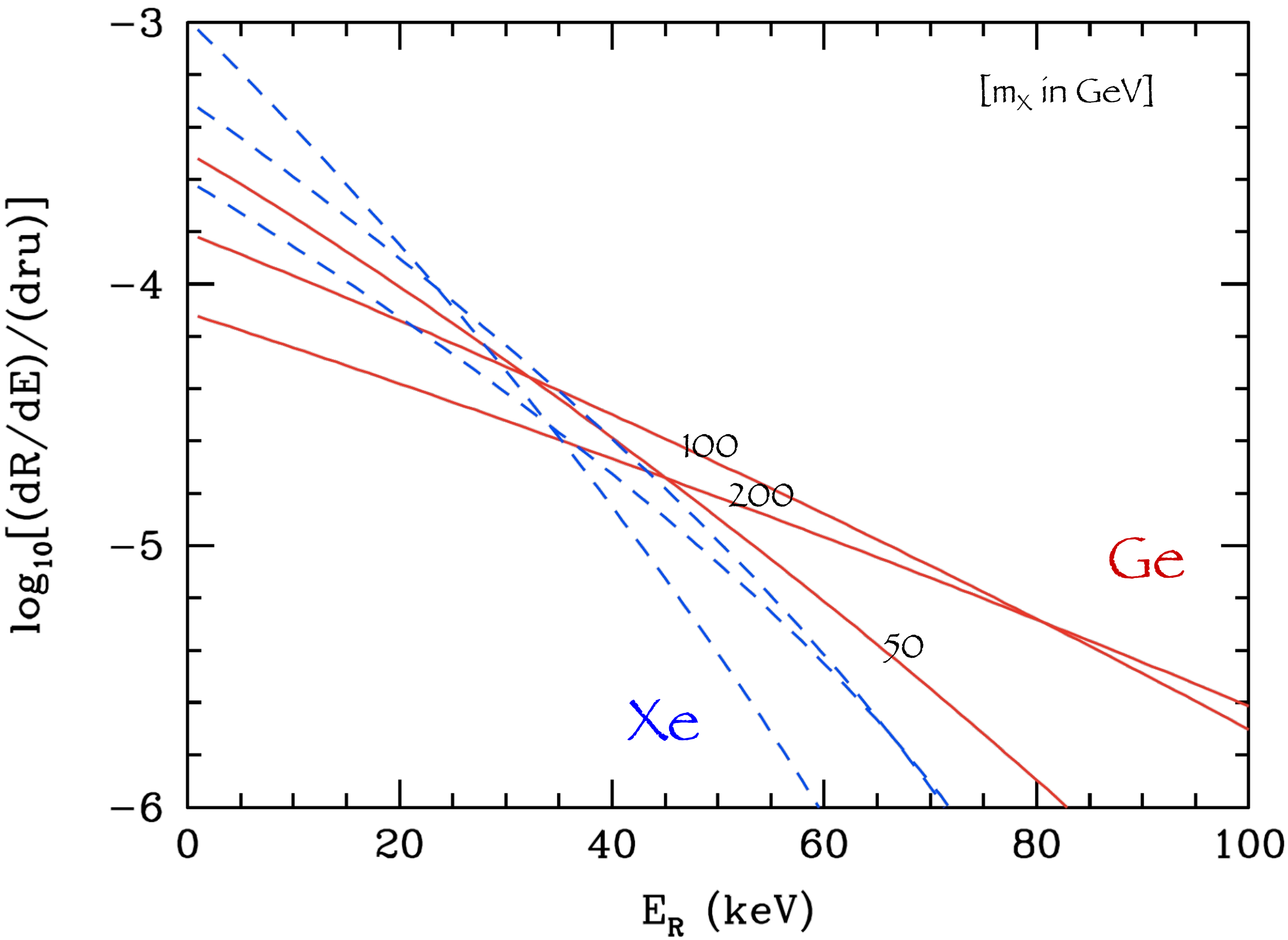




$$v_{\text{min}} = [m_N E_R / (2\mu_A^2)]^{1/2}$$

$$\mathcal{I}(v_{\text{min}}) = \int_{w \geq v_{\text{min}}} d^3w \; \frac{f_{\text{ES}}(\vec{w})}{w}$$

Differential Rate – Energy Dependence



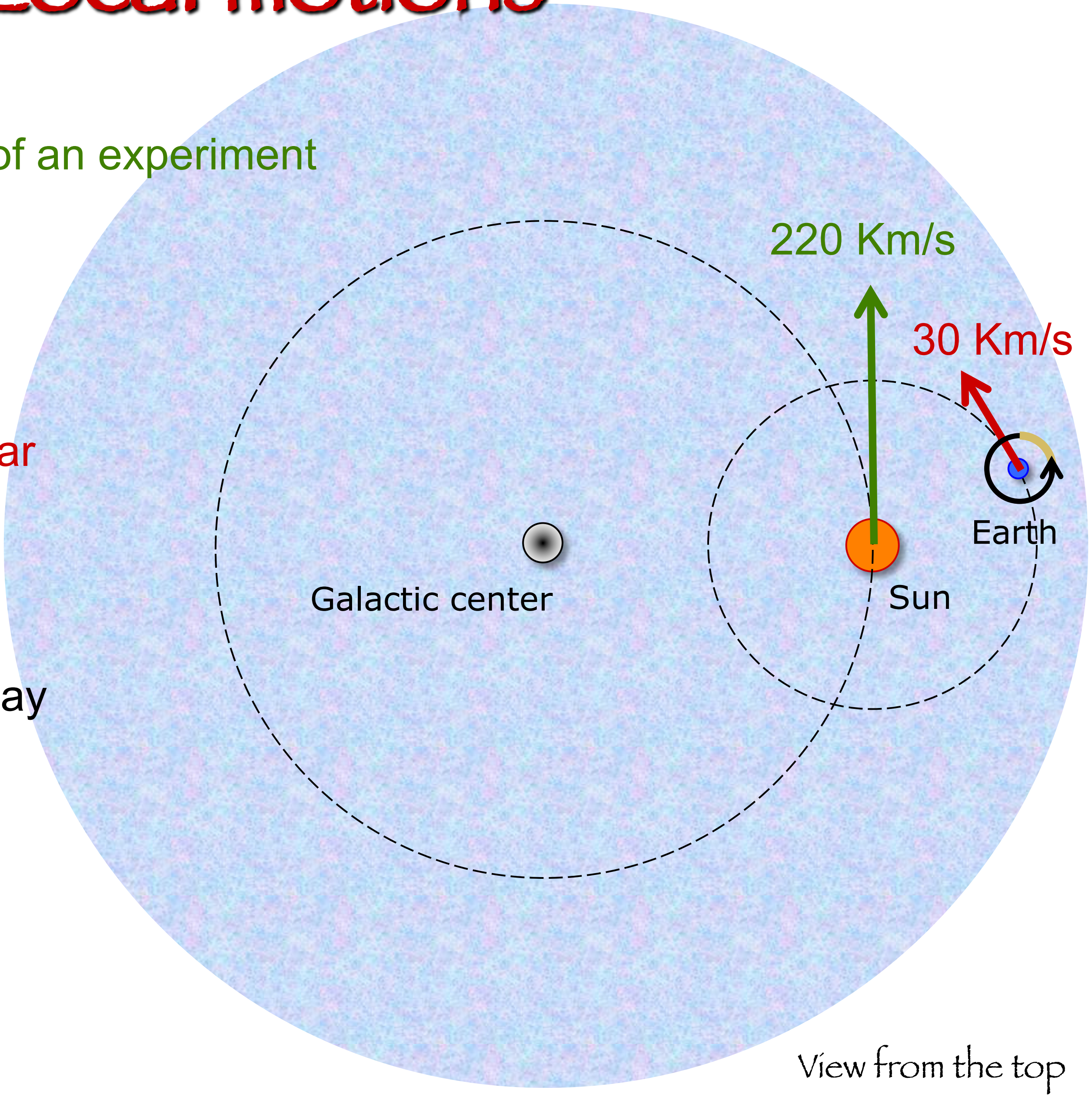
Local motions

Stationary over the lifetime of an experiment

Directional boost

Orbital motion - Period: 1 year

Diurnal rotation - Period: 1 day



$$\mathcal{I}(v_{\min}) = \int_{w \geq v_{\min}} d^3w \ \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot};v_{\rm esc}]}$$

Typical signatures of direct detection

Stationary over the lifetime of an experiment

Directional boost

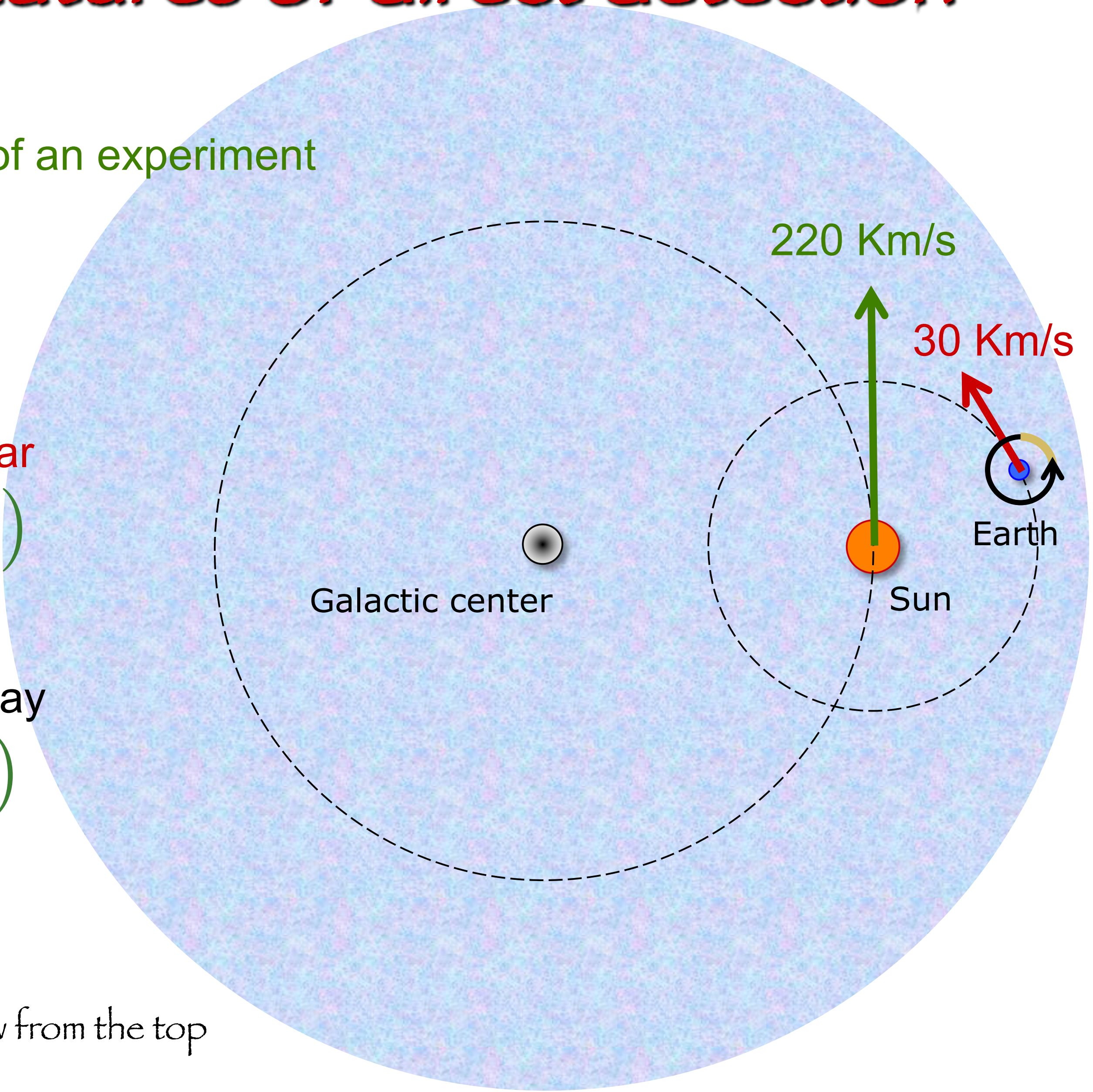
Directionality $\vec{v}$

Orbital motion - Period: 1 year

Annual modulation $\vec{v}(t)$

Diurnal rotation - Period: 1 day

Diurnal modulation $\vec{v}(t)$



View from the top

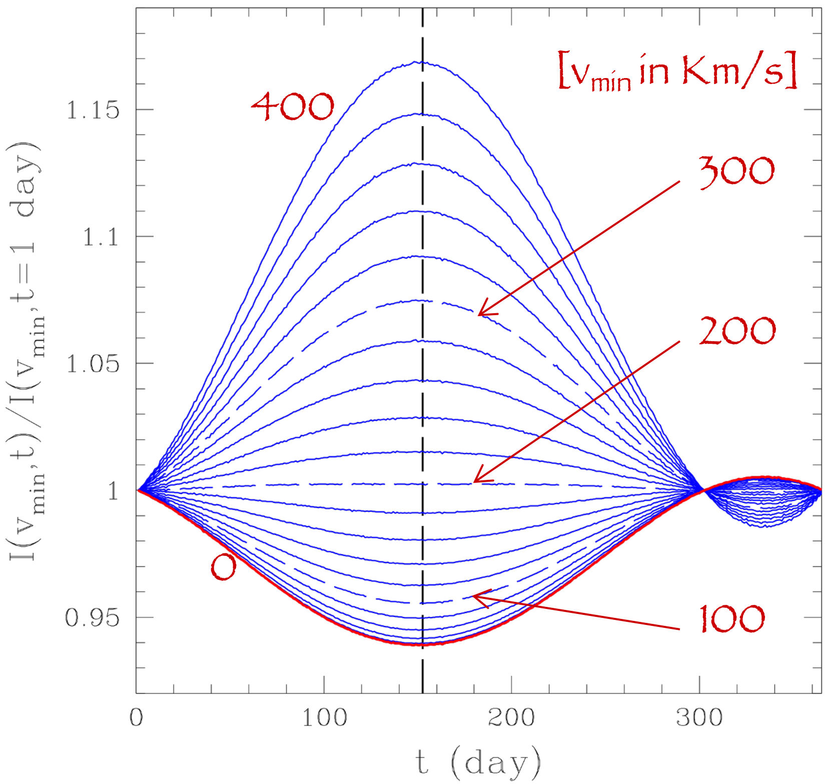
Annual Modulation of the rate

$$\frac{dR}{dE_R}[\eta(t)] = \frac{dR}{dE_R}[\eta_0] + \frac{\partial}{\partial\eta}\left(\frac{dR}{dE_R}\right)_{\eta=\eta_0} \Delta\eta\ \cos[\omega(t-t_0)]$$

$$= S_0(E_R) + S_m(E_R)\ \cos[\omega(t-t_0)]$$

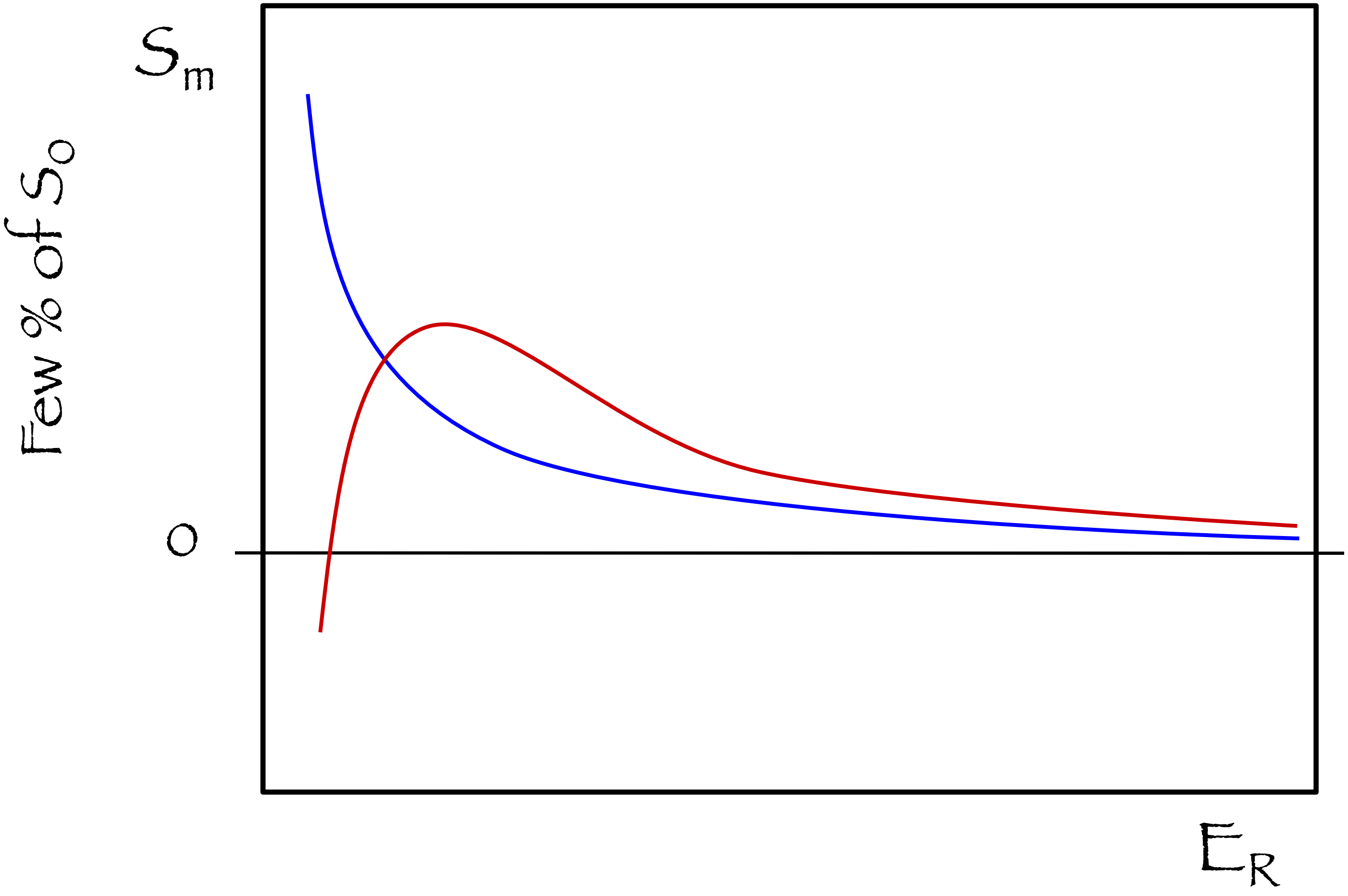
$$\eta(t) = v(t)/v_0$$

Annual modulation



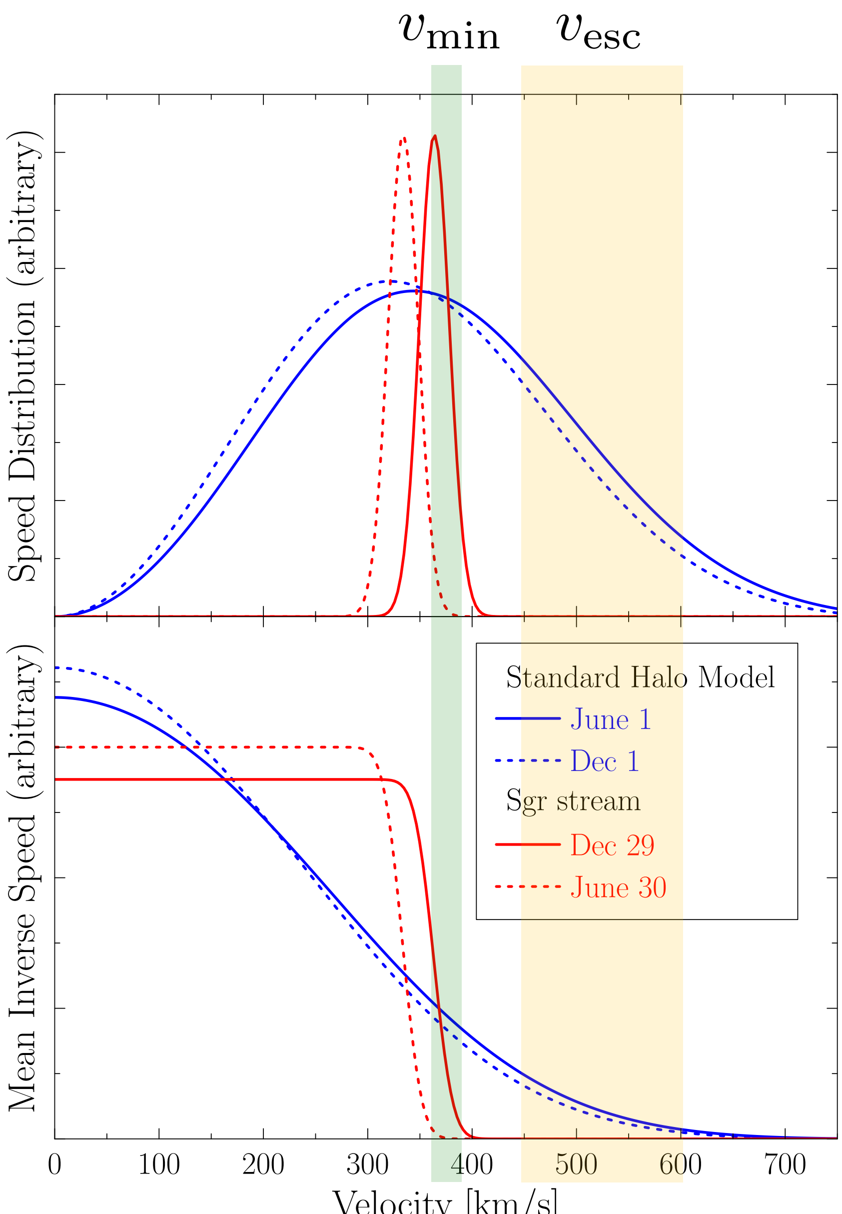
f(v): isotropic maxwellian

Modulation amplitude - energy dependence

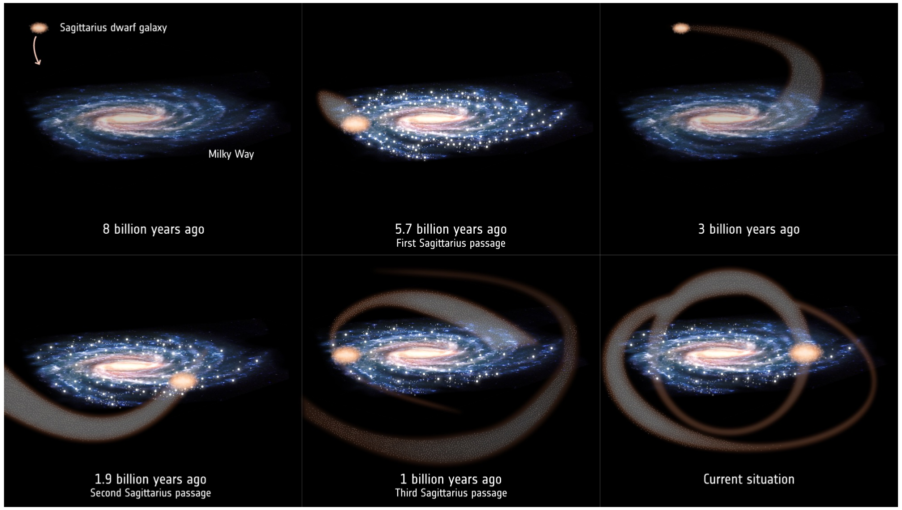


DM velocity distribution: streams?

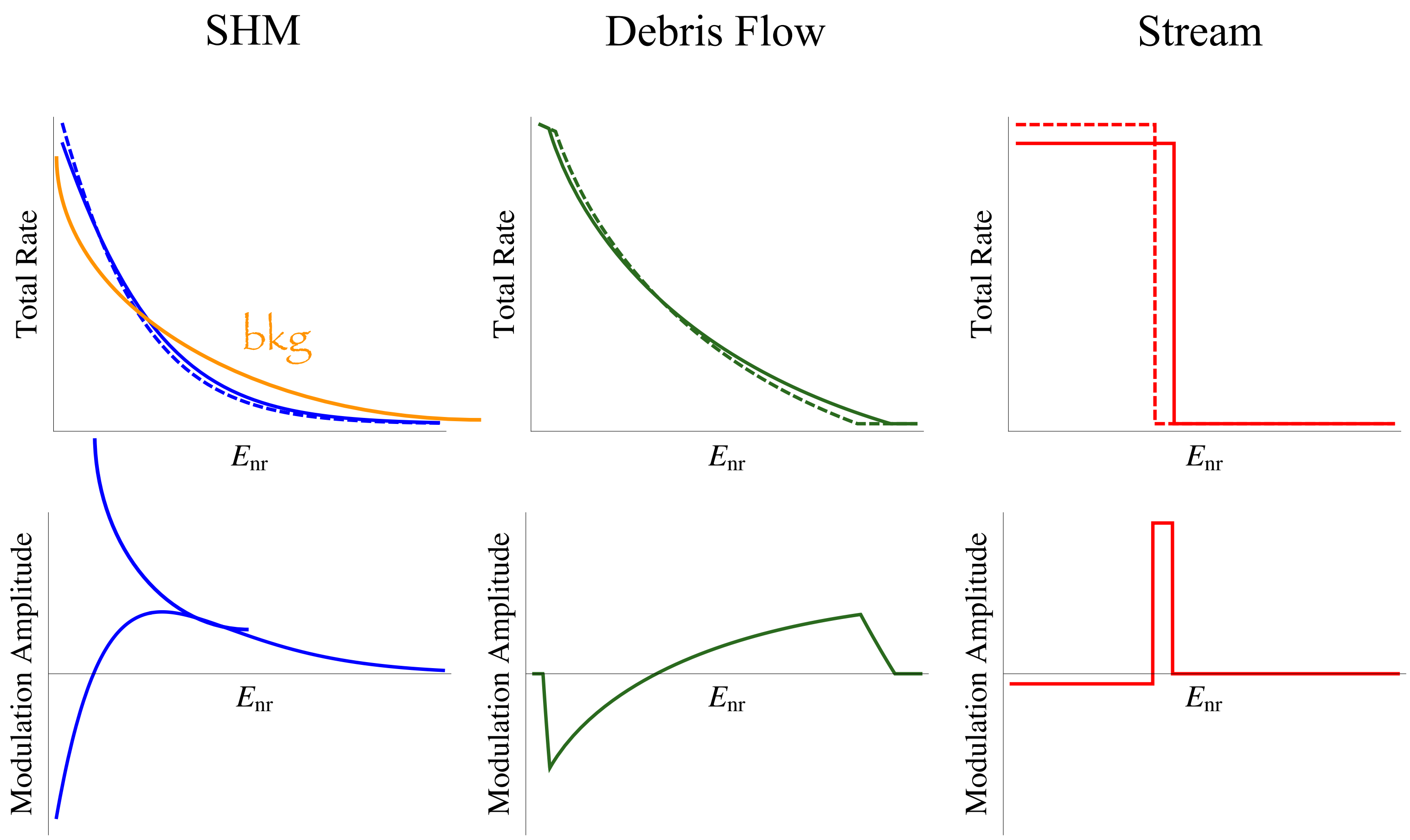
Freese, Lisanti, Savage, 1209.3339



Sagittarius stream

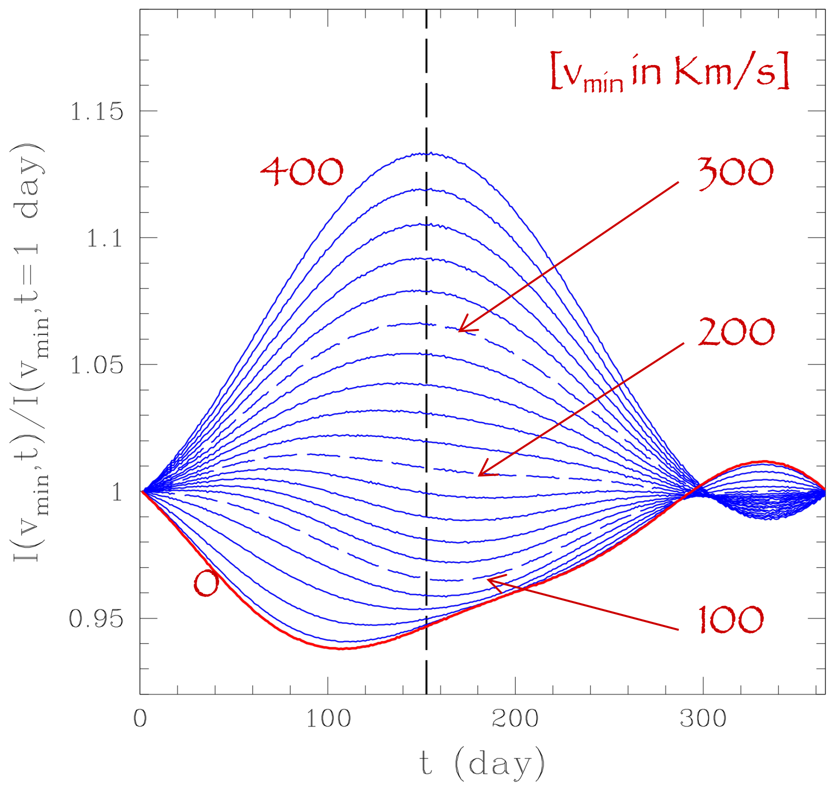


DM velocity distribution



Freese, Lisanti, Savage, 1209.3339

Annual modulation: effect of anisotropies



f(v): anisotropic maxwellian

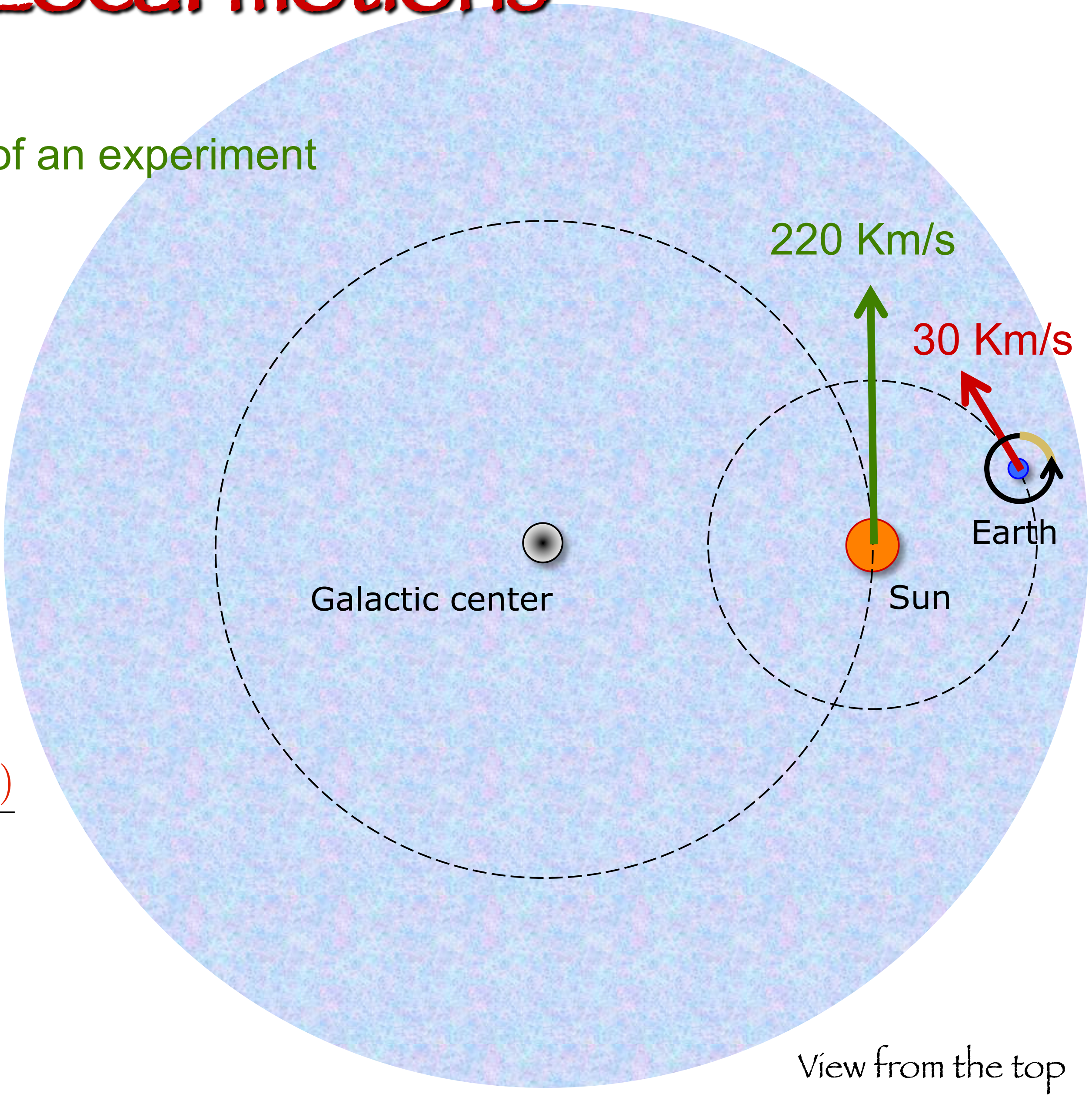
Local motions

Stationary over the lifetime of an experiment

Directional boost

Directionality

$\vec{v}$

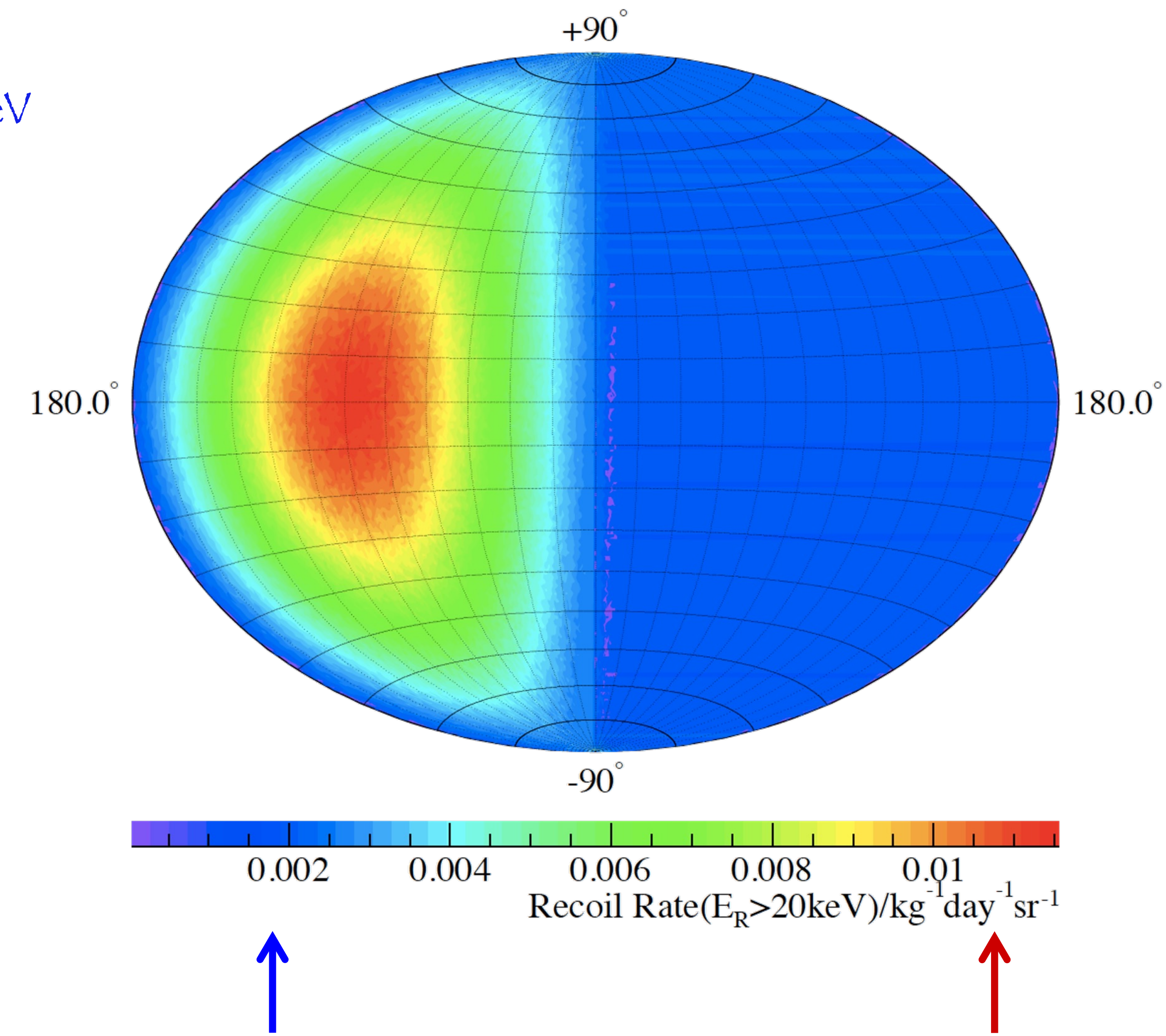


$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot};v_{\rm esc}]}$$

Directionality of the recoil

m_χ = 100 GeV



DM particle features extraction

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\rm scalar}^{(\rm nucleon\ )}\right] F^2\left(E_R\right) \mathcal{I}\left(v_{\rm min}\right)$$

$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \ \frac{f_{\rm ES}(\vec{w})}{w}$$

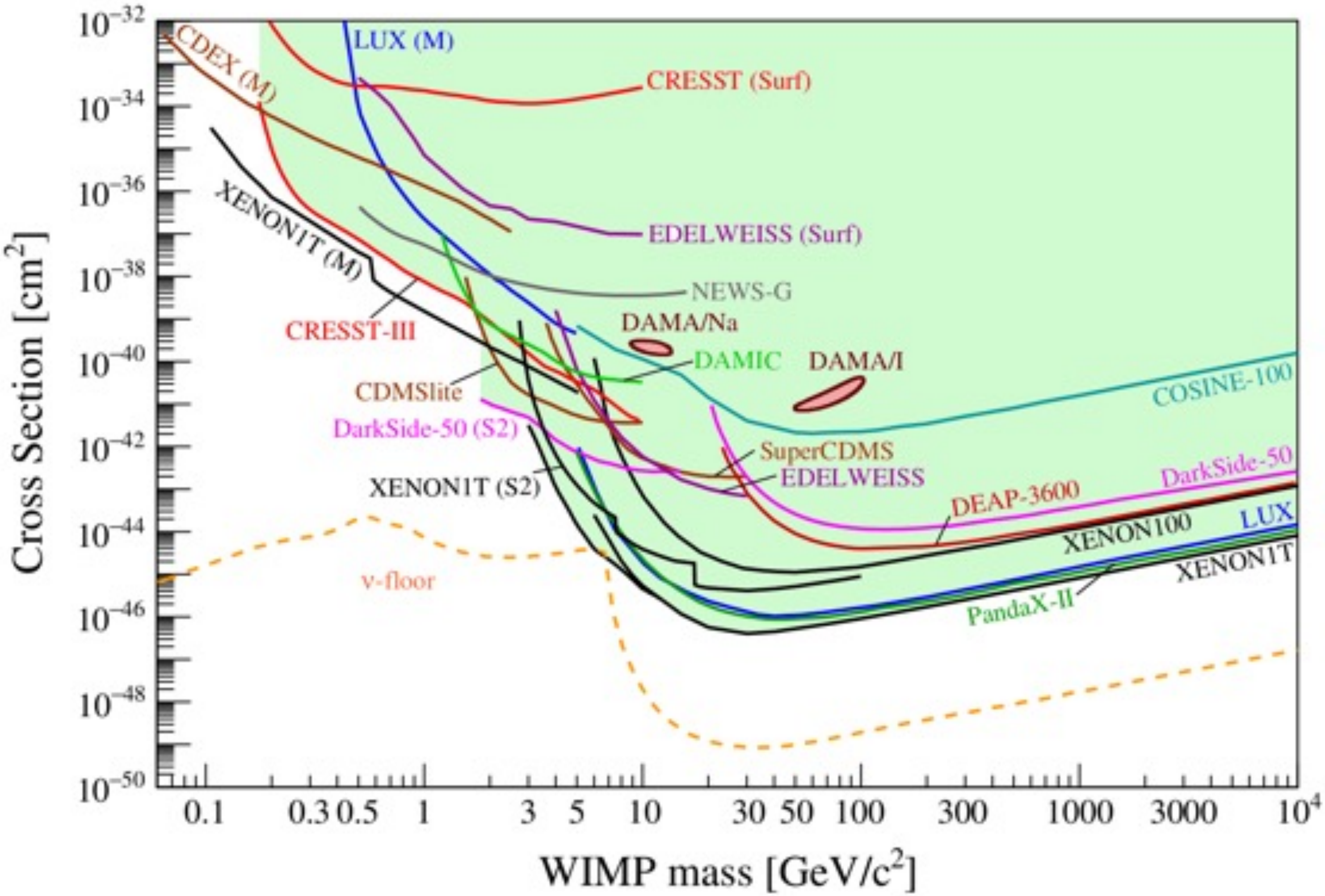
$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)\big|_{[v_{\rm rot};v_{\rm esc}]}$$

$$v_{\rm min} = \left[m_N E_R/(2\mu_A^2)\right]^{1/2}$$

$$E_R \rightarrow E_{\rm det}$$

$$E_{\rm ee} = q(E)\, E_R$$

Spin-independent = O_1 operator

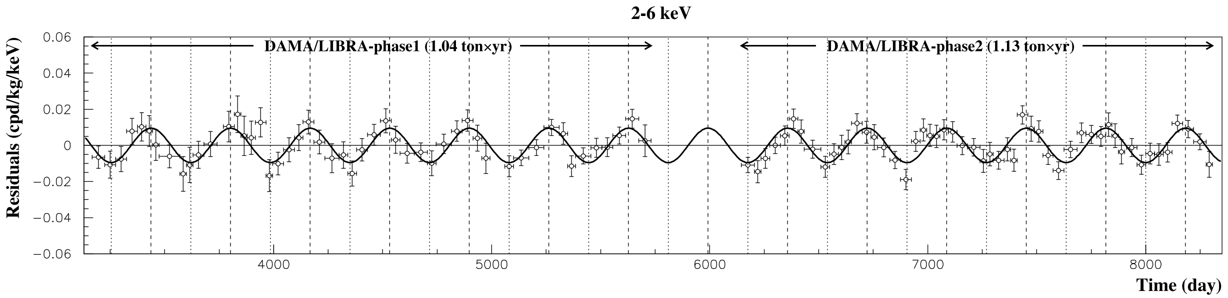


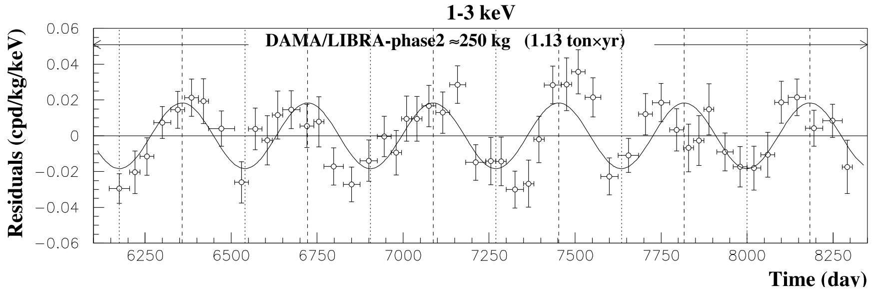
APPEC Committee Report, arXiv:2104.07634

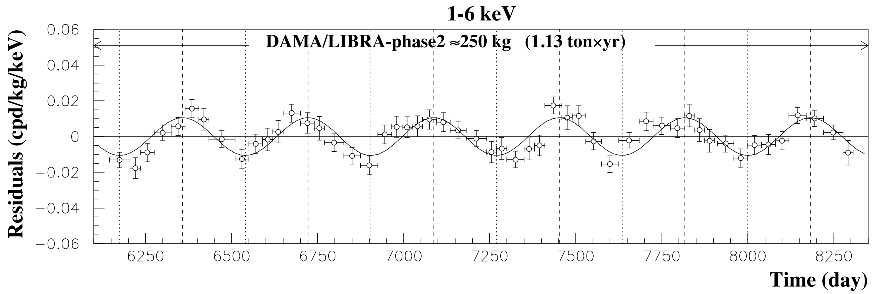
DAMA/Libra

The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at 12.9s CL (2.46 ton × yr)

Sm =(0.0103±0.0008) cpd/kg/keV

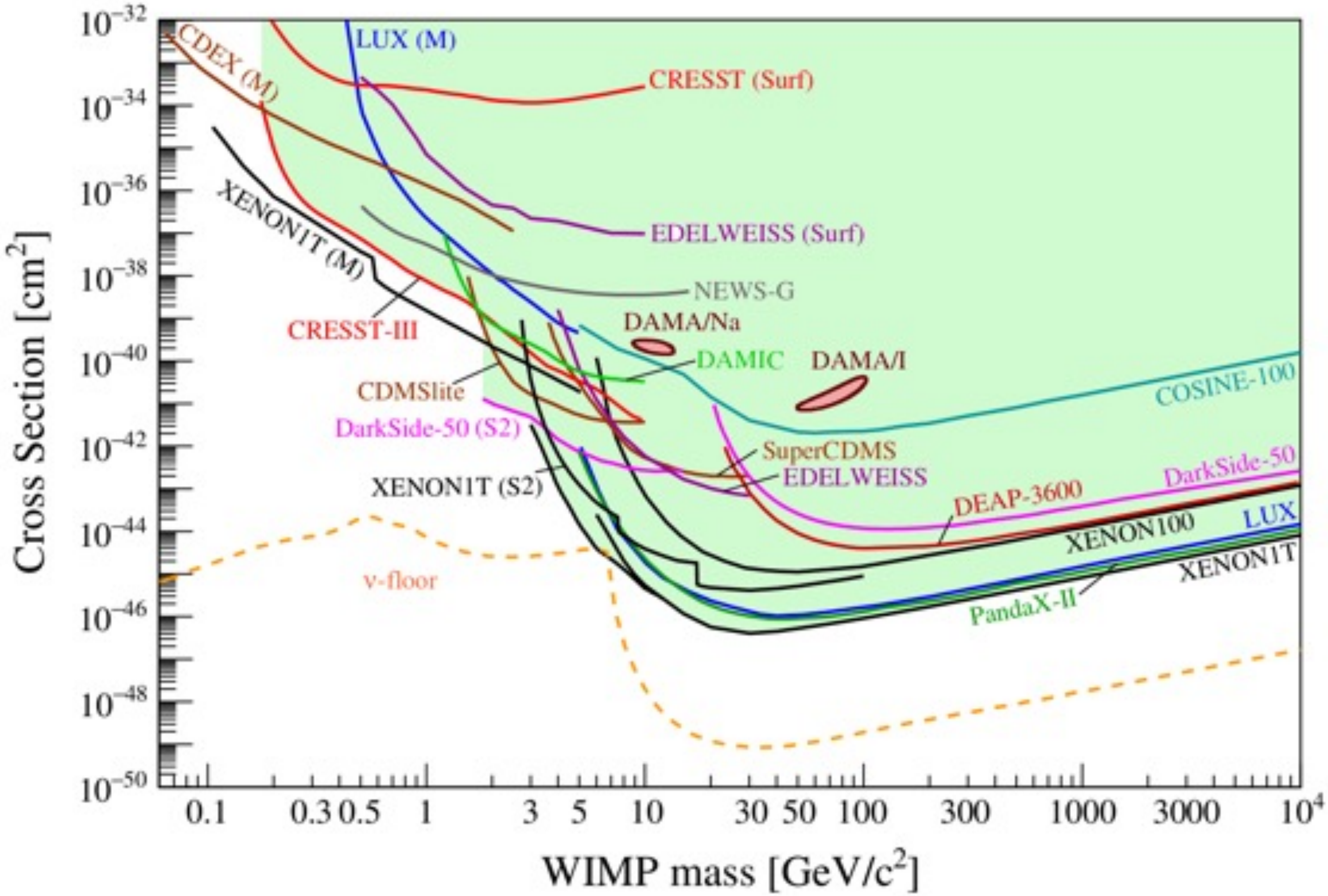






Spin-independent = O_1 operator

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma^{(\text{nucleon})}_{\text{scalar}}\right] F^2(E_R)\, \mathcal{I}(v_{\min})$$

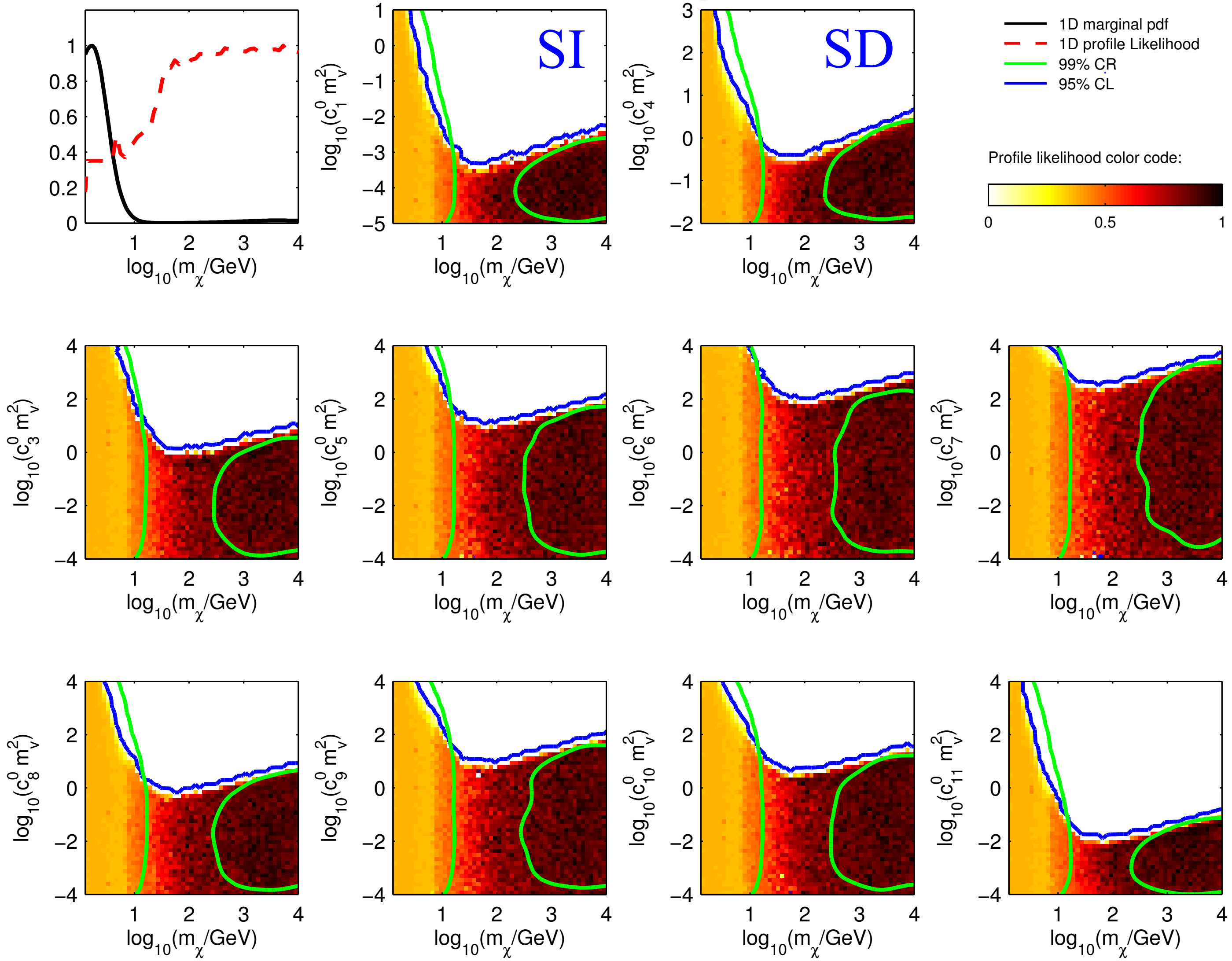


APPEC Committee Report, arXiv:2104.07634

Full set of operators

Catena, Gondolo, JCAP 09 (2014) 045

See also: Scheck et al (SuperCDMS), PRD 91 (2015) 092004



Combined analysis of
CDMS, XENON, LUX, COUPP, PICASSO, SIMPLE

Light WIMPs - Migdal effect

When the nucleus recoils, electrons do not 'rigidly' follow, but can have transition to a different energy level or to the continuum, resulting in:

excitation

ionization

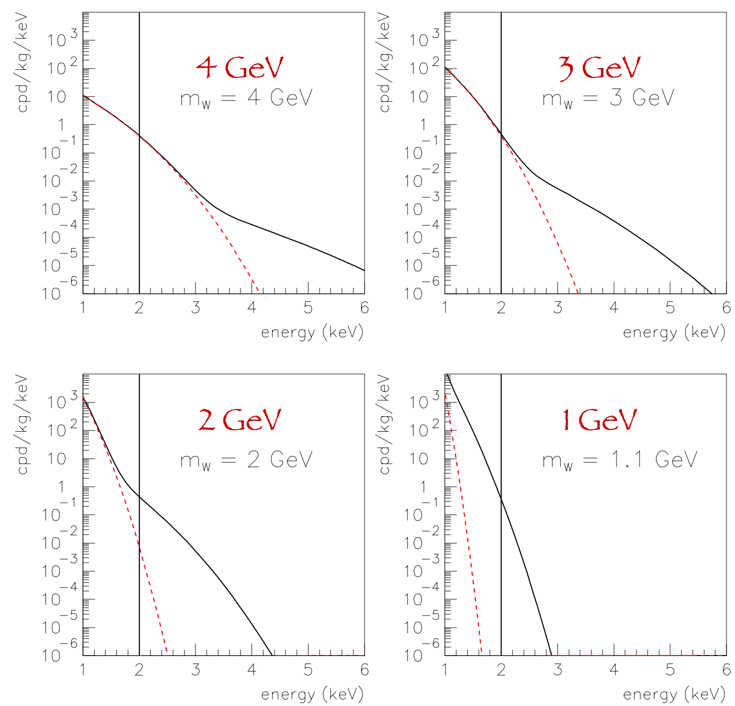
with e.m. released in addition to the recoil signal

Transition to the continuum: emission of radiation

Rearrangement of atomic shells

Emission of radiation

Meitner-Auger electrons(*)



Relevant especially for light WIMPs

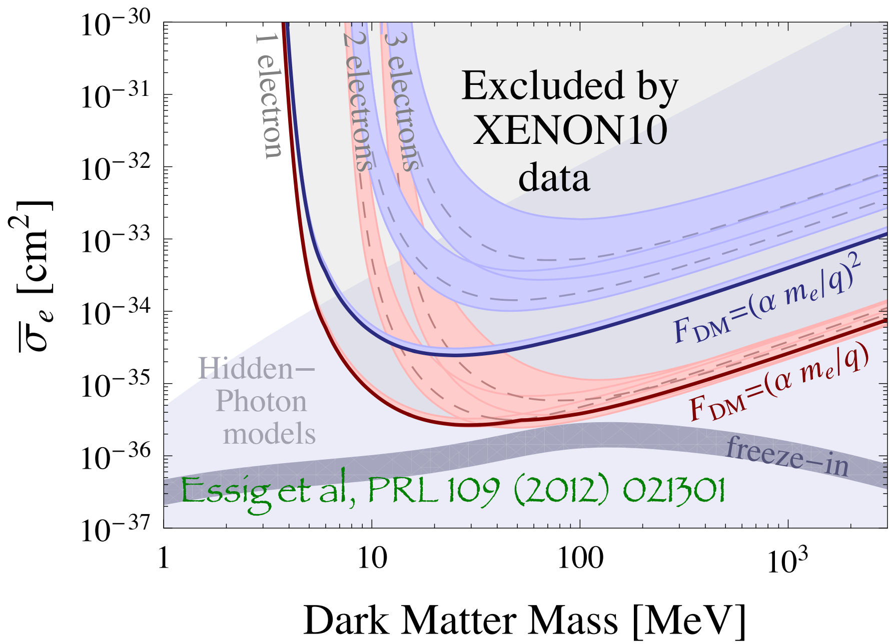
(*) Filling the inner shell vacancy, energy is transfered to another electron which is then emitted

Very light DM

- Very light DM (down to the warm regime):
  - Available kinetic energy can be as low as meV (for KeV DM)
  - Too low deposited energy on nuclear target
- Possibilites:
  - Nuclear interactions on light targets, e.g. liquid He
  - Electron recoils

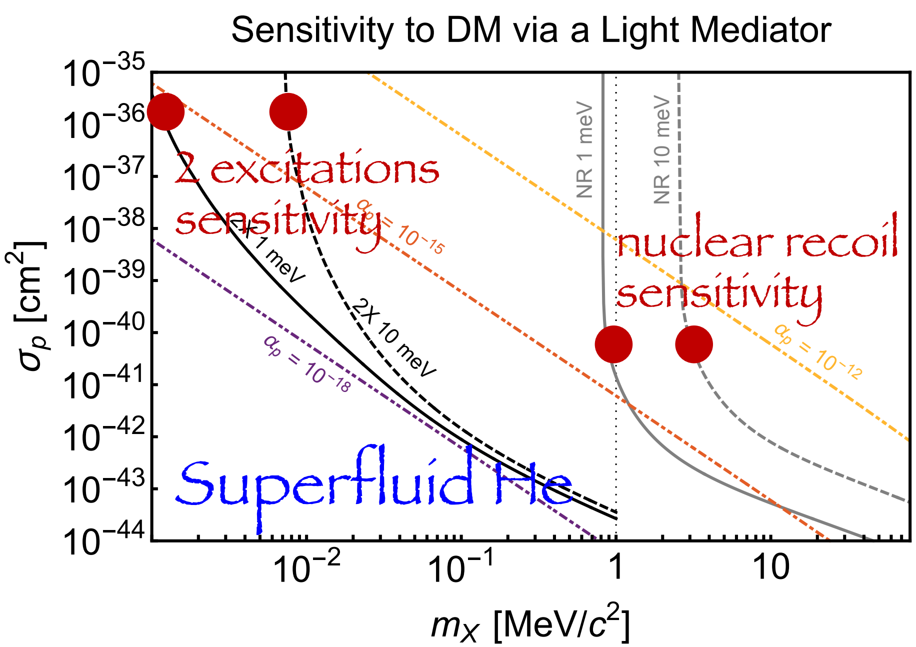
Guo, McKinsey, PRD 87 (2013) 115001

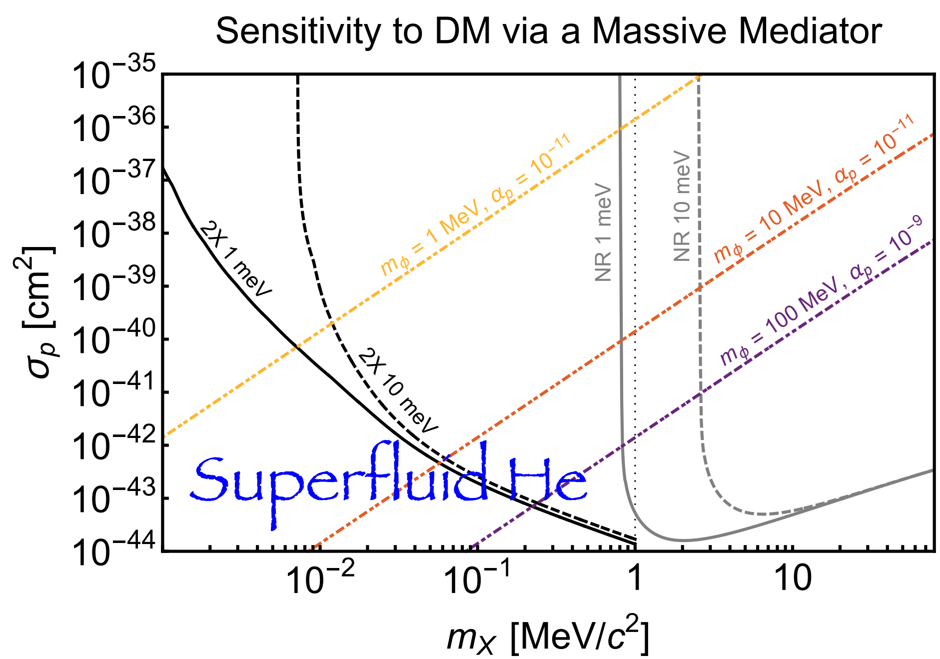
Essig et al, PRD 85 (2012) 076007
Essig et al, 1509.01598
Agnese et al (SuperCDMS) PRL 112 (2014) 041302
Essig et al, PRL 109 (2012) 021301



Essig et al, PRL 109 (2012) 021301

Super light DM





To go below 10 MeV DM: conversion of the full tiny energy needed

» Superconductors — electron interactions

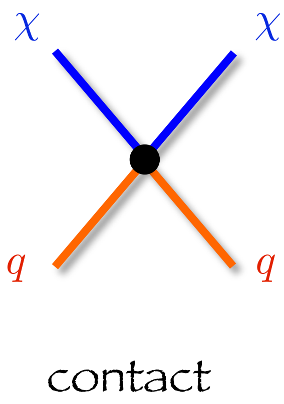
Hochberg et al, 1512.04533

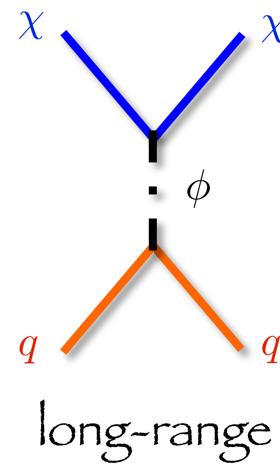
Hochberg et al, PRL 116 (2016) 011301

» Superfluid He — nuclear interactions

Schutz, Zurek, 1604.08206

Other type of interactions: e.g. long range





very light mediator
e.g. dark photon or mirror photon

$$\frac{d\sigma\left(v,E_R\right)}{dq^2}=\frac{2m_N\lambda}{\left(q^2+m_\phi^2\right)^2}\frac{1}{v^2}F^2\left(E_R\right)$$

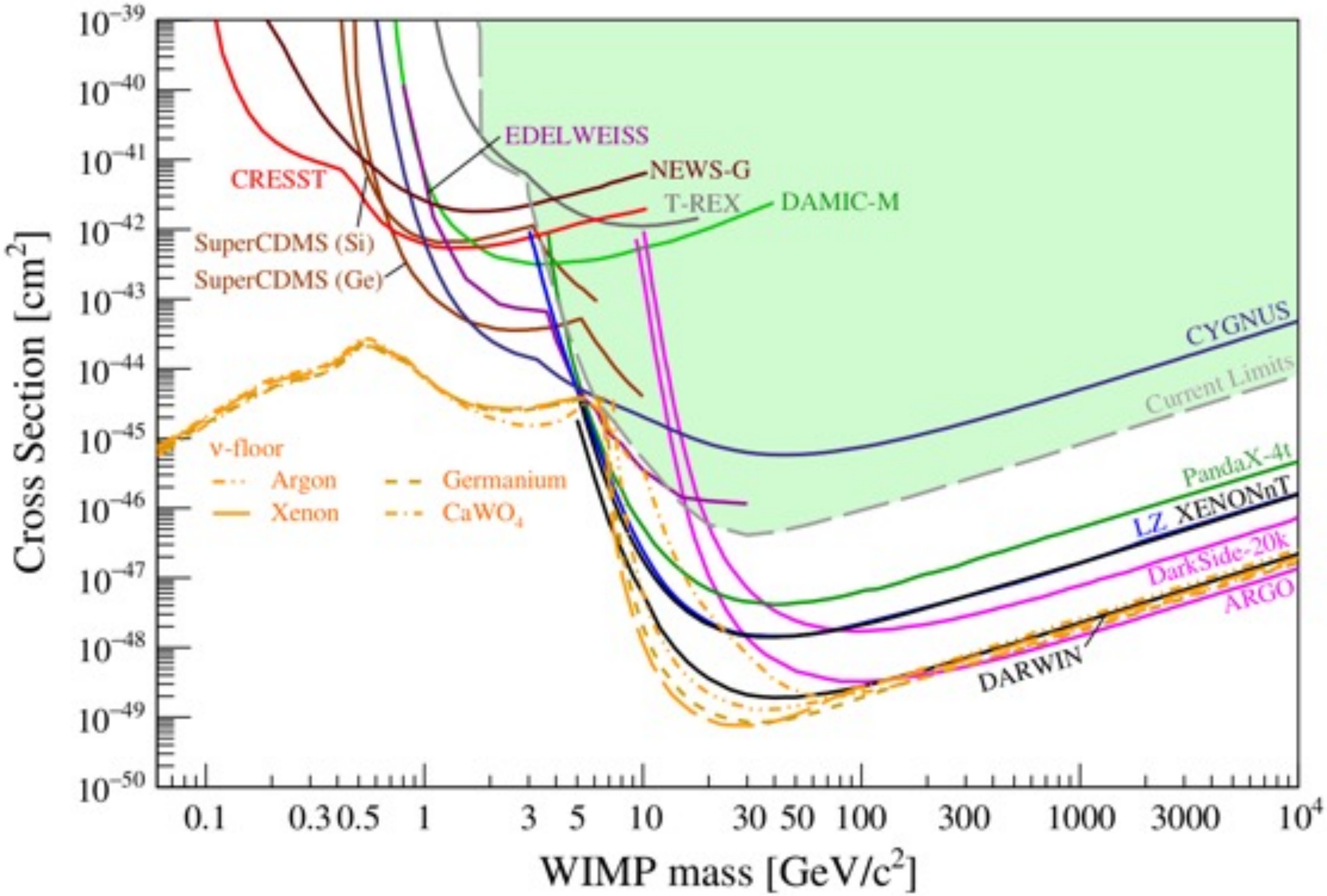
$q^2=2m_NE_R$ momentum transfer

m_ϕ mass of the mediator

$$\frac{d\sigma\left(v,E_R\right)}{dE_R}=\frac{m_N}{2\mu_{\chi p}^2}\frac{1}{v^2}Z^2\sigma_{\phi\gamma}F^2\left(E_R\right) \qquad m_\phi^2\gg q^2$$

$$\frac{d\sigma\left(v,E_R\right)}{dE_R}=\frac{\lambda}{E_R^2}\frac{1}{v^2}F^2\left(E_R\right)\propto E_R^{-2} \qquad m_\phi^2\ll q^2$$

Prospects: Projected Sensitivities



APPEC Committee Report, arXiv:2104.07634

Prospects

- Annual modulation: ANAIS
  COSINE 100
  SABRE
  COSINUS-2pi

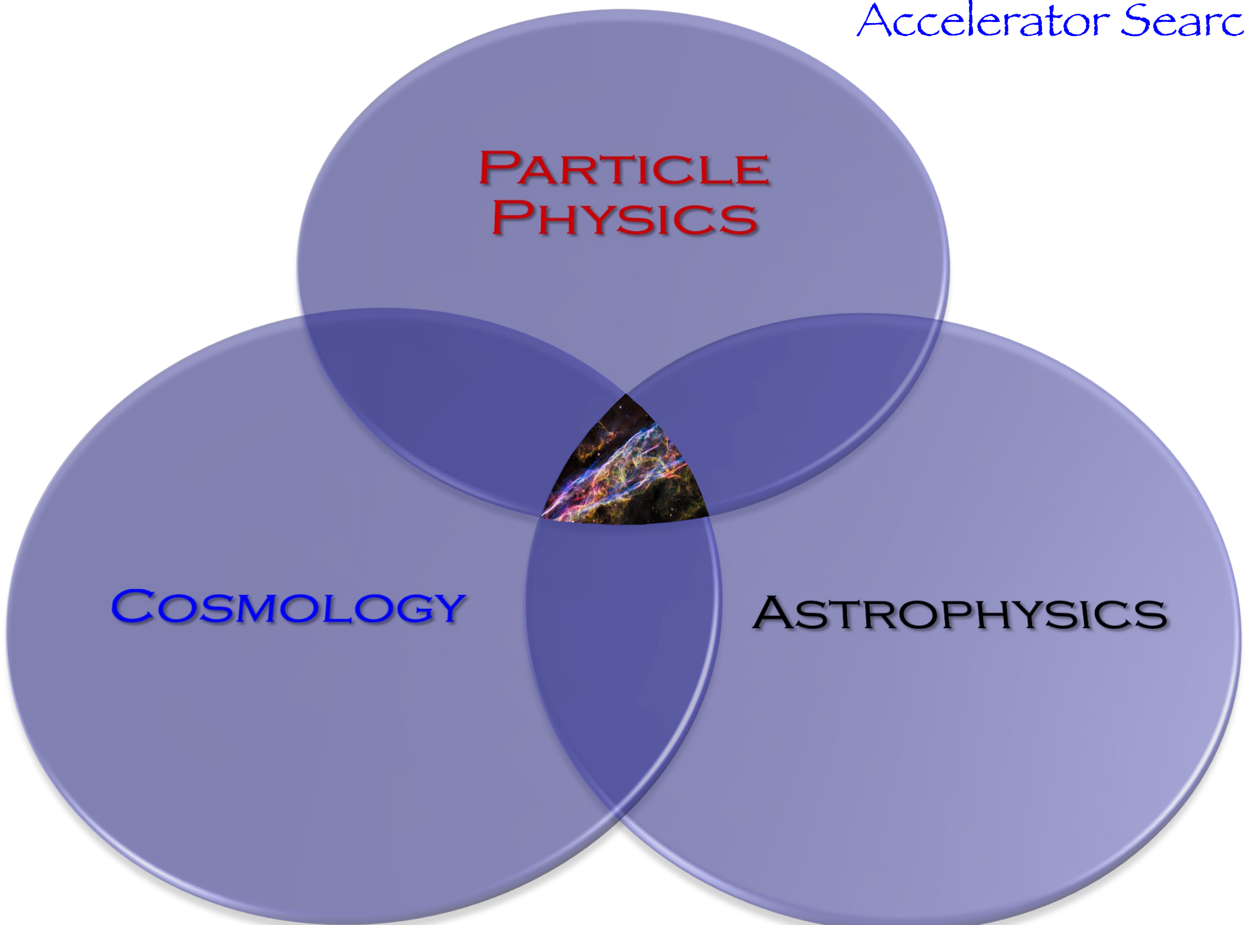
- Diurnal modulation: DAMA with larger mass might access it

- Directionality:
  - Nuclear emulsion (NEWS)
  - Gas TPC (CYGNO)
  - Negative Ion Time Expansion Chamber
  - Carbon nanotubes, grafene
  - Anysotropic crystals (ADAMO)
  - DRIFT
  - MIMAC, DMTPC, NEWAGE, D3, …

Wrap up

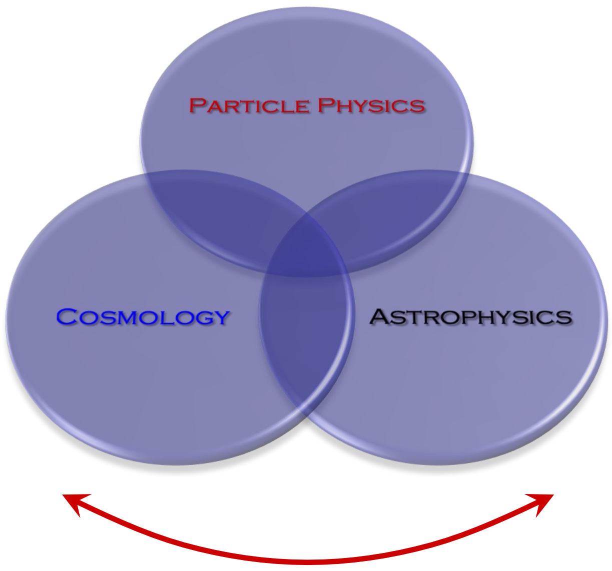
The Particle Dark Matter Crossroad

Particle Candidate: Models of New Physics
(Superymmetry, Extra-dimensions, ...)
Accelerator Searches

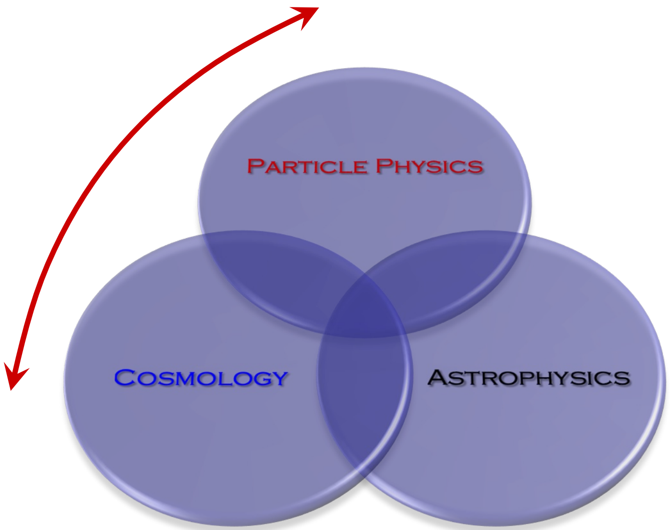


Cosmology of the
Dark Matter Particle

Astrophysical Signals of the
Dark Matter Particle

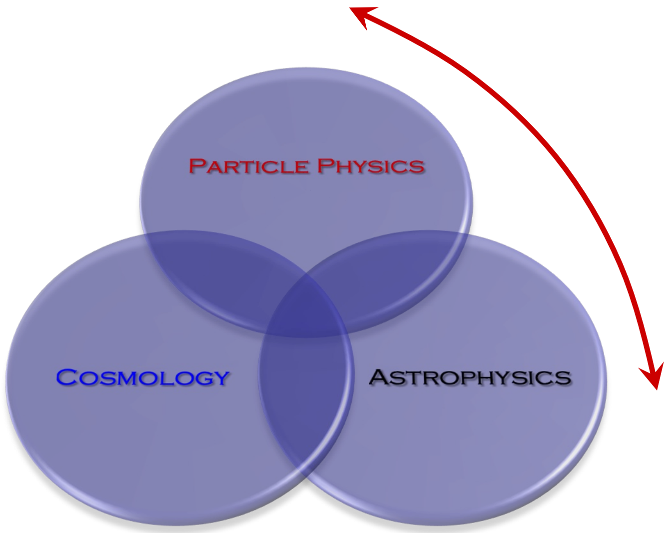


- Cosmological structure formation modelling predicts different LSS distribution depending on the dynamical properties of DM
  - CDM
  - WDM
  - HDM
- Standard paradigm: collisionless CDM
- Observationally CDM works basically well, however:
  - Galaxy formation models in ΛCDM make the brightest satellites in the largest subhalos which seem more massive and concentrated than in real Milky Way galaxies
  - Analyses of rotation curves of spiral galaxies indicate that the DM halo is cored (contrary to the spiky ΛCDM case)
- CDM has to abandoned for a warmer form of DM?
- Baryon feedback?



- The cosmological abundance of a specific particle DM candidate is the output of a delicate interplay between:
  - Cosmological evolution
  - DM particle fundamental interactions
- The abundance is typically set by a chemical decoupling mechanism (symmetric or asymmetric), but it may be related to out-of-equilibrium processes (e.g.: decay of heavier particle)

- Kinetic decoupling typically detemines the free-streaming scale of DM candidates and therefore their behaviour in structure formation
- Particle DM candidates behave as CDM/WDM/HDM depeding (also) on their particle physics properties:
  - CDM: typical paradigm is thermal WIMP
    axions: misalignment mechanism
  - WDM: KeV or MeV weakly interacting particles (RH nu)
  - HDM: typically eV-scale weakly interacting particles



- If DM is a particle, is should manifest its particle physics properties in the same environments where DM is observed to exist:
  - Galaxies
  - Clusters
  - The cosmic web

- Non-gravitational astrophysical signals of DM should therefore be present: multi-messenger and multi-wavelength searches
- These messengers
  - their flux
  - what kind
  - their energy ranges

  depend on the particle physics properties
  - its mass
  - Its interactions