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

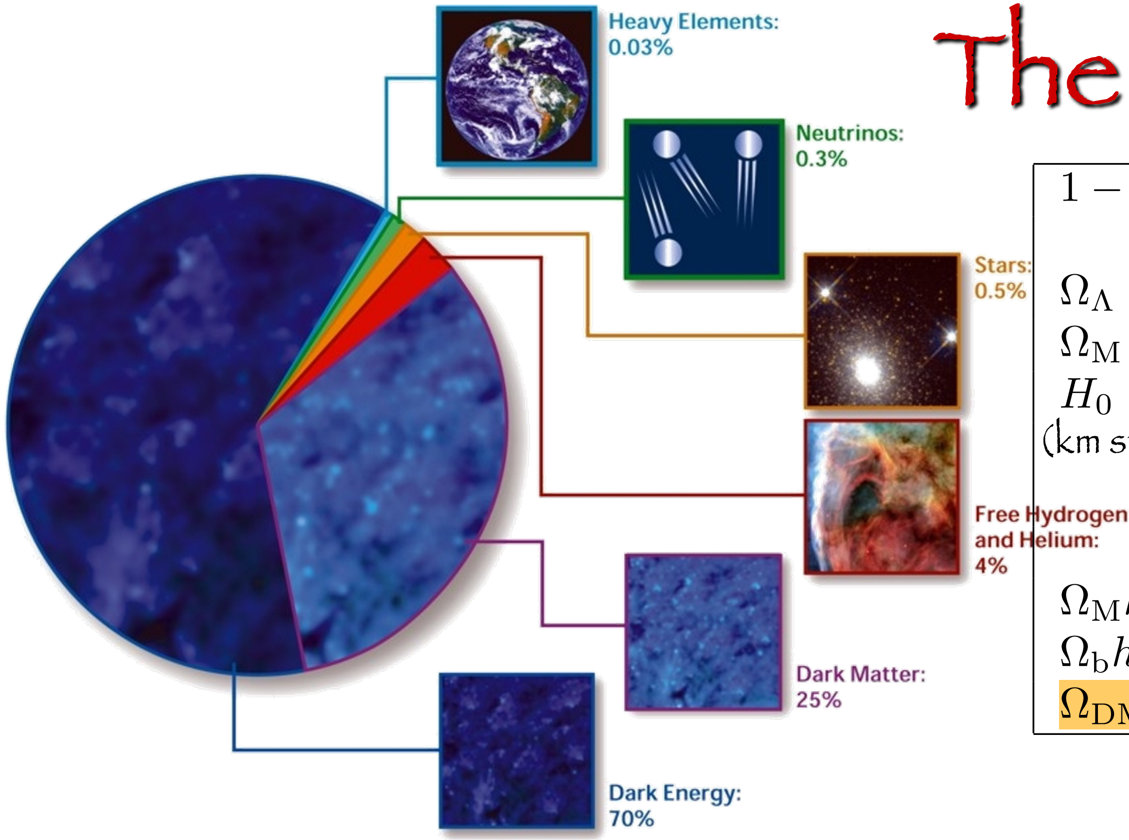
- Electrons and positrons
- Antiprotons
- Antideuterons

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

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

Ω_Λ Luminosity distance of high-z SNIa

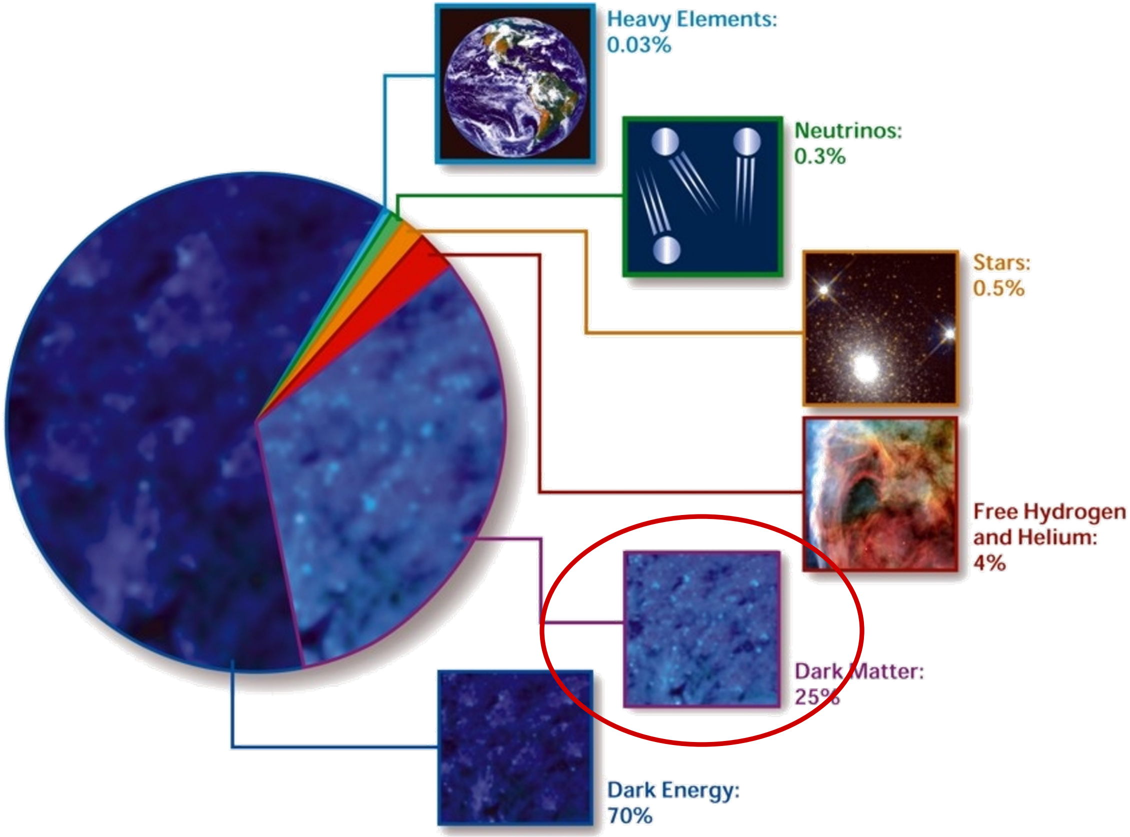
$\Omega_{\rm M}$ Clustered mass abundance

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

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

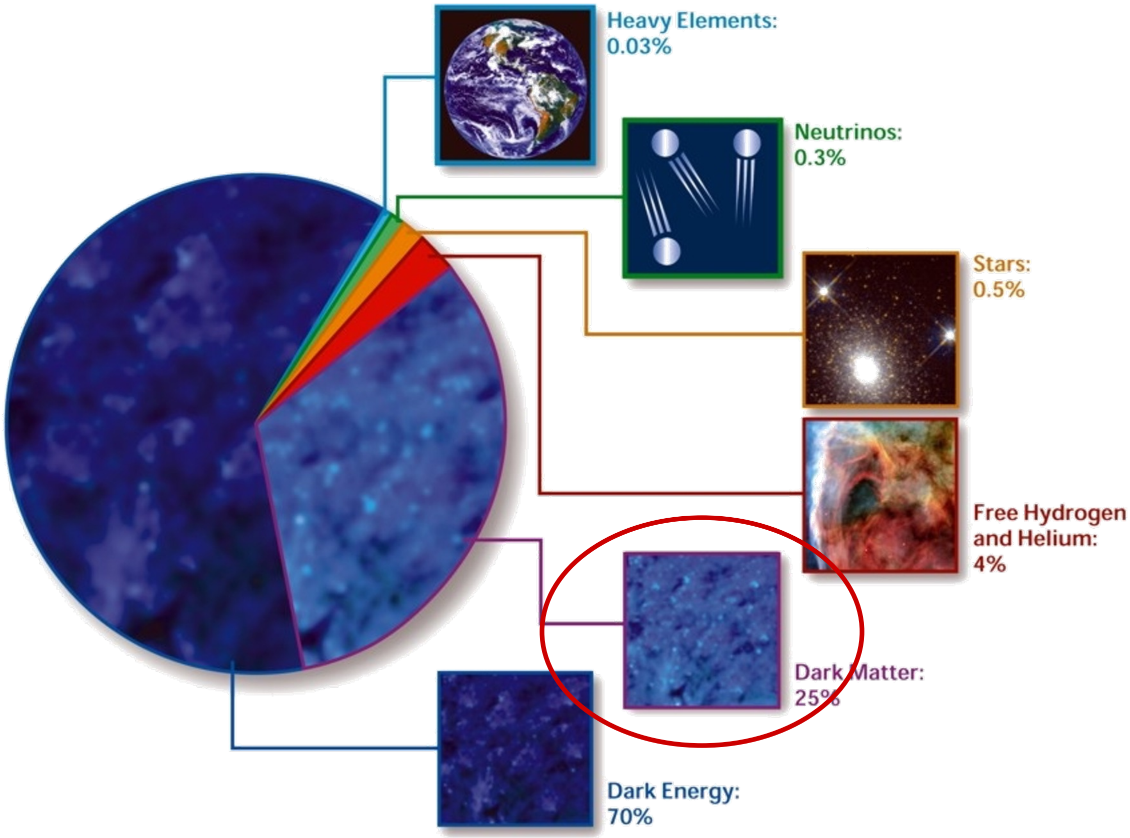
- Decelerate for most of its history
- Accelerate since "recent" time and at very "old" times (inflation)

Dark Matter



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

Dark Matter



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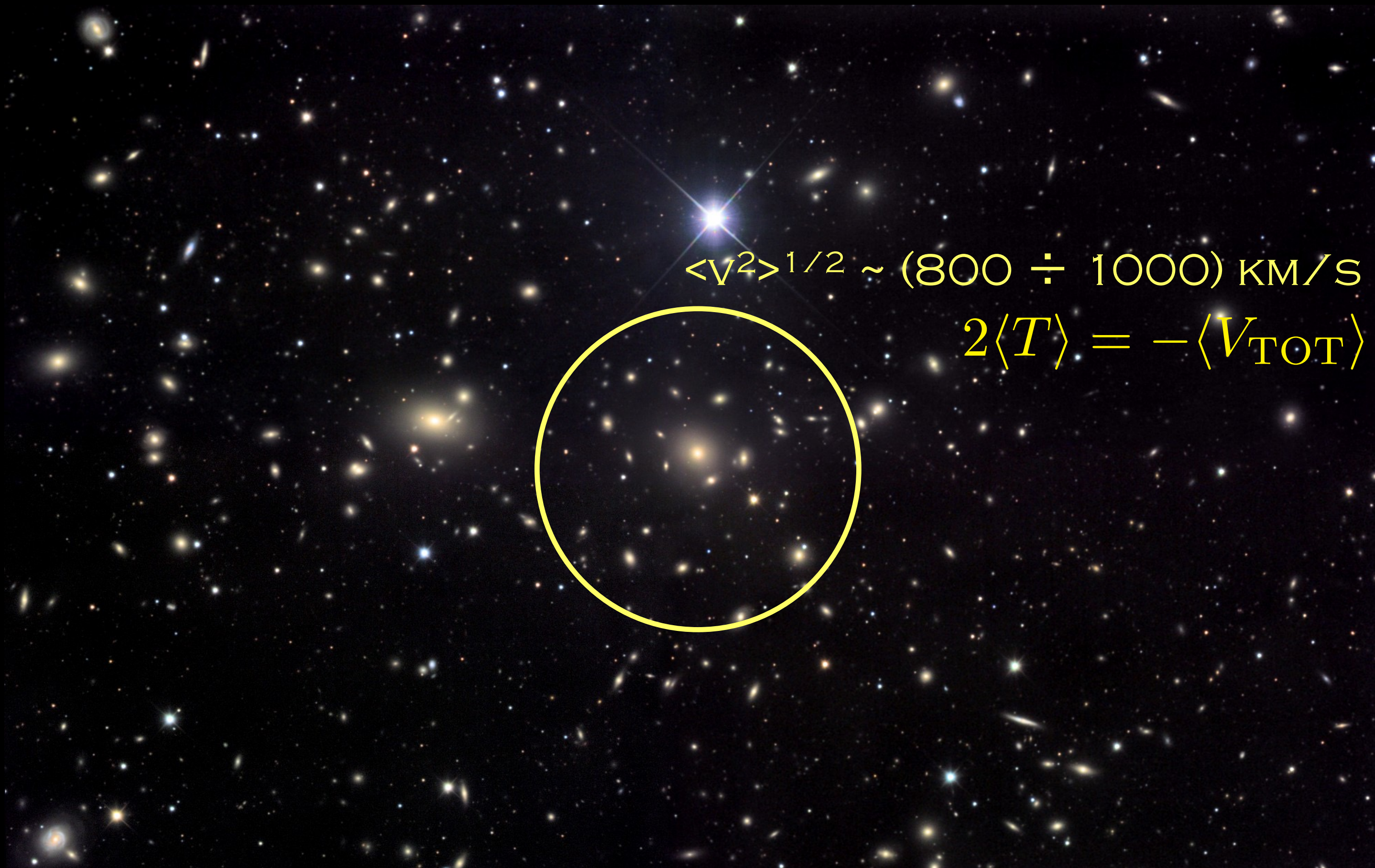
Zwicky, 1933 →

Virial theorem

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

Galaxy cluster

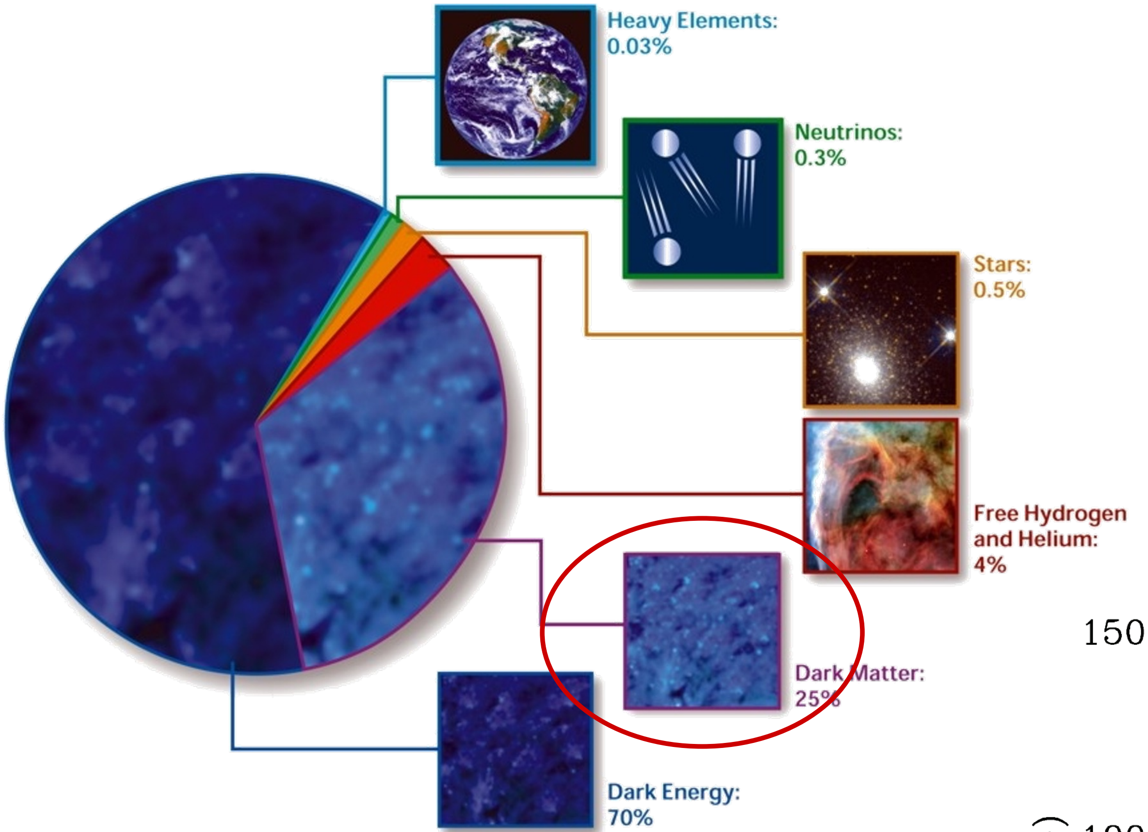
Zwicky (1933)



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

Galaxies : Gas : DM = 1 : 9 : 90

Dark Matter



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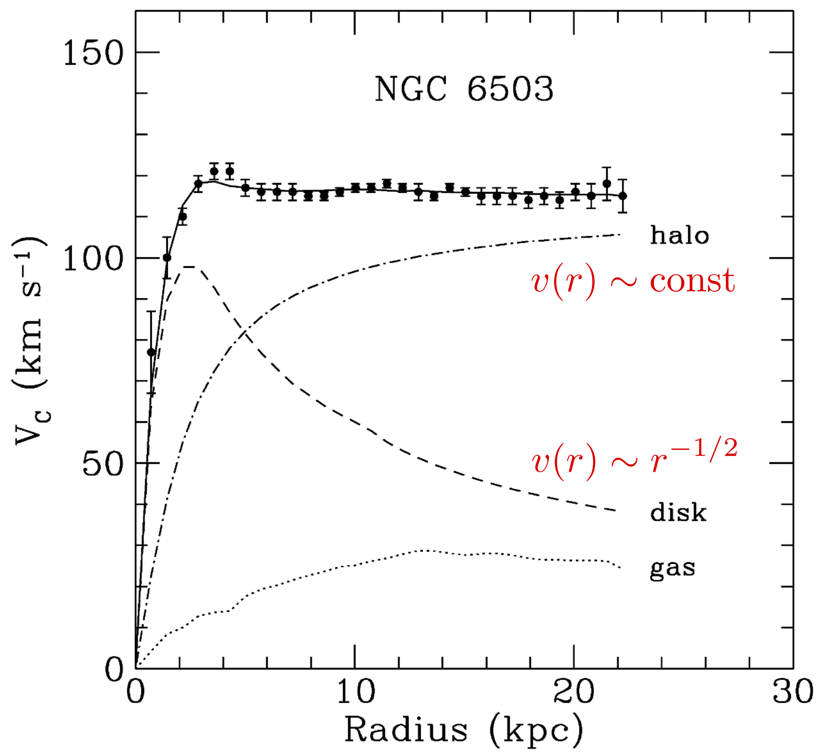
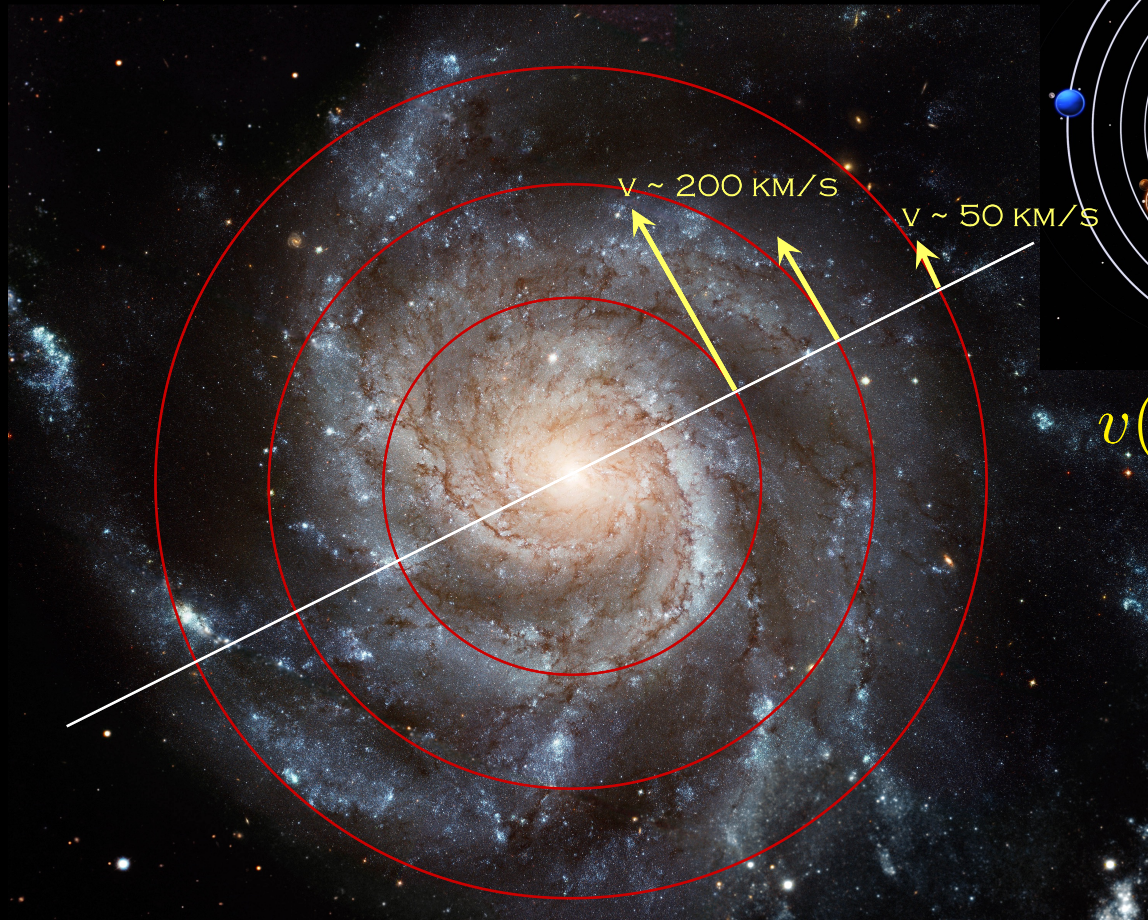
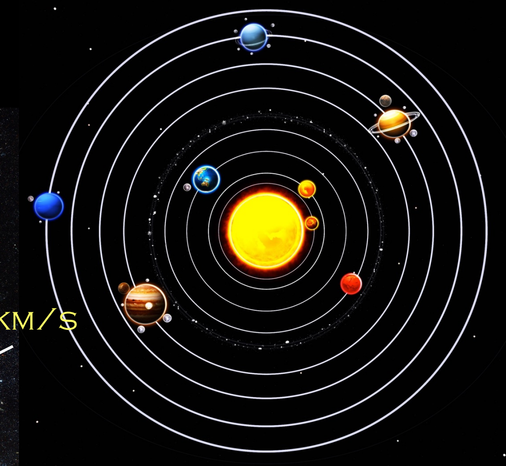
Rubin, early '70s →

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



Spiral Galaxy

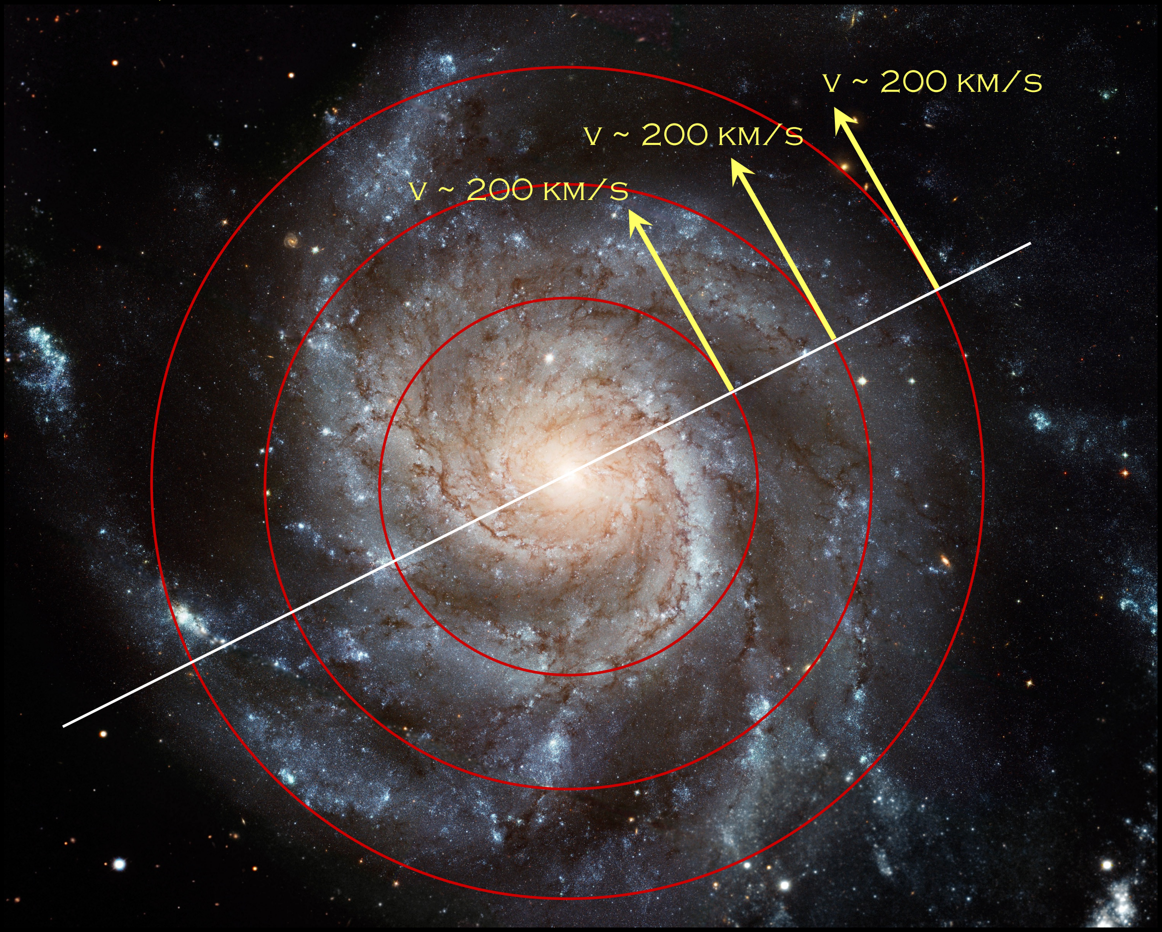




$$v(r) \propto r^{-1/2}$$

Spiral Galaxy

Rubin (1970)

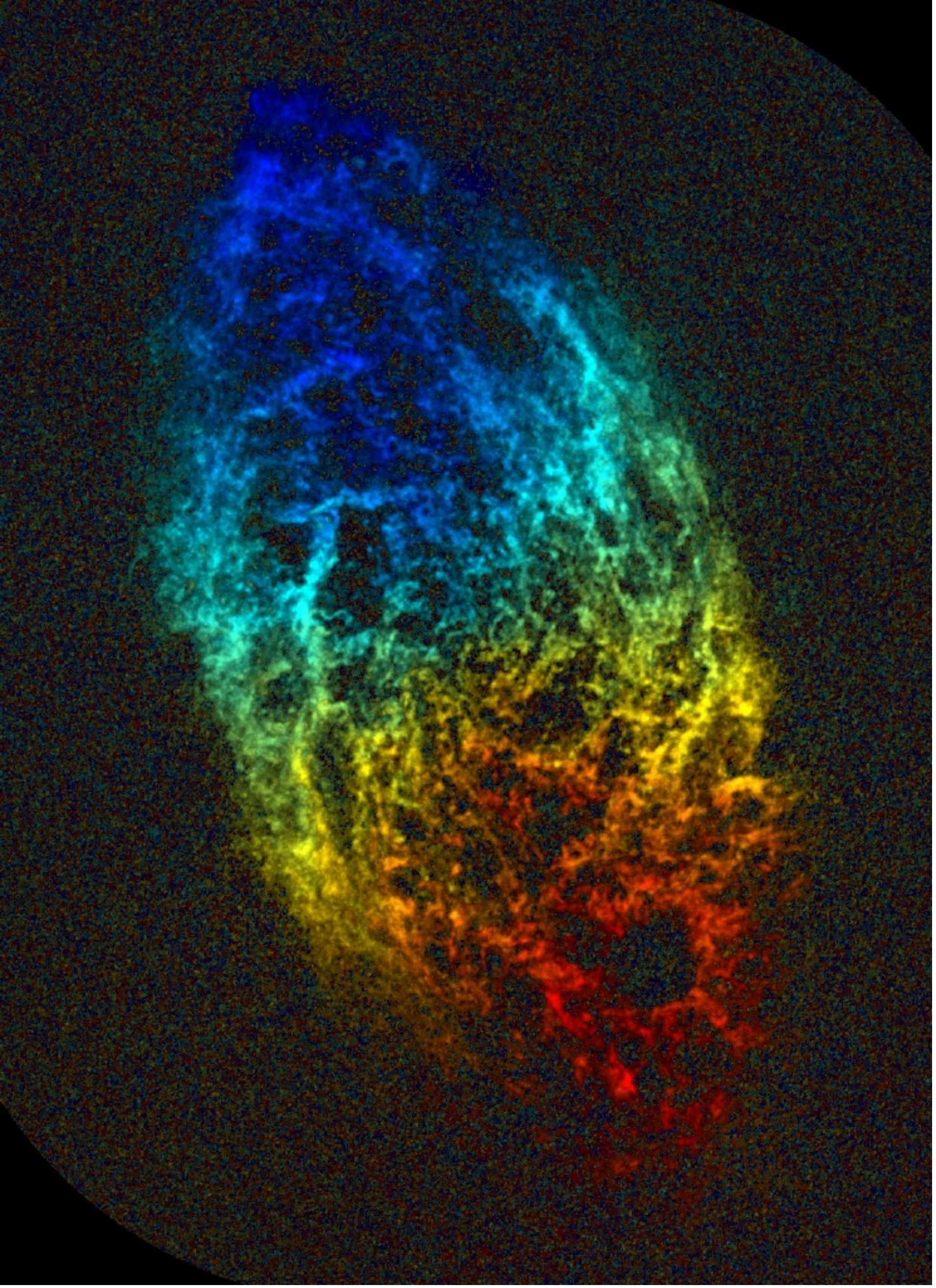


Periferic stars are faster than expected

Faster = More mass

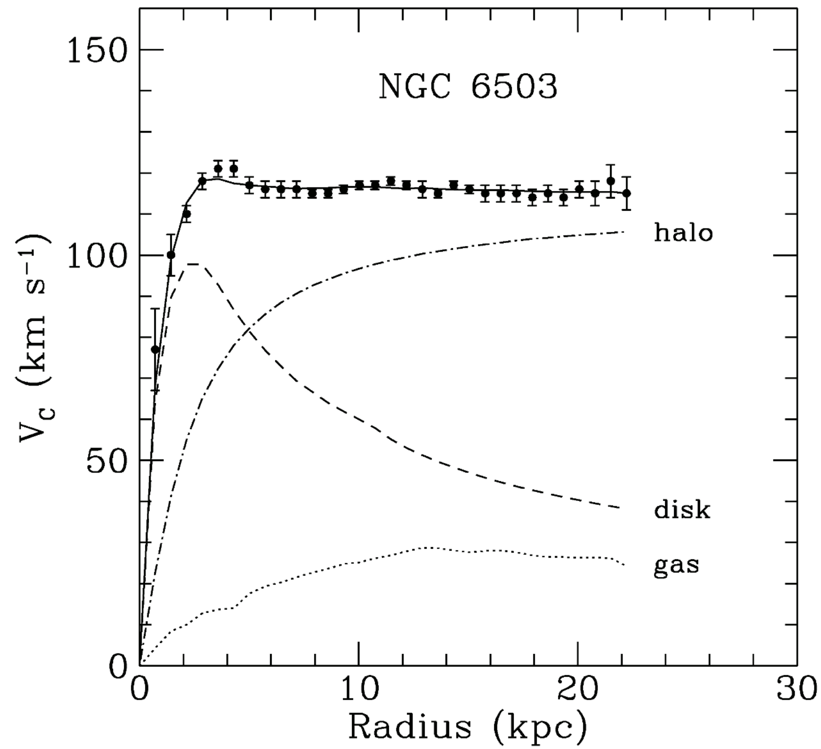
Much more mass than luminous mass

Dark Matter

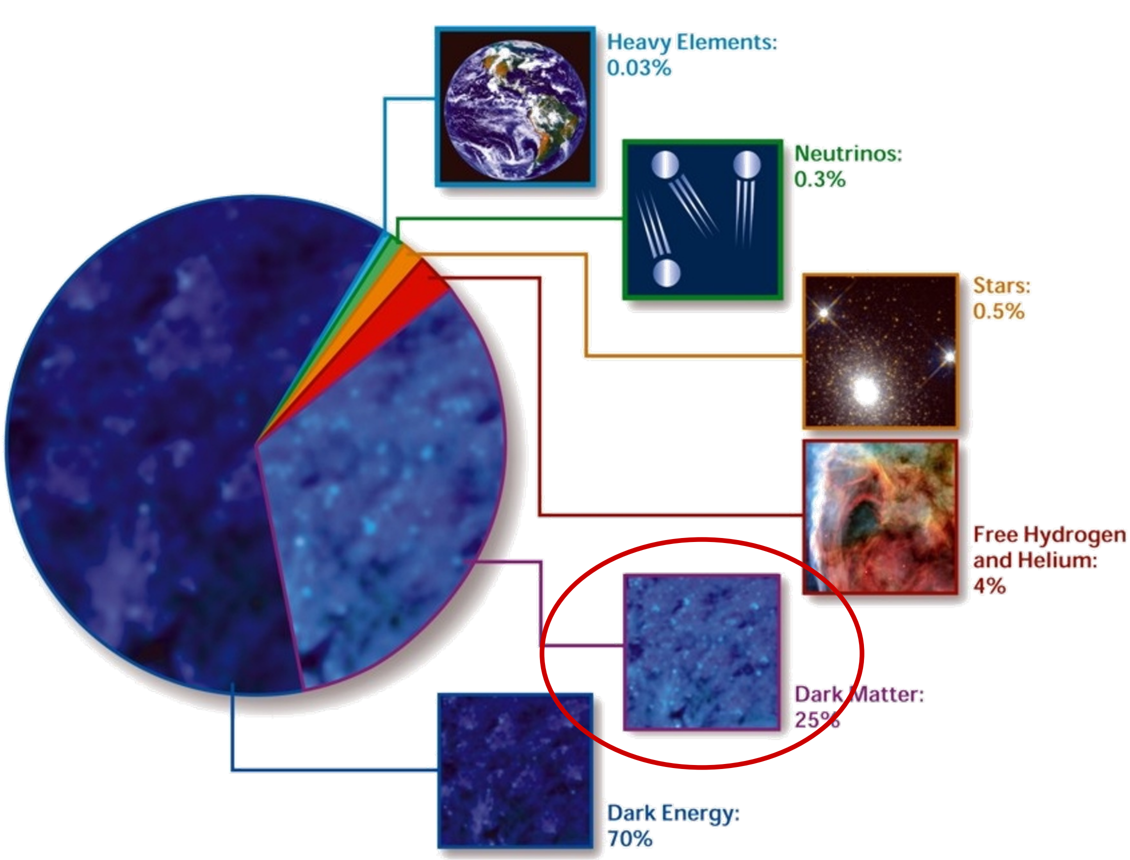


M33
Hydrogen gas
Doppler image

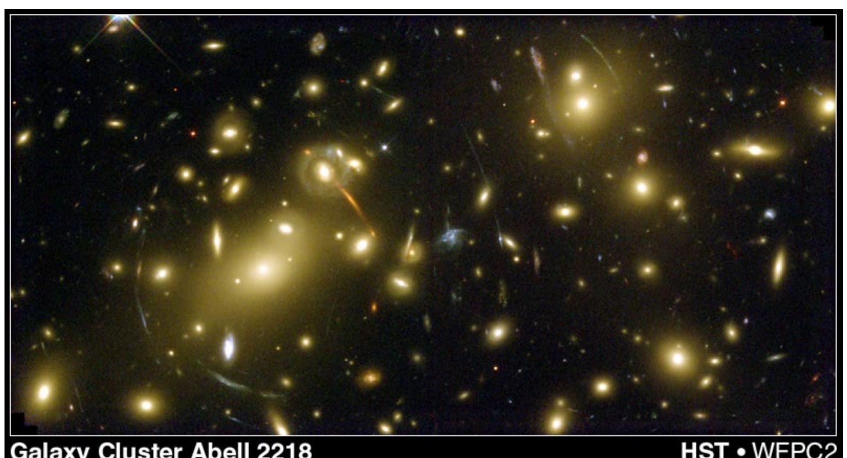
$$v(r) \propto \sqrt{M(r)/r}$$

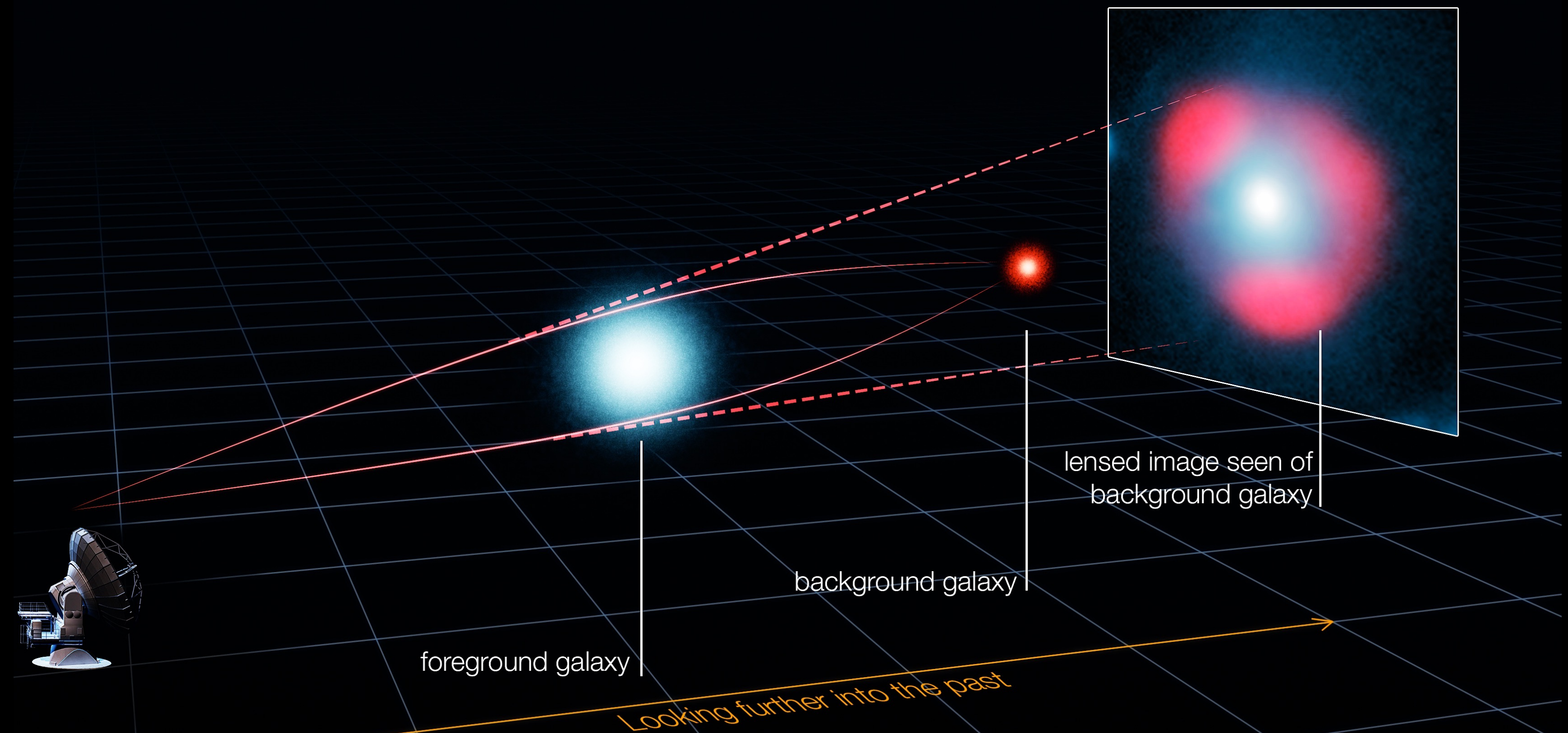


Dark Matter



- 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)

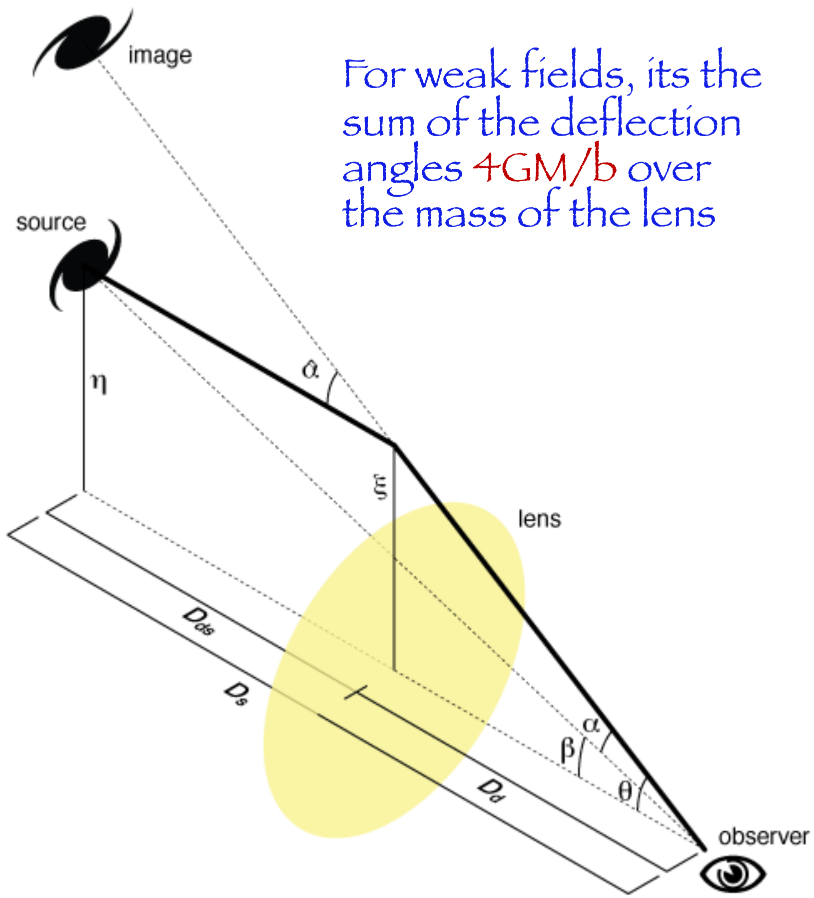
$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

Deflection angle

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

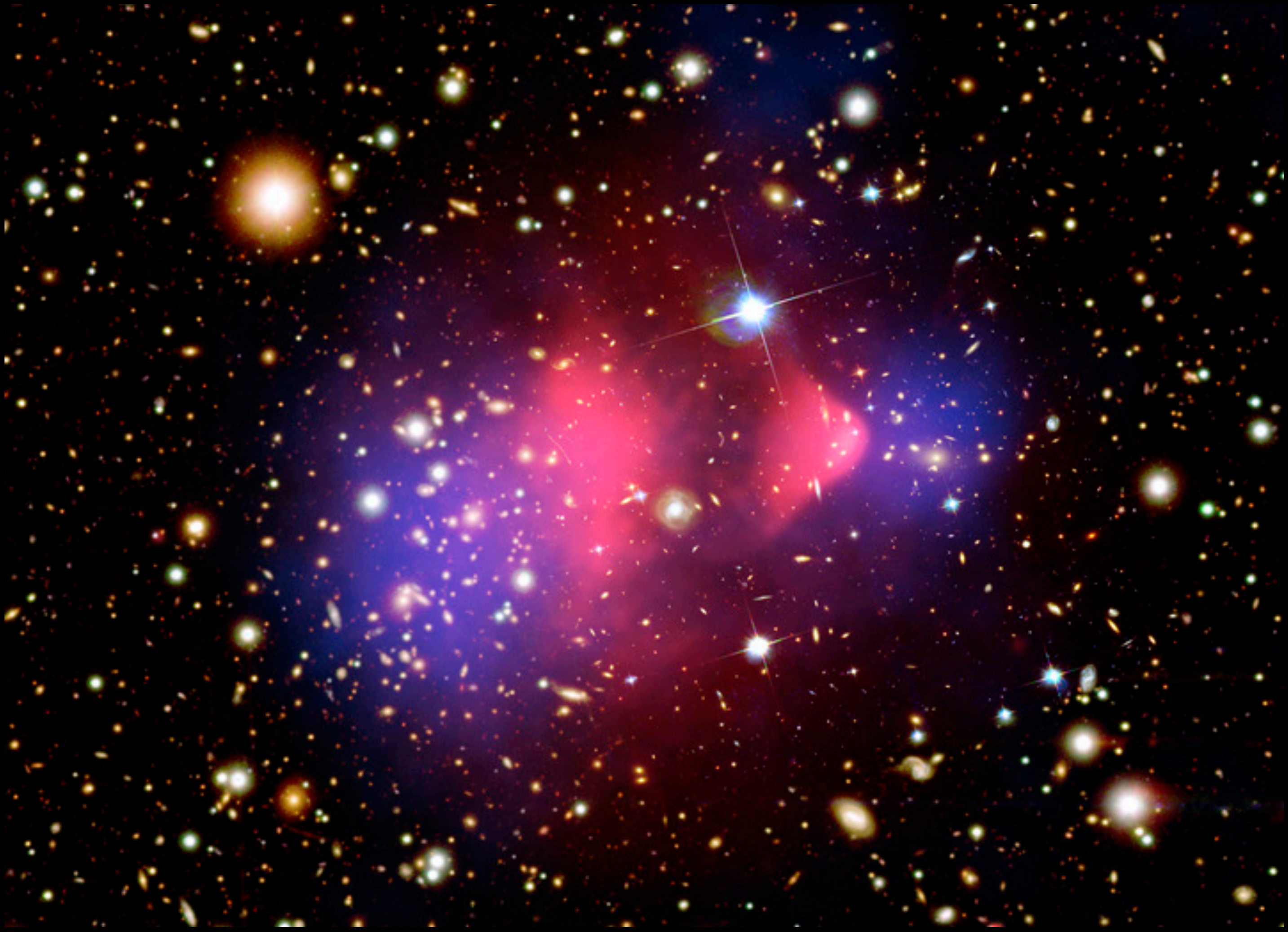
Projected mass density

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



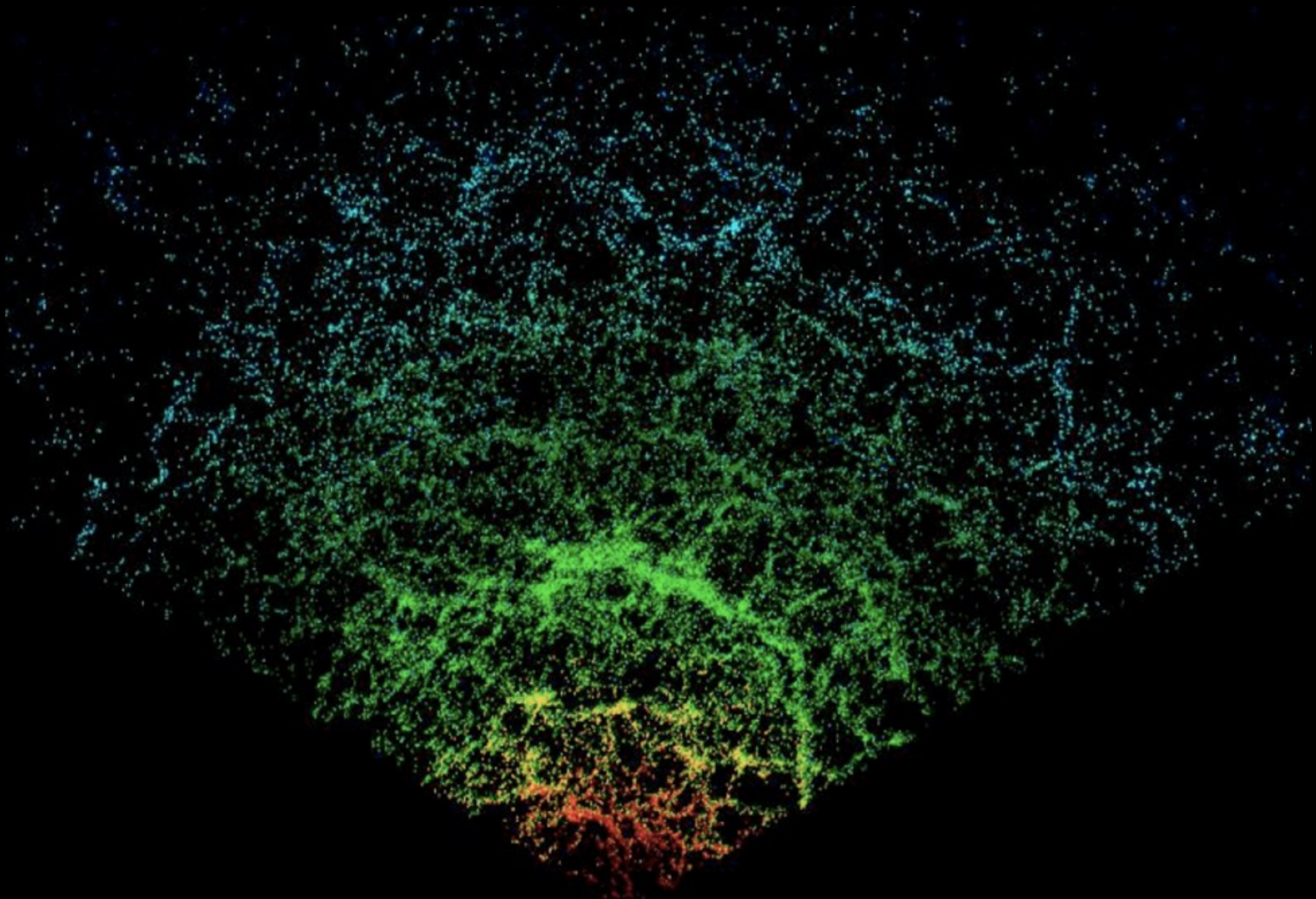
For weak fields, its the sum of the deflection angles 4GM/b over the mass of the lens

The “Bullet cluster” (1E 0657-558)

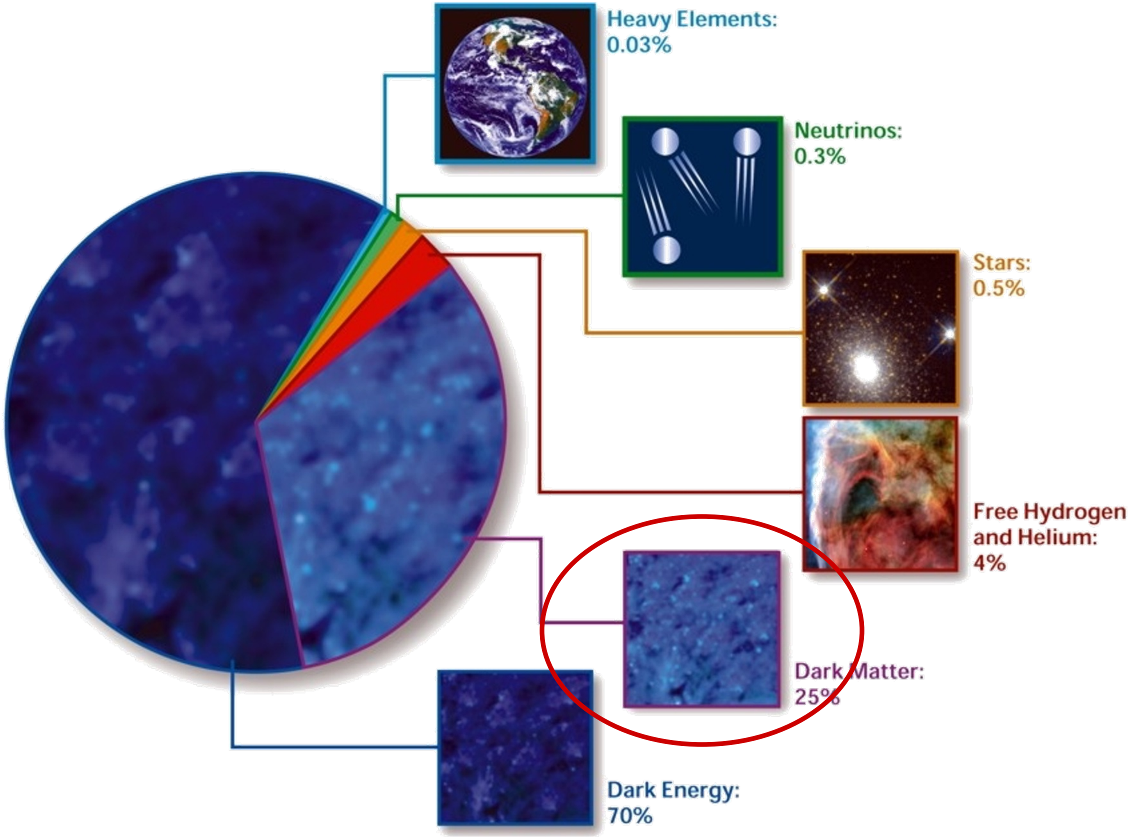


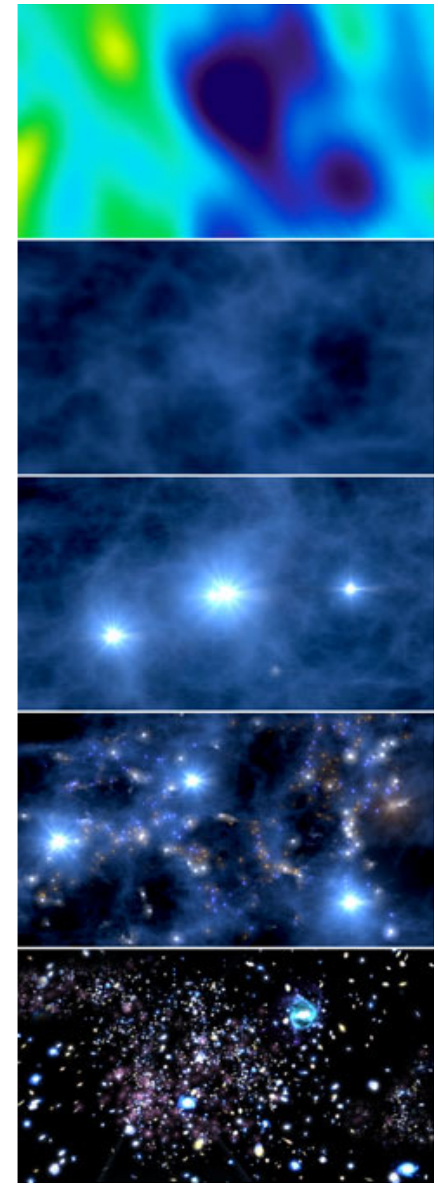
Colliding galaxy clusters

Universe at large scales



Dark Matter

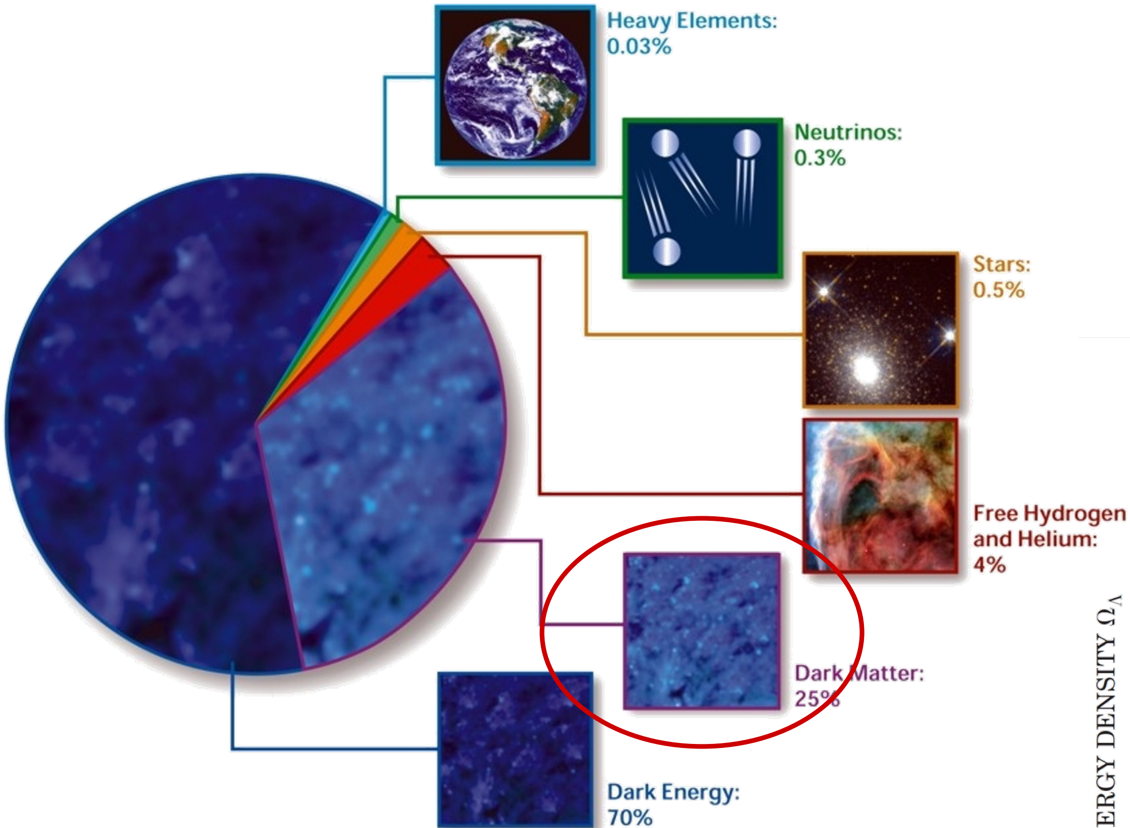


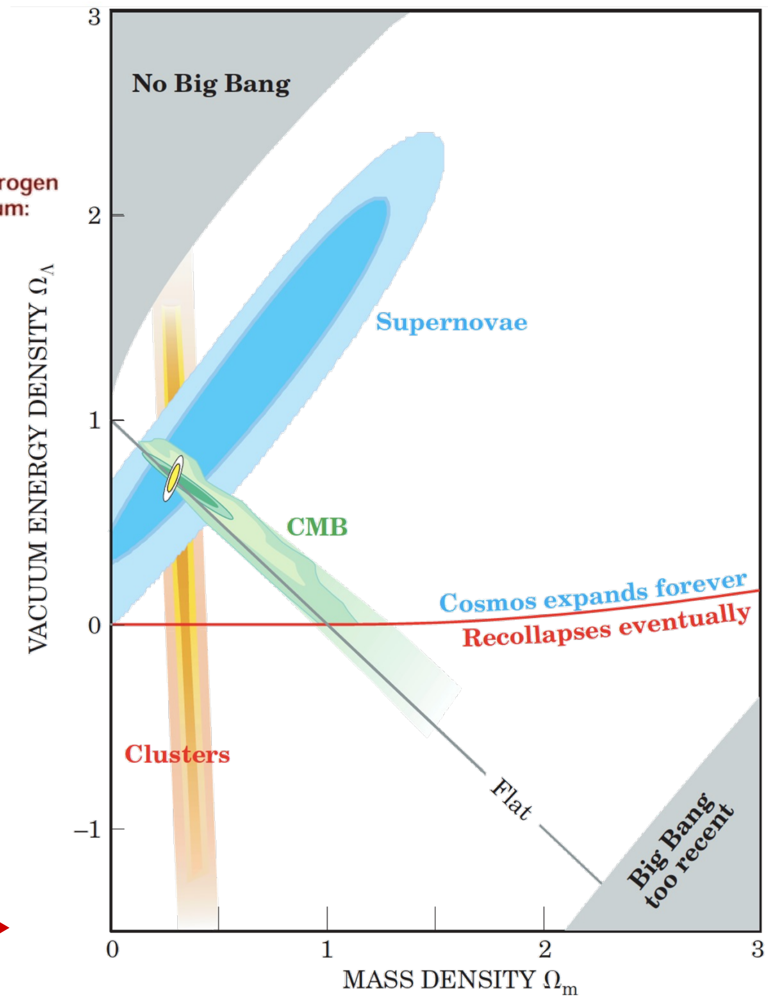


Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

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

Dark Matter





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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

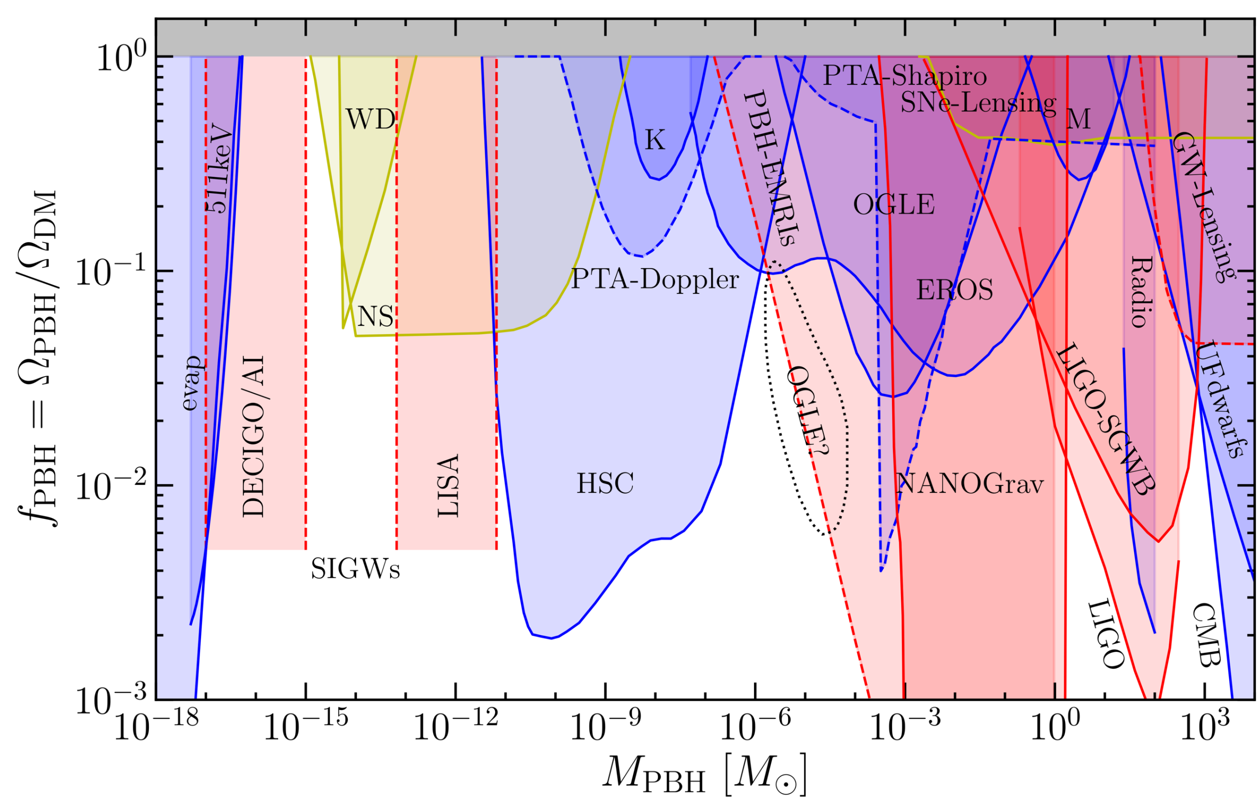
$$T_{\mathrm{BH}} = \frac{\hbar c^3}{8\pi k_B G M} \sim 10^{-7}\ \mathrm{K}\ \frac{M_\odot}{M}$$

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

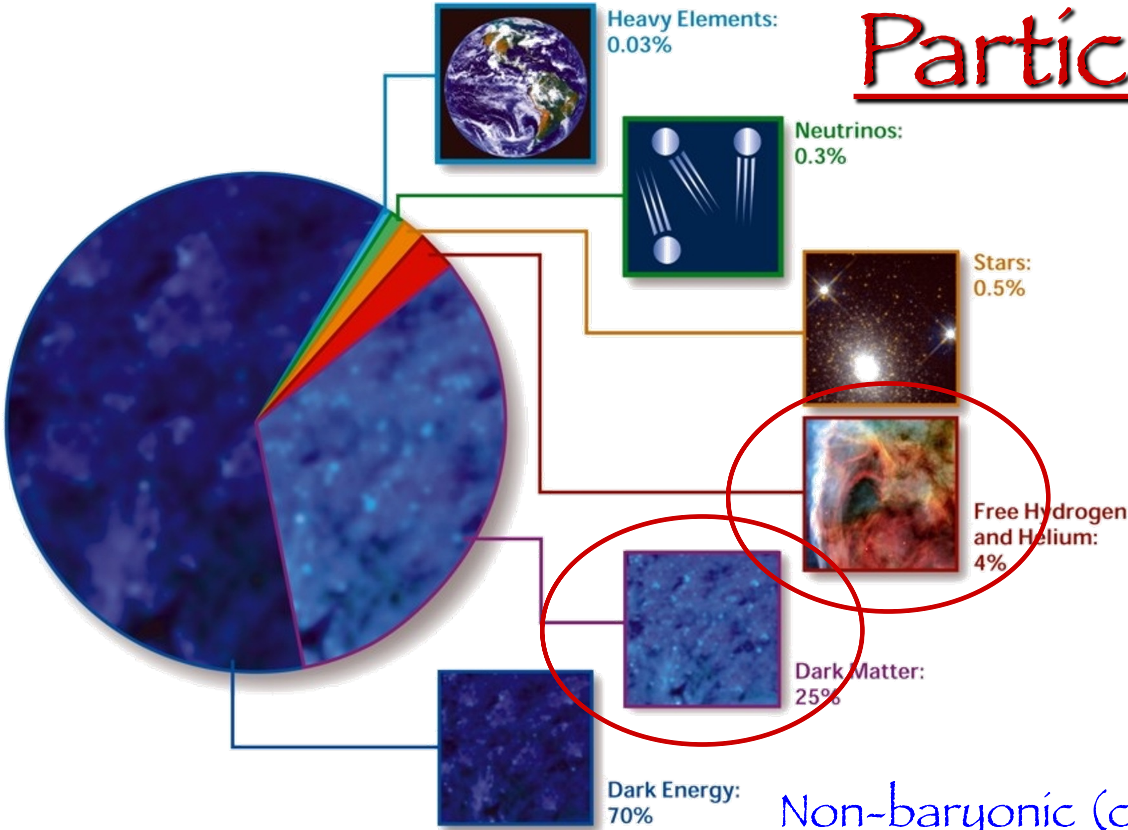
PBH with masses below 10^{15} g have already evaporated

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

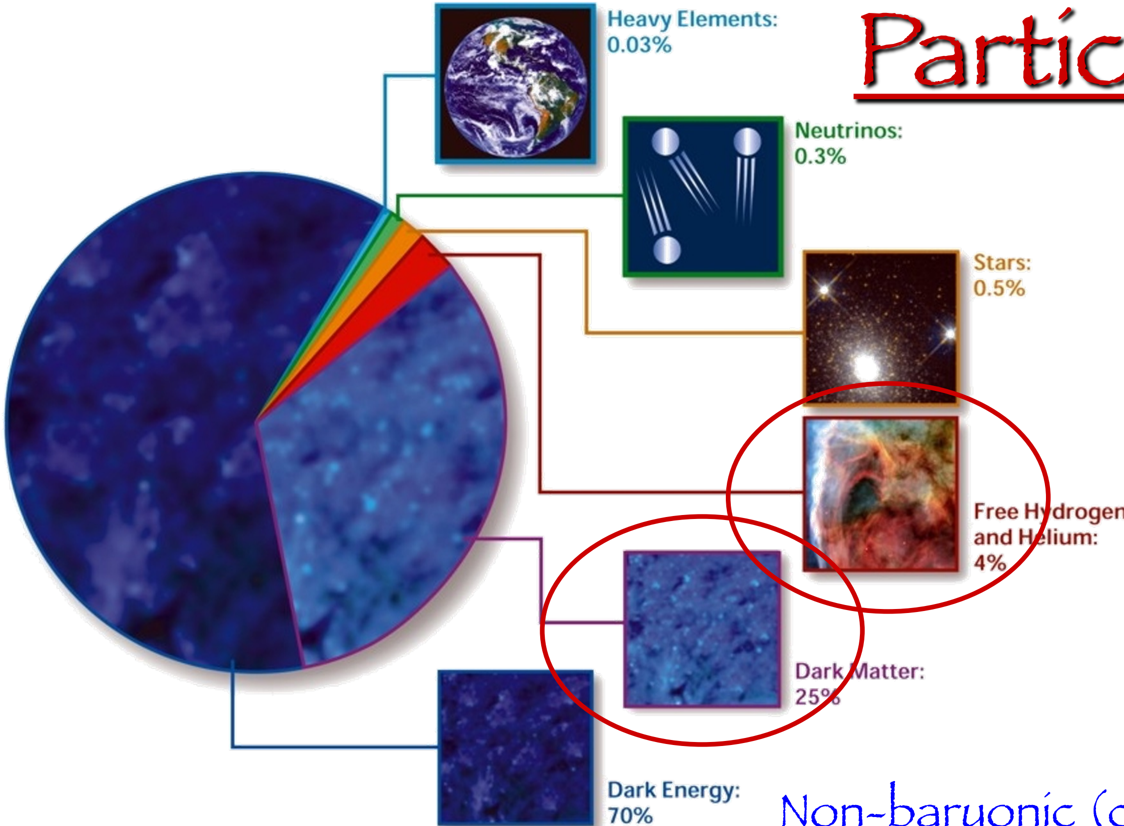
No candidate in the Standard Model (*)

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 (*)

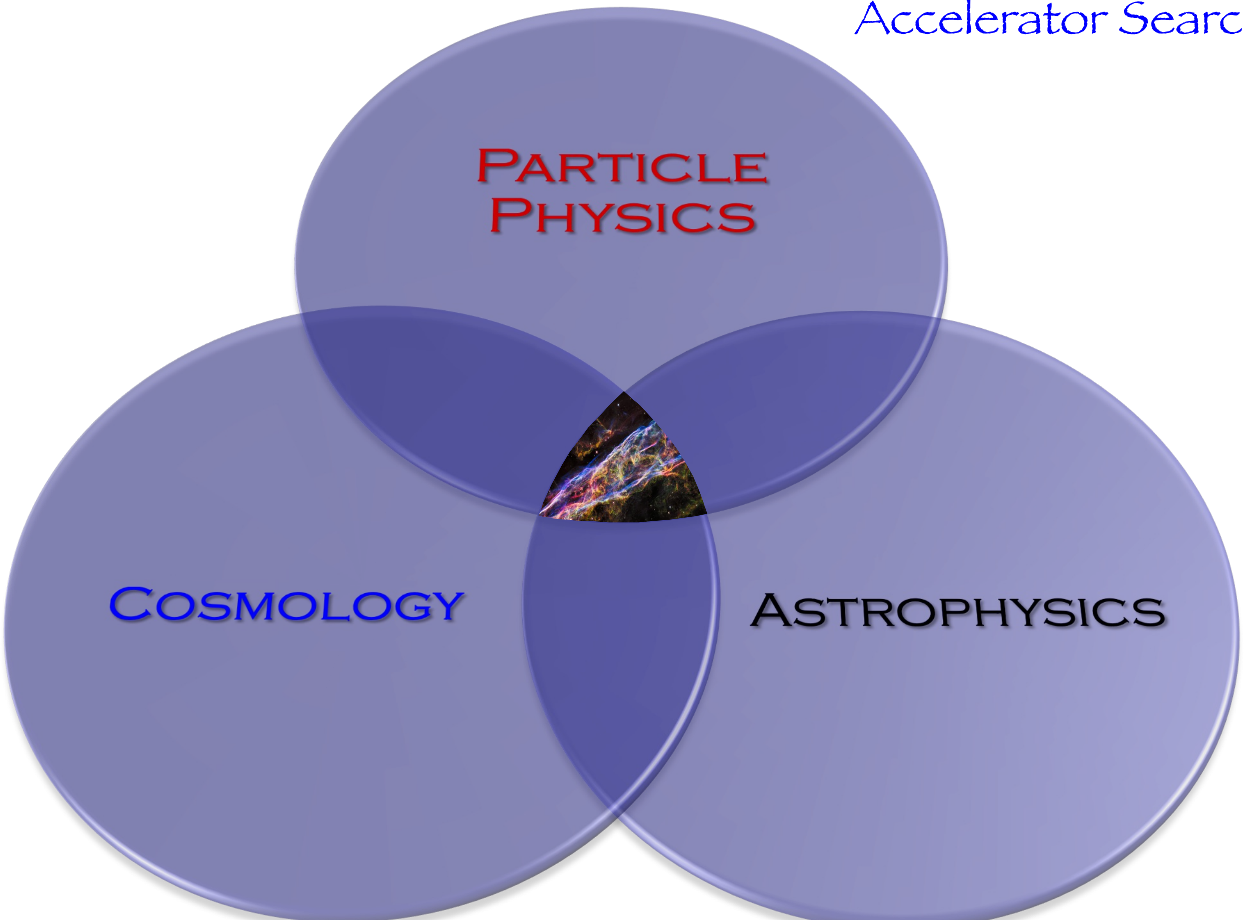
New fundamental Physics

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

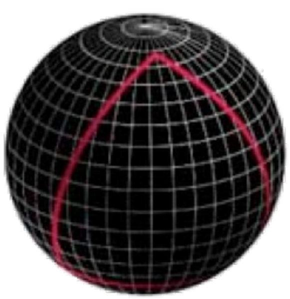
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{3} T_{\mu\nu}$$

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

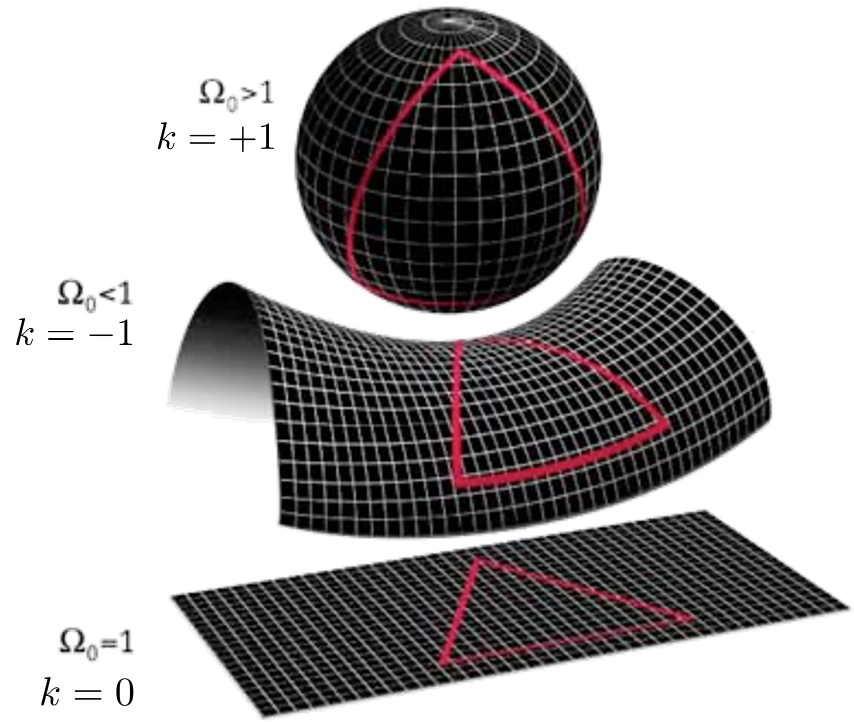
Density parameter $\Omega_i = \rho_i / \rho_c$

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

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	$p = -\rho$

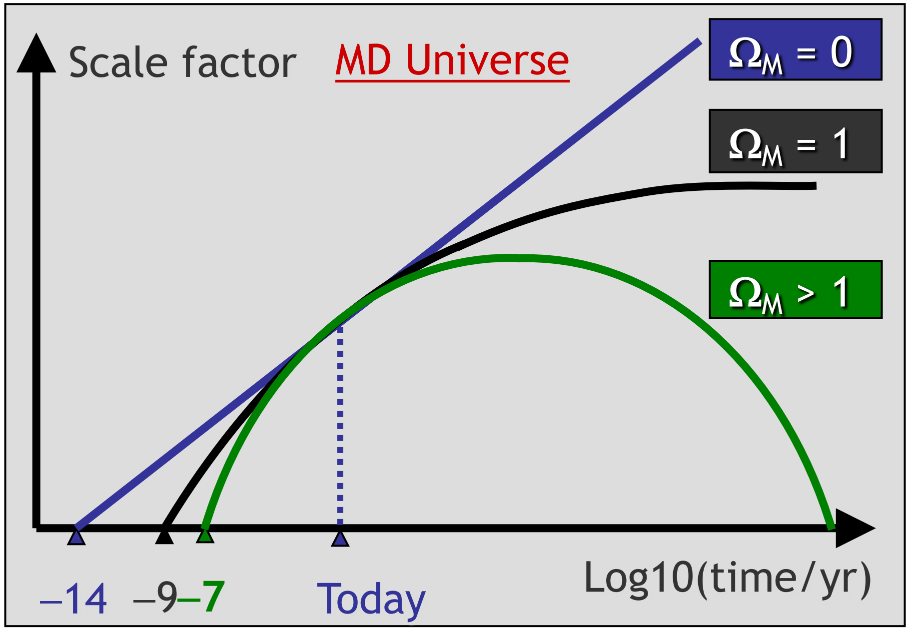
The evolution of the U. (i.e. of the scale factor in time) depends on its content (and on its geometry), ad dictated by the Einstein equations

Flat Universe

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

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

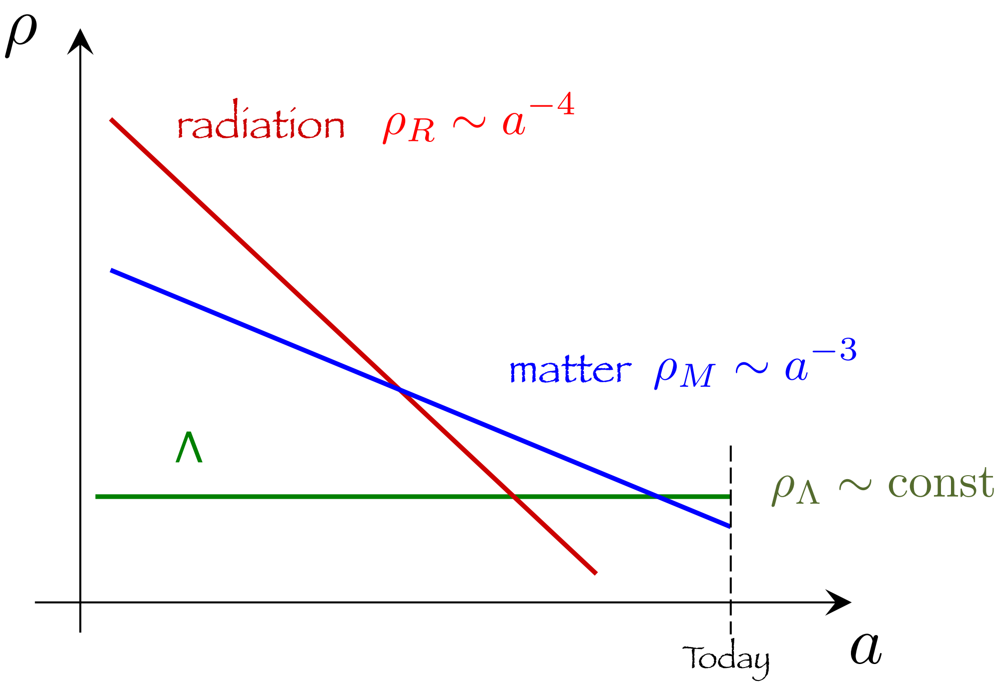
ΛD U. $a(t) = a_0\ \exp H_0(t - t_0)$



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	$\frac{2\pi^2}{45} g_i T^3$	$\left(\frac{7}{8}\right) \frac{2\pi^2}{45} g_i T^3$	

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

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

$$S = sa^3 = \text{const}$$

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

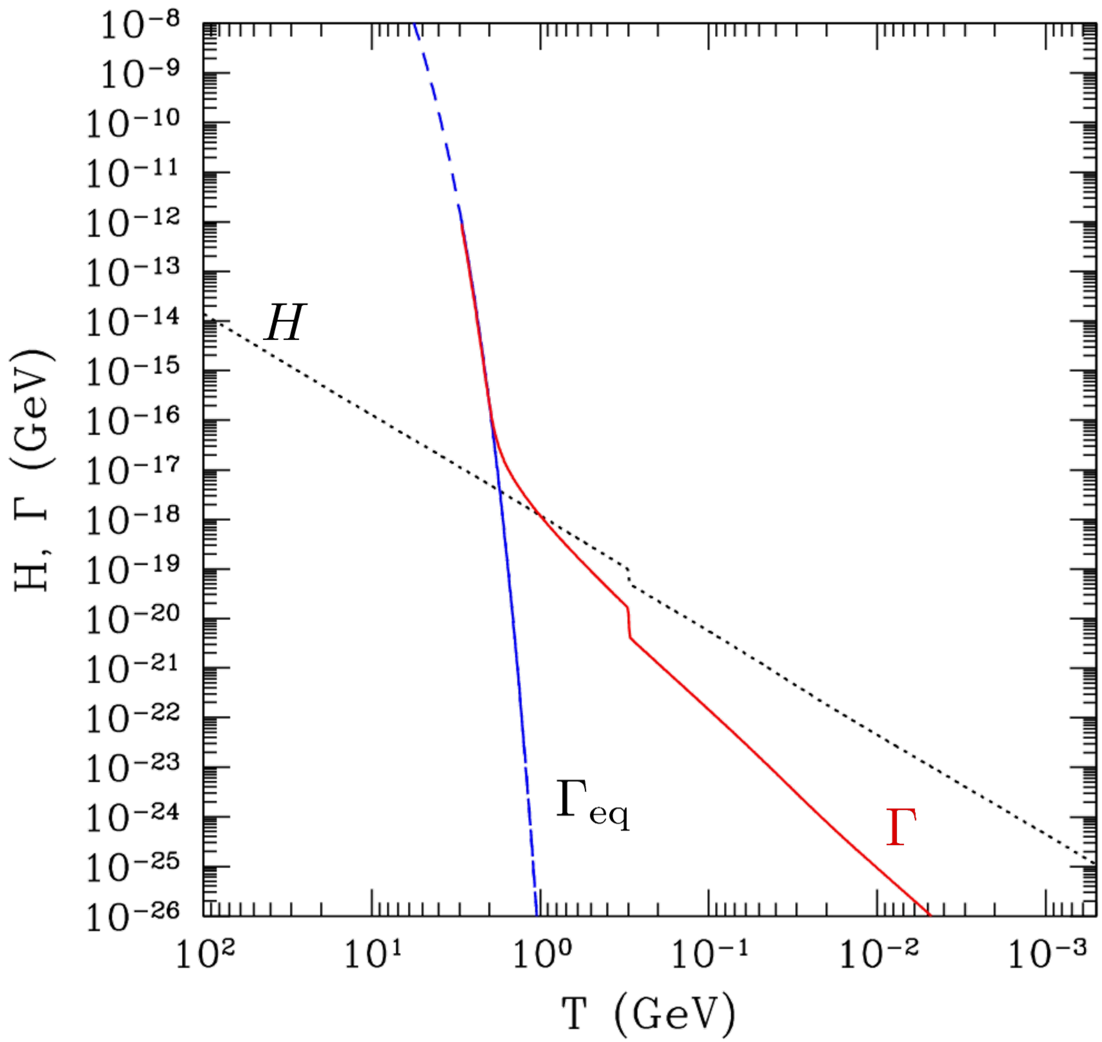
$H = \dot{a}/a$: expansion rate

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

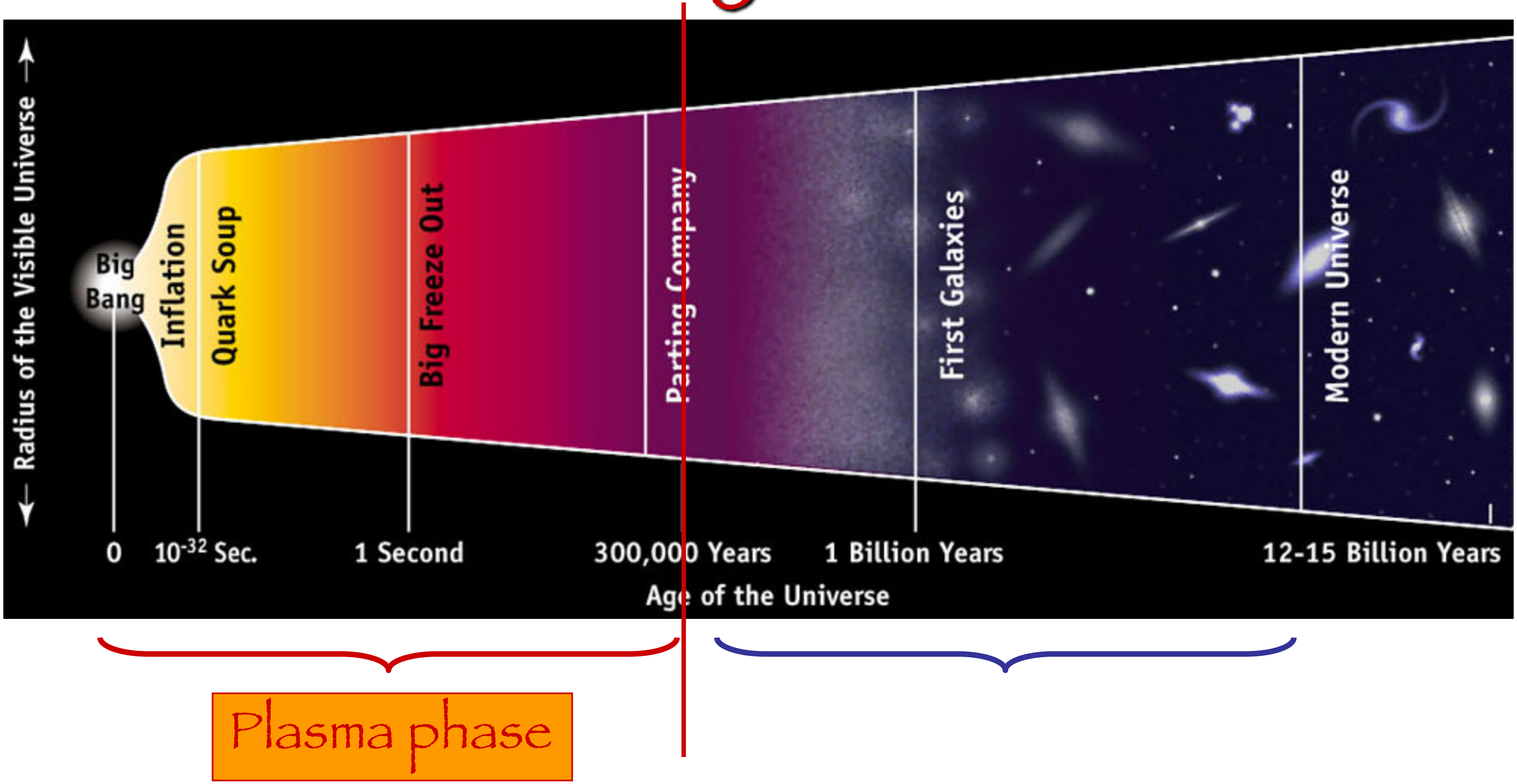
Particle thermalization in the early Universe

$\Gamma > H$ equilibium

$\Gamma \leq H$ out of equilibium

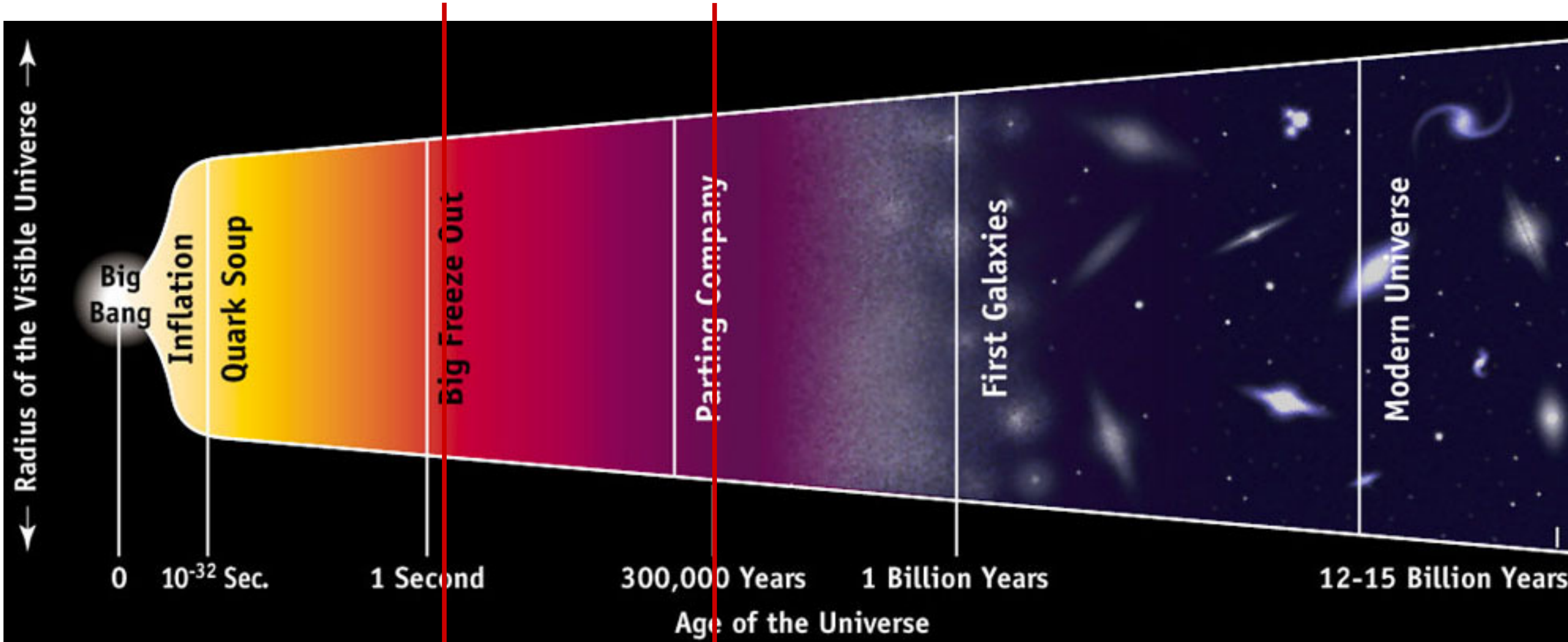


Thermal history of the Universe



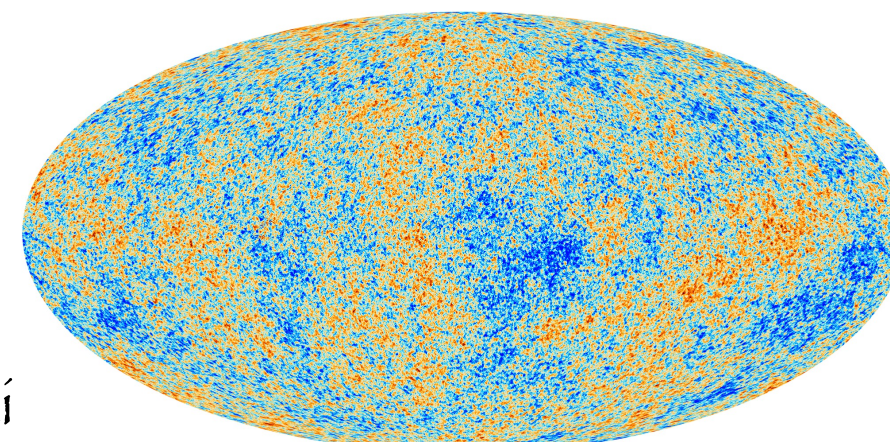
In this primordial phase, U. evolution is determined by particle interactions

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.

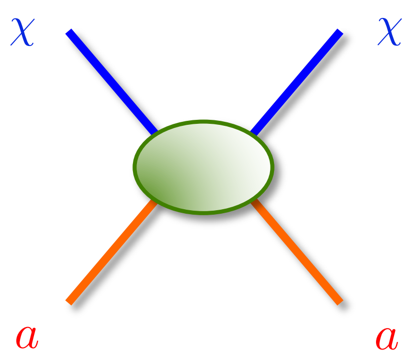
$$L[f_i] = E\frac{\partial f_i}{\partial t} - \frac{\dot{a}}{a}|\vec{p}|^2\frac{\partial f_i}{\partial E}$$

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

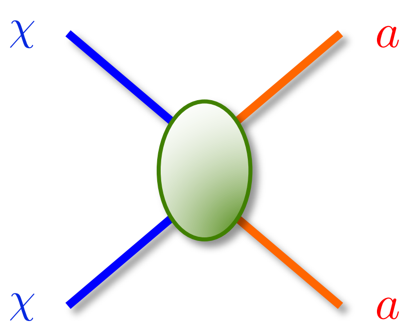
$$C[f_i; f_j, f_k, ...] = C_{\text{elastic}}[f_i; f_j, f_k, ...] + C_{\text{inelastic}}[f_i; f_j, f_k, ...]$$

Collision operator

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



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

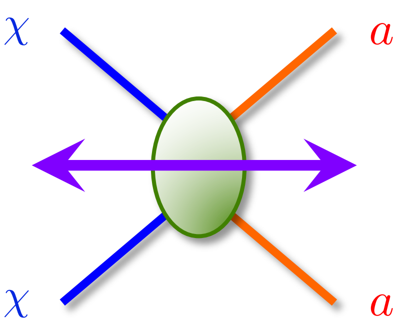
After integration over momenta (and some mathematical manipulation) a Boltzmann eq. for the number density can be cast in the form:

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

dilution due to expansion

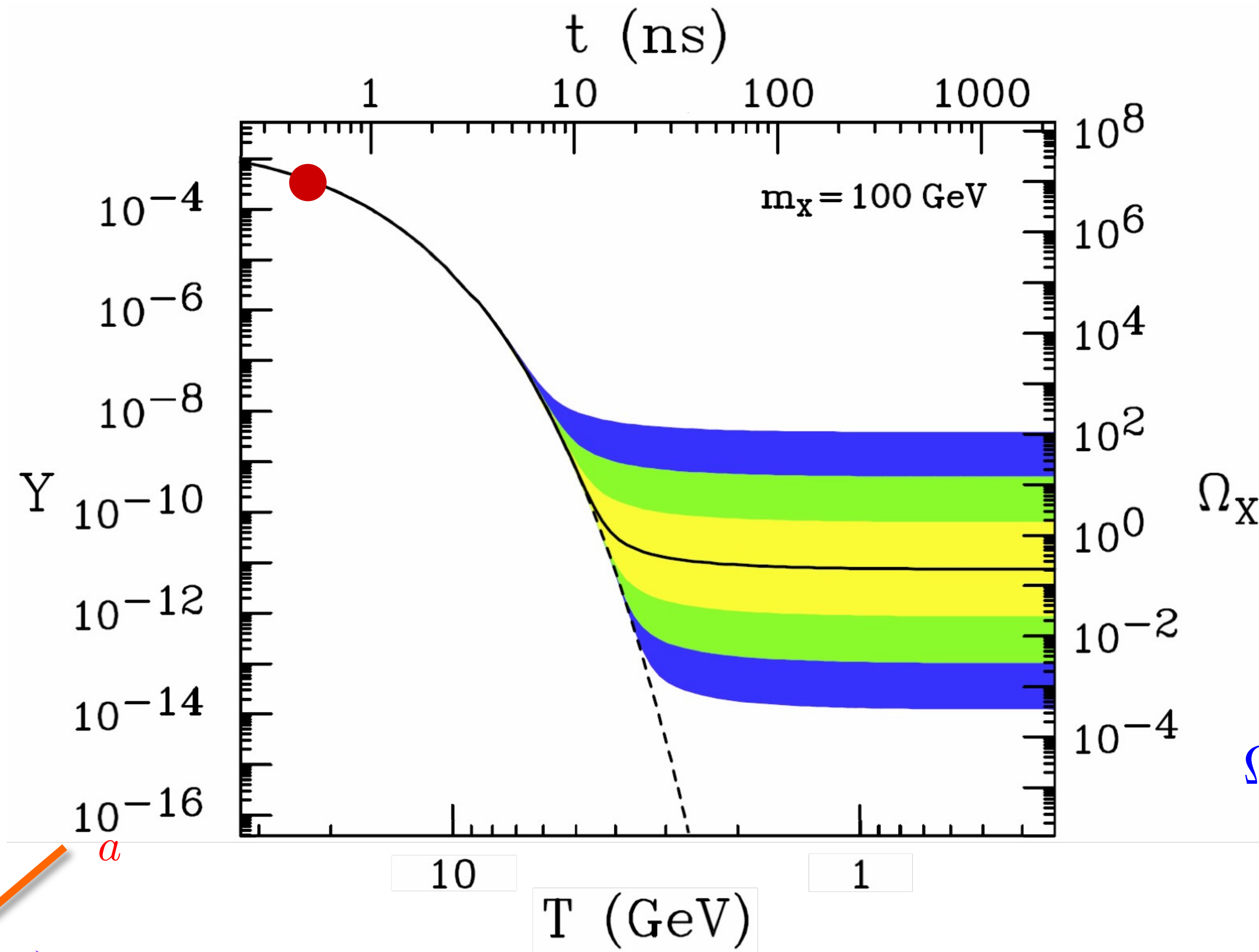
dilution due to annihilation

production due to inverse annihilation

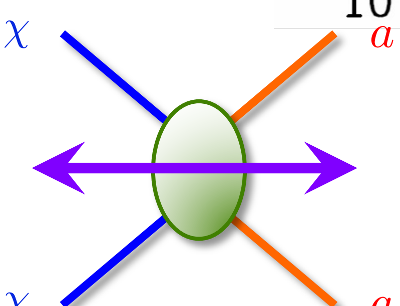


Abundance evolution

$Y = n/s$



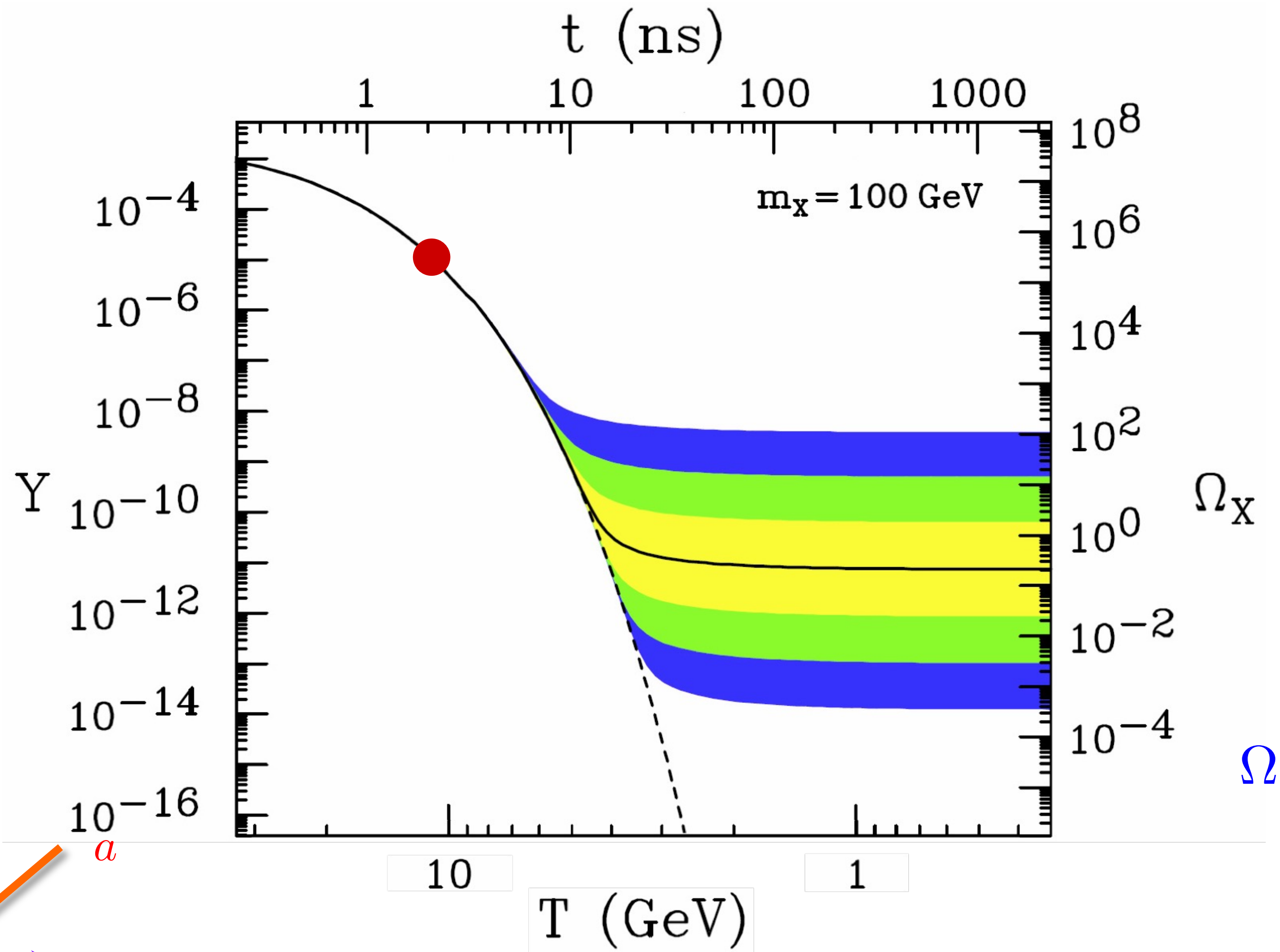
$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$



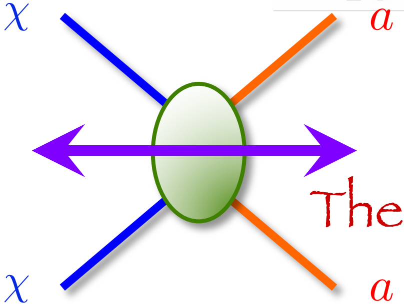
particle in equilibium

Abundance evolution

$Y = n/s$



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

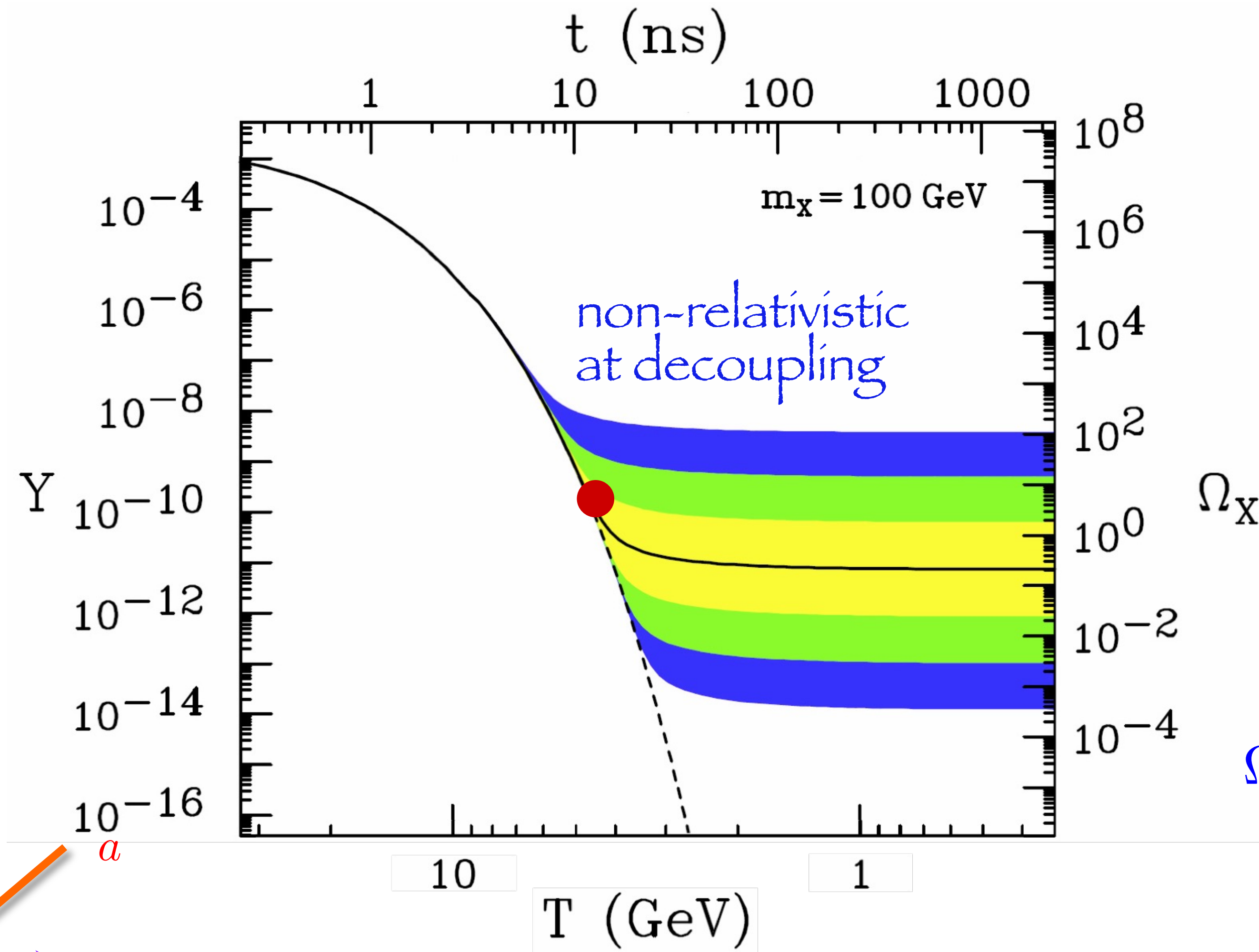


The universe cools down

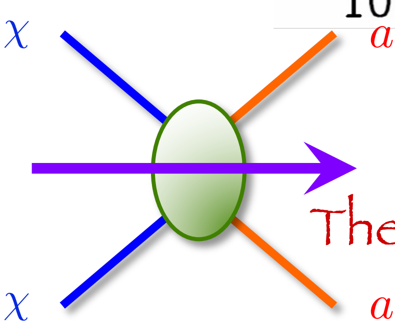
particle in equilibium

Abundance evolution

$Y = n/s$



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

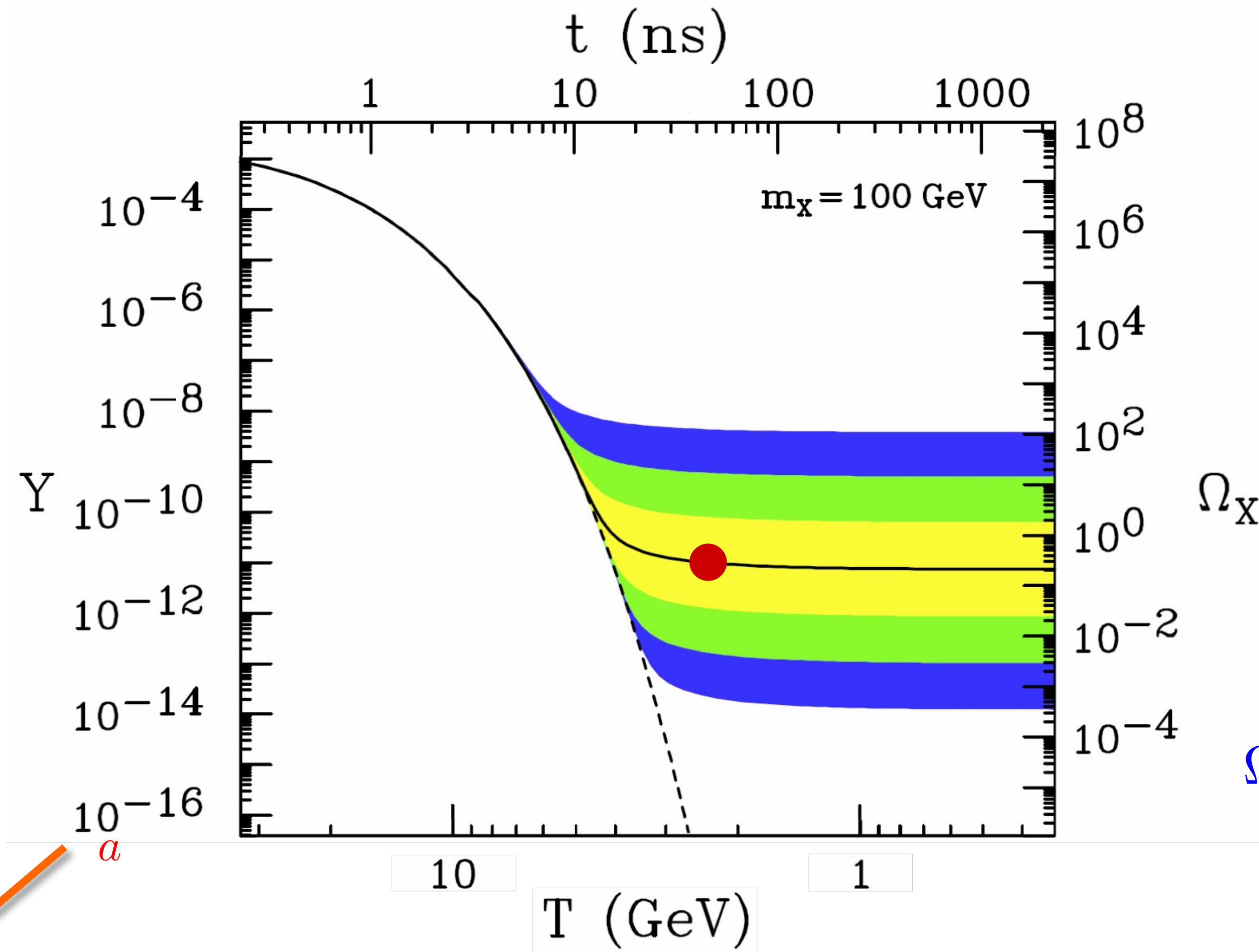


The universe cools down

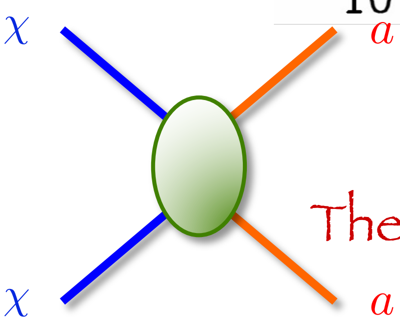
particle detaches from the plasma
"freeze-out" of its abundance

Abundance evolution

$Y = n/s$



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

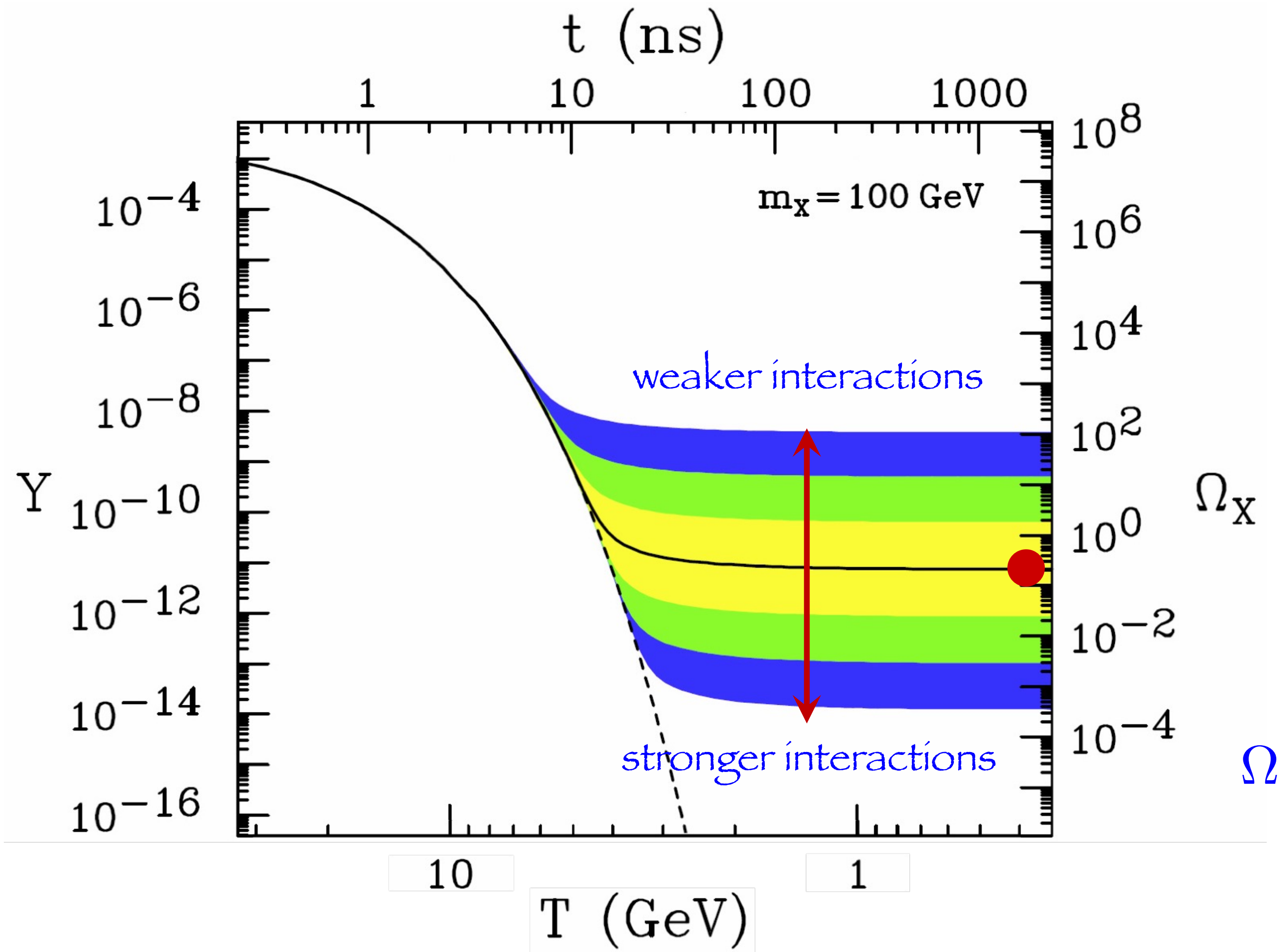


The universe cools down

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

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

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

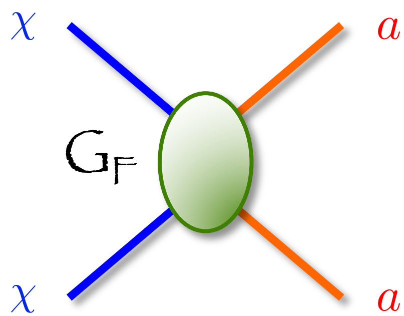
m_{DM} (GeV)	ξ
1	4
10	0.4
100	0.04
1000	0.004

In more details

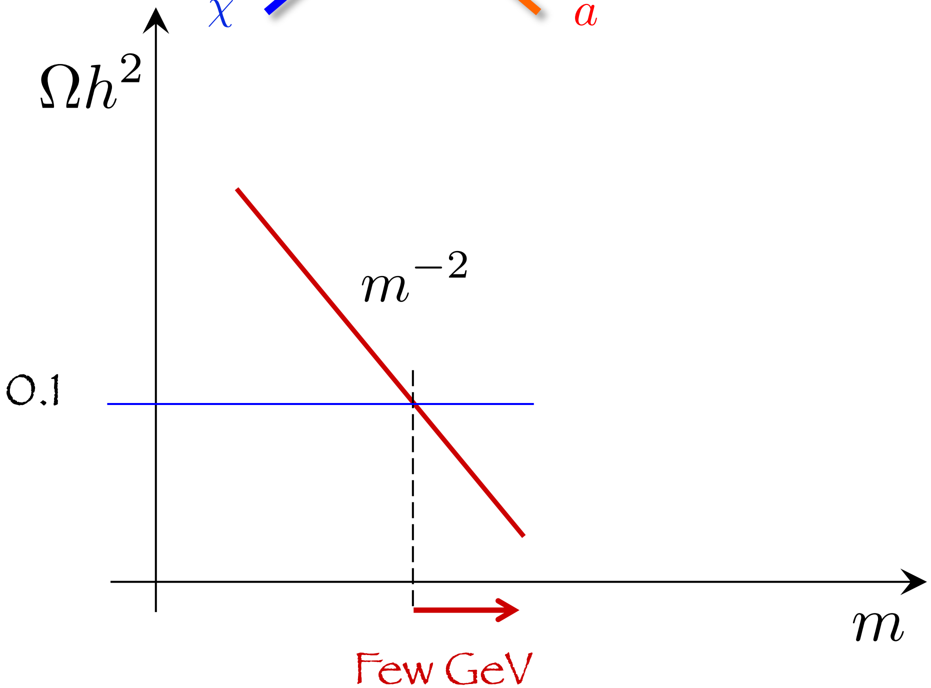
$m \ll m_Z$ $\quad \langle \sigma_{\rm ann} v \rangle \sim G_F^2 m_{\rm DM}^2$ $\quad s = q^2 \sim (2\, m_{\rm DM})^2$

non-relativistic

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



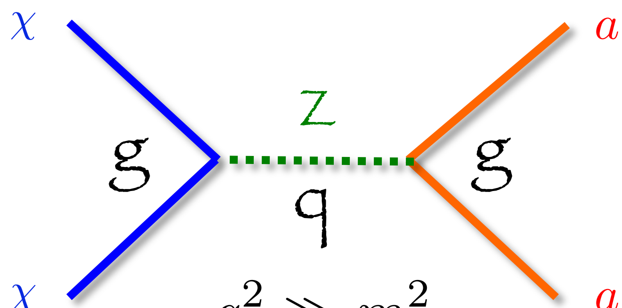
Fermi limit



Lee-Weinberg bound

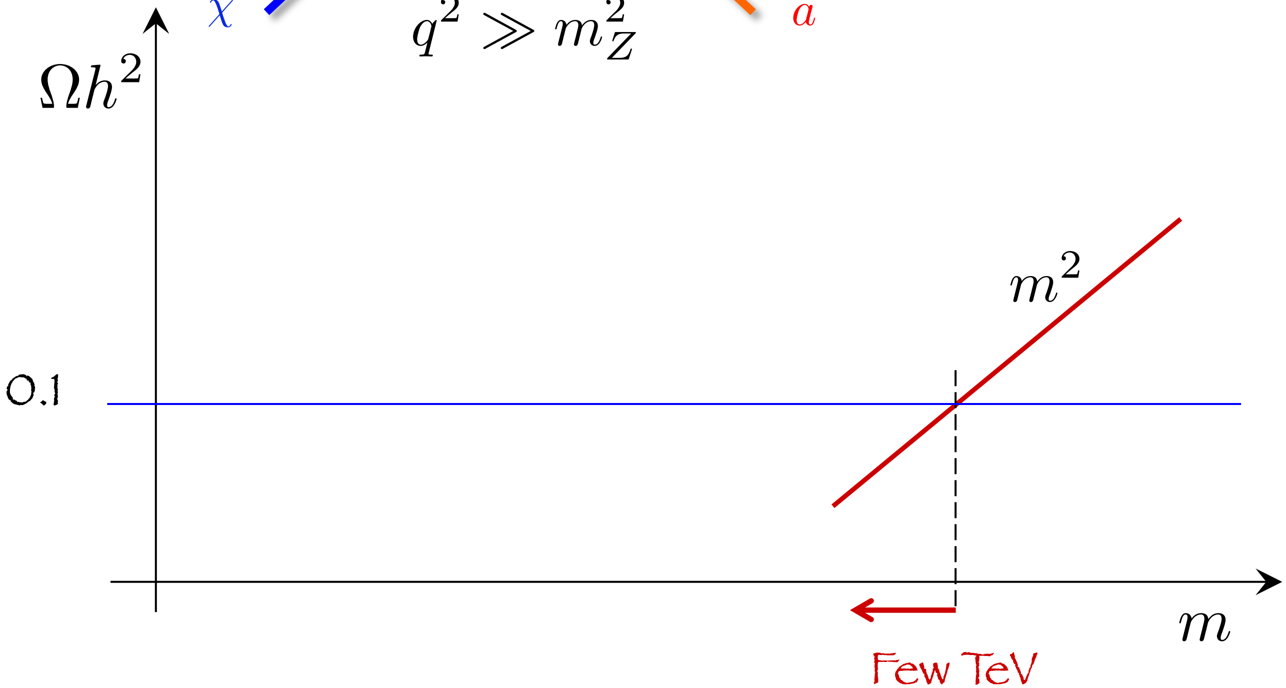
In more details

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

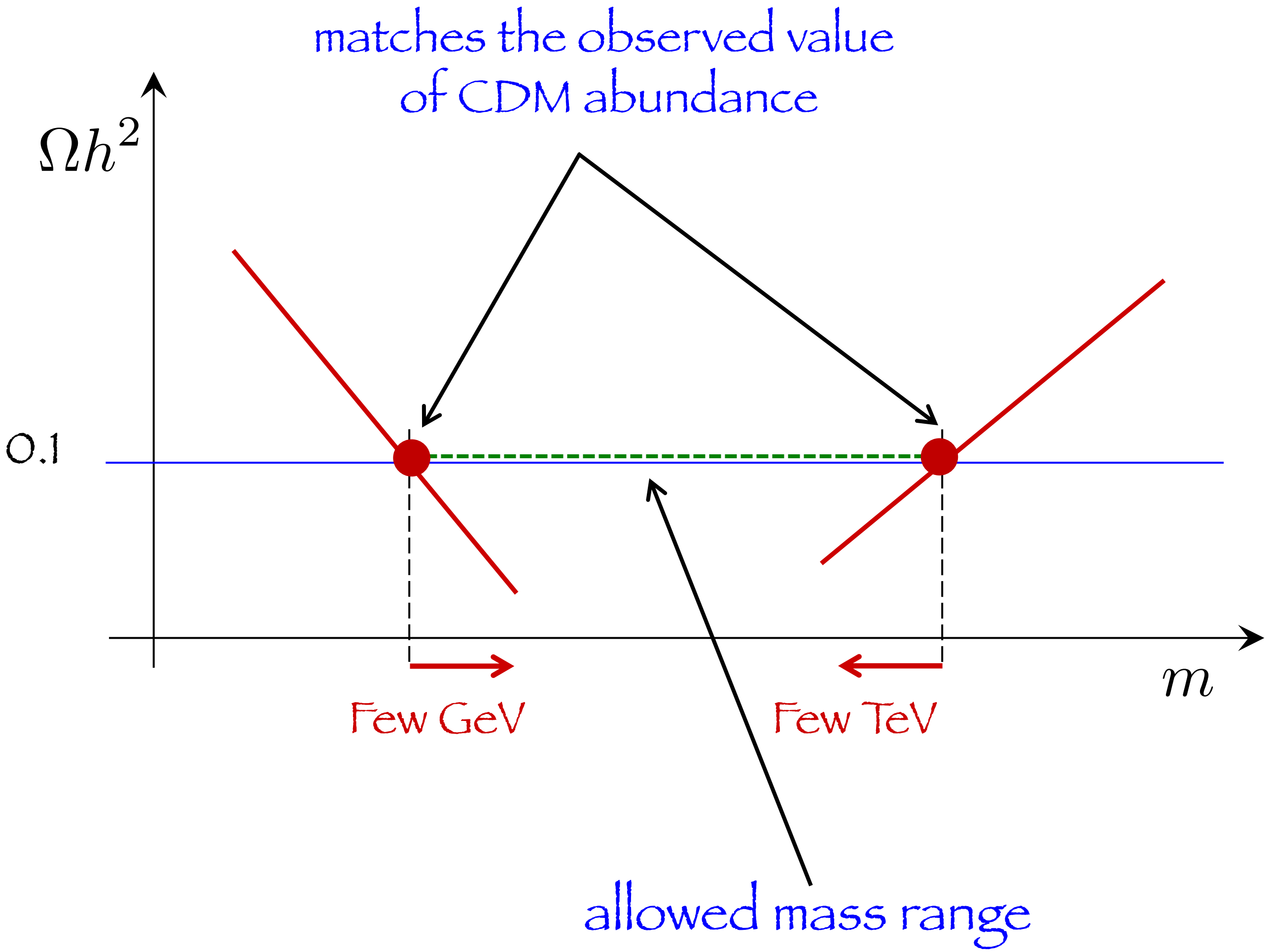


$q^2 \gg m_Z^2$

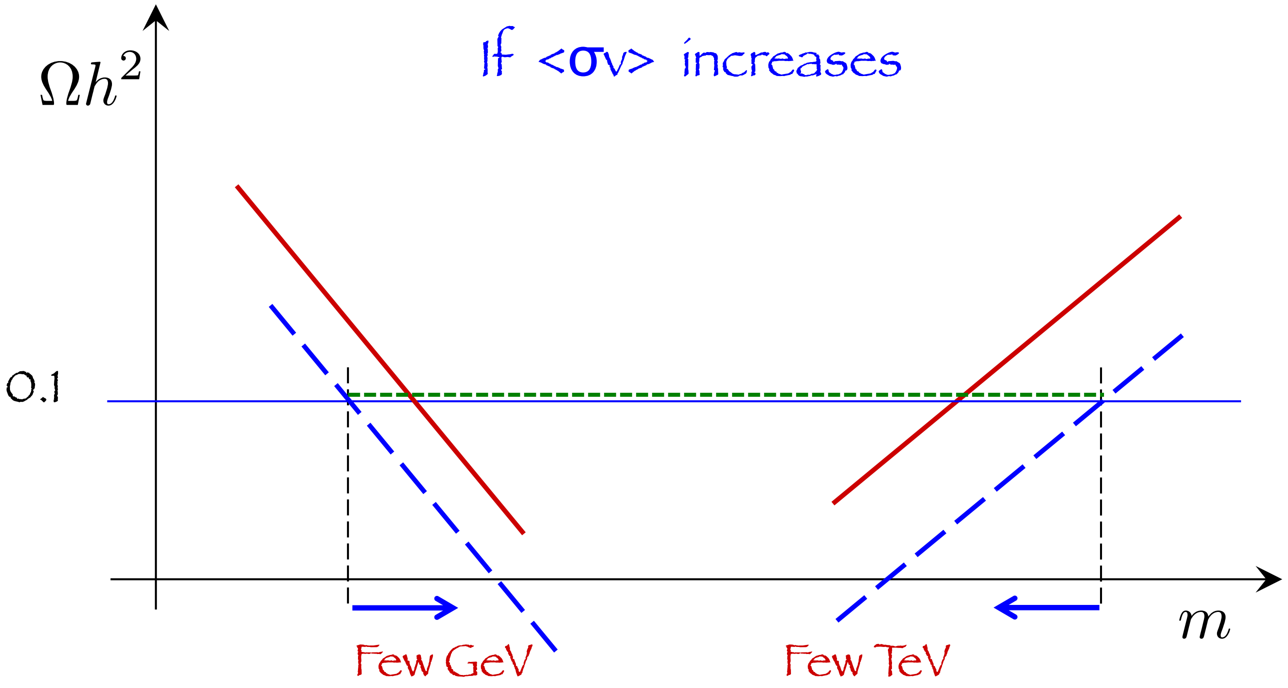
Effectively massless Z



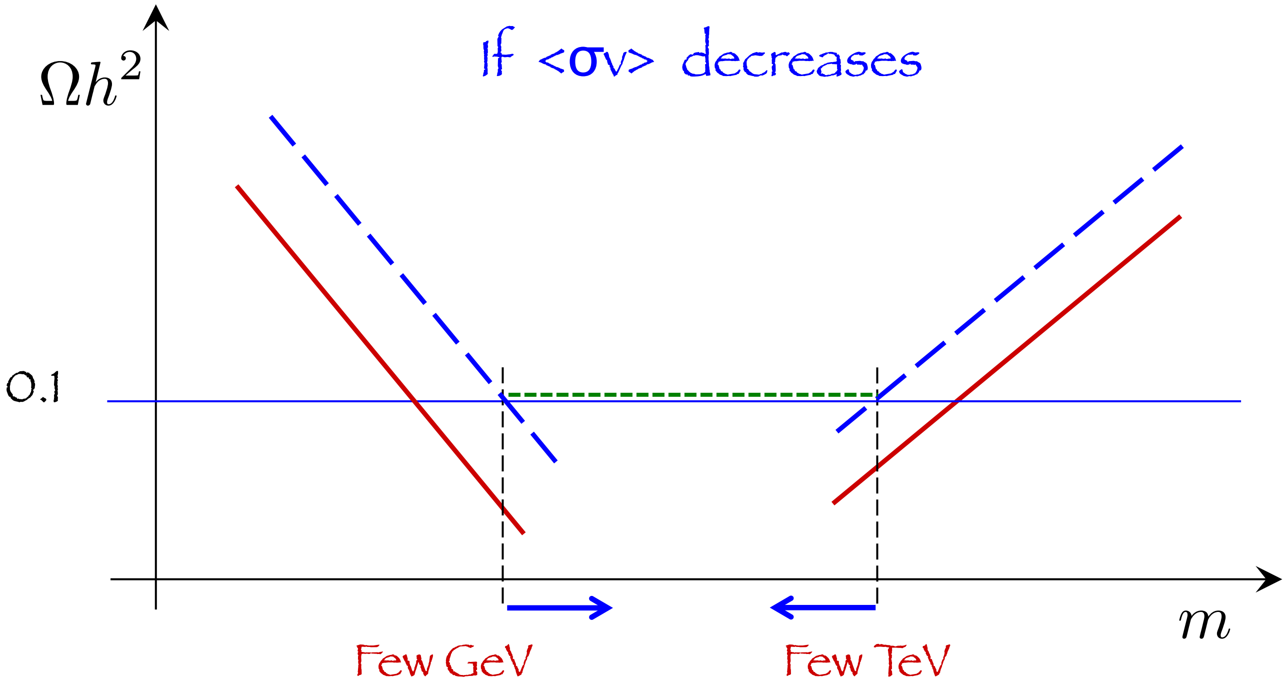
Summarizing



Dependencies



Dependencies



Additional features

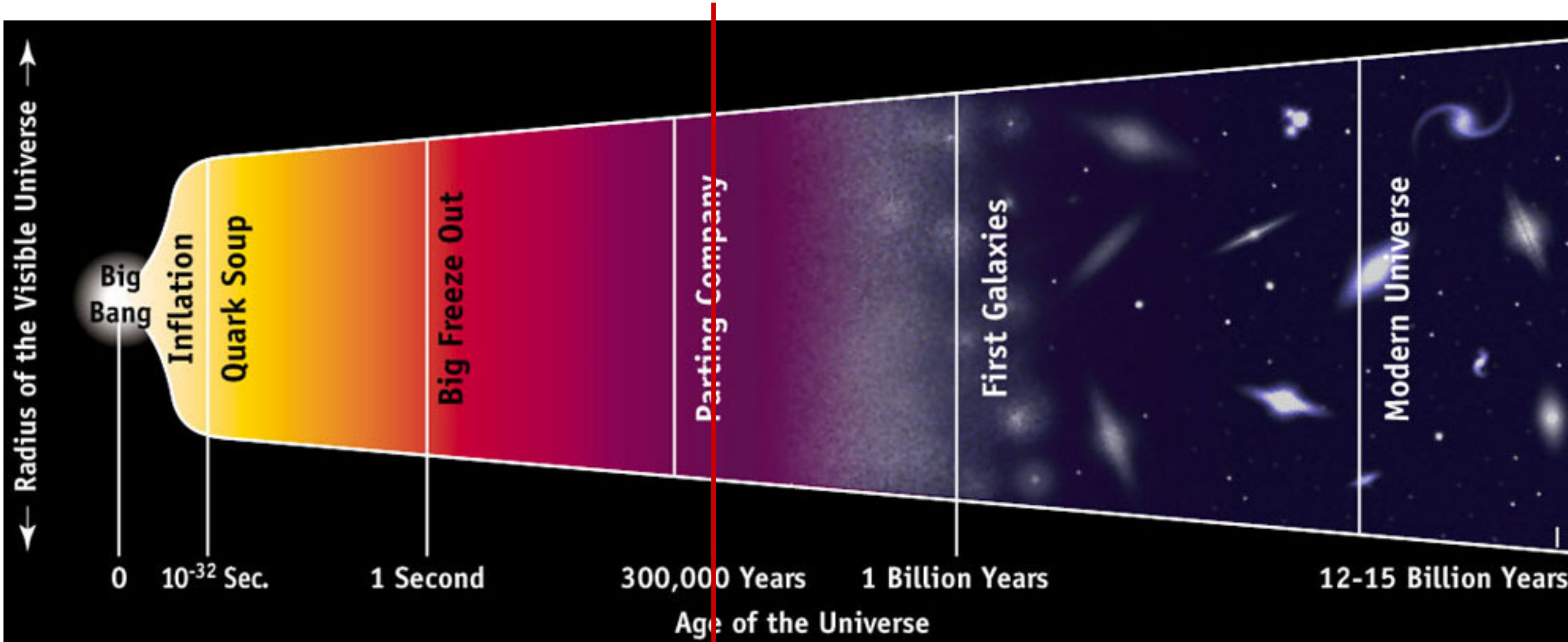
- Poles (Z, H, others) — $m_{\rm DM} \sim m_Z/2\,,\, m_H/2$
- Coannihilations — $m_{\rm DM} \sim m_{\rm sligthly\ heavier\ state}$
- Sommerfeld enhancements — light mediator

The WIMP "miracle"

Loosely speaking a WIMP with:

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

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



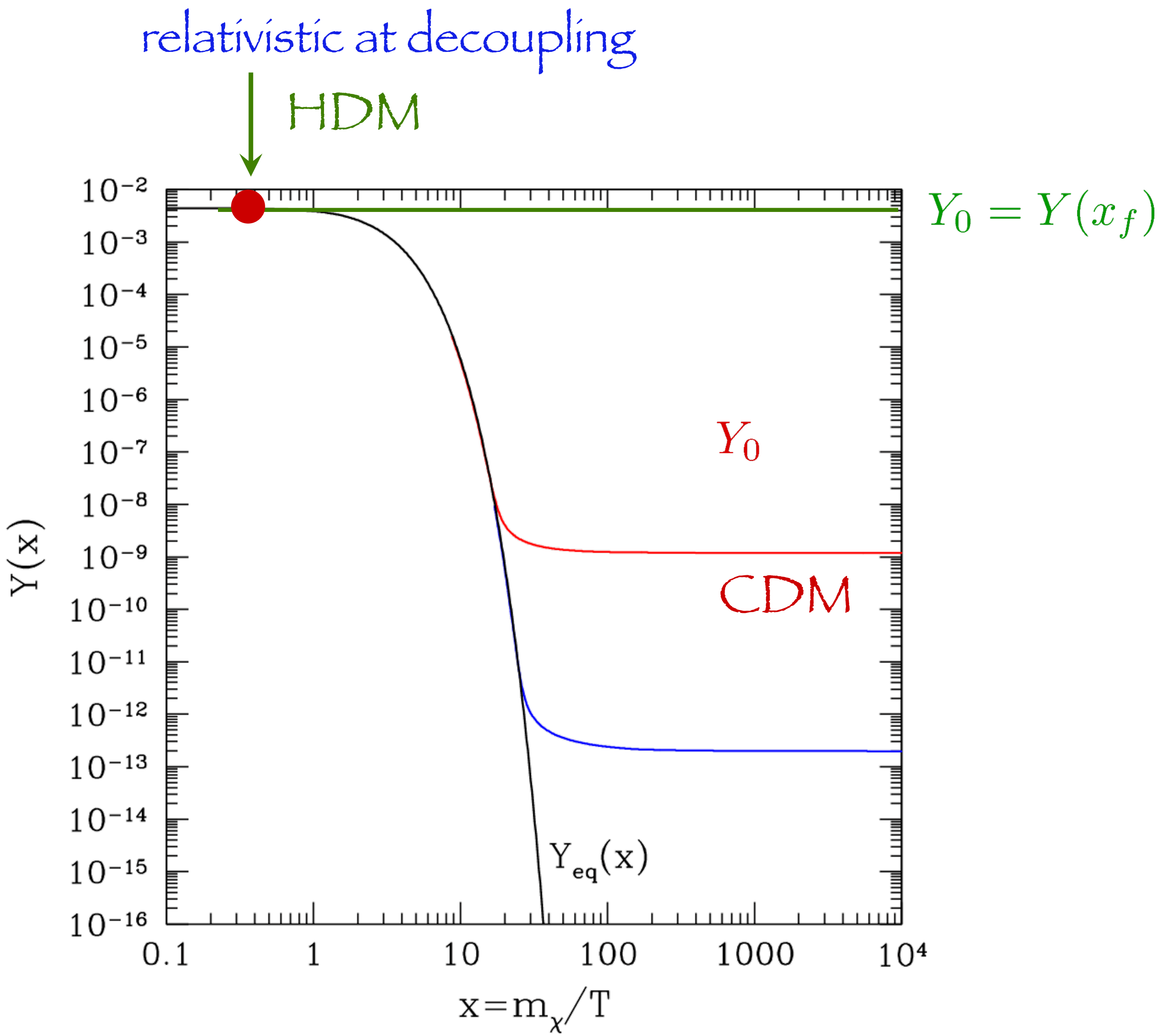
T	10^{16} GeV	1 MeV	0.23 eV

BBN CMBR

CDM

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

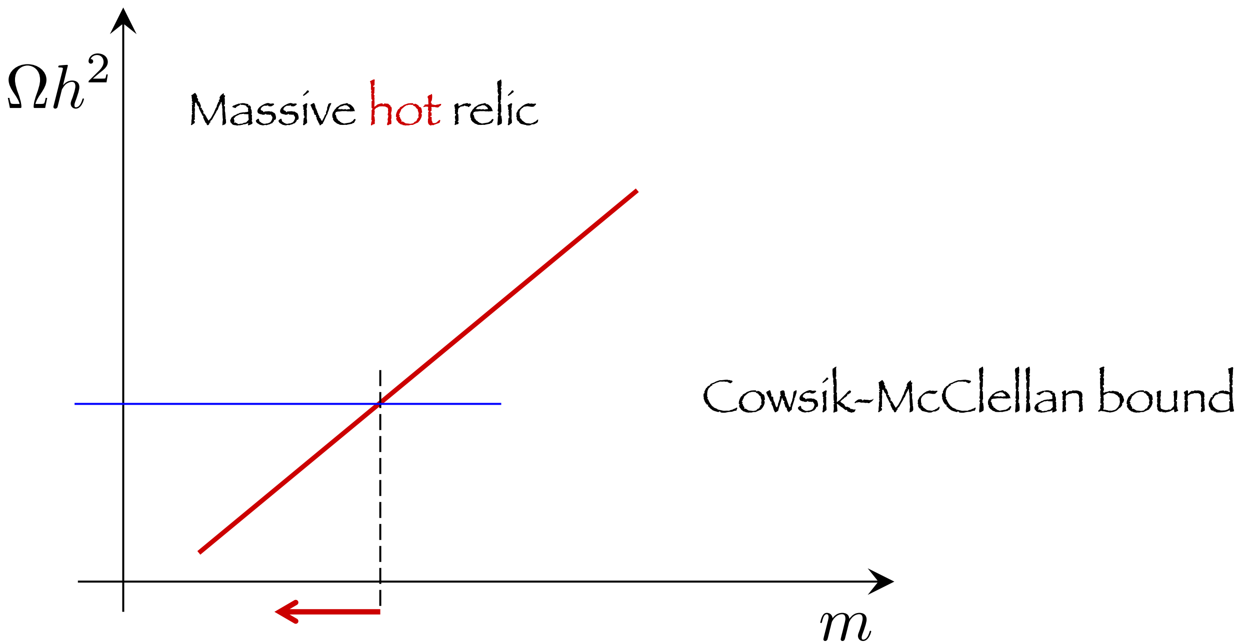
Light thermal relics



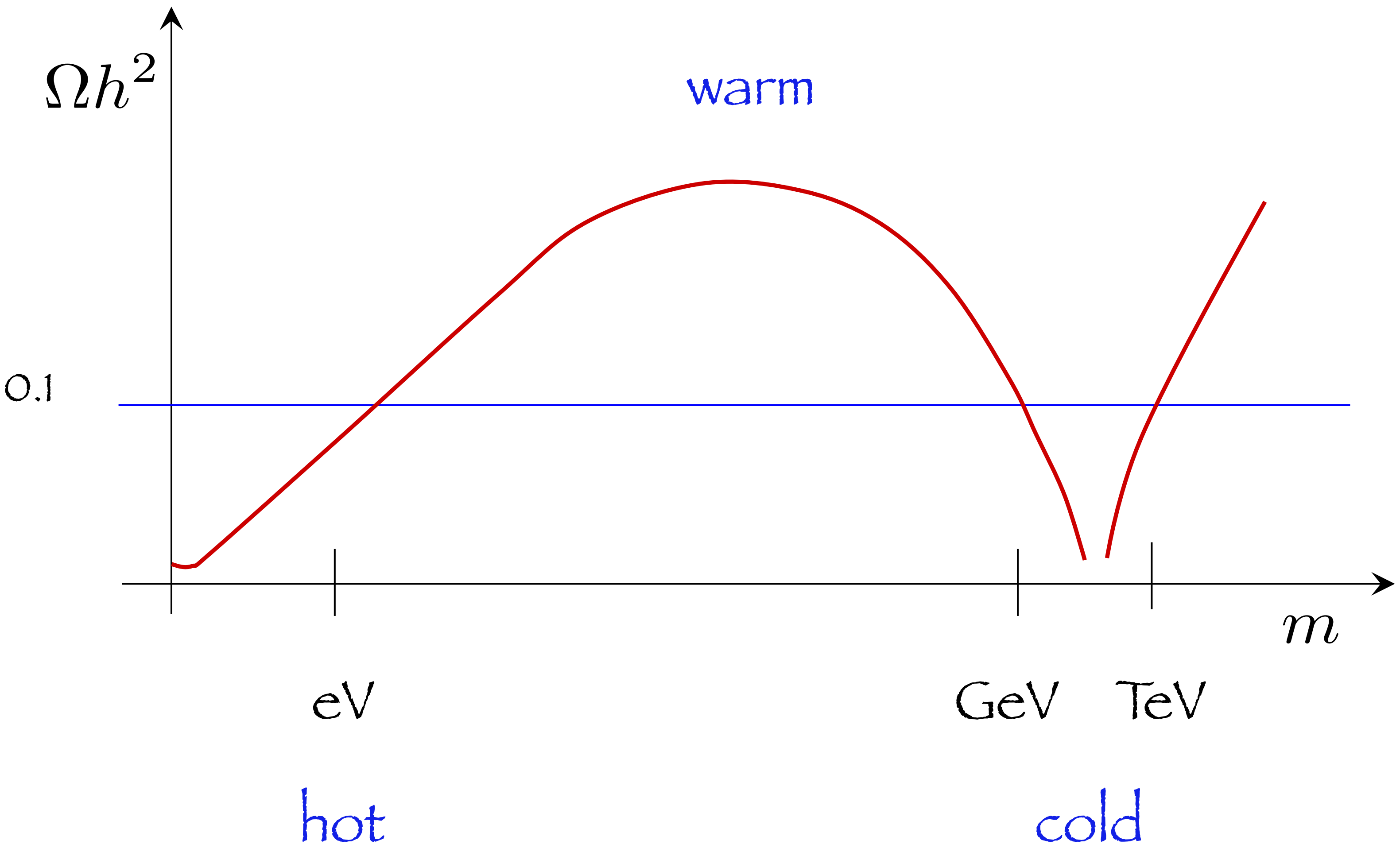
Light relics as HDM (e.g. neutrinos)

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

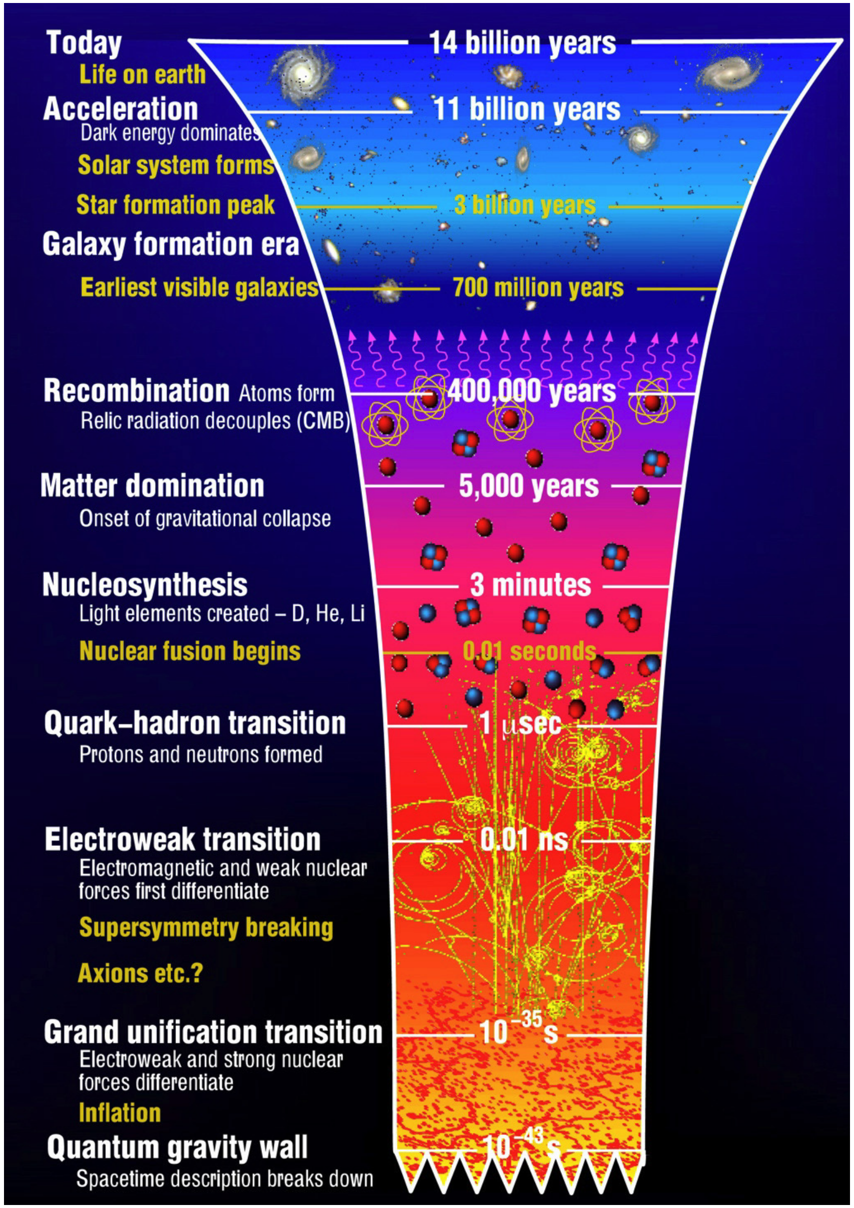
$$\Omega_\nu h^2 \leq (\Omega_{\rm DM} h^2) = 0.13 \longrightarrow \sum_i m_i \leq 12\ \text{eV}$$



Summary for a thermal relic



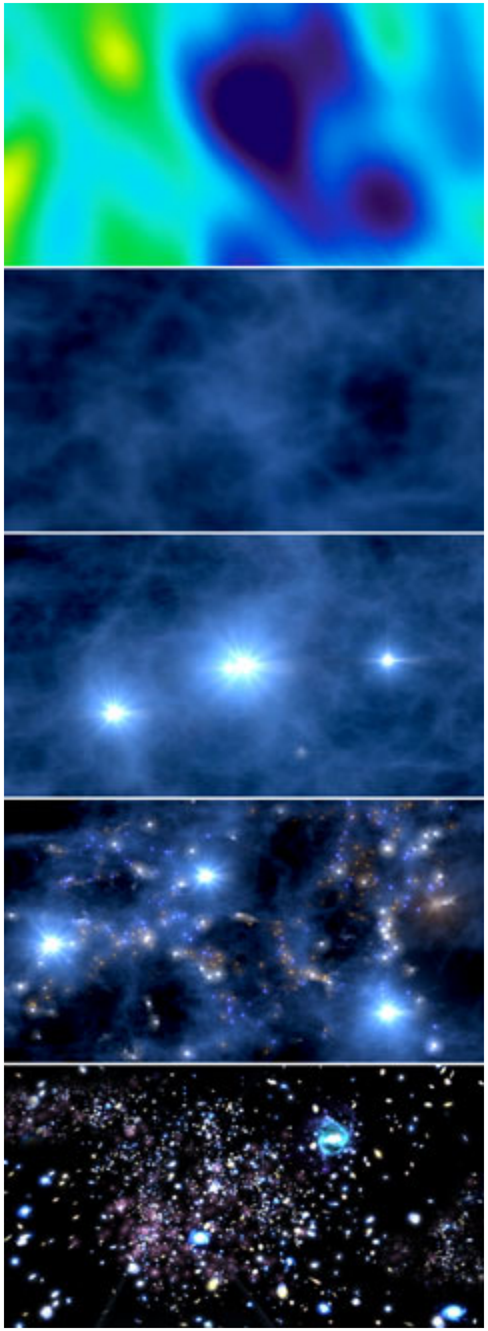
Early Universe



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)

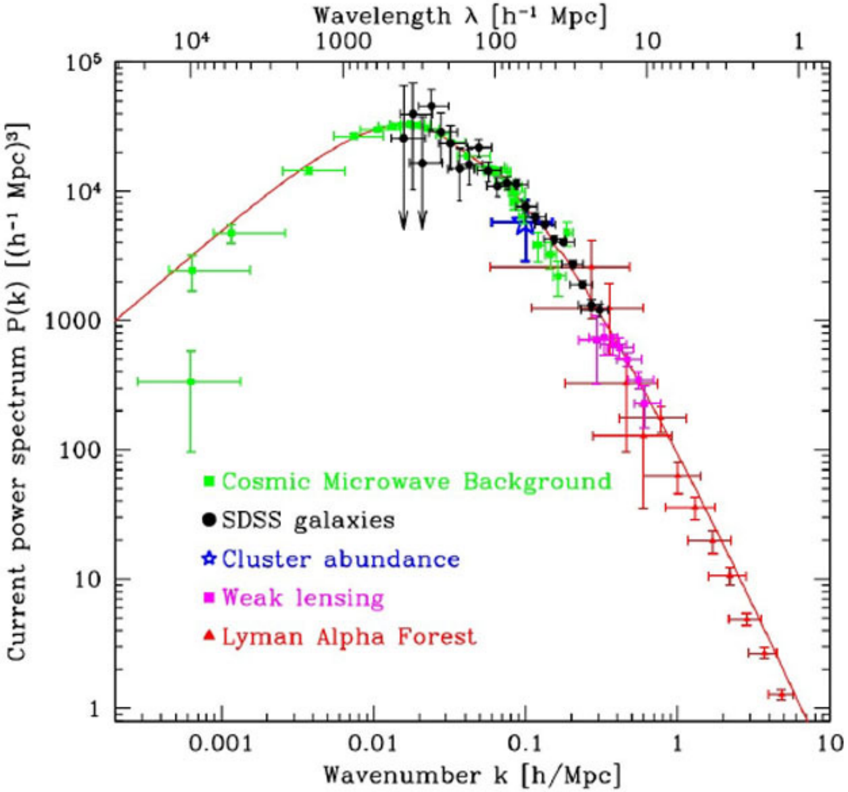
Structure formation (galaxies, clusters, filaments, voids)

Why cold? Power Spectrum

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

large scales: linear
small scales: non-linear

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



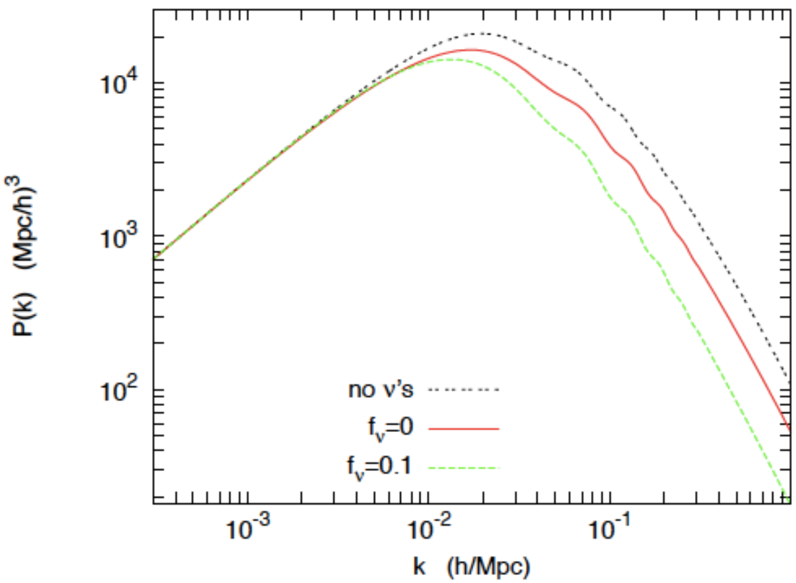
FT

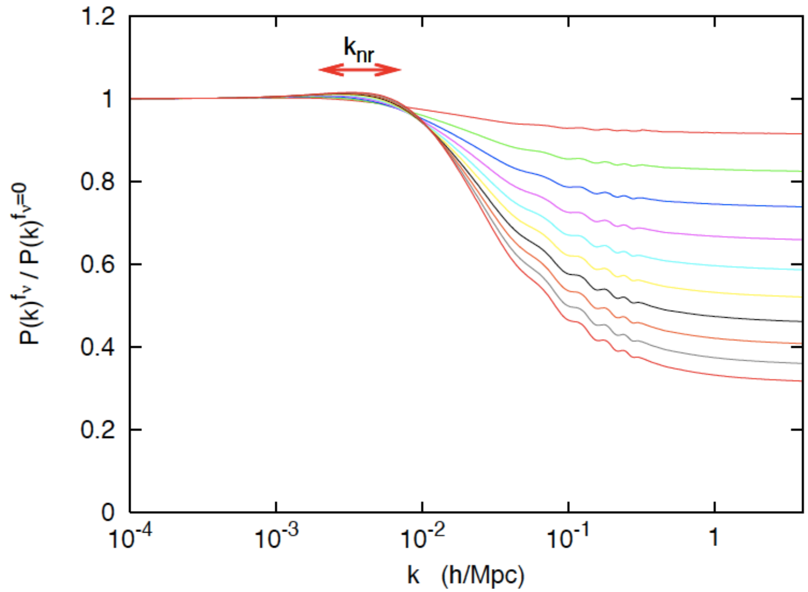
$$\langle \delta(\vec{k})\delta(\vec{k}') \rangle = (2\pi)^3 \delta^3(\vec{k} - \vec{k}')\, P(k)$$

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 $\sum_i m_i \leq (0.9 \div 1.7)\ \mathrm{eV}$ $\Omega h^2 \leq (0.0097 \div 0.018)$

Atm. neutrinos $\sqrt{\Delta m_{13}^2} = 0.047\ \mathrm{eV}$ $\Omega h^2 \geq 0.0005$

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

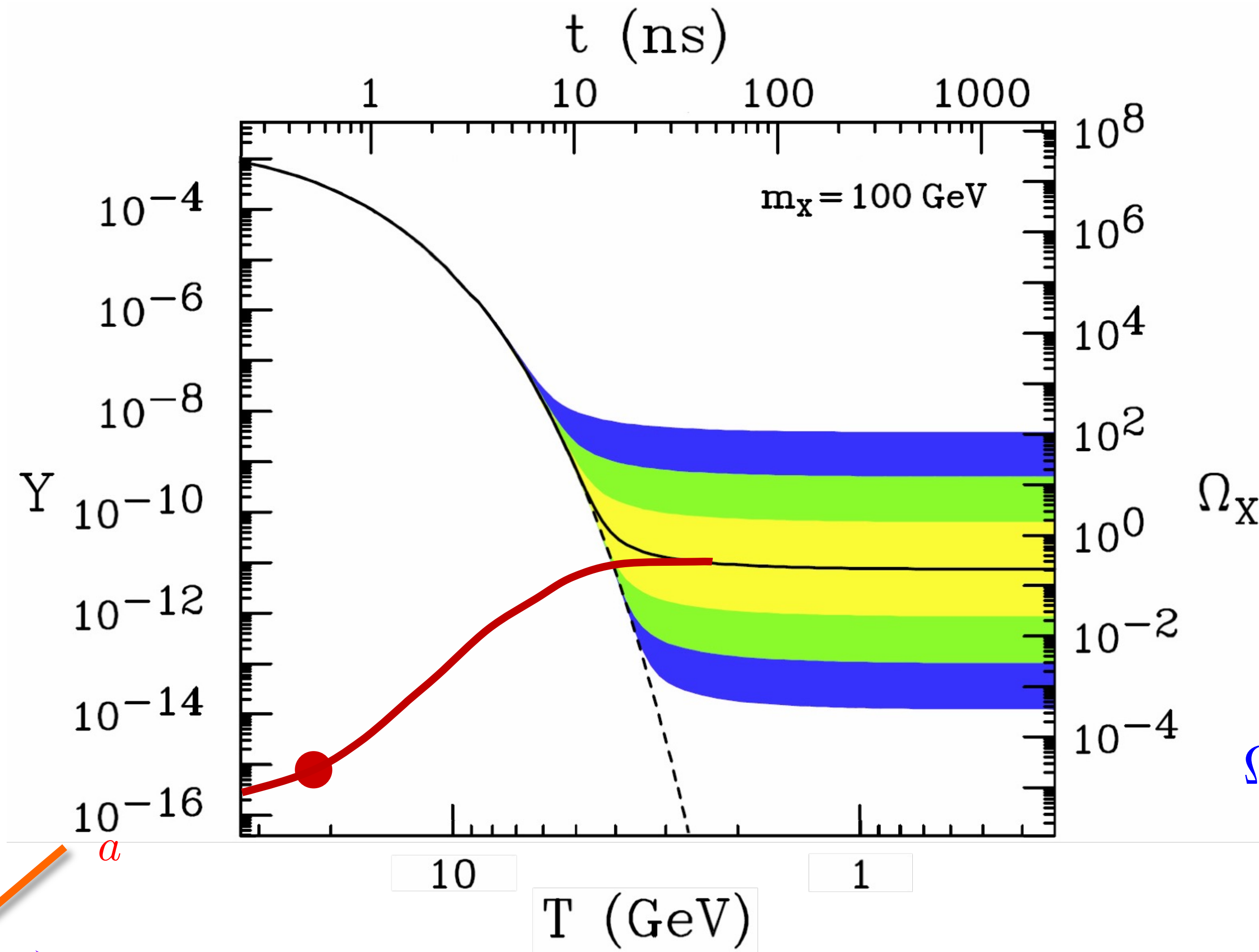
- The relic abundance is set by the asymmetry, not thermal freeze-out
- This may link DM abundance to baryon asymmetry

Non-thermal production

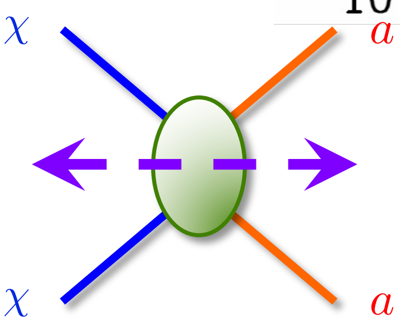
- DM produced by the decay of a heavier particle
- Peculiar cosmological dynamics (e.g.: misalignment for axions)
- Oscillations from “friendly” states (e.g. sterile neutrinos)

Freeze-in mechanism

$Y = n/s$



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

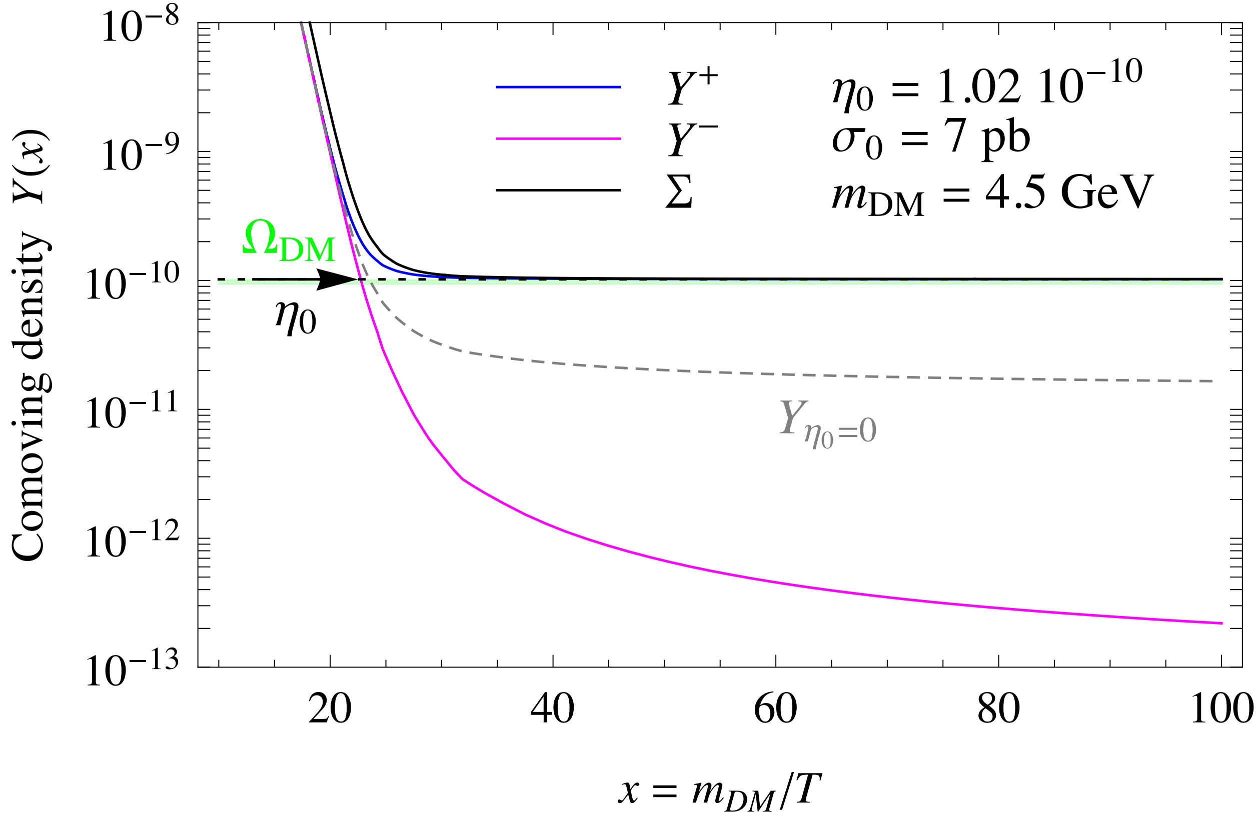


particle never in full equilibium

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

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

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 → 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 <$\sigma_N v$>)

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

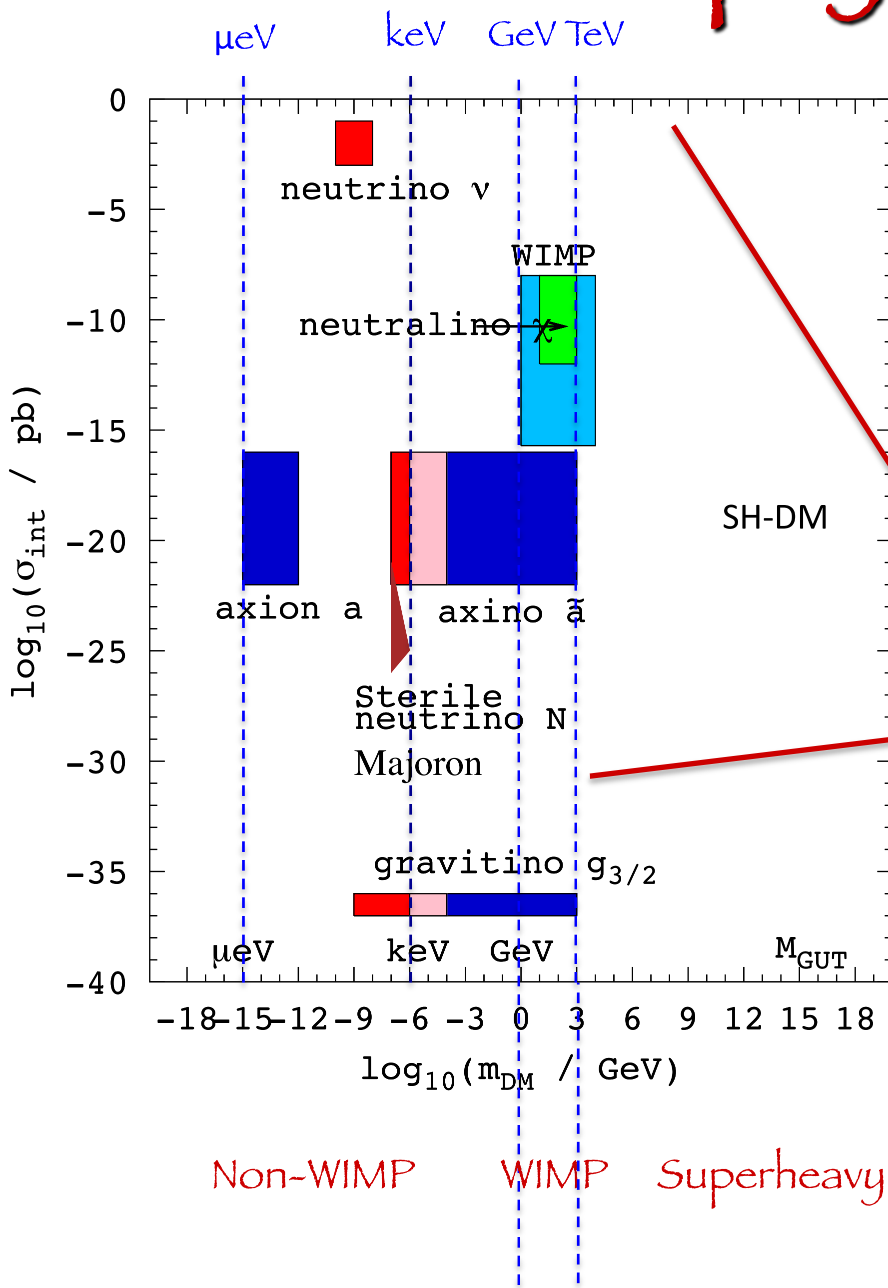
- Weak
  - Light (standard) neutrinos, (heavier) RH neutrinos (...)
  - Weakly Interacting Massive Particles (WIMPs) paradigm for thermal CDM
  - (...)
- Strong-type
  - Mirror DM
  - Technicolor DM
  - (...)
- Gravitational-type
  - Gravitino
  - (...)
- Electromagnetic
  - Open window if $100(q_X/e)^2 < m_X < 10^8(q_X/e)$ 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	}	$\tilde{\chi}^\pm_{1,2}$	chargino
	H^-		Higgs boson	$\tilde{H}_1^-$	higgsino	}		
	H^+		Higgs boson	$\tilde{H}_2^+$	higgsino	}		
	B		B-field	$\tilde{B}$	bino	}	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
	W^3		W^3-field	$\tilde{W}^3$	wino	}		
h	H_1^0	scalar	Higgs boson	$\tilde{H}_1^0$	higgsino	}		
H	H_2^0	scalar	Higgs boson	$\tilde{H}_2^0$	higgsino	}		
A	H_3^0	pseudoscalar	Higgs boson					

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	$\tilde{\chi}^\pm_{1,2}$	chargino
	H^-		Higgs boson	$\tilde{H}_1^-$	higgsino		
	H^+		Higgs boson	$\tilde{H}_2^+$	higgsino		
	B		B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
	W^3		W^3-field	$\tilde{W}^3$	wino		
h	H_1^0	scalar	Higgs boson	$\tilde{H}_1^0$	higgsino		
H	H_2^0	scalar	Higgs boson	$\tilde{H}_2^0$	higgsino		
A	H_3^0	pseudoscalar	Higgs boson				

Neutral particles: sneutrinos, neutralinos [gravitinos]

SUSY breaking $\longrightarrow$ massive SUSY partners

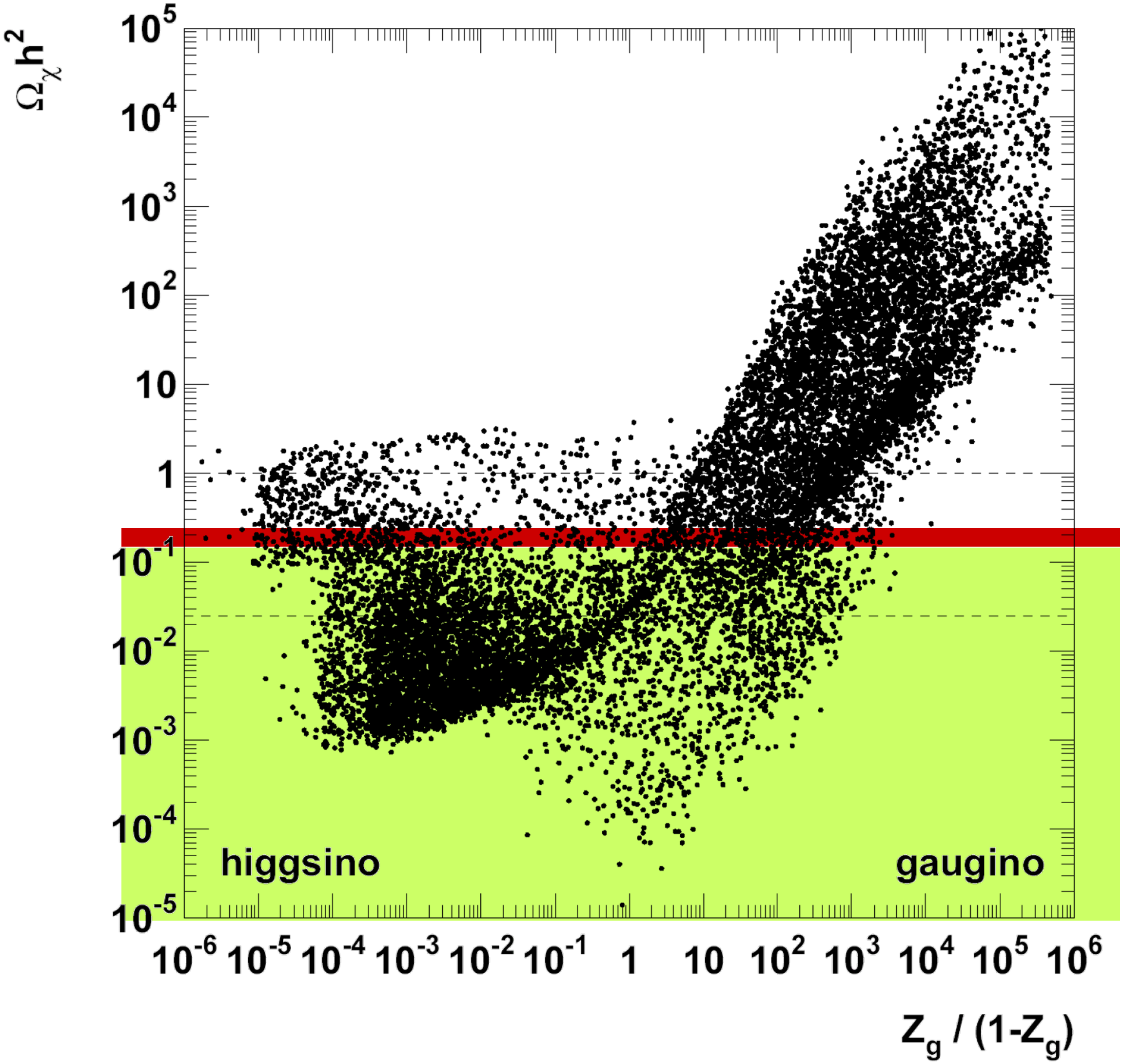
R PARITY $\longrightarrow$ LSP: stable

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

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

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

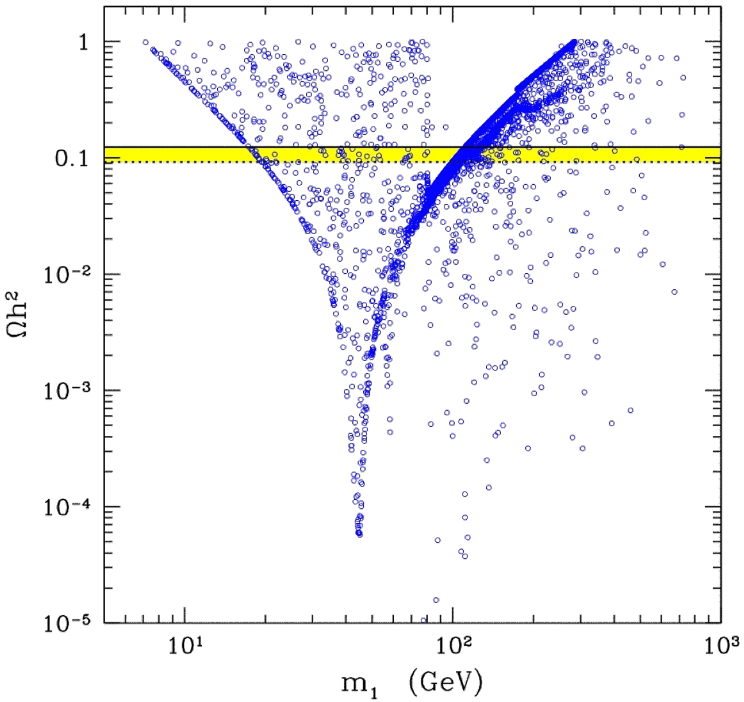
Neutralino in a generic MSSM



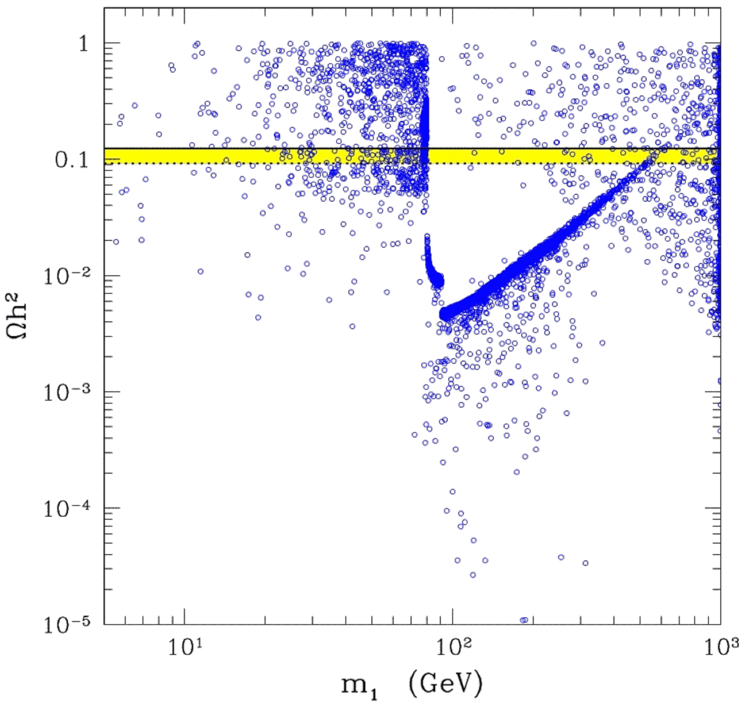
Sneutrino dark matter

MSSM at the EW scale with terms that induce neutrino masses

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



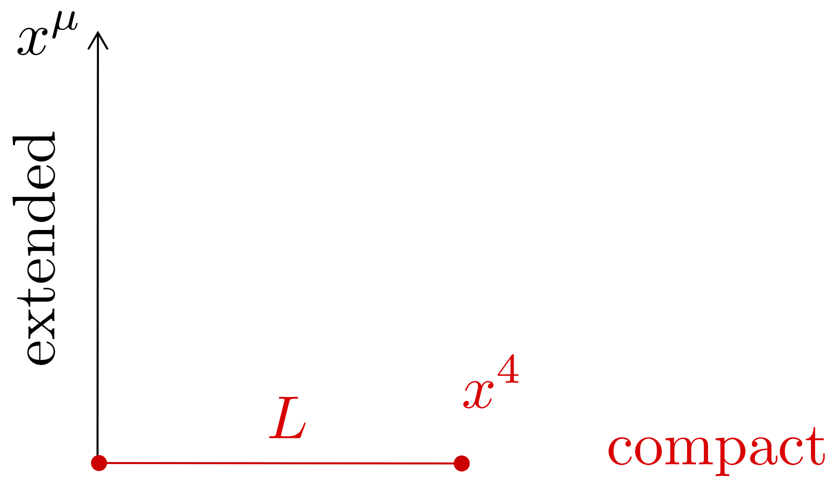
Left+Right models



“Majorana” models

Extra dimensions (Kaluza Klein theories)

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



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

$n = 0$ 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 $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
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

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

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

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

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

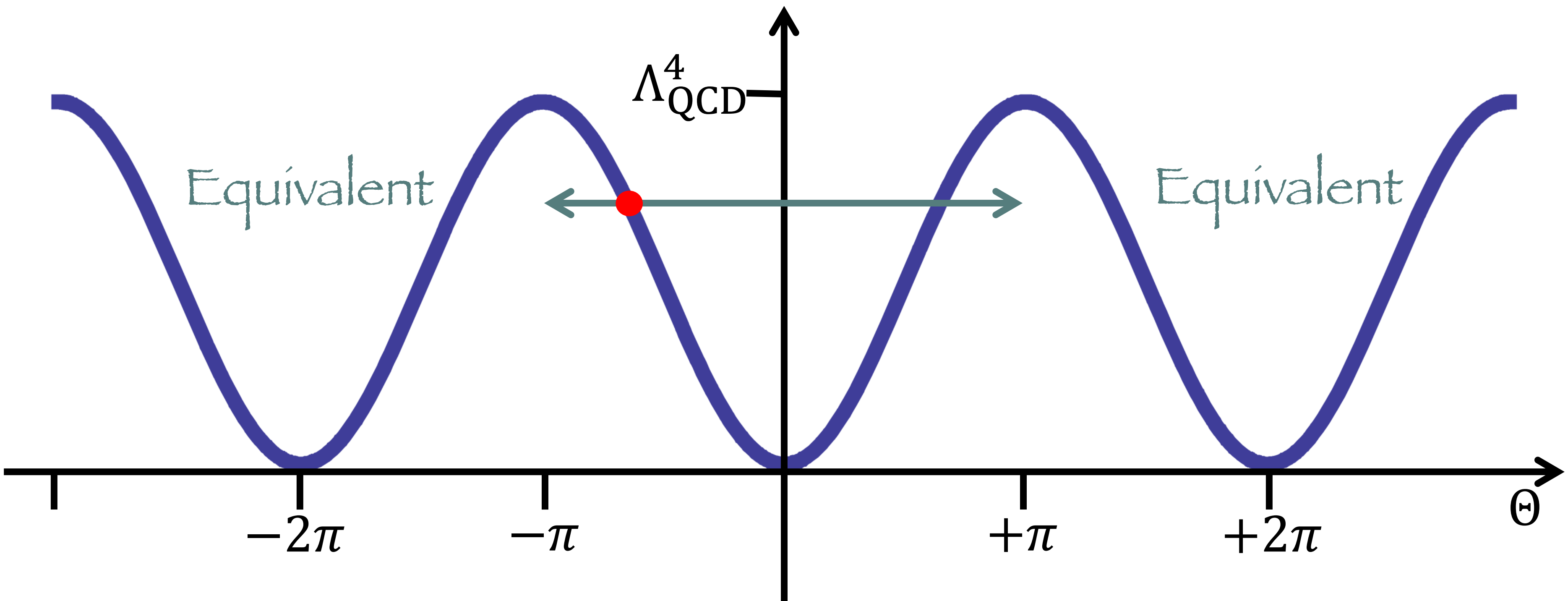
$$d_n \lesssim 2 \cdot 10^{-26}\, e\,\mathrm{cm}$$

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

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

Strong CP Problem

QCD vacuum energy $V(\Theta)$



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

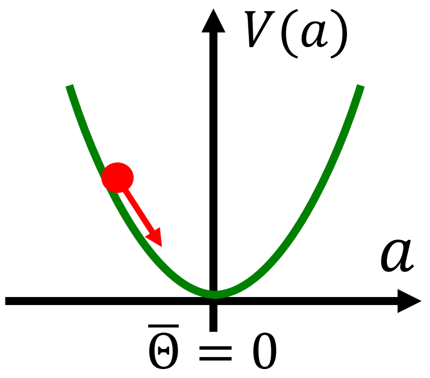
Peccei-Quinn solution:

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

θ_{eff} Set to zero by QCD dynamics

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

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

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

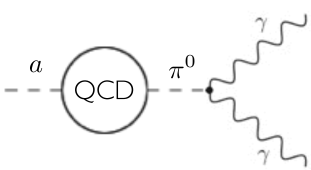
This is induces axion properties

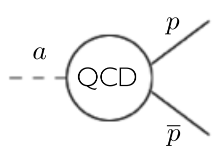
Axion properties

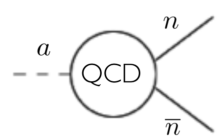
Axion mass

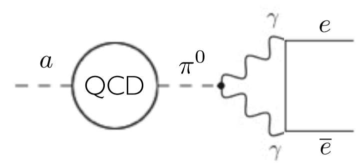
$$\sim \frac{\Lambda_{\rm QCD}^4}{f_a^2} \quad \longrightarrow \quad m_a \sim \Lambda_{\rm QCD}^2/f_a \simeq 0.1\ {\rm eV}\left(\frac{10^8\ {\rm GeV}}{f_a}\right)$$

Axion coupling to photons, protons, neutrons and electrons







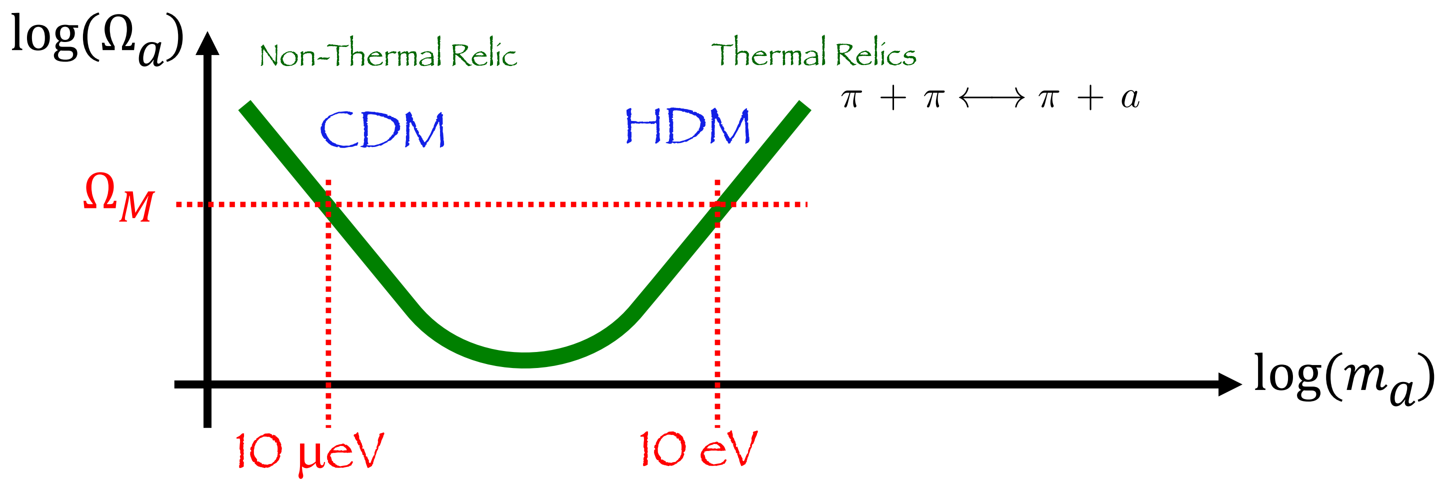


$C_\gamma = -1.92(4)$ $\quad$ $C_p = -0.47(3)$ $\quad$ $C_n = -0.02(3)$ $\quad$ $C_e \simeq 0$

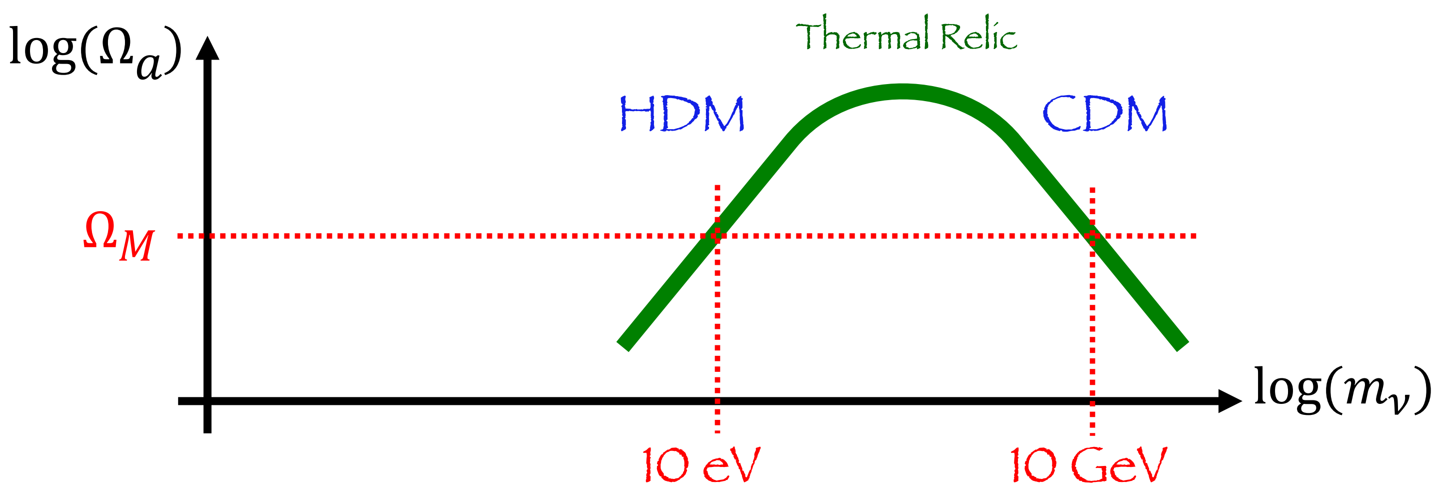
$$\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad C_\Psi m_\Psi \frac{a}{f_a}[i\overline{\Psi}\gamma_5\Psi] \qquad (\Psi = p, n, e\,)$$

Cosmological abundance

Axions



Neutrinos
WIMPs

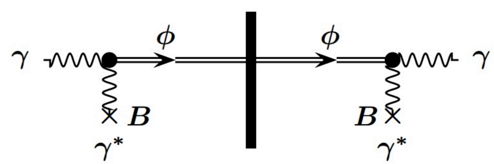


Axions/ALP search strategies

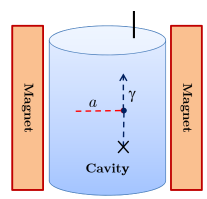
Serches typically rely on the axion-photon coupling, which can produce axion-photon conversion in a magnetic field (Primakoff effect):

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

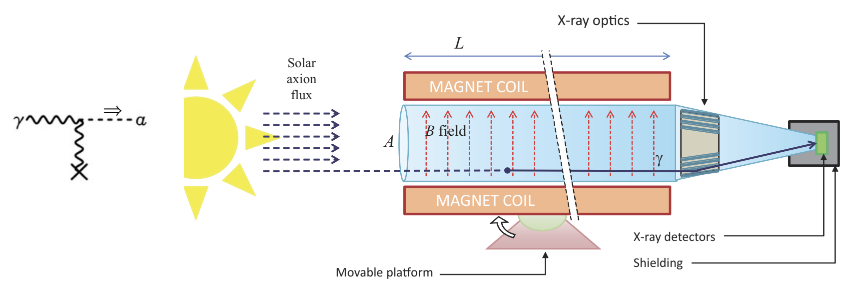
Light shining through walls



Haloscopes (axion DM)



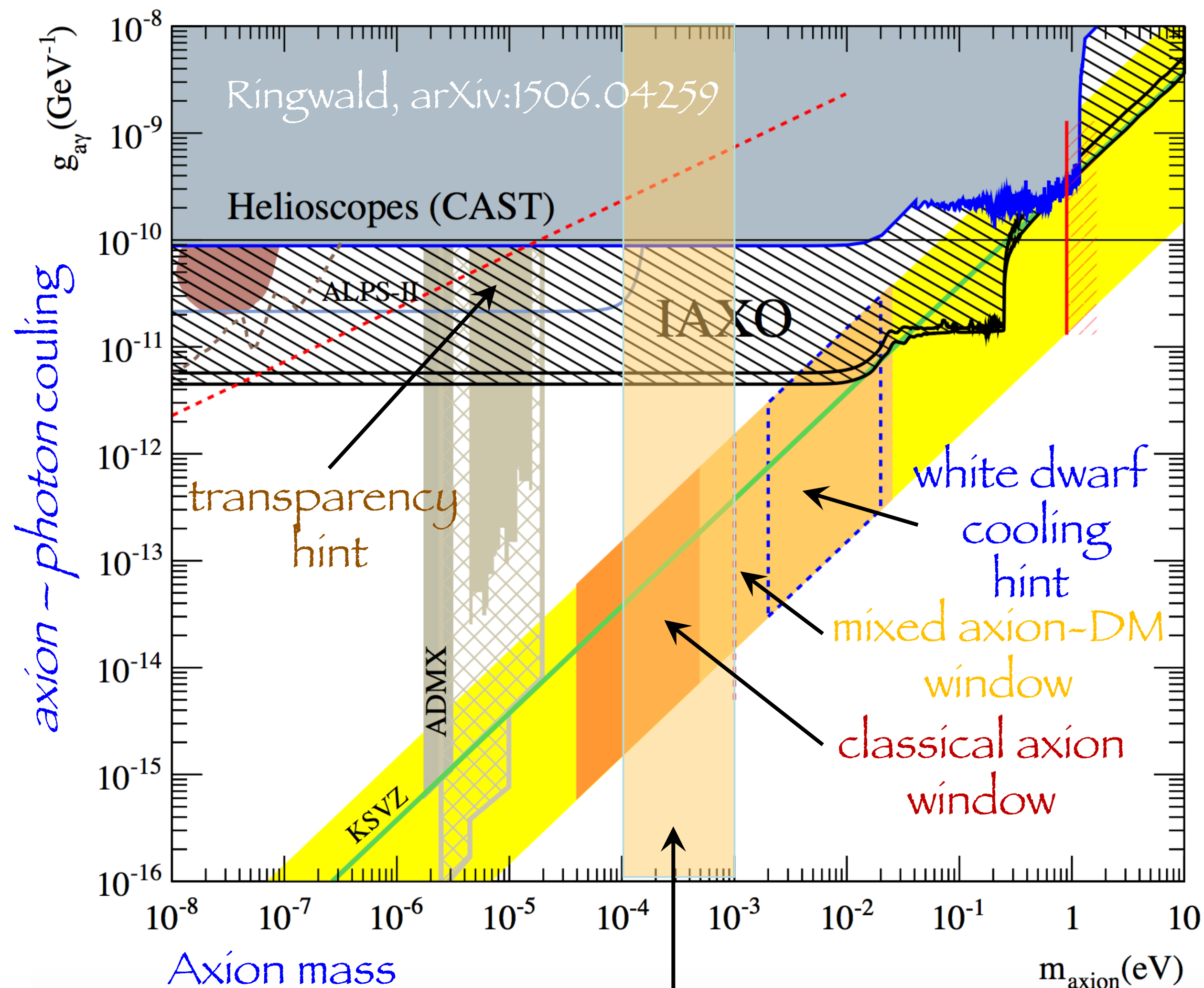
Helioscopes (axions from the Sun)



Cooling of stars

(...)

Axions and ALPs



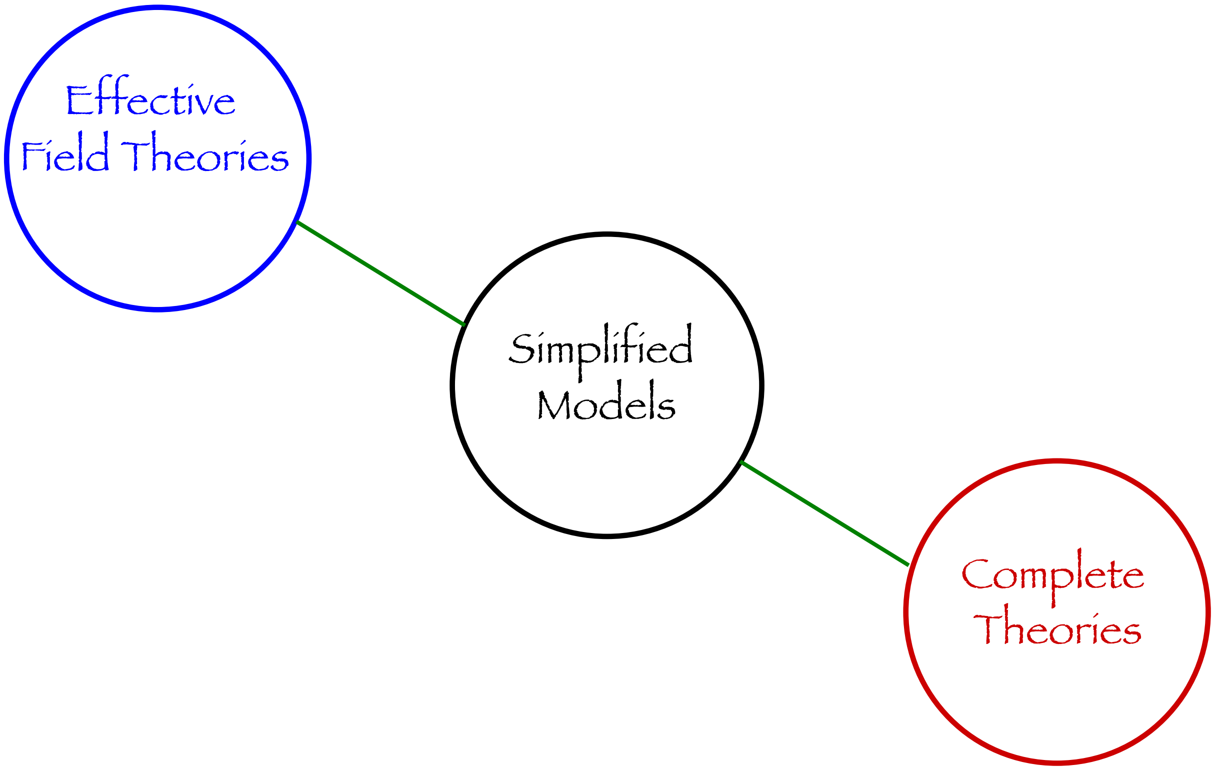
Techniques:

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

QUAX: high-frequency magnetometer
axion-electron coupling

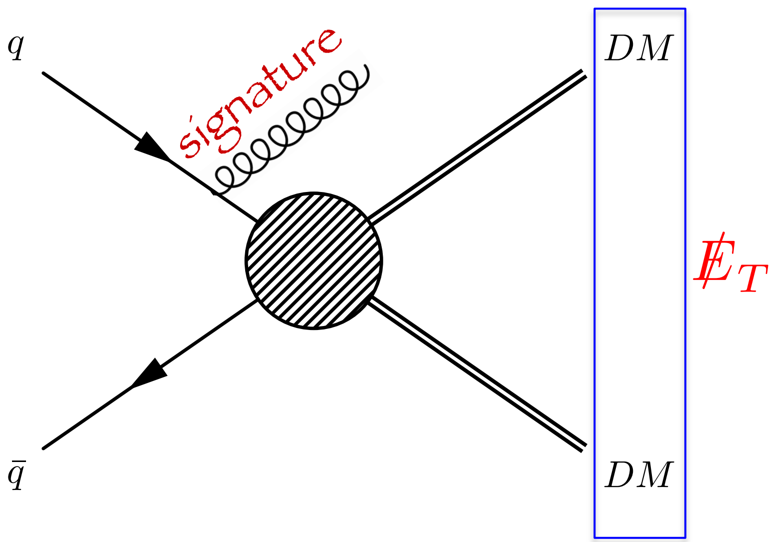
LABORATORY SEARCHES

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

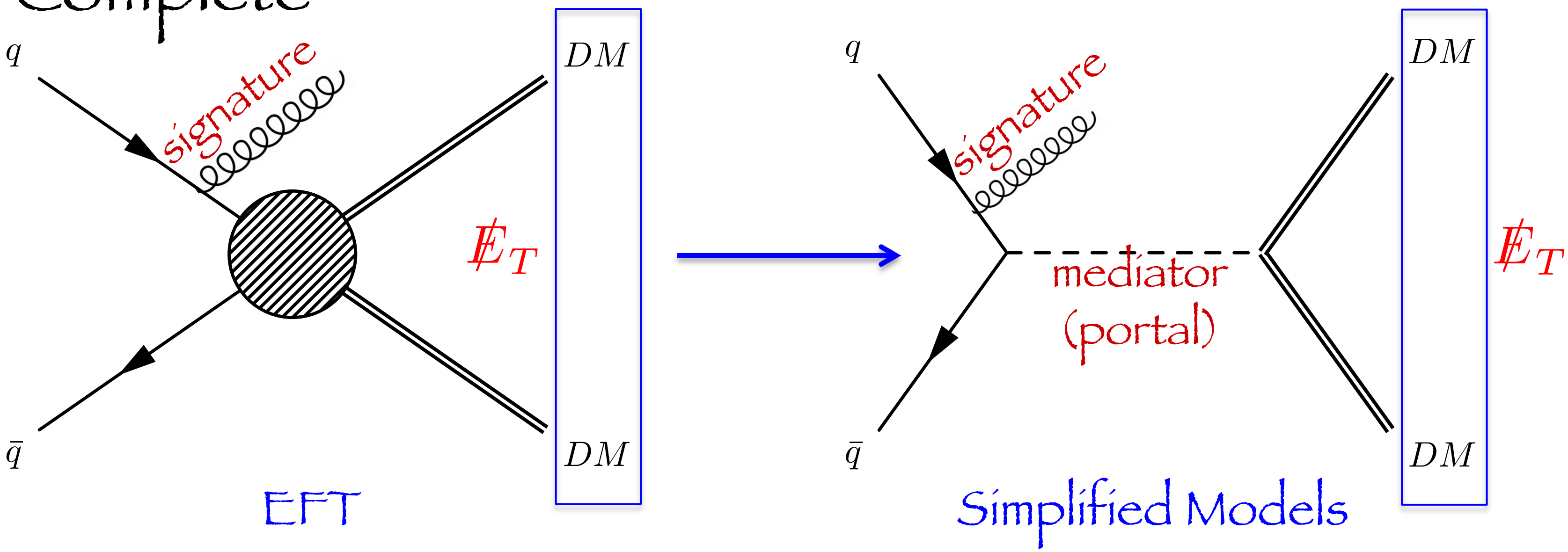
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$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

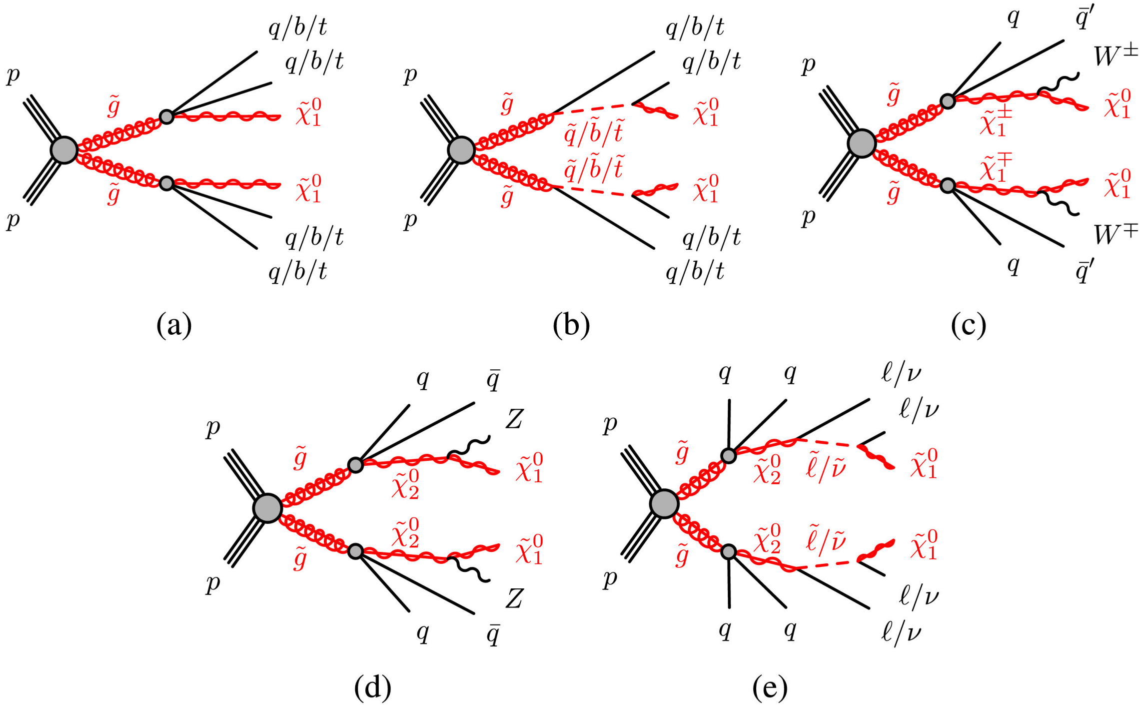
Complete models: e.g. SUSY

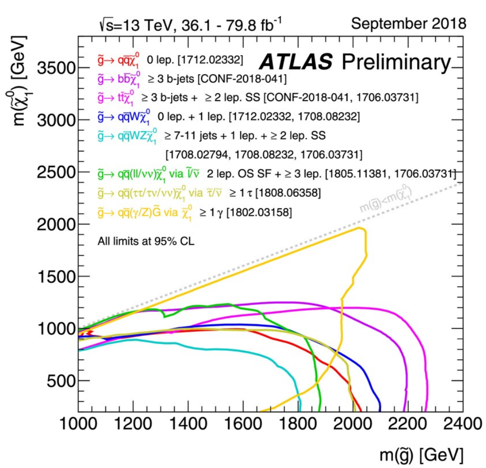
mSUGRA	4 parameters	High-energy related	Very constrained
Non-Universal SUGRA	4+2, 4+5, 4+N parameters	High-energy related	Somehow less contrained
MSSM	115 parameters	Low energy	Maximal freedom
pMSSM	20 parameters	Low energy	Very free
(...)	(...)	(...)	(...)

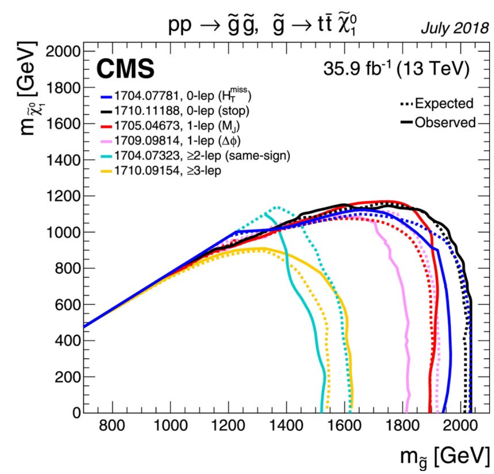
To have DM:

- 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

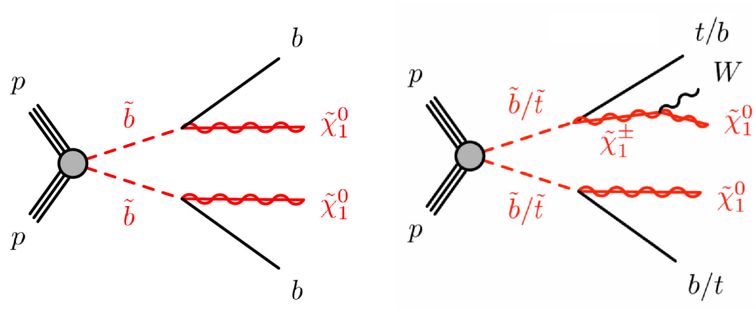
Complete models: e.g. SUSY



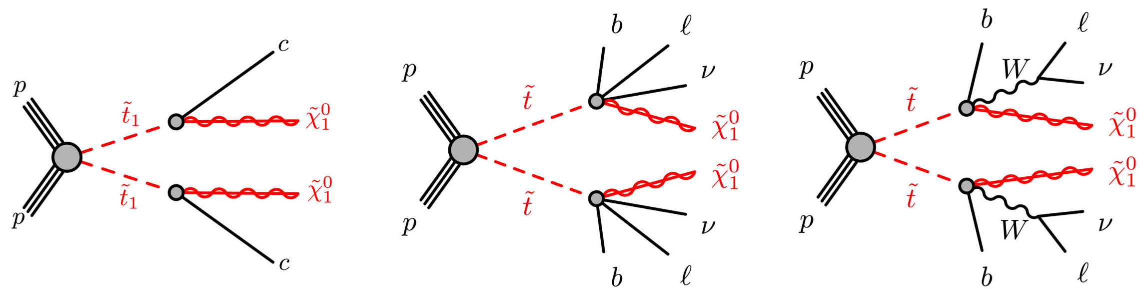




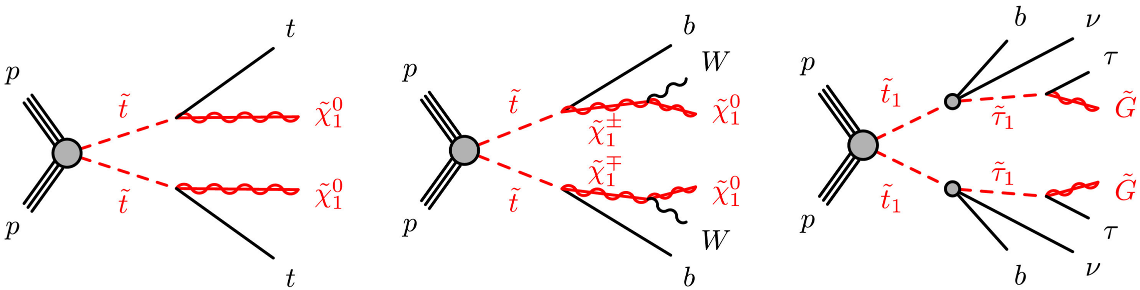
Complete models: e.g. SUSY



(a) (b)

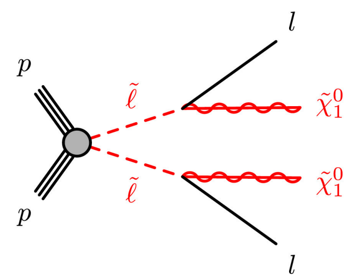


(a) (b) (c)

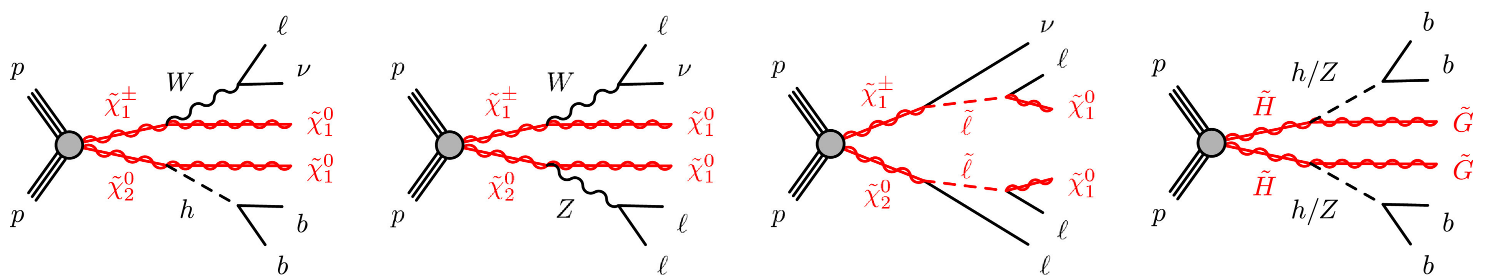


(d) (e) (f)

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"