How Dark is Dark?
How to unveil the hidden nature of dark matter

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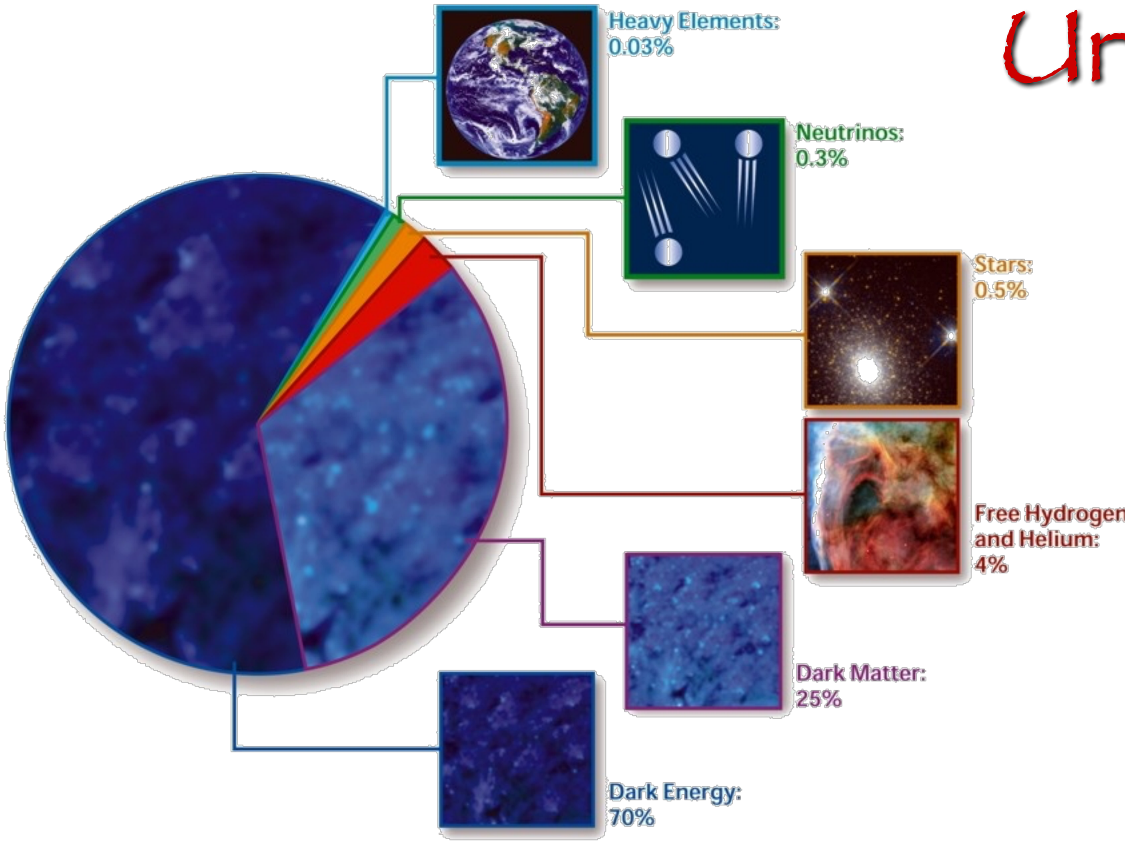
What's the problem?

How can we solve it?

Why does it have something to say about particles?

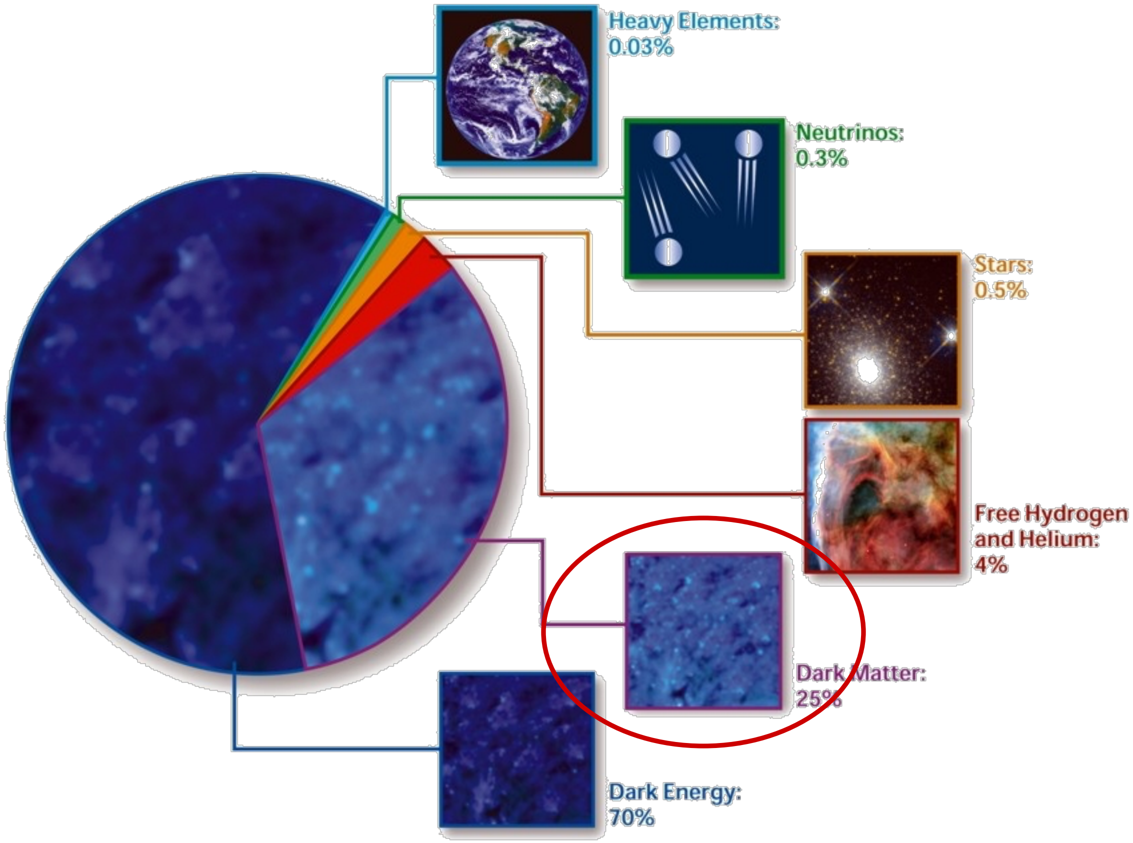
OK, it's a dark matter: but how dark is dark? Can we shed some light on it?
(or: Can it shed some light to us?)

Universe is "odd"



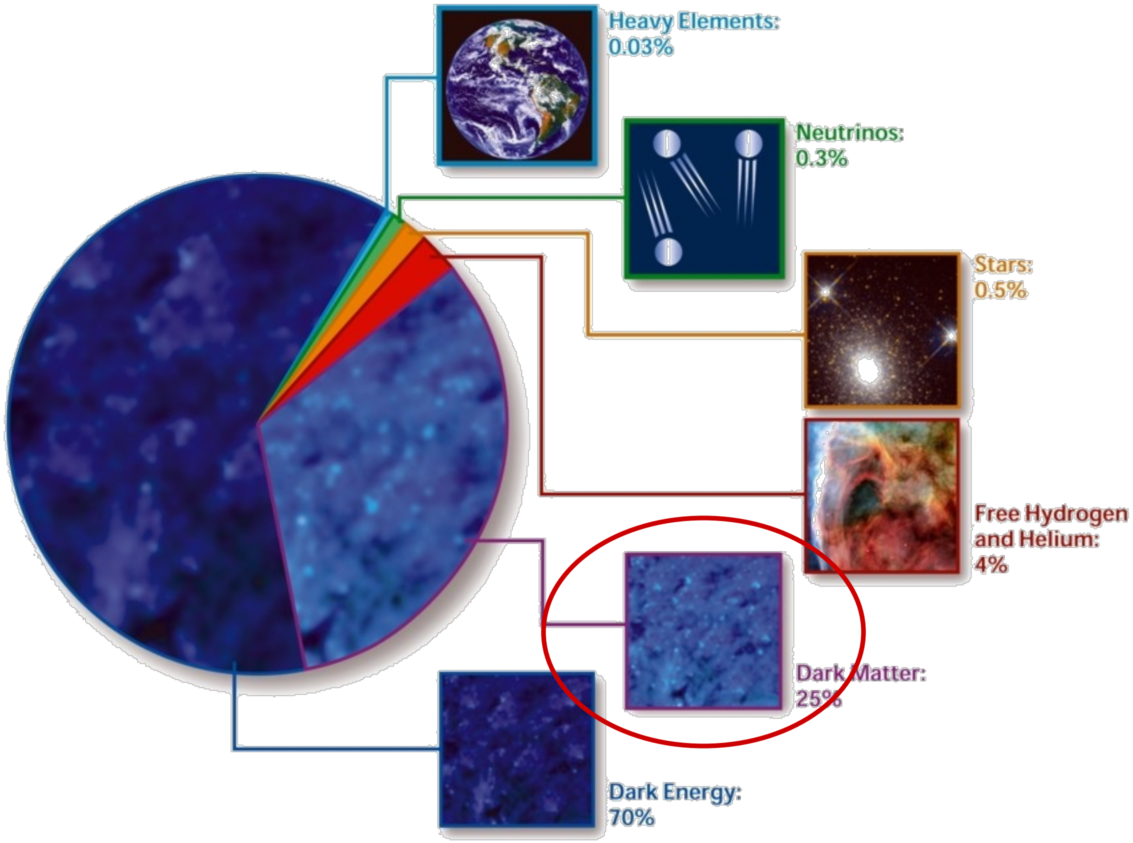
70% Dark Energy
26% Dark Matter
4% Nuclear matter

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 —Zwicky, 1933→ Virial theorem

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

Rotational curves of galaxies

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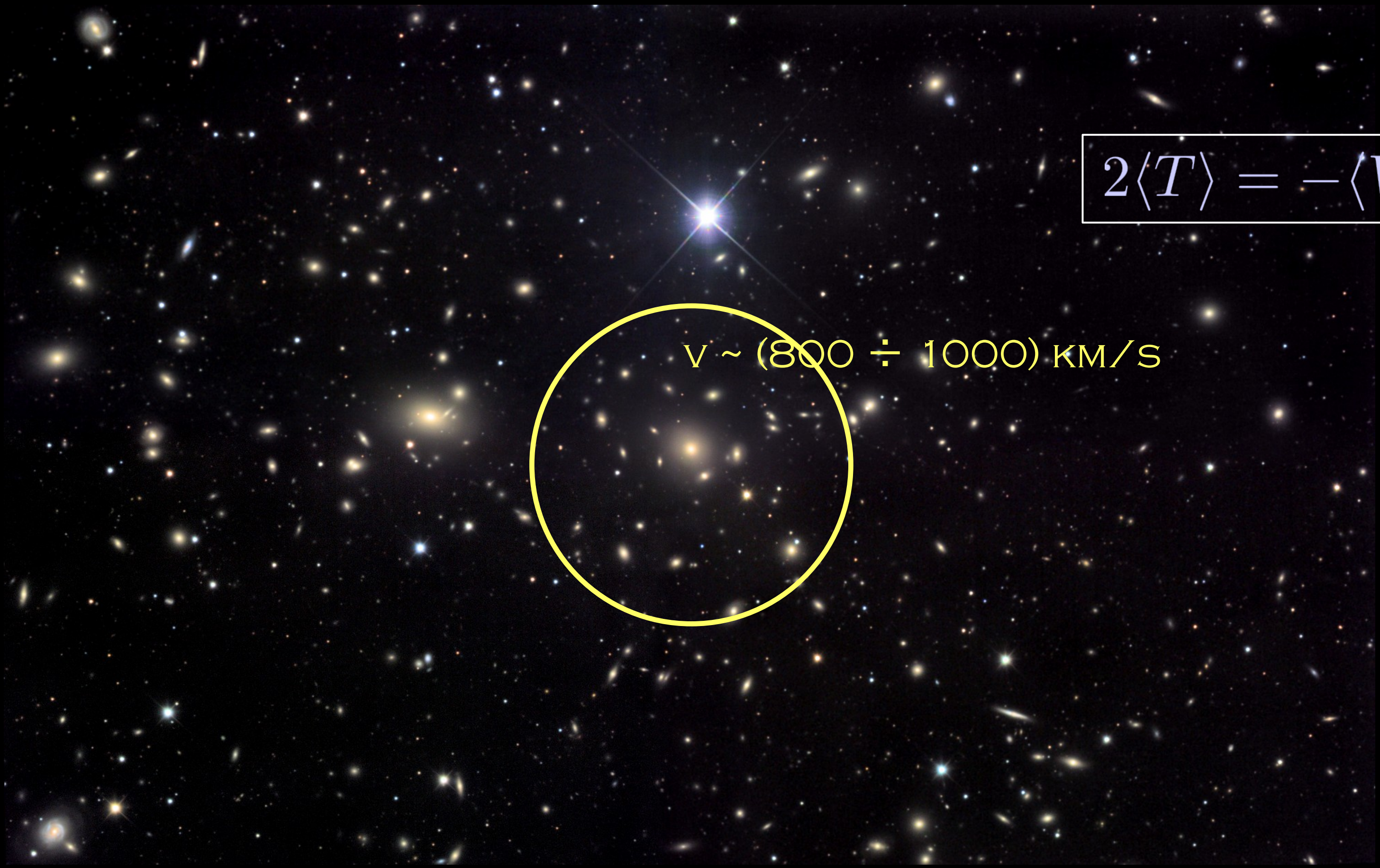
Galaxy cluster

Zwicky (1933)

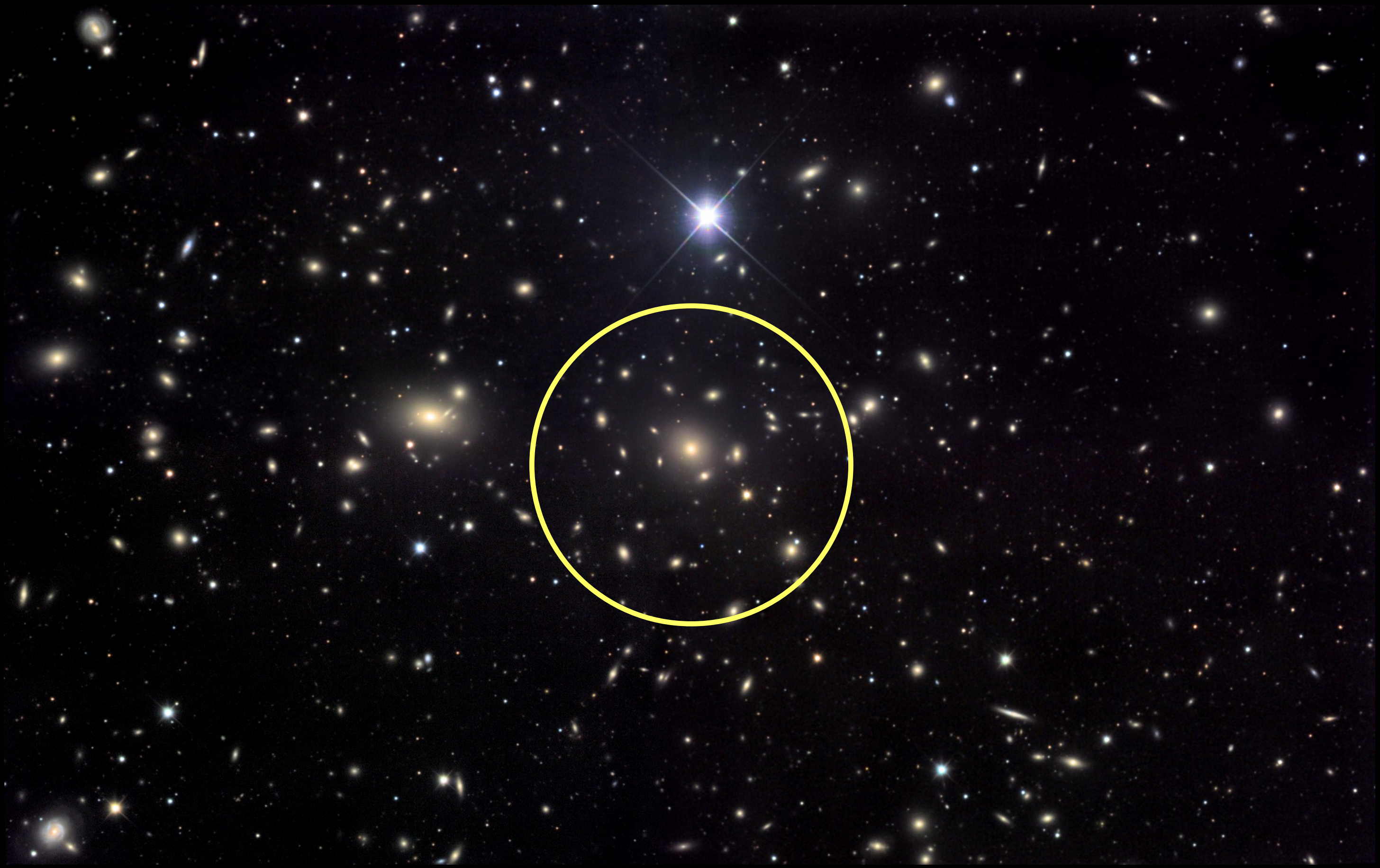


$$2\langle T\rangle = -\langle V_{\rm TOT}\rangle$$

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

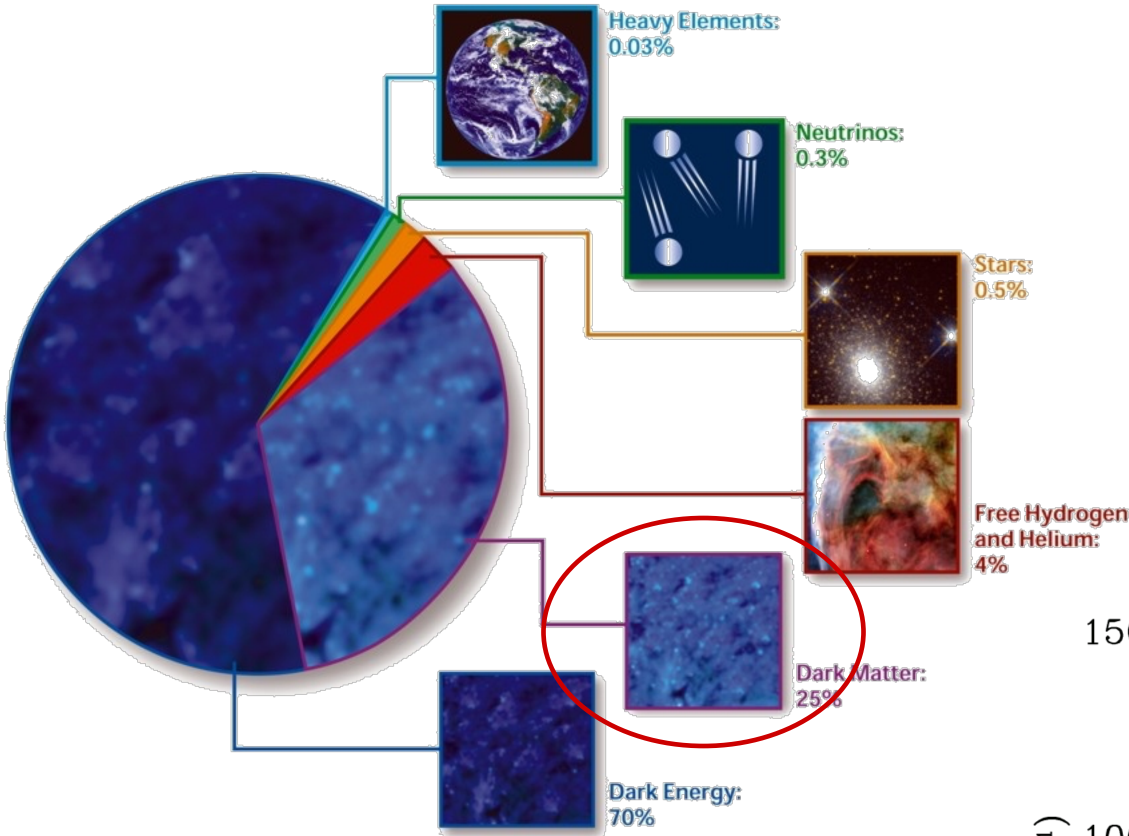
Much more mass than the visible one is needed

Galaxy cluster

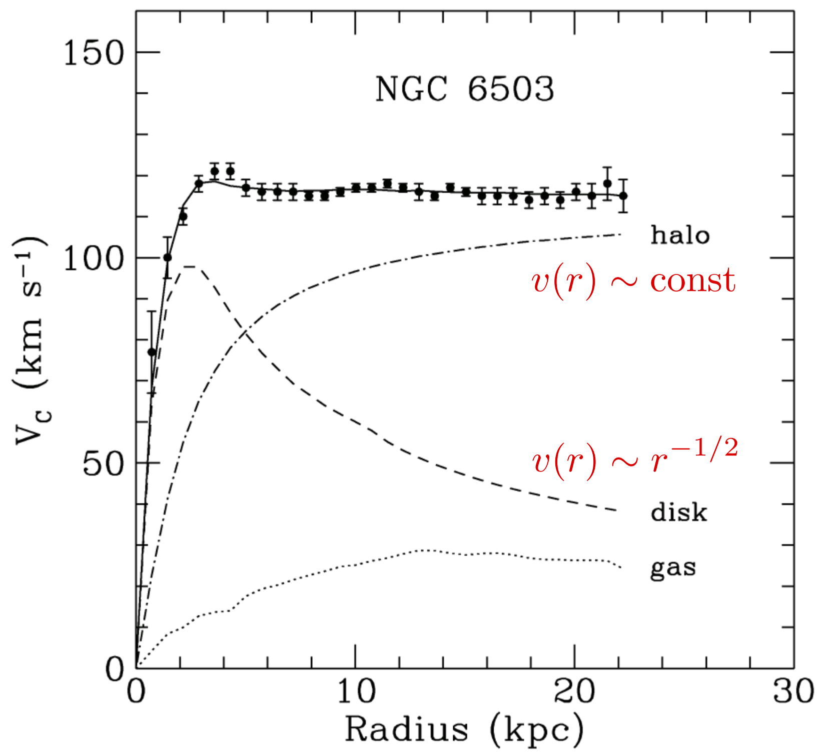


Galaxies	1%
Gas	9%
Dark Matter	90%

Dark Matter



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



Dynamics of galaxy clusters

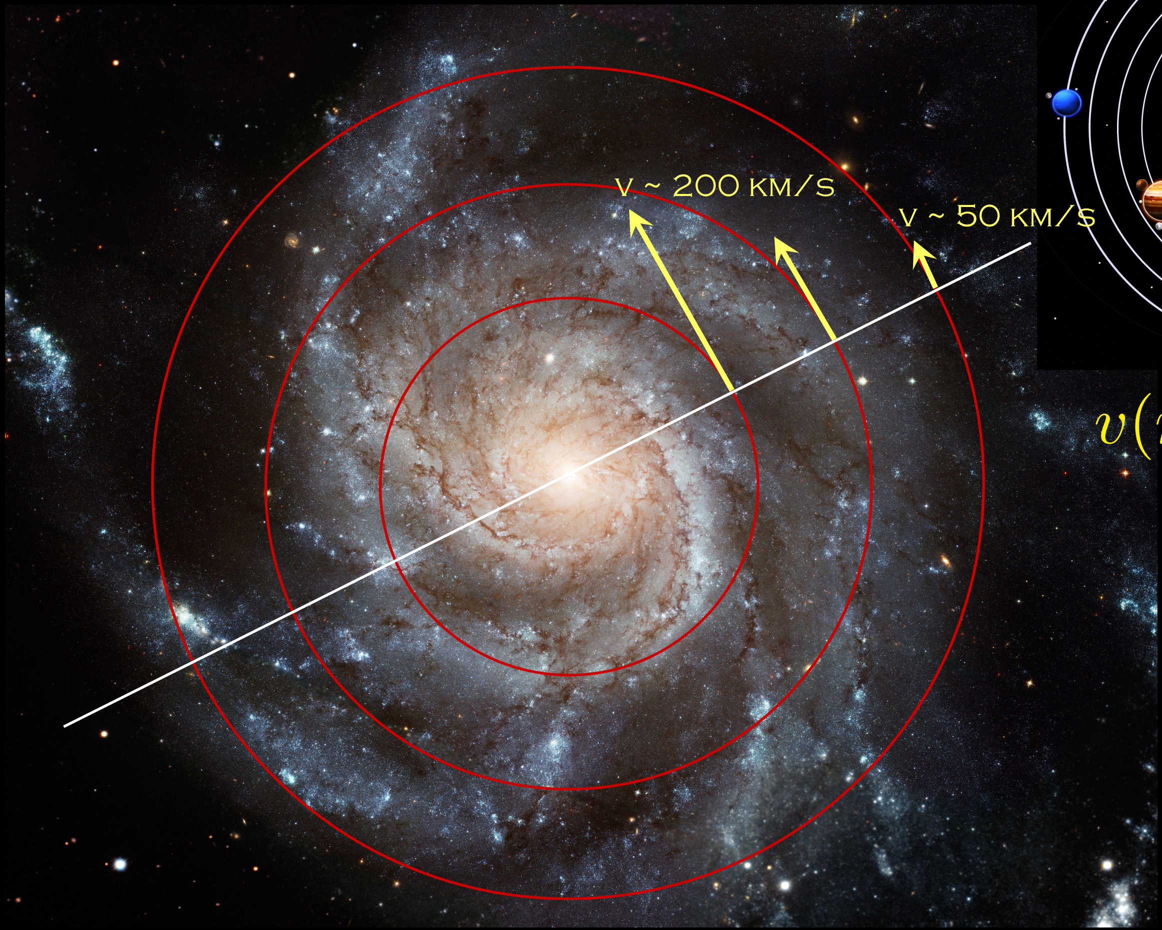
Rotational curves of galaxies → Rubin, early '70s

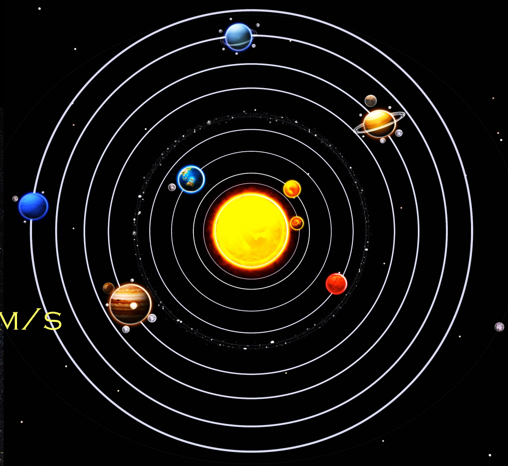
Weak lensing

Structure formation from primordial density fluctuations

Energy density budget

Spiral Galaxy

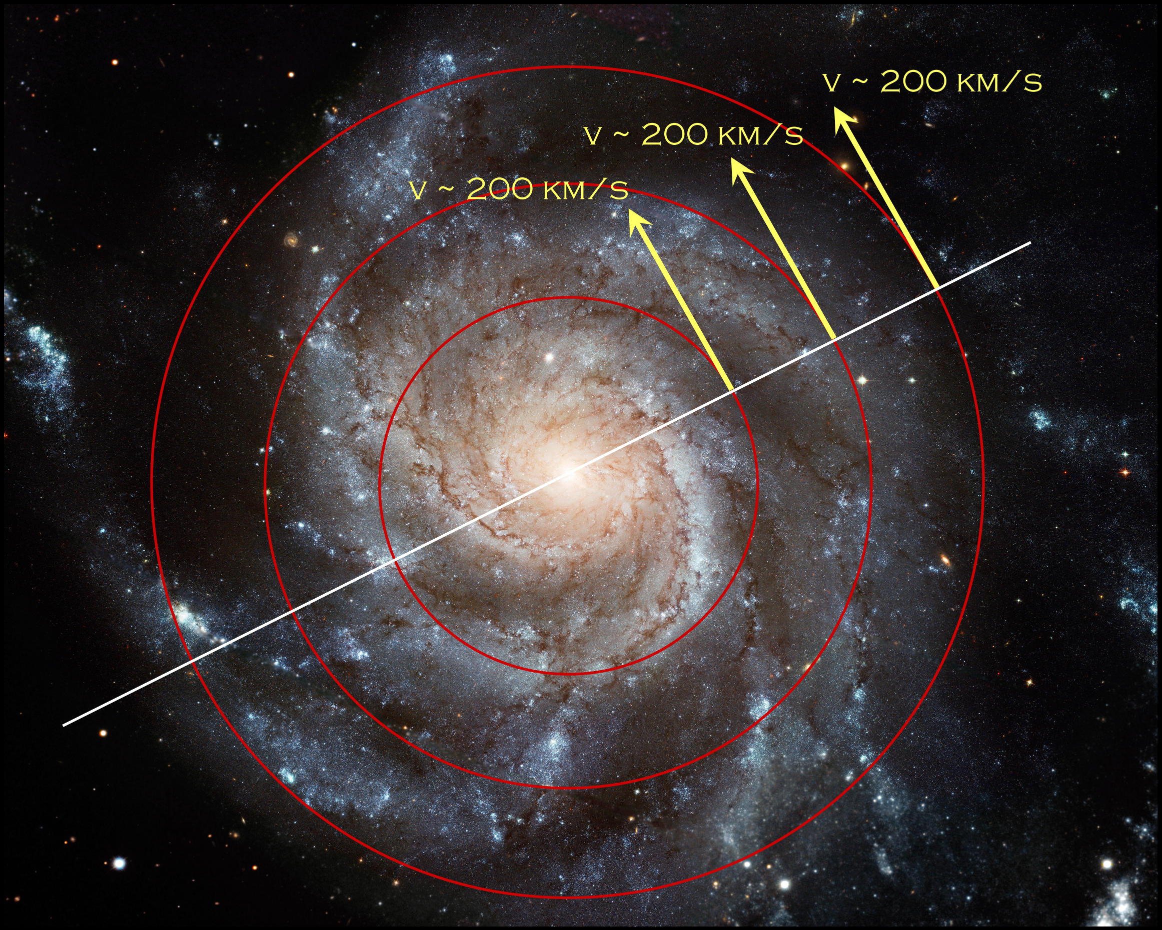




$$v(r) \propto r^{-1/2}$$

Spiral Galaxy

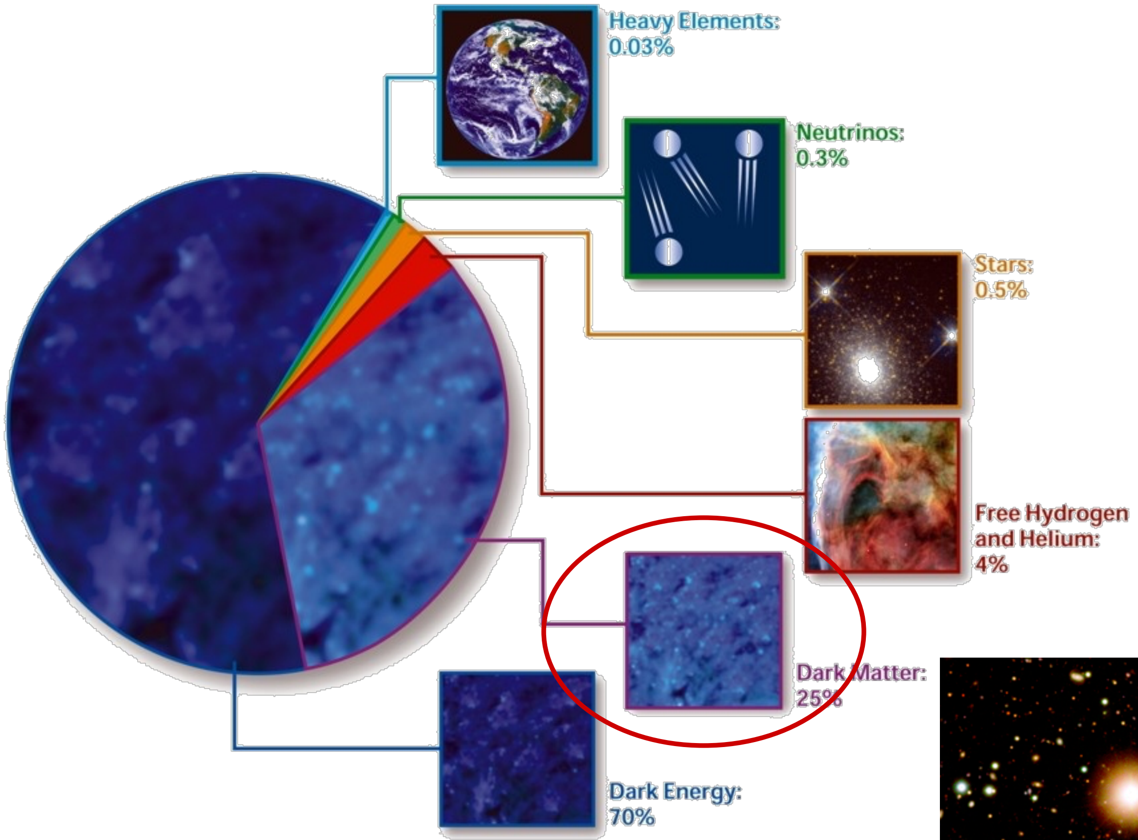
Rubin (1970)



Periferic stars are faster than expected
Faster = More mass

Much more mass than luminous mass
Dark Matter

Dark Matter



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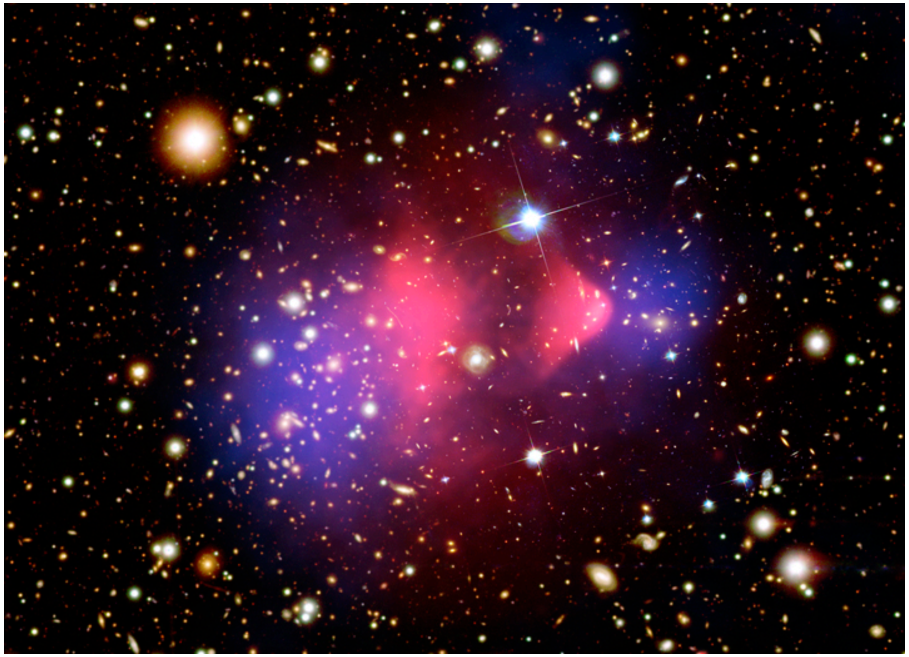
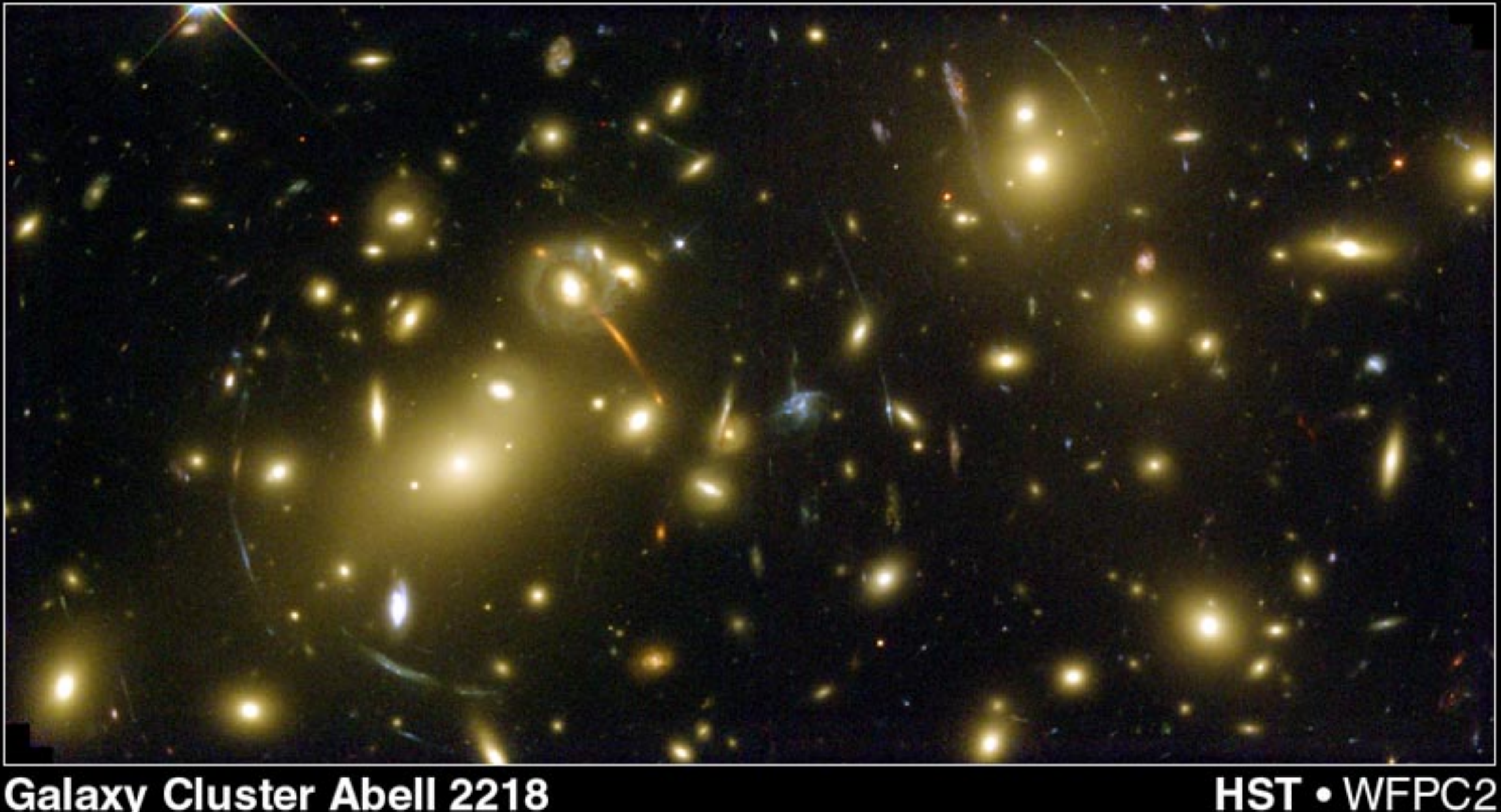
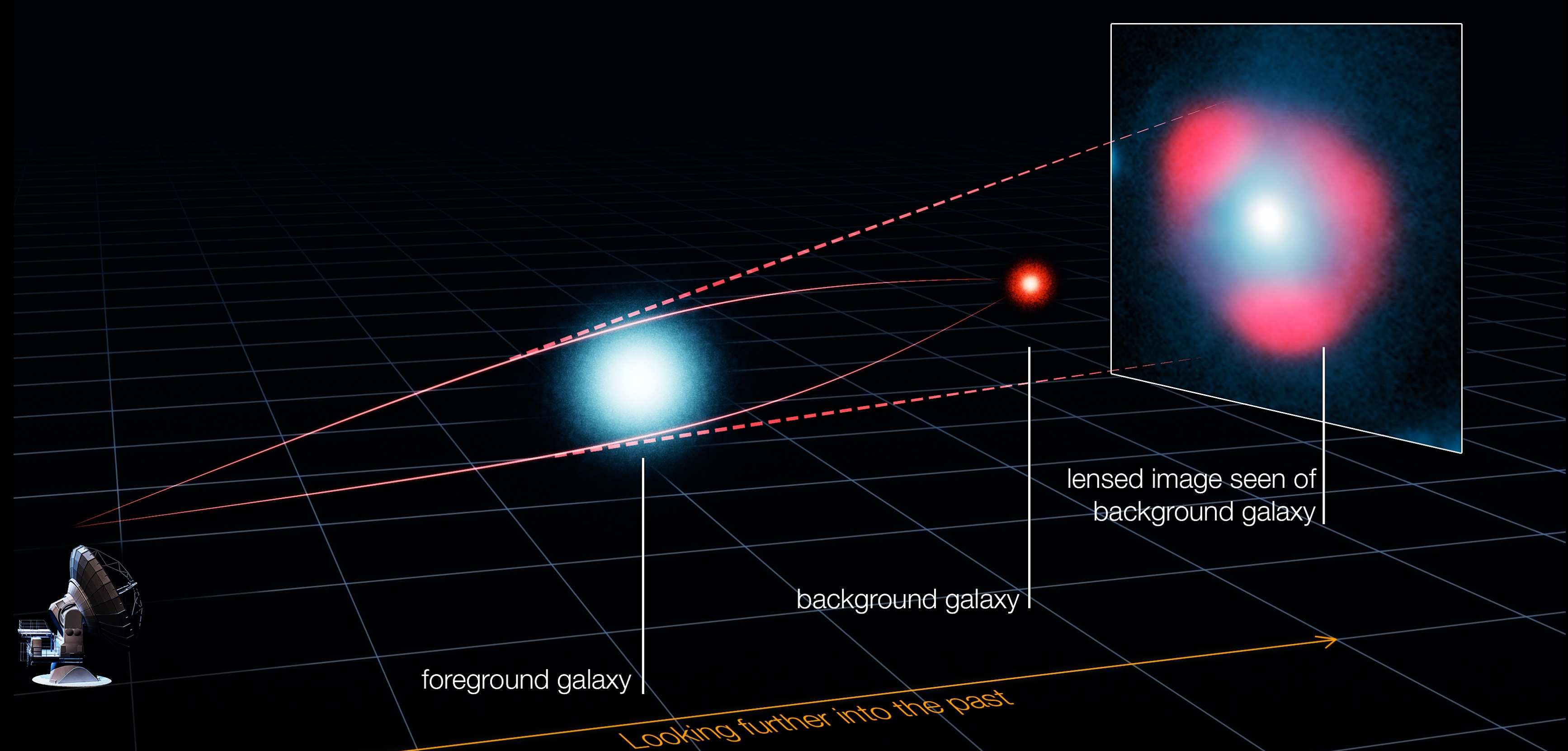




Gravitational lensing


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)

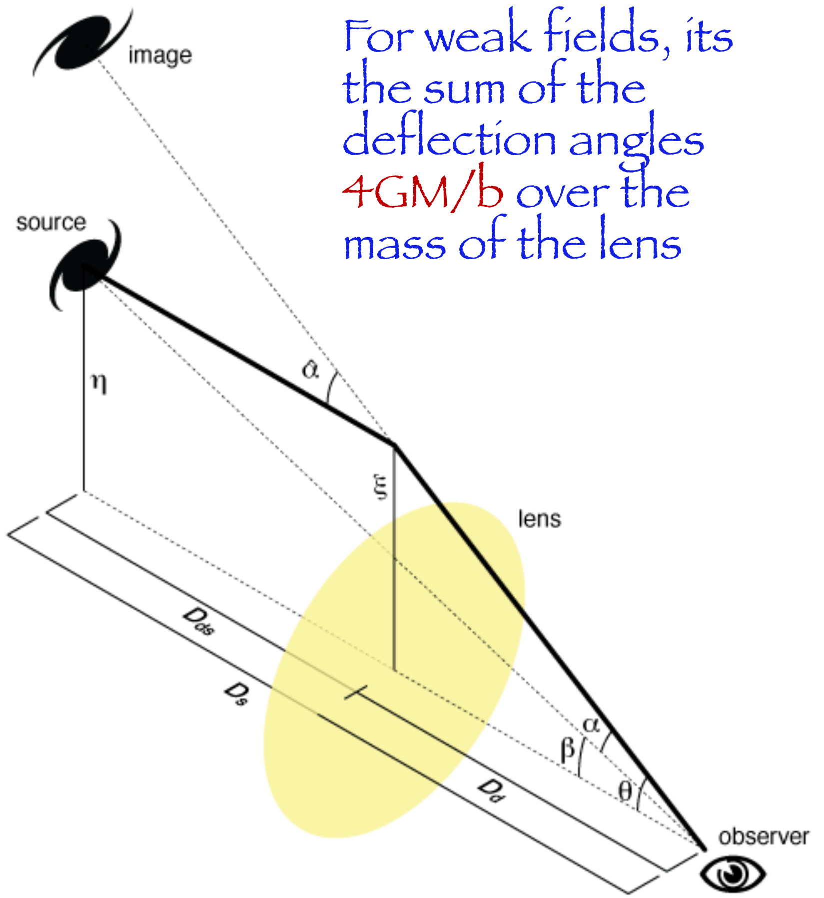
$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

Deflection angle

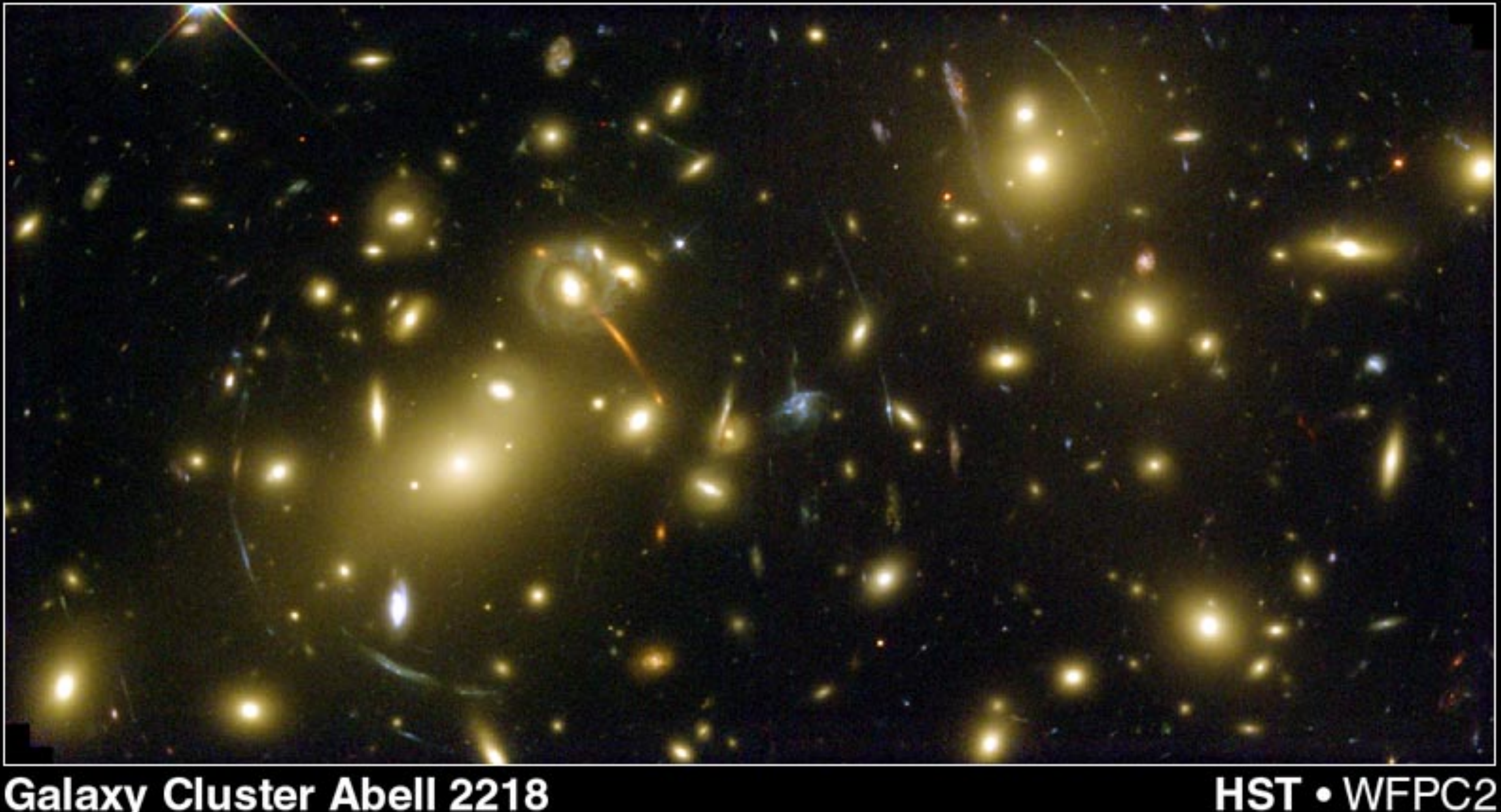
$$\alpha(\vec{\theta}) = 4G\int \frac{(\vec{\xi} - \vec{\xi'})\Sigma(\vec{\xi'})}{|\vec{\xi} - \vec{\xi'}|^2}\, d^2\xi'$$

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

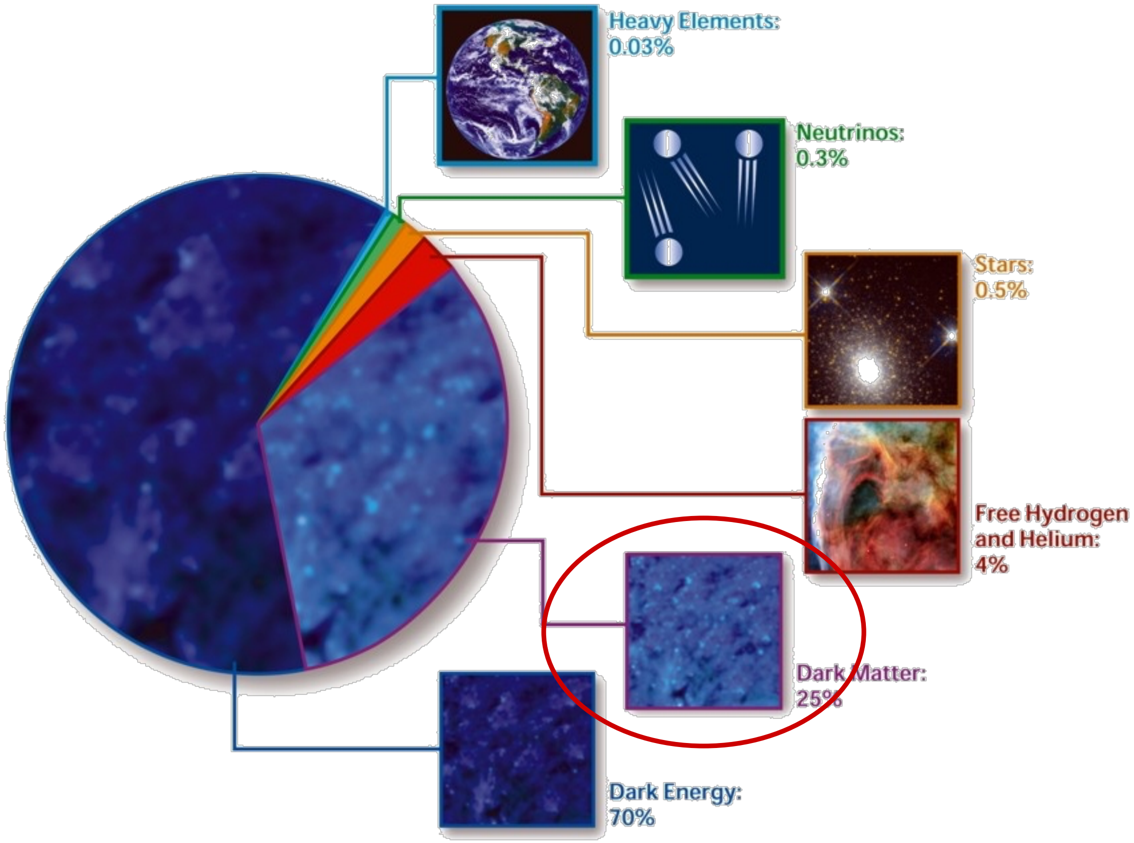


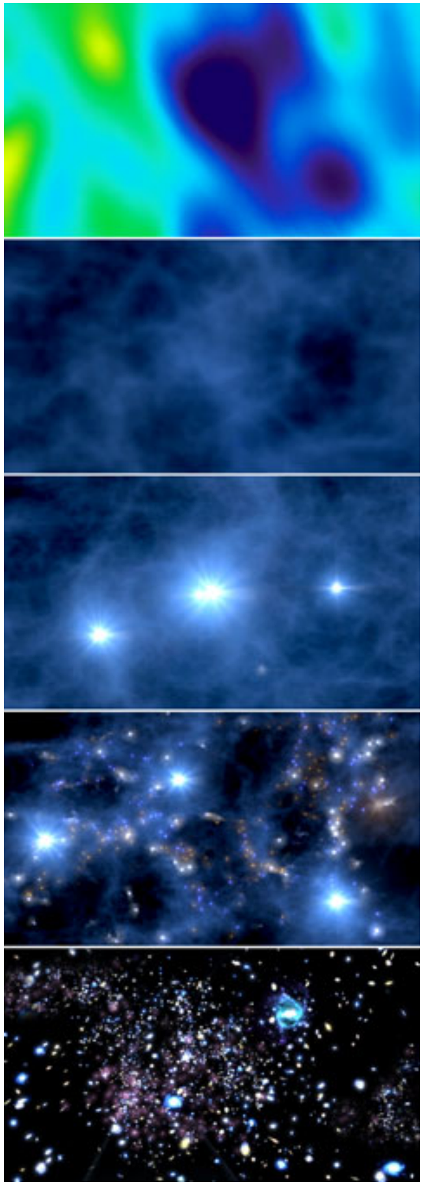
Gravitational lensing

A large amount mass between the background galaxies and us can be inferred by the strong lensing effect

Universe at large scales

Dark Matter





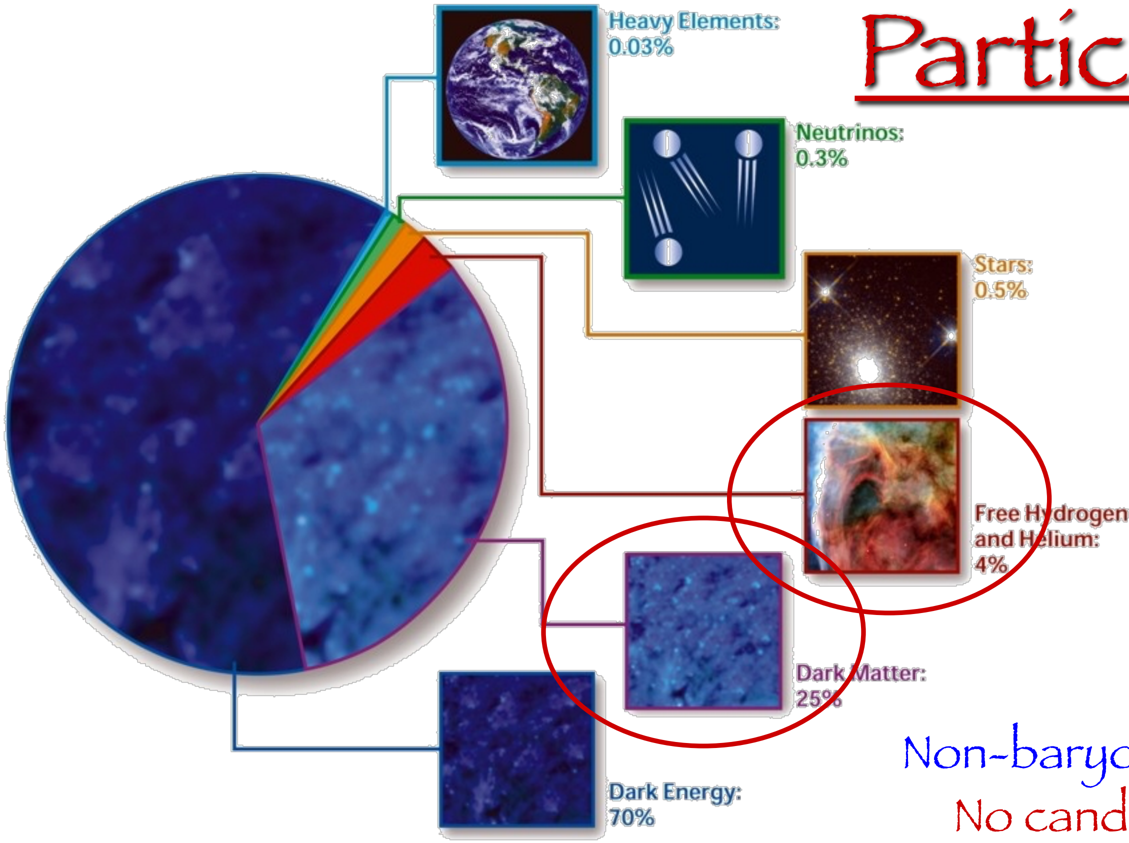
Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

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

Formation of structures in LCDM

Simulated Universe

Particle Dark Matter



Non-baryonic (cold) dark matter is needed

No candidate in the Standard Model(*)

New fundamental Physics

Dynamics of galaxy clusters

Rotational curves of galaxies

Weak lensing

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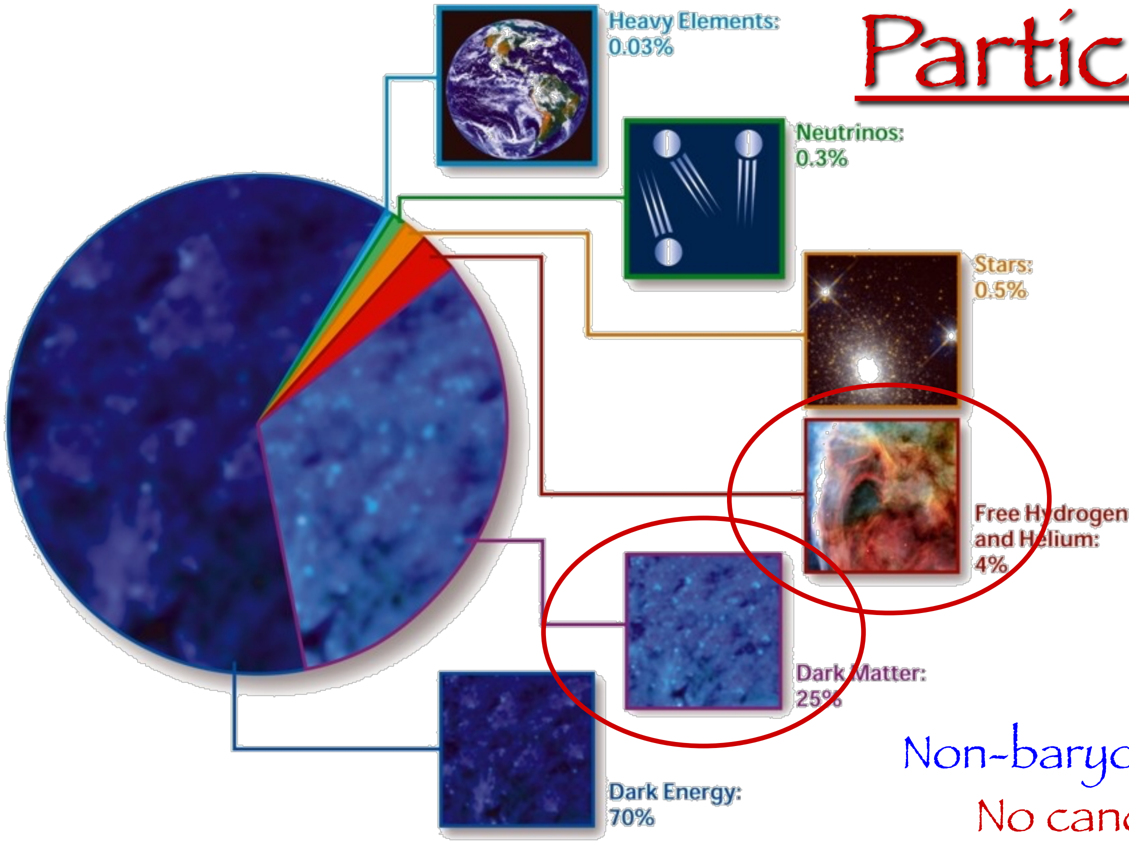
(*) Standard neutrino:

Too light: act as HDM (not CDM)

Particle Dark Matter



Non-baryonic (cold) dark matter is needed

No candidate in the Standard Model

New fundamental Physics

Dynamics of galaxy clusters
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Two fundamental questions

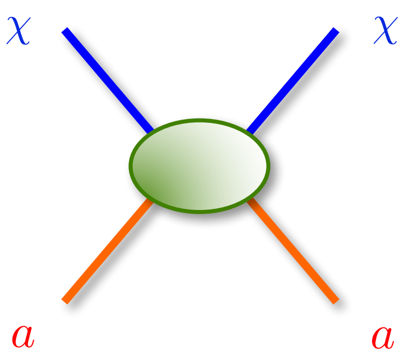
- Identify the particle candidate
- Identify a non-gravitational signal, manifestation of its particle nature

Alternatively: primordial black holes *might* solve the DM problem (debated issue)

If a particle, where it does come from?

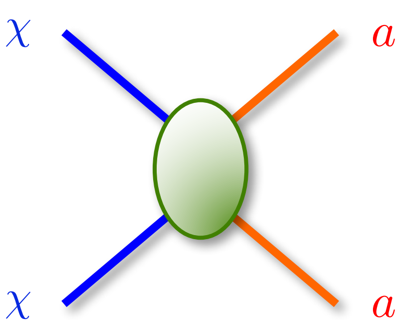
Produced, through some mechanism, in the early Universe

The early Universe is a plasma:



Elastic processes — kinetic equilibrium

Reshuffle particles energies and momenta

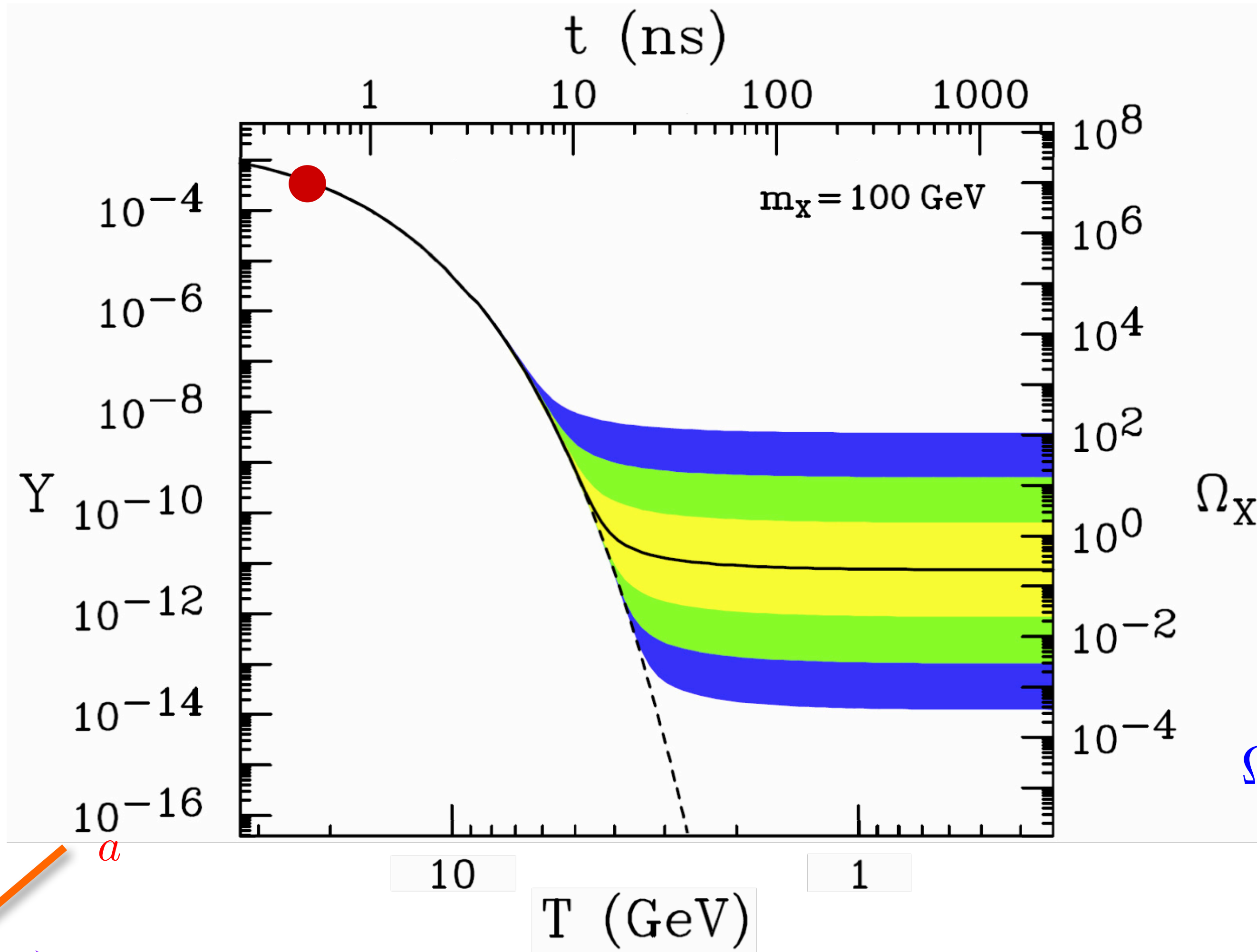


Inelastic processes — chemical equilibrium

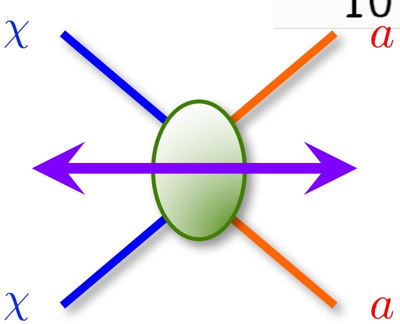
Create or destroy particles in the plasma

Abundance evolution

$Y = n/s$



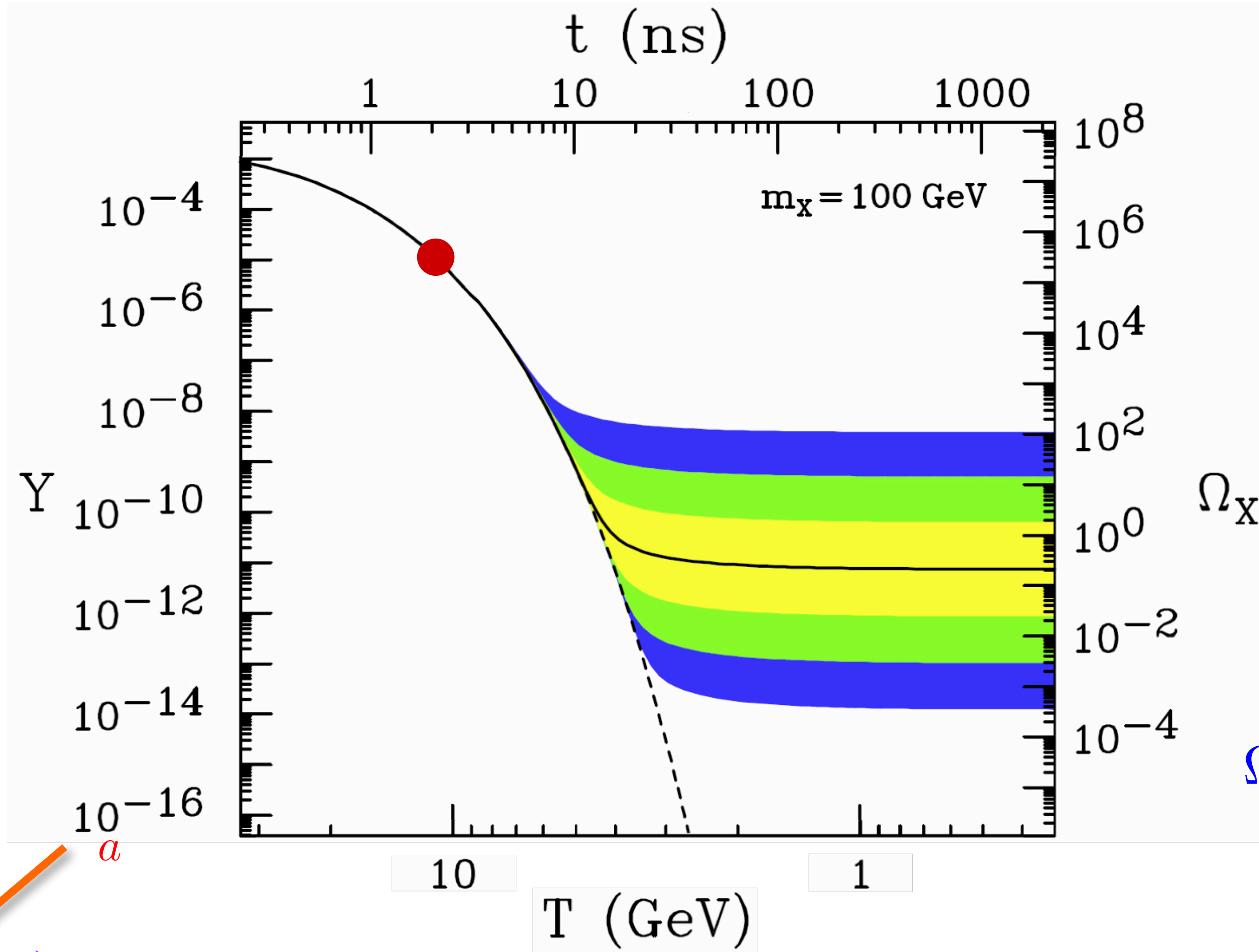
$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$



Particle in equilibrium

Abundance evolution

$Y = n/s$



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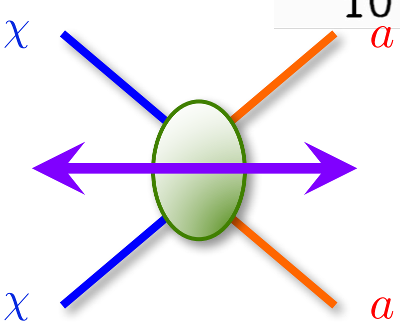
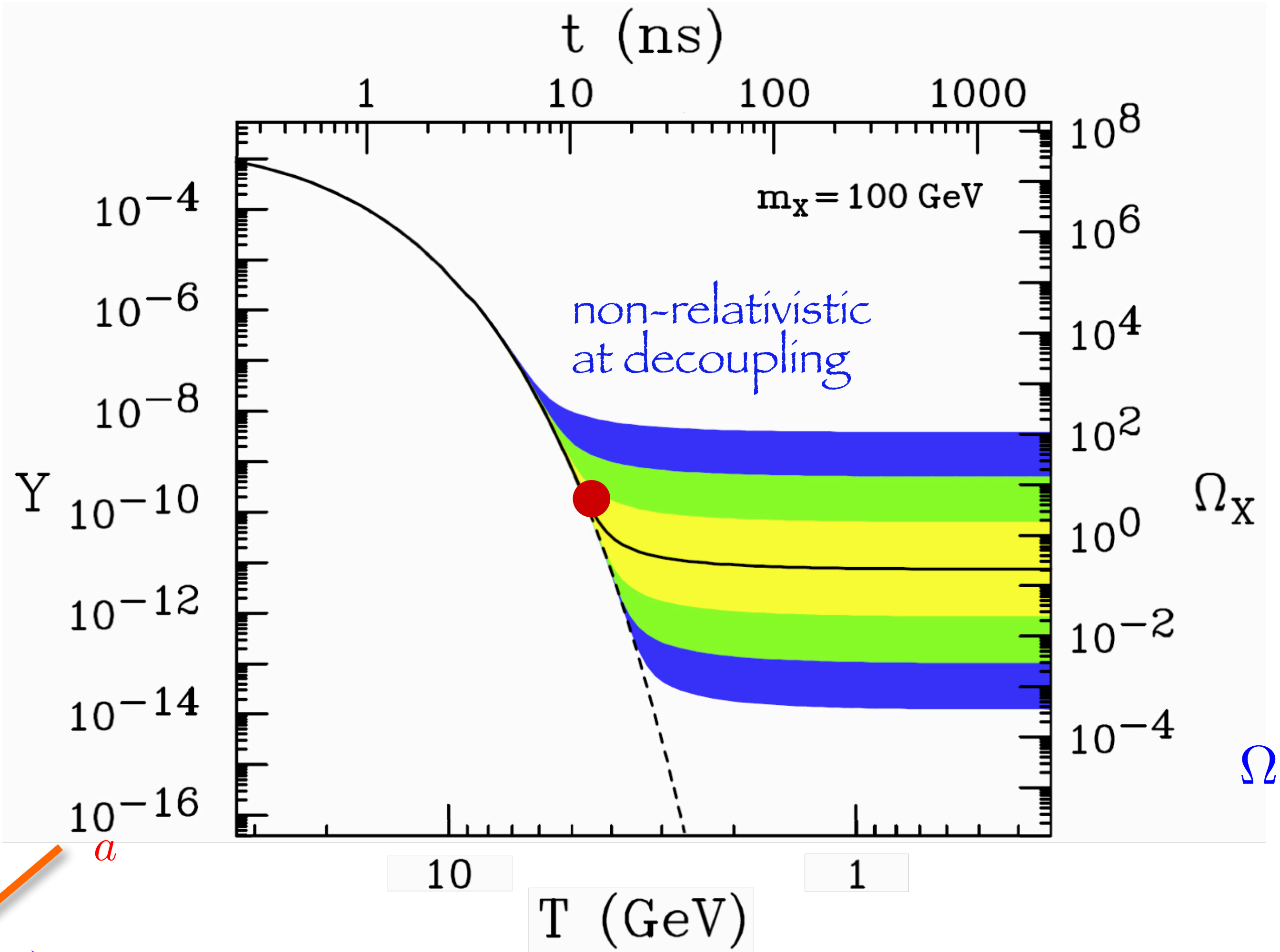


The universe cools down

Particle in equilibrium

Abundance evolution

$Y = n/s$



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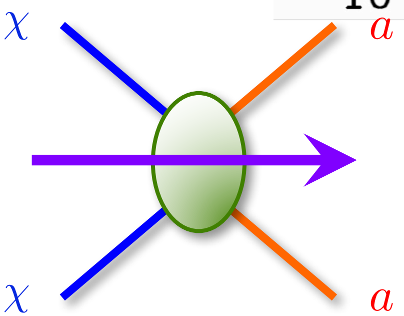
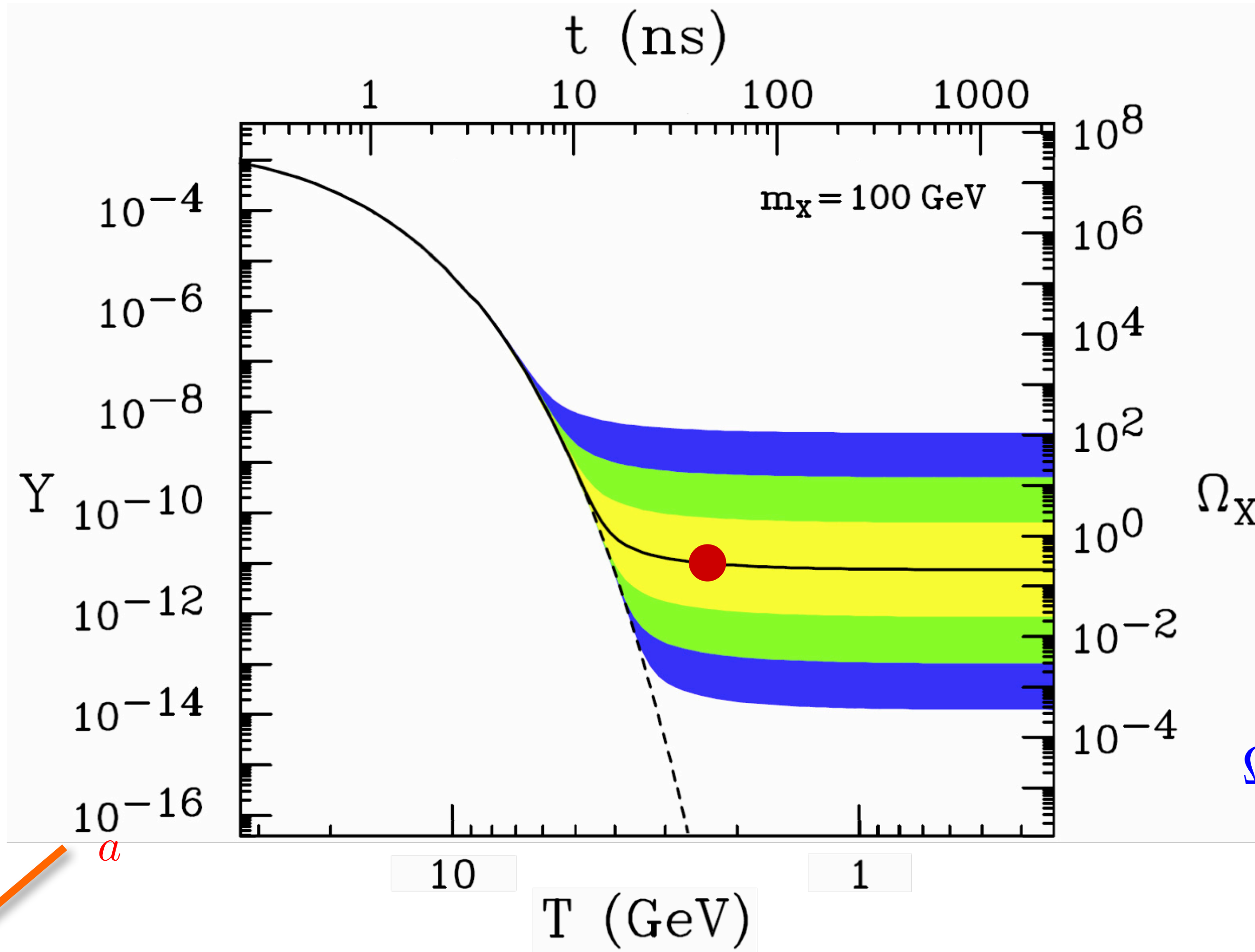


The universe cools down

Particles detache from the plasma
"freeze-out" of its abundance

Abundance evolution

$Y = n/s$



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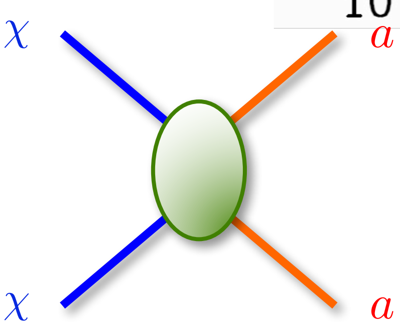

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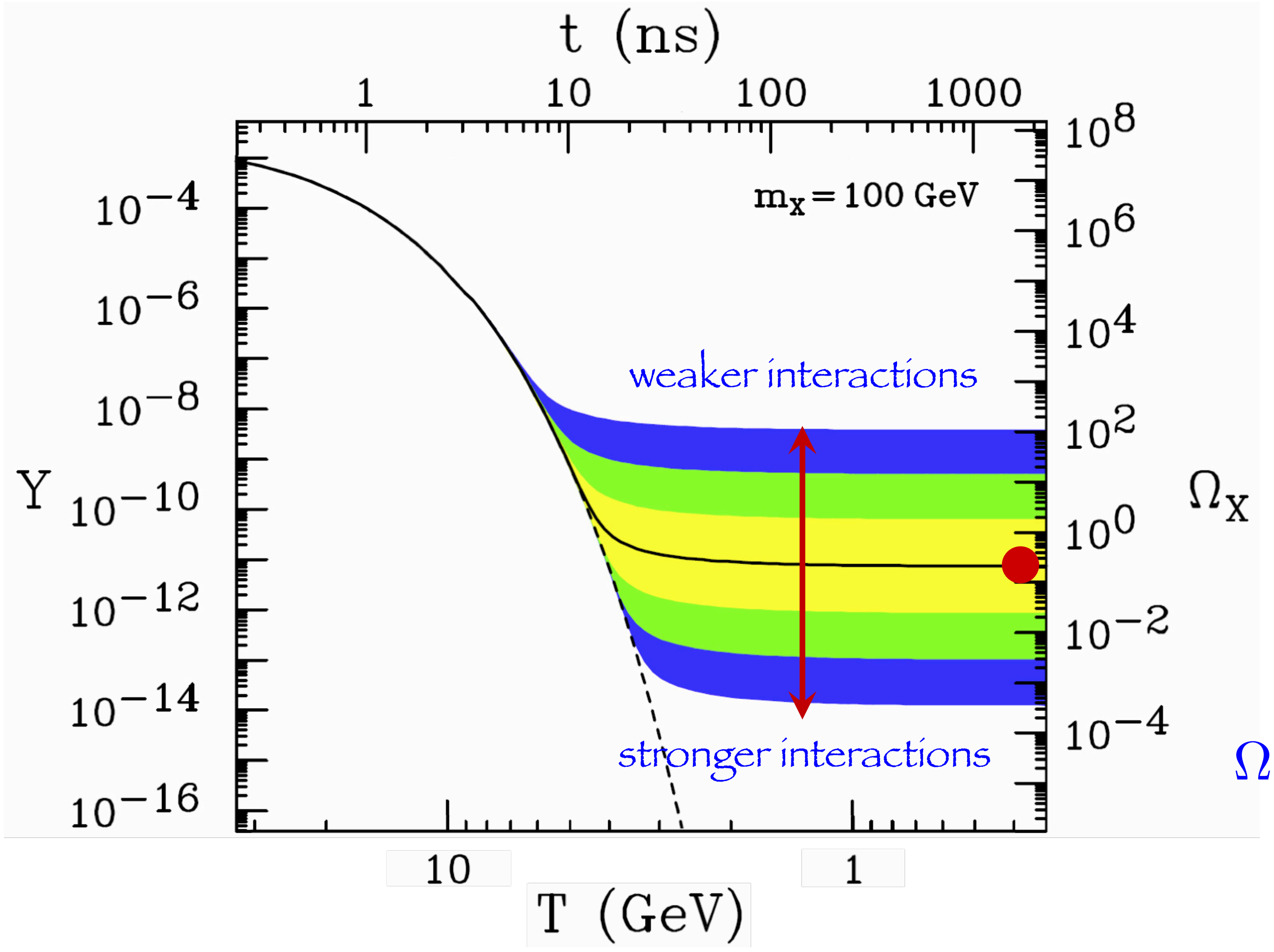


$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

The universe cools down

Abundance today (relic)

Succesfull "thermal" DM candidate

- 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

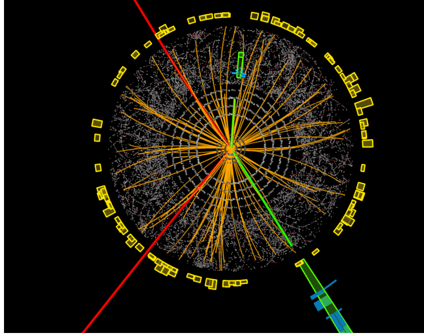
Non-thermal production

- 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)

What's dark matter?

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

A multiple approach

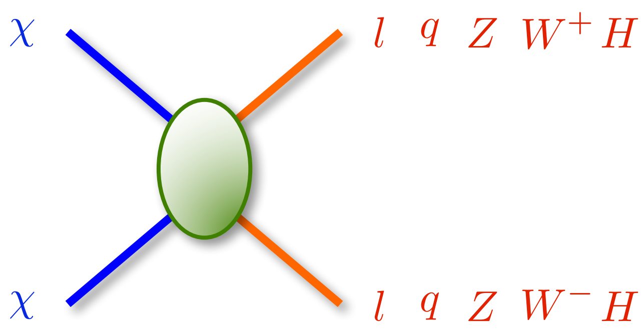


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy

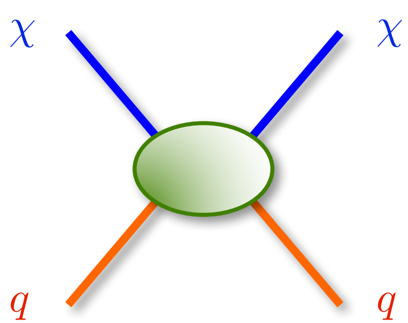
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all … profit of all opportunities

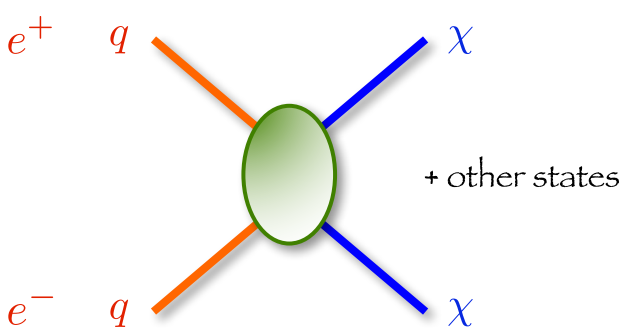
Mechanisms of DM signal production



Annihilation (or decay)

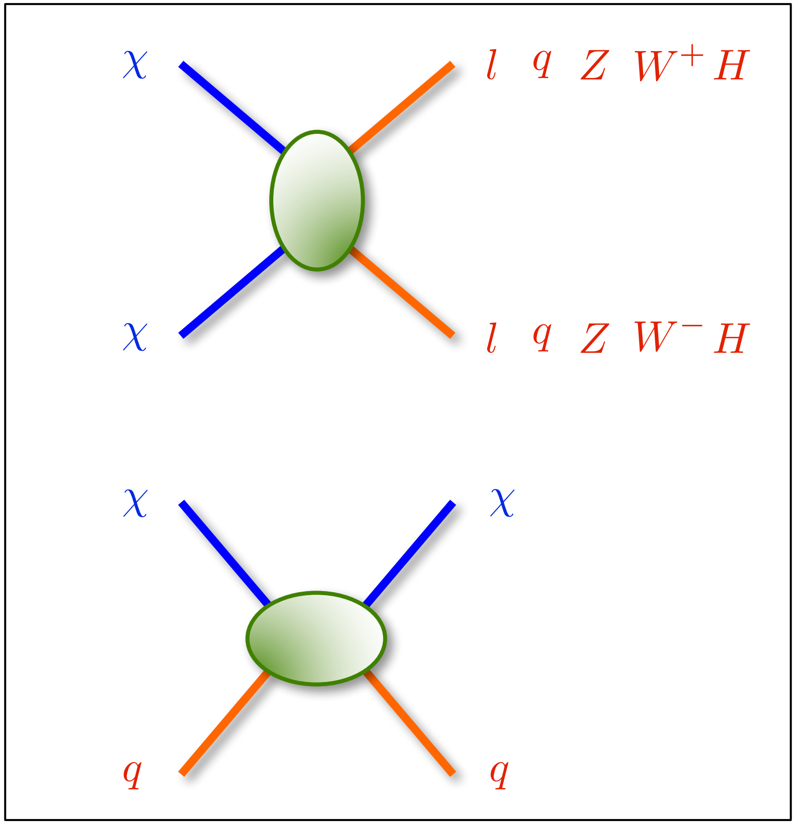


Scattering with ordinary matter



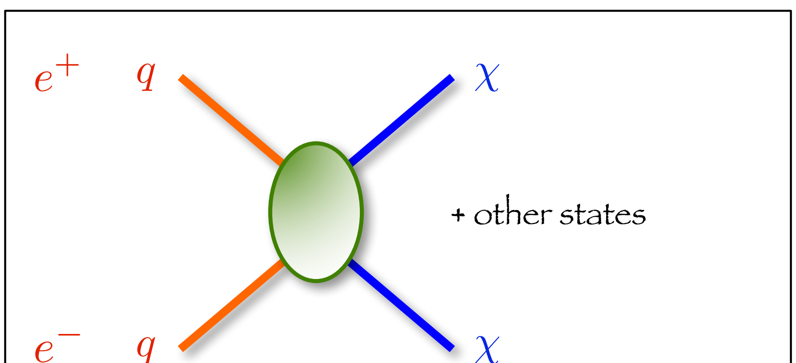
Production at accelerators

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

SUSY extension of the Standard Model

SUPERSYMMETRY: FERMION $\longleftrightarrow$ BOSON

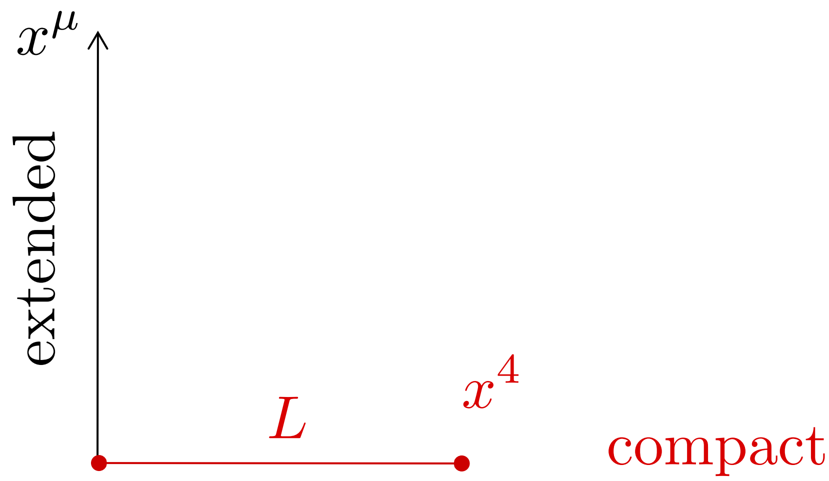
	Normal particles/fields			Supersymmetric partners			
				Interaction eigenstates		Mass eigenstates	
	Symbol		Name	Symbol	Name	Symbol	Name
	$q = d, c, b, u, s, t$		quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
	$l = e, \mu, \tau$		lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	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

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

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

Further models and candidates

Models with additional scalars [GeV-TeV, WIMP]

- Singlet
- Doublet (e.g.: 2 higgs doublet model)
- Triplet

Models based on extended symmetries [GeV-TeV, WIMP]

- GUT inspired
- Discrete symmetries

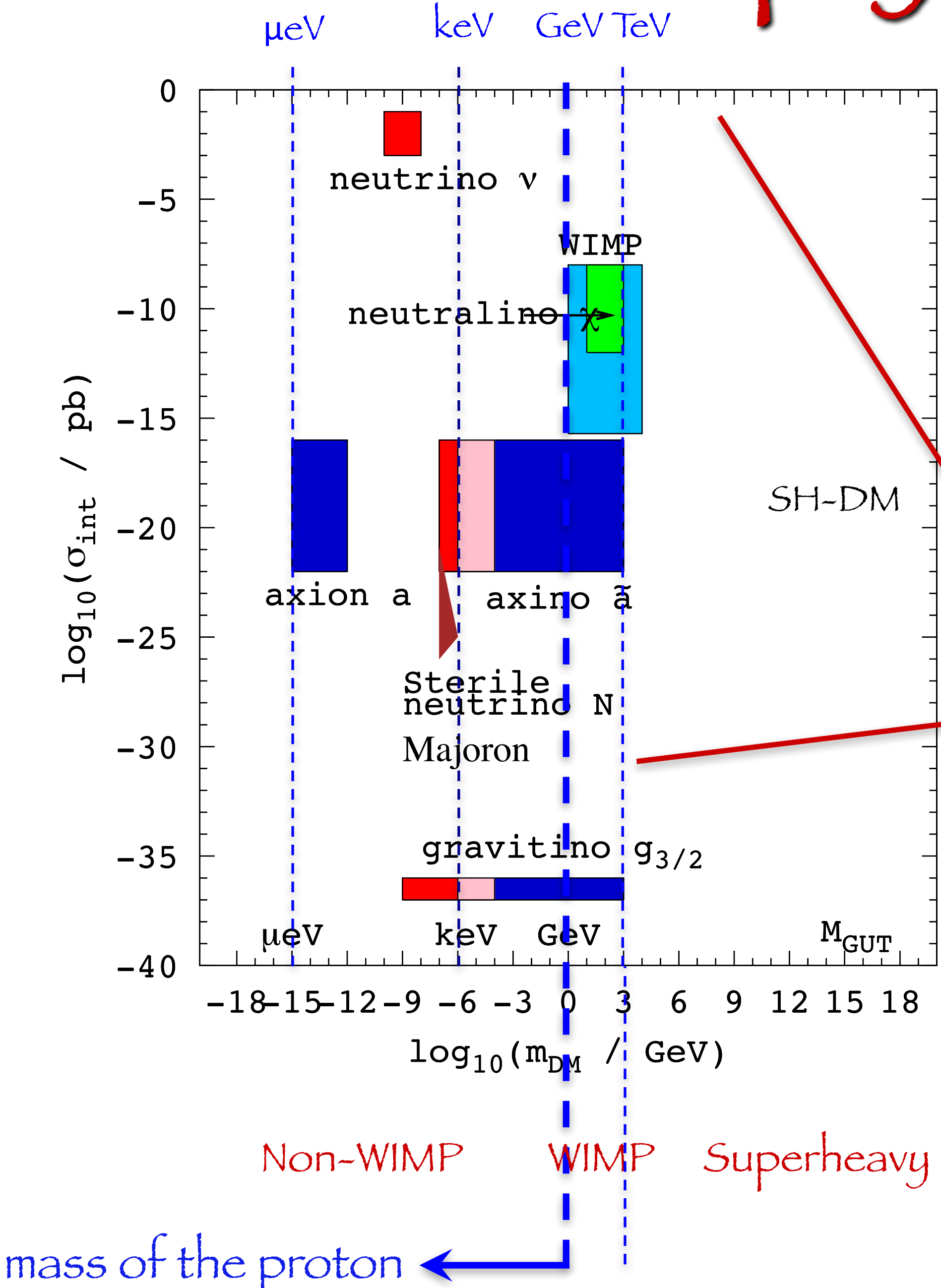
Mirror dark matter

Sterile neutrinos [keV, non WIMP, warm]

Axion [μeV, non WIMP, cold]

ALP (axion-like-particles, light scalars)
[> 10^{-22} eV, non WIMP, cold (BE condensate)]

Particle physics scales



"Strong (-ish)"

Self-interacting
Technicolor DM
...

"EM (-ish)"

Millicharged DM
Electric/magnetic dipole
...

Weak

WIMP

Gravitational

Relic from the early Universe
Thermal
Non thermal
Dynamically: non relativistic (cold)
collisionless

Try to produce the DM particle in a controlled environment ...

High-E accelerators: for WIMPs (GeV-TeV)

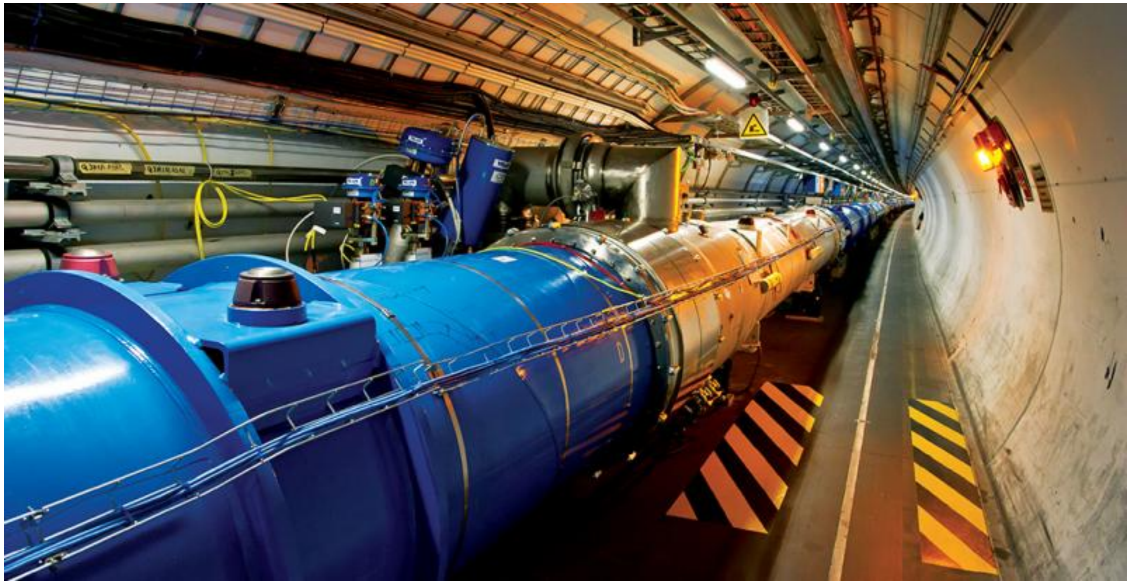
Emma Tolley on Tuesday

Low-E accelerators: for lighter states

Paolo Valente on Wednesday

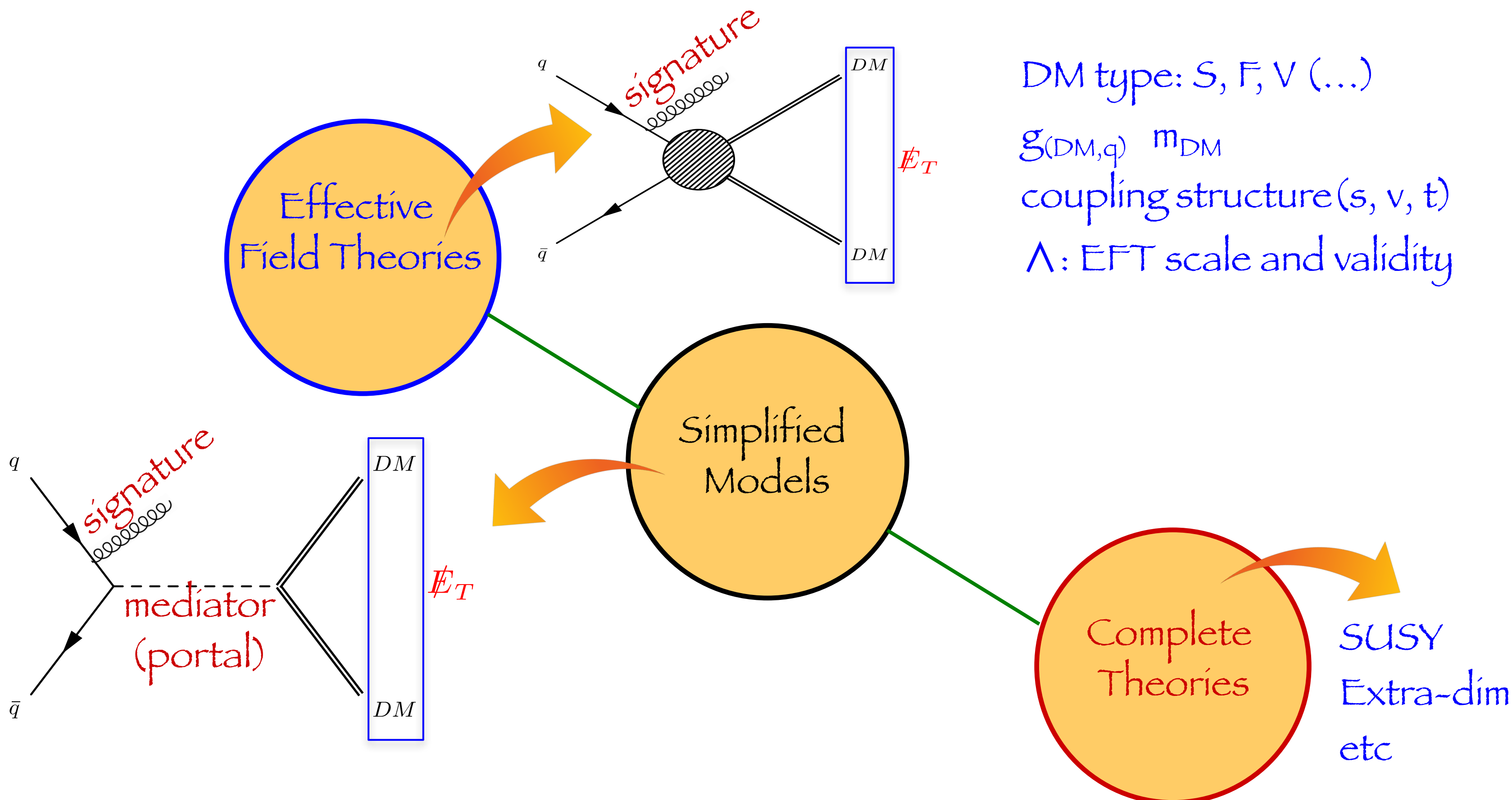
Beam dumps, others: for axions, ALPs

Giovanni Carugno on Wednesday



WIMPs at accelerators

Focus now is on the Run II of LHC



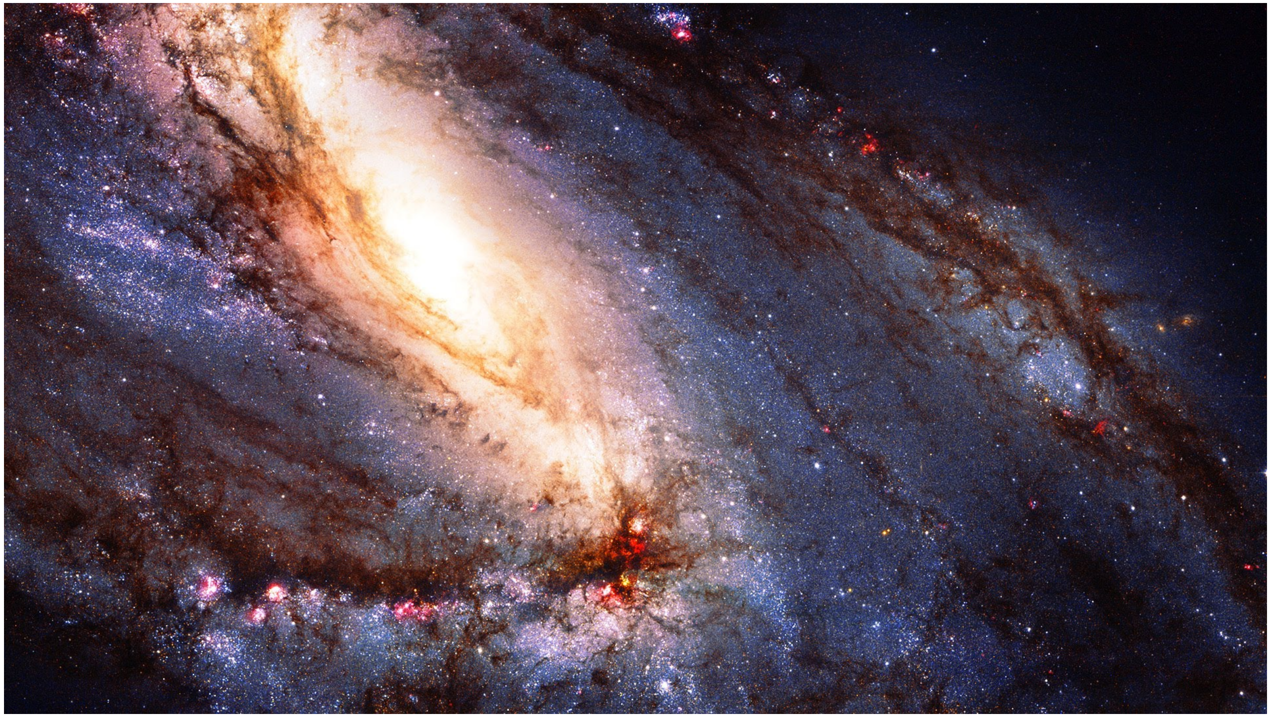
DM type: S, F, V (...)
Portal: S, F, V, T

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

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^-) under way, and studies for accessing invisible decays
- Rich experimental program:
  - Hadronic beams: SHIP e NA62 at CERN
  - Electron beams
  - Meson decays

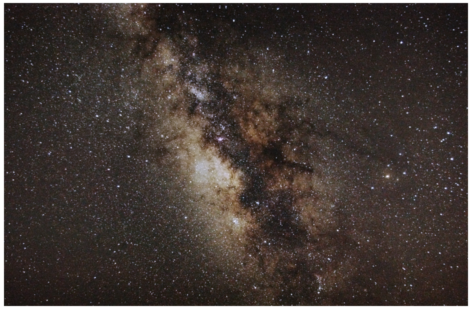
Look at the DM particle where DM is …

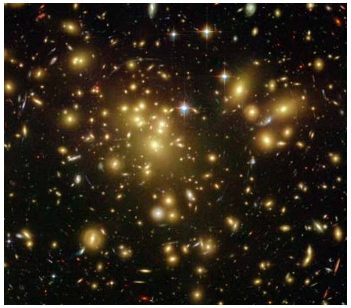


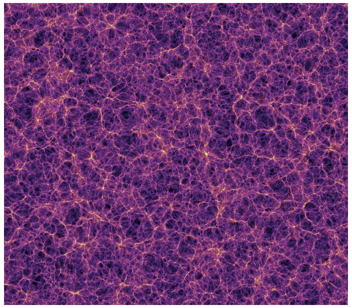
Where to search for a signal ...

We can exploit every structure where DM is present ...

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"



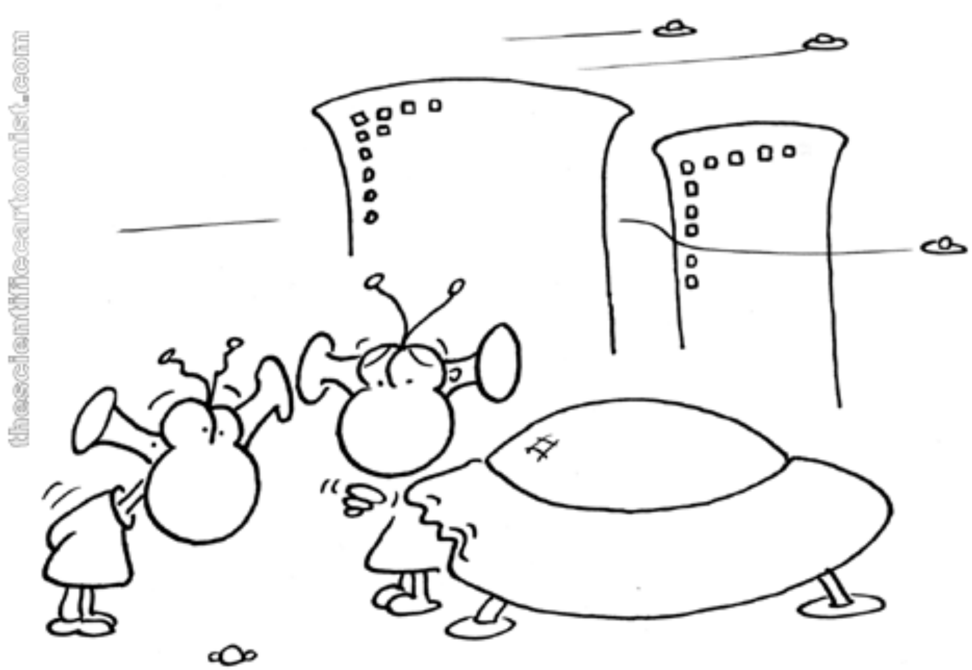




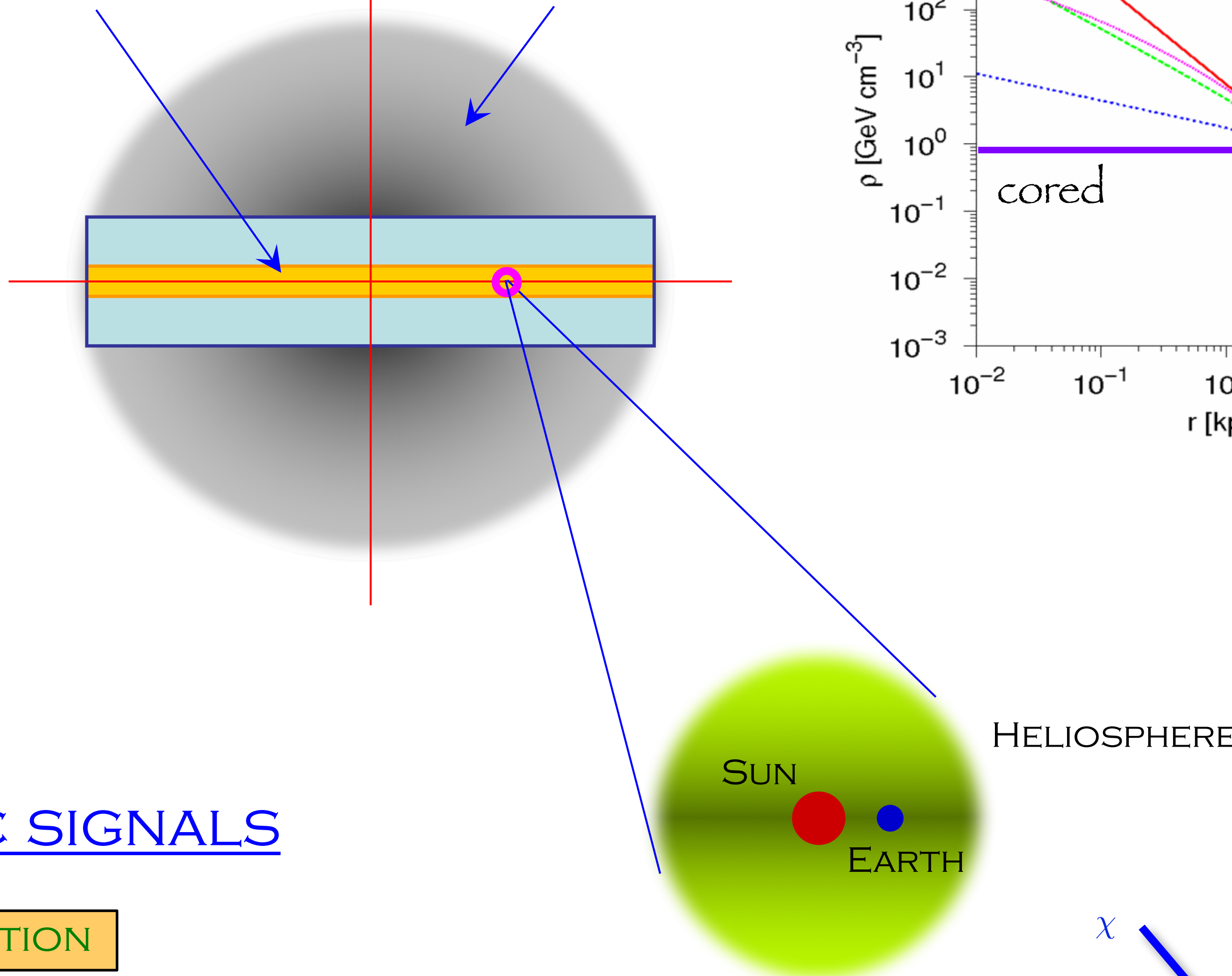
DM as a particle might ...

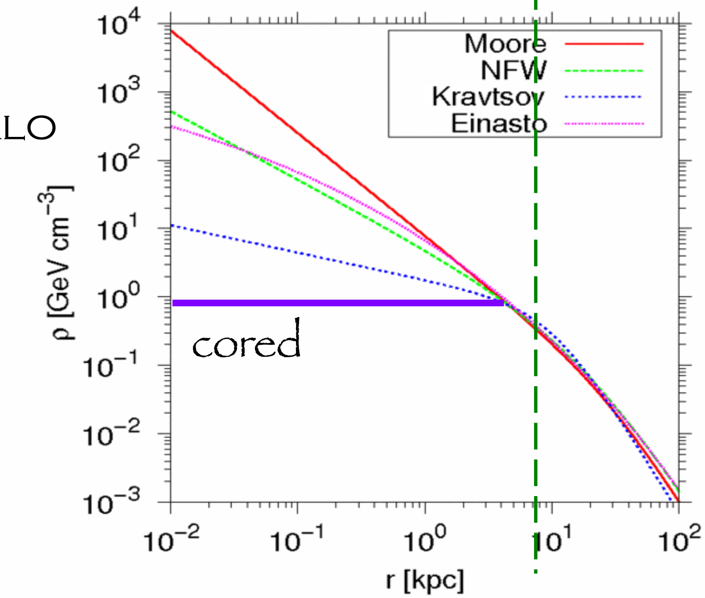
Interact with ordinary matter — Direct detection

Produce effects in astrophysical environments, like in stars



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



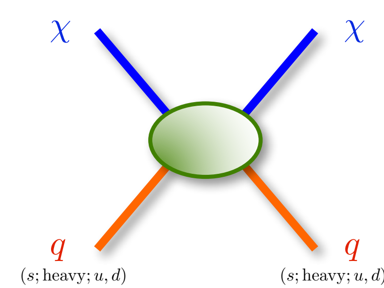


Galactic signals

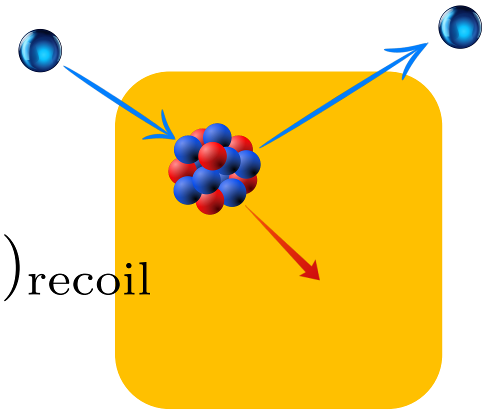
Direct detection

Feels ony the local DM density (not space distribution)

Feels how DM is locally distributed in velocity space



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)

Giuliana Fiorillo on Friday

Typical signatures of direct detection

- Stationary over the lifetime of an experiment
  Directional boost

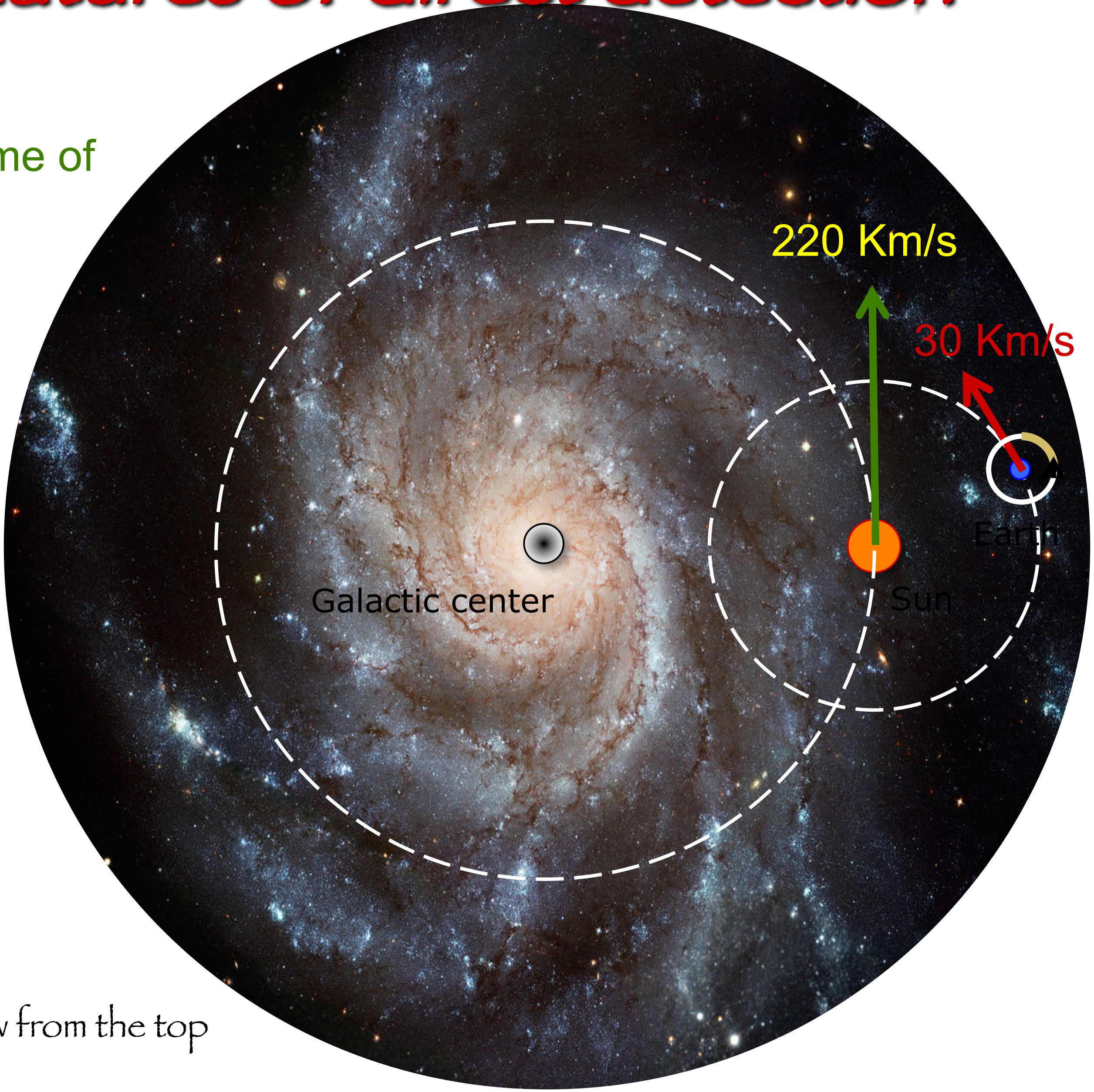
  Directionality

- Period: 1 year

  Annual modulation

- Period: 1 day

  Diurnal modulation



View from the top

Annual modulation

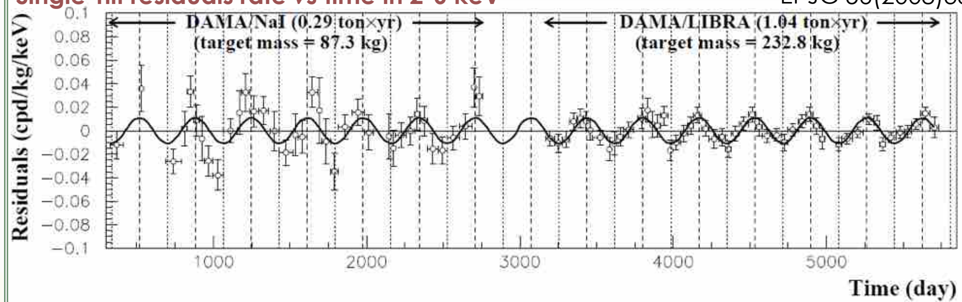
DAMA, 9.2σ with 1.33 ton x yr, 15 cycles

Model Independent Annual Modulation Result

DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate *vs* time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



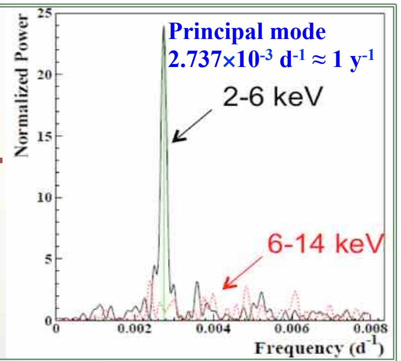
continuous line: t_0 = 152.5 d, T = 1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

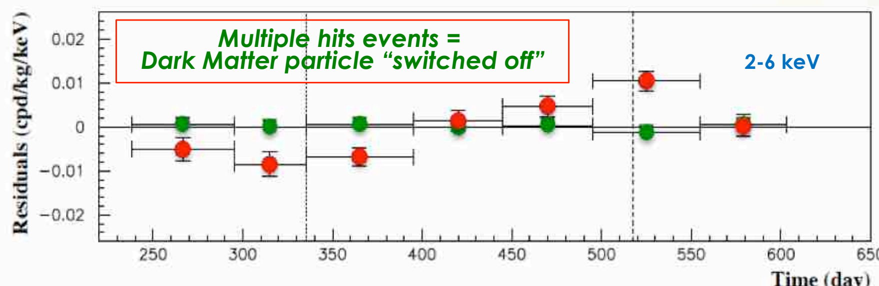
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y
9.3 σ C.L.

Power spectrum



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A=-(0.0005±0.0004) cpd/kg/keV



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

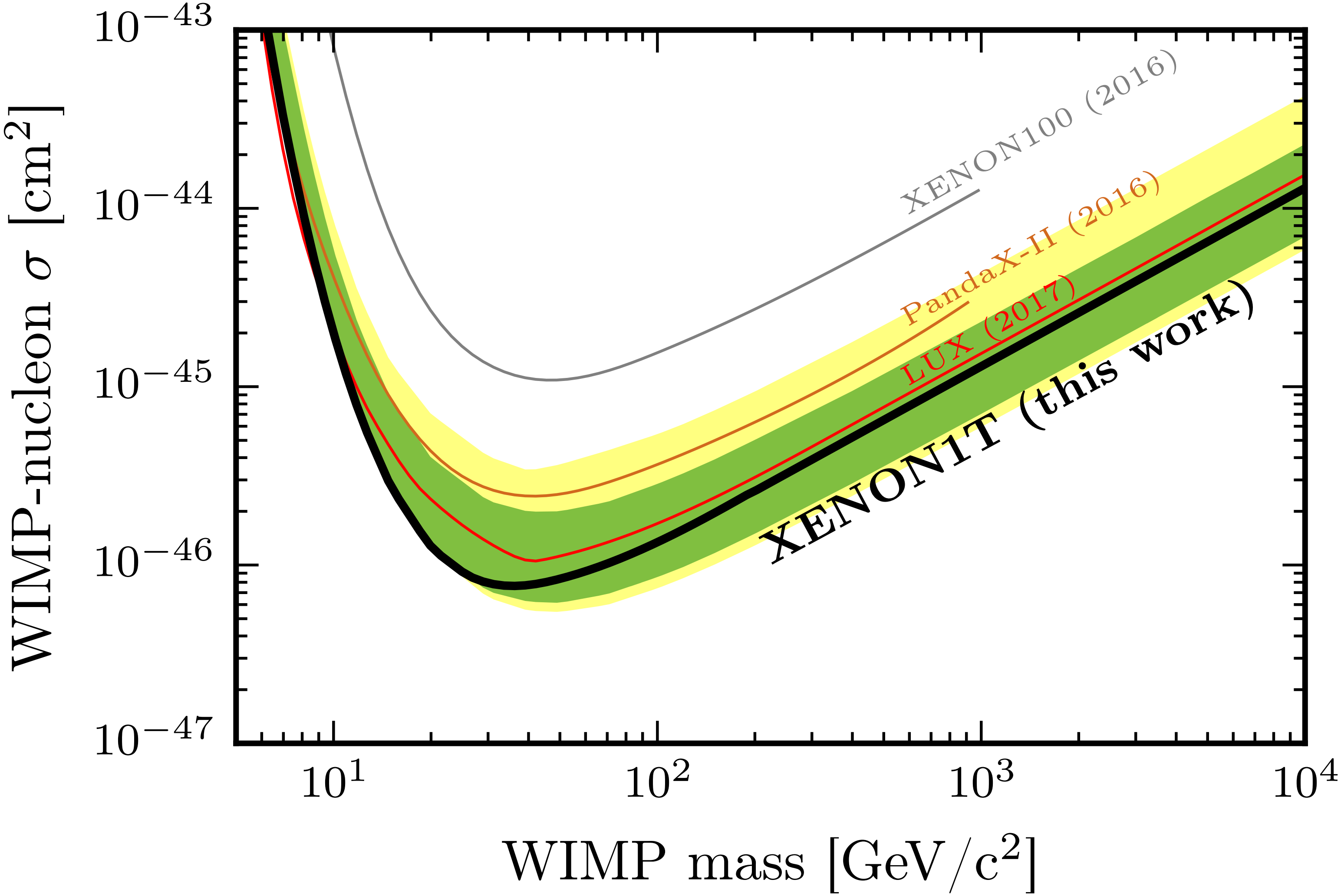
No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at more than 9σ C.L.

From Belli's talk at TAUP 2015, http://taup2015.to.infn.it

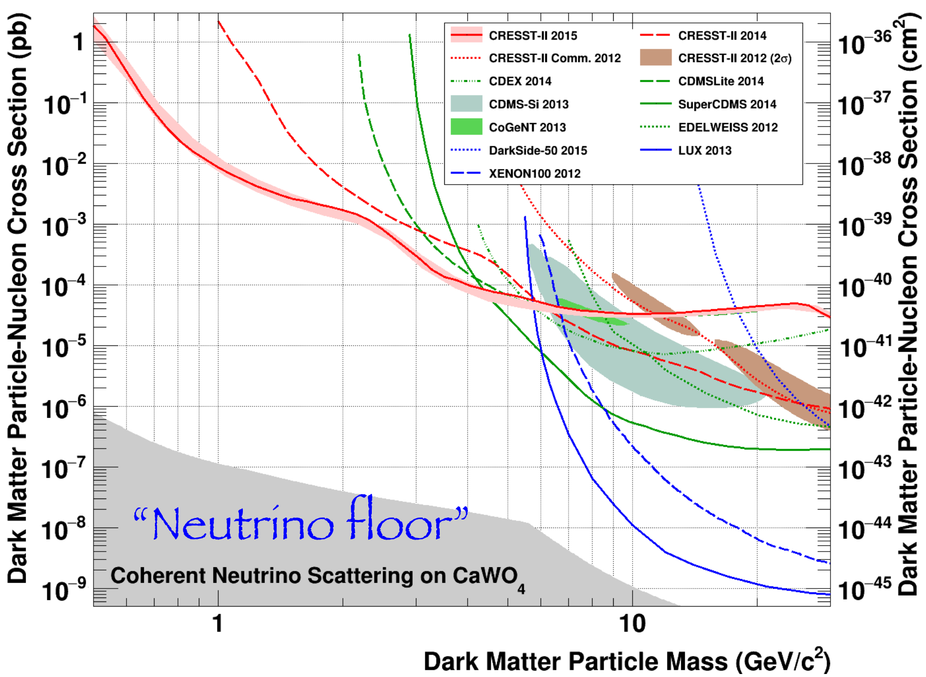
High WIMP mass

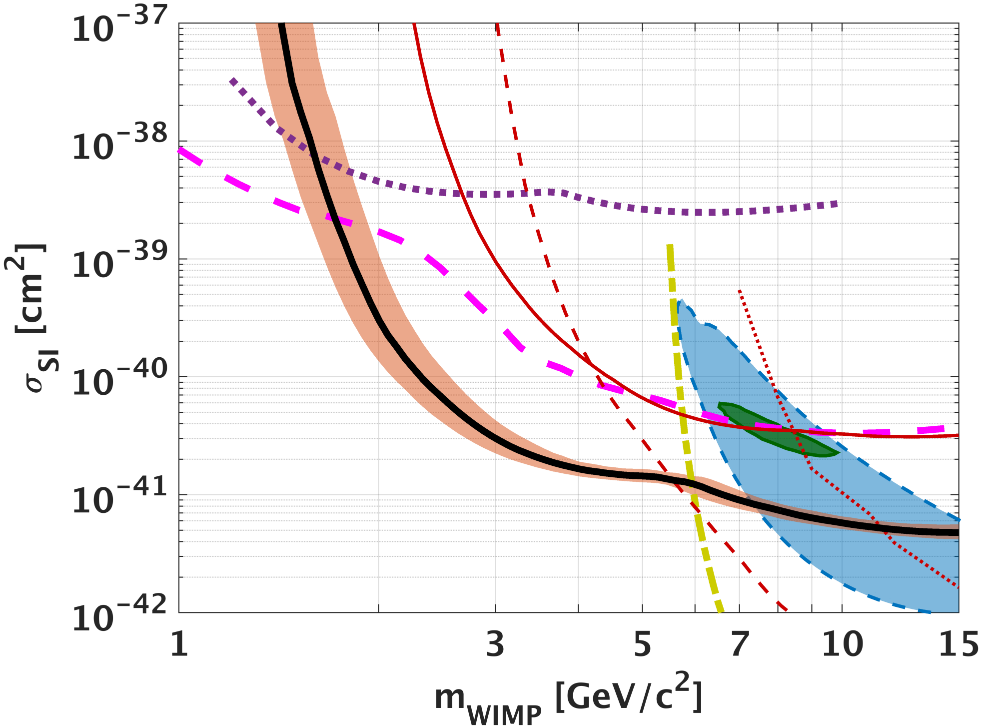
Contact-type scalar interactions (O_1)



Aprile et al (XENON 1T Collab), 1705.06655

Low WIMP mass





Angloher et al (CRESST), EPJC 76 (2016) 25

Agnese et al (SuperCDMS) PRL 116 (2016) 071301

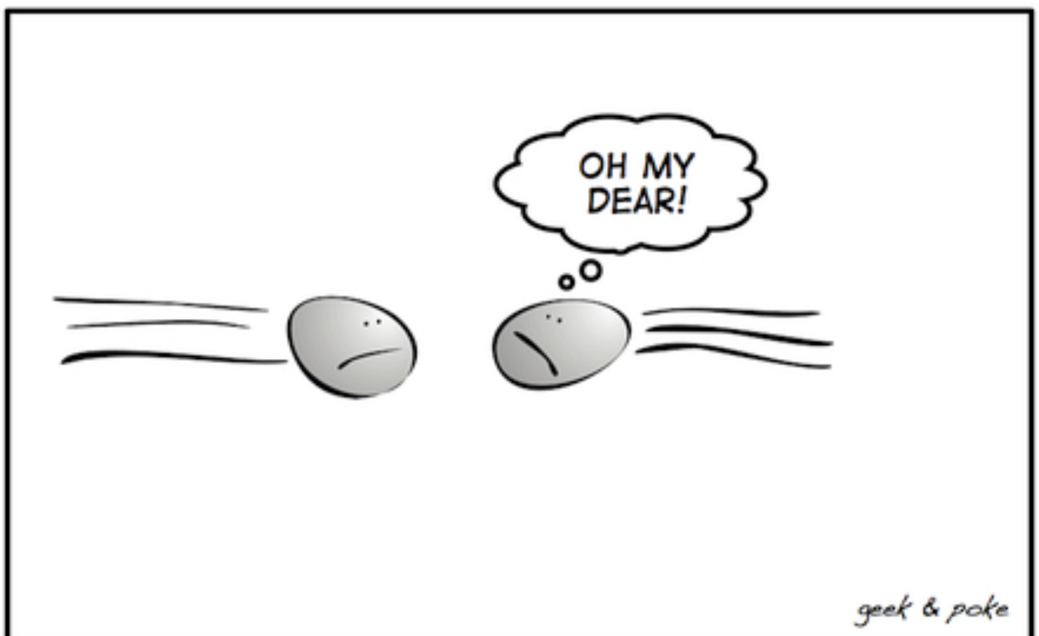
Contact-type scalar interactions (O_1)

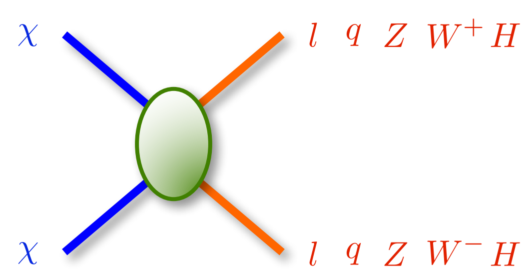
DM as a particle might ...

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)

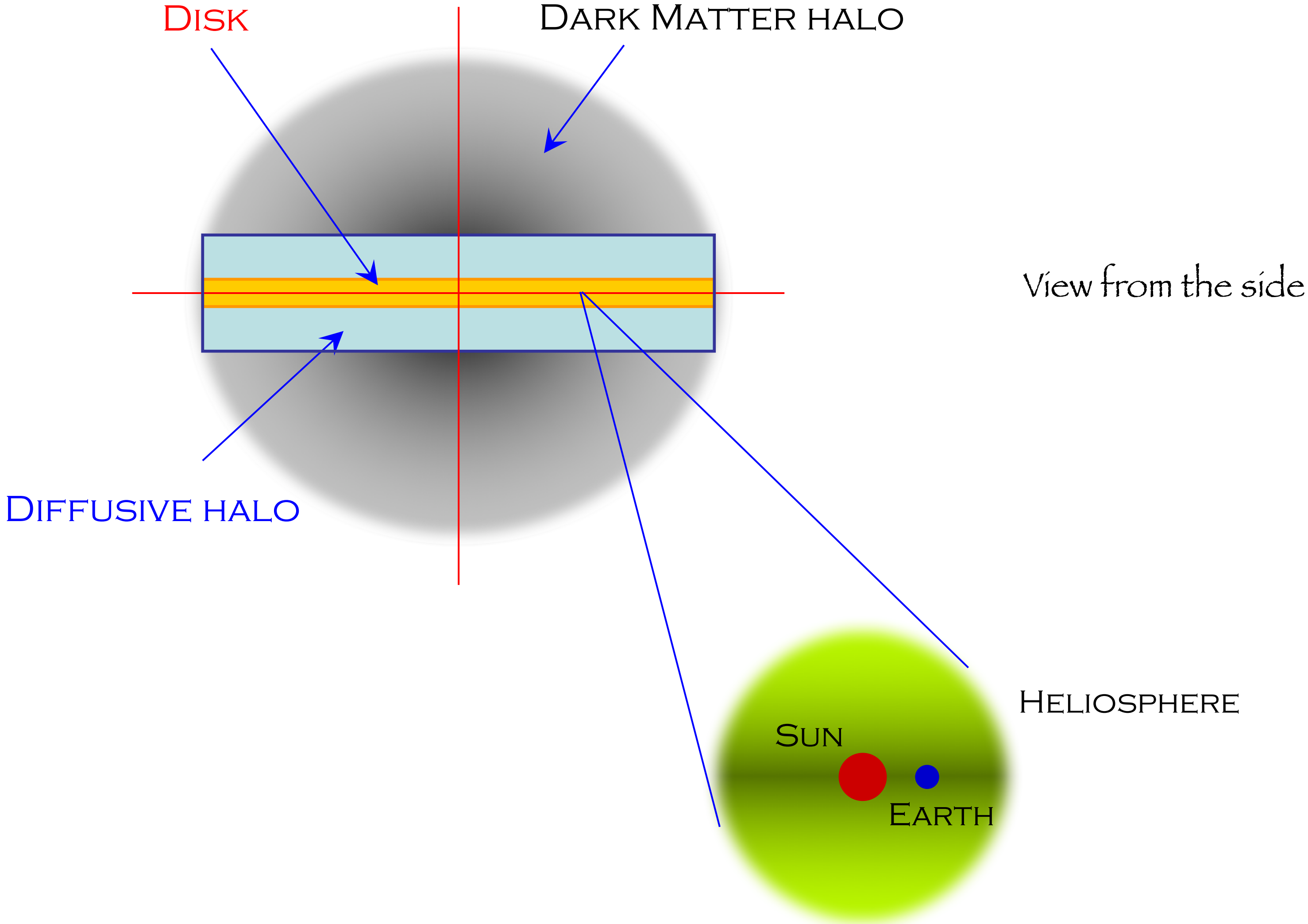


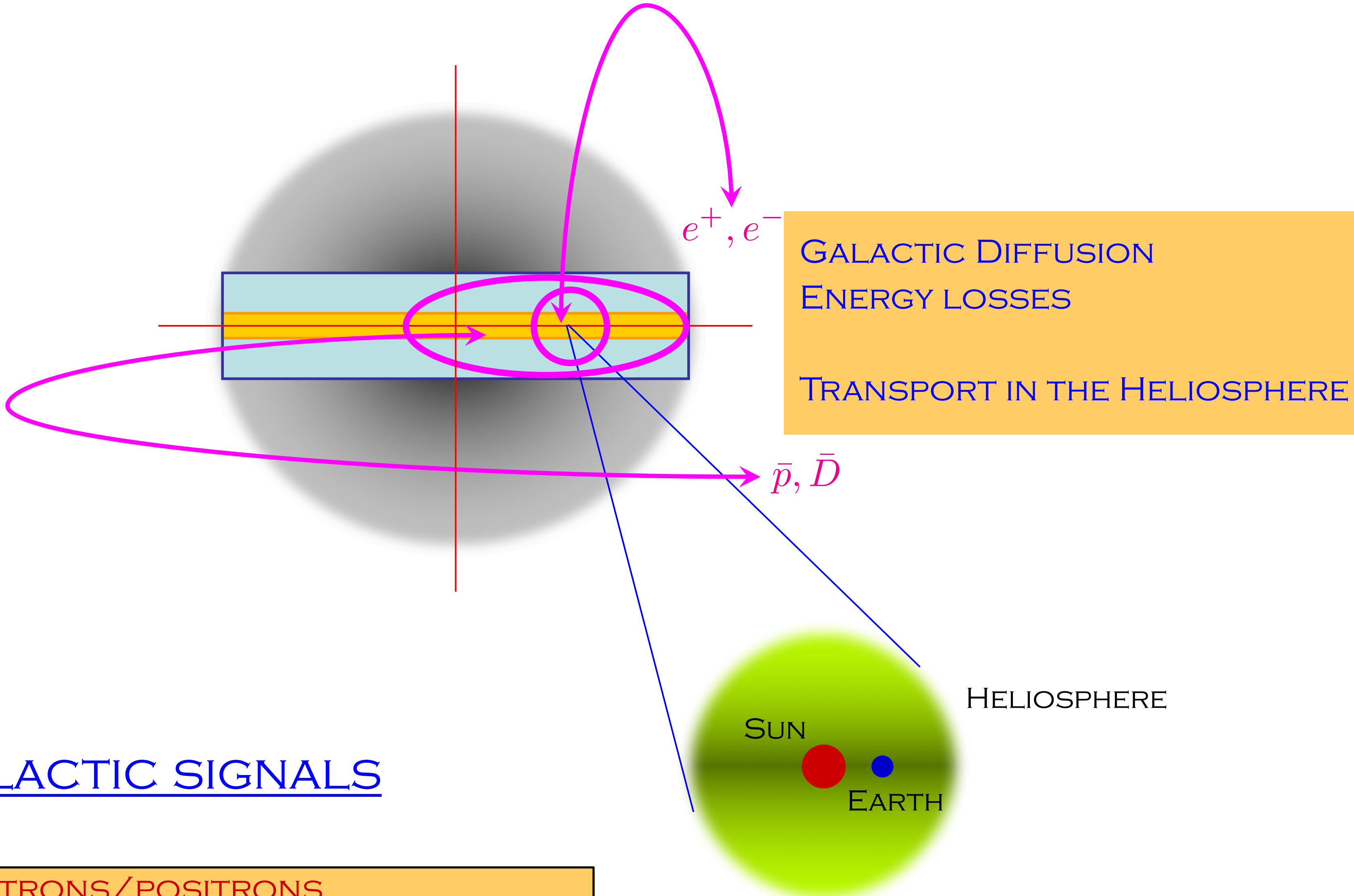


Messengers

- Charged CR ($e^{\pm}$, antip, antiD)
- Neutrinos
- Photons
  - Gamma-rays
    - Prompt production
    - IC from $e^{\pm}$ on ISRF and CMB
  - X-rays
    - IC from $e^{\pm}$ on ISRF and CMB
  - Radio
    - Synchro from $e^{\pm}$ on mag. field

Galactic environment

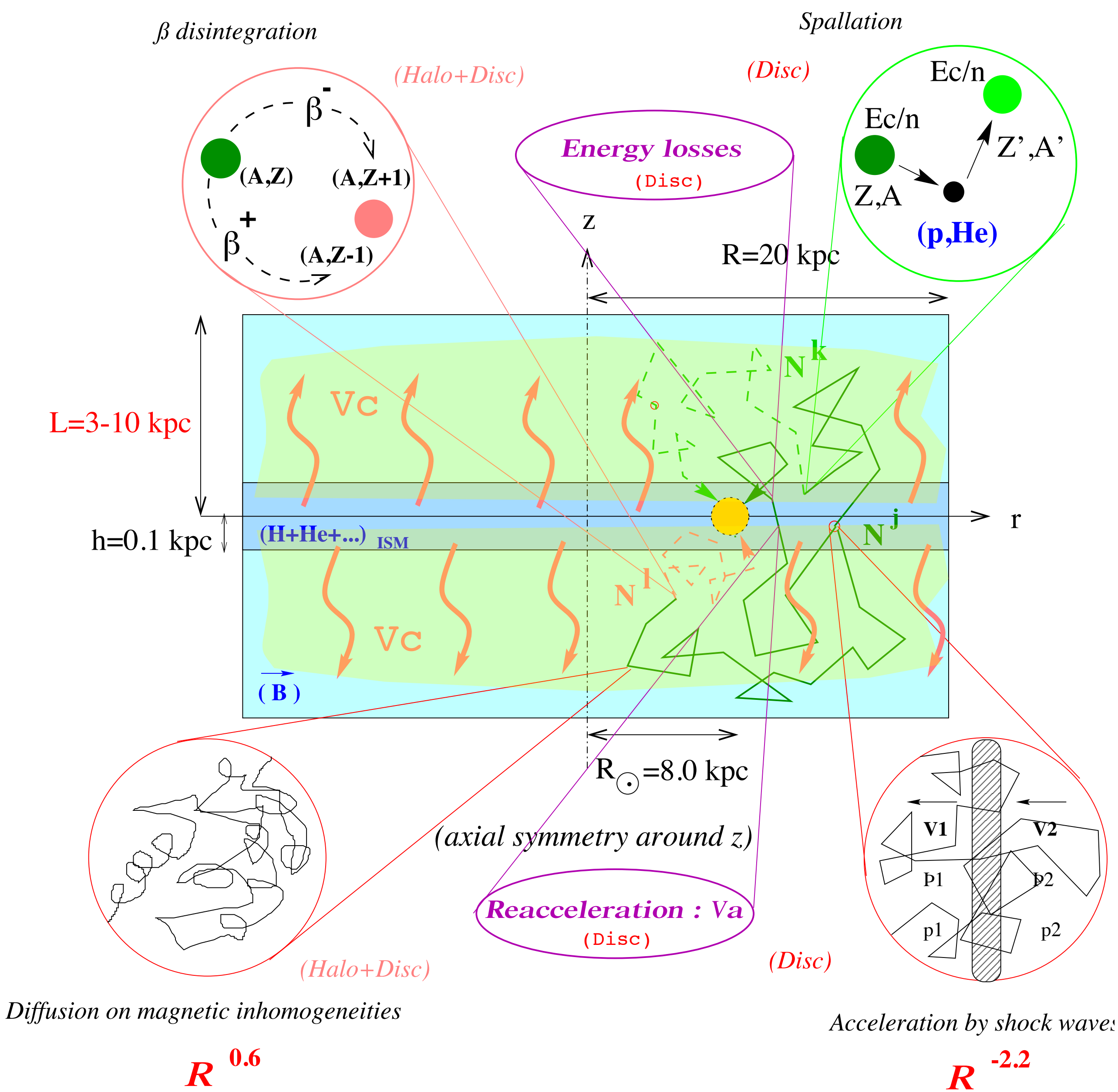




Galactic signals

Electrons/positrons
Antiprotons
Antideuterons

Galactic environment



Transport equation

$$\frac{\partial N_j}{\partial t}$$

Diffusion [K]
Convection [V]
Adiabatic losses (in expanding plasma)

$$+\left[-\vec{\nabla}\cdot(K(E,\vec{r})\vec{\nabla}) + \vec{\nabla}\cdot\vec{V}(\vec{r}))\right] N_j$$

Catastrophic losses (for nuclei)
elastic : N + ISM -> N + ISM
inelastic : N + ISM -< X + (...)

$$+\left(\Gamma_{\rm rad} + \Gamma_{\rm inel}\right) N_j$$

Energy losses [b]
e+/e- : synchrotron
inverse Compton
brems (free-free)
ionization, Coulomb
Nuclei : ionization, Coulomb
Diffusion in momentum space (reacceleration) [K]

$$+\frac{\partial}{\partial E}\left(b_j(E)N_j - K_j(E)\frac{\partial N_j}{\partial E}\right)$$

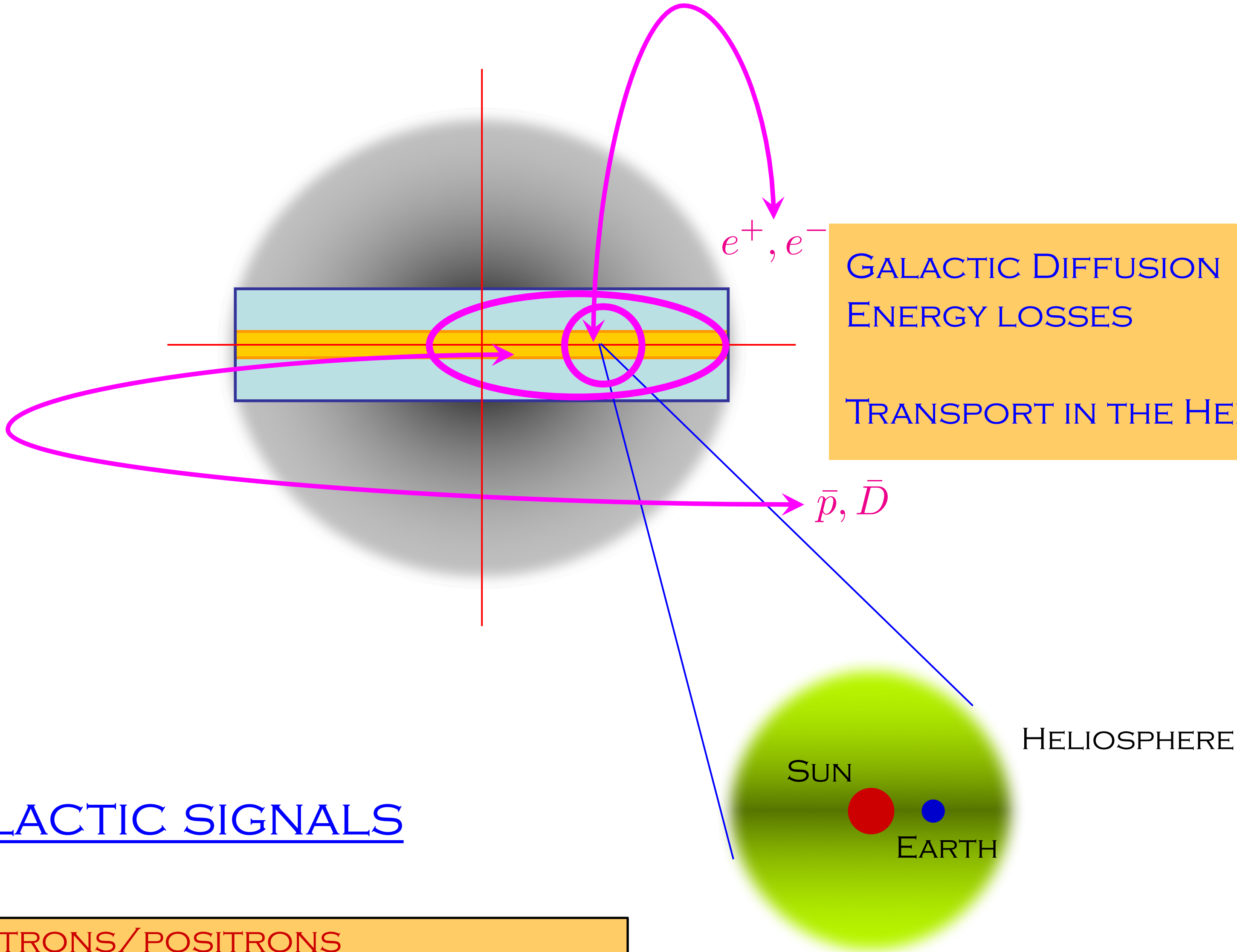
$$=$$

Primary source

$$Q_j(E,\vec{r})$$

Secondary sources

$$+\sum_{m_i>m_j}\Gamma_{i\to j}N_i$$

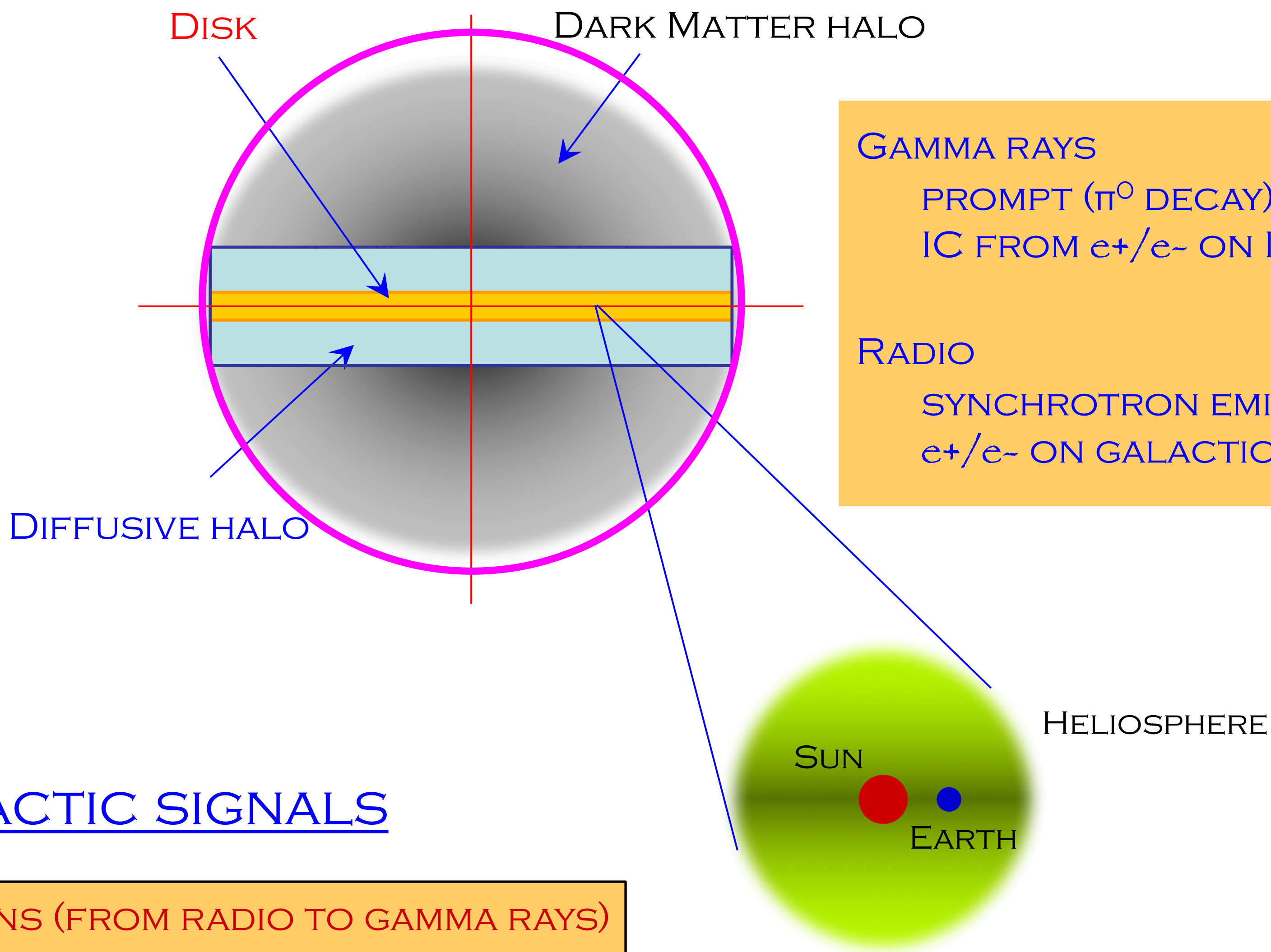


Galactic Diffusion
Energy losses

Transport in the Heliosphere

Galactic signals

- Electrons/positrons
- Antiprotons
- Antideuterons



Gamma rays

prompt (π^0 decay)

IC from e+/e- on ISRF

Radio

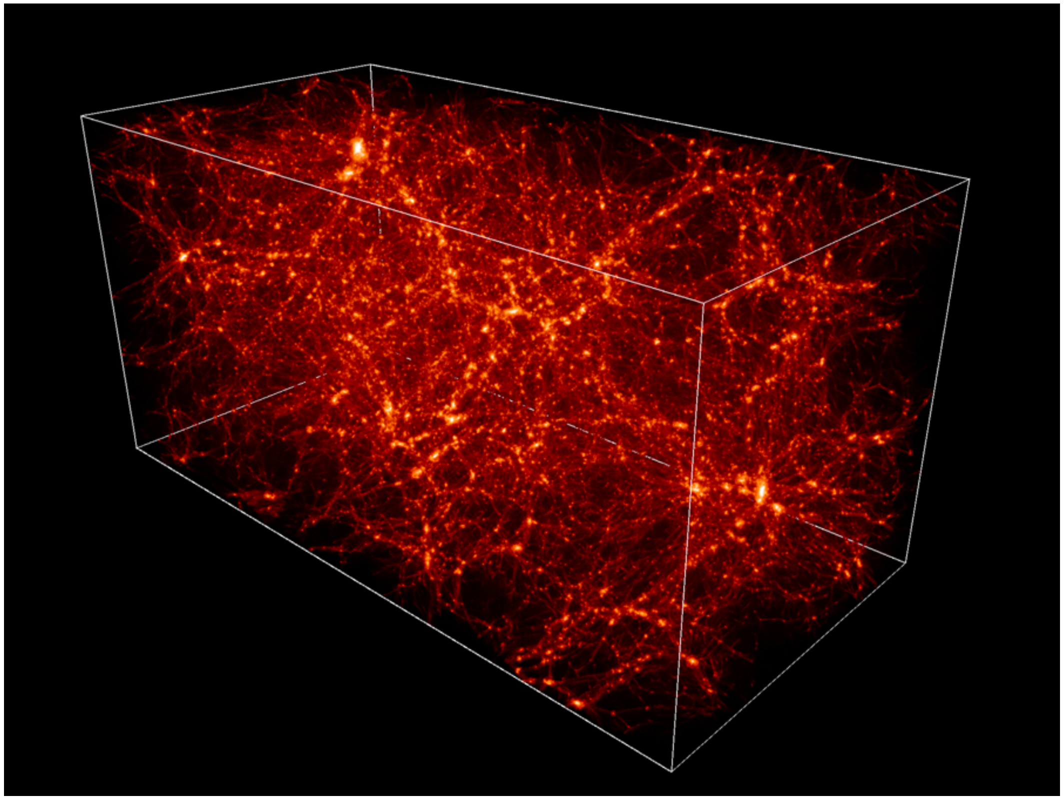
synchrotron emission from e+/e- on galactic B

Galactic signals

Photons (from radio to gamma rays)

Neutrinos from the Galaxy

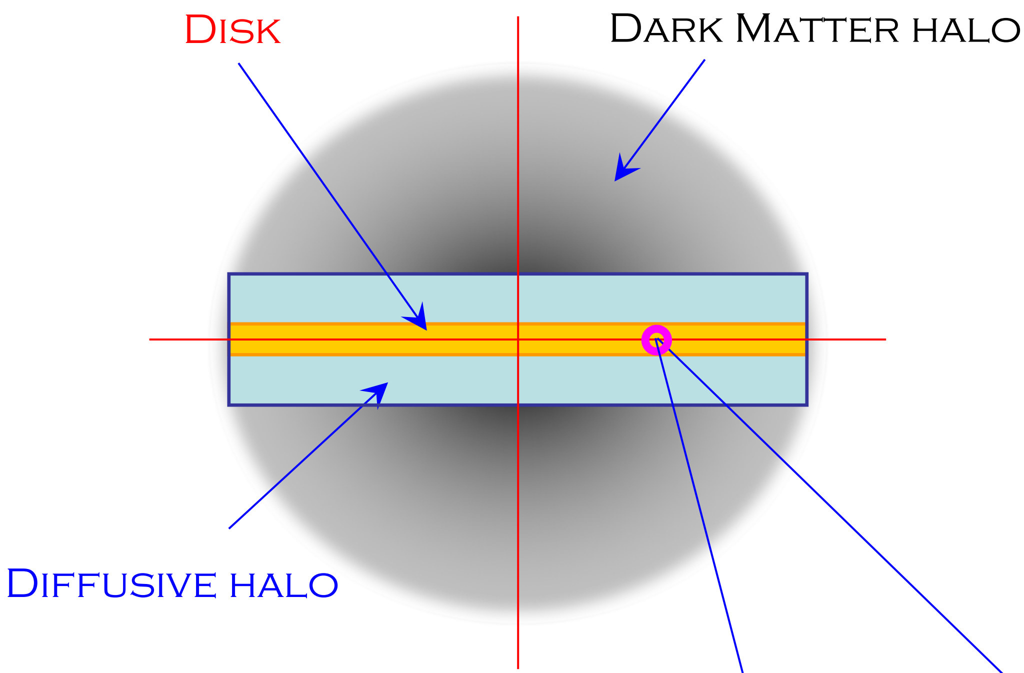
Extra-galactic environment

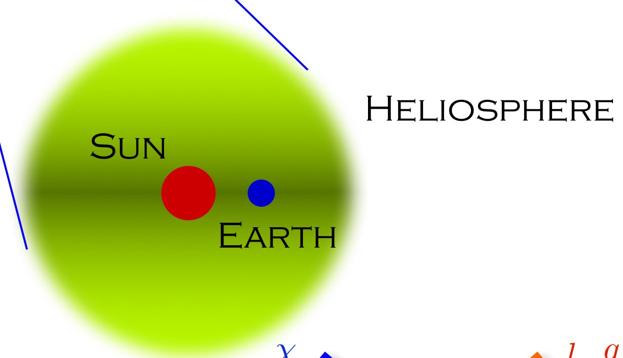


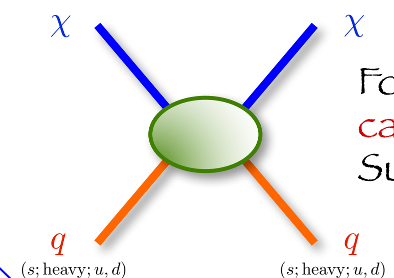
Extragalactic signals

Photons: gamma, X, radio
Neutrinos

Sunyaev-Zeldovich effect on CMB
Optical depth of the Universe

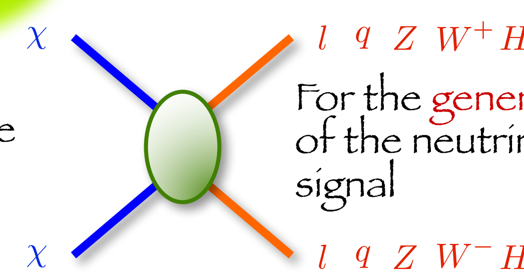






For gravitational capture in the Sun and Earth

GALACTIC SIGNALS



For the generation of the neutrino signal

Feels ony the local DM density (not space distribution)

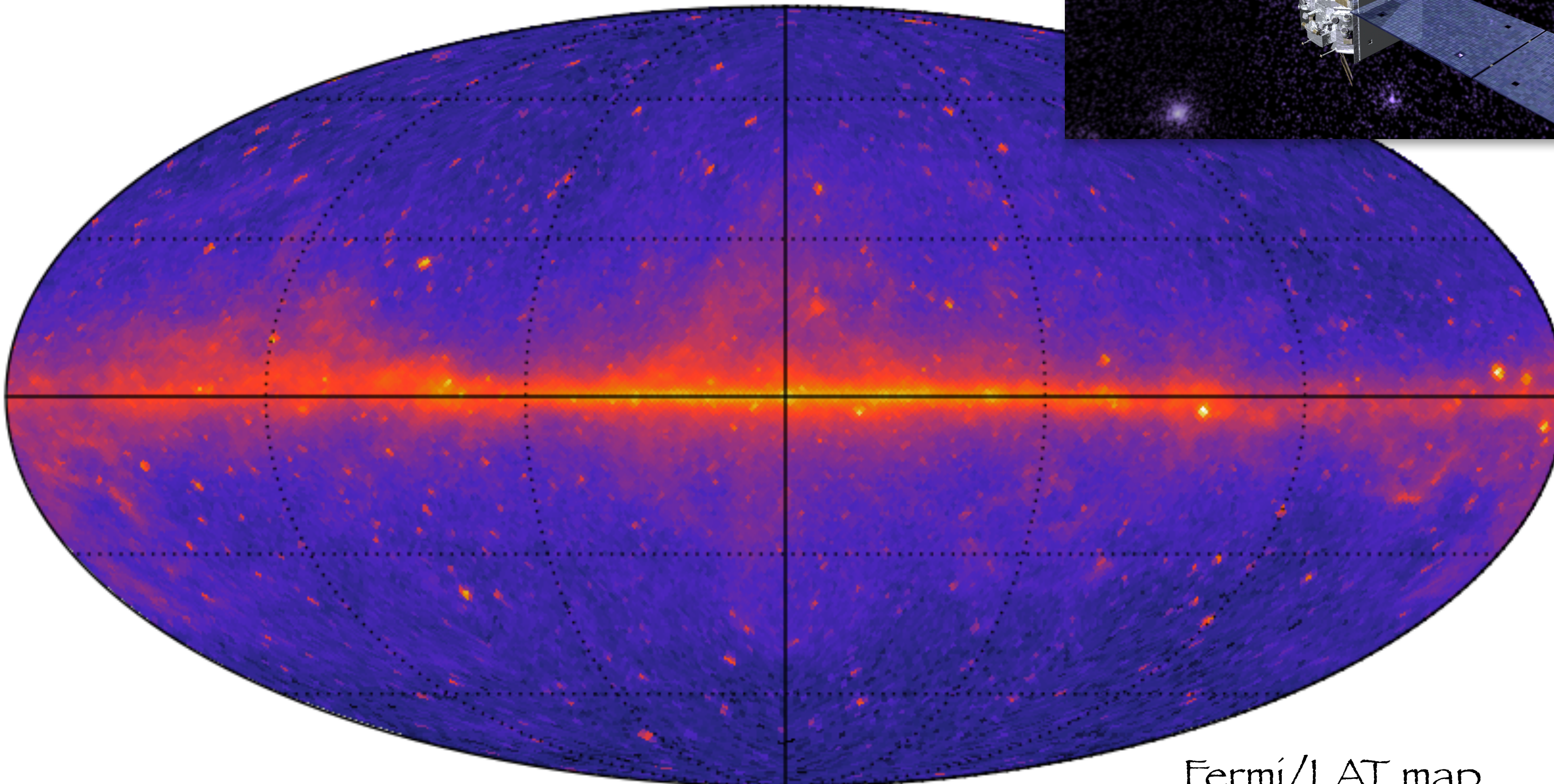
Feels (somehow) how DM is locally distributed in velocity space

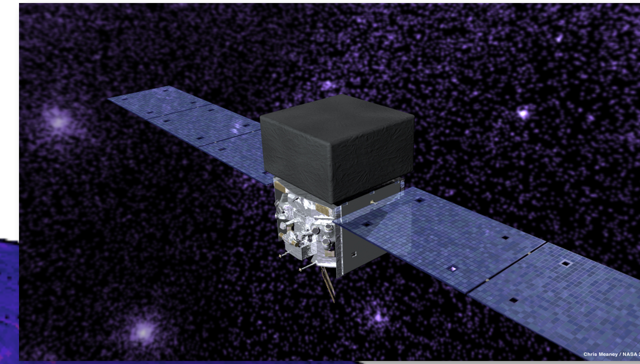
NEUTRINOS FROM EARTH AND SUN

Charged cosmic rays signals

Be patient for a few more minutes:
Bruna Bertucci's talk is coming next!

Gamma ray sky





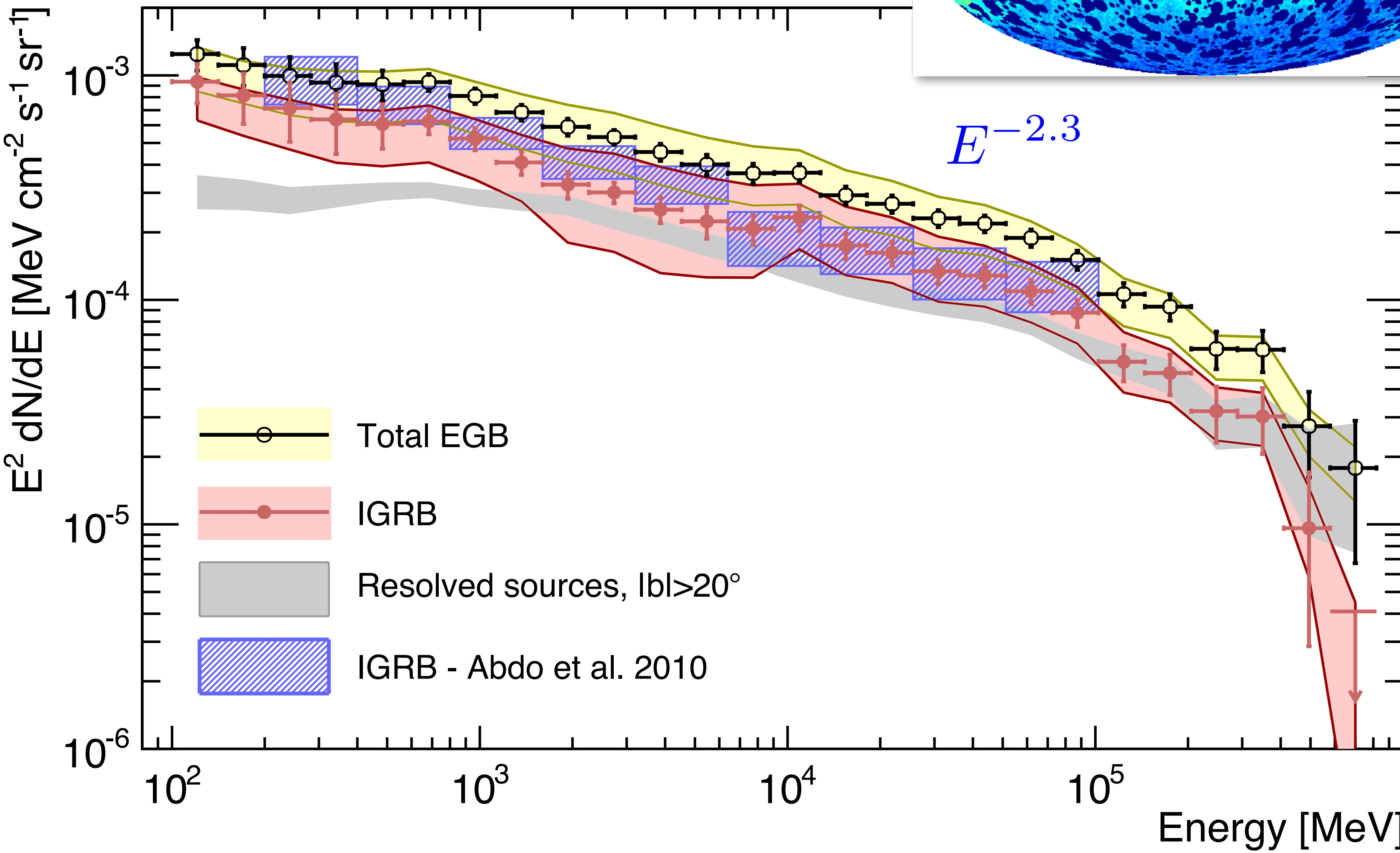
Fermi/LAT map

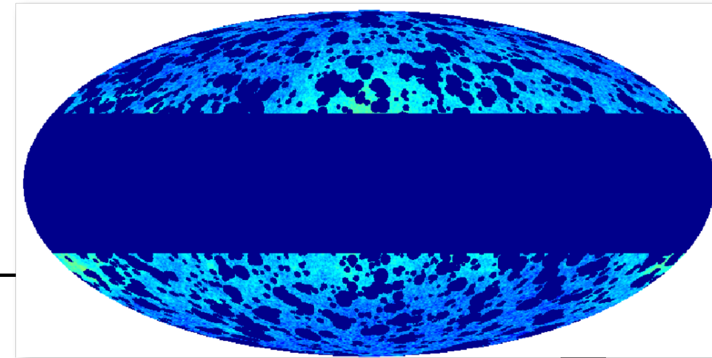
Galactic foreground emission

Resolved sources

Diffuse Gamma Rays Backgound (DGRB)

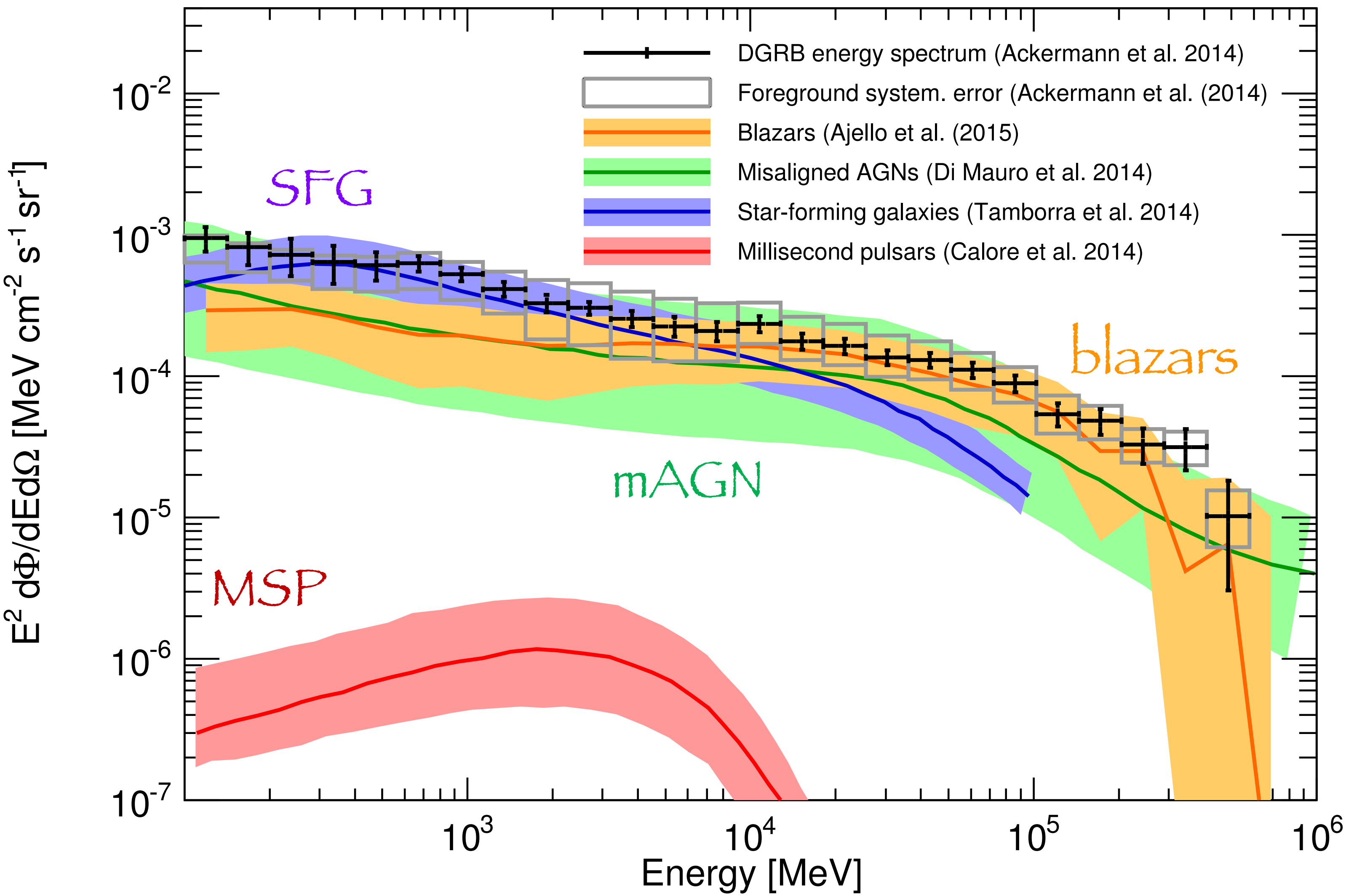
DGRB Intensity





Ackerman et al. (Fermi Collab.) Ap. J. 799 (2015) 86

DGRB Intensity

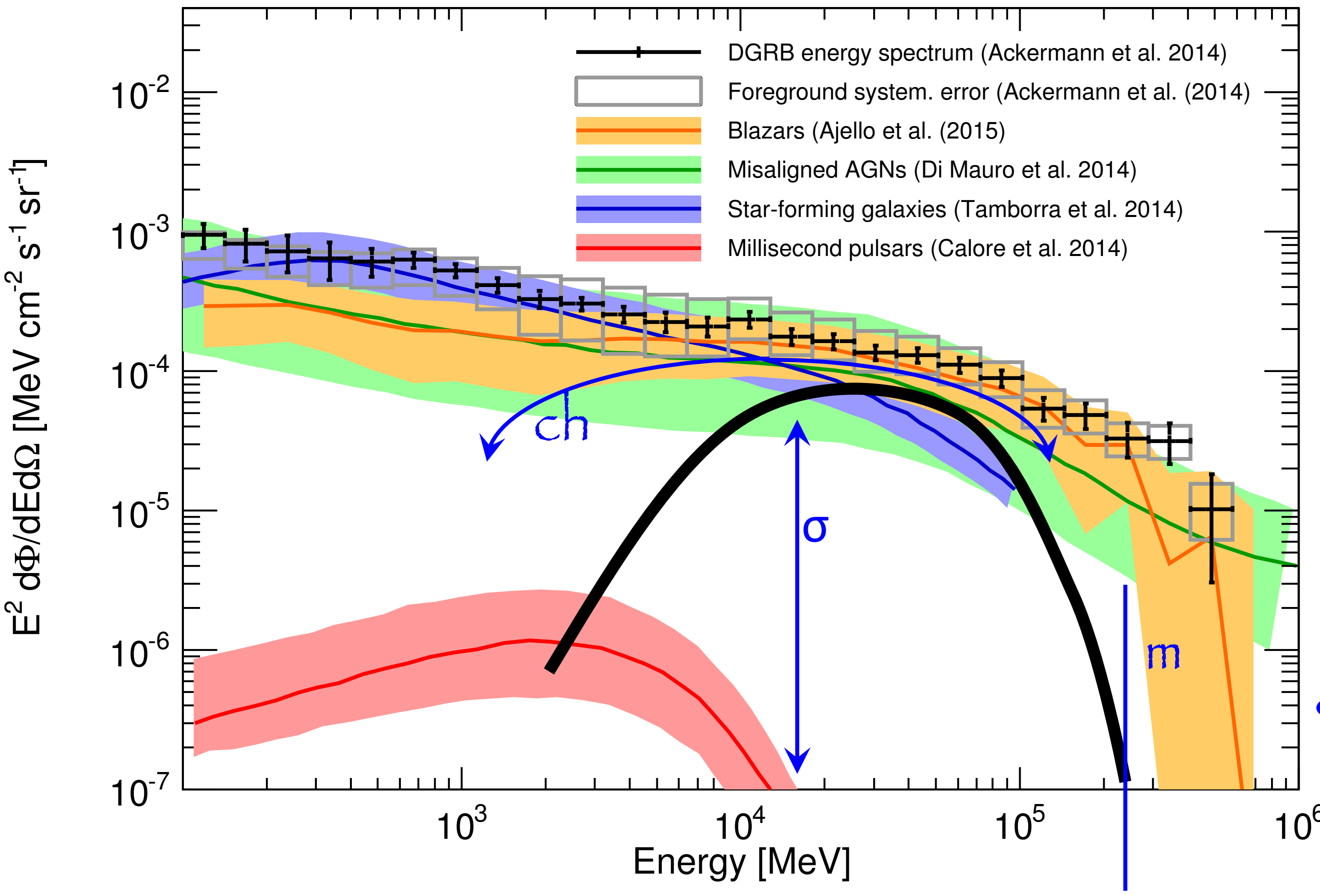


Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

DGRB and Dark Matter

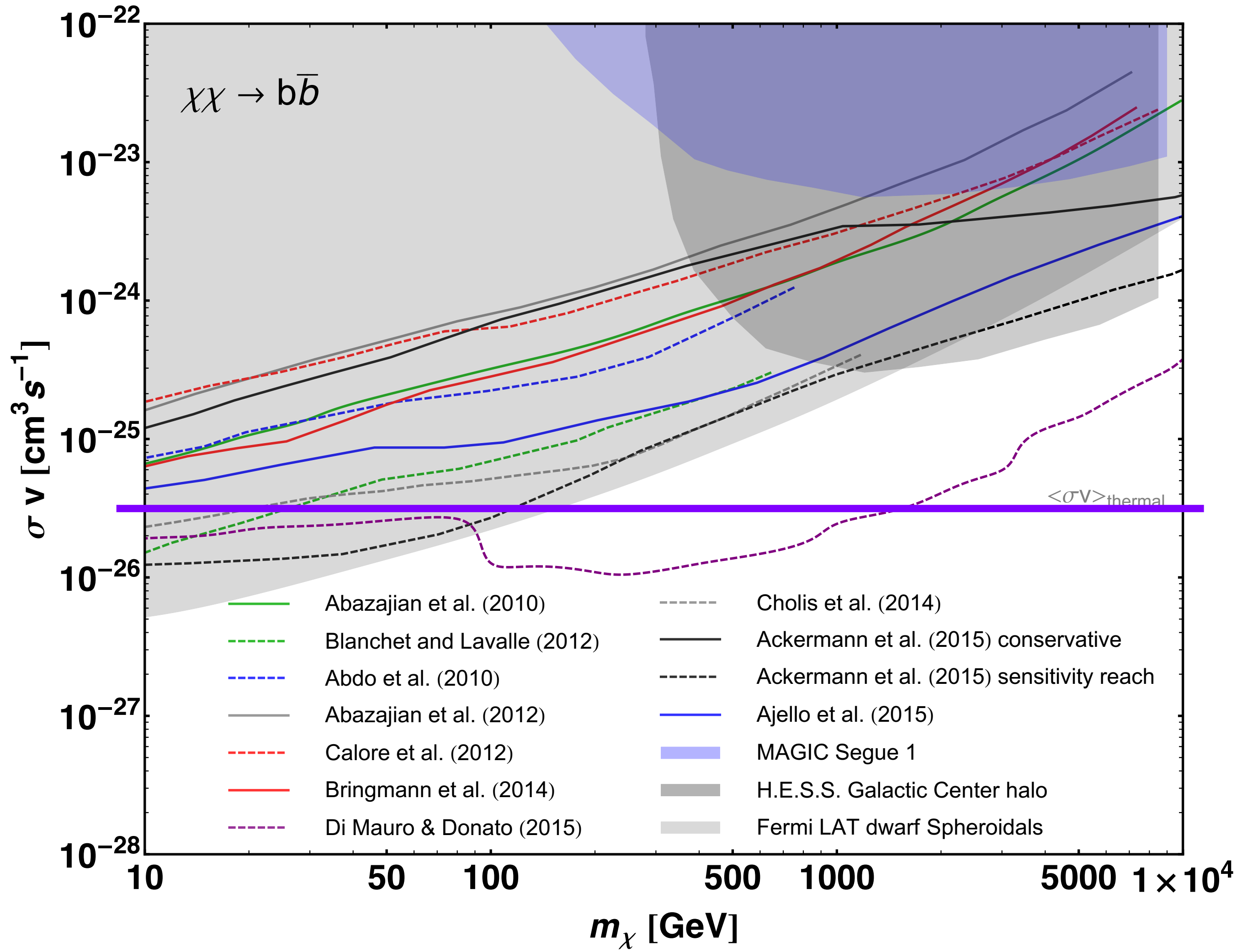
The Good: Spectral behaviour different from astro sources:
(σ,m, channel)

The Bad: Can be quite subdominant in intensity



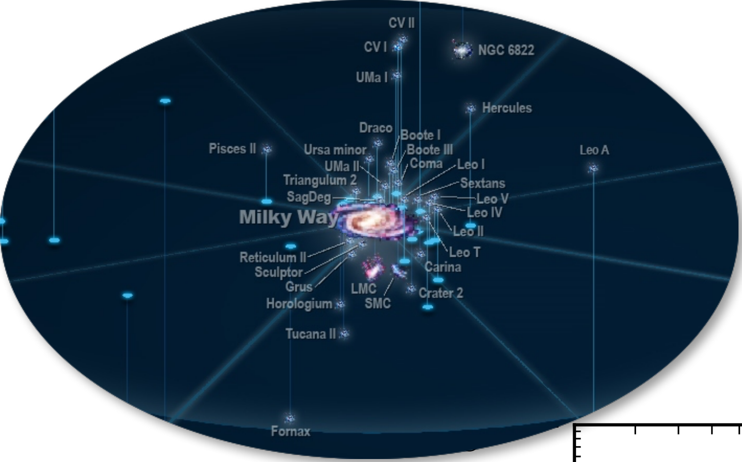
$$\Phi(E) \sim \langle \sigma v \rangle \left(\frac{\rho_{\rm DM}}{m_{\rm DM}} \right)^2 F(E)$$

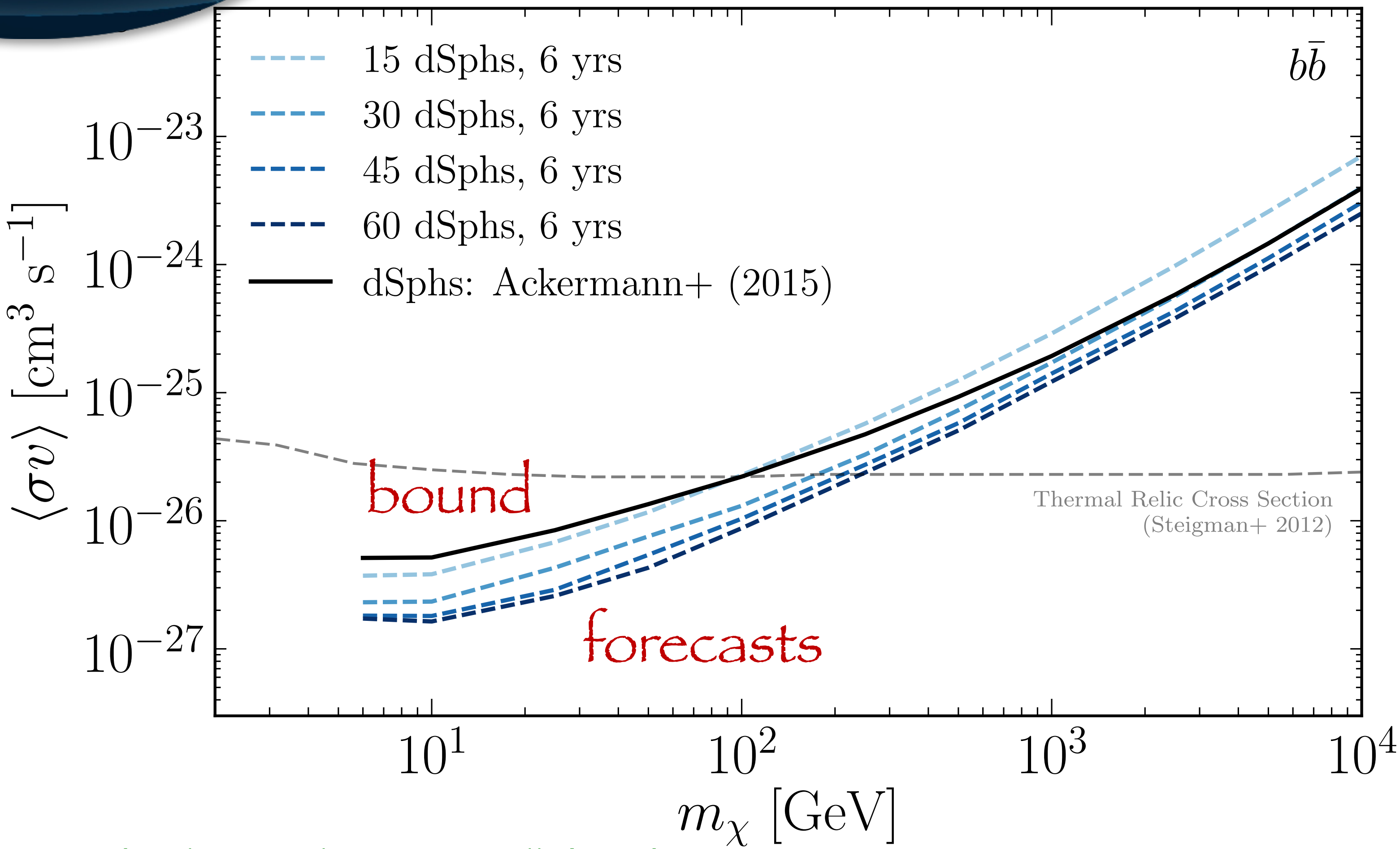
DGRB intensity bounds on DM



Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

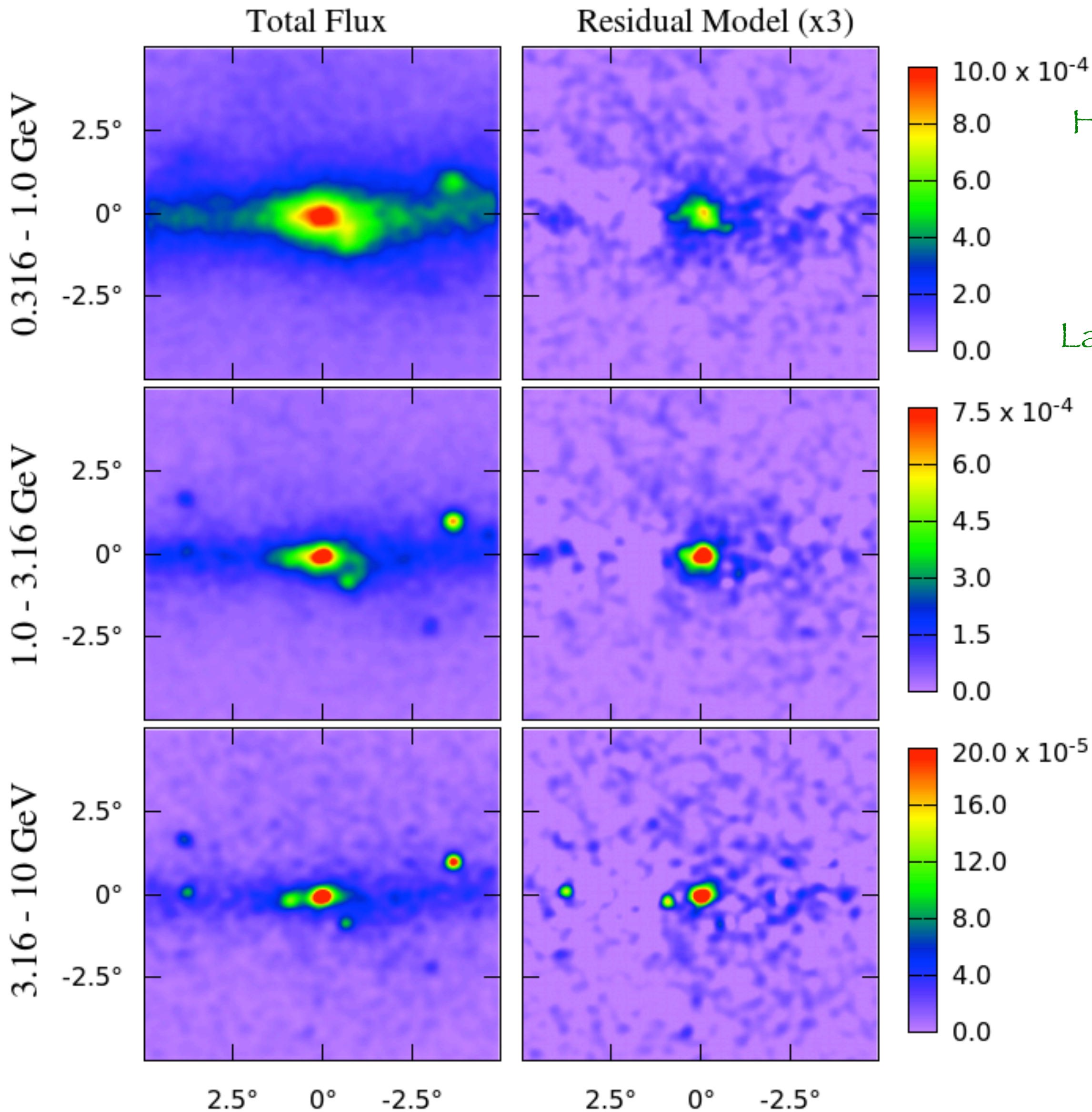
Dwarf galaxies





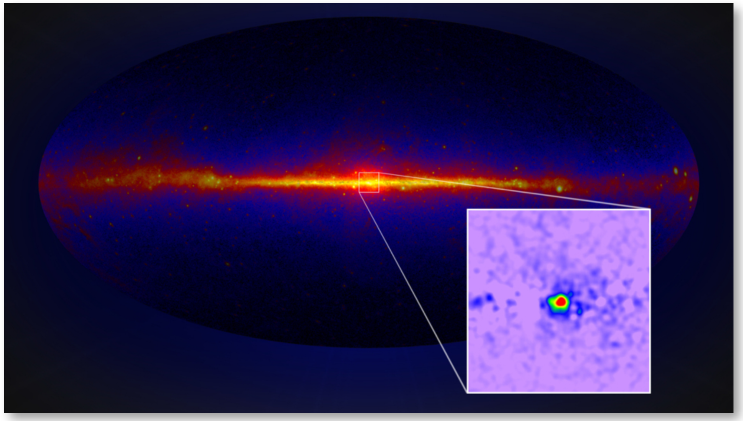
Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Galactic center: an "excess" ?

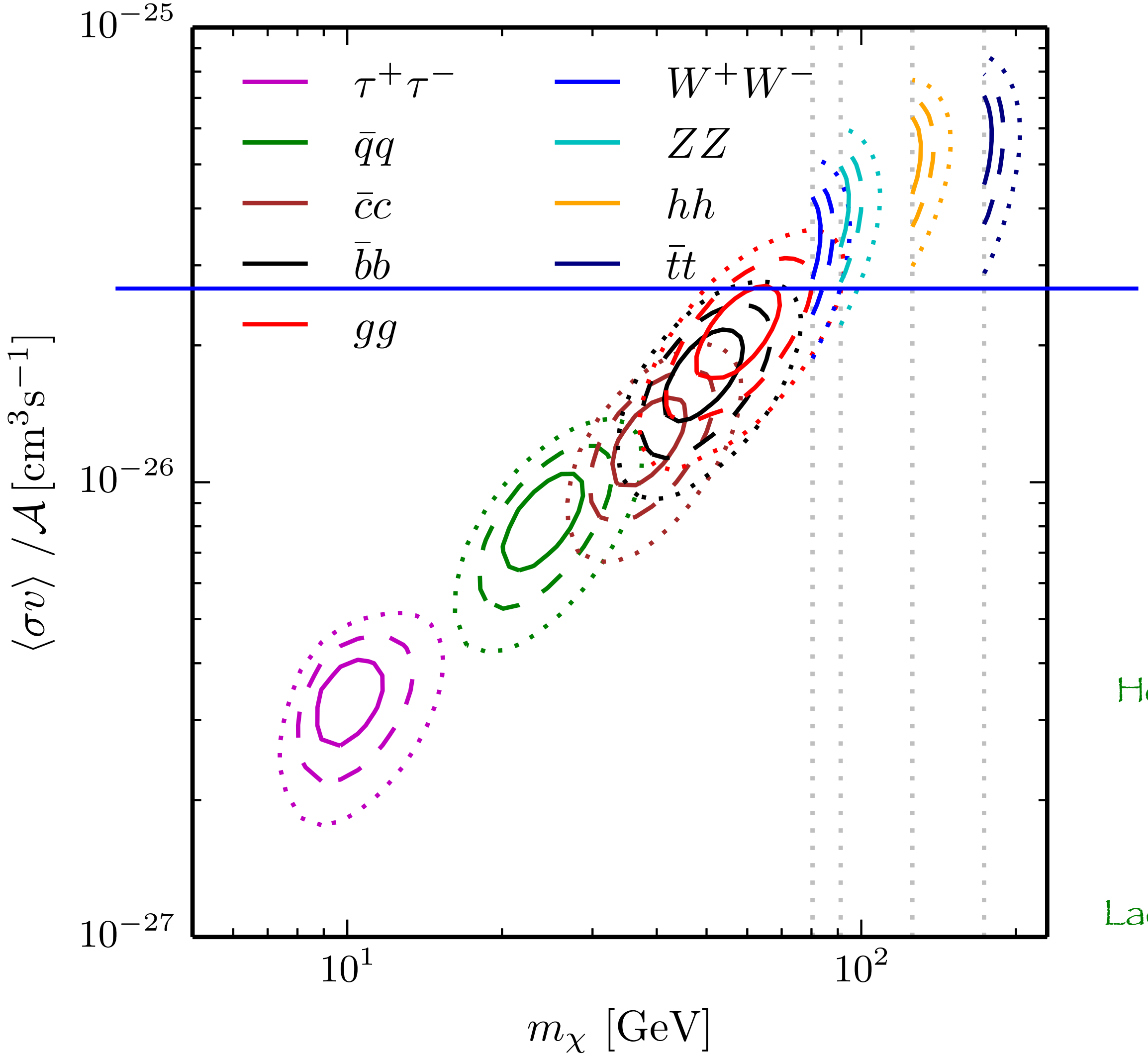


Daylan et al, Phys Dark Univ 12 (2016) 1

Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508
Calore et al, PRD 91 (2015) 063003



DM interpretation



Calore et al, PRD 91 (2015) 063003

Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508

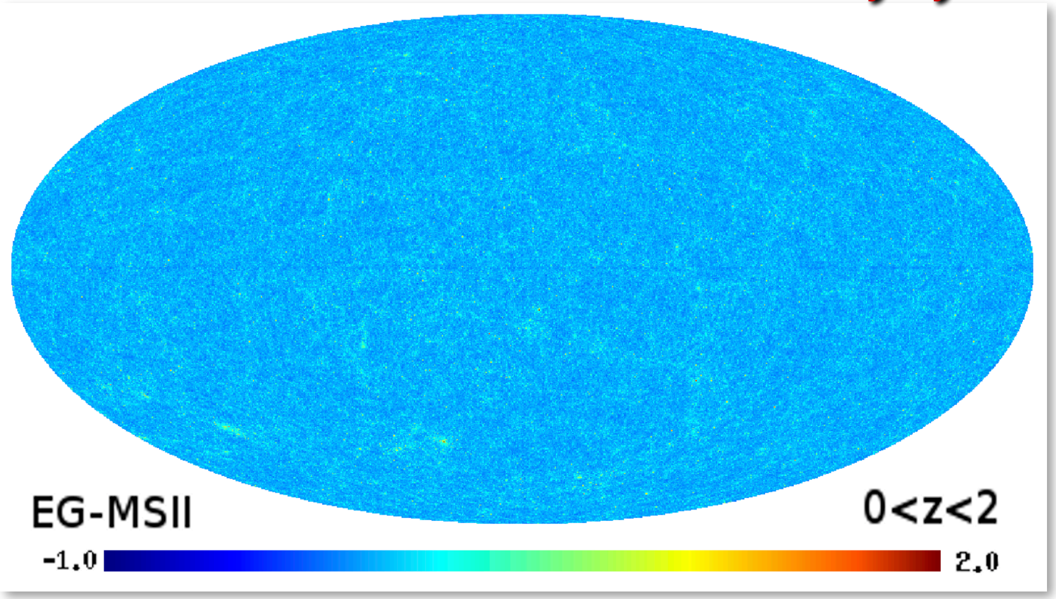
Alternative approaches?

- Indirect detection signals are intrinsically anisotropic
  (being produced by DM structures, present at any scale)

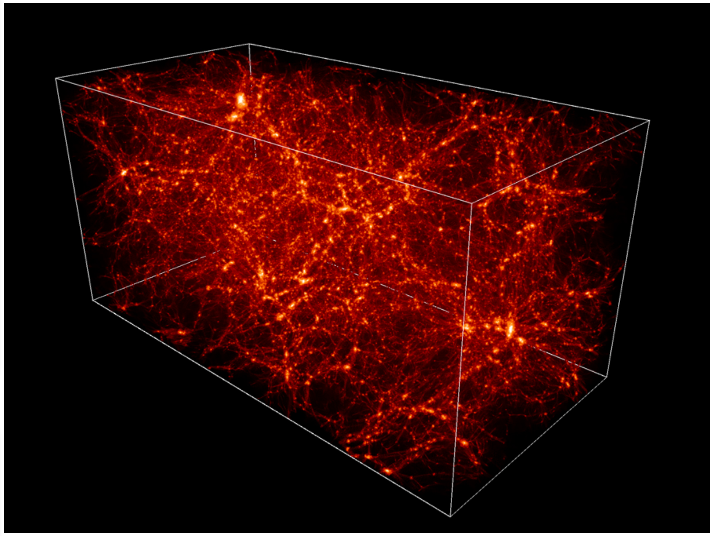
- EM signals (and neutrinos) more directly trace the underlying DM distribution: they need to exhibit some level of anisotropy
  - "Bright" DM objects: would appear as *resolved* sources
    - e.g: gamma or radio halo around clusters, dwarf galaxies or even subhalos
  - Faint DM objects: would be *unresolved* (i.e. below detector sensitivity)
    - Diffuse flux: at first level isotropic
      at a deeper level anisotropic

Alternative approaches?

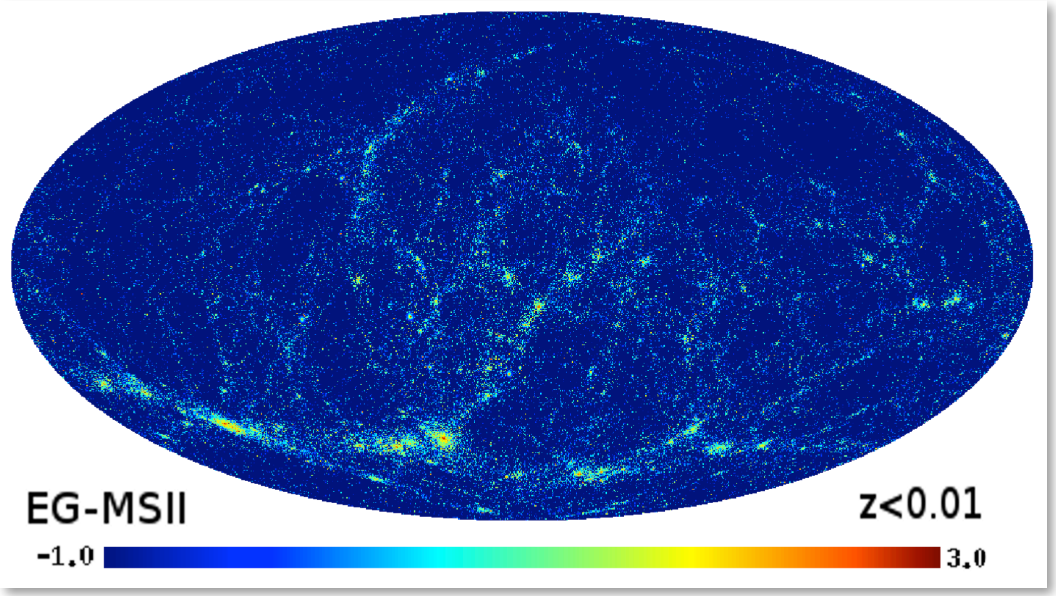
(simulated maps)



Extra galactic emission
Higher redshift



Emission is intrisically anisotropic



Extra galactic emission
Lower redshift

Anisotropic emission

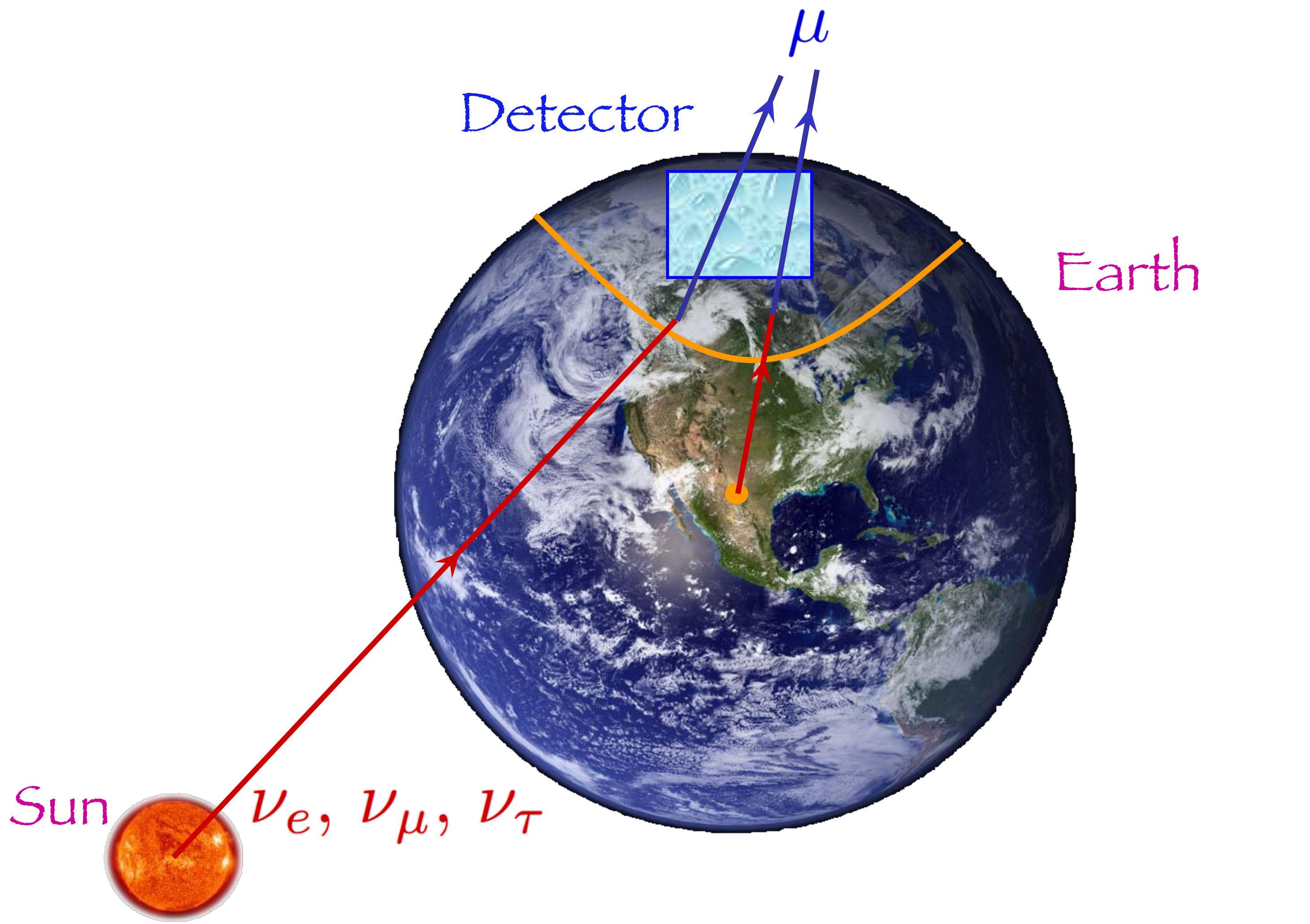
Even though sources are too dim to be individually resolved, they can affect the

statistics of photons

across the sky

Currently under study

Neutrinos from Earth and Sun



and neutrinos from the Galaxy

Neutrinos from Earth and Sun

- Capture:
  - Galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally captured

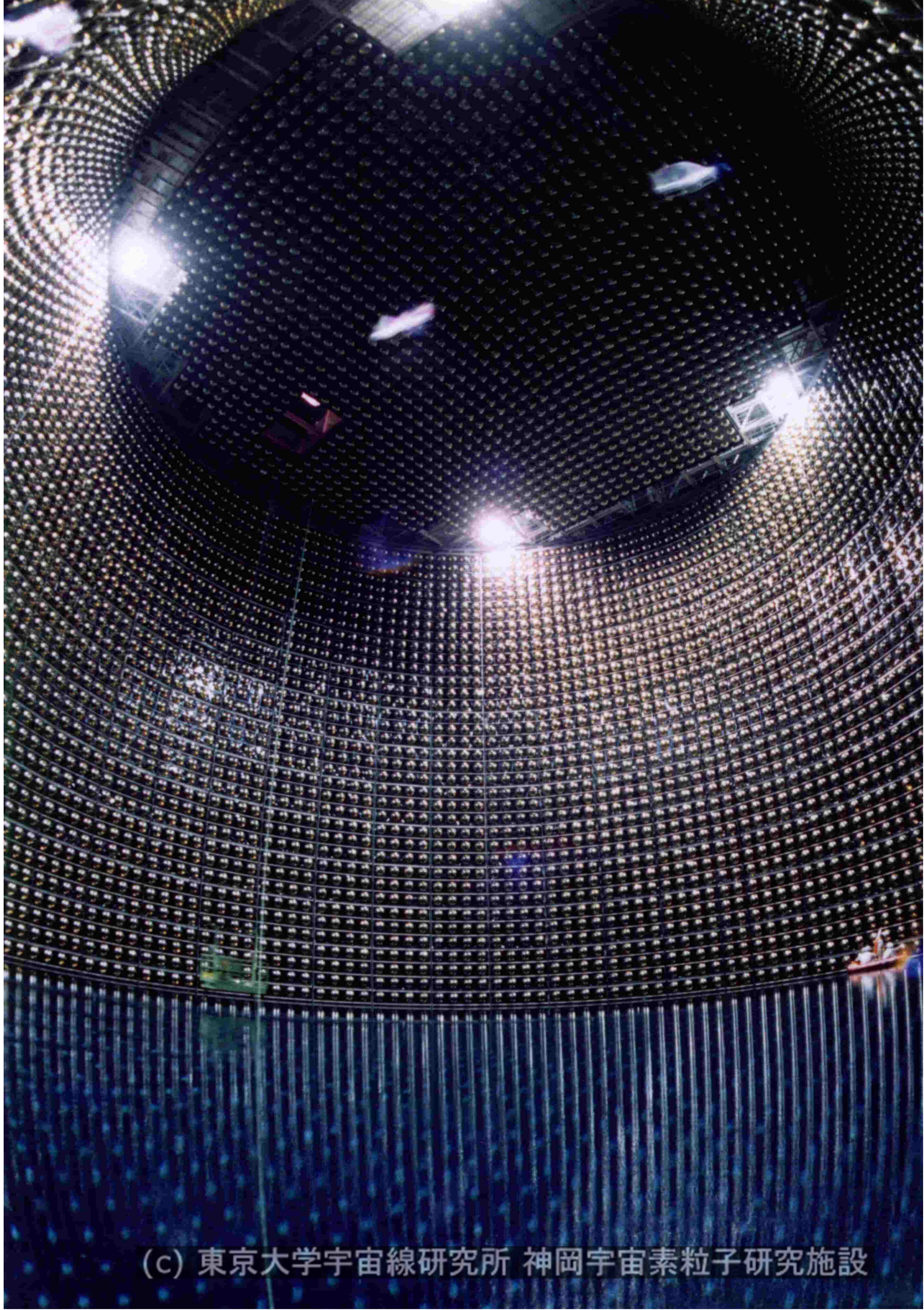
$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\sigma_i \frac{\rho_\chi}{m_\chi} \bar{v}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2} \langle\phi\rangle_i\right] \xi(\infty) S_i$$

- Accumulation:
  - After subsequent interactions they tend to drop into the innermost parts of the Earth and the Sun, where they accumulate

- Annihilation:
  - When the energy density in the inner parts of the Earth and the Sun increases enough, they may start to annihilate

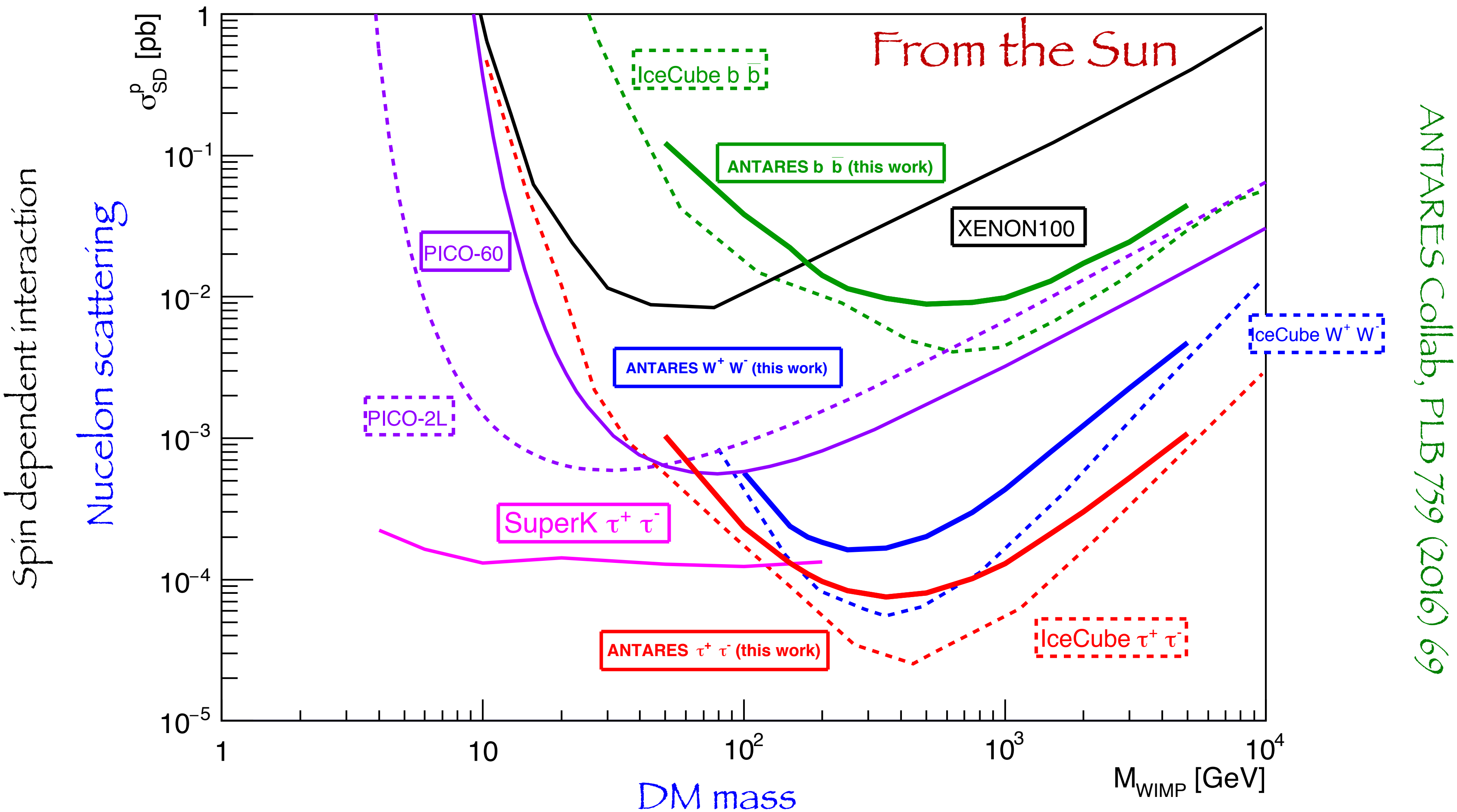
$$\Gamma_A = \frac{C}{2} \tanh^2\left(\frac{t_0}{\tau_A}\right) \longrightarrow \frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_{\mathcal{F}} \mathrm{BR}(\chi\chi \to \mathcal{F}) \frac{dN_\nu^{\mathcal{F}}}{dE_\nu}$$

Super Kamiokande



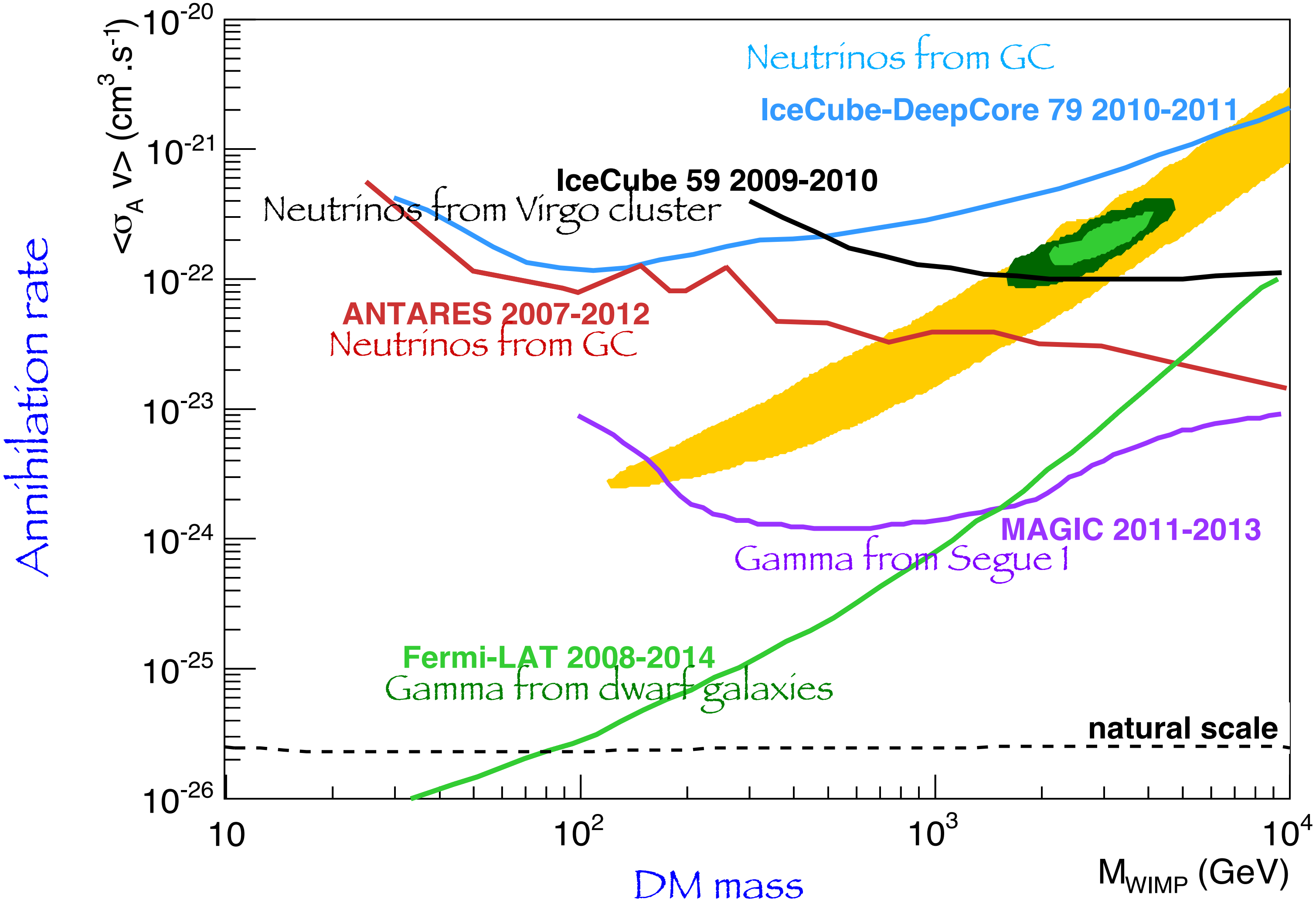
ANTARES

Bounds on capture cross section



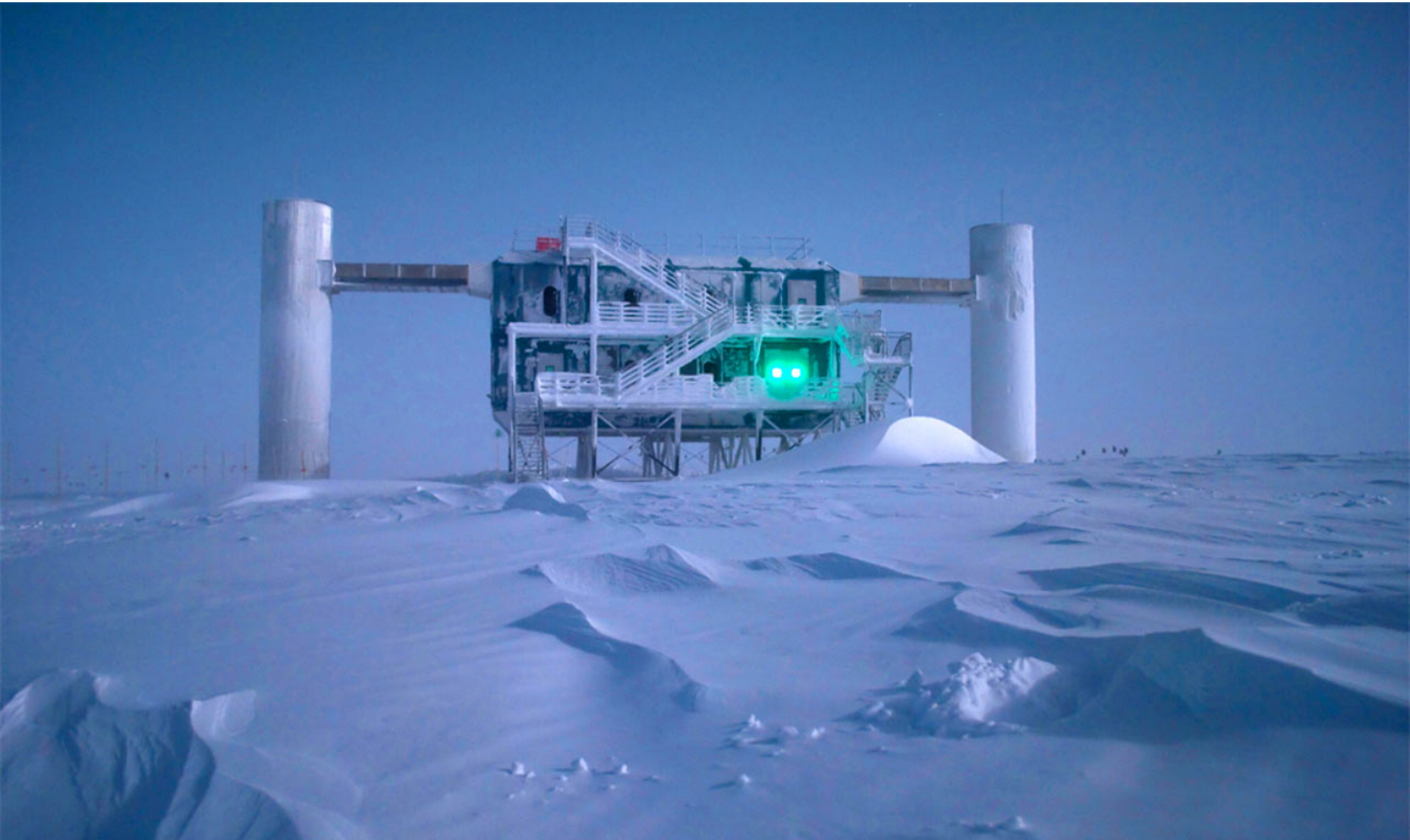
Warning: bounds are typically derived under the assumption of perfect equilibration between capture and annihilation (and contact interactions)

Bounds on annihilation cross section

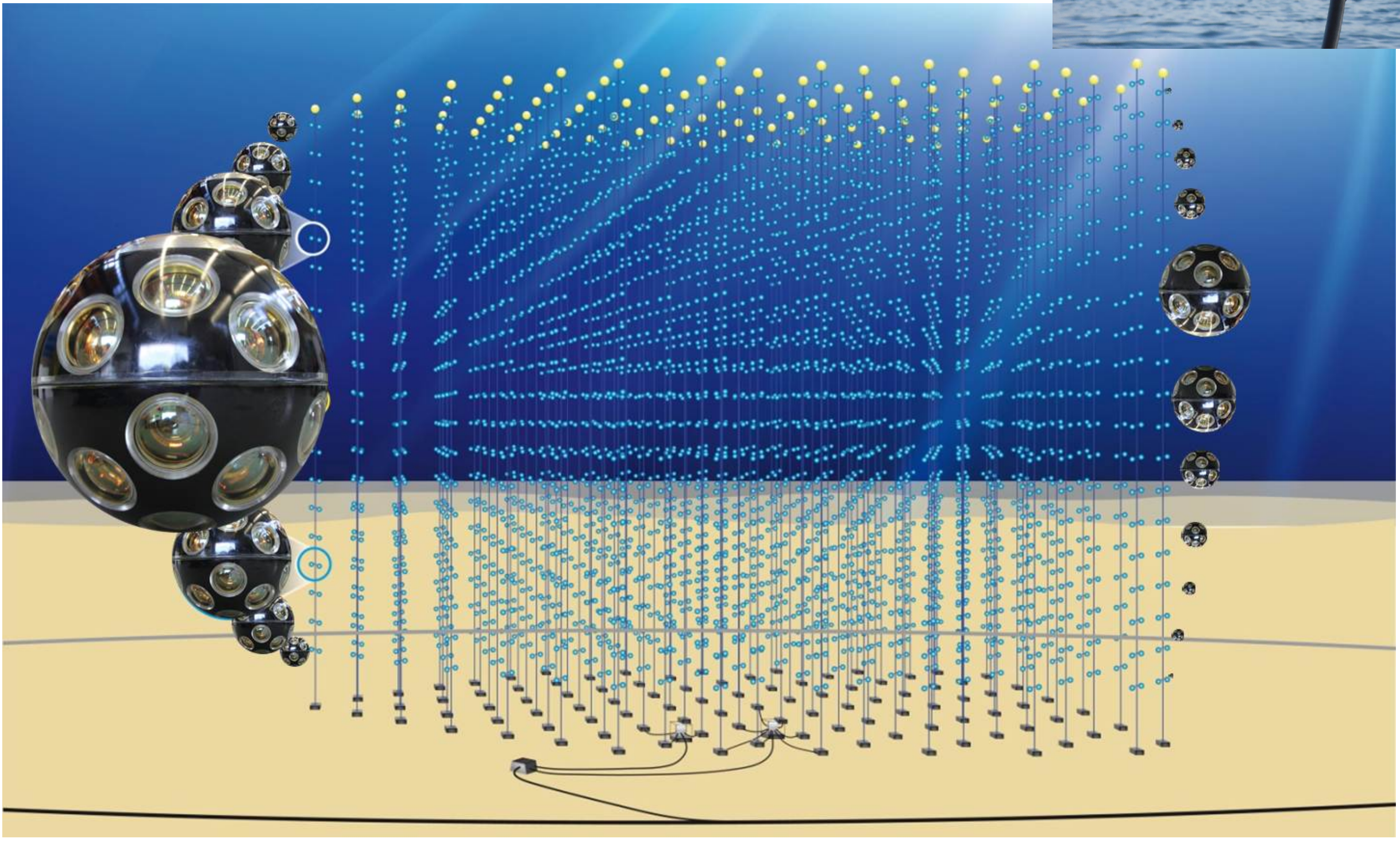


ANTARES Collab, JCAP 1510 (2015) 068

IceCube

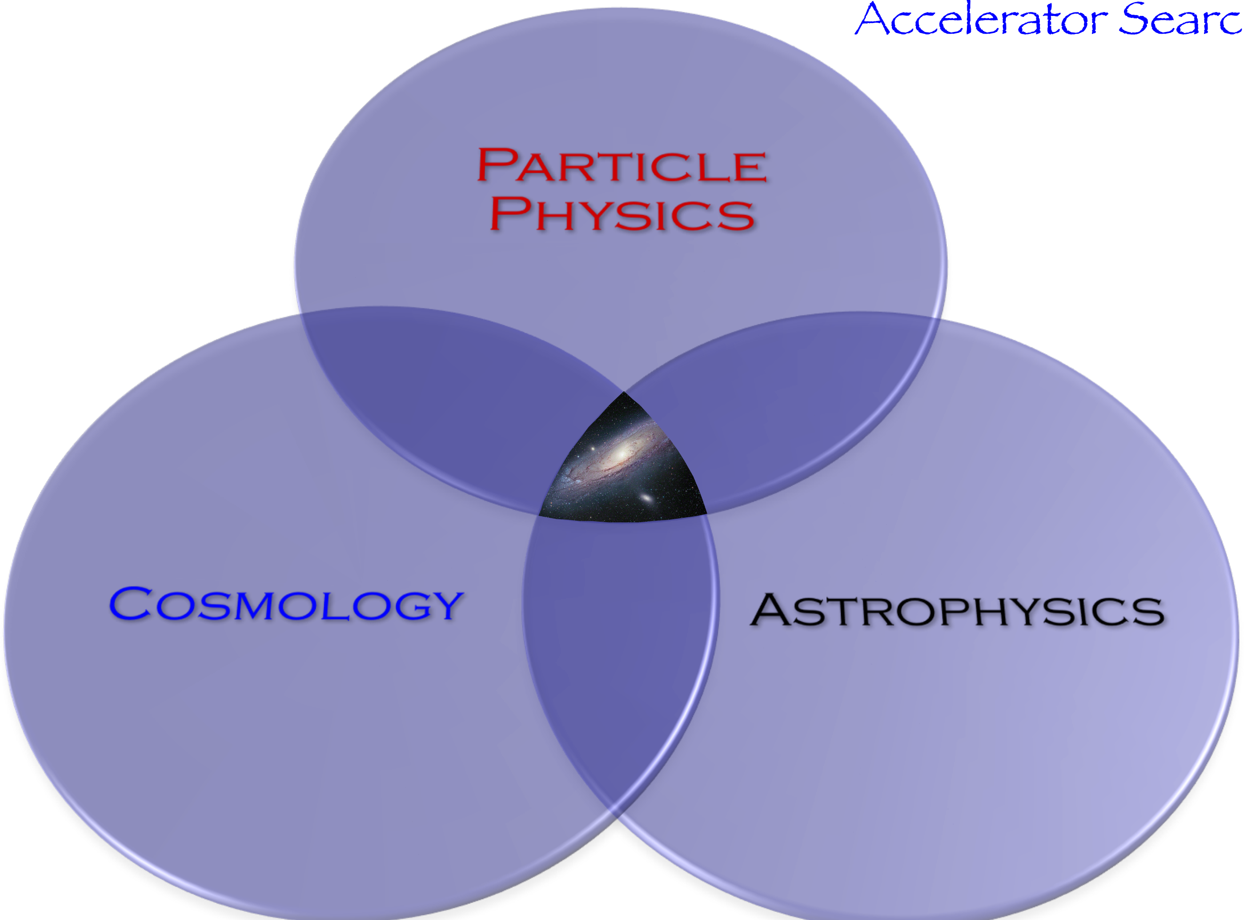


Km3NET



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