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

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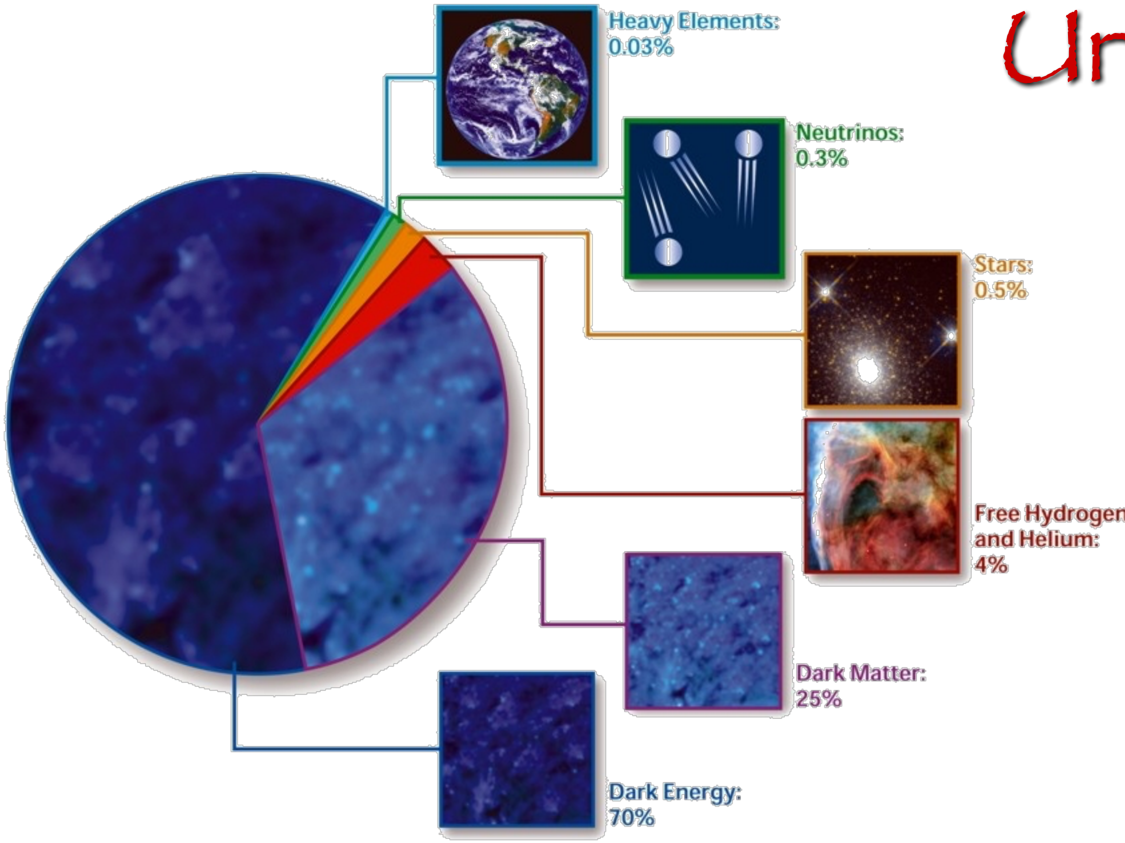
What's the problem?

How can we solve it?

Why can 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"

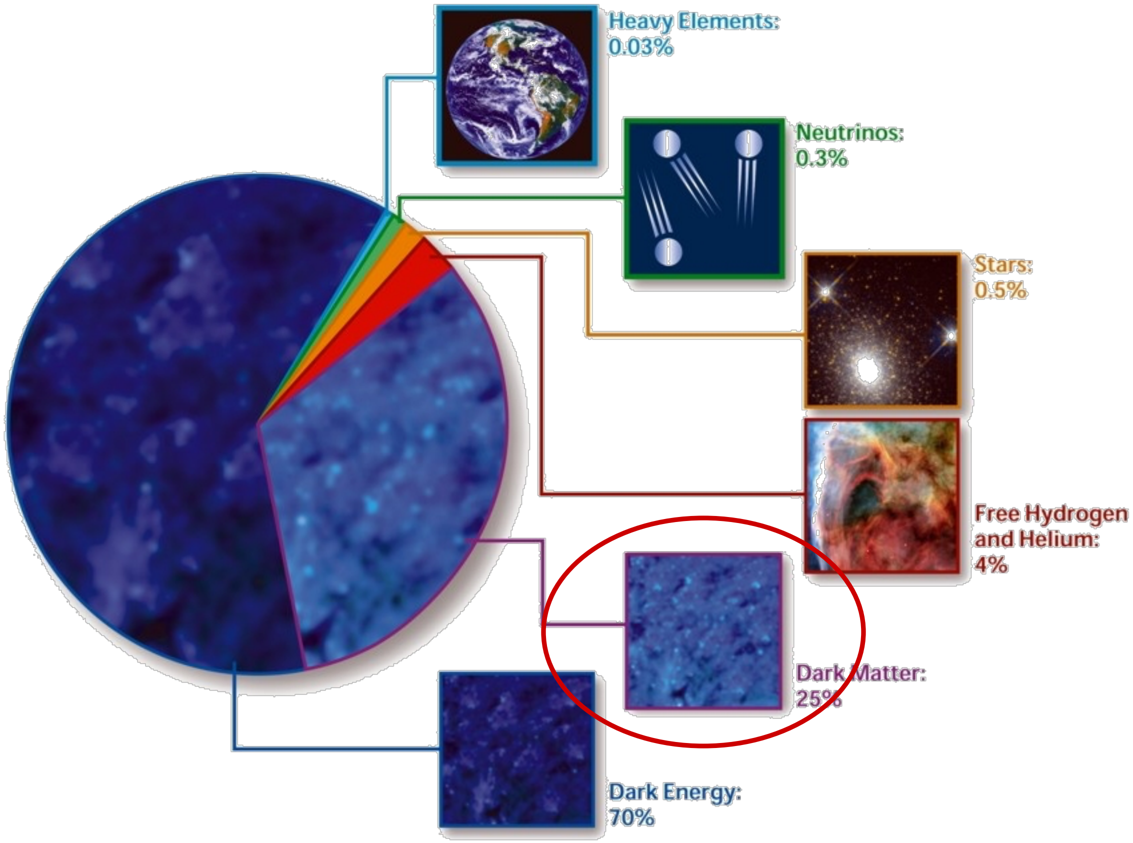


70% Dark Energy

26% Dark Matter

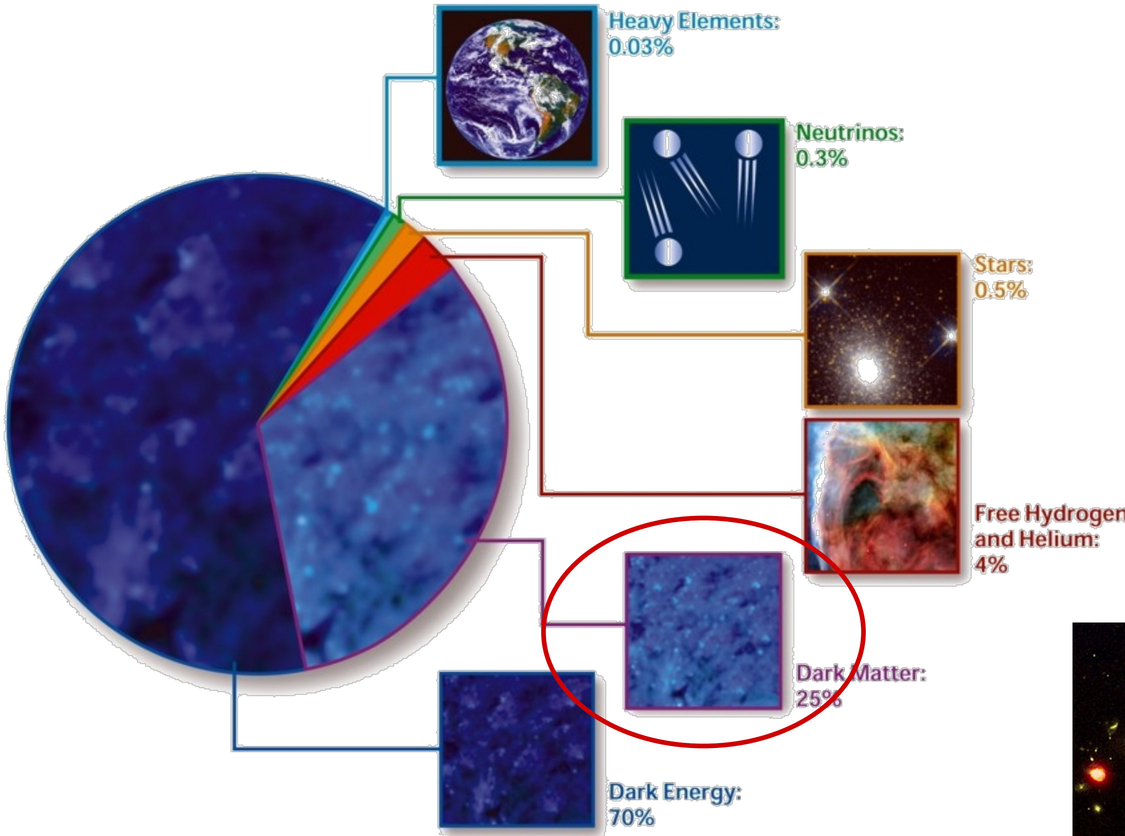
4% Nuclear Matter

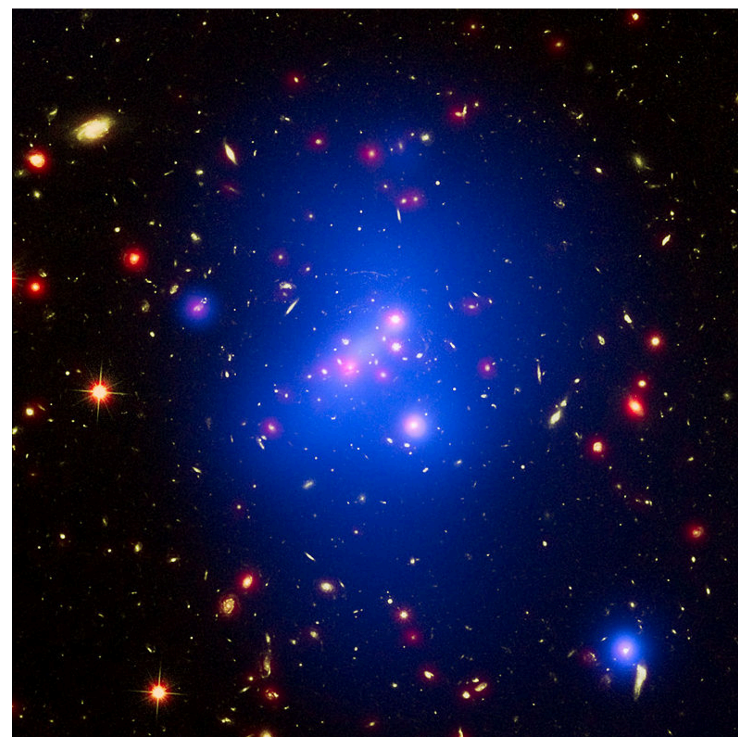
Dark Matter



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

Dark Matter





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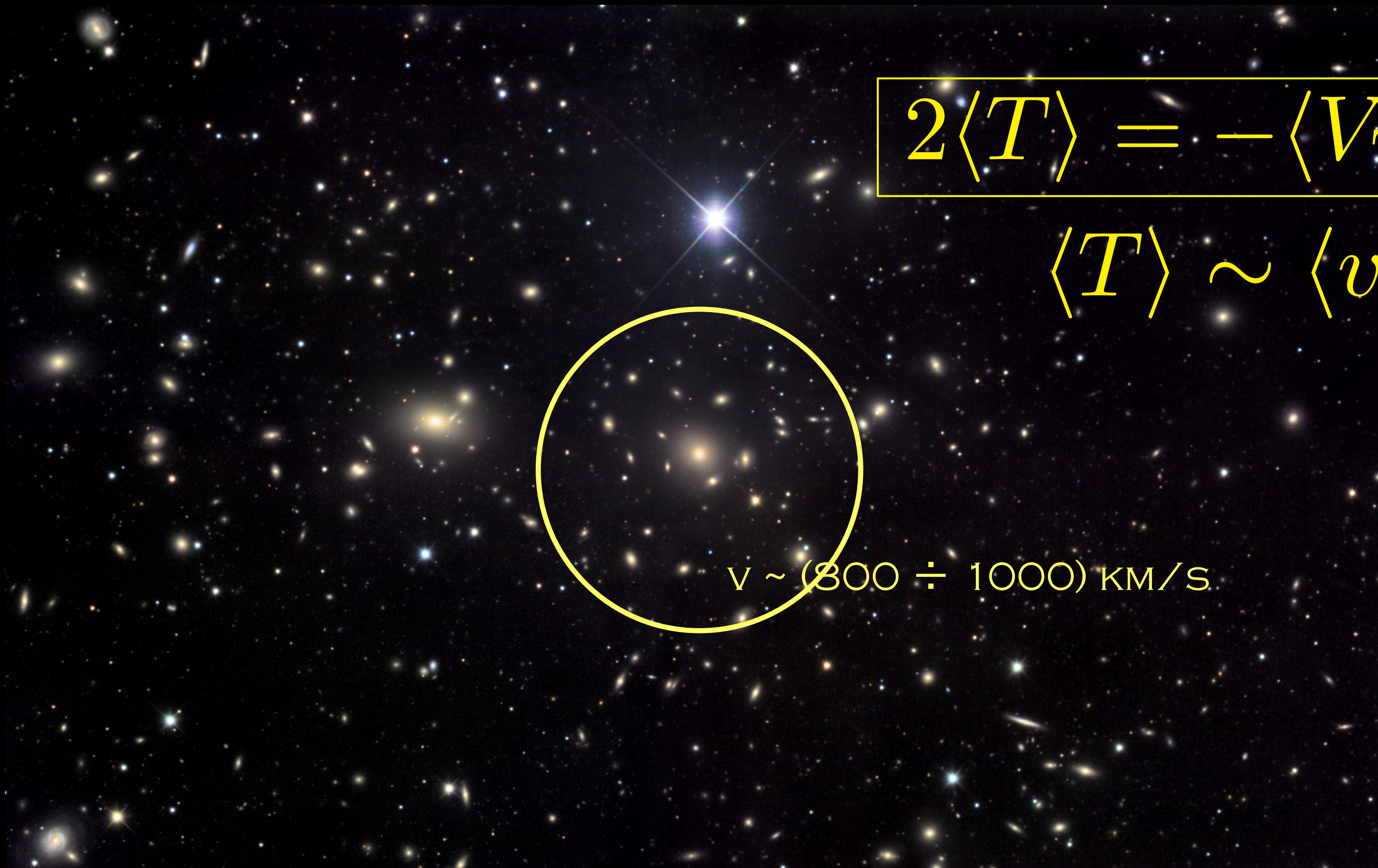
Galaxy cluster

Zwicky (1933)



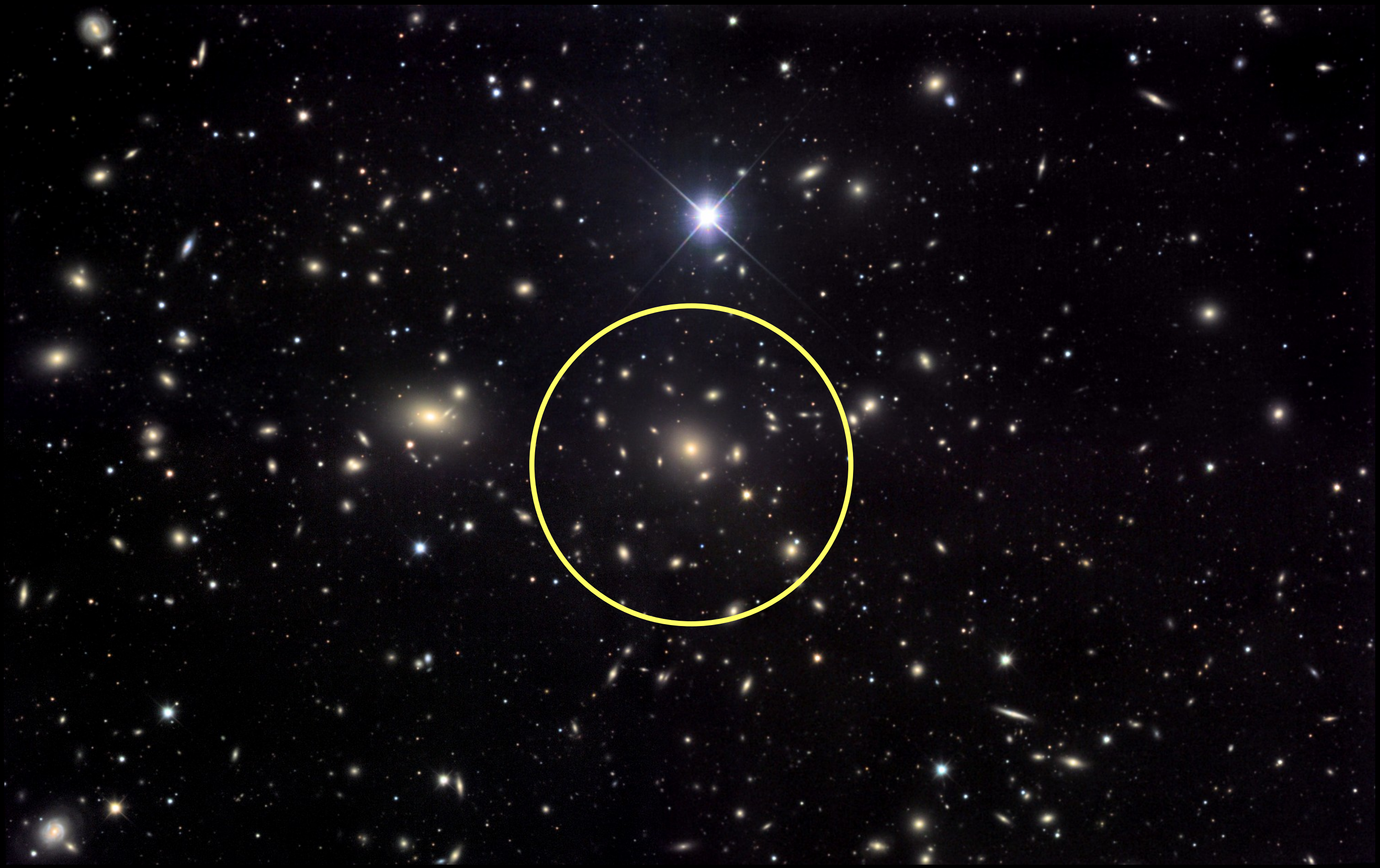
$$\boxed{2\langle T\rangle = -\langle V_{\mathrm{TOT}}\rangle}$$

$$\langle T\rangle \sim \langle v^2\rangle$$

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

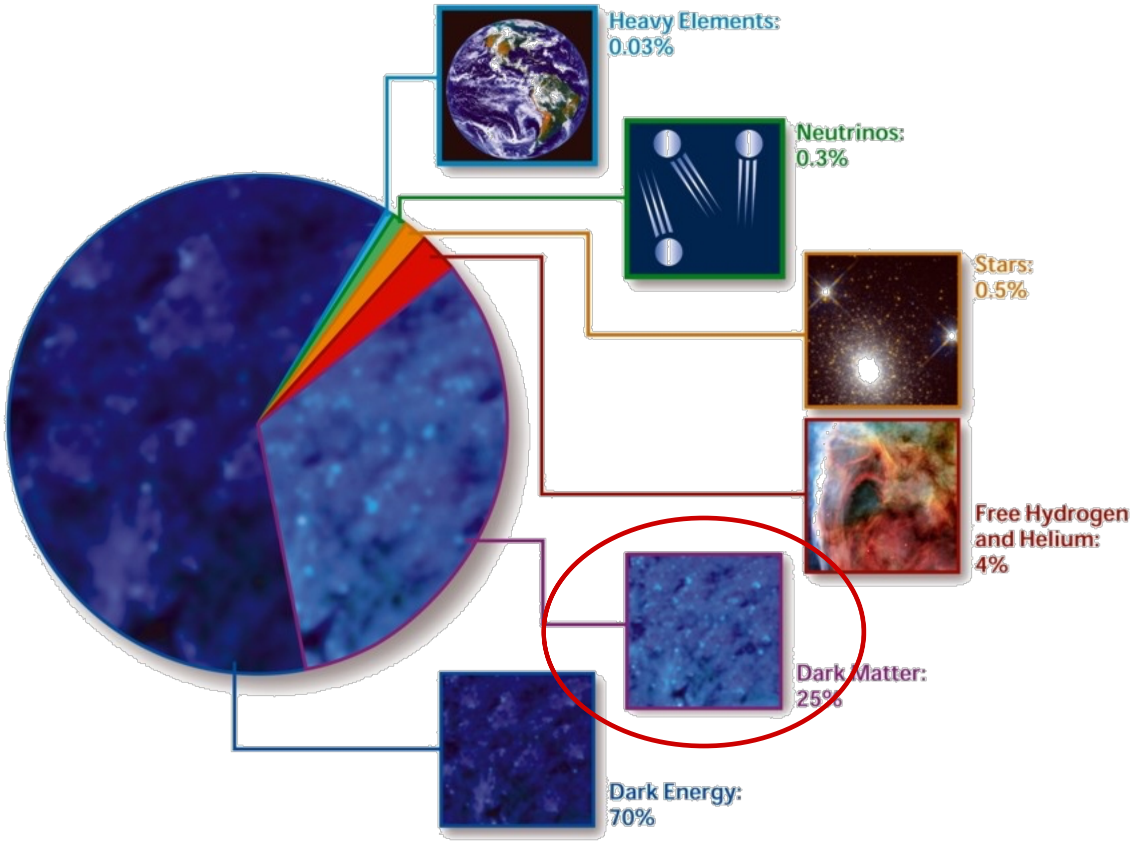
Much more mass than the visible one is needed

Galaxy cluster



Galaxies	1%
Gas	9%
Dark Matter	90%

Dark Matter



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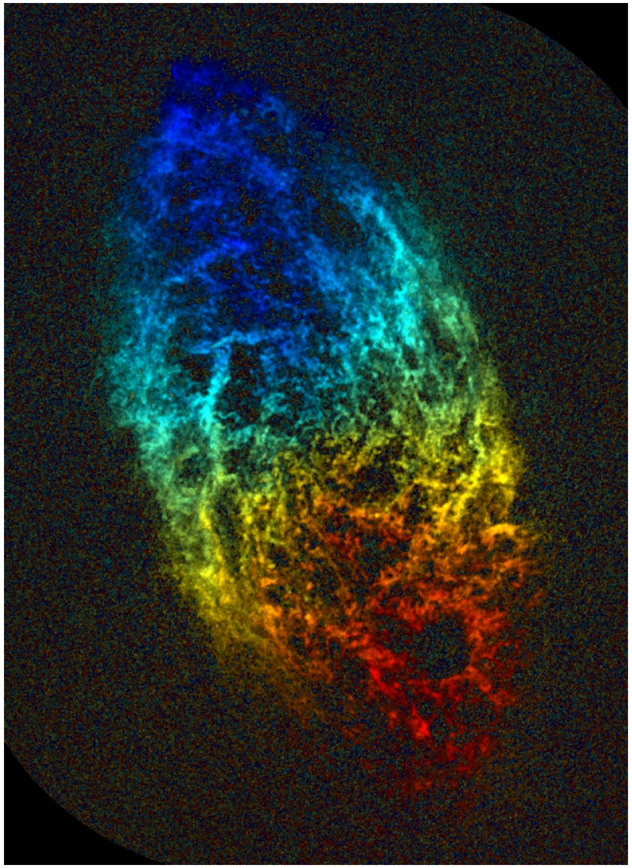
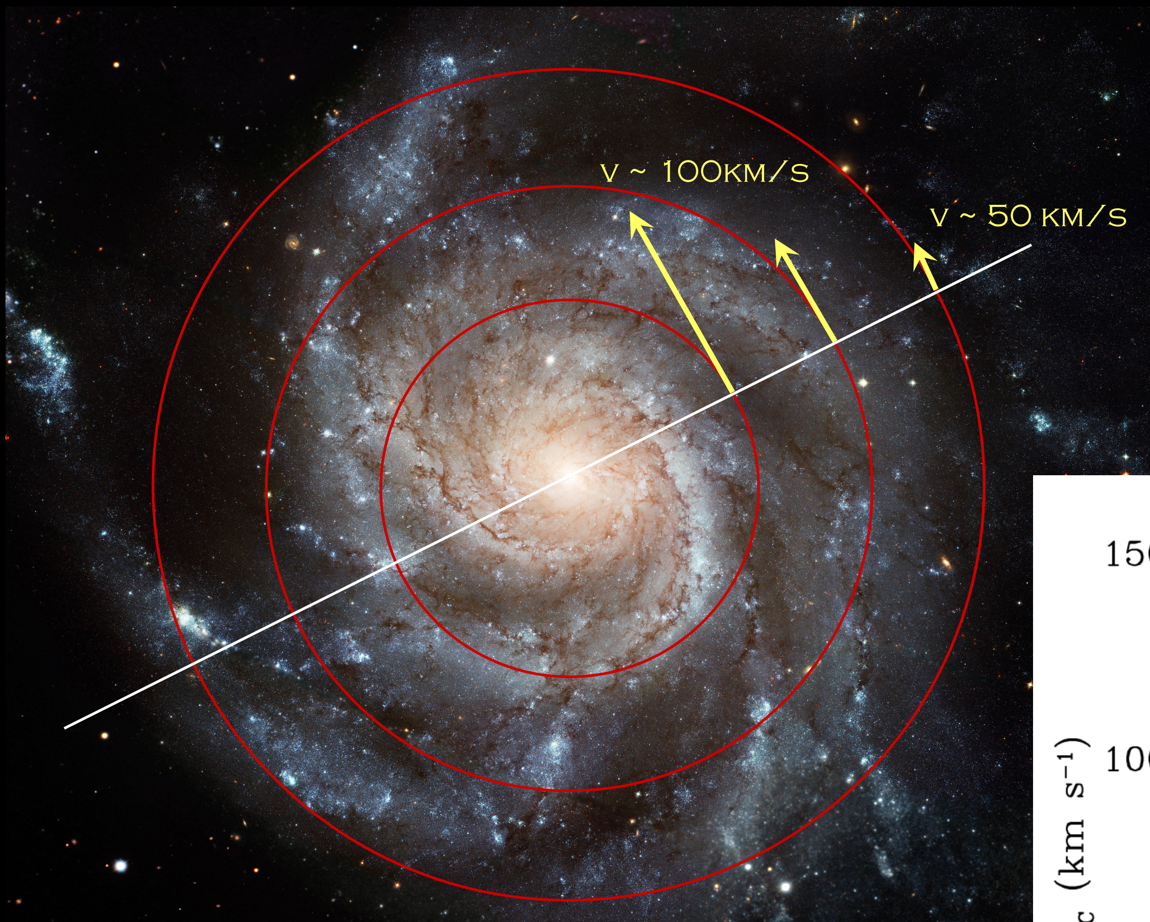
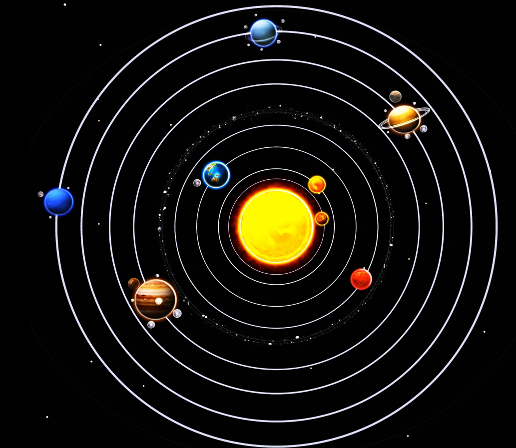
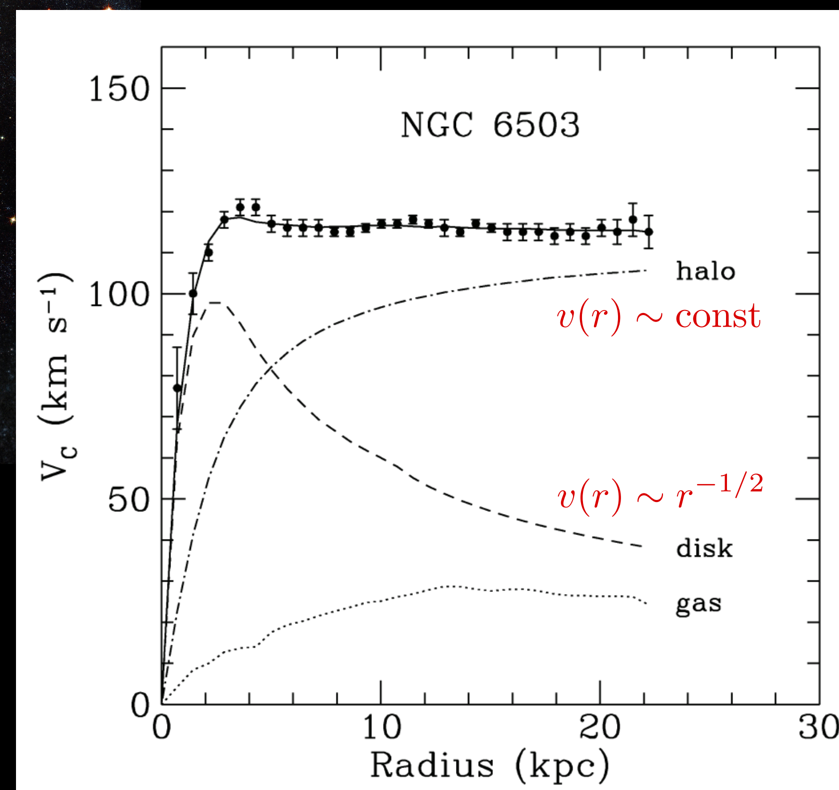


Spiral Galaxy

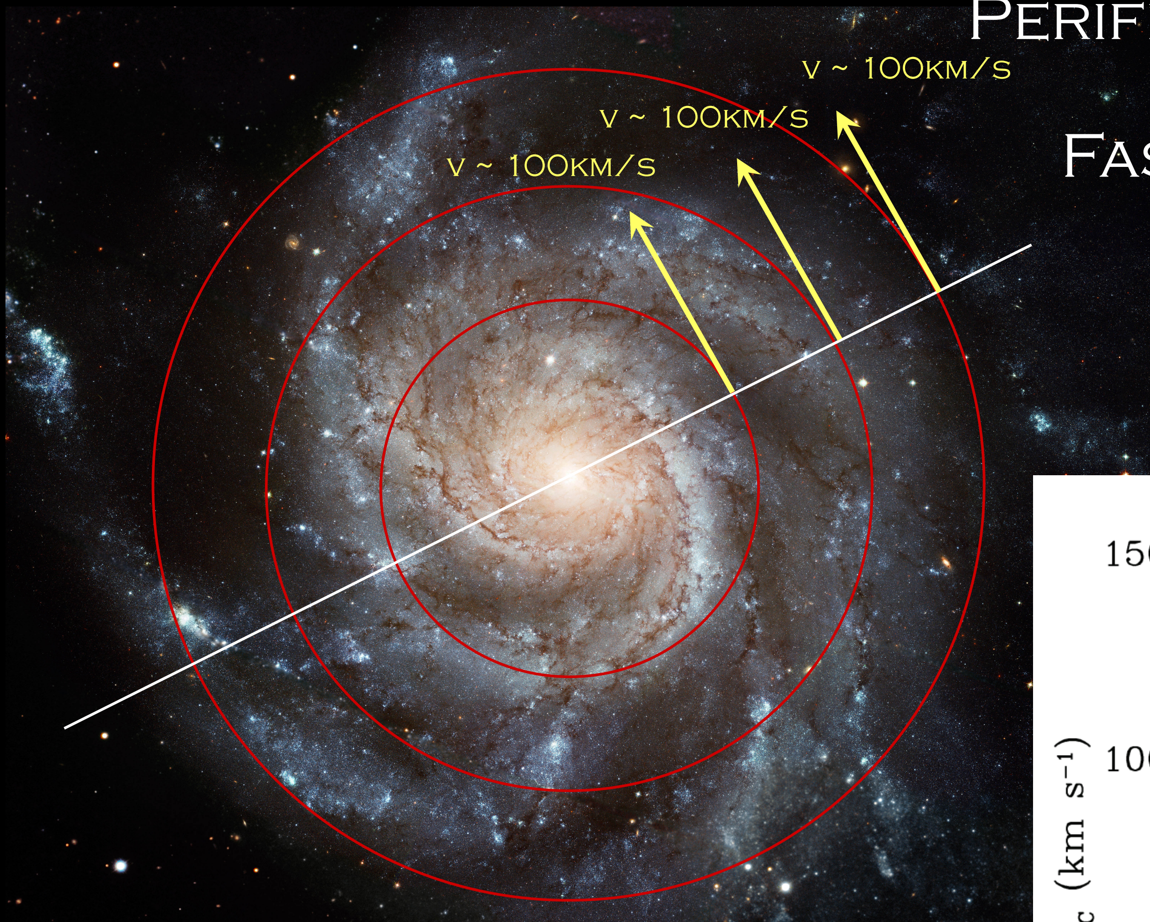




$$v(r) \propto r^{-1/2}$$



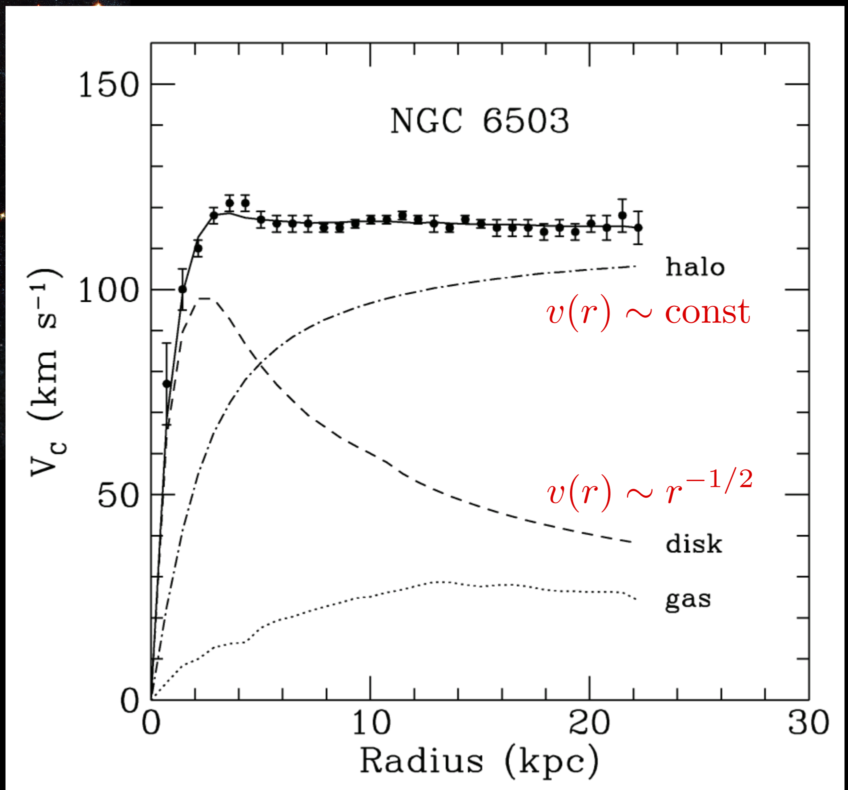
Spiral Galaxy



Periferic stars are faster than expected

Faster = More mass

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

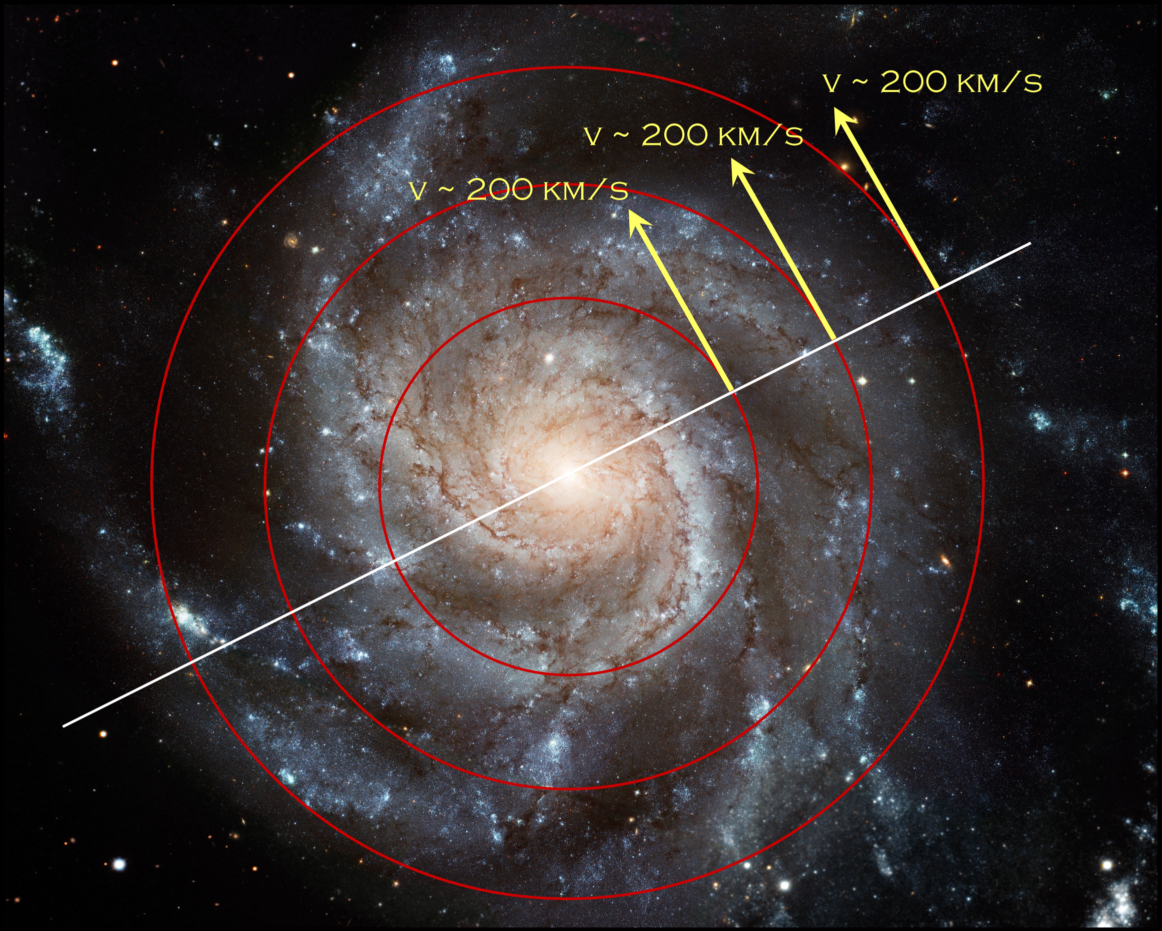


Much more mass than luminous mass

Dark Matter

Spiral Galaxy

Rubin (1970)

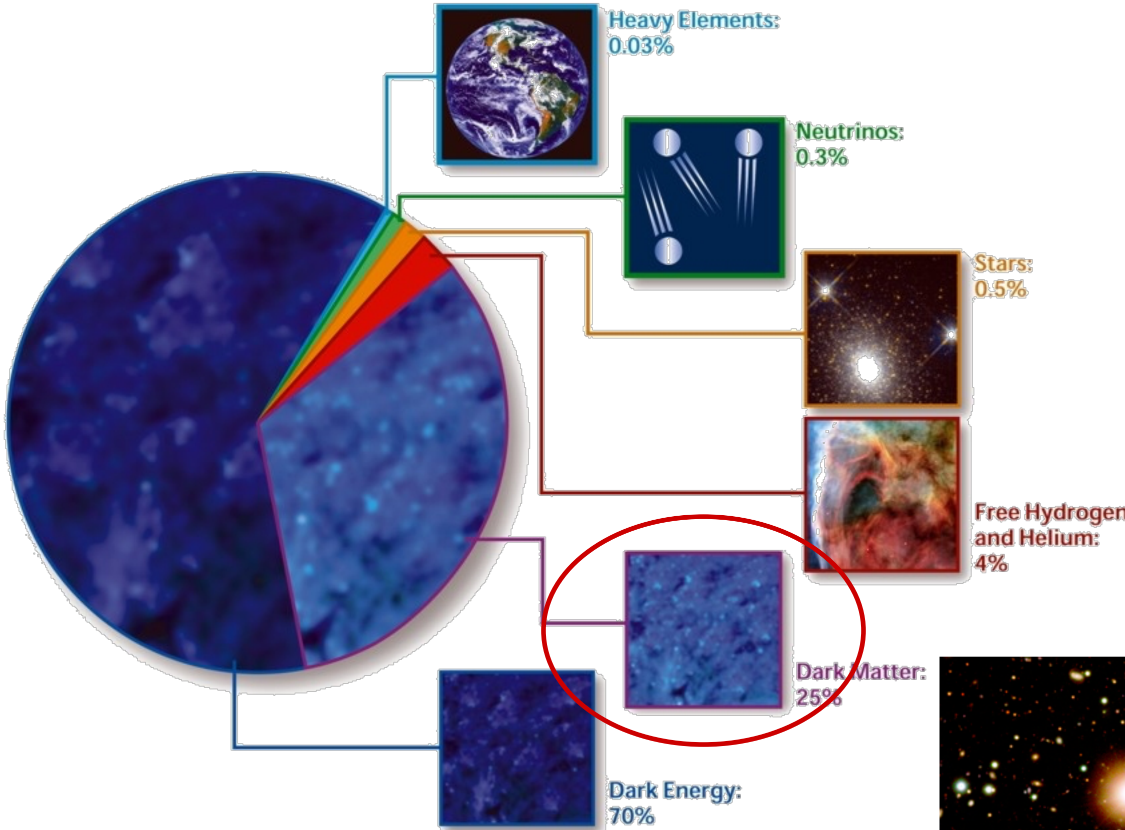


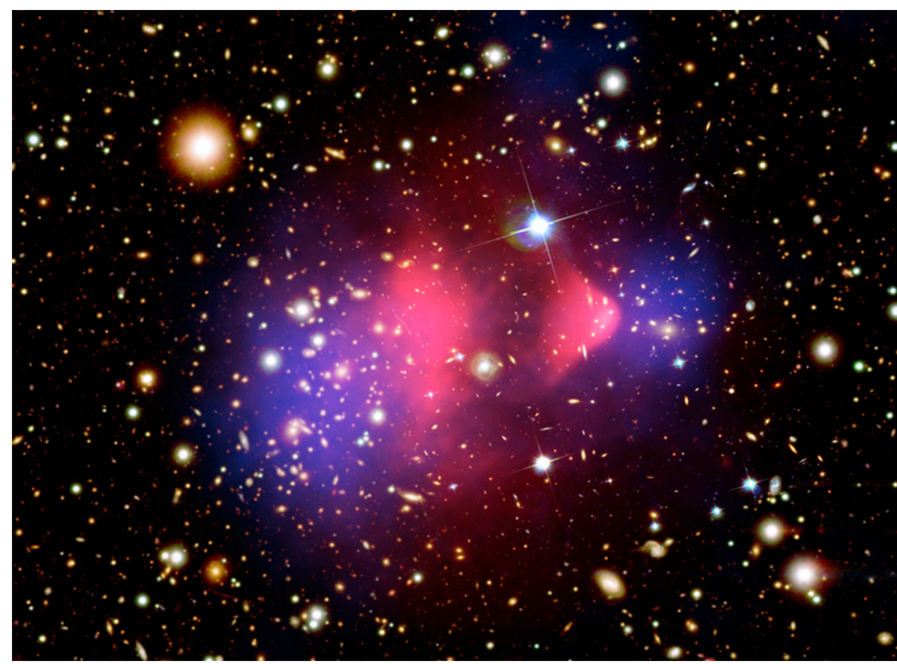
Periferic stars are faster than expected
Faster = More mass

Much more mass than luminous mass

Dark Matter

Dark Matter





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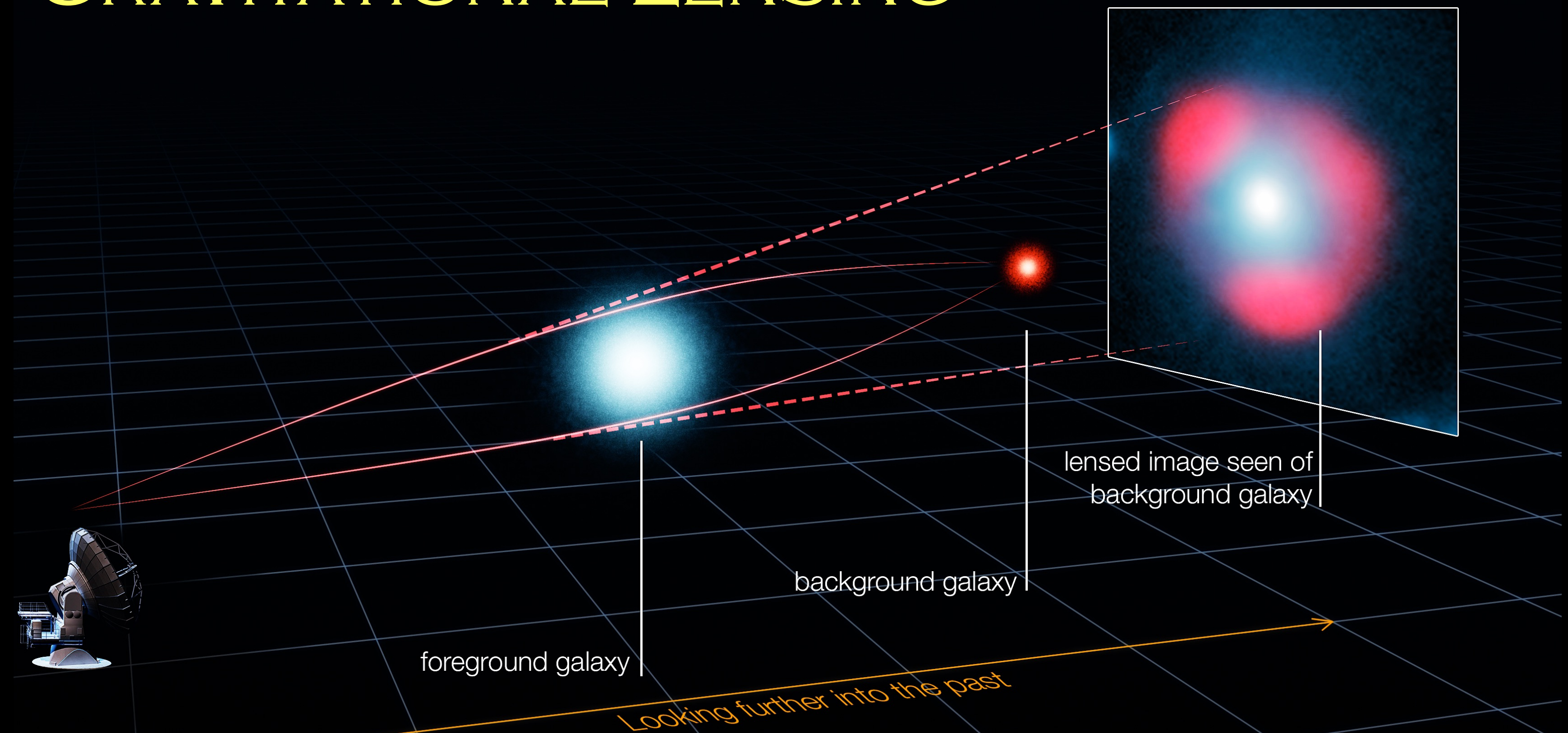
Gravitational Lensing



Lens equation

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

Lens equation (can have multiple solutions)

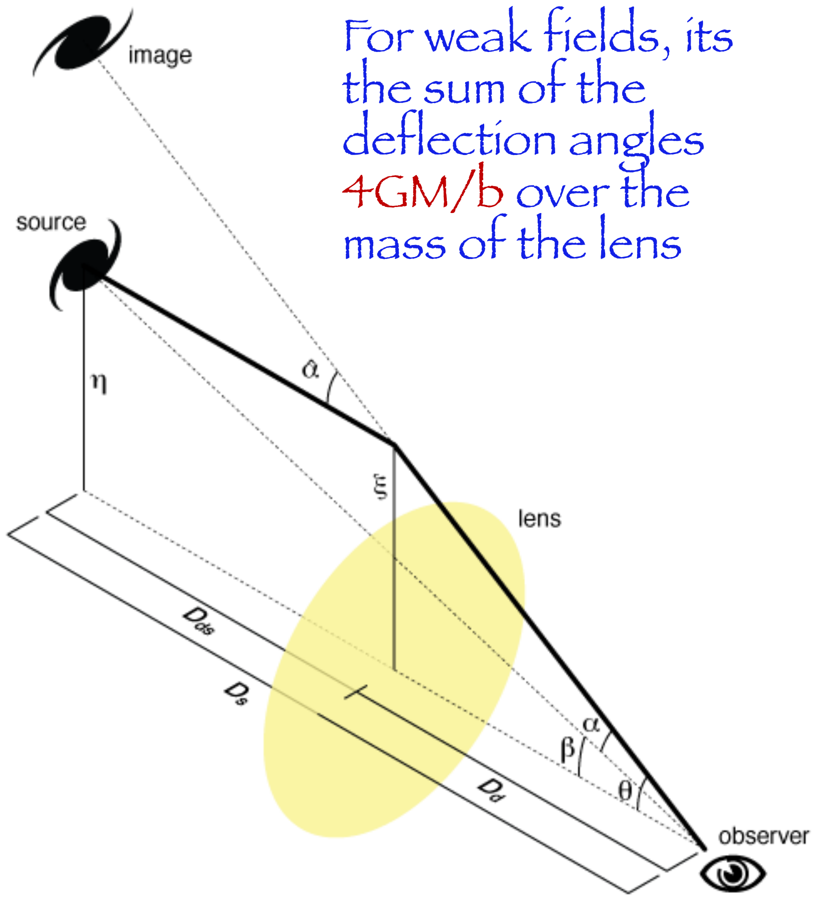
$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

Deflection angle

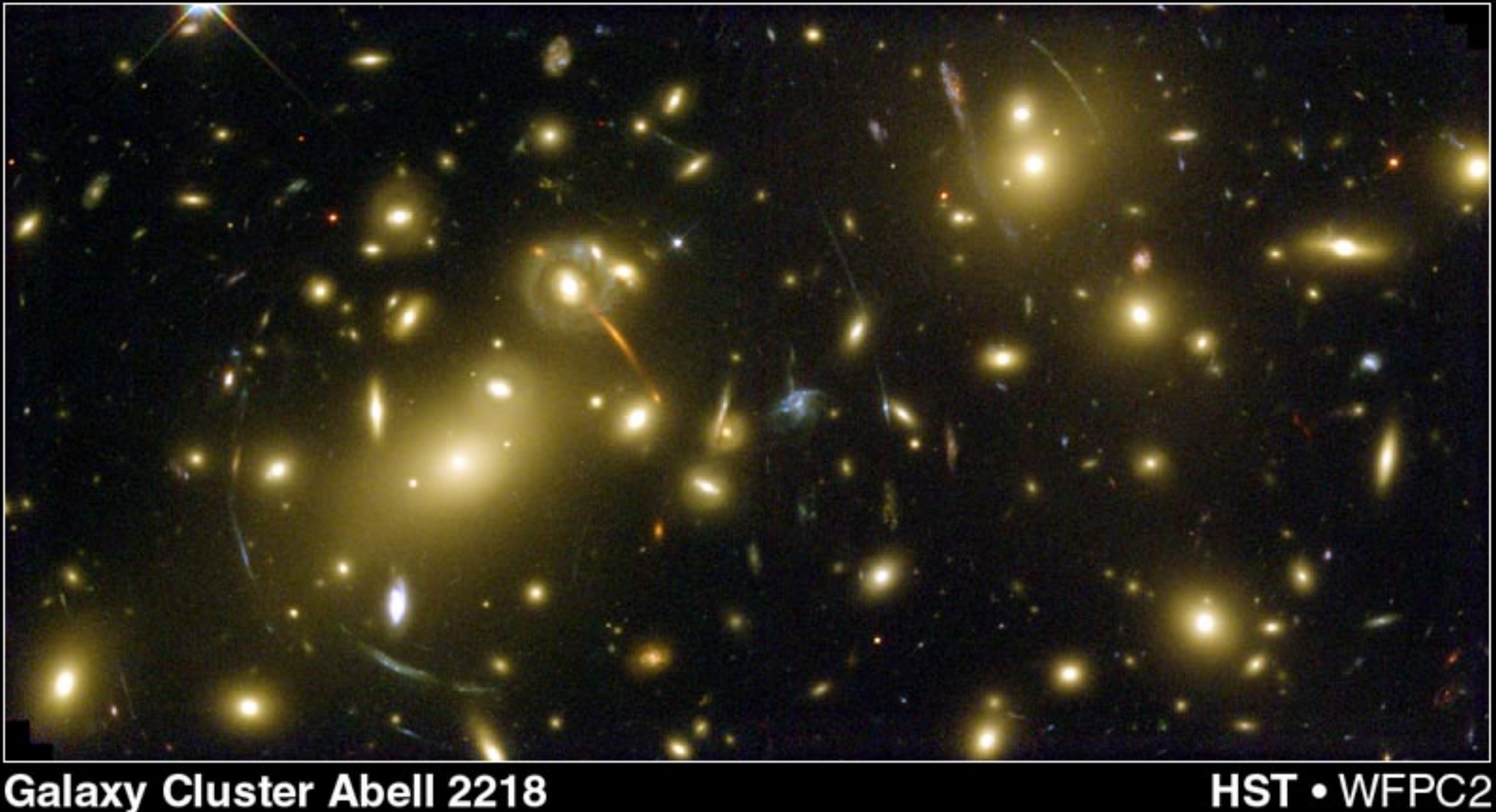
$$\alpha(\vec{\theta}) = 4G\int \frac{(\vec{\xi} - \vec{\xi'})\Sigma(\vec{\xi'})}{|\vec{\xi} - \vec{\xi'}|^2}\, d^2\xi'$$

Projected mass density

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



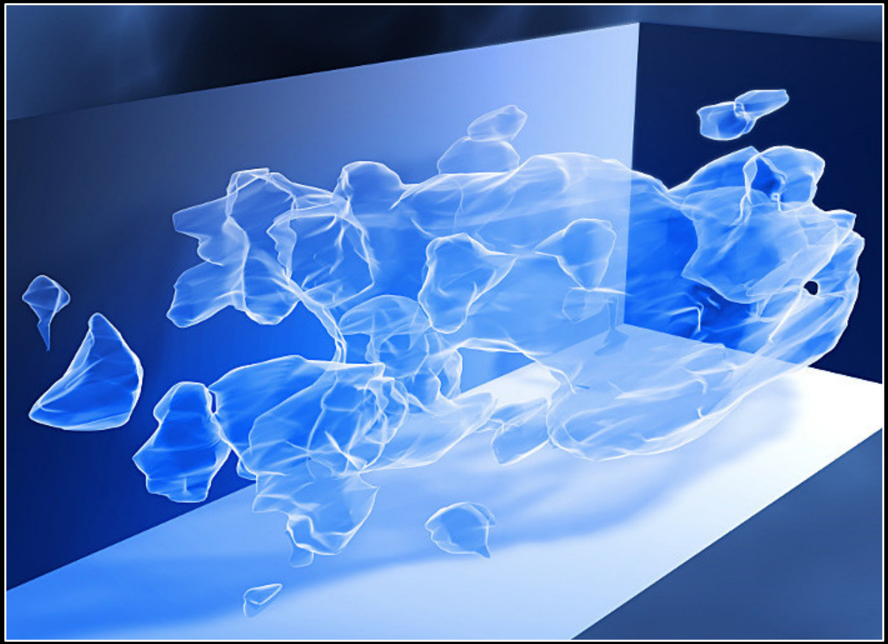
For weak fields, its the sum of the deflection angles 4GM/b over the mass of the lens



Gravitational lensing

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

Strong lensing

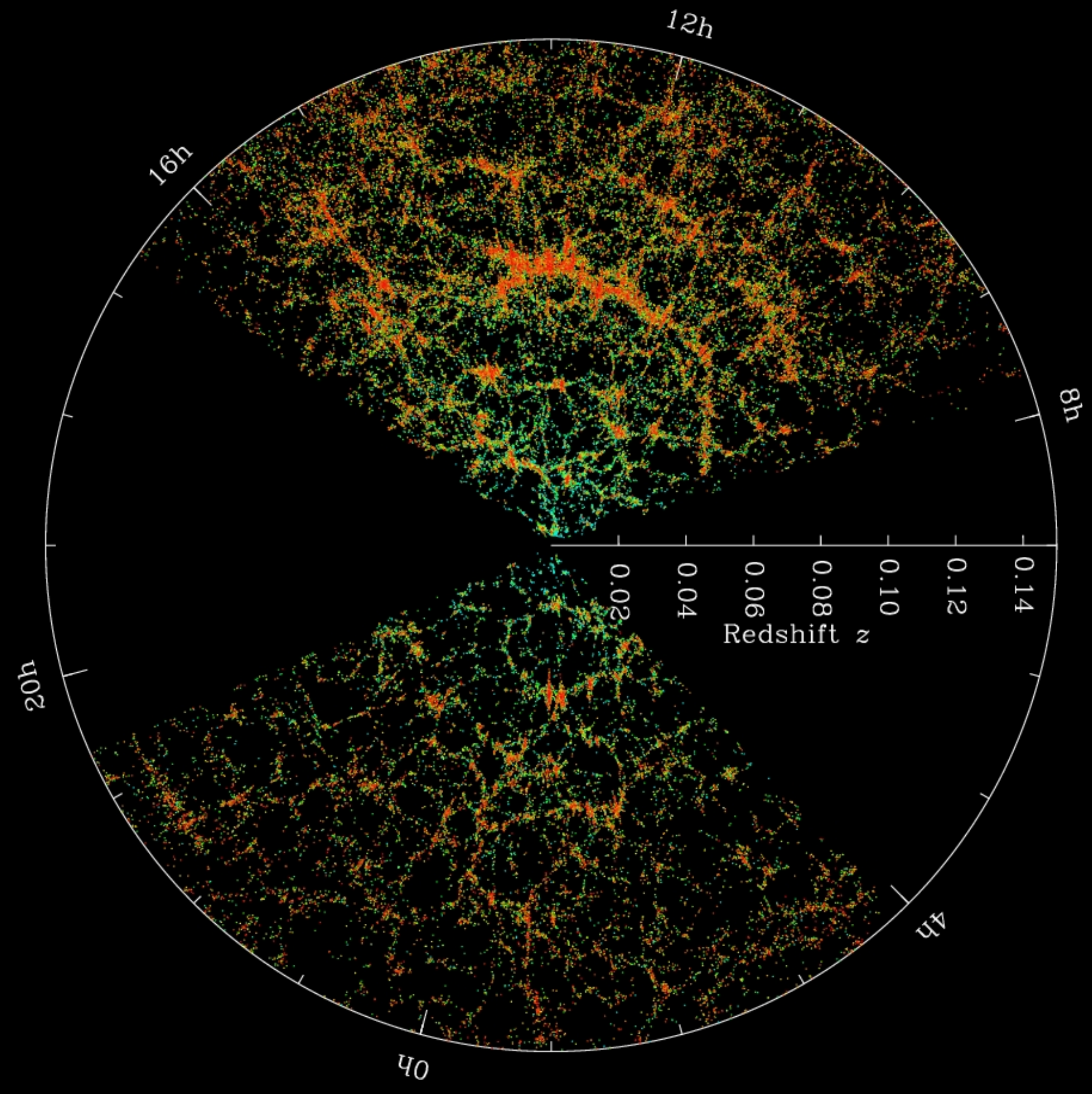


Weak lensing

Gravitational lensing

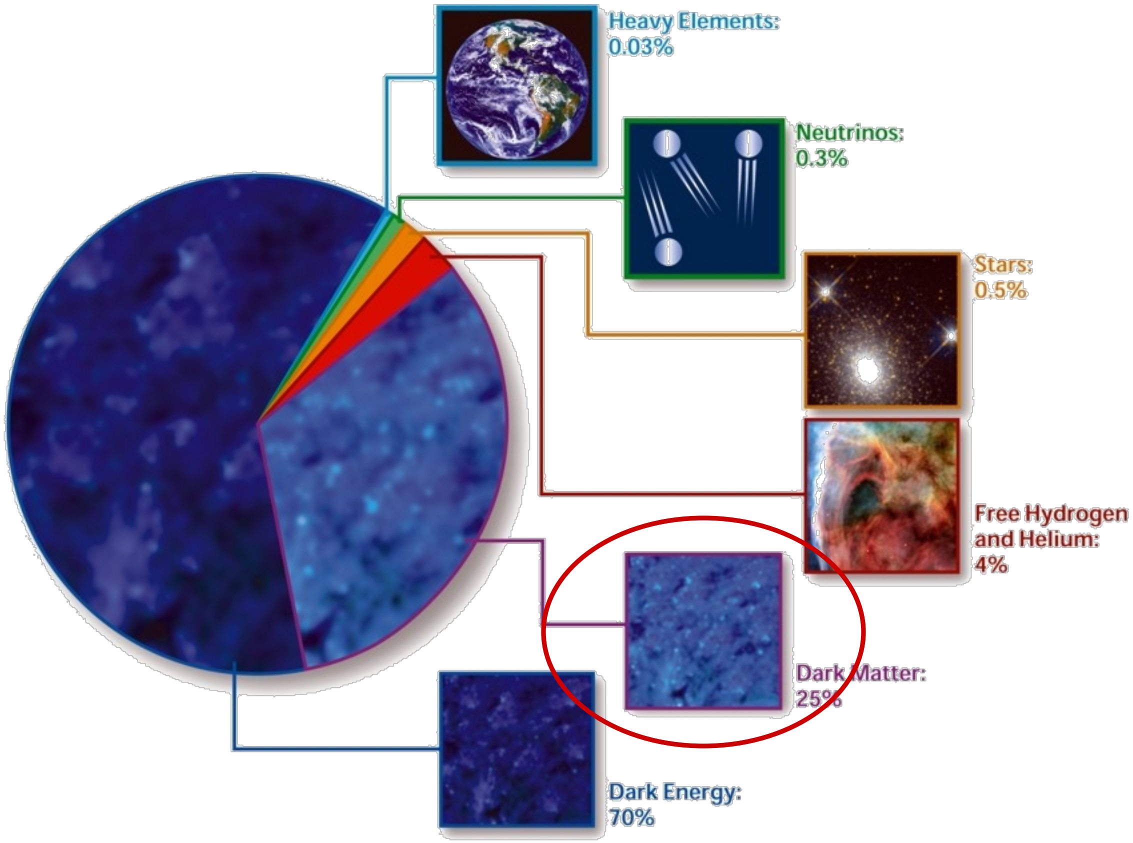
A large amount of mass between the background galaxies and us can be inferred by the lensing effect

Universe at large scales



Sloan Digital Sky Survey

Real Universe



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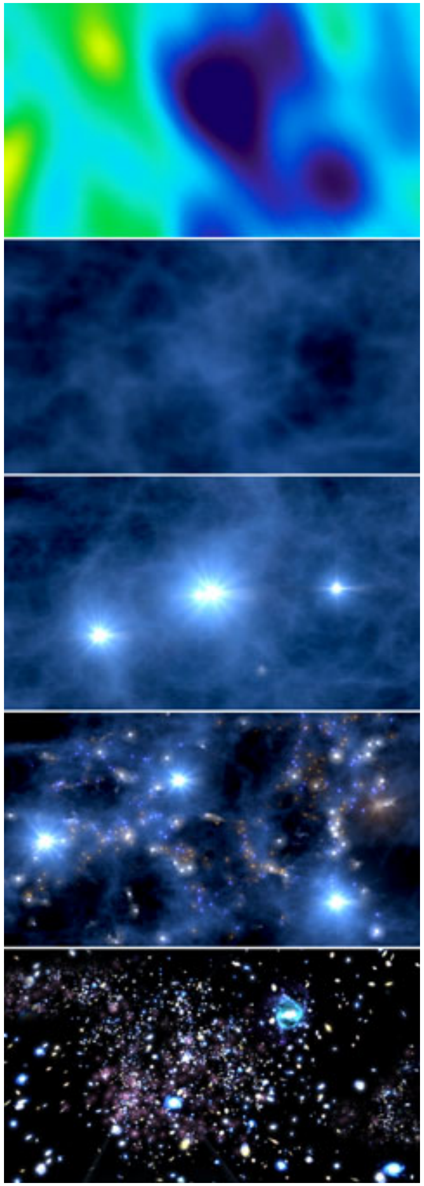
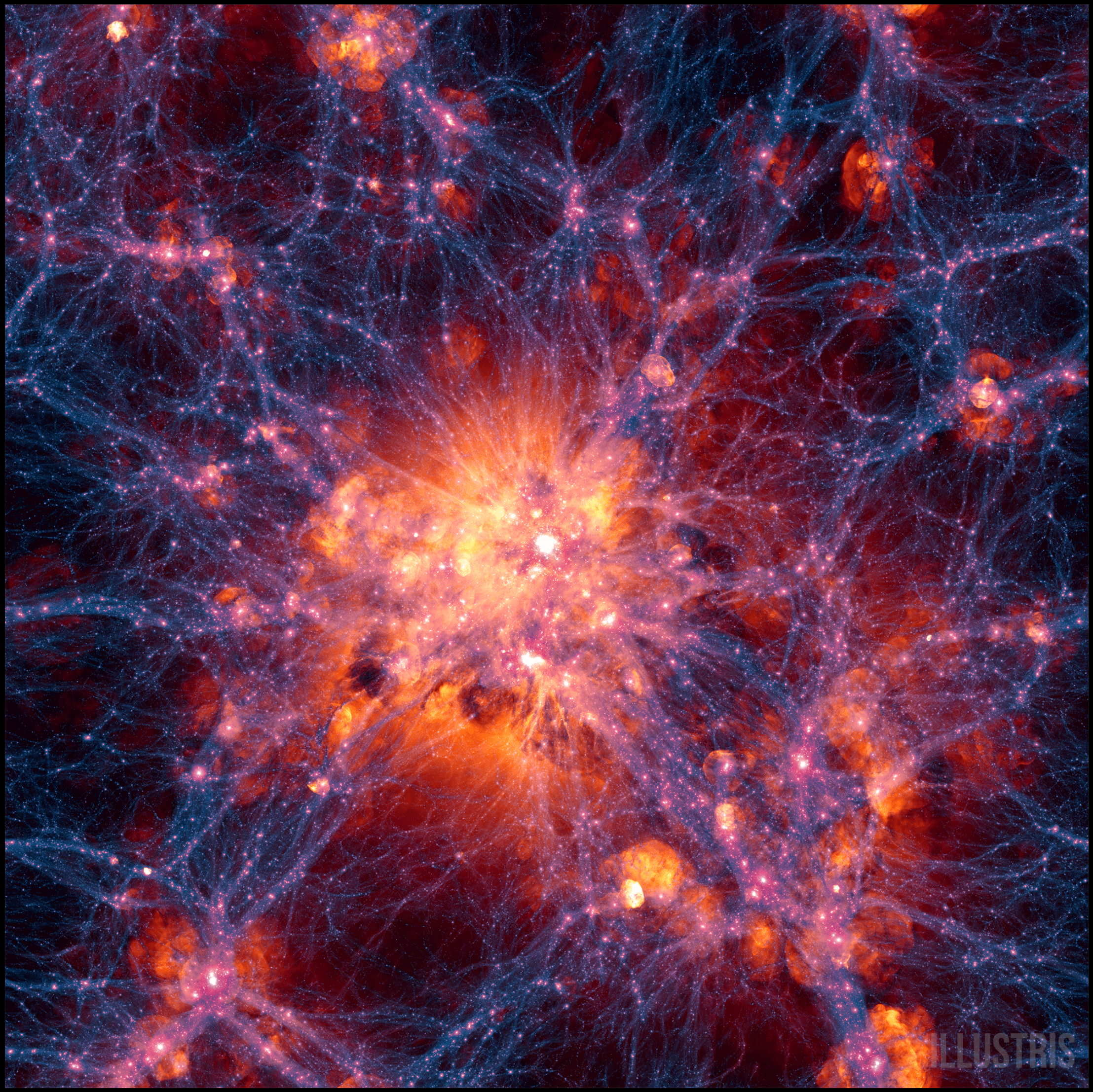


DM needs to be (mainly) cold and (mainly) non-collisional

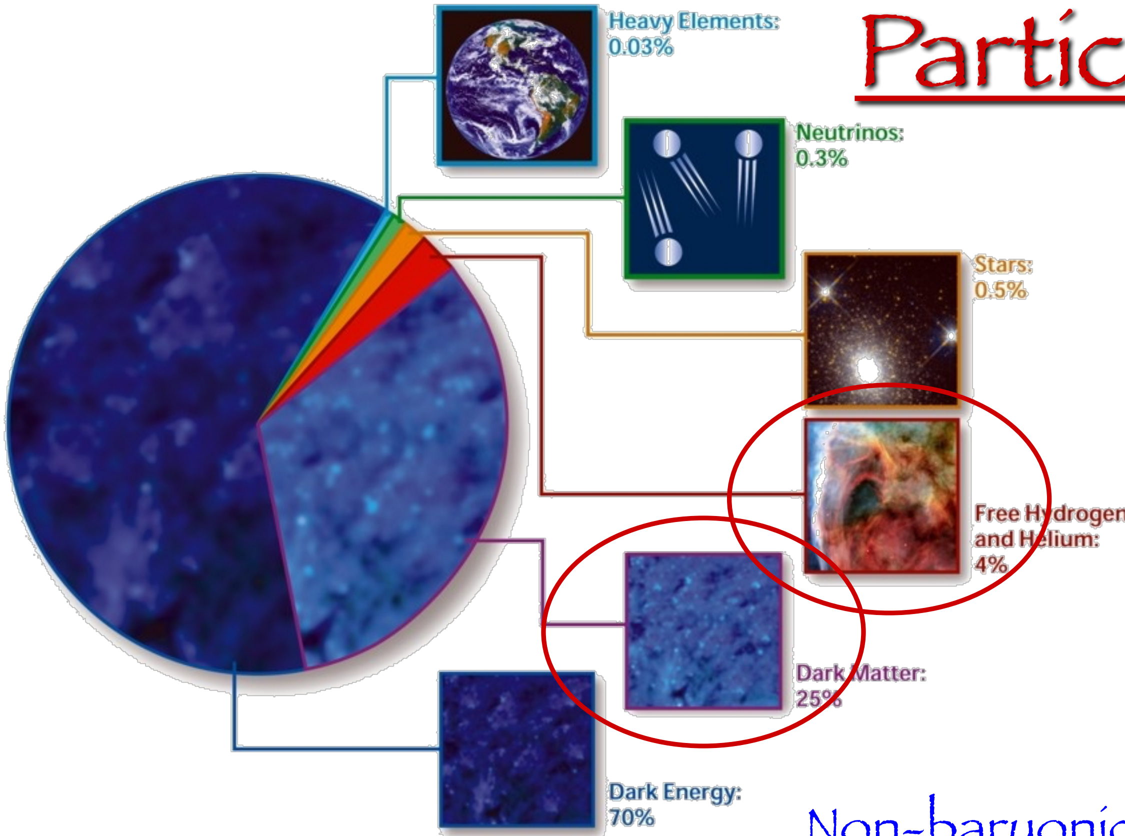
Structures in LCDM



Illustris simulation

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

Gravitational lensing

Structure formation from primordial density fluctuations

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(*) Standard neutrino:

Too light: act as HDM (not CDM)

Solutions not involving new particles

The DM issue is not a problem of particles, but of gravity

MOND

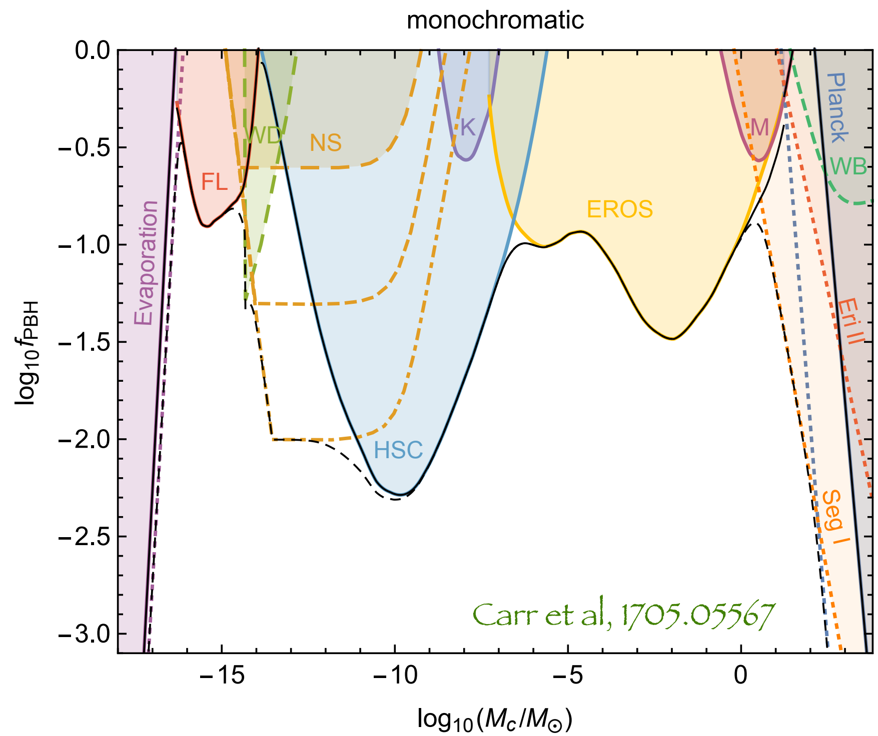
Gravity beyond General Relativity

Primordial black holes *might* solve the DM problem

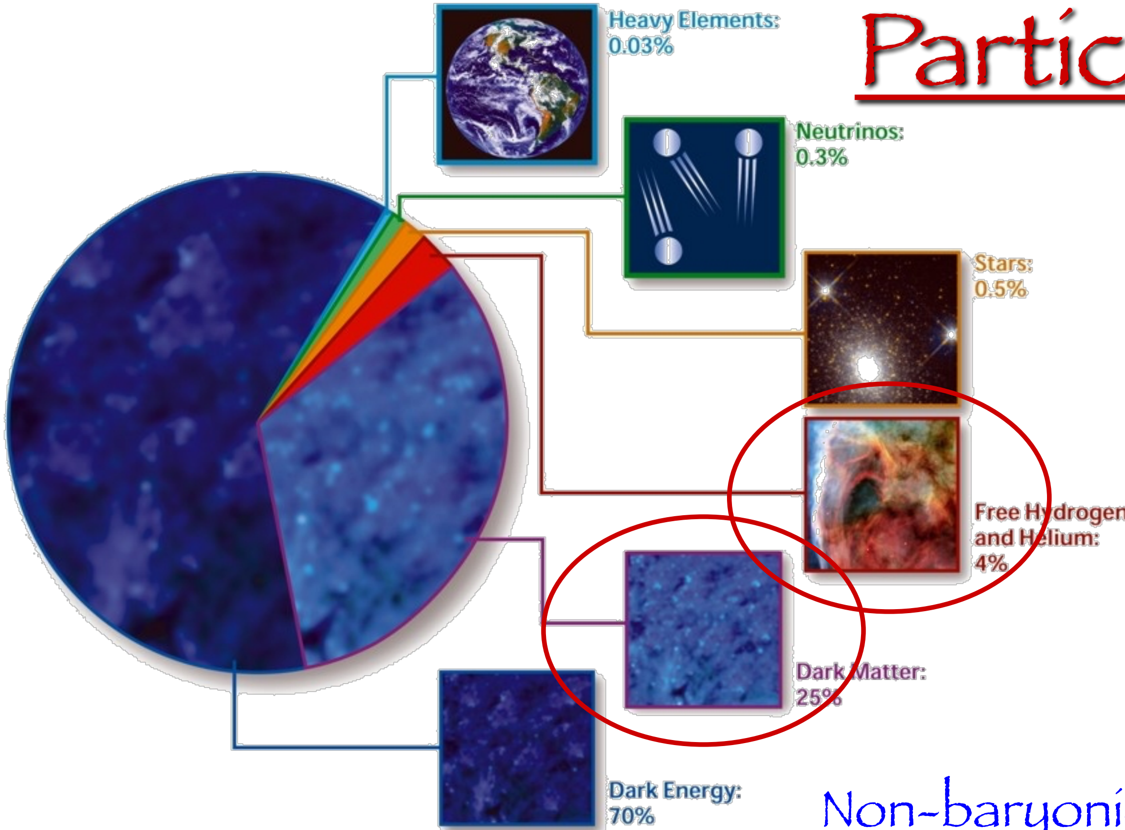
They do not count as baryonic matter

Currently under debate

FL:	femtolensing of GRB
NS:	neutron star catpure
WD:	white dwarf explosion
HSC:	microlensing from Subaru
K:	microlensing from Kepler
EROS:	microlensing from EROS
MACHO:	microlensing from MACHO



Particle Dark Matter



Non-baryonic (cold) dark matter is needed

No candidate in the Standard Model

New fundamental Physics

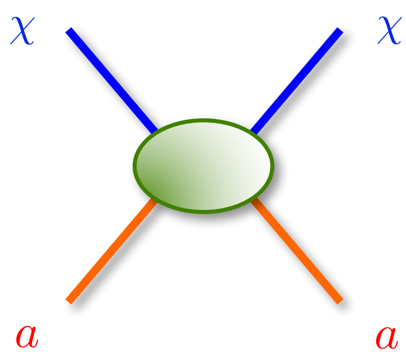
Two fundamental questions

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

If a particle, where it does come from?

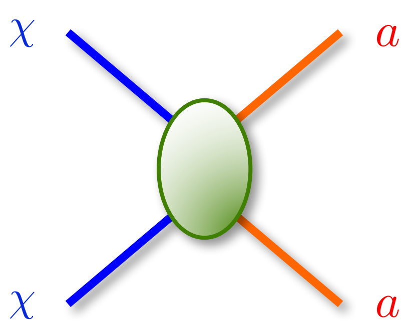
Produced, through some mechanism, in the early Universe

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

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

$$L[f_i] = \frac{df_i}{d\lambda}$$

For the Friedmann Universe (homogeneous + isotropic)

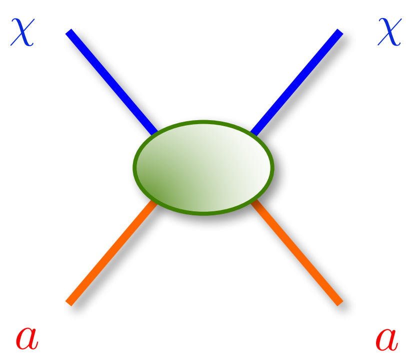
$$L[f_i] = E\frac{\partial f_i}{\partial t} - \frac{\dot{a}}{a}|\vec{p}|^2\frac{\partial f_i}{\partial E}$$

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

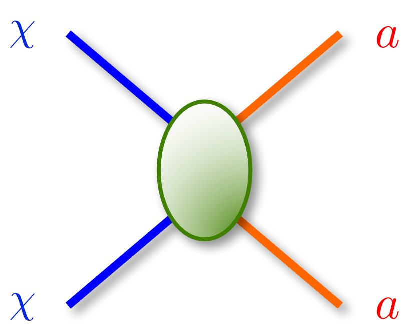
$$C[f_i; f_j, f_k, ...] = C_{\rm elastic}[f_i; f_j, f_k, ...] + C_{\rm inelastic}[f_i; f_j, f_k, ...]$$

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 $n_i(T)$

Particles in equilibrium the plasma

Relativistic $\langle E \rangle_i \sim T \gg m_t$

$n_i \sim T^3$

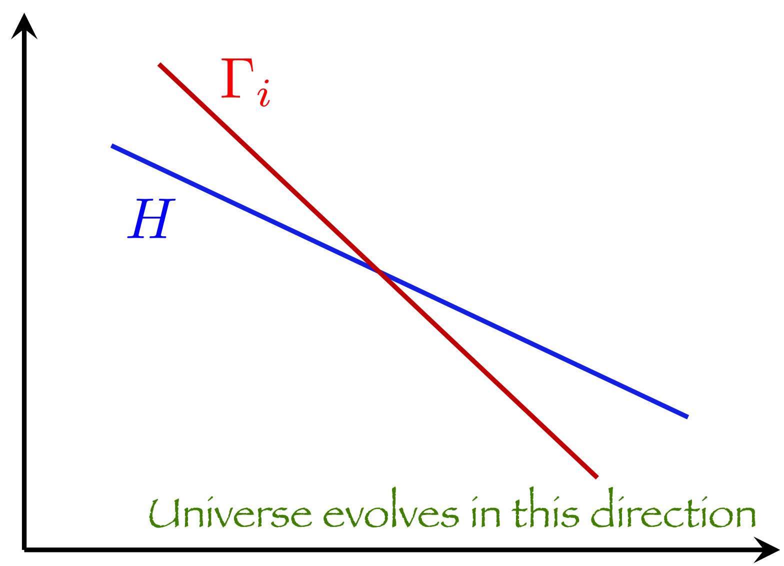
Non relativistic $\langle E \rangle_i \sim m_i \gg T$

$n_i \sim \exp\left(-m/T\right)$

But they cannot stay in equilibrium forever: it's a matter of rates

$$\Gamma_i = \sum_{j=\text{other}} n_j \langle \sigma v \rangle_{ij}$$

$$H$$



Boltzmann eq. for the number density

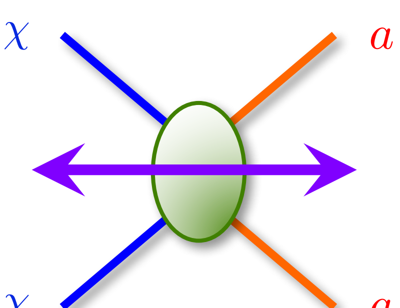
After integration over momenta (and some mathematical manipulation) a Boltzmann eq. for the number density can be cast in the form:

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

dilution due to expansion

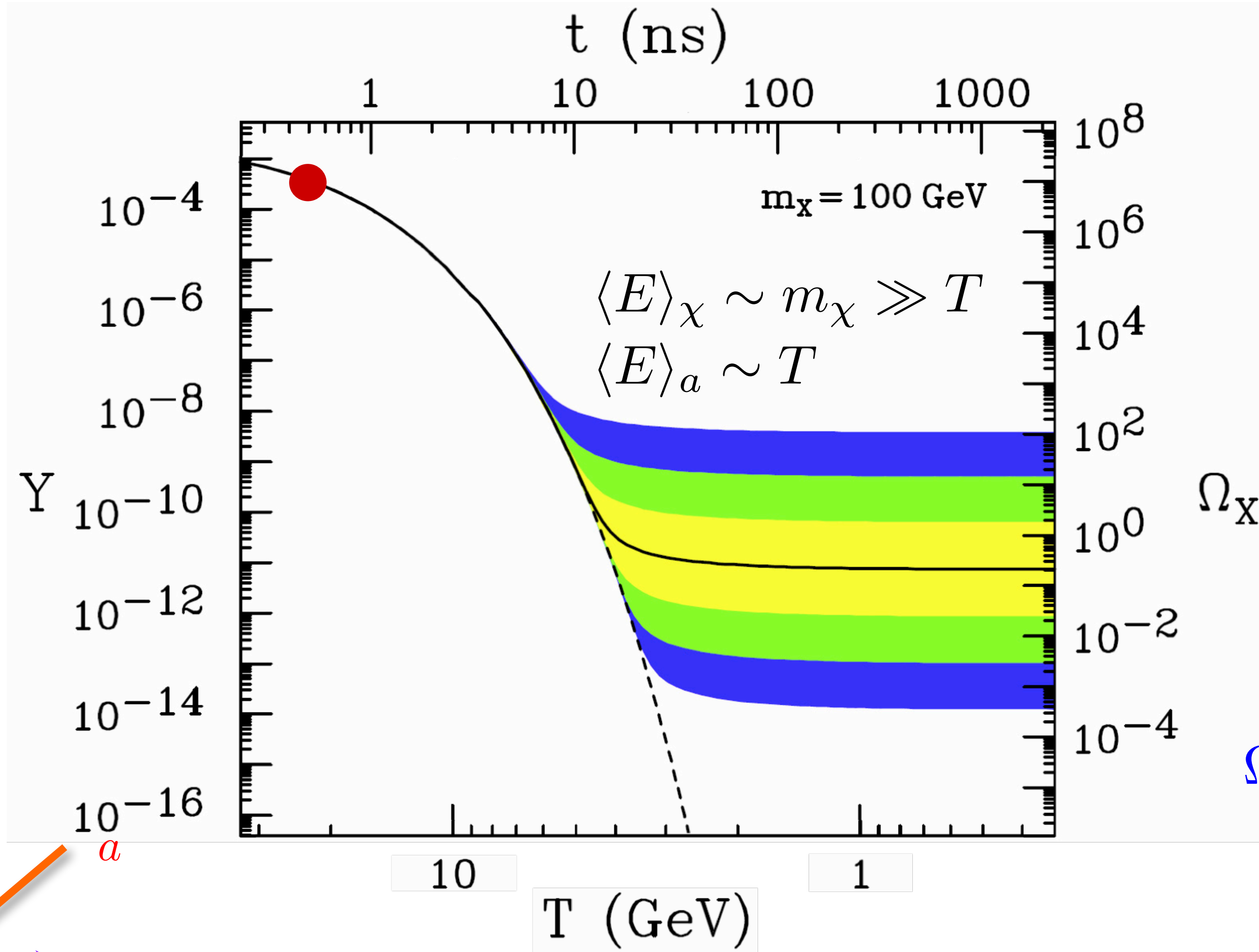
dilution due to annihilation

production due to inverse expansion

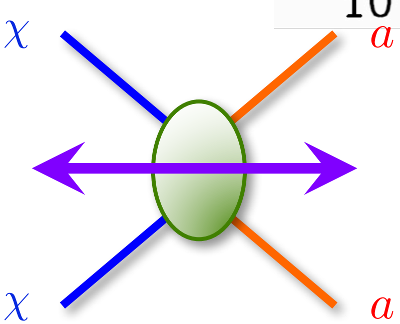


Abundance evolution for a cold relic

$Y = n/s$



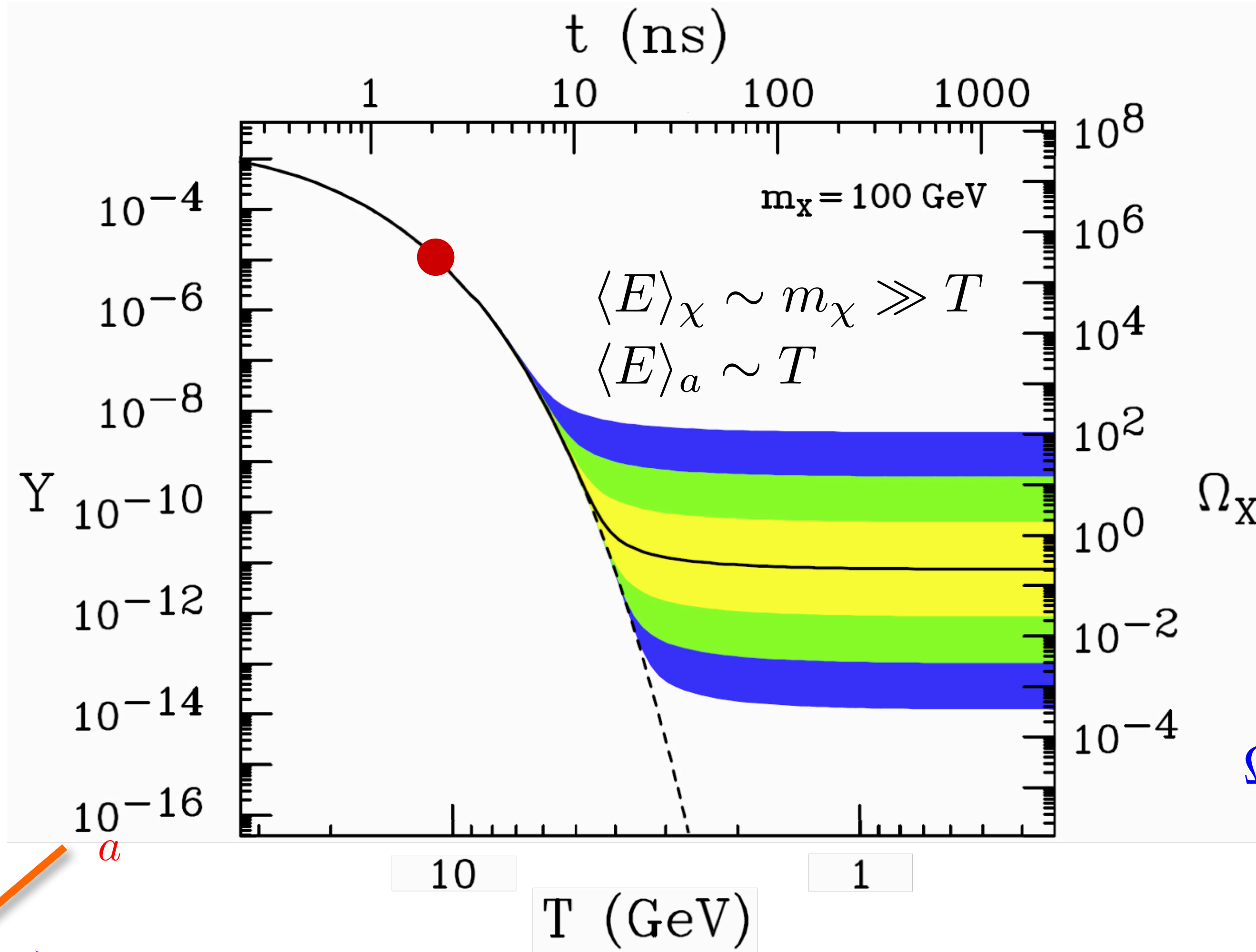
$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$



Particle in equilibrium

Abundance evolution

$Y = n/s$



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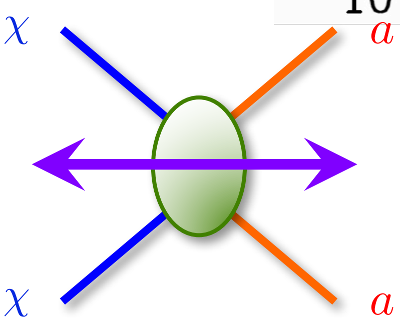
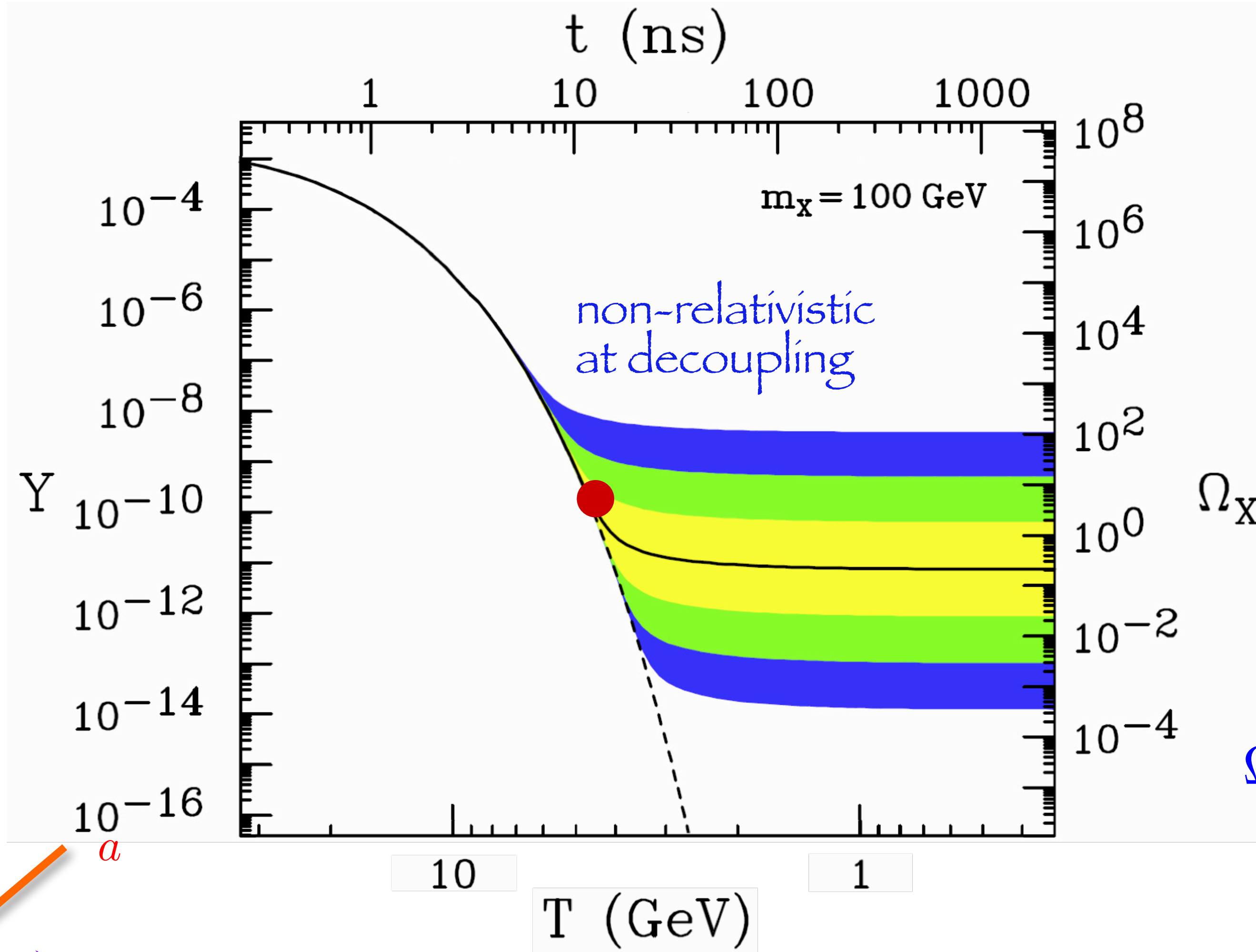


The universe cools down Particle in equilibrium

Abundance evolution

$Y = n/s$



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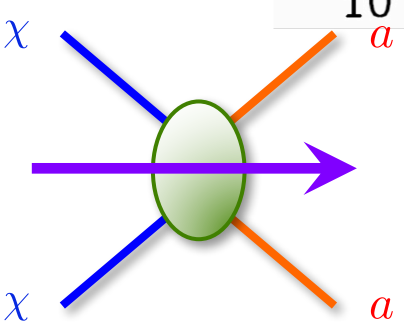
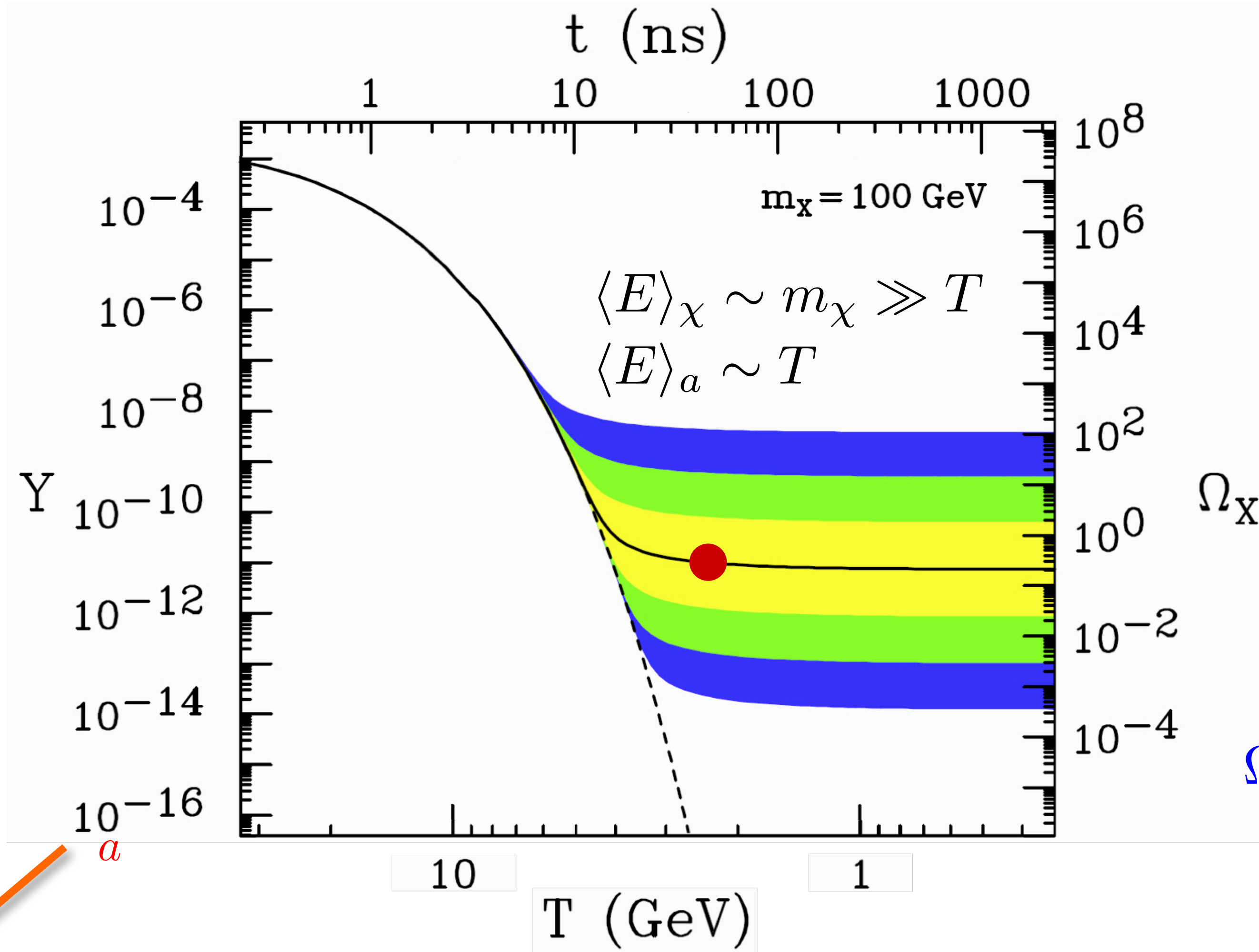


The universe cools down

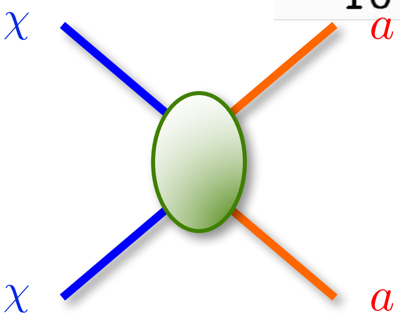
Particle detaches from the plasma
"freeze-out" of its abundance

Abundance evolution

$Y = n/s$



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



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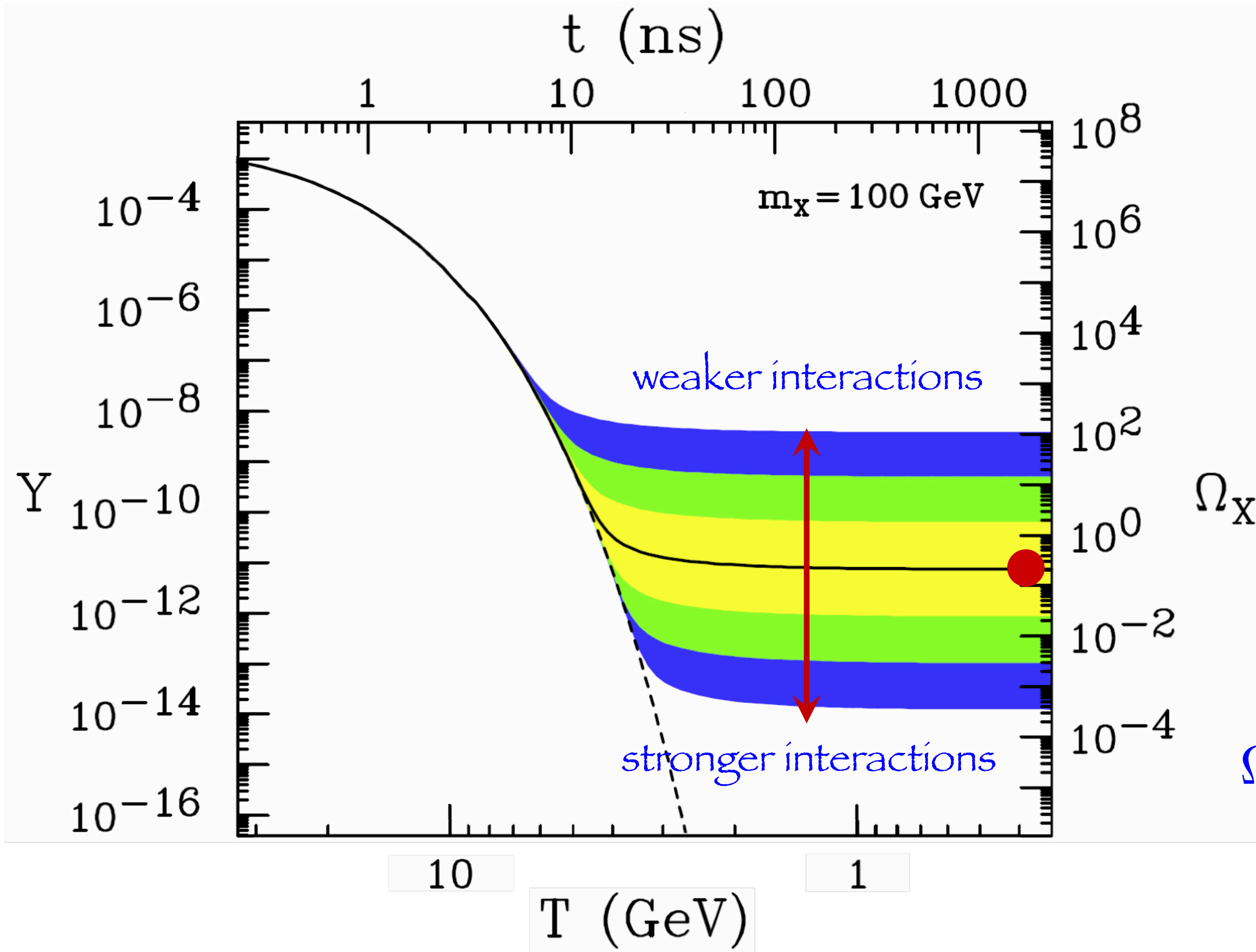


$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

The universe cools down

Abundance today (relic)

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

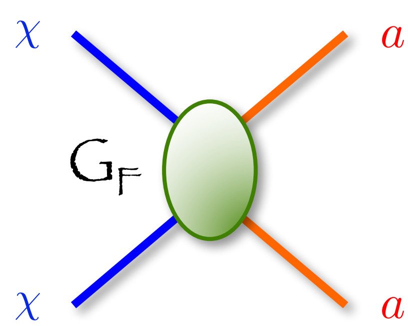
$m \ll m_Z$

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

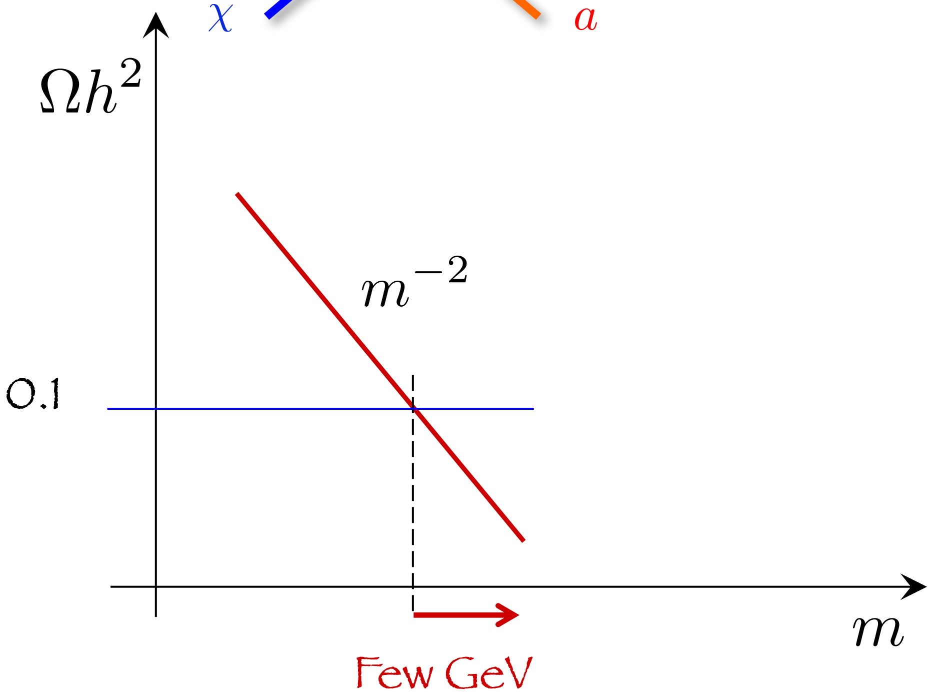
$$s = q^2 \sim (2\, m_{\rm DM})^2$$

non-relativistic

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



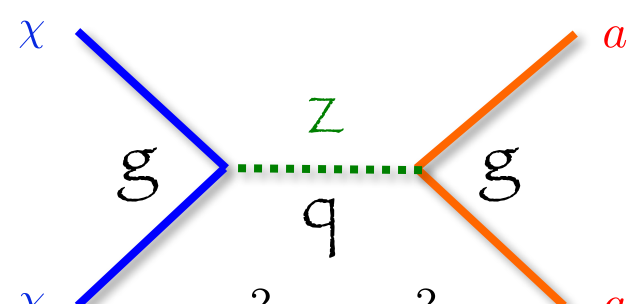
Fermi limit



Lee-Weinberg bound

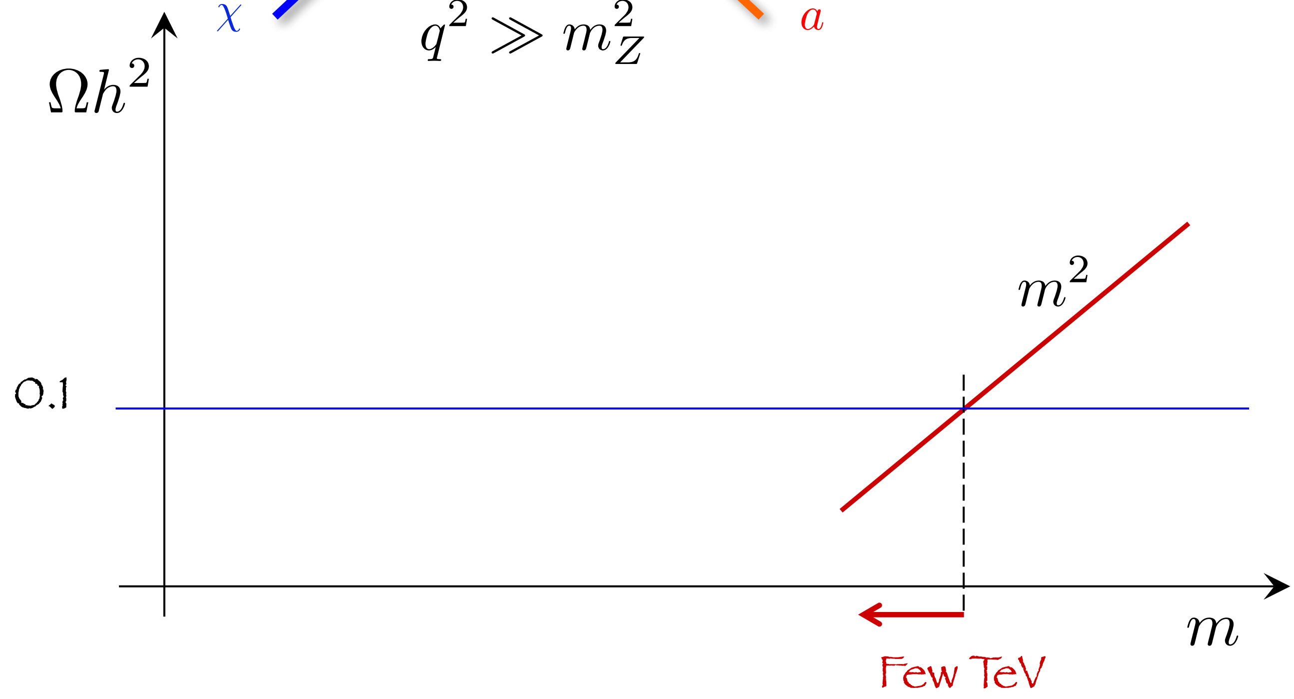
In more details

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

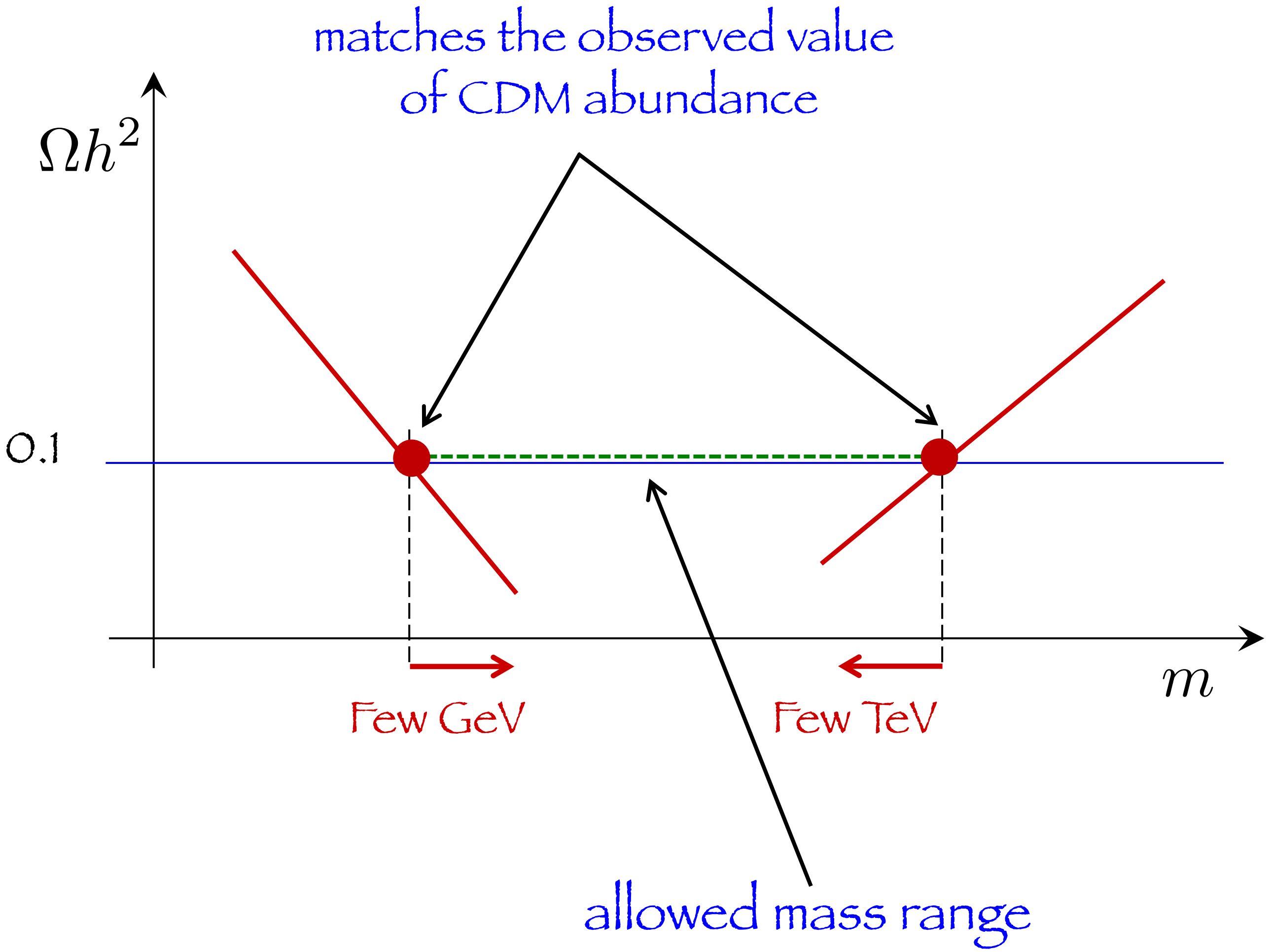


$$q^2 \gg m_Z^2$$

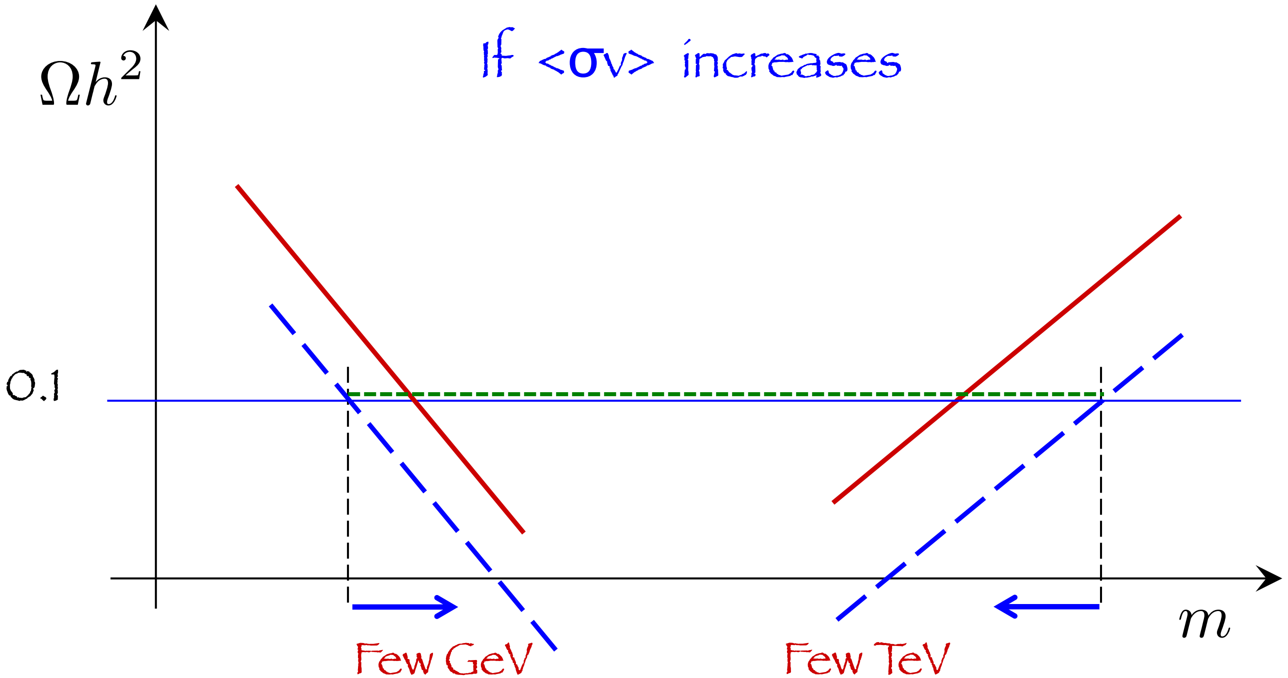
Effectively massless Z



Summarizing



Dependencies



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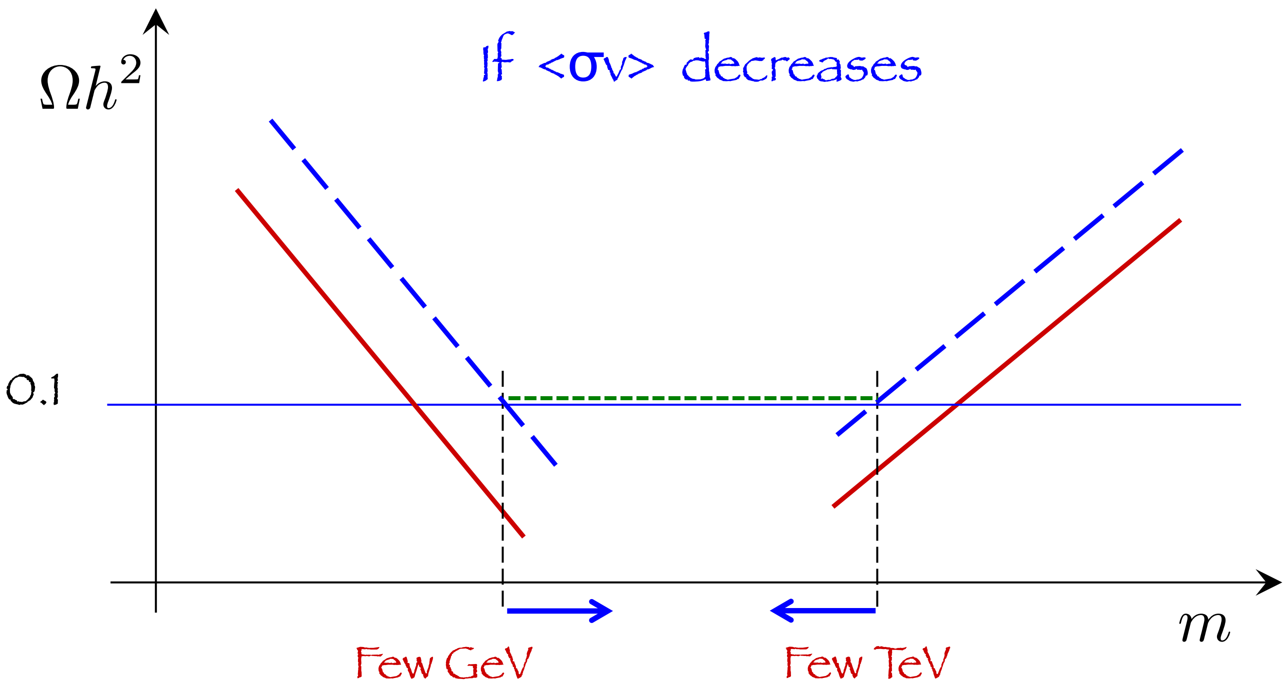


Additional features

- 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 particle 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

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

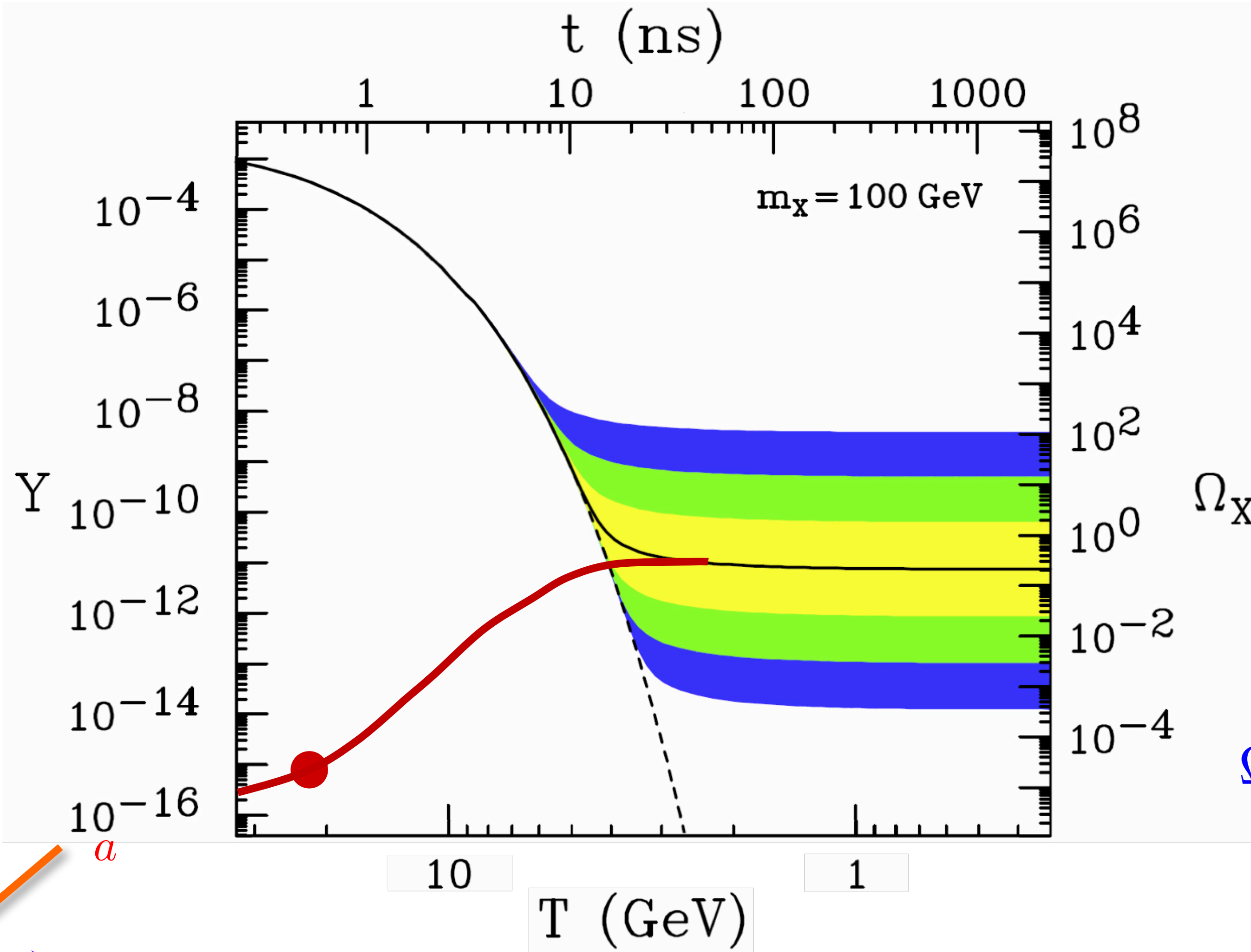
- The relic abundance is set by the asymmetry, not thermal freeze-out
- This may link DM abundance to baryon asymmetry

Non-thermal production

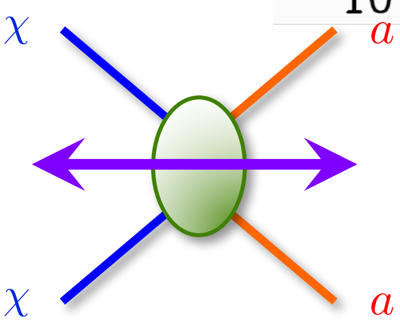
- DM produced by the decay of a heavier particle
- Peculiar cosmological dynamics (e.g.: misalignment for axions)
- Oscillations from "friendly" states (e.g. sterile neutrinos)

Freeze-in mechanism

$Y = n/s$



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

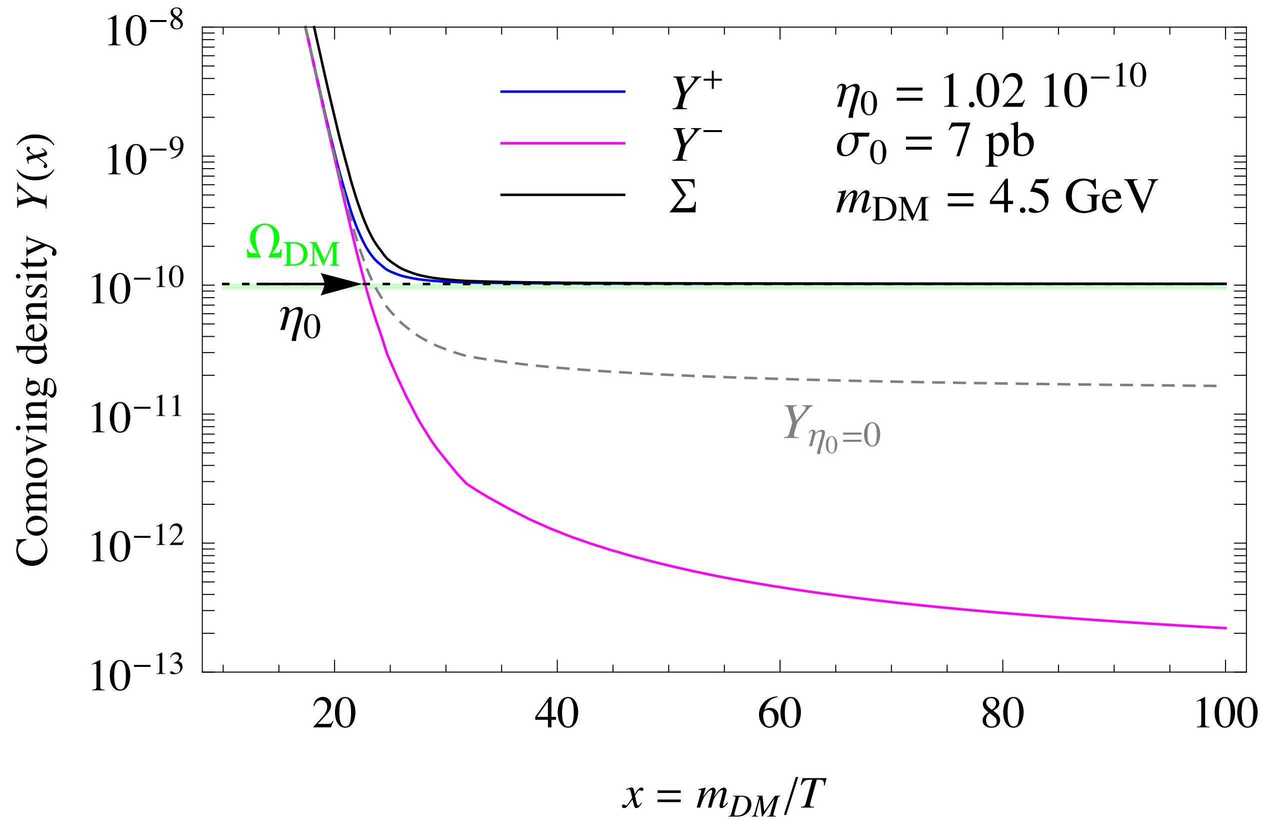


particle never in full equilibium

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: $\dfrac{\Omega_\chi}{\Omega_b} \sim 5$

$$|n_\chi - n_{\bar{\chi}}| \sim (n_b - n_{\bar{b}}) \sim n_b$$ (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 dependent 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 $\langle\sigma_N v\rangle$)

From oscillations

ν_S sterile neutrino

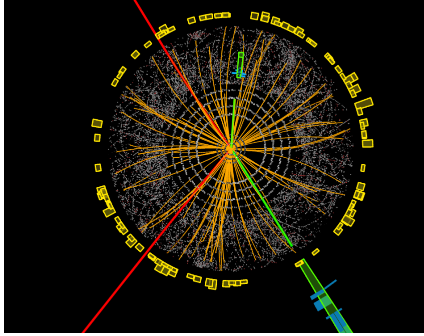
Needs to be very weakly mixed

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

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

Formation of BE condensates

A multiple approach

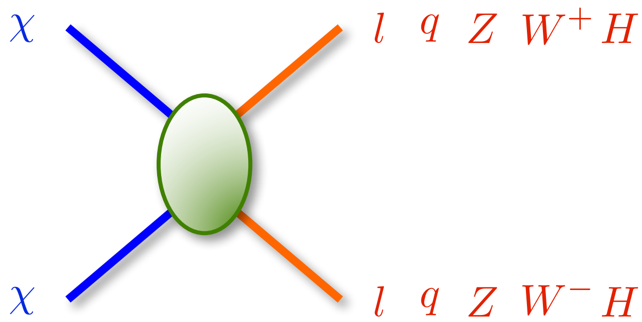


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy

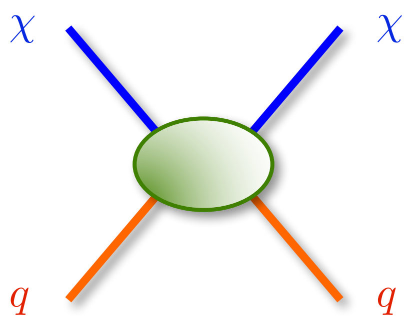
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all ... profit of all opportunities

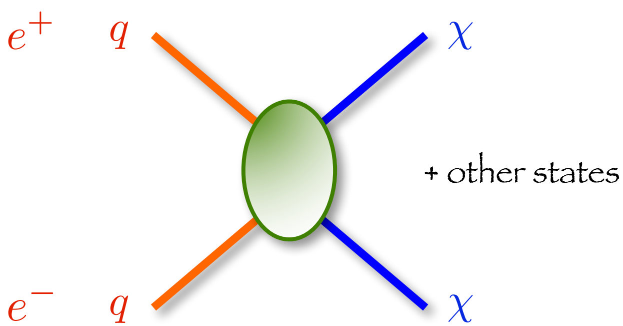
Mechanisms of DM signal production



Annihilation (or decay)

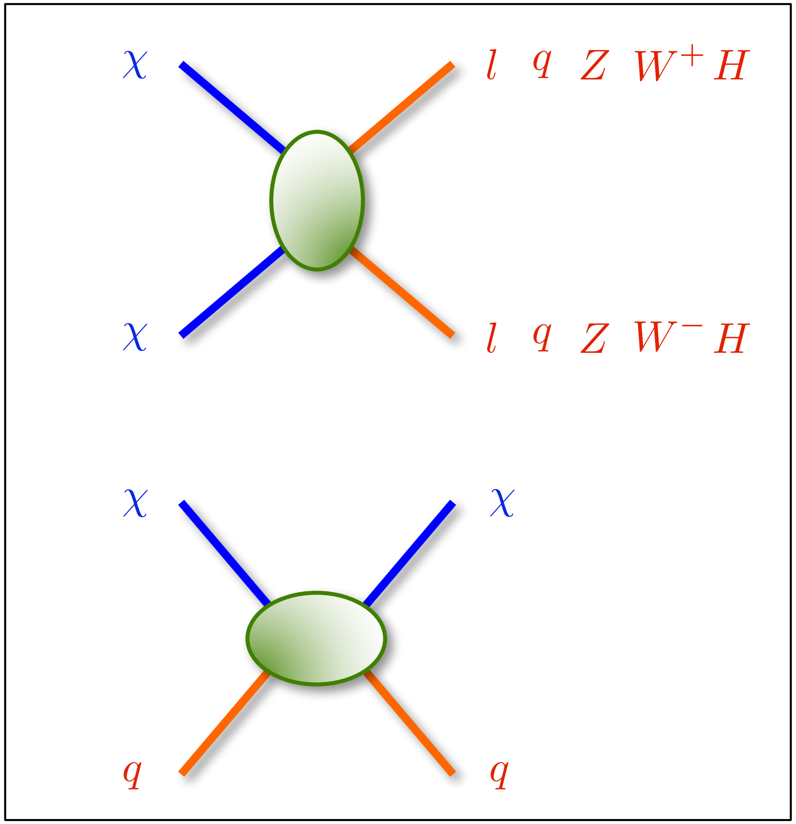


Scattering with ordinary matter



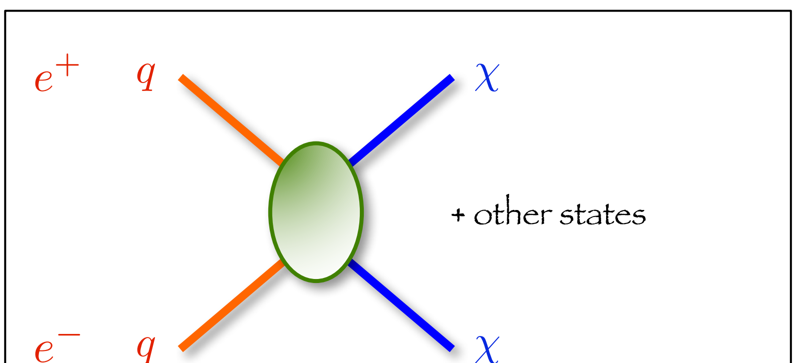
Production at accelerators

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

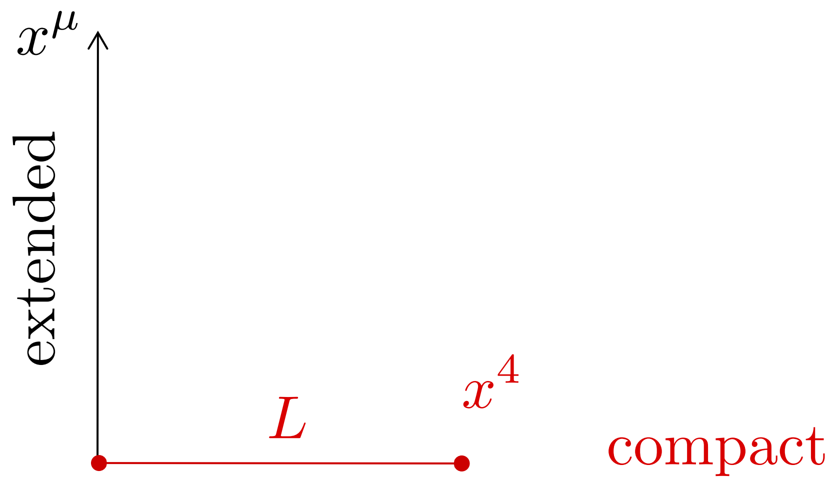
	Normal particles/fields		Supersymmetric partners			
			Interaction eigenstates		Mass eigenstates	
	Symbol	Name	Symbol	Name	Symbol	Name
	$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
	$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
	$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	$\boxed{\text{sneutrino}}$
	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	$\tilde{H}_1^0$	higgsino	$\tilde{\chi}_{1,2,3,4}^0$	$\boxed{\text{neutralino}}$
H	H_2^0 scalar	Higgs boson	$\tilde{H}_2^0$	higgsino		
A	H_3^0 pseudoscalar	Higgs boson				

2 Higgs doublets

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

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

$\boxed{\text{KK parity}} \longrightarrow \boxed{\text{LKP: stable}}$

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]

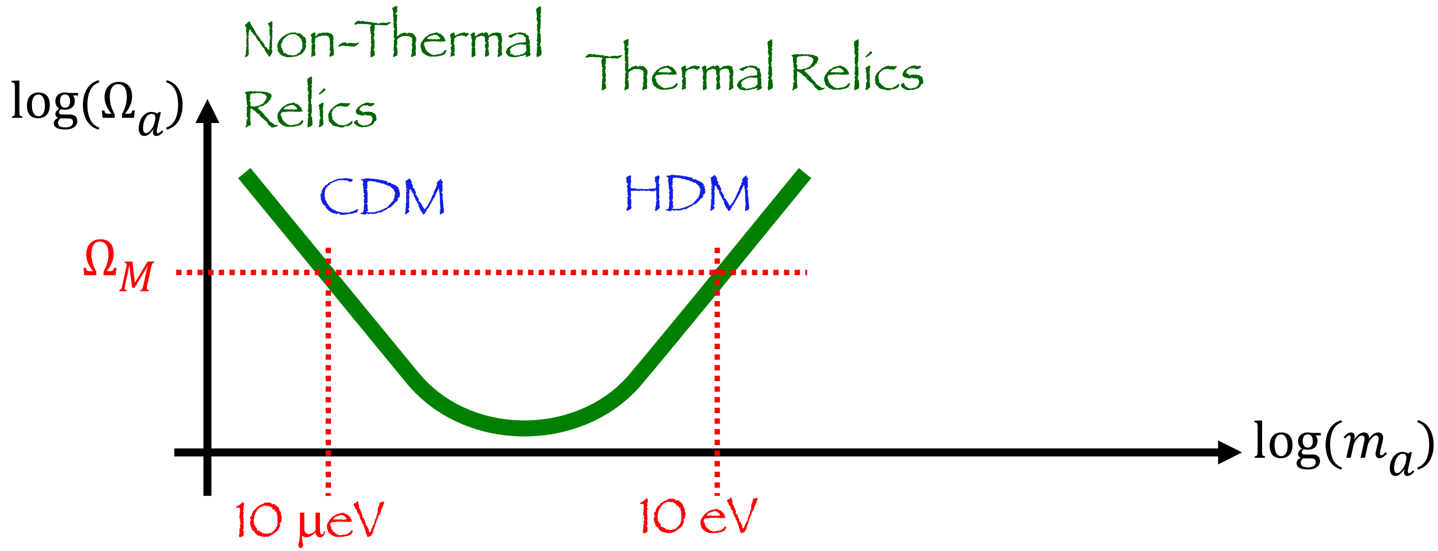
ALP (axion-like-particles, light scalars)
[> 10^{-22} eV, non WIMP, cold (BE condensate)]

Axion

- Axions arise as a dynamical way to solve the strong-CP problem
- Being particles, they can have a cosmological role
- They can be:
  - Thermally produced: hot dark matter
  - Non-thermally produced: born as nonrelativistic, classical field oscillations - very small mass, yet cold dark matter

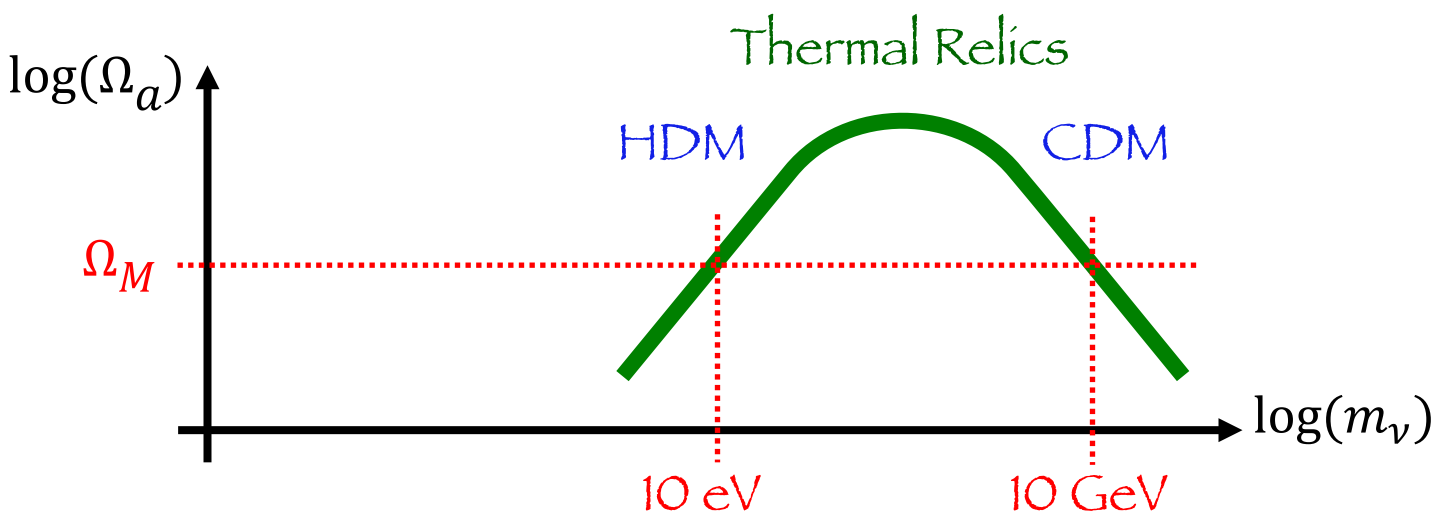
Relic abundance curves

Axions

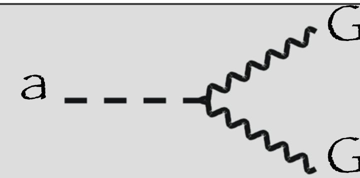
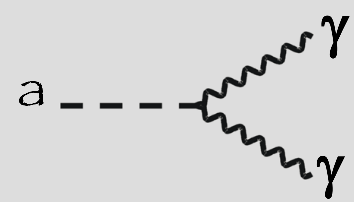
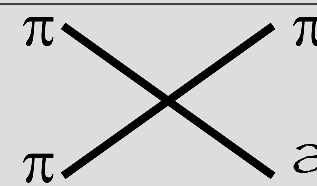
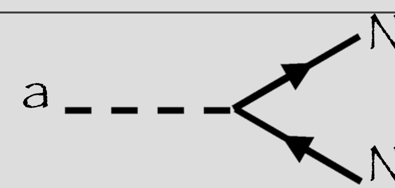
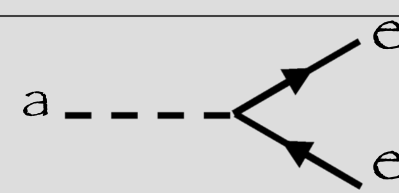


Neutrinos

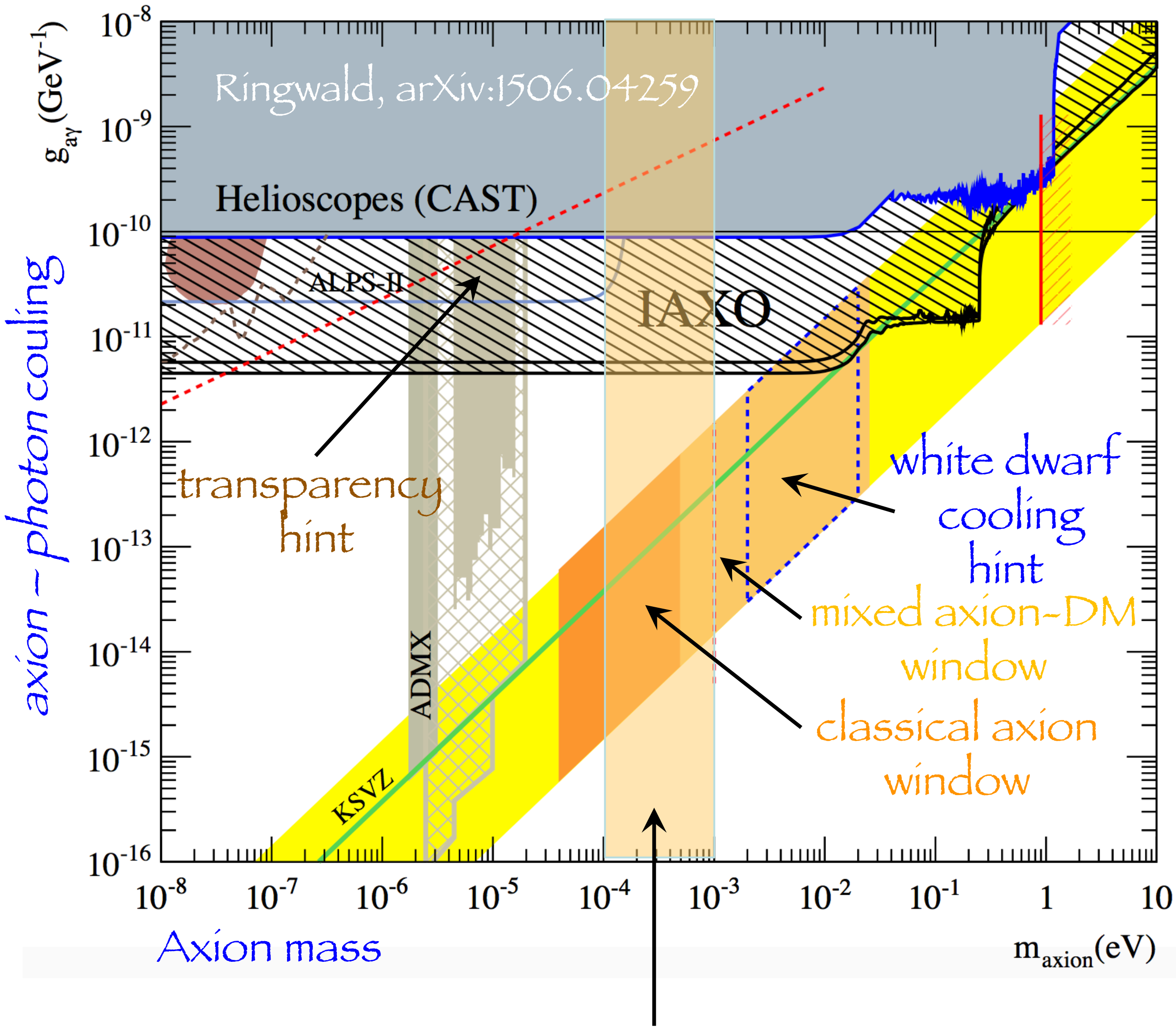
WIMPs



Axion Properties

Gluon coupling (generic)	$L_{aG} = \frac{\alpha_s}{8\pi f_a}\, G\tilde{G}a$	
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\,\frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4}\, F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$L_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}\left(\pi^0\pi^+\partial_\mu\pi^- + \cdots\right)\partial^\mu a$	
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\partial_\mu a$	
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a}\,\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$	

Axions and ALPs



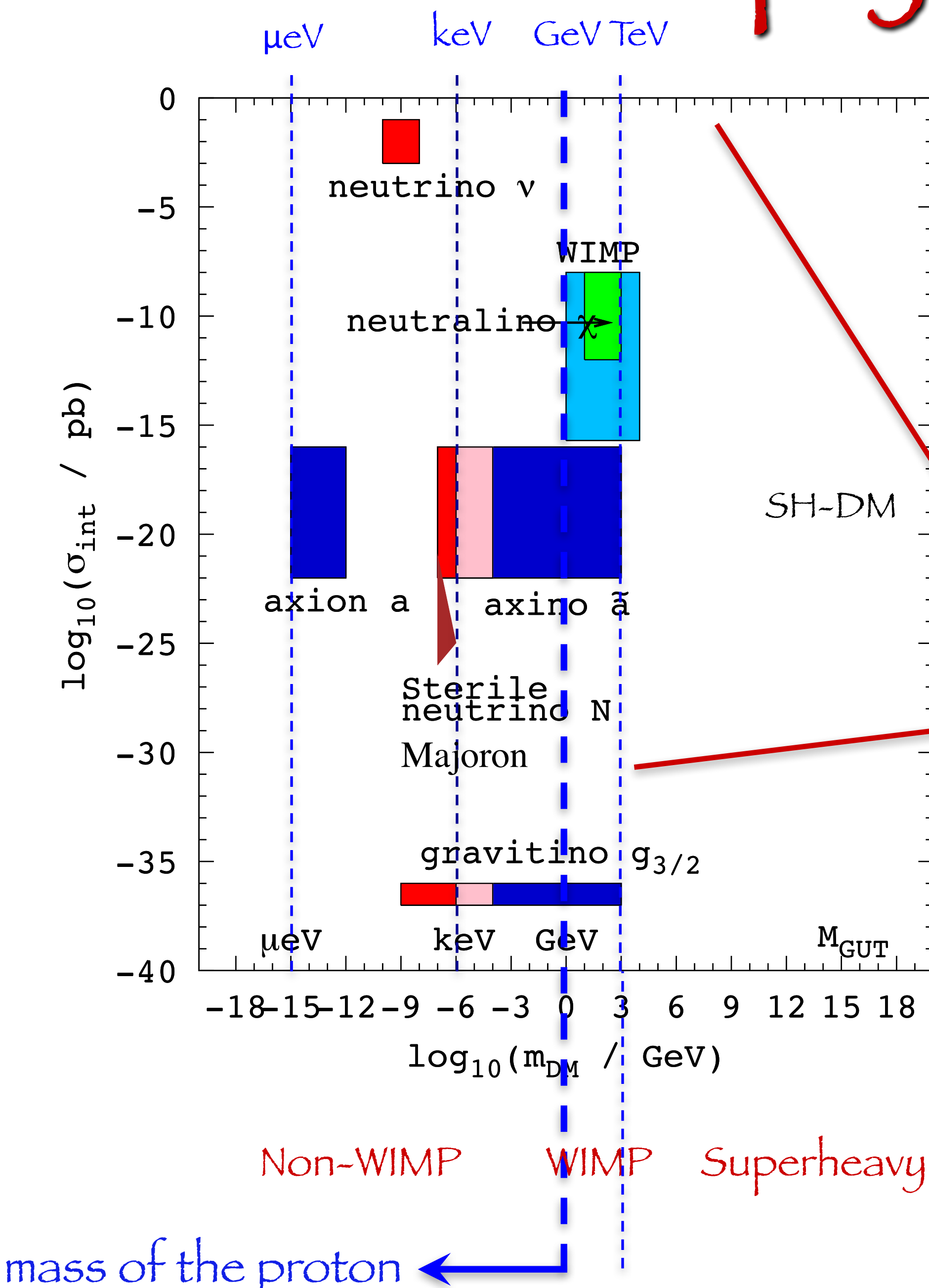
Techniques:

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

QUAX: high-frequency magnetometer

axion-electron coupling

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)

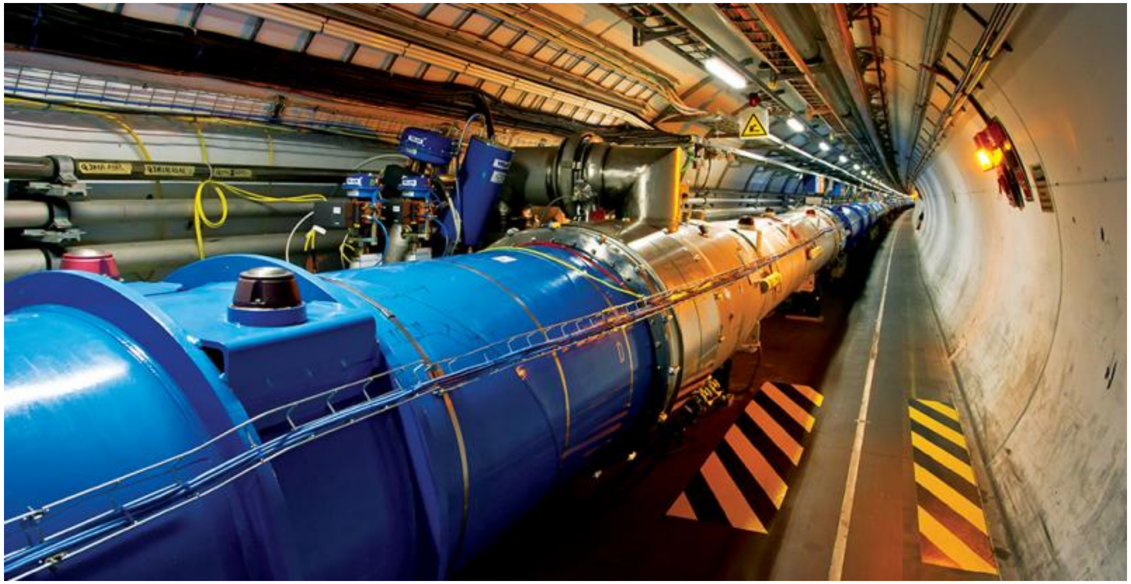
collisionless

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."

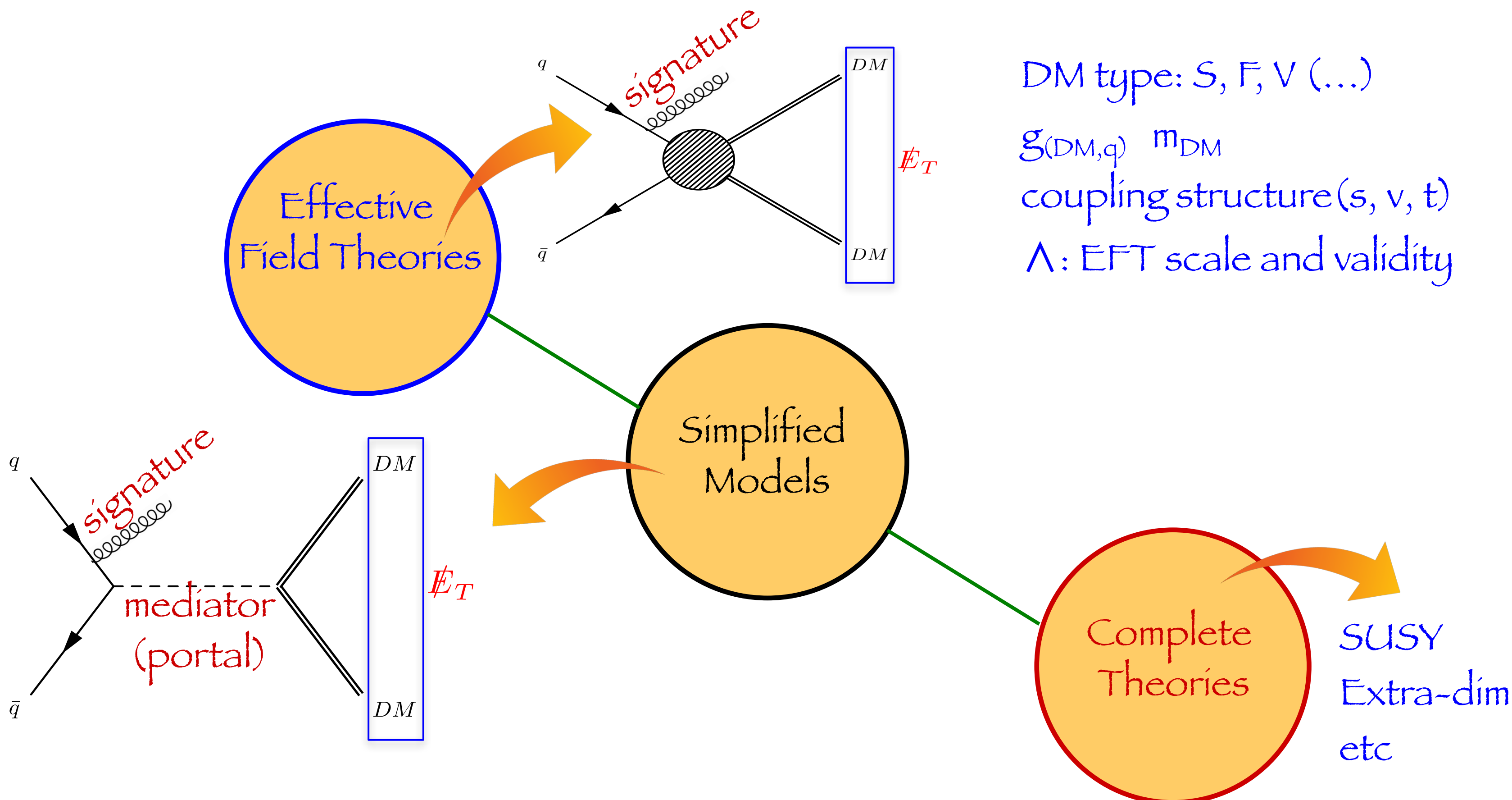
Try to produce the DM particle in a controlled environment

High-E accelerators:	for WIMPs (GeV-TeV)
Low-E accelerators:	for lighter states
Beam dumps, others:	for axions, ALPs



WIMPs at accelerators

Focus now is on the LHC runs



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

Portal: S, F, V, T

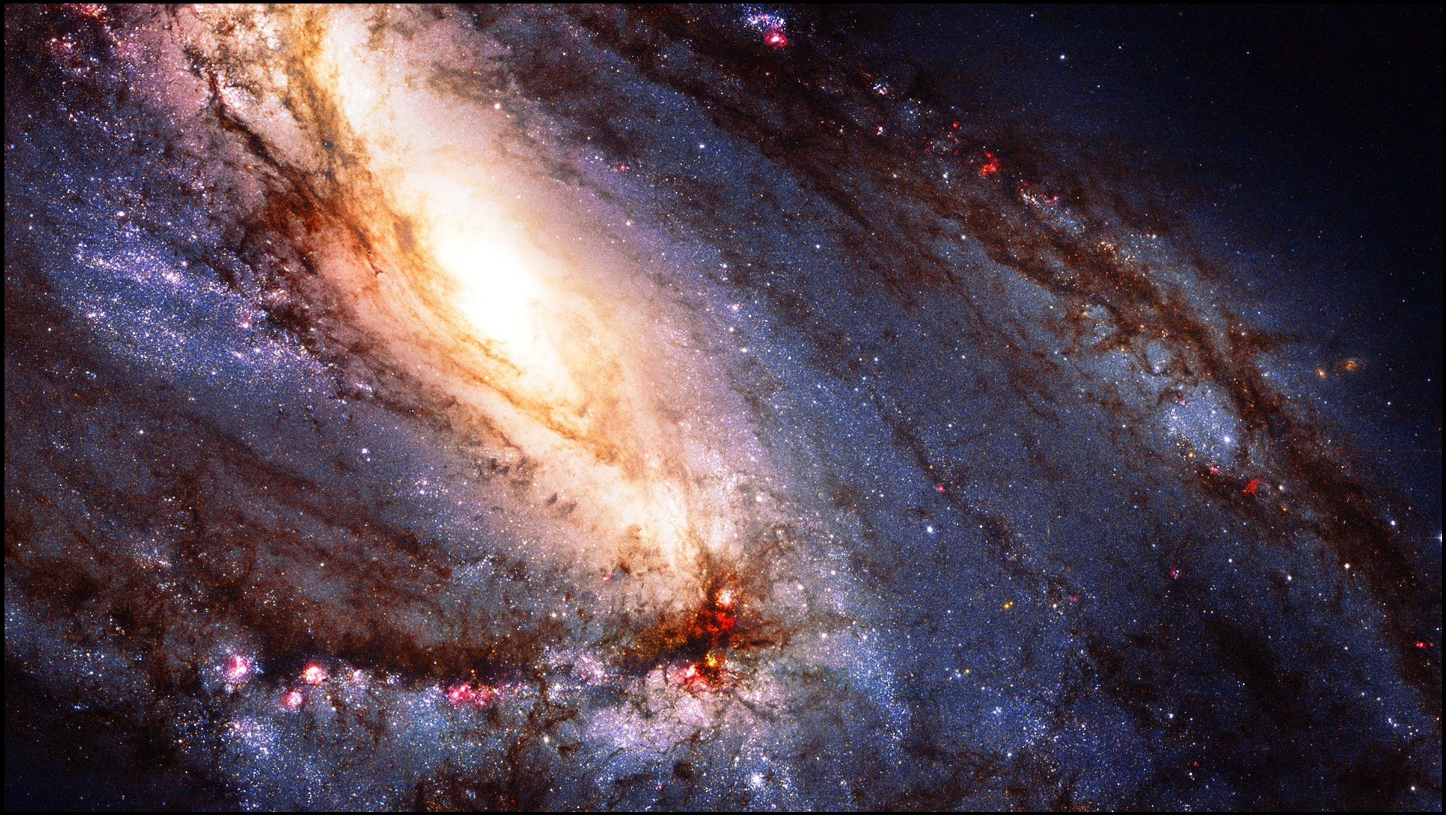
$g_{(DM,med)}$ m_{DM}

$g_{(med,\,q)}$ 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^-), and studies for accessing invisible decays
- Rich experimental program:
  - Hadronic beams
  - Electron beams
  - Meson decays

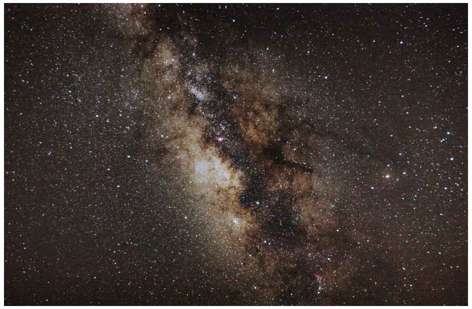
Look at the DM particle where DM is ...

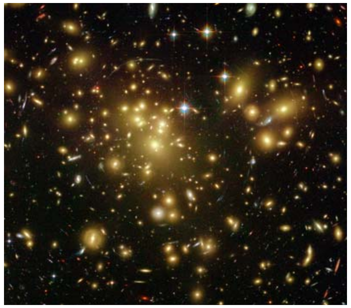


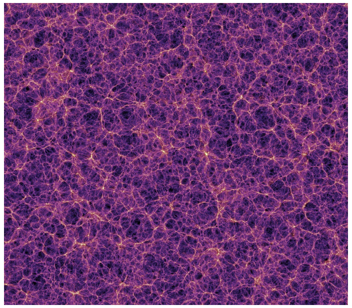
Where to search for a signal ...

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"



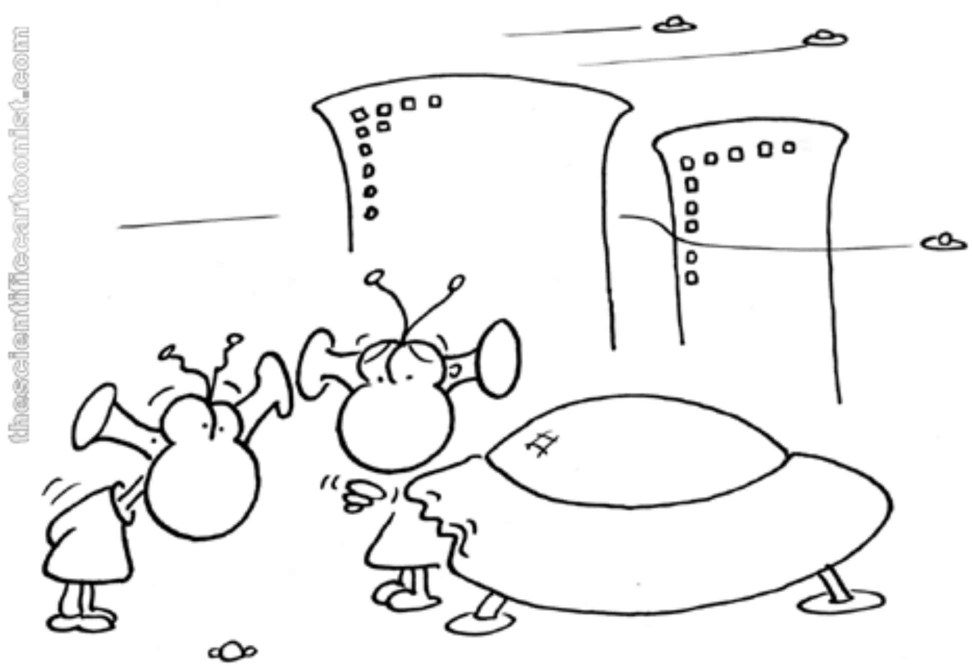




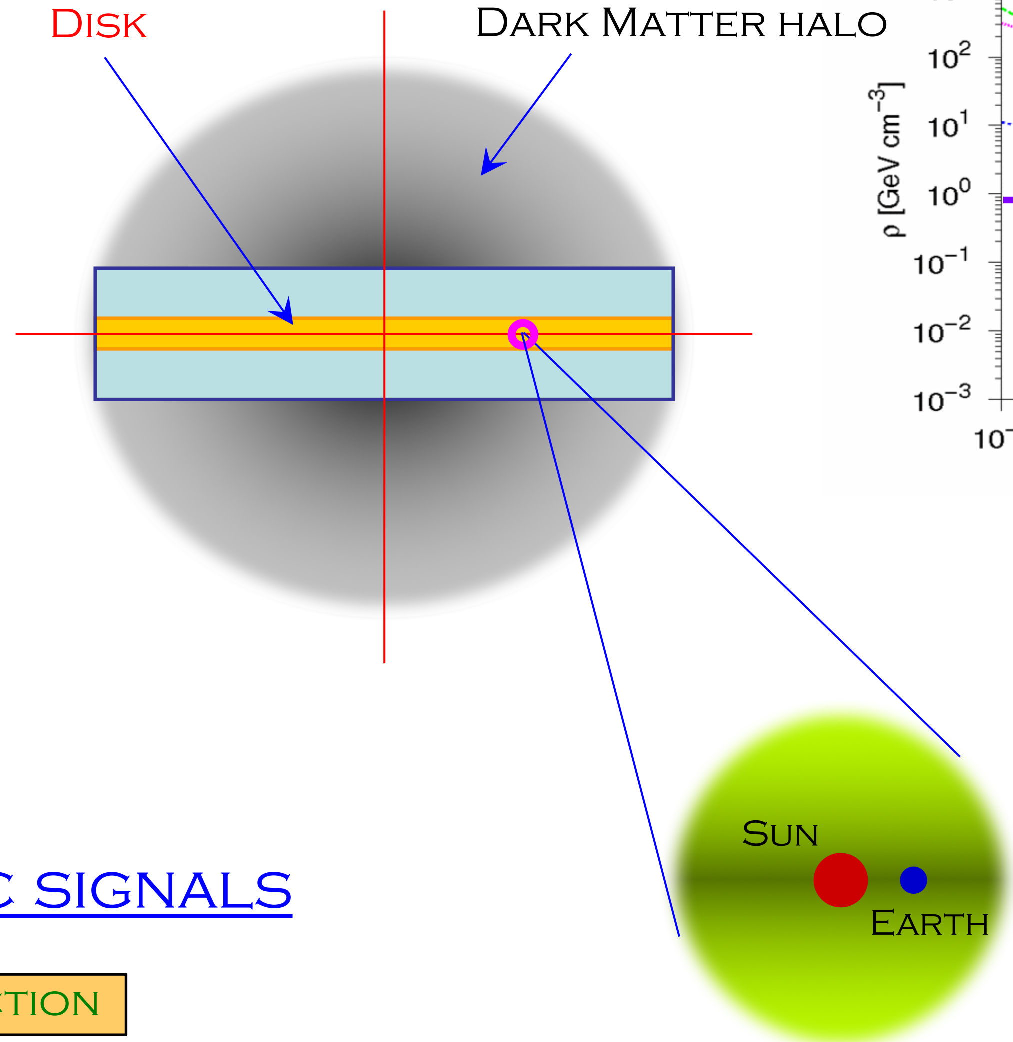
DM as a particle might ...

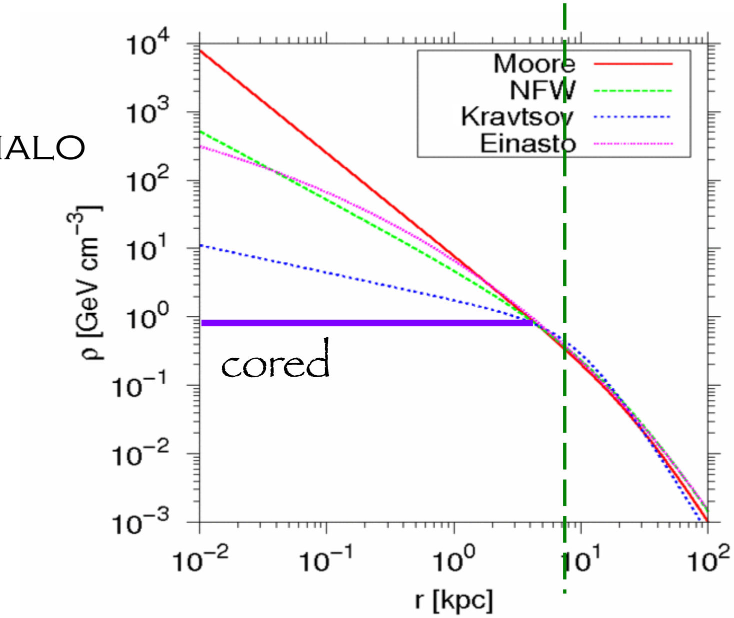
Interact with ordinary matter — Direct detection

Produce effects in astrophysical environments, like in stars



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



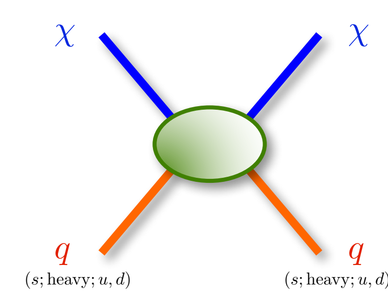


Galactic signals

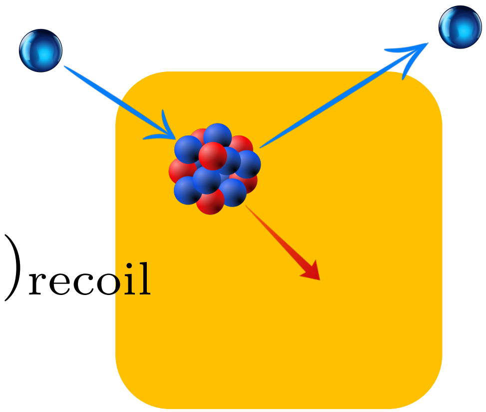
Direct detection

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)

Typical signatures of direct detection

- Stationary over the lifetime of an experiment
  Directional boost

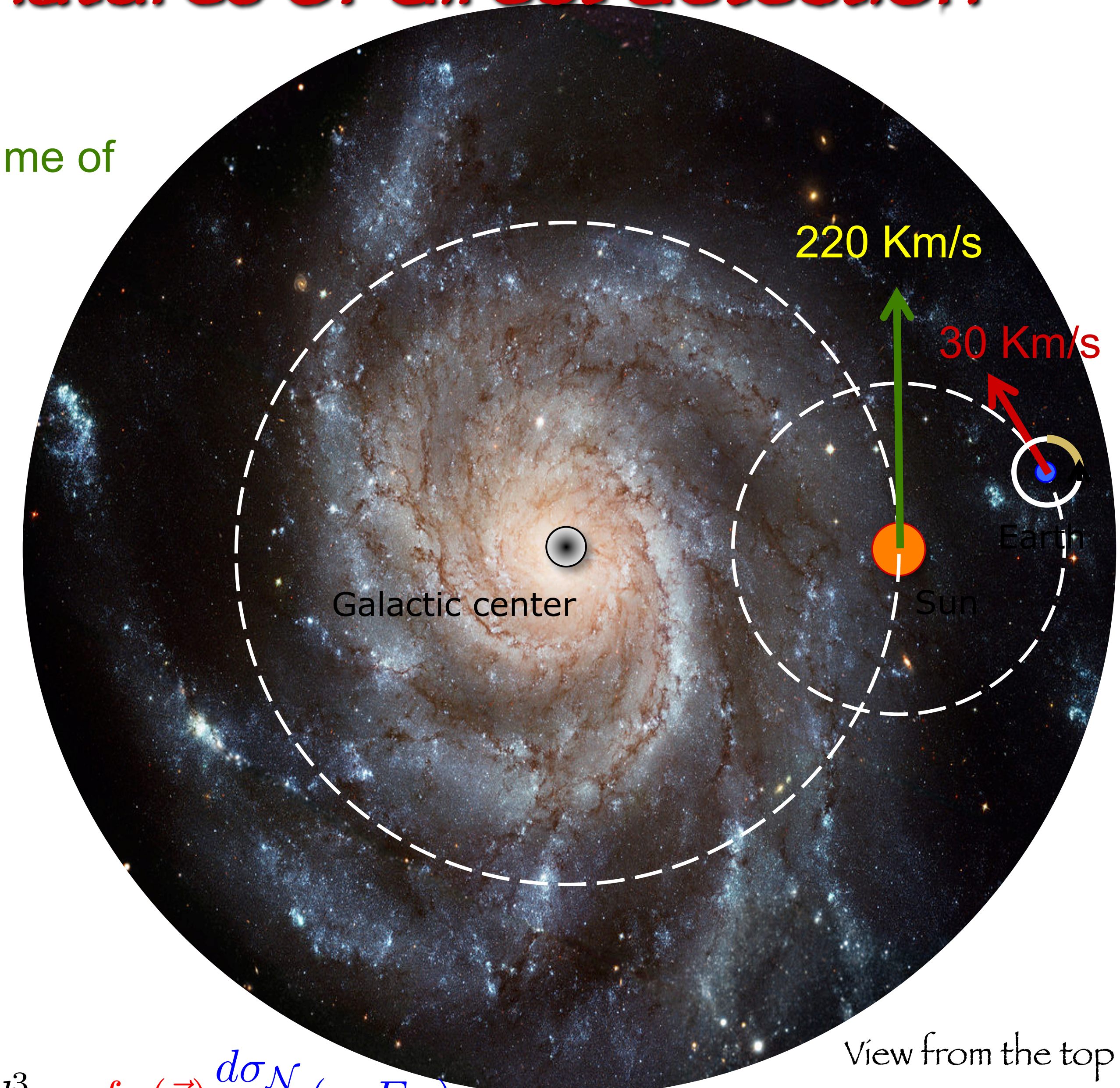
  Directionality

- Period: 1 year

  Annual modulation

- Period: 1 day

  Diurnal modulation



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

Annual modulation

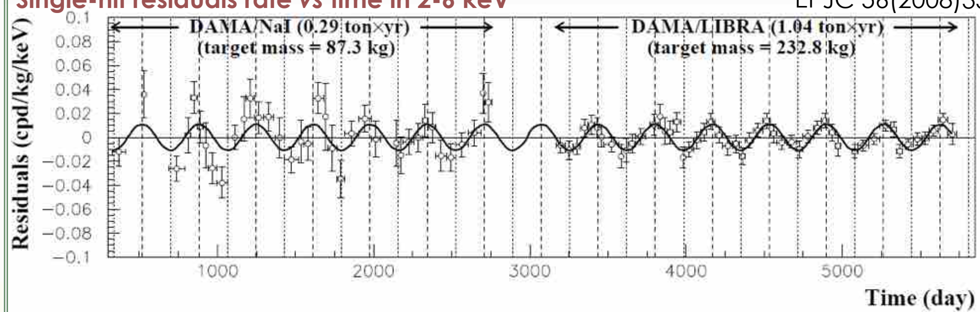
DAMA, 9.2σ with 1.33 ton x yr, 15 cycles

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

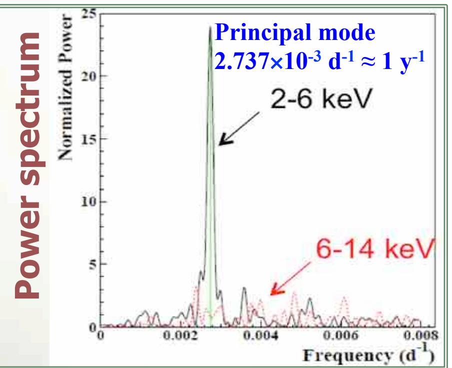


continuous line: t_0 = 152.5 d, T = 1.0 y

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

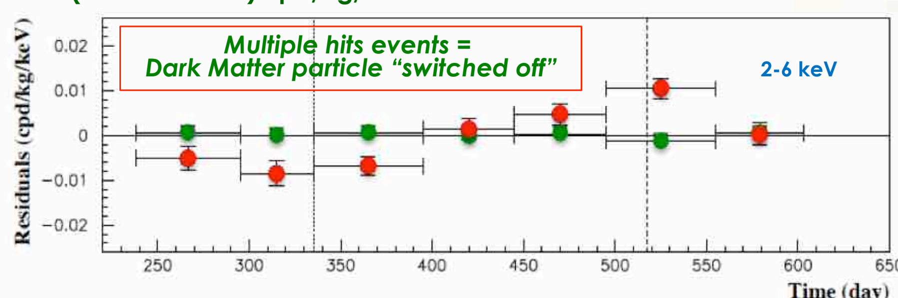
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

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.



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

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



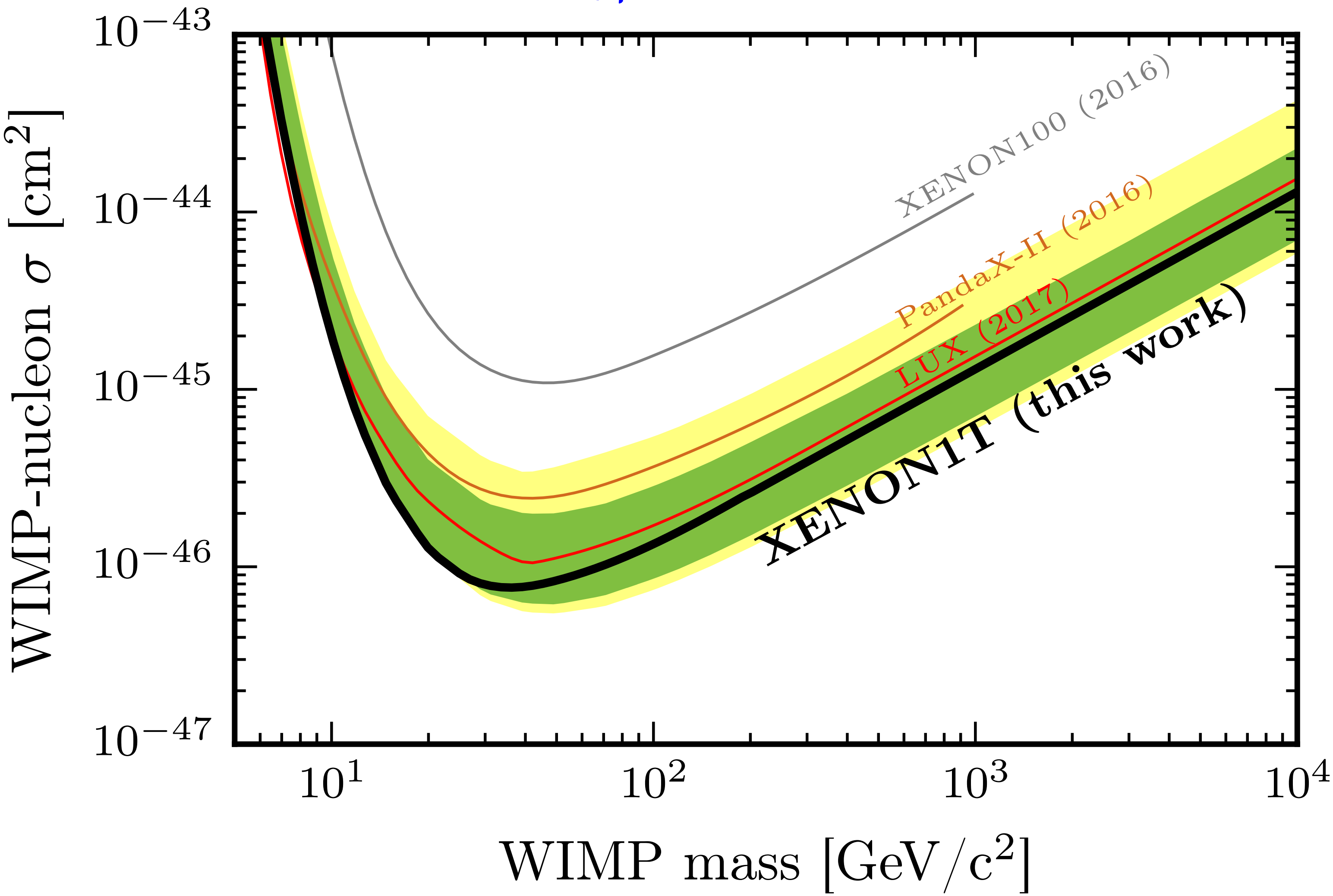
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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

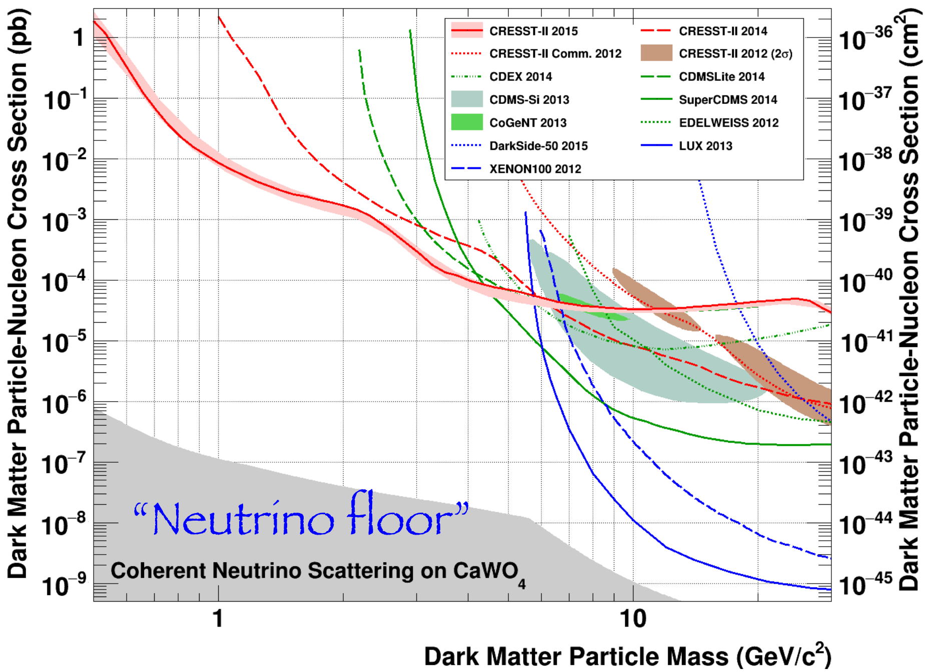
High WIMP mass

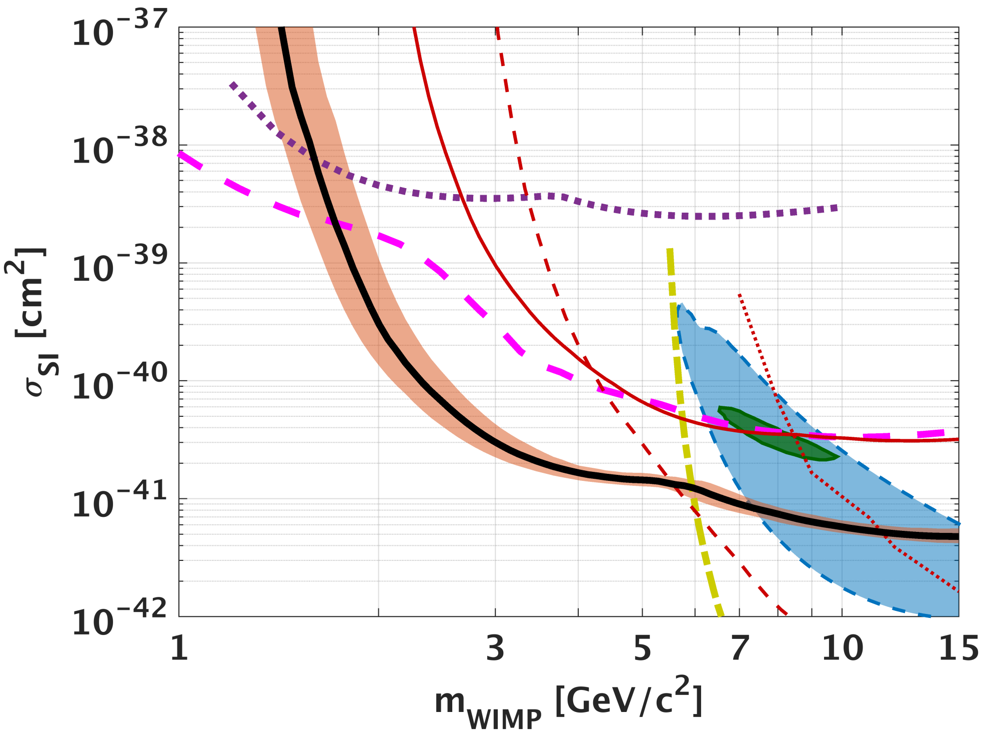
Contact-type scalar interactions (O_1)



Aprile et al (XENON 1T Collab), 1705.06655

Low WIMP mass





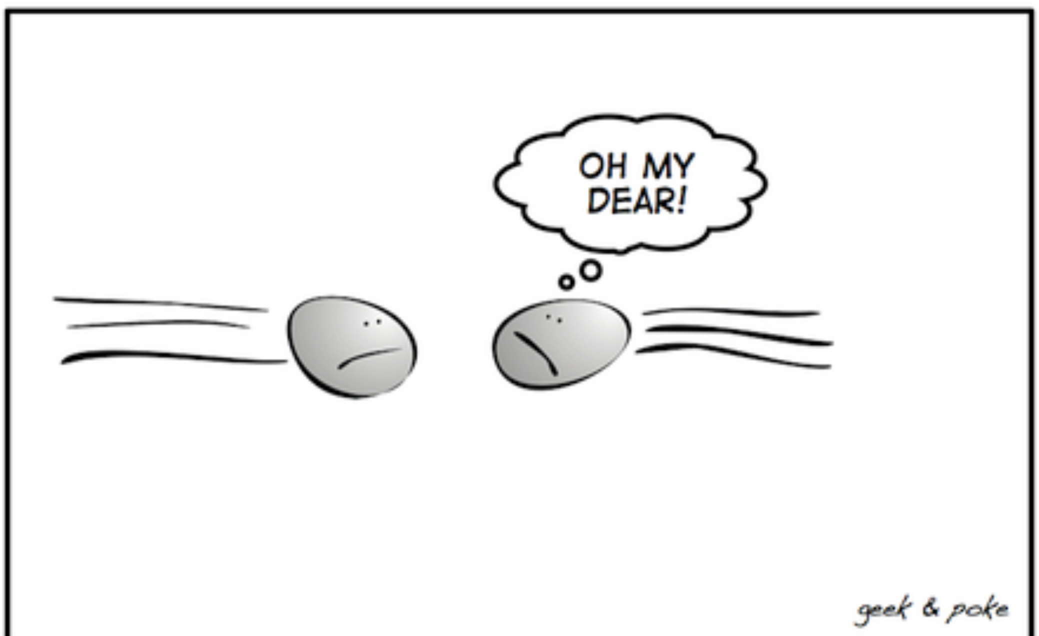
Angloher et al (CRESST), EPJC 76 (2016) 25

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

Contact-type scalar interactions (O_1)

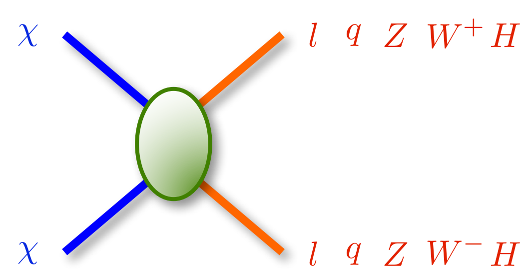
DM as a particle might ...

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)

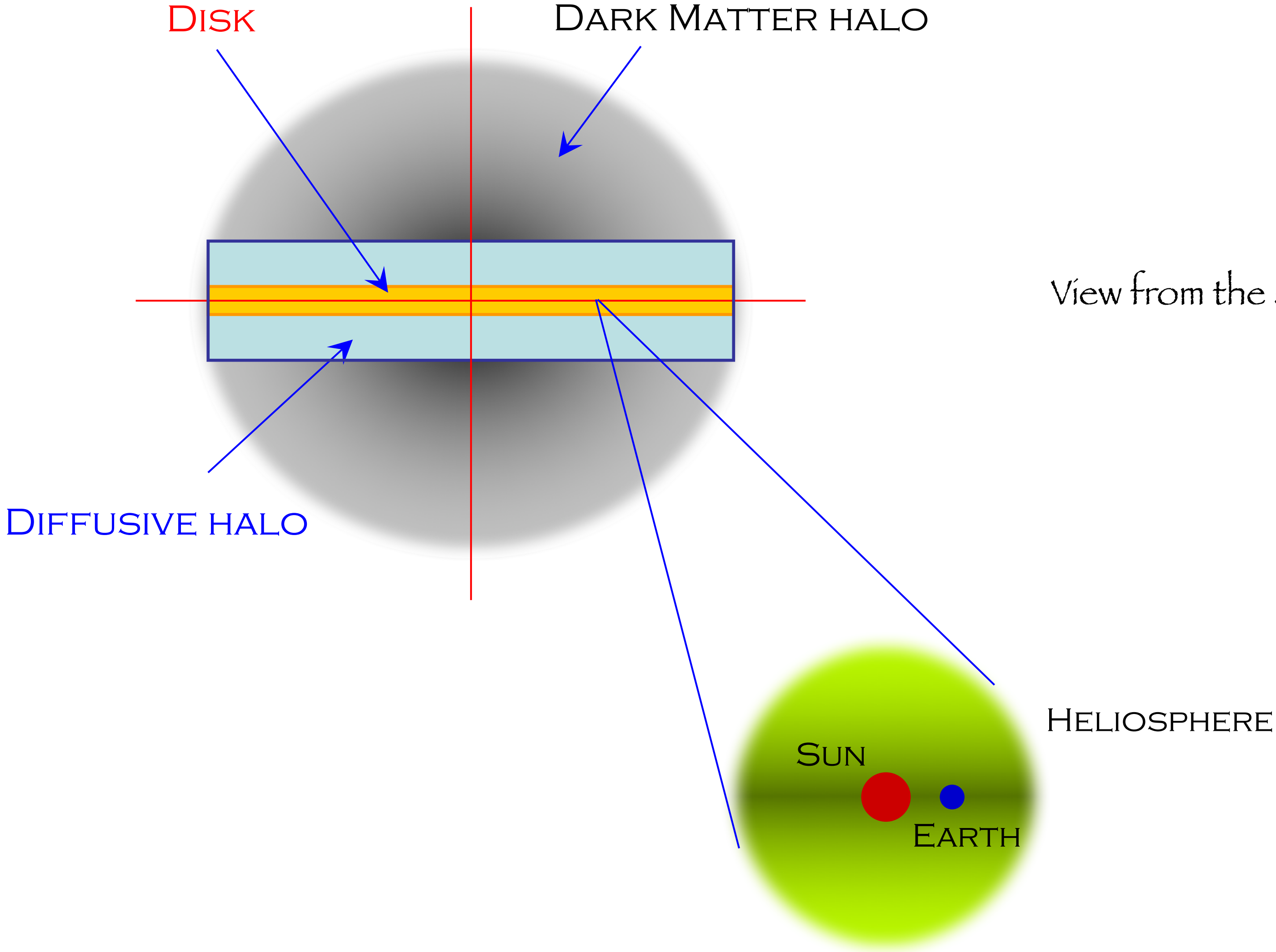
Neutrinos

Photons

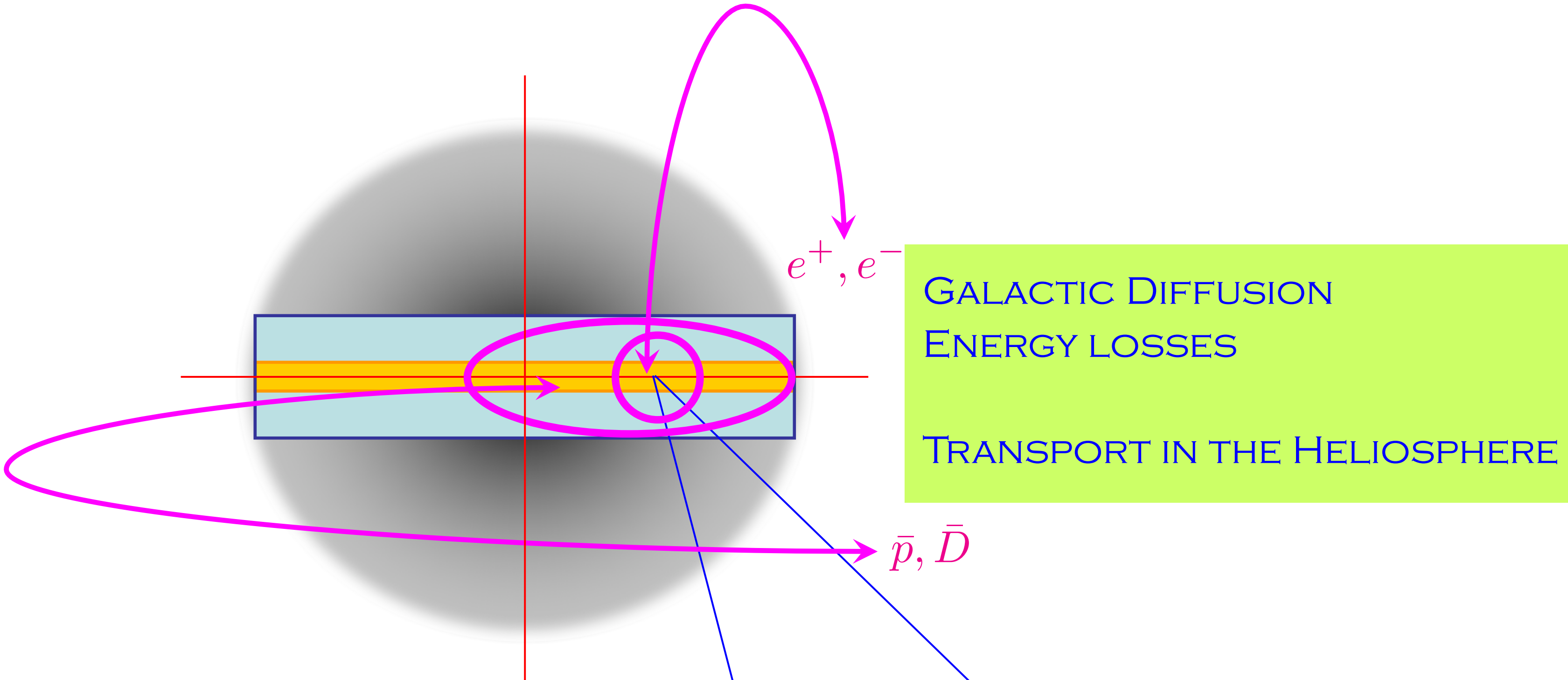
- Gamma-rays
  - Prompt production
  - IC from $e^{\pm}$ on ISRF and CMB
- X-rays
  - IC from $e^{\pm}$ on ISRF and CMB
- Radio
  - Synchro from $e^{\pm}$ on mag. field

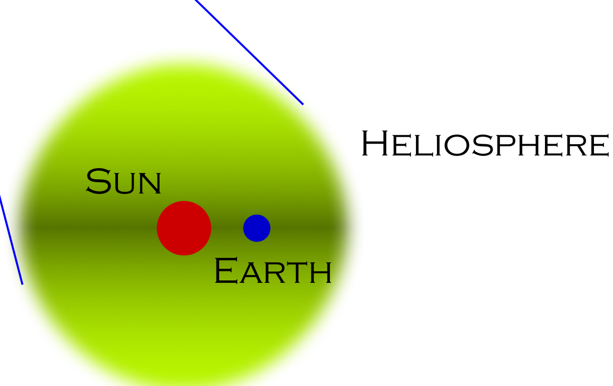
$$\chi\chi \longrightarrow (\bar{l}l, \bar{q}q, ZZ, W^+W^-, GG, HH)^{\text{had}}_{\text{dec}} \longrightarrow \gamma\,,\ \nu\,,\ e^{\pm}\,,\ \bar{p}, \bar{D}$$

Galactic environment



View from the side

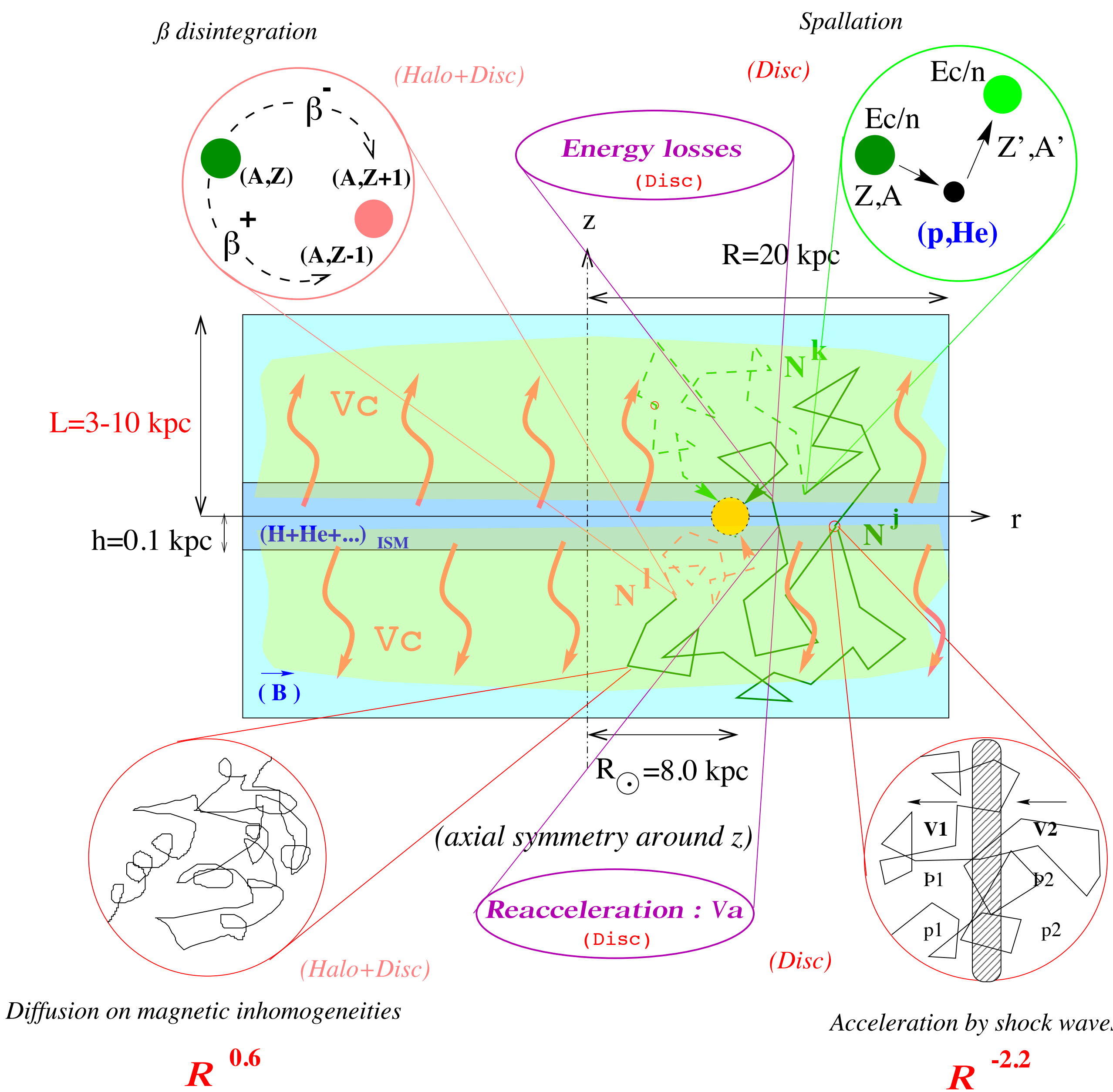




Galactic signals

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

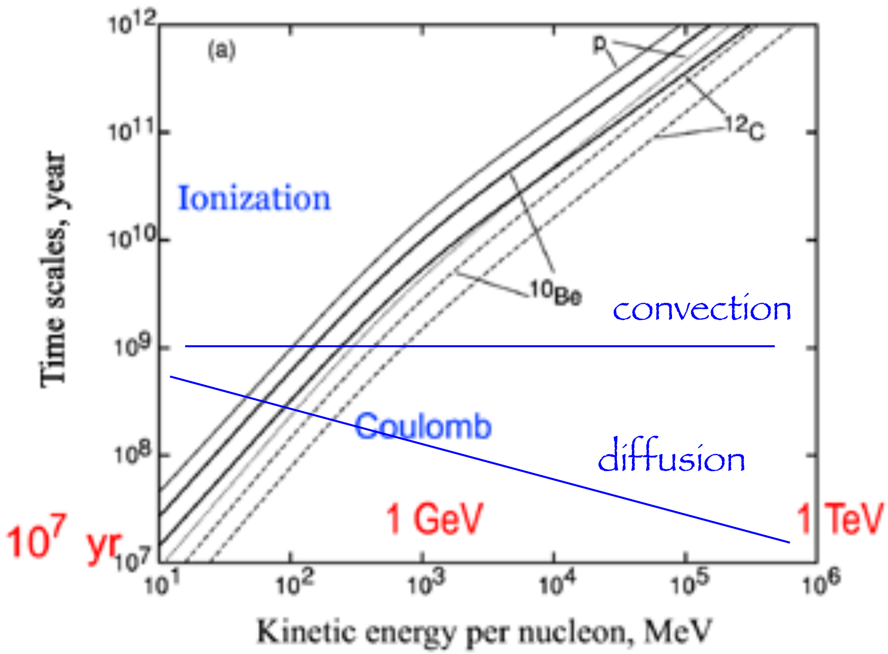
$$Q_j(E,\vec{r})$$

Secondary sources

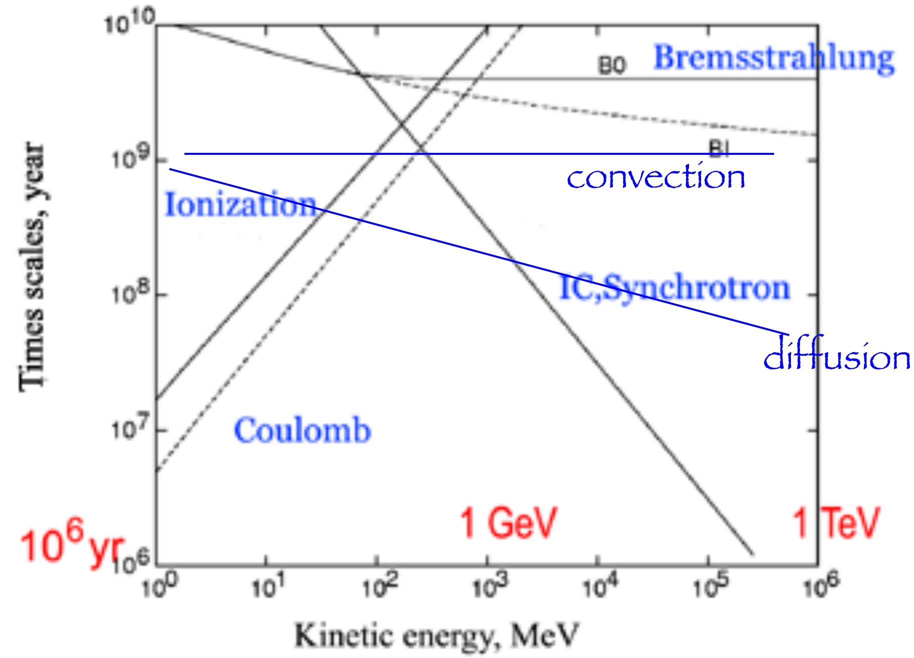
$$+\sum_{m_i>m_j}\Gamma_{i\rightarrow j}N_i$$

Time scales

nucleons



electrons & positrons



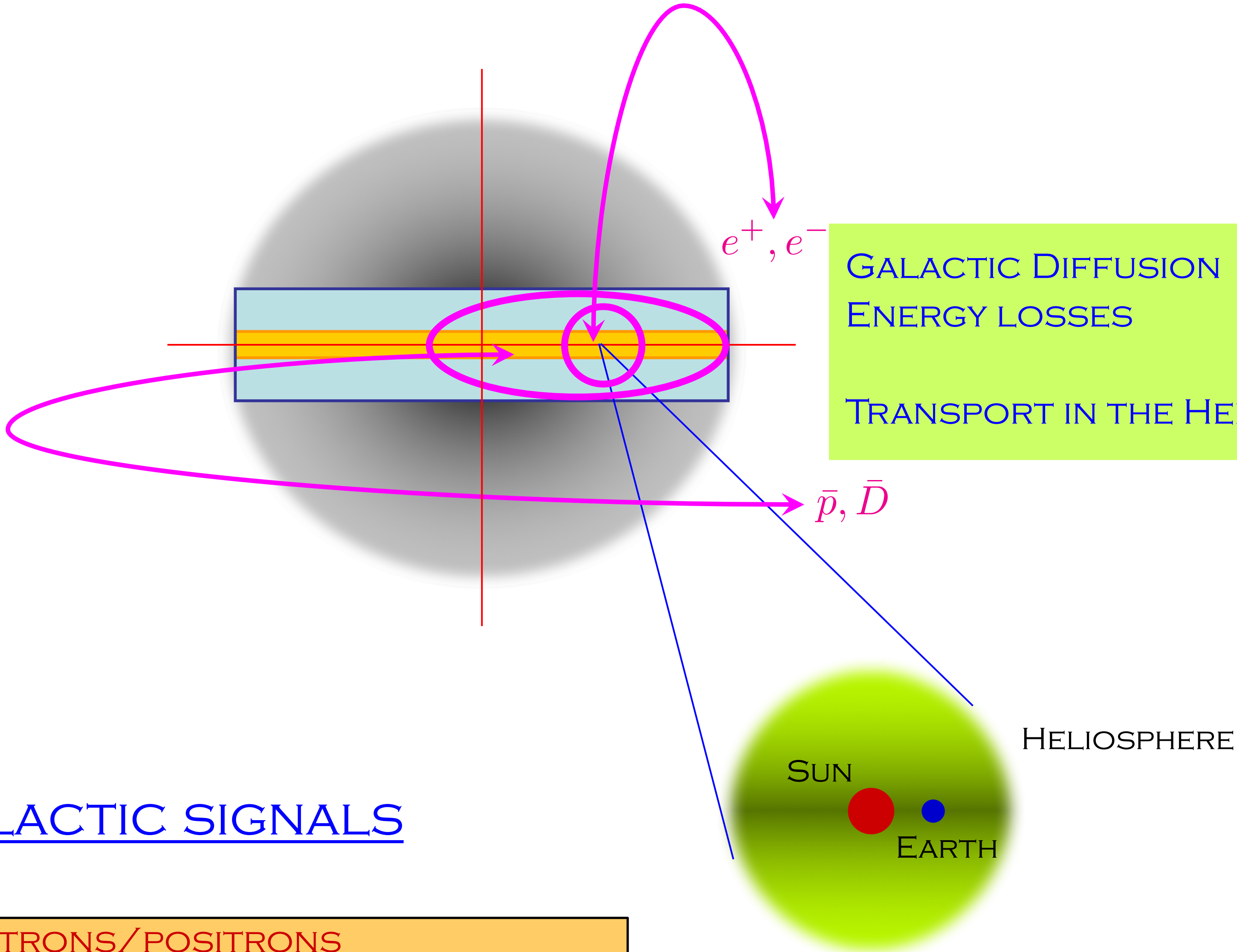
Dominant effects

Nuclei escape from the Galaxy
Leptons loose their energy

Local origin

Low energy radioactive nuclei
High energy electrons and positrons

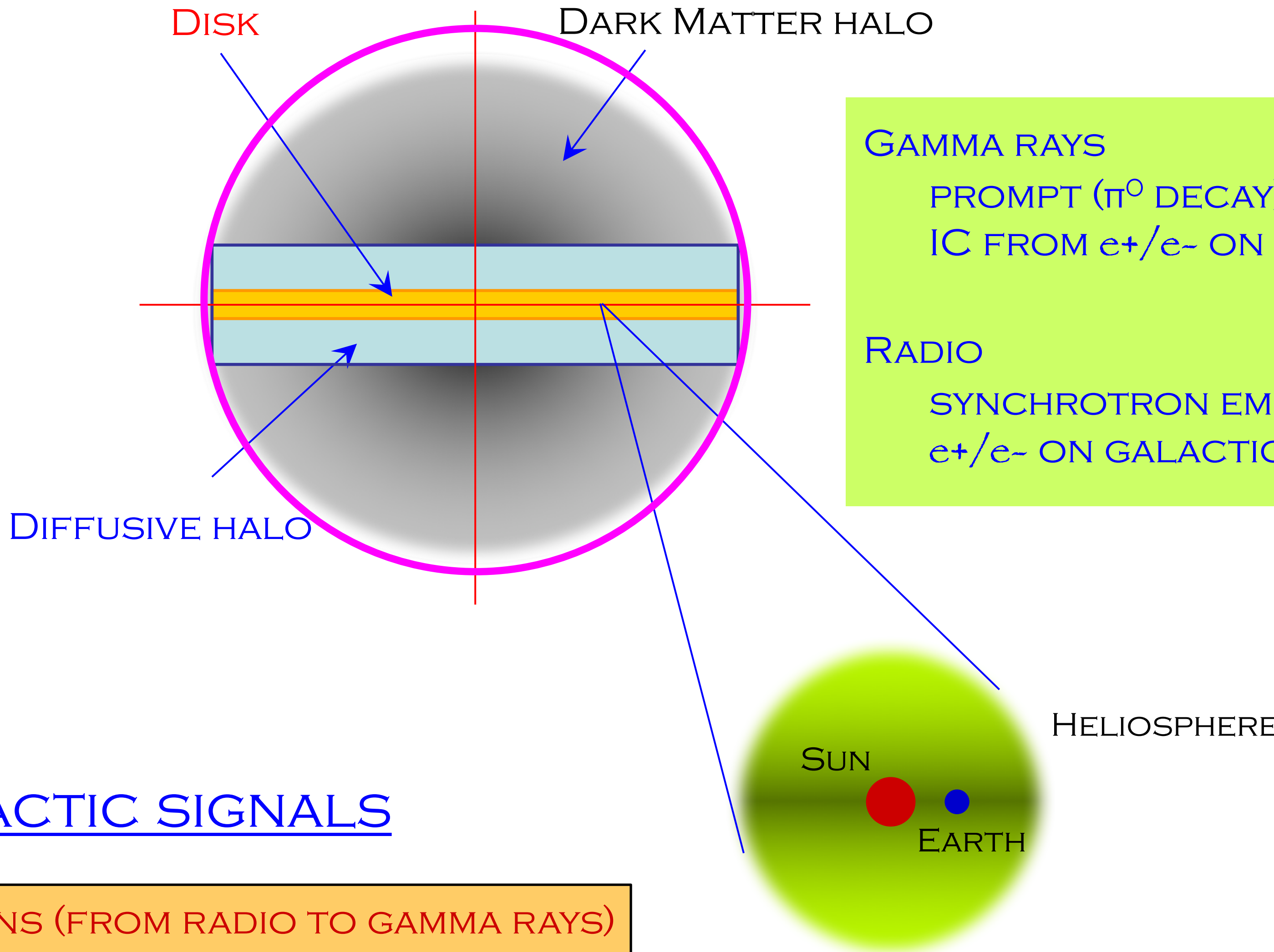
Galactic signals



Galactic Diffusion
Energy losses

Transport in the Heliosphere

Electrons/positrons
Antiprotons
Antideuterons



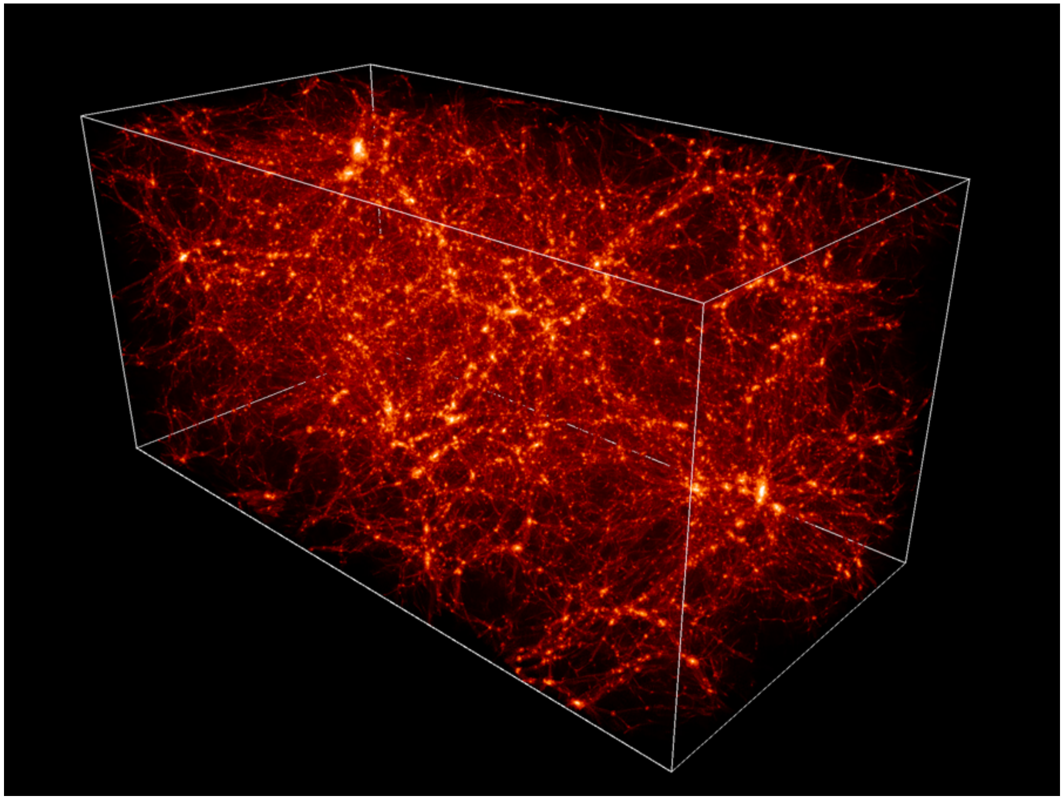
Gamma rays
- prompt (π^0 decay)
- IC from e+/e- on ISRF

Radio
- synchrotron emission from e+/e- on galactic B

Galactic signals

Photons (from radio to gamma rays)
Neutrinos from the Galaxy

Extra-galactic environment

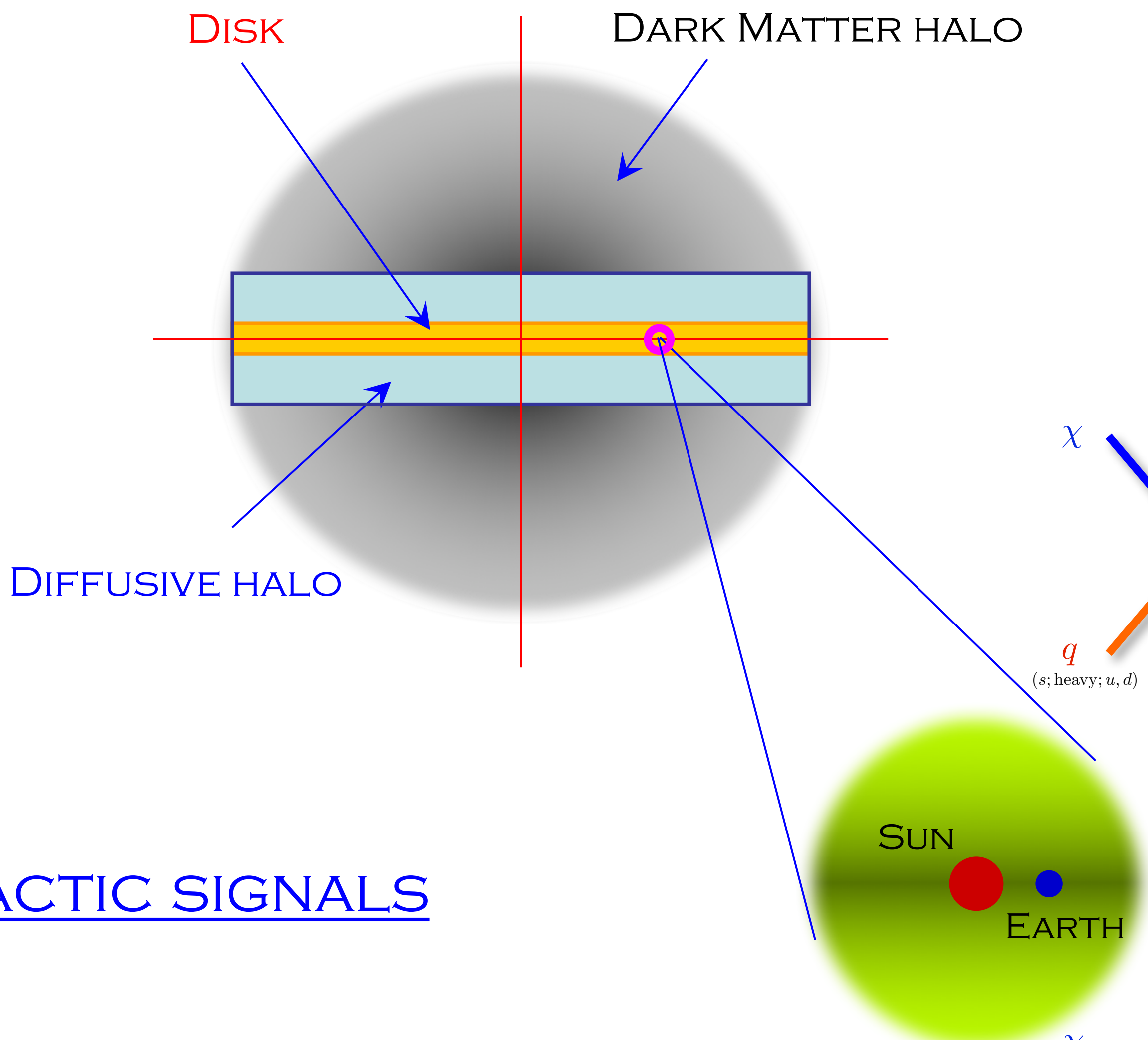


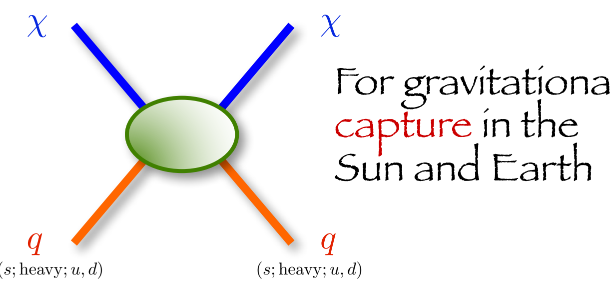
Extragalactic signals

Photons: gamma, X, radio
Neutrinos

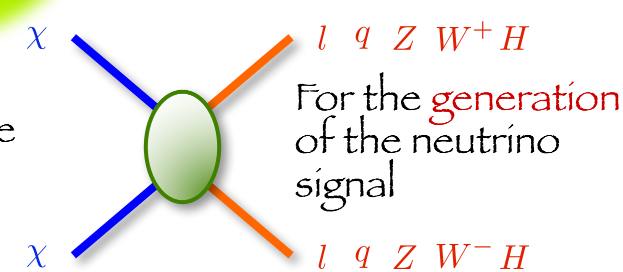
Sunyaev-Zeldovich effect on CMB
Optical depth of the Universe

Galactic signals





Feels ony the local DM density (not space distribution)
Feels (somehow) how DM is locally distributed in velocity space



Neutrinos from Earth and Sun

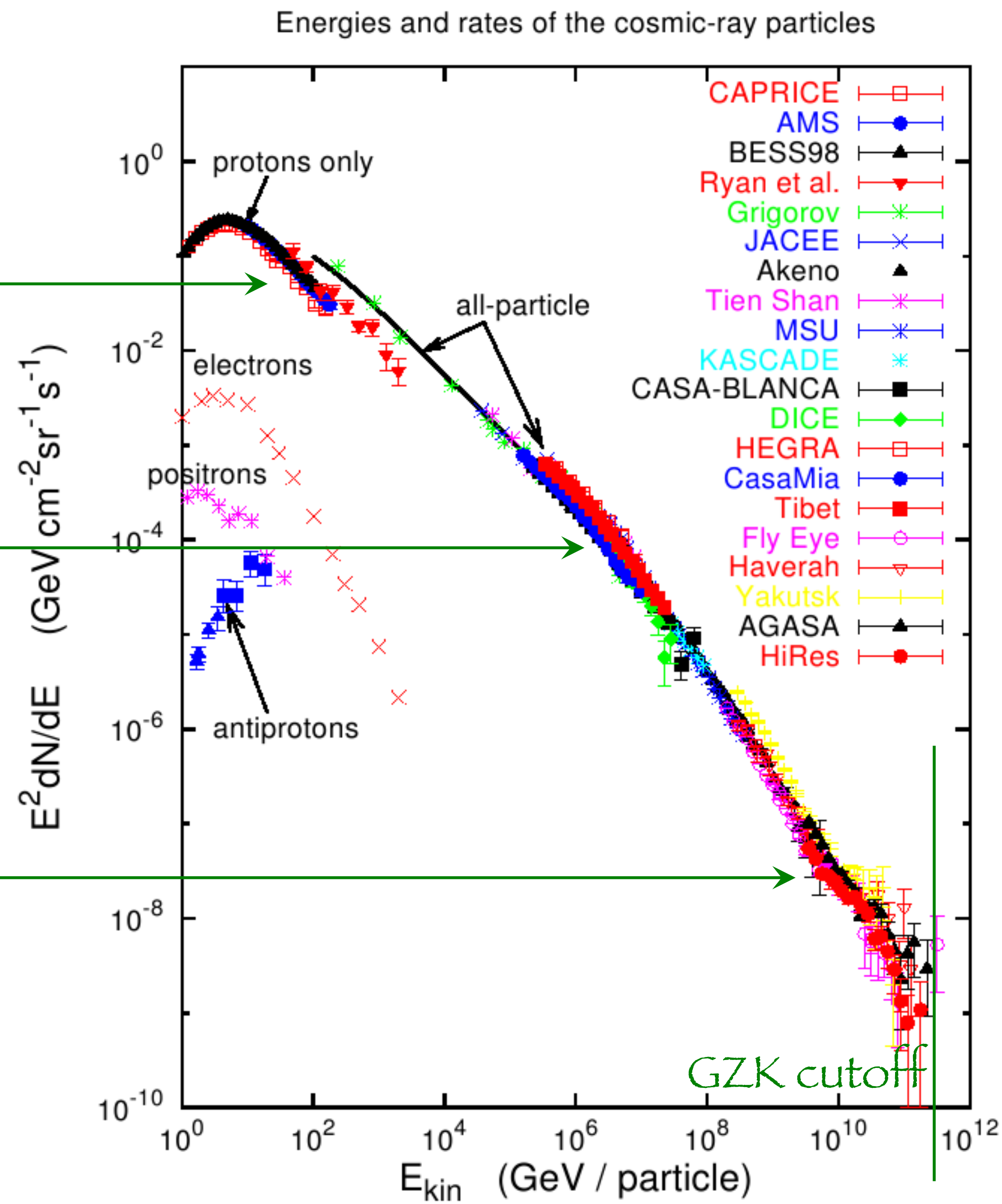
Charged cosmic rays signals

Cosmic rays

1 particle per m^2 sec

Knee
1 particle per m^2 year

Ankle
1 particle per km^2 year

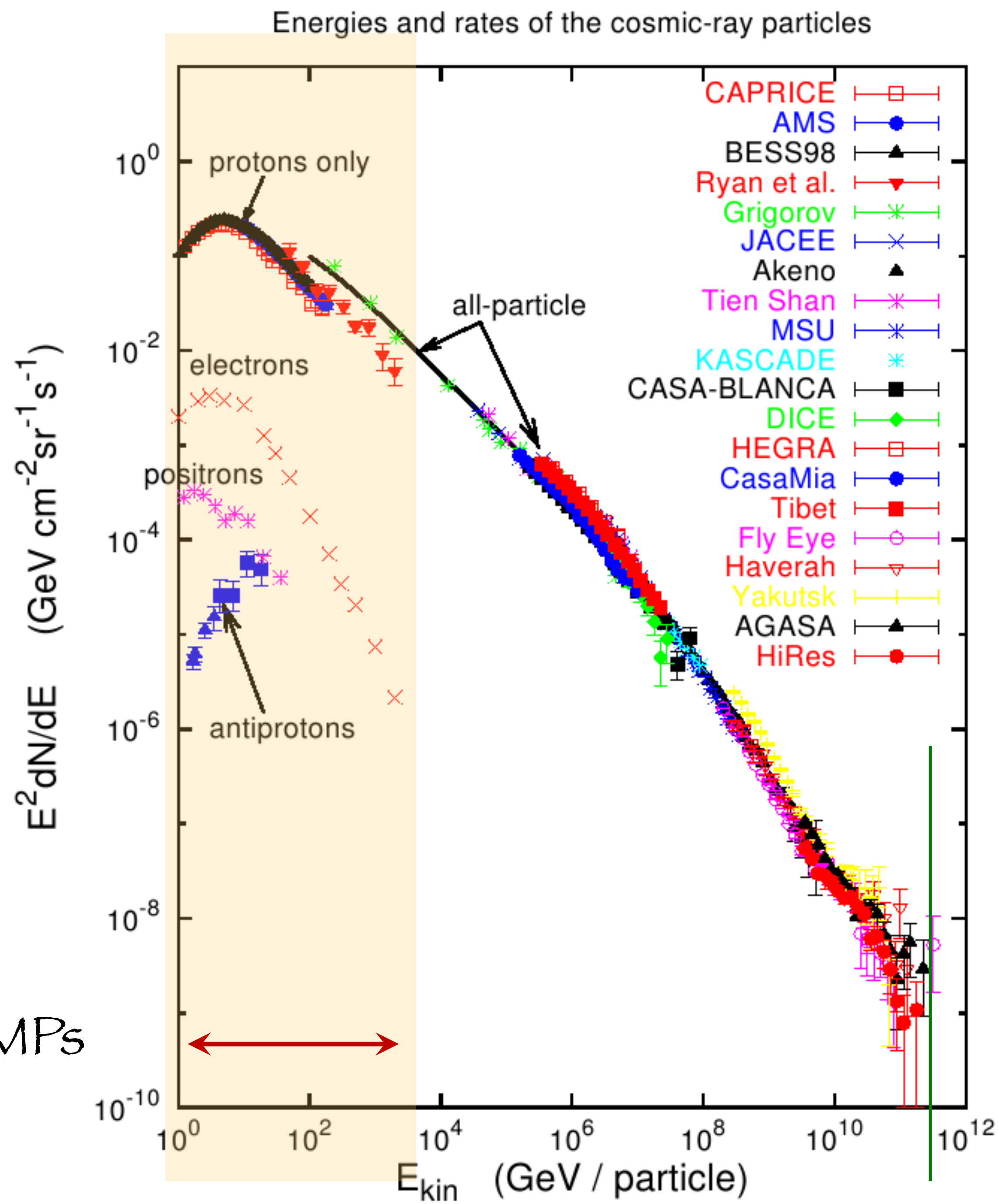


Cosmic rays

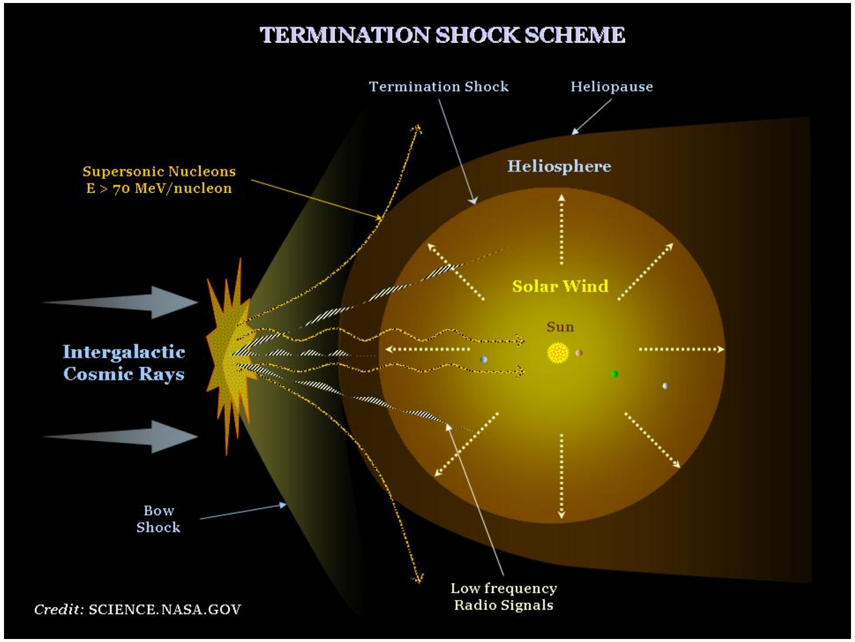
Antimatter << Matter

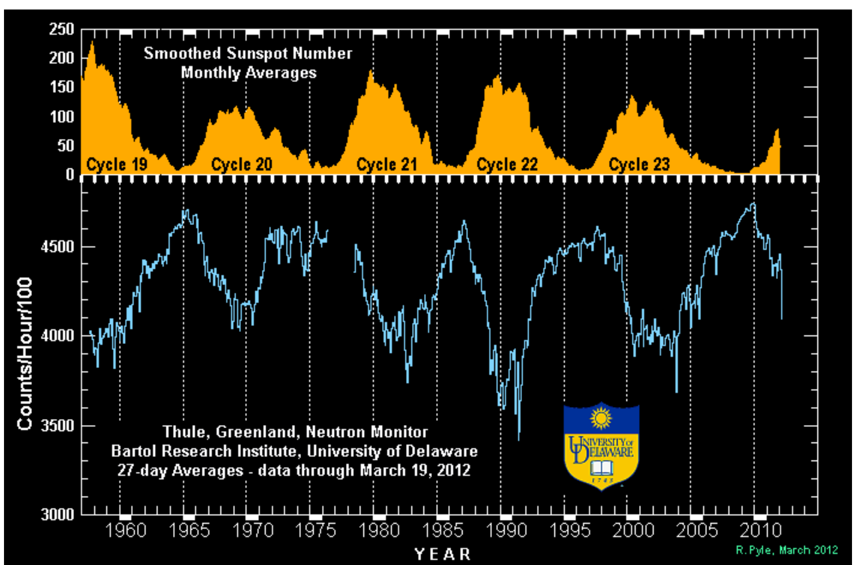
Better to search for the DM signal in the antimatter channel

Energies relevant for WIMPs



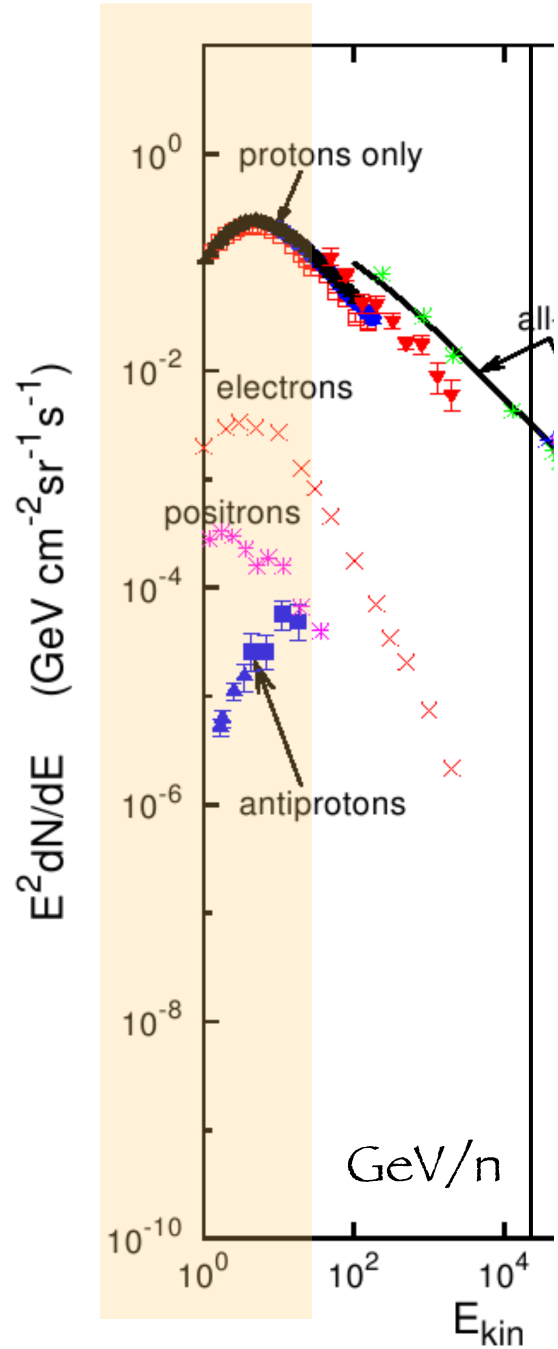
Cosmic rays





Affected by solar wind

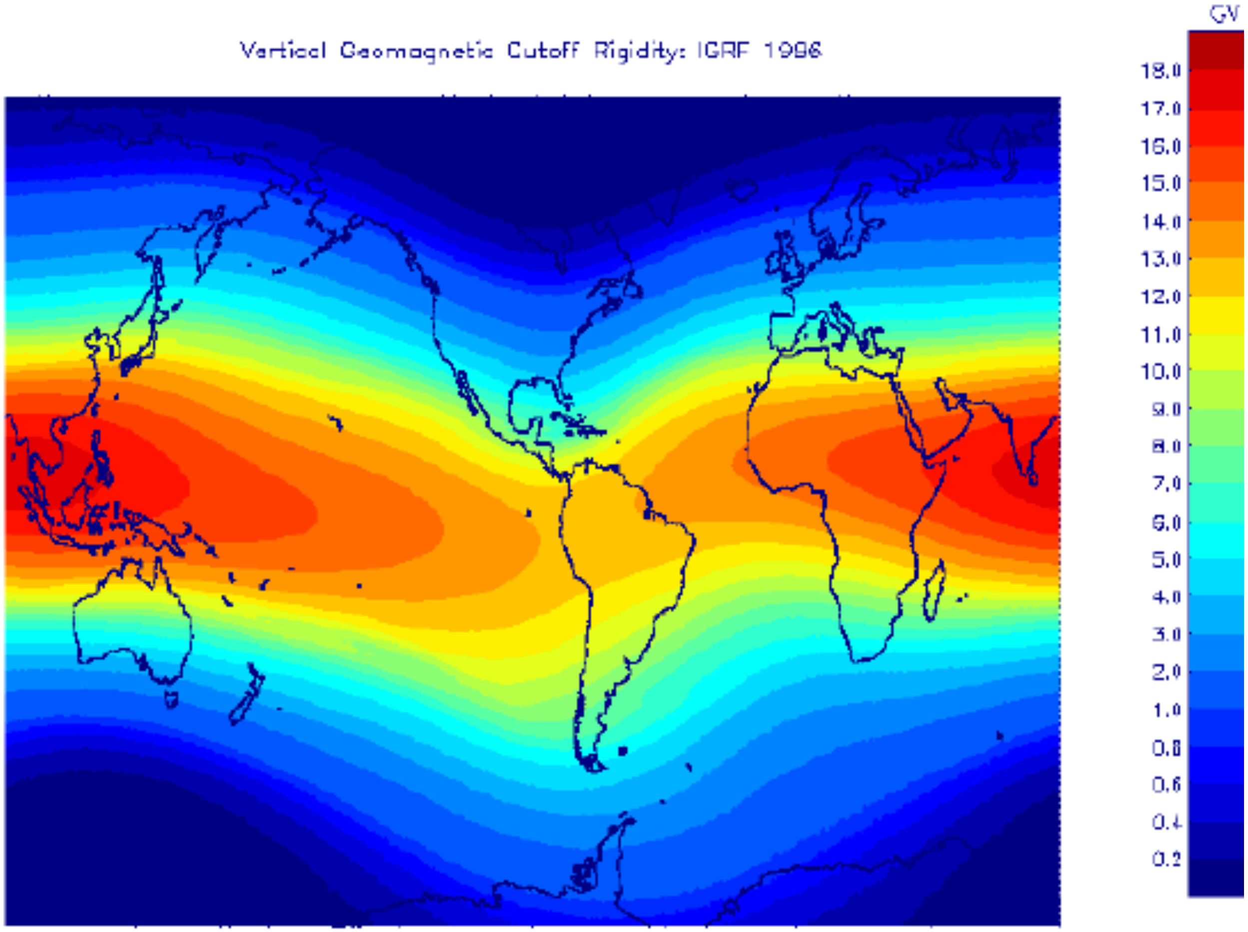
E < 30 GeV

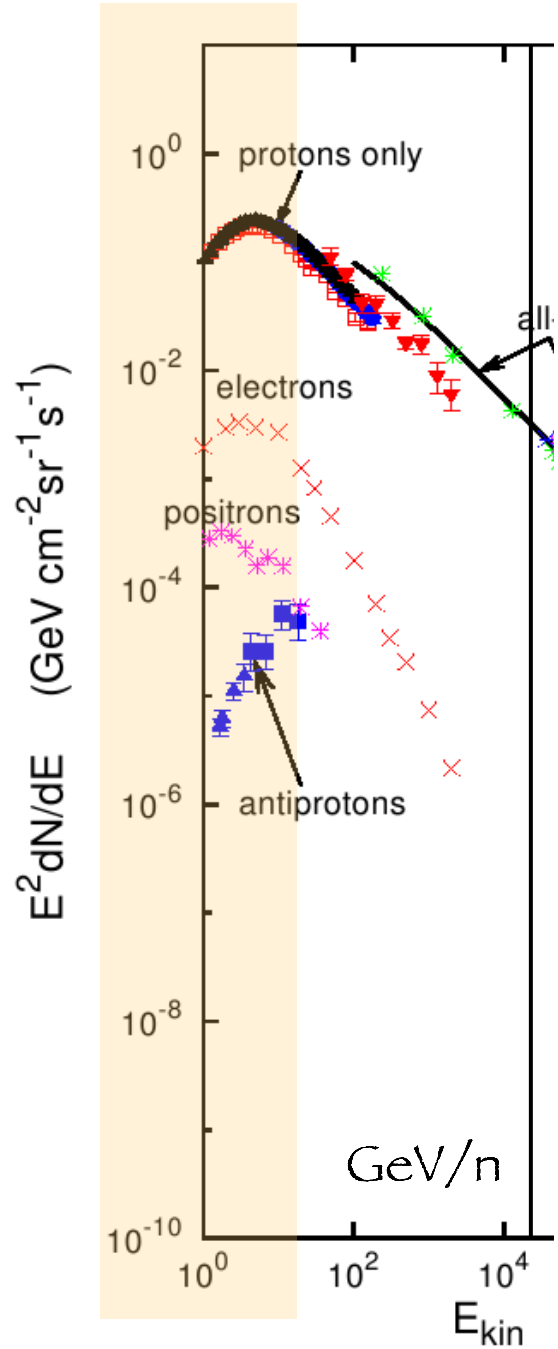


Cosmic rays

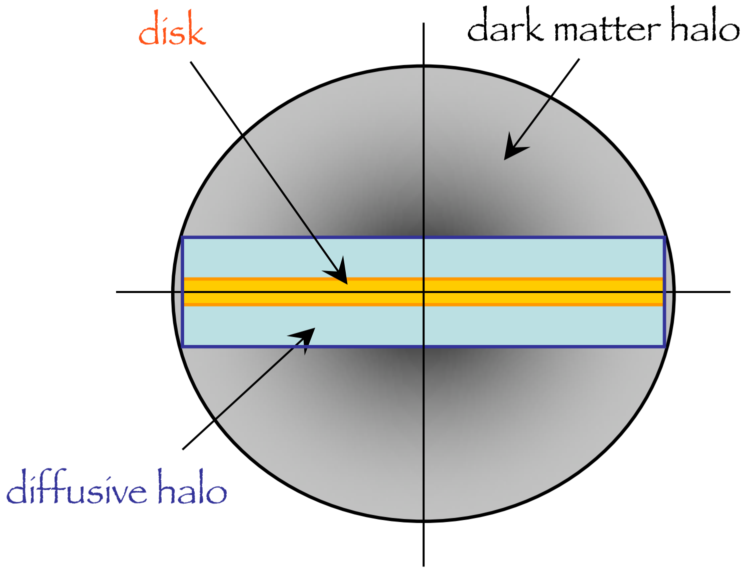
Affected by Earth magnetic field

Geomagnetic cutoff: $R_C \approx 15 \cos^4(\text{lat})$ GV





Cosmic antiprotons



Secondaries (background)

$$
\begin{array}{rcl}
p_{\mathrm{CR}} + p_{\mathrm{ISM}} & \longrightarrow & \bar{p} \\
p_{\mathrm{CR}} + He_{\mathrm{ISM}} & \longrightarrow & \bar{p} \\
He_{\mathrm{CR}} + p_{\mathrm{ISM}} & \longrightarrow & \bar{p}
\end{array}
$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

$$\chi\chi \longrightarrow (\ldots) \longrightarrow p\bar{p}$$

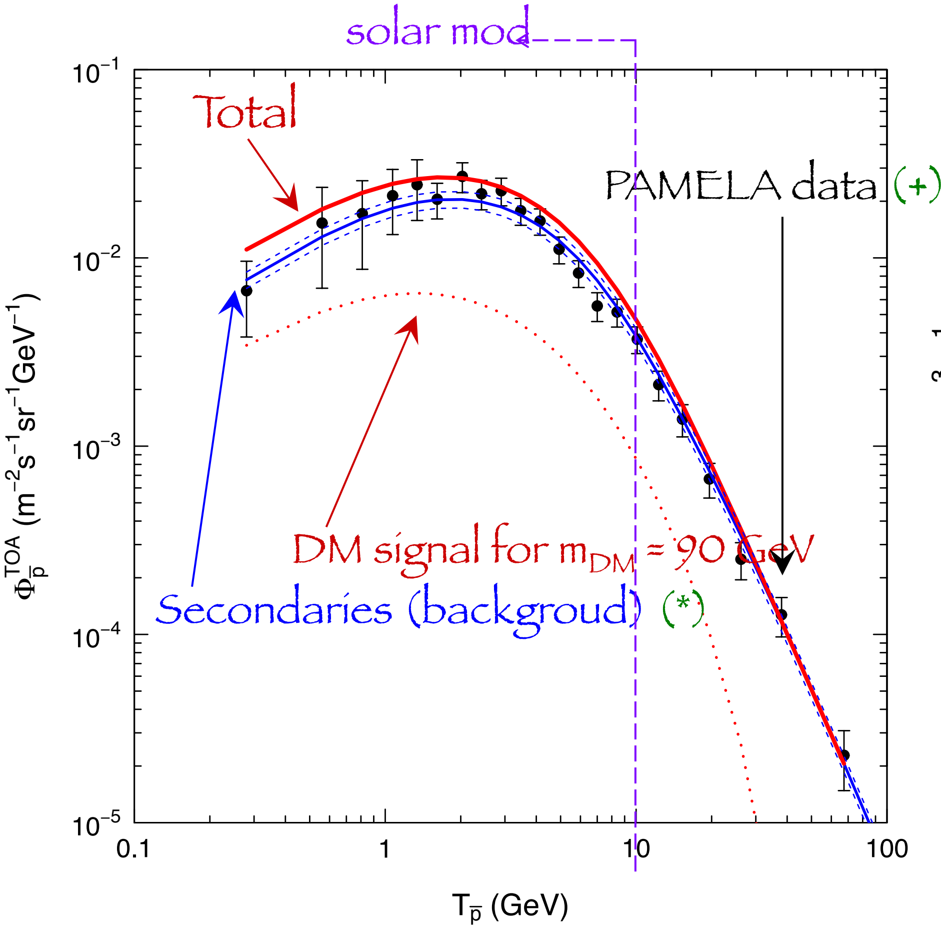
Produced in the DM halo

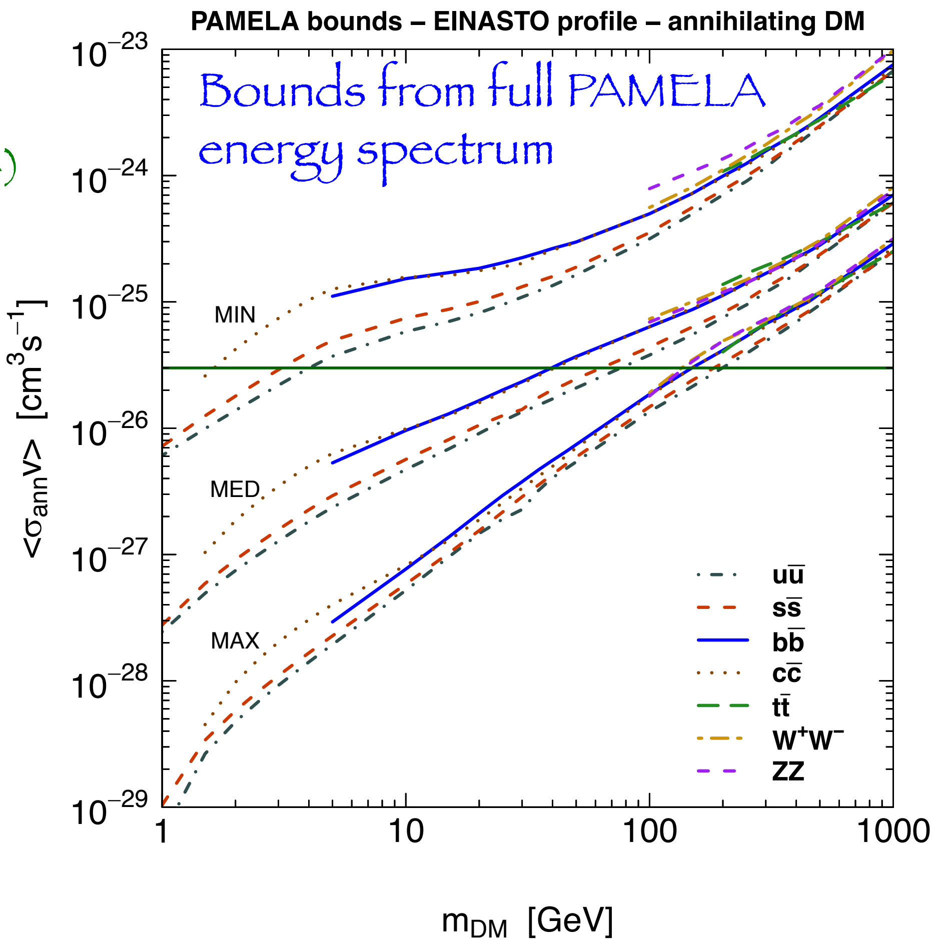
Propagation and energy redistribution in the diffusive halo

$$q^{\mathrm{DM}}(r,z,E) = \langle\sigma v\rangle\, g(E) \left(\frac{\rho_\chi(r,z)}{m_\chi}\right)^2$$

$$g(E) = \sum_{\mathcal{F}} \mathrm{BR}(\chi\chi \to \mathcal{F}) \left(\frac{dN}{dE}\right)_{\mathcal{F}}$$

Antiprotons bounds on DM





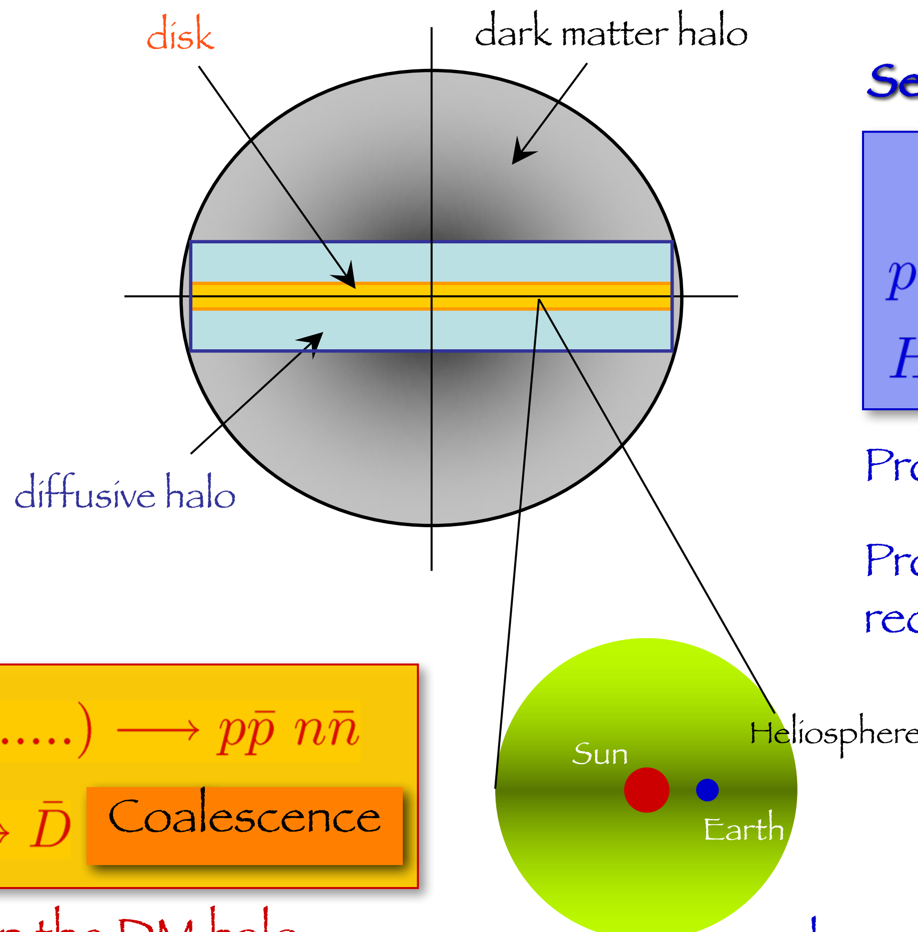
(*) Donato, Maurin, Brun, Delahaye, Salati, PRL 102 (2009) 071301
(+) Adriani et al. (PAMELA Collab.), PRL 105 (2010) 121101

NF, Maccione, Vittino, JCAP 09 (2013) 031

Caveat: the bounds are reported (as is usual) under the hypothesis that the DM candidate is the dominant DM component, regardless of its thermal properties in the early Universe

Cosmic antideuterons

Donato, Fornengo, Salati, PRD 62 (2000) 043003



solar modulation

Secondaries (background)

$$p_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$
$$p_{\,\mathrm{CR}} + He_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$
$$He_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

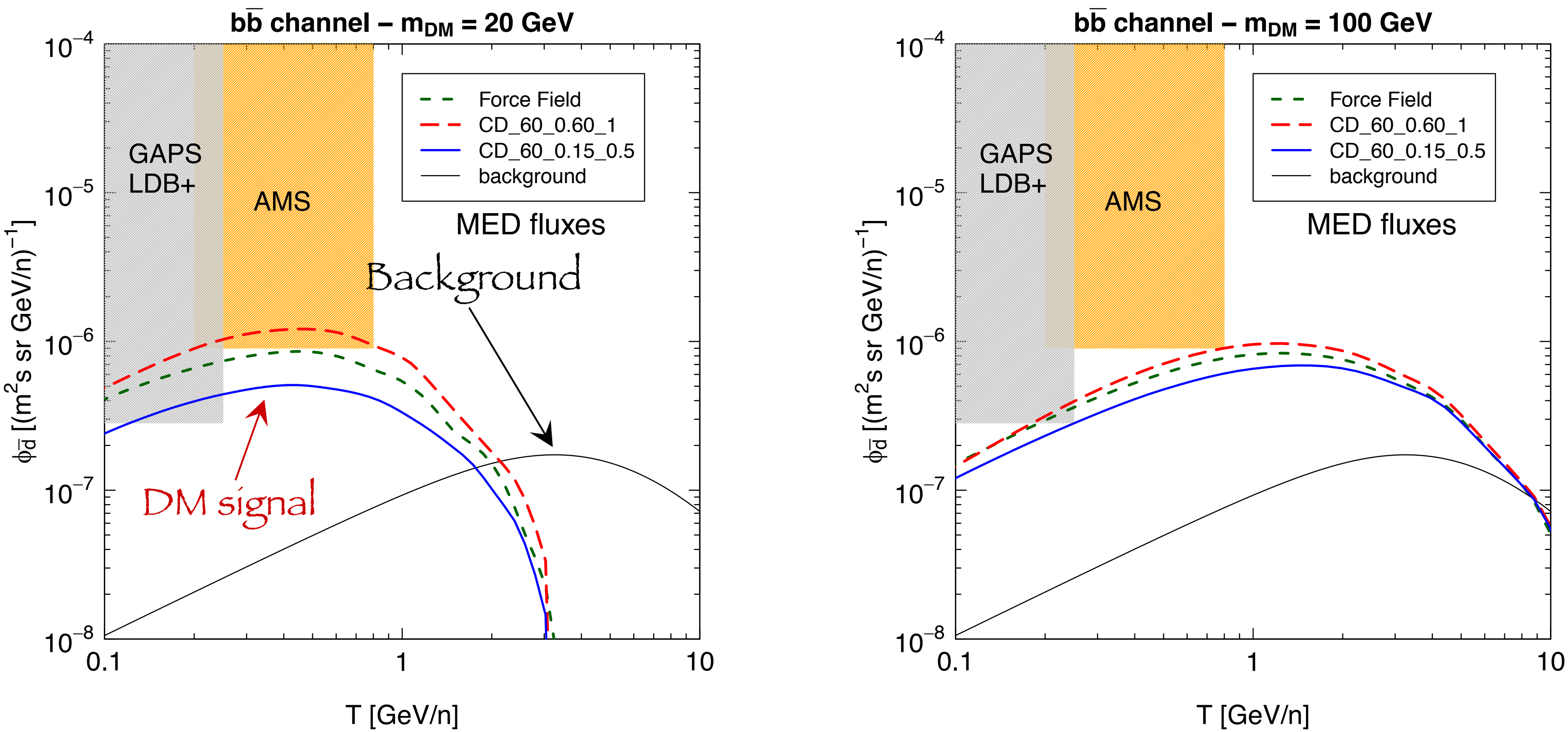
DM signal

$$\chi\chi \longrightarrow (.....) \longrightarrow p\bar{p}\ n\bar{n}$$
$$\bar{p} + \bar{n} \longrightarrow \bar{D}$$ Coalescence

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

Detection prospects



DM configurations allowed by antiproton bounds

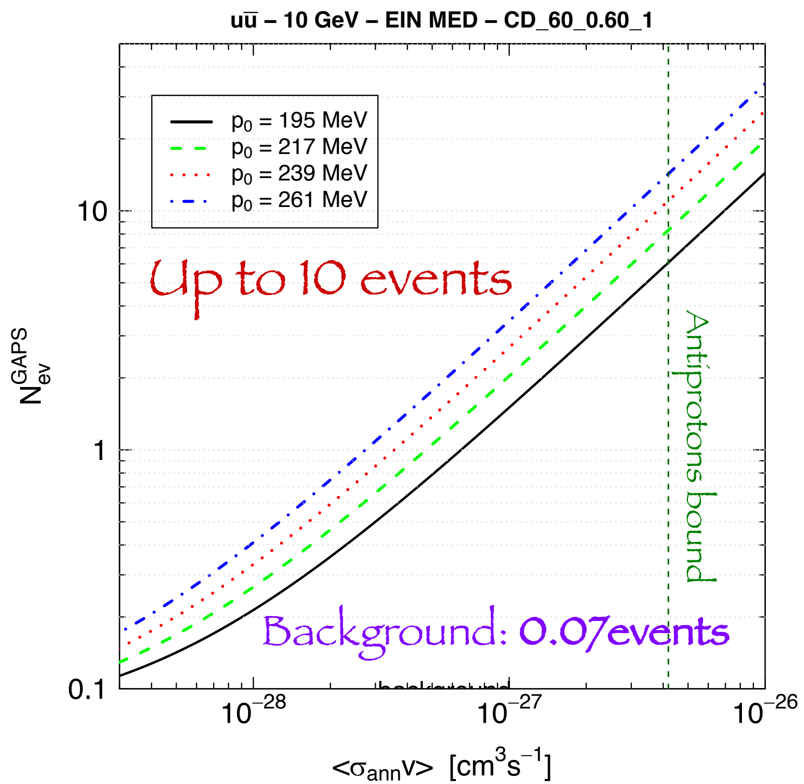
Relevant detection prospects for Dbar energies
<u>below few Gev/n</u>

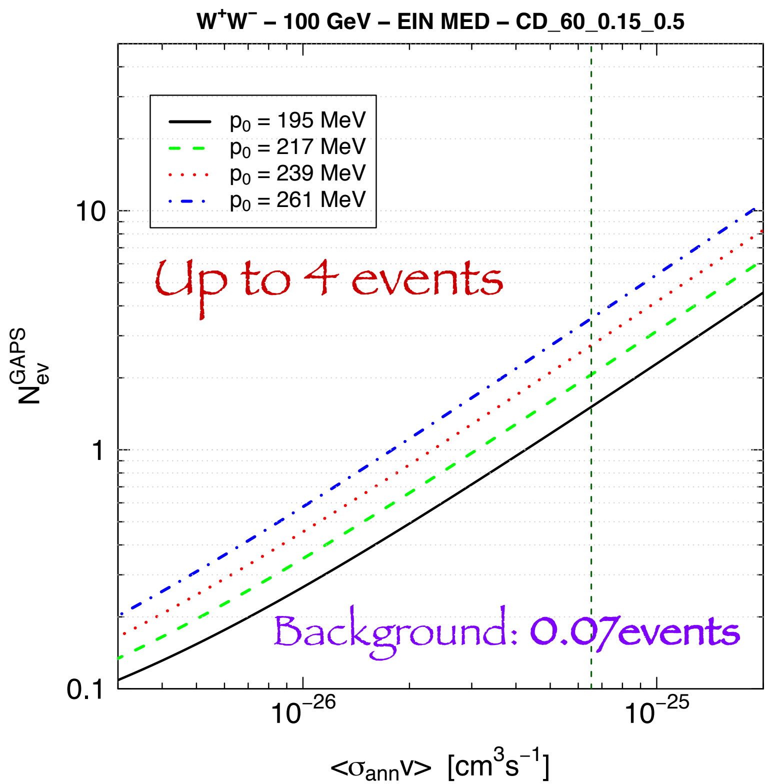
Experimental expected sensitivities : 3σ C.L.

GAPS LDB+ : 1 detected event
AMS : 2 detected events
(because of differet backgrounds)

NF, Maccione, Vittino, JCAP 1309 (2013) 031

Events expected





For GAPS LDB+ setup

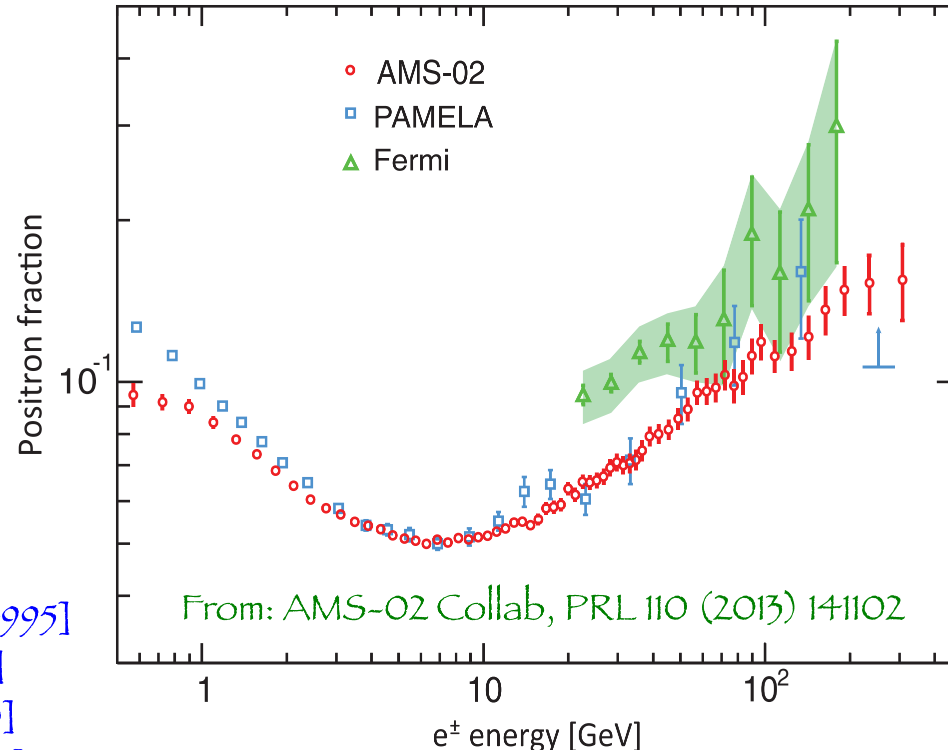
For GAPS LDB+ setup

DM configurations allowed by antiproton bounds

NF, Maccione, Vittino, JCAP 1309 (2013) 031

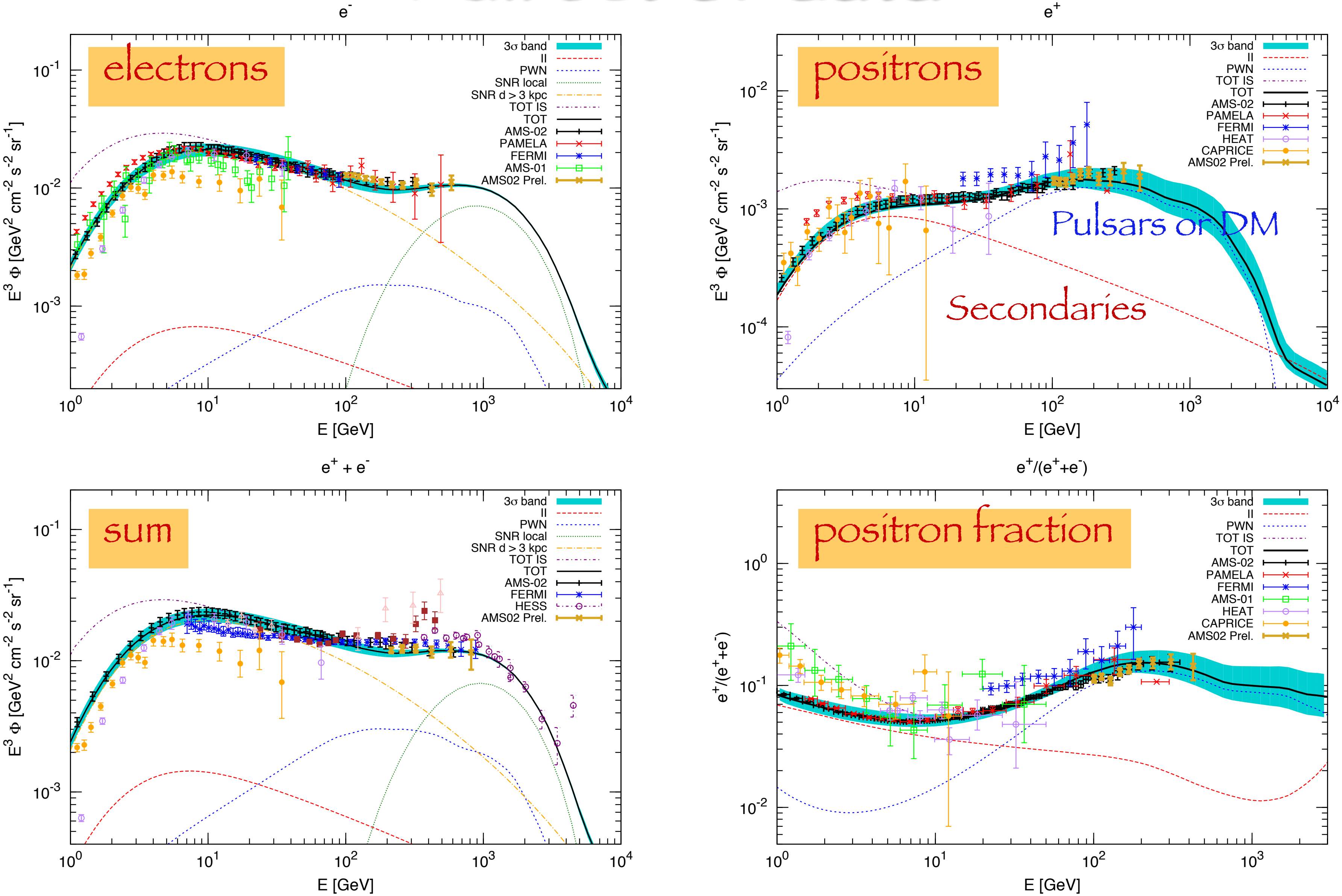
Cosmic-rays leptons

- Excellent data on cosmic-rays leptons are available from space-borne detectors, from about up 0.5 GeV to few hundreds of GeV
  - e^- Flux
  - e^+ Flux
  - $(e^- + e^+)$ Flux
  - $e^+/(e^- + e^+)$



PAMELA Collab, Nature 458 (2009) 607 [arXiv:0810.4995]
PAMELA Collab, PRL 111 (2013) 081102 [arXiv:1308.0133]
PAMELA Collab, PRL 106 (2011) 201101 [arXiv:1103.2880]
Fermi LAT Collab, PRL 108 (2012) 011103 [arXiv:1109.0521]
Fermi LAT Collab, PRD 82 (2010) 09004 [arXiv:1008.3999]
AMS-02 Collab, PRL 110 (2013) 141102
AMS-02 Collab, 33rd ICRC Conference (2013)
AMS-02 Collab, 33rd ICRC Conference (2013)

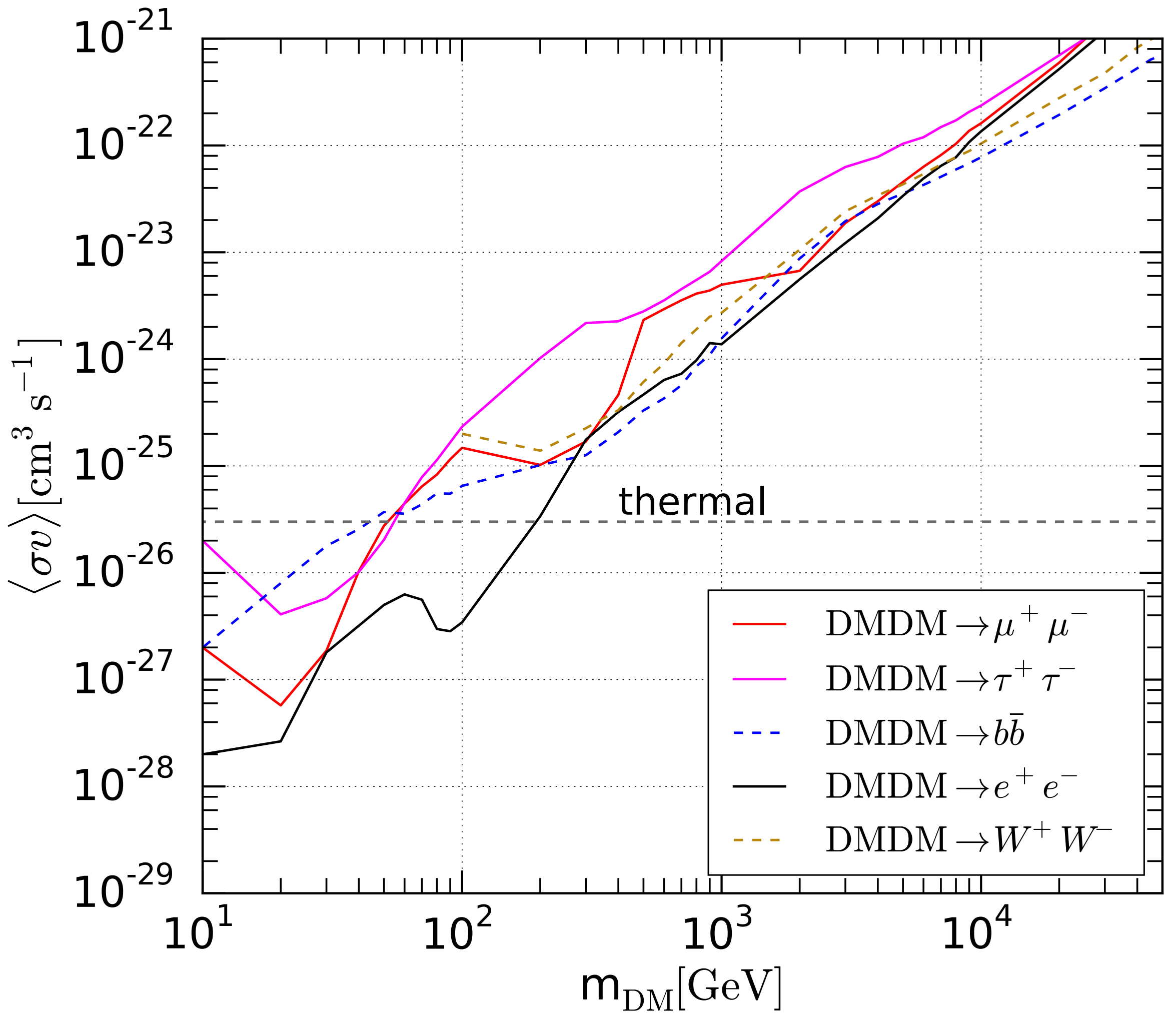
Full set of data



A local source of positrons is needed

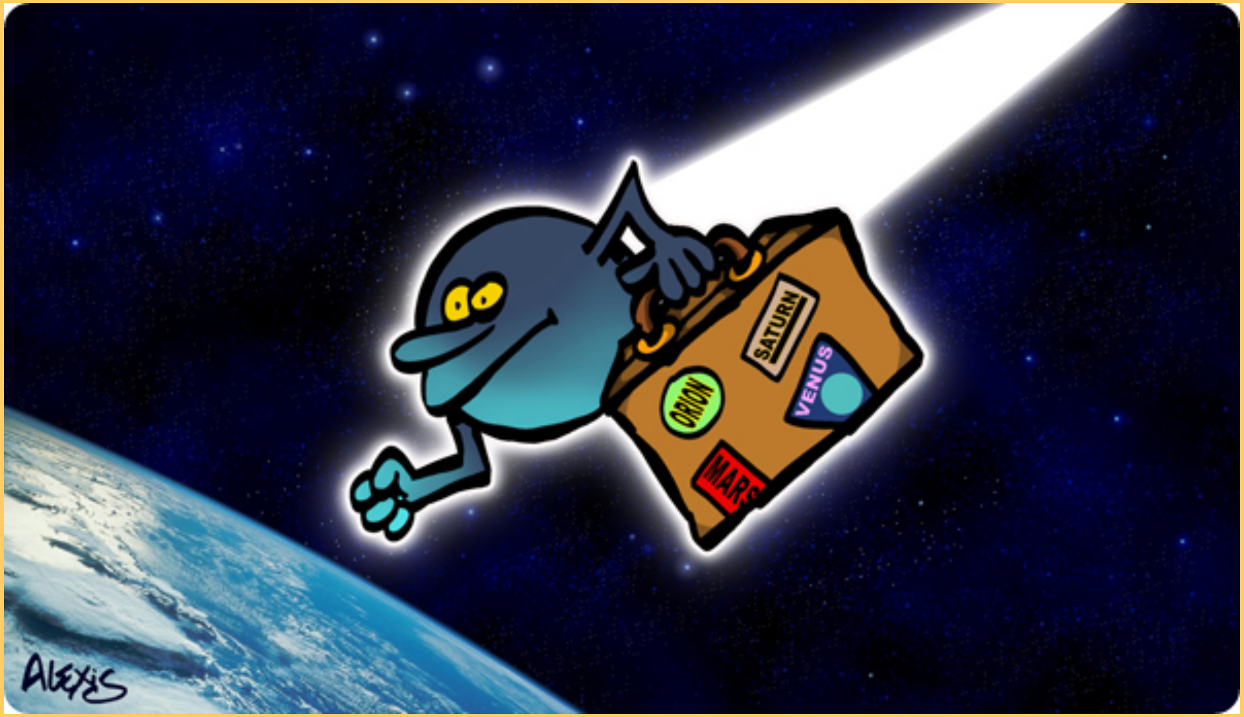
Bounds on DM

Bounds on DM

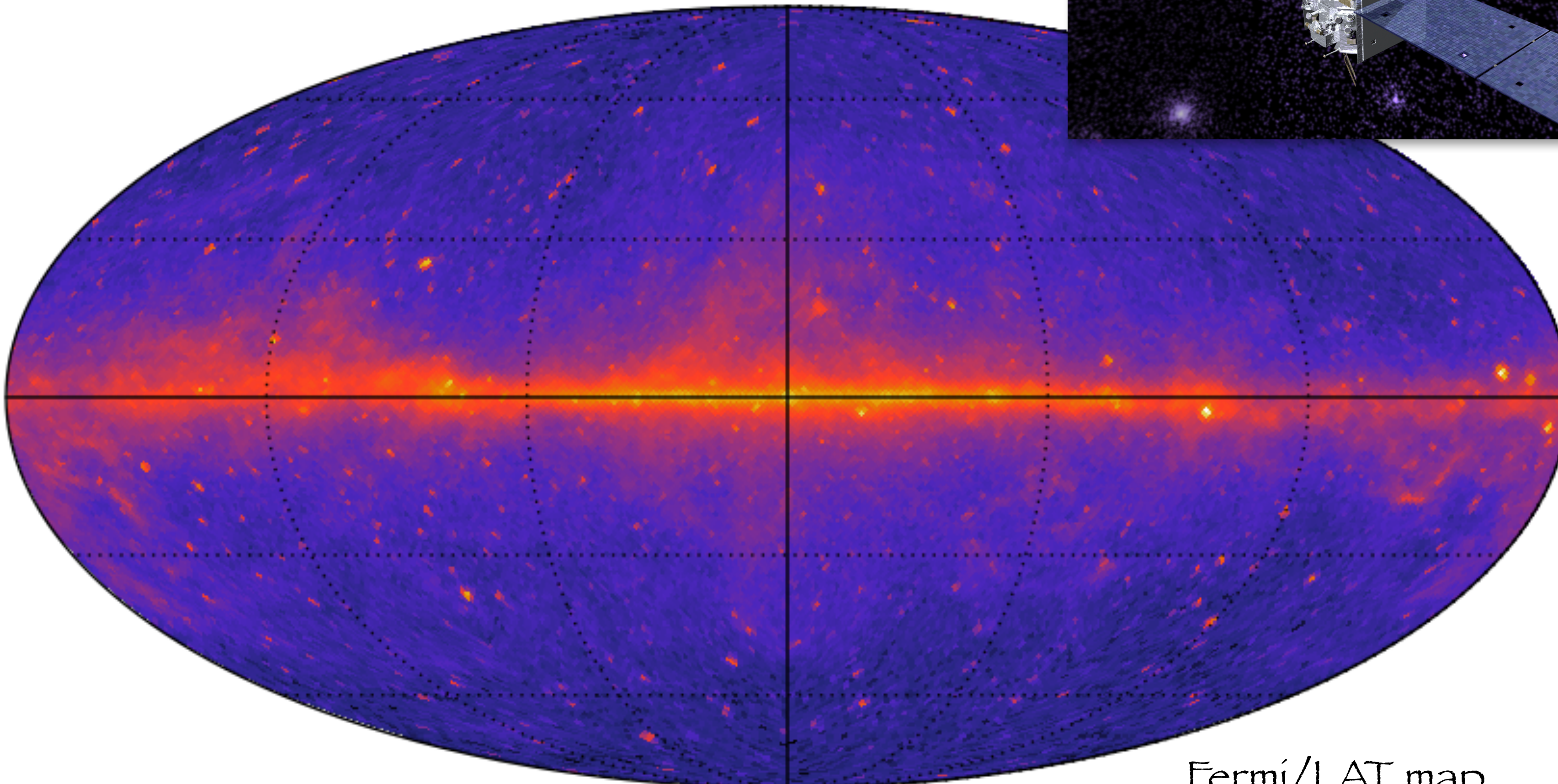


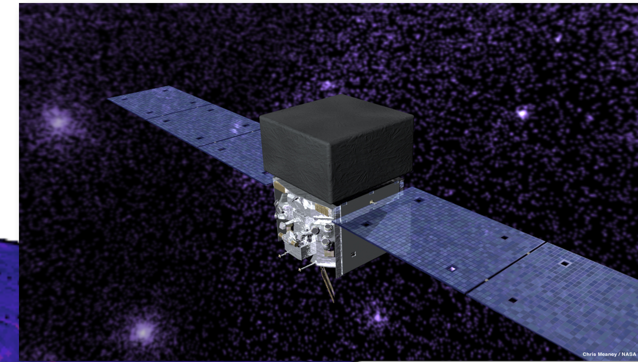
Di Mauro, Donato, NF, Vittino, JCAP 1605 (2016) 031

Gamma ray signal



Gamma ray sky





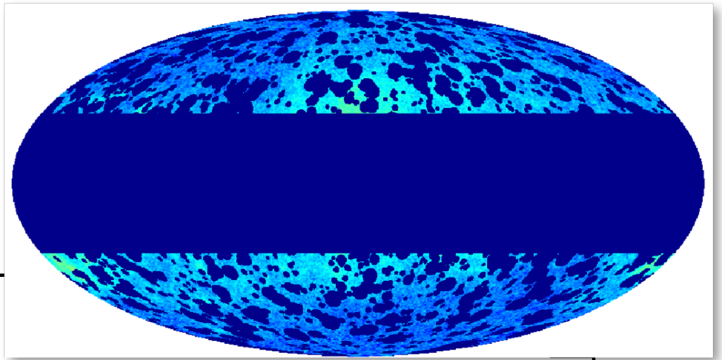
Fermi/LAT map

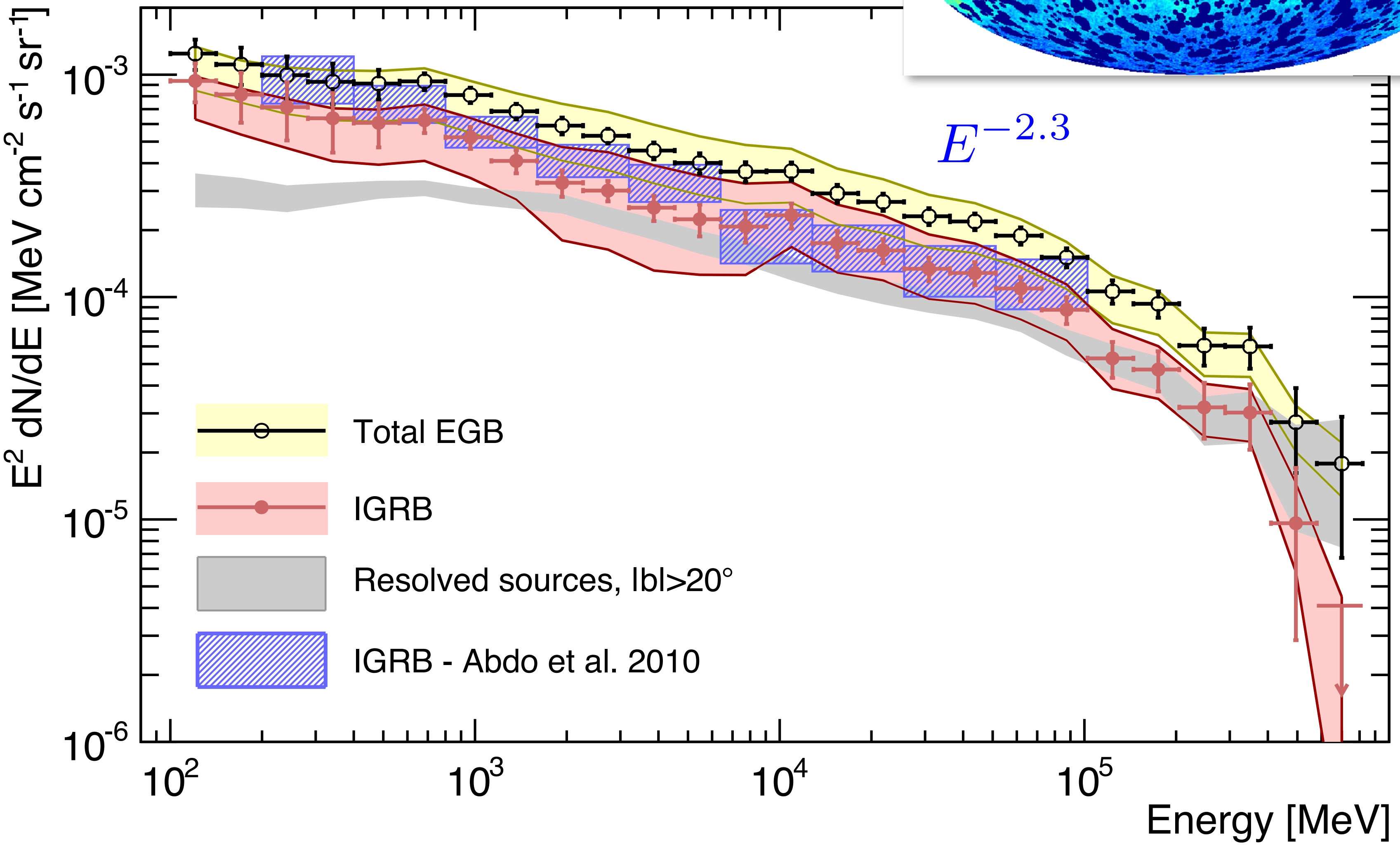
Galactic foreground emission

Resolved sources

Diffuse Gamma Rays Backgound (DGRB)

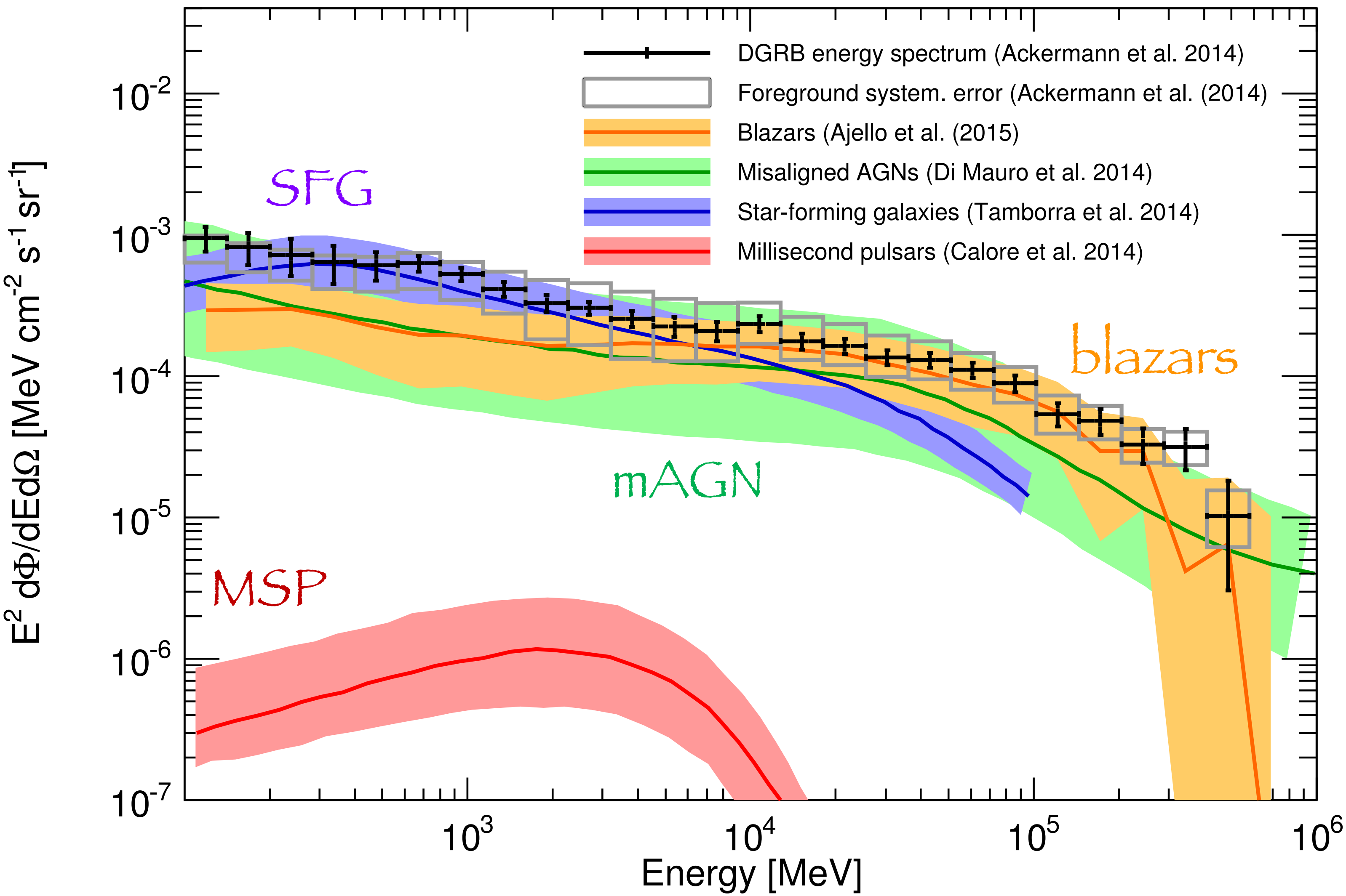
DGRB Intensity





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

DGRB Intensity



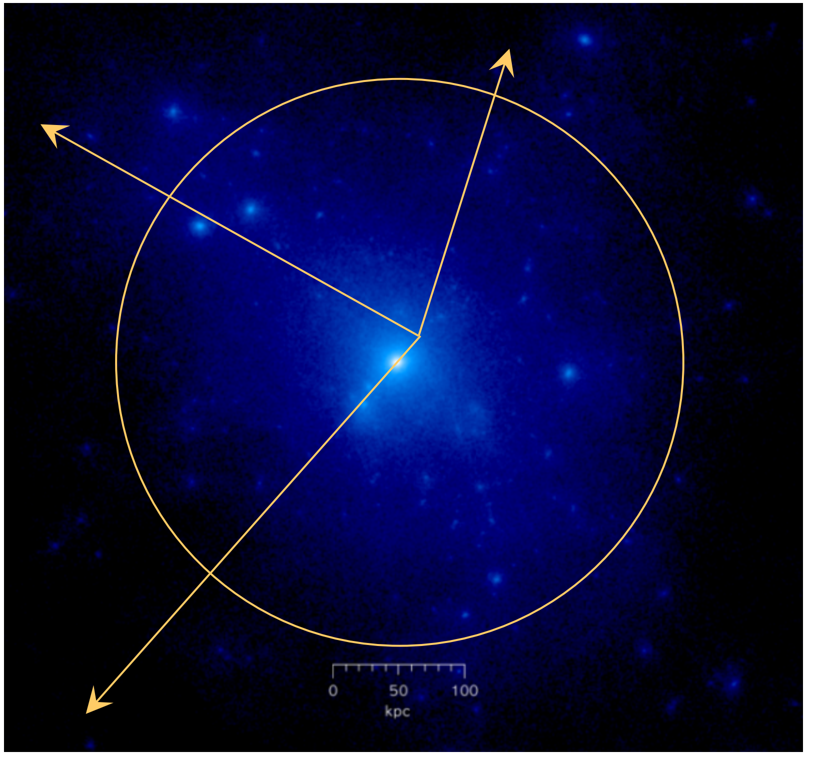
Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

Gamma-ray flux from galactic DM

Flux: $$\boxed{\Phi_\gamma^{\mathrm{DM}}(E_\gamma,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle_0}{2m_\chi^2}\; g_\gamma(E_\gamma)\; I(\psi)}$$

L.o.S. integral: $$I(\psi) = \int_{\mathrm{l.o.s.}} \rho^2(r(\lambda,\psi))d\lambda$$

$$\rho(\vec{r}) = \rho_{\mathrm{halo}}(\vec{r}) + \sum_i \rho_{\mathrm{sub}}(\vec{r}_s)_{\vec{r}}$$



… and from extra galactic DM

Halo density profile

Host halo $$\mathcal{L}_a^{hh}(E,z,M) = E\,\frac{(\sigma_a v)}{2\,M_\chi^2}\int_0^{R_v} d^3r\,\frac{d\tilde{N}_i}{dE}\,[(1-f)\,\rho(M,r,z)]^2$$

Sub halo $$\mathcal{L}_a^{sh}(E,z,M) = E\,\frac{(\sigma_a v)}{2\,M_\chi^2}\int_{M_{\rm cut}^s}^{M} dM_s\,\frac{dn_s}{dM_s}(M_s,f,M)\int_0^{R_v} d^3r_s\,\frac{d\tilde{N}_i}{dE}\,\rho_s^2(M_s,r_s,z)$$

Mass function

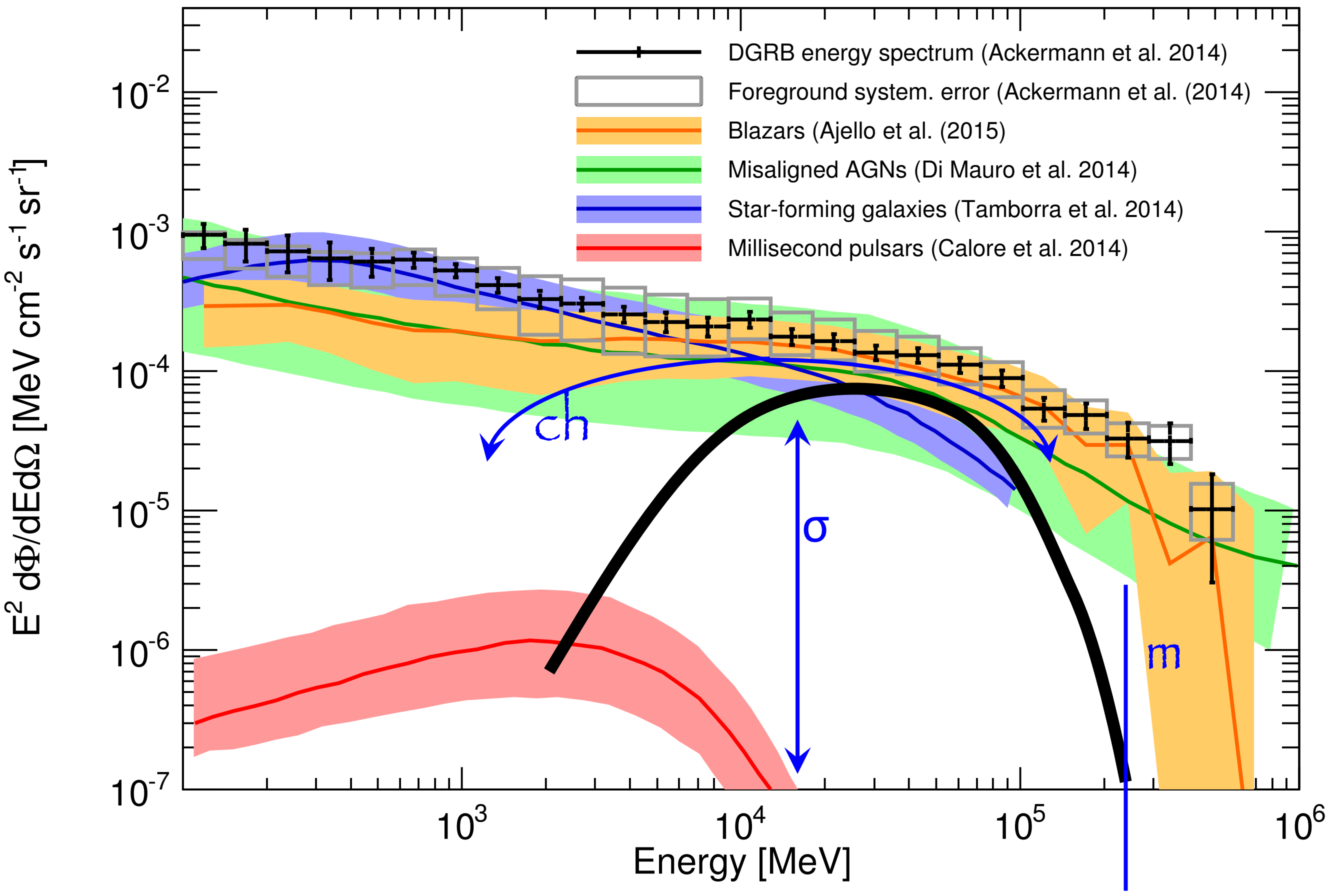
Sub-halo density profile

$$\int dM_s\,(dn_s/dM_s)\,M_s = f M$$

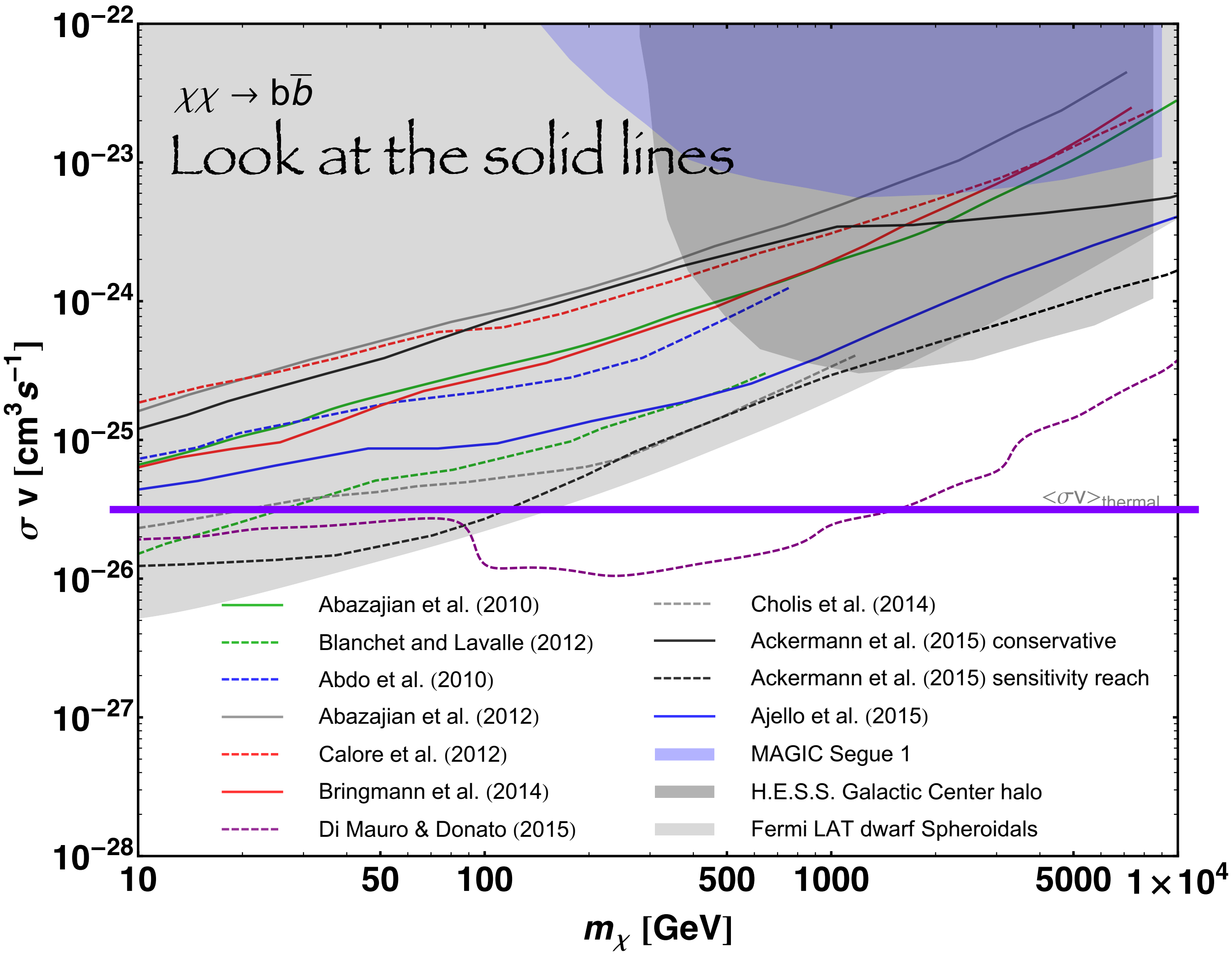
DGRB and Dark Matter

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

The Bad: Can be quite subdominant in intensity

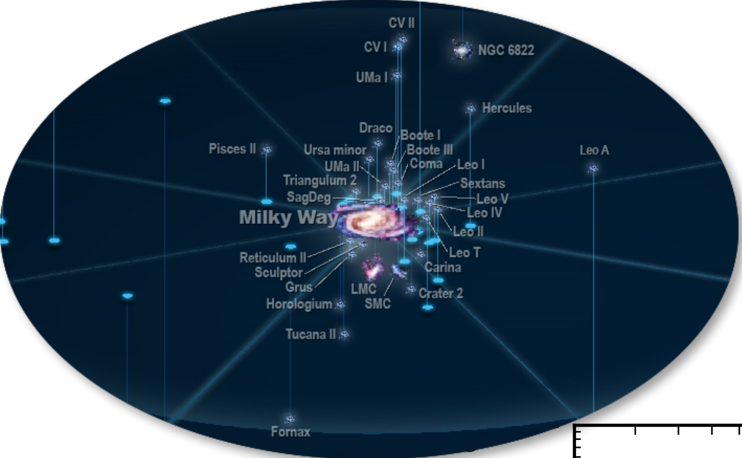


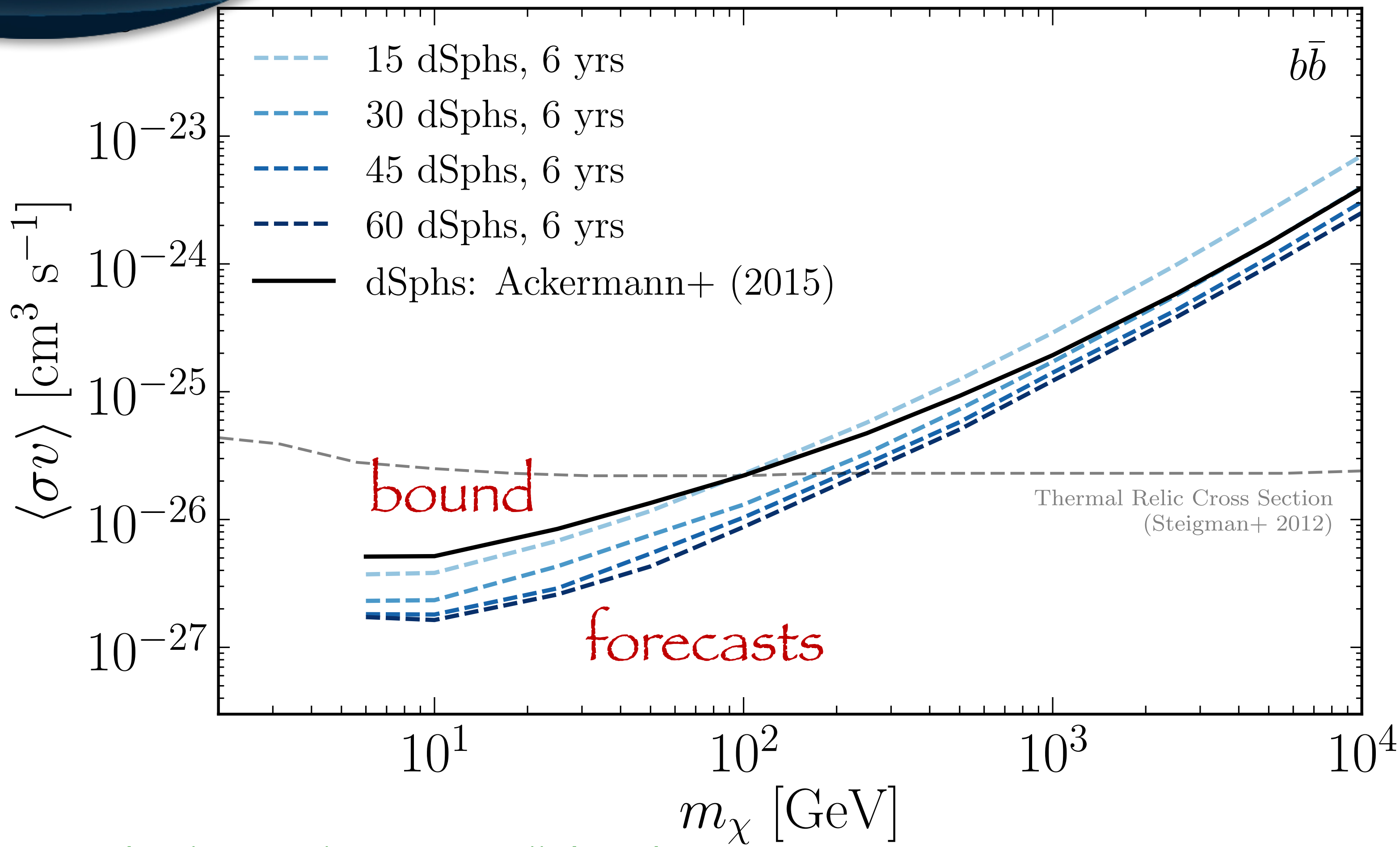
DGRB intensity bounds on DM



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

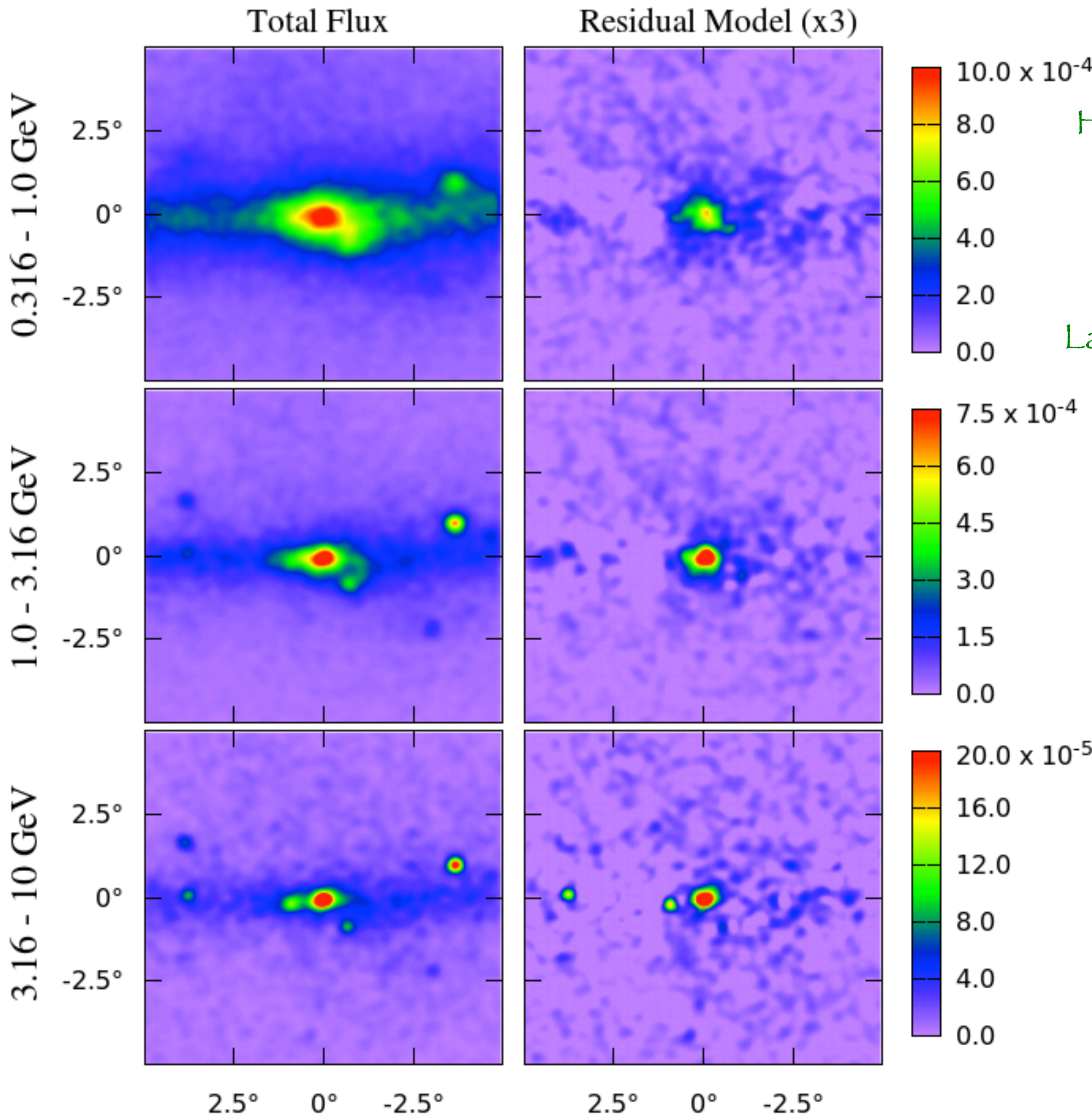
Dwarf galaxies





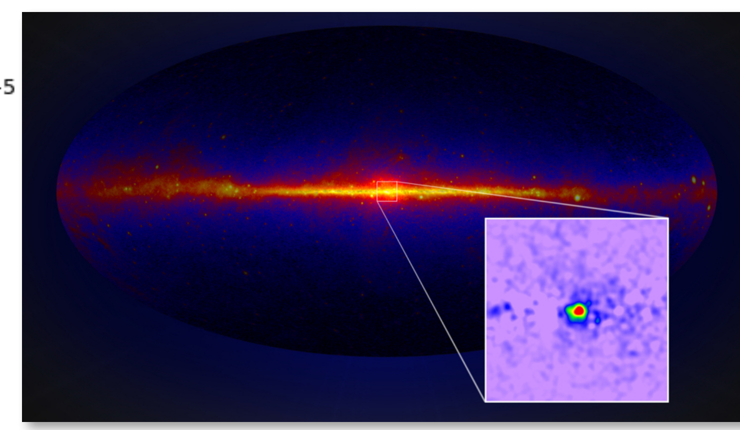
Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Galactic center: an "excess" ?

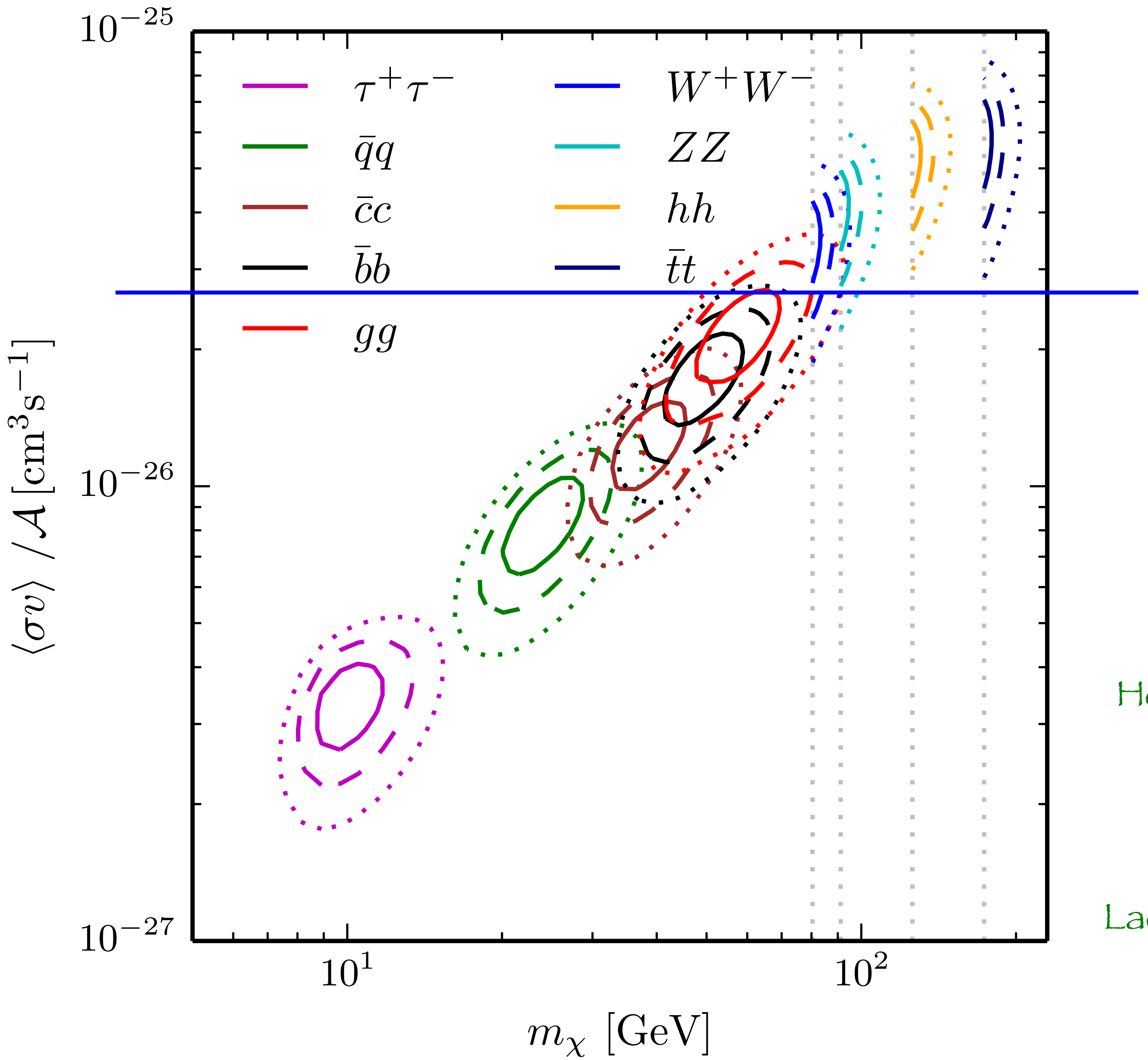


Daylan et al, Phys Dark Univ 12 (2016) 1

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

Non DM solutions
- Unresolved pulsars
- CR outbursts

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

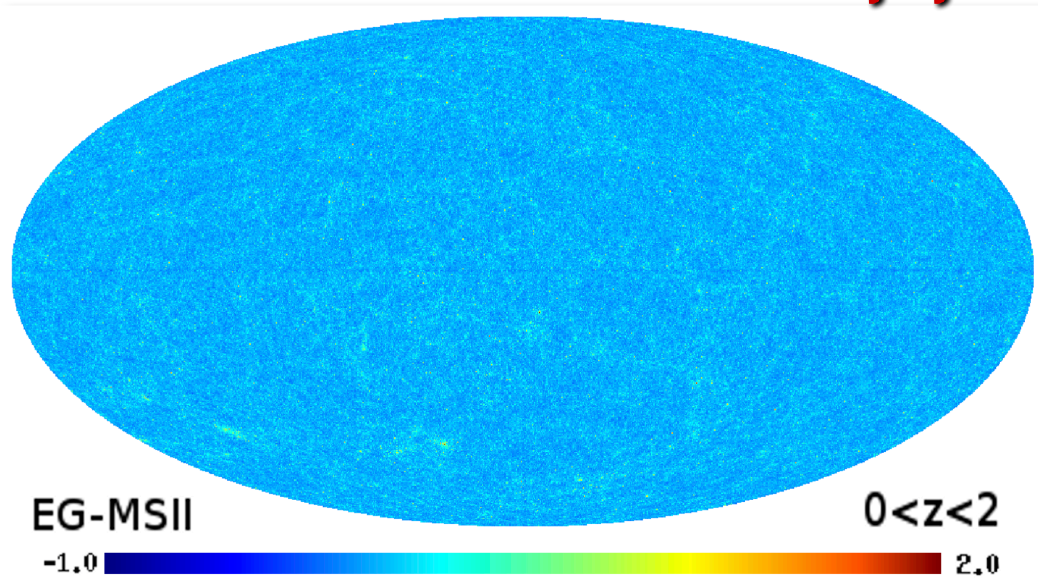
Alternative approaches?

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

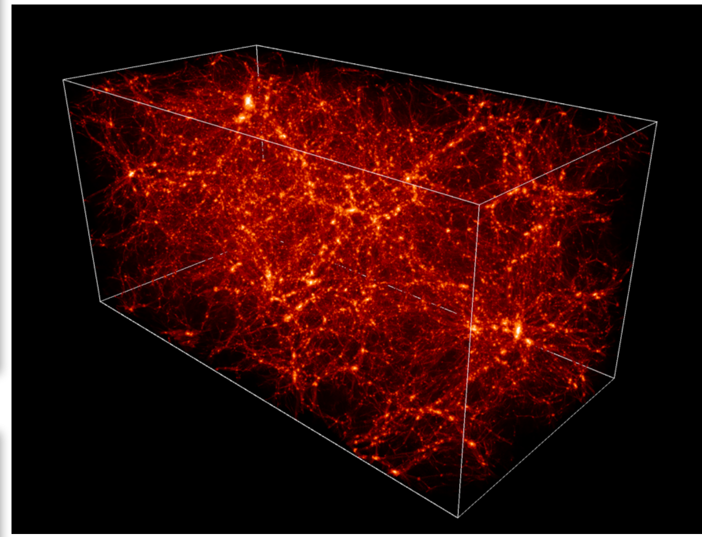
- EM signals (and neutrinos) more directly trace the underlying DM distribution: they need to exhibit some level of anisotropy
  - "Bright" DM objects: would appear as *resolved* sources
    - e.g: gamma or radio halo around clusters, dwarf galaxies or even subhalos
  - Faint DM objects: would be *unresolved*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

Alternative approaches?

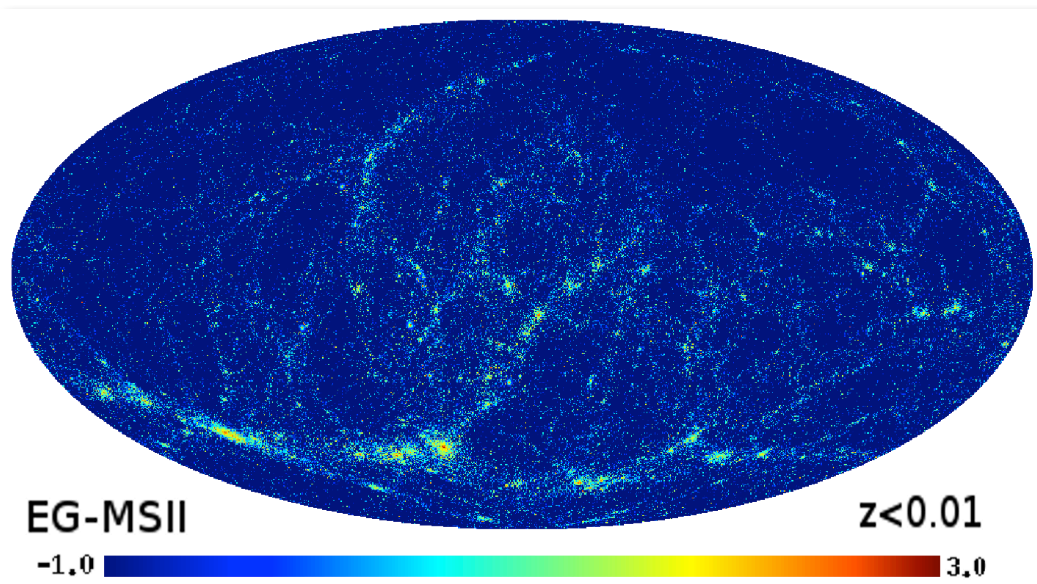
(simulated maps)



Extra galactic emission
Higher redshift



Emission is intrisically anisotropic



Extra galactic emission
Lower redshift

Anisotropic emission

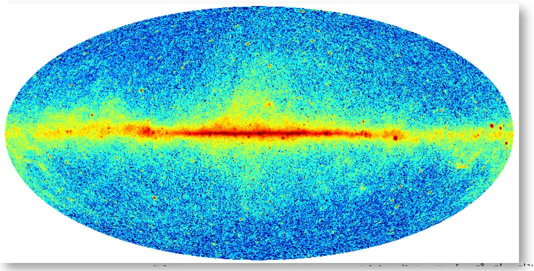
Even though sources are too dim to be individually resolved, they can affect the

<u>statistics of photons</u>

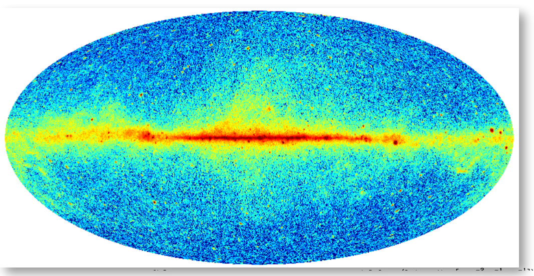
across the sky

Currently under study

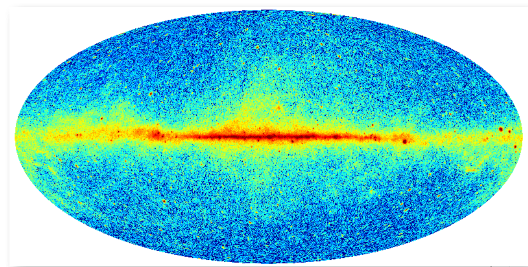
Photon statistics



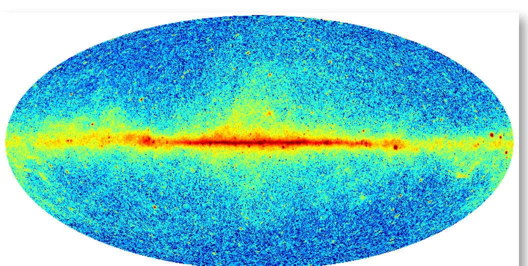
Photon pixel counts (1 point PDF)



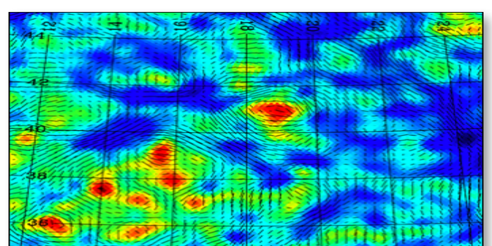
×



2 point correlator
angular power spectrum



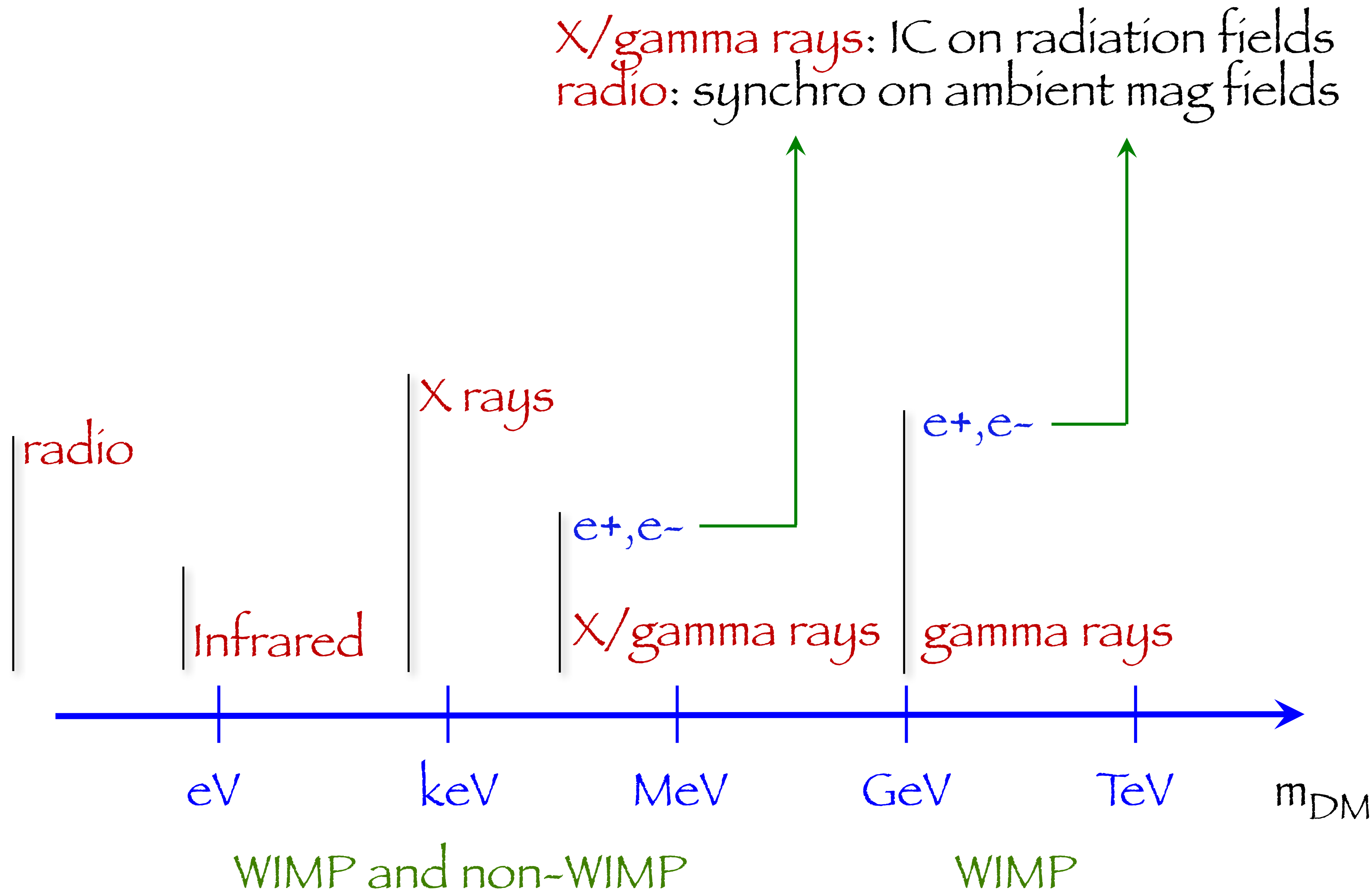
×



2 point correlator
angular power spectrum

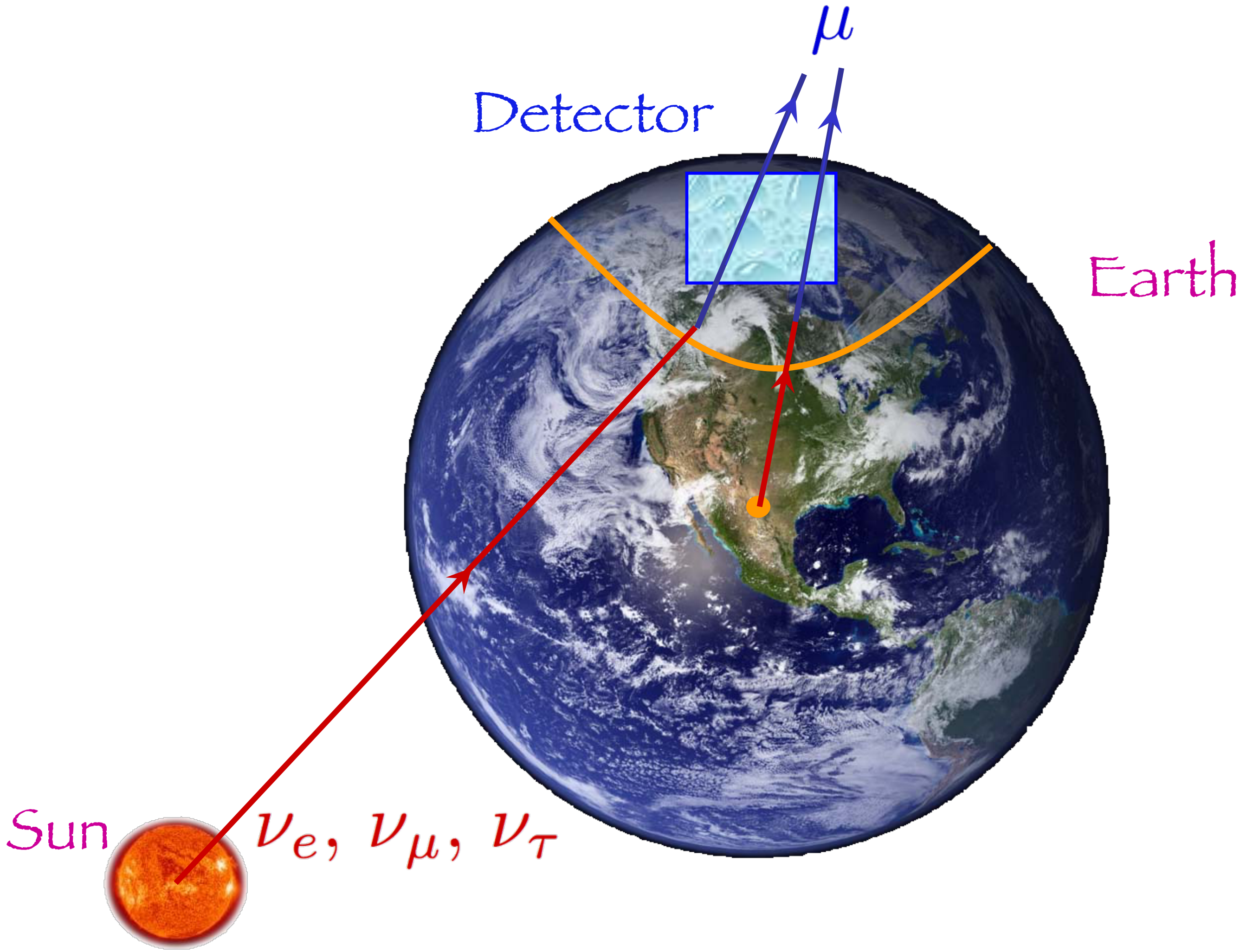
$$\langle I_i(\vec{n}_1) I_j(\vec{n}_2) \rangle \longrightarrow C_{ij}(\theta) \longrightarrow C_l^{ij}$$

The Multi-wavelength Landscape



Neutrinos

Neutrinos from Earth and Sun



and neutrinos from the Galaxy

Neutrinos from Earth and Sun

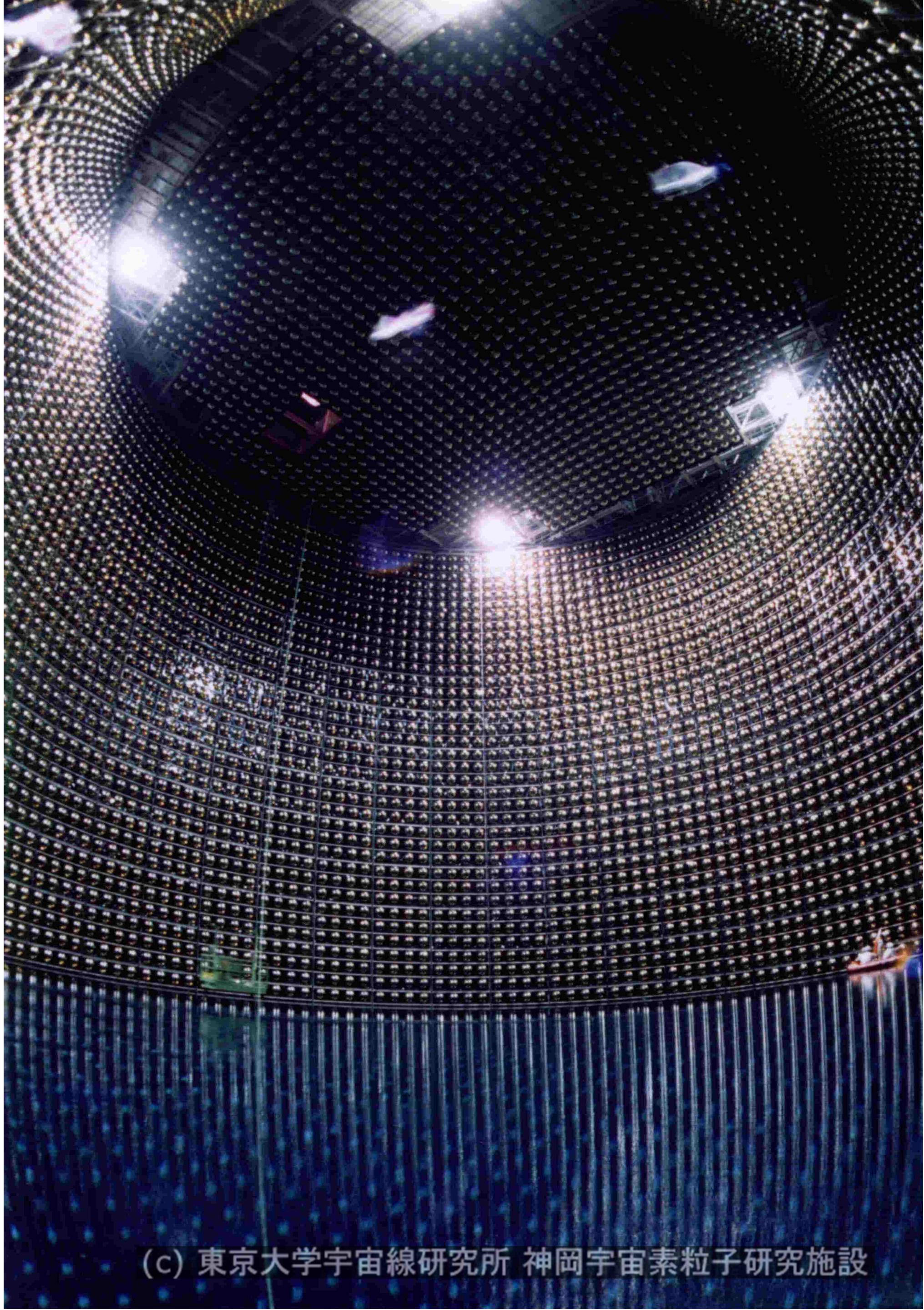
- Capture:
  - Galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally captured

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

- 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

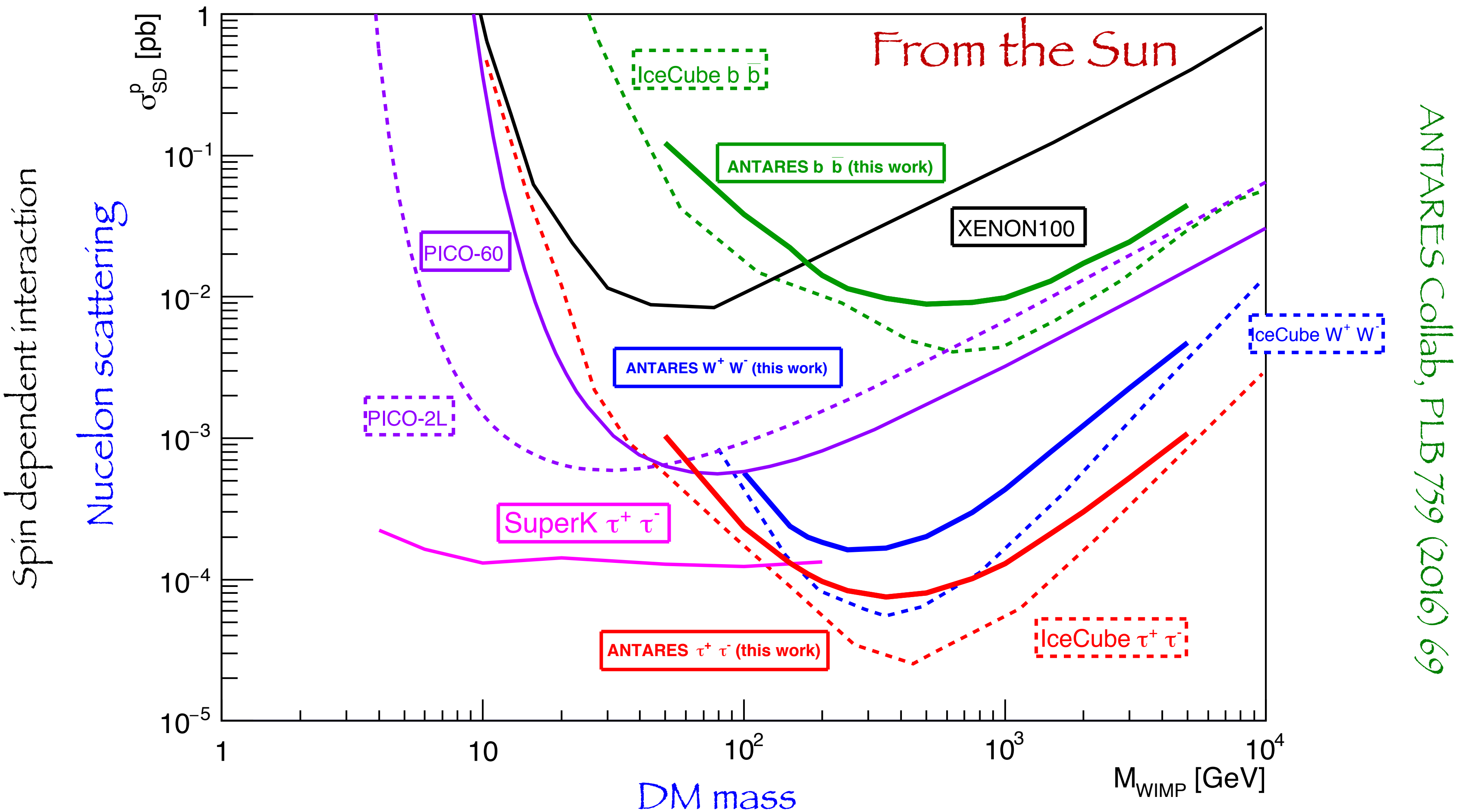
$$\Gamma_A = \frac{C}{2} \tanh^2\left(\frac{t_0}{\tau_A}\right) \longrightarrow \frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_{\mathcal{F}} \mathrm{BR}(\chi\chi \to \mathcal{F}) \frac{dN_\nu^{\mathcal{F}}}{dE_\nu}$$

Super Kamiokande



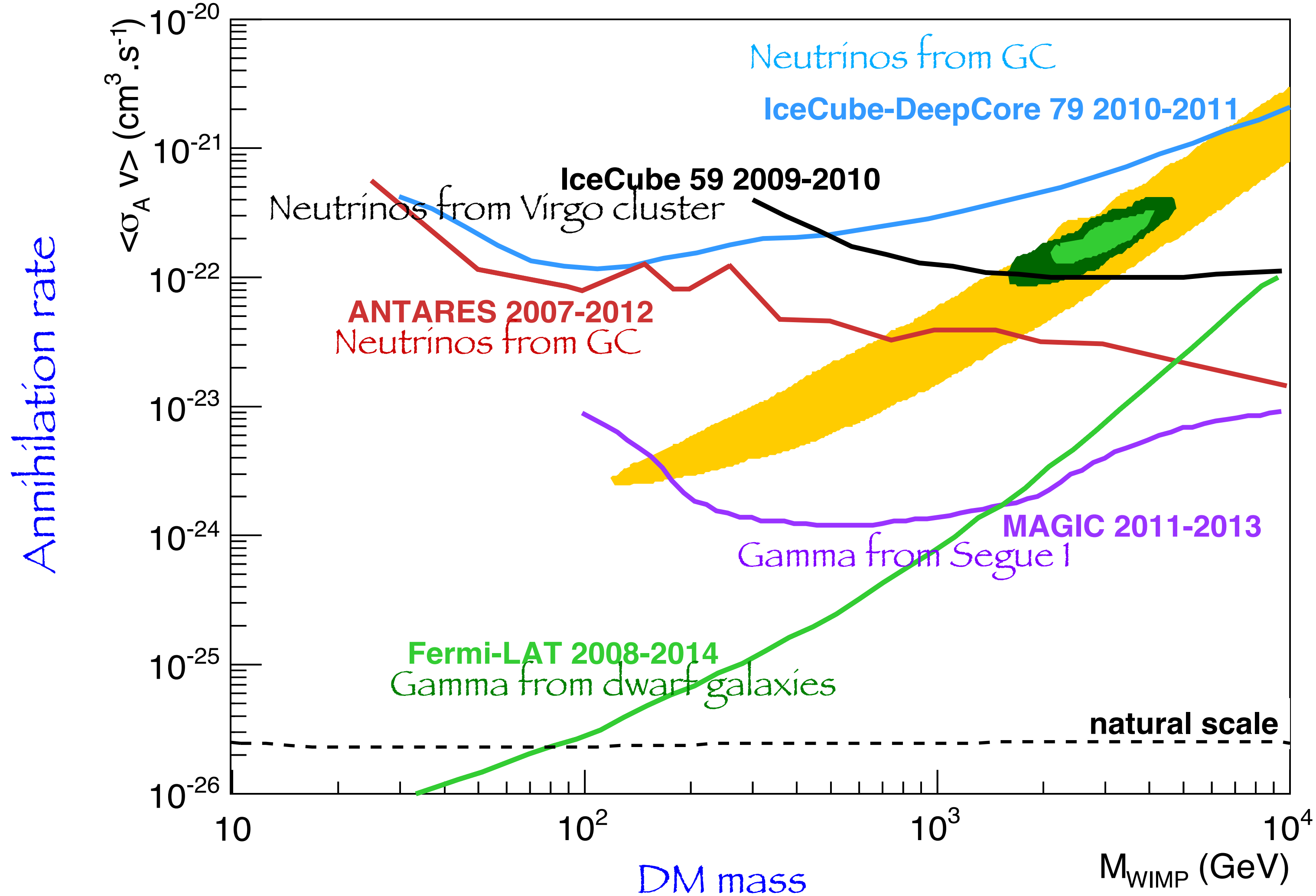
ANTARES

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



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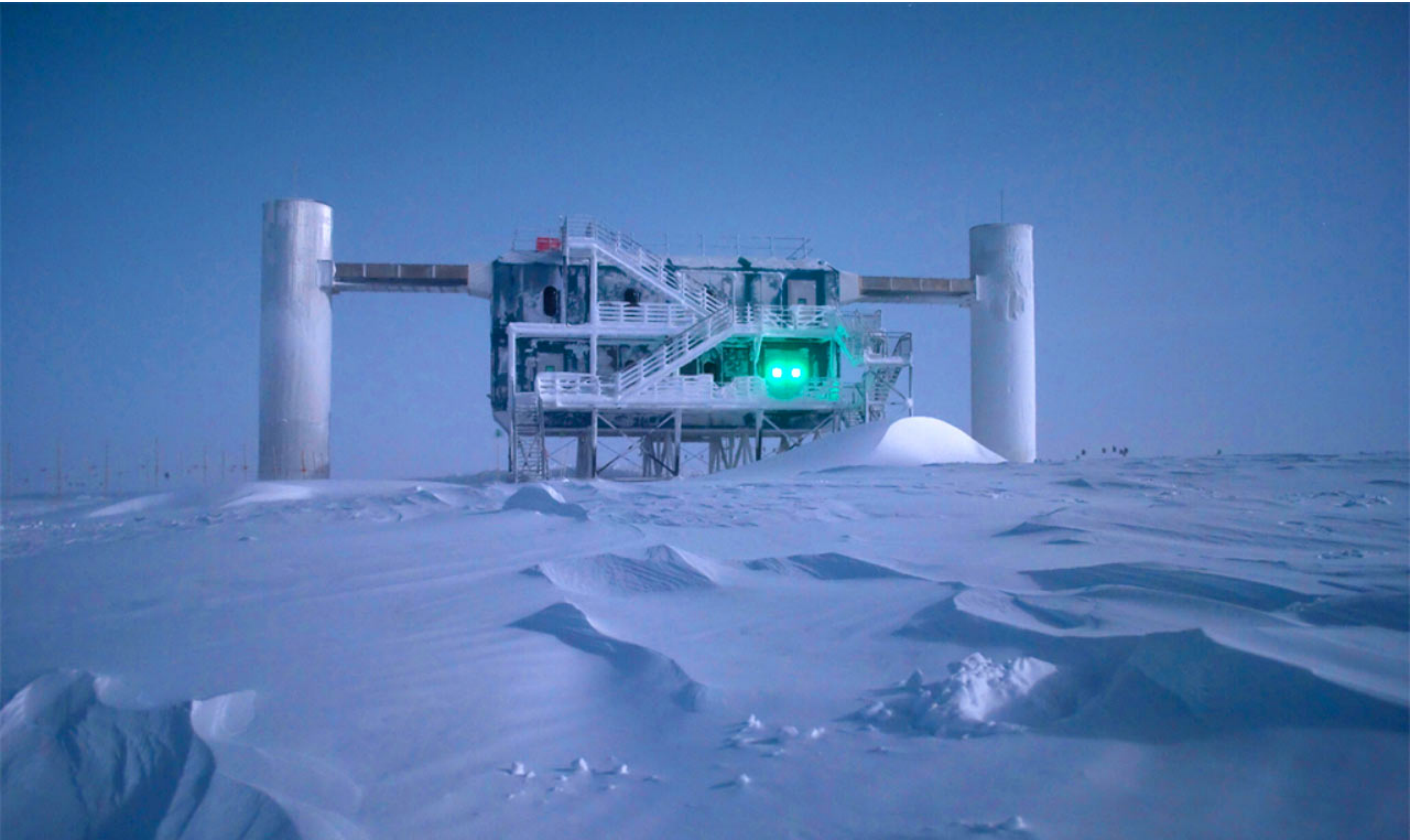
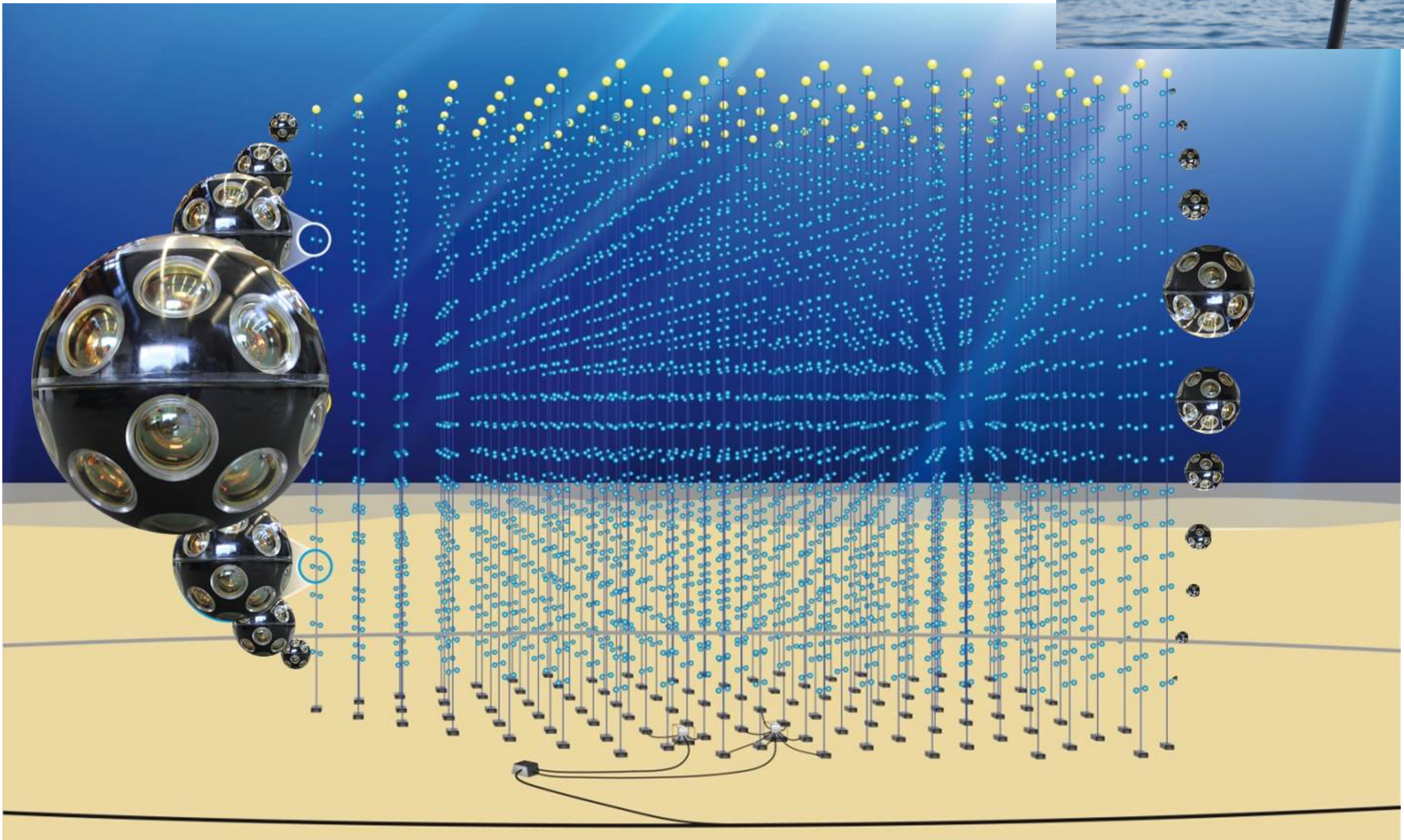
IceCube

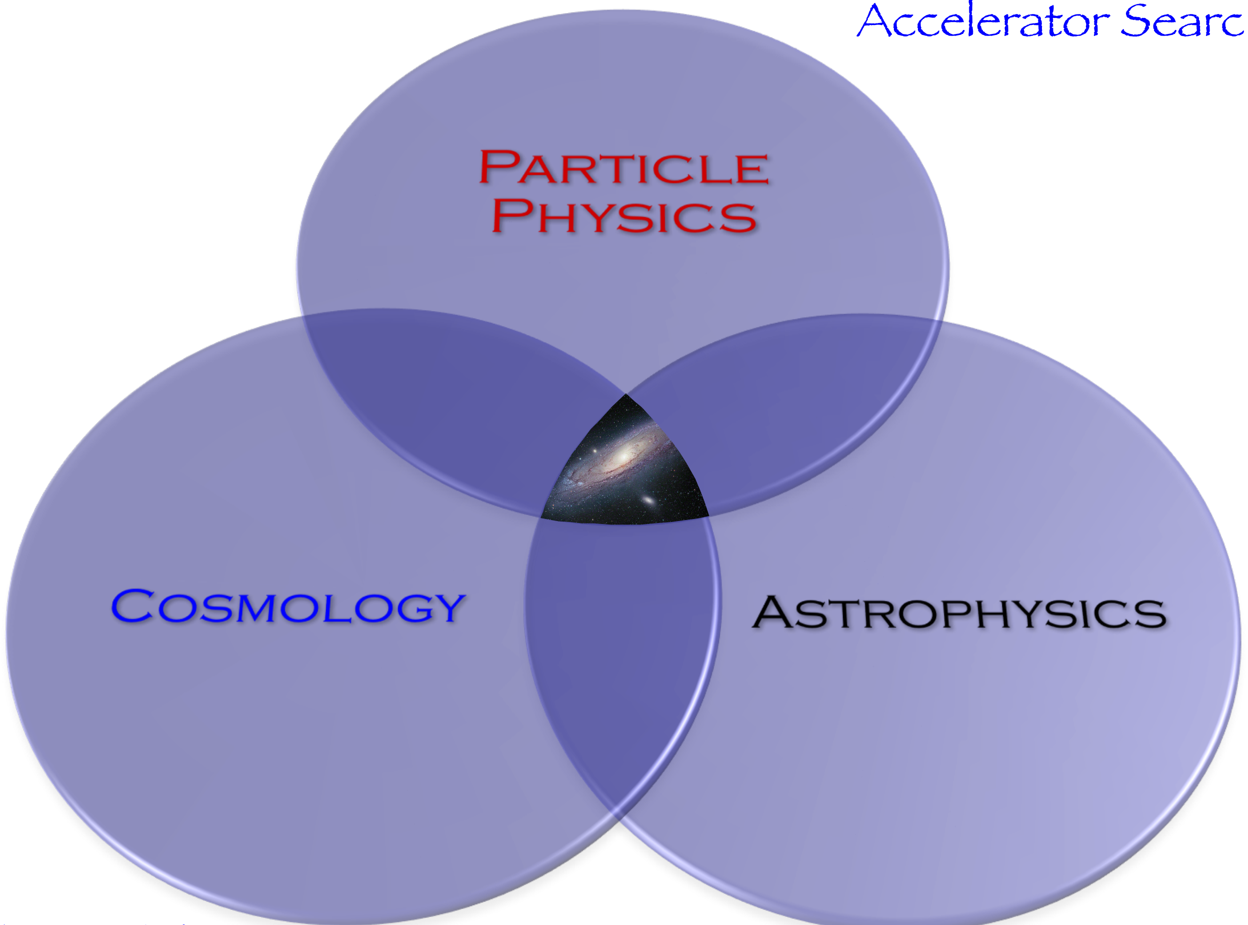


Km3NET



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