How Dark is Dark?

How to unveil the hidden nature of dark matter

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Dark Matter

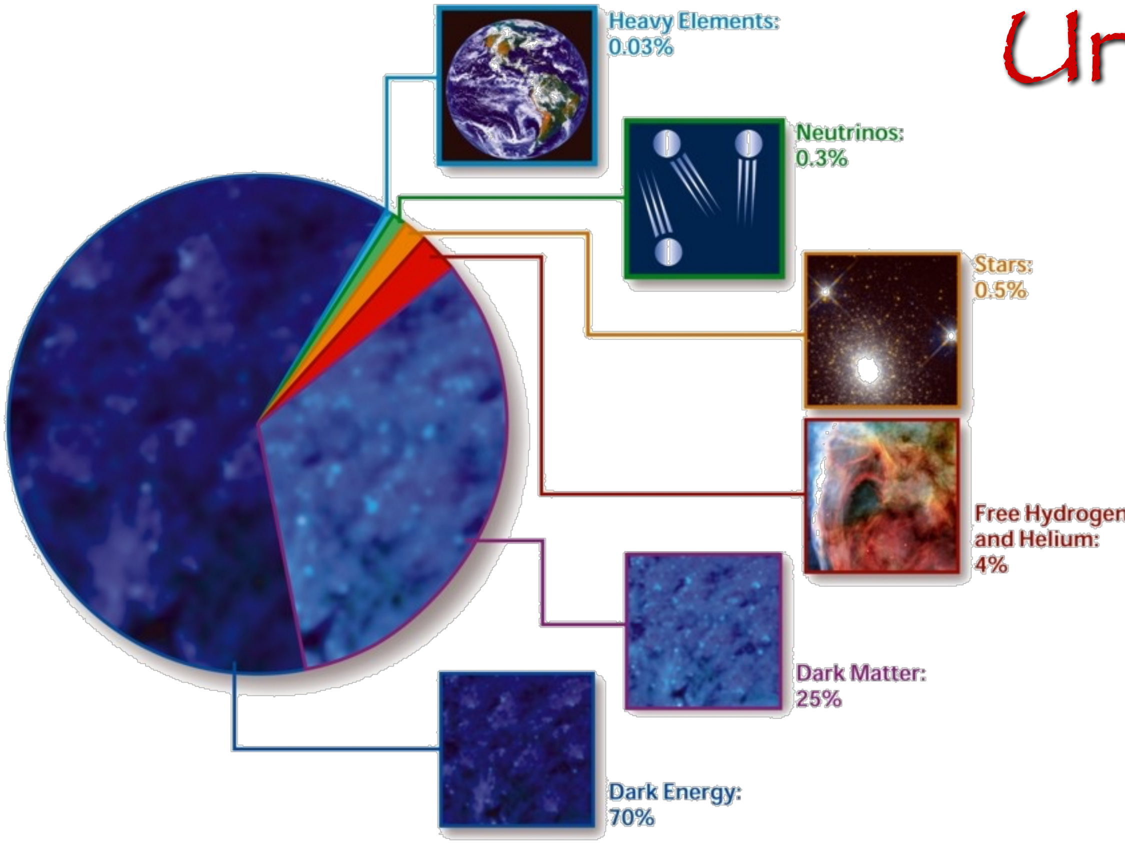
What's the problem?

How can we solve it?

Why can it have something to say about particles?

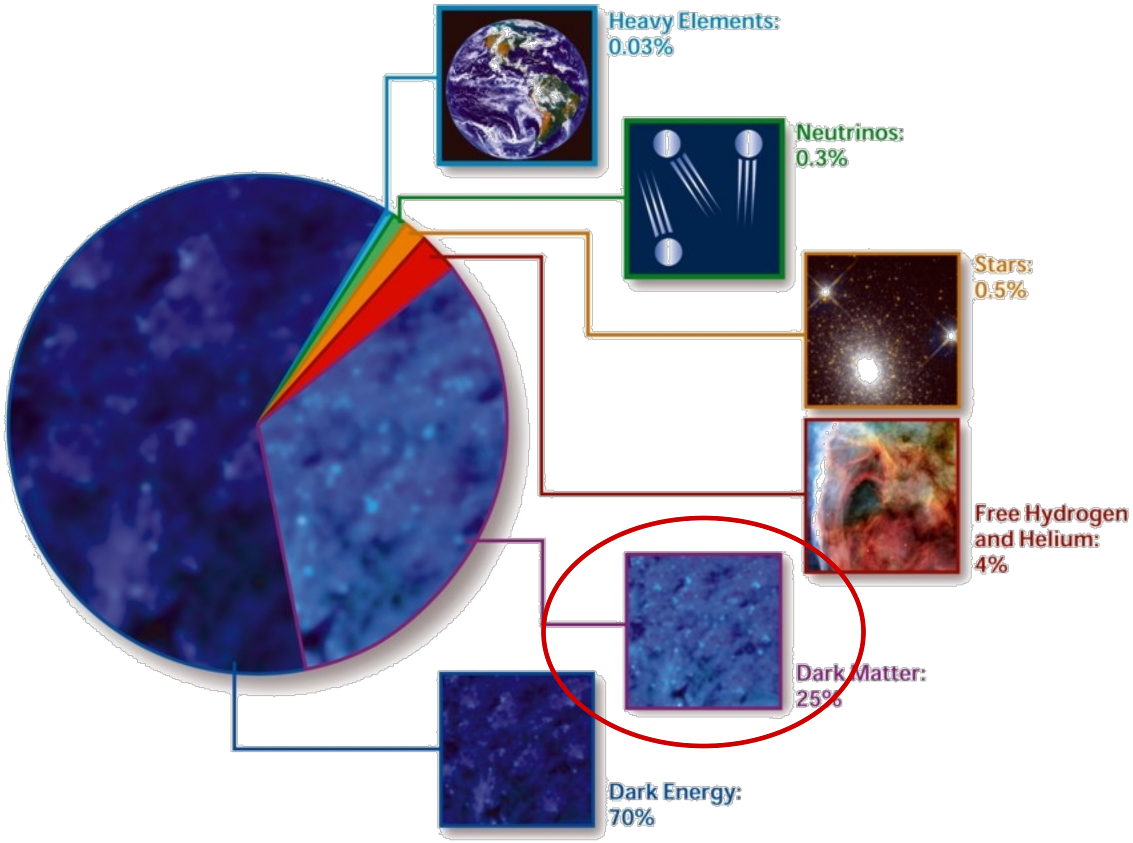
OK, it's a dark matter: but how dark is dark? Can we shed some light on it?
(or: Can it shed some light to us?)

Universe is “odd”



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

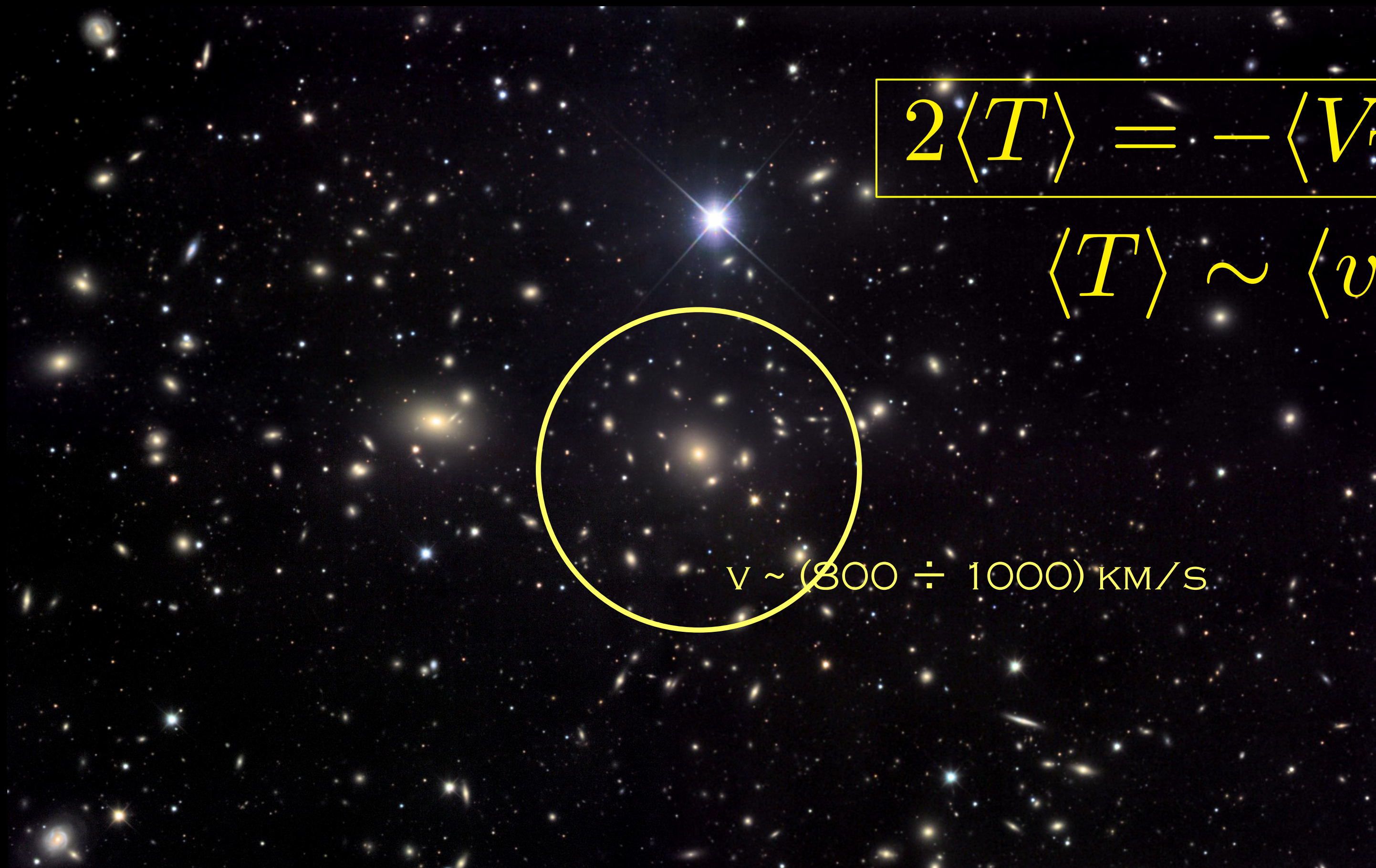
Dark Matter



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

Galaxy cluster

Zwicky (1933)



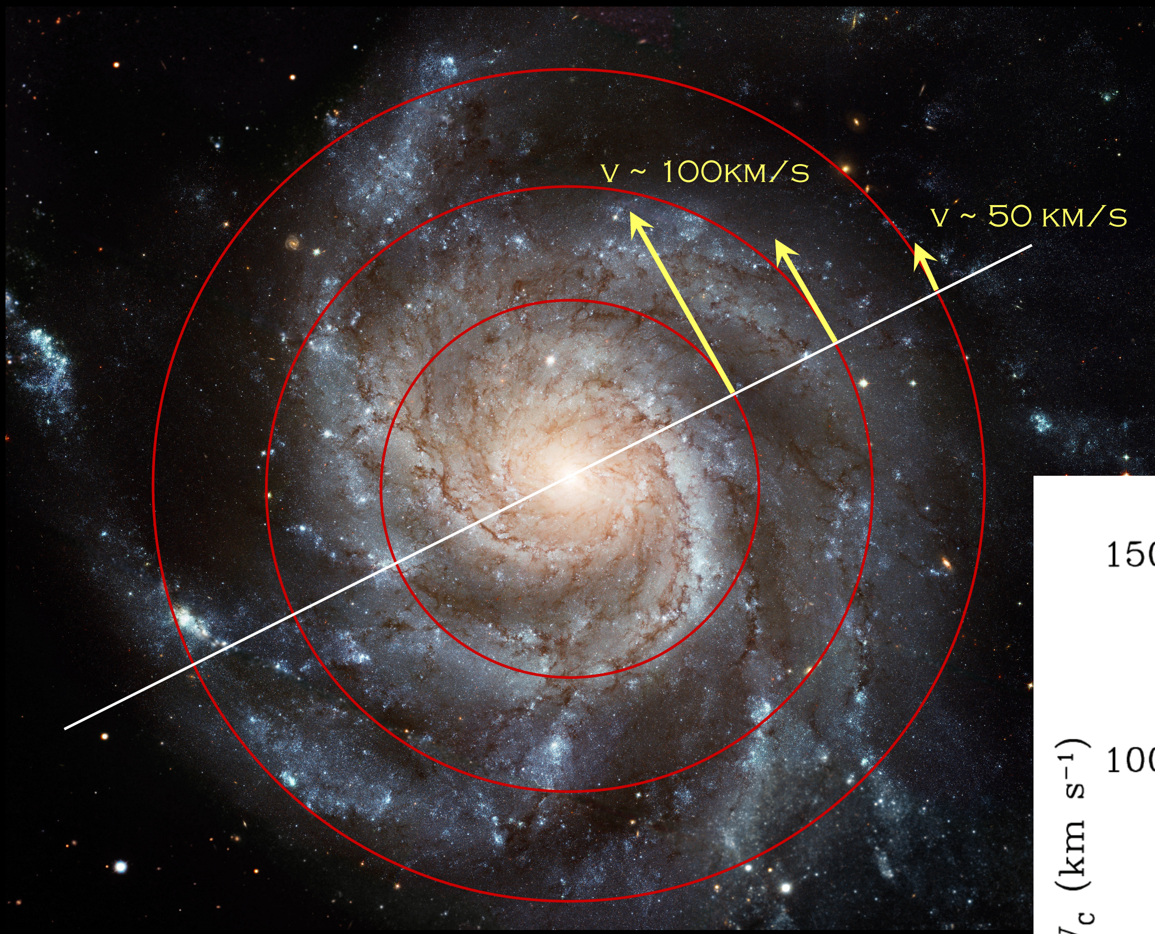
$$2\langle T\rangle = -\langle V_{\mathrm{TOT}}\rangle$$

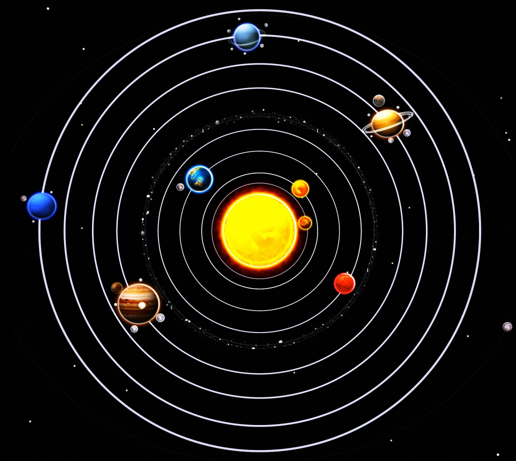
$$\langle T\rangle \sim \langle v^2\rangle$$

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

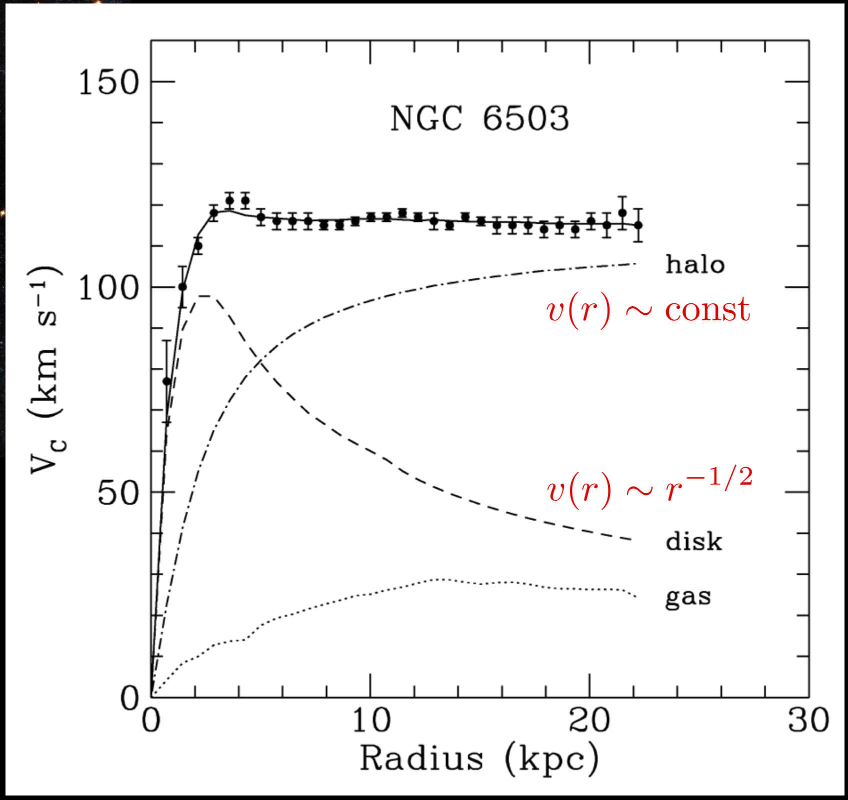
Much more mass than the visible one is needed

Spiral Galaxy



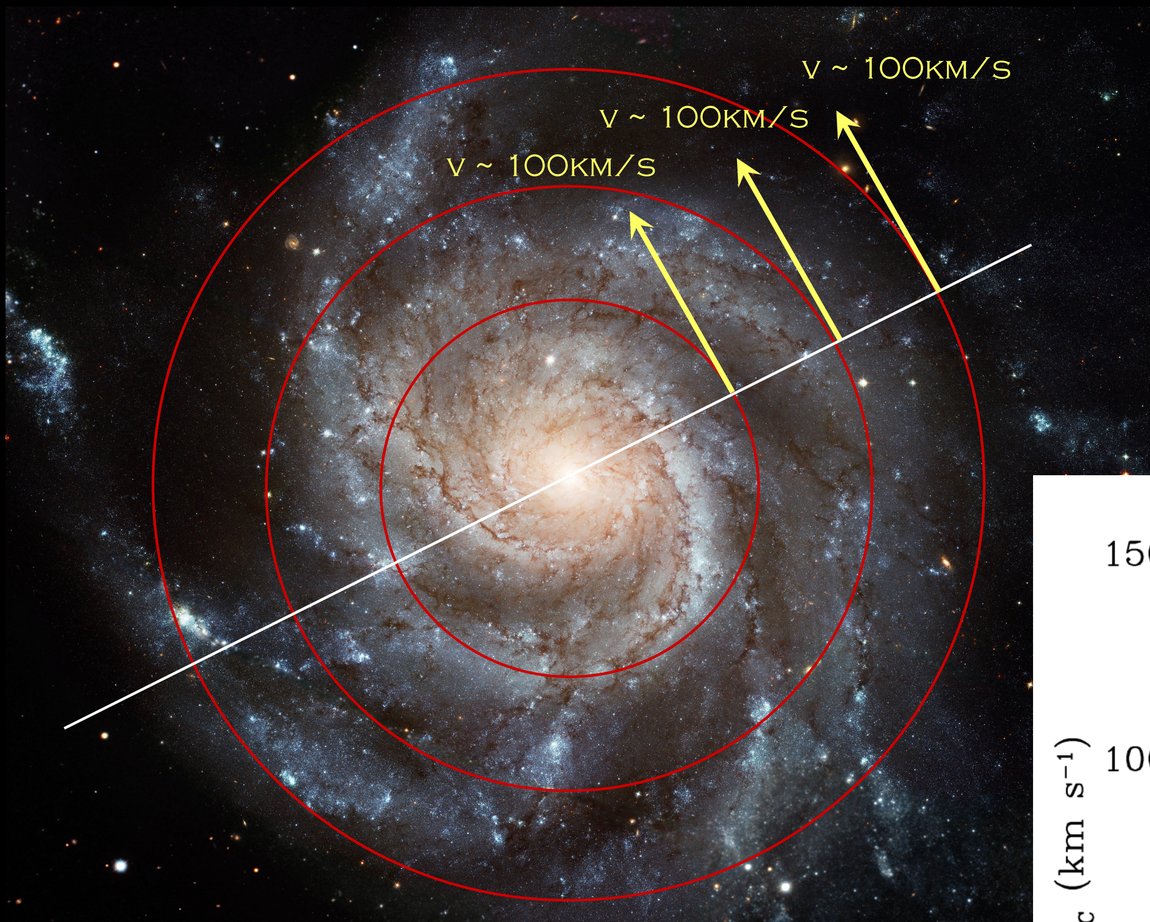


$v(r) \propto r^{-1/2}$

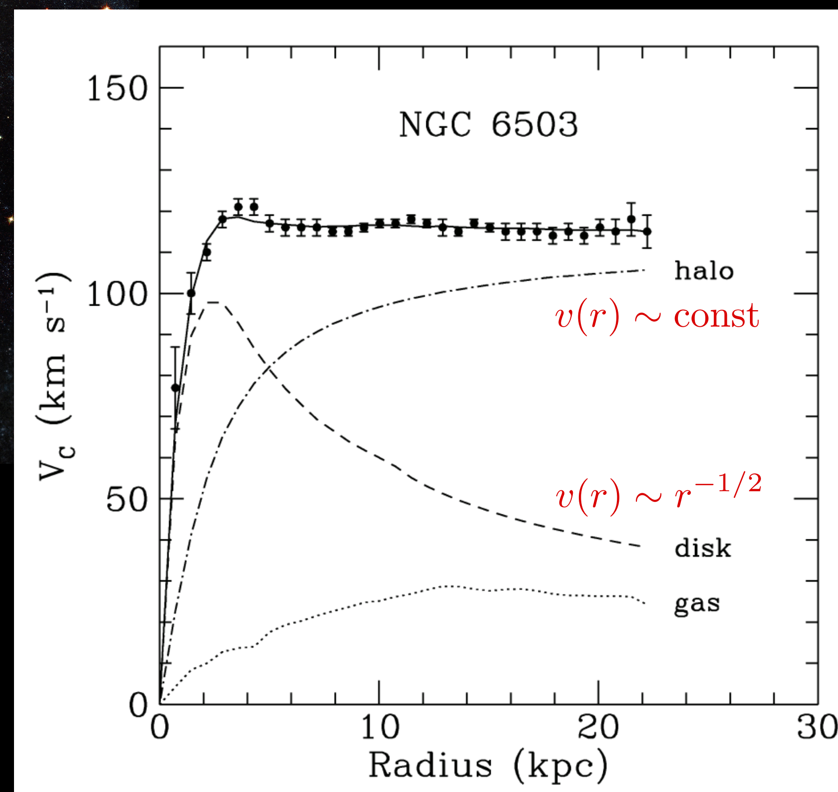


Spiral Galaxy

Rubin (1970)



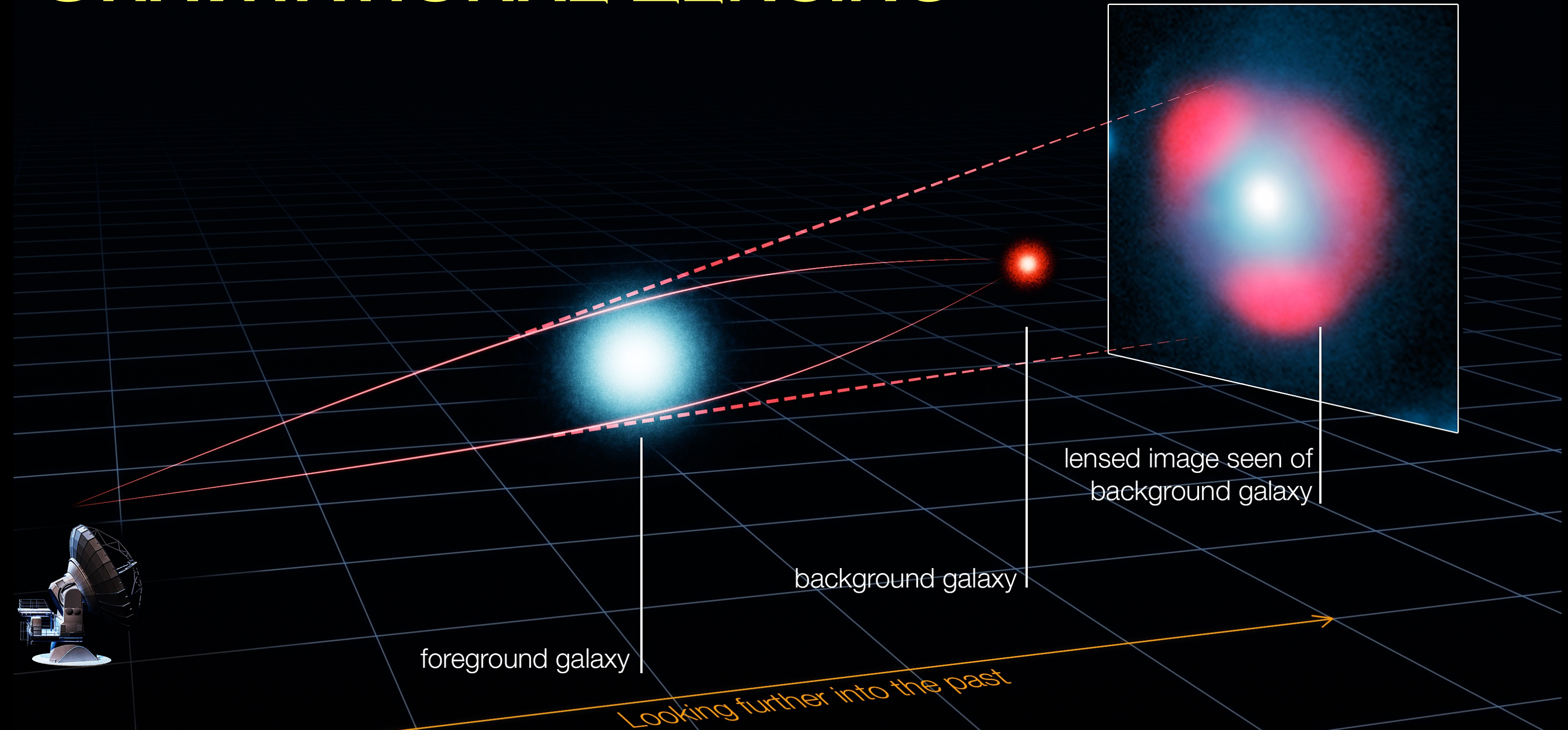
$$v(r) = \sqrt{M(r)/r}$$



Periferic stars and gas are faster than expected

Faster = More mass

Gravitational Lensing



Lens equation

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

Lens equation (can have multiple solutions)

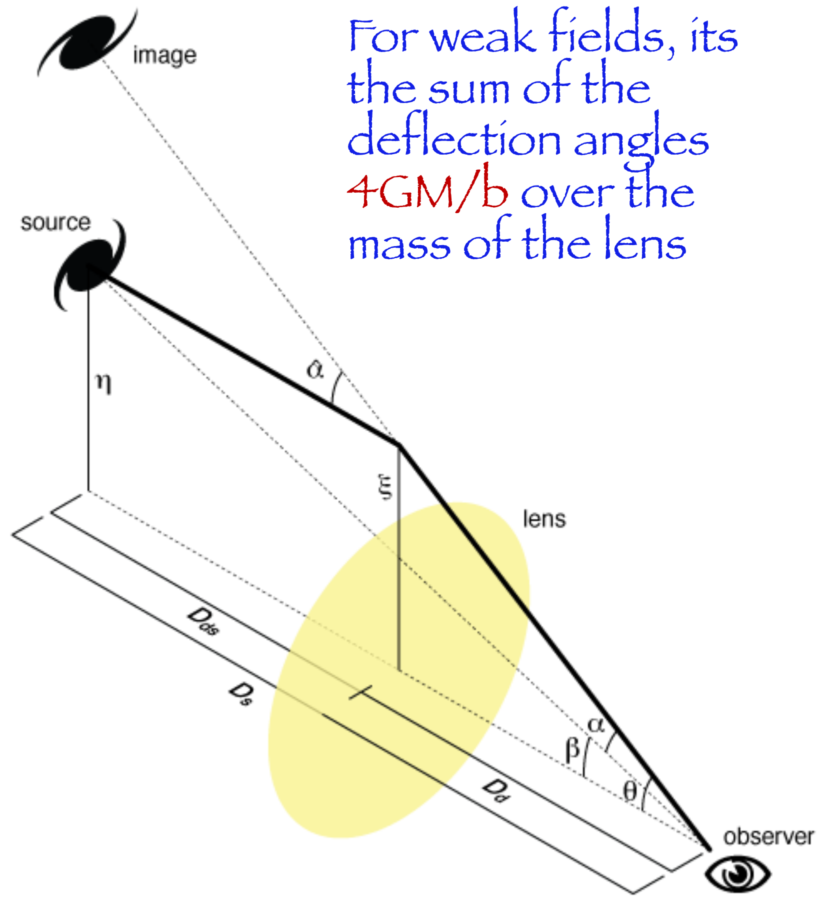
$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

Deflection angle

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

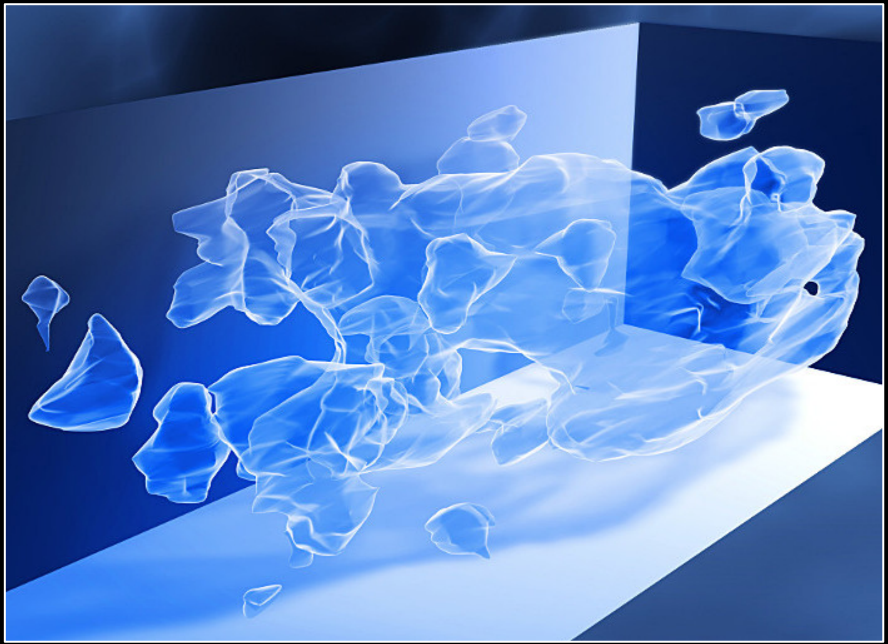
Projected mass density

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



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

Strong lensing

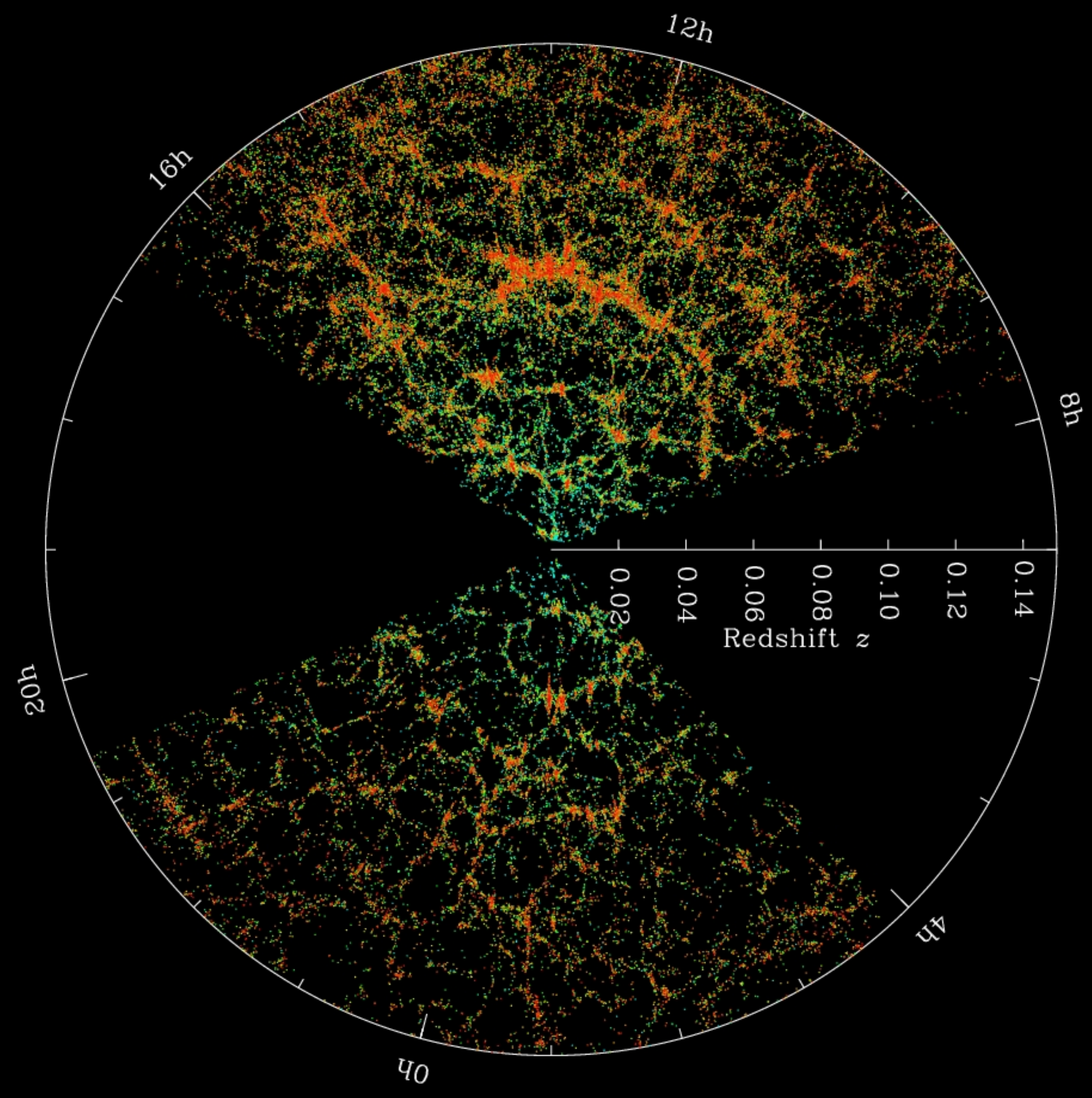


Weak lensing

Gravitational lensing

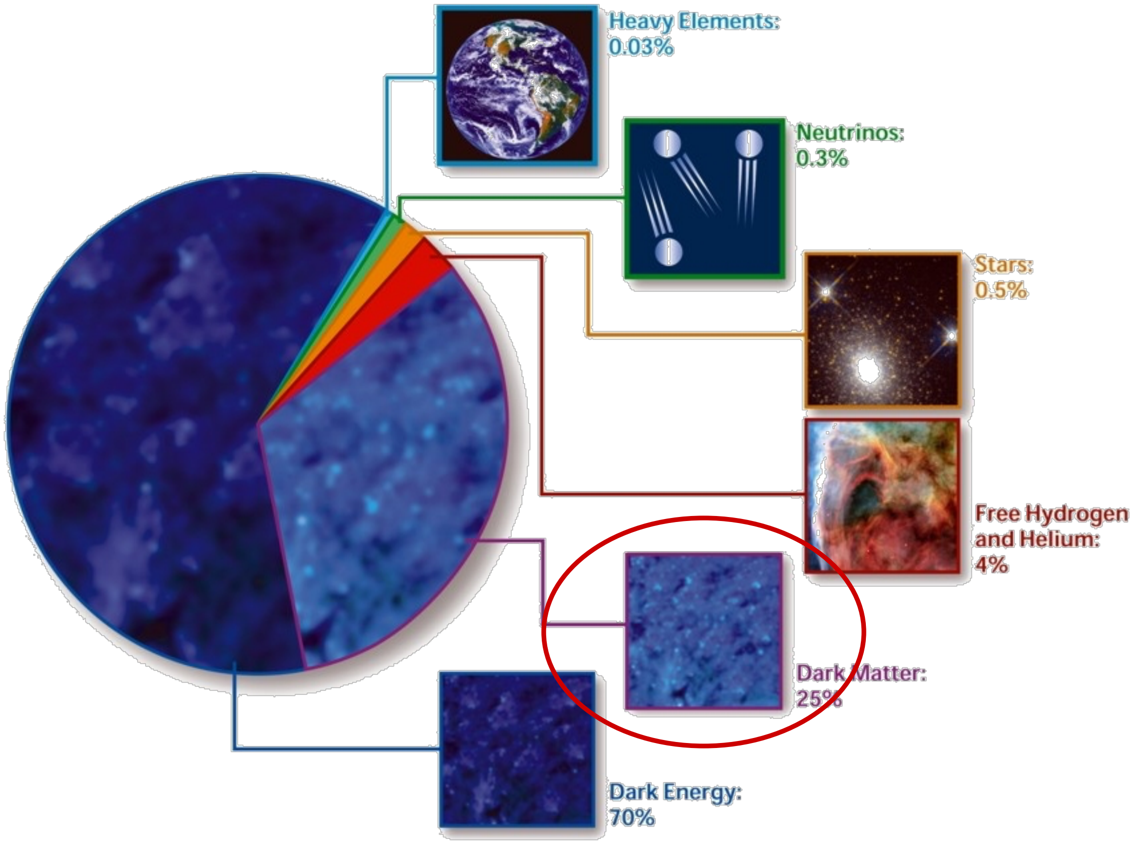
A large amount of mass between the background galaxies and us can be inferred by the lensing effect

Universe at large scales

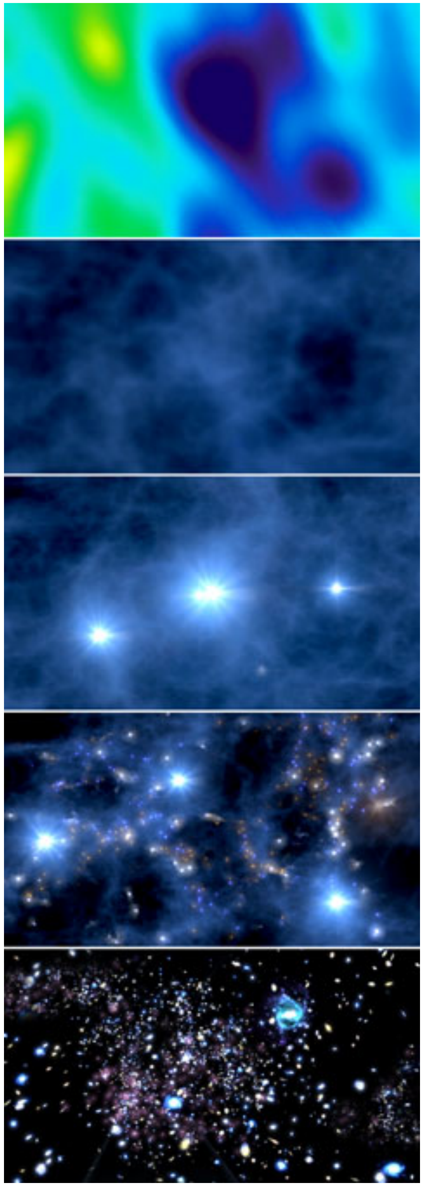


Sloan Digital Sky Survey

Real Universe

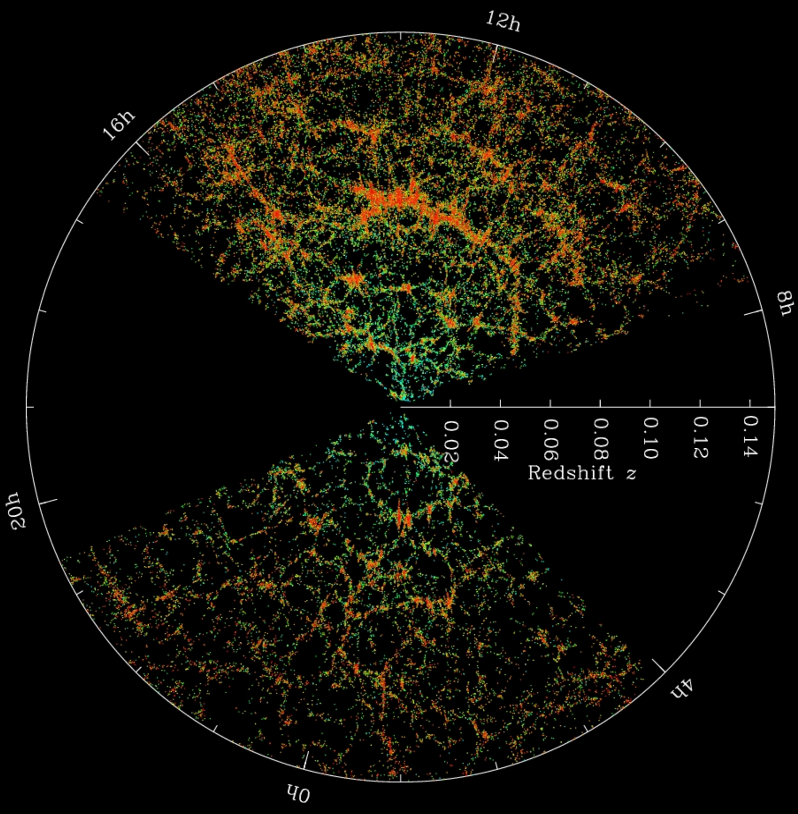


Structure formation from primordial density fluctuations

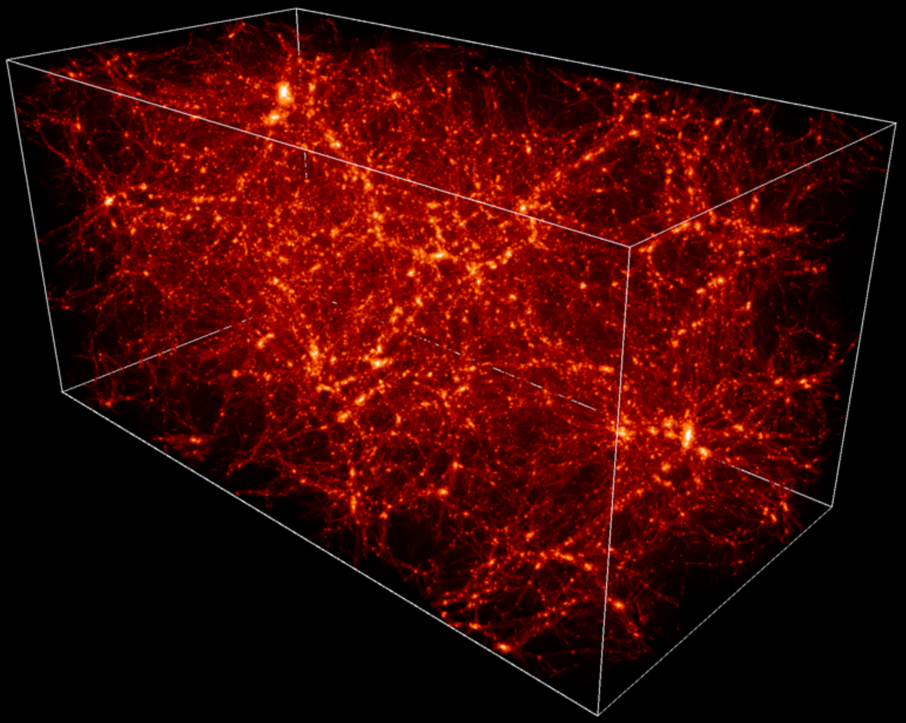


DM needs to be (mainly) cold and (mainly) non-collisional

Structures in LCDM

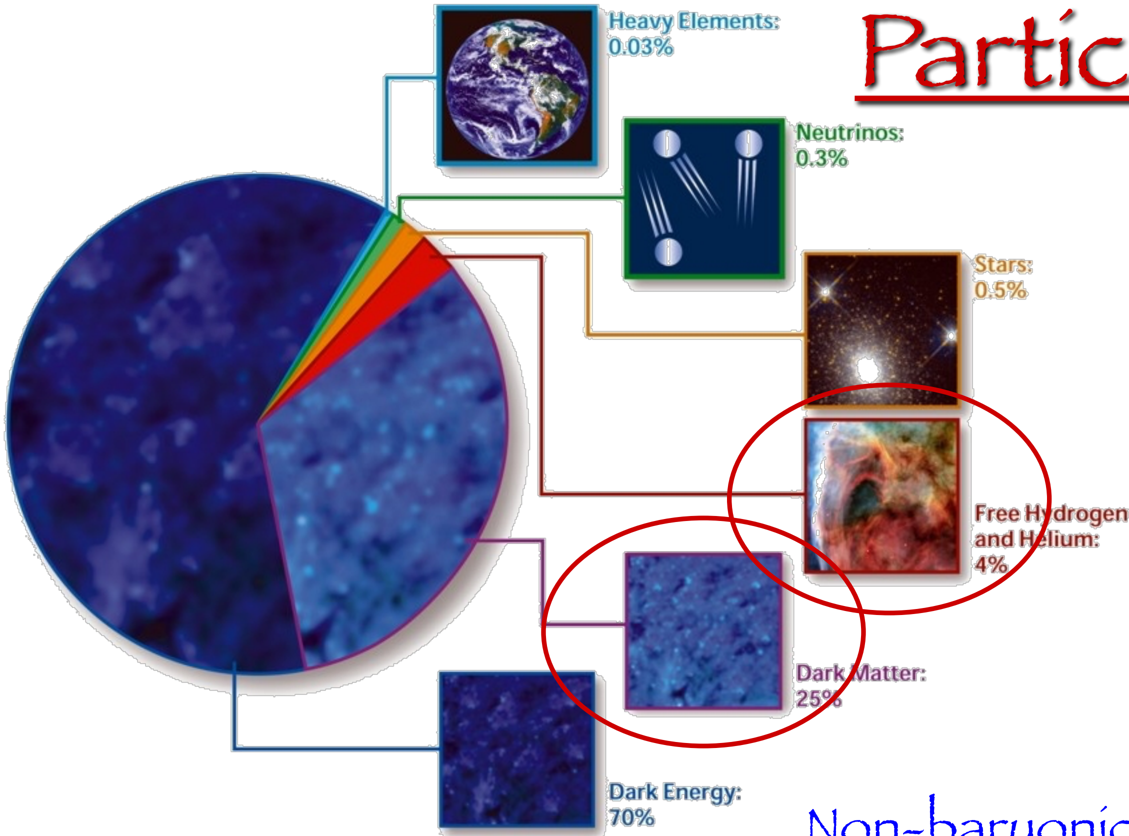


Real Universe



Simulated Universe

Particle Dark Matter



Non-baryonic (cold) dark matter is needed

No candidate in the Standard Model(*)

New fundamental Physics

(*) 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

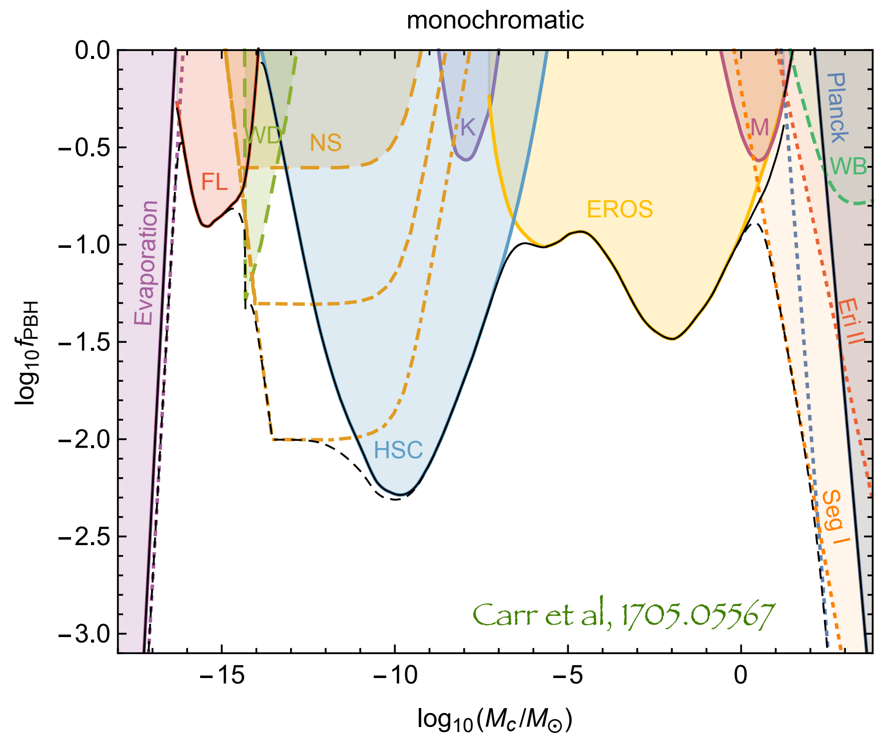
Gravity beyond General Relativity

Primordial black holes *might* solve the DM problem

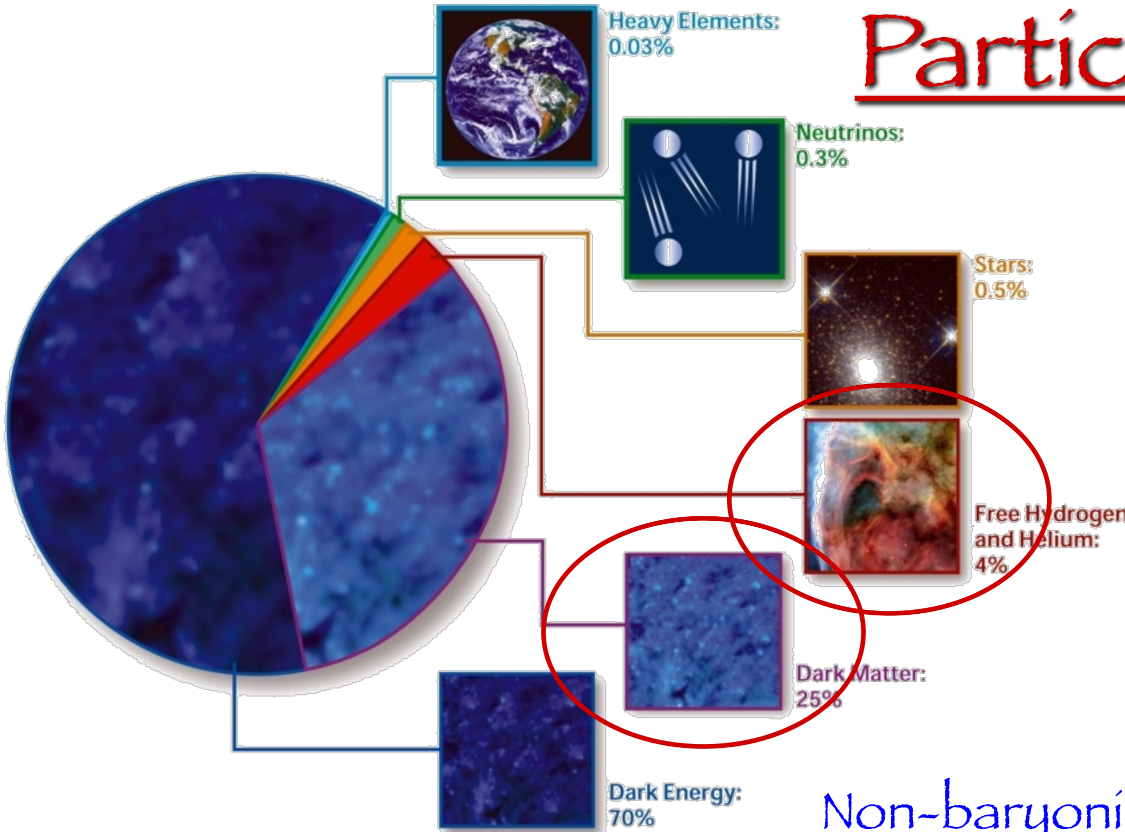
They do not count as baryonic matter

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

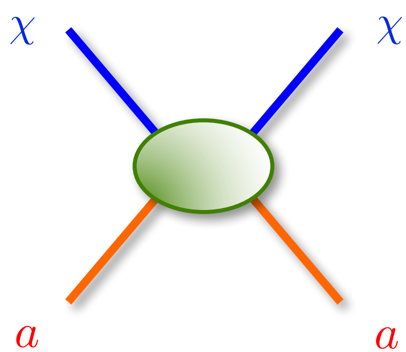
Two fundamental questions

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

If a particle, where it does come from?

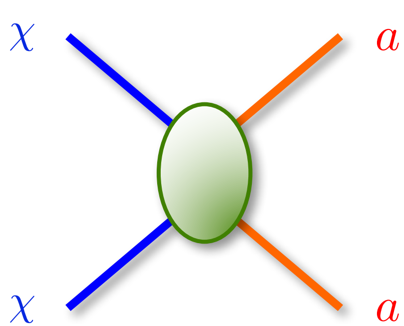
Produced, through some mechanism, in the early Universe

The early Universe is a plasma:



Elastic processes — kinetic equilibrium

Reshuffle particles energies and momenta

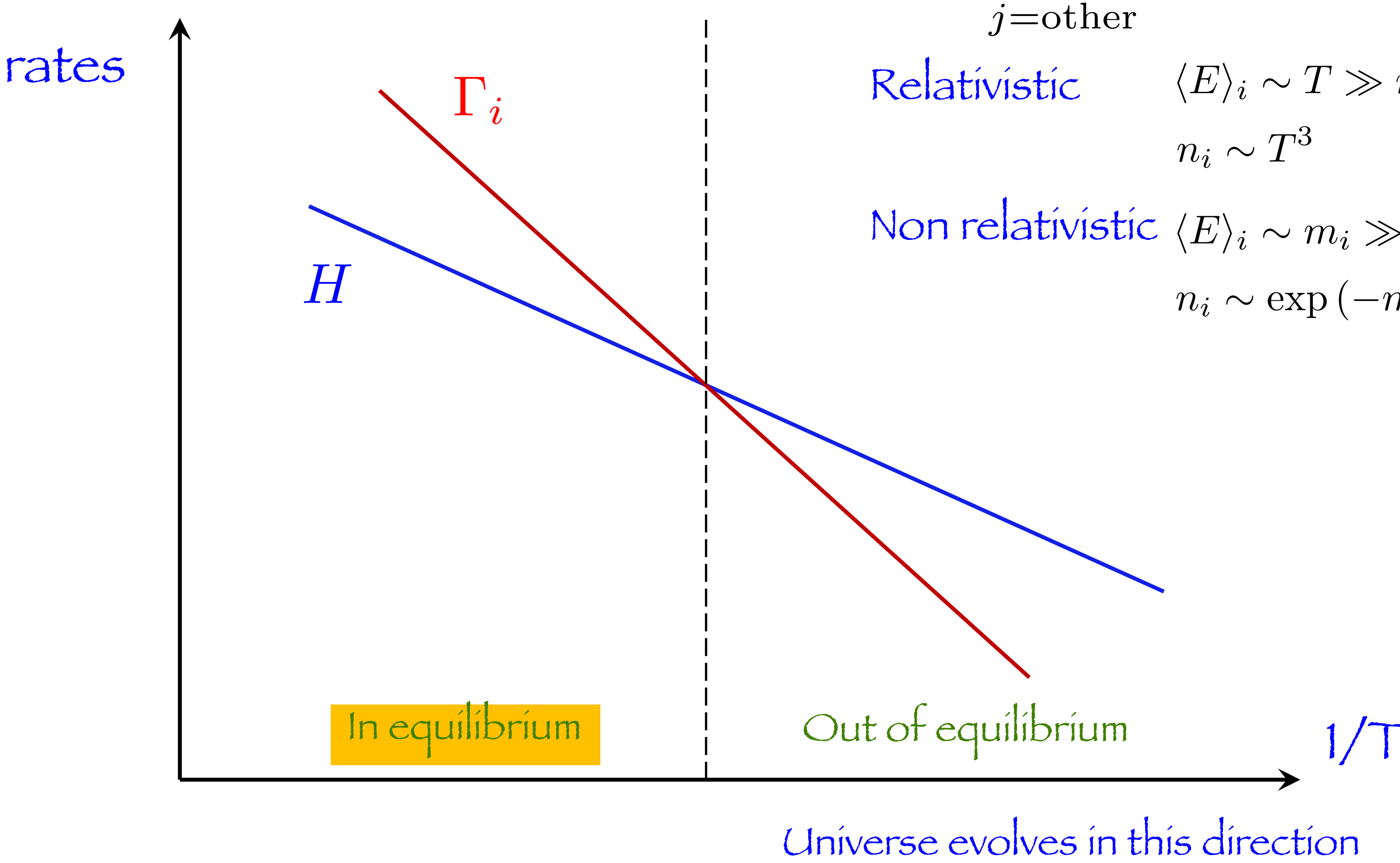


Inelastic processes — chemical equilibrium

Create or destroy particles in the plasma

Equilibrium in the plasma

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



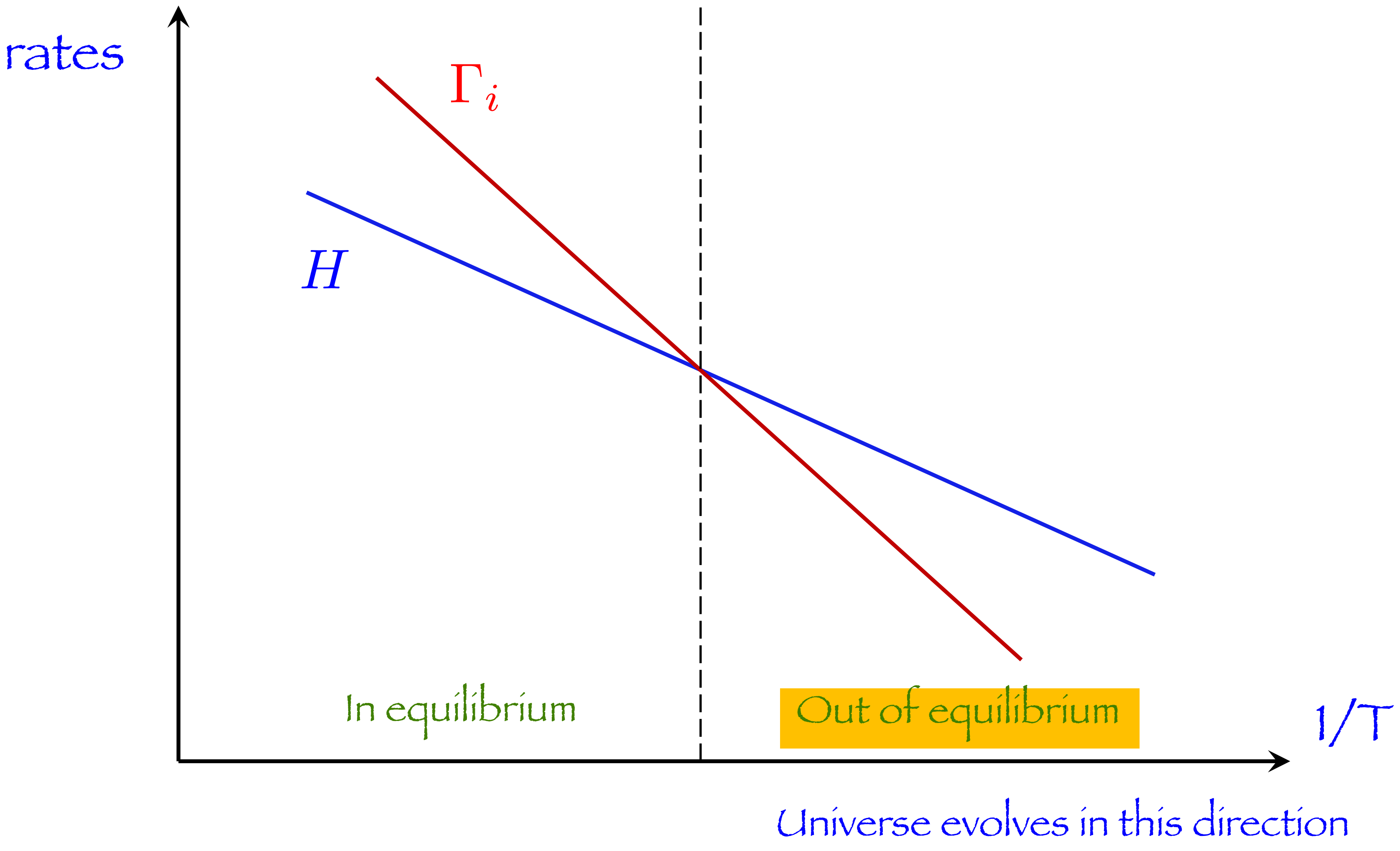
Relativistic $\langle E \rangle_i \sim T \gg m_i$

$n_i \sim T^3$

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

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

Out of equilibrium



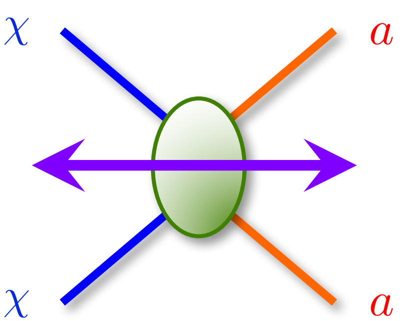
Boltzmann eq. for the number density

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

dilution due to expansion

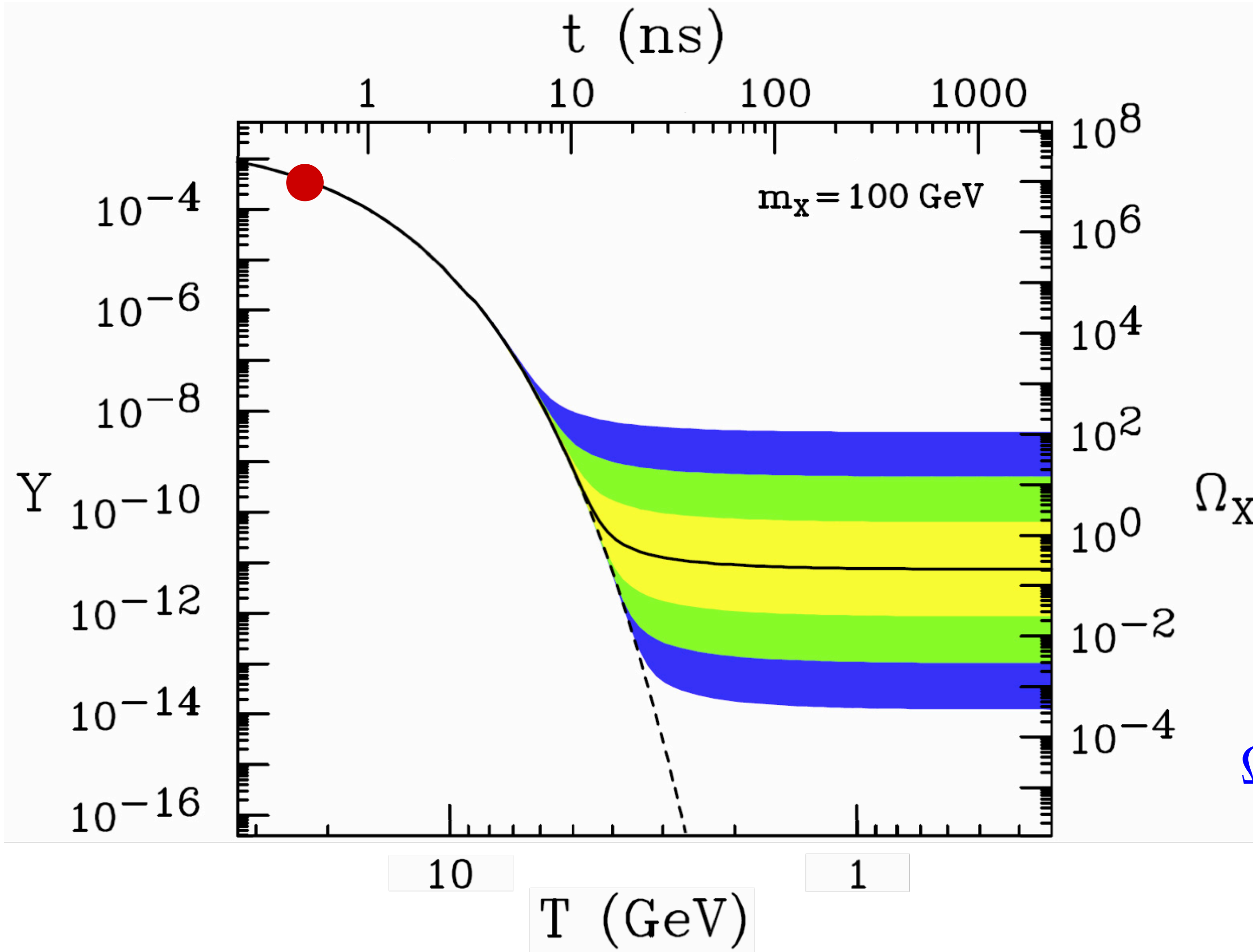
dilution due to annihilation

production due to inverse annihilation



Abundance evolution for a cold relic

$Y = n/s$



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

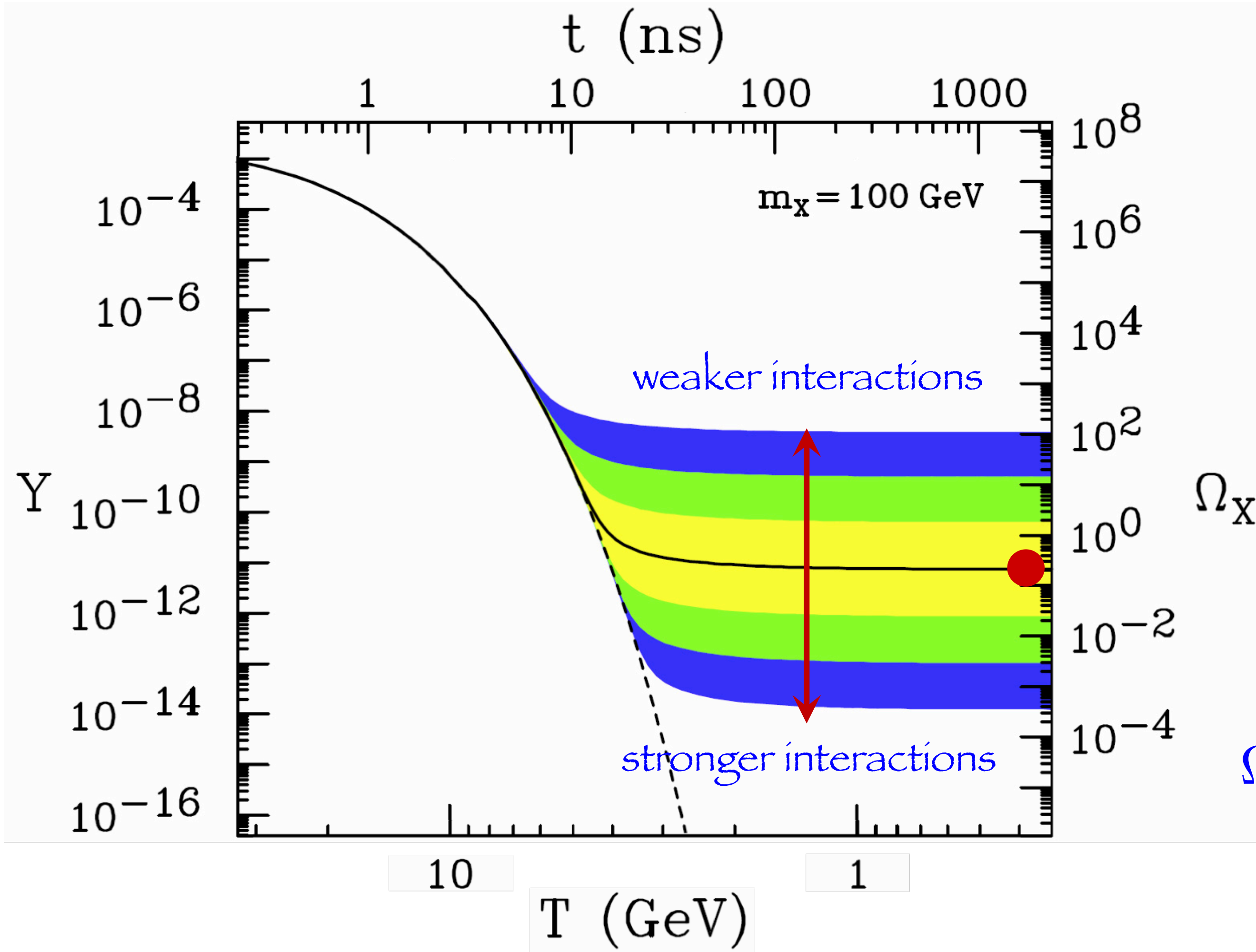
$\langle E \rangle_\chi \sim m_\chi \gg T$

$\langle E \rangle_a \sim T$

Particle in equilibrium

Abundance evolution

$Y = n/s$



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

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

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

$$\langle \sigma v \rangle_{\mathrm{ann}} = 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

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

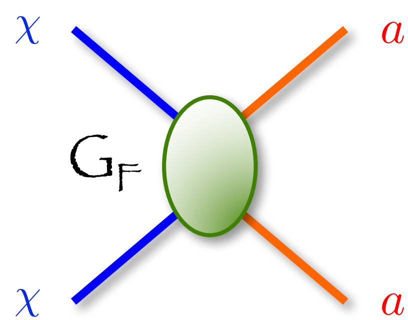
$m \ll m_Z$

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

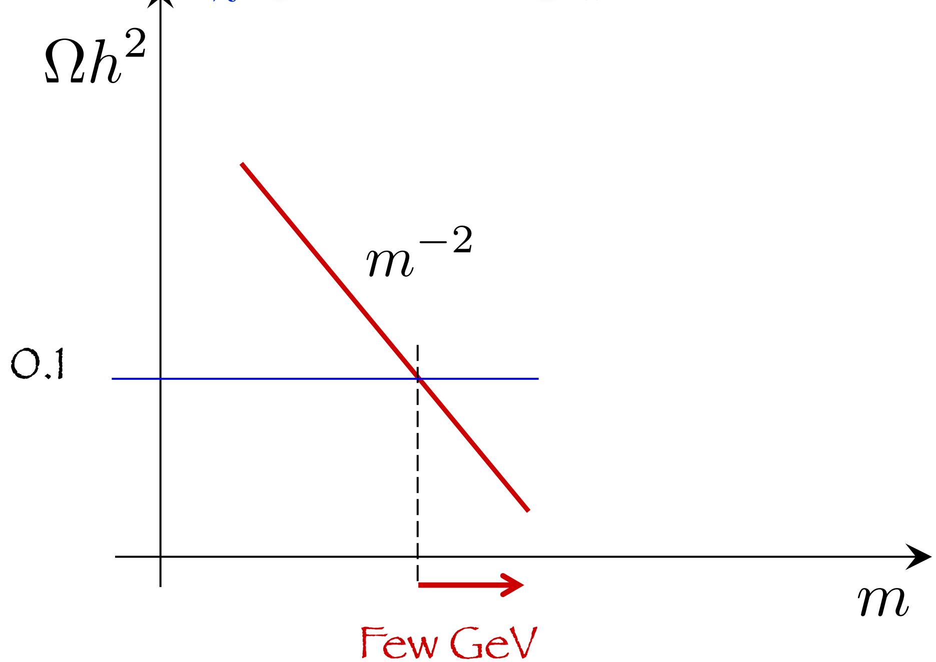
$$s = q^2 \sim (2\, m_{\rm DM})^2$$

non-relativistic

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



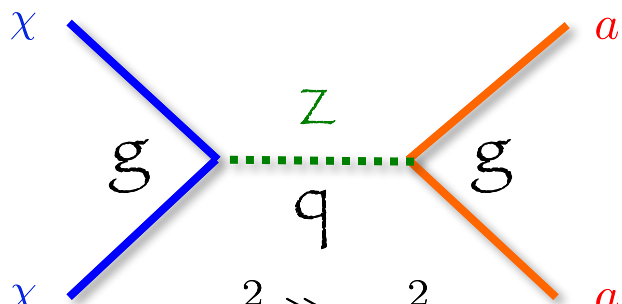
Fermi limit



Lee-Weinberg bound

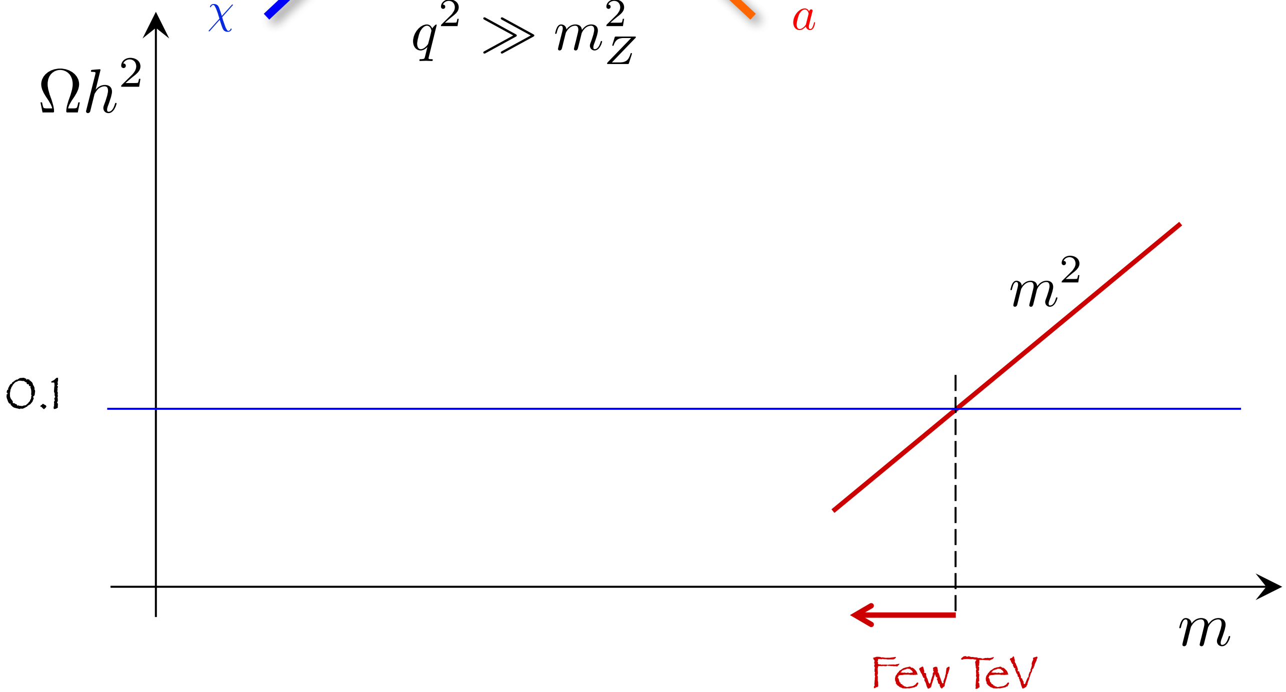
In more details

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

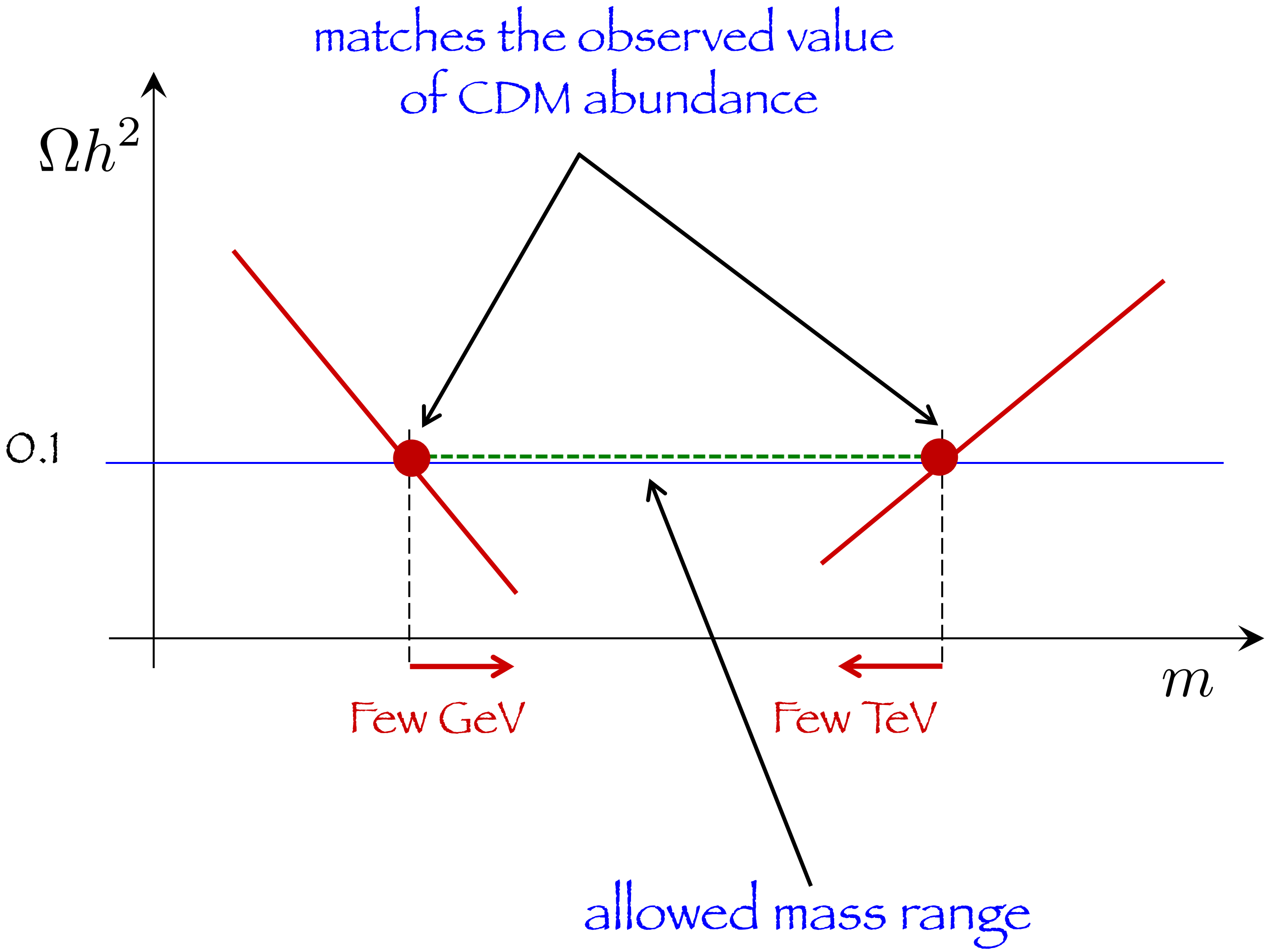


$q^2 \gg m_Z^2$

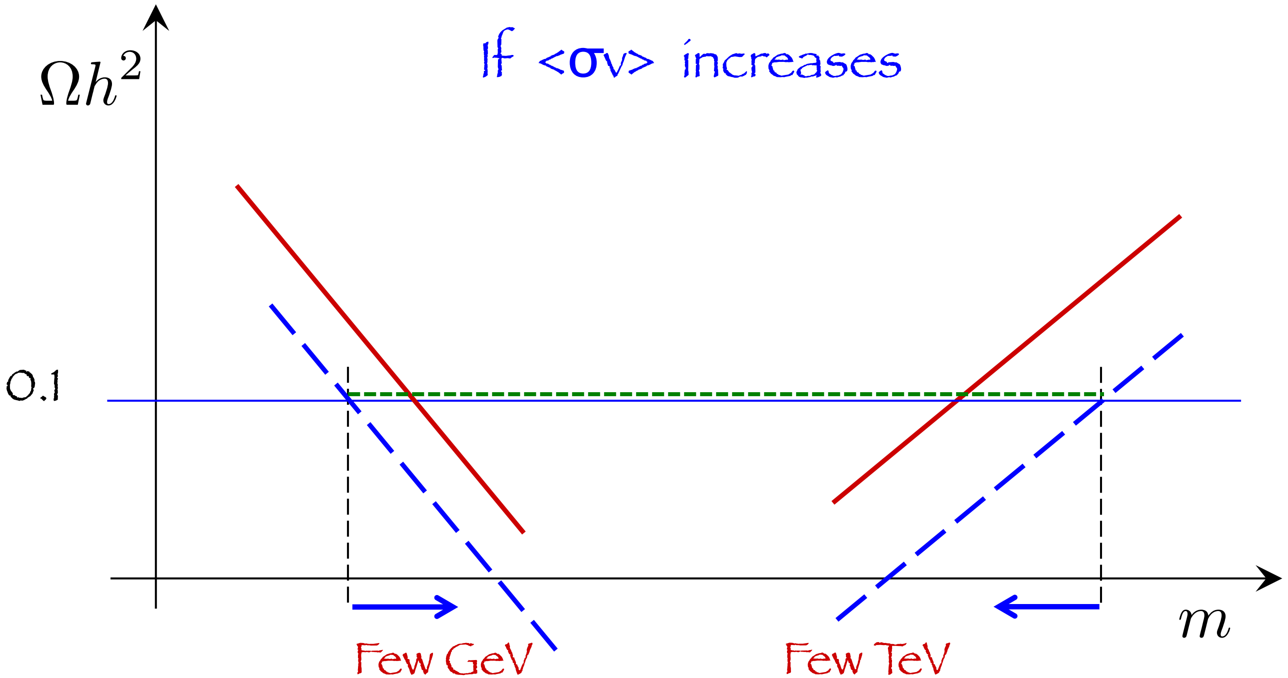
Effectively massless Z



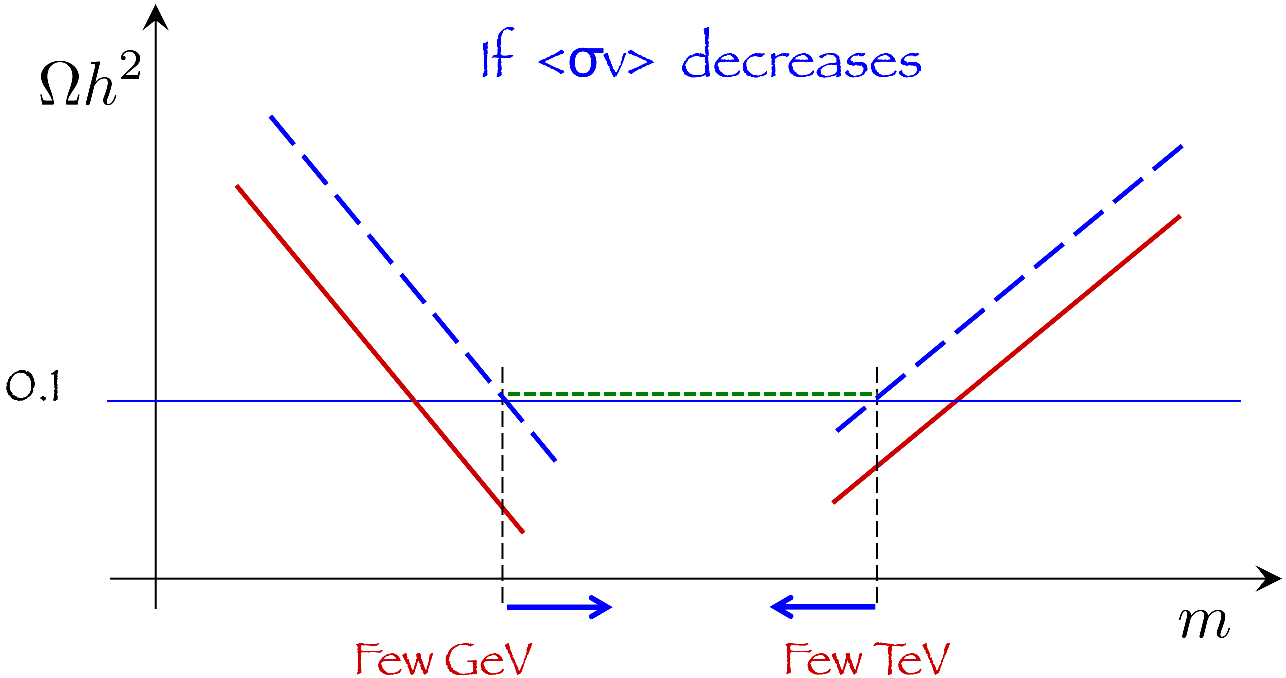
Summarizing



Dependencies



Dependencies



Additional features

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

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

Sommerfeld enhancements light mediator

The WIMP "miracle"

Loosely speaking a particle with:

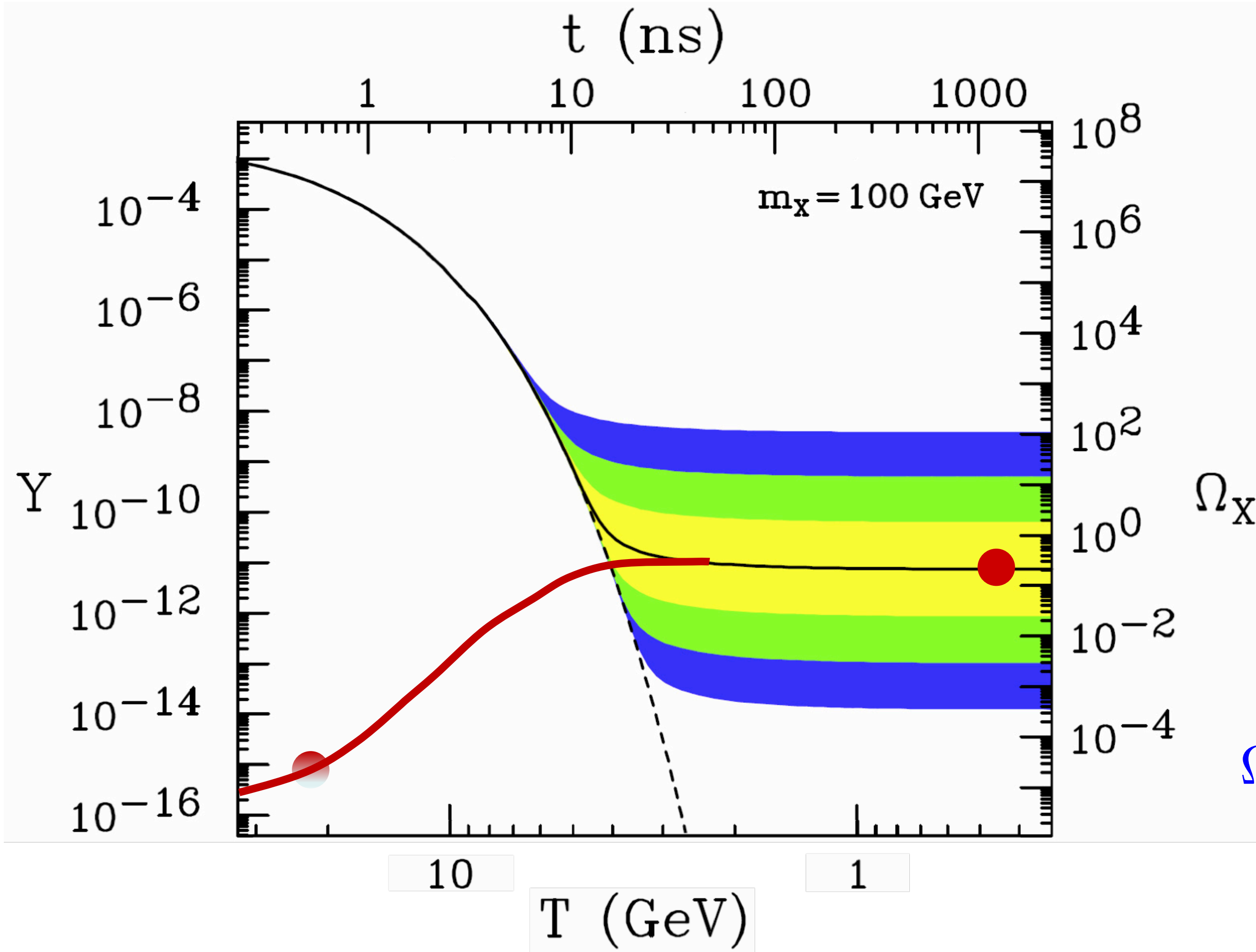
- Mass: sligthely sub-GeV to multi-TeV
- Interactions: weak type

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

And clearly it must stable (at least on cosmological time-scales. i.e. lifetime > age og the Universe)

Freeze-in mechanism

$Y = n/s$



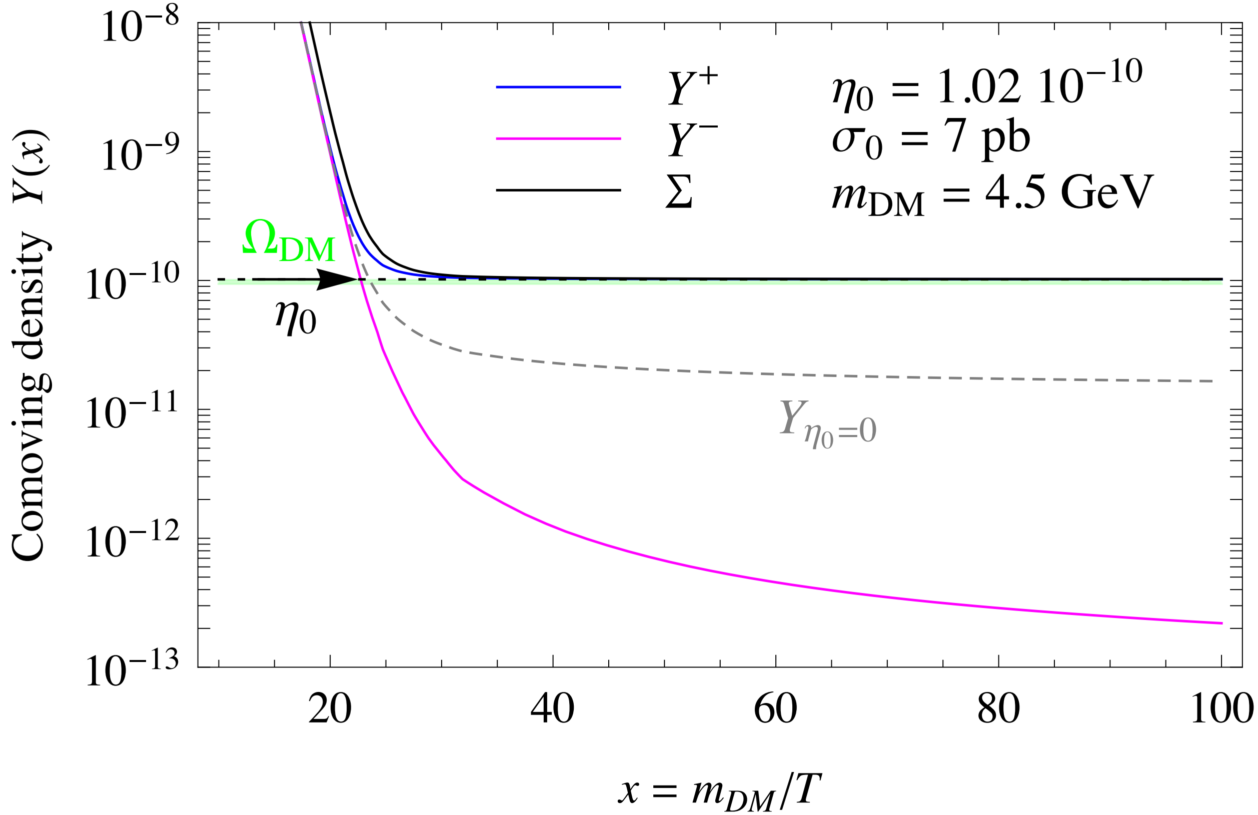
$$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$$

Particle never in full equilibium

Asymmetric DM

Asymmetry can arise because of:

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



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 <σ_Nv>)

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

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."

Models and candidates

Supersymmetry, Extra-dimensions [GeV-TeV, WIMP]

Minimal dark matter [TeV, WIMP]

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

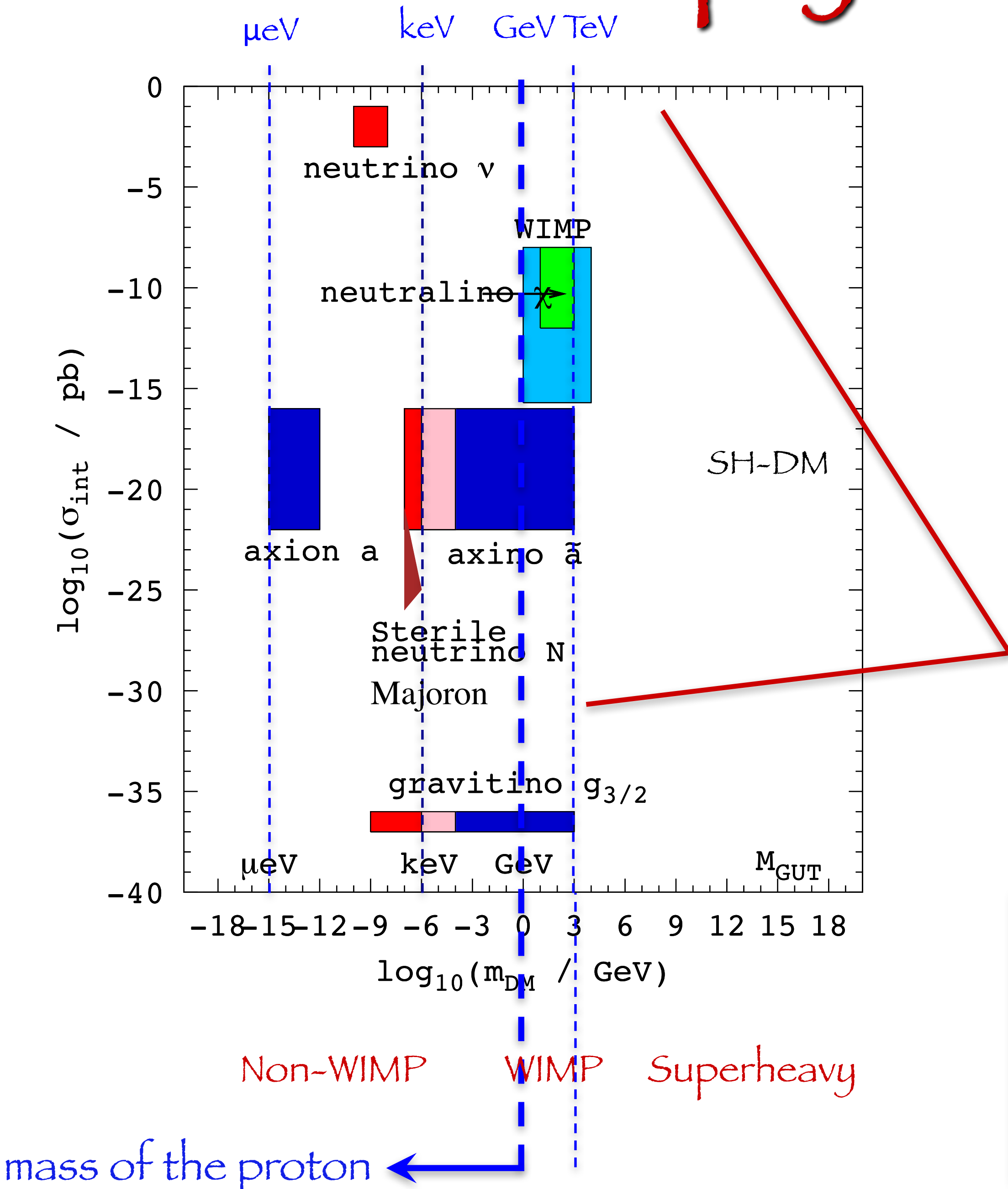
Mirror dark matter

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

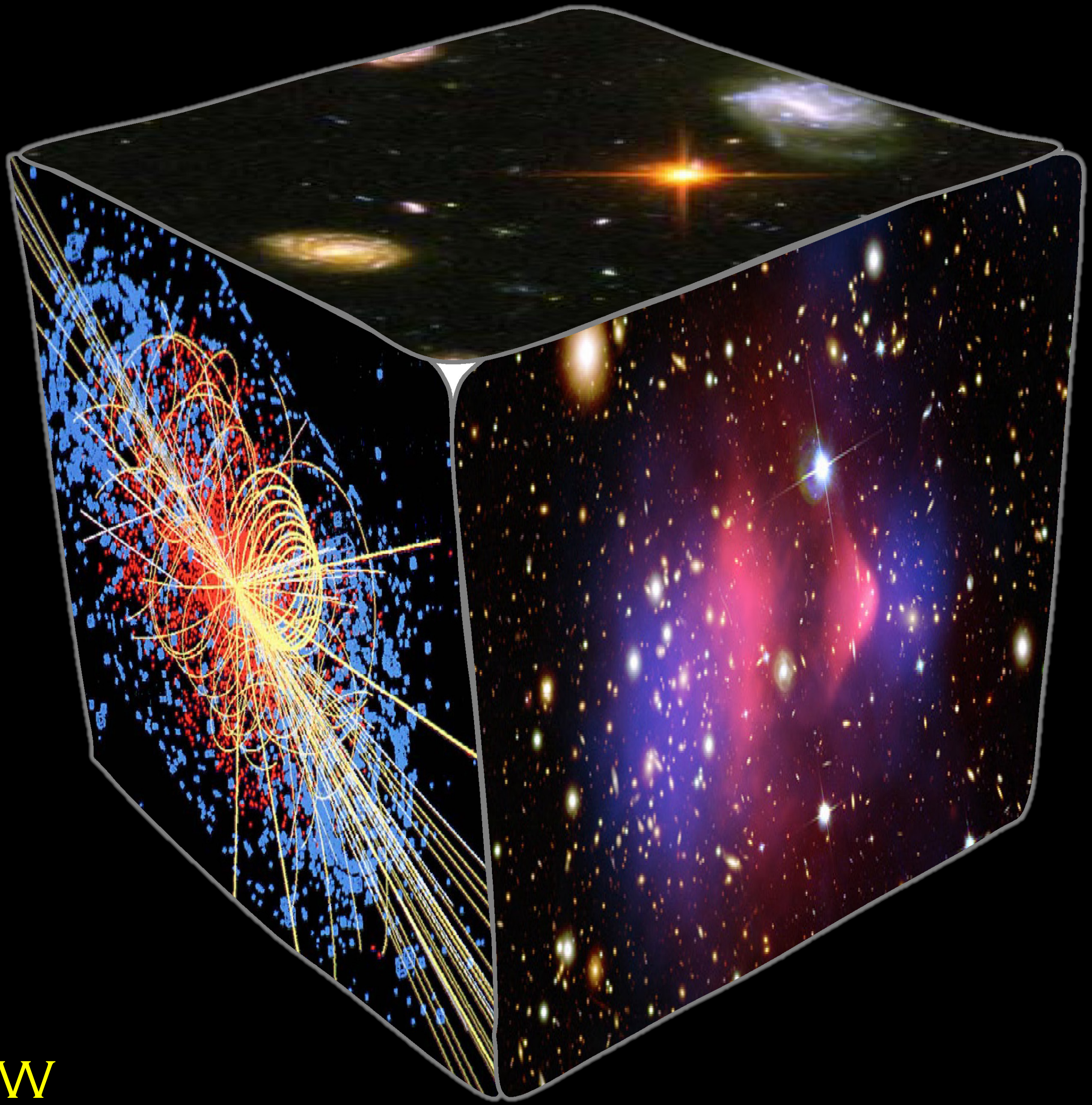
Relic from the early Universe

Thermal

Non thermal

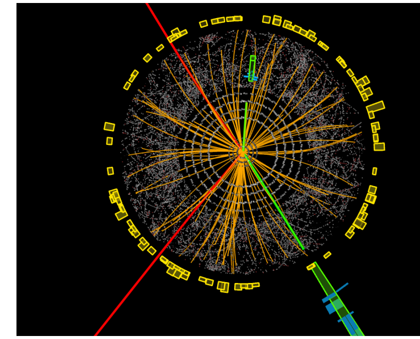
Dynamically: non relativistic (cold)

collisionless



Where and how to look for these new particles?

A multiple approach

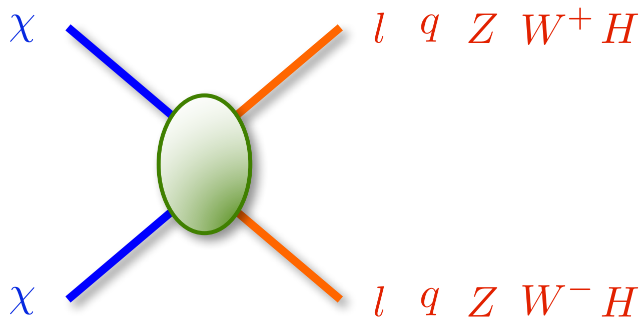


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy

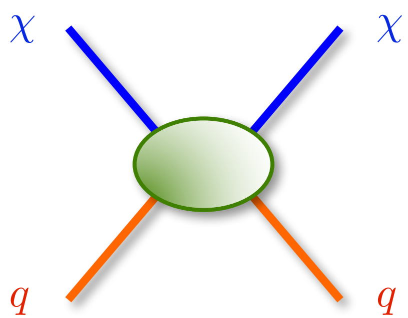
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

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

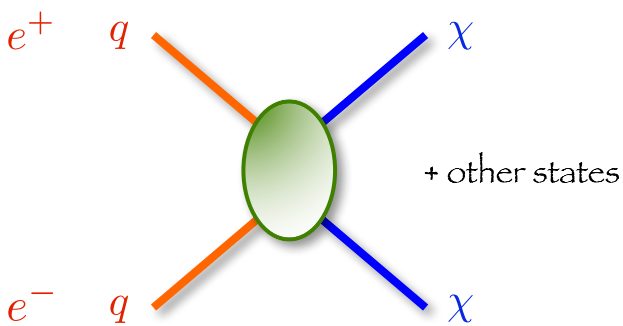
Mechanisms of DM signal production



Annihilation (or decay)

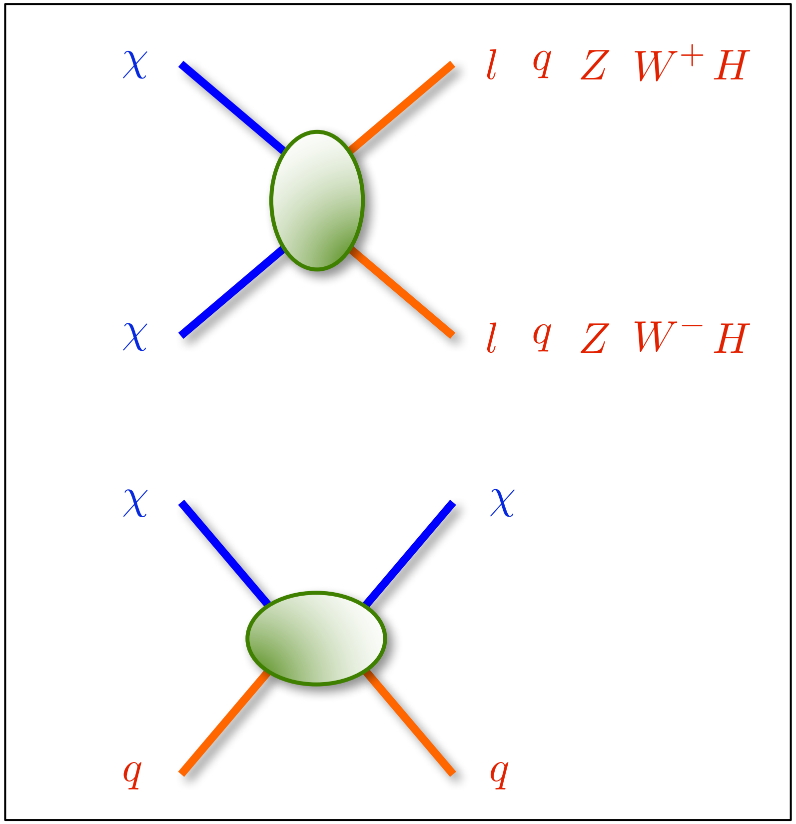


Scattering with ordinary matter



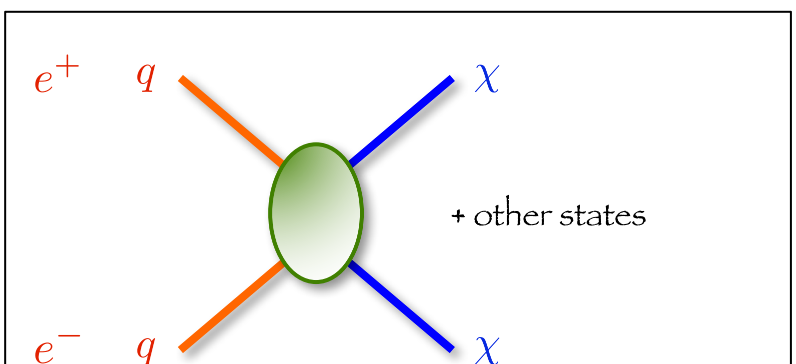
Production at accelerators

Mechanisms of DM signal production



Signals occur in astrophysical context

Directly test DM the particle-physics nature of DM



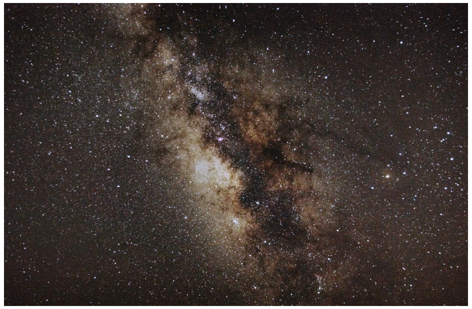
Signal produced in accelerators

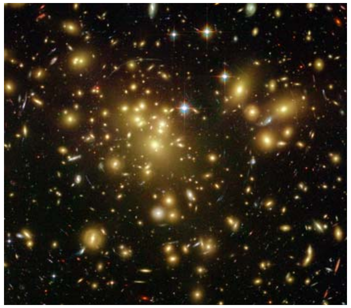
Directly tests New Physics: compatibility with DM needs to be cross-checked with cosmology adn astrophysics

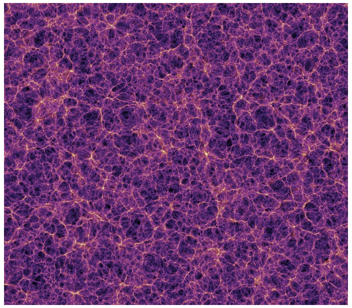
Where to search for a signal …

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"



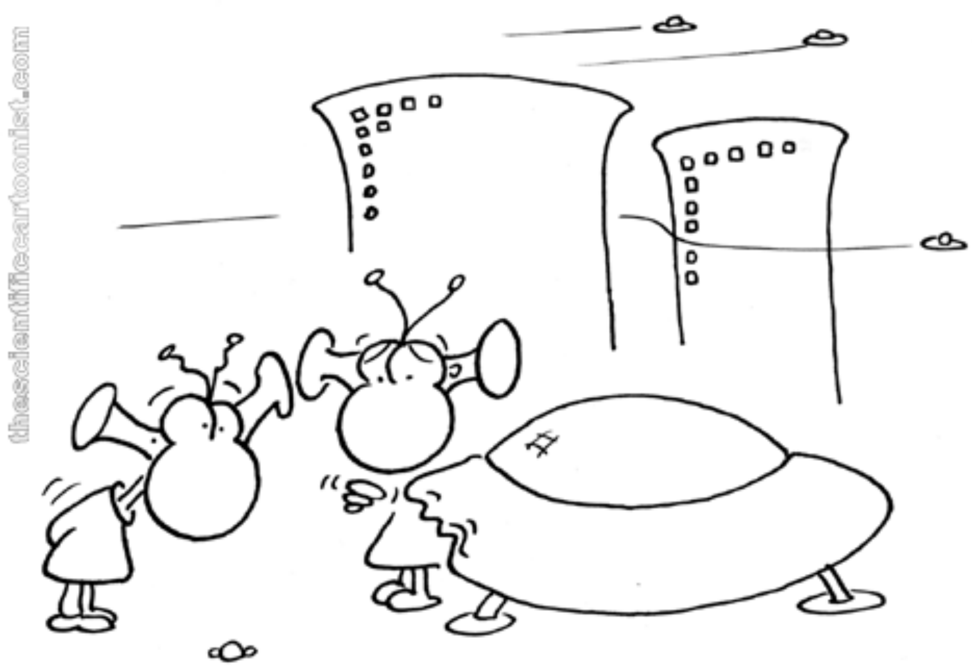




DM as a particle might ...

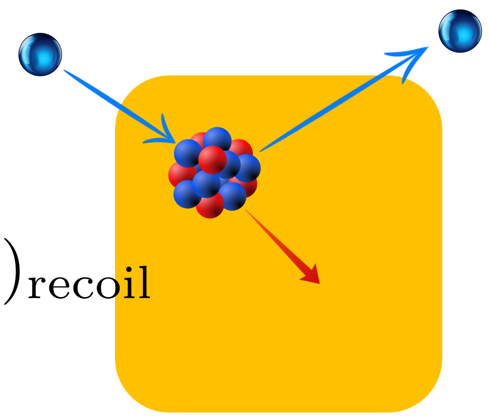
Interact with ordinary matter — Direct detection

Produce effects in astrophysical environments, like in stars



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

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

Set of operators

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Typical signatures of direct detection

- Stationary over the lifetime of an experiment
  Directional boost

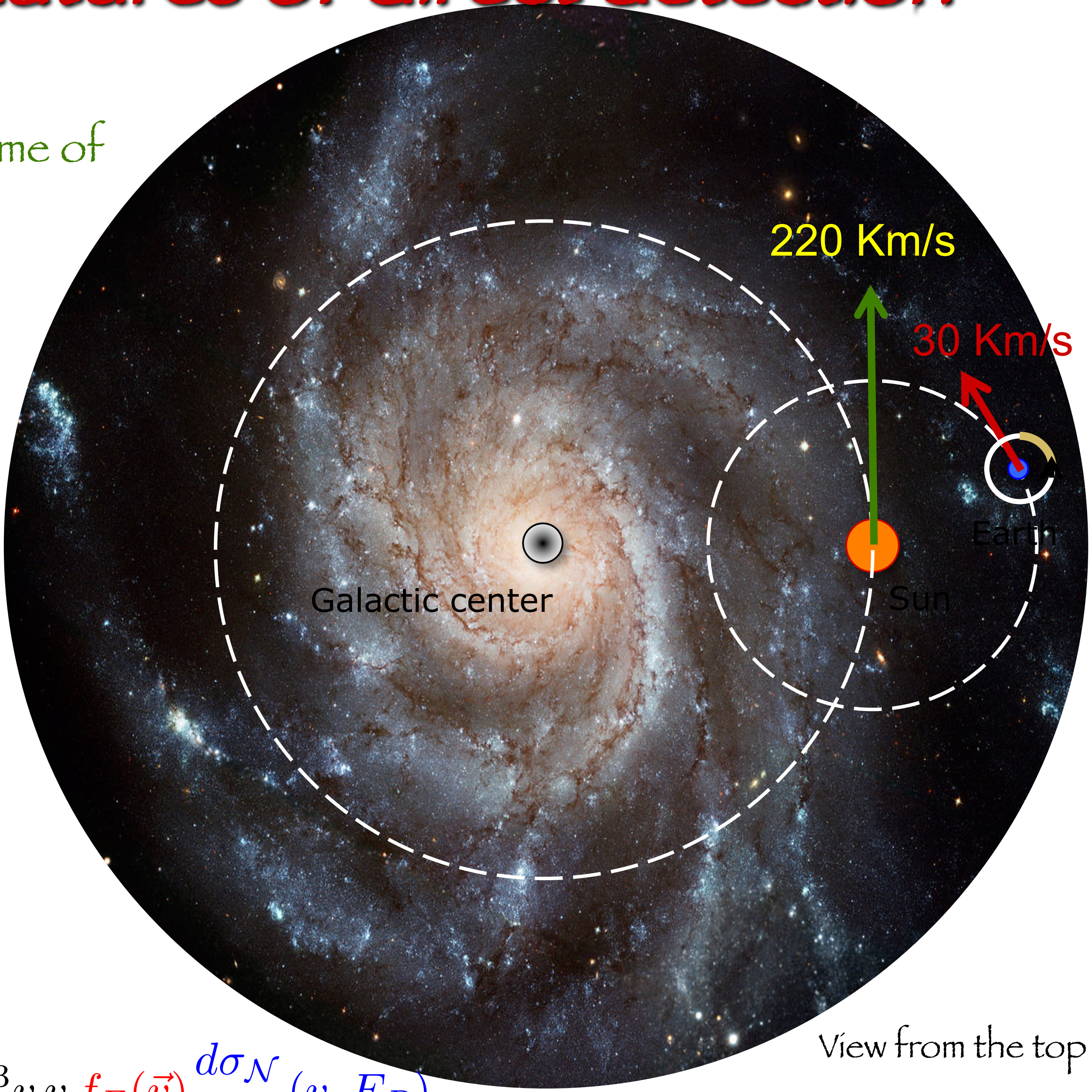
  Directionality

- 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

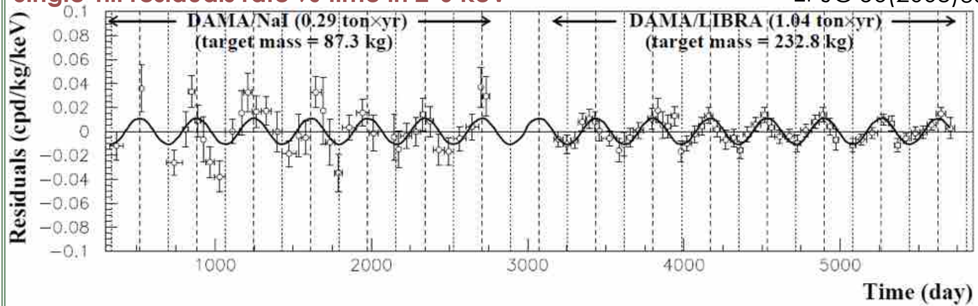
DAMA, 9.2σ with 1.33 ton x yr, 15 cycles

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



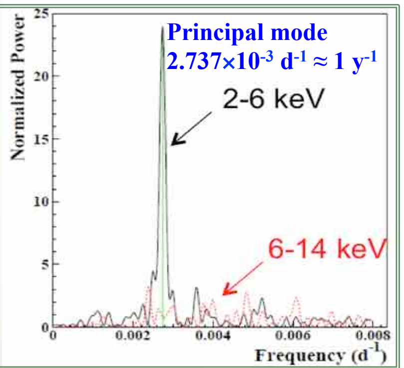
continuous line: t_0 = 152.5 d, T = 1.0 y

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}

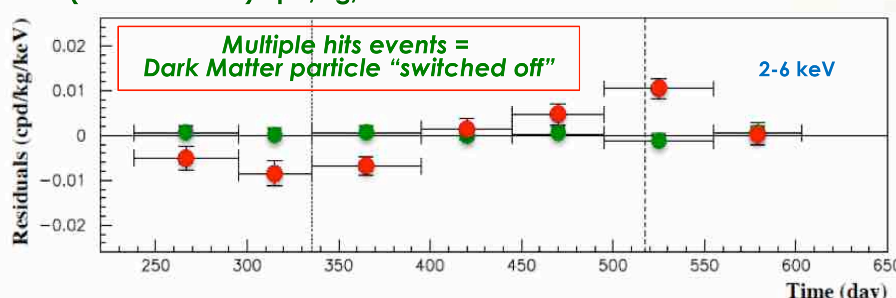
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y
9.3 σ C.L.

Power spectrum



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



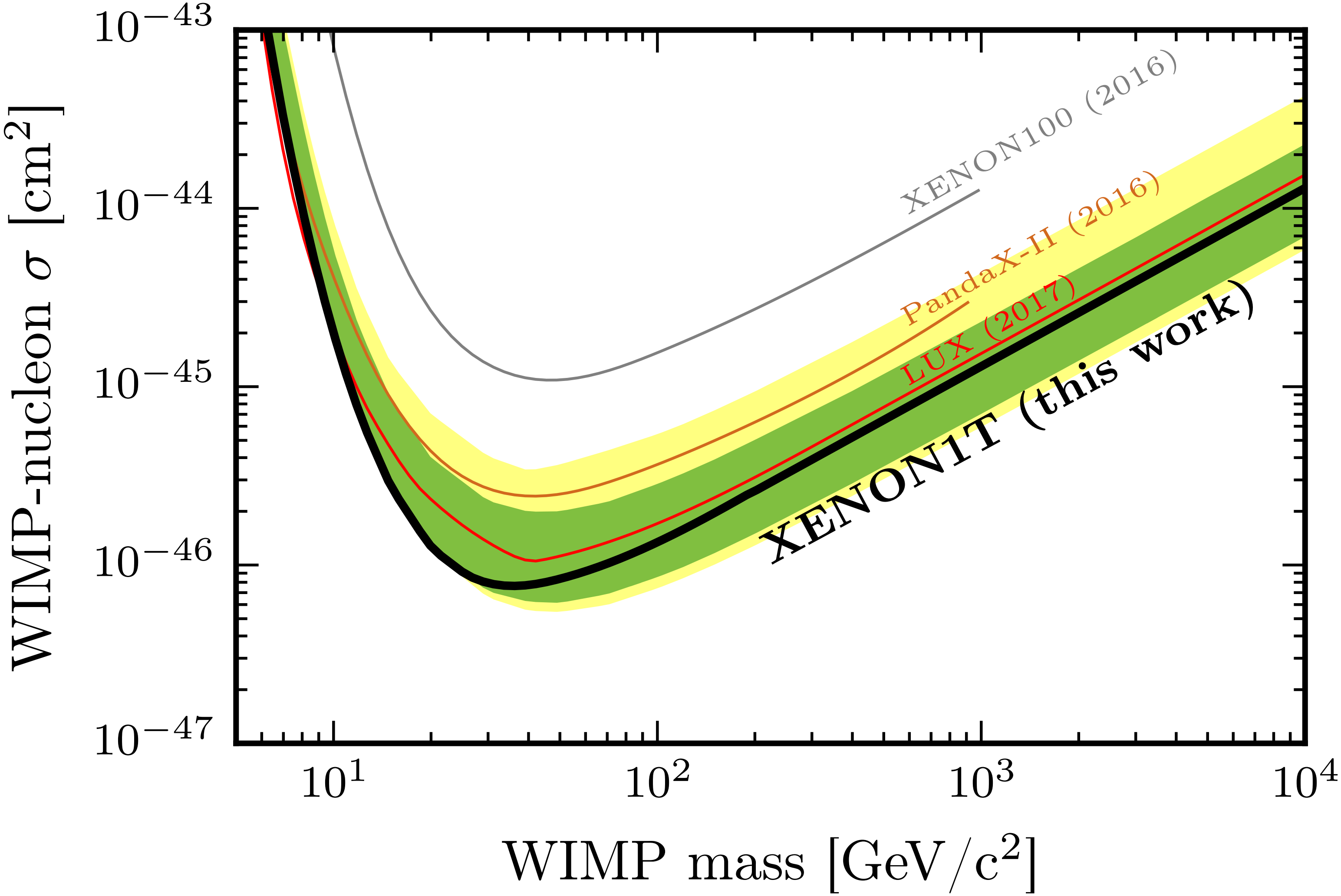
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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

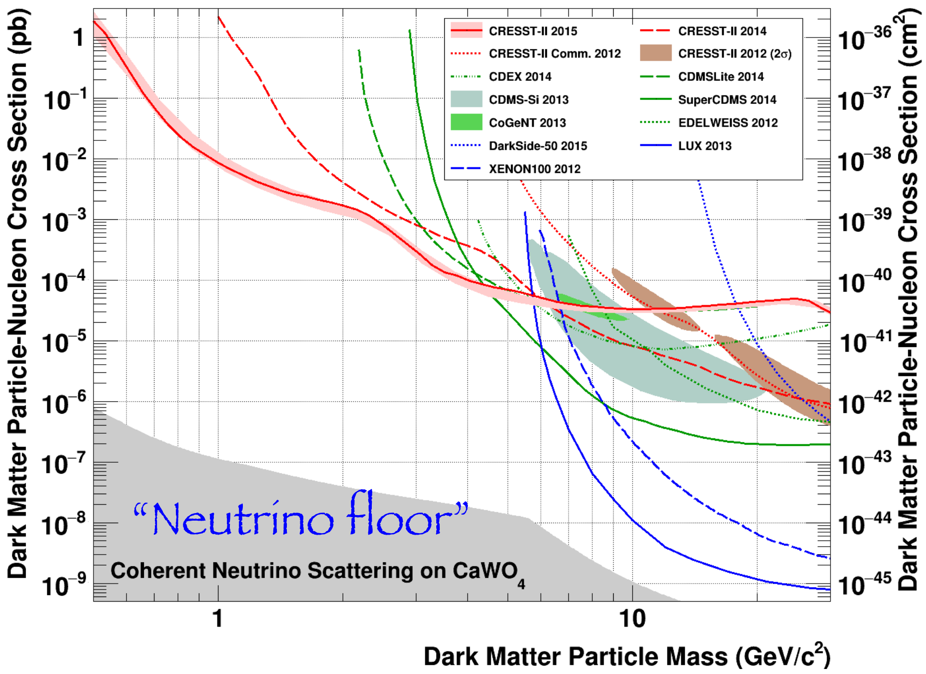
High WIMP mass

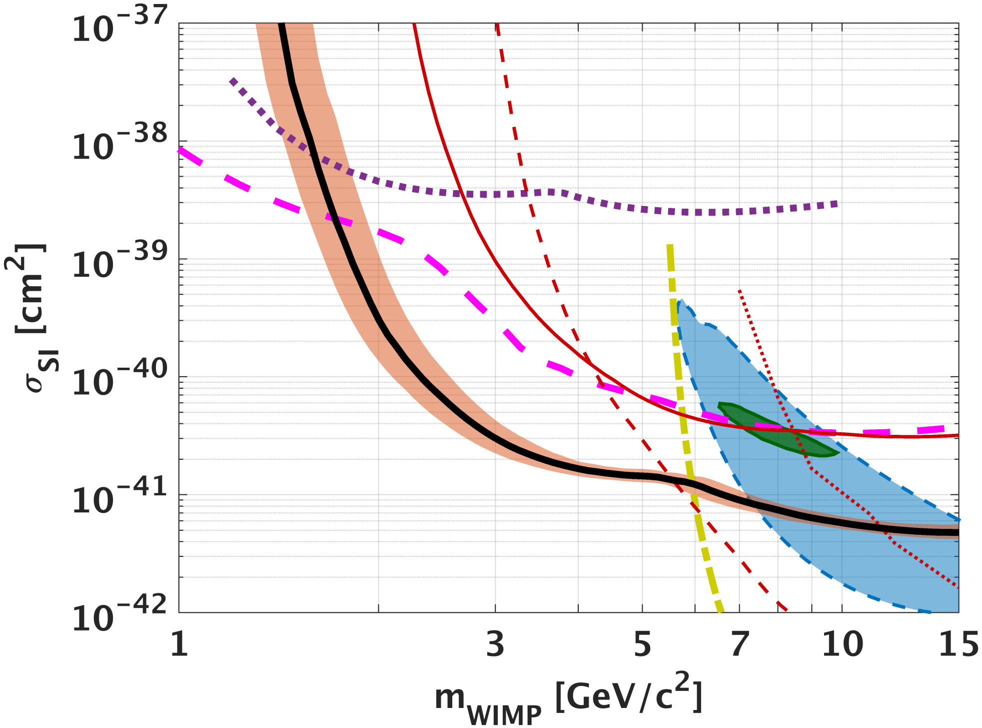
Contact-type scalar interactions (O_1)



Aprile et al (XENON 1T Collab), 1705.06655

Low WIMP mass





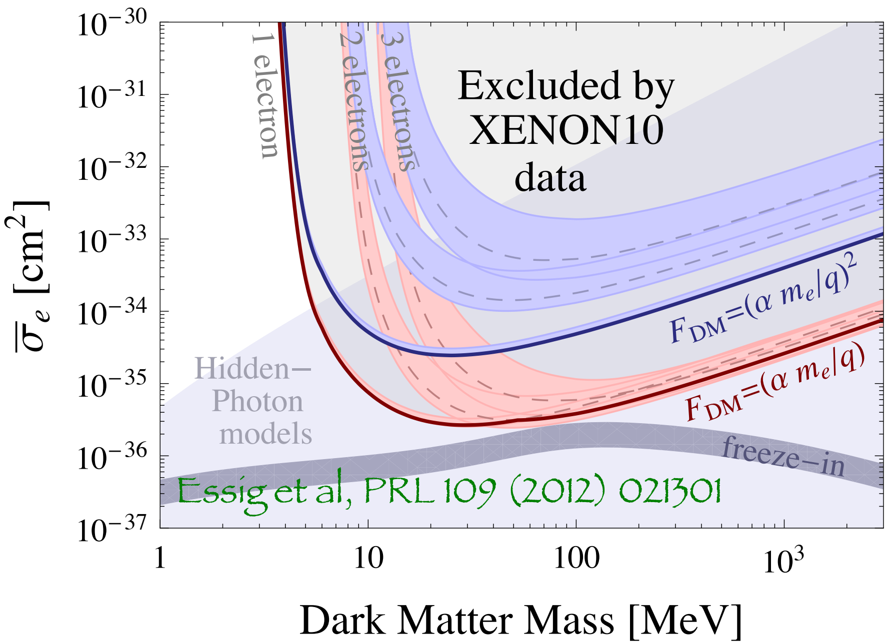
Angloher et al (CRESST), EPJC 76 (2016) 25

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

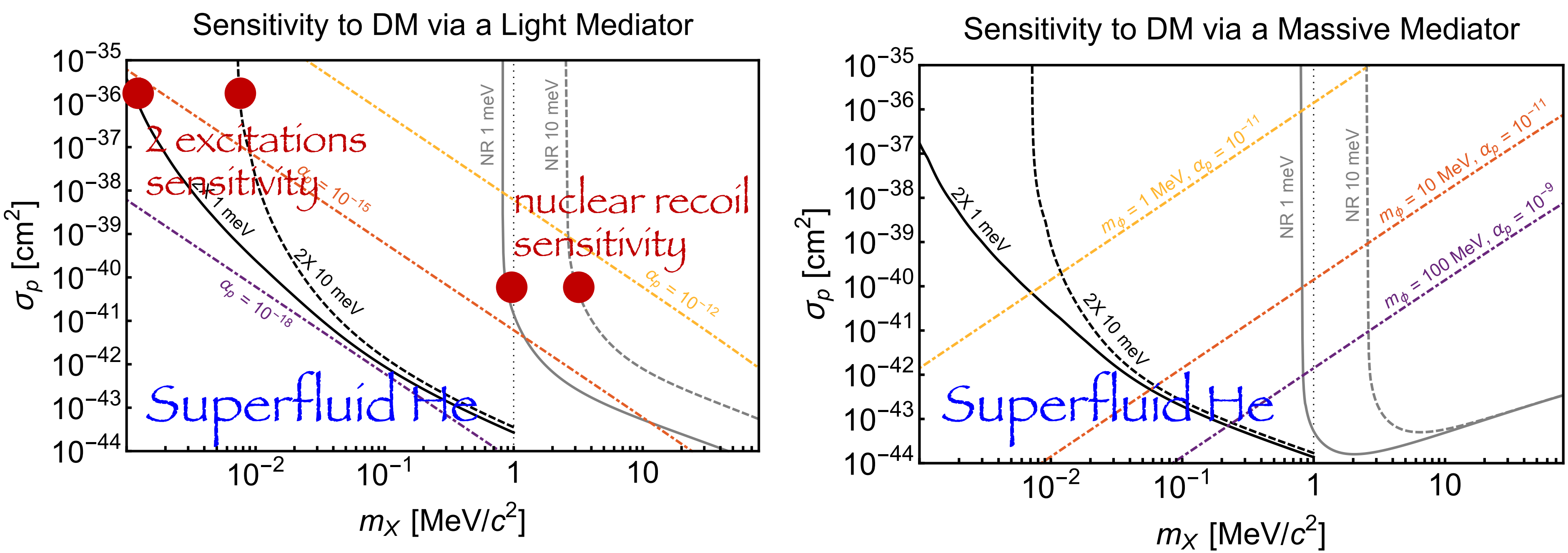
Contact-type scalar interactions (O_1)

Very light DM

- Very light DM (down to the warm regime):
  - Available kinetic energy can be as low as meV (for KeV DM)
  - Too low deposited energy on nuclear target
- Possibilites:
  - Nuclear interactions on light targets, e.g. liquid He
    Guo, McKinsey, PRD 87 (2013) 115001
  - Electron recoils
    Essig et al, PRD 85 (2012) 076007
    Essig et al, 1509.01598
    Agnese et al (SuperCDMS) PRL 112 (2014) 04
    Essig et al, PRL 109 (2012) 021301



Super light DM



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

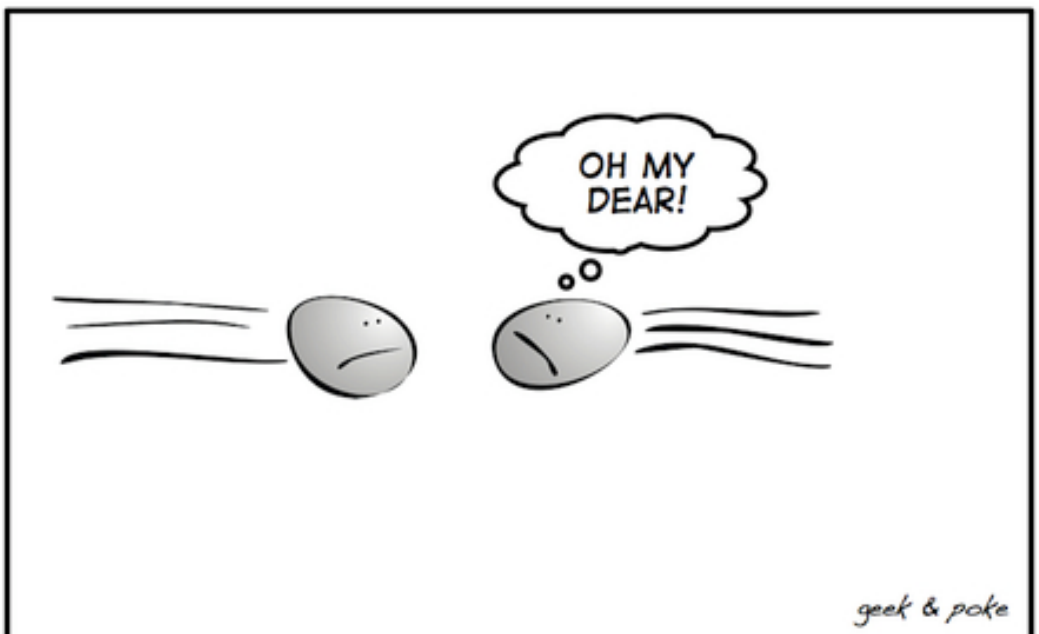
- » Superconductors — electron interactions
  - Hochberg et al, 1512.04533
  - Hochberg et al, PRL 116 (2016) 011301
- » Superfluid He — nuclear interactions
  - Schutz, Zurek, 1604.08206

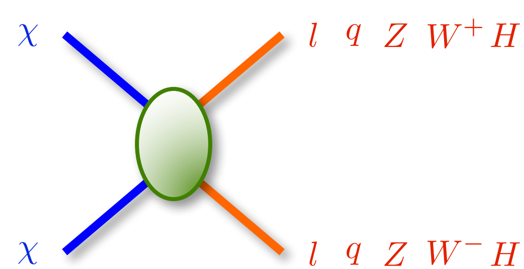
DM as a particle might ...

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)





Cosmic messengers

Charged CR ($e^\pm$, antip, antiD)

Neutrinos

Photons

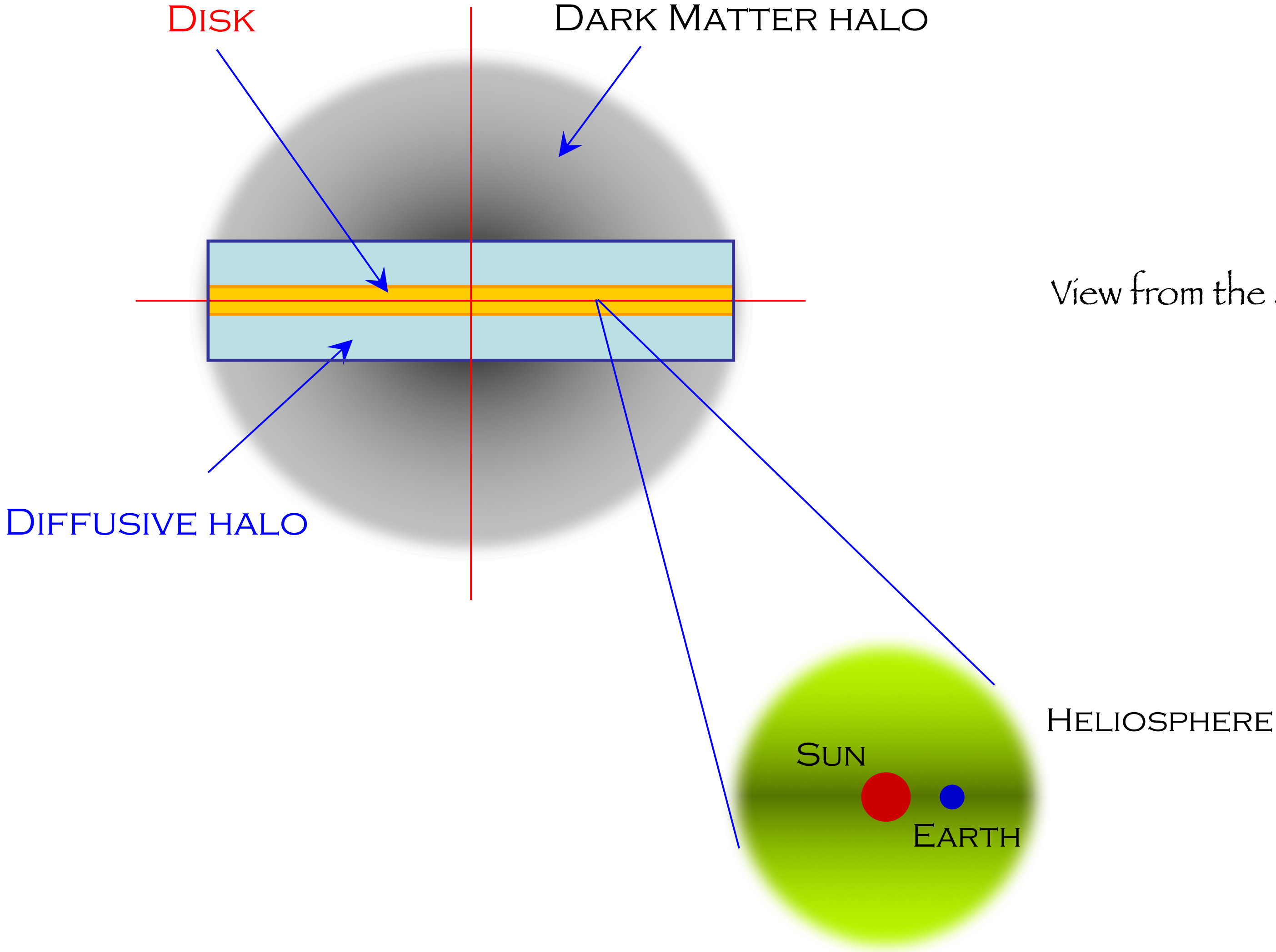
- Gamma-rays
  - Prompt production
  - IC from $e^\pm$ on ISRF and CMB
- X-rays
  - IC from $e^\pm$ on ISRF and CMB
- Radio
  - Synchro from $e^\pm$ on mag. field

multi-wavelength

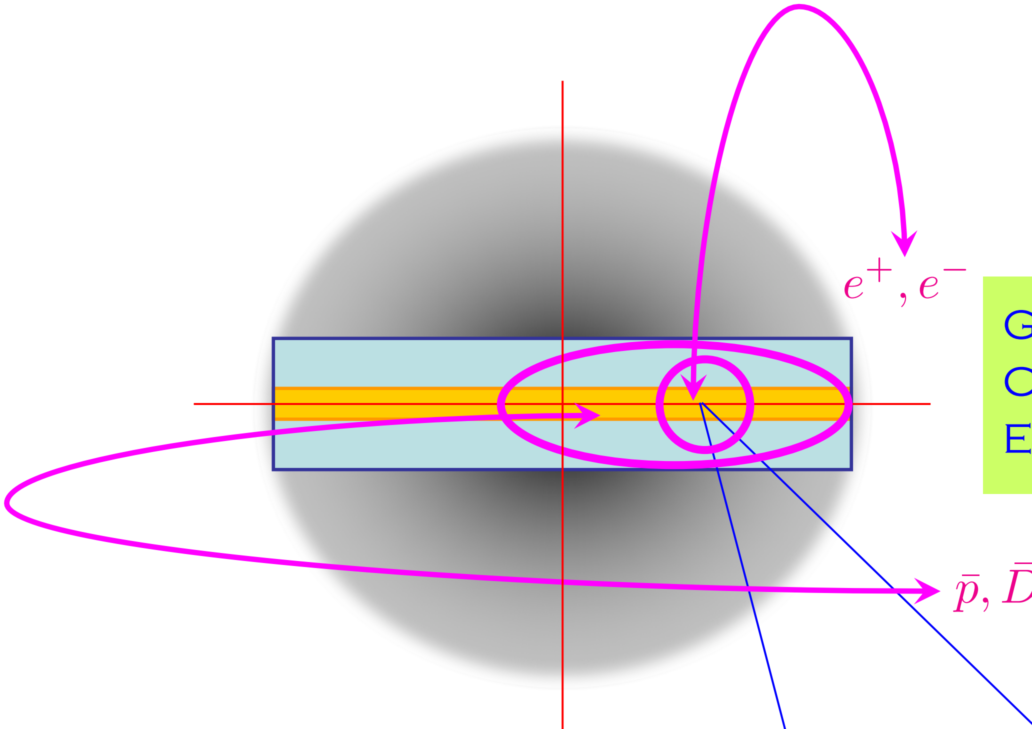
multi-messenger

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

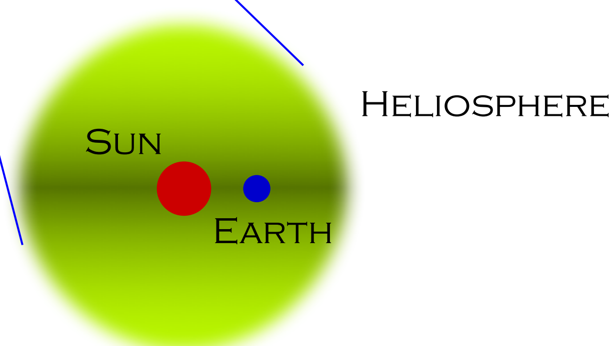
Galactic environment



View from the side



Galactic Diffusion
Convection
Energy losses



Galactic signals

Electrons/positrons
Antiprotons
Antideuterons

Transport in the Heliosphere

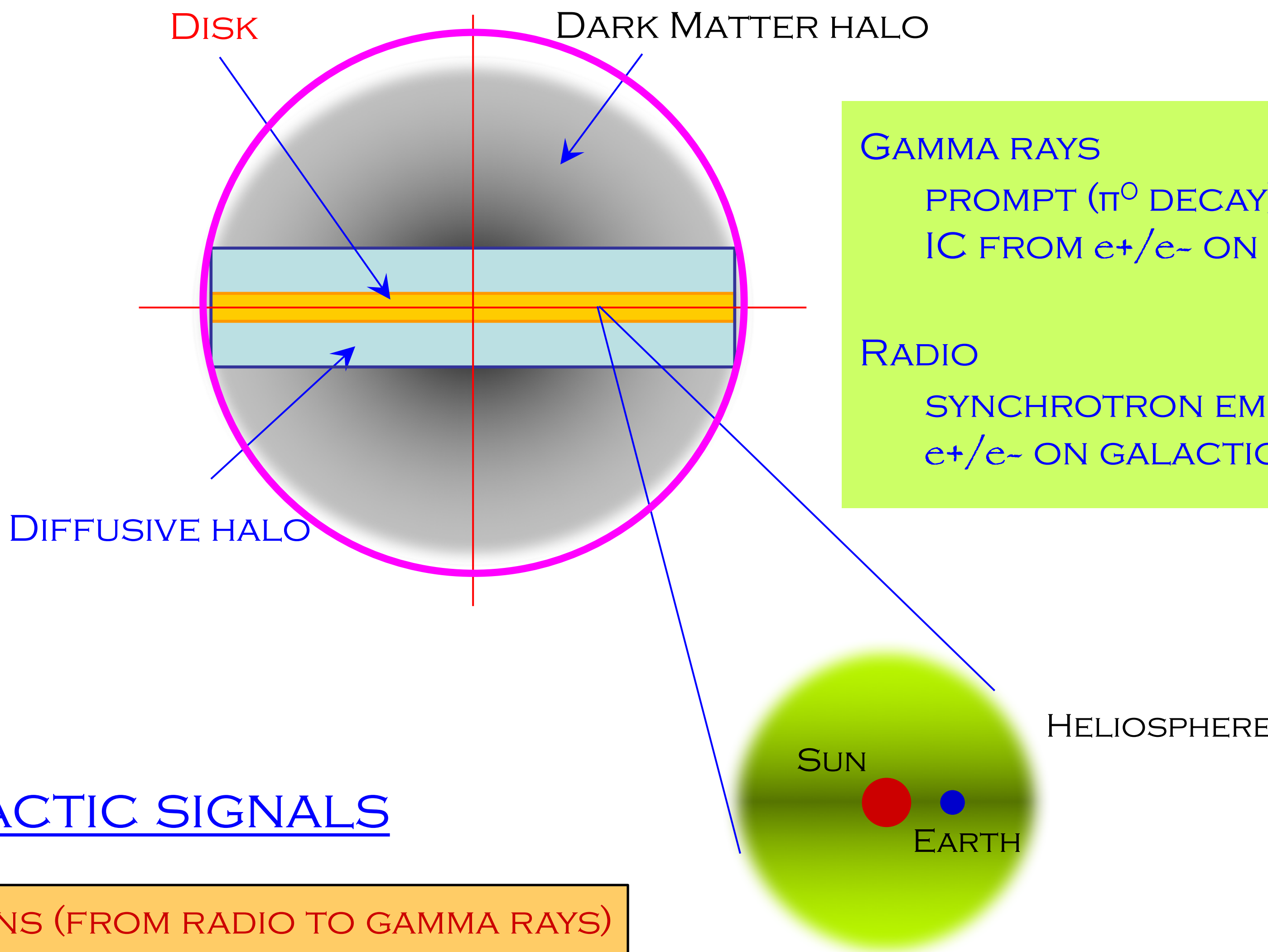
Gamma rays

prompt (π^0 decay)

IC from e+/e- on ISRF

Radio

synchrotron emission from e+/e- on galactic B

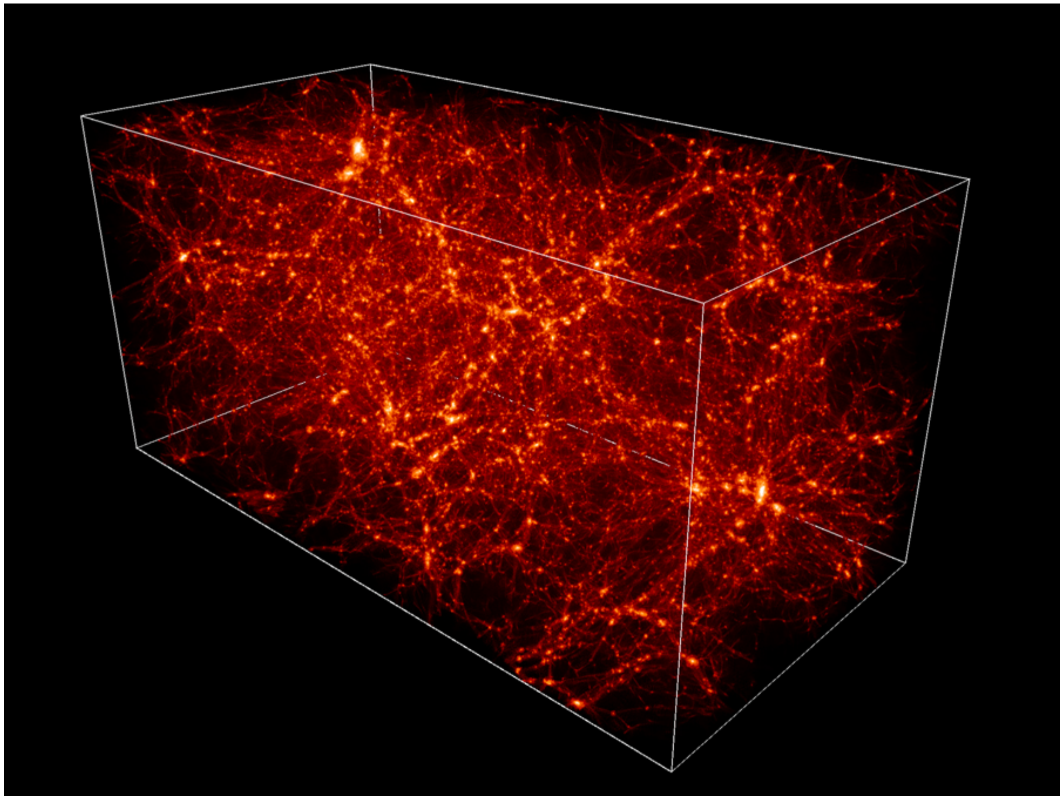


Galactic signals

Photons (from radio to gamma rays)

Neutrinos from the Galaxy

Extra-galactic environment

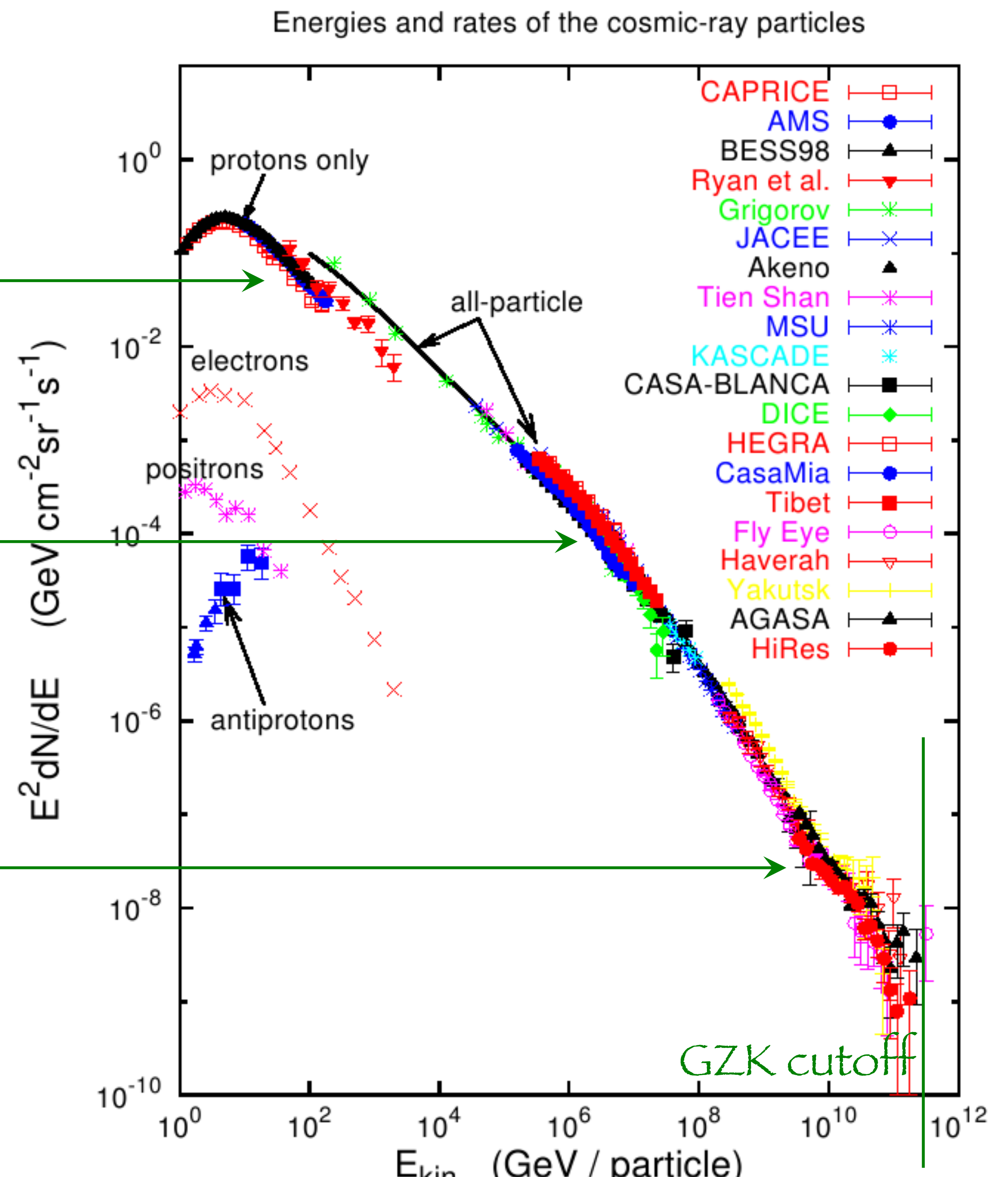


Extragalactic signals

Photons: gamma, X, radio
Neutrinos

Sunyaev-Zeldovich effect on CMB
Optical depth of the Universe

Cosmic rays



1 particle per m^2 sec

Knee

1 particle per m^2 year

Ankle

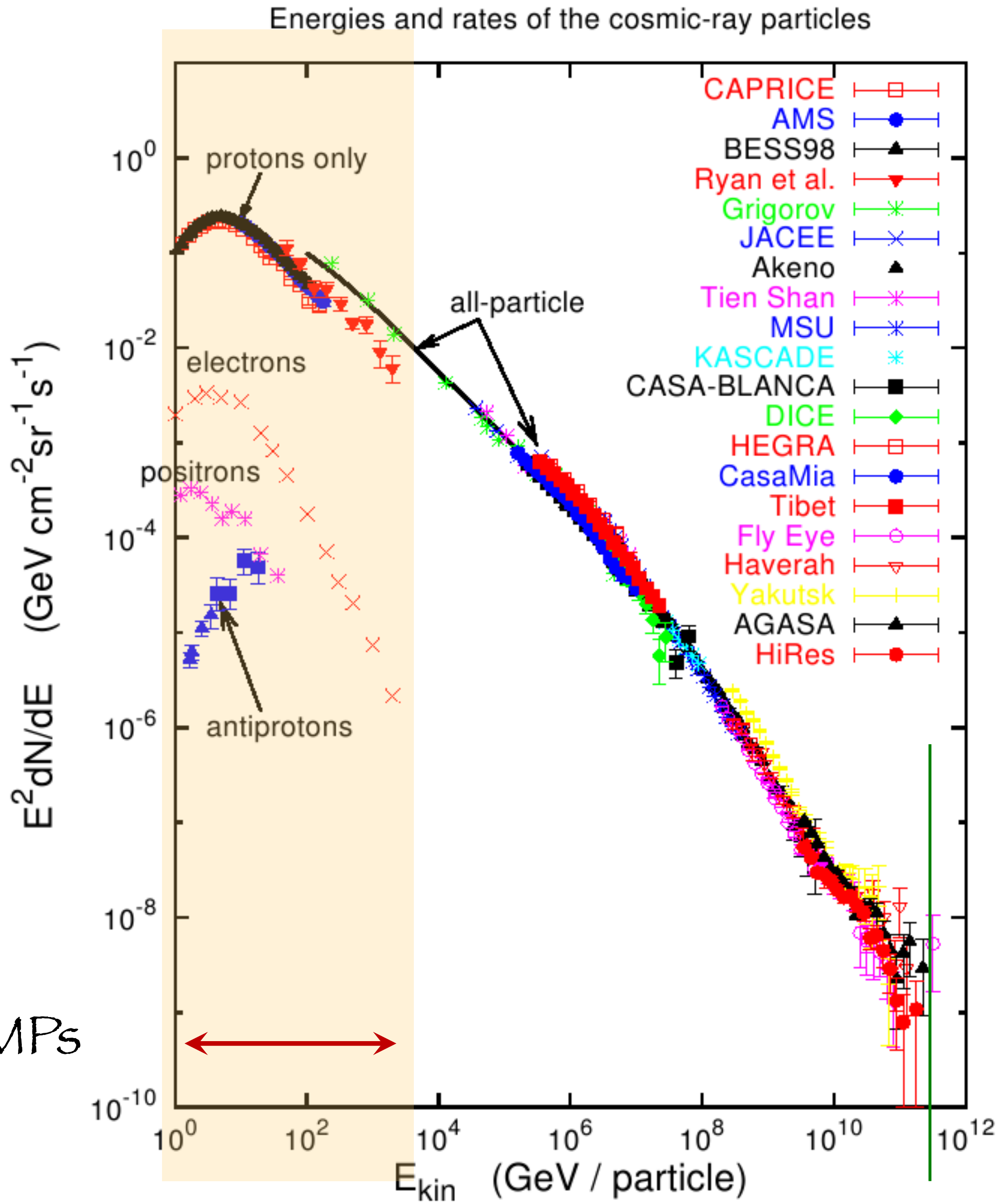
1 particle per km^2 year

Cosmic rays

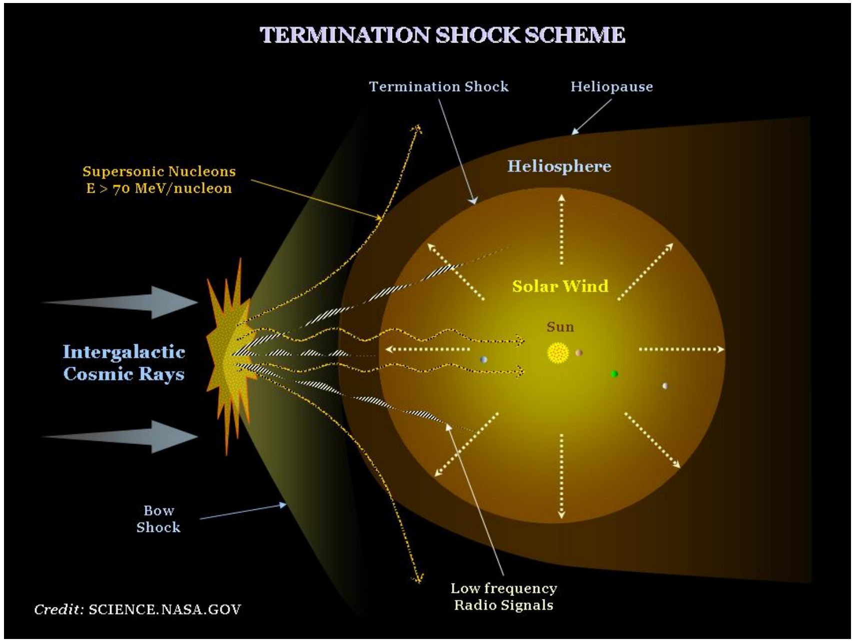
Antimatter << Matter

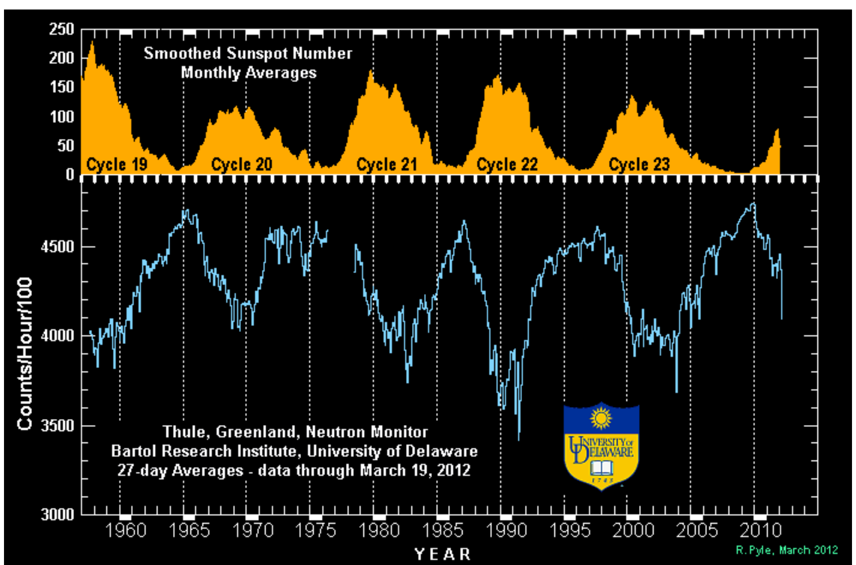
Better to search for the DM signal in the antimatter channel

Energies relevant for WIMPs



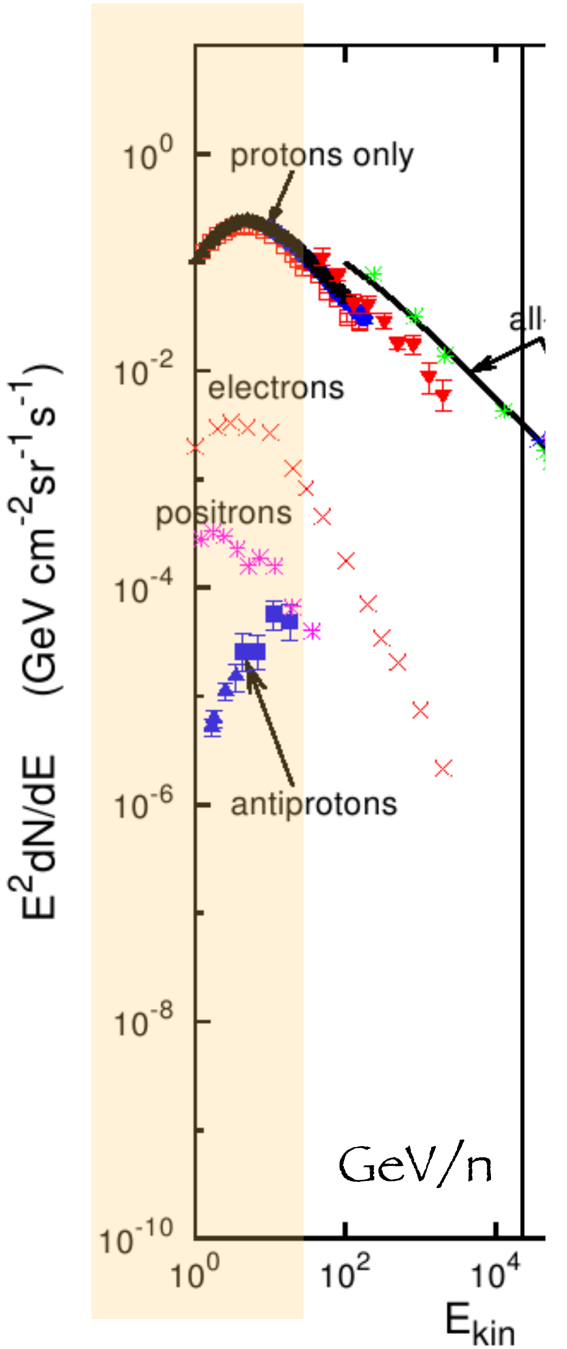
Cosmic rays





Affected by solar wind

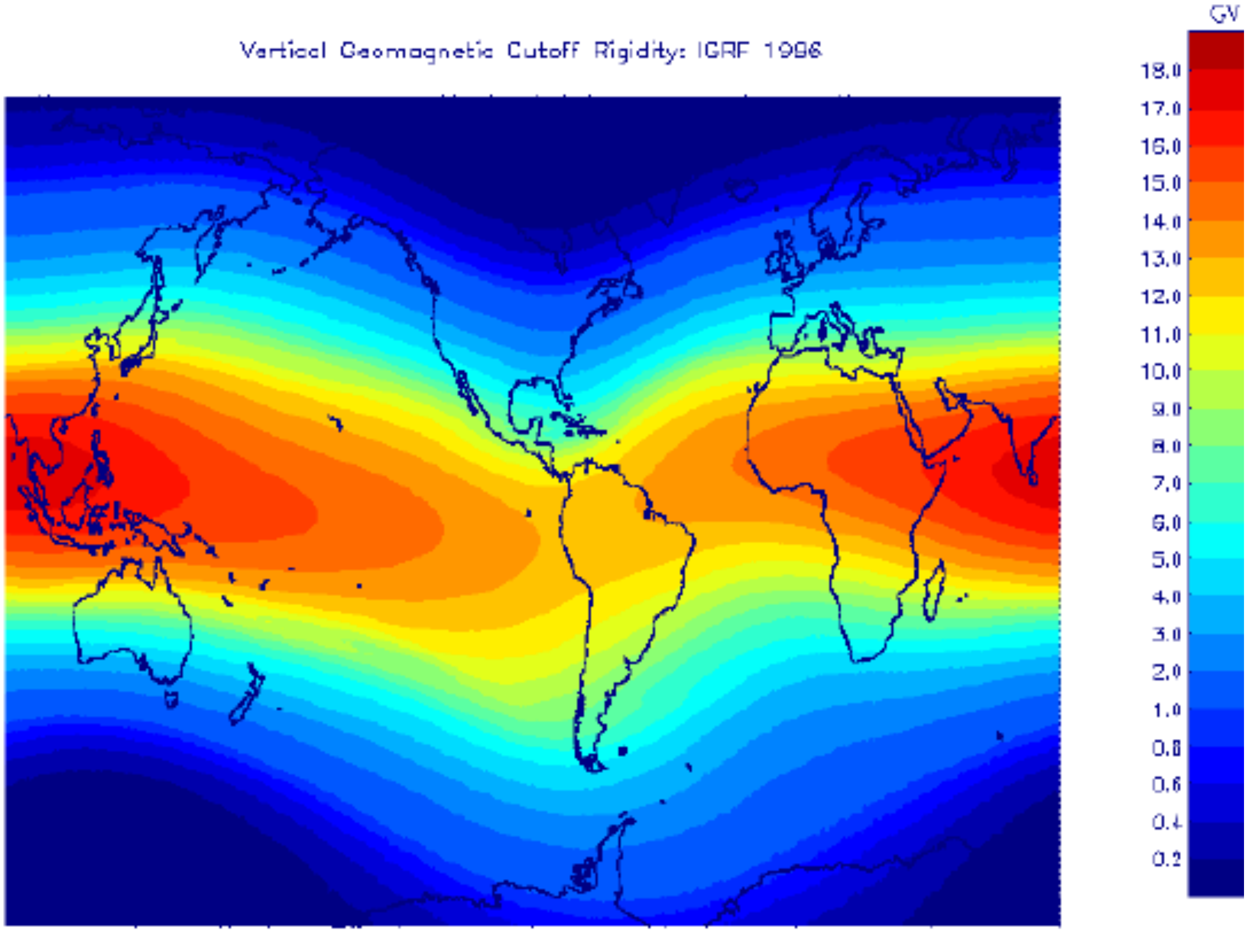
E < 30 GeV

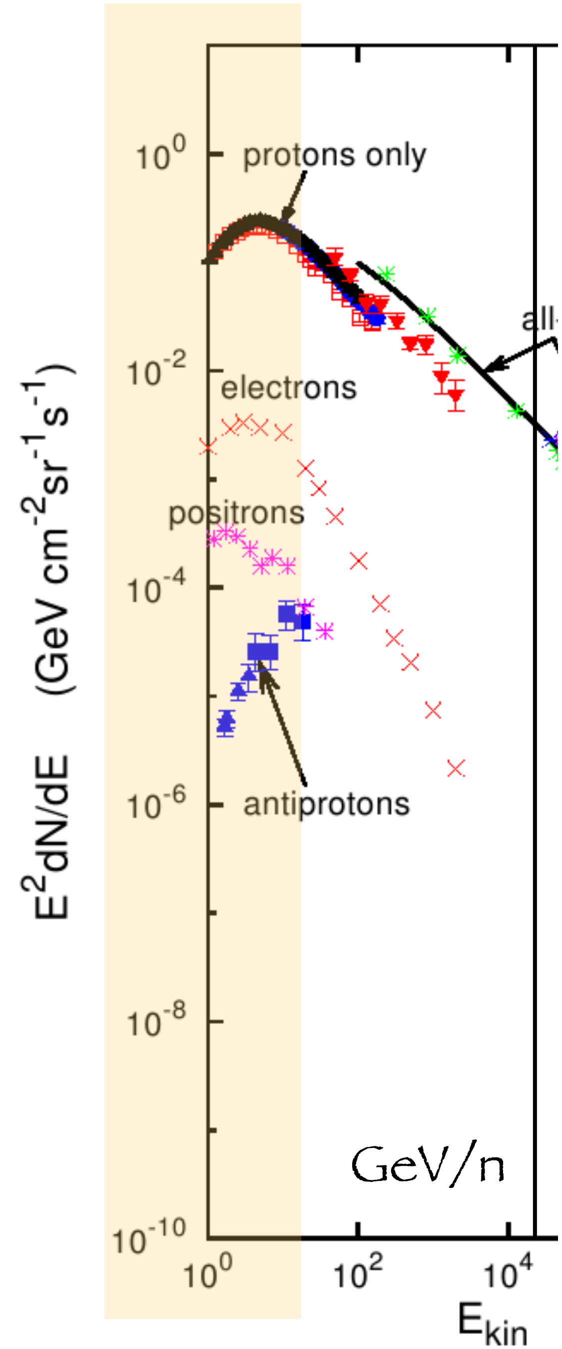


Cosmic rays

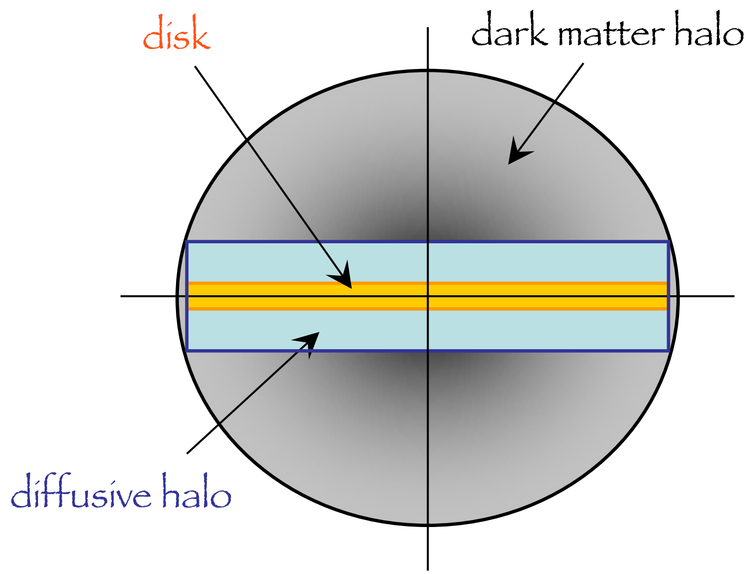
Affected by Earth magnetic field

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





Cosmic antiprotons



Secondaries (background)

$$p_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{p}$$
$$p_{\rm CR} + He_{\rm ISM} \longrightarrow \bar{p}$$
$$He_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{p}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

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

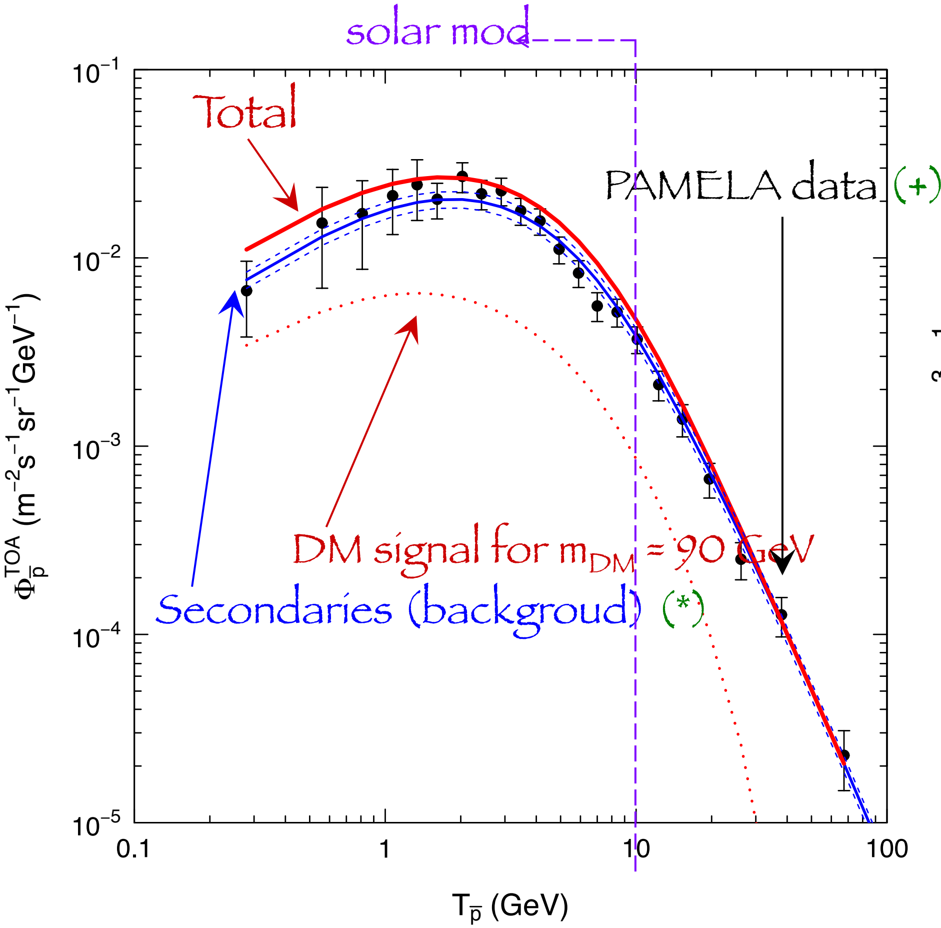
Produced in the DM halo

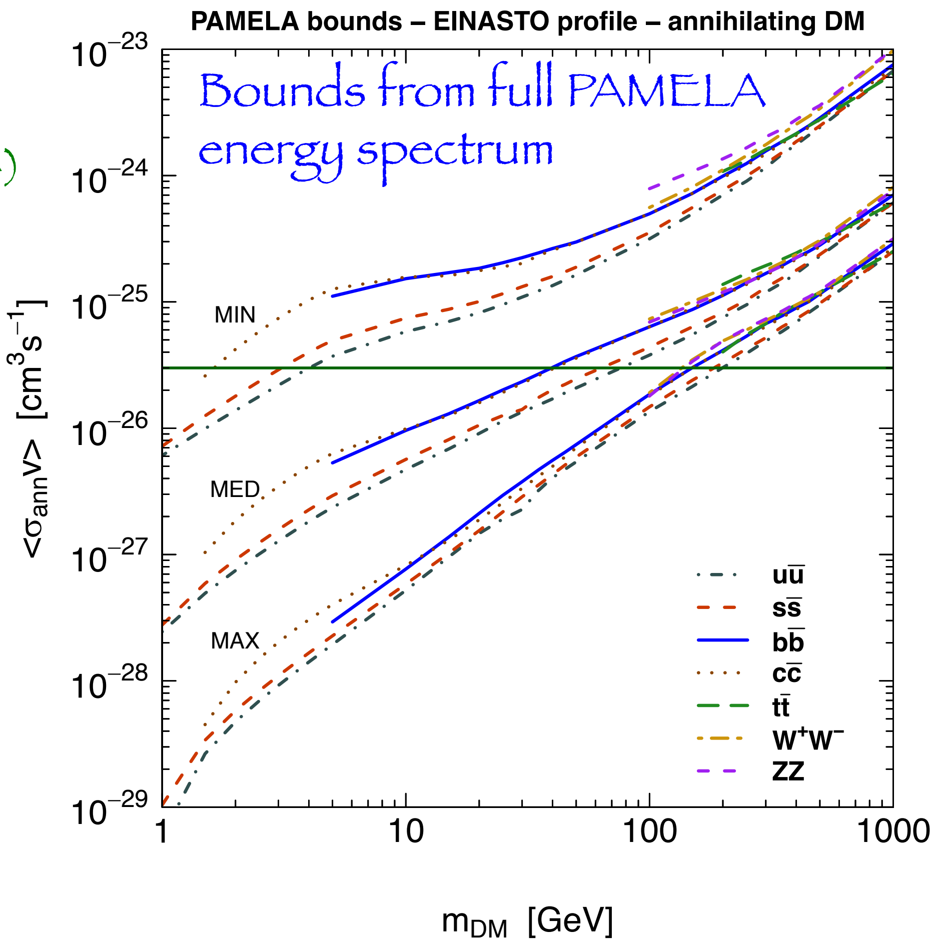
Propagation and energy redistribution in the diffusive halo

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

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

Antiprotons bounds on DM





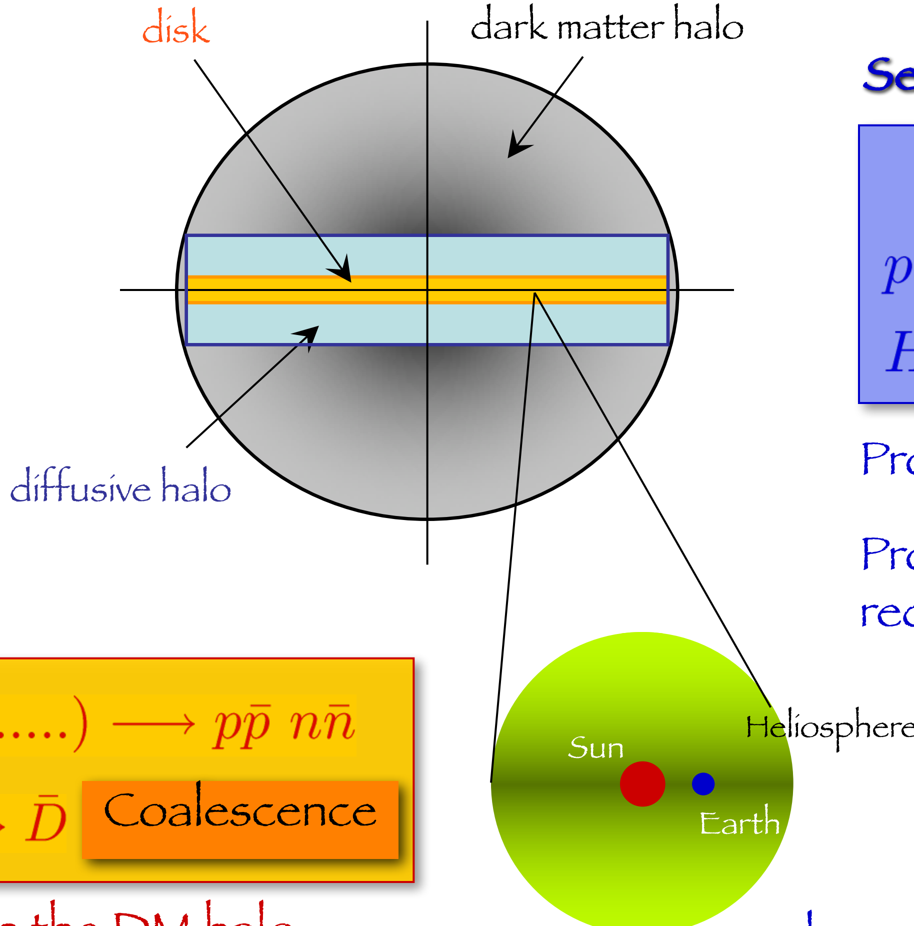
(*) Donato, Maurin, Brun, Delahaye, Salati, PRL 102 (2009) 071301
(+) Adriani et al. (PAMELA Collab.), PRL 105 (2010) 121101

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

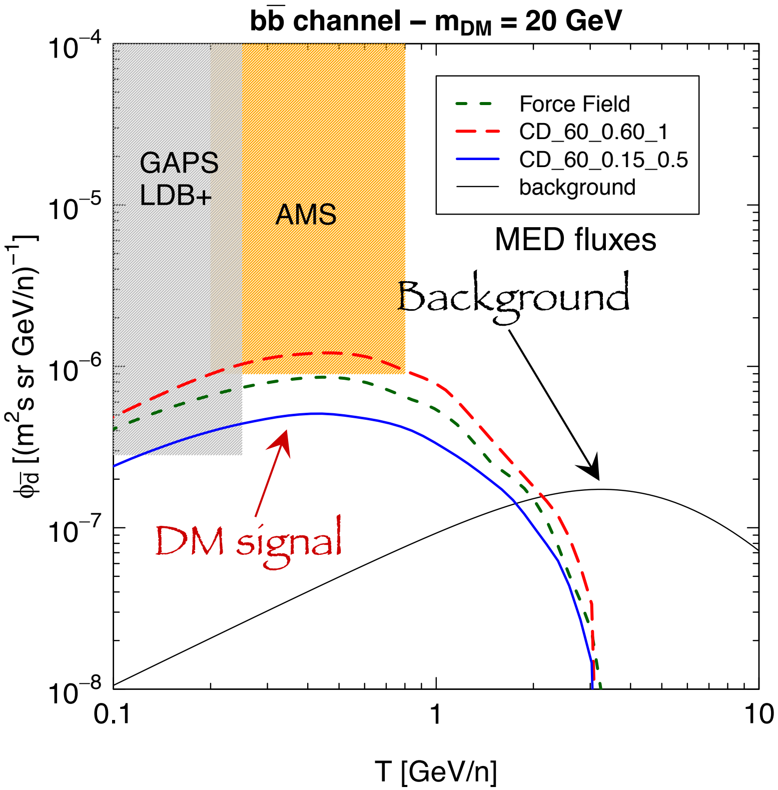
$$\chi\chi \longrightarrow (.....) \longrightarrow p\bar{p}\ n\bar{n}$$

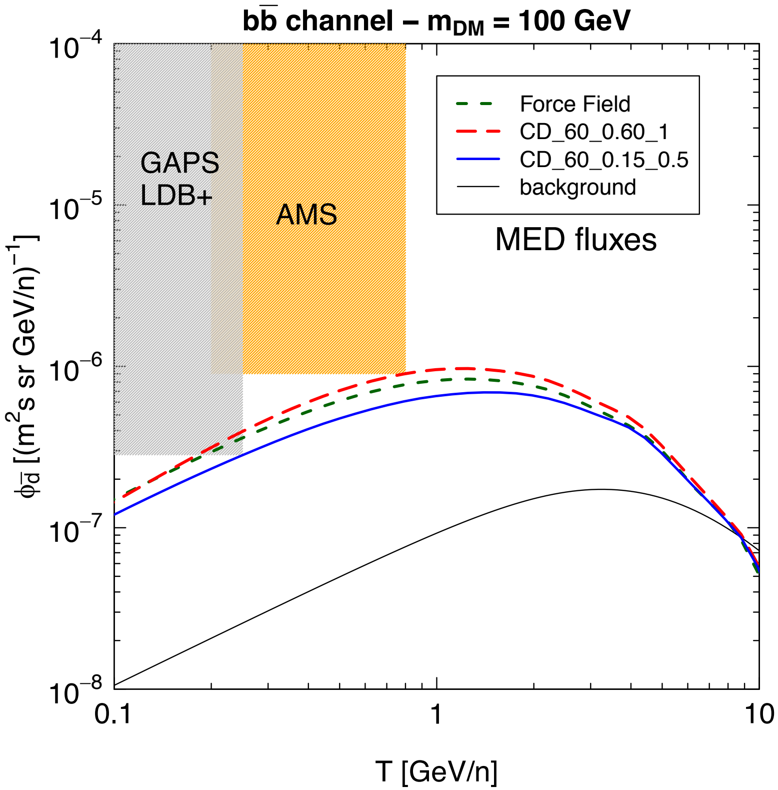
$$\bar{p} + \bar{n} \longrightarrow \bar{D}$$ Coalescence

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
below few Gev/n

Experimental expected sensitivities : 3σ C.L.

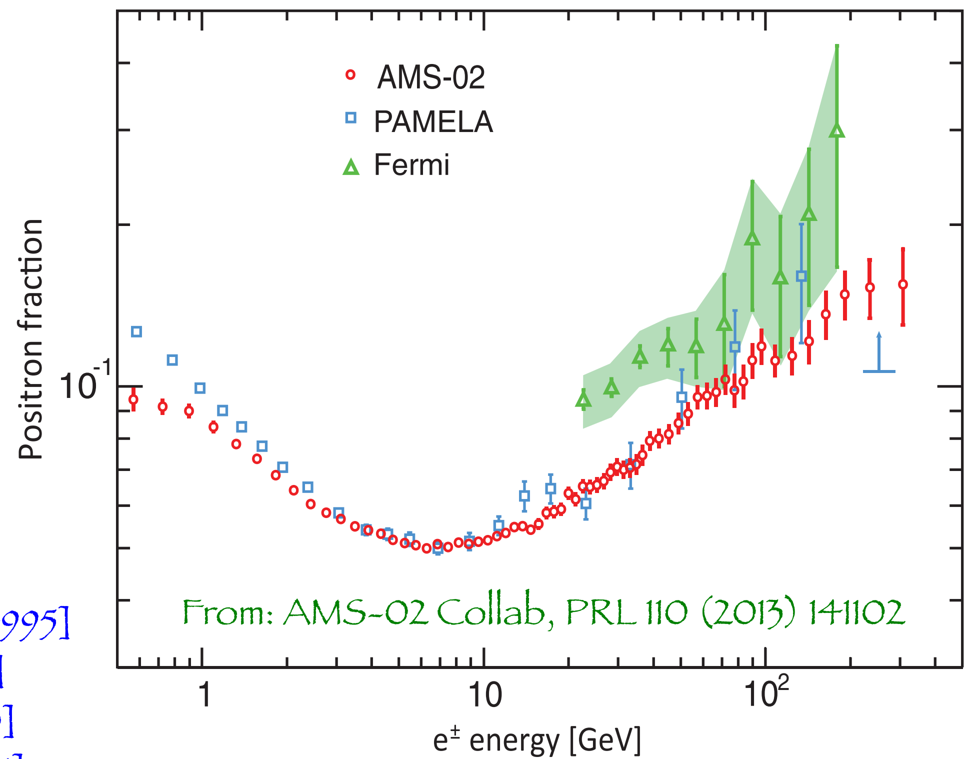
GAPS LDB+ : 1 detected event
AMS : 2 detected events
(because of differet backgrounds)

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

Cosmic-rays leptons

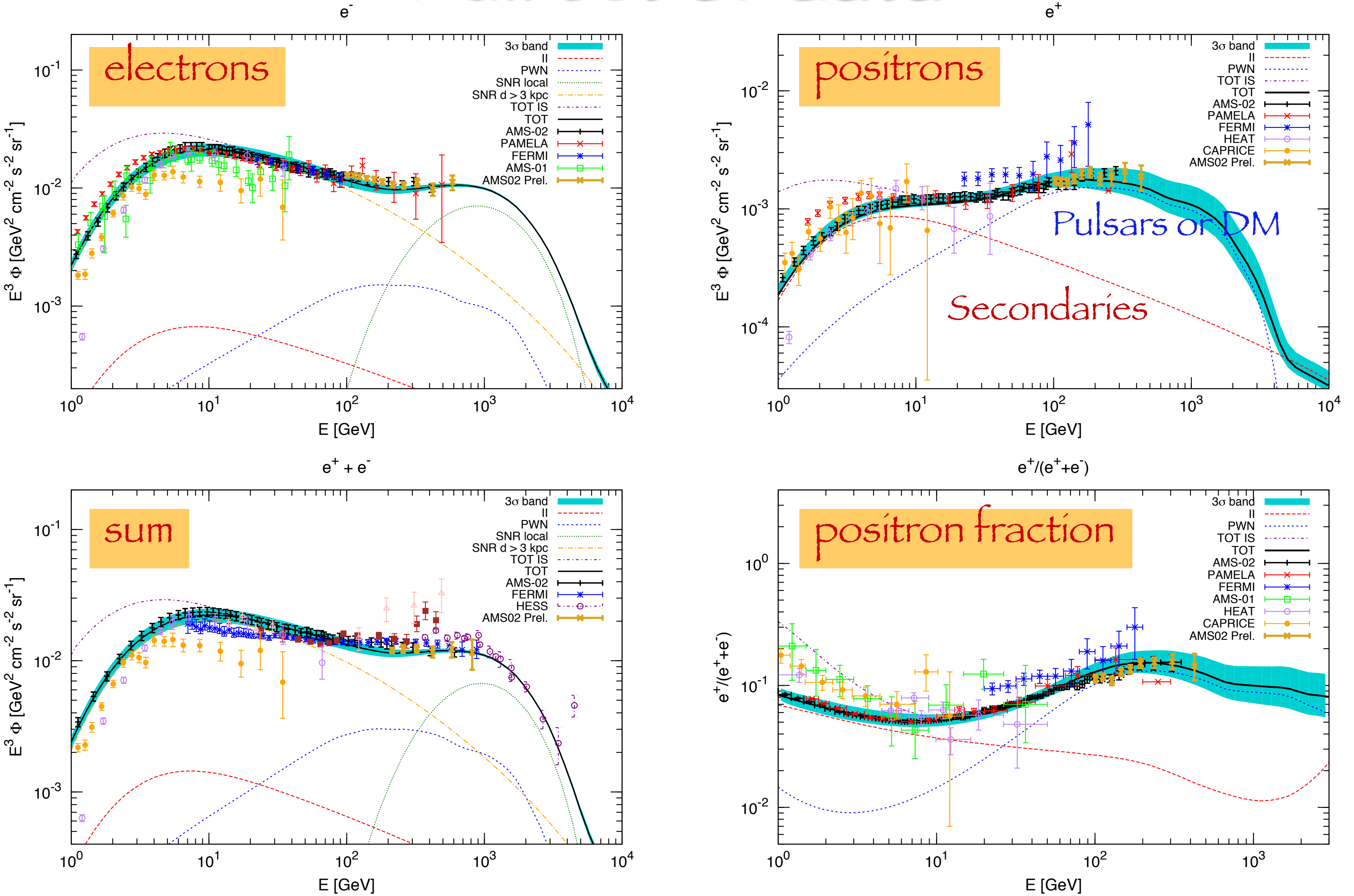
Excellent data on cosmic-rays leptons are available from space-borne detectors, from about up 0.5 GeV to few hundreds of GeV

- 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)

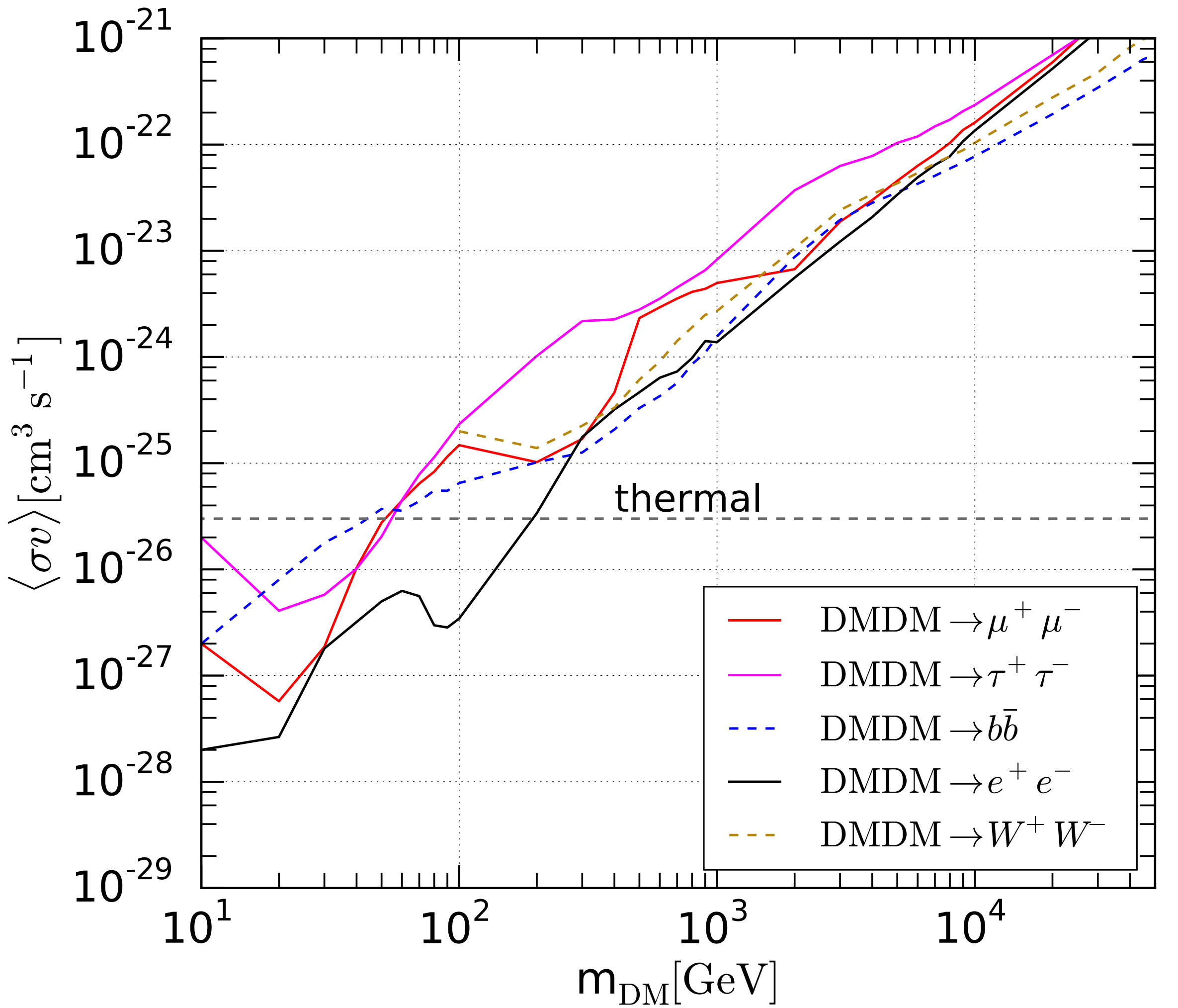
Full set of data



A local source of positrons is needed

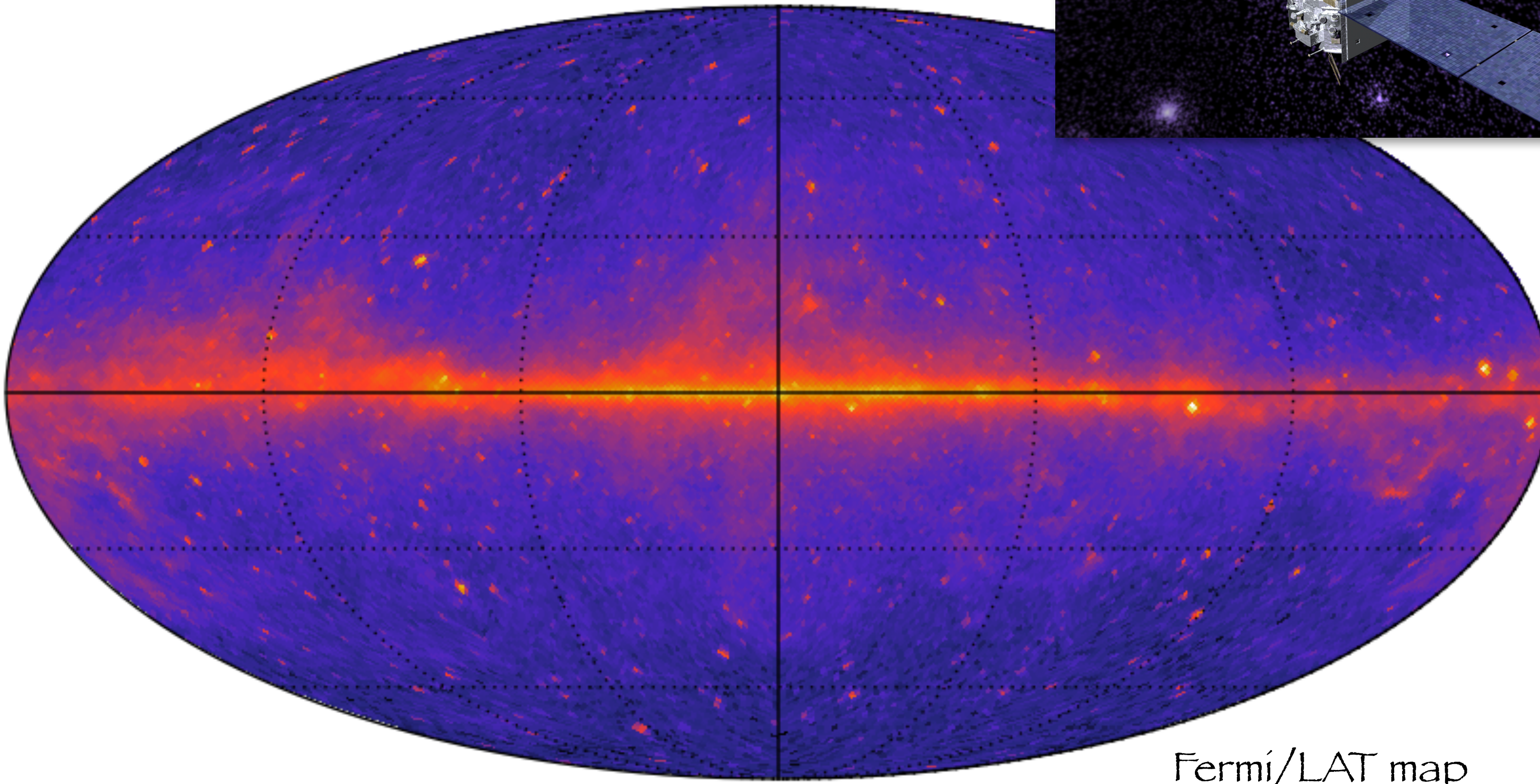
Bounds on DM

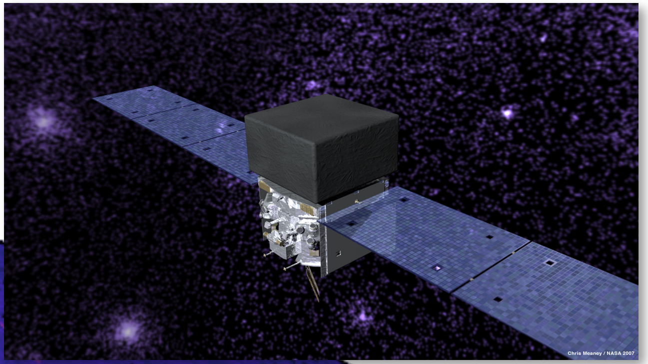
Bounds on DM



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

Gamma ray sky

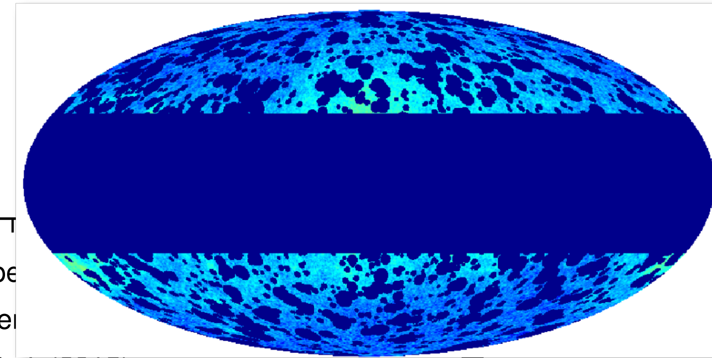


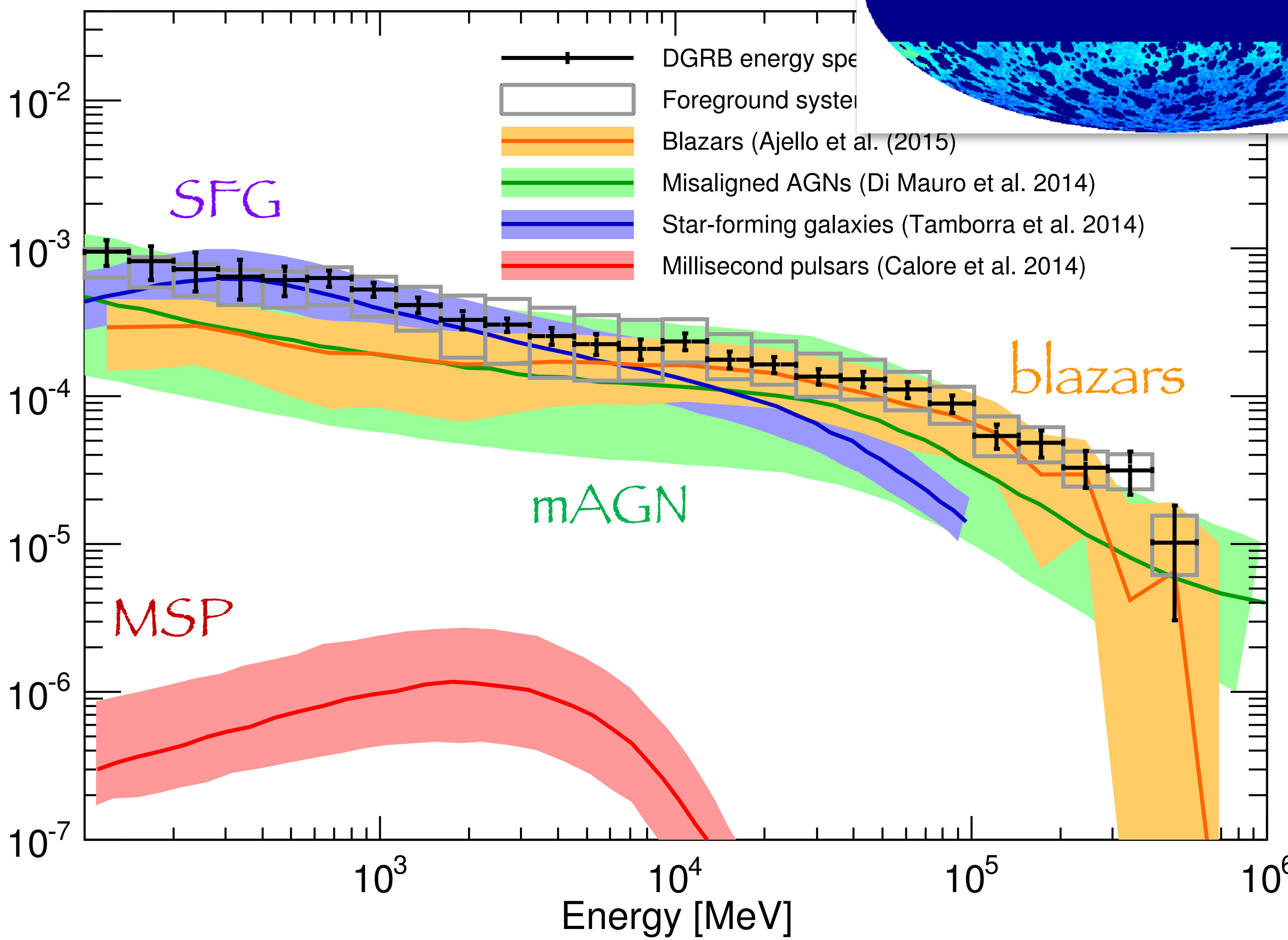


Fermi/LAT map

Galactic foreground emission
Resolved sources
Diffuse Gamma Rays Backgound (DGRB)

DGRB Intensity





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

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

Gamma-ray flux from galactic DM

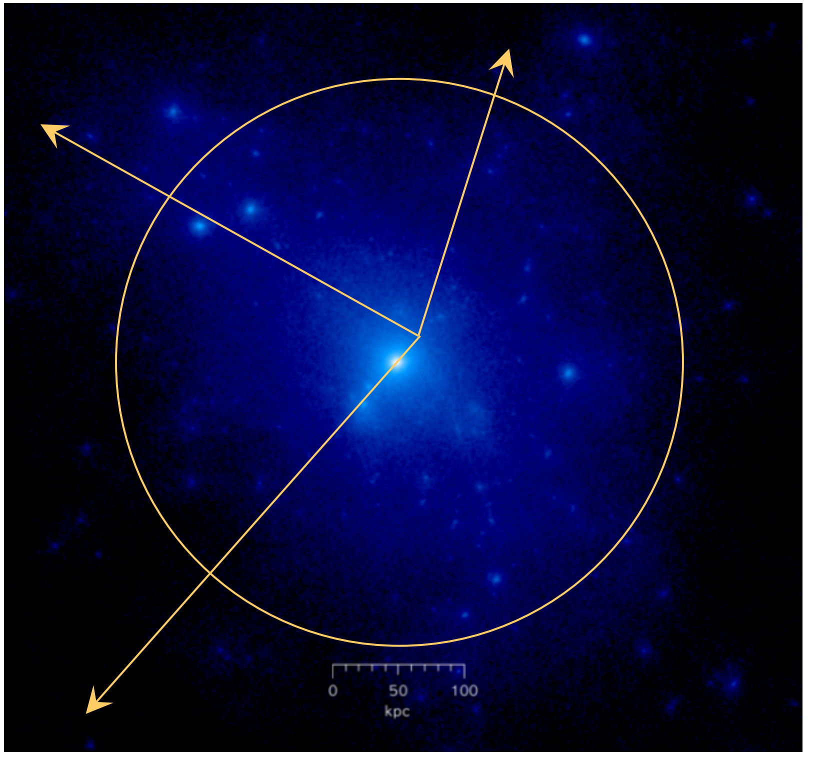
Flux:

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

L.o.S. integral:

$$I(\psi) = \int_{\rm l.o.s.} \rho^2(r(\lambda,\psi))d\lambda$$

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



… and from extra galactic DM

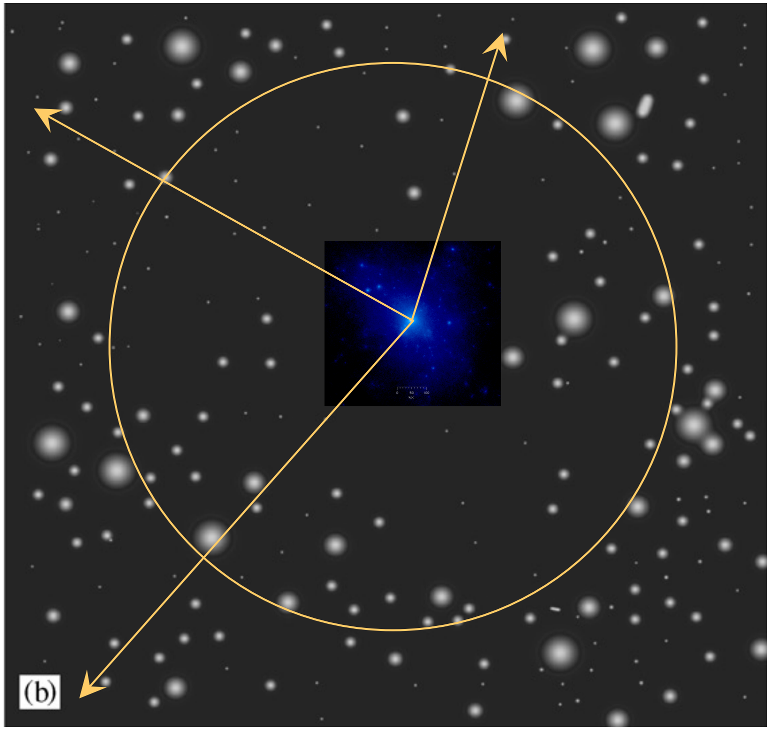
Halo density profile

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 density profile

Mass function

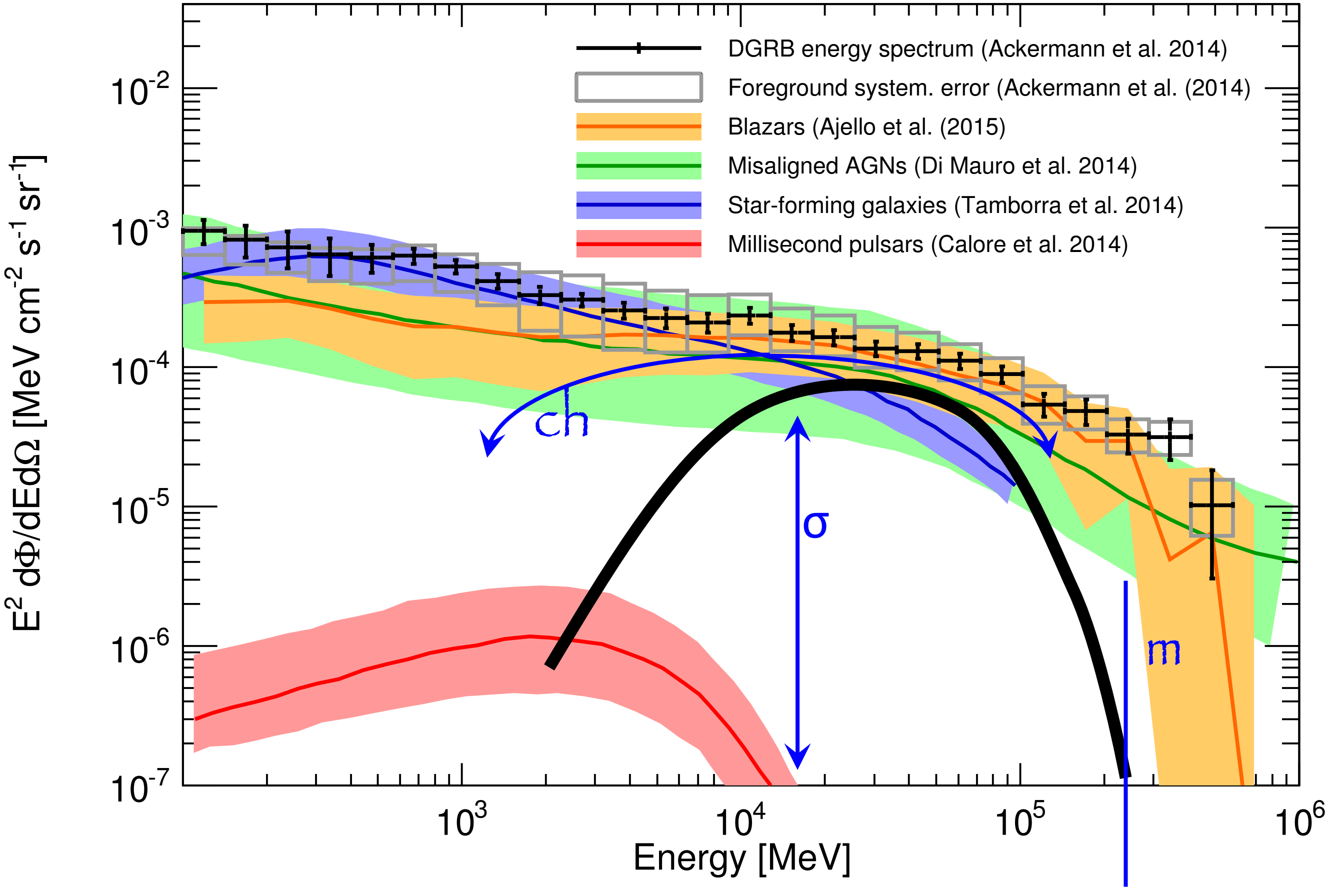
Sub halo $$\mathcal{L}_a^{sh}(E,z,M) = E\,\frac{(\sigma_a v)}{2\,M_\chi^2}\int_{M_{\rm cut}^s}^{M} dM_s\,\frac{dn_s}{dM_s}(M_s,f,M)\int_0^{R_v} d^3r_s\,\frac{d\tilde{N}_i}{dE}\,\rho_s^2(M_s,r_s,z)$$



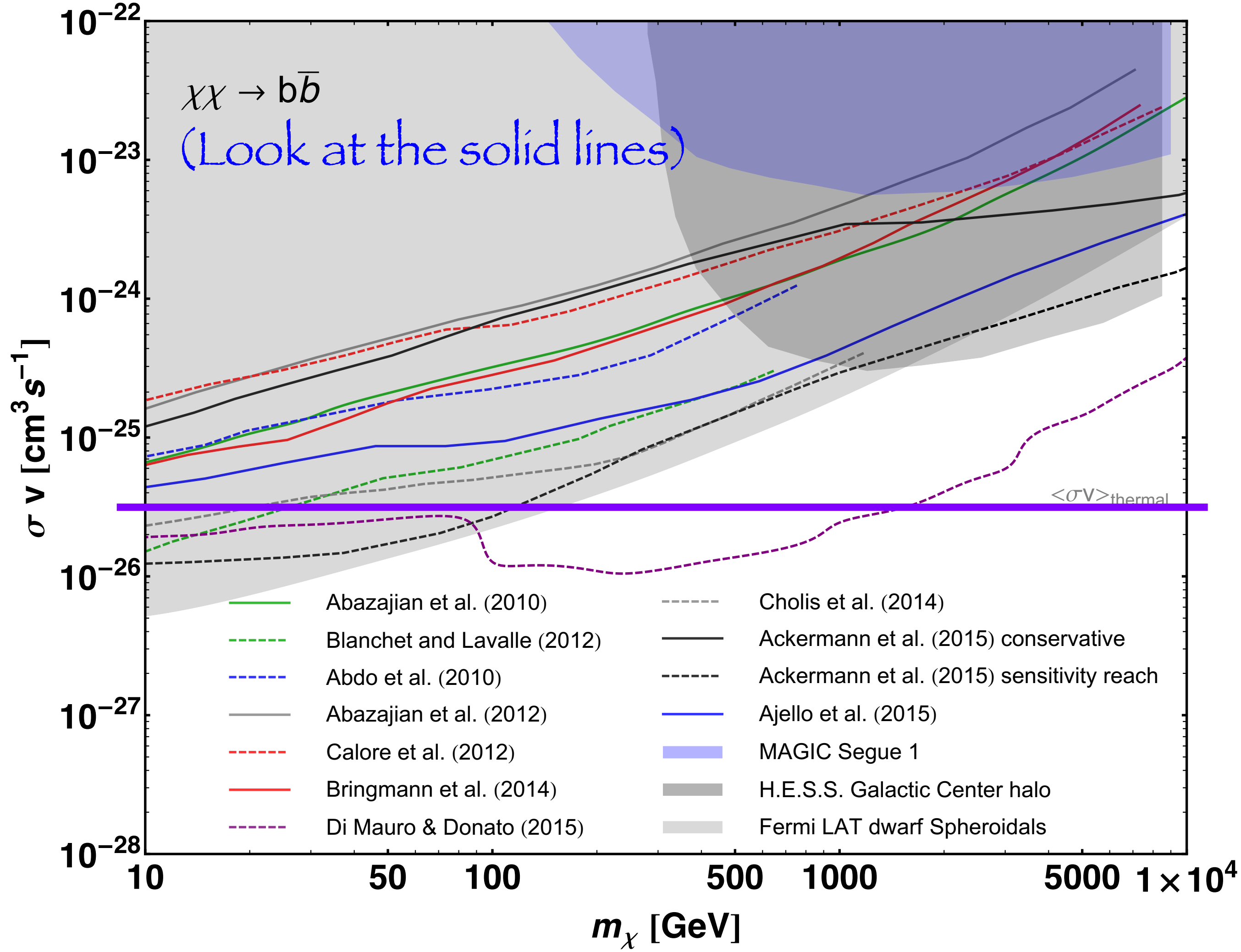
DGRB and Dark Matter

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

The Bad: Can be quite subdominant in intensity

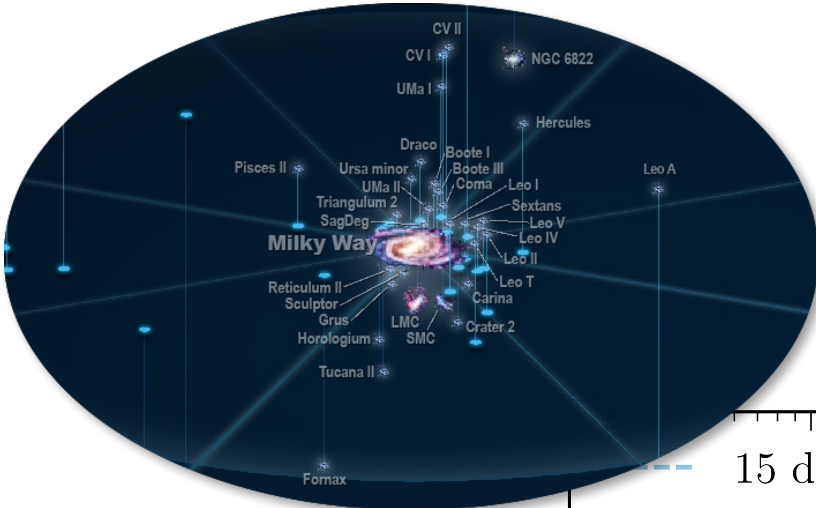


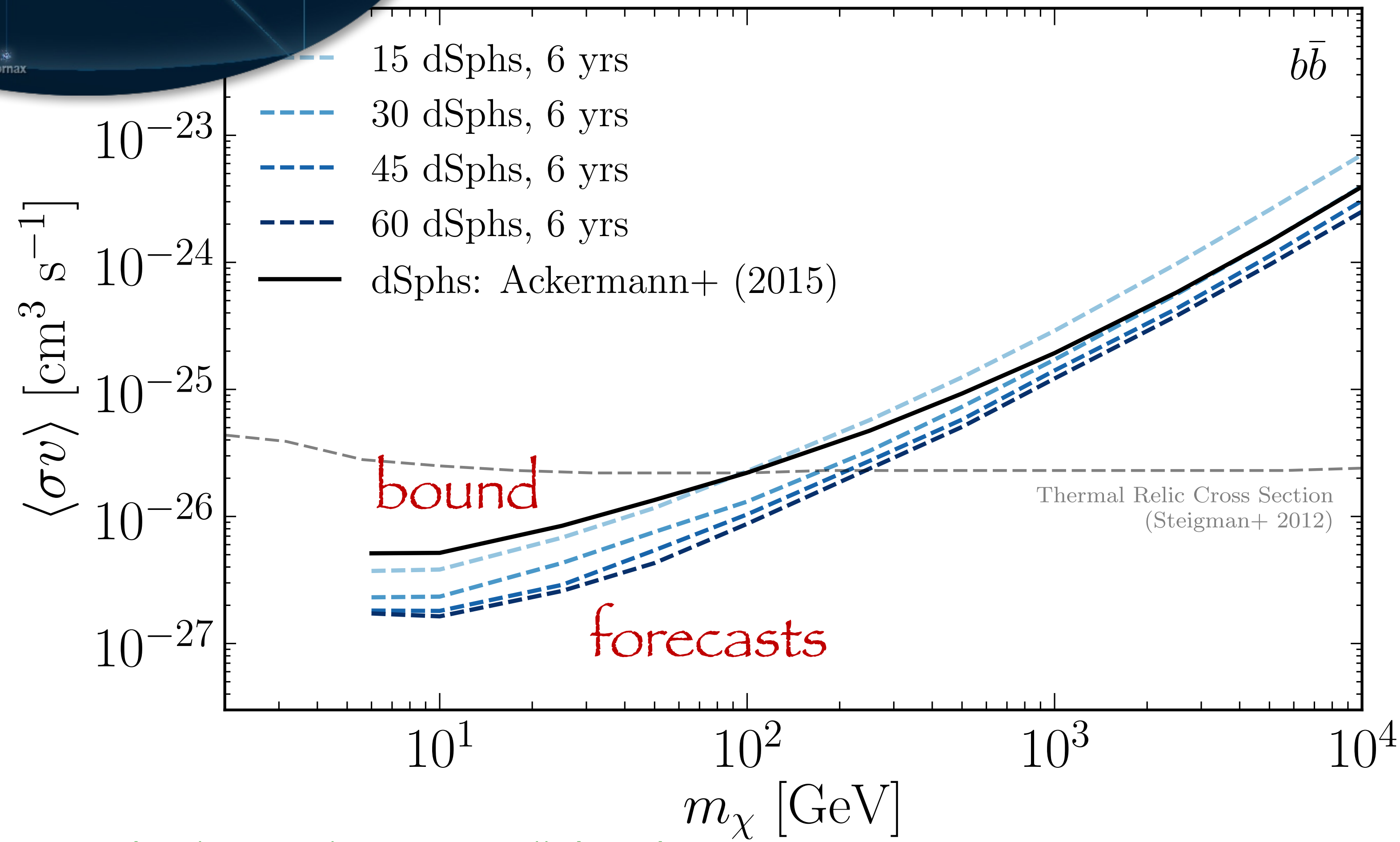
DGRB intensity bounds on DM



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

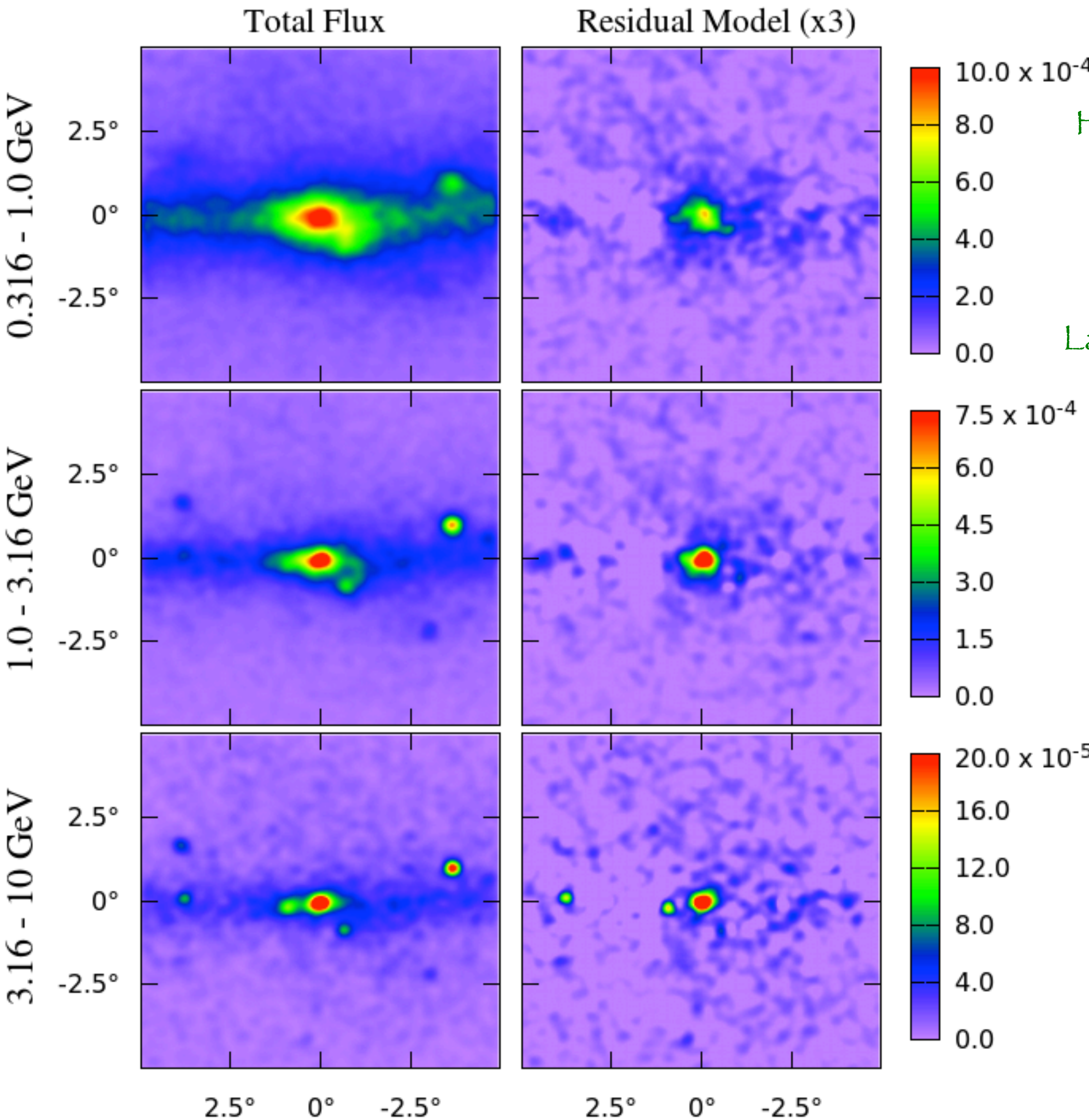
Dwarf galaxies





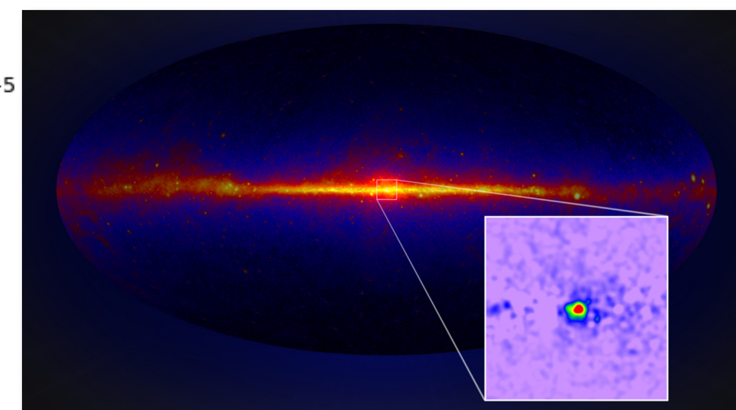
Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Galactic center: an "excess" ?

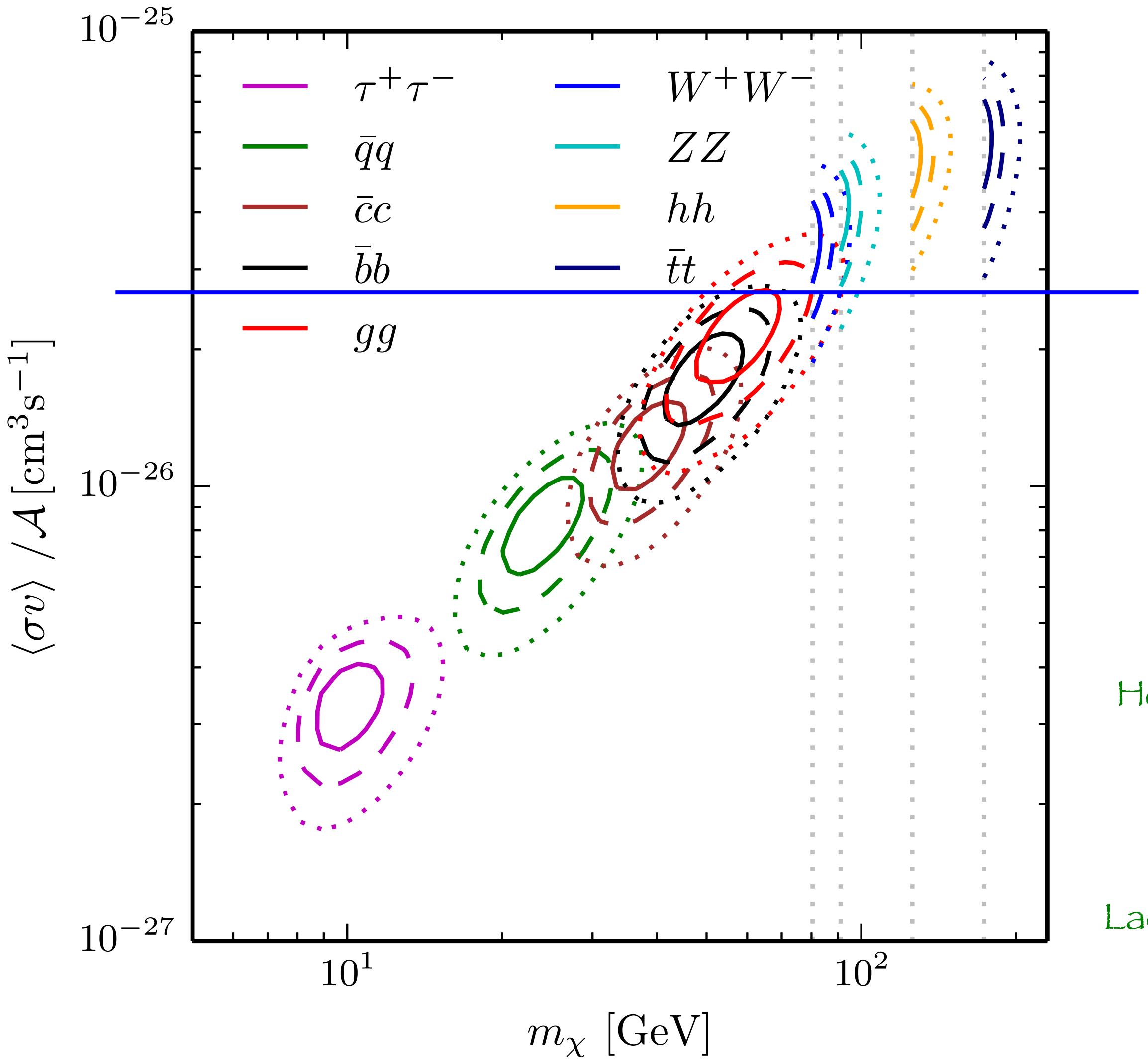


Daylan et al, Phys Dark Univ 12 (2016) 1

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

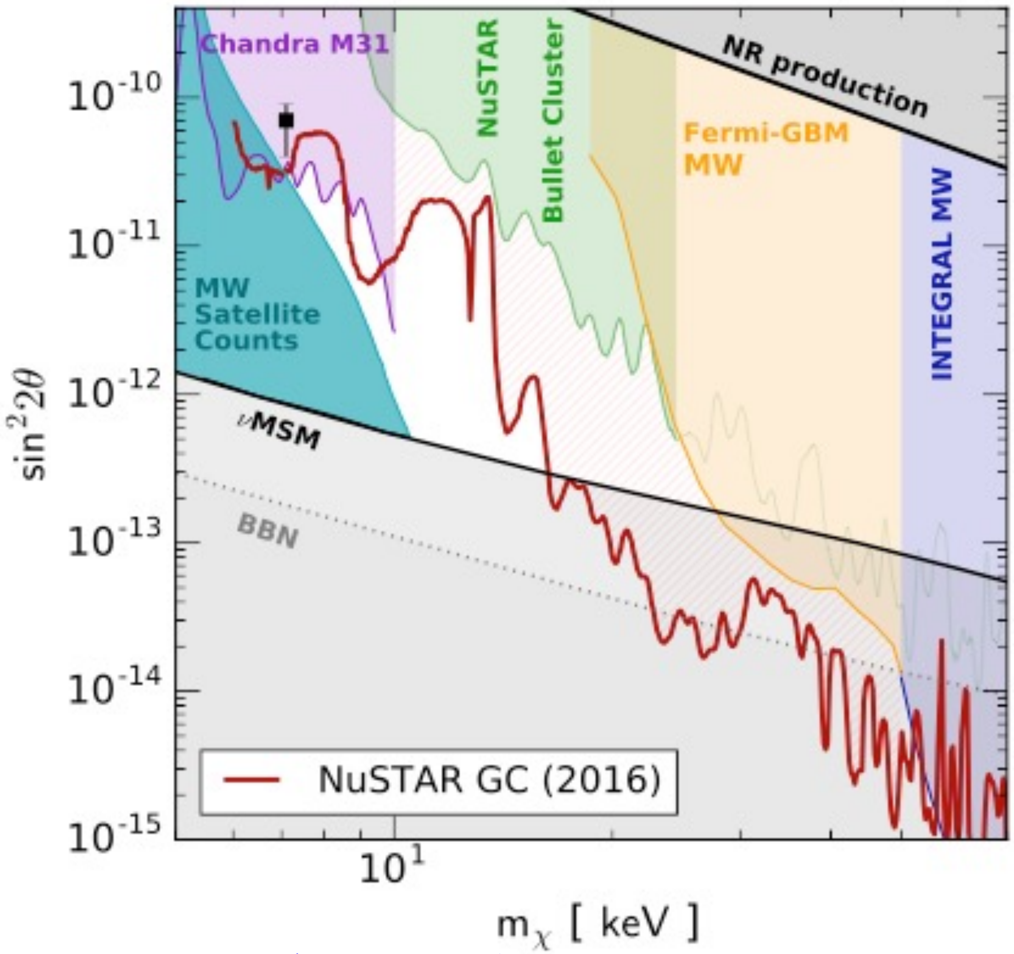
Unresolved pulsars

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

Lower frequencies and non-WIMP

X rays



New bounds from nuSTAR @ GC

Perez et al, 1609.00667

3.5 KeV line

73 galaxy clusters

Perseus cluster + Andromeda

Bulbul et al, ApJ 789 (2014) 13

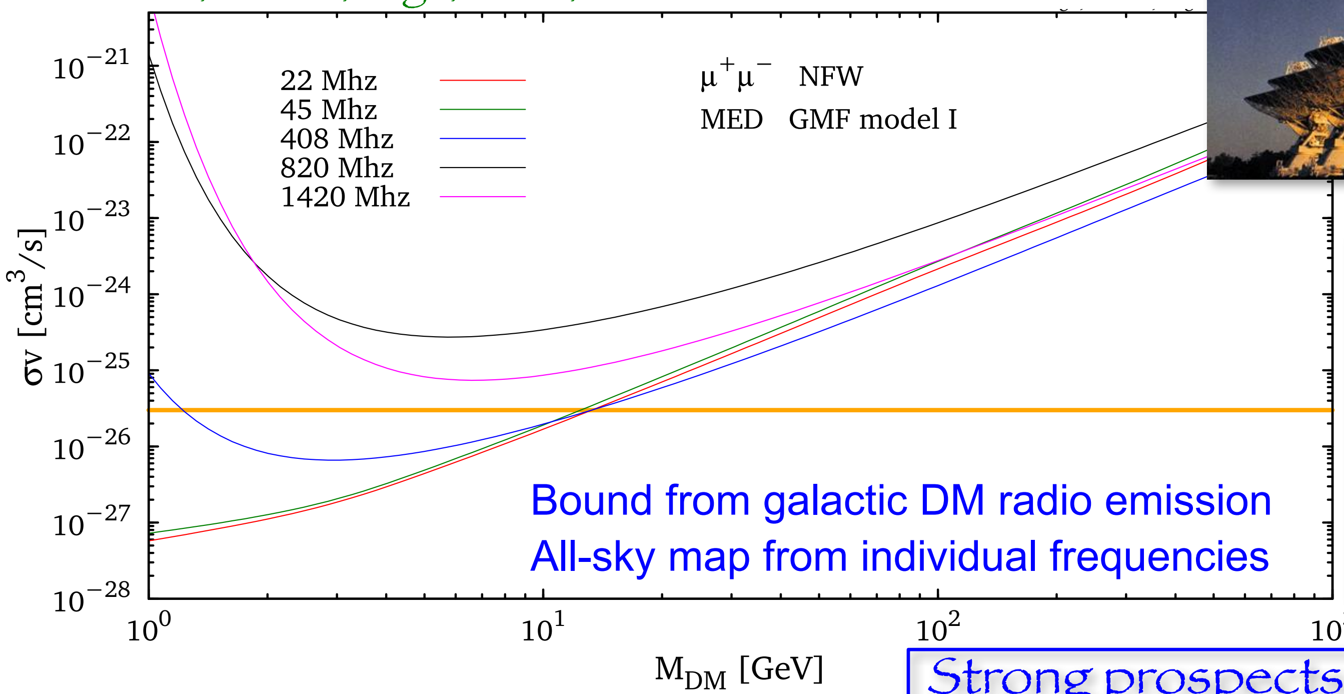
Boyarski et al, PRL 113 (2014) 251301

Sterile neutrino DM decay?

De-excitation lines?

Radio frequencies

NF, Lineros, Regis, Taoso, JCAP 01 (2012) 005



For:

e+,e- GeV-TeV

B microG

synchro: MHz - GHz

Strong prospects: SKA and precursors, Lofar, ...

Lower frequencies better for lighter DM

Constraining power also depends on sky-coverage and sensitivity of the survey

NF, Lineros, Regis, Taoso, JCAP 03 (2012) 033

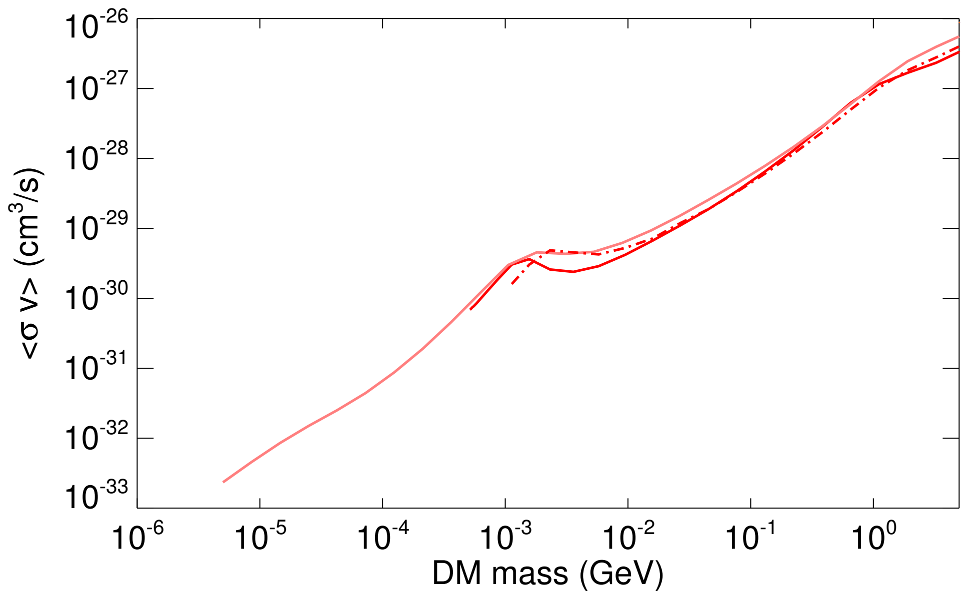
Extragalactic radio has a similar (slightly worse) constraining power (but different uncertainties in modeling)

Egorov, Pierpaoli, PRD 88 (2013) 023504

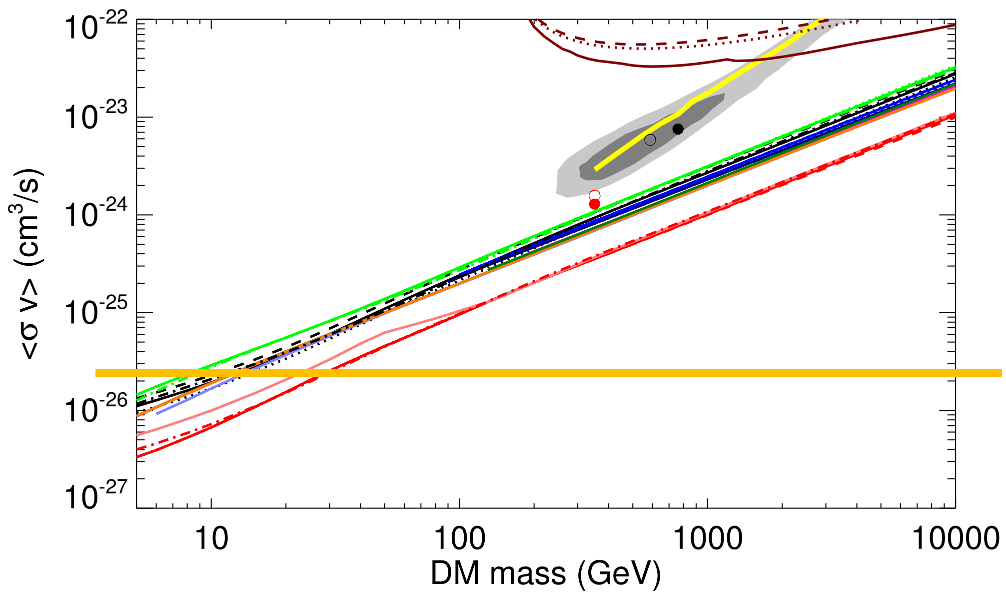
Regis et al, JCAP 1410 (2014) 016

Bounds from specific target start to be competitive (dwarf galaxies; Andromeda)

CMB



Slatyer, PRD 93 (2016) 023527



Injection of ionizing particles during the cosmic dark ages

Increase in the residual ionization fraction and affect CMB

See also:

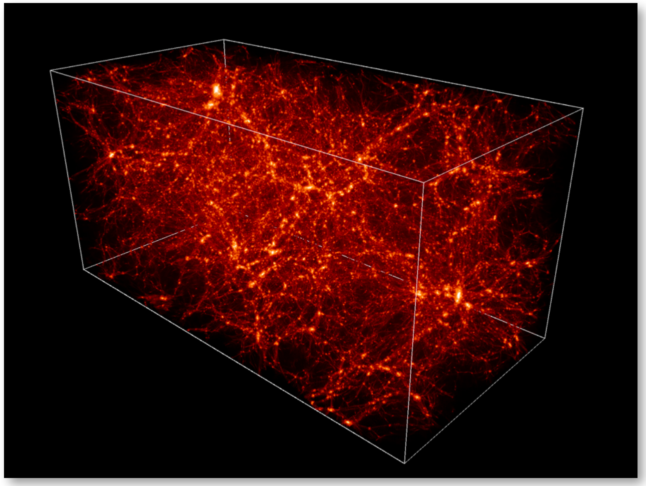
- Zhang et al, PRD 76 (2007) 061301
- Galli et al, PRD 80 (2009) 023505
- Slatyer et al, PRD 80 (2009) 043526
- Kanzakiet et al, Prog. Theor. Phys. 123 (2010) 853
- Hisanoet et al, PRD 83 (2011) 123511
- Hutsi et al., A&A 535 (2011) A26
- Galli et al, PRD 84 (2011) 027302
- Finkbeiner et al, PRD 85 (2012) 043522
- Slatyer et al, PRD 87 (2013) 123513 (2013)
- Galli et al, PRD 88 (2012) 063502
- Lopez-Honorez et al, JCAP 1307 (2013) 046
- Madhavacheril et al, PRD 89 (2014) 103508

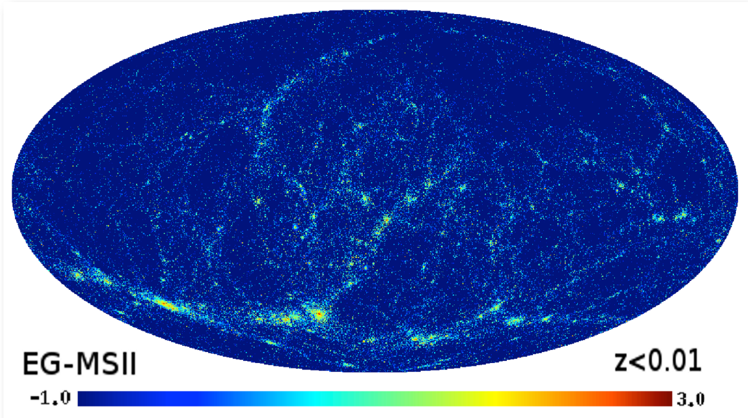
Diffuse signals: faint & not isotropic ...

Being the cumulative sum of independent sources (astro/DM)

To first approximation: isotropic

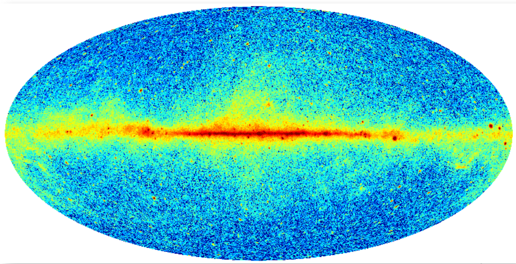
At a deeper level: anisotropies are present





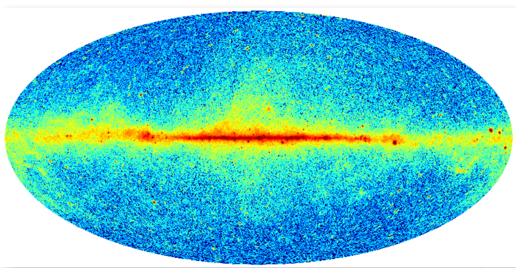
Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky

Photon statistics

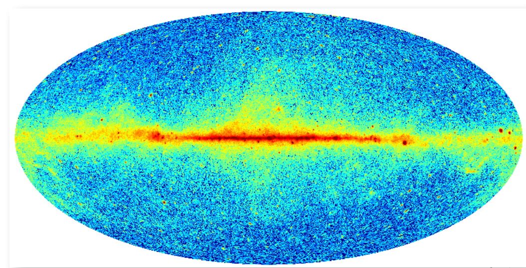


Photon pixel counts (1 point PDF)

Feels the distribution of sources



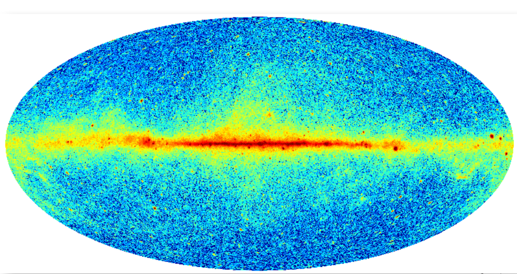
×



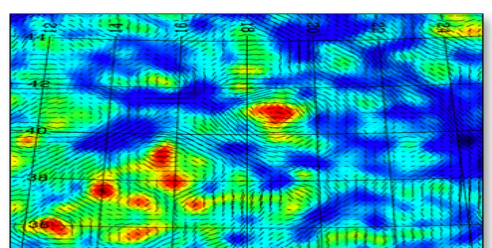
Auto-correlation

Feels the fluctuations of the photon field (induced by the underlying DM field)

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



×



Cross-correlation with LSS or cosmic shear

Feels the fluctuations of the photon field and correlates it to its origin (the underlying DM field)

Cross Correlations

Gamma rays x Galaxy catalogs (LSS)

X–CORR DETECTED

- Xia, Cuoco, Branchini, Viel, APJS 217 (2015) 15 — Fermi x (SDSS + 2MASS + NVSS)
- Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301 — "
- Cuoco, Xia, Regis, Branchini, NF, Viel, ApJS 221 (2015) 29 — "
- Shirasaki, Horiuchi, Yoshida, PRD 92 (2015) 123540 — Fermi x SDSS LRG

Gamma rays x Cosmic shear

X–CORR NOT DETECTED (YET …)

- Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502 — Fermi x CFTHLenS
- Shirasaki et al, PRD 94 (2016) 063522 — Fermi x (CFTHLenS + RCSLenS)
- Troester et al, MNRAS 467 (2017) 2706 — Fermi x (CFTHLenS + RCSLenS + KiDS)

Gamma rays x CMB lensing

X–CORR DETECTED

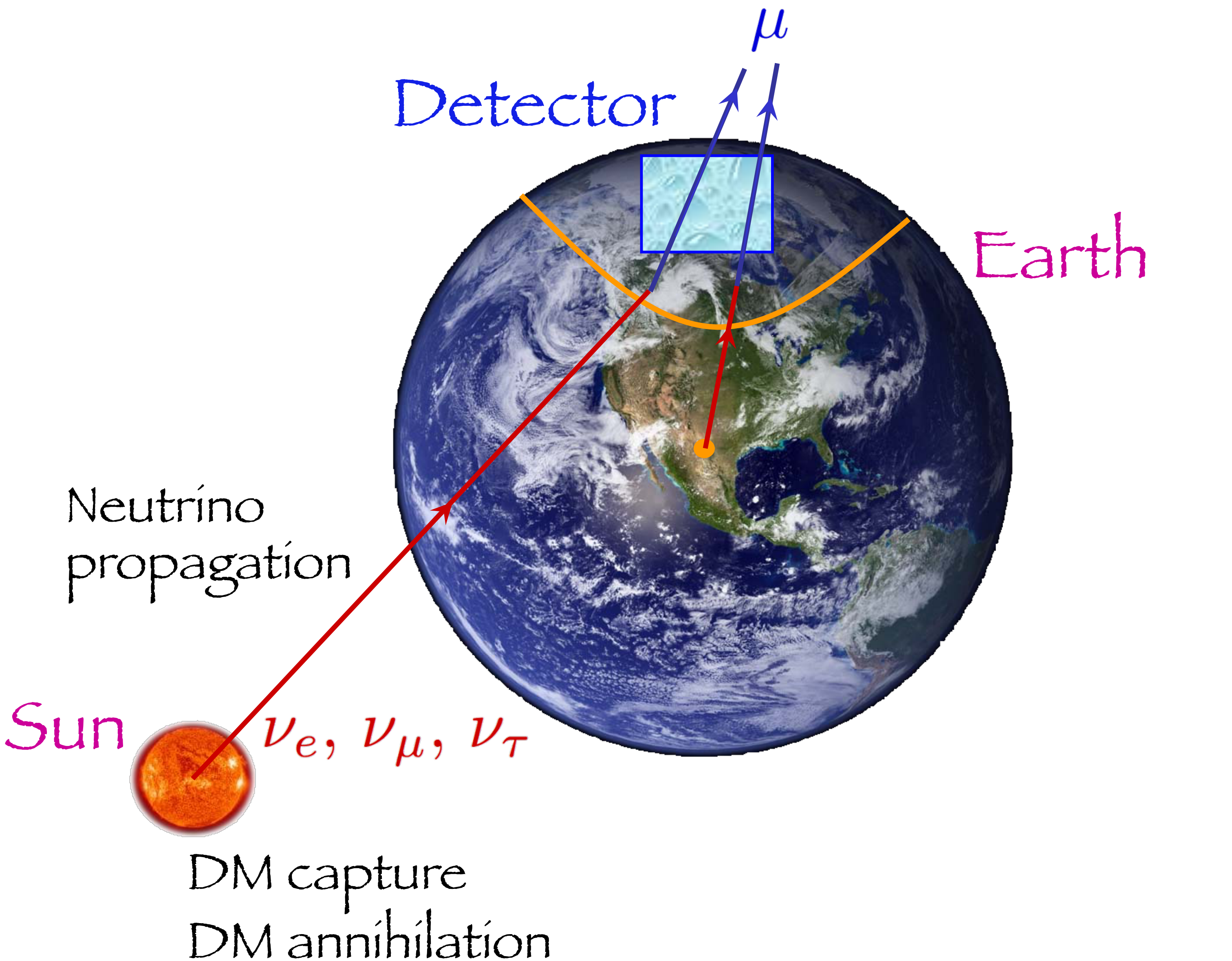
- NF, Perotto, Regis, Camera, ApJ 802 (2015) L1 — Fermi x Planck

Gamma rays x Galaxy clusters

X–CORR DETECTED

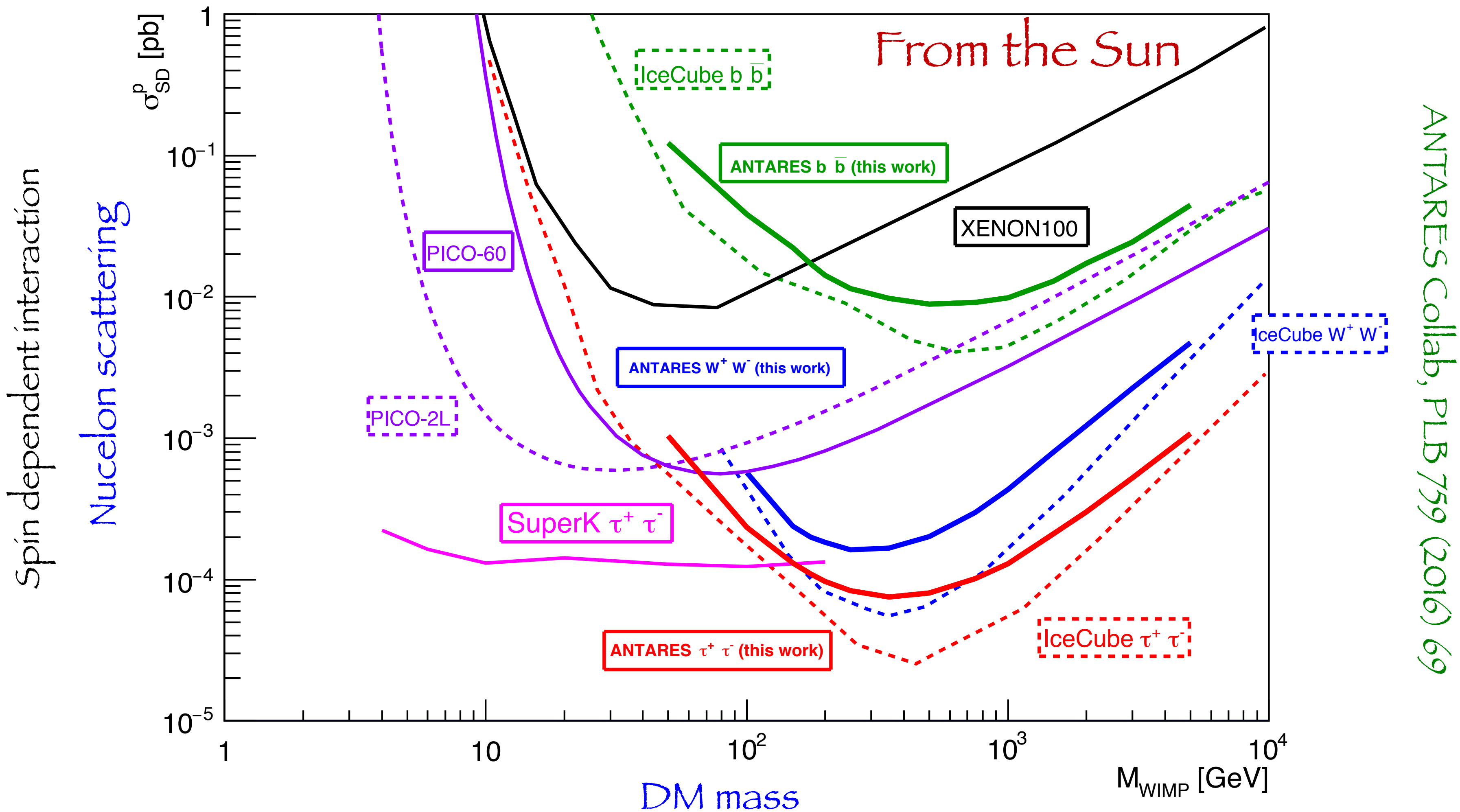
- Cuoco et al, ApJS 228 (2017) 1 — Fermi x (redMaPPer + WHL12 + PlanckSZ)

Neutrinos from Earth and Sun



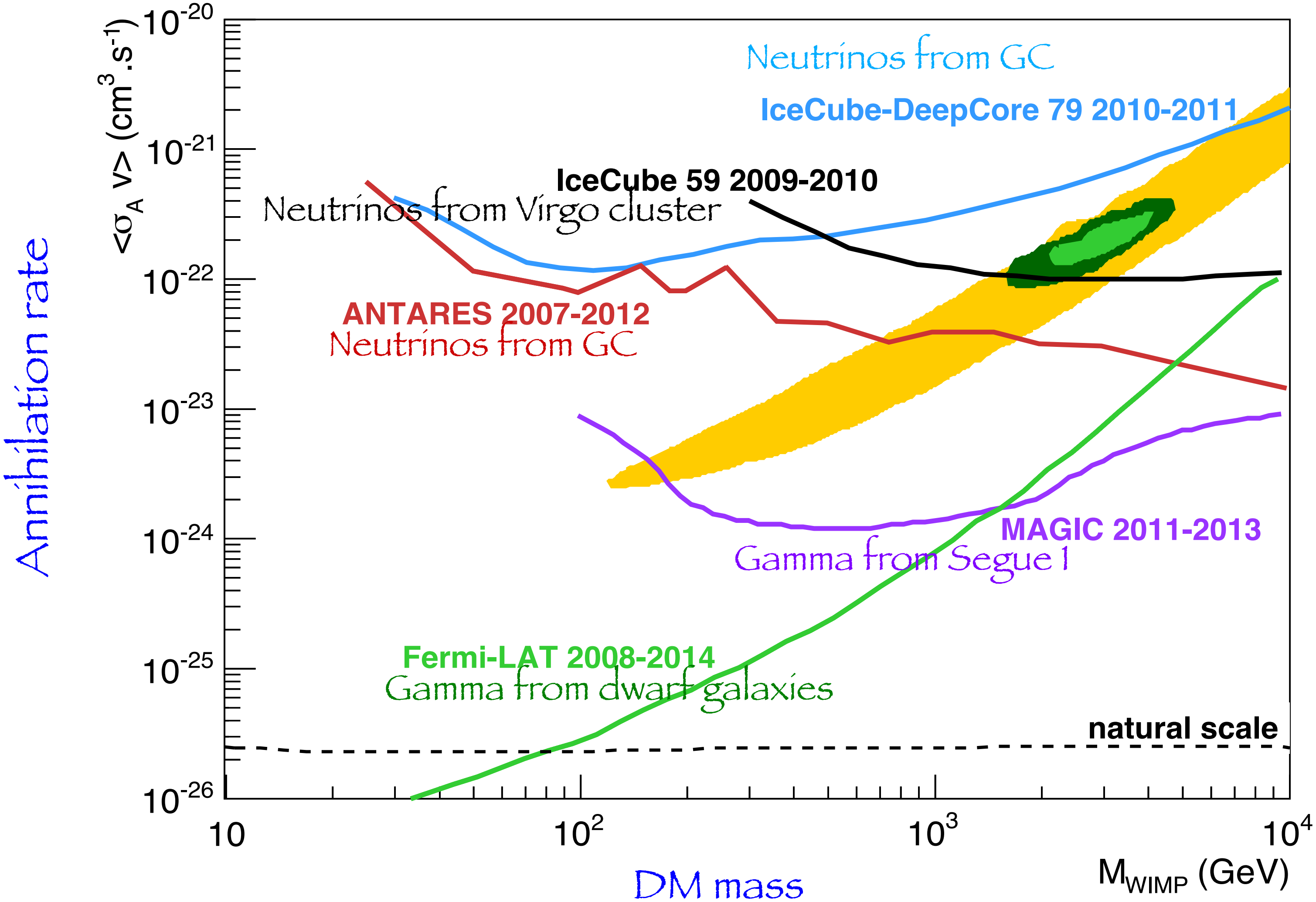
and neutrinos from the Galaxy

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

Conclusions

- The solution to the DM problem requires to identify (or disprove) its particle physics nature: either way, New Physics is there

- This can be done only through a coordinated and multifaceted effort which gets input both from:
  - Accelerator physics
  - Astrophysical and cosmological probes

- WIMP — Current techniques have started probing the region of interest
  It is the right moment to push forward

- Non WIMP — The interest has been recently strongly revived, new ideas
  Window of opportunity complementary to WIMPs

- A signal of DM is clearly faint, but the opportunities are rich:
  multimessenger, multiwavelength, multitechnique