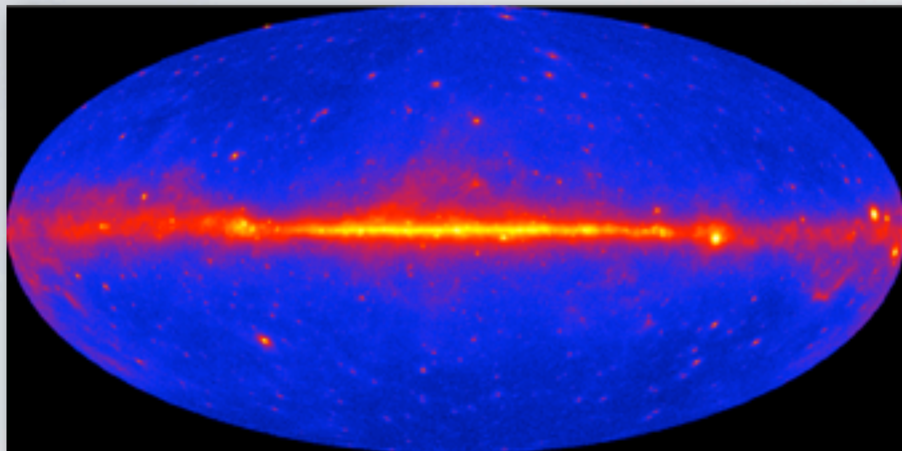
Astrophysical signals of dark matter: III. Indirect (WIMP) detection



Pasquale Dario Serpico

First ICTP Advanced School on Cosmology - 18-29/05/2016

OUTLINE

- WIMPs are promising dark matter candidates which can be searched for with different strategies
- Final lecture: devoted to (several, not all!) indirect search strategies.
- Gamma Rays
- Neutrinos
- Charged cosmic rays
- Moving from constraints to possible detection? Some lessons

Apologies: will leave out some other interesting "indirect" probes: radio, X-ray, energy transfer/stellar constraints, subtle anisotropy-related techniques...

WHAT DOES IDM STRATEGY MEAN?

That one looks for consequences of DM interactions elsewhere (not in the Lab!), such as decays, annihilations, energy transfer to baryons.

- ★ *It's a natural thing to do (DM is seen "elsewhere"!)*
- ★ *these features may imply an impact on cosmology or astrophysics.*
- ★ *It is an additional handle on properties one cannot probe otherwise in the Lab.*

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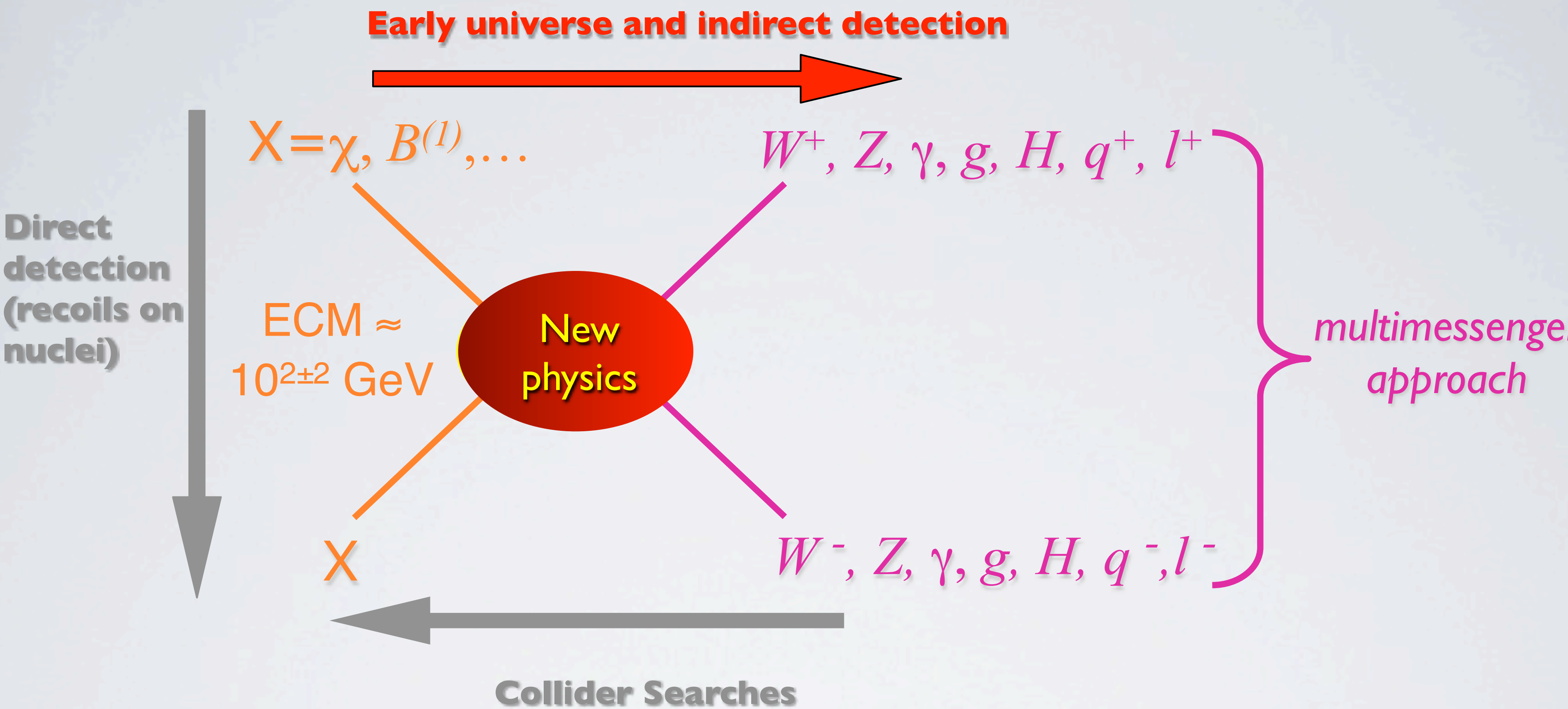
✓ **The presence of indirect signatures is by no means guaranteed (model-dependent)**

✓ **It needs not to be a GeV-TeV-scale signature, neither necessarily an annihilation one (notable example: ~ keV sterile neutrino X-ray decay line)**

✓ **There is no <u>astrophysical or cosmological</u> evidence whatsoever for the electroweak scale being the right one for explaining the DM problem.**

WIMP SEARCH STRATEGY



The link with early universe stands modulo some caveats

- $\langle\sigma v\rangle_{T\simeq 0} \overset{?}{\sim} \langle\sigma v\rangle_{T=T_f}$ Ok for S-wave annihl., otherwise must be specified
- Signatures DO depend on b.r. of different channels (only total rate in early universe)
- rates depend on astrophysical distribution of DM... observations/simulations needed!

GAMMA RAYS

☺ Retain directionality (angular info!)

☺ Relatively easy to detect
(potentially high statistics)

☹ A lot of backgrounds (known and unknown)

Flux (from non cosmologically distant sources) often written in a factorized form

particle physics
(we assume its own antip.)

"astrophysics"
(**J-factor**, written *a-dimensional*)

$$\Phi_\gamma(E_\gamma,\Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}}\rho^2(\ell,\Omega)\,\mathrm{d}\ell$$

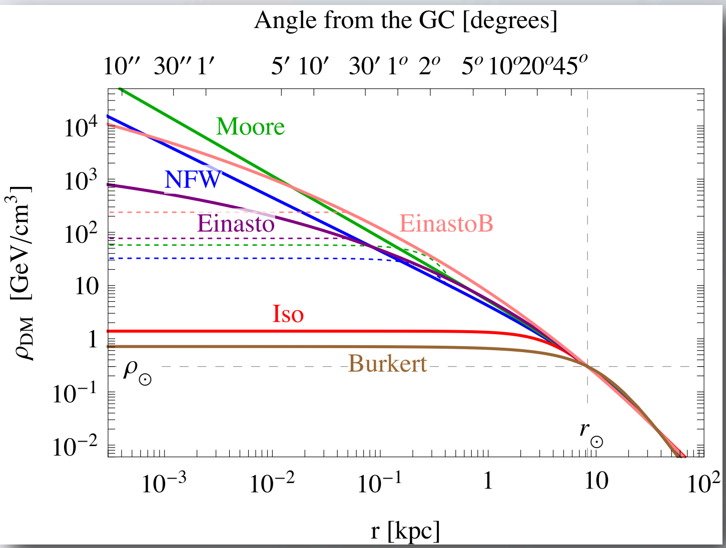
[particle] ⊗ (astro) factorization holds if

- **σ v is v-independent**
(otherwise goes under integral, over v distribution)
- **if *prompt emission* dominates**
(for secondary emission, need to follow $e^{\pm}$, more on that later)

NOTE: ANNIHILATION VS. DECAY

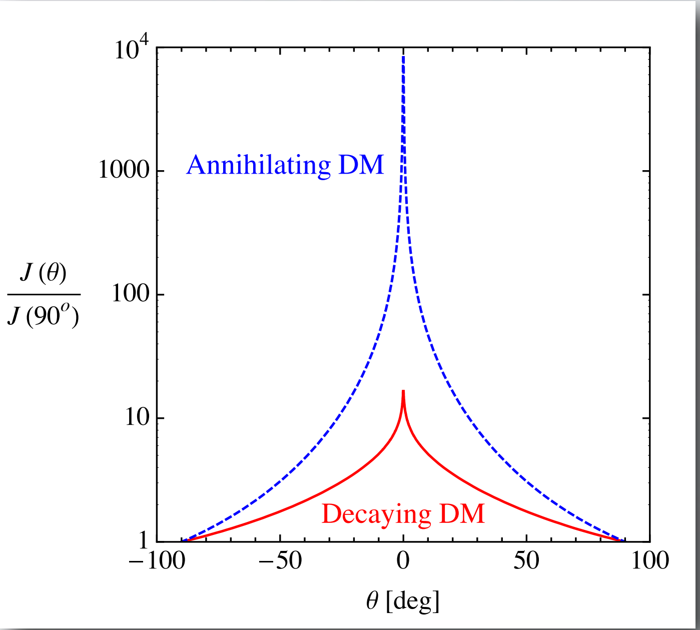
Annihilation depends quadratically on DM density, i.e. depends on poorly known clumpiness of DM, prediction should rely heavily on simulation/theory

$$\Phi_\gamma(E_\gamma,\Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}}\rho^2(\ell,\Omega)\,\mathrm{d}\ell$$



A Decay signal responds to the integrated DM density, i.e. same source of DM gravitational effects. This is relatively well known, whenever DM is dynamically relevant.

$$\Phi_\gamma = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{\Gamma}{4\pi\, m_X}\int_{\mathrm{los}}\rho(\ell,\Omega)\mathrm{d}\ell$$

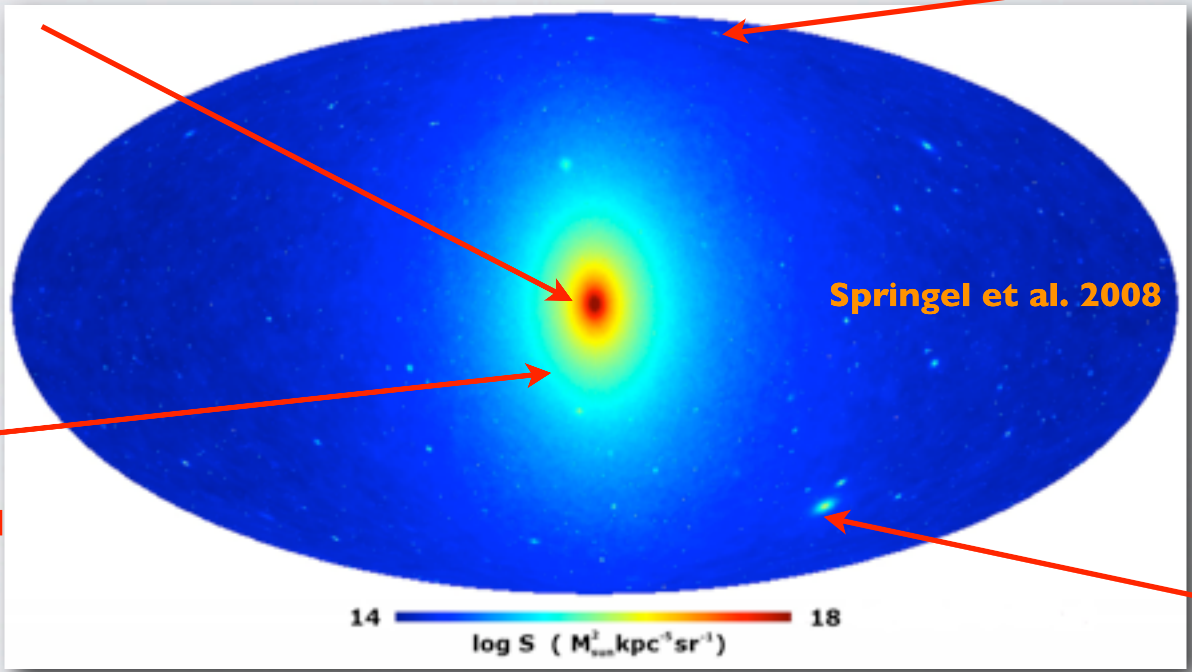


WHERE TO LOOK FOR GAMMA'S (ASTRO FACTOR)?

What is the picture of the "DM - gamma sky" suggested by simulations?

Galactic Center
high statistics, point-like
and diffuse backgrounds
<u>halo-model dependence</u>

Extragalactic
high statistics, lot of
diffuse backgrounds



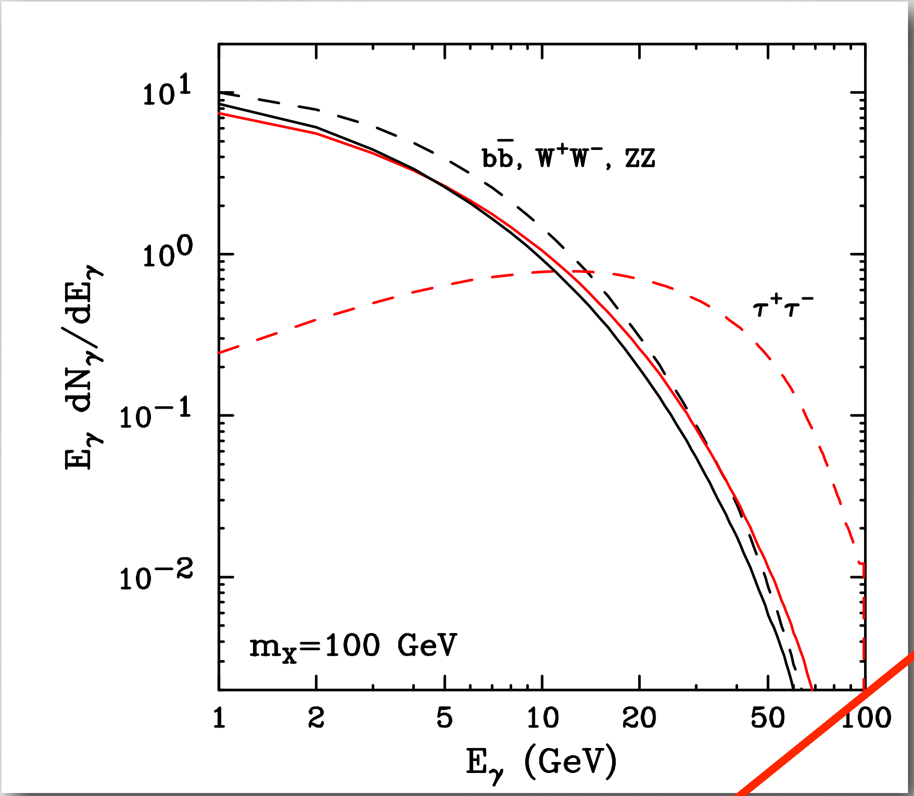
Springel et al. 2008

MW Halo
high statistics,
high diffuse background

Satellites
(or Clusters)
low background (?)
low statistics

Lines/Spectral Features
(everywhere...)

PREDICTED SPECTRA: CONTINUUM



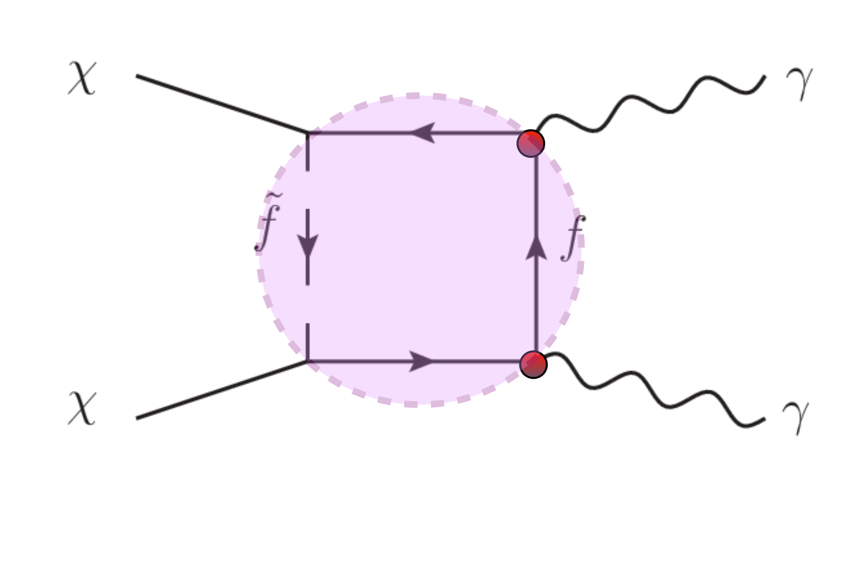
usually handled via e.g. PYTHIA incorporated in dedicated software

- ✓ whenever DM annihilates into quarks or gauge bosons, continuum photon spectrum is quasi-universal, as a result of decays/fragmentations
- ✓ Near the endpoints (~DM mass), or for leptonic final states, peculiarities may be present.
- ✓ Significant *secondary* (byproducts of electrons e-losses) gamma radiation may be emitted from electrons. Requires treatment as for charged particles, and astrophysical medium is important.

PREDICTED SPECTRA: LINES

- Line annihilation requires two-body final state channels containing at least one photon (for SM final states, $\gamma\gamma$, γZ, γH) yielding the spectrum

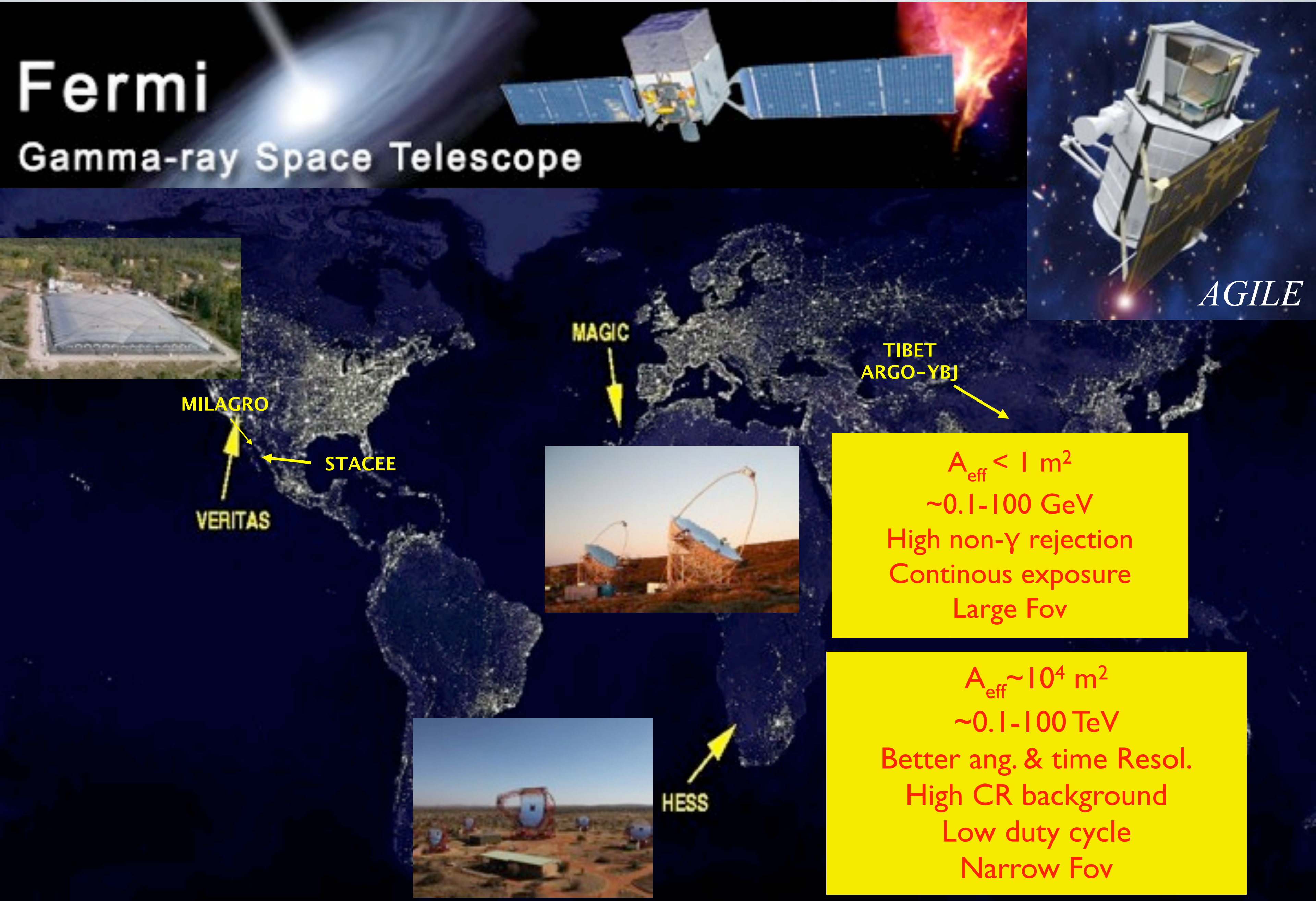
$$\frac{dN}{dE} \propto \delta(E - E_\gamma)\,, \quad E_\gamma \leq m_\chi$$



- This must be a loop-level process, suppressed with respect to the tree-level by $\alpha^2 \sim 10^{-4}$

- Usually it's theoretically difficult to produce line flux which is observable, while fulfilling bounds on continuum

TYPES OF GAMMA TELESCOPES



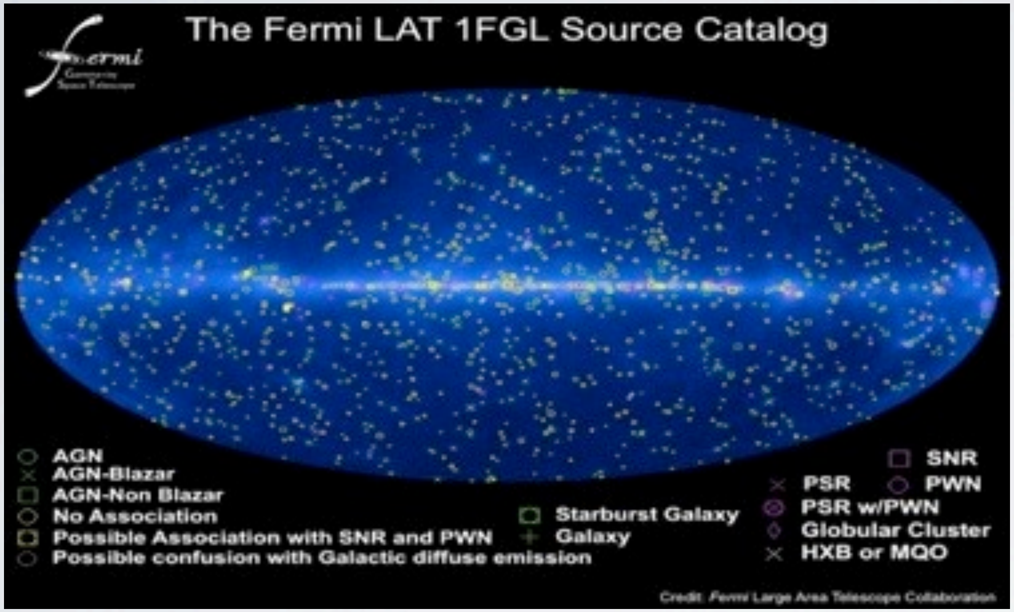
$A_{eff} < 1\ m^2$
~0.1-100 GeV
High non-γ rejection
Continous exposure
Large Fov

$A_{eff} \sim 10^4\ m^2$
~0.1-100 TeV
Better ang. & time Resol.
High CR background
Low duty cycle
Narrow Fov

WHAT DO THEY SEE? A CROWDED & BRIGHT SKY!

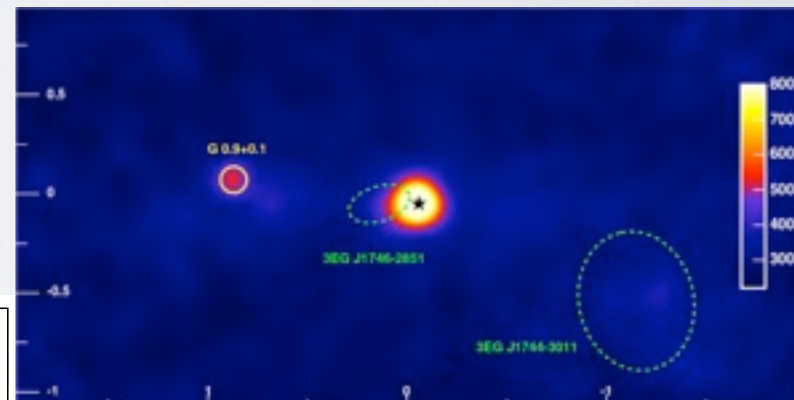
What Fermi or ACTs see looks nothing like DM expectations: backgrounds are often important!

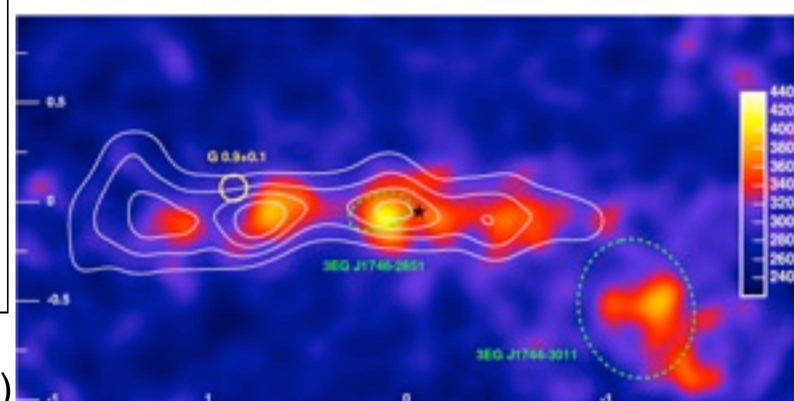
their understanding is the main challenge in tightening IDM bounds (or interpreting some hints)

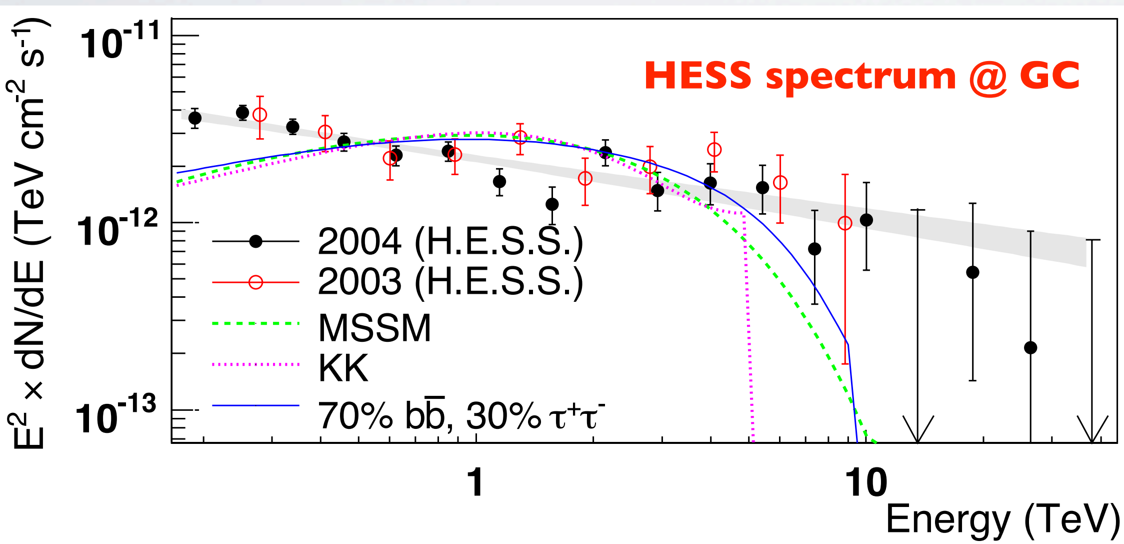


Fermi sky > GeV

HESS Gal. Center & Galactic Ridge morphology

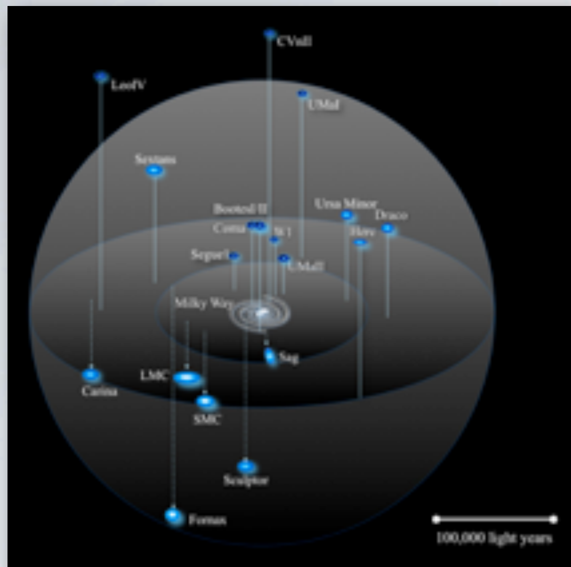






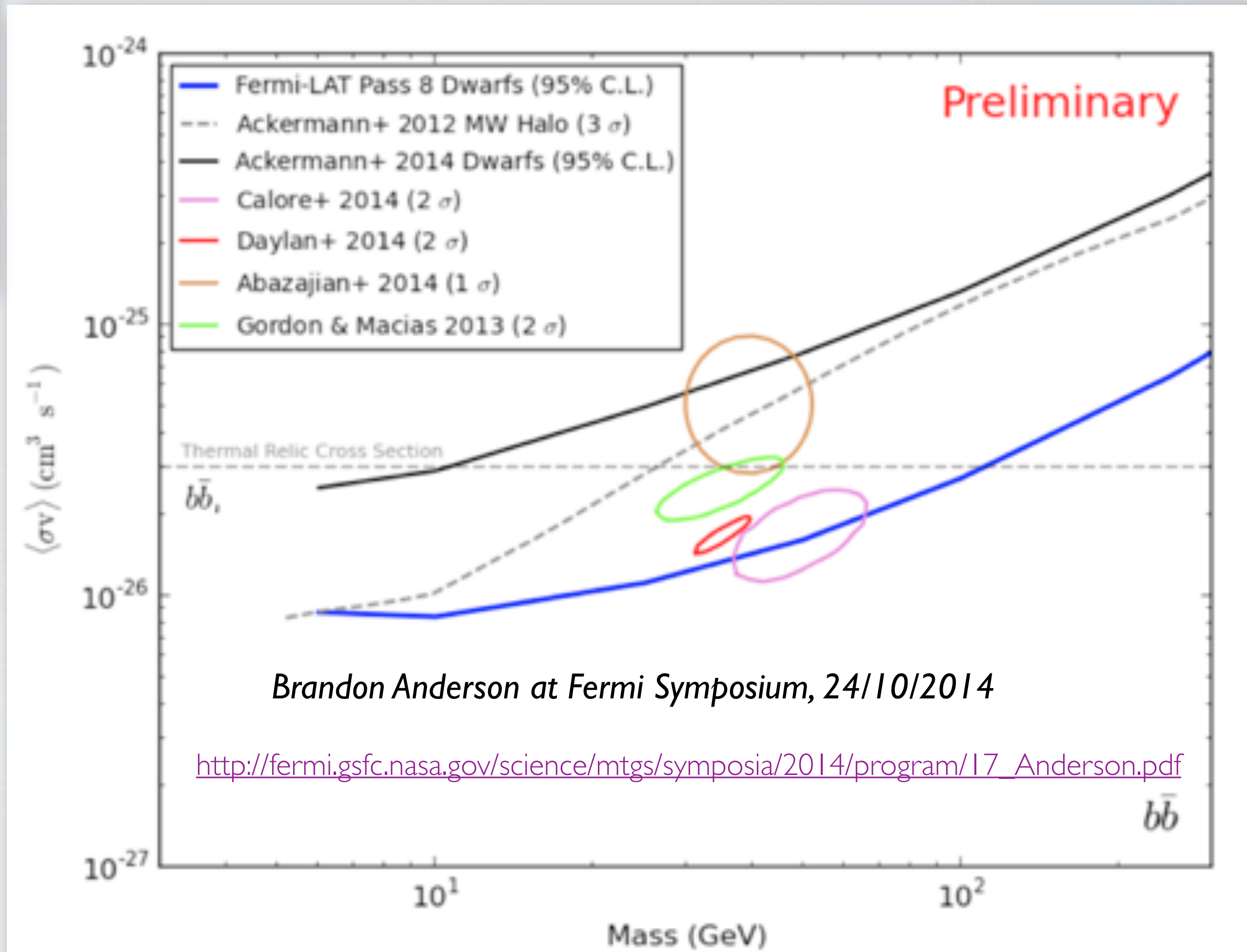
CONSTRAINTS

DWARF GALAXY GAMMA BOUNDS



✦ Depends on distance and volume average of DM density² (hence DM distribution & normalization) The bounds are as robust as these are. Nominally exclude "generic thermal" S-wave relics annihilating into b's up to ~ 100 GeV

satellites of Milky Way with high DM/ baryon content (1 to 3 orders of magnitude higher than the MW)
Almost ideal S/N

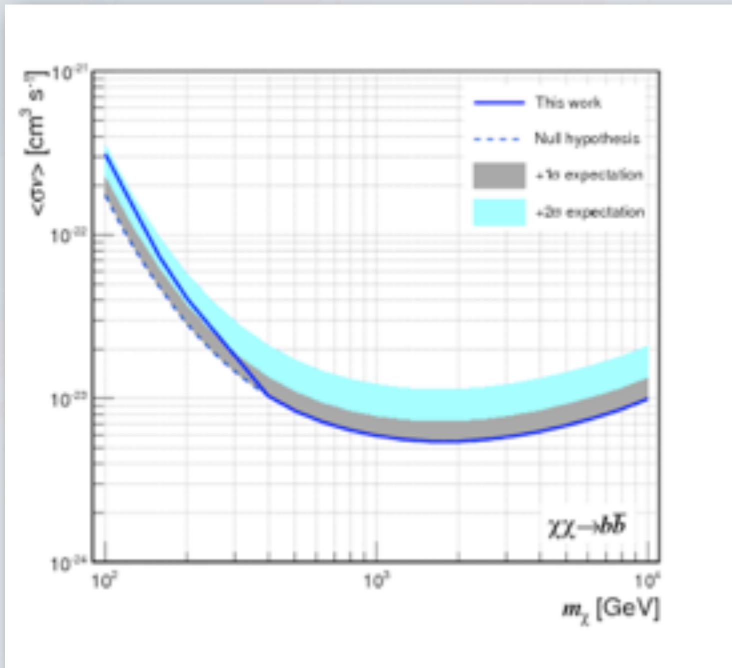


Brandon Anderson at Fermi Symposium, 24/10/2014

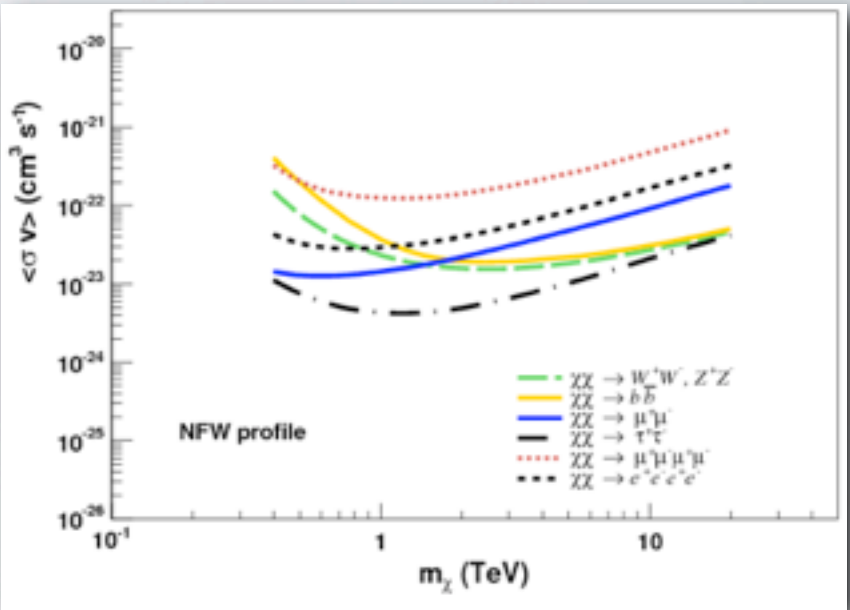
http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2014/program/17_Anderson.pdf

DWARF GALAXY GAMMA BOUNDS

By the way, DwSphs do remain among the most promising targets for ground based Cherenkov Telescopes such as MAGIC, HESS,VERITAS... & future CTA, but in a different range of masses

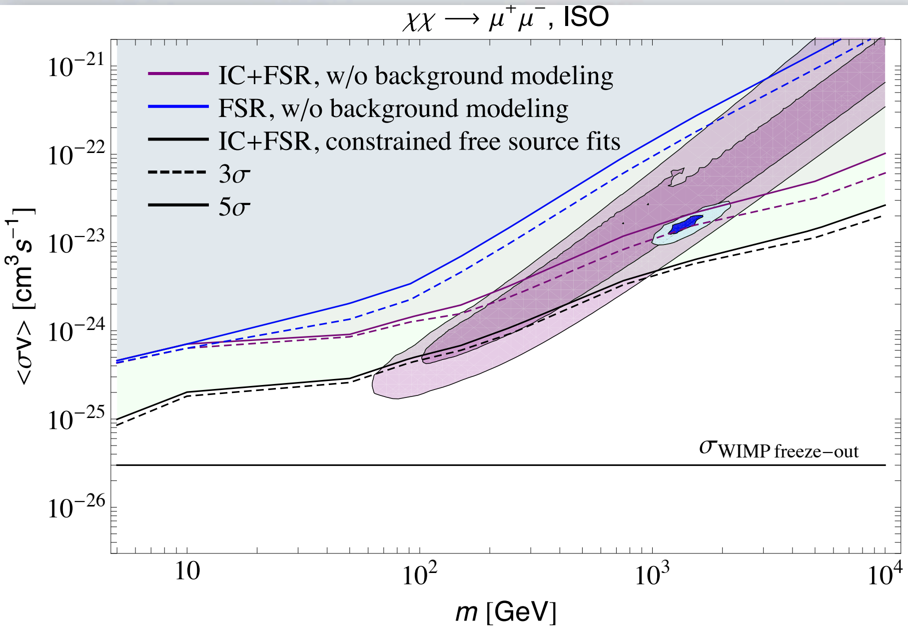


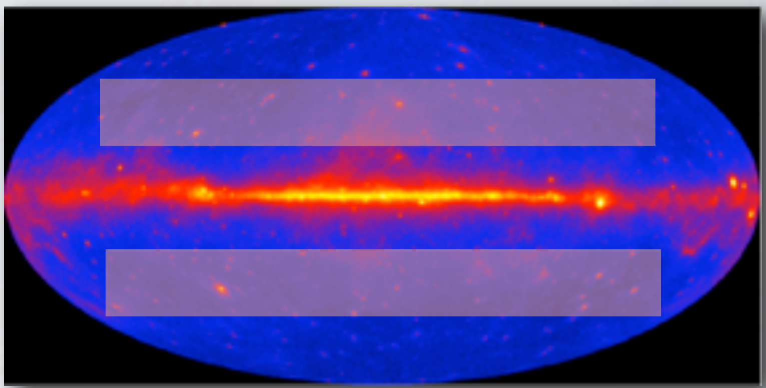
J.Aleksić et al. [MAGIC Collaboration]
"Optimized dark matter searches in deep observations of Segue 1 with MAGIC,"
JCAP 1402, 008 (2014)



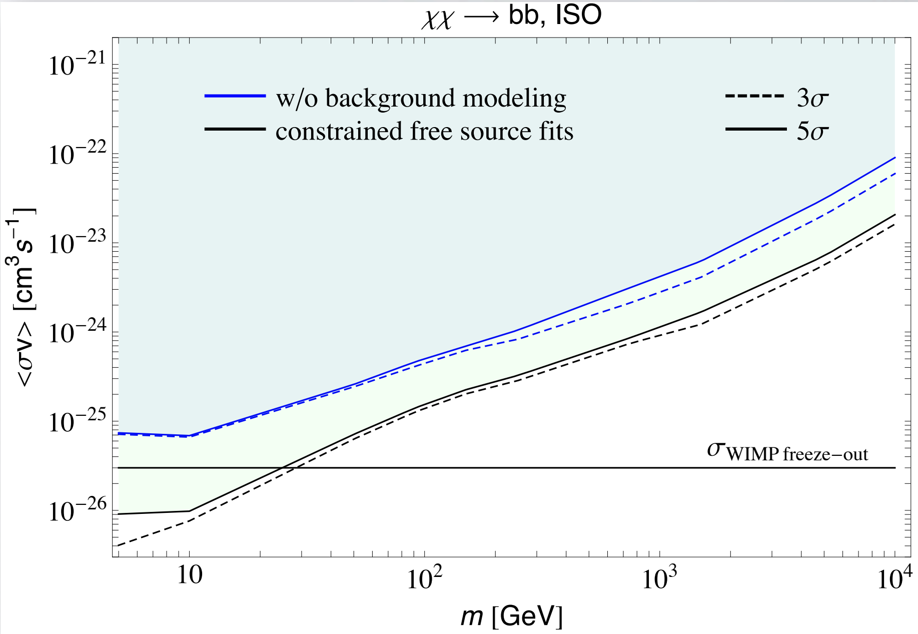
A. Abramowski et al. [HESS Collaboration],
"Search for dark matter annihilation signatures in H.E.S.S. observations of Dwarf Spheroidal Galaxies,"
Phys. Rev. D 90, 112012 (2014)

GALACTIC DIFFUSE





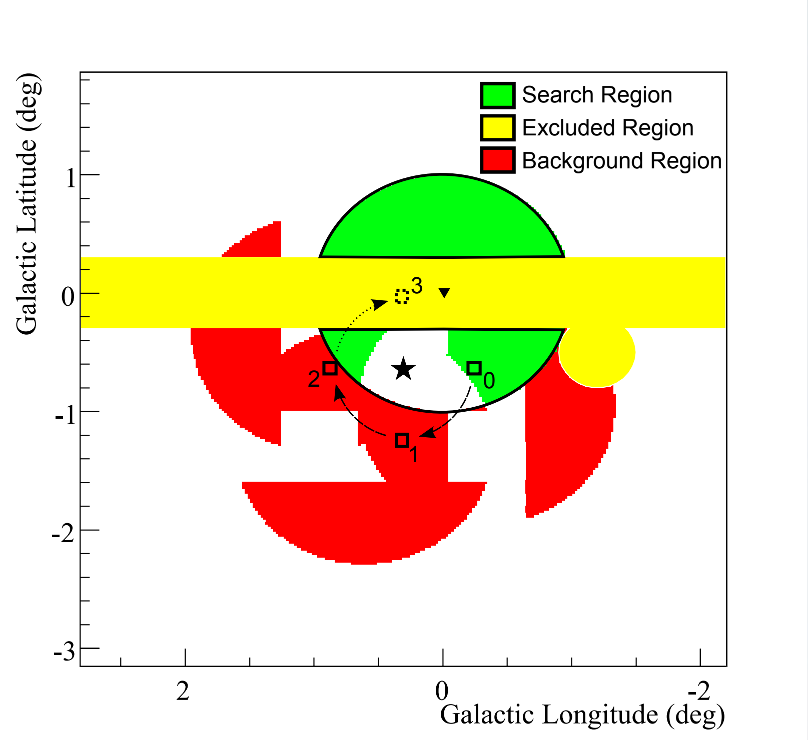
Relatively robust in terms of signal, quite strong constraints (~comparable with "old" dwarf results) if one accounts for astrophysical backgrounds

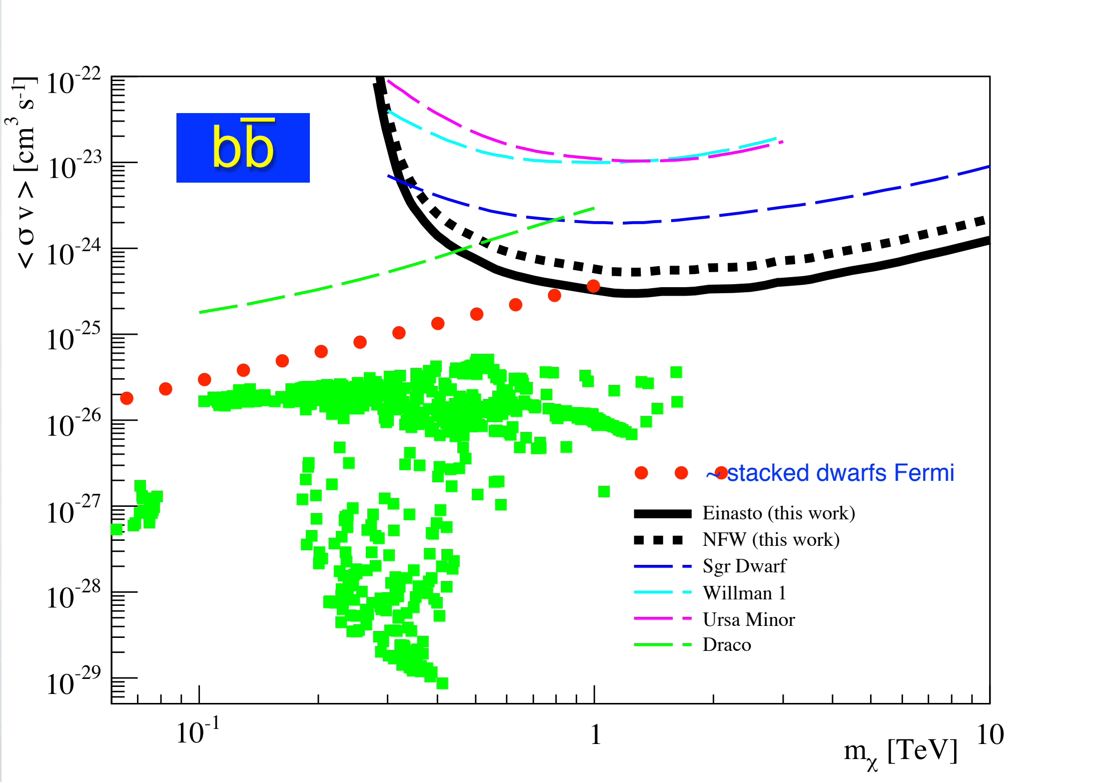


Ackermann et al. [Fermi-LAT], 1205.6475 (w or w/o astro background)

GAL. CENTER BY HESS

- GC has complex astrophysics, look away!
- Select signal region close to GC but as much as possible free from backgrounds
- Select "similar geometry" region where signal is expected to be smaller for background subtraction





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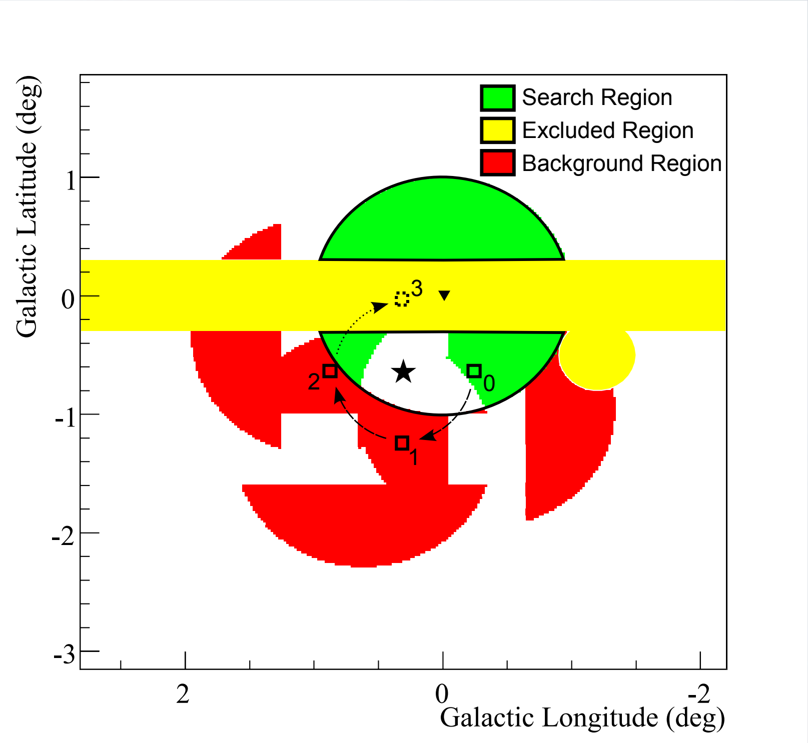
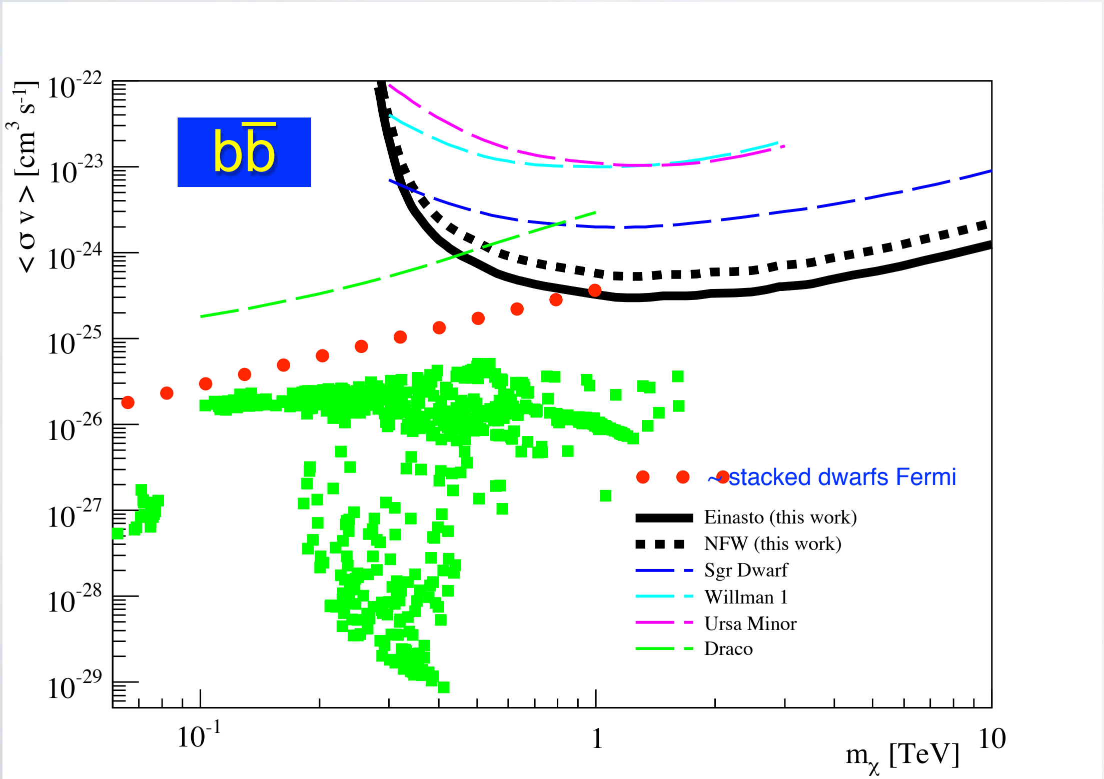




most stringent bound on DM from IACTs I'm aware of (but halo-model dependent)

Modulo comparatively small differences (dedicated time, latitude, E-threshold, field of view) this also applies to VERITAS and MAGIC: only modest improvements can be achieved with present generation IACTs

EXTRAGALACTIC FLUX

Standard expression of the flux (**Exercise:** justify this, starting from the expression for the Galactic case)

$$\phi(E) = \frac{c\,\langle\sigma v\rangle(\Omega_{\rm DM}\rho_c)^2}{8\pi\, m_\chi^2}\int dz \frac{e^{-\tau}(1+z)^3}{H}\,\zeta(z)\,\frac{dN}{dE'}$$

where $\zeta(z) \equiv \langle \delta^2(z,\hat{\Omega})\rangle$

traditionally estimated in Halo Model as

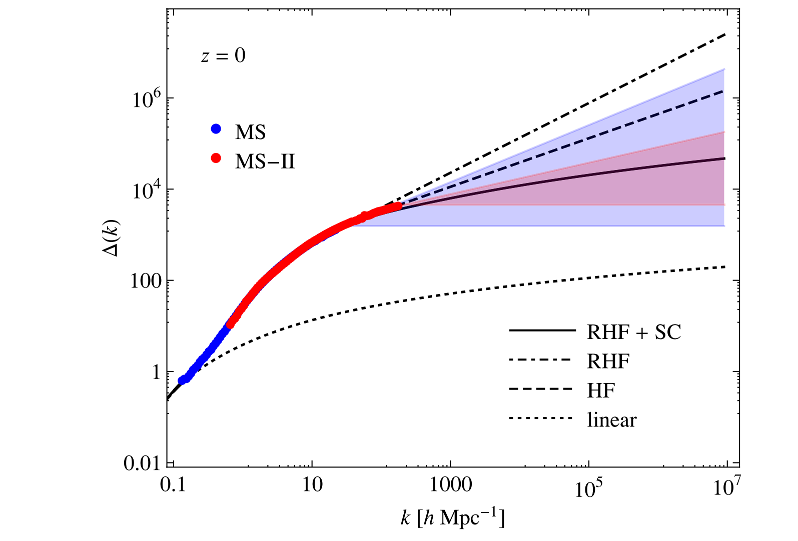
$$\zeta(z) = \frac{1}{\Omega_{\rm M}\rho_c}\int_{M_{\rm min}} dM\,\frac{dn}{dM}\,M\,\frac{\Delta_v(z)}{3}\,\langle F\rangle$$

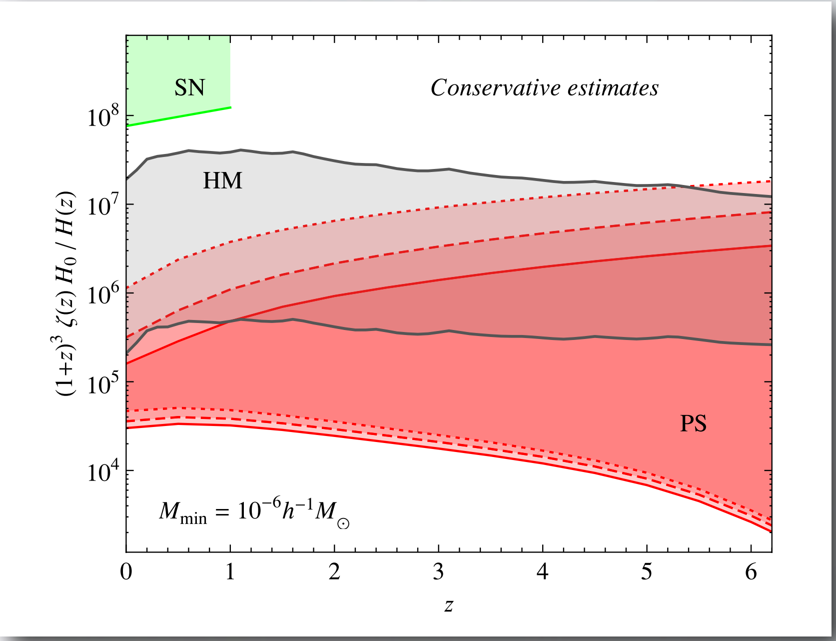
but each term depends on halo profile, concentration, different subpopulations… all subject to (wild) extrapolation.

In reality, the signal we're interested in only depends on non-linear power spectrum!

$$\zeta(z) \equiv \lim_{r\to 0}\int^{k_{\max}} \frac{d\,k}{k}\,\frac{\sin kr}{kr}\,\Delta_{NL}(k,z)$$

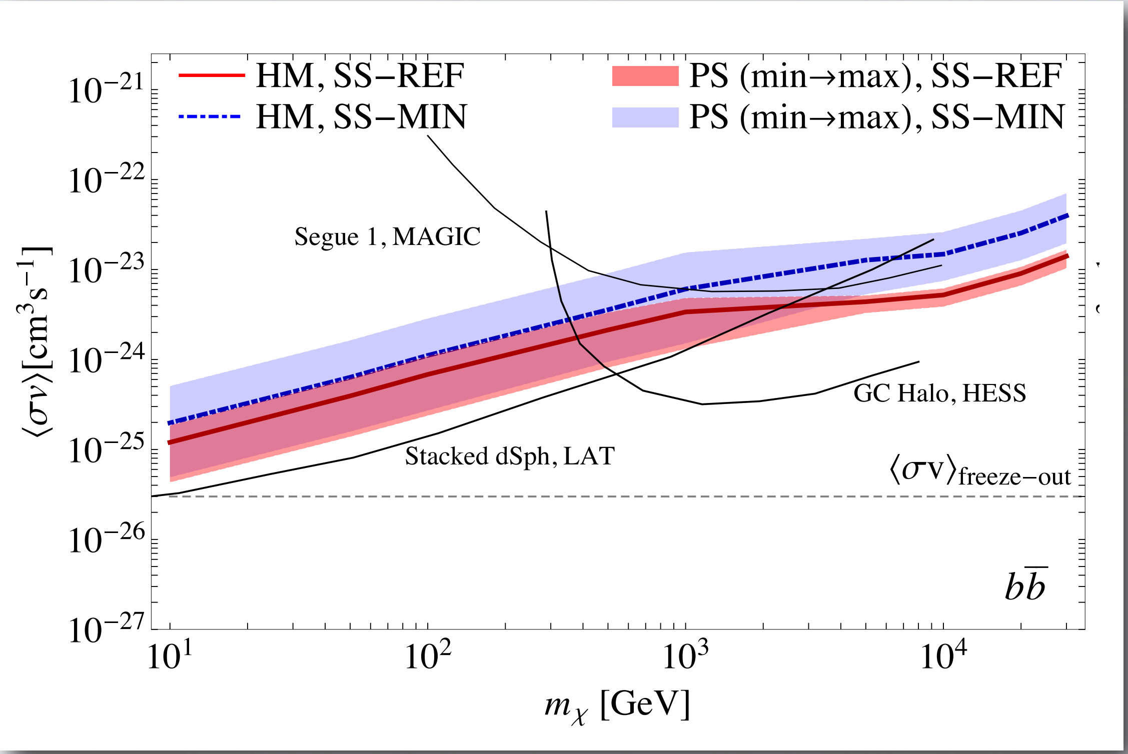
PS et al. MNRAS Letters 421, L87 (2012), Sefusatti et al. MNRAS 441, 1861 (2014)





EXTRAGALACTIC BOUNDS

Among best Fermi bounds for heavy DM, due to the "calorimetric" nature of IGRB. Comparable with IACT bounds, but very different systematics: does not depend on the profile in our Galaxy, does not depend on present-day properties, only, but integrates over cosmic history, etc.



M.Ackermann et al. [Fermi-LAT Collaboration], arXiv:1501.05464

NEUTRINOS

In principle, can be used as diagnostics similarly to photons, same formulae apply for the flux (modulo gamma spectrum replaced by neutrino spectrum). Additionally

Some advantage

☺ Do not suffer significant absorptions (will see soon a clever way to exploit this feature)

☺ Little (known) backgrounds

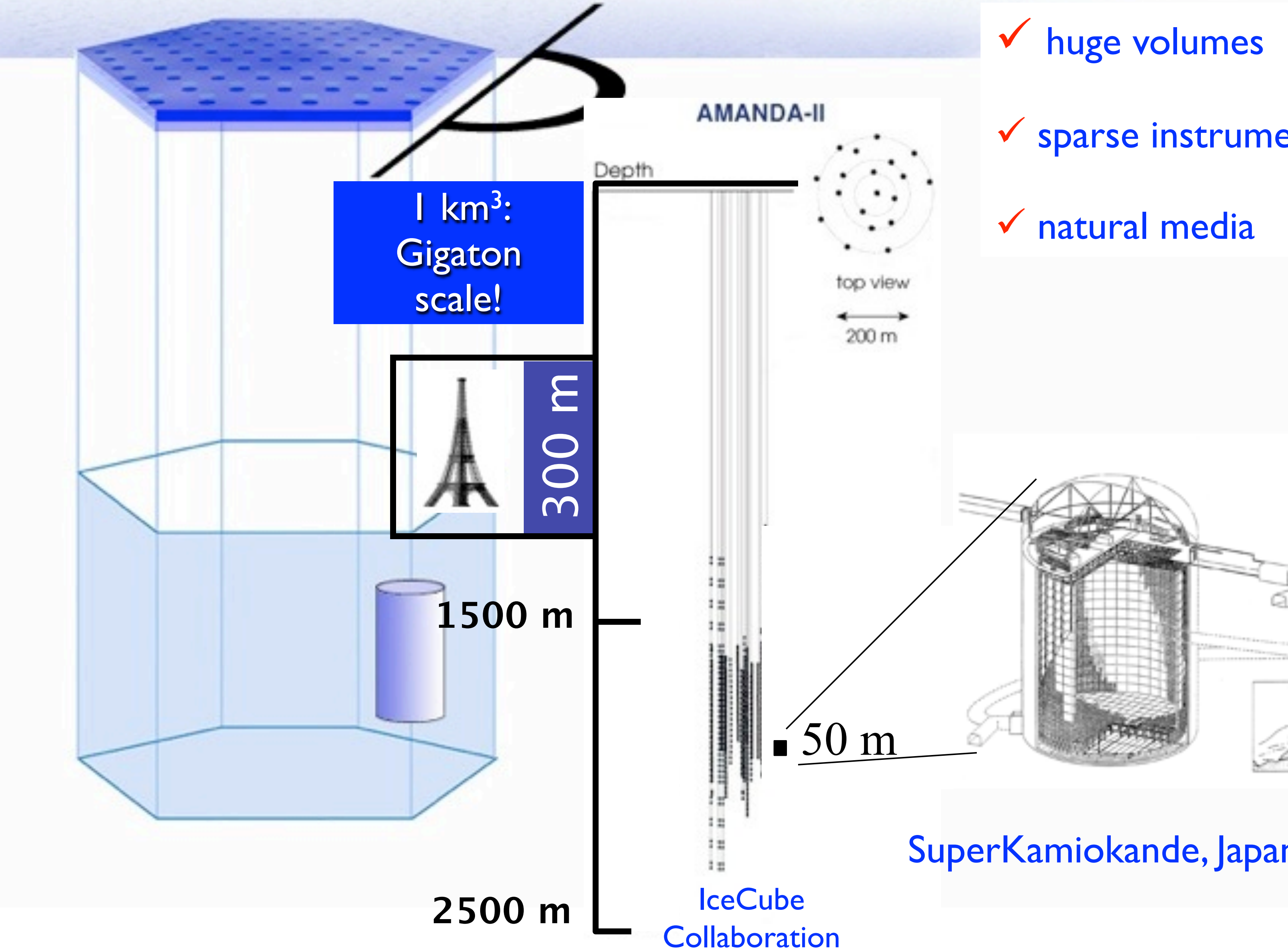
☹ "Little" problem: hard to detect!

σ(TeV)~ pb
σ(PeV) < nb

Solutions?

GIANT DETECTORS

- ✓ huge volumes
- ✓ sparse instrumentation
- ✓ natural media



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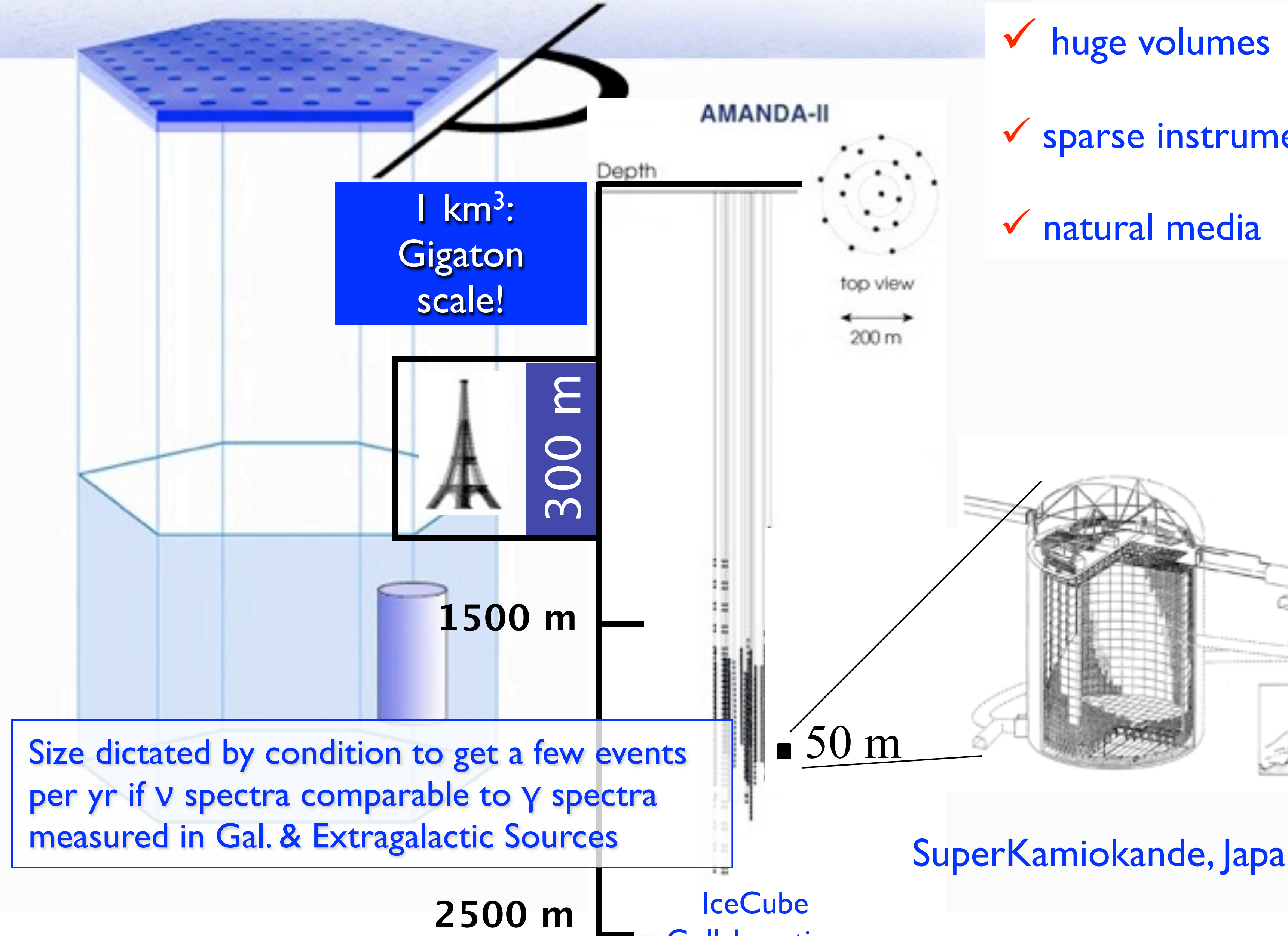


Size dictated by condition to get a few events per yr if ν spectra comparable to γ spectra measured in Gal. & Extragalactic Sources

IceCube Collaboration

SuperKamiokande, Japan

HALO BOUNDS

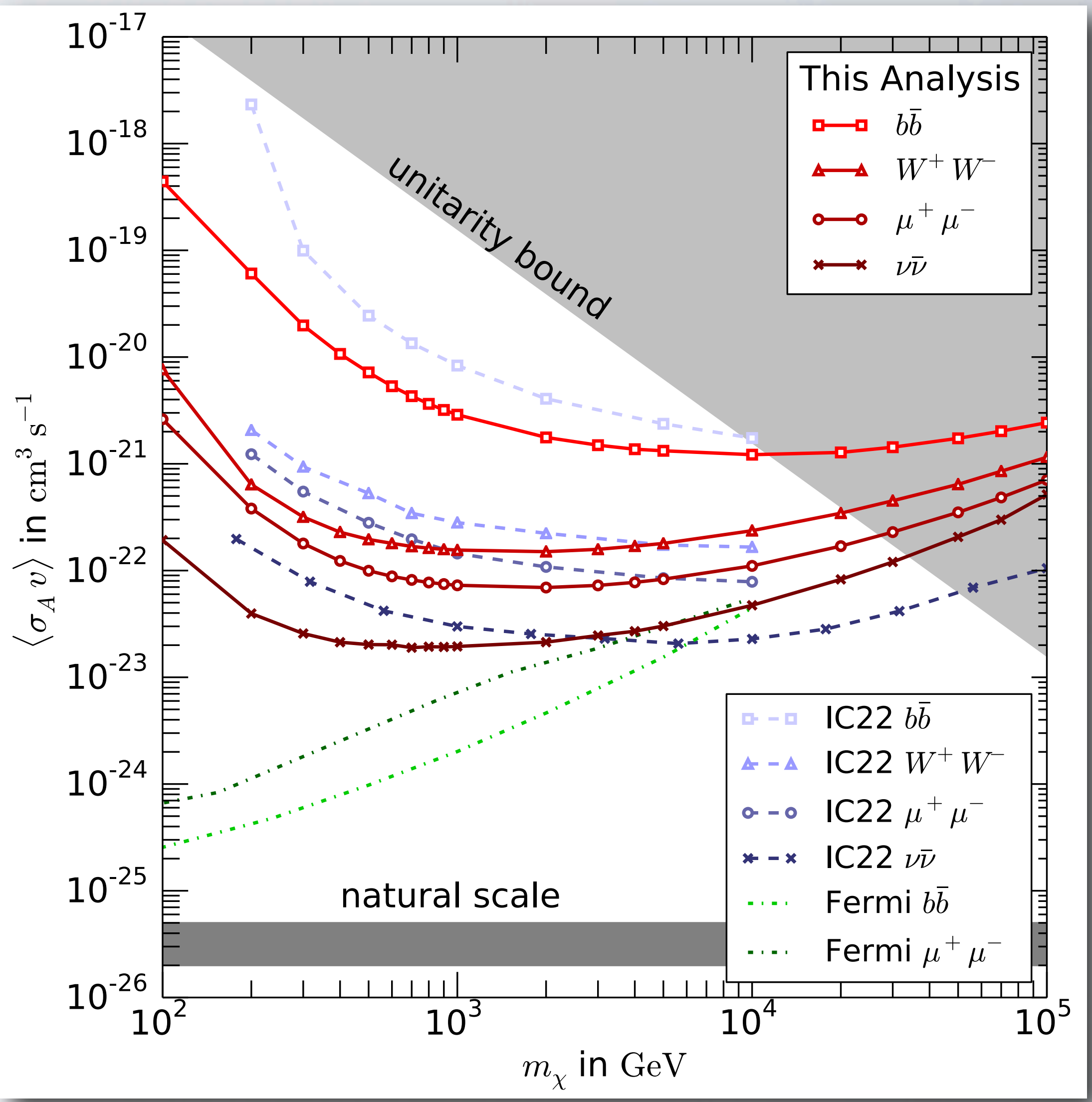
Current bounds
(slightly better bounds at low masses by Antares)

typically only better than Fermi gamma ray ones above O(10) TeV, depending on the channel

M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C 75, no. 1, 20 (2015) [arXiv:1406.6868]

But neutrinos offer another possibility:

just like in DD idea, DM can scatter on the matter of celestial bodies



CAPTURE IN CELESTIAL BODIES

What happens to the DM when it scatters against a nucleus in a celestial body? (A star, a planet...)?
If it loses sufficient energy, its residual velocity may be < escape velocity from that location

In that cases, it becomes gravitationally trapped, and in subsequent interactions it will continue lose energy sinking to the core of the object

"Capture rate"

$$C \propto \sigma \, \rho_{\rm DM}$$

"almost like" DD experiments!

W. H. Press and D. N. Spergel, "Capture by the sun of a galactic population of weakly interacting massive particles," Astrophys. J. 296, 679 (1985).

...

A. Gould, "Cosmological density of WIMPs from solar and terrestrial annihilations," Astrophys. J. 388, 338 (1992).

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"Capture rate"

$$C \propto \sigma\, \rho_{\rm DM}$$

"almost like" DD experiments!

more sensitive to low-E tail, as well as averaged over time...

$$C \simeq \sigma_{0,p} \frac{\rho_\odot\, \epsilon_p\, M_\odot}{m_\chi\, m_p} \times \int_0^1 d\mathcal{M}\, [v_\circ^2 - \mathcal{M}(v_\circ^2 - v_s^2)] \int_0^{u_{\rm max}} du \frac{f_1(u)}{u} \left[1 - \frac{u^2}{u_{\rm max}^2}\right], \quad u_{\rm max}(\mathcal{M}) \equiv \frac{\sqrt{4\, m_\chi\, m_p}}{m_\chi - m_p} \nu(\mathcal{M})$$

W. H. Press and D. N. Spergel, "Capture by the sun of a galactic population of weakly interacting massive particles," Astrophys. J. 296, 679 (1985).

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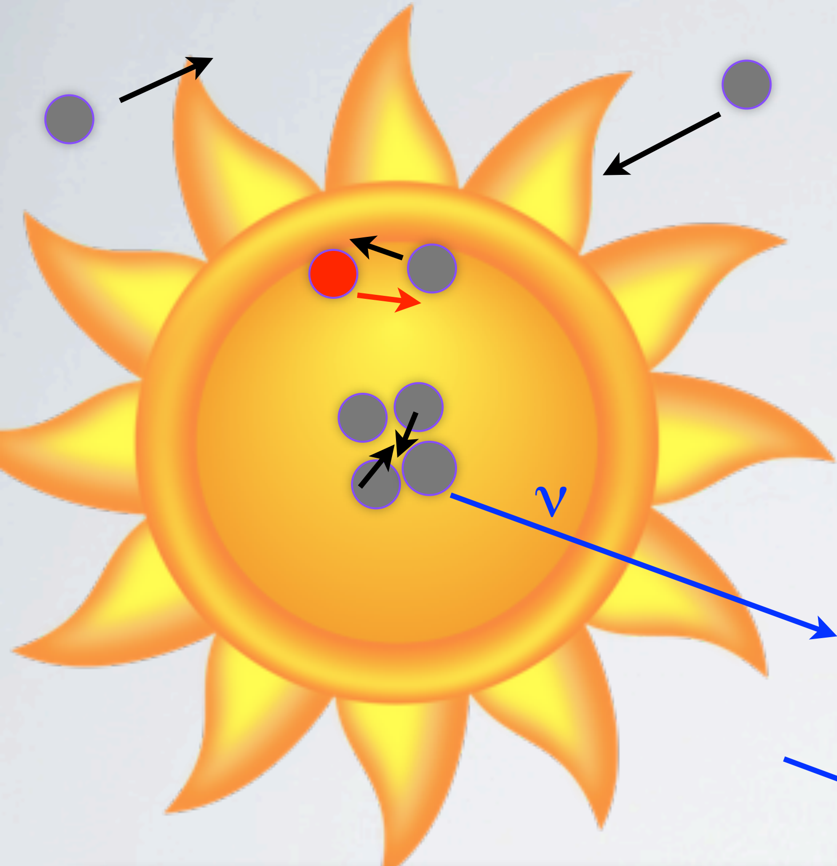
...

SIGNAL RATE



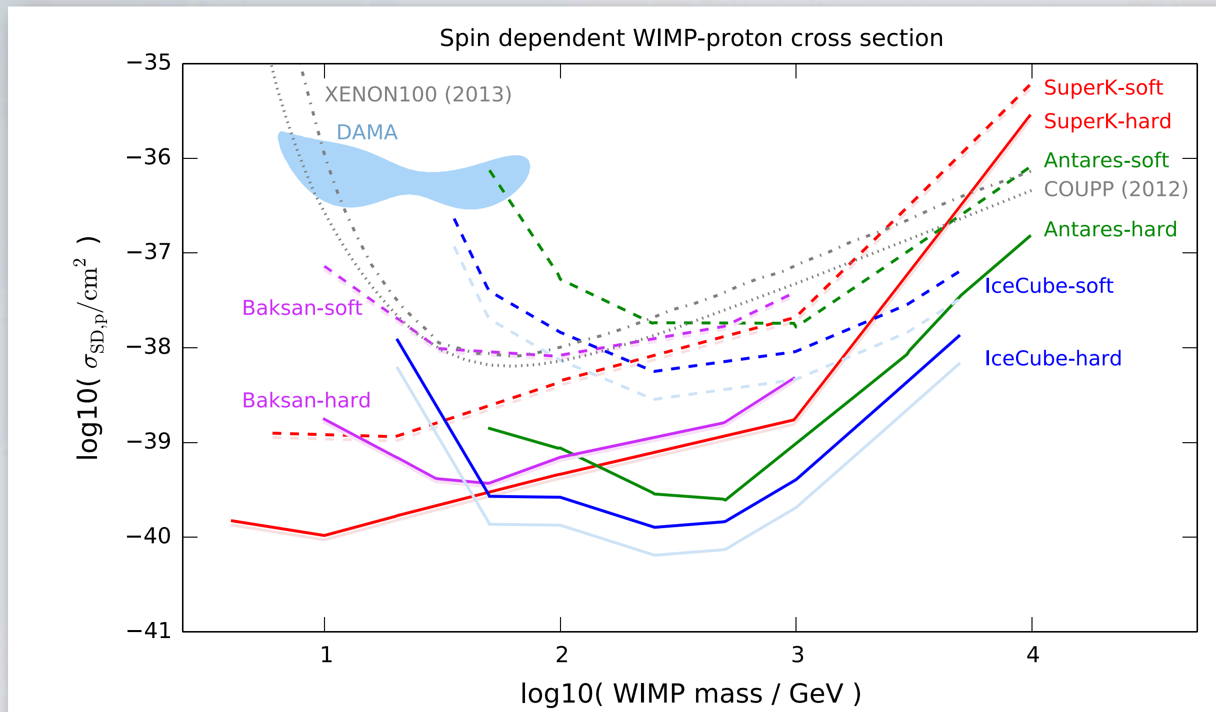
DM can only accumulate till the "loss channel" (e.g. via mutual annihilation) does not balance new captures. Since bodies are transparent to (sufficiently low-E) neutrinos, we may signals from the core of the Sun/ core of the Earth in neutrino detectors!

$$\dot{N} = C - C_A N^2$$

If equilibrium is reached btw the two, the annihilation signal rate writes:

$$\Gamma_A = \frac{C_A}{2} {N_{\rm eq}}^2 = \frac{C}{2}$$

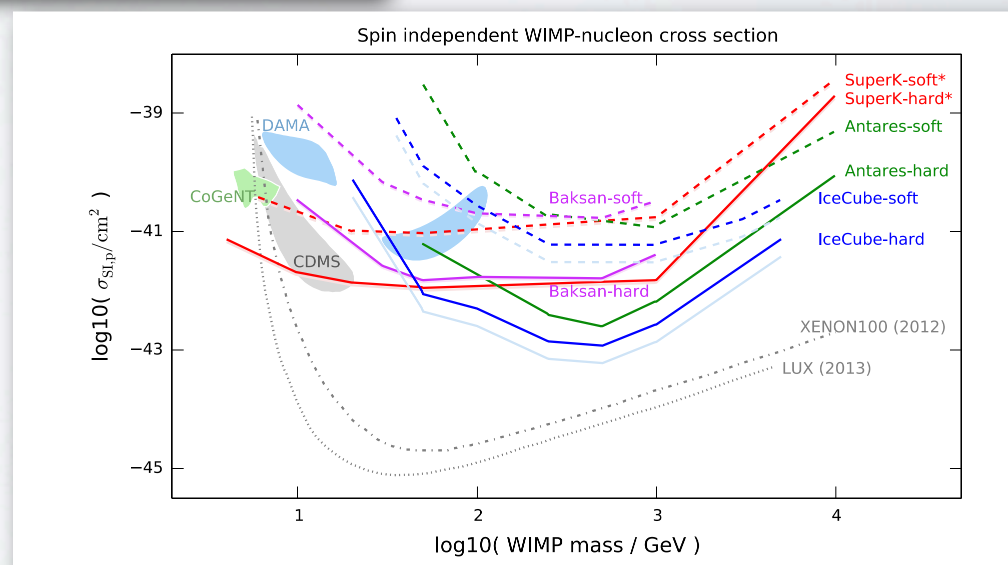
BOUNDS ON SPIN-DEPENDENT SIGMA



Sun mostly made by protons (with spin!), relative strength of bounds in favour of neutrino telescopes for Spin-dependent interactions

Also, bounds probe especially low velocity part of the *f*-distribution, and an average of the density crossed by the Sun... more details in

PS and G. Bertone, "Astrophysical limitations to the identification of dark matter: indirect neutrino signals vis-a-vis direct detection recoil rates," Phys. Rev. D 82, 063505 (2010) [arXiv:1006.3268]



CMB CONSTRAINTS

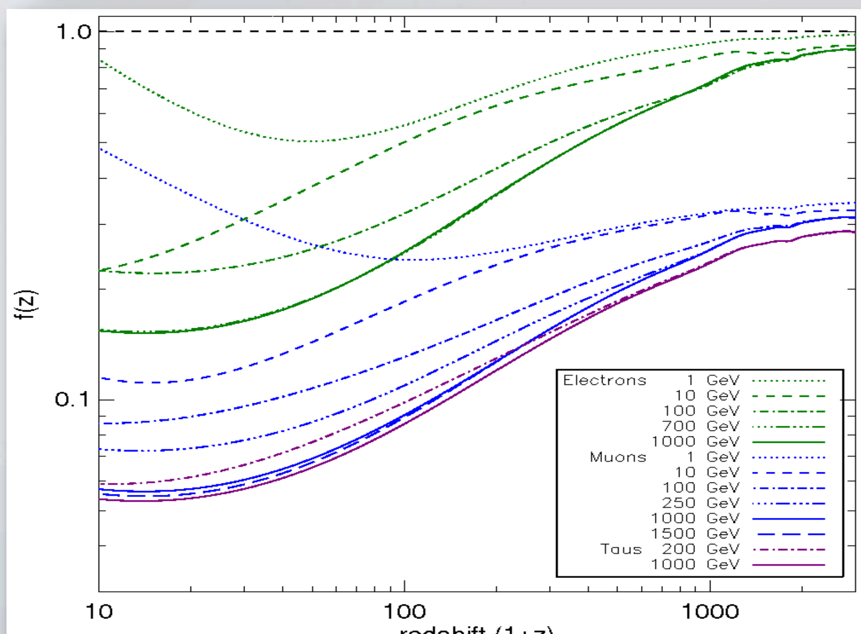
Energy injected via DM annihilation can provide extra ionization sources

$$\frac{dE}{dt} = \rho_c^2(1+z)^6\Omega_{\rm DM}^2\, p_{\rm ann}$$

where the key-parameter CMB is sensitive to is $p_{\rm ann}$, describing fraction effectively useful for ionization (as opposed as heating/excitation), depends on DM model (final state).

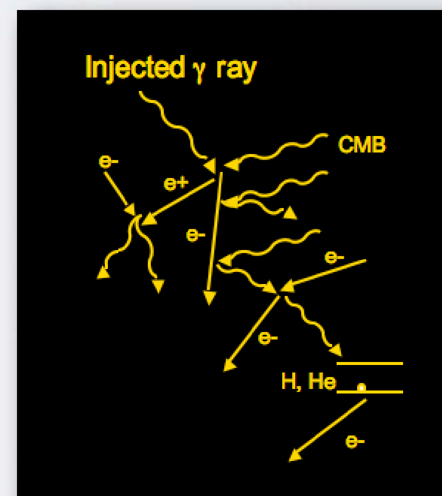
[rest mass energy]

$$p_{\rm ann} = \frac{\langle \sigma v \rangle}{8\pi m_X^2}[4\pi][2m_X]f(z)$$

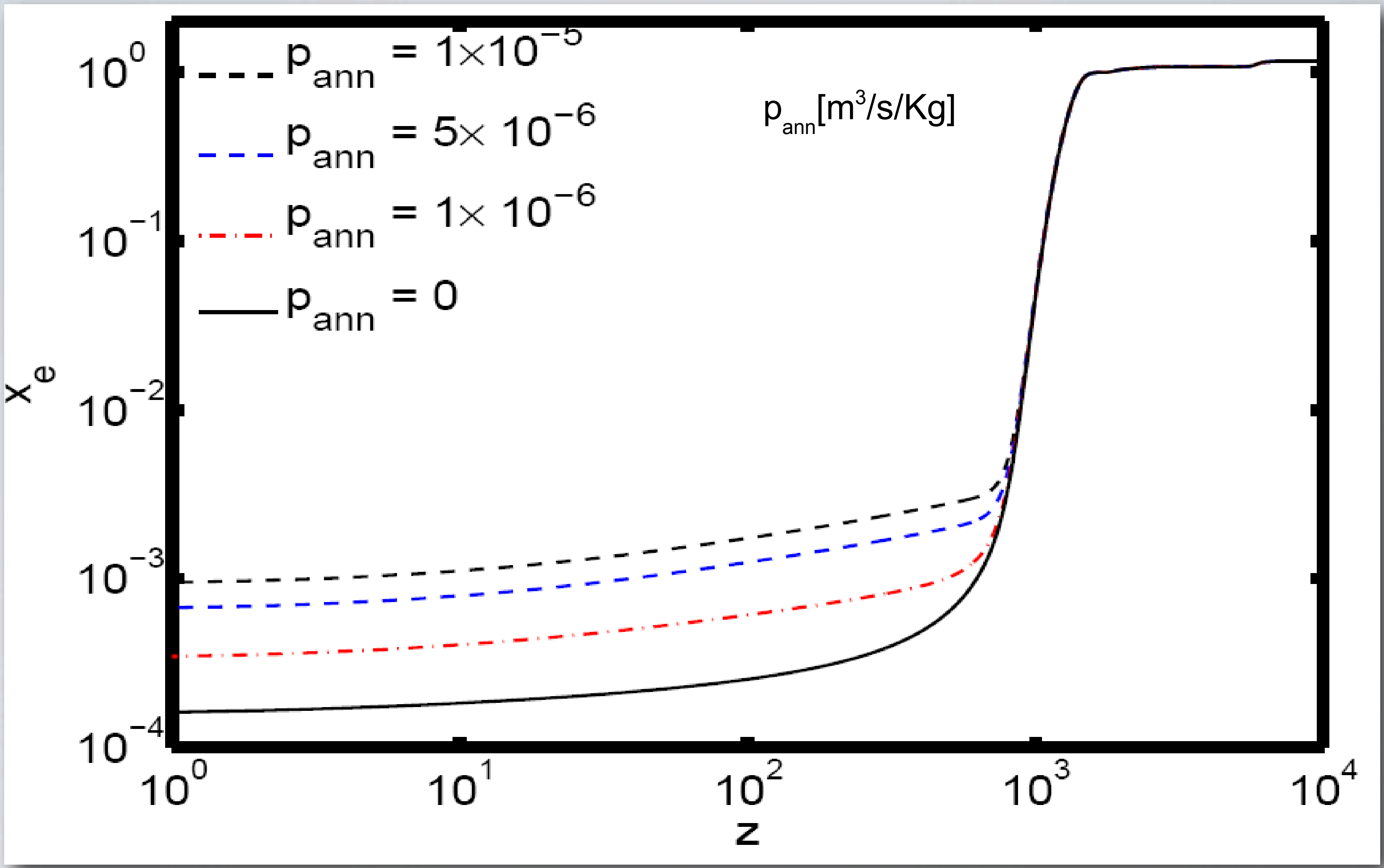


f(z) computation requires following e.m. cascade properties down to (sub-)keV energies

T. Slatyer et al. 2009

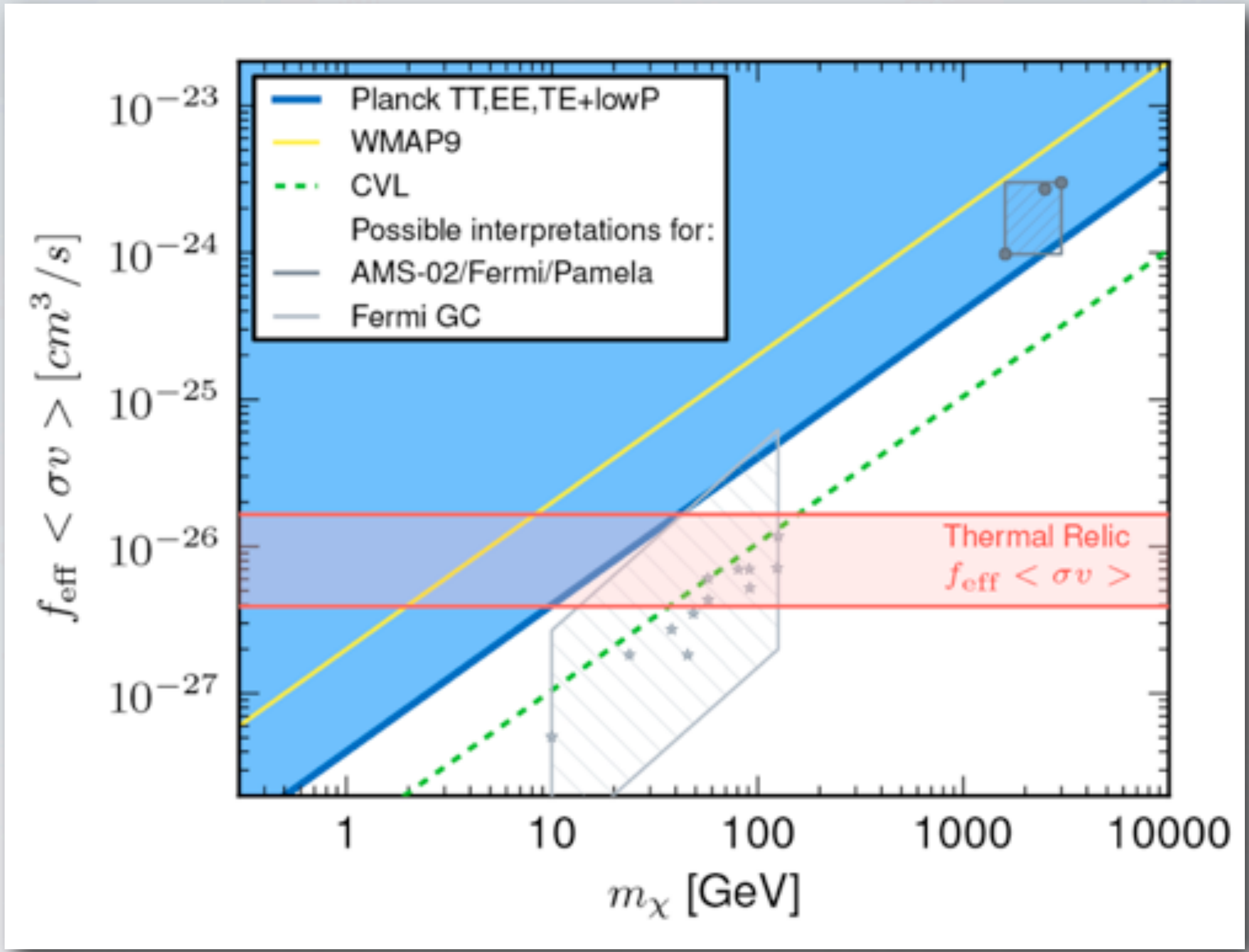


THE PHYSICAL EFFECT



ionization fraction, hence optical depth, mainly affected (notably by f(z~600))
Need to run full CMB machinery to account for parameter degeneracies...

CMB CONSTRAINTS

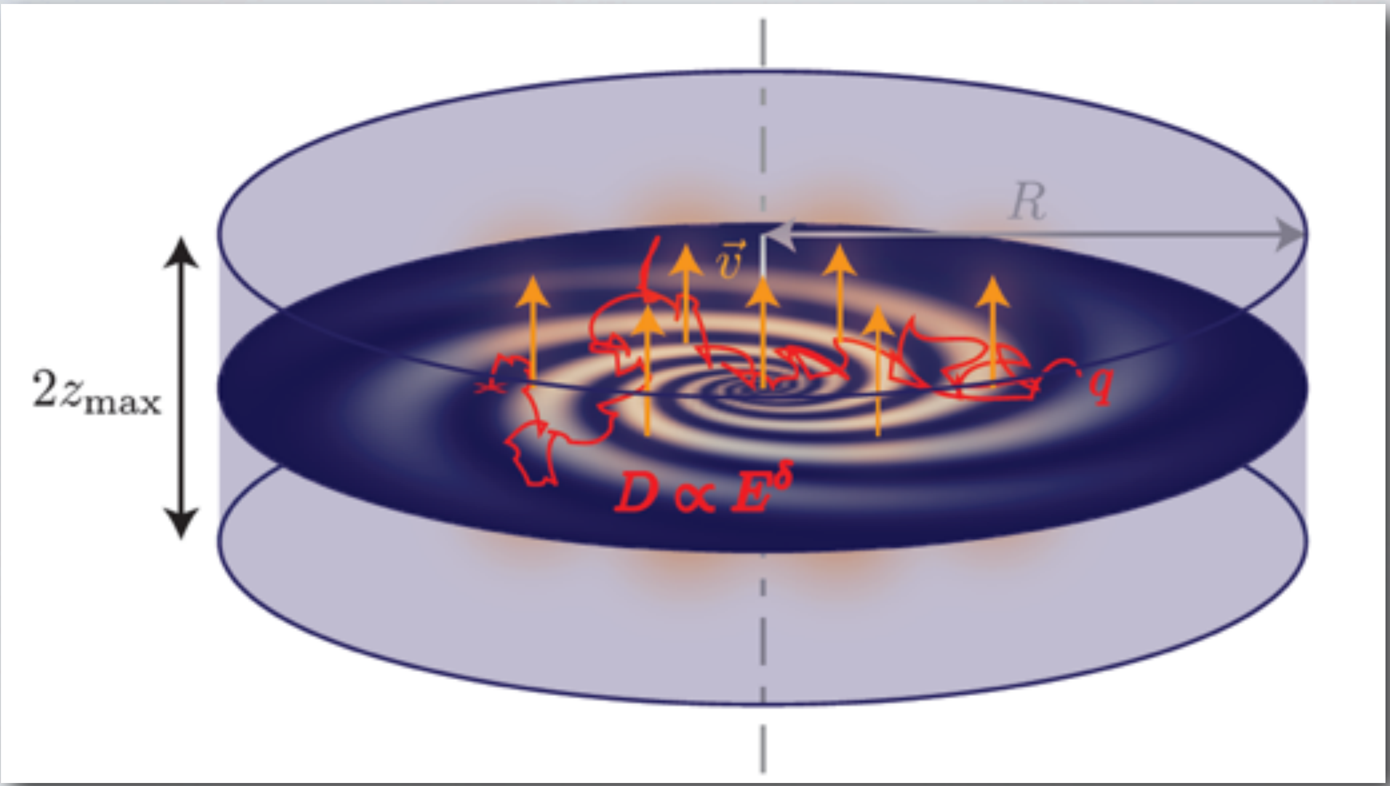


Same ballpark of "low-z", astrophysical constraints
(maybe better for leptonic final states, worse for baryonic ones)

Planck latest release, announced 01/12/2014

CHARGED PARTICLES

Not only DM physics (sigma's, b.r.) and astrophysics (halo distribution) matter, but also plasma astrophysics (diffusion in the Galaxy)
Antimatter is preferred due to lower astro background



Functional of the spectrum and astrophysics!

$$\Phi_a(E_a) = \left[\frac{dN_a}{dE_a}(E_a)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\mathcal{F}_a(E_a,\ldots)$$

Additional complication for e+e-: relevant E-losses, local effects...

DIFFUSION-LOSS EQUATION

Source term (t, **x**, **p** -dep.)
Includes dec./frag. for heavier nuclei

Diffusion

Energy loss

$$\frac{\partial\Phi}{\partial t} = Q + \vec{\nabla}\cdot(D_{sp}\vec{\nabla}\Phi) - \frac{\partial}{\partial p}(\dot{p}\Phi) +$$

Convection velocity

$$+ \frac{\partial}{\partial p}\left[p^2 D_{mom}\frac{\partial(p^{-2}\Phi)}{\partial p}\right] - \vec{\nabla}\cdot(\vec{V}\Phi) + \frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla}\cdot\vec{V})\Phi\right] +$$

$$- \frac{\Phi}{\tau_{frag}} - \frac{\Phi}{\tau_{decay}}$$

Adiabatic flow term

Diffusive reacceleration

Fragmentation and decay terms, of "collisional" nature

In general, eq. rewritten for (differential) CR density

$$\Phi(\mathbf{x},p,t) \equiv p^2\int d\Omega_{\mathbf{p}} f(\mathbf{p}) \sim 4\pi\, p^2 f(p)$$

HOW TO DEAL WITH IT? NUMERICAL CODES

http://galprop.stanford.edu/

http://www.dragonproject.org/Home.html

http://lpsc.in2p3.fr/usine/

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DRAGON Documentation: Index Page

1.0.0

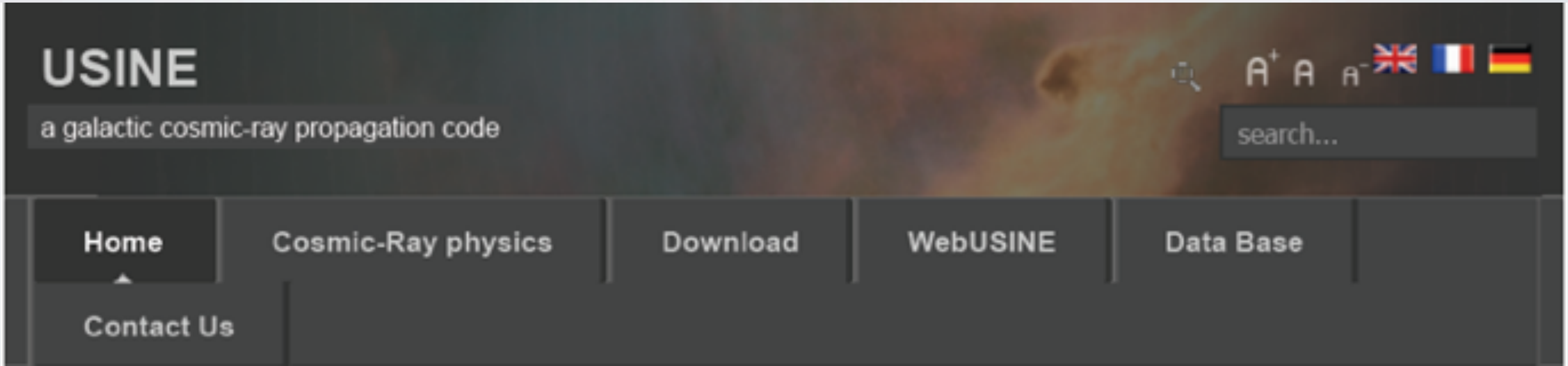
Introduction

The CR propagation equation from a continuos distribution of sources can be written in the general form

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} = Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ji}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Here $N^i(p,r,z)$ is the number density of the i -th atomic species; p is its momentum; β its velocity in units of the speed of light c; σ_{in} is the total inelastic cross section onto the ISM gas, whose density is n_{gas}; σ_{ij} is the production cross-section of a nuclear species j by the fragmentation of the i -th one; D is the spatial diffusion coefficient; v_c is the convection velocity. The last term on the l.h.s. describes diffusive reacceleration of CRs in the turbulent galactic magnetic field.

DRAGON adopts a second-order Cranck-Nicholson scheme with Operator Splitting and time overrelaxation to solve the diffusion equation. This provides fast a solution that is enough



TO GRASP THE PHYSICS, SOME SIMPLIFICATION

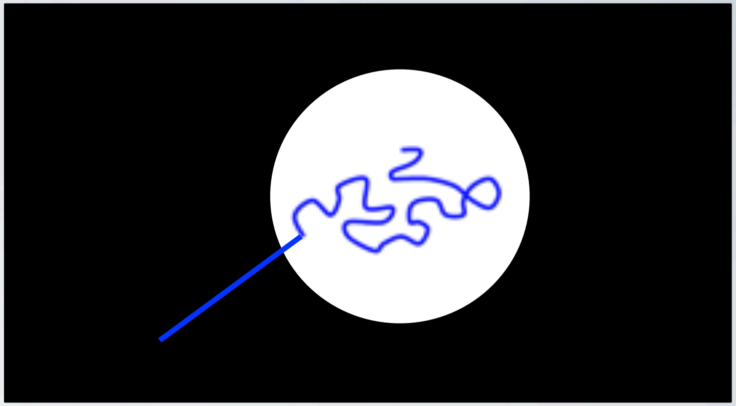
Most of the above mentioned effects relevant especially at low energies.
Diffusion & source effects are probably the dominant ones at high-energies

For most observables, "geometry" can be recast in an effective description
(after all, we observe ~ isotropic flux!)

Although detailed quantitative analyses require numerical treatment, let us see how astrophysical parameters of propagation influence observables, including DM ones

LEAKY BOX APPROXIMATION

For stationary, homogeneous & isotropic problems, the diffusion operator can be effectively replaced by an effective "diffusive confinement" time τ_{diff}

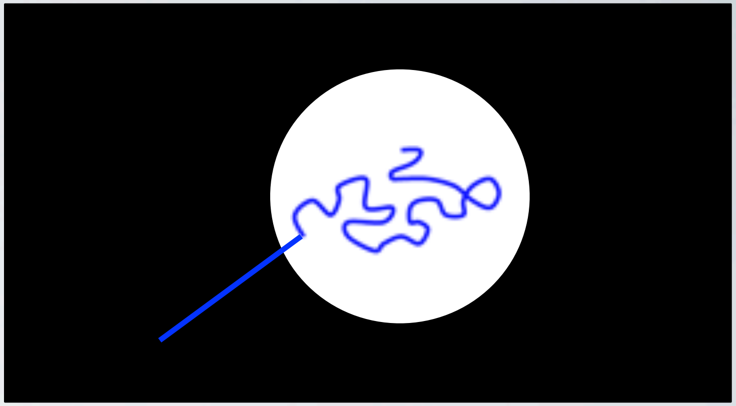


$$\frac{\partial \Phi}{\partial t} - D\nabla^2\Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} - \frac{\Phi}{\tau_{\rm diff}(E)} = Q$$

We shall justify this shortly...

LEAKY BOX APPROXIMATION

For stationary, homogeneous & isotropic problems, the diffusion operator can be effectively replaced by an effective "diffusive confinement" time τ_{diff}



$$\frac{\partial \Phi}{\partial t} - D\nabla^2 \Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} - \frac{\Phi}{\tau_{\rm diff}(E)} = Q$$

We shall justify this shortly...

At steady state

$$\Phi = Q(E)\tau_{\rm diff}(E)$$

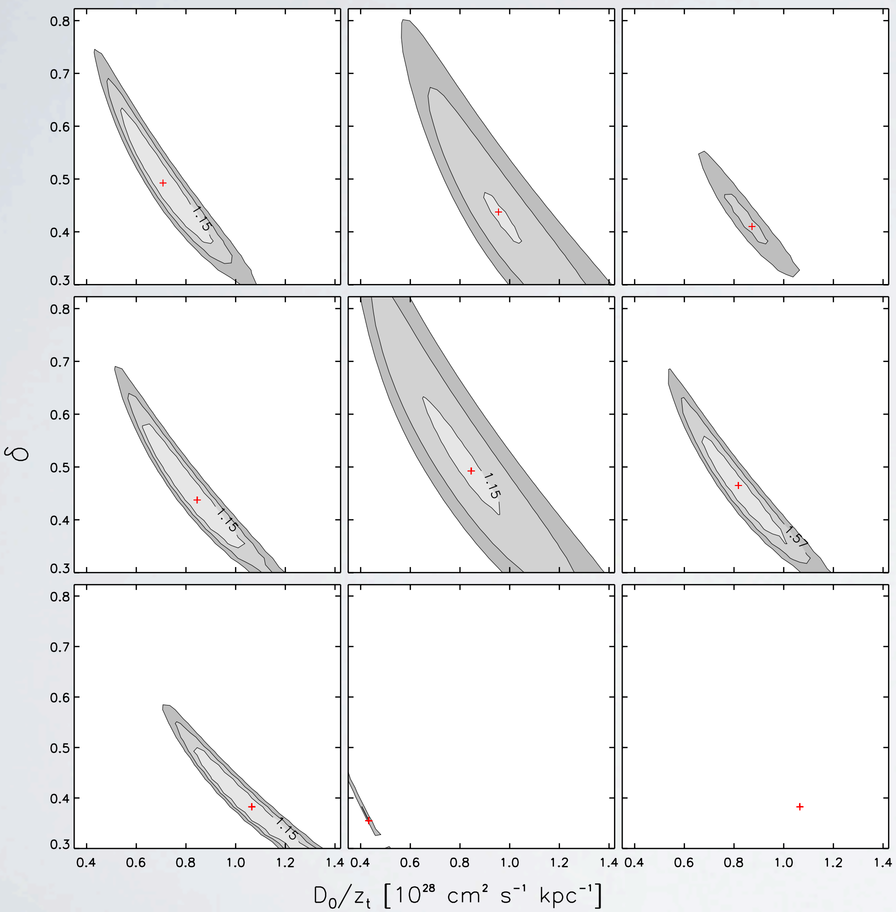
Note that, if diffusion dominates, we can also infer that the source spectra are in general different than those CR observed at the Earth

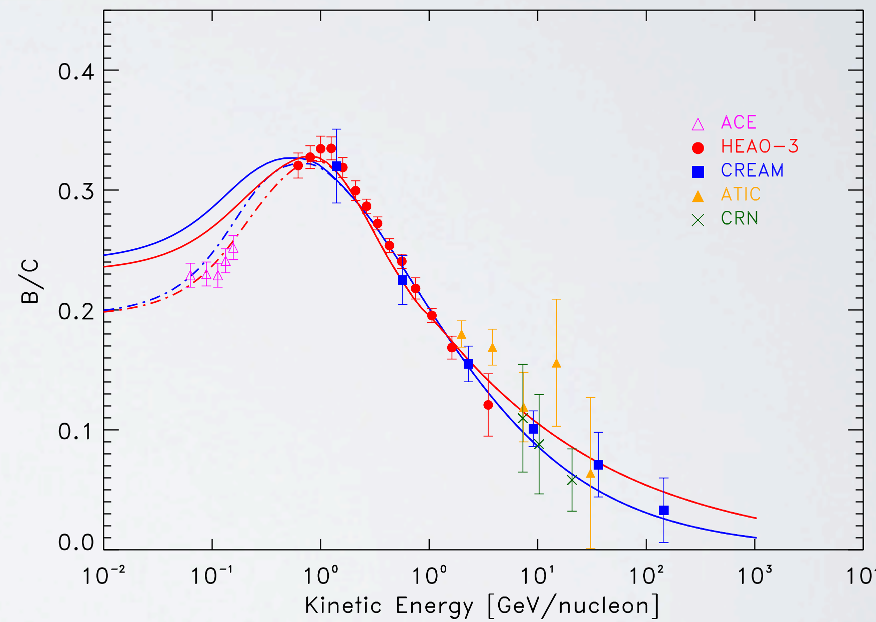
SEC/PRIMARY AS DIAGNOSTICS

If a type of nucleus is not present as primary, but only produced as secondary via collisions (this includes e.g. antiprotons), then

$$\Phi_s = Q_s\,\tau_{\rm diff} \propto \sigma_{p\to s}\Phi_p\tau_{\rm diff}$$

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{\rm diff}(E) \propto D(E)^{-1} \propto E^{\delta}$$





$$D(R) \simeq 10^{28} \div 10^{29} \left(\frac{R}{3\,\mathrm{GV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

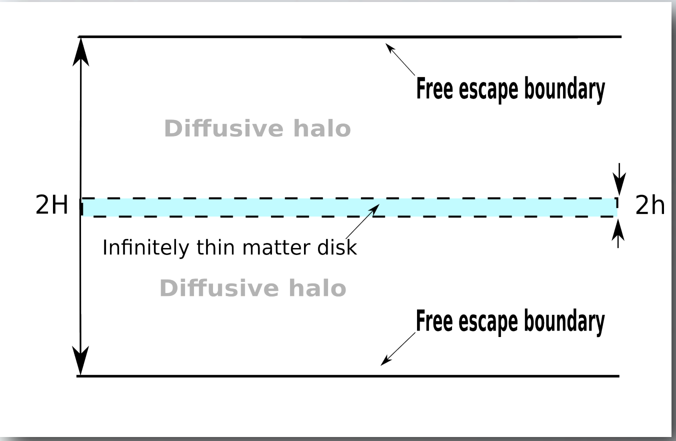
G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso and L. Maccione, Astropart. Phys. 34, 274 (2010)

SIMPLE GALAXY FOR A CR ASTROPHYSICIST

Extended diffusion halo (radial size much larger than its height R»H), with diffusion only (indep. of vertical height) as well as sources and gas (responsible for catastrophic losses) confined to a much thinner"plane" of height **2h**, with density of gas **n** and injection spectrum per unit time **q_0(p)**.
CR freely escape outside H. By symmetry, the only inhomogeneity in solution may be function of z.
The steady state transport equation simplifies into

$$-\frac{\partial}{\partial z}\left(D\frac{\partial f}{\partial z}\right) = q_0(p)\, 2h\delta(z) - \sigma\, v\, n\, 2h\, f\delta(z)\,.$$

$$z \neq 0 \qquad f(z,p) = a(p) + b(p)|z|$$



boundary conditions impose

$$f(z,p) = f_0(p)(1 - |z|/H)$$

$$-2D(p)\left.\frac{\partial f}{\partial z}\right|_0 + \sigma\, v\, n\, 2h\, f_0 = q_0(p)\, 2h$$

Which immediately shows that in the plane, we recover effective leaky box result!

SIMPLE GALAXY FOR A CR ASTROPHYSICICIST, II

$$f_0(p) = q_0(p)\tau_{\rm eff}(p)\,, \quad \text{where} \quad \tau_{\rm eff}^{-1}(p) = \tau_d^{-1}(p) + \tau_\sigma^{-1}(p)$$

diffusion timescale

$$\tau_d(p) = \frac{H\,h}{D(p)} \approx 10^7\,{\rm yr}\,\frac{H}{3\,{\rm kpc}}\,\frac{h}{100\,{\rm pc}}\,\frac{10^{28}\,{\rm cm}^2{\rm s}^{-1}}{D}$$

collisional timescale

$$\tau_\sigma(p) = \frac{1}{\sigma\,v\,n} \approx 10^7\,{\rm yr}\left(\frac{1\,{\rm cm}^{-3}}{n}\right)\left(\frac{100\,{\rm mb}}{\sigma}\right)$$

Let us apply this equation to the case of secondaries, i.e. nuclei only produced by spallation during propagation. The distribution of secondaries in the plane, f_S is sourced by the injected nuclides per unit time, i.e. **$q_0(p) = f_P/\tau_{P\to S}$**, with f_P being the primary population. Hence we obtain the solution for the ratio of primary to secondary distribution, assuming that the effective propagation time is species-independent

$$\frac{f_S(p)}{f_P(p)} \simeq \frac{\tau_{{\rm eff},P}}{\tau_{\sigma_{P\to S}}} \simeq \frac{\sigma_{P\to S}\,v\,n\,H\,h}{D(p)}$$

note the degeneracy D/H!

EXERCISE

Apply same method to the case of a source distributed in the whole diffusive halo (not exact, but proxy for the DM case)

$$-\frac{\partial}{\partial z}\left(D\frac{\partial f}{\partial z}\right) = q_{\rm DM}(p) - \sigma\, v\, n\, 2\, h\, f\delta(z)$$

Prove that

$$f(z,p) = f_0(p)\left(1 - \frac{|z|}{H}\right) + \frac{q(p)}{D}\left(H\,|z| - z^2\right)$$

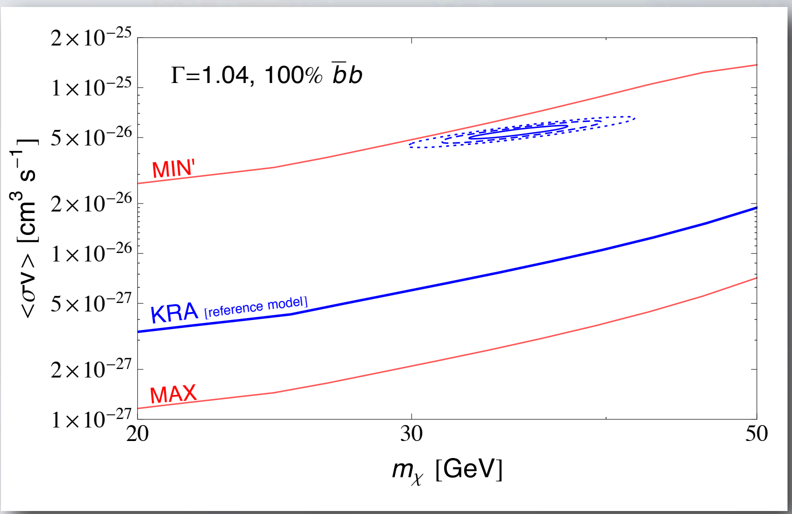
from which follows

$$f_0(p) = q(p)\frac{H}{h}\tau_{\rm eff}(p)$$

i.e., a DM-like source distribution does NOT have the same dependence on astrophysical parameters as conventional sources, much more uncertain!

ANTIPROTON BOUNDS

T. Bringmann, M. Vollmann and C. Weniger, "Updated cosmic-ray and radio constraints on light dark matter: Implications for the GeV gamma-ray excess at the Galactic center," 1406.6027



M. Cirelli, D. Gaggero, G. Giesen, M. Taoso and A. Urbano, "Antiproton constraints on the GeV gamma-ray excess: a comprehensive analysis," 1407.2173

more conservative conclusions

[...] finding that the uncertainties on the propagation model, and in particular on the halo height, play a major role. Moreover, we discuss the role of solar modulation, taking into account possible charge dependent effects [...]. The limits that we obtain *severely constrain the DM interpretation* of the excess in the hadronic channel, for standard assumptions on the Galactic propagation parameters and solar modulation. However, they considerably relax if more conservative choices are adopted

Bear in mind that sometimes "conservative" choices may be TOO conservative, e.g.

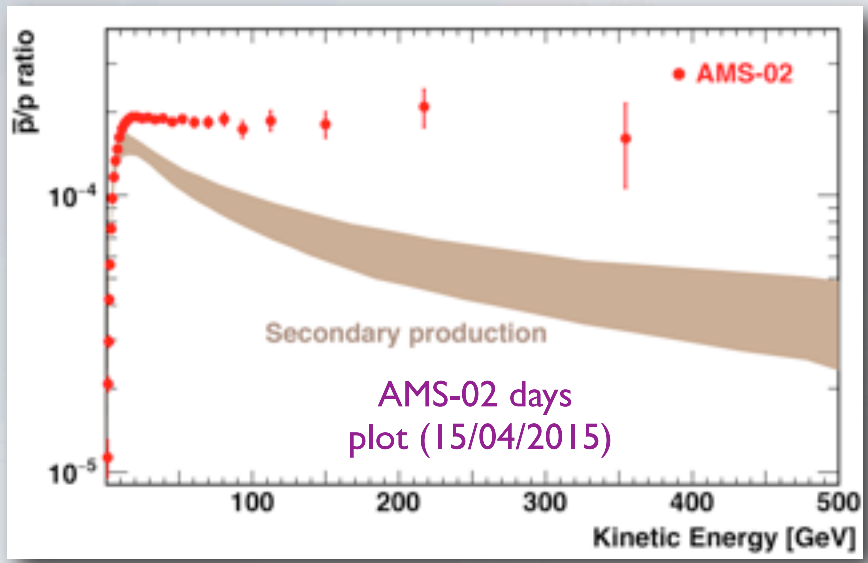
G. Di Bernardo et al. "Cosmic Ray Electrons, Positrons and the Synchrotron emission of the Galaxy: consistent analysis and implications," JCAP 1303, 036 (2013) 1210.4546

J. Lavalle, D. Maurin and A. Putze, "Direct constraints on diffusion models from cosmic-ray positron data: Excluding the MIN model for dark matter searches," 1407.2540

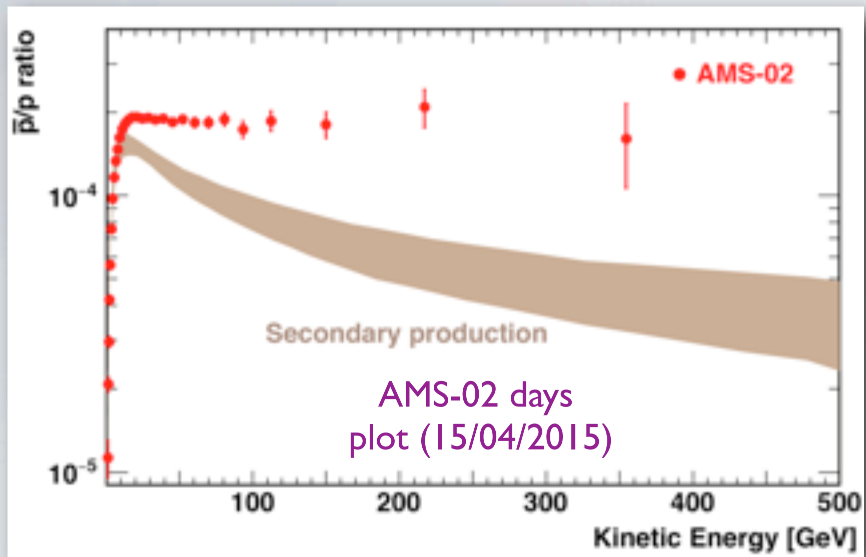
too thin halos are for example excluded...

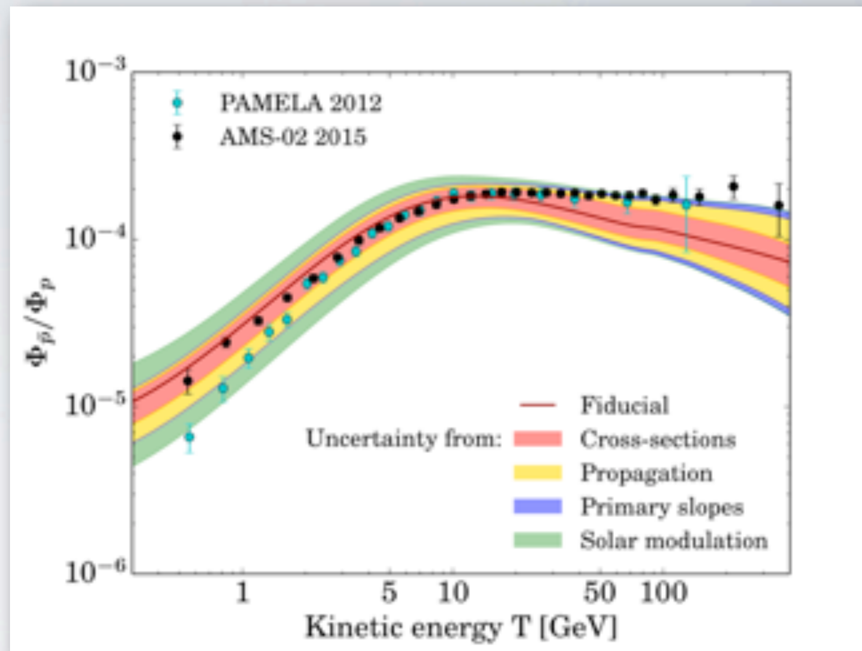
AMS-02 data (not necessarily antip!) should certainly help

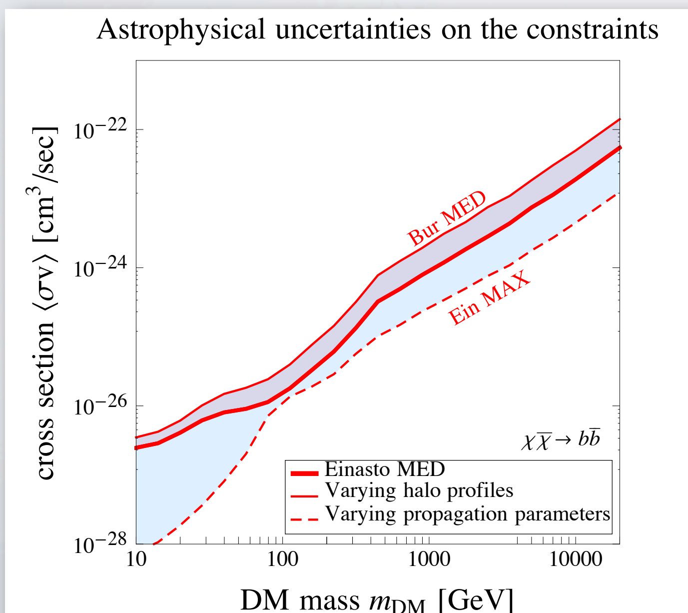
(NEW) ANTIPROTON BOUNDS



(NEW) ANTIPROTON BOUNDS







More realistic account of uncertainties
(and potential impact on DM bounds)

G. Giesen et al. "AMS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for Dark Matter," arXiv:1504.04276

Let's wait for proper analyses of the whole set of AMS data (including, notably, secondary nuclei)

CHARGED LEPTONS? NOT 1ST CHOICE...

Reason 1: E-losses imply that inhomogeneities and local stuff matter!

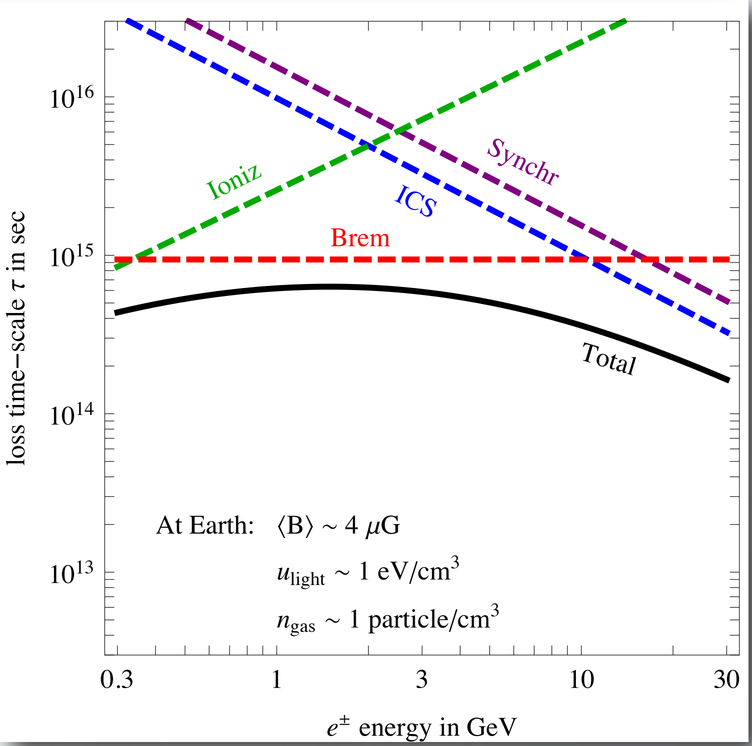
Both SR & IC E-loss rates have ~ quadratic dependence $\epsilon_\gamma E \ll m^2$

$$\left(\frac{dE}{dt}\right)_{\rm syn} = -\frac{4}{3}\sigma_T\left(\frac{E}{m}\right)^2 u_B \qquad \left(\frac{dE}{dt}\right)_{\rm IC} \approx -\frac{4}{3}\sigma_T\left(\frac{E}{m}\right)^2 u_\gamma$$

Diffusive and E-loss timescales comparable at ~GeV, the latter dominates at higher and higher energies, since for both synchr. and Inverse Compton losses have stronger E-dependence

$$\tau_{loss} = E \Big/ \frac{dE_{e^\pm}}{dt} \sim 1/E$$

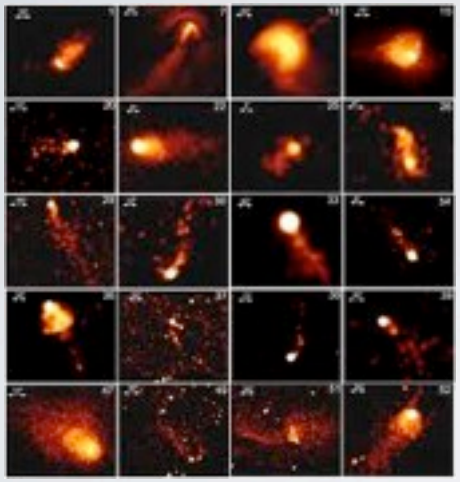
"Continuum" source approx. breaks down, need to account for discrete nature of sources... which can only be done "statistically", since some time-dependent ones (bursts) might be long gone (e.g. invisible in photons, which do not suffer diffusive propagation delays...)



CHARGED LEPTONS? NOT 1ST CHOICE...

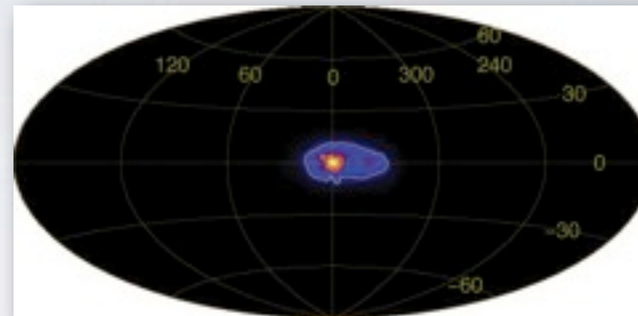
Reason 2: <u>Many</u> astrophysical sources sources of leptons are known...

This includes almost certain sources of positrons, such as pulsars/pulsar wind nebulae (relativistic accelerators, seen in photons from radio to TeV bands, right spectrum and energetics...), X-ray binaries (whose distribution seems to correlate with 511 keV radiation from e+e- annihilation...)

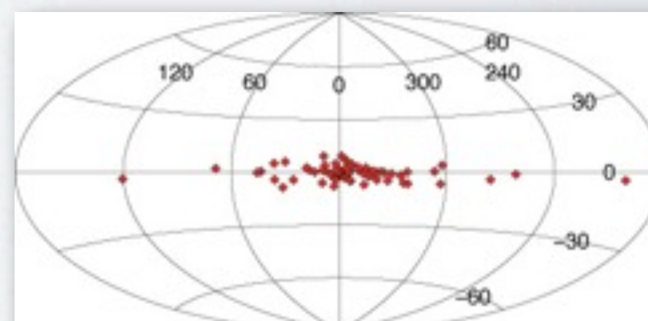


<u>There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.</u>

<u>Shakepeare's Hamlet, scene V.</u>



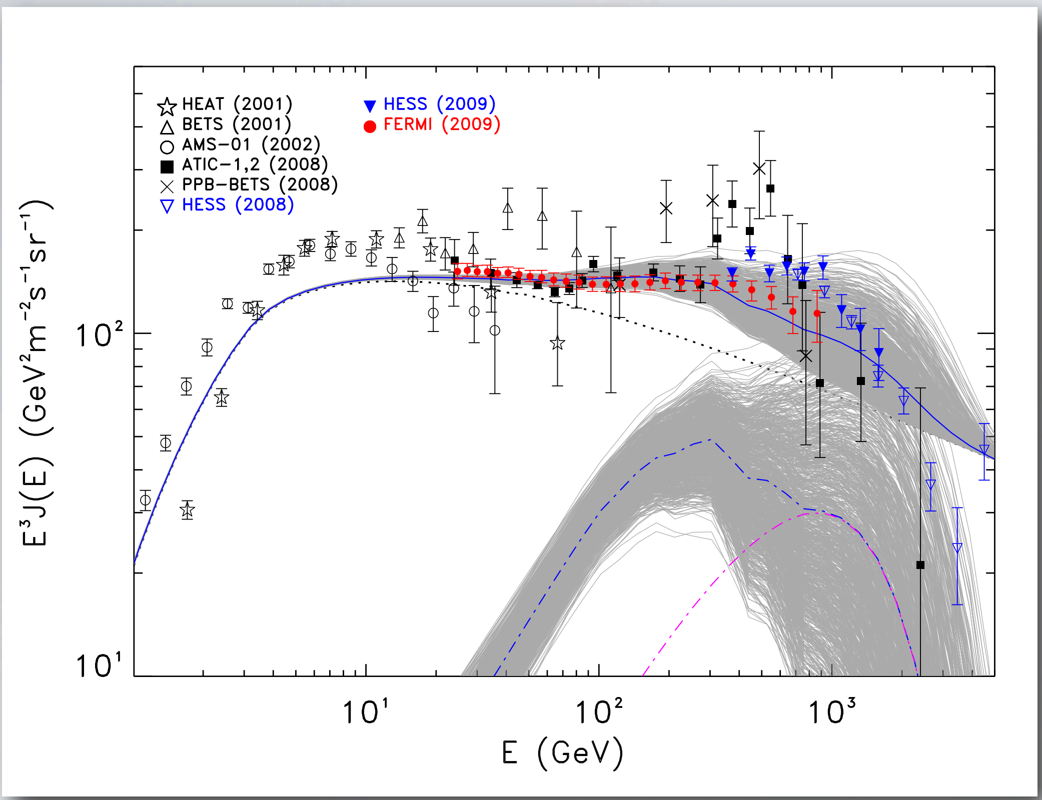
511 keV radiation



Not surprisingly, many of these possibilities have been shown to be capable to explain the CR lepton data (although IMO often need to stretch or fine-tune them parameters a bit but for PWN...)
For a review

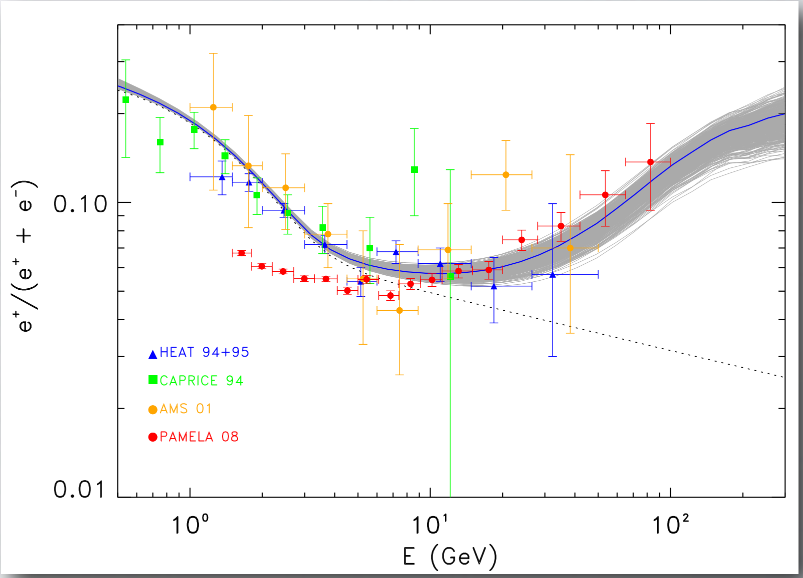
PS "Astrophysical models for the origin of the positron 'excess'," Astropart. Phys. 39-40, 2 (2012) [arXiv:1108.4827 [astro-ph.HE]].

EXAMPLE



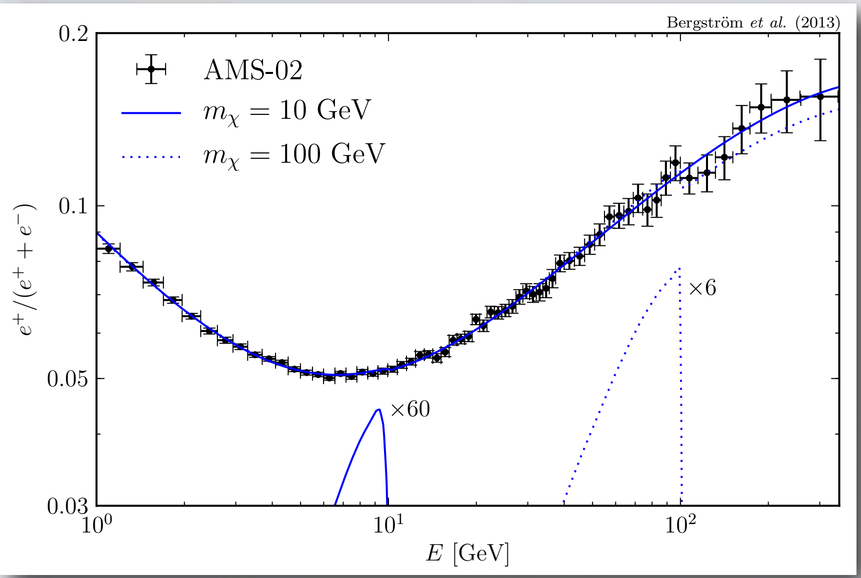
D. Grasso et al.,
Astropart. Phys. 32, 140 (2009)
[arXiv:0905.0636]

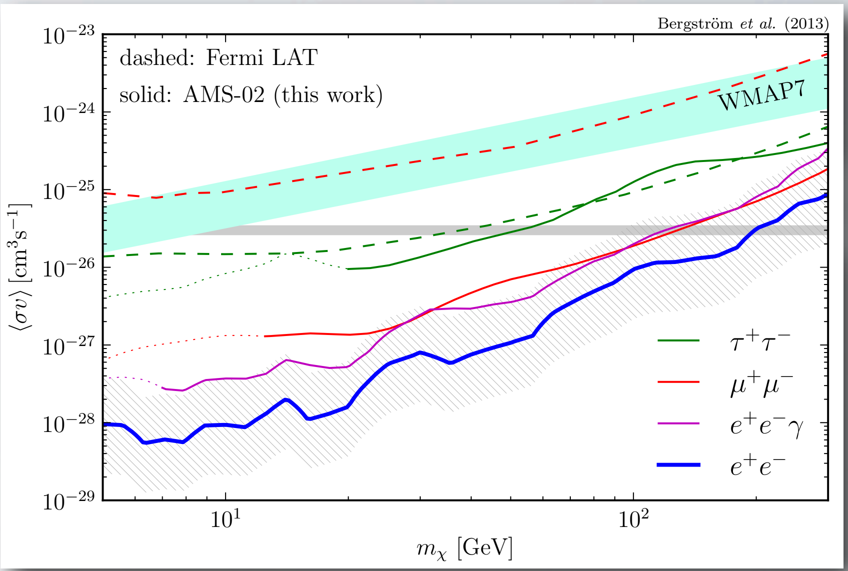
clearly... astrophysics can fit quite well the data.



STILL SOME BOUNDS FOLLOW...

notably from absence of "sharp drops" in the data, which can be expected especially for dominance of light lepton final states
(but the day one sees one or several drops, interpretation as DM will be ambiguous!)





L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger,
"New limits on dark matter annihilation from AMS cosmic ray positron data,"
Phys. Rev. Lett. 111, 171101 (2013) [arXiv:1306.3983]

STATUS AND PERSPECTIVES

Can indirect methods "detect" dark matter?

✤ In principle, yes. In practice, we are discovering that the discovery potential in more and more channels is limited by the knowledge of "astrophysical backgrounds"

✤ Apart for improving our knowledge of astrophysics, the main hope relies on *correlated* signals in many channels, each one hard to explain without DM.

✤ Also, it would be important to move beyond "blind" searches. Perhaps most credible discovery is an indirect "excess" predicted/suggested by collider or direct detection hints.

Anyway, it's a crucial tool!

If a signal is found in other channels (collider/DD) We still *need* ID:

- To confirm that whatever we find in the Lab is the same "dark stuff" responsible for astrophysical and cosmological observations (it's impossible to discover DM at LHC alone...)
- To access particle information not otherwise available in the Lab (annihilation cross section or decay time, b.r.'s)
- to infer cosmological properties of DM (e.g. power spectrum of DM at very small scales) not accessible otherwise.

SUMMARY OF WHAT WE LEARNED

- We got a long way from the situation in the 80's mentioned by D. Weinberg, when many options for DM were on the market (massive neutrinos, missing baryons/MACHOs...)

- Indirect probes (astrophysics & cosmology) tell us a lot: BSM physics is needed for explaining DM!

- In several models for the nature/production of DM, a number of associated signals (direct, indirect, at colliders) is expected. This is notably the case for WIMP models, appealing since associated to new physics at the weak scale

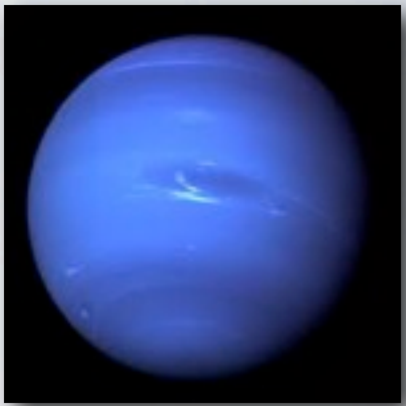
- The good news is that, at least for WIMPs, we have many strategies to detect those signals, and the efforts are paying off: for instance, gamma-searches, antiproton searches, even CMB are all becoming constraining for thermal relics up to ~100 GeV

- The bad news is that the "parameter space" of the theoretically unknown is pretty big, so there is no guarantee that we'll find any positive result soon.

This is a high risk/high reward topic of research:
we have some chance of a game-changing discovery
but absolutely no guarantee of it
(although likely to learn lots of-sometimes interesting-astrophysics along the way)

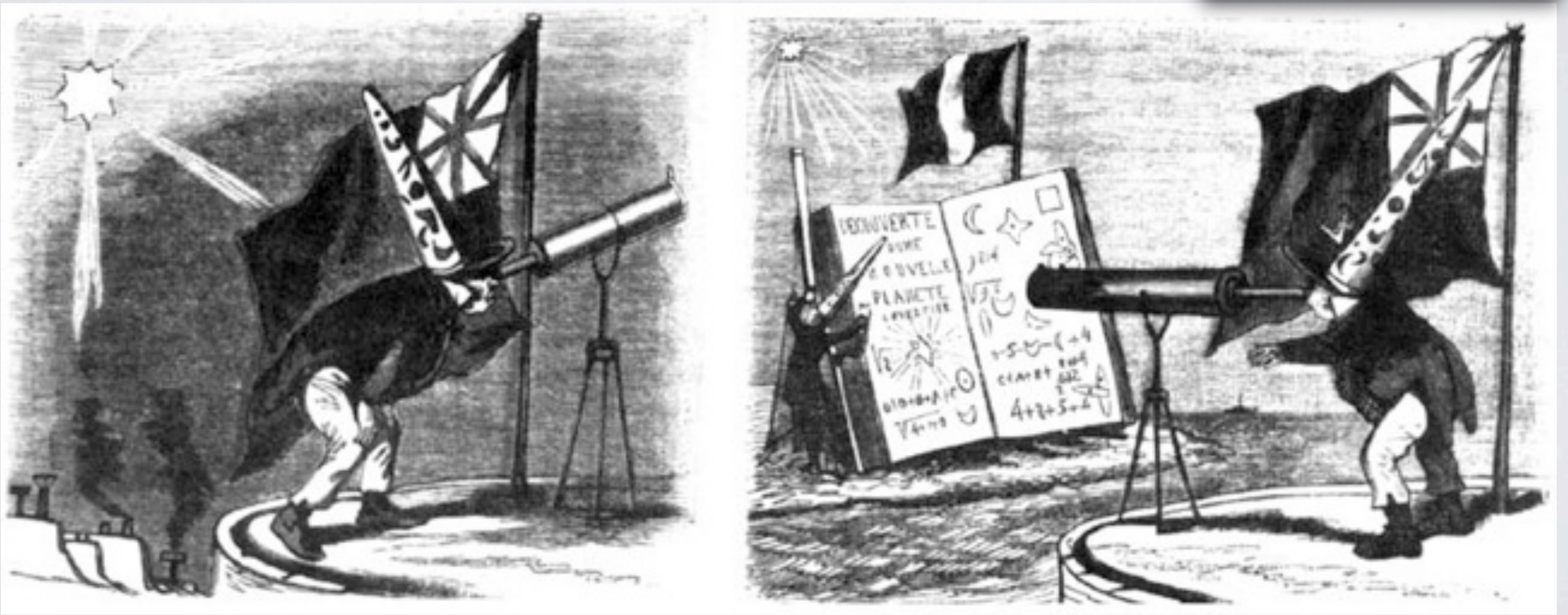
IF YOU'RE PESSIMIST, REMEMBER

An additional "species" inferred from gravitational effects has been already identified (*electromagnetically detected*) once!



Adams (1844-45) and independently Le Verrier (1845-46) interpreted irregularities in Uranus's orbit as due to perturbation by a yet unknown planet, calculating its orbital elements "by inversion"

On September 24, 1846 Galle found that "the planet whose place you [Le Verrier] have [computed] *really exists*"

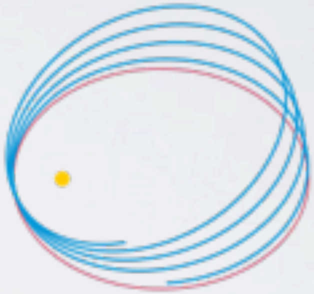


A cartoon published in France at the time of the controversy over the discovery of Neptune Adams is shown looking for it in vain and then finding it in the pages of Leverrier's book.

BUT... SOMETIMES SURPRISES SHOW UP!

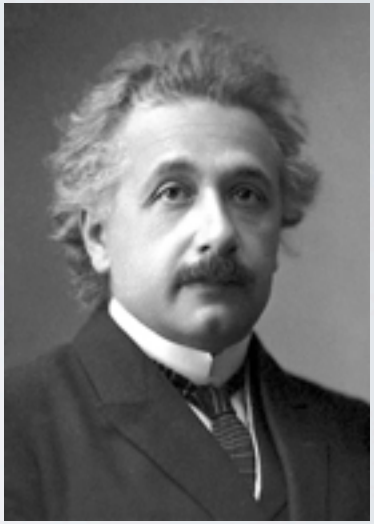
In 1859, Le Verrier analyzed the effect of gravitational perturbations of other planets on the perihelion shift of Mercury, finding a residual "anomalous" shift of 38 arcsec/century.

He re-used his "old" trick, hypothesizing that this was the result of another planet, which he named *Vulcan* whose orbital elements he inferred.



This planet was claimed to be found *several times*...

... but its existence was eventually disproved and Mercury's anomaly (re-evaluated in 43 arcsec/century) was finally explained thanks to GR effects (first major postdiction that convinced A. Einstein that GR was right)



hence, "Dark Matter" (just like "Modified Gravity") has already been discovered... but only after several trials & errors, hard work, and fake claims: Be patient, and be ready for the unexpected, too!