Indirect Dark Matter Searches

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Outline

*** Introduction**
Basic concepts + Some important cosmological and particle physics aspects

*** Gamma-rays**
Galactic scale: Galactic center (GC), Dwarf Spheroidal Galaxies (Dsphs), diffuse emission
Extragalactic: other galaxies, galaxy clusters, diffuse extragalactic

*** Antimatter cosmic rays:**
Antiprotons
Positrons
Antideuterons

*** Radio**
Diffuse emission
CMB

*** Neutrinos**
Galactic neutrinos
Solar neutrinos

*** Complementarity with other searches**

*** Conclusions & Perspectives**

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Biblio:

Dark matter models and detection:
* Griest, Jungmann & Kamionkowski, Phys. Rept. (1996)
* Bergström, Rept. Prog. Phys. (2000) – hep-ph/0002126

Indirect detection:
* Lavalle & Salati, arXiv:1205.1004
* Cirelli, Strumia et al, arXiv:1012.4515
* Bringmann & Weniger, arXiv:1208.5481

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- **Gamma-rays**
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  - (Extragalactic: other galaxies, galaxy clusters, diffuse extragalactic)

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  - Antiprotons
  - Positrons
  - Antideuterons

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  - Diffuse emission
  - CMB

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  - Galactic neutrinos
  - Solar neutrinos

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**NB: This lecture => Focus on WIMPs
(Weakly Interacting Massive Particles)
=> weak couplings to matter fields
=> can be produced in pairs in the early Universe if temperature > mass
=> indirect detection if self-annihilation/decay allowed
(very large fraction of WIMP models: SUSY, Xdim, sterile neutrinos, etc.)**

Dark Matter candidates

Different mass/energy scale depending on
inherent theoretical motivations

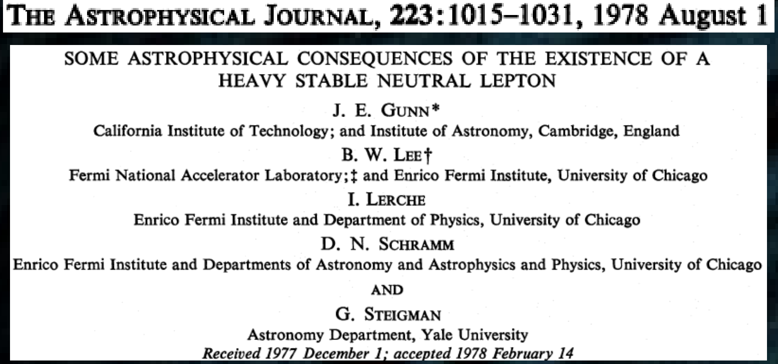
What does particle physics tell us about DM ?

Motivations	**Strong CP problem in QCD [sub-eV]**	**Neutrino masses [keV]**	**Origin, stability and naturalness of the Higgs sector (EWSB) [GeV-TeV]**	**Dark matter [GeV-TeV]**
Framework & Candidate(s)	**Peccei-Quinn ++ axion ++ or axion-like (ALPs) (string-inspired)**	**RH-neutrinos + seesaw ++ sterile neutrino ++ ++ Asymmetric DM ++**	**SUSY, Xdim, IDM ++ LWP ++ (lightest whatever particle)**	**++ Neutral scalar, Fermion, or vector ++**
Additional benefits		**Leptogenesis**	**e.g.: EWSB, GUT, inflation**	**GUT**

Hints for new physics?
* asymmetry matter/antimatter
* neutrino masses
* if new scale < Planck, then hierarchy problem in the Higgs sector.
* (dark matter and dark energy)

What do particle experiments tell?
* gmu-2 (but theoretically contrived)
* vanilla SUSY in tension, other well motivated still racing (eg NMSSM)
* LHC found the first elementary (?) scalar … 50 yrs after prediction … let's be a little bit more patient ...

Indirect dark matter detection in the Milky Way



THE ASTROPHYSICAL JOURNAL, 223:1015–1031, 1978 August 1

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

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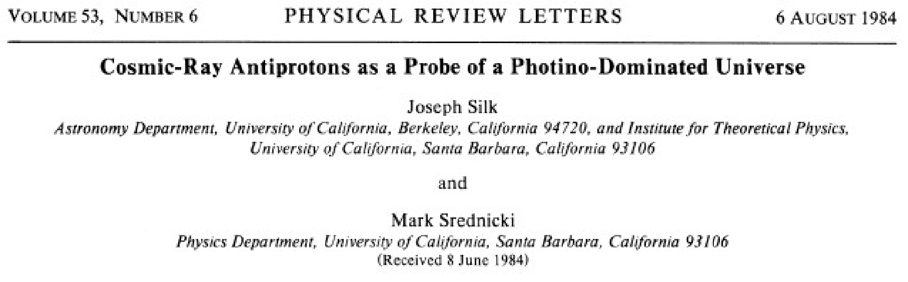

VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

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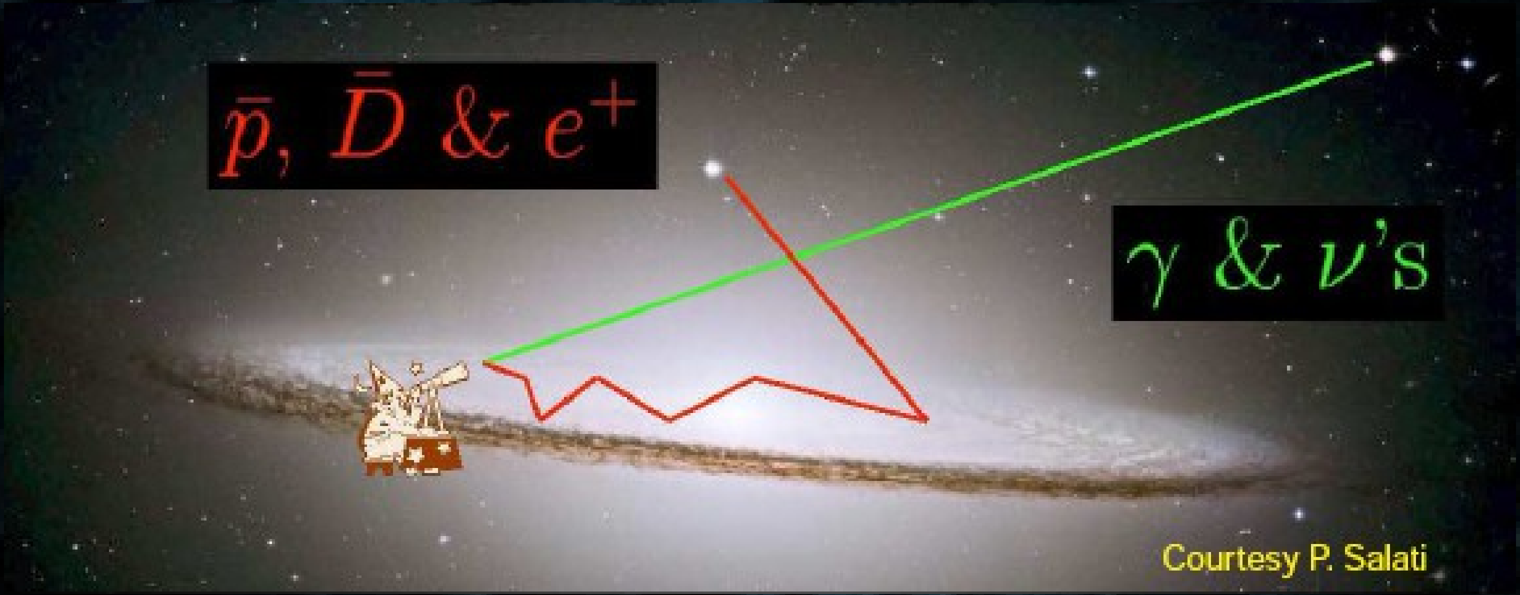

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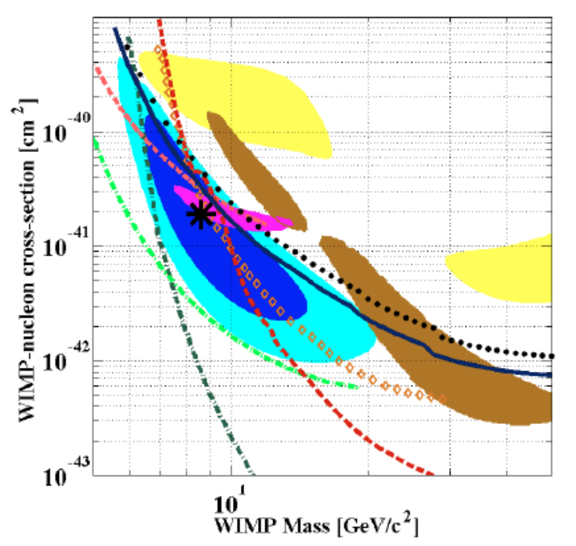
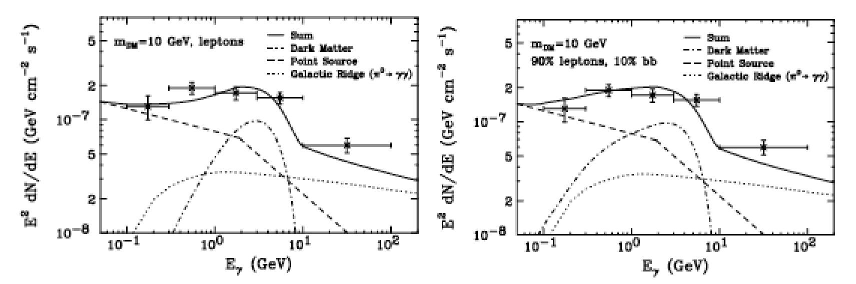
- γ-rays : lines, spatial + spectral distribution of signals vs bg
- Antimatter cosmic rays: secondary origin of astro contrib, therefore low bckgd (in principle)
- Neutrinos: Sun most promising target

But:
- Do we control backgrounds?
- Specific spectral differences in signals vs backgrounds?
- Careful estimates of theoretical errors for signals and backgrounds very important (difficult exercise in practice)

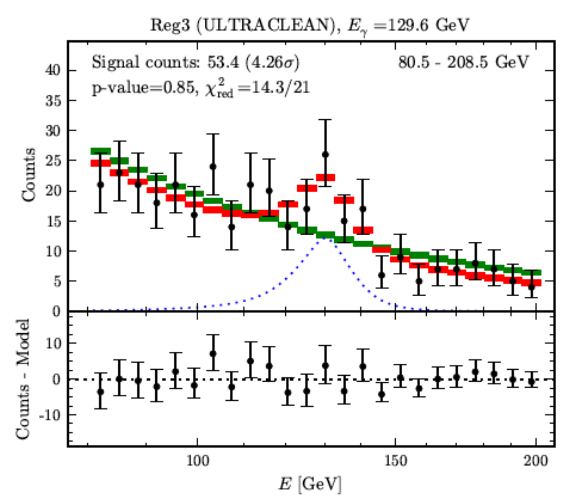
Dark matter has long been discovered !



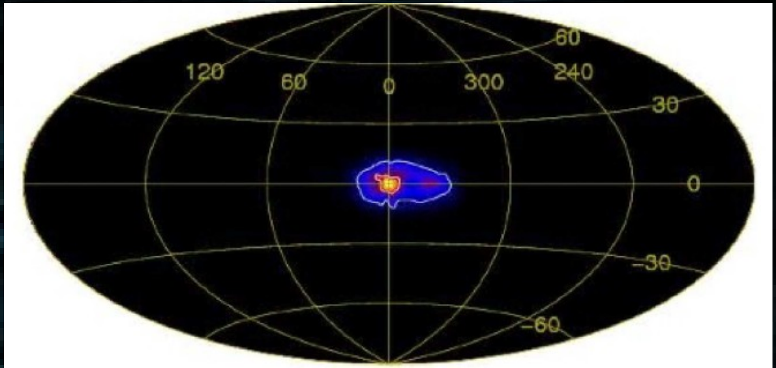
Agnese++ 13
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
→ DM around 10 GeV



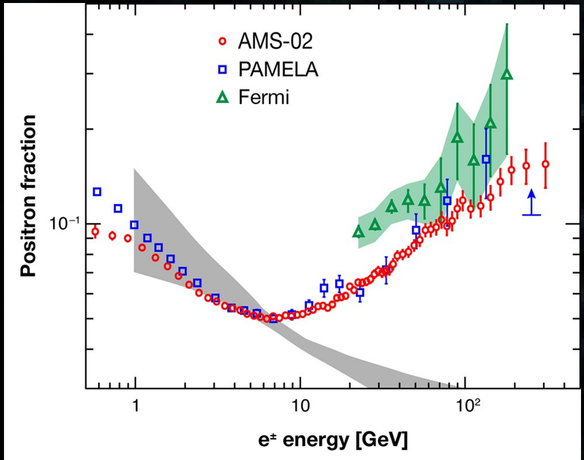
Hooper++ 12: gamma-rays + radio at GC
→ DM around 10 GeV



Around the GC
Weniger++, Su++ 12
→ DM around 130 GeV



511 keV, Knödlséder/Weidenspointner++ 05 - 08
Boehm, Hooper++ 04 → DM around 1 MeV



HEAT/PAMELA/AMS positron excess
Bergström++, Cirelli++ 08 → DM around 300-1000 GeV

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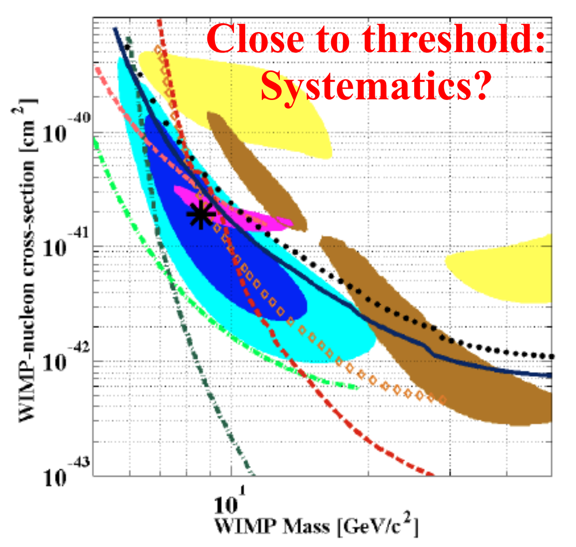

Close to threshold: Systematics?

Agnese++ 13
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
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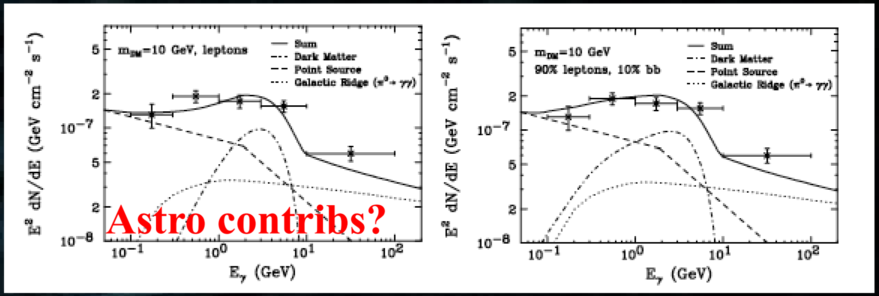

Astro contribs?

Hooper++ 12: gamma-rays + radio at GC
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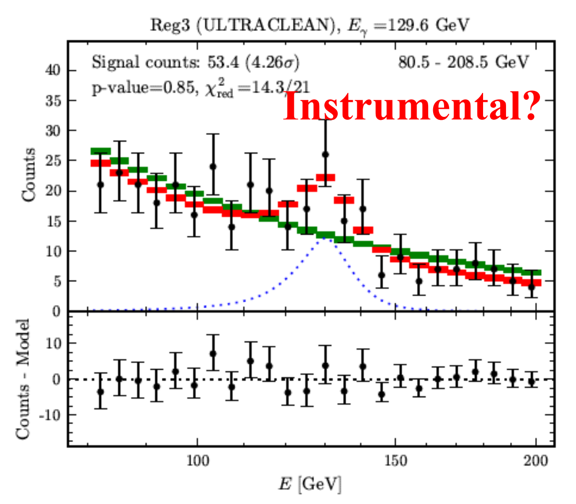
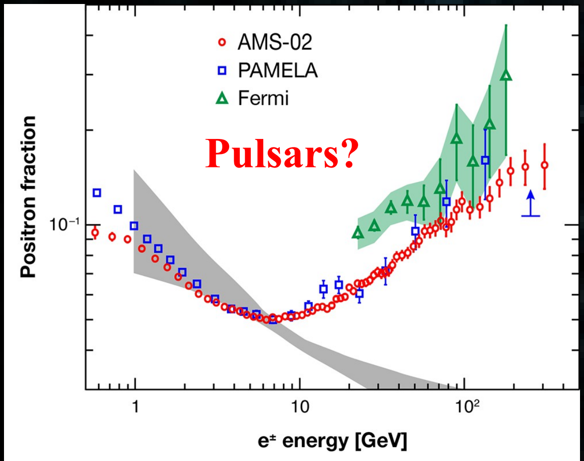


Instrumental?

Around the GC
Weniger++, Su++ 12
→ DM around 130 GeV

All point toward different mass scales :
1 MeV / 10 GeV / 130 GeV / 500 GeV

Hard to explain with a single DM candidate
(except maybe for XDM,
Weiner++ 04-12, Cline++, etc.)



Pulsars?

HEAT/PAMELA/AMS positron excess
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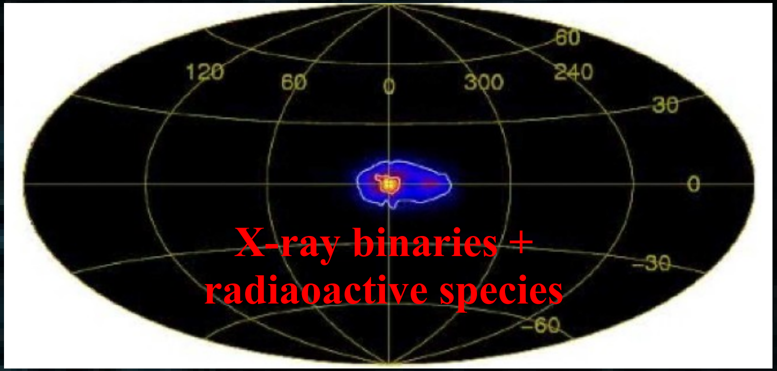
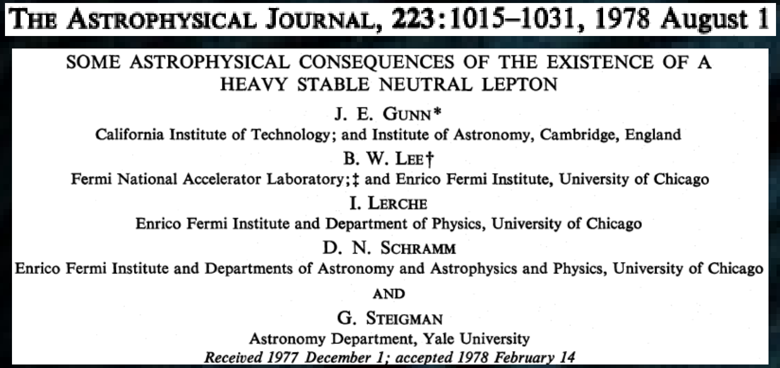


X-ray binaries + radiaoactive species

511 keV, Knödlsëder/Weidenspointner + 05 - 08
Boehm, Hooper++ 04 → DM around 1 MeV

Indirect dark matter detection in the Milky Way



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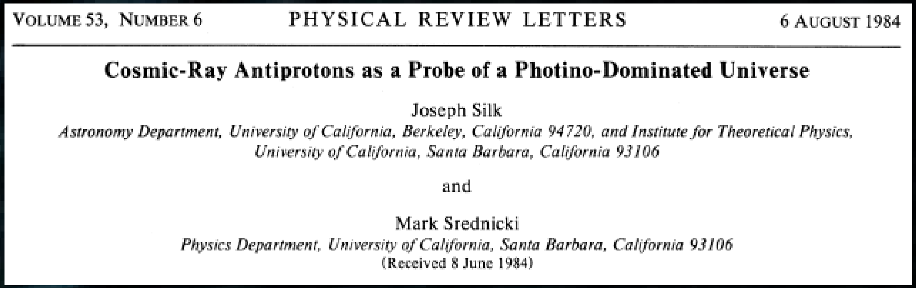

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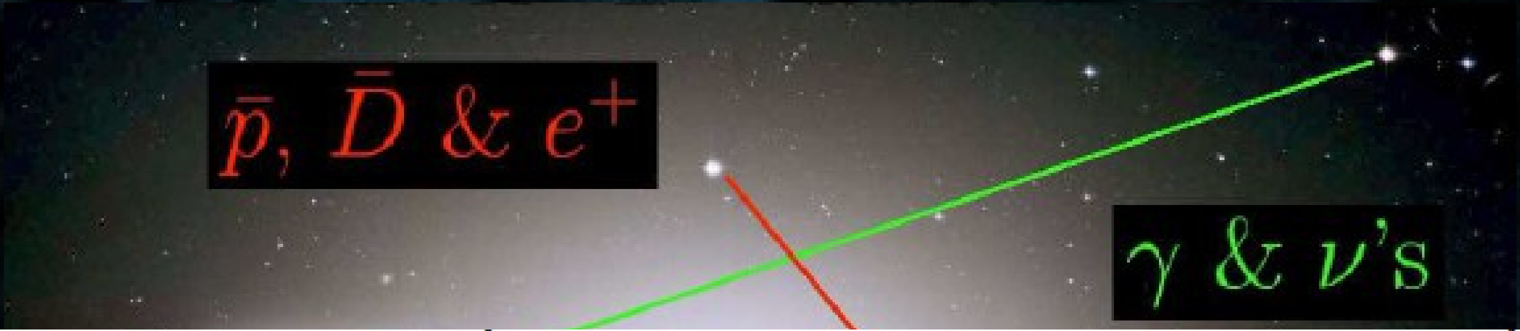

$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \underbrace{\frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2}_{S}\int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\, \mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

Particle physics input
Astrophysics (gravitational)
Cosmic-ray transport (trivial for gamma-rays)

Courtesy P. Salati

Main arguments:
- Annihilation final states lead to: gamma-rays + antimatter
- γ-rays : lines, spatial + spectral distribution of signals vs bg
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But:
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Early universe considerations (1)

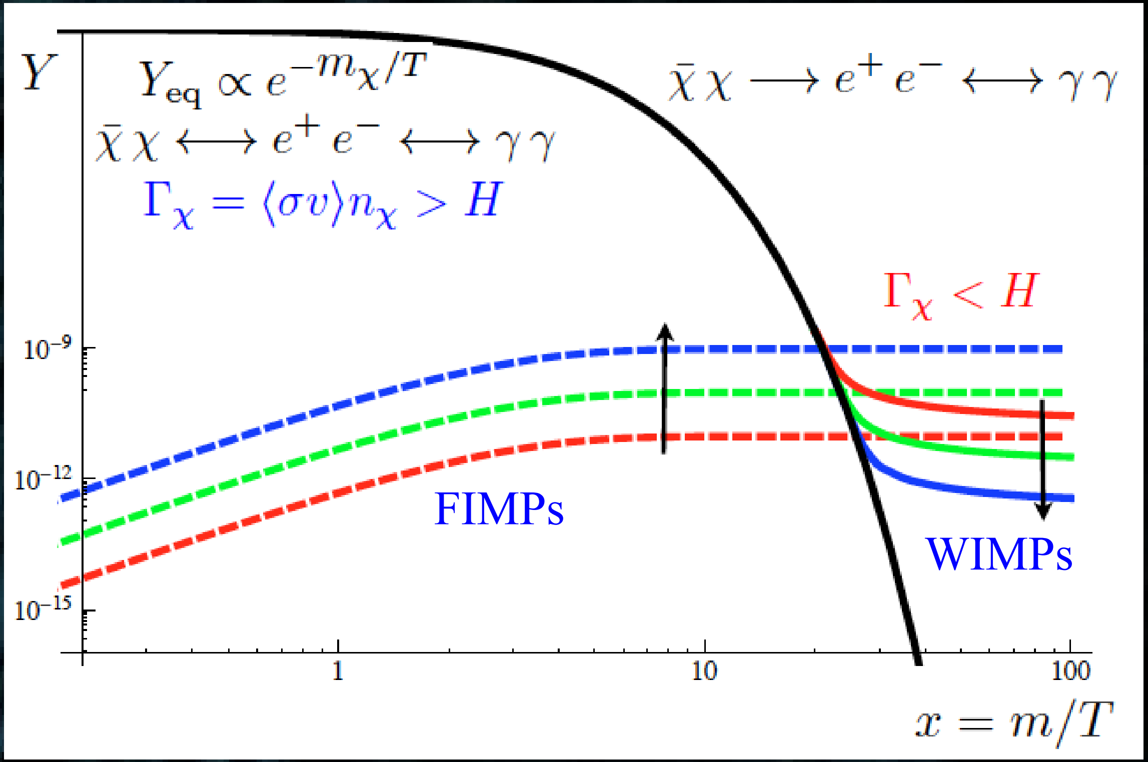
Production:

- Coupling to matter fields => thermal production in pairs if T > m$_{\text{wimp}}$ (NB: implicit assumption about reheating).
- Weak couplings => thermal/chemical equilibrium quickly reached (WIMPs) <=> production/annihilation rates >> expansion rate.
- Feeble (weaker) couplings => equilibrium never reached <=> slow production (large density of plasma), annihilation inefficient (low density of DM particles).

Decoupling:

- Occurs when expansion rate >> annihilation rate (equilibrium before, e.g. WIMPs), or when T < m (e.g. FIMPs).

→ see e.g. Gondolo & Gelimini 91, Gondolo & Edsjo 97



Hall++ (10)

In practice:

- Solve the Boltzmann equation

$$\frac{dn_\chi}{dt} = -3\,H\,n - \langle\sigma v\rangle\,\{n_\chi^2 - n_{\rm eq}^2\}$$

$$Y_\chi \equiv \frac{n_\chi}{s}$$

$$\frac{dY_\chi}{dt} = -s(T)\,\langle\sigma v\rangle\,\{Y_\chi^2 - Y_{\rm eq}^2\}$$

$$x \equiv m_\chi/T \propto m_\chi/v^2$$

$$\frac{dY_\chi}{dx} \propto -\frac{g_\star^{1/2}(x)}{x^2}\,\langle\sigma v\rangle\,\{Y_\chi^2 - Y_{\rm eq}^2\}$$

General conclusions for WIMPs:

- Cosmological abundance fixes annihilation cross section.
- Canonical value for ~100 GeV WIMPs

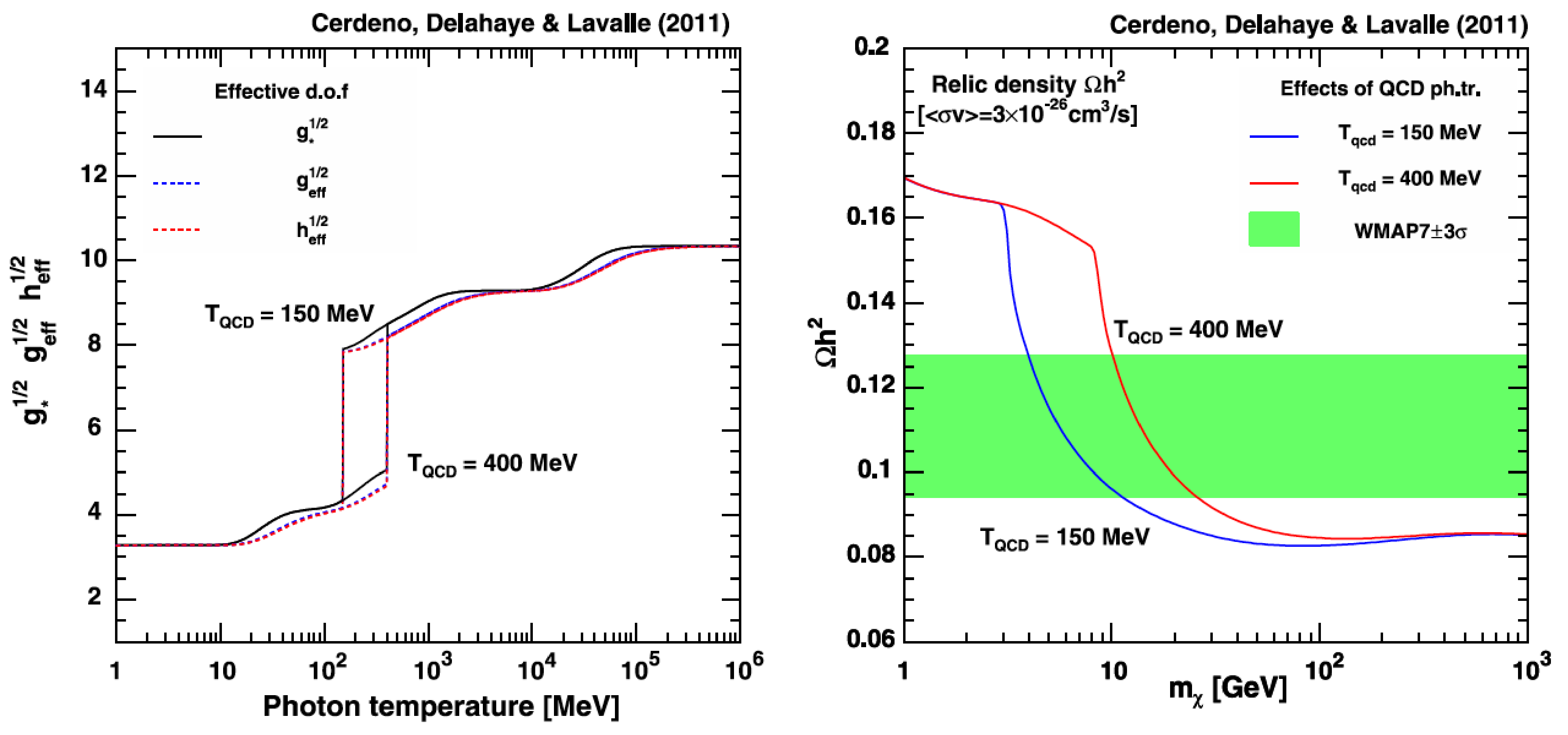
$$x_{\rm dec} \approx 20$$

$$\Omega_\chi \propto 1/\langle\sigma v\rangle$$

$$\langle\sigma v\rangle \approx 3\times 10^{-26}\,{\rm cm}^3/{\rm s}$$

Early universe considerations (2)

How accurate is the canonical cross-section value $< \sigma v> = 3.10^{-26}$ cm^3/s ?



Advice: beware of standard lores (unless clearly understood):

=> The canonical value is not accurate!

*** QCD phase transition effect! Relativistic degrees of freedom strongly reduced (factor of 4) when quarks get confined into hadrons.

=> $< \sigma v>$ larger by factor of 1.5 below 10 GeV

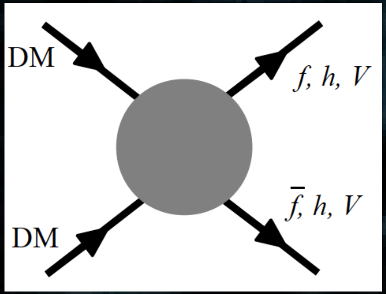
=> $< \sigma v>$ smaller by factor of 1.3 below 10 GeV

$$\Omega_\chi \,\tilde{\propto}\, \frac{1}{g_\star^{1/2}(x_{\rm dec})\,\langle\sigma v\rangle}$$

More in Geneviève's course!

Particle physics considerations (1)

WIMPs annihilate almost at rest (non-relativistic velocities).
Models predict their nature: boson/fermion (Dirac/Majorana).
=> Simple symmetry arguments may help figure out
whether indirect detection is relevant or not.



$$\langle \sigma v \rangle \approx \underbrace{\overbrace{a}^{\text{in galaxies}} + b/x + \mathcal{O}(x^{-2})}_{\text{relic density}}$$

$$x_{\text{dec}} \approx 20 \quad \longleftrightarrow \quad x_{\text{MW}} = \frac{3}{\beta^2_{\text{MW}}} \approx 10^6$$

=> P-wave contribution (dependent on v) is suppressed in Galaxies by 5 orders of magnitude wrt early universe
=> In general, indirect searches only relevant to models with dominant S-wave contributions.

** Focus on S-wave
=> Annihilation at rest implies a few additional features, if one looks at a pair of WIMPs more closely
=> Majorana fermion pair at rest: C=1; S-wave => L=0 => S=0 => CP=-1 => process selection!

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$$C(\text{Majorana pair}) = 1$$

$$CP = (-1)^{2L+S+1} = (-1)^{S+1}$$

$$\begin{aligned} J^{PC}(\lambda) &= 0^{++} \\ J^{PC}(i\,\lambda\,\gamma_5) &= 0^{-+} \\ J^{PC}(\lambda\,\gamma^\mu) &= 1^{--} \\ J^{PC}(\lambda\,\gamma^\mu\,\gamma_5) &= 1^{++} \end{aligned}$$

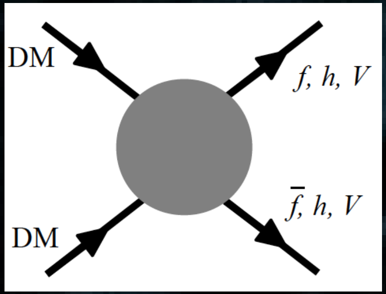
=> important for complementarity with direct searches!

++ Helicity suppression

$$\langle \sigma v \rangle \propto m_f^2$$

Particle physics considerations (2)

Exception: Sommerfeld effect (mediator mass << WIMP mass)
<=> long-range attractive force in some cases



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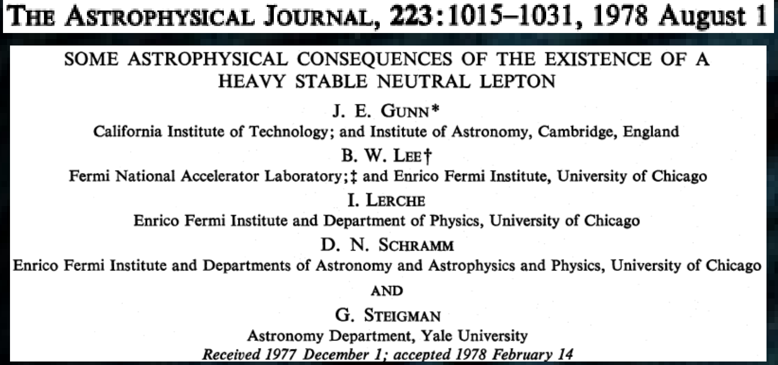

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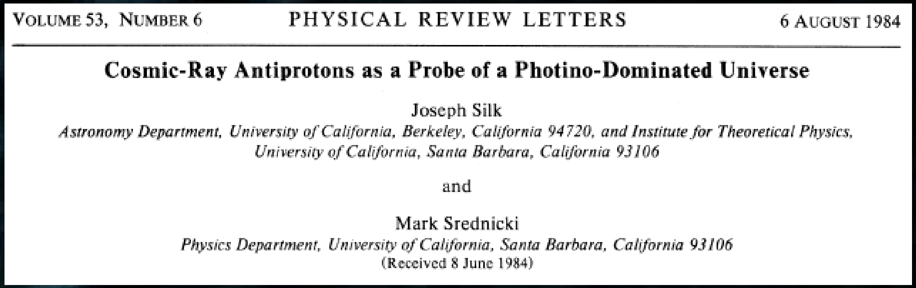

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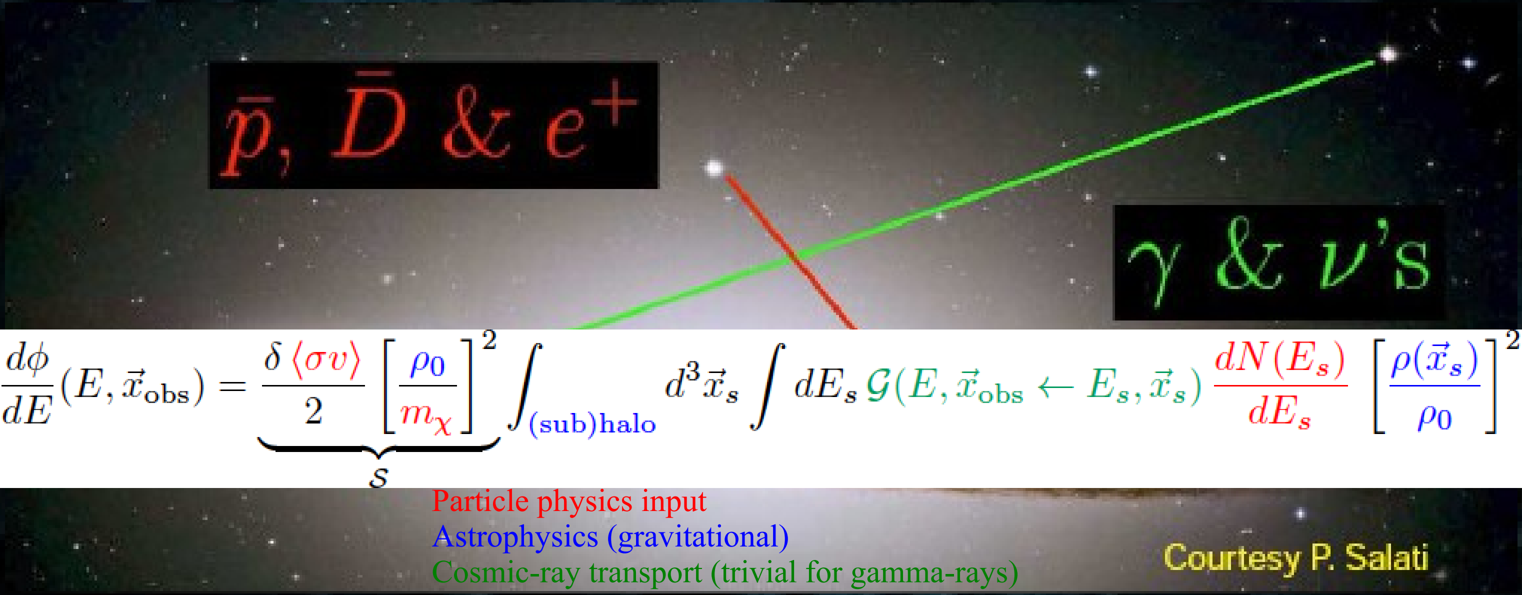

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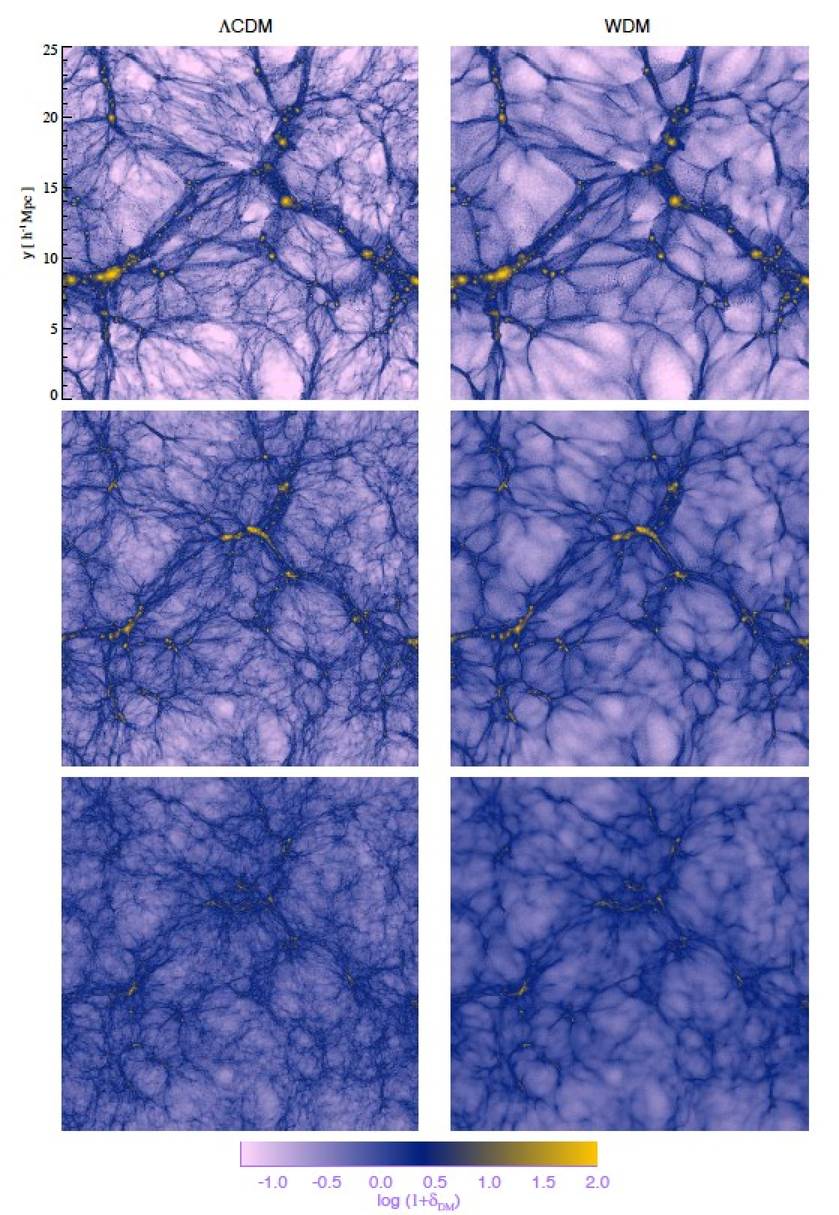
Cosmo/astro considerations (1-4)

Viel++ (11)



Indirect proofs for DM:

Observed (gravitational effects) from sub-galactic to cosmological scales

CDM successes:

- Leads to successful theory of structure formation

=> CDM seeds galaxies, galaxies embedded in DM halos

- Non-linear collapse probed with cosmological N-body simulations
- Including baryons is an ongoing (difficult) task but seems promising
- Most of observed properties (CMB / clusters / galaxies) reproduced from theory

Alternatives to DM: Modified gravity ????

- Interesting and difficult theoretical direction
- Fails in forming galaxies without DM (eg large CMB multipoles)

=> DM required even in modified gravity models!!!!

Free-streaming scale must at least allow for Dwarf Galaxies:

Fermionic DM => Tremaine & Gunn 79, Boyarsky+ 06: m > 1 keV

=> WDM and/or CDM allowed

Small scale issues for CDM (too much power on small scales):

So-called "Cusp-core problem"

=> CDM predicts cusps + concentrated centers, observations cores

(e.g. Navarro-Frenk-White profile)

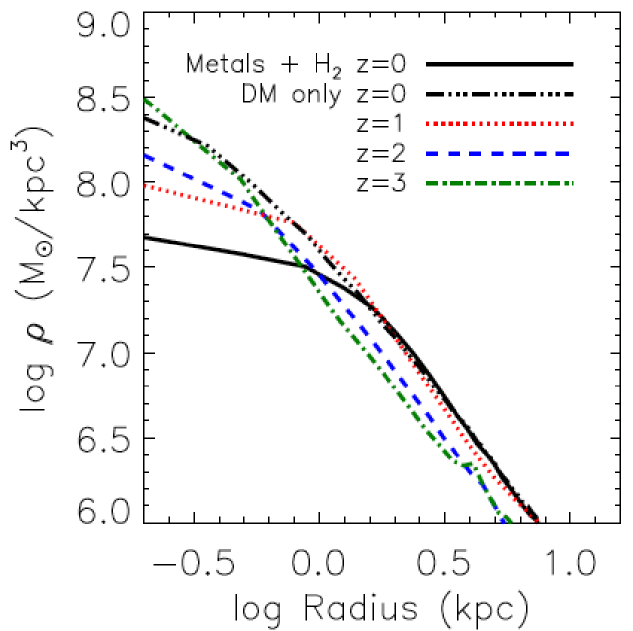
More subhalos than observed (≤ dwarf galaxy mass)

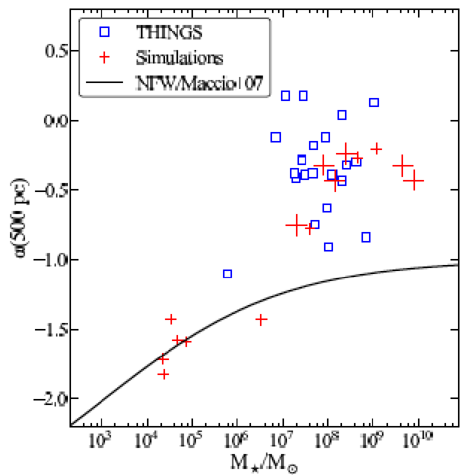
*** more have been detected recently (SDSS)

*** inefficient star formation, feedback effects (UV pressure, SN)

The core-cusp problem (mostly in late-type LSB galaxies, e.g. de Blok 10)

Governato++ (12)
CDM + more realistic physics for baryons => cusps are flattened
(star formation: radiative feedback from massive star + SN feedback)

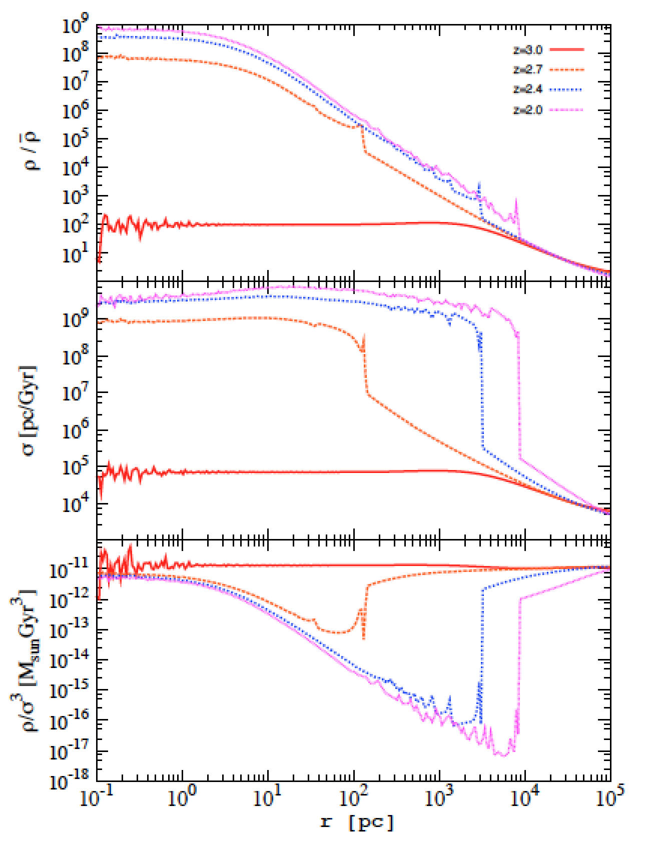




Conclusions:
→ WDM alone does not solve the issue:
* must be close to CDM to form DSphs (> 1-10 keV)
* then core radii are way too small wrt observations

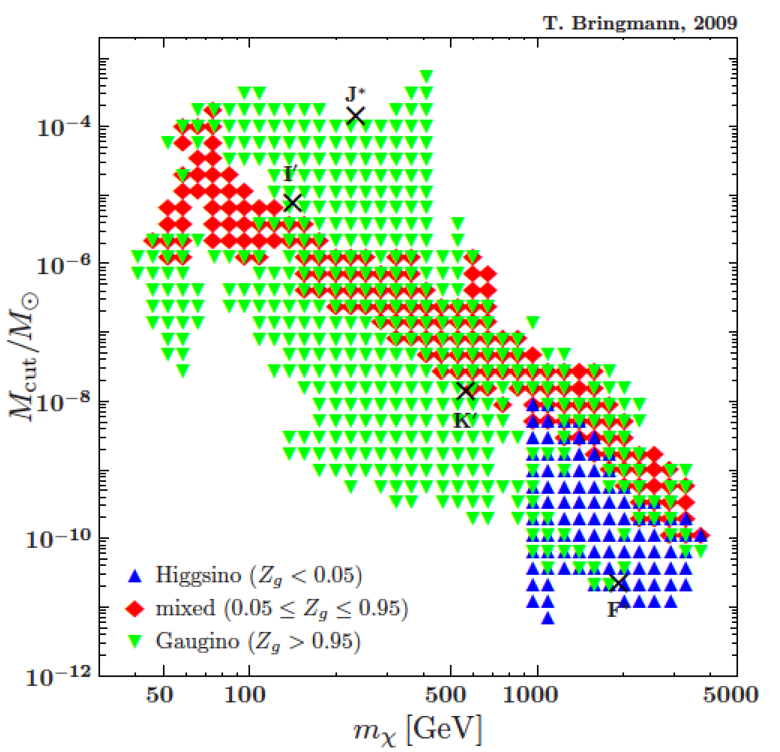
→ CDM in better shape when baryons are included
(still some debate)

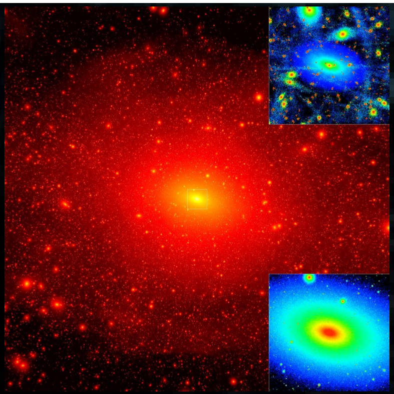
Villaescuela-Navarro & Dalal (10)
WDM does not prevent cusp formation
(Core radius / virial radius < 0.001)



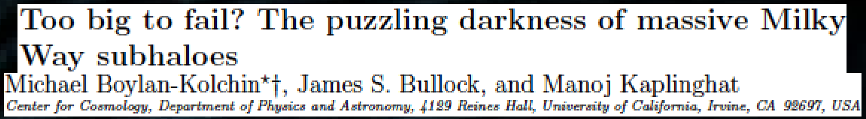
The subhalo problem: too many, too concentrated

Bringmann (09):
The minimal proto-halo scales for SUSY WIMPs





Via Lactea II simulation (MW-like galaxy)
Diemand++ (08) – CDM only
=> > 20,000 subhalos with $M > 10^{6\text{-}7}$ Msun



Too big to fail? The puzzling darkness of massive Milky Way subhaloes

Michael Boylan-Kolchin*†, James S. Bullock, and Manoj Kaplinghat

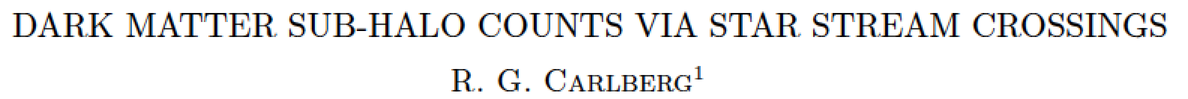
Center for Cosmology, Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697, USA

<u>"Too big to fail":</u>
* CDM => massive, concentrated subhalos => should form stars, but not observed (ultra-faint SDSS DSphs not enough)

Potential solutions come from baryonic effects:
* feedback (Governato ++12)
* H2-regulated star formation (Kuhlen++ 12-13)

Other solutions from particle physics:
* Self-interacting DM (Spergel & Steinhard 00)

=> Biggest challenge for CDM
=> Investigate baryonic effects in detail



DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

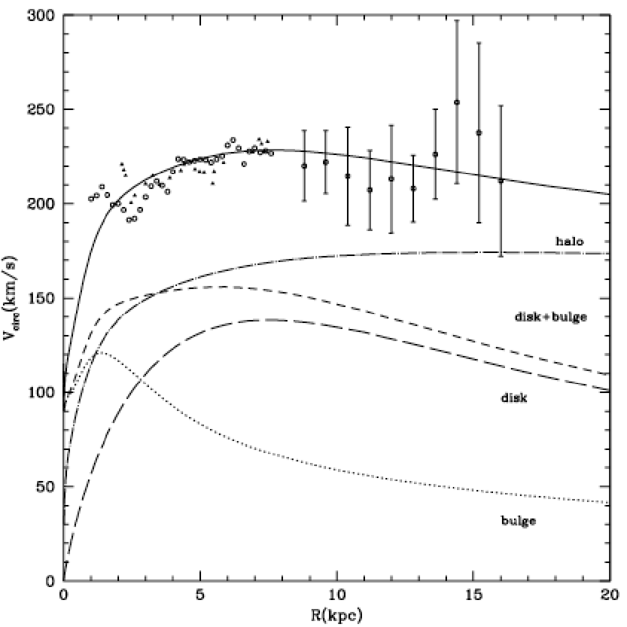
R. G. CARLBERG[1]

Carlberg (arXiv:1109.6022):
Gaps in star streams: NW (M31), Pal 5, Orphan, EBS (MW)
=> ~ 10^5 subhalos with $M > 10^5$ Msun
(potentially large systematic errors)

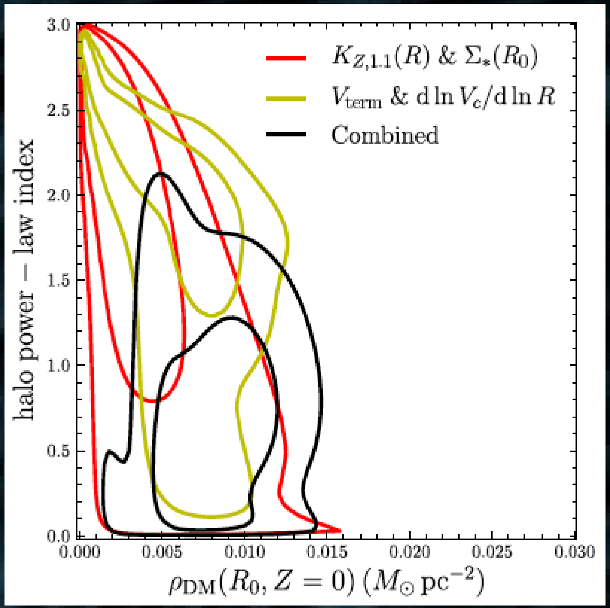
See also Ly-alpha studies.

How to constrain the DM density in the Galaxy?

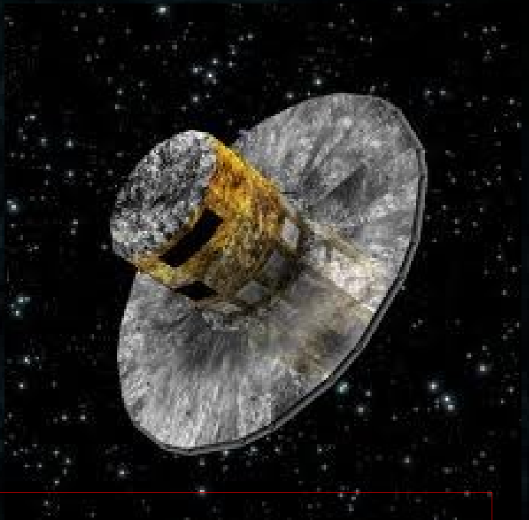
Klypin++ 02



Bovy & Rix 13



Gaia will help!
(launch expected Nov. 2013)
=> accurate positions and velocities for 10^8 stars!



Dynamical methods (rotation curves)

* rely on assumption for DM profile + baryon modeling
* assume hydrodynamical equilibrium
* many degeneracies in parameters
=> typical results:
Widrow++ 09: ρ(local) = 0.3+-0.1 GeV/cm3
Catena & Ullio 09: ρ(local) = 0.39+-0.02 GeV/cm3

Vertical velocity dispersion (à la Oort 1930's)

* accurate star velocities required
* less dependent on DM profile assumption
=> typical results:
Salucci++ 10: ρ(local) = 0.43+-0.11 GeV/cm3
Bovy & Rix 13: ρ(local) = 0.3+-0.1 GeV/cm3

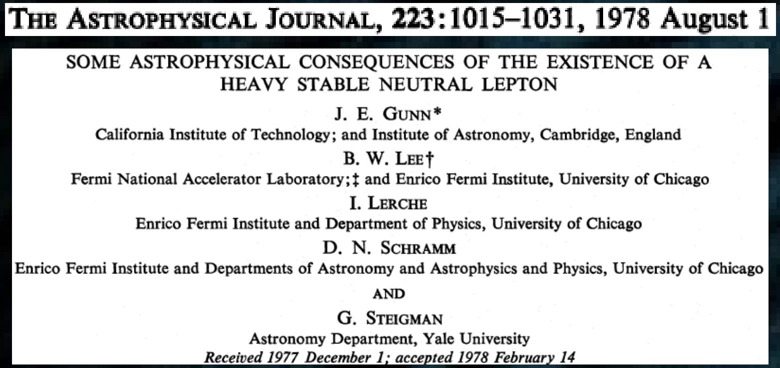
Combine both:

=> constraints on profile index
Bovy & Rix 13: index < 1.5

Summary:

* reasonable constraints on (averaged) local DM density
* central parts of the Galaxy poorly constrained
=> baryons play an important role
=> need more observations/tests (numerical simulations)

Indirect dark matter detection in the Milky Way



THE ASTROPHYSICAL JOURNAL, 223:1015–1031, 1978 August 1

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

J. E. GUNN*
California Institute of Technology; and Institute of Astronomy, Cambridge, England
B. W. LEE†
Fermi National Accelerator Laboratory;‡ and Enrico Fermi Institute, University of Chicago
I. LERCHE
Enrico Fermi Institute and Department of Physics, University of Chicago
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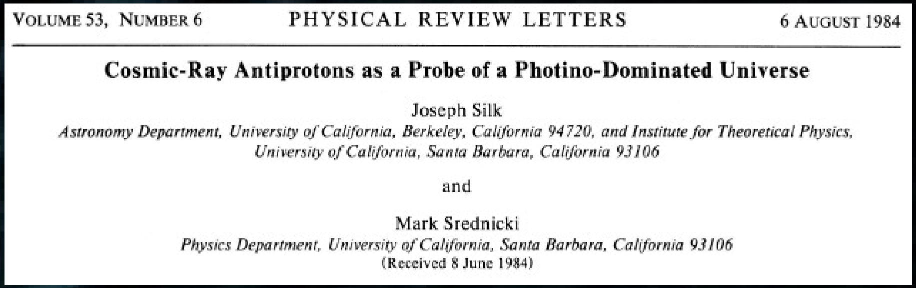
AND
G. STEIGMAN
Astronomy Department, Yale University
Received 1977 December 1; accepted 1978 February 14



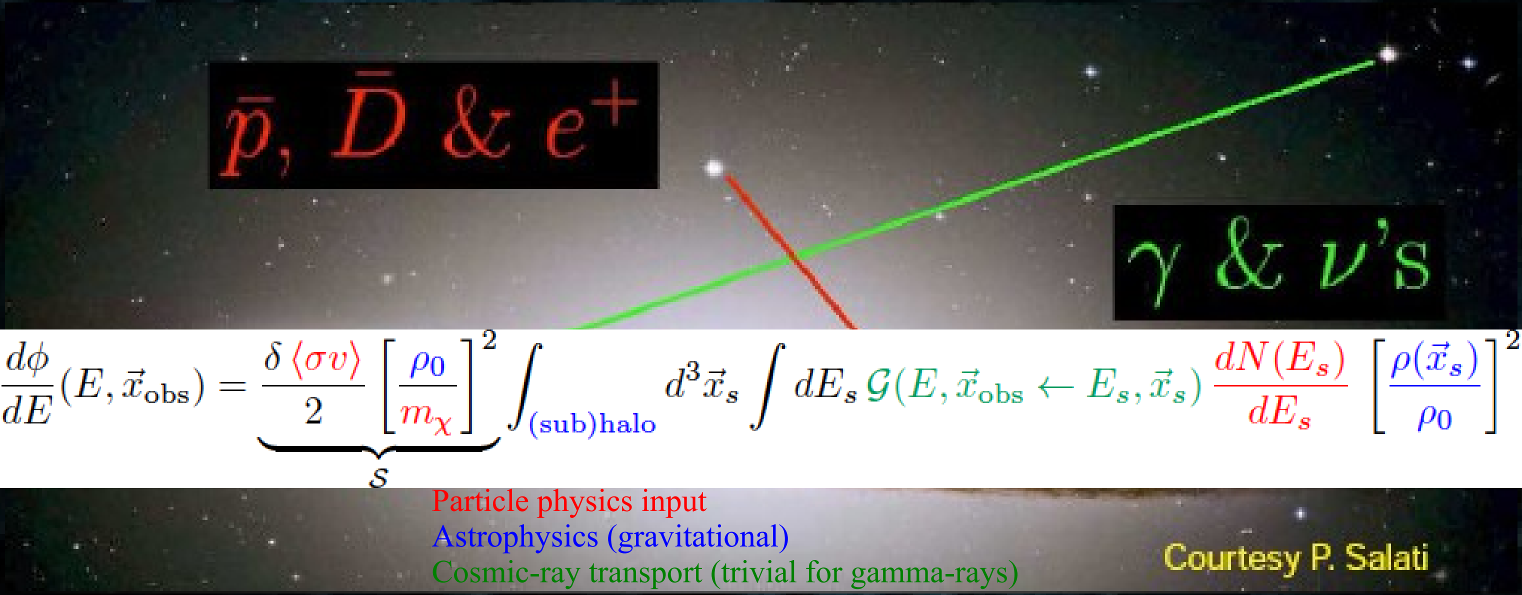
VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

Joseph Silk
Astronomy Department, University of California, Berkeley, California 94720, and Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

and

Mark Srednicki
Physics Department, University of California, Santa Barbara, California 93106
(Received 8 June 1984)



$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \underbrace{\frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2}_{S} \int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\, \mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

Particle physics input
Astrophysics (gravitational)
Cosmic-ray transport (trivial for gamma-rays)

Main arguments:

- Annihilation final states lead to: gamma-rays + antimatter
- γ-rays : lines, spatial + spectral distribution of signals vs bg
- Antimatter cosmic rays: secondary origin of astro contrib, therefore low bckgd (in principle)
- Neutrinos: Sun most promising target

But:

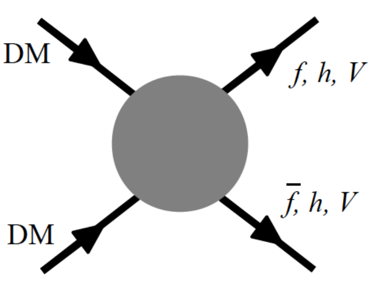
- Do we control backgrounds?
- Specific spectral differences in signals vs backgrounds?
- Careful estimates of theoretical errors for signals and backgrounds very important (difficult exercise in practice)

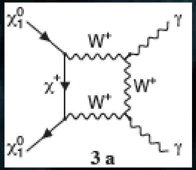
Indirect dark matter detection in the Milky Way

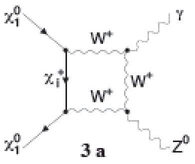
Gamma-rays

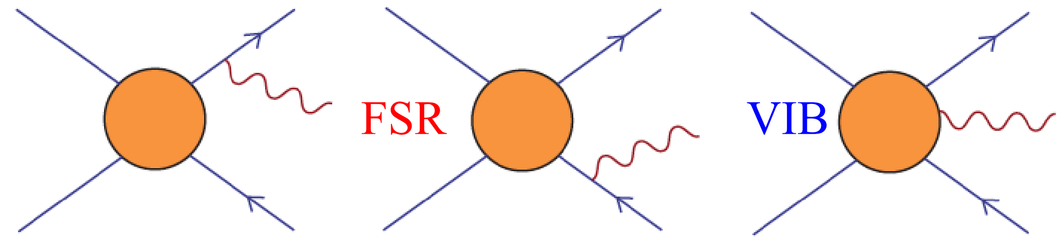
Bergström++

Gamma-ray signals: spectral signatures

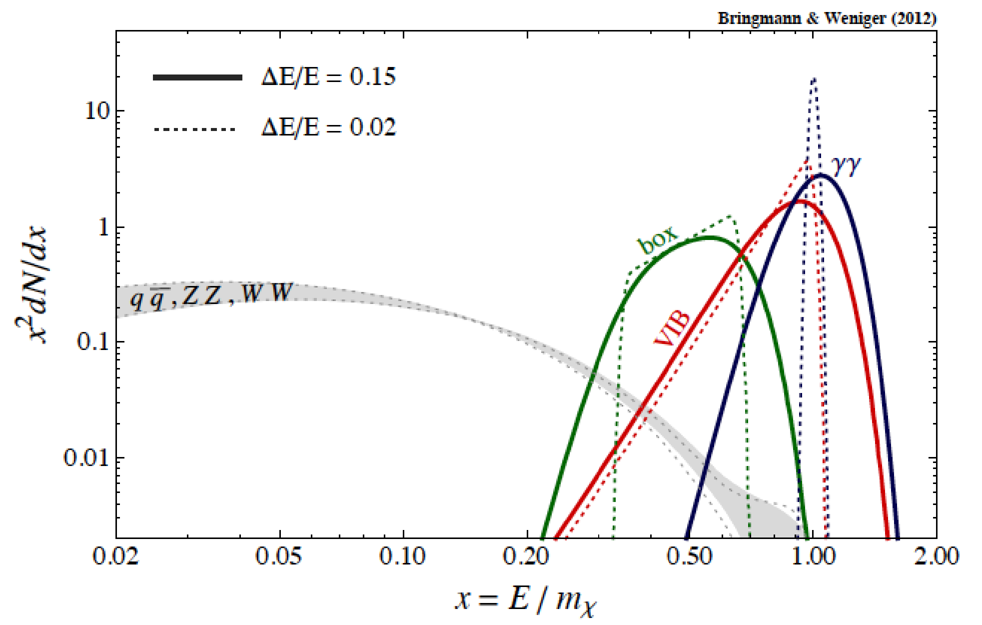








Bringmann++ 09



Bringmann & Weniger 12

DM signals depend on annihilation final states:

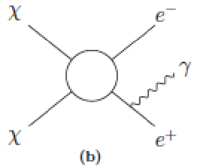
1) Gamma-ray lines/boxes: the cleanest signatures! (but loop suppressed) =>eg: γγ, γX, ϕϕ → 4γ

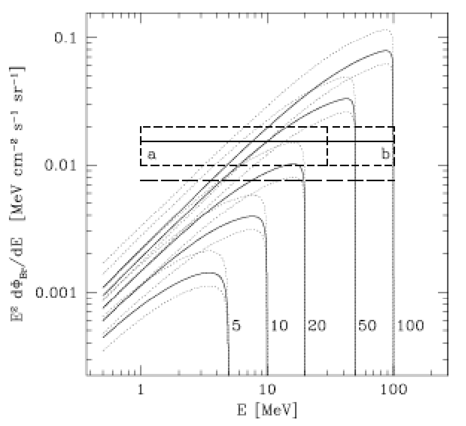
2) quarks, massive bosons => typical hadronization spectra (pion production/decay) => continuous spectrum, close to E^{-2}, with exponential cut-off => rather soft spectrum

3) Virtual internal Bremsstrahlung (VIB) may be significant if final states are bosons and mediator mass degenerate with WIMP mass (strongly model-dependent) => hard spectrum

…

x) (mostly for non-susy): FSR for annihilation into charged leptons => hard spectrum.

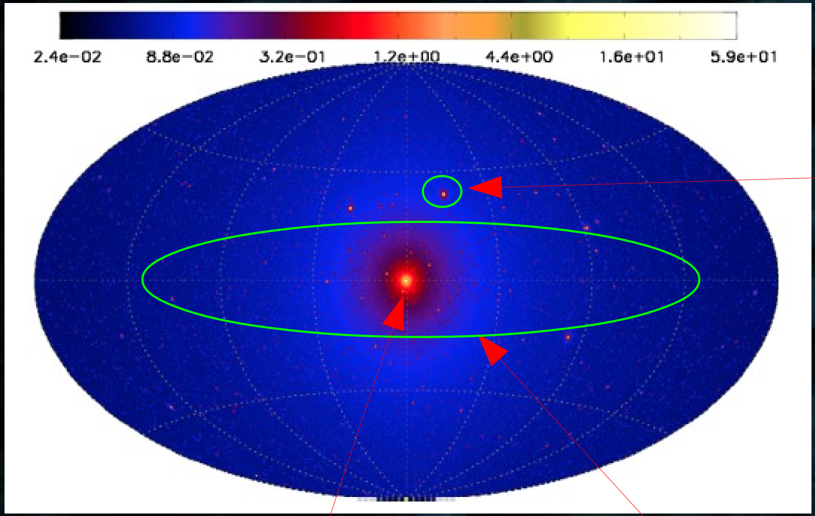




Beacom++ 05

Gamma-ray targets

Pieri, JL++ 11

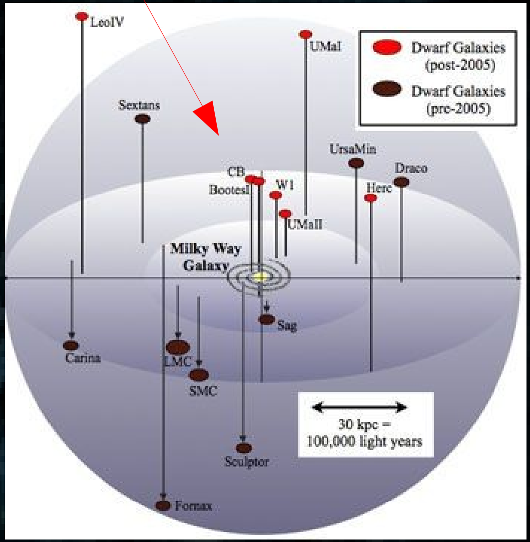


Big DM subhalos
* unknown objects if star formation inefficient
=> potential unidentified gamma-ray sources.
* known Dwarf Spheroidal Galaxies (~20) – no other HE astrophysical processes expected there.

Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

Galactic Center
* Closest/Largest expected annihilation rate
* Large theoretical uncertainties (signal and background)

@kek



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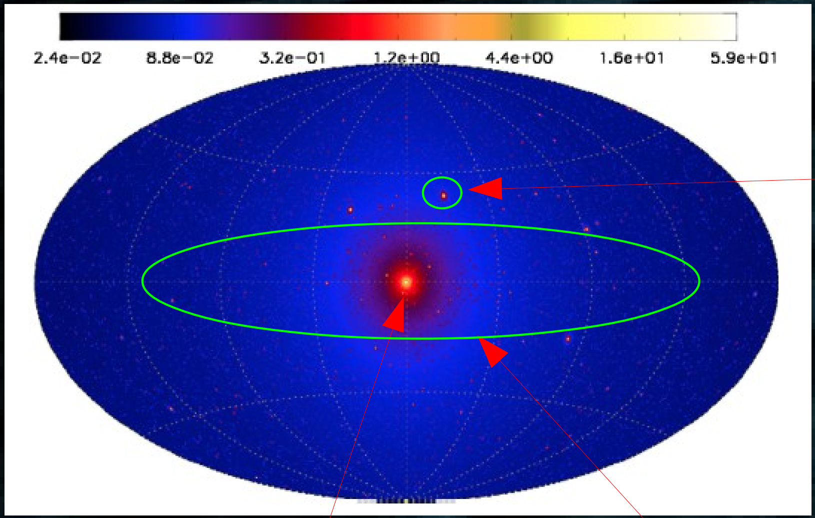
Pieri, JL++ 11



Big DM subhalos
* unknown objects if star formation inefficient
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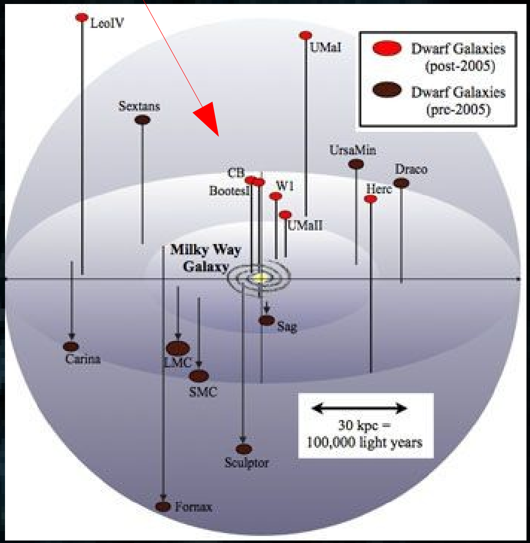
* known Dwarf Spheroidal Galaxies (~20) – no other HE astrophysical processes expected there.

If no line observed elsewhere, DSphs are the most secure for a discovery.

@kek



Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

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* Closest/Largest expected annihilation rate
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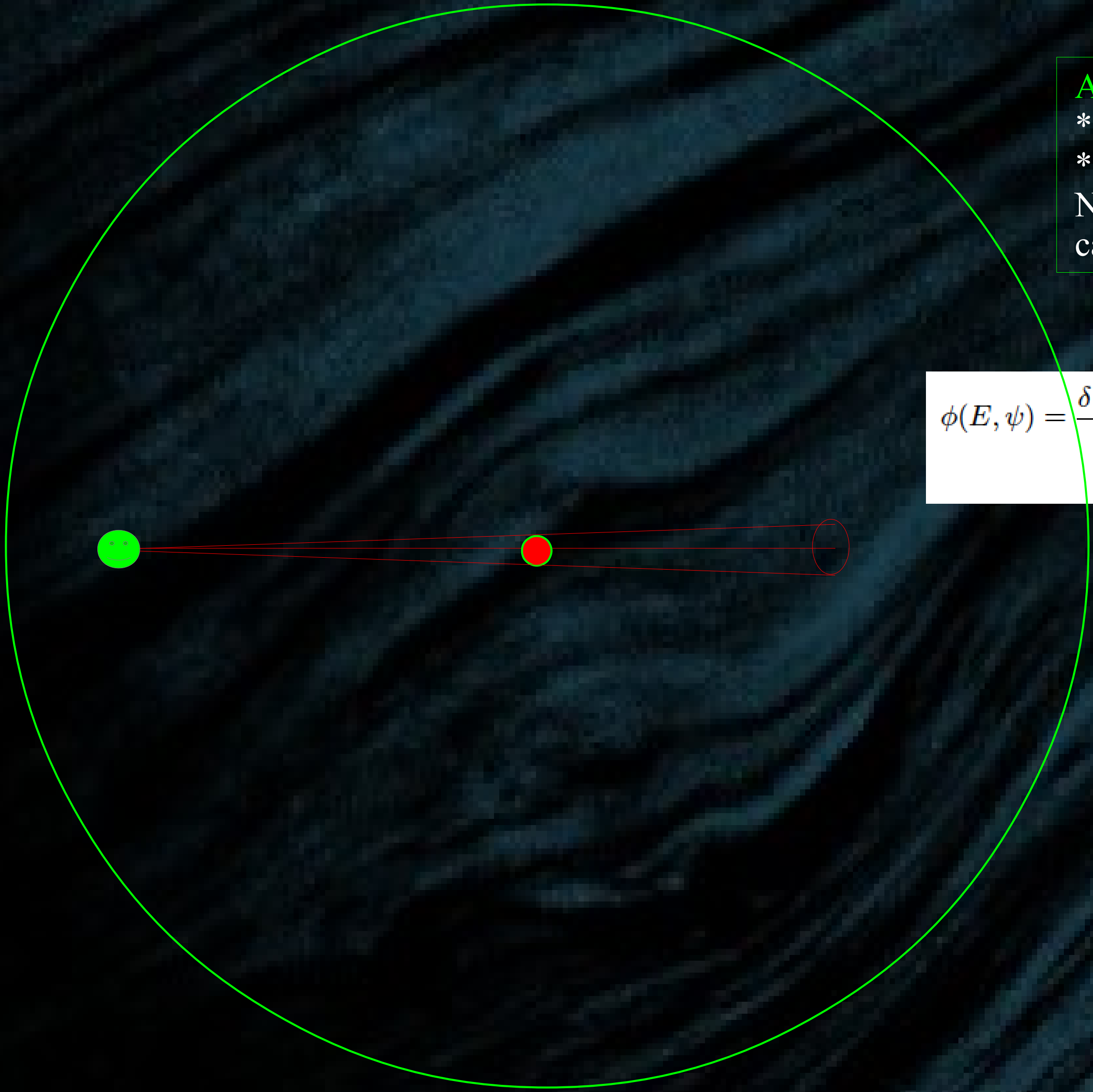
Gamma-rays from the Galactic Center: recipe



Assume spherical DM halo (a piece of it)
* Line-of-sight integral
* Aperture angle given by experimental resolution
NB: PSF should be included for very accurate calculations.

$$\phi(E,\psi) = \frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2 \left\{\sum_i \mathcal{B}_i\,\frac{dN_i(E)}{dE}\right\} \int \frac{d\Omega}{4\pi}\,\underbrace{\int_0^\infty dl\,\left[\frac{\rho(r(l,\psi,\theta,\phi))}{\rho_0}\right]^2}_{R_\odot\,J(\psi)}$$

$$r = \sqrt{l^2 + R_\odot^2 - 2\,l\,R_\odot(\cos\theta\,\cos\psi - \cos\phi\,\sin\theta\,\sin\psi)}$$

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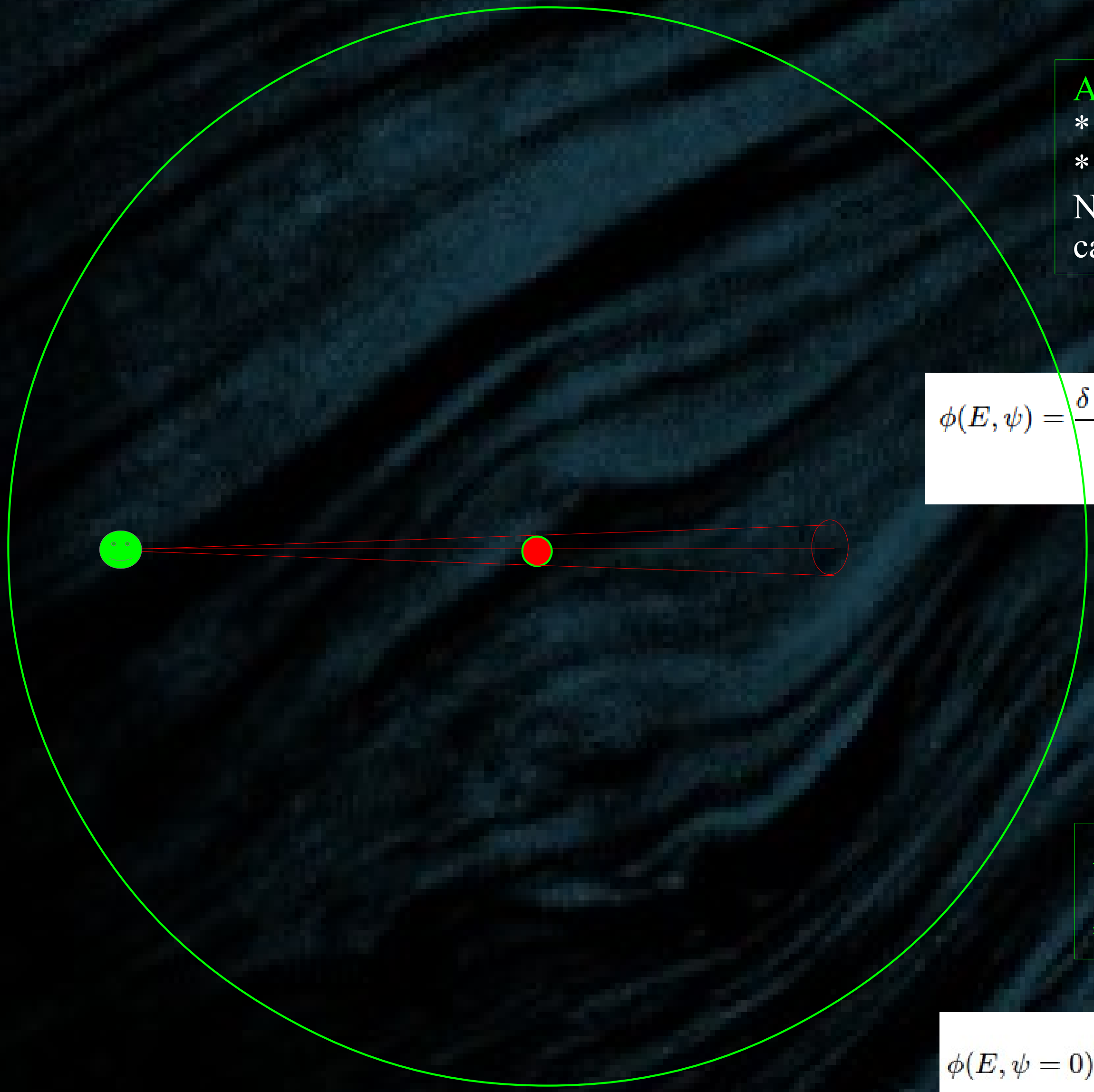

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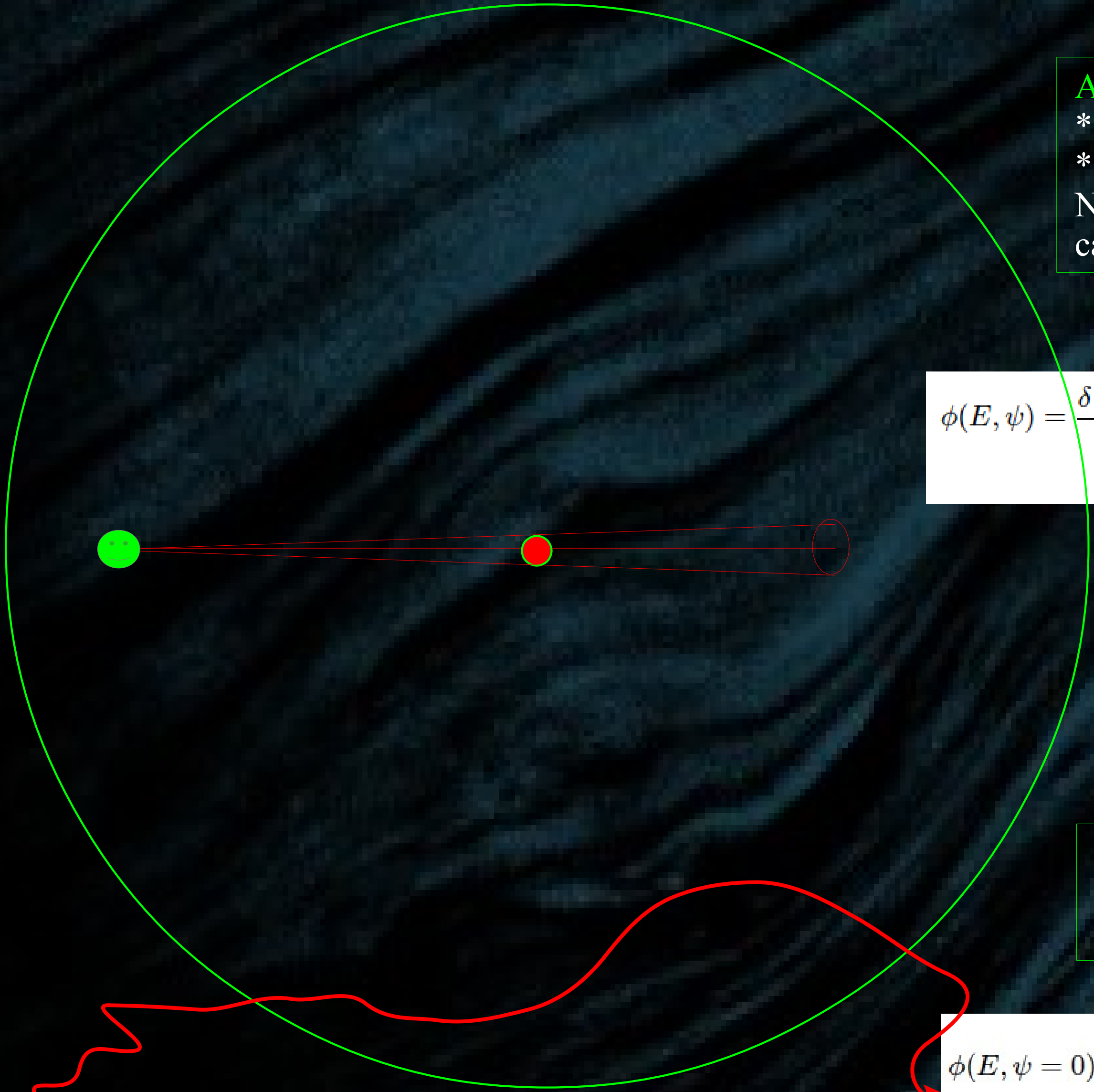
Annihilation concentrates at the very center in most of cases (cuspy halos)!!!
=> makes it much simpler for rough estimates!

$$\phi(E,\psi=0) \overset{r_{\rm res}\ll R_\odot}{\approx} \frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2 \left\{\sum_i \mathcal{B}_i\,\frac{dN_i(E)}{dE}\right\} \frac{1}{R_\odot^2}\int_0^{r_{\rm res}} dr\,r^2\left[\frac{\rho(r)}{\rho_0}\right]^2$$

Gamma-rays from the Galactic Center: recipe



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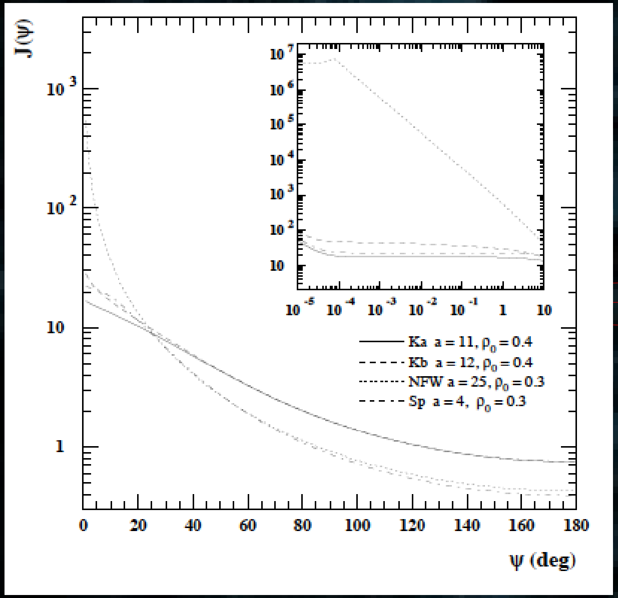
Gamma-rays from the Galactic Center: recipe

Bergström++ 98



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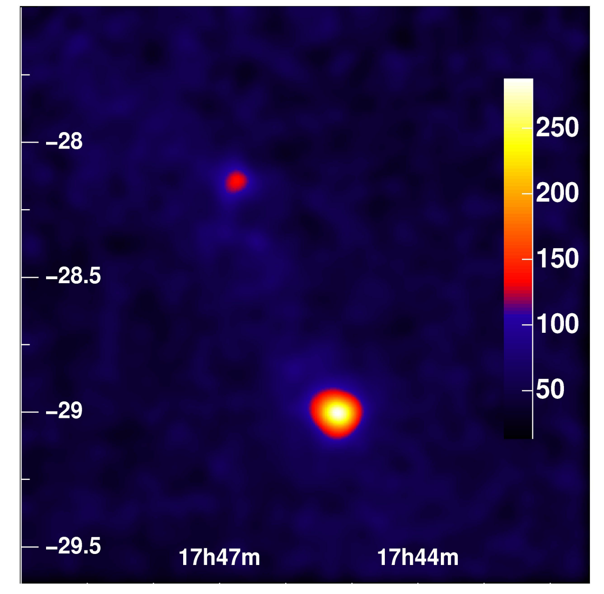
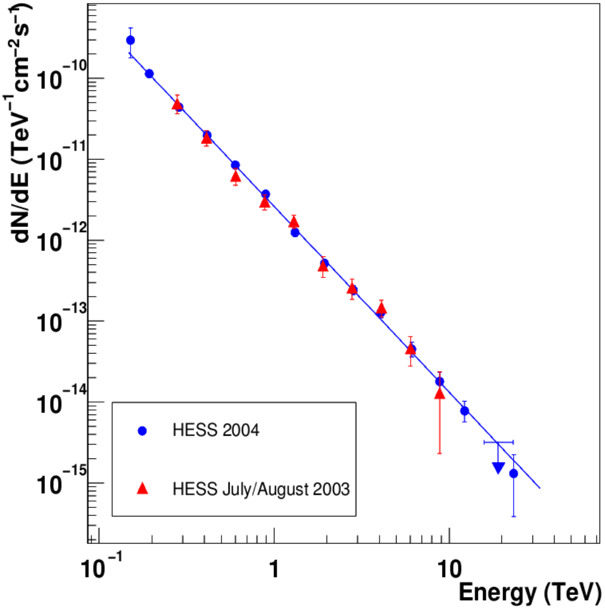
Summary:
- large theoretical uncertainties due to unknown halo shape

=> several orders of magnitude in the very center.

NB: recipe valid for any DM (sub)halo

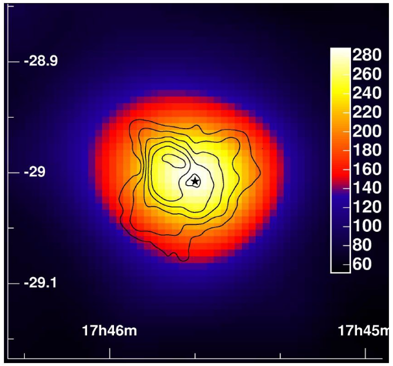
Gamma-rays from the Galactic Center: data? (1)





HESS Collab. 04

TeV GC data:
* Point source detected – Sg A*
* looks like standard astro source
* large theoretical uncertainties due to unknown halo shape
=> several orders of magnitude in the very center.



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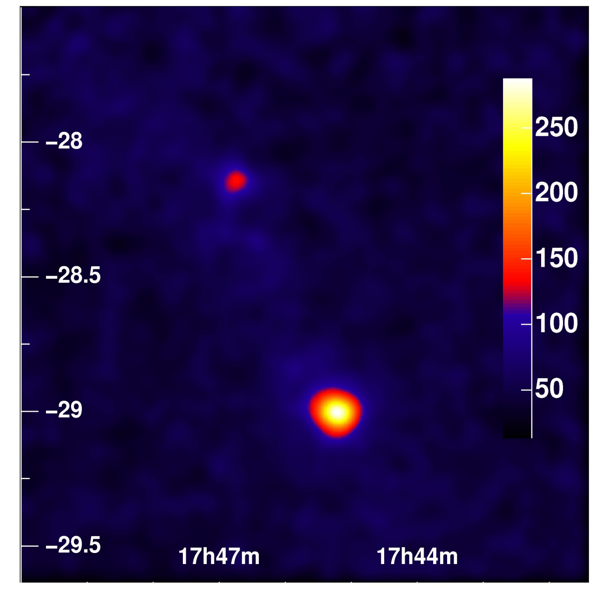

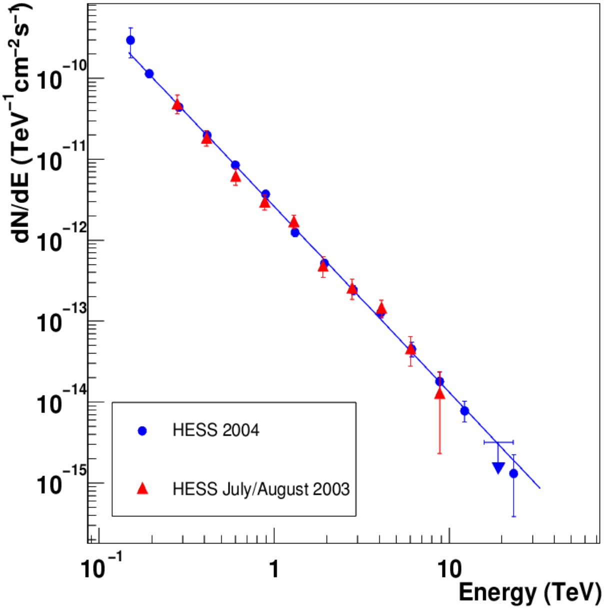

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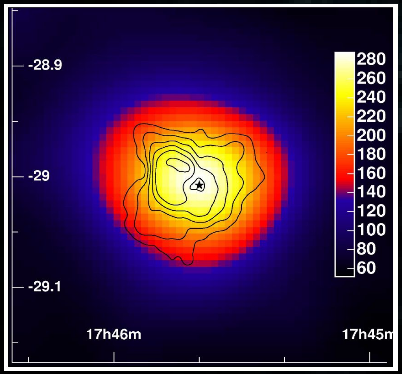
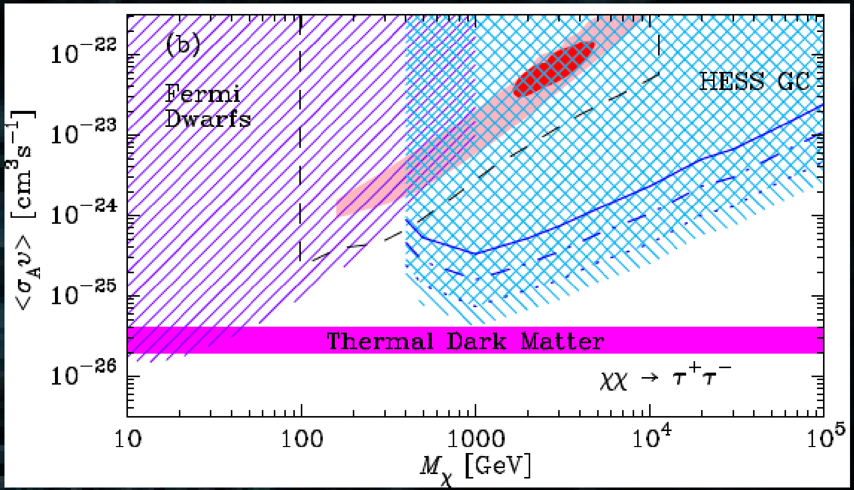


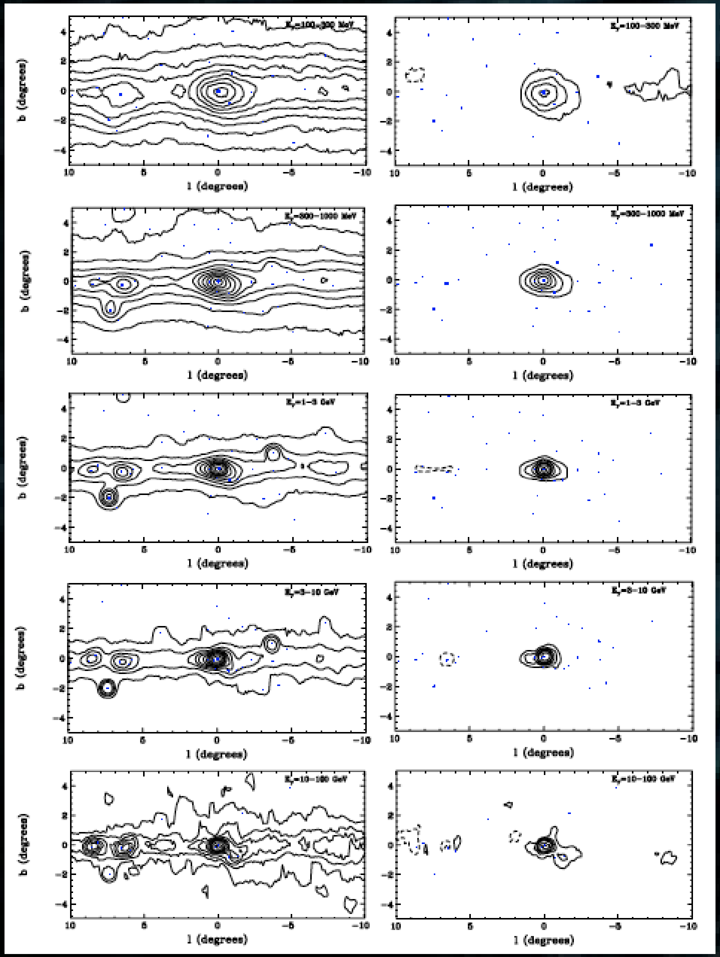
All you cannot (do not want to) use as signal interpretation can be used for setting limits!

=> This implies assuming a density profile (keep that in mind)

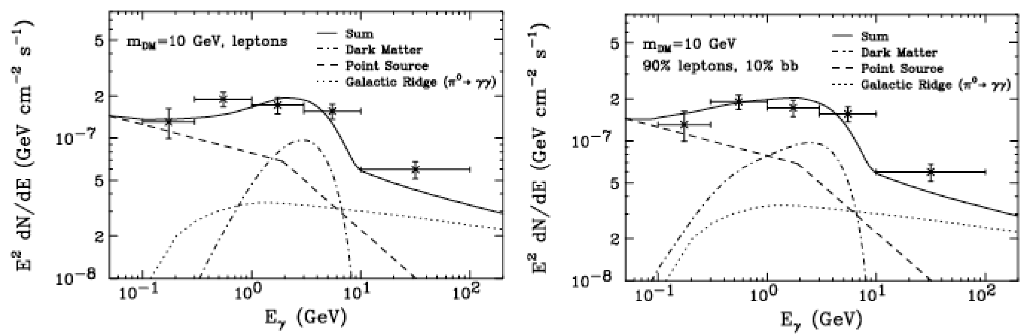


Abazajian & Harding 12

Gamma-rays from the Galactic Center: data? (2)



Hooper & Linden 12

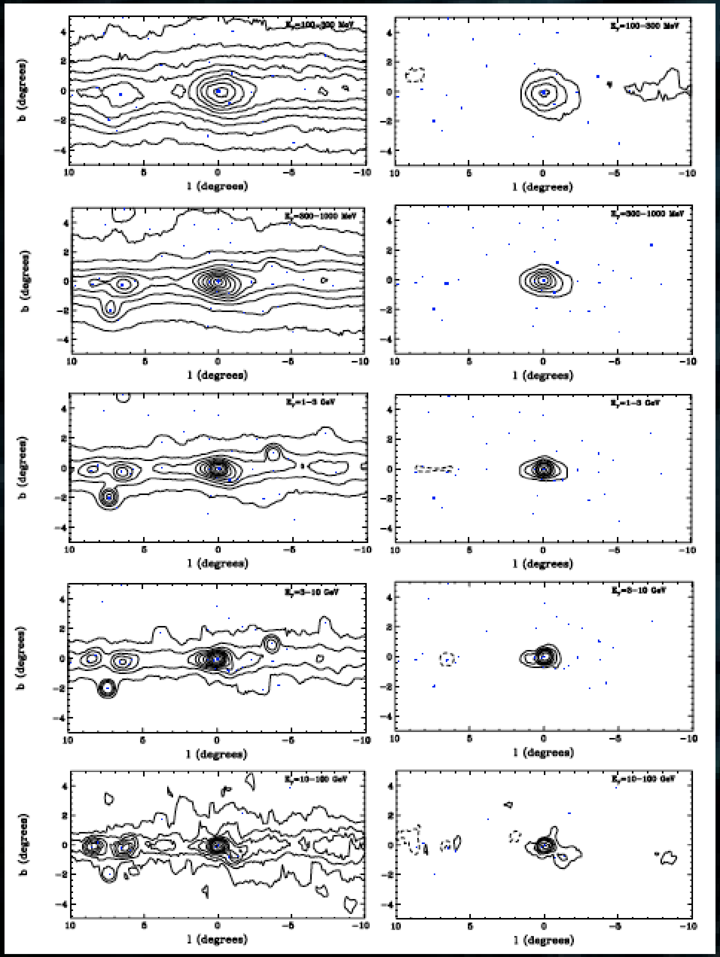


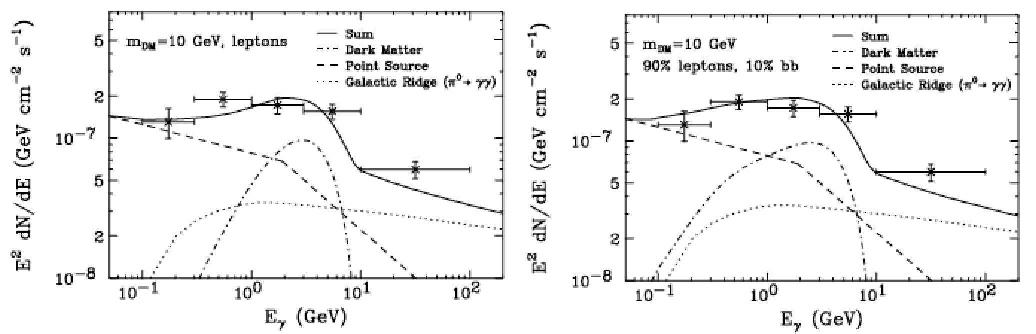
Fermi data are public: enjoy!

The point:
=> After “background” subtraction in a 1° region, some authors find some gamma-ray excess around a few GEV.

Criticism:
=> Which background?
* CR physics not under control at GC
* ISM loosely constrained there
* Contamination by unresolved sources (eg millisecond pulsars).

Gamma-rays from the Galactic Center: data? (2)





Hooper & Linden 12

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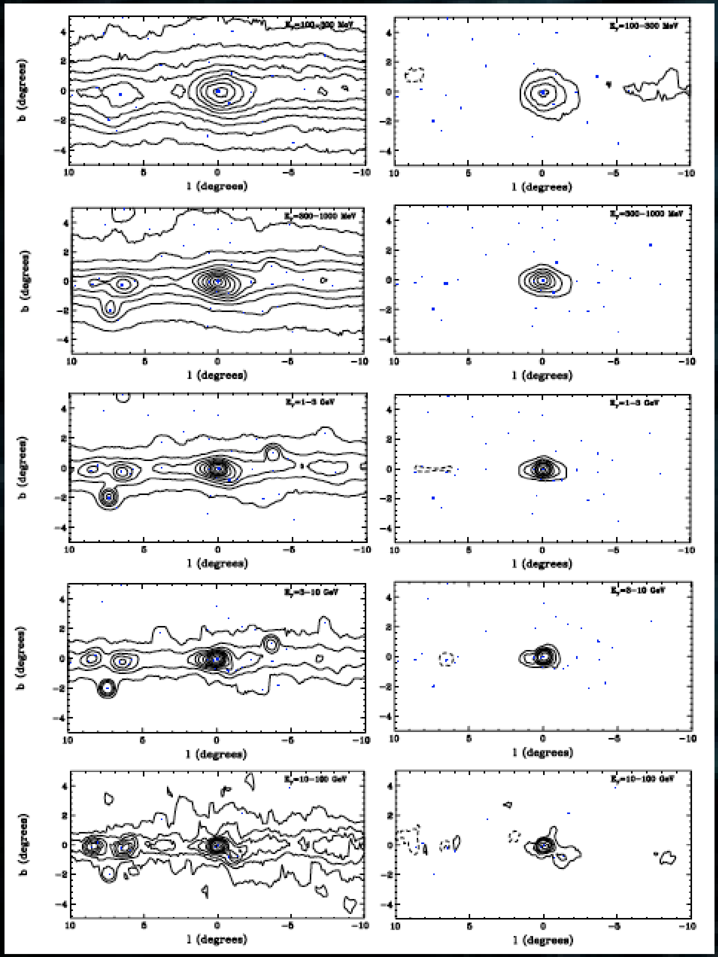
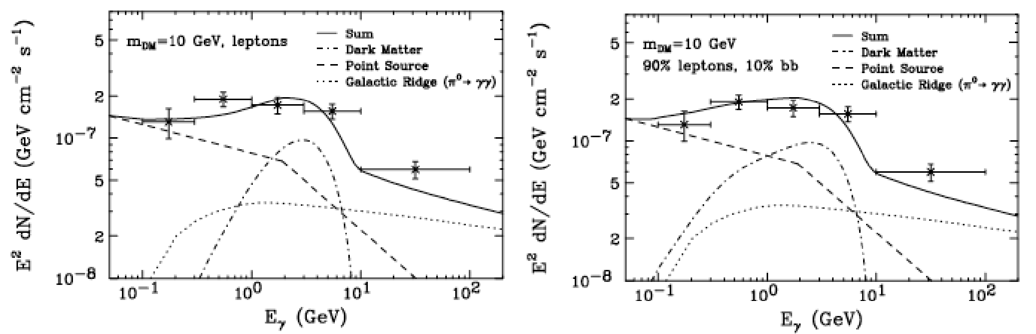
=> pulsars promoted to most important background in indirect searches! (see later)

Gamma-rays from the Galactic Center: data? (2)



Hooper & Linden 12



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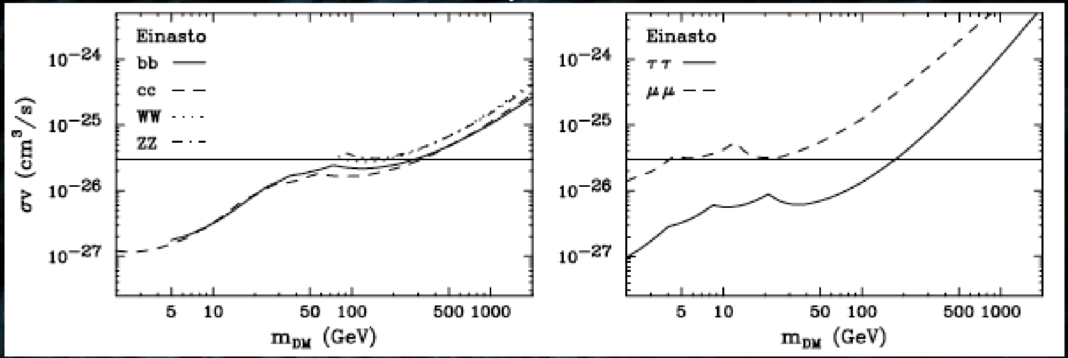
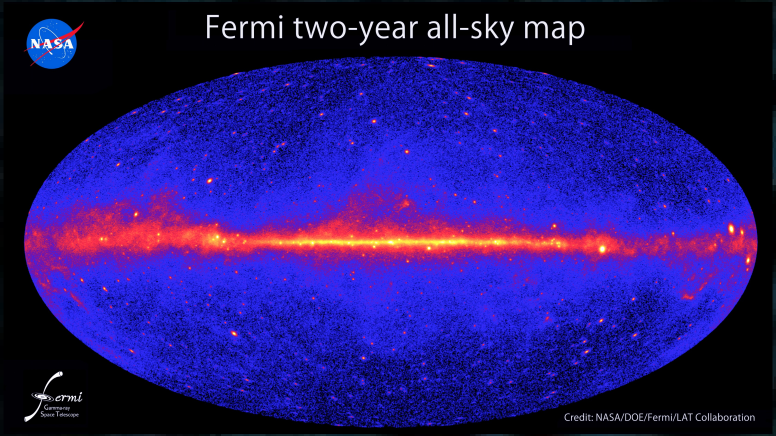
=> Reverse game: go to limits!
(assuming DM profile)



Hooper++ 12

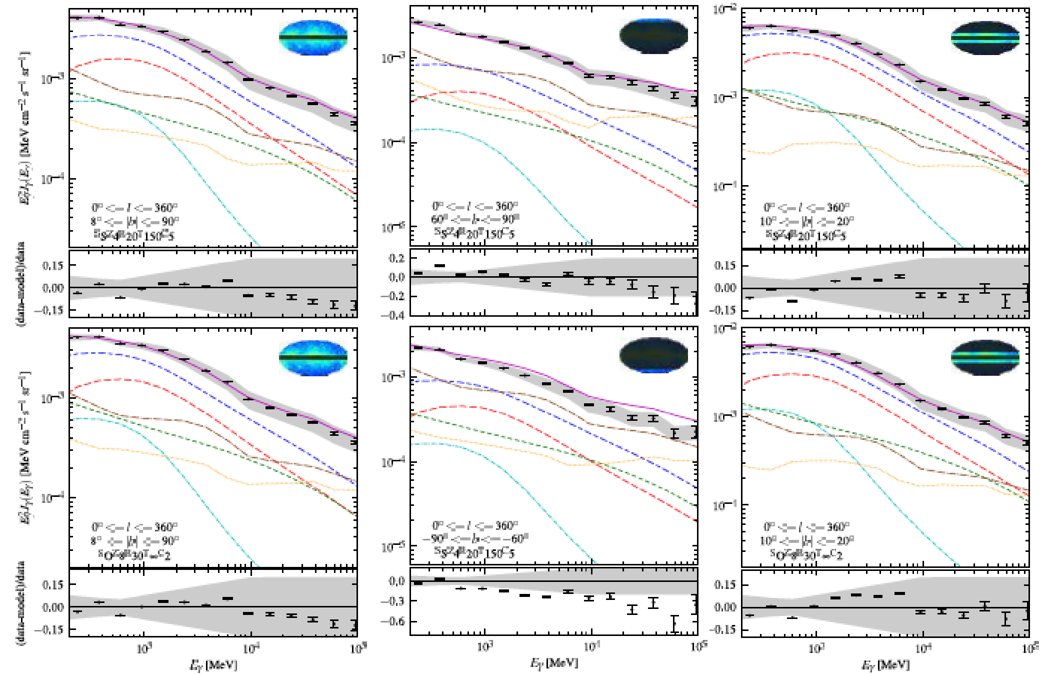
Gamma-ray backgrounds (at last)

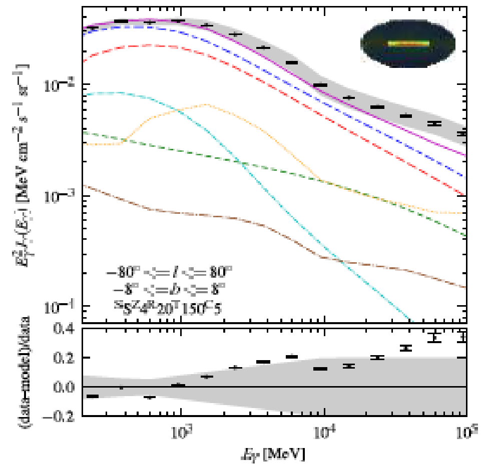


Real skymap of signal + backgrounds
(Fermi Collab.)

Backgrounds:
* CR interaction with ISM => neutral pions + IC (diffuse background)
* unresolved astrophysical sources
* extragalactic astro contributions
* (for other DM sources – eg DSphG) smooth DM halo contribution

=> Despite rather good understanding (except in some cases), difficult to predict with good accuracy.





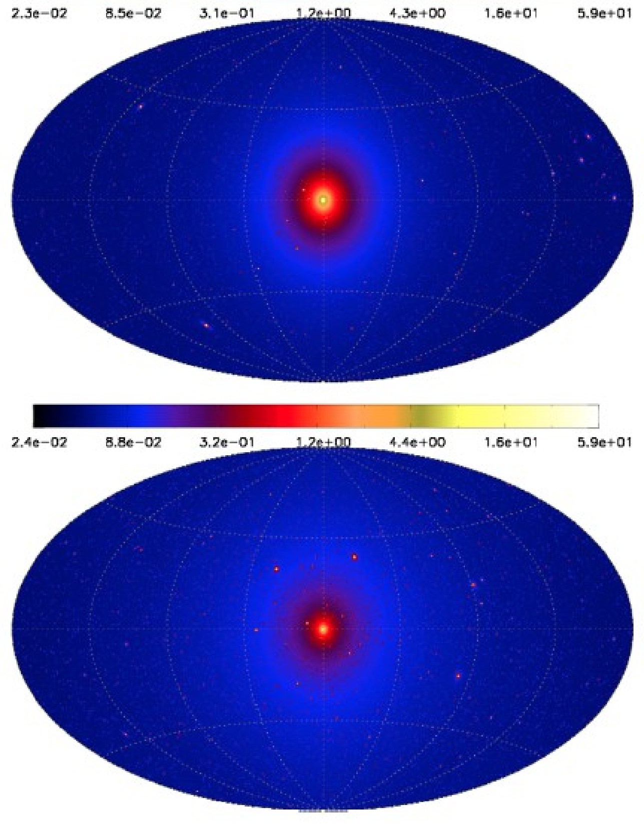
Total Galactic diffuse
Neutral pions (p+H)
Inverse Compton
Bremsstrahlung

Detected sources
Isotropic background

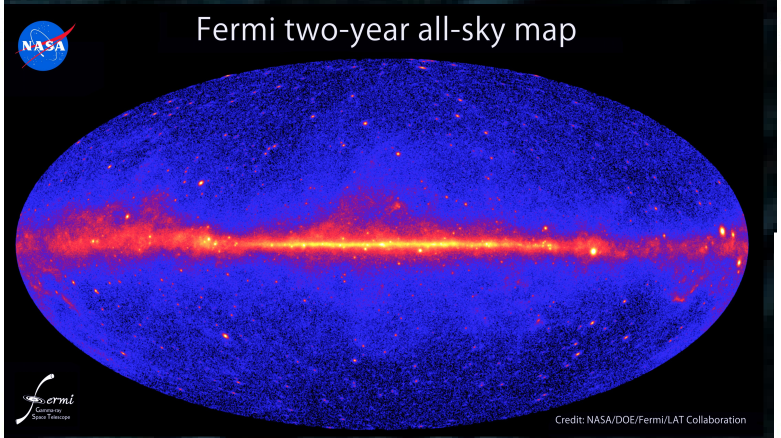
Fermi Collab. 12
Galprop model(s)
(neglecting DM!)

Gamma-ray signal / background

Pieri, JL++ 11



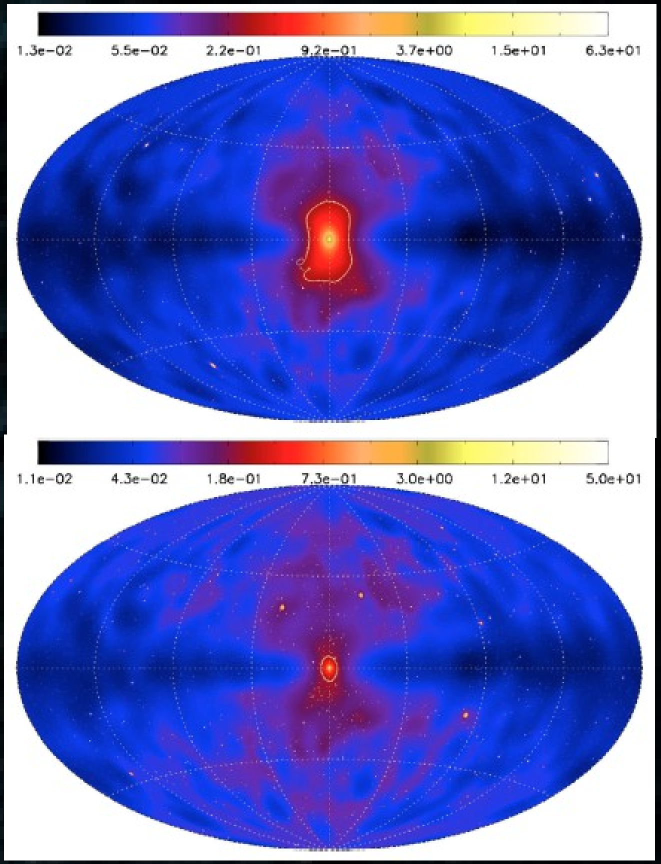
DM annihilation maps assuming Aquarius (Springel++) model (top), and Via Lactea II (Diemand++) model (bottom)



Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration

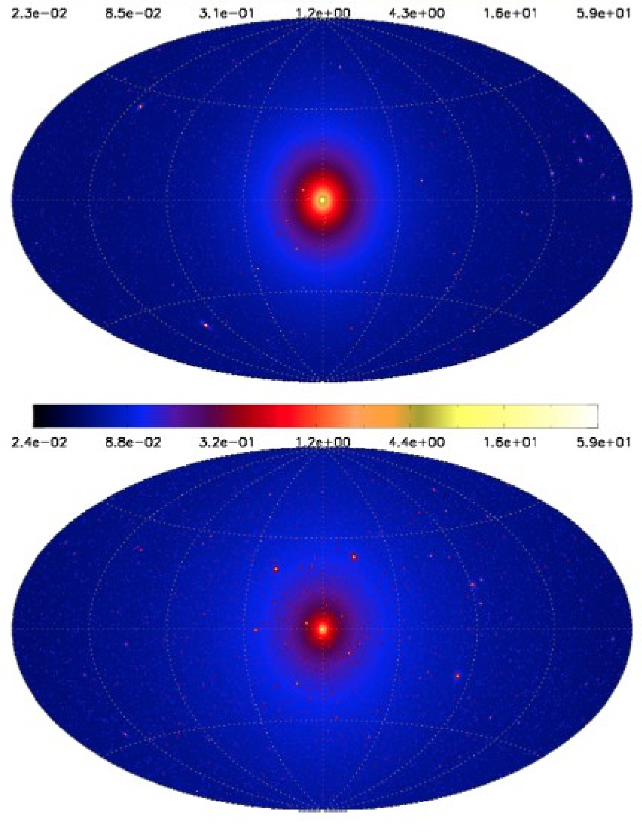
Pieri, JL++ 11



Signal / noise ratio

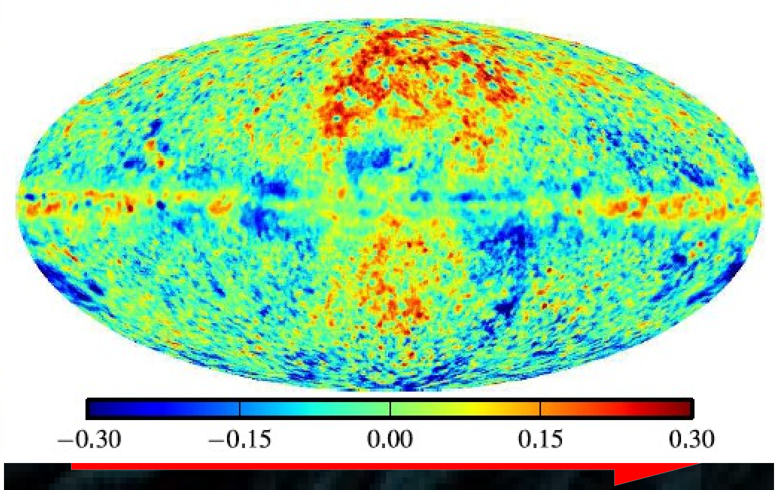
Gamma-ray signal / background

Pieri, JL++ 11

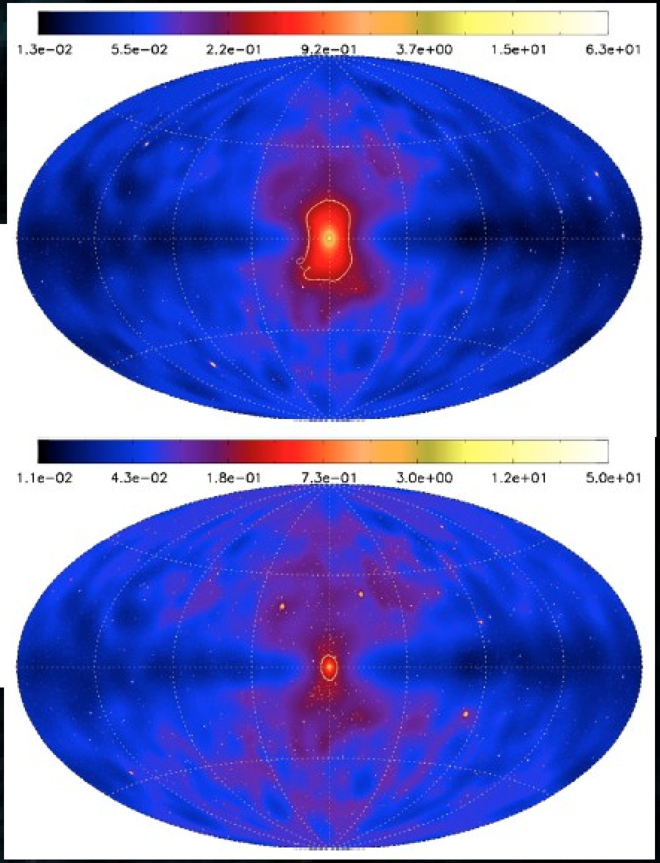


DM annihilation maps assuming Aquarius (Springel++) model (top), and Via Lactea II (Diemand++) model (bottom)

Real residuals!



Pieri, JL++ 11



Signal / noise ratio

Diffuse emission: a top bottom approach

Cosmological simulation:
self-consistent modeling of a galaxy (DM, gas, stars)

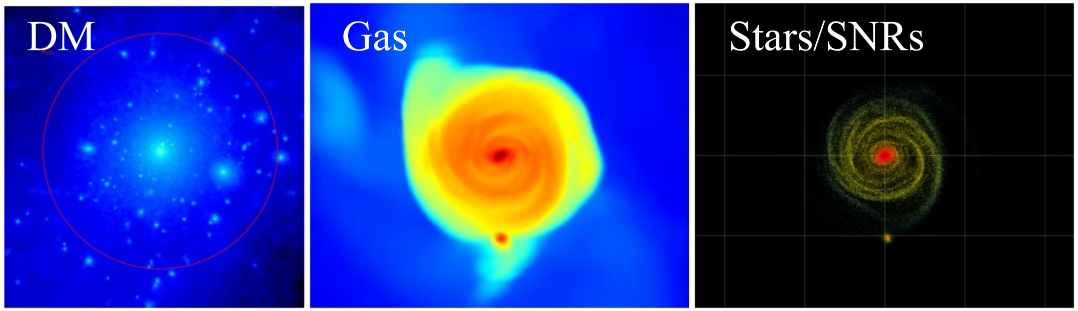
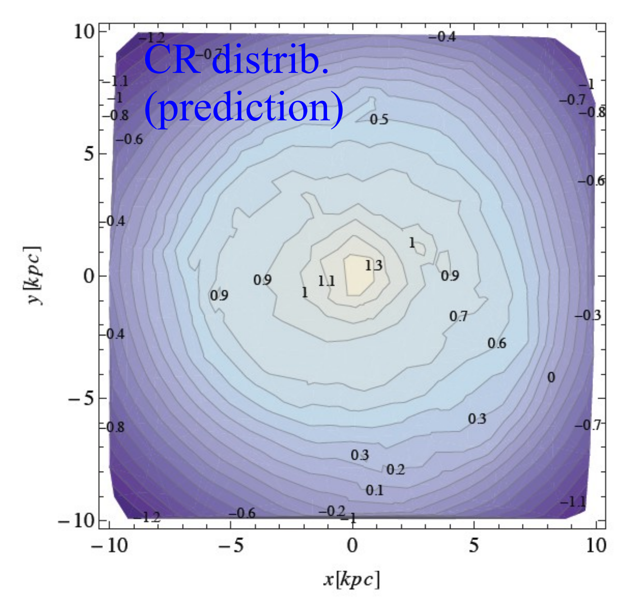
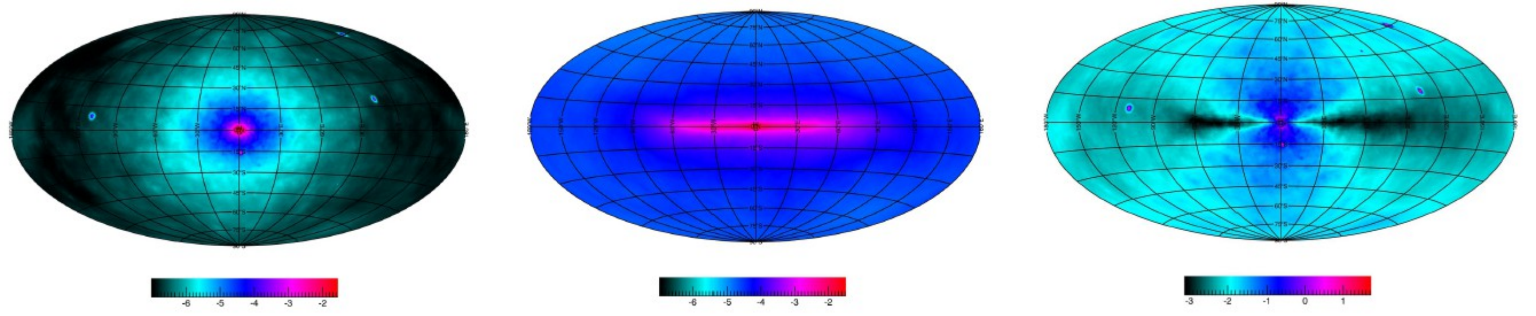


FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

Nezri, JL, Teyssier,1204.4121

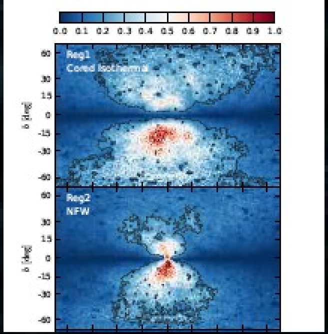


Skymaps:
DM (100 GeV b-bbar) – astro processes – DM/astro



<u>Advantages:</u>
* all ingredients are identified and localized (sources and gas)
* check the relevance of current assumptions
<u>Limits:</u> spatial resolution

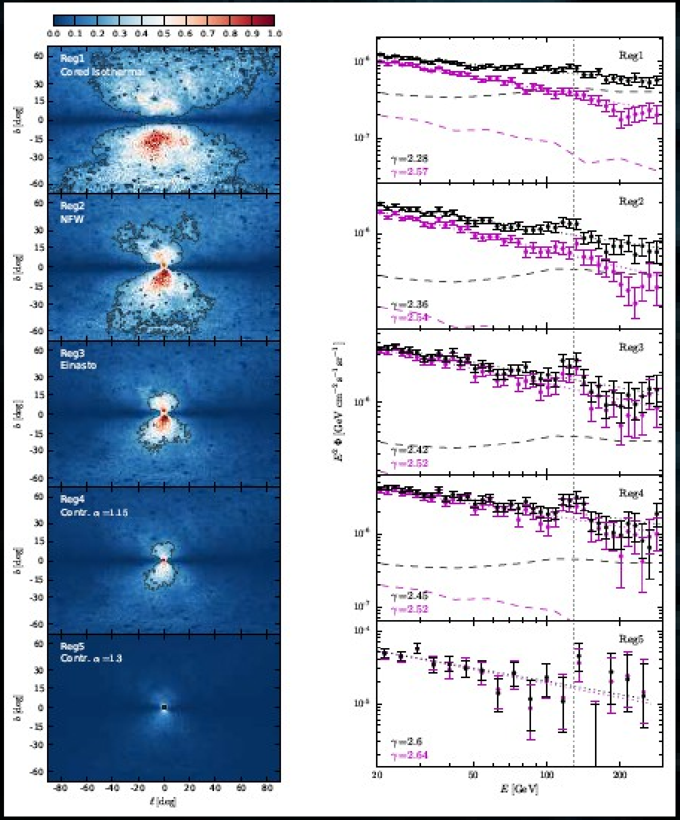
=> preliminary results encouraging, work in progress



Compare e.g. with Weniger 12
(optimized region for 130 GeV line)

Defining optimal regions: example of the 130 GeV line

Weniger 12



Methodology:

1) consider different possibilities for DM halos
2) for each, determine regions where signal/background is maximal
3) look for DM features in these regions (eg lines)
4) compare analysis with regions where signal should be absent

=> Weniger (12) found a gamma-ray line at 130 GeV

Defining optimal regions: example of the 130 GeV line

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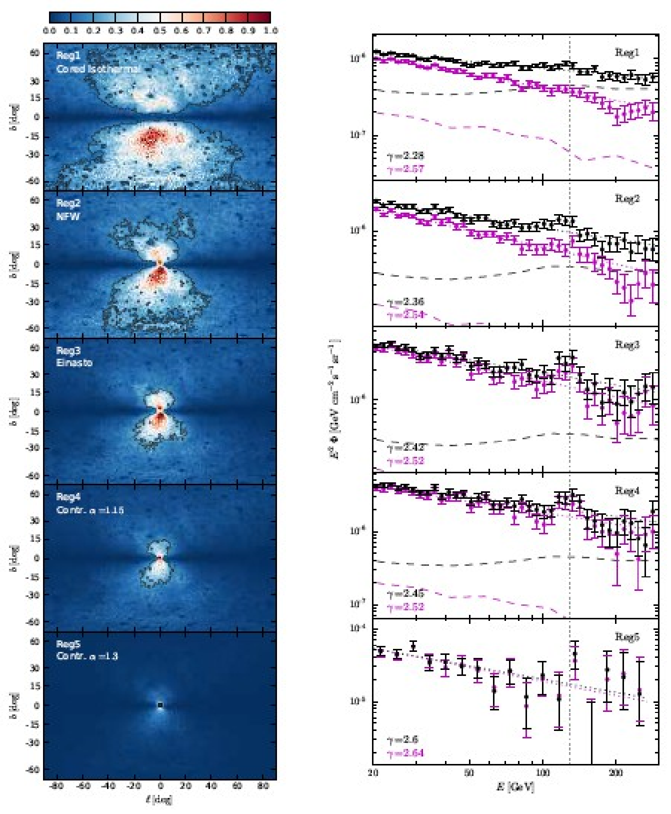
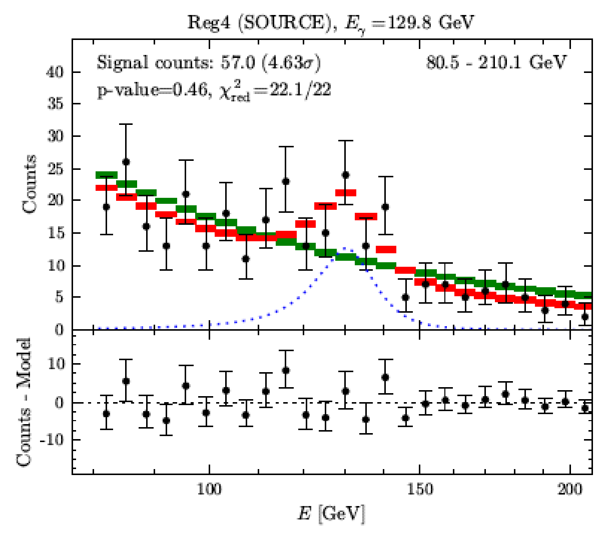
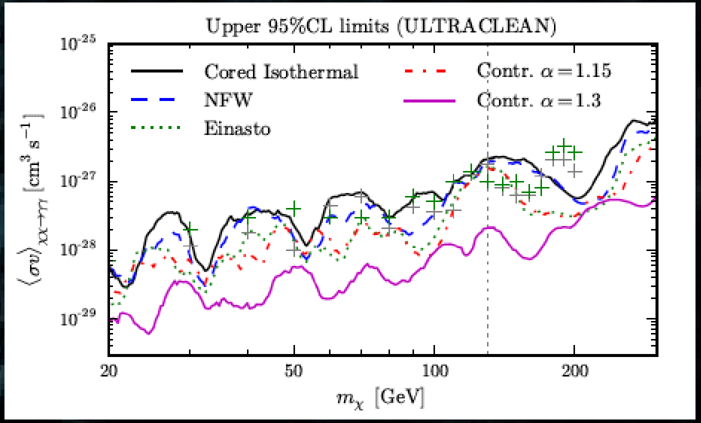
Weniger 12







Defining optimal regions: example of the 130 GeV line

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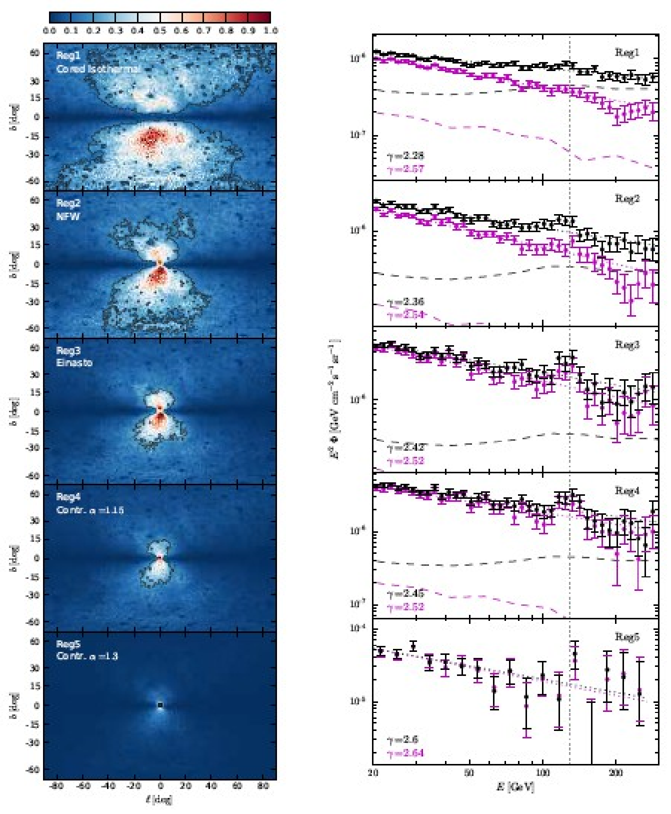
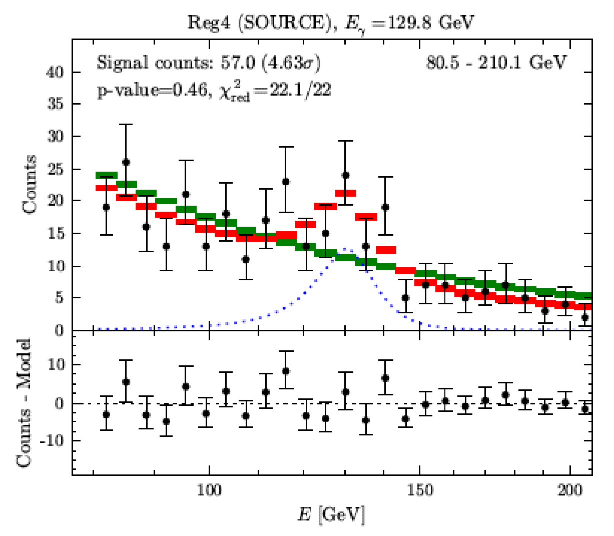
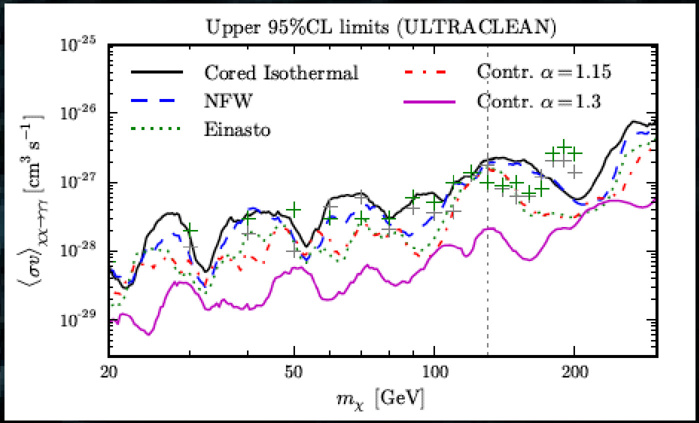
Weniger 12



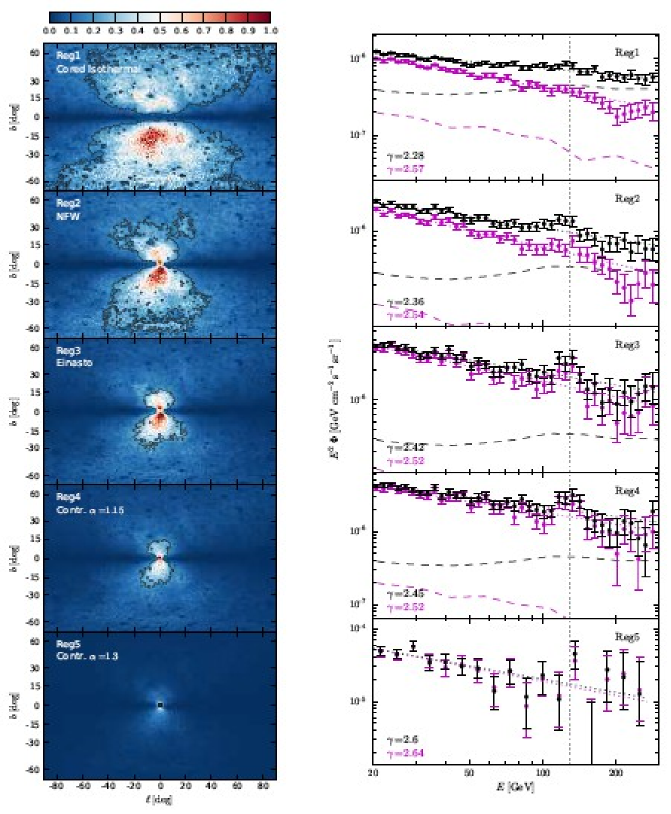




BUT:
- * a few events
- * same feature observed in albedo events (close to Earth)
- * systematic effects likely significant – hard to estimate

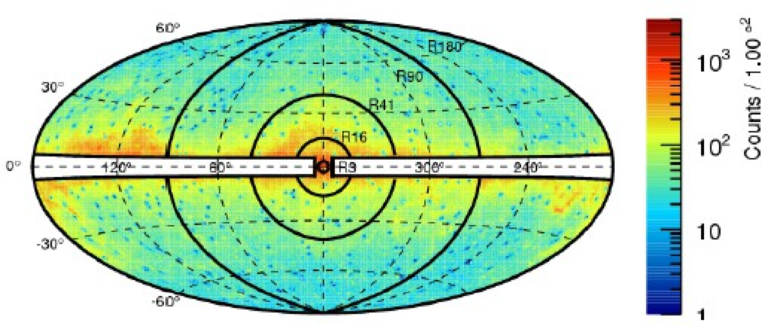
Defining optimal regions: example of the 130 GeV line

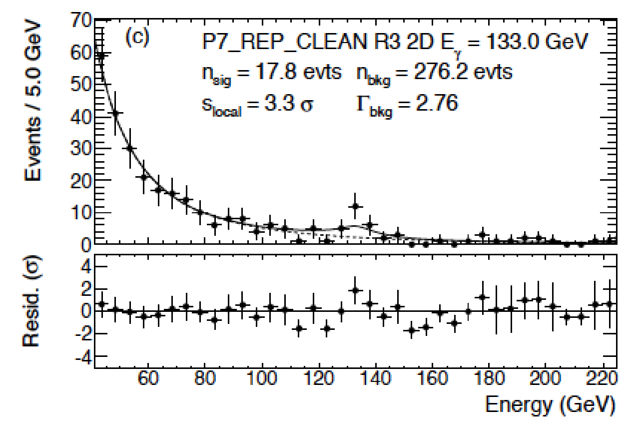
Weniger 12

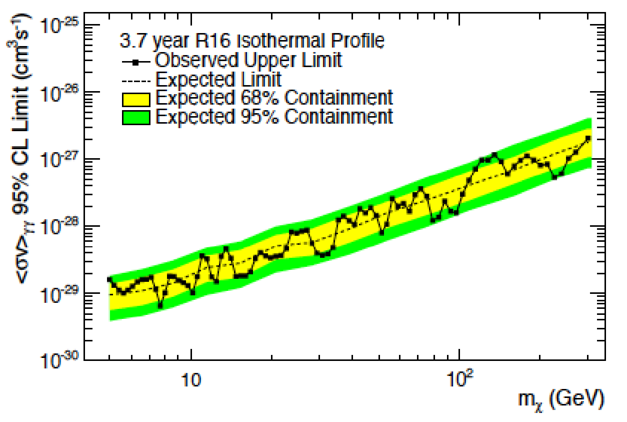


Status of 130 GeV line:
* no more significant
* but still something which cannot be due to known systematics
=> wait for data accumulation + new analysis (PASS8)

and …. HESS-2 !!!!







Fermi Collab. 13
(PASS6 → PASS7)

BUT:
* a few events
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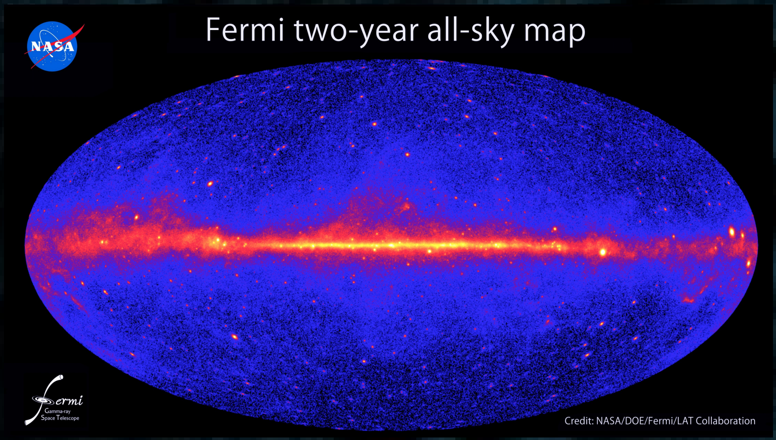
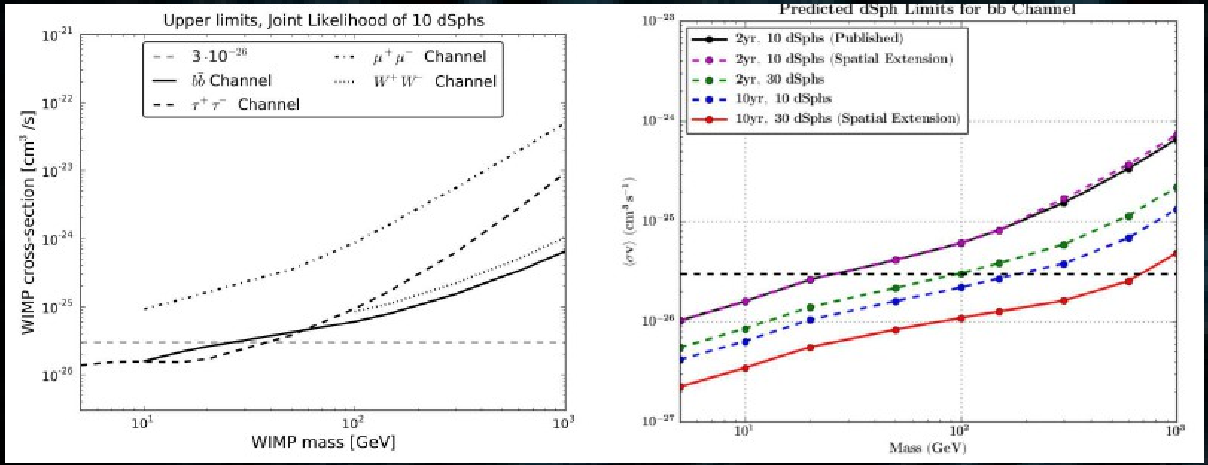
Indirect detection with gamma rays: Summary



Gamma-ray targets/features:

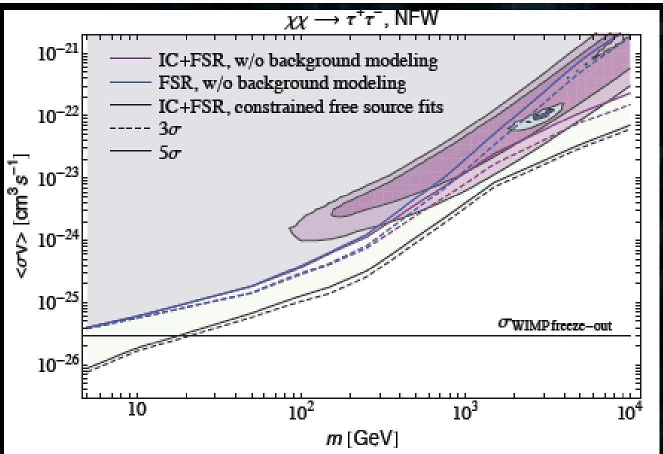
- Dwarf Spheroidal Galaxies: DM-dominated
- Galactic center
- Diffuse gamma-ray sky (high latitudes)
- Gamma-ray lines (all targets)

Best running experiment is Fermi (ACTs like HESS have larger energy thresholds and limited fields of view).



Constraints from DSphs:

- Geringer-Sameth & Koushiappas (11), Fermi collab. (11)
- Constraints on WIMP masses < 20-30 GeV (DM → tau leptons, quarks)
- Start probing WIMP parameter space
- Sensitivity will have increased by factor of 3 in 2018 => 100 GeV mass range within reach

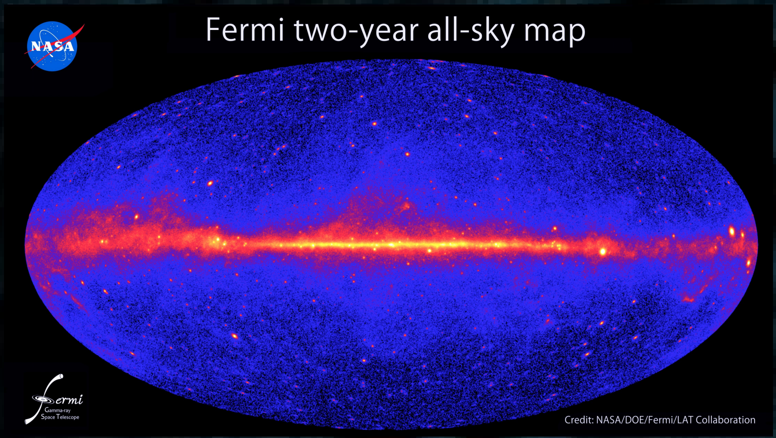


Fermi Collab (11-13)

Constraints from Diffuse emission (high-latitude constraints):

- Fermi collab. (12), Abazadjan++ (11-12), etc.
- Constraints on the so-called PAMELA region

Indirect detection with gamma rays: Summary



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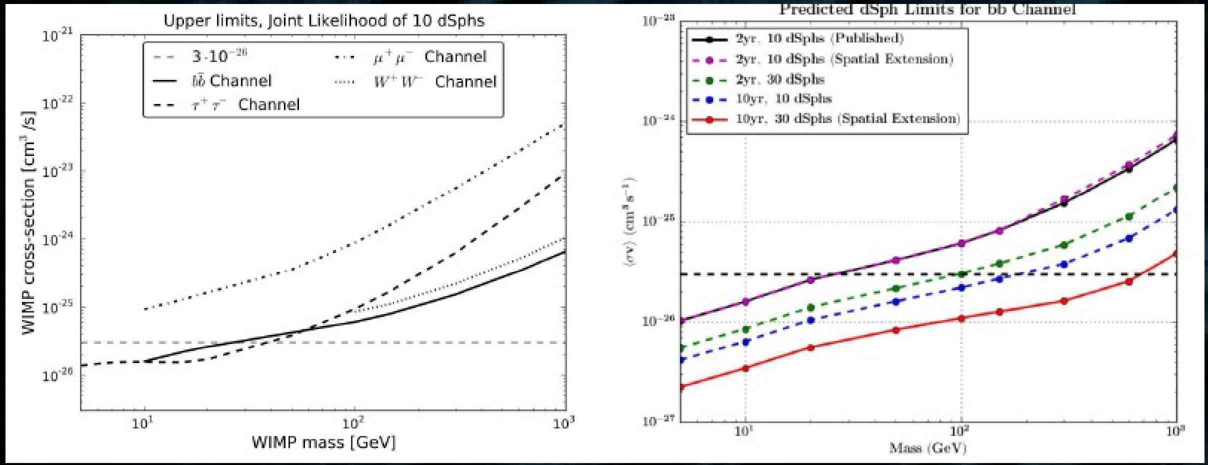

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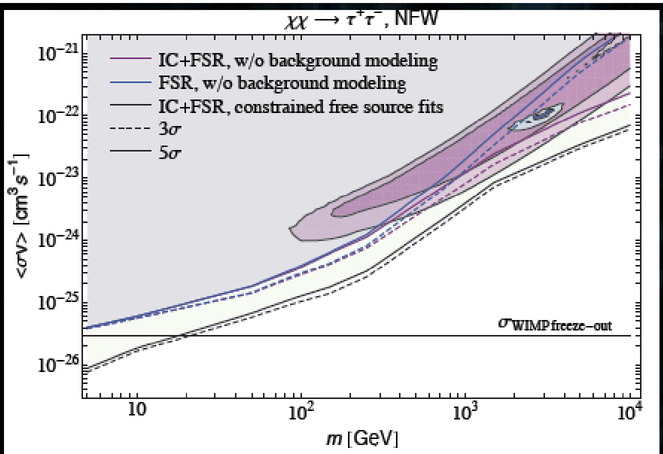


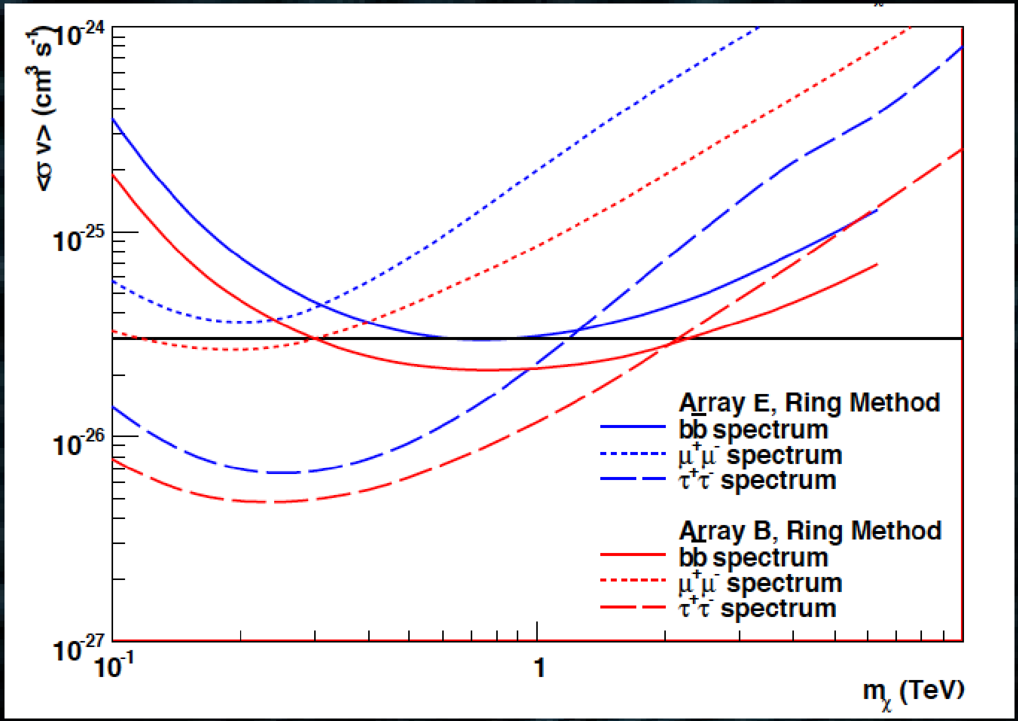
Extragalactic sources: galaxies and galaxy clusters
- M31 detected, some clusters scrutinized

… But: background contamination difficult to estimate
=> local is best for gamma-rays.

Future:
* Fermi until 2016/2018
* HESS-2
* Gamma-400 + CTA + ????

CTA sensitivity?

Doro++ 13 – central MW region



Survey of the GC region very important
=> CTA very competitive

Other targets more difficult (DSphG, etc.) –
Fermi likely better for those targets.

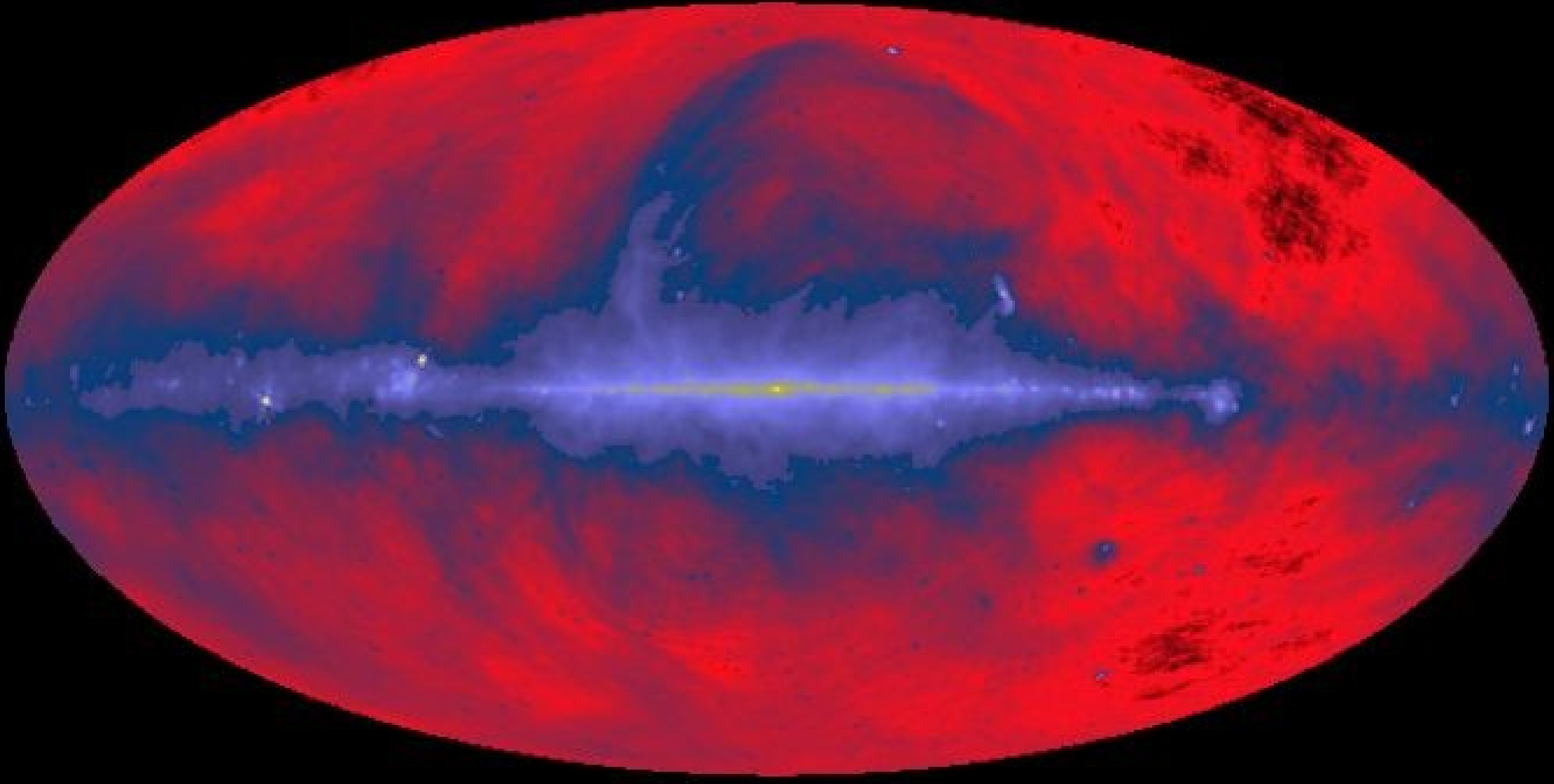
Indirect dark matter detection in the Milky Way

Antimatter cosmic rays

Bergström++
Bottino++
Salati++
Silk++

Transport of Galactic cosmic rays: The standard picture

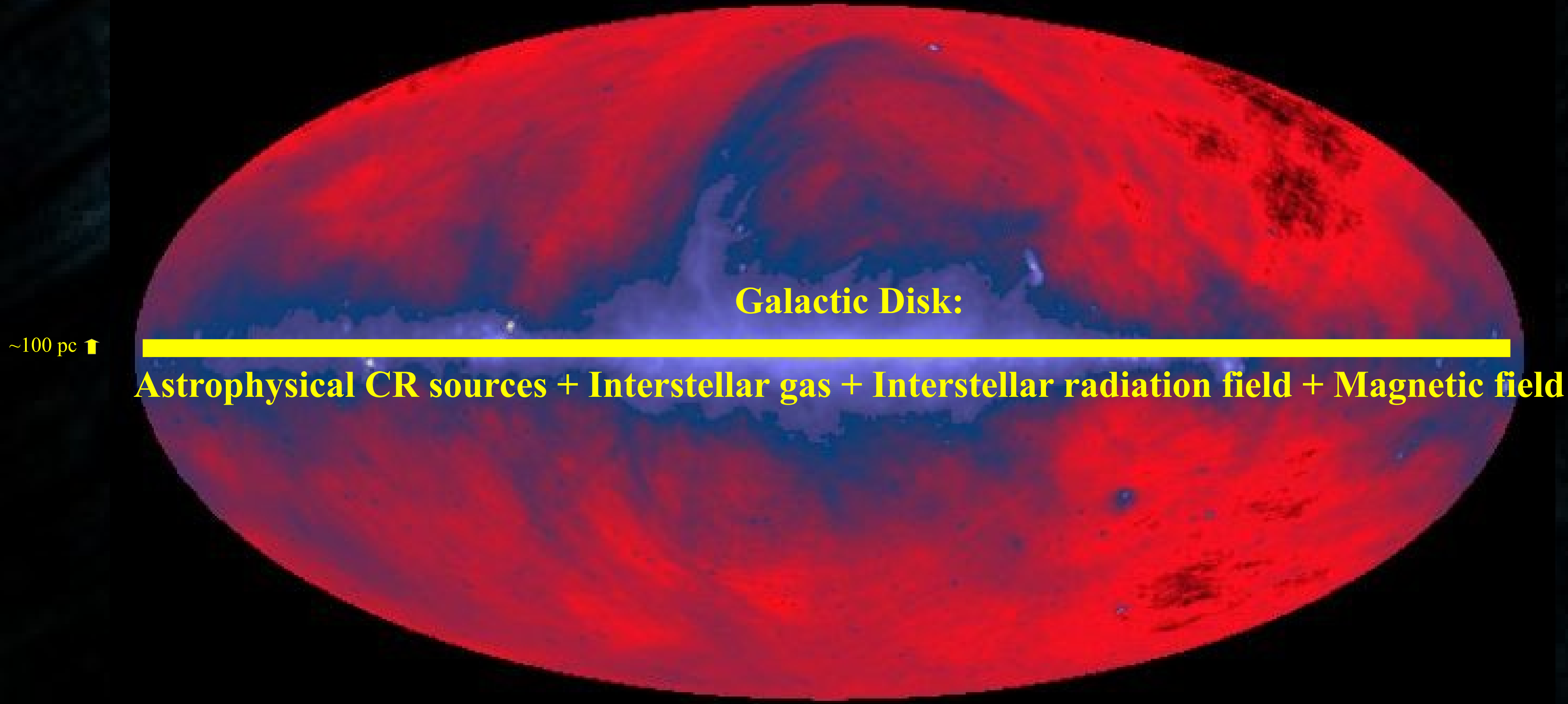
408 MHz all-sky map



From Haslam++ 82

Transport of Galactic cosmic rays: The standard picture

408 MHz all-sky map



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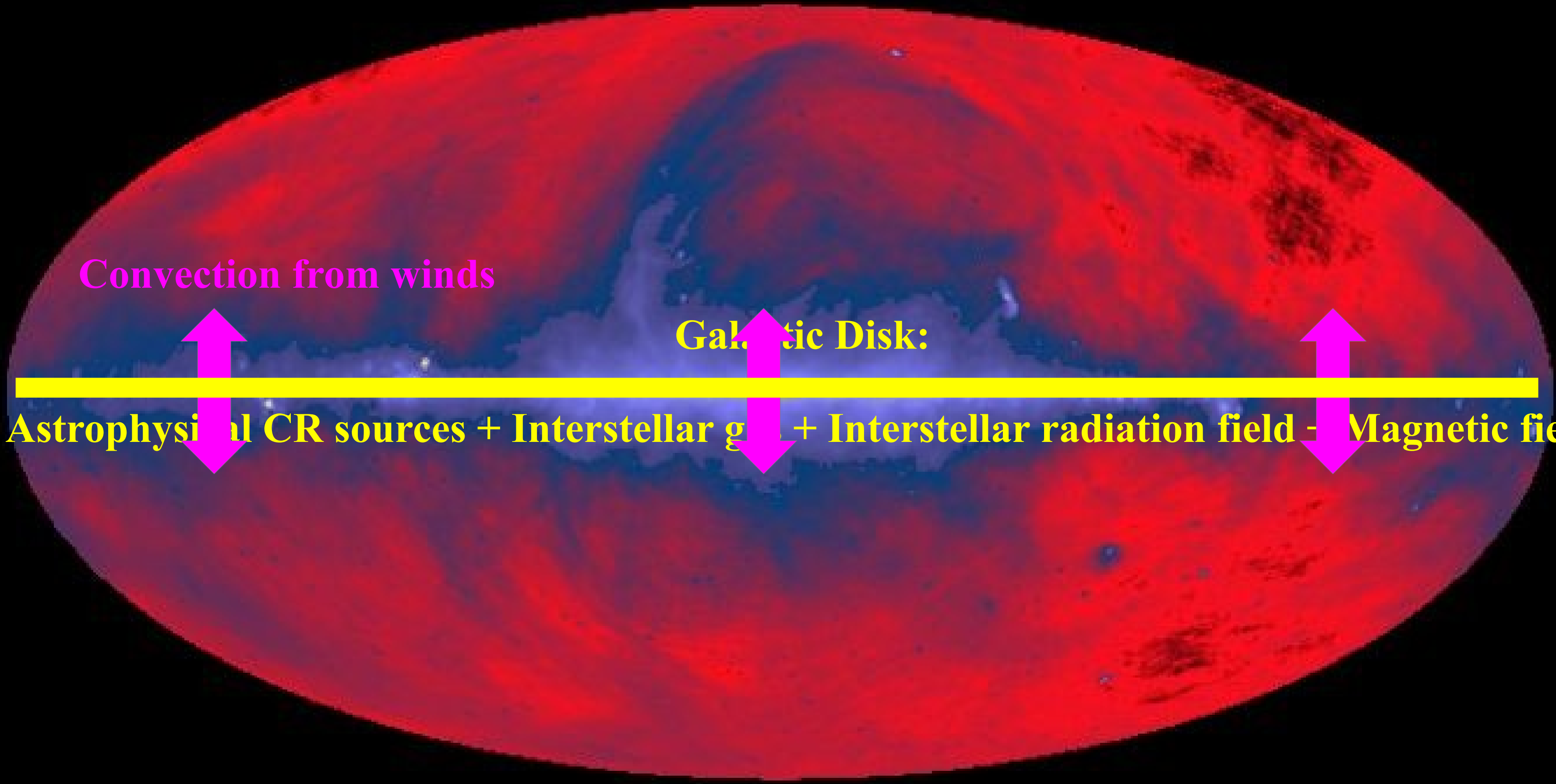


Convection from winds

Galactic Disk:

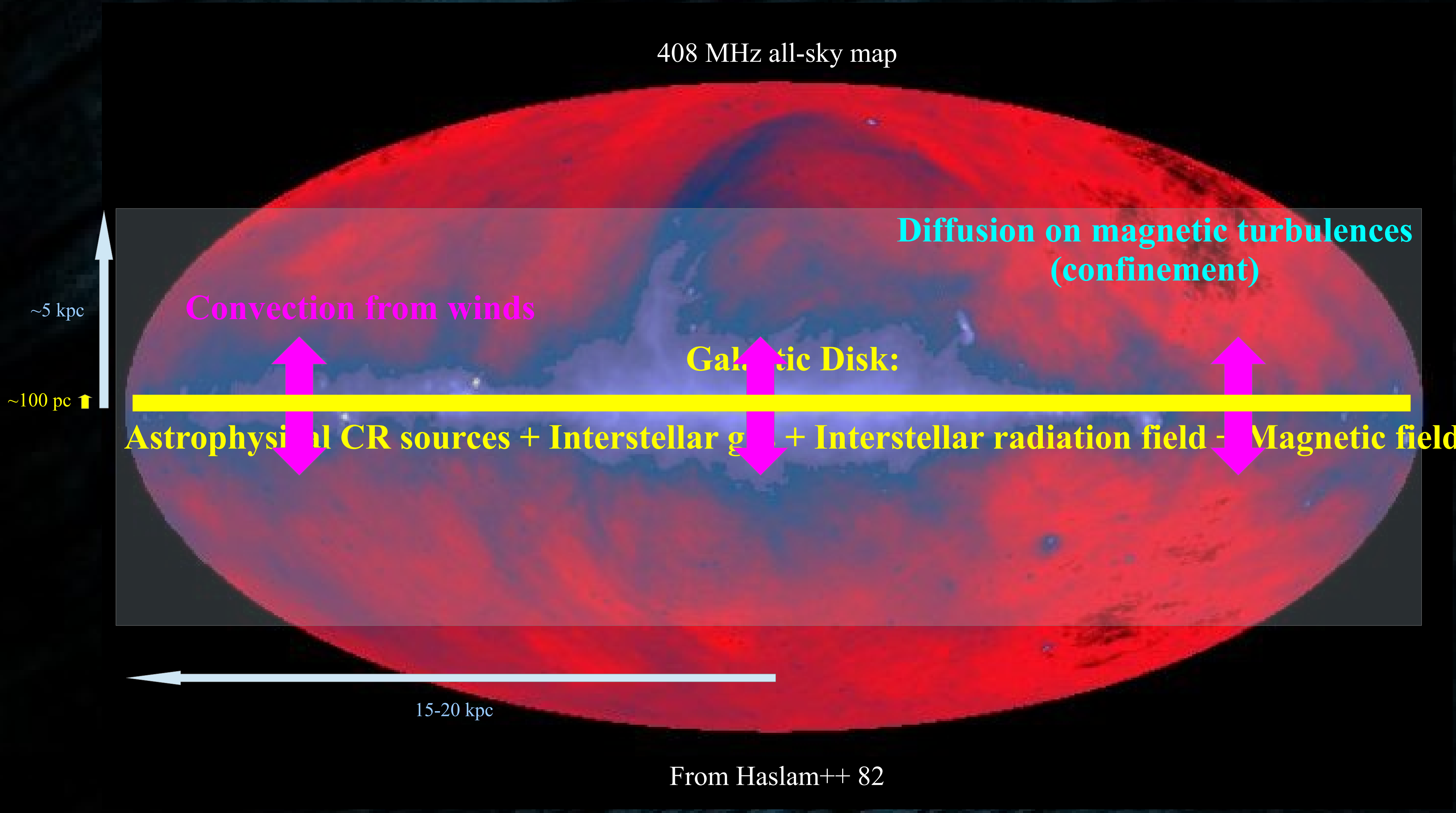
~100 pc

Astrophysical CR sources + Interstellar gas + Interstellar radiation field + Magnetic field

From Haslam++ 82

Transport of Galactic cosmic rays: The standard picture

408 MHz all-sky map



Diffusion on magnetic turbulences (confinement)

Convection from winds

Gal tic Disk:

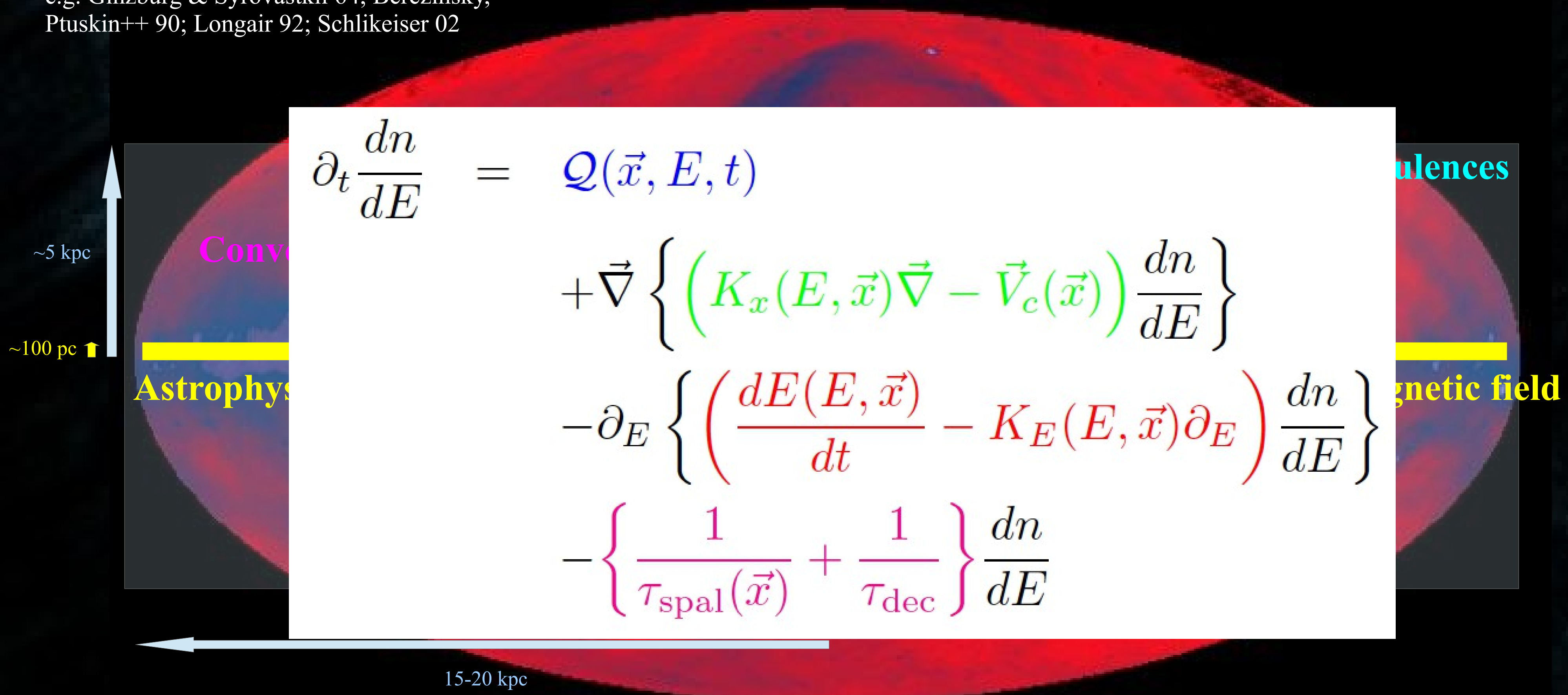
Astrophysi al CR sources + Interstellar g + Interstellar radiation field Magnetic field

From Haslam++ 82

Transport of Galactic cosmic rays: The standard picture

e.g. Ginzburg & Syrovastkii 64; Berezinsky, Ptuskin++ 90; Longair 92; Schlikeiser 02

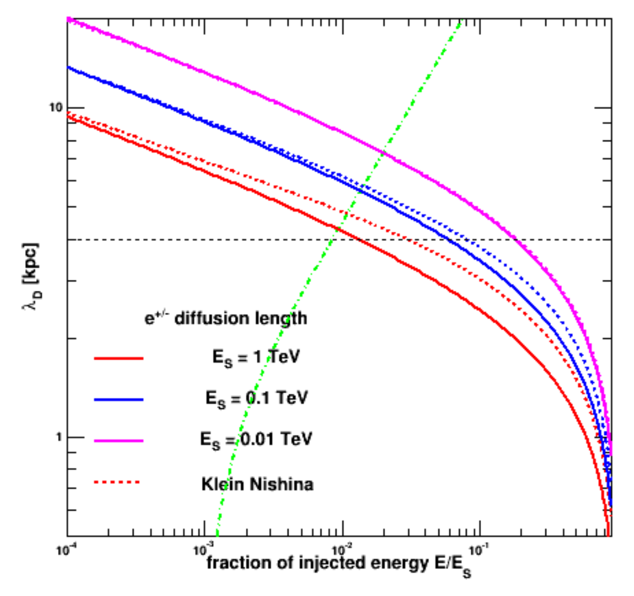
408 MHz all-sky map



$$
\begin{aligned}
\partial_t \frac{dn}{dE} = \; & \mathcal{Q}(\vec{x}, E, t) \\
& + \vec{\nabla}\left\{\left(K_x(E,\vec{x})\vec{\nabla} - \vec{V}_c(\vec{x})\right)\frac{dn}{dE}\right\} \\
& - \partial_E\left\{\left(\frac{dE(E,\vec{x})}{dt} - K_E(E,\vec{x})\partial_E\right)\frac{dn}{dE}\right\} \\
& - \left\{\frac{1}{\tau_{\mathrm{spal}}(\vec{x})} + \frac{1}{\tau_{\mathrm{dec}}}\right\}\frac{dn}{dE}
\end{aligned}
$$

From Haslam++ 82

Indirect detection with antimatter CRs



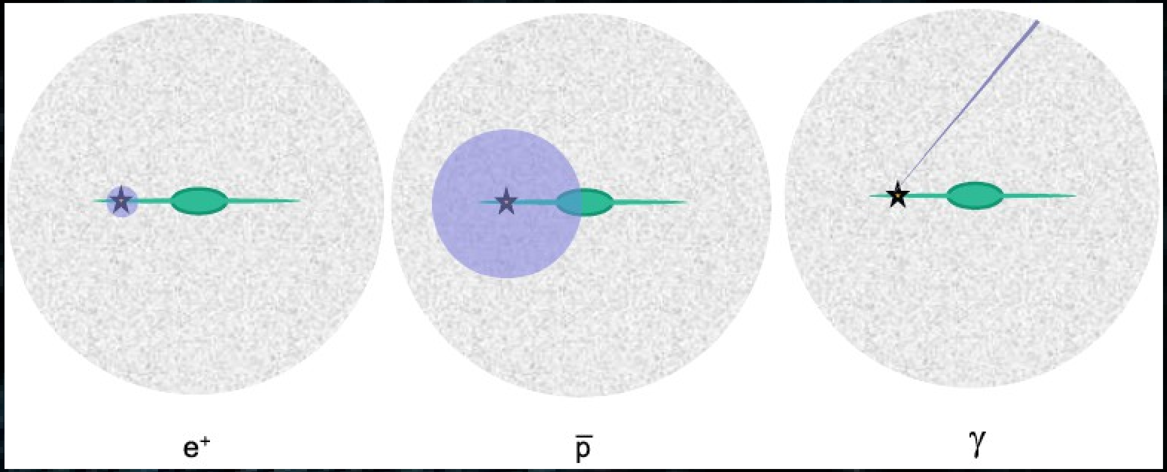
JL++ 08

2 types of messenger:
* “antinuclei”: antiproton / antideuteron
* positrons
=> different propagation properties.

Antinuclei: spatial diffusion + spallation + convection
Positrons: spatial diffusion + energy losses

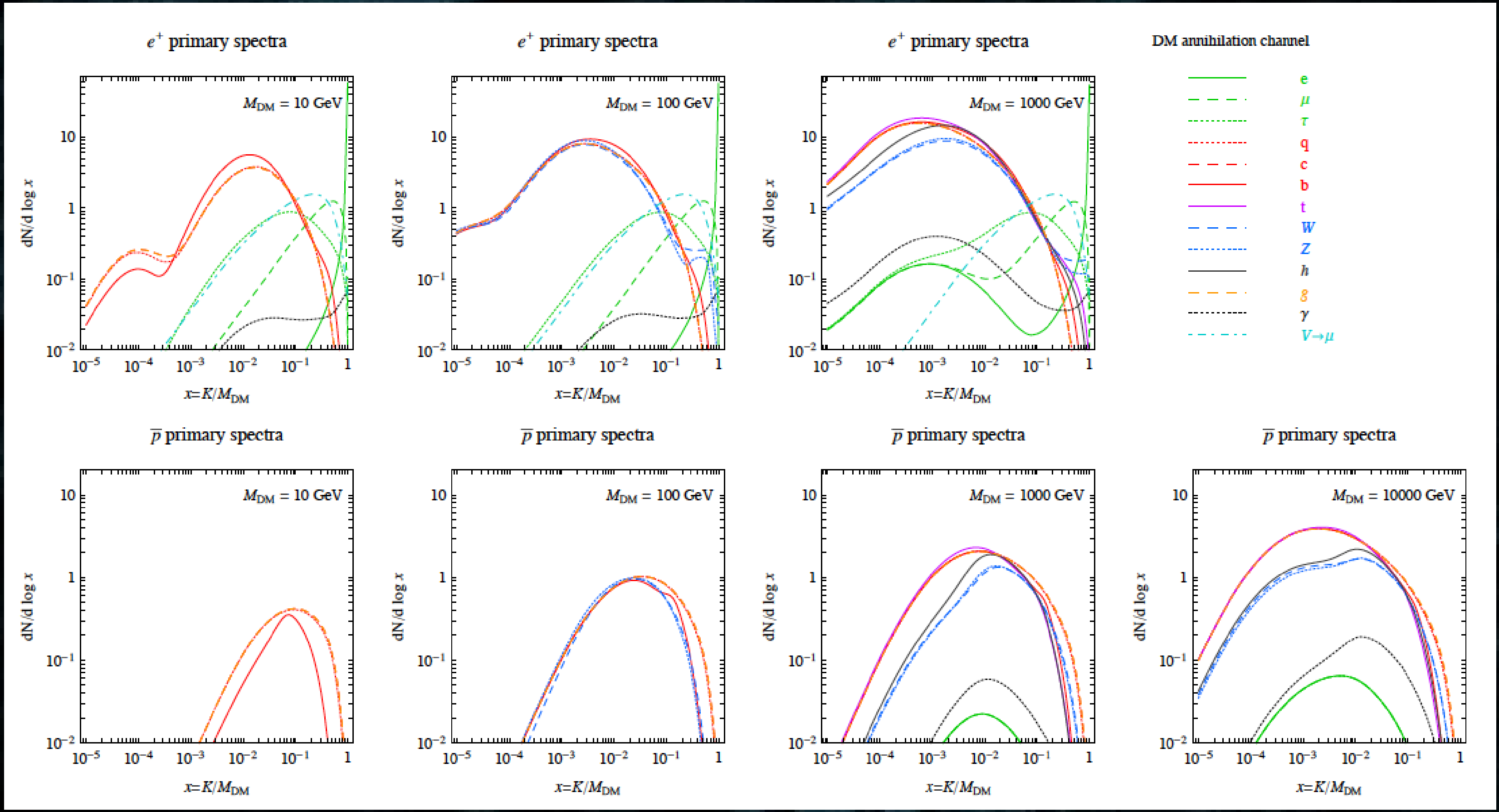
=> different propagation scales!
=> probe different parts of the MW
=> less sensitive to halo shape
NB: boundary effects when l>L or/and l>R

Bergström 09



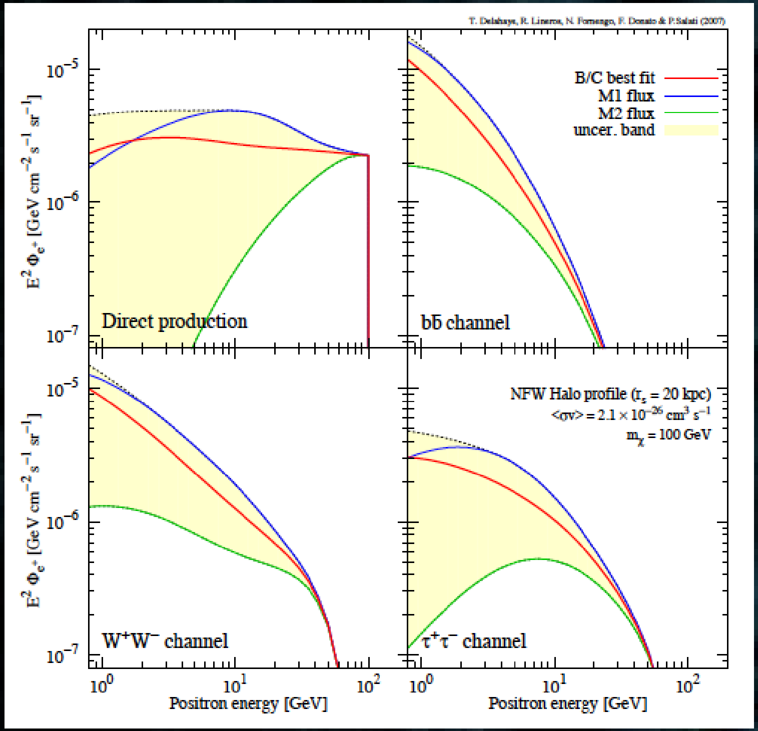
Annihilation spectra

Cirelli++ 10

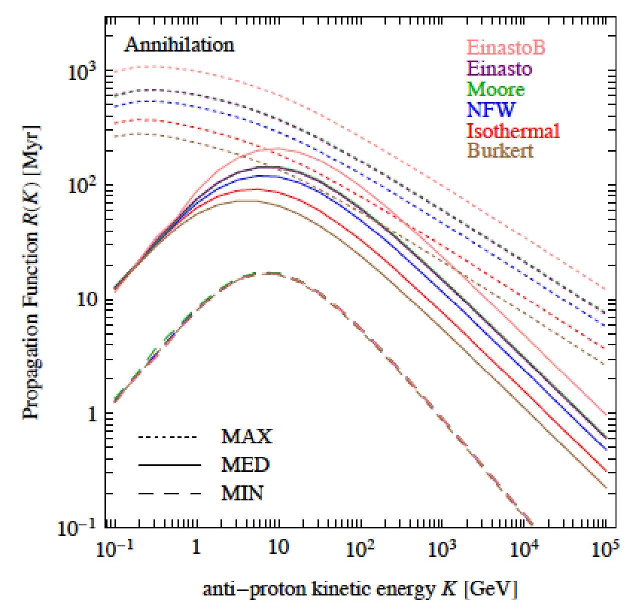


Propagated spectra

Delahaye++ 08



Cirelli++ 10



$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \underbrace{\frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2}_{\mathcal{S}} \int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\, \mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

Positrons:
* High-energy flux (close to WIMP mass) set by local quantities => independent of transport and halo shape.
* Low energy very sensitive to transport and halo shape (the latter if L permits)

Antiprotons:
* inherent large propagation scale above 1 GeV => more sensitive to transport and halo shape (depending on L)

Solving the transport equation

Two main approaches:

* Full numerical solvers (e.g. Galprop):

→ allow to include many details (spatial dependencies, different functional forms for diffusion coefficient, etc.)

→ but often used as a blackbox (loss of physical insight for non-expert, convergence check not automatic

* Semi-analytic methods:

→ catch the physics

→ fast for inferring theoretical uncertainties

2 main classes of semi-analytic methods:

* Green function approach

→ easy to use when possible

* Bessel expansions

→ rely on cylindrical symmetry assumption

→ suited for nuclei/antinuclei

$$\frac{\partial \psi}{\partial t} + \partial_z (V_C\, \psi) - K\, \Delta\psi + \partial_E \{ b^{\rm loss}(E)\, \psi - K_{EE}(E)\, \partial_E \psi \} = q(\mathbf{x}, E)$$

$$\psi(\mathbf{x}, E) \equiv \psi(r, z, E) = \sum_{i=1}^{+\infty} P_i(z, E)\, J_0(\alpha_i\, r/R)$$

$$\begin{gathered} \partial_z (V_C\, \bar{P}_i) - K\, \partial_z^2 \bar{P}_i + K \left\{ \frac{\alpha_i^2}{R^2} \right\} \bar{P}_i \\ + 2\, h\, \delta(z)\, \partial_E \left\{ b^{\rm loss}(E)\, \bar{P}_i - K_{EE}(E)\, \partial_E \bar{P}_i \right\} = \\ - 2\, h\, \delta(z)\, \Gamma_{\bar{\rm p}}^{\rm ann}\, \bar{P}_i + Q_{{\rm p},i}^{\rm prim}(z, E) + 2\, h\, \delta(z)\, \left\{ Q_{{\rm p},i}^{\rm sec} + Q_{{\rm p},i}^{\rm ter} \right\} \end{gathered}$$

$$\begin{gathered} \bar{\mathcal{A}}_i\, \bar{P}_i(0, E) + 2\, h\, \partial_E \left\{ b^{\rm loss}(E) \bar{P}_i(0, E) - K_{EE}(E)\, \partial_E \bar{P}_i(0, E) \right\} = \\ 2\, h\, \left\{ Q_{{\rm p},i}^{\rm sec} + Q_{{\rm p},i}^{\rm ter} \right\} + 2 \int_0^L dz\, Q_{{\rm p},i}^{\rm prim}(z, E)\, e^{-\dfrac{V_C z}{2K}}\, \mathcal{F}_i(z) \; . \end{gathered}$$

$$\bar{\mathcal{A}}_i(E) = V_C + 2\, h\, \Gamma_{\bar{\rm p}}^{\rm ann}(E) + K(E)\, S_i \coth \left\{ \frac{S_i L}{2} \right\}$$

$$\text{where} \quad S_i^2 = (V_C/K)^2 + (2\, \alpha_i/R)^2 \; ,$$

$$\mathcal{F}_i(z) = \sinh \left\{ \frac{S_i}{2} (L - z) \right\} / \sinh \left\{ \frac{S_i}{2} L \right\}$$

$$\left\{ -K\Delta + V_c \frac{\partial}{\partial z} + 2h\Gamma_{\rm tot}\delta(z) \right\} \mathcal{G}^{\,\rm p} = \delta(\boldsymbol{r} - \boldsymbol{r}').$$

$$\mathcal{G}_{\odot}^{p}(r, z) = \frac{\exp^{-k_v z}}{2\pi K L} \times \sum_{n=0}^{\infty} c_n^{-1} K_0 \left(r \sqrt{k_n^2 + k_v^2} \right) \sin\, [k_n L]\, \sin\, [k_n (L - z)]$$

$$2 k_n \cos k_n L = -k_d \sin k_n L,$$

$$c_n = 1 - \frac{\sin k_n L \cos k_n L}{k_n L}$$

$$k_v \equiv V_c/(2K) \quad \text{and} \quad k_d \equiv 2h\, \Gamma_{\rm tot}/K + 2k_v.$$

$$\lambda^2 \equiv 4 \int_E^{E_s} dE' \, \frac{K(E')}{b(E')}$$

$$\mathcal{G}_r(\boldsymbol{r}, E \leftarrow \boldsymbol{r}_s, E_s) = \frac{1}{\pi\, \lambda^2} \exp \left\{ - \frac{(\boldsymbol{r} - \boldsymbol{r}_s)^2}{\lambda^2} \right\}$$

$$\mathcal{G}_z(z, E \leftarrow z_s, E_s) = \sum_{n=-\infty}^{+\infty} \frac{(-1)^n}{\sqrt{\pi}\lambda} \exp \left\{ - \frac{(z - z_{s,n})^2}{\lambda^2} \right\}$$

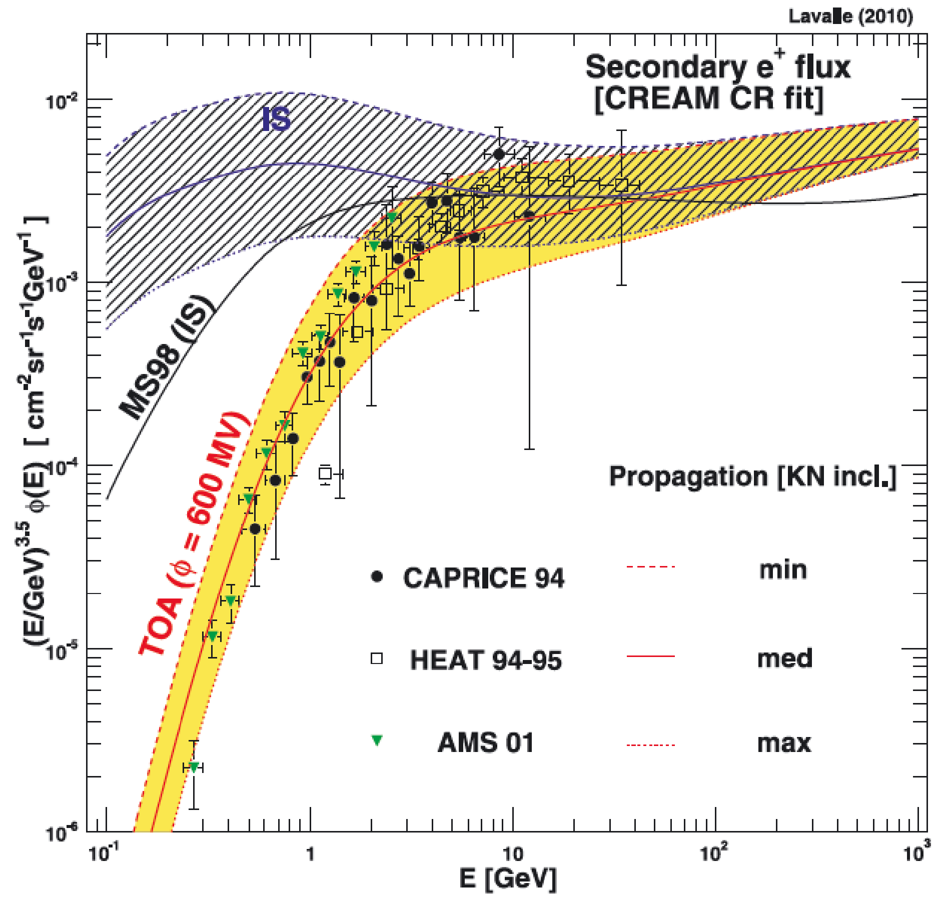
$$\mathcal{G}_z(z, E \leftarrow z_s, E_s) = \frac{1}{L} \sum_{n=1}^{+\infty} \left\{ e^{-\left[\frac{k_n \lambda}{2}\right]^2} \phi_n(z) \phi_n(z_s) + e^{-\left[\frac{k_n' \lambda}{2}\right]^2} \phi_n'(z) \phi_n'(z_s) \right\} ,$$

$$k_n = (n - 1/2)\pi/L \quad ; \quad k_n' = n\pi/L \; ;$$

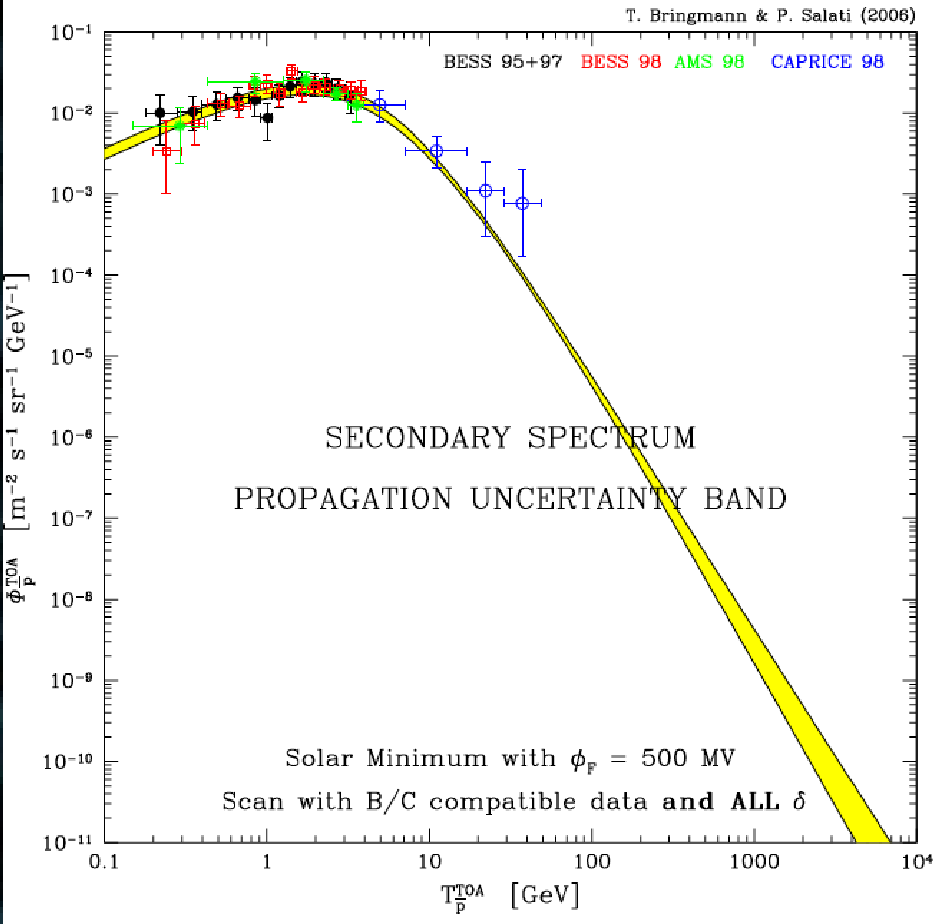
$$\phi_n(z) = \sin\, (k_n (L - |z|)) \quad ; \quad \phi_n'(z) = \sin\, (k_n' (L - z))$$

Backgrounds

Delahaye++ 09,
Lavalle 11



Bringmann & Salati 07



Positrons:

* good matching below 10 GeV, rather large uncertainties due to transport

* above 10 GeV ? 🙂

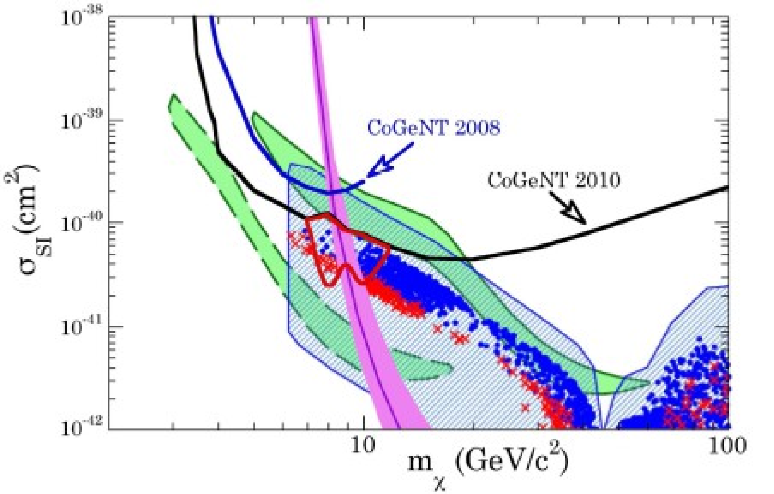
Antiprotons:

* very good matching to data

=> use them as constraints

Antiprotons as powerful constraints

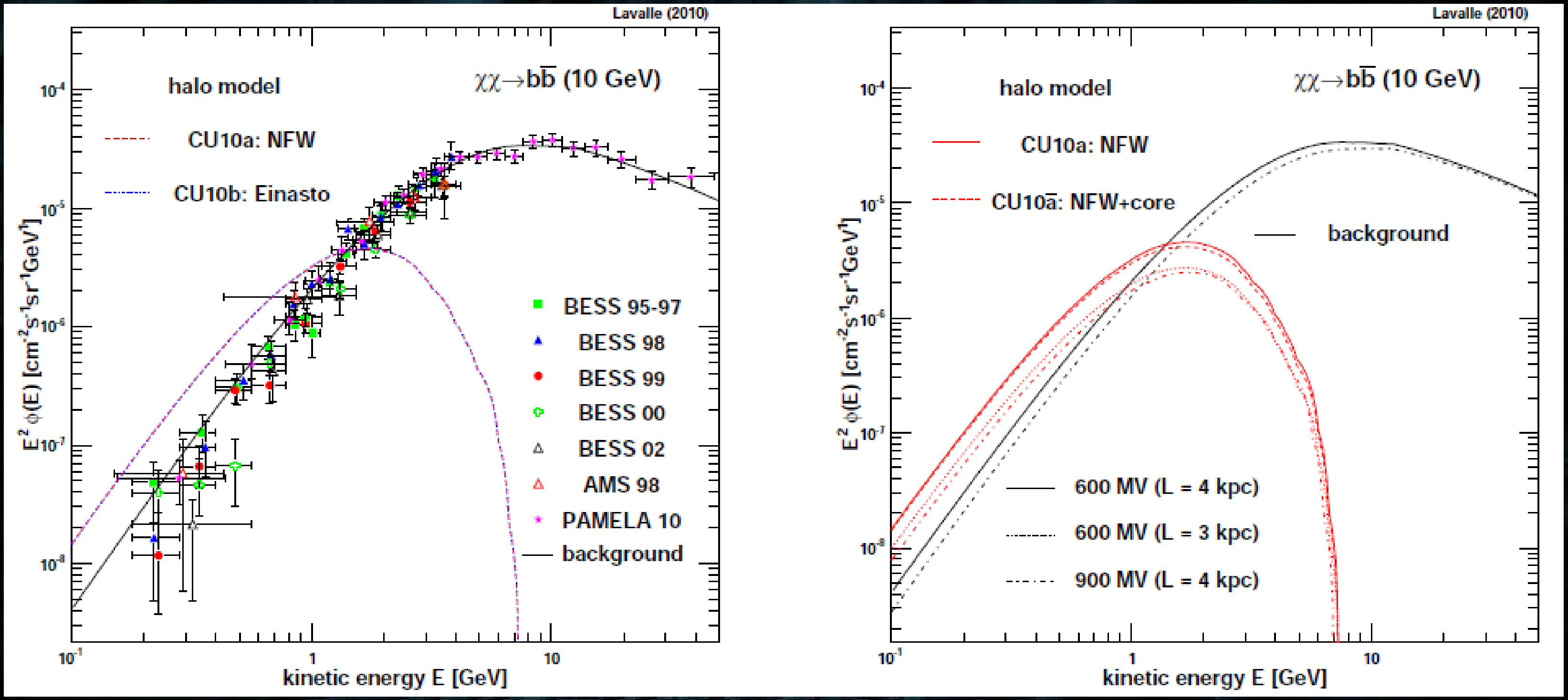
CoGeNT Collab (2010), Bottino+ (2010)



DAMA+CDMS+COGENT mass regions
(+ GC fit by Hooper++)
=> WIMP mass ~10 GeV

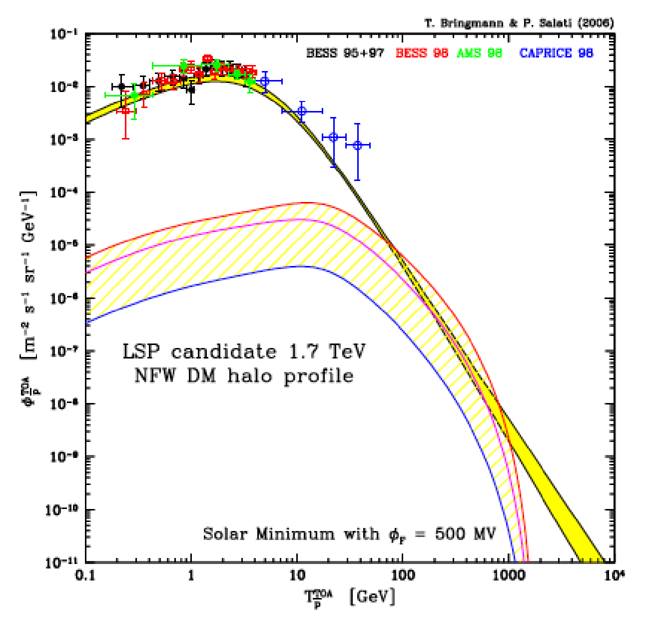
Couplings to quarks => annihilation may produce antiprotons (not generic for Majorana fermions, only s-wave contributions)
Large antiproton flux expected (scales like $1/m^2$)
** Uncertainties due to the size of the diffusion zone?

Lavalle 10



Back to the size of the diffusion zone

Bringmann & Salati (2007)



Maurin++ 01 & Donato++ 02
=> attempts to bracket theoretical uncertainties

Besides best fit transport model (dubbed *med*), proposal for 2 extreme configurations:

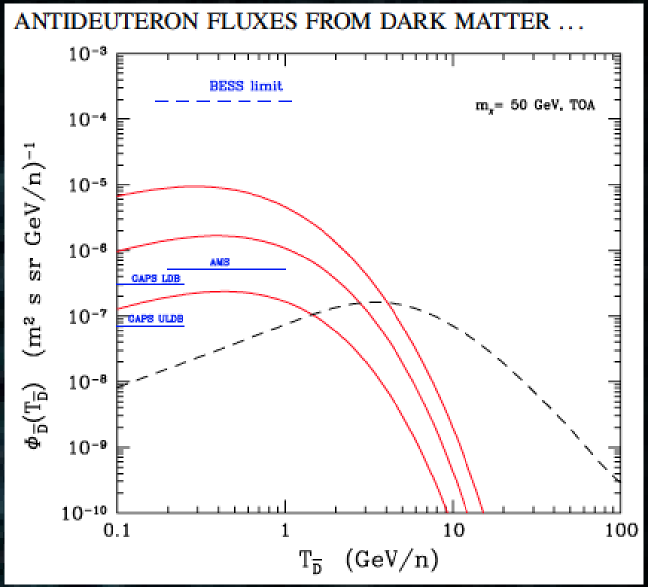
min: L = 1 kpc
max: L = 15 kpc

minimizing and maximizing the DM-induced fluxes, respectively.

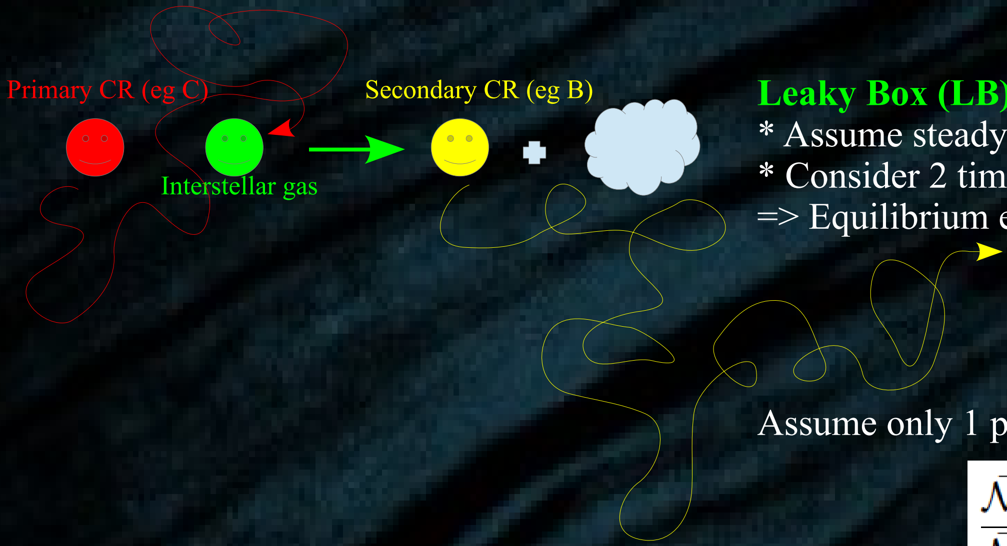
NB: much less effect on high-energy positrons (Lavalle++ 07, Delahaye++ 08) – short propagation scale.

The game people usually play:
1) you want your model to survive antiproton constraints:
=> take a small L
2) you want to advertise your model for detection:
=> take L from med to max.

Maurin, Donato, Fornengo (2008)



Where do constraints on L come from?



Leaky Box (LB) model: the simplest approach.
* Assume steady state, forget about specific diffusion zone.
* Consider 2 timescales: escape from Galaxy + spallation timescale
=> Equilibrium equation (Ni averaged CR density for species labelled i):

$$\frac{\bar{N}_i}{\tau_{\rm esc}} + \frac{\bar{N}_i}{\tau_i} = Q_i + \sum_j \frac{\bar{N}_j}{\tau_{j\to i}}$$

Assume only 1 primary (p) and 1 secondary species (s), write down s/p:

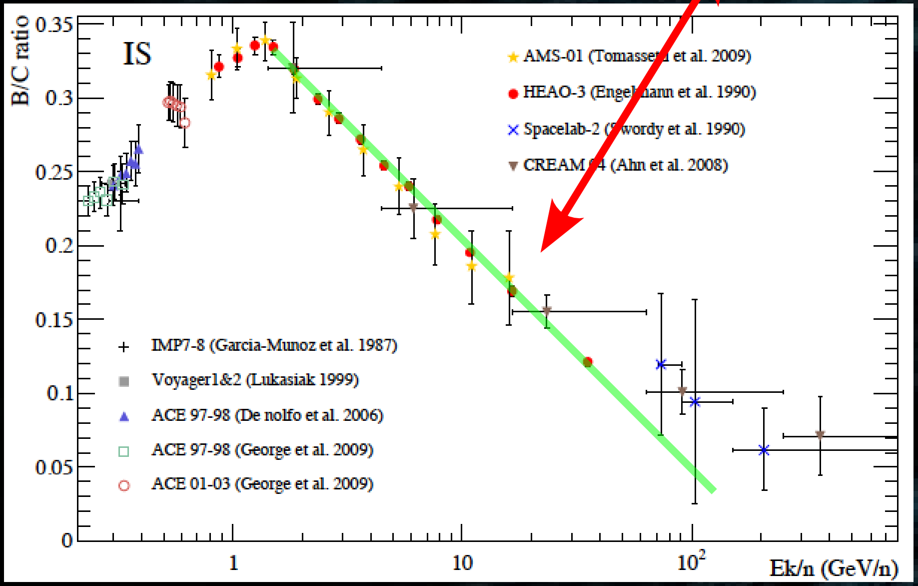
$$\frac{\bar{N}_s}{\bar{N}_p} = \frac{\tau_s\,\tau_{\rm esc}}{\tau_p\,(\tau_{\rm esc}+\tau_s)} \xrightarrow{\tau_{\rm esc}\ll\tau_s} \frac{\tau_{\rm esc}(E)}{\tau_p}$$

Compare with data:

$$\tau_{\rm esc}(E) \propto \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{-\delta}$$

~ 20 Myr (1 GeV/n)

Putze++ 11



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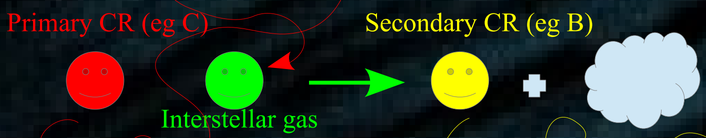

Small-scale example of a
potentially leaky box ...

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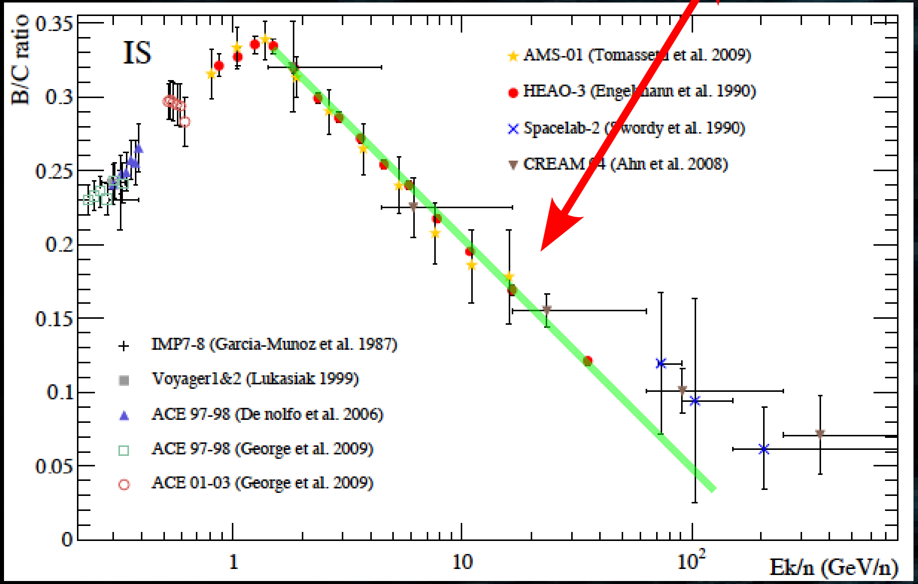

Where do constraints on L come from?

Leaky Box (LB) model: the simplest approach.

* Assume steady state, forget about specific diffusion zone.

* Consider 2 timescales: escape from Galaxy + spallation timescale

=> Equilibrium equation (Ni averaged CR density for species labelled i):

$$\frac{\bar{\mathcal{N}}_i}{\tau_{\rm esc}} + \frac{\bar{\mathcal{N}}_i}{\tau_i} = \mathcal{Q}_i + \sum_j \frac{\bar{\mathcal{N}}_j}{\tau_{j\to i}}$$

Assume only 1 primary (p) and 1 secondary species (s), write down s/p:

$$\frac{\bar{\mathcal{N}}_s}{\bar{\mathcal{N}}_p} = \frac{\tau_s\,\tau_{\rm esc}}{\tau_p\,(\tau_{\rm esc}+\tau_s)} \xrightarrow{\tau_{\rm esc}\ll\tau_s} \frac{\tau_{\rm esc}(E)}{\tau_p}$$

Small-scale example of a potentially leaky box ...

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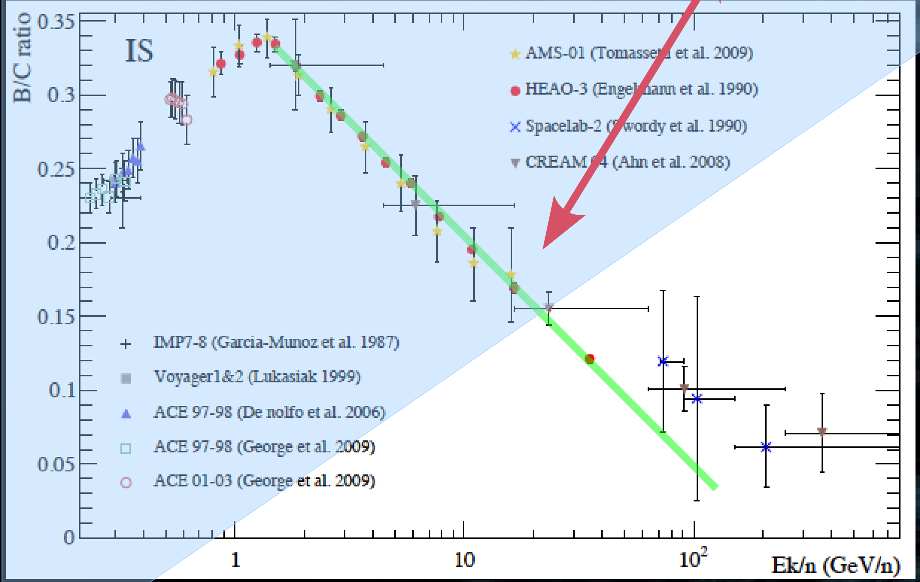
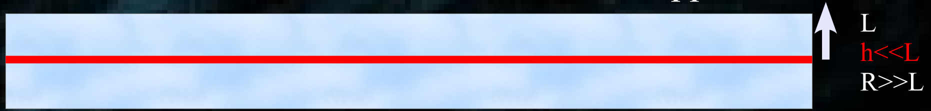
Putze++ 11



1D diffusion model: the next-to-mininal approach



* Assume steady state, specify diffusion zone (boundary conditions).

* Consider isotropic/homogeneous diffusion + realistic spallation

=> Diffusion equation (for a primary species):

$$-K(E)\frac{d^2\mathcal{N}}{dz^2} + 2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N} = 2\,h\,\delta(z)\,q$$

Solve for z≠0, reinject in diff. eq., then integrate over z in vanishing slice ±ε:

$$\begin{cases} \mathcal{N}(z) = \mathcal{N}(0)\,\frac{L-|z|}{L} \\ \frac{K(E)}{h\,L}\,\mathcal{N}(0) + n_{\rm ism}\,v\,\sigma\,\mathcal{N}(0) = q \end{cases}$$

Clear analogy with escape =>

$$\tau_{\rm esc}(E) = \frac{h\,L}{K(E)}$$

Diffusion coefficient amplitude degenerate with diffusion halo size L!

Breaking degeneracies?

→ Use secondary CR species that do not reach boundaries!

→ Radioactive species as cosmic clocks! (lifetime < residence time ~ 20 Myr)

Diffusion equation for radioactive secondary CRs (neglect spallation):

$$-K(E)\frac{d^2\mathcal{N}_r}{dz^2} + \frac{\mathcal{N}_r}{\tau_{\rm dec}} = 2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N}$$

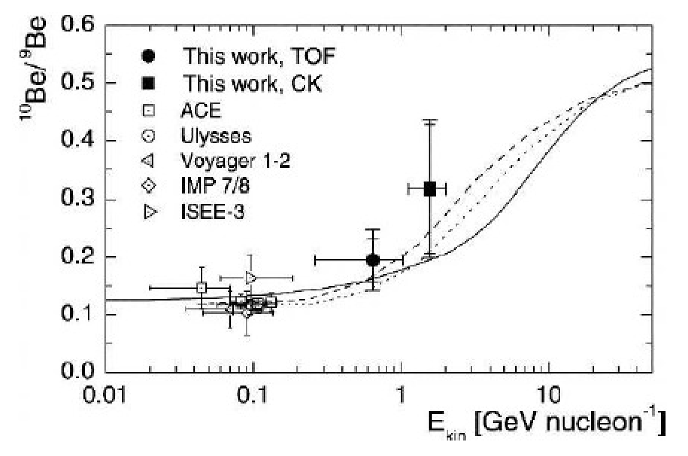
If $\sqrt{K(E)\,\tau_{\rm dec}} \ll L$ then:

$$\begin{cases} \mathcal{N}_r(z) = \mathcal{N}_r(0)\,\exp\left\{-\frac{|z|}{\sqrt{K(E)\tau_{\rm dec}}}\right\} \\ \frac{\mathcal{N}_r(0)}{\mathcal{N}(0)} = \frac{h\,n_{\rm ism}\,\sigma\,v}{\sqrt{K(E)\tau_{\rm dec}}} \end{cases}$$

K(E) / L degeneracy broken!

=> K(E)/L from stable secondaries, then K(E) from radioactive (e.g. Strong++ 07)

Strong++ 07



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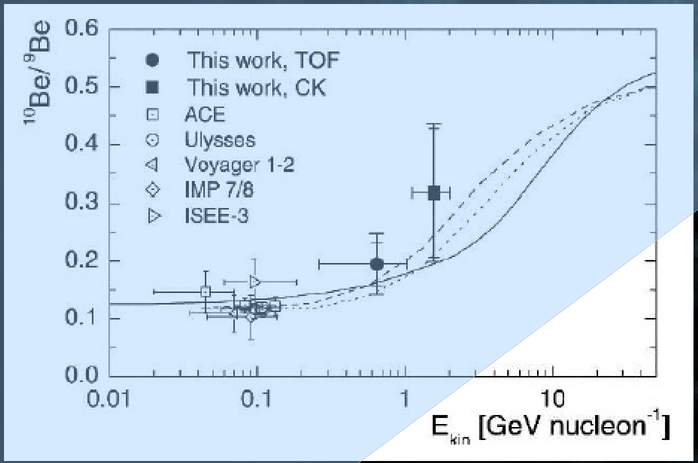
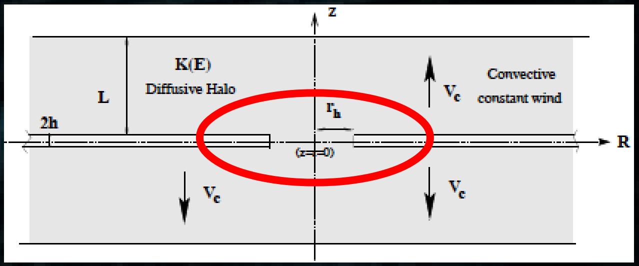
Strong++ 07



1D model with local bubble (void)
Putze++ 11



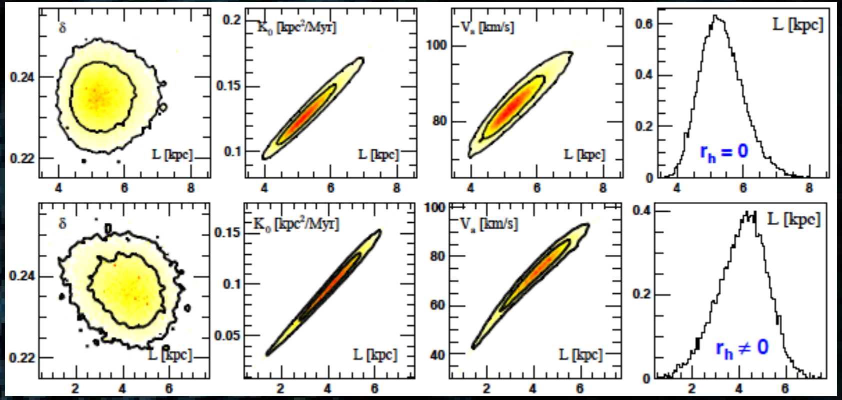
CAVEATS:

* Low quality data (difficult measurements)

* Propagation length scale ~ 100 pc => must account for details of the ISM down to this scale

=> local under-dense region (dubbed "local bubble", e.g. Cox 97)

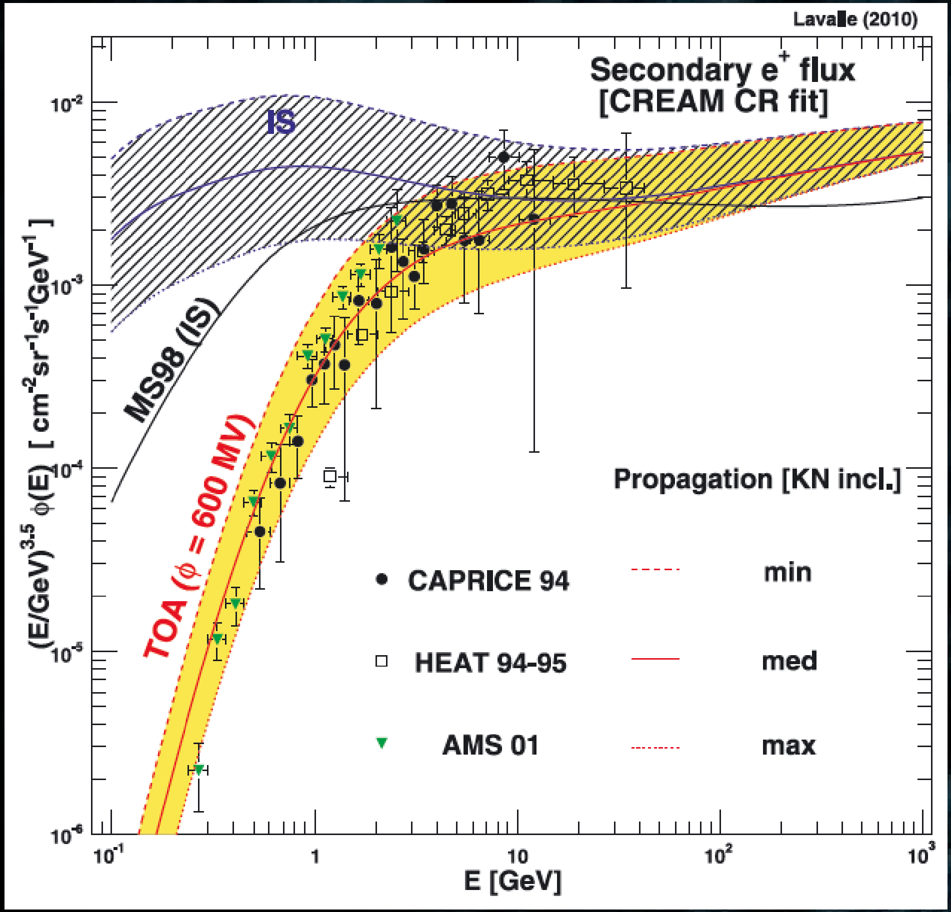
=> impact on transport parameter estimates (e.g. Donato++ 02; Putze++ 11)



Uncertainties in the diffusion halo size? (digression to positrons)

Secondary positrons
(eg. Delahaye++09, Lavalle 11)

$$\phi_{e^+} \propto 1/\sqrt{K_0}$$



$$\frac{K_0}{L} \approx \mathrm{Cst}$$

Small L models in tension with positron data

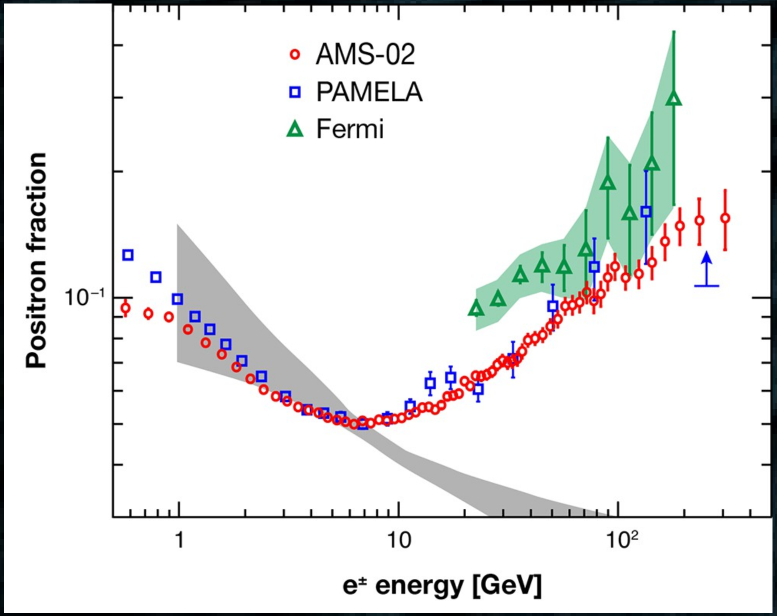
=> L > 1 kpc => Very conservative statement!

Perspectives:

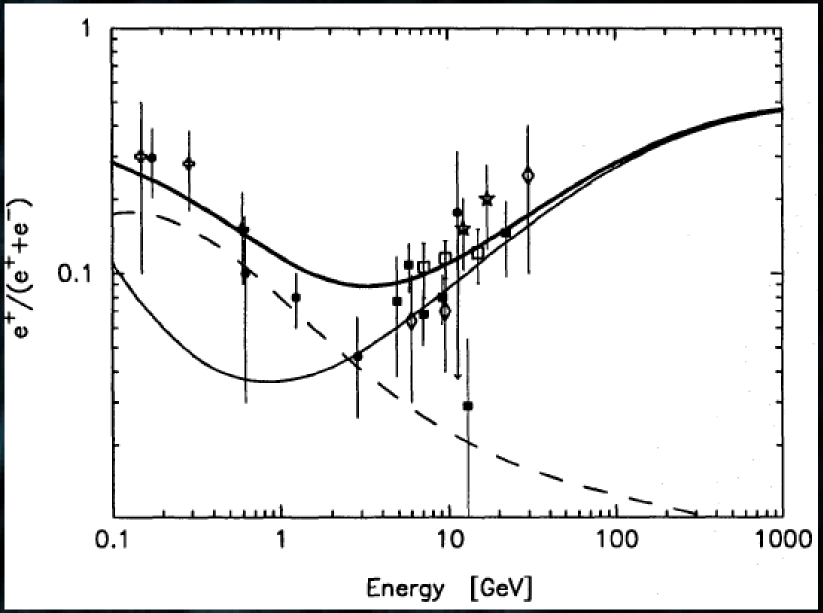
- PAMELA/AMS data still to come

=> Ongoing work with Maurin and Putze

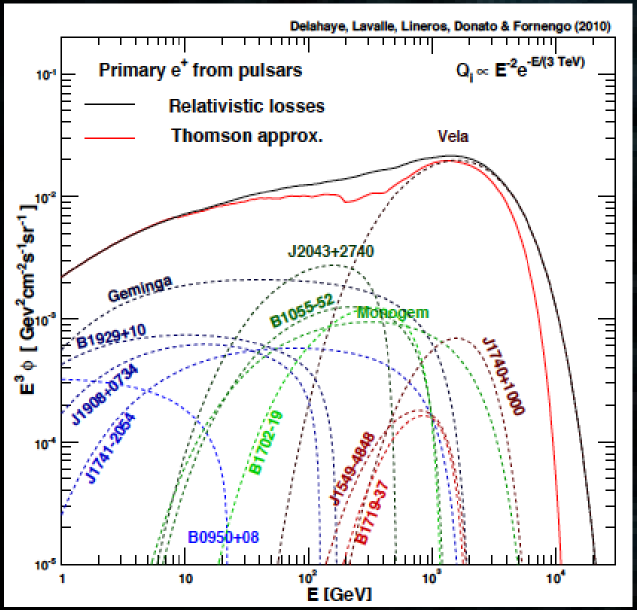
The positron fraction



AMS Collab (2013)



Aharonian++ 95



We know pulsars can make it in principle.
Going to realistic modeling is complicated (eg Delahaye++ 10).
=> separate distant/local sources, and accommodate the full data (e-, e+, e+e-, e+/e+e-) …

=> Pulsar wind nebulae (PWNe) as positron/electron sources
=> SNRs as electron sources (each PWN must be paired with an SNR)

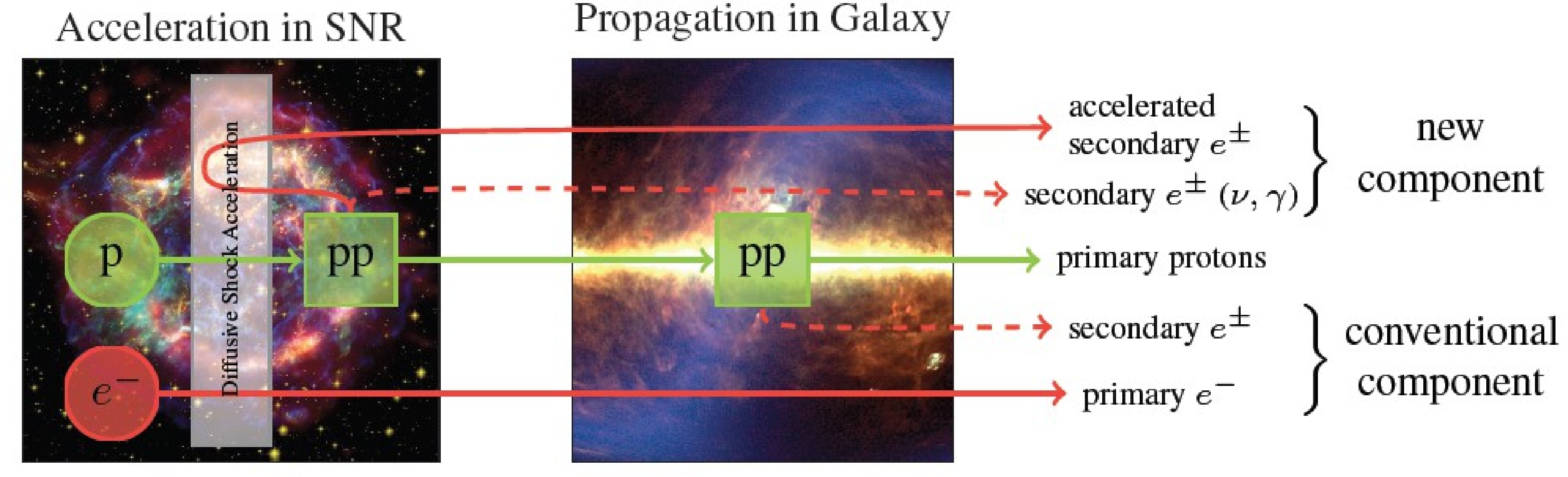
=> you may fit amplitudes / spectral indices … then what?

** Observational constraints!

=> use pulsar period, multiwavelength data for all observed sources … but … not that simple.

Other astrophysical solution(s)

Secondaries generated in SNRs are accelerated like primaries:
Berezhko++ 03, Blasi 09, Blasi & Serpico 09,
Mertch & Sarkar 09, Ahler++ 09


Acceleration in SNR

Propagation in Galaxy

accelerated secondary $e^\pm$

secondary $e^\pm$ (ν, γ)

} new component

primary protons

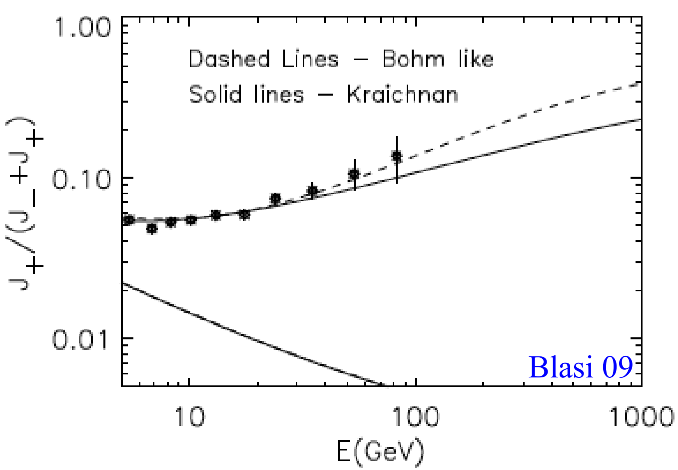
secondary $e^\pm$

primary e^-

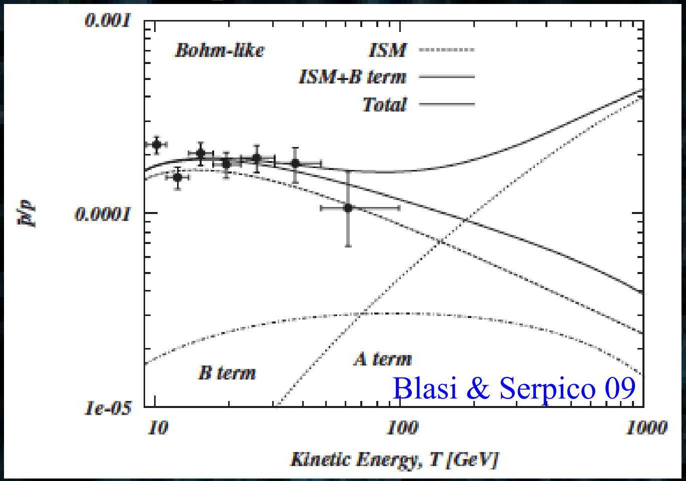
} conventional component

(from Ahler++ 09)

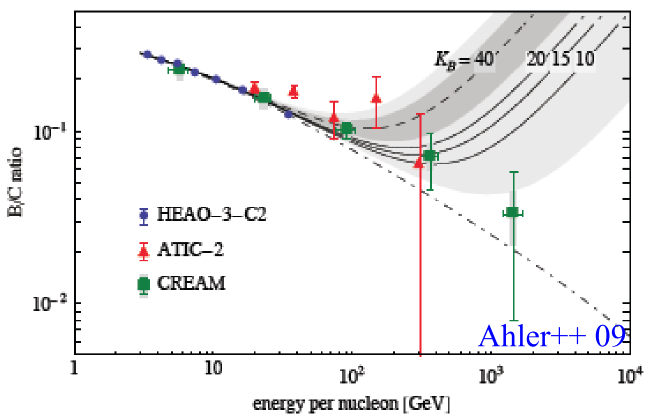
Positron fraction



Antiproton fraction



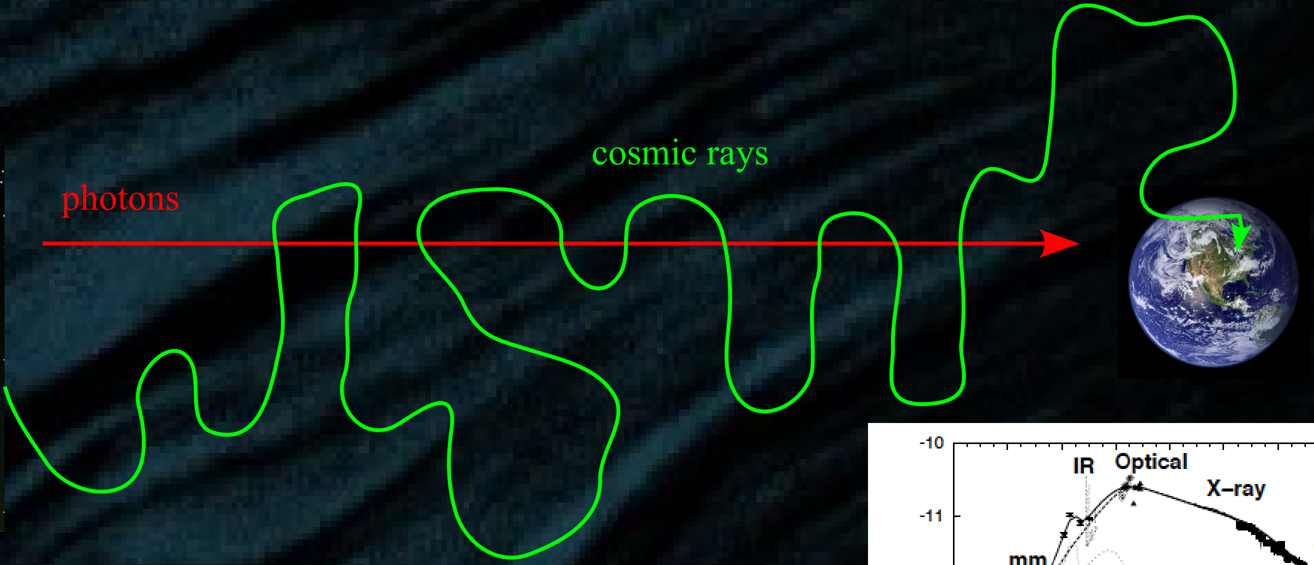
B/C ratio



Associated signatures: rising antiproton fraction (like DM) and B/C ratio

Modeling the electron/positron sources?

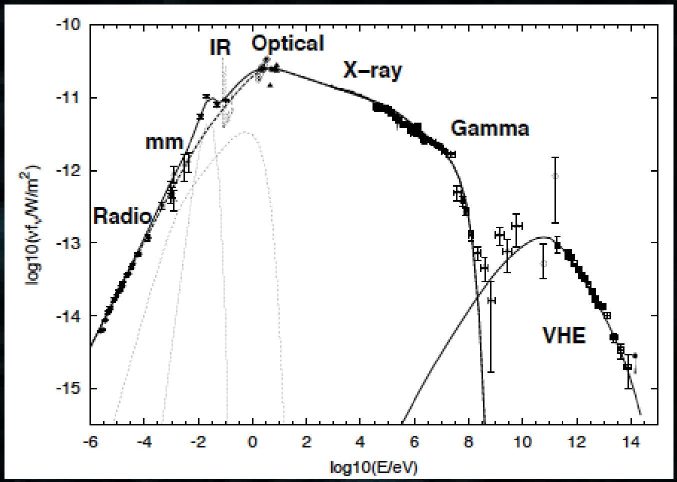
Crab nebula (ESA)
(just for illustration,
not relevant for e+/e-)



$$\text{photon obs. time} = \frac{d}{c} \approx 300\,\text{yr} \left[\frac{d}{100\,\text{pc}}\right]$$

$$\text{transport time} \approx \frac{d^2}{K(E)} \approx 30\,\text{kyr} \left[\frac{E}{1\,\text{TeV}}\right]^{-1/2} \left[\frac{d}{100\,\text{pc}}\right]^2$$

$$\text{E-loss time} \quad = \int_E^{E_s} dE'\, b(E') \approx 300\,\text{kyr @ 1 TeV}$$



Horns & Aharonian 04
Crab SED

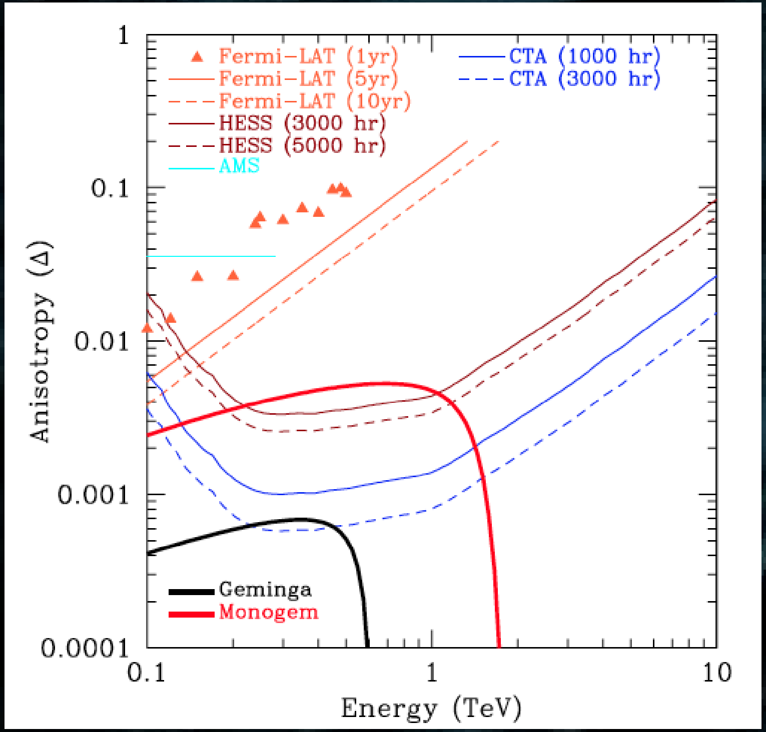
Different timescales:
1) E-loss time > source age > transport time
2) transport time >> photon time
=> cannot directly use photon data
=> requires dynamical models for sources (time evolution)

Very complicated problem:
1) photon data: CRs which are mostly still confined in sources (escape issue)
2) coupled evolution of magnetic fields and CR density

Some attempts at the source level (eg Ohira++ 10-11), but much more work necessary.

Work in prep. with Y. Gallant and A. Marcowith (LUPM).

Anisotropy as a test?



Linden & Profumo 13

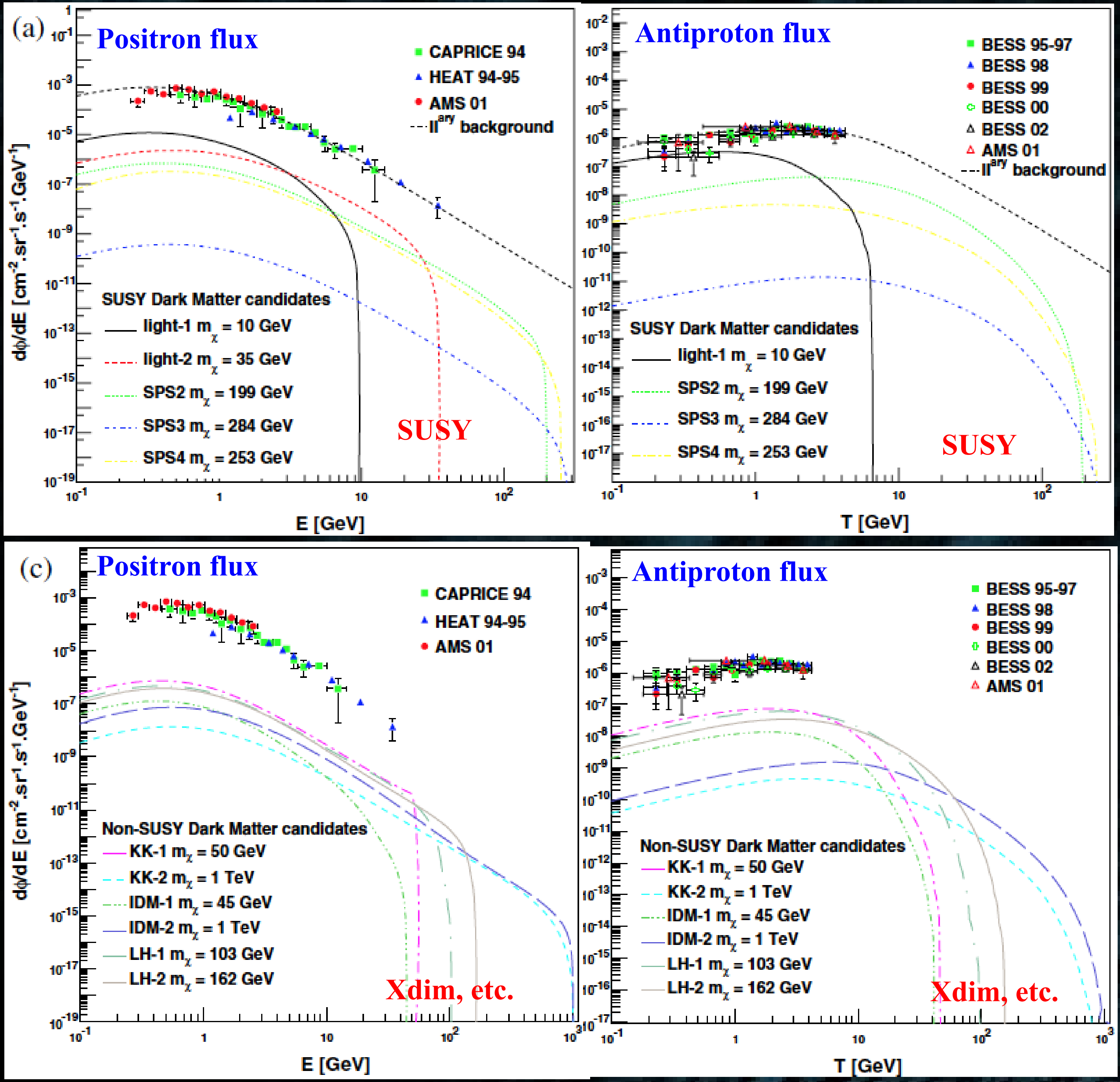
Caveats:

* model-dependent (diffusion halo size again!)
* contributions of other sources (eg dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole

Still:

* physically meaningful information
* should be provided for all CR species separately (eg positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS may reach the necessary sensitivity

DM interpretation of the positron excess?



Lavalle++ 08

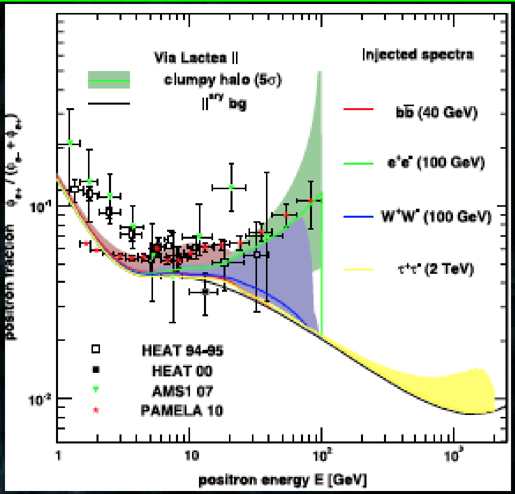
Main generic points:

* Annihilation cross section too small

* Associated antiproton flux prevents large positron flux

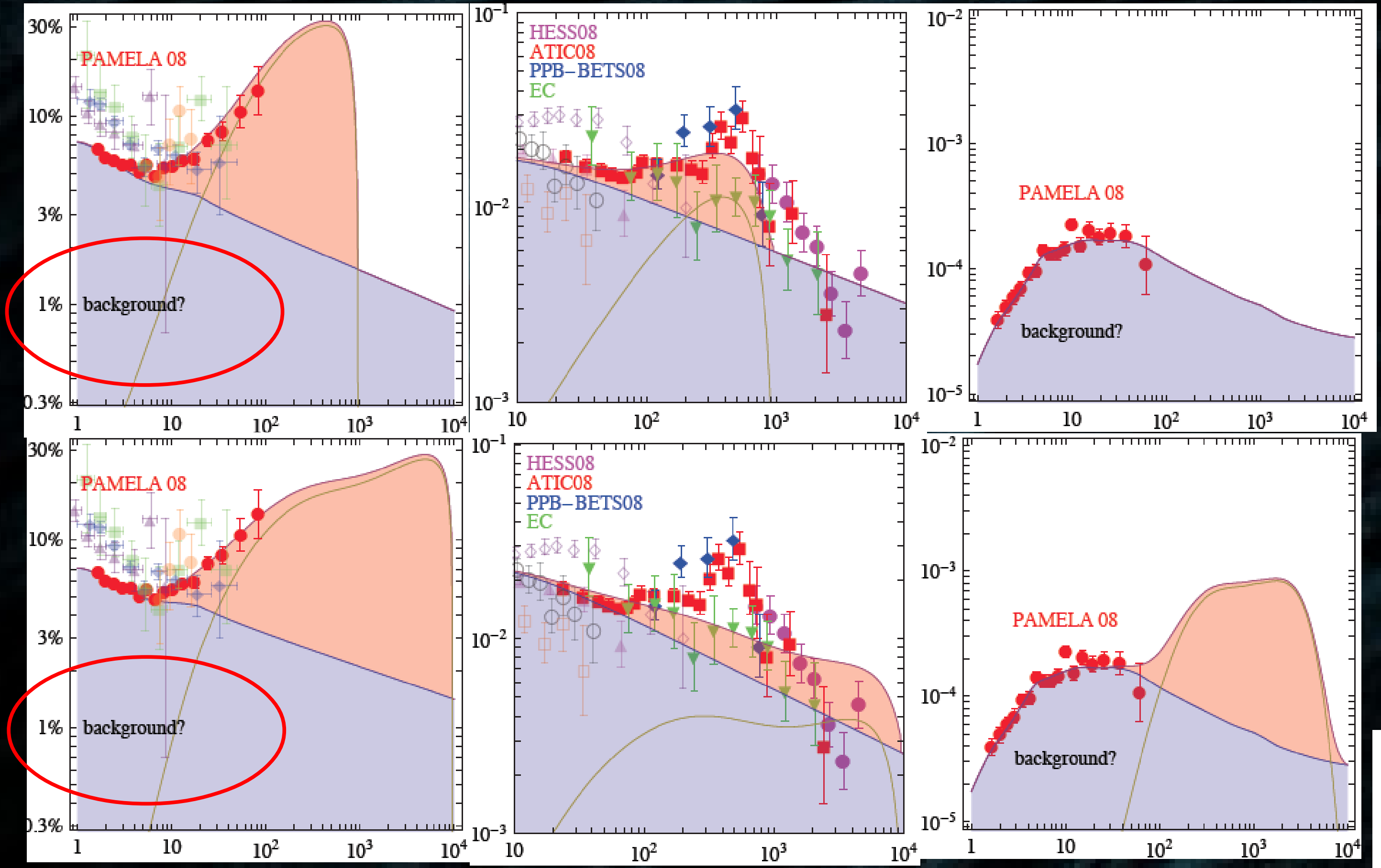
=> boost annihilation rate
=> suppress antiprotons < 100GeV

Example: could fit PAMELA data with 100 GeV DM → e+e- (small boost from DM subhalos).
*** but AMS up to 350 GeV
=> blackboard?

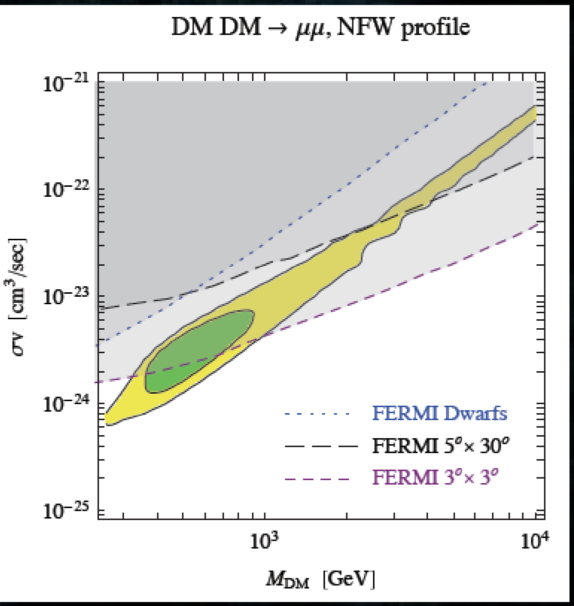


Pieri, JL++ 11

DM interpretation of the positron excess?



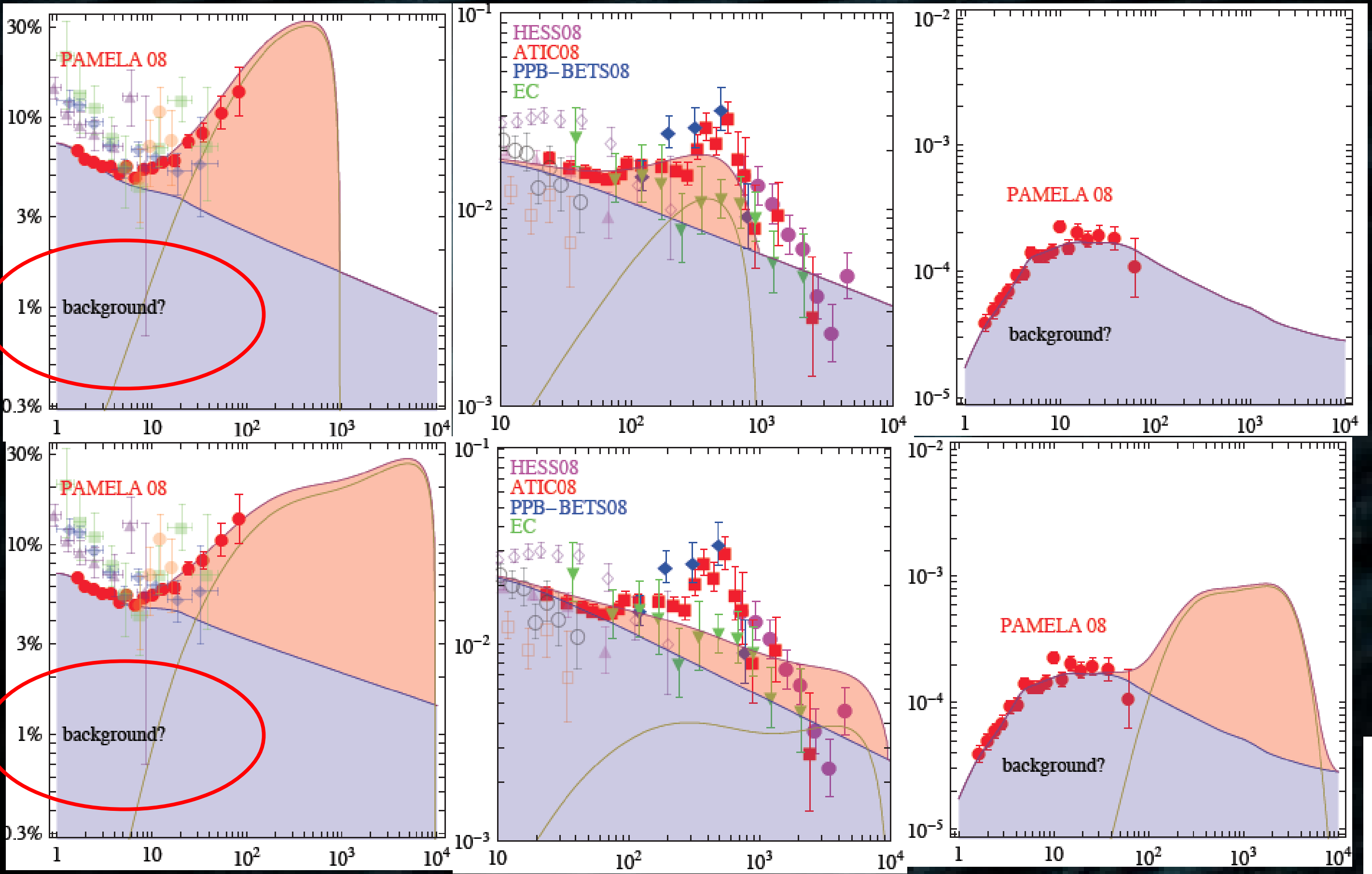
Cirelli, Strumia++ 08-13



Method:
* background (!!!) + annihilation cross-section as free params.
Conclusions:
* severe antiproton constraints => multi-TeV or leptophilic models

But …

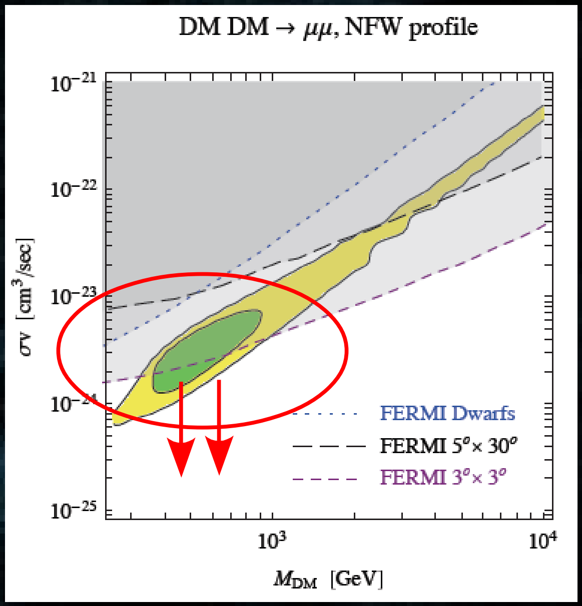
DM interpretation of the positron excess?



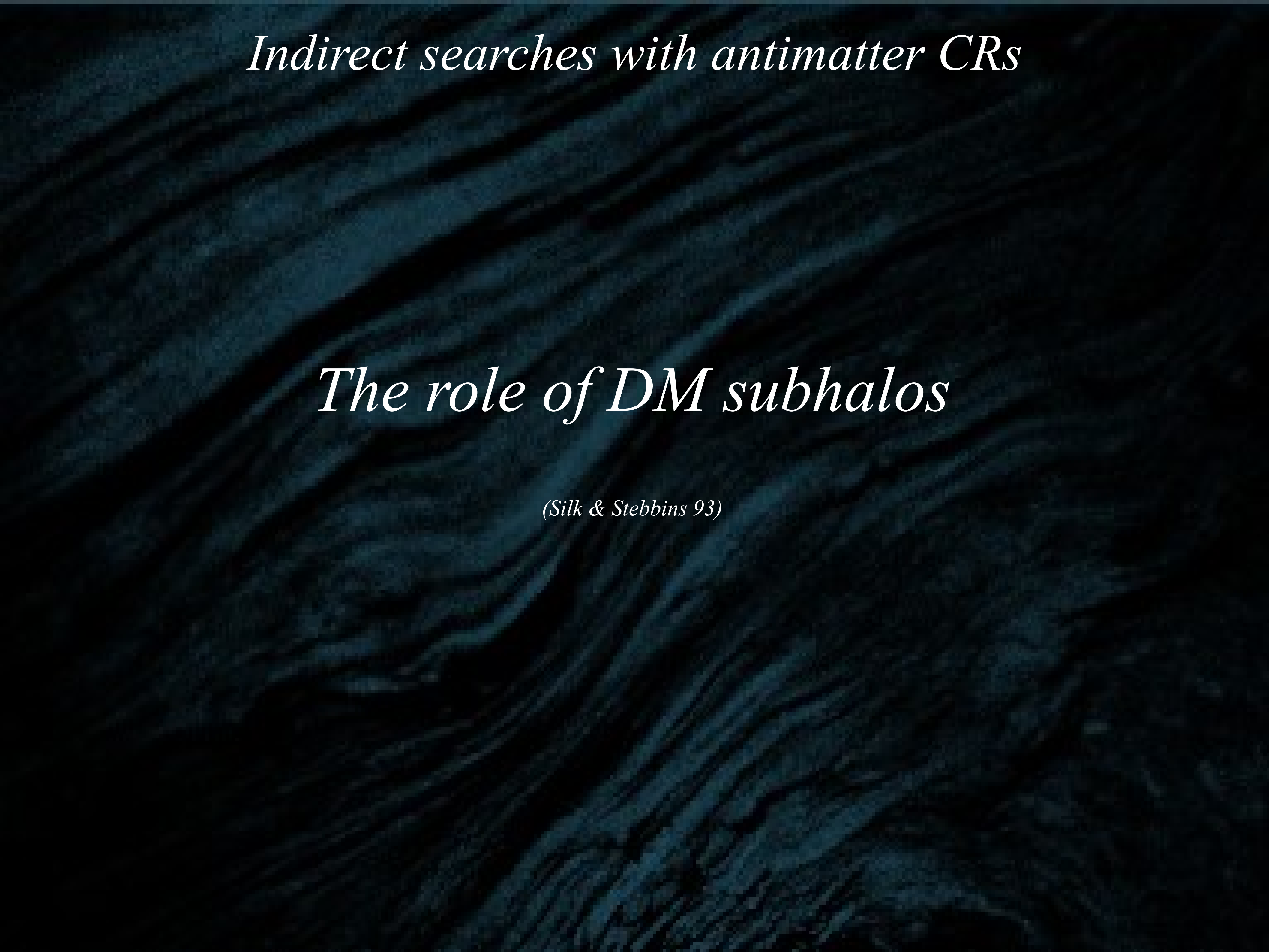
Cirelli, Strumia++ 08-13

Method:
* background (!!!) + annihilation cross-section as free params.
Conclusions:
* severe antiproton constraints => multi-TeV or leptophilic models

But … local DM: 0.3 → 0.4 GeV/cm3, DM subhalos => BF ~ 2-3
=> factor of 4-5 possible



Indirect searches with antimatter CRs



The role of DM subhalos

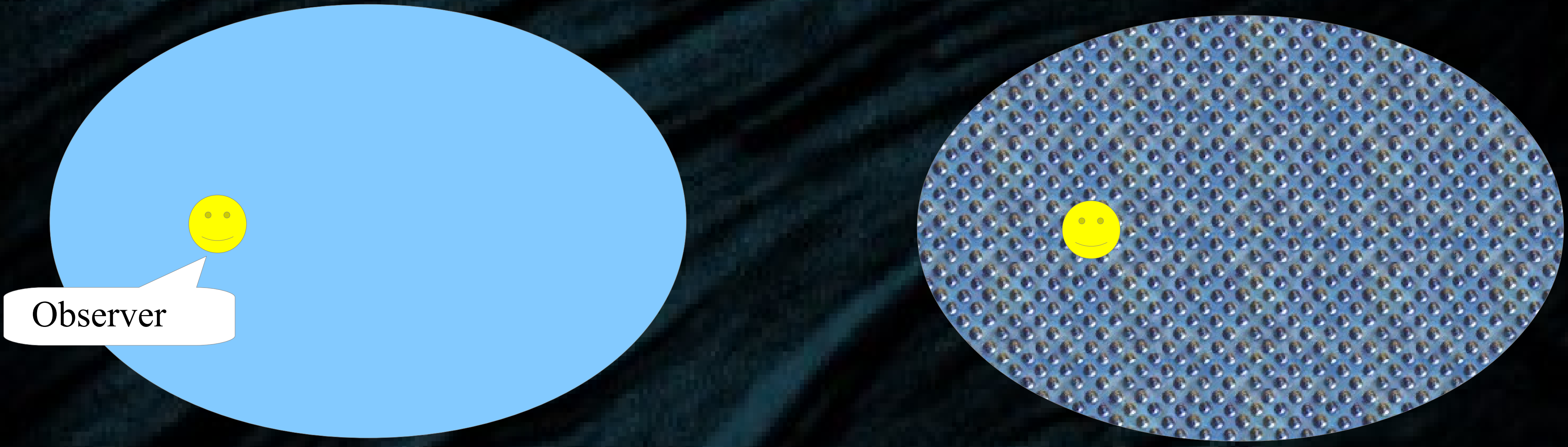
(Silk & Stebbins 93)

Boost factor ? … well, in fact, boost factors

$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

The volume over which the average is performed depends on the cosmic messenger!

*Boost factor ? … well, in fact, boost factor**s***



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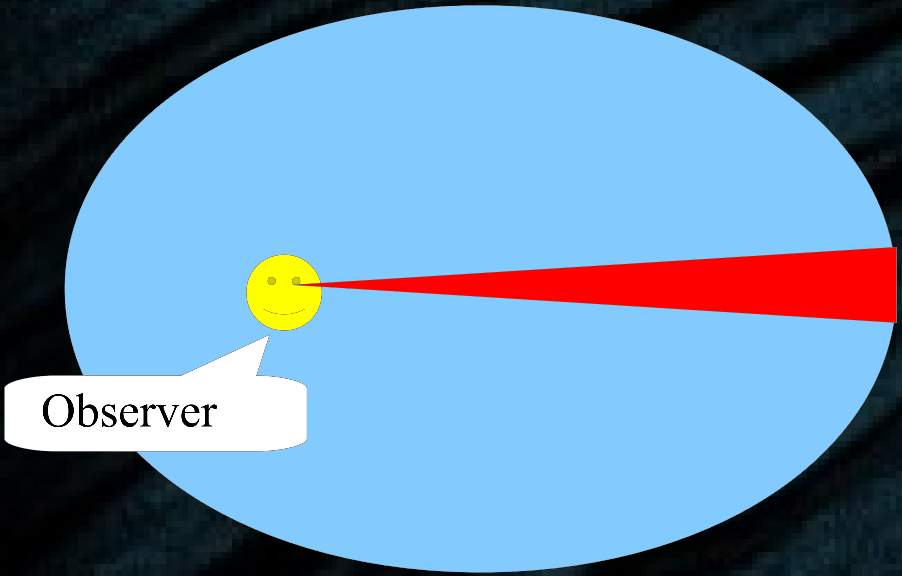
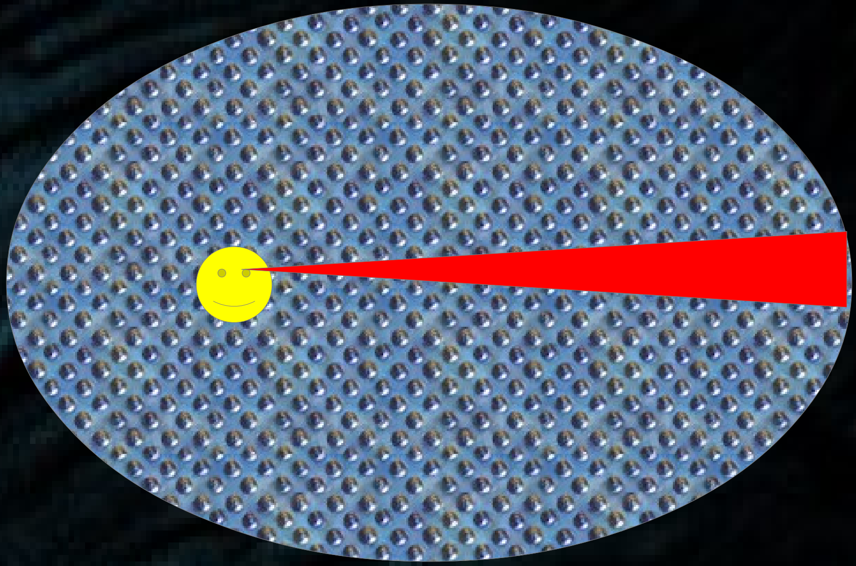
The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

*Boost factor ? … well, in fact, boost factor**s***





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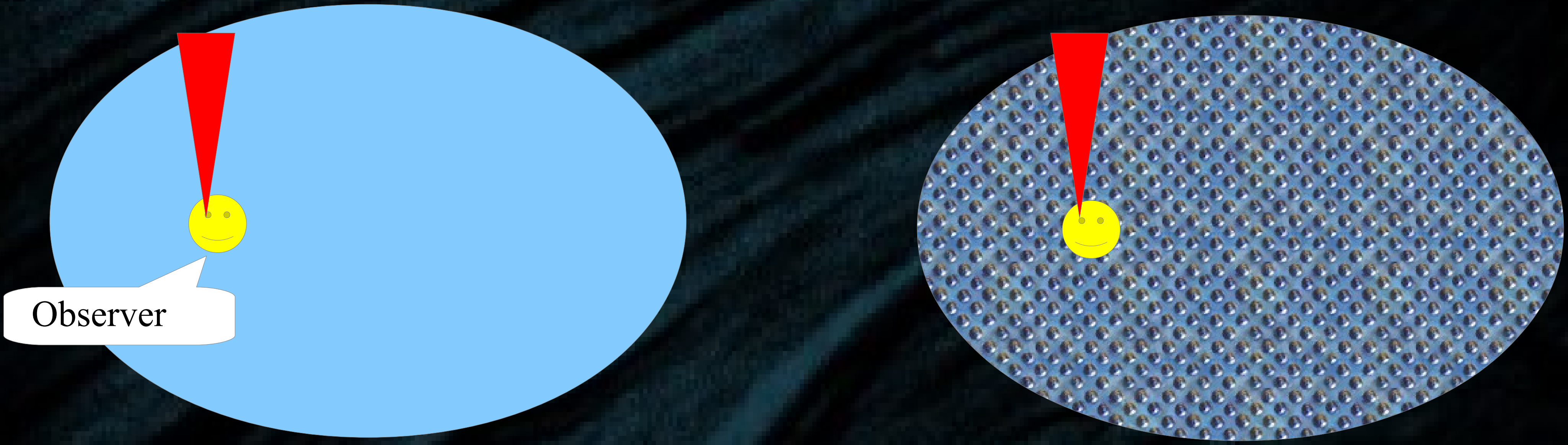
The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

Boost factor ? ... well, in fact, boost factors



$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

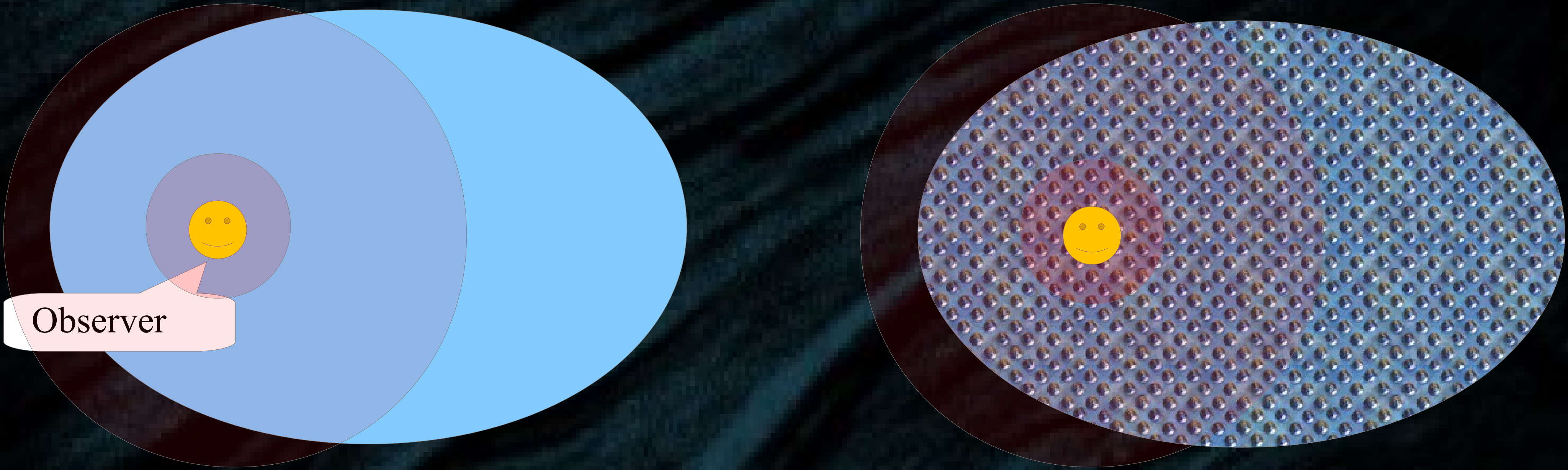
The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution

a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

Boost factor ? … well, in fact, boost factors



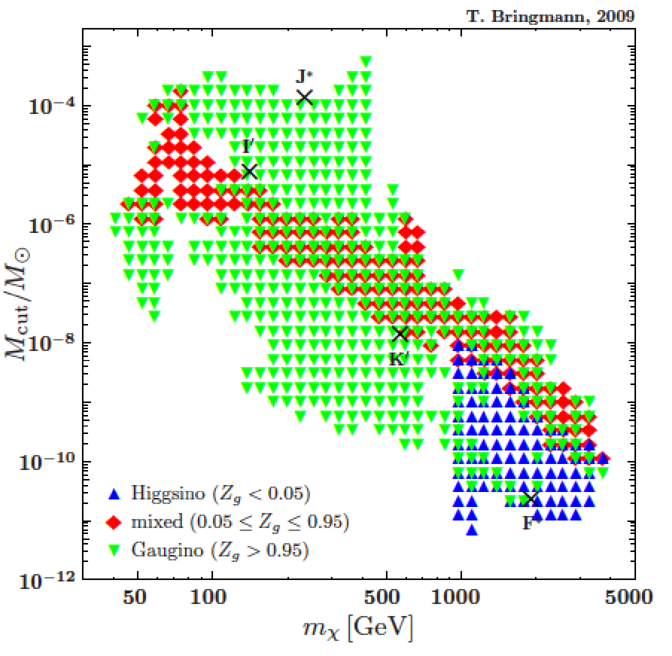
$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

The volume over which the average is performed depends on the cosmic messenger!

1) **Prompt gamma-rays:** point a telescope to a certain direction, and average over a volume set by the angular resolution
   - a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**
   - b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

2) **Cosmic rays:** stochastic motion, define energy-dependent propagation scale.
   - a) Large propagation scale: if enough to feel regions close to GC, then **B ~ 1**
   - b) Small propagation scale: if we are sitting on a clump, then **B>>1**, otherwise **B moderate**

Impact of subhalos on the positron flux



Bringmann 09

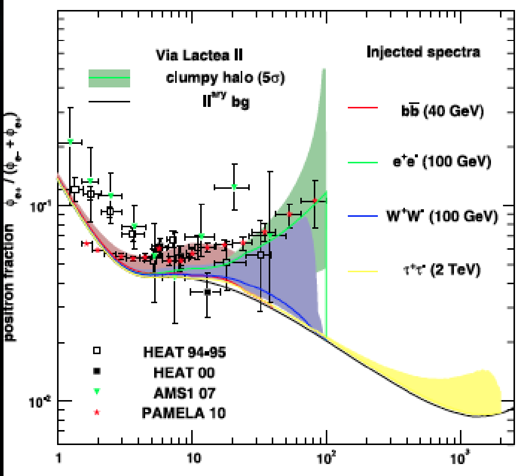
If DM is cold, subhalos must exist and survive tidal stripping (eg Berezinsky++ 05).

Very small masses can be achieved, fixed by the WIMP free streaming scale (eg Bringmann 09).

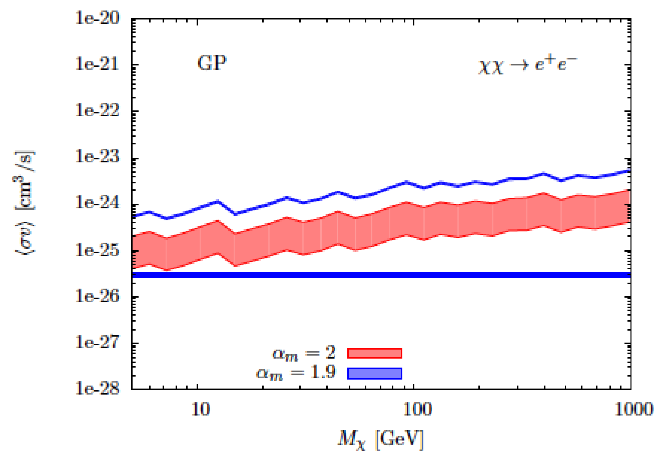
Properties studied in cosmological simulations, but limited by resolution => M > 10^4 Msun only.

Latest dedicated studies show profiles more cuspy than NFW at cut-off mass (eg Ishiyama++ 10, Anderhalden++ 13).

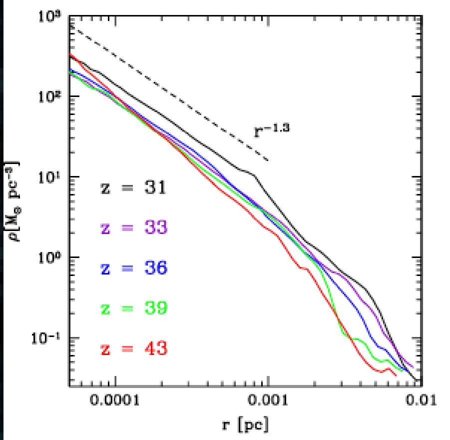
=> PAMELA could be explained by 100 GeV WIMPs (not AMS)



Positron fraction
JL++ 07, Pieri, JL++ 10



Diffuse gamma-rays
Blanchet & JL 12



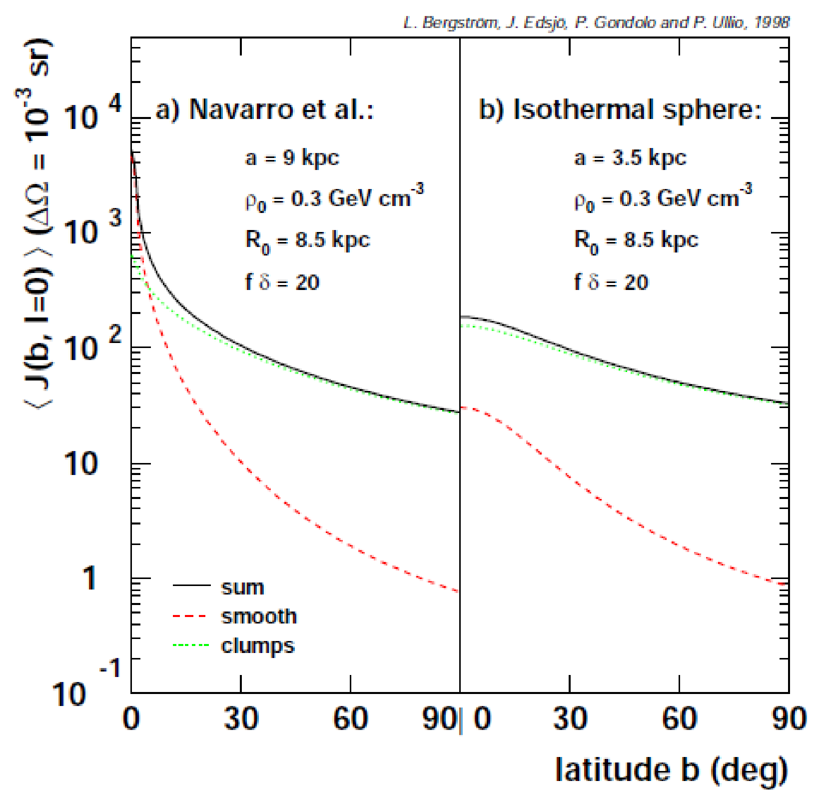
Anderhalden, Diemand 13

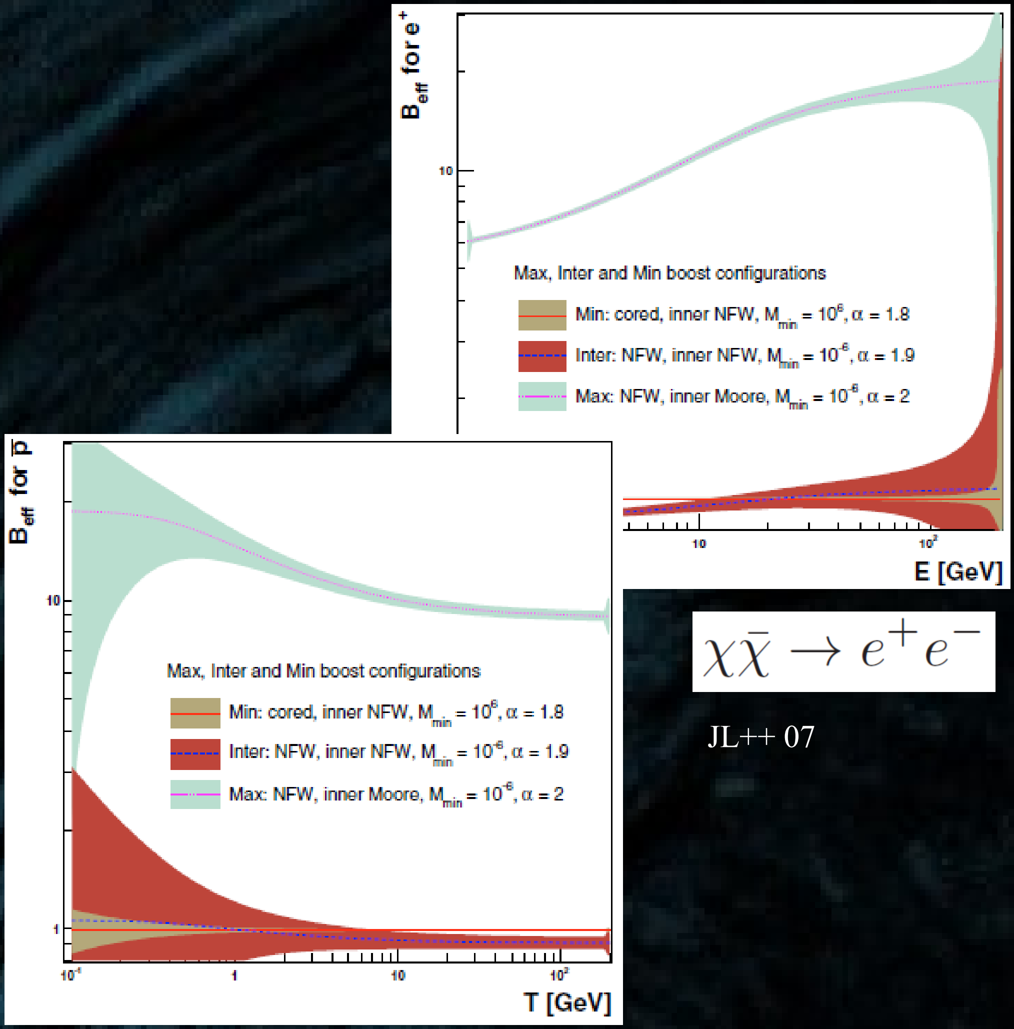
Subhalos: summary

Diffuse gamma rays:
Large boost on high latitudes (though still low absolute flux).
Must be included for diffuse gamma-ray analyses, though
affected by theoretical uncertainties.

Antimatter cosmic rays:
Moderate boost factor (<20) which depends on energy.
Potentially large fluctuations expected, depending on
configurations and energy.

Bergström++ 98





$$\chi\bar{\chi} \to e^+e^-$$

JL++ 07

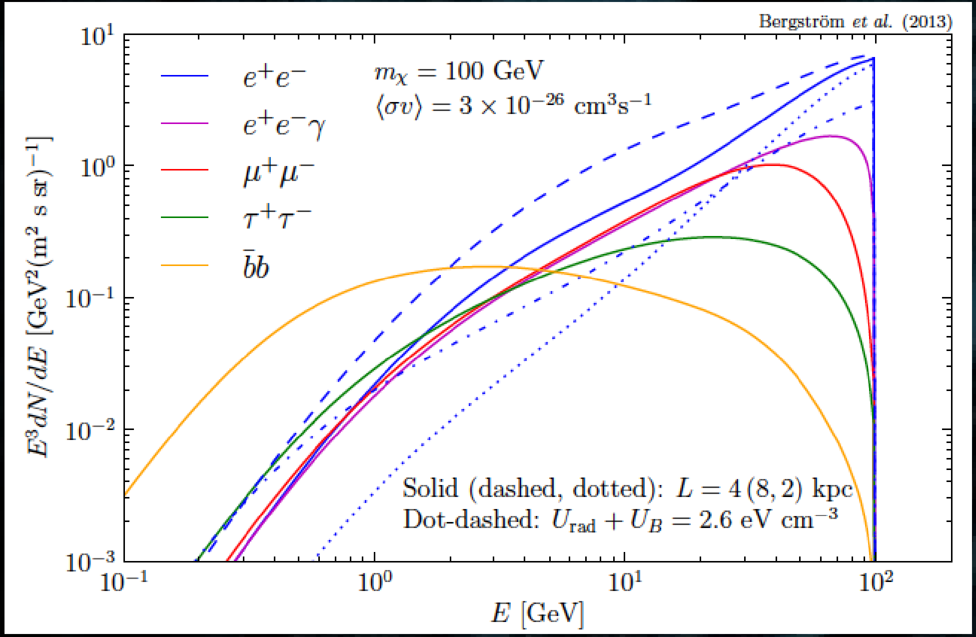
$$\chi\bar{\chi} \to \ldots \to X + \bar{p}$$

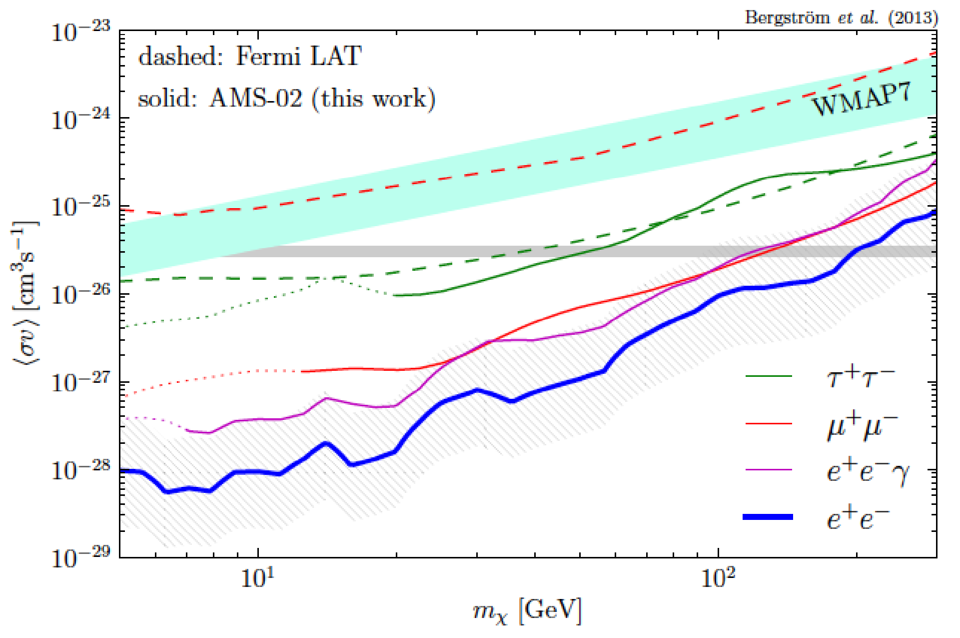
Caution:

- Boost factors depends on species!
- Large fluctuations inherent when small number of objects concerned (e.g. HE positrons, or predictions of subhalos to be resolved with gamma-ray telescopes)

Upside down approach to positron data

Bergström++ 13





=> very competitive constraints on leptophilic models!

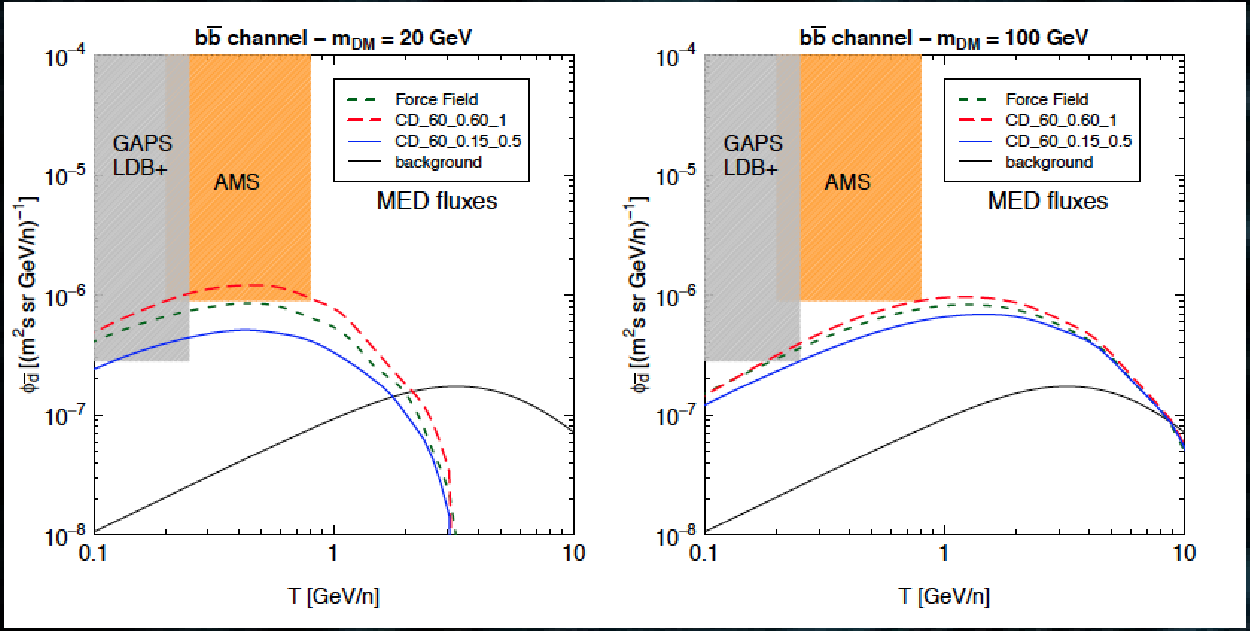
NB1: formally impossible to exclude DM contribution … BUT we know pulsars do exist (with the relevant properties) … you bet?

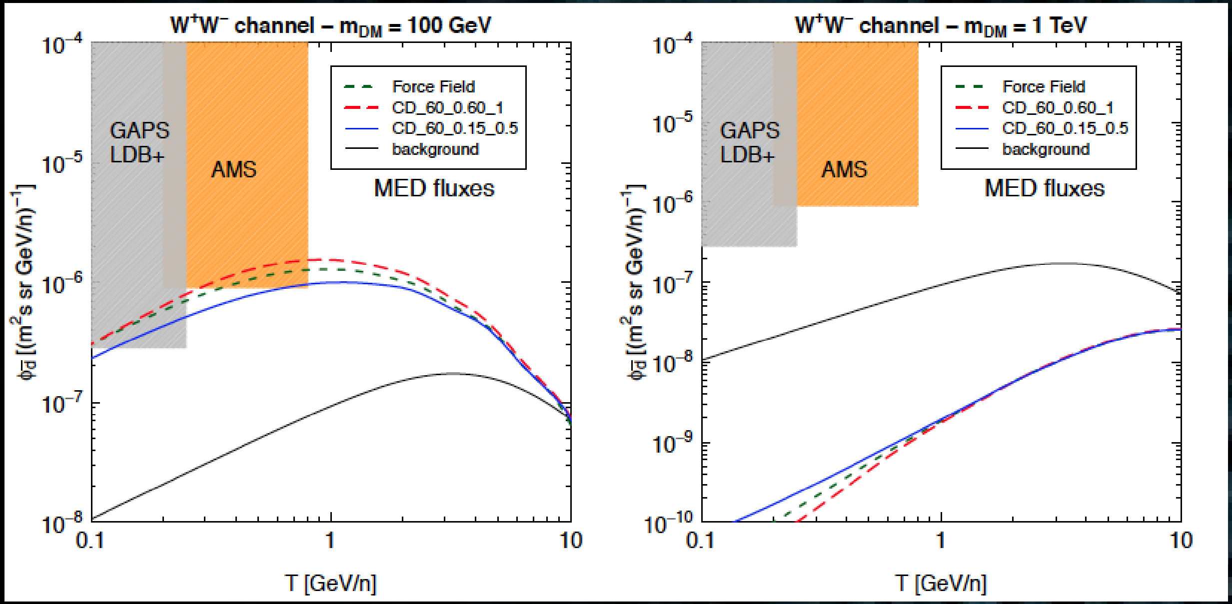
NB2: the answer will be clear sooner or later (the role of scientific research); still an interesting research line: any new contribution is encouraged!

(Review on the positron fraction excess in Serpico 10)

To conclude this section: Antideuterons

Fornengo++ 13 – also Donato, Salati++ 00





Production:
* coalescence model(s)
=> have improved the last 2 years
=> collinear momenta of anti-n and anti-p
=> small spatial separation

Detection:
* complicated … (discriminate wrt antip and e-)

Predictions:
* favorable signal/noise
* detectable mass range already significantly probed by pbars …

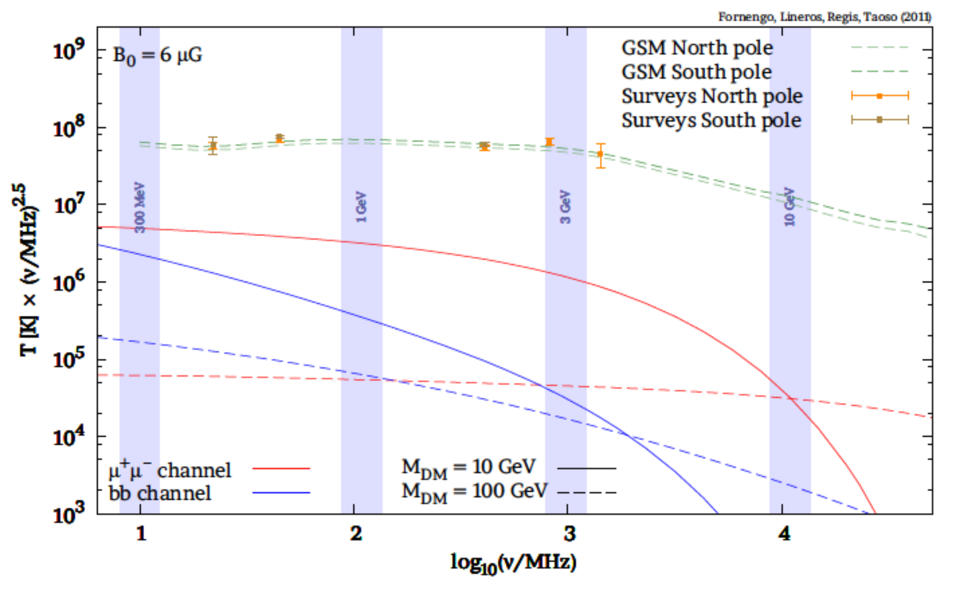
AMS-02 and GAPS will try

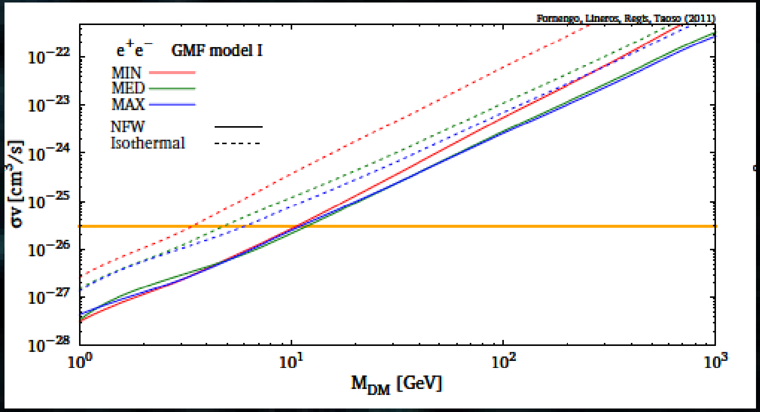
Indirect dark matter detection

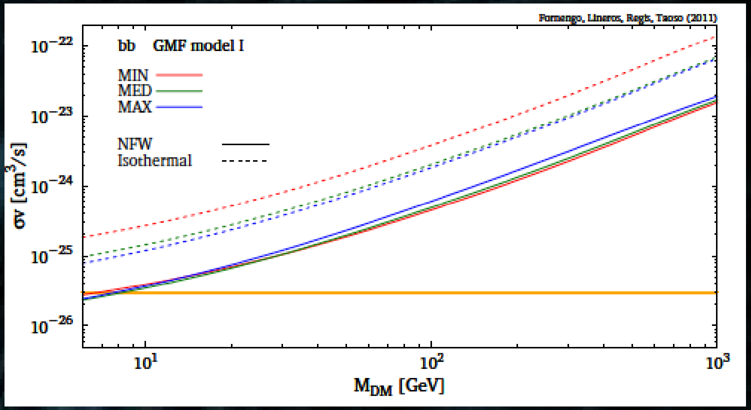
Radio signals

Radio emission

Fornengo++ 11

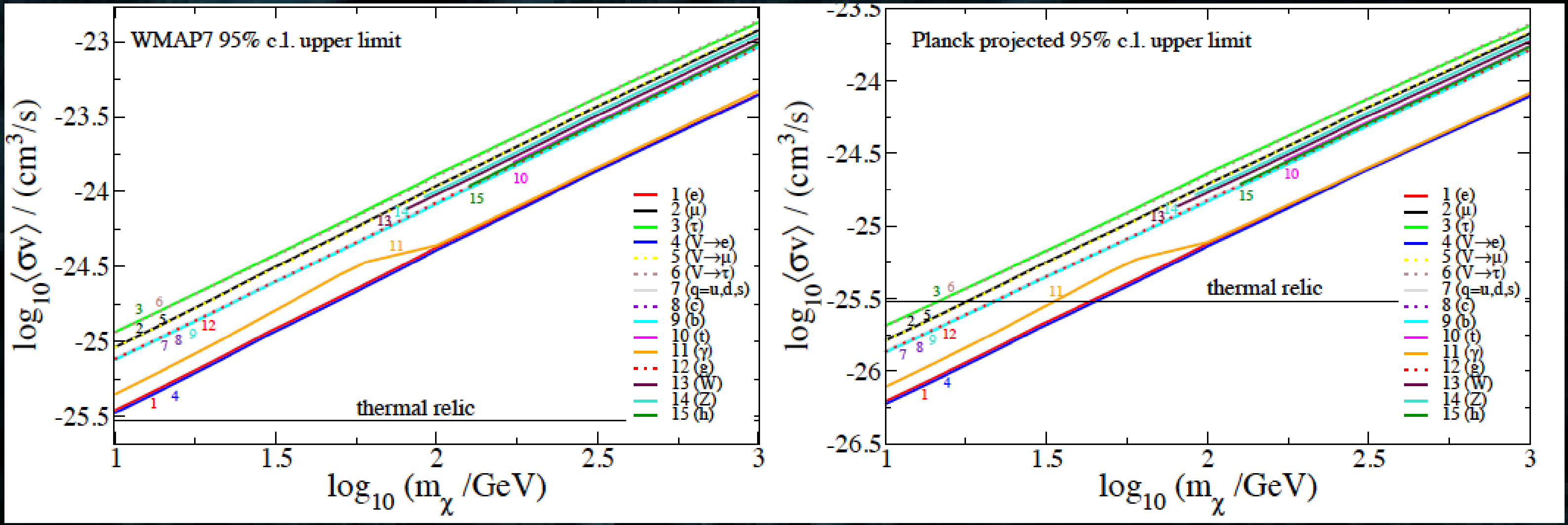






Radio constraints very loose for diffuse component.
=> Get much stronger at the Galactic center (<< 10 pc!)
=> But large uncertainties on B-field and on DM distribution.

Radio constraints: CMB!



Cline & Scott 13

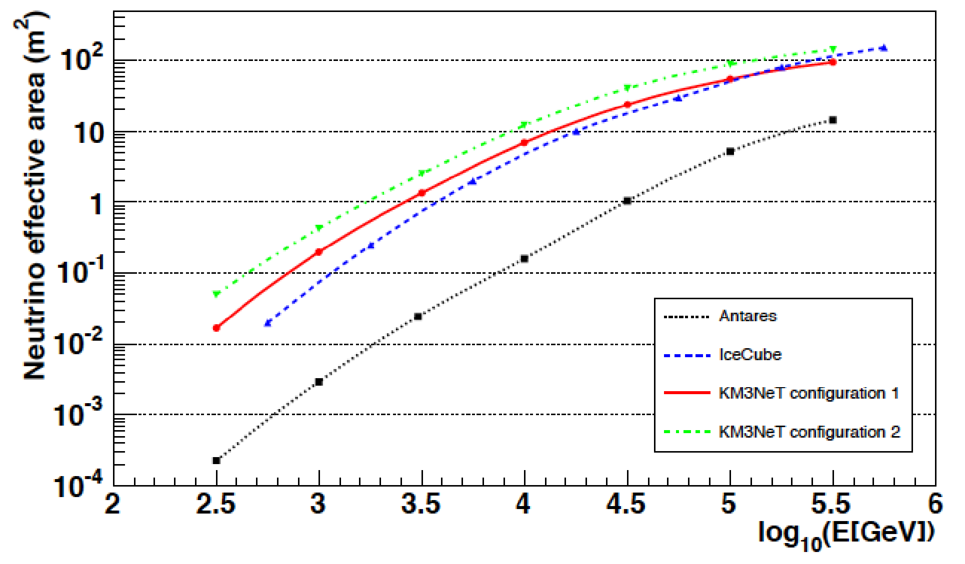
See also: Scott++ 91, Dodelson & Jubas 92, Hansen & Haiman 04, Chen & Kamionkowski 04, Natarajan & Schwarz 09, Galli++ 09, etc.

Indirect dark matter detection

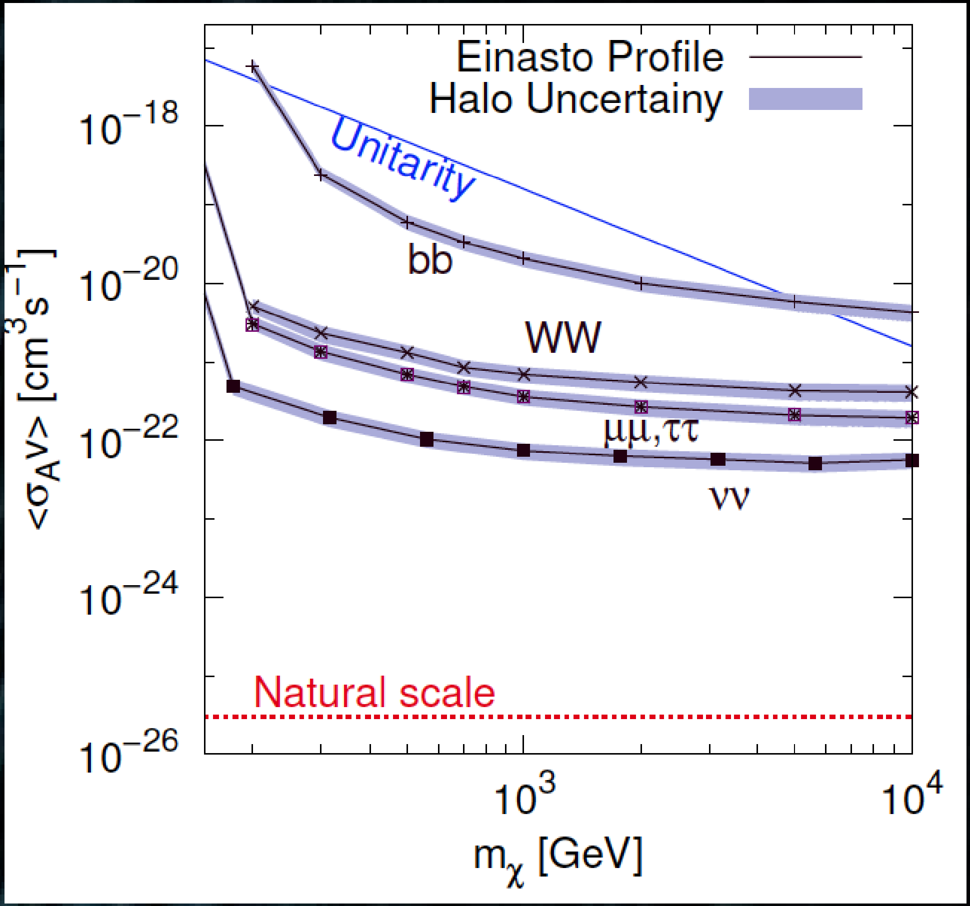
Neutrinos

Galactic neutrinos

Carr++ 07 (ICRC)



Icecube Collab. 11

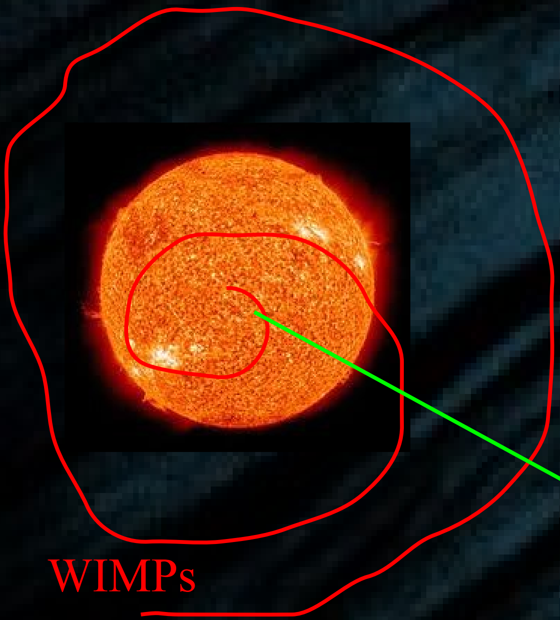


Neutrinos are weakly interacting particles => huge detection volume = small effective detection area

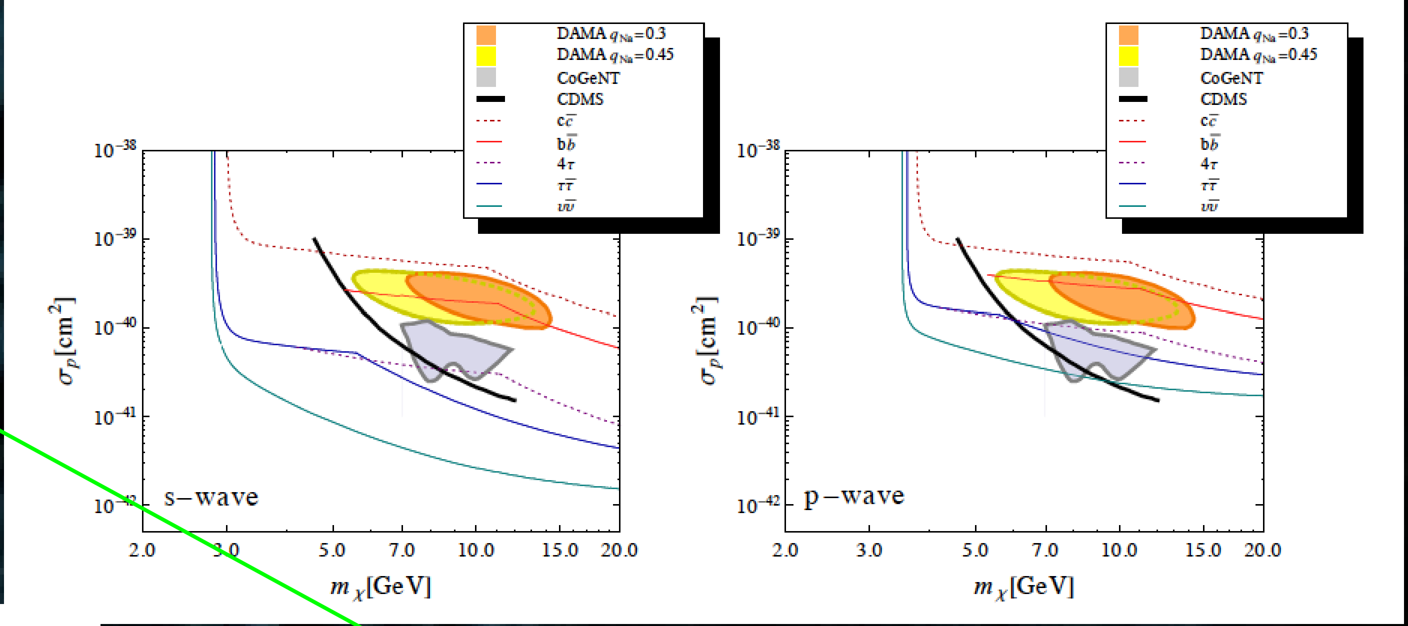
Icecube area (1 TeV) = Fermi area (10 GeV) (with 1-2° angular resolution, factor of 2 energy resolution => bckg discrimination more difficult).

Galactic searches not competitive :(

Neutrinos from the Sun
(clean DM signature)



Kappl & Winkler (11)



$$\frac{dC_{\odot,i}}{dV} = \frac{\rho_\chi \, \rho_{\odot,i}(r)}{2m_\chi\mu_i^2}\,\sigma_i \int_0^\infty du\, \frac{f(u)}{u}\int_{E_{R,\min}}^{E_{R,\max}} dE_R\, |F(E_R)|^2$$

$$\dot N = C_\odot - A_\odot N^2 - E_\odot N$$

$$N = \sqrt{\frac{C_\odot}{A_\odot}}\tanh(\sqrt{C_\odot A_\odot}\, t)$$

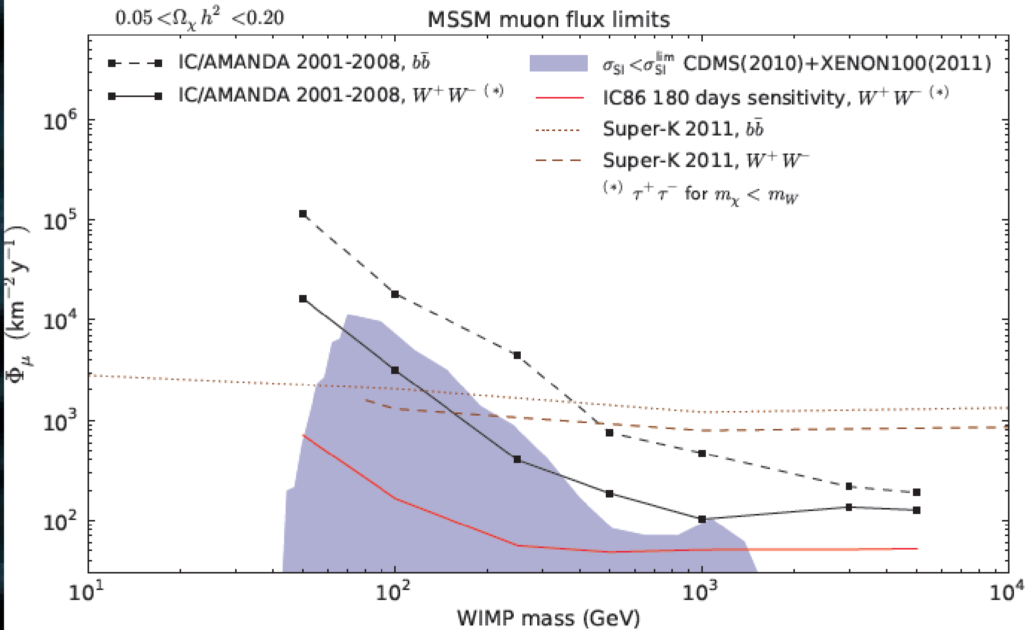
$$\Gamma_\odot = \frac{1}{2} A_\odot N^2 = \frac{1}{2} C_\odot \tanh^2\left(\sqrt{C_\odot A_\odot}\, t_\odot\right)$$

WIMPs captured in the Sun
(gravitation + elastic scattering off material)
=> can annihilate
=> at equilibrium: annihilation = capture rate

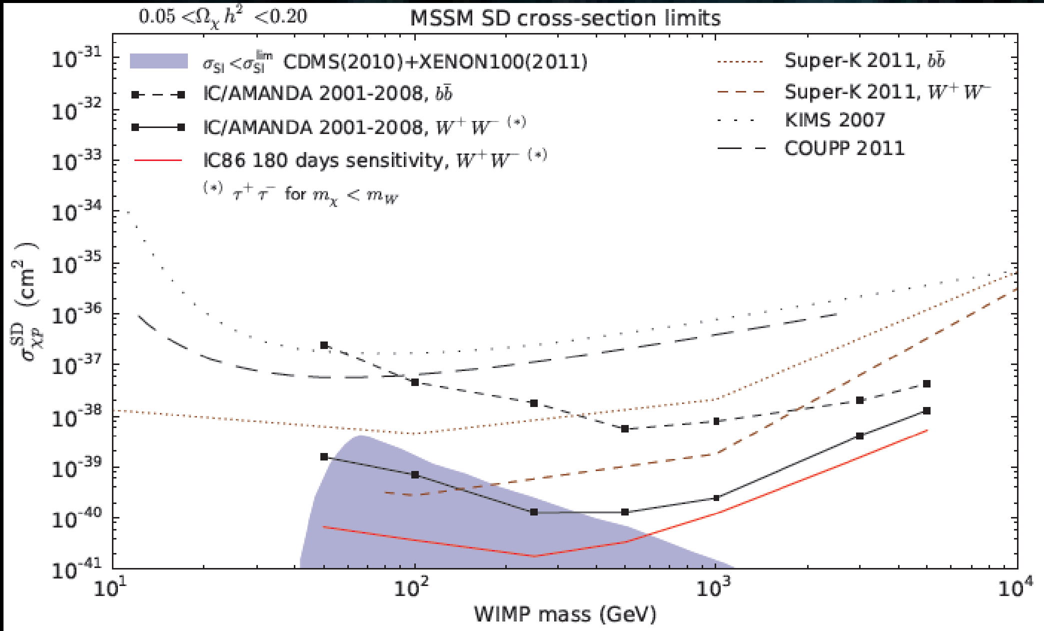
Super-Kamikande very powerful for GeV particles
Amanda/Icecube and Antares/Km3 only for WIMP masses > 50 GeV

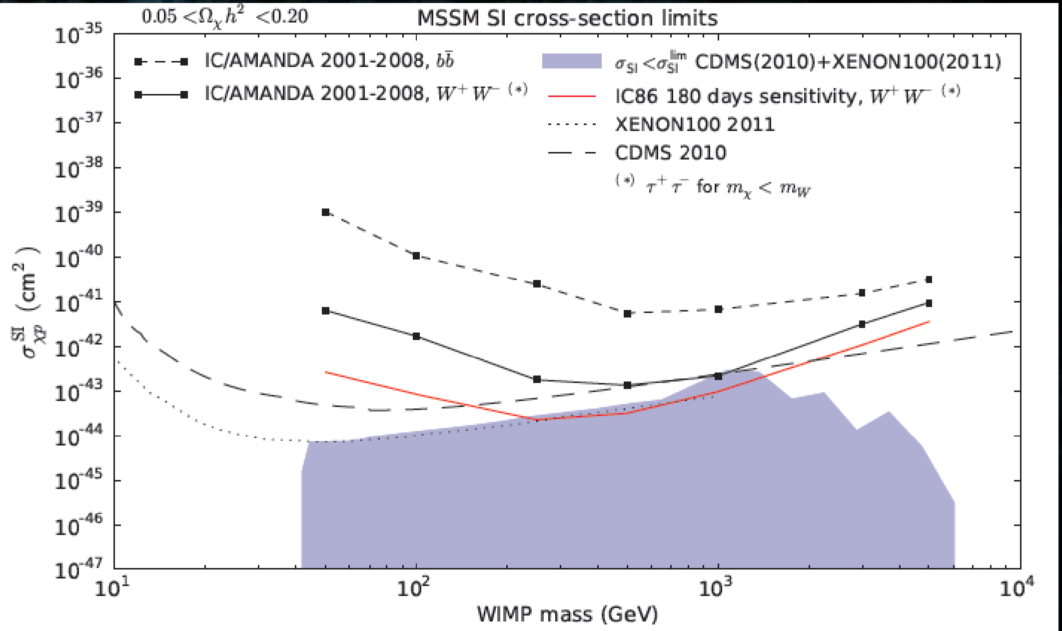
→ Leptophilic WIMPs strongly constrained
→ Quarkophilic WIMPs survive

Icecube limits



Icecube Collab. 11

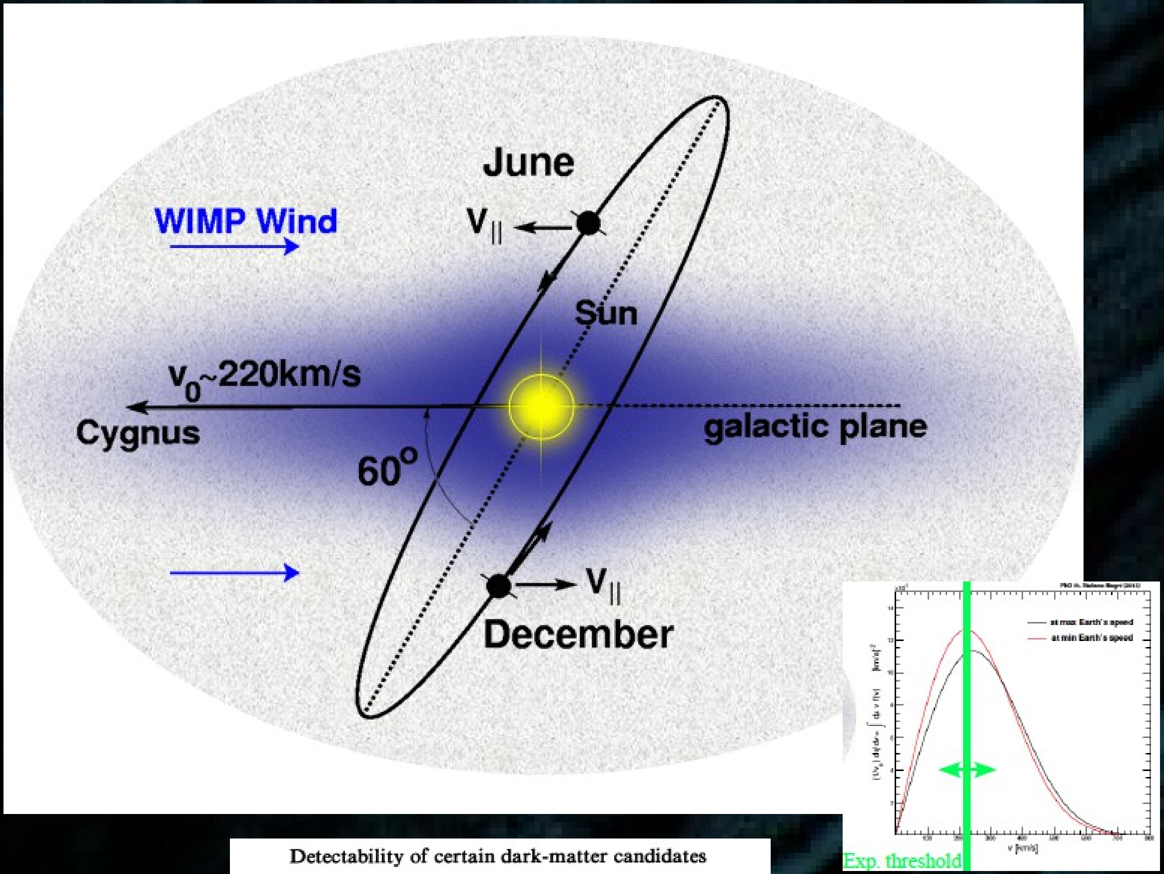




Indirect dark matter detection

Complementarity

Direct detection of DM



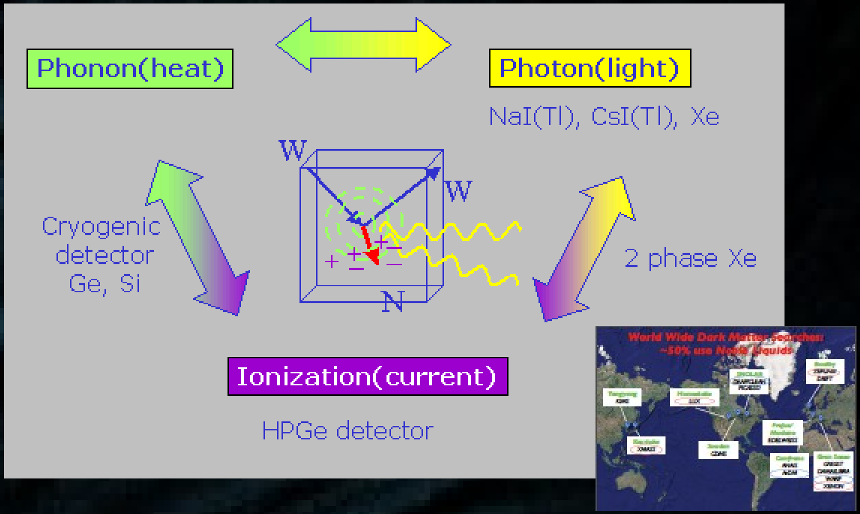
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

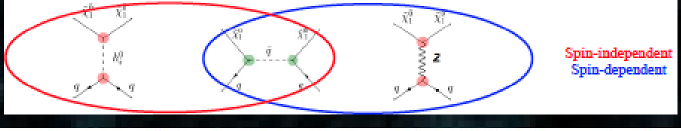
Direct detection (Goodman & Witten 85, Drukier++ 86)

Backgrounds: Cosmic-rays, radioactivity
=> deep underground shielded detectors

Smoking-gun signal: annual modulation (a few % of evt rate)
Drukier++ (86), Freese++ (88)



Different detection methods, different systematics:
Scintillation: DAMA, CRESST, XENON
Ionization : CDMS
Phonon (Ge): CDMS
=> discriminate electronic/nuclear recoils



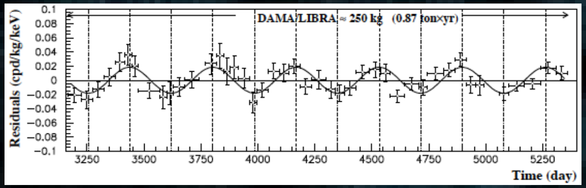
$$\sigma_{\chi-N} \propto \begin{cases} \underbrace{\alpha_v\,\bar\chi\,\gamma_\mu\,\chi\,\bar q\,\gamma^\mu\,q}_{\text{non-Majorana WIMPs}} \; + \alpha_{\text{scal.}}\,\bar\chi\,\chi\,\bar q\,q & \propto A^2 \;\; \text{(spin-independent)} \\ \alpha_{a-v}\,\bar\chi\,\gamma_\mu\,\gamma_5\,\chi\,\bar q\,\gamma^\mu\,\gamma_5\,q & \propto (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2 \;\; \text{(spin-dependent)} \end{cases}$$

$$\frac{d\Gamma_{\chi-N}}{dE_r}(E_r,t) = \frac{\sigma_{\chi-N}\,\rho_\odot}{2\,m_\chi\,\mu_r^2}\,F^2(E_r)\int_{v>v_{\min}} d^3\vec v\,\frac{f(\vec v,t)}{v}$$

Local DD rate depends on local DM phase-space
(number density, velocity distribution)

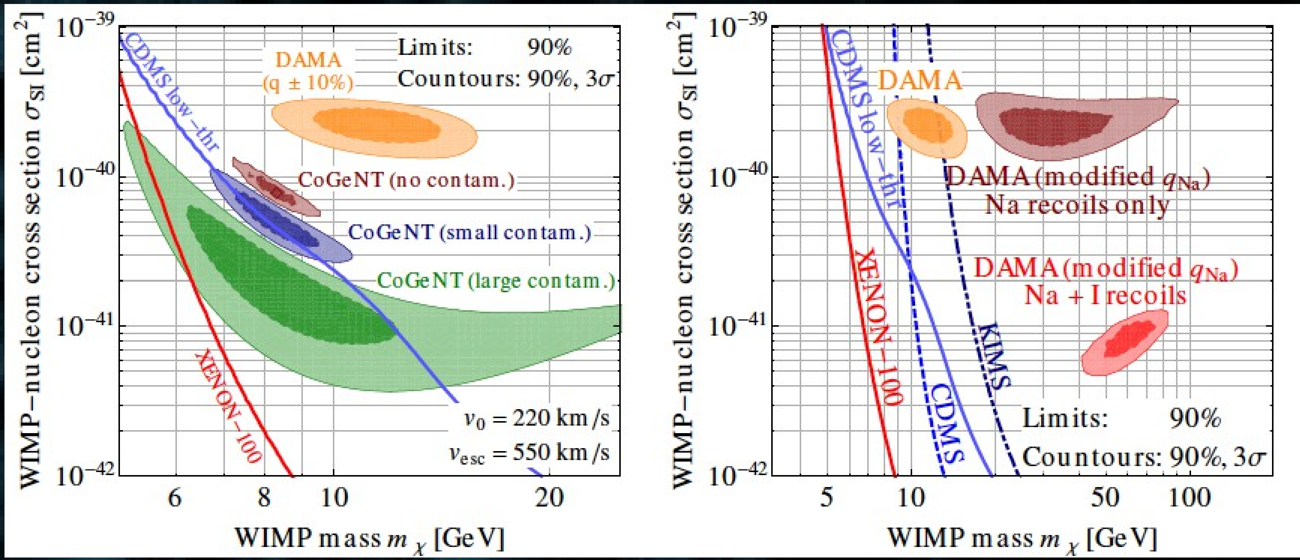
Typical WIMP-nucleon cross section << 10^{-4} pb !!!!

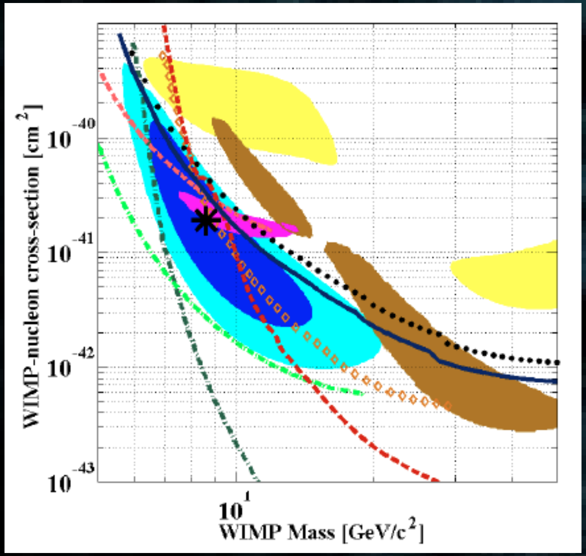
Direct detection of DM: dazed hints



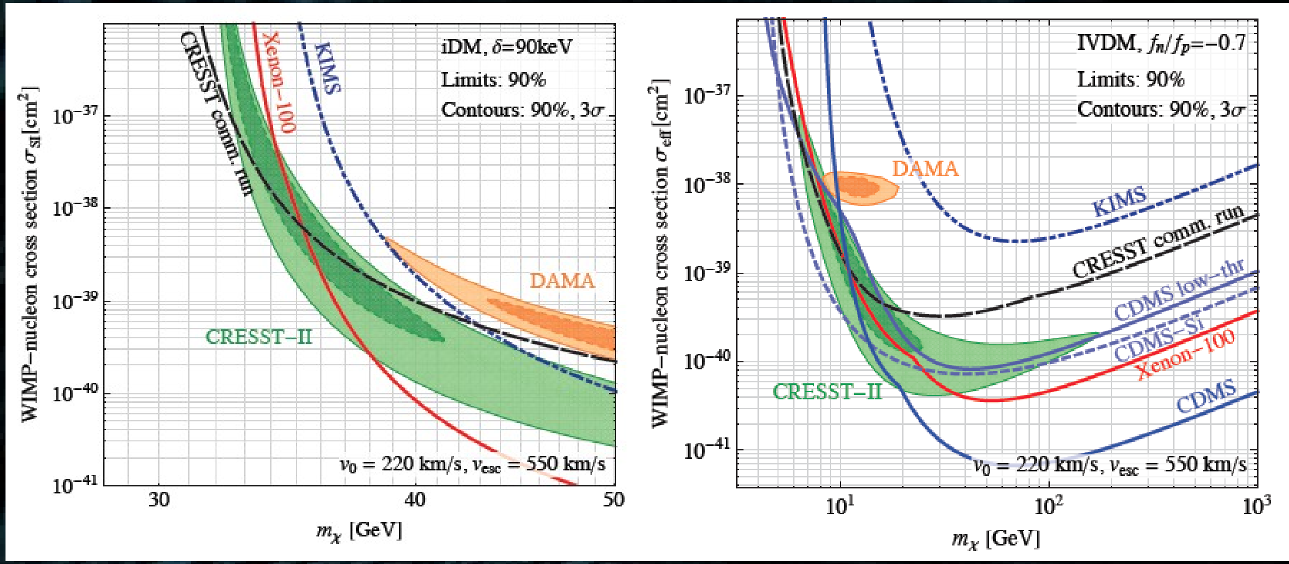
Annual modulation *detected* by DAMA
Bernabei++(98-13)

Kopp++ (11) – spin-independent analysis





CDMS/Si (Agnese++ 13)
=> 3 evts / 0.41 +-0.2 +- 0.25 expected
=> 2-3 sigma “excess”

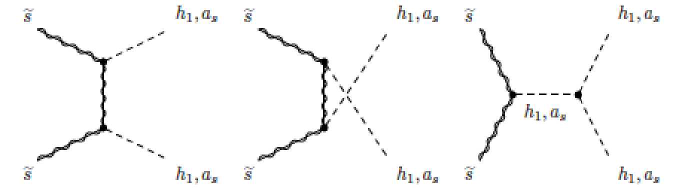


Two types of hints:

* Annual modulation:
Detection by DAMA, not confirmed
*Excess events: (low significance < 3 sigma)
CoGeNT, CRESST, CDMS/Si
**** But constraints by XENON-10/100
=> hard to reconcile/interpret

=> Exciting! (model-building not standard)
=> Close to threshold: large systematics
=> need more data!

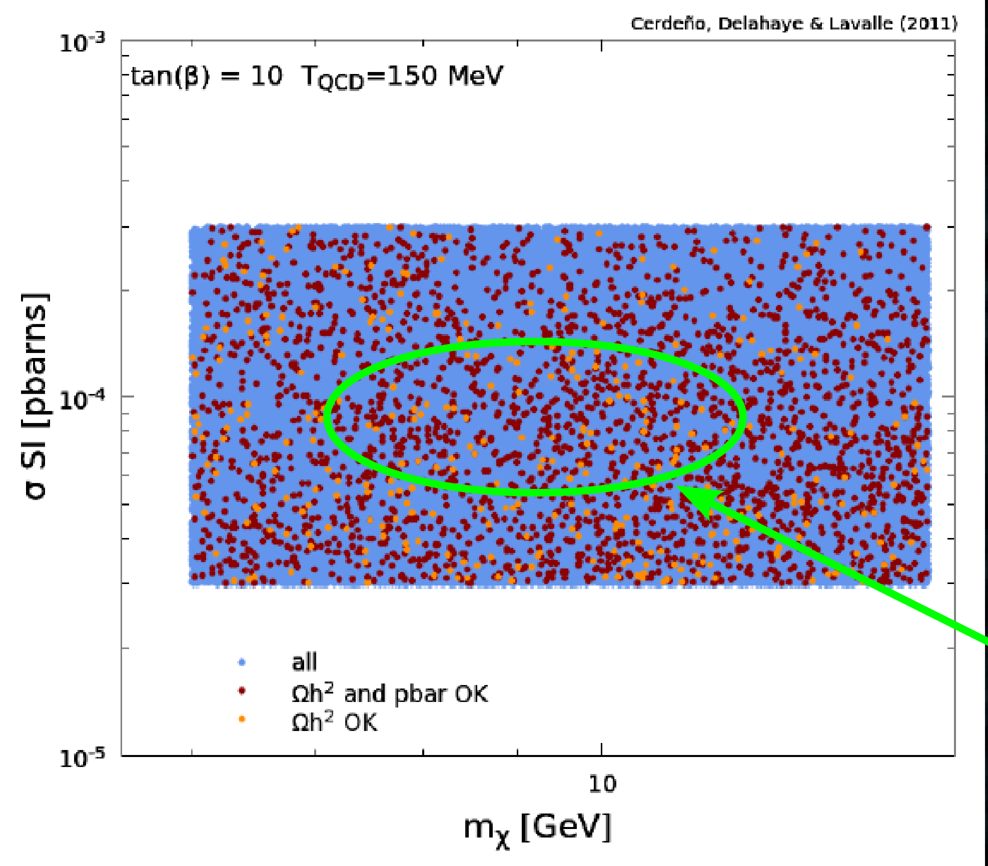
Direct detection of singlino-like WIMPs



Setup:
- Singlino-like WIMP
- Realistic Higgs sector with mixing angles: additional singlet-like CP-even (*h*) and CP-odd (*a*) light Higgs bosons

Constraints:
- Some collider constraints (=> large singlet fraction)
- Direct detection signal dominated by *h* exchange (MSSM Higgs decoupled)
- DD signal region encompasses CoGeNT
- 2 mchi > m*a* + m*h*

Cerdeno, Delahaye & JL 11



Color index:

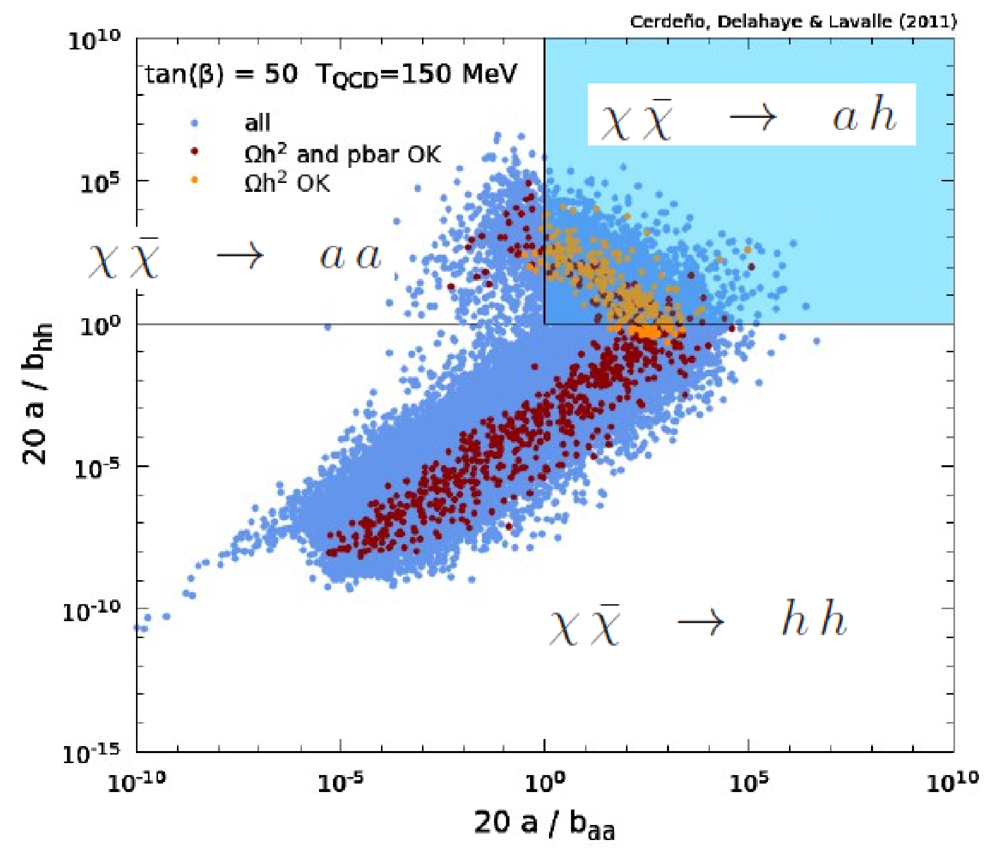
● Excluded relic d.
● Relic d. OK
● Relic d. OK but pbar excess

CoGeNT region

Free parameters:
- Masses
- Couplings
- tanbe

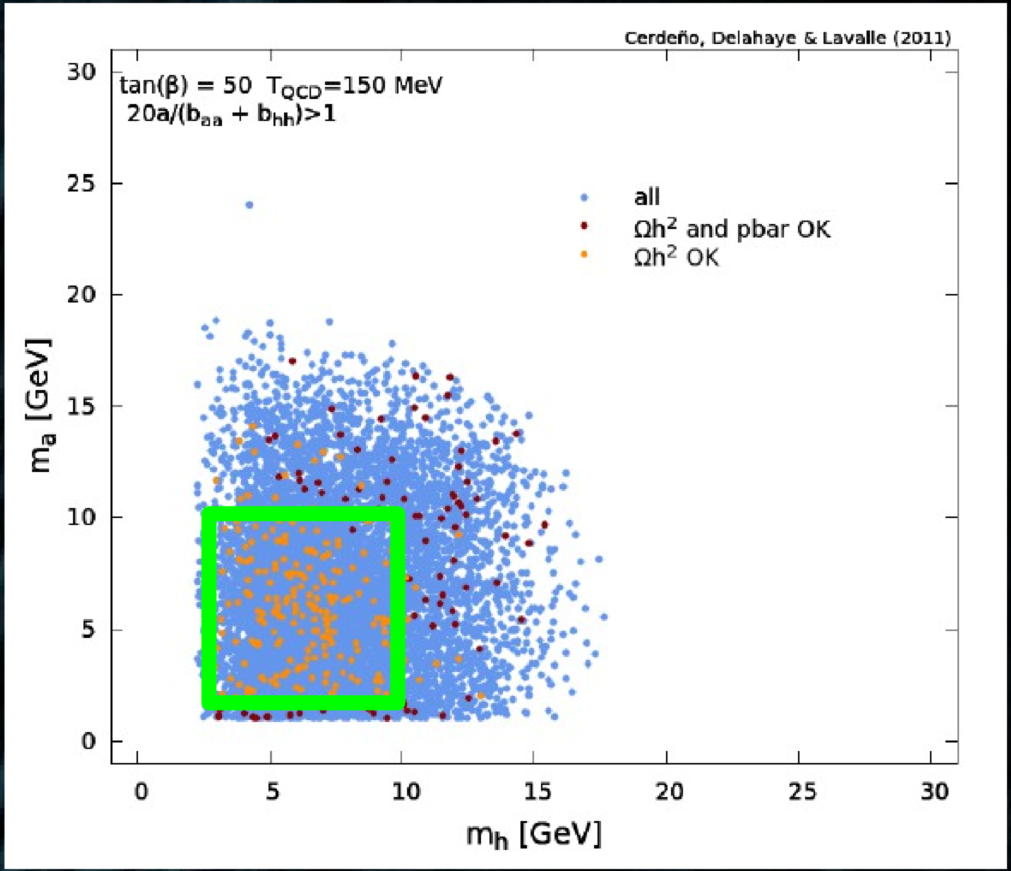
Understanding the results: S-to-P wave ratio and mass range

Indirect detection signal => pure S-wave required



$$\langle \sigma v \rangle \approx a + b/\{x \equiv m_\chi/T\}$$

Light Higgs bosons masses



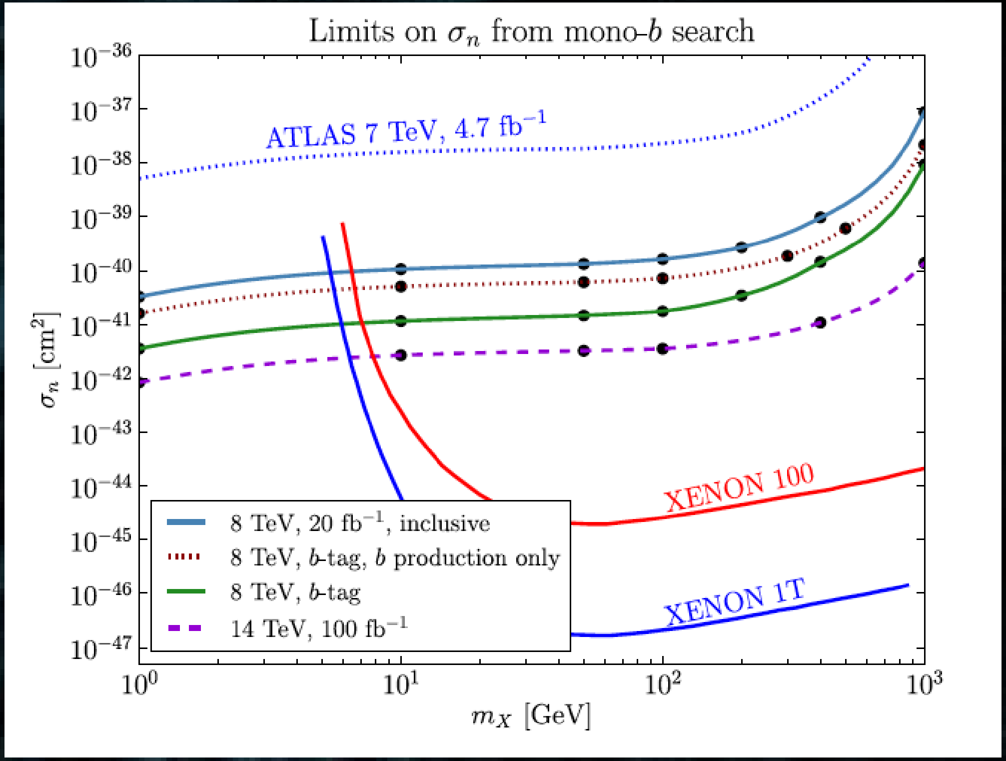
m < 2 mp or m~2 mb~10 GeV do not produce antiprotons

Colliders?

Usually model-dependent

=> likely best model-independent is monojet + missing ET (b/t tagging).

Lin++ 13



Conclusions

- Dark matter particle scenario strongly motivated
- WIMP excellent candidate because naturally arising in BSM models + detectable/excludable

- Best indirect targets: gamma-ray line(s), DSphG, HE solar neutrinos
- Antimatter and diffuse: provide strong constraints, more difficult for discovery
- Exciting because experiments unveil “excesses” very often … but standard astrophysics can also very often explain afterward …
- Lot of theoretical efforts to reduce systematic errors in signal and background predictions (eg. CR transport, galaxy simulations, etc.)
- Many running experiments: Fermi, AMS-02, HESS2, Planck, etc.

- Complementarity with other search approaches is the best strategy => mandatory, but difficult (interdisciplinary)

- Fascinating (though difficult) topic: frontier of particle physics, cosmology, astrophysics
- Most of the WIMP parameter space will be probed within 10 yrs (LHC + direct + indirect searches) => discovery or despair … stay tuned!

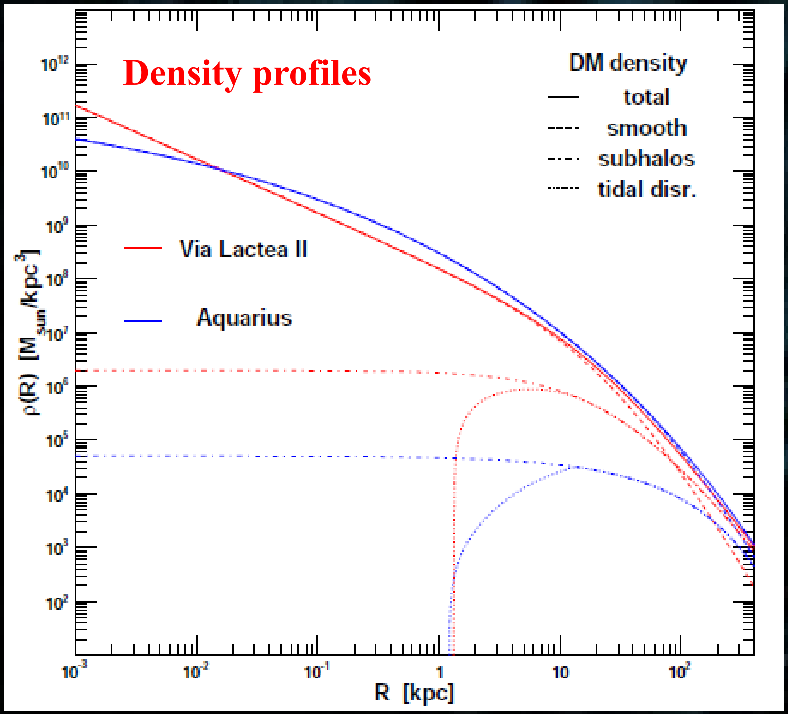
Backup

γ-rays: theoretical uncertainties

Different simulations give different results, eg:
- * Via Lactea II (Diemand et al 08)
- * Aquarius (Springel et al 08)

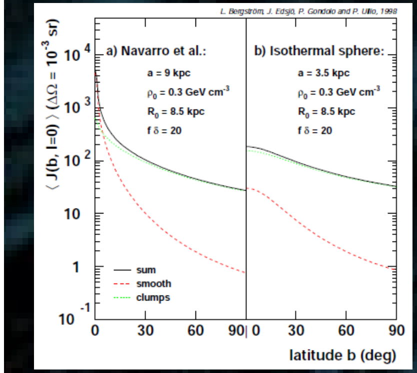
Among differences:
subhalo properties!

Analytical & MC study of
VLII and Aquarius
Pieri, Lavalle, Bertone & Branchini 09

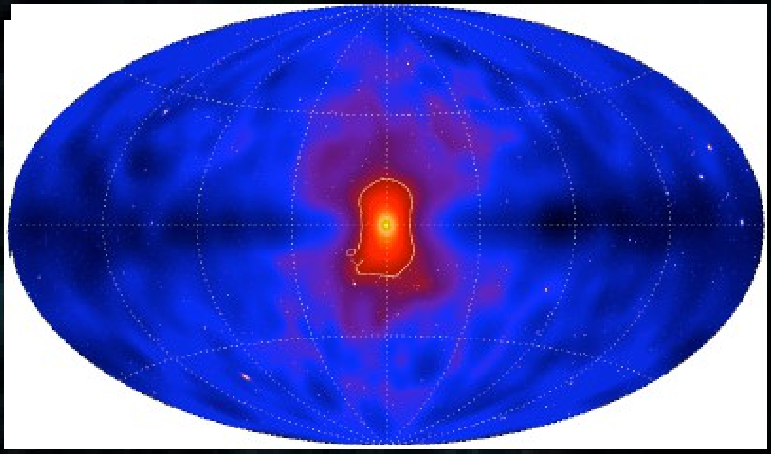


Flux: smooth wins against clumps
on small l, but loses on large l

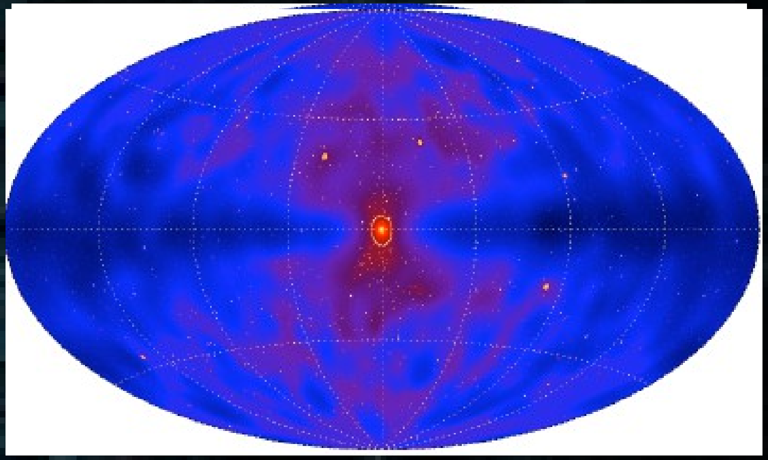
Bergström et al 99



Aquarius



Via Lactea II



<u>Predictions (Fermi 5 yrs):</u>

(i) signal from GC provided understanding of Bg
(ii) few (~ 5) observable subhalos