Indirect Dark Matter Searches
Gamma-ray lines and Company

- Introduction & Motivation
- Searches in the positron fraction
- Searches for gamma-ray lines
- Outlook & Conclusions

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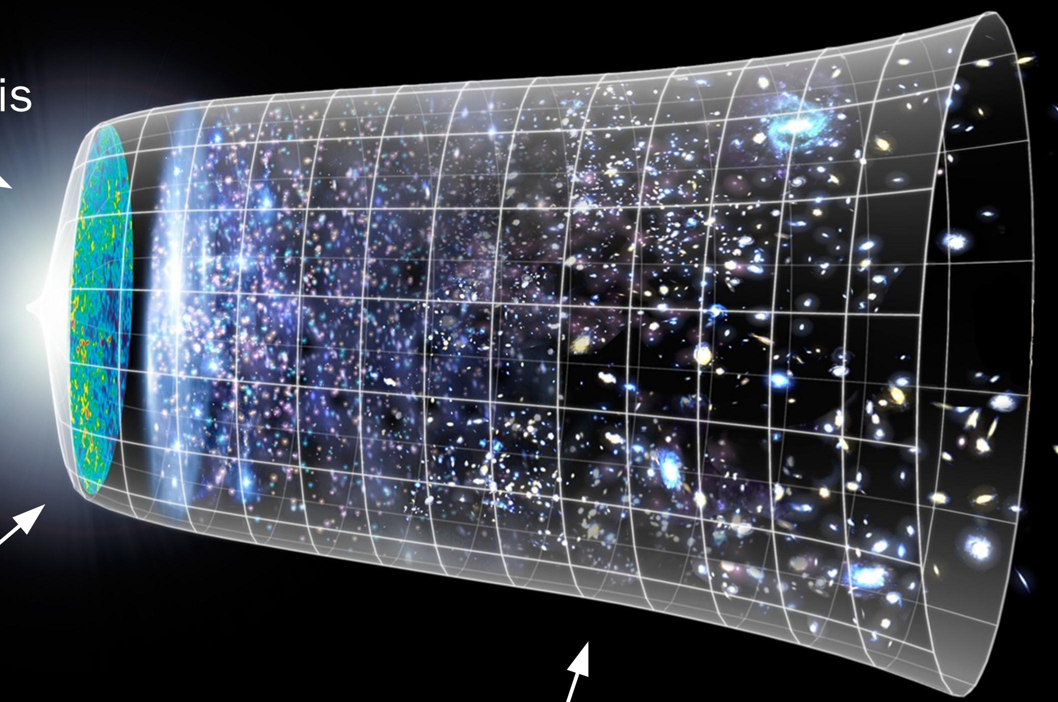
8 October 2013
Workshop on the Future of Dark Matter
Astro-Particle Physics: Insides and Perspectives
ICTP, Trieste

80 Years of Evidence for Dark Matter

Primordial Nucleosynthesis

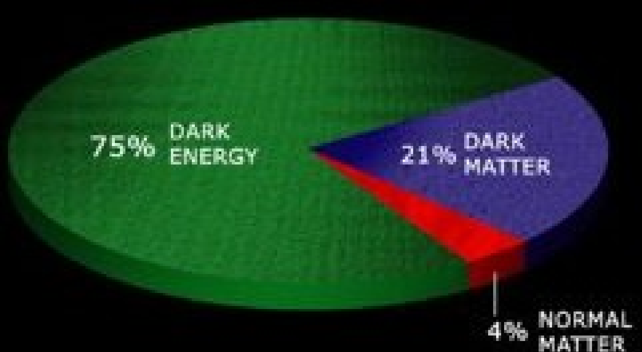


CMB Anisotropies

Large Scale Structures

Galaxy Clusters & X-rays, weak lensing & kinematics

Energy budget today:



Spiral Galaxy rotation curves
Dwarf spheroidal galaxies
...

Uncertainty principle & MACHO searches: Mass somewhere between 10^{-22} GeV and 10^{50} GeV
[Hu *et al.*, 2000; Tisserand *et al.*, 2007]

...and we have not a @$&# clue what it is.

Models for Dark Matter

Many models and scenarios were proposed: SuperWIMPs, WIMPzillas, Modified Newtonian Dynamics (MOND), Massive Compact Halo Objects (MACHOs), primordial black holes, Asymmetric Dark Matter, ⋯

A few models emerged that solve shortcomings of SM, provide DM, and are not already excluded. They include (but are not limited to):

Axions

Pseudo Goldstone boson of broken Peccei-Quinn symmetry
Why: Solves strong CP problem
Props: Super light (**<<1 eV**), super weakly interacting, super cold

Sterile Neutrinos [Reviews: Boyarsky *et al.*, 2009; Drewes, 2013]

Minimal extension of standard model with right-handed neutrinos
Why: Explains baryon asymmetry & neutrino masses
Props: **keV masses**, very weakly interacting, non-thermal production

Weakly interacting massive particles (WIMPs) [Reviews: Jungman *et al.*, 1996, Bertone *et al.*, 2005]

Generic neutral particle with masses and coupling at electroweak scale
Why: Can solve gauge hierarchy problem
Props: The currently leading hypothesis for what dark matter is made of

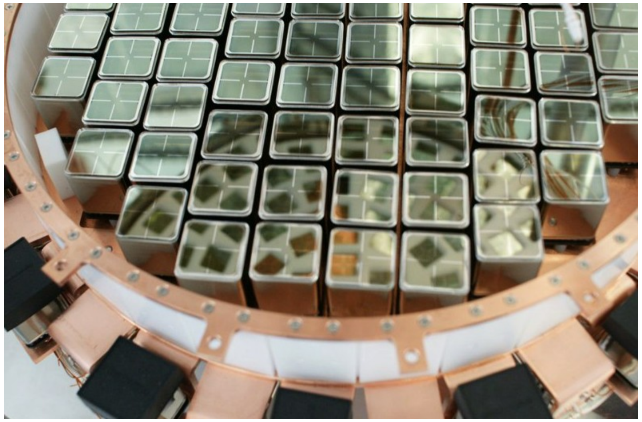
The decade of WIMP searches / discoveries

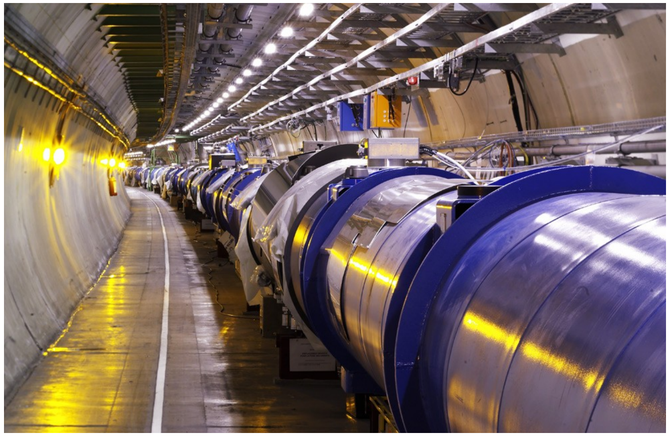
Indirect searches

- Only way to directly test *freeze-out mechanism!*
- Gamma rays are “golden channel”, more data, new strategies, tentative signals
- New anti-matter results just got released (AMS-02), more to come soon (later GAPS)
- Neutrinos are probed at decreasingly low energies (IceCube)
- Further constraints from Planck polarization data

Direct searches

- Only way to directly measure local properties of DM
- Tentative signals/BG in DAMA/LIBRA, CoGeNT, CDMS-Si, CRESST
- More limits from LUX, XENON 1T, later DARWIN, ...
- 2 orders of magnitude better sensitivity expected during this decade

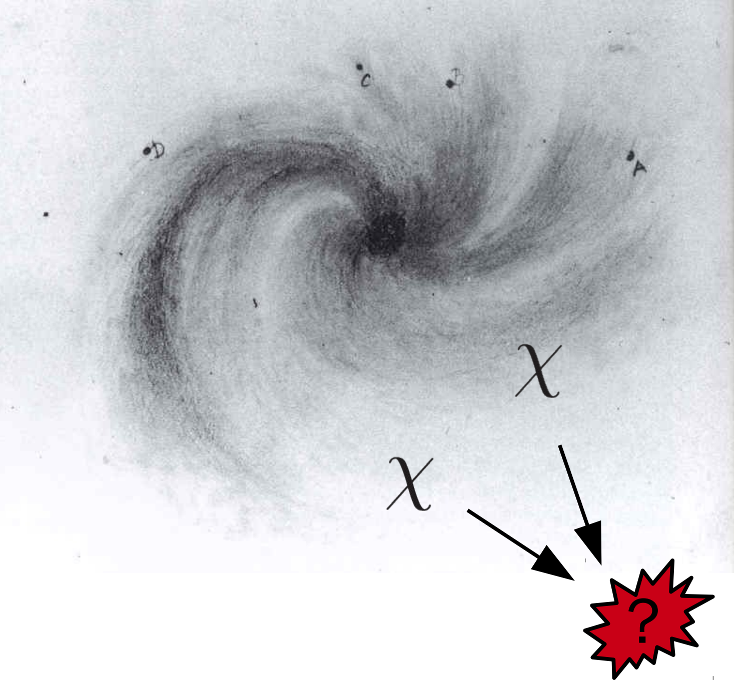




Collider searches

- Only way to make our own DM particles
- Generic searches (mono-jets, mono-photons, ...) put strong constraints on dark matter models
- Even stronger limits on specific scenarios like MSSM
- Nothing non-SM found yet
- But there is hope: restart in 2015 with higher center-of-mass energy

Indirect Searches for Dark Matter



γ

Gamma rays
- Very simple propagation (geodesics)
- Absorption negligible on Galactic scales
- Point towards their sources

Talks by: A. Cuoco, M. Regis, G. Gomez, S. Murgia, I. Cholis

B-field

$\bar{p},\ e^+,\ \ldots$

Charged cosmic rays
- Electrons/positrons, nuclei
- Propagation distorted by galactic magnetic fields
- Sizable energy losses & interactions

Talk by: F. Donato

Today's dark matter **annihilation cross-section** is roughly given by

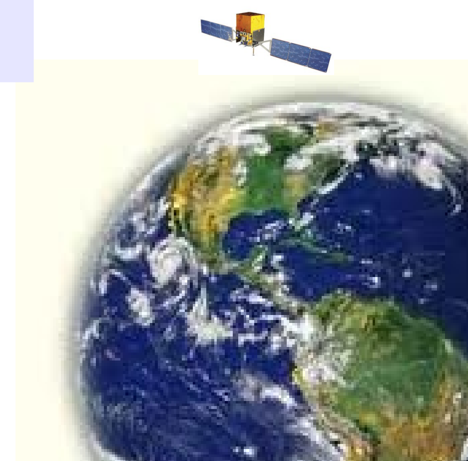
$$\langle\sigma v\rangle_{\rm tot} \sim 3\times10^{-26}{\rm cm^3 s^{-1}}$$

Conditions during freeze-out are very different from today: The velocity averaged annihilation cross-sections can differ by orders of magnitude.

ν

Neutrinos
- Simple propagation
- But: hard to measure

Talk by: N. Whitehorn

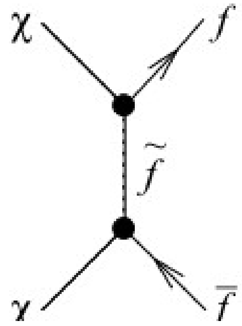


Annihilation branching fractions: anything goes

<u>The most popular DM model:</u>
The lightest MSSM neutralino

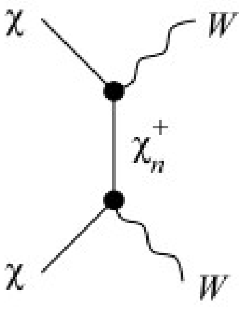
Bino:
t-channel annihilation into <u>leptons</u>

e.g.



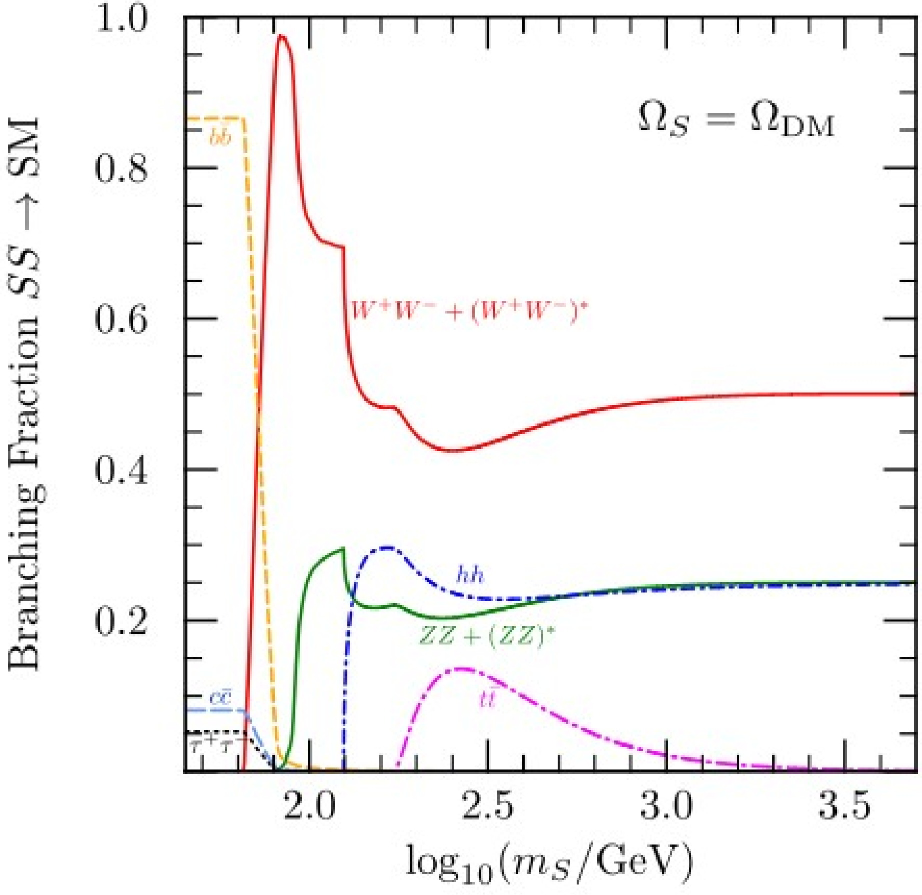
Higgsino and Wino:
(co-)annihilation into gauge bosons

e.g.



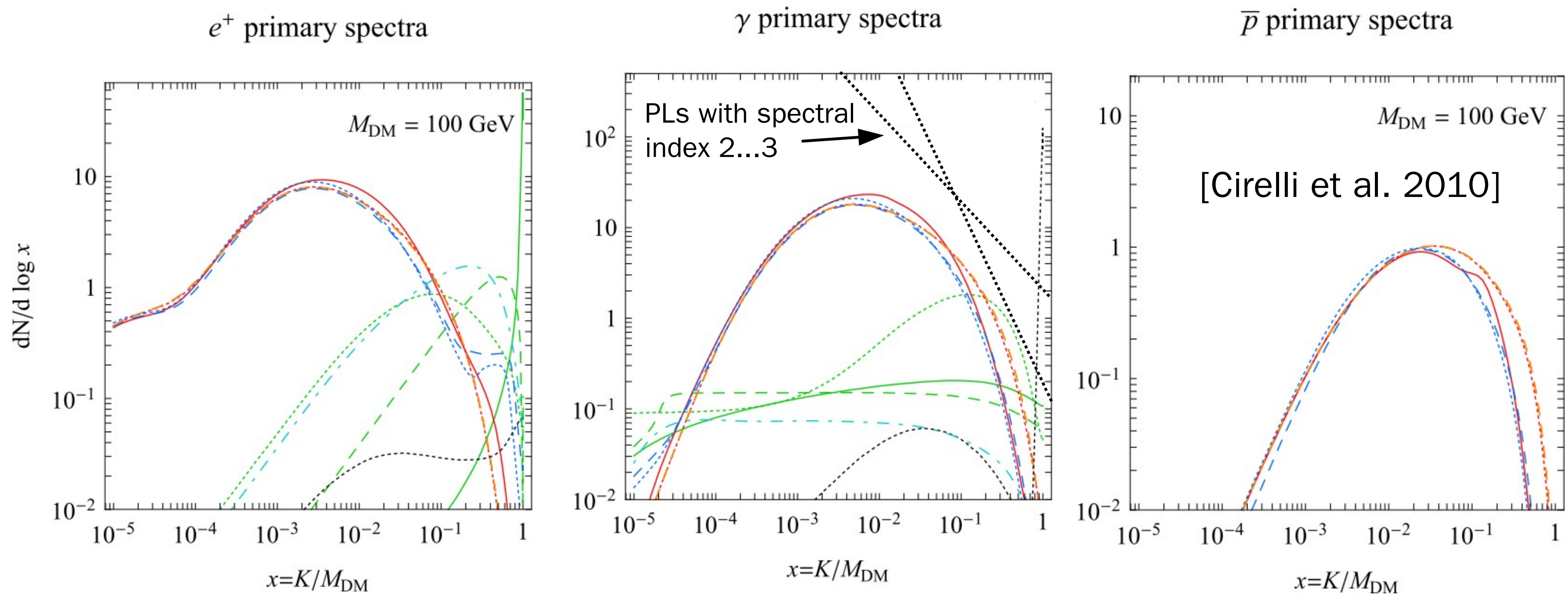
<u>The most simple DM model:</u>

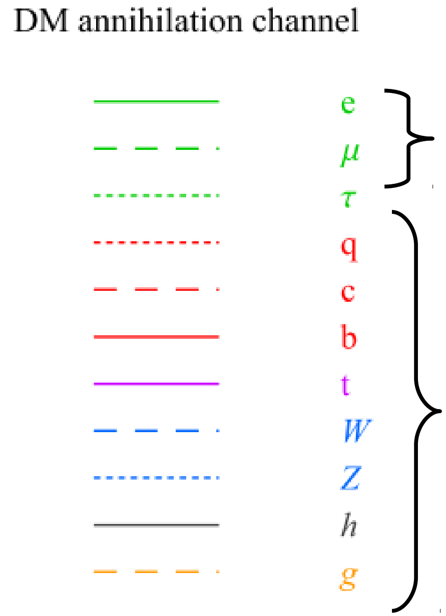
$$V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2$$



[Cline *et al.*, 2013]

Annihilation spectra – 2-body final states





- Hard spectra with pronounced bumps close to kin. threshold
- Photons from final-state radiation (FSR) and π^0-decay
- Electrons: direct or from three-body and/or meson-decay

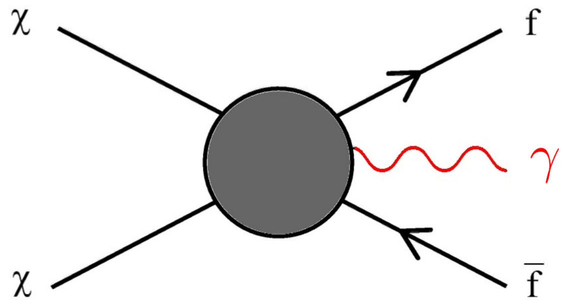
- Softer spectra with broad bumps 10 – 100 times below kin. thresh.
- Photons: mostly π^0-decay after hadronization
- Electrons: mostly meson-decay after hadronization

$$\chi\chi \rightarrow \bar{X}X$$

Internal Bremsstrahlung

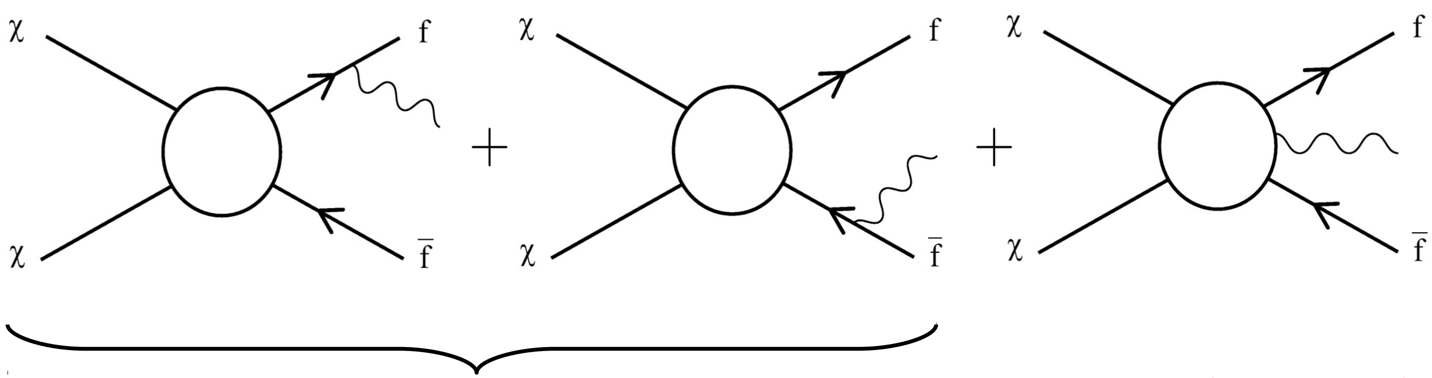
Charged final states give rise to **internal bremsstrahlung (IB)**

$$\chi\chi \to f\bar{f} \quad \overset{\mathcal{O}(\alpha)}{\Longrightarrow}$$



Two contributions:

=



"Final State Radiation"

1^{st} order in $(m_f/m_\chi)^2$

"Virtual Internal Bremsstrahlung"

0^{th} order in $(m_f/m_\chi)^2$

[Figs. from T. Bringmann; Bringmann *et al.*, 2008]

Monochromatic Photons

Gamma-ray lines

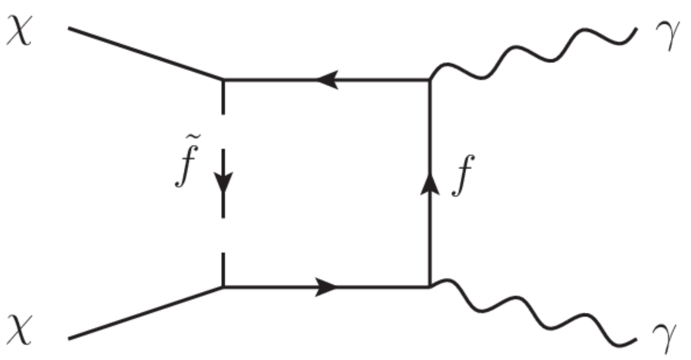
- are produced via two-body annihilation

$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$

- have a trivial energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

Direct annihilation into photons is loop-suppressed:



Generic branching ratios are frustratingly small:

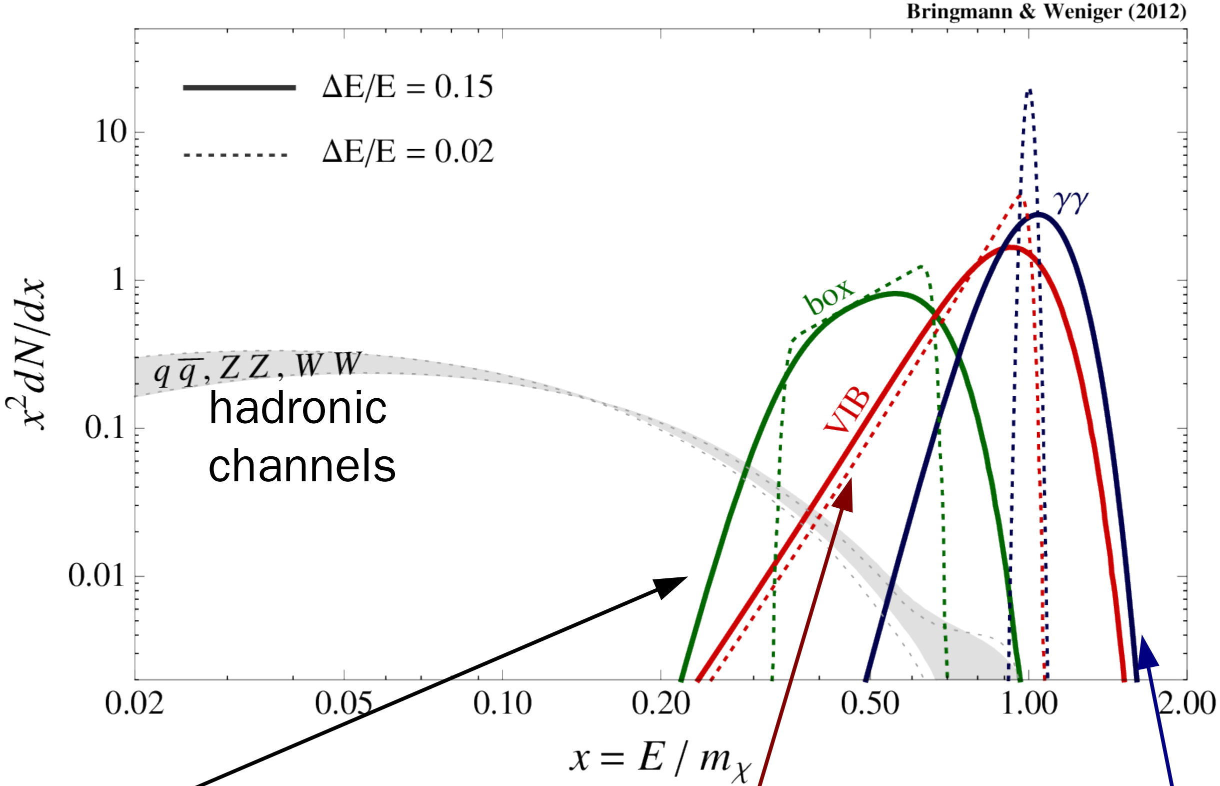
$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$

This would be impossible to detect.

But, larger line fluxes are not impossible:

- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- "Higgs in Space!" [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]
- ...

Gamma-ray annihilation spectra – radiative corrections



(Box-like spectra)

- Cascade-decay into monochromatic photons
- already at tree level

Internal Bremsstrahlung (IB)

- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f} f \gamma$$

Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

$$\chi\chi \to \gamma\gamma$$

compare to:

$$\chi\chi \to e^+ e^-$$

Cosmic-ray positrons

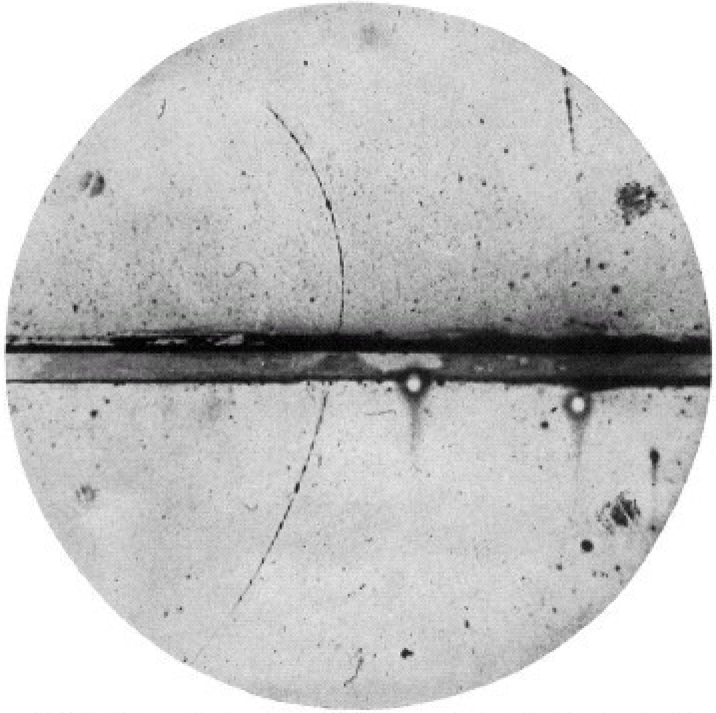
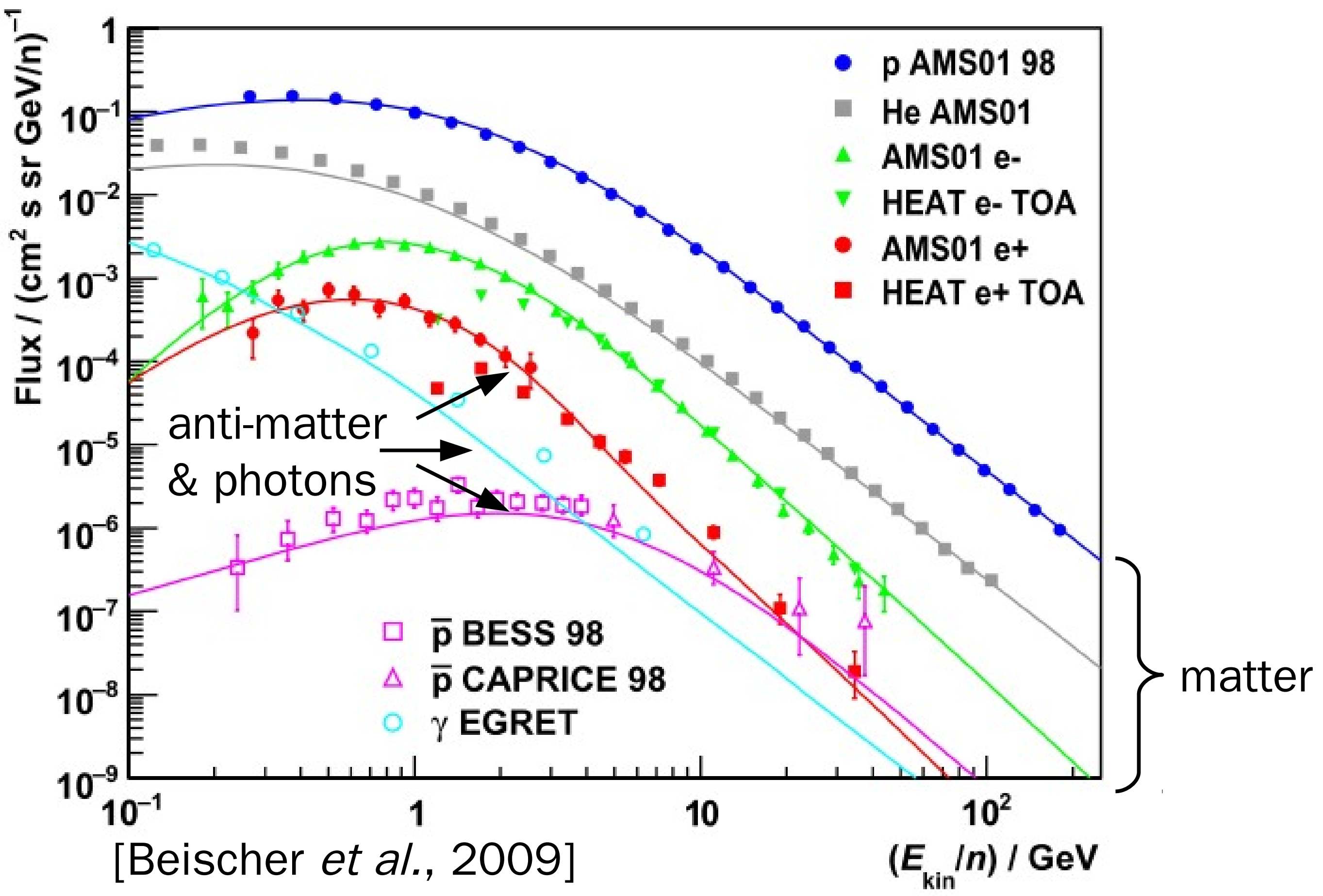


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Comparison of different CR species



[Beischer *et al.*, 2009]

- **Dark matter annihilation/decay** would produce the same amount of particles as anti-particles (modulo models with CP violation)

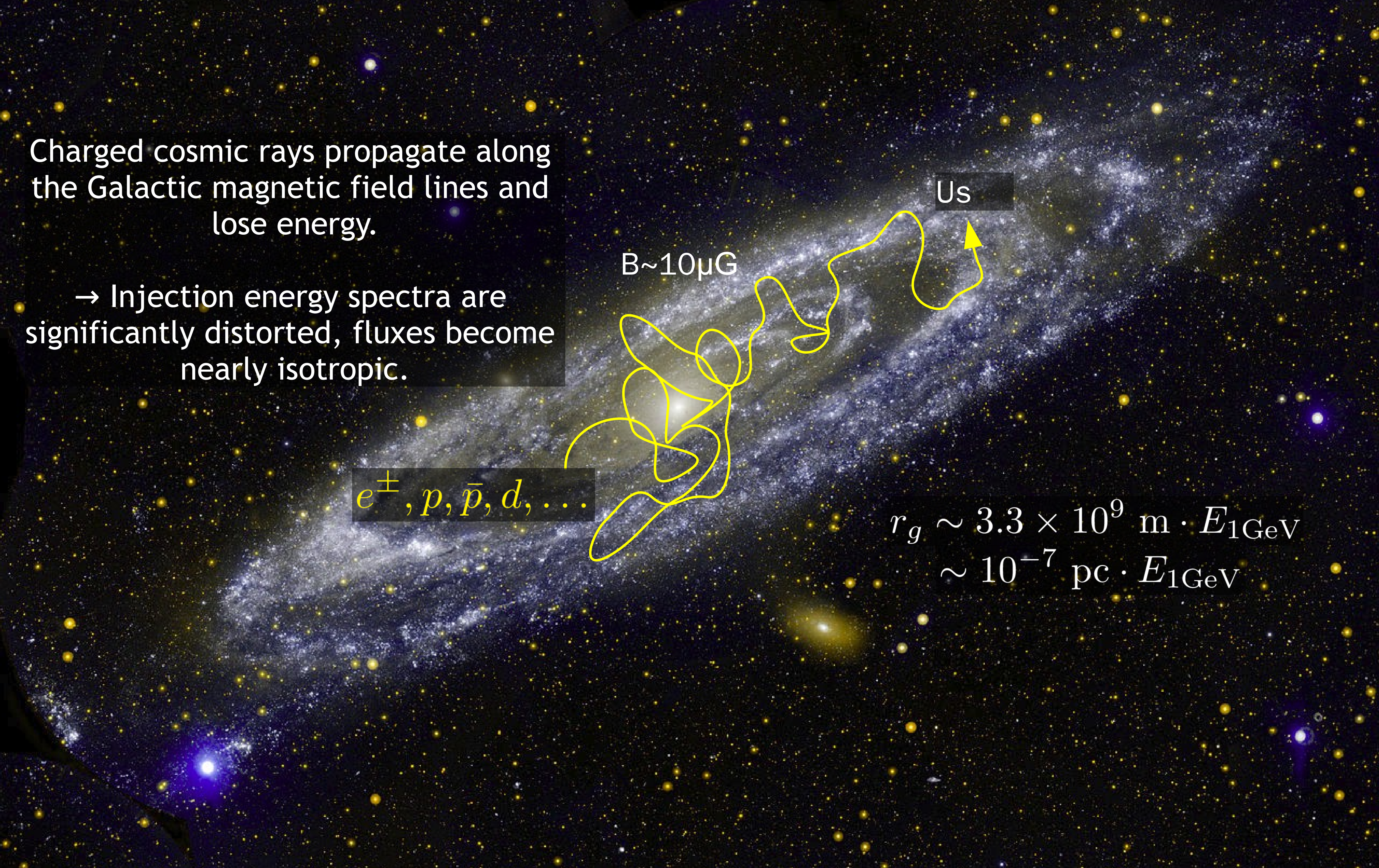
$$f = \frac{\Phi_{e^+}}{\Phi_{e^-} + \Phi_{e^+}}$$

Galactic cosmic rays

Galaxy as seen by a particle physicist:

Charged cosmic rays propagate along the Galactic magnetic field lines and lose energy.

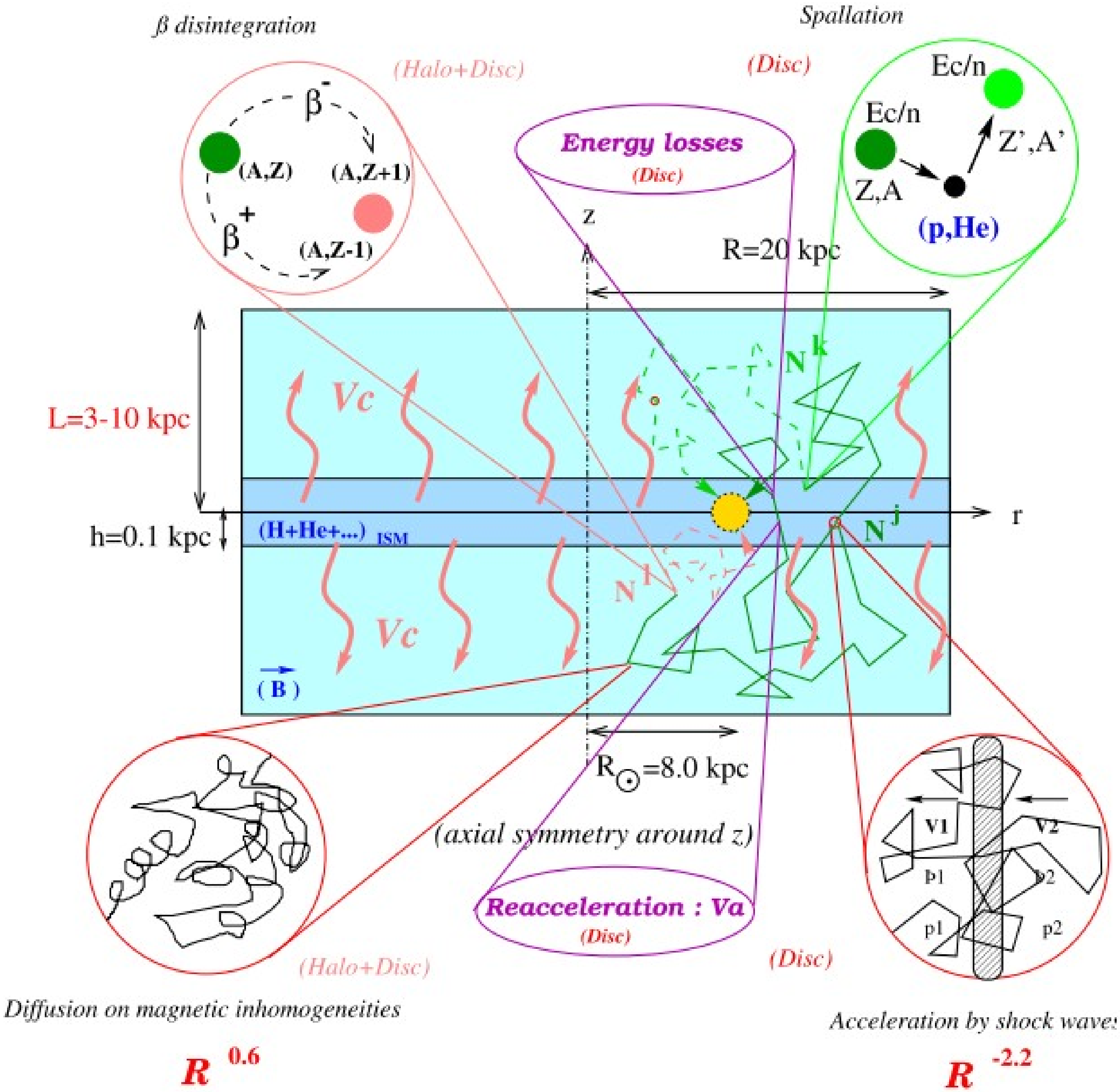
→ Injection energy spectra are significantly distorted, fluxes become nearly isotropic.



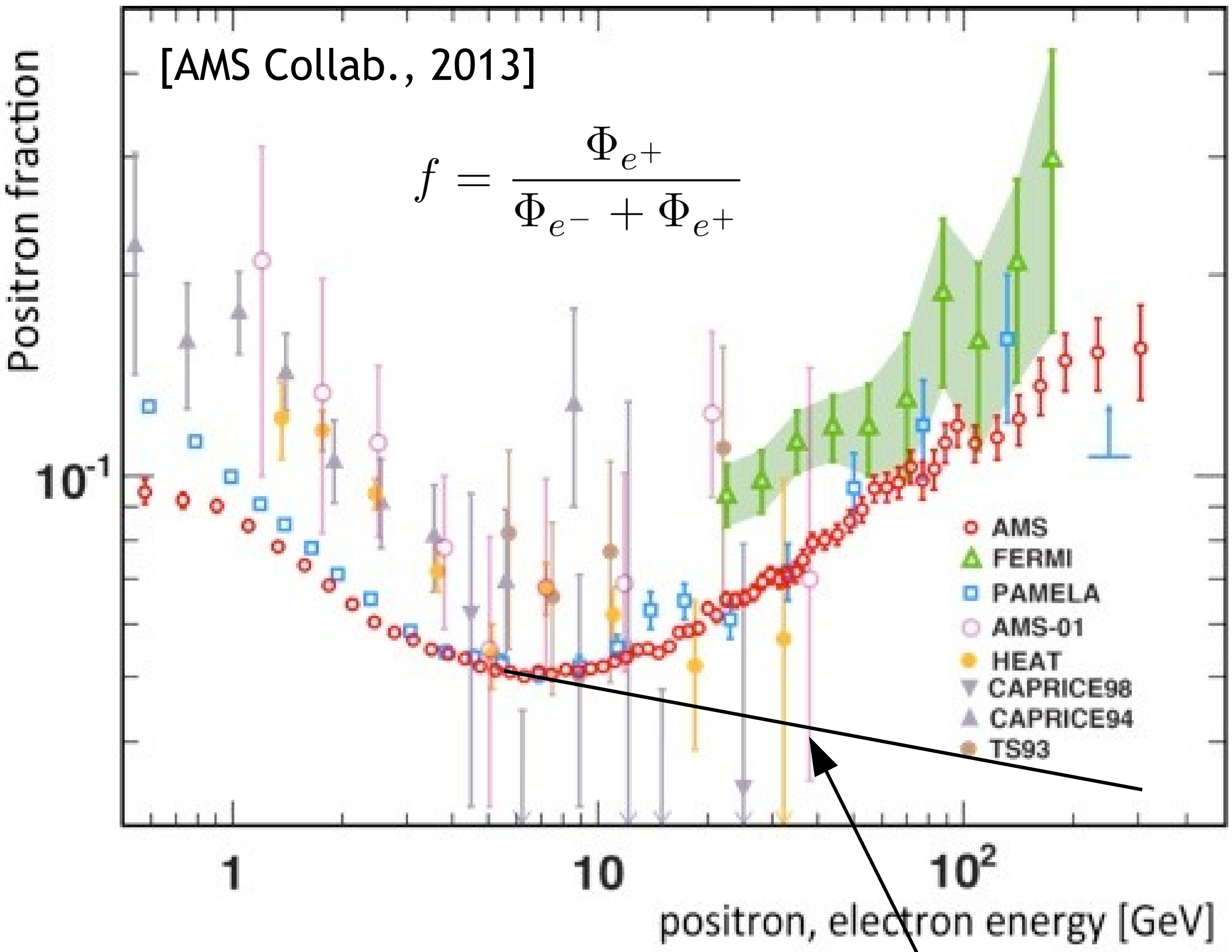
$$r_g \sim 3.3 \times 10^9 \ \mathrm{m} \cdot E_{1\mathrm{GeV}}$$
$$\sim 10^{-7} \ \mathrm{pc} \cdot E_{1\mathrm{GeV}}$$

The Galaxy as seen by a Cosmic Ray Physicist:

[excellent review: Lavalle & Salati (2012)]

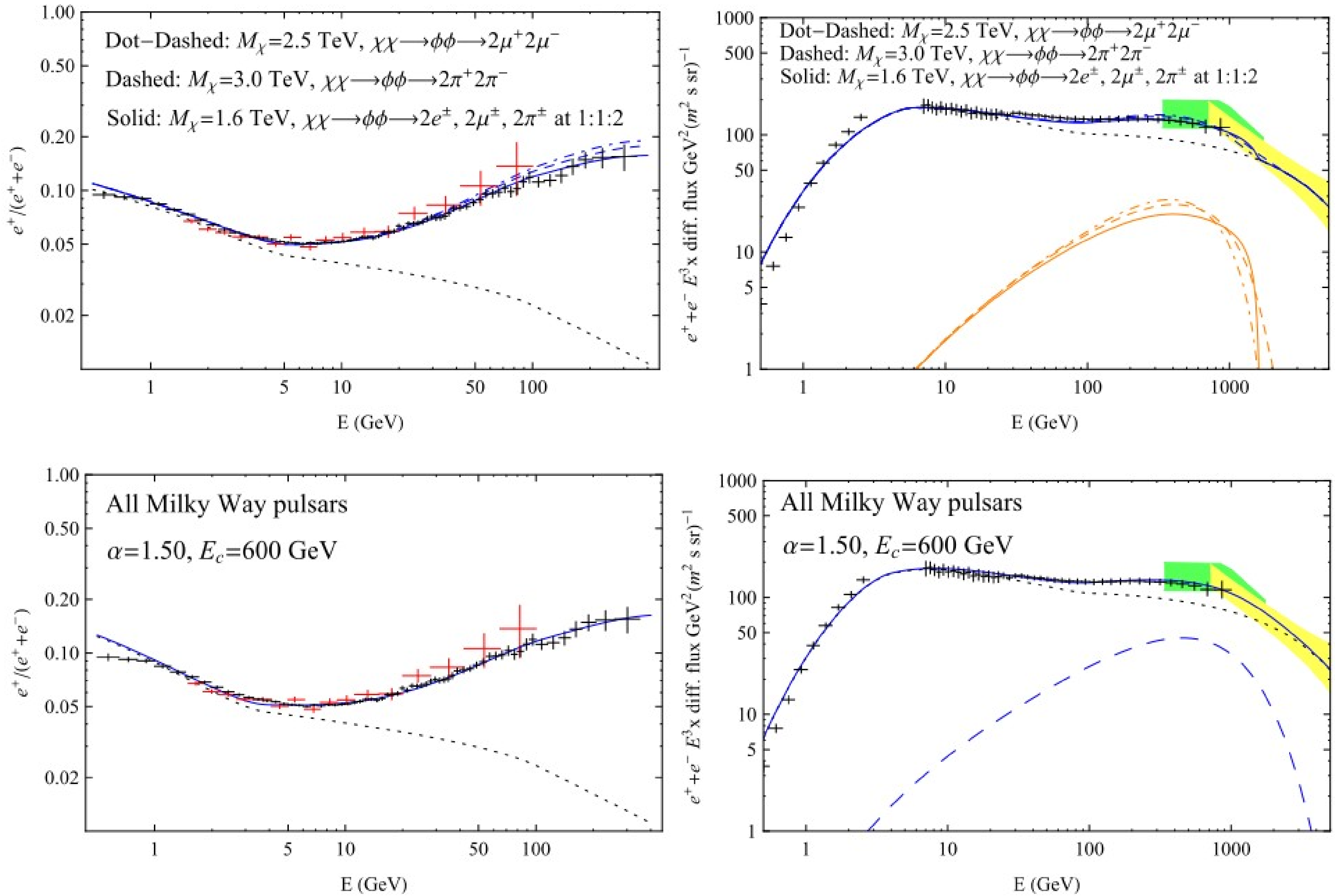


Rise in the positron fraction above 10 GeV



Positron fraction from secondary production should <u>decrease</u>

DM can explain the rise – nearby pulsars as well



[Cholis & Hooper (2013)]

CR electron and positron propagation

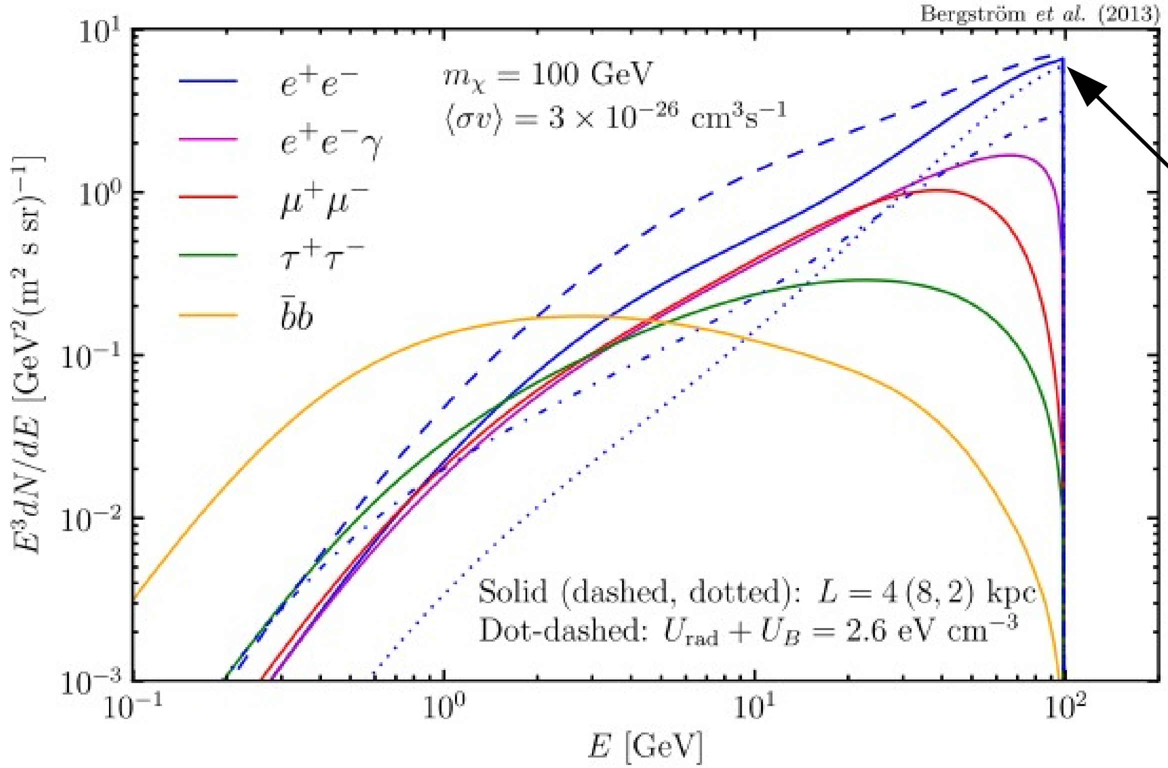
Propagation of electron and positrons is dominated by energy losses:

$$\frac{\partial f}{\partial t} - \nabla\left(\mathcal{K}(E,\vec{x})\nabla f\right) - \frac{\partial}{\partial E}\left(b(E,\vec{x})f\right) = Q(E,\vec{x})$$

Energy losses by: Synchrotron radiation & Inverse Compton Scattering

$$b_{\rm ICS}(E_e) = \frac{4}{3}\sigma_{\rm T}\gamma_e^2 \underbrace{\int_0^\infty d\epsilon\; \epsilon f_{\rm CMB}(\epsilon)}_{\equiv \rho_{\rm CMB}} \quad \text{and} \quad b_{\rm syn}(E_e) = \frac{4}{3}\sigma_{\rm T}\gamma_e^2 \frac{B^2}{2}$$

Propagated spectra for different final states:



$$\frac{dN}{dE}_{\rm peak} \propto \frac{1}{b}$$

→ Electron spectrum becomes step-function

A spectral analysis...

<u>Phenomenological</u> **background model** (works & is simple, but not exceedingly realistic)

$$f = \frac{\Phi_{e+}}{\Phi_{e-} + \Phi_{e+}} \qquad \Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

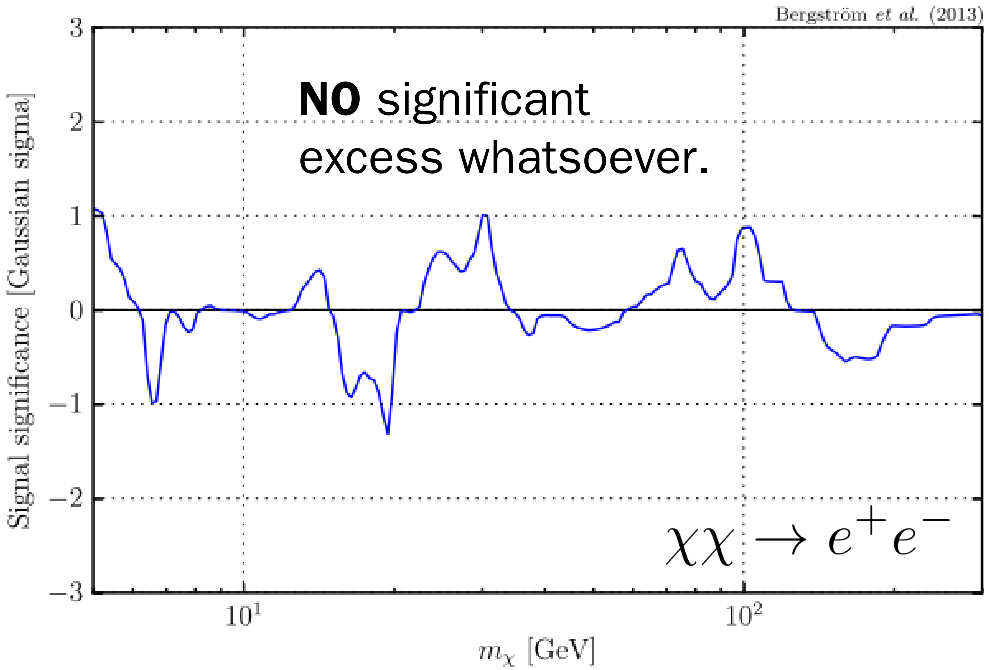
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

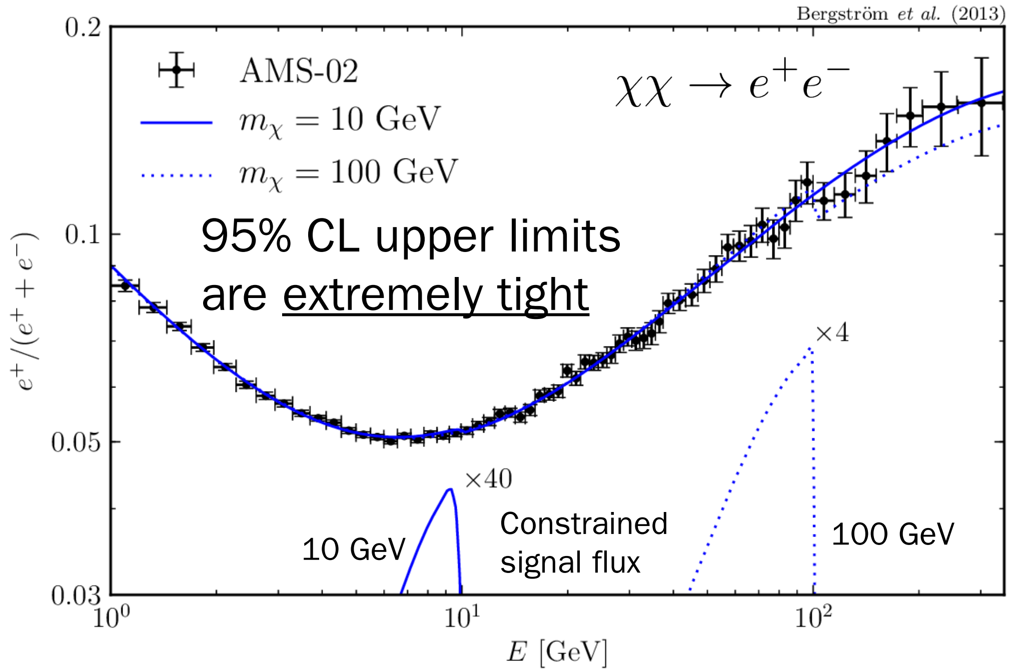
[Aguilar *et al*., 2013]

Agnostic approach: allow **any** primary e+/e- source

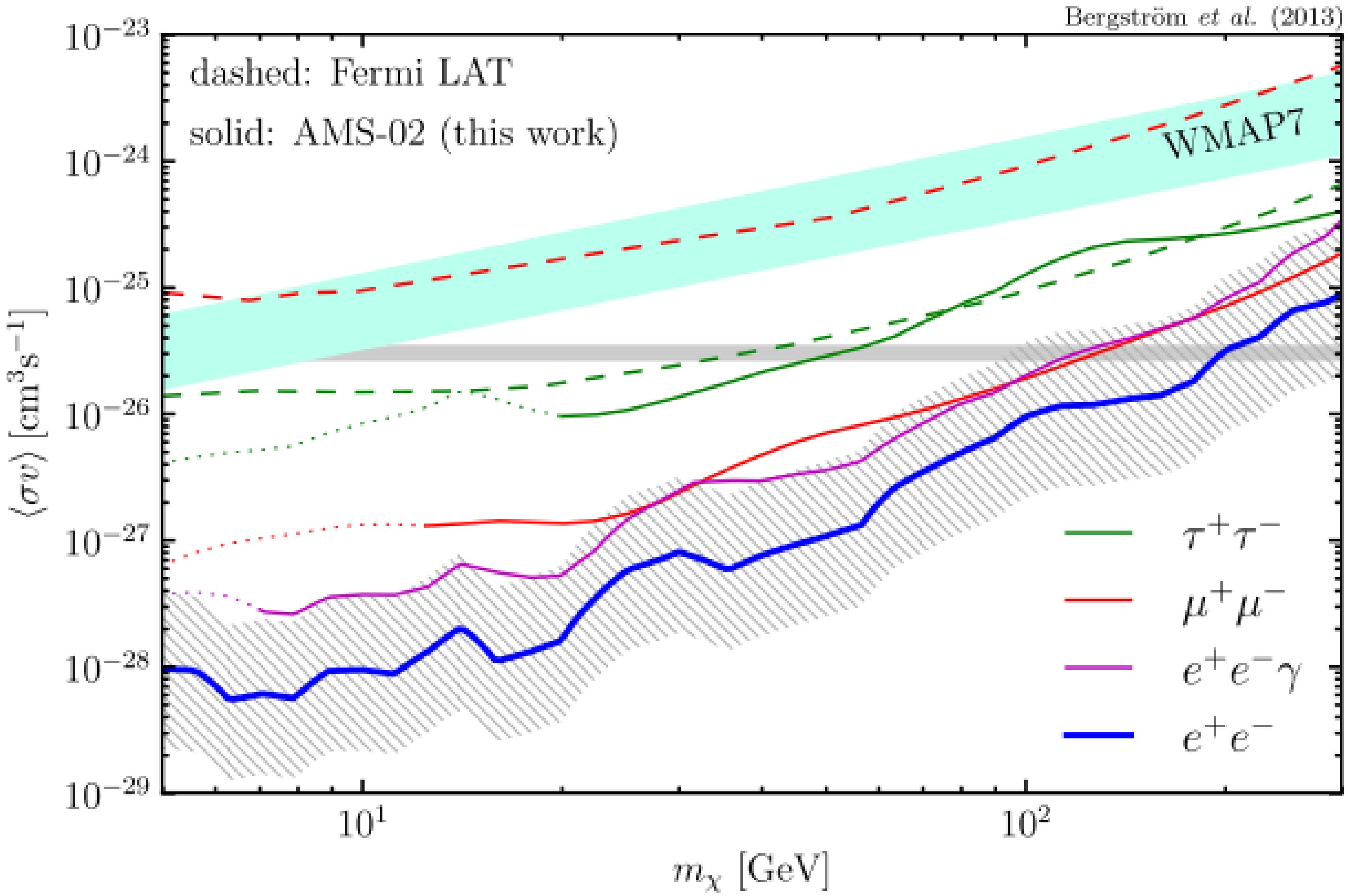
Fit to the data:

- free parameters: signal normalization, γ_{e-}, γ_s, C_s, C_{e-} and E_s .
- systematic and statistical errors are added in quadrature
- energy dispersion is neglected





...gives rise to the strongest limits on leptonic channels!



[for related analysis with positron <u>flux</u> see Ibarra *et al.*, 2013]

For electrons (and muons), these limits top previous ones by 1-2 orders of magnitude!

Main uncertainties (hashed band)

- local DM density: 0.25 – 0.7 GeV cm^{-3}
- local radiation/B-field density: 3 – 8 μG
  → factor of 4

Up to 300 GeV, our limits <u>are stronger than</u>
- Limits from the CMB (including Planck forecast)
- Limits from dwarf spheroidal galaxies

[To appear in Phys. Rev. Lett.]

Why this is not just terribly wrong

Effect of solar modulation

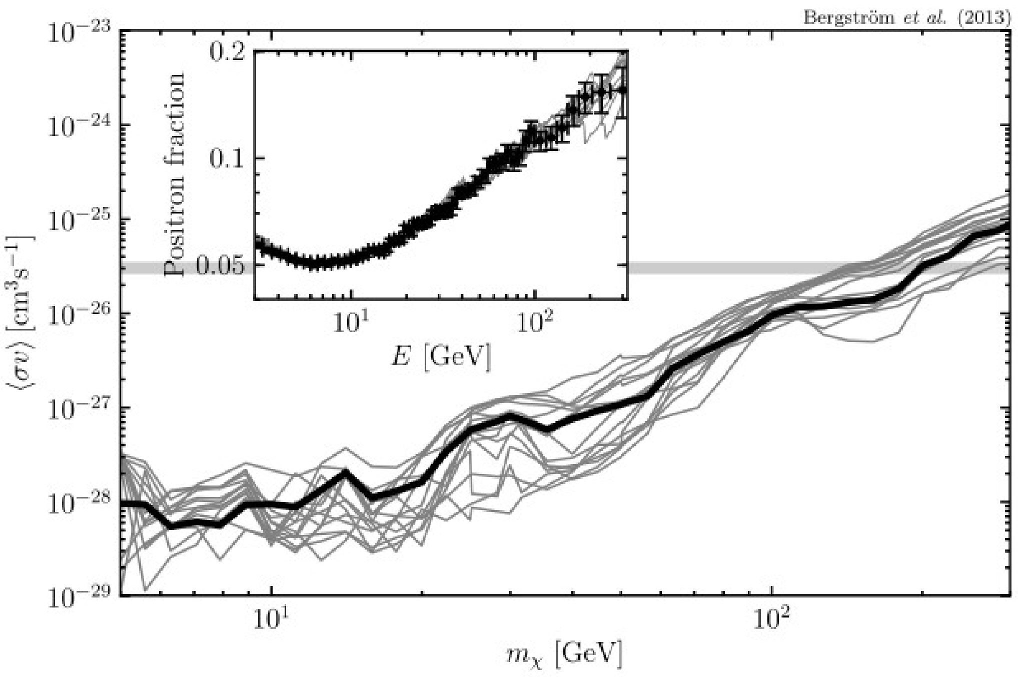
- Force-field approximation: affects fluxes down to 5 GeV by less then 20 – 40%.

Physical background models

- still have to fit data → no big change expected
- we find O(3) variations for different physical background models (that fit the positron fraction slightly worse than the simple model above)

DM signal could hide between pulsar bumps

- We simulated multi-pulsar backgrounds
  - taking pulsar distances, P & Pdot from ATNF catalog (w/o MSPs, <4kpc)
  - random variation of fraction that goes into e+/e- pairs (~O(5%))



Outlook: marginalize over background realizations + propagation models → make limits as robust as Fermi LAT dwarf spheroidal limits

Searches for gamma-ray lines and the 130 GeV feature

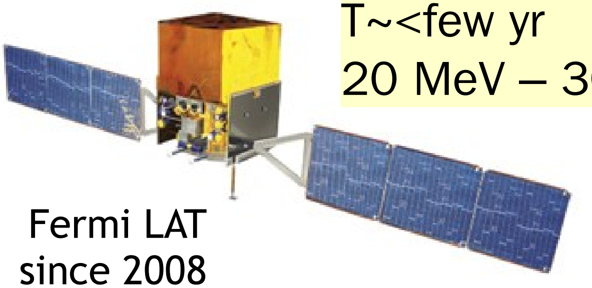
Current gamma-ray experiments
GeV to TeV energy range

Ground based:
(Atmospheric Cherenkov Telescopes)

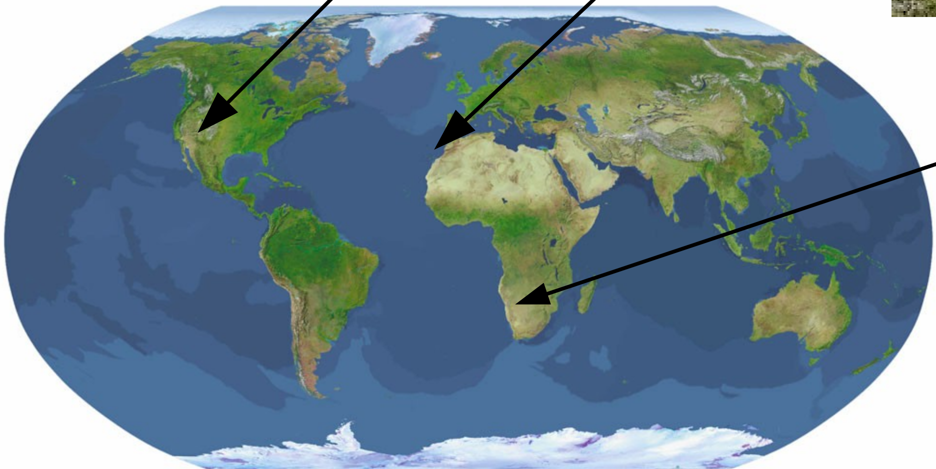
A_{eff}~1km^2
T~<100h
>10 GeV

Space based:
(Pair conversion detector)

A_{eff}~0.8 m^2
T~<few yr
20 MeV – 300 GeV

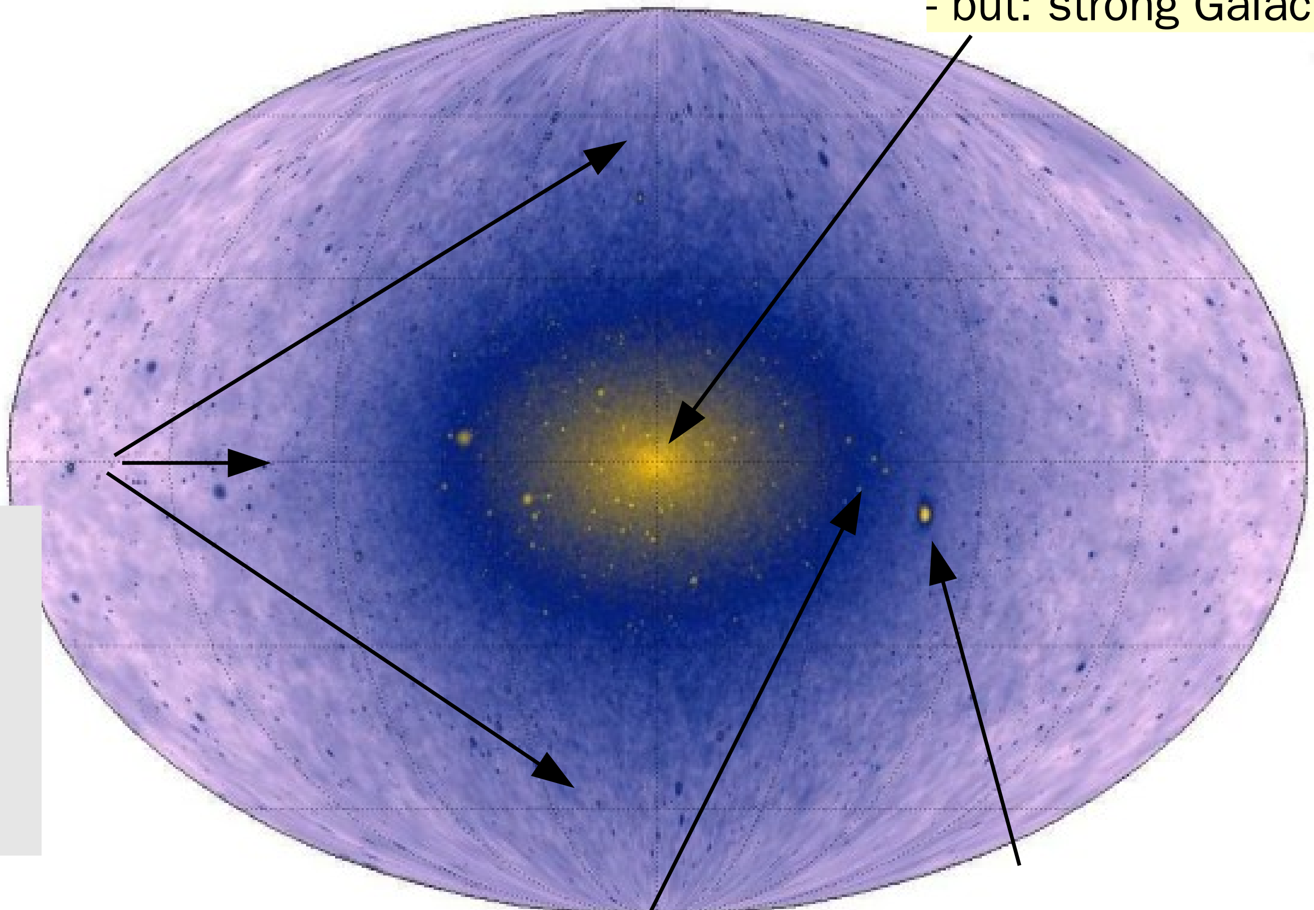


Fermi LAT
since 2008



Potential targets for DM searches

Dark matter signal predicted by N-body simulations:
[Kuhlen et al. 2007]



Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: strong Galactic emission

Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic signal
- nearly isotropic
- only visible close to Galactic poles
- angular information
- **Galaxy clusters!**

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

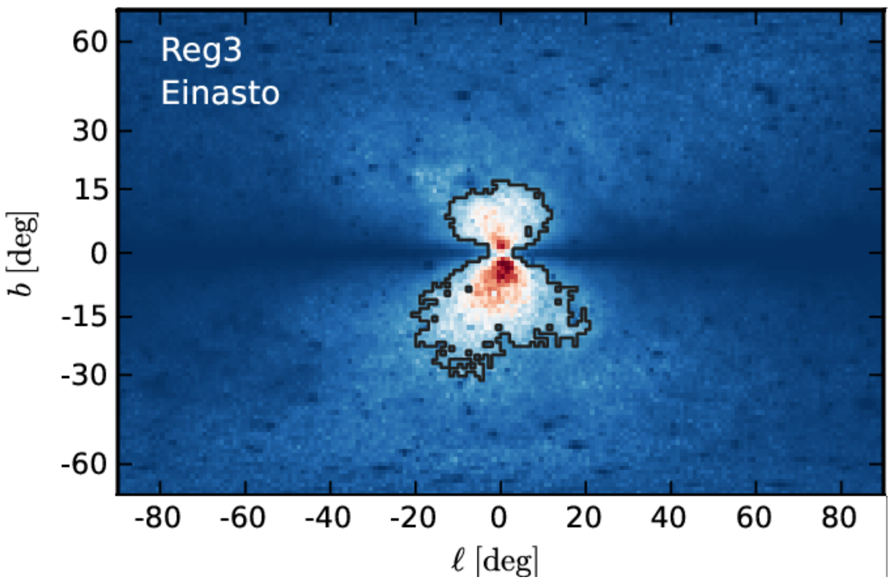
“Dwarf Spheroidal Galaxies”
- contain small number of stars
- otherwise dark (no gamma-ray emission)

Line searches: The general strategy

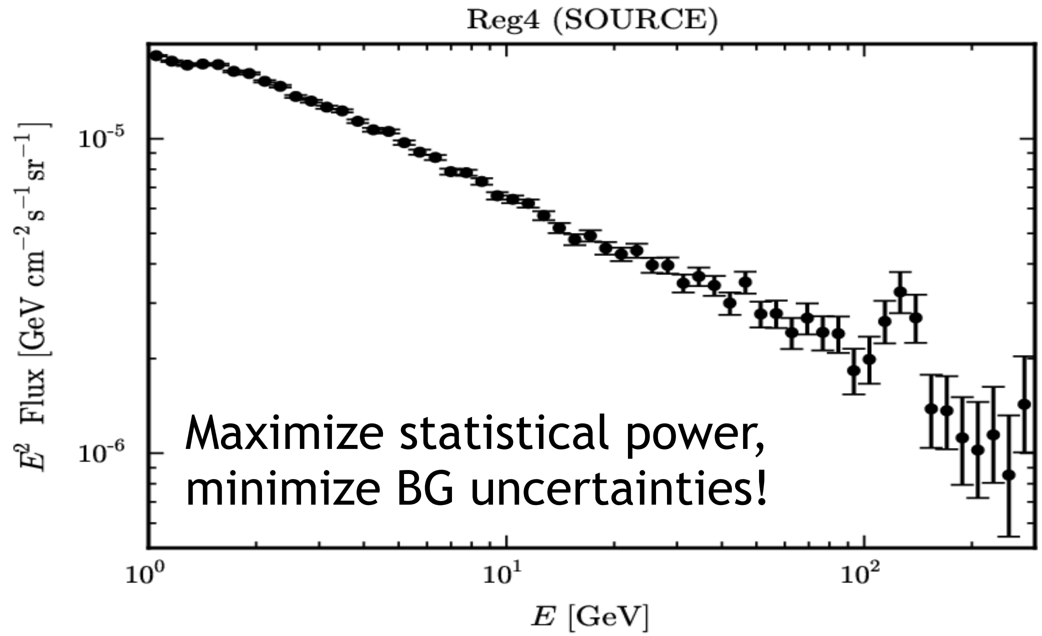
I) Identify best ROI

Maximize S/N!

[Bringmann *et al.*; CW, 2012]



II) Spectral analysis

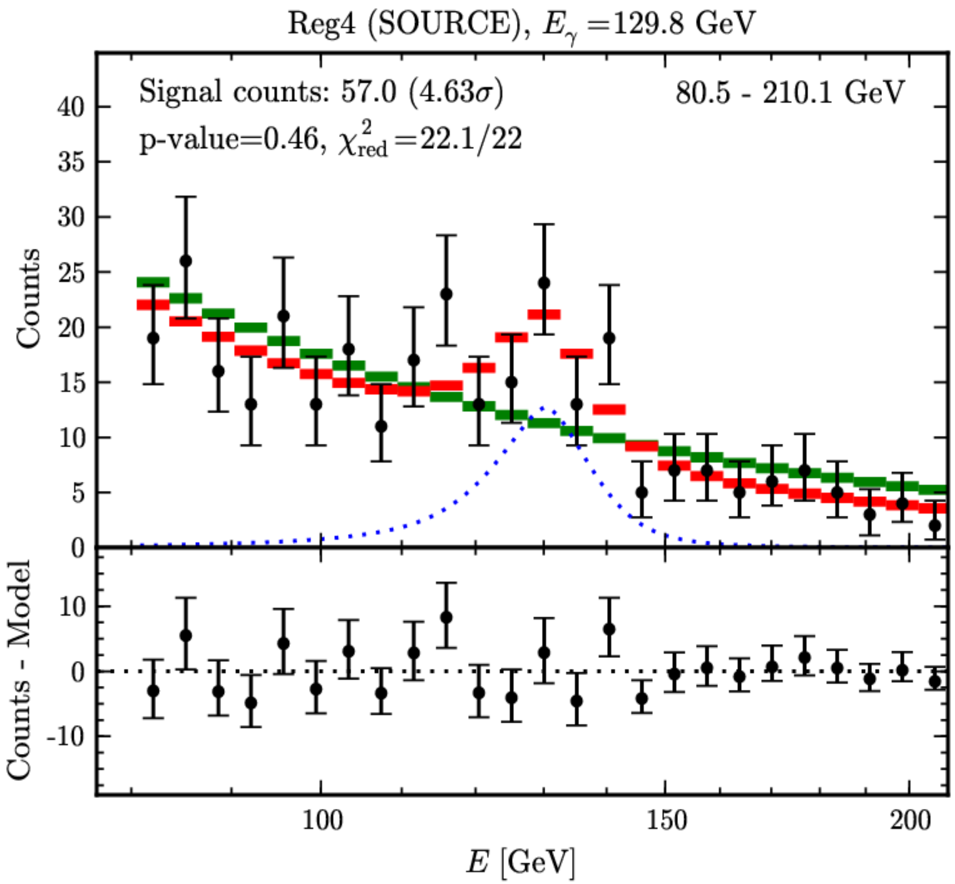


Fit with Power-law background + line model (three free parameters)

$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta E^{-\gamma}$$

Different analysis differ (almost) only in what ROI and energy range is used in the fit

The 130 GeV feature – How it started

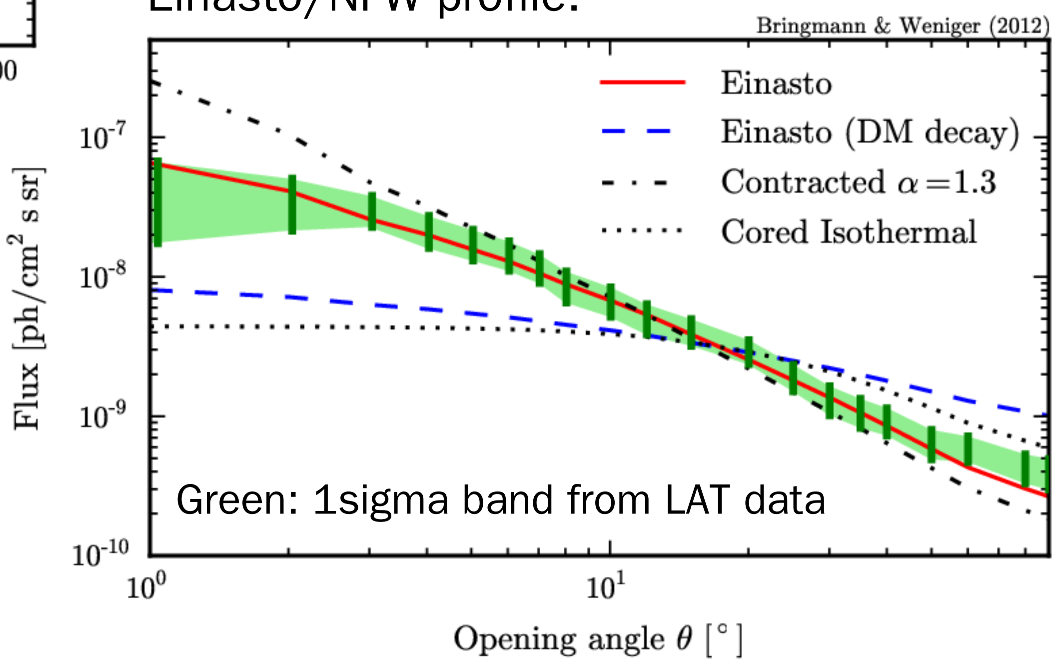


[Bringmann *et al.*; CW; 2013]

<u>Using:</u>
43 months of SOURCE class events (P7V6)

we found a line-like excess at 130 GeV with local significance of 4.6 sigma
(→ global significance 3.2 sigma)

Morphology largely compatible with Einasto/NFW profile:



Follow up studies

Fermi 130 GeV gamma-ray excess and dark matter annihilation in sub-haloes and in the Galactic centre

May 2012

Elmo Tempel,[a,b] Andi Hektor[a] and Martti Raidal[a,c,d]

Abstract. We analyze publicly available Fermi-LAT high-energy gamma-ray data and confirm the existence of clear spectral feature peaked at $E_\gamma = 130$ GeV. Scanning over the Galaxy we identify several disconnected regions where the observed excess originates from. Our best optimized fit is obtained for the central region of Galaxy with a clear peak at 130 GeV with statistical significance 4.5σ. The observed excess is not correlated with Fermi bubbles. We com
four standard mo
with data. Since
data disfavors all
Einasto halo prof
cross-section to t
section. If the ob
identified the mos
two-body annihil
searched for at th

Many more great papers: Profumo, Linden, JCAP 1207 (2012) 011; Ibarra, Gehler, Pato, JCAP 1207 (2012) 043; Dudas et al., arXiv:1205.1520; Cline, PRD86 (2012) 015016; Choi, Seto, PRD86 (2012) 043515; Kyae, Park, arXiv:1205.4151; Lee, Park, Park, arXiv:1205.4675; Boyarsky, Malyshev, Ruchayskiy, arXiv:1205.4700; Rajaraman, Tait, Whiteson, arXiv:1205.4723; Acharya et al., arXiv:1205.5789; Buckley, Hooper, PRD86 (2012) 043524; Geringer-Samet, Koushiappas, PRD86 (2012) 021302; Li, Yuan, PLB715 (2012) 35; Chu et al., arXiv:1206.2279; Das, Ellwanger, Mitropoulos, JCAP 1208 (2012) 003; Kang et al., arXiv:1206.2863; Weiner, Yavin, arXiv:1206.2910...

STRONG EVIDENCE FOR GAMMA-RAY LINE EMISSION FROM THE INNER GALAXY

Meng Su[1,3], Douglas P. Finkbeiner[1,2]

Draft version June 15, 2012

June 2012

ABSTRACT

Using 3.7 years of *Fermi*-LAT data, we examine the diffuse $80 - 200$ GeV emission in the inner Galaxy and find a resolved gamma-ray feature at $\sim 110 - 140$ GeV. We model the spatial distribution of this emission with a $\sim 3°$ FWHM Gaussian, finding a best fit position 1.5° West of the Galactic Center. Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5σ ($5.0\sigma/5.4\sigma$ after trials factor correction for one/two line case) assuming an NFW density profile centered at $(\ell, b) = (-1.5°, 0°)$ with a power index $\alpha = 1.2$. The energy spectrum of this structure is consistent with a single spectral line (at energy 127.0 ± 2.0 GeV with $\chi^2 = 4.48$ for 4 d.o.f.). A pair of lines at 110.8 ± 4.4 GeV and 128.8 ± 2.7 GeV provides a marginally better fit (with $\chi^2 = 1.25$ for 2 d.o.f.). The total luminosity of the structure is $(3.2 \pm 0.6) \times 10^{35}$ erg/s, or $(1.7 \pm 0.4) \times 10^{36}$ photons/sec. The energies in the two-line case are compatible with a 127.3 ± 2.7 GeV WIMP annihilating through $\gamma\gamma$ and γZ (with $\chi^2 = 1.67$ for 3 d.o.f.). We describe a possible change to the *Fermi* scan strategy that would accumulate S/N on spectral lines in the Galactic center 4 times as fast as the current survey strategy.

And recently: The official Fermi team analysis

Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

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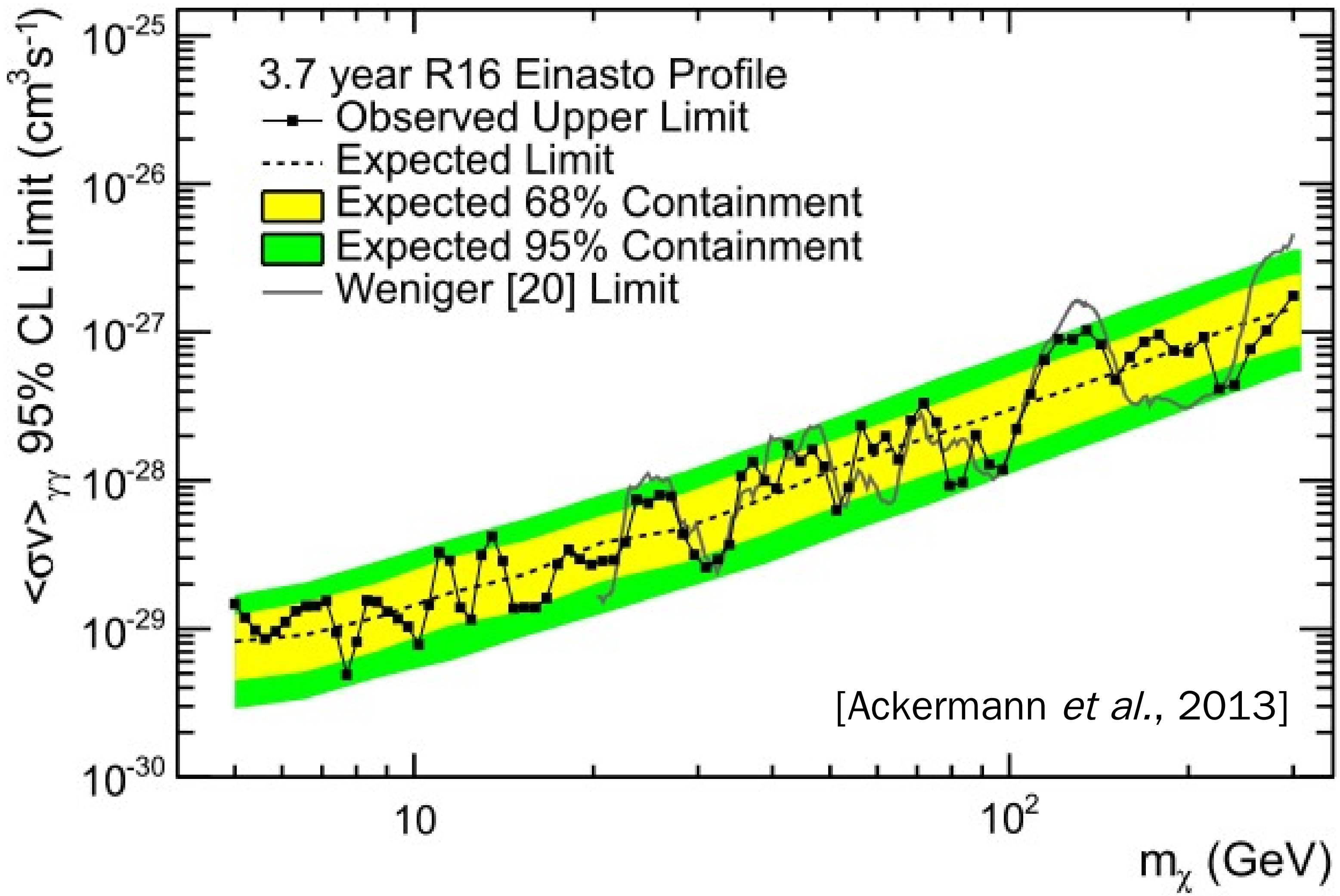
Weakly Interacting Massive Particles (WIMPs) are a theoretical class of particles that are excellent dark matter candidates. WIMP annihilation or decay may produce essentially monochromatic γ rays detectable by the *Fermi* Large Area Telescope (LAT) against the astrophysical γ-ray emission of the Galaxy. We have searched for spectral lines in the energy range 5–300 GeV using 3.7 years of data, reprocessed with updated instrument calibrations and an improved energy dispersion model compared to the previous *Fermi*-LAT Collaboration line searches. We searched in five regions selected to optimize sensitivity to different theoretically-motivated dark matter density distributions. We did not find any globally significant lines in our *a priori* search regions and present 95% confidence limits for annihilation cross sections of self-conjugate WIMPs and decay lifetimes. Our most significant fit occurred at 133 GeV in our smallest search region and had a local significance of 3.3 standard deviations, which translates to a global significance of 1.5 standard deviations. We discuss potential systematic effects in this search, and examine the feature at 133 GeV in detail. We find that both the use of reprocessed data and of additional information in the energy dispersion model contribute to the reduction in significance of the line-like feature near 130 GeV relative to significances reported in other works. We also find that the feature is narrower than the LAT energy resolution at the level of 2 to 3 standard deviations, which somewhat disfavors the interpretation of the 133 GeV feature as a real WIMP signal.

- 133 GeV feature with 3.3 (1.5) sigma significance before (after) trials. Reasons for smaller significance:
  - **Reprocessed data (updated calorimeter calibration)**
  - **2-D fit (including quality of energy reconstruction <u>and</u> energy)**
  - **More data**
- Feature seems to be narrower than the LAT energy resolution

Good news: Limits are consistent!



- Almost perfect agreement between limits from R16 region and our Reg3 (both optimized for Einasto profile)
- But: bump at 130 GeV is weaker than in previous analysis

1) Reprocessed data

Using reprocessed data, the significance drops by ~1.5σ (in Reg3 ROI, 43 months, like in CW 2012, with 65 – 260 GeV energy range):

P7REP CLEAN
4.3σ (P7V6 CLEAN) → 2.8σ (P7REP CLEAN)

P7REP SOURCE
4.6σ (P7V6 SOURCE) → 3.2σ (P7REP SOURCE)

2) 2-dim fit

Including the incidence-angle dependence of the energy resolution in the fit, the significance drops further:

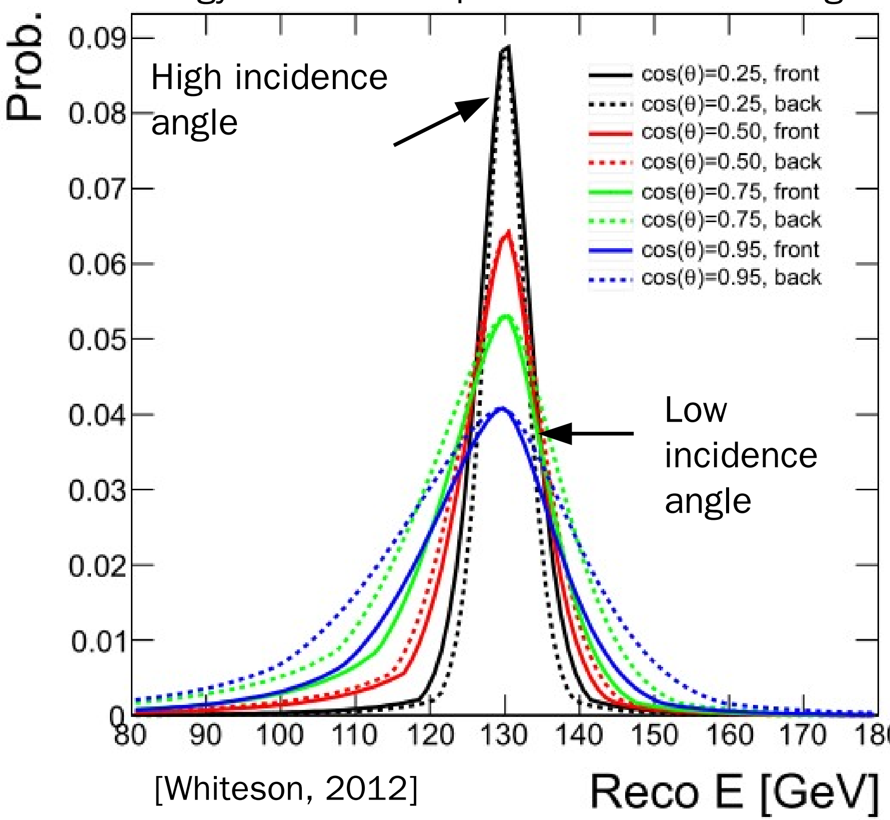
P7REP CLEAN
2.8σ (1-D) → 2.4σ (2-D)

P7REP SOURCE
3.2σ (1-D) → 2.9σ (2-D)

This is in good agreement with Ackermann *et al.*, (2013).

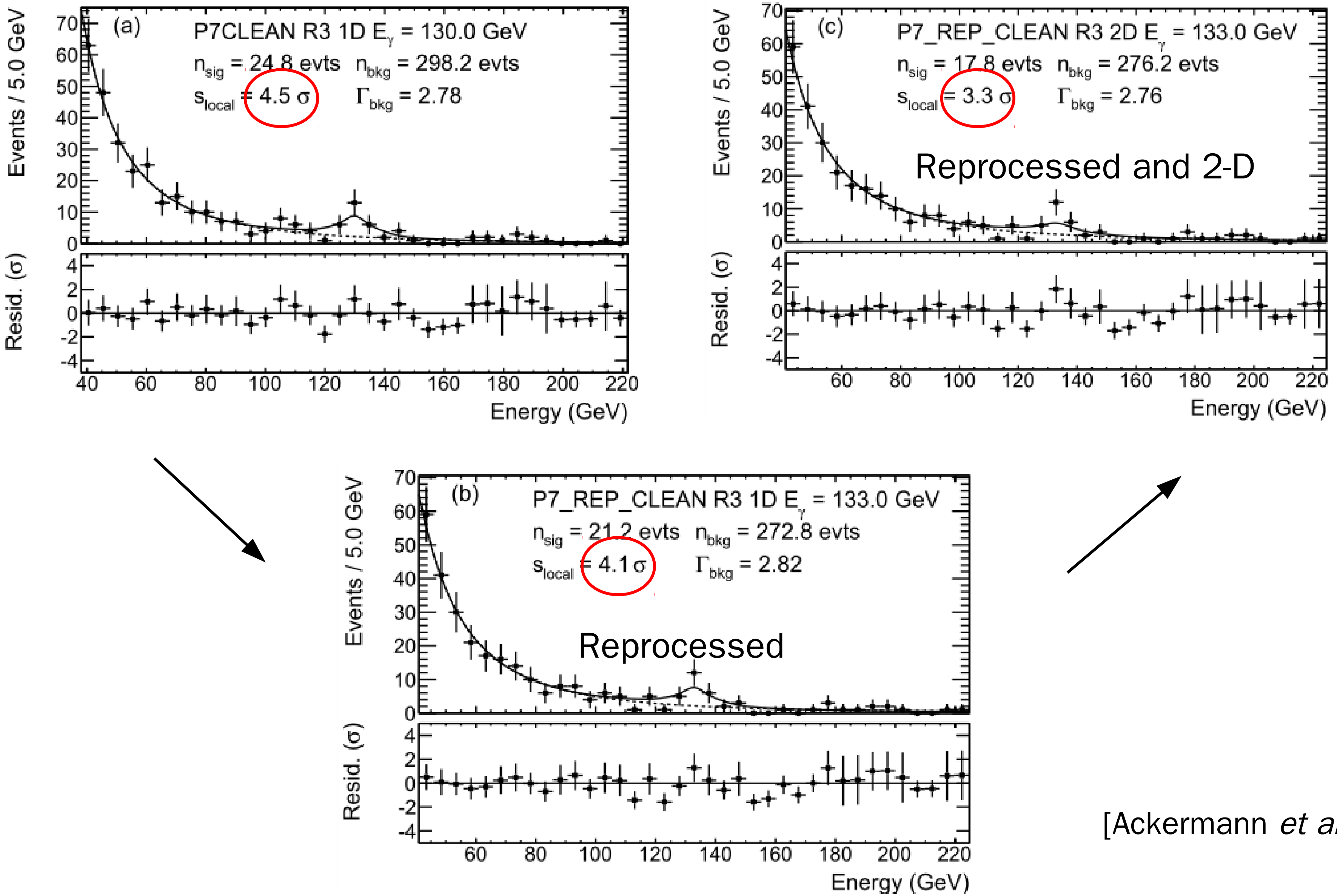
Note: We use inclination angle in 2-D fit; Fermi coll. uses energy reconstruction quality estimator P_E

Energy resolution depends on incidence angle



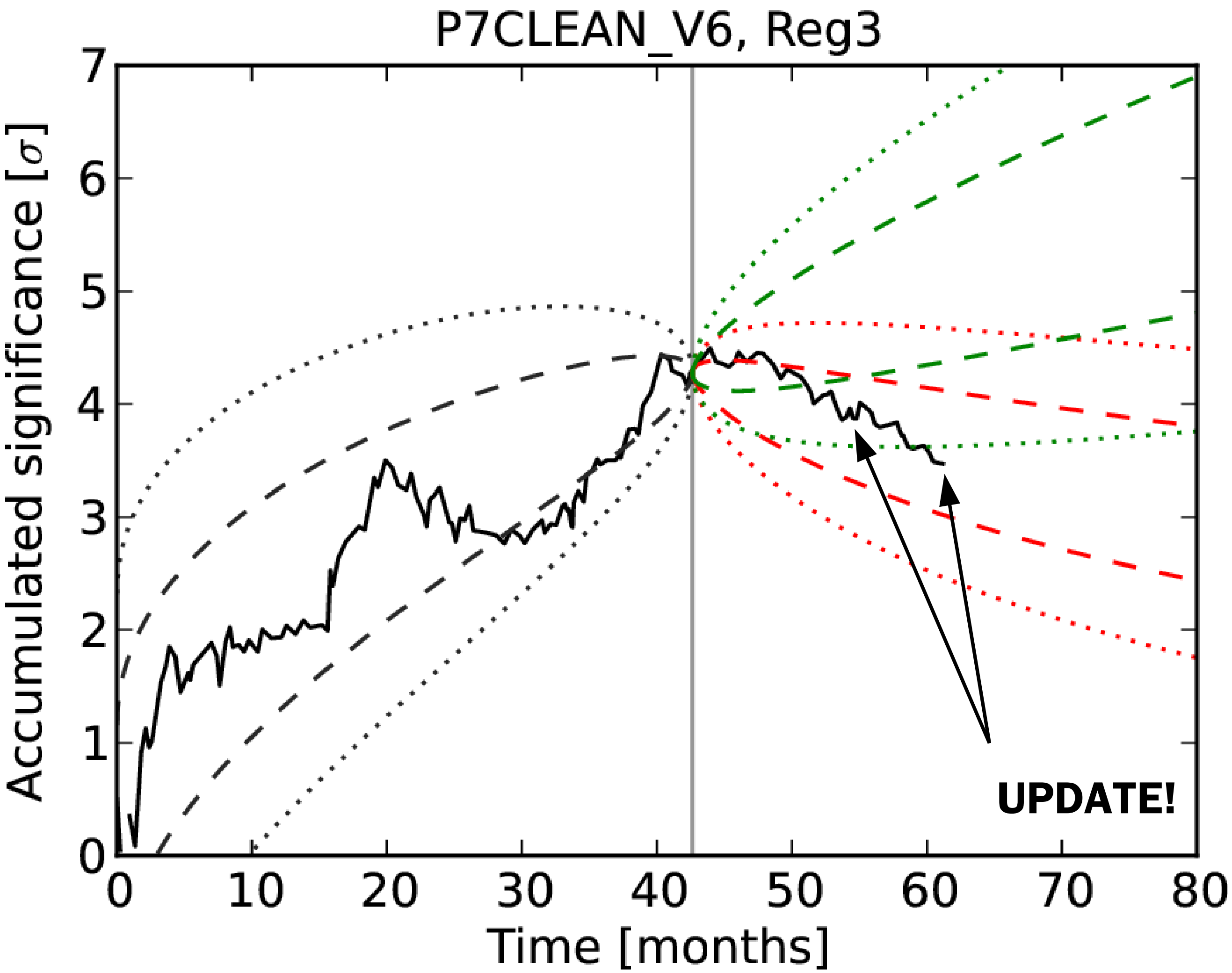
[Whiteson, 2012]

Fermi team analysis



[Ackermann *et al.*, 2013]

3) More data: Time-evolution of 130 GeV excess



Dashed/dotted lines:
68% and 95% CL containment regions for **real signal** and **statistical fluke**.

$$x_{\mathrm{real}}(t) = x_0 \sqrt{\frac{t}{t_0}}$$

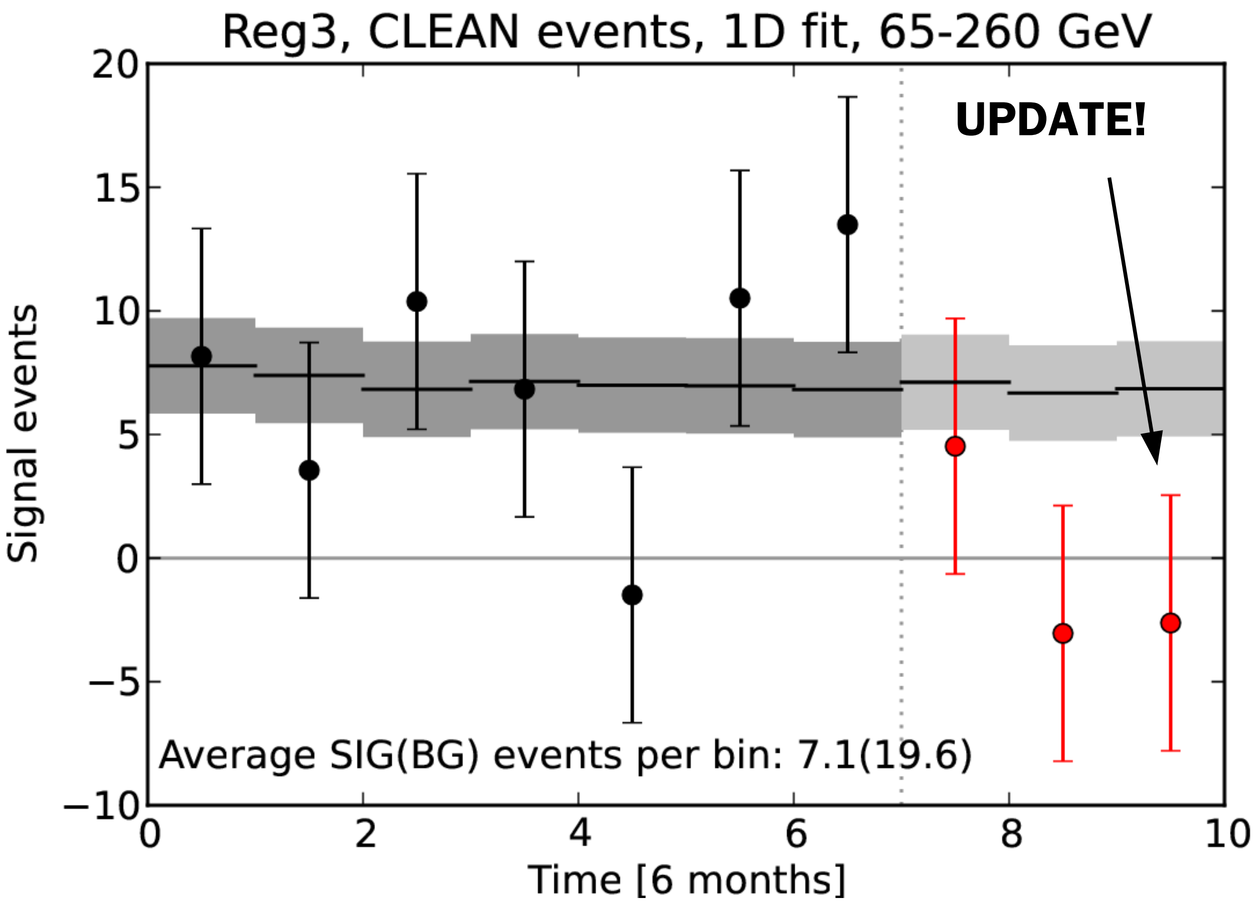
$$x_{\mathrm{fluke}}(t) = x_0 \sqrt{\frac{t_0}{t}}$$

→ Behaves like expected for a statistical fluke

65-260 GeV energy range, 129.8 GeV line energy, 1D PDF, assuming Gaussian noise with S/B~0.35 (details in CW 2013, 1303.1798)

3) More data: “signal”-photons in 6-month bins

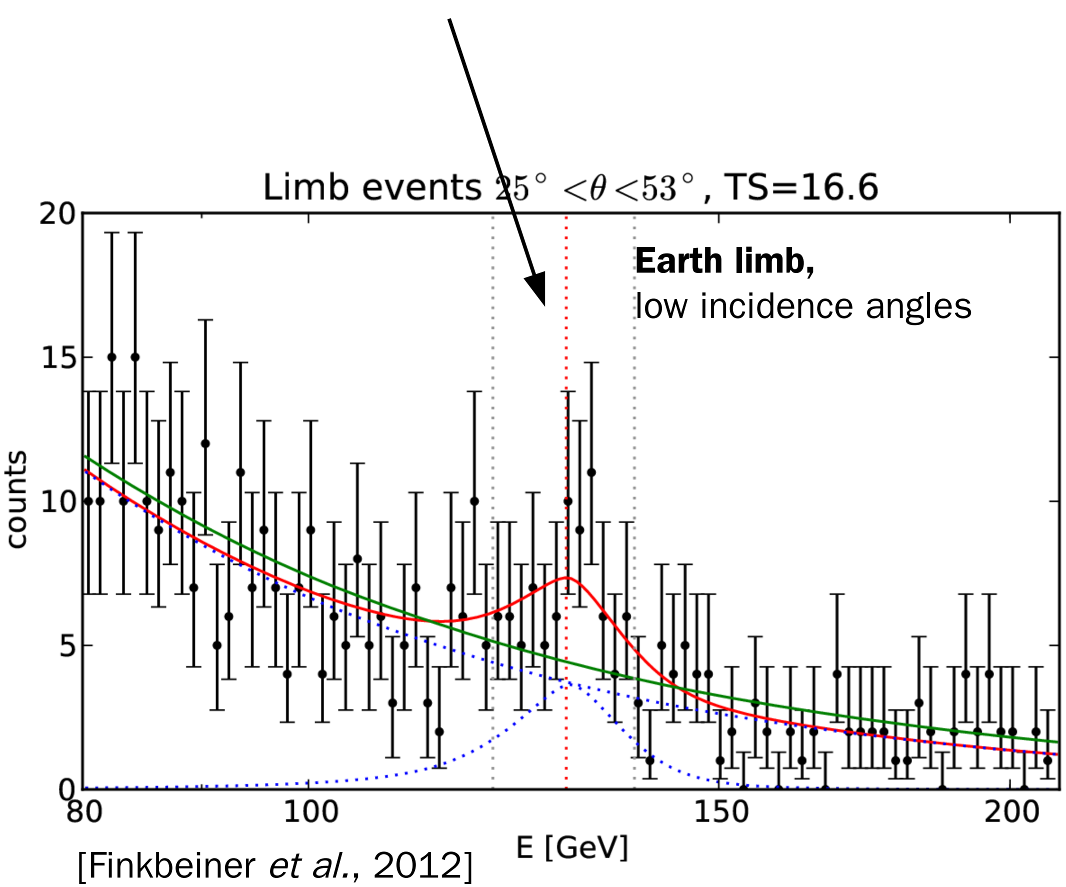
Different plot for same thing:



Red: Number of events in signal region (determined by likelihood fit) from 4 February 2012 to 4 August 2013.

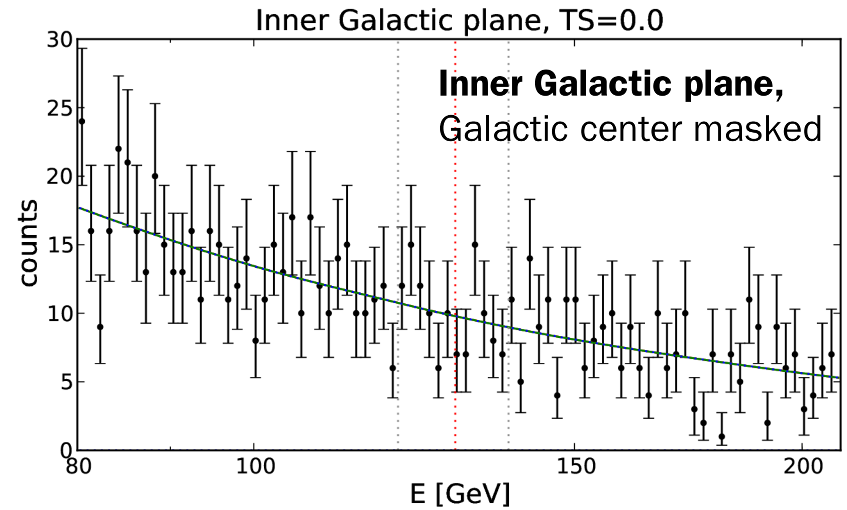
The Earth limb as test sample

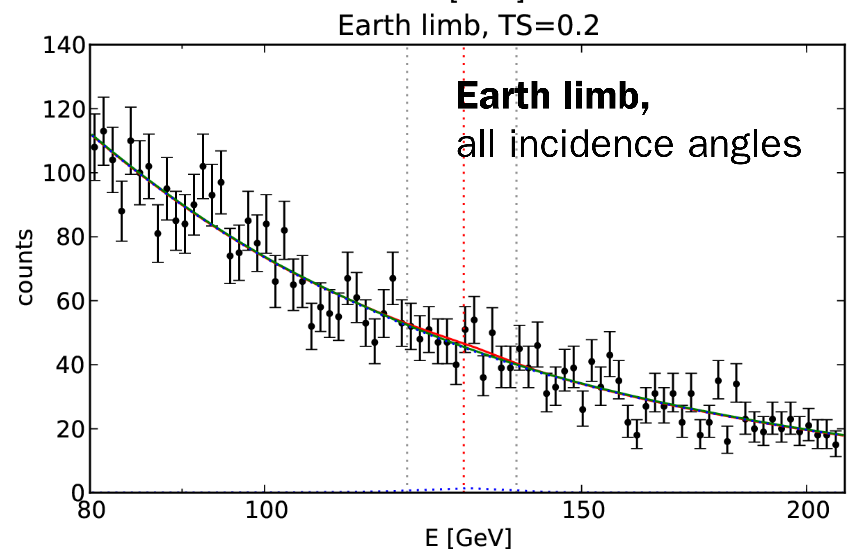
Low incidence angle (<60deg) Earth limb events show a feature at 130 GeV with ~3σ significance. This suggests an instrumental cause of 130 GeV features.
[see Finkbeiner *et al.*, Hektor *et al.*, *2012*, Ackermann *et al.* 2013]



[Finkbeiner *et al.*, 2012]

But, **nothing** found in other test regions:





Summary of 130 GeV features found in the Fermi LAT sky up to now

- **130 GeV line at Galactic Center**
  something between 3.3σ and 6.5σ (1σ – 5σ global) depending on the method; weak indications for a second line at ~114 GeV
  [Bringmann et al., CW, Tempel et al., Su&Finkbeiner, prel. Fermi coll., 2012]
- **Earth Limb line**
  A ~3σ line at 130 GeV in low-incidence-angle Earth limb data
  [Finkbeiner et al., Hektor et al.,2012; Ackermann et al., 2013]
- **Galaxy Clusters**
  3.6σ indication for two lines at 110 and 130 GeV in a stacked analysis of 18 galaxy clusters (requires factor ~1000 substructure boost to explain the signal)
  [Hektor et al., 2012]
- **Unassociated sources**
  3.3σ indication for two lines at 110 and 130 GeV in stacked analysis of unassociated LAT point sources
  [Su&Finkbeiner 2012]
- **The Sun (ROI with 5 deg radius)**
  3.2σ indication for a ~130 GeV line in a 5deg circle following the Sun
  [Whiteson 2013]

Statistics vs. systematics vs. real signal

	Pro	Con
Statistics	No recent 130 GeV photons	130 GeV excesses found in other targets
Systematics	130 GeV excesses found in other targets (Earth limb, Sun, ...)	No consistent story, despite considerable effort from many sides!
New Physics	Corroborating evidence from galaxy clusters It *was* a really impressive signature (morphology, spectrum)	About everything else.

If it is...

...a statistical fluke

- Behavior in last 1½ years point in that direction (on top of systematics?)
- <u>Current survey mode would be enough to exclude</u> original signal hypothesis with high confidence at end of the mission (Aug 2018?).

...an instrumental systematics

- Will be hopefully settled with PASS8 (and more limb data?) **Talk by L. Latronico**

...a real signal

- It will be <u>clearly</u> reproduced in trial-free data from Feb 2012 to Aug 2018.

Modified survey mode

Impact on 130 GeV feature analysis

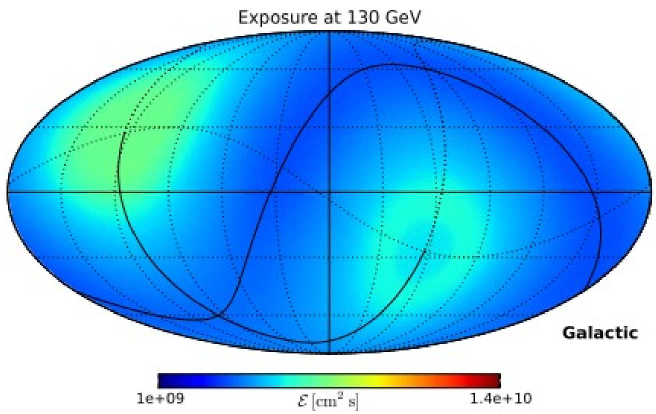
Background:

Fermi mission solicited “white papers” from the scientific community, proposing alternative observation strategies (March 2013).

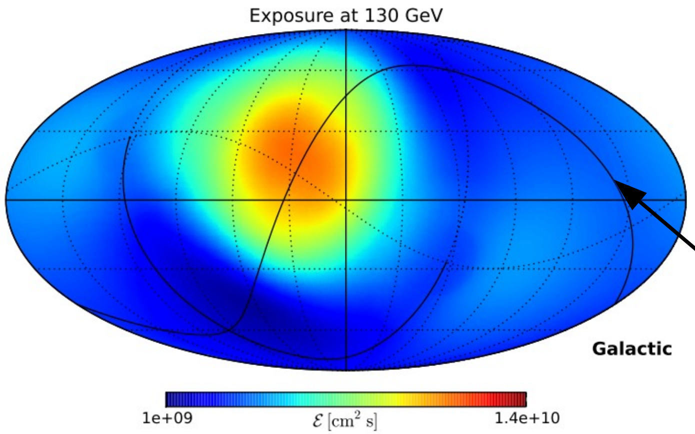
Five white papers were submitted, two discussing the impact on gamma-ray line searches (Digel *et al.*; CW *et al.*, 2013).

Proposal:

Standard survey mode:



Modified survey mode ("Option 4"):



Credit to Fermi mission for development of survey proposals

Equatorial plane

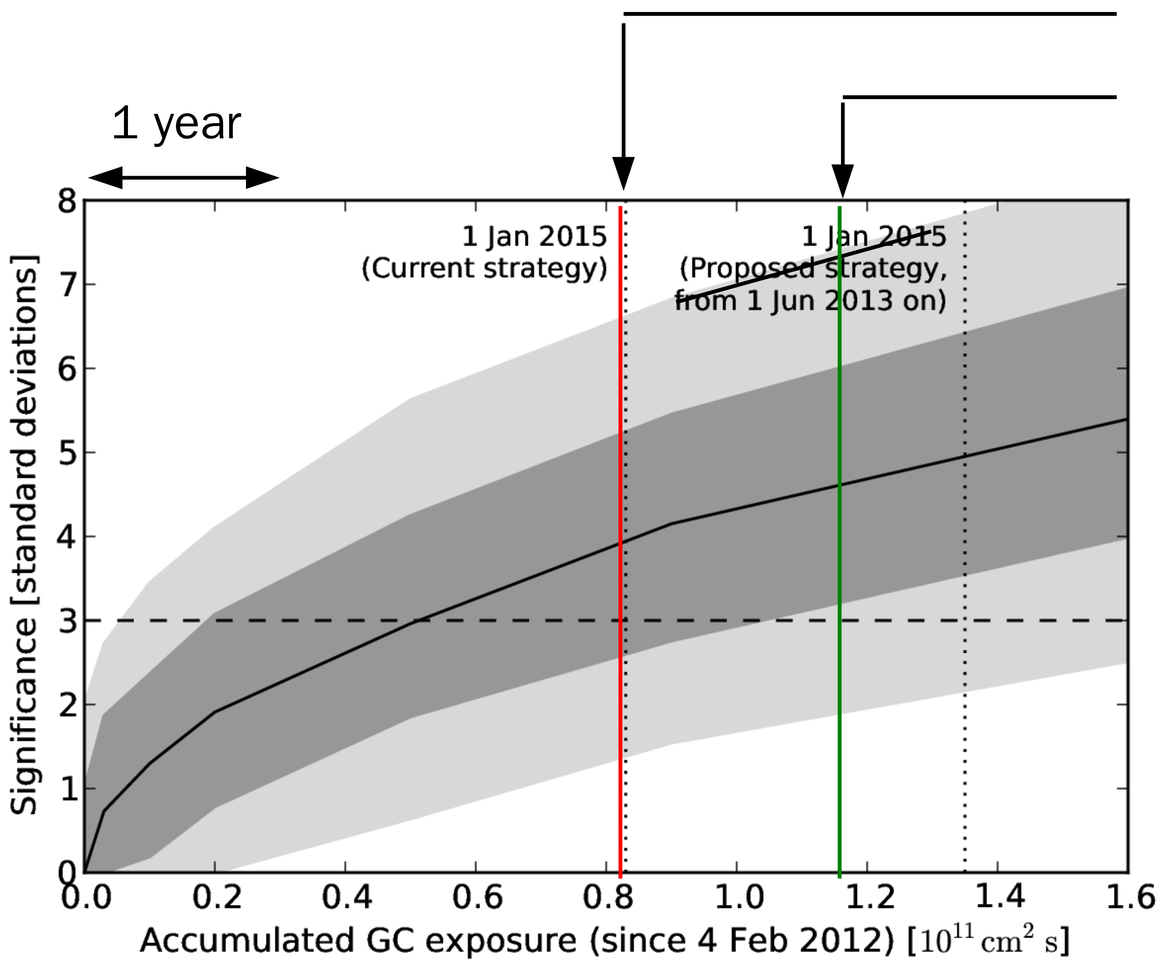
Option 4:

- Slew to target position when target is exiting 30 deg from Earth occultation
- Target: **not** the GC, but R.A. = 261.4 deg and Dec follows orbital plane
- Otherwise follow 50 deg rocking survey mode (current survey strategy)

Consequences:

- Option 4: less than 2% overall exposure loss w.r.t standard survey mode (averaged over orbital precession period of ~53 days)
- Factor 2.2 increase of exposure rate at GC

Impact on 130 GeV feature: Reg3 P7V6, data since Feb 2012



With current survey mode /

with modified survey mode from Dec 2013 on

until end of 2014.

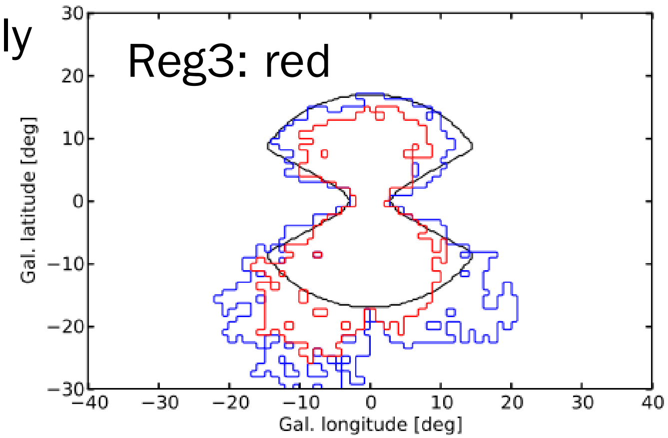
Gray bands: 68% and 95% CL containment for real signal

What do we gain?

Definition signal hypothesis: line around April 2012, 1-D only

- Reg3 CW analysis (P7V6): 4.3σ f~0.35
- R3 Fermi analysis (P7REP): 4.1σ f~0.79
- R16 Fermi analysis (P7REP): 2.2σ f~0.20

$$f = \frac{n_{\rm sig}}{b_{\rm eff}} \simeq \frac{TS}{n_{\rm sig}}$$



Feb 2012 to Dec 2014 (Aug 2018)	current strategy	modified strategy from Dec 2013	
• Reg3 CW analysis (P7V6):	**3.9σ** (5.8σ)	**4.7σ** (8.0σ)	← previous slide
• R3 Fermi analysis (P7REP):	3.7σ (5.6σ)	4.5σ (7.7σ)	
• R16 Fermi analysis (P7REP):	2.0σ (3.0σ)	2.4σ (4.1σ)	

Note: numbers indicate at which significance a real signal should be reproduced, or at which level one can exclude a statistical fluke.

If, when and why

Panel recommendation: (August 2013)
Undertake new observation strategy (“option 4” or similar)

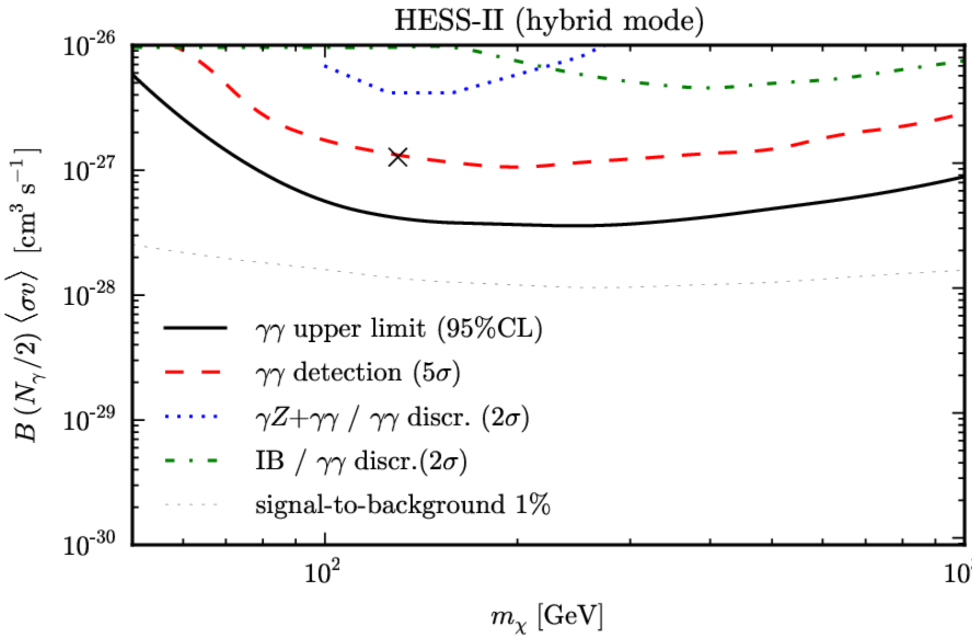
- Implementation by December 2013
  (right now: solicit community comment and run observatory thermal models)
- Run for one year
- Review after one year (back to survey mode?)

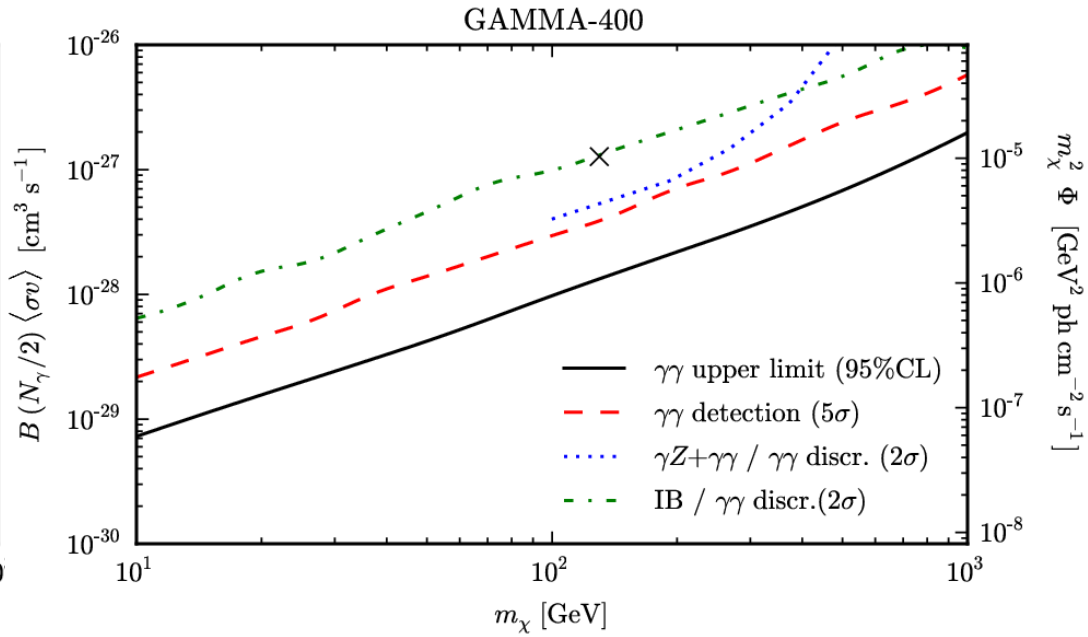
<u>Final decision by Fermi Mission sometime soon.</u>

Motivation:

- **G2 cloud** approaching SgrA* is rare opportunity to study nearest massive BH. Predictions for gamma-rays uncertain, but many telescopes will monitor passage (NuSTAR, Swift, Chandra, ...)
- **Blind gamma-ray pulsation searches** will profit from maximizing source count rates over a short period of time (months to a year) → discovery of new young energetic pulsars towards GC (MSPs only slightly affected)
- **Gamma-ray line feature**

Future: HESS-II, GAMMA-400, CTA, …





[Bergström et al., 2012]

HESS-II (hybrid mode)

- 50 hours of observation of galactic center
- enough to rule out signature or confirm it at 5 sigma (if systematics are under control)
- GC close to zenith from March 2013 on
- 230 hours per season in principle possible
- results end of 2014?

[parameters from J. Lefaucheur+ (Gamma 2012, Heidelberg)]

GAMMA-400

- 5 years of survey mode (5sigma detection would take ~10 months)
- Allows discrimination between VIB and monochromatic photons
- detection of γZ down to 20% relative branching ratio
- launch in 2018?

Conclusions

- This is the (last or first) “decade of WIMPs”

- Searches for spectral features in cosmic-ray fluxes are a powerful method to identify and constrain Dark Matter models

- The AMS-02 positron fraction data has fantastically small error-bars

  → we derived the by far strongest (and robust) limits on leptonic DM annihilation by means of a spectral analysis

- The LAT data contains a spectral feature at the Galactic center that would be in principle a candidate for a line signal from dark matter annihilation.

  There are indications for

  - ~~an astrophysical cause~~
  - instrumental effects (Earth limb, 2d fit)
  - a rare statistical fluctuation (data since Feb 2012, 2d fit, reprocessed data)
  - signal of dark matter annihilation? (Spatial distribution, second line, galaxy clusters)...
  - → need more data
- More data from Galactic center (likely from a modified survey strategy) will solve that problem for good.

- Future: more Fermi data, HESS-II, GAMMA-400, CTA...

Thank you