IPhT CEA-Saclay

Marco Taoso

The Galactic Center GeV excess and its constraints

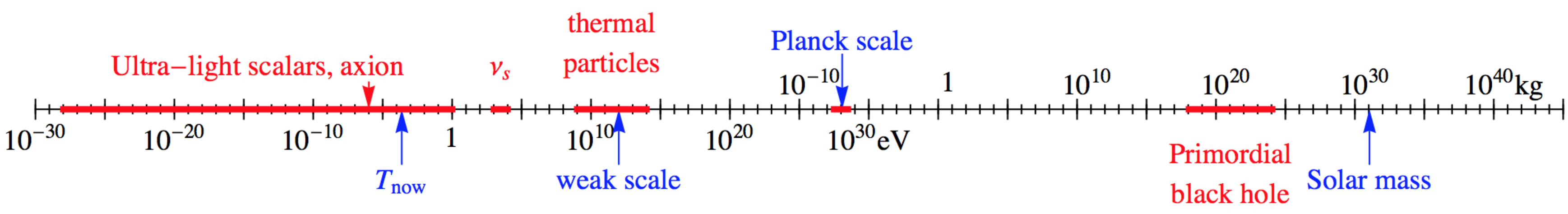
GDR Terascale

Heidelberg 11-13/12 2014

What do we know about DM?

Mass and cross sections largely unconstrained

Courtesy of M.Cirelli



WIMPs paradigma

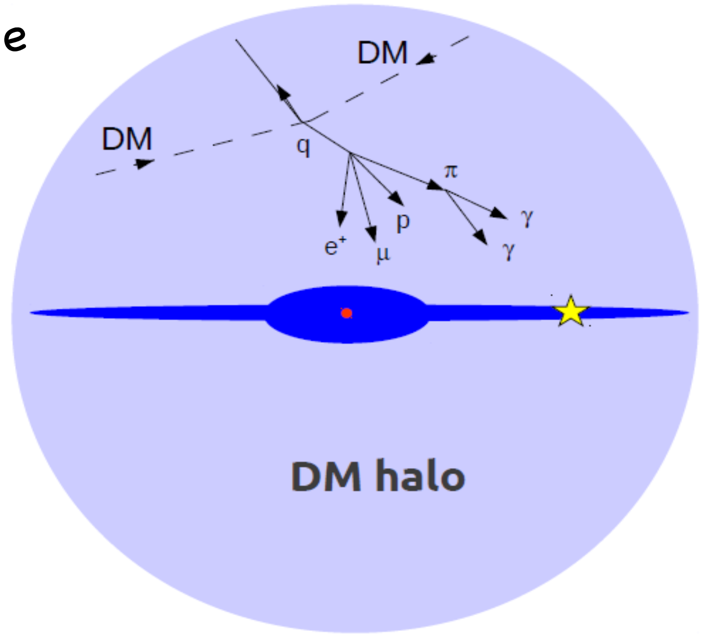
Thermal relic from the early Universe

Connection with BSM at the Terascale

Multiple way to test the scenario: collider, direct detection, indirect searches

Testing WIMPs

If WIMPs are s-wave annihilators the annihilations cross-section in the present Universe is not small
->
Detectable fluxes of annihilation products?



WIMP annihilation products

Gamma-rays
No attenuation: spatial and energy info

Charged cosmic-rays
Anti-p, positrons, anti-D

Neutrinos

How and where to look for DM annihilations

$$\Phi \propto \int ds d\Omega \ \rho^2_{DM}(s,\Omega)$$

Dwarf galaxies

Large Mass/Luminosity ratio

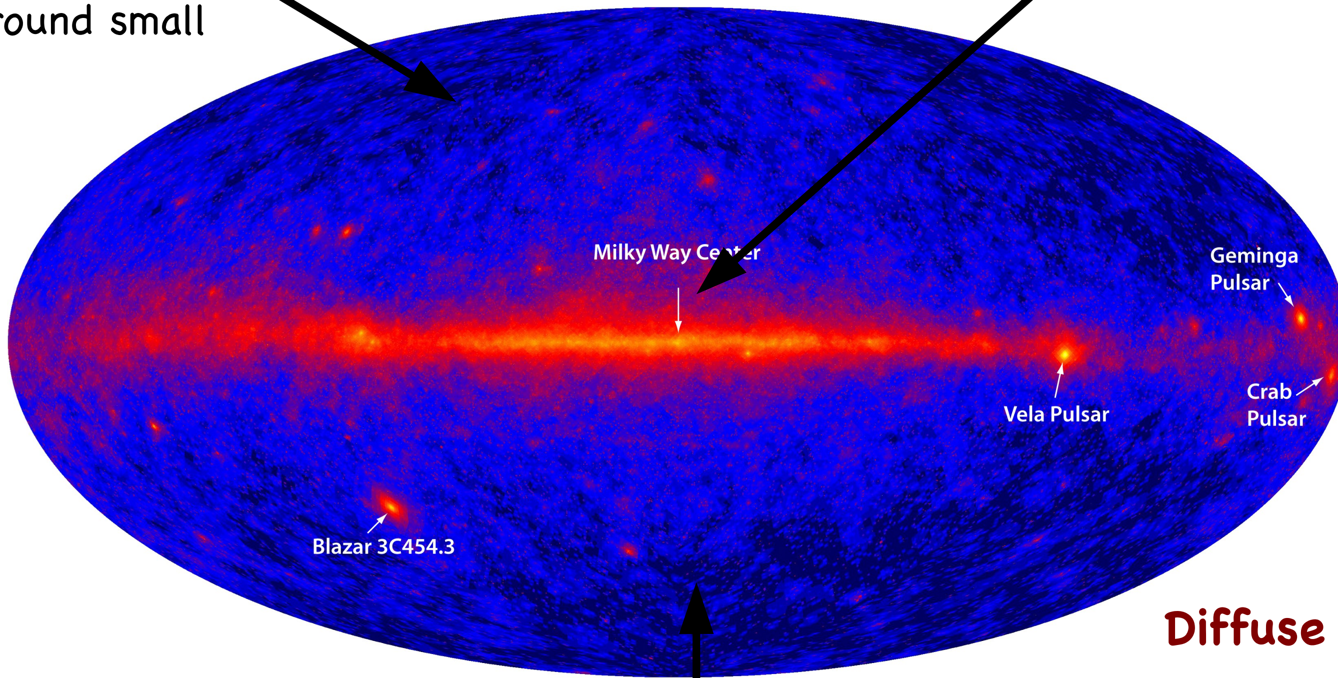
Nearby

Astro background small

Galactic center

+ Large DM density

- lots of sources, large bkg



DM clumps

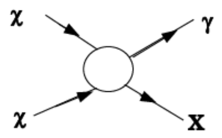
Diffuse galactic halo

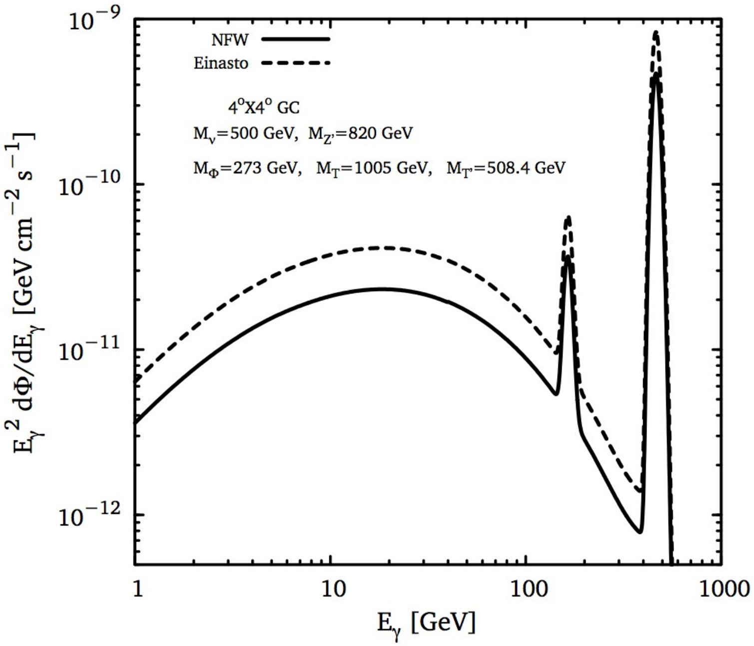
Clusters of galaxies

Extragalactic diffuse emission

Line searches

Generated at loop level in WIMPS models or from DM decays





+ distinct feature, not expected from astro sources

+ from line position get info on DM mass

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

- small signal in many models

Exceptions exist!

E.g. for class of models with s-channel mediators see

Jackson, Servant, Shaughnessy, Tait, MT 1302.1802, 1303.4171, 0912.004

Line searches

Searches of spectral features in optimized window around GC

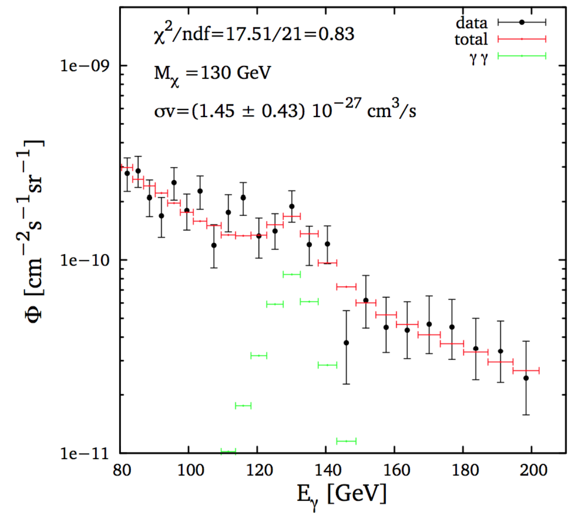
2012

Evidence of a line around 130 GeV @ 3-4 σ

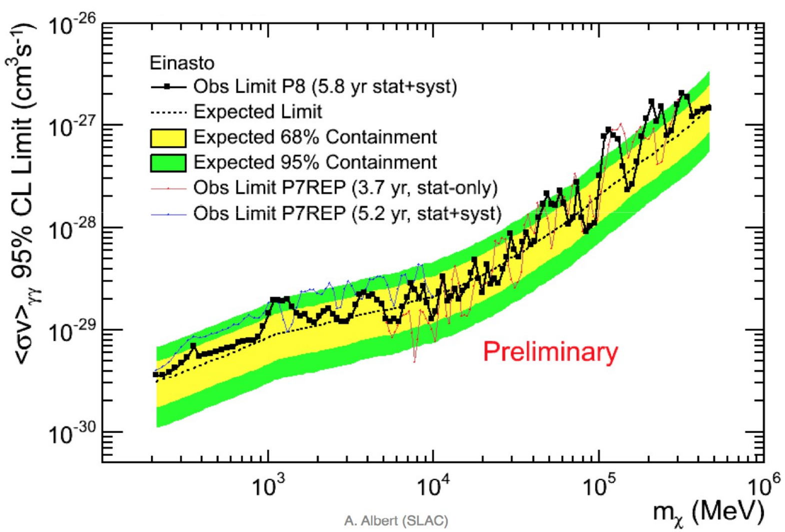
Weniger, 2012

2014

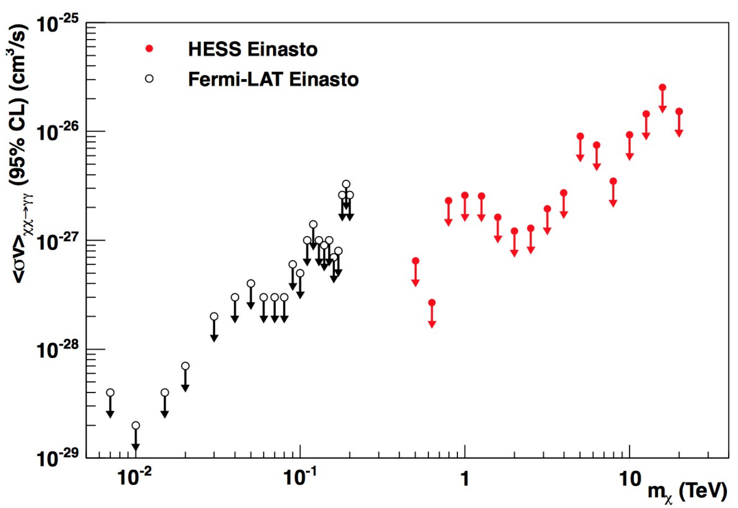
No globally significant lines



New ingredients: more data + improved energy reconstruction



From Albert, Fermi Coll., Fermi Symposium 2014



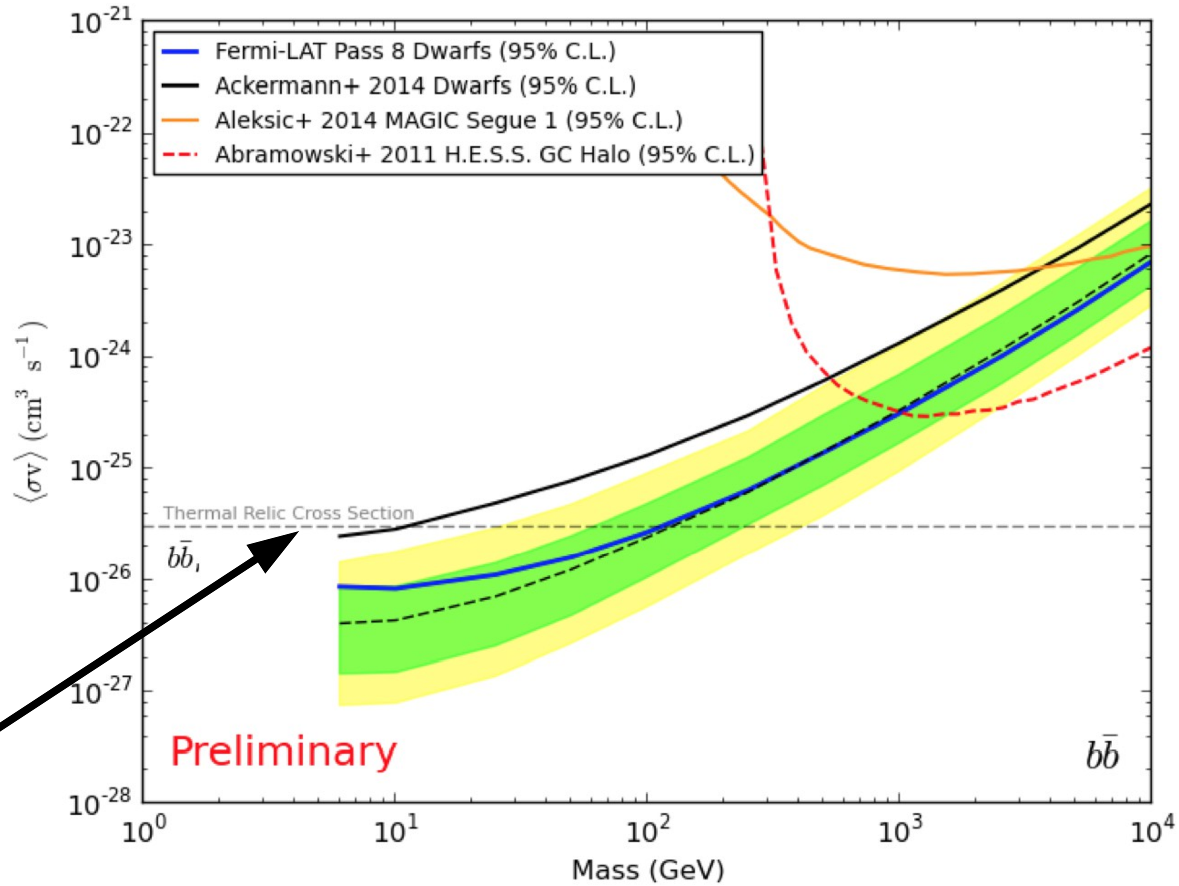
Hess Collaboration 2013

Dwarf galaxies

DM density profile extracted
from stellar velocity dispersions

Uncertainties on density profile
Included in likelihood analysis

Joint-analysis on 15 targets

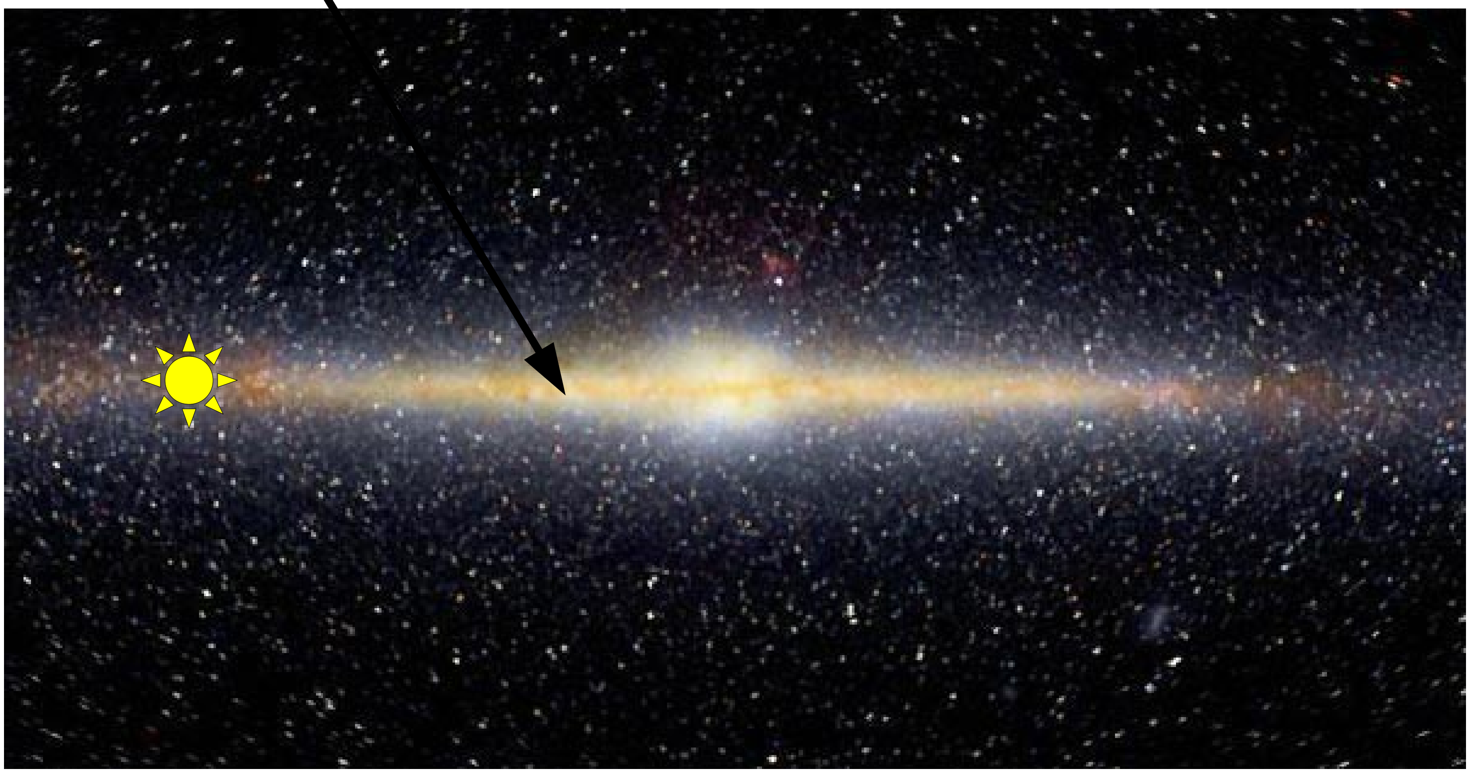


Thermal cross-section

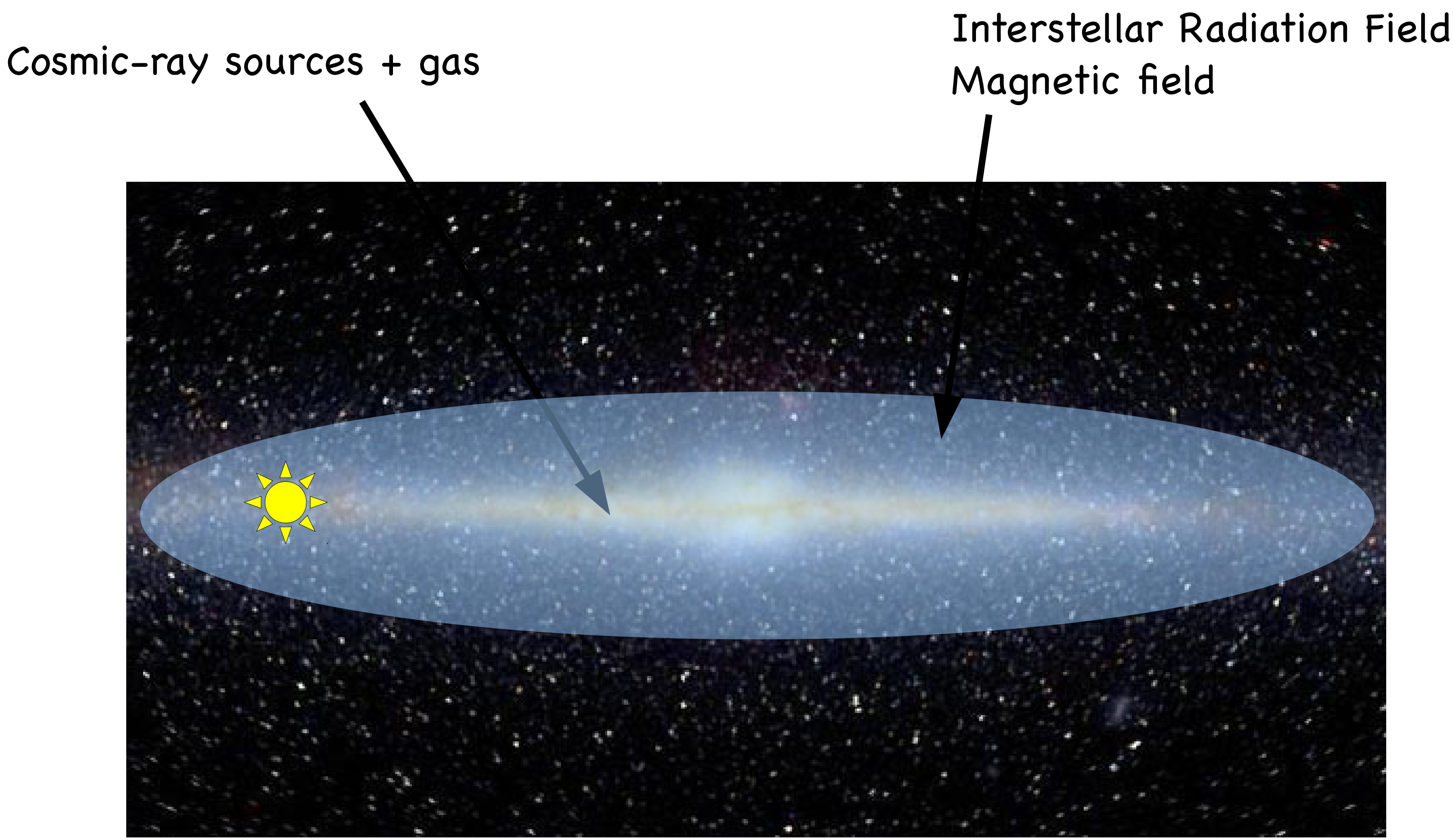
From Anderson, Fermi Coll., Fermi Symposium 2014

Sketch of the gamma-ray emission of our galaxy

Cosmic-ray sources + gas



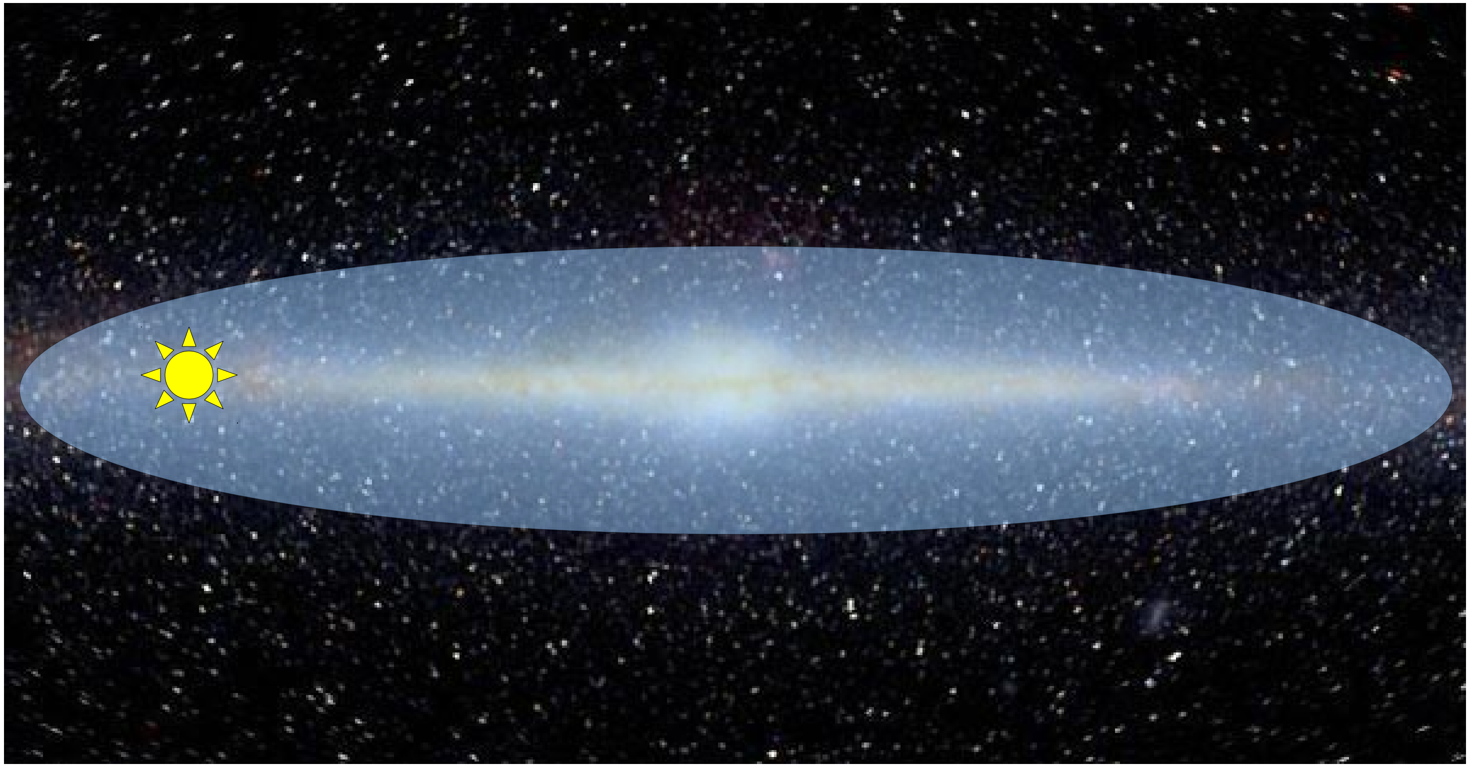
Sketch of the gamma-ray emission of our galaxy



Sketch of the gamma-ray emission of our galaxy

Diffuse gamma-ray emission from

CR protons on gas, pions decays
CR electrons: Inverse Compton on ISRF + bremstrahlung on gas



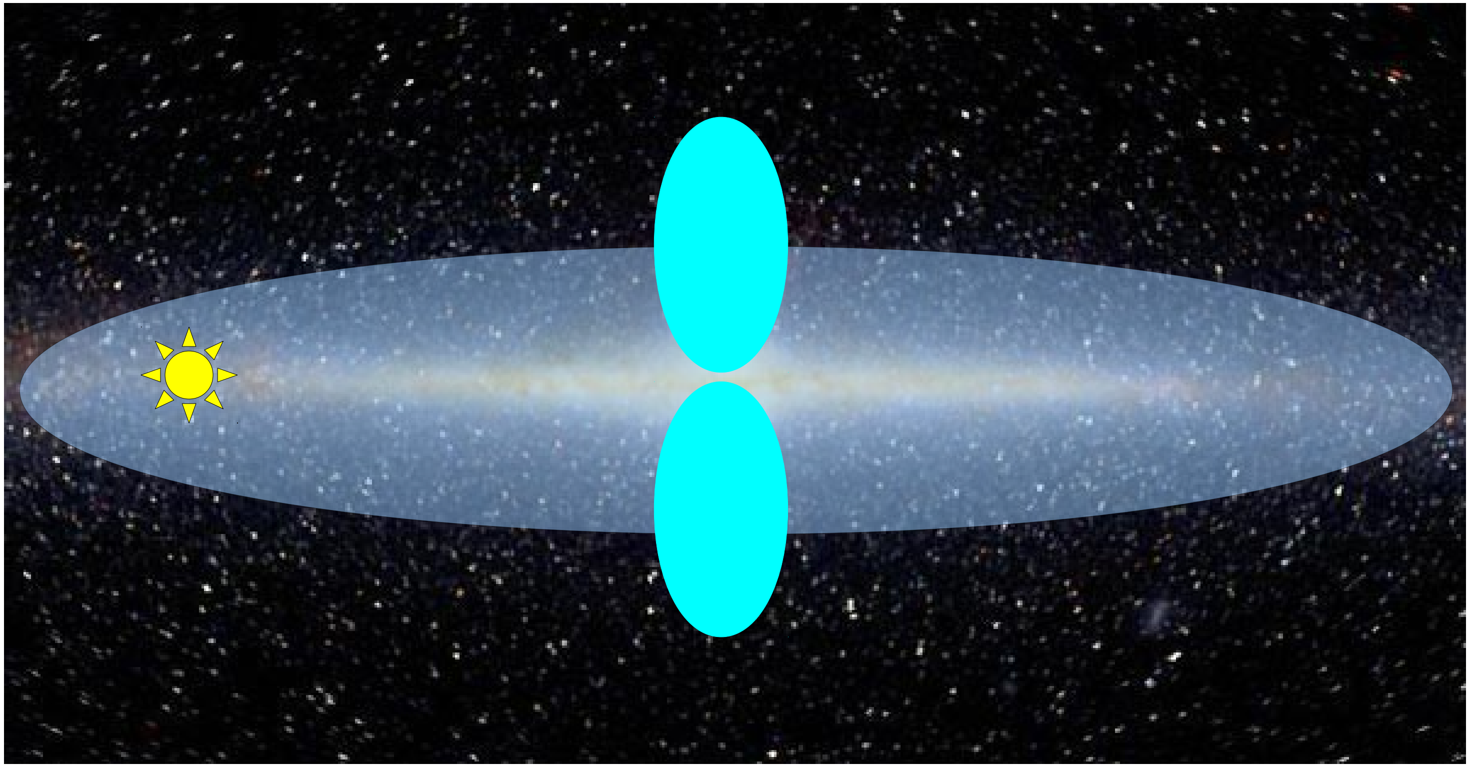
Sketch of the gamma-ray emission of our galaxy

Fermi Bubbles

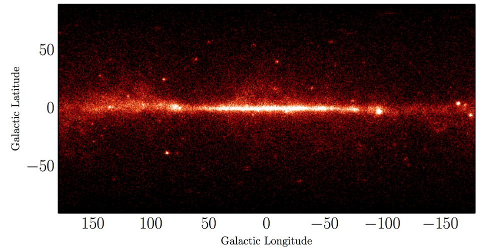
Large extended lobes of gamma-ray emission.

Correlated emission detected in WMAP e Planck micro-wave maps

Several scenarios on the market. Origin still open question

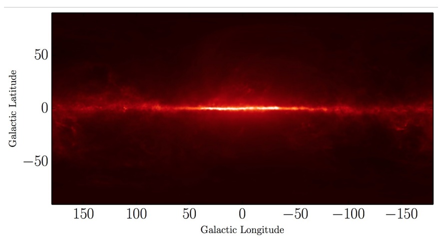


Galactic center analysis

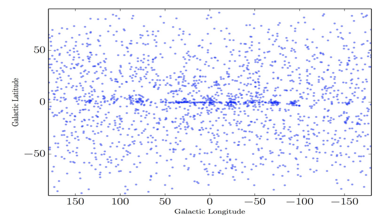


Fermi-LAT sky

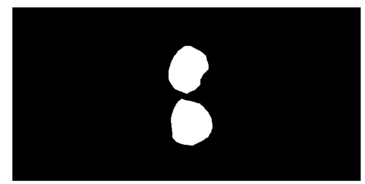
CR diffuse emission



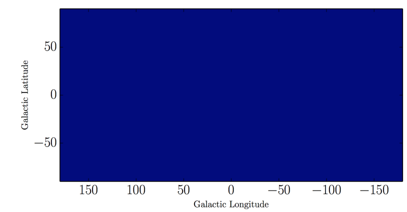
Point sources



Bubbles



Isotropic extragalactic emission



Inputs for CR diffuse emission maps: CR propagation models, CR sources distribution
ISRF (from IR obs and stellar population synthesis), gas maps (from spectral lines observations, e.g. HI from 21cm survey)

Components intensity fitted to the data

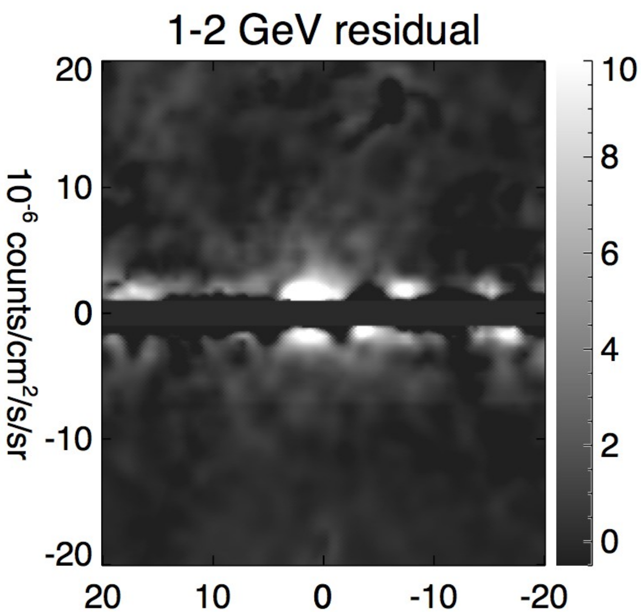
Galactic center excess

Gamma-ray excess at energies around few GeVs detected around the Galactic Center

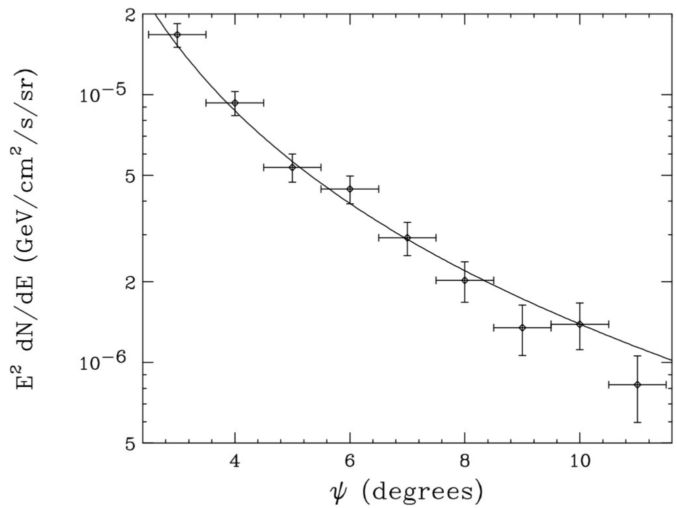
Formally (with statistical uncertainties only) excess detected at very large significance

Morphology: extended (at least 10 degrees), spherically symmetric, centered at GC
Spectrum of residuals peaked in the GeV range

Data-Model



Extended. Not a point source



Daylan et al. 1402.6703

Incomplete list of analysis: Goodenough et al., Hooper et al., Abazajian et al., Macias et al., Macias et al., Zhou et al., Huang et al., Calore et al.,

Properties of the excess

1) Does the conclusions depend on the details of the foreground modeling?

Excess persist for a large class of foreground models.
However not all the theoretical model uncertainties explored!

2) Which properties of the excess seem more robust against systematical uncertainties?

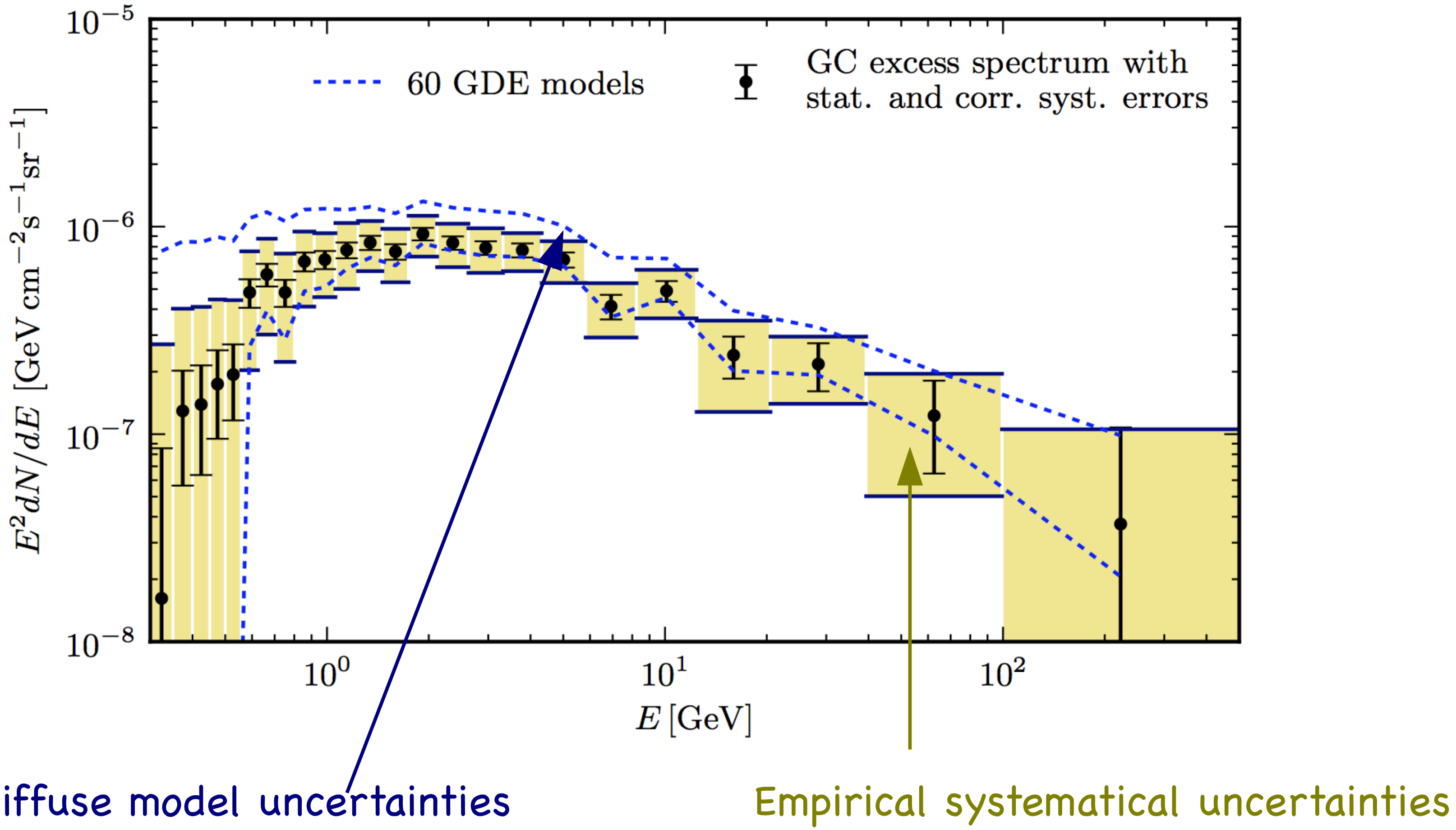
Spherical, extended at least up to 10 deg, centered at the GC, peaked @ few GeV

3) What is more uncertain?

Energy spectrum shape and its precise normalization

Calore et al. 1409.0042

Properties of the excess

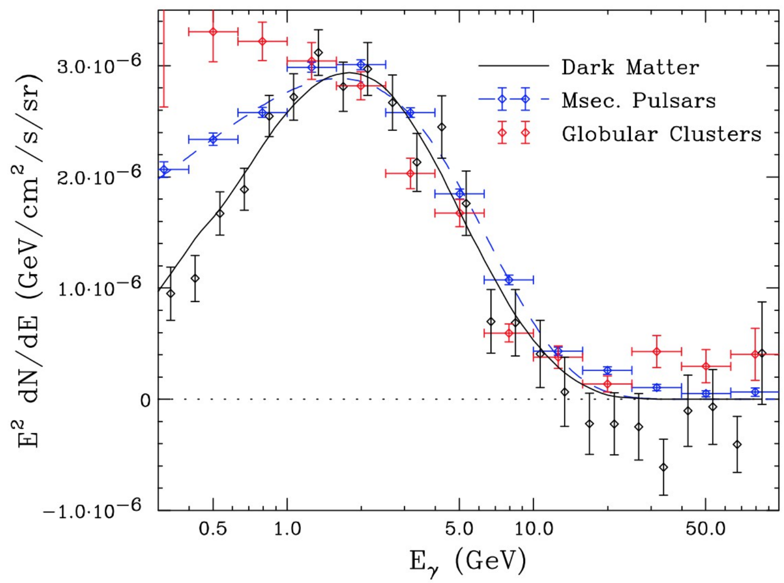


Calore et al. 1409.0042

Milli-second pulsars?

MSP detected by FERMI in globular clusters and in region of few kpc from us
Should be a lot in star forming regions, possibly the GC
Population of **unresolved MSP** may explain the excess

Cholis et al. 1407.5625



✓ Spectrum from population of detected MSP and globular clusters

Similar to GC excess spectrum

? Enough sources ?

From catalogue of detected sources derive luminosity function and check whether bright detectable sources are consistent with FERMi obs.

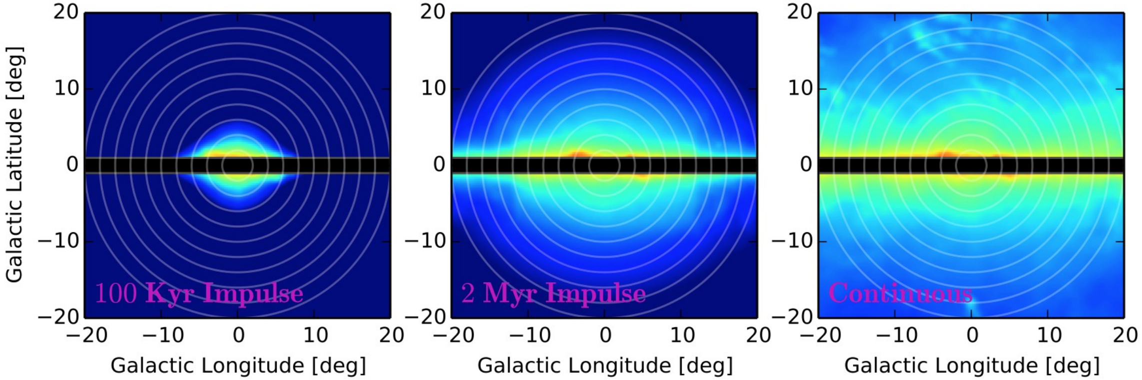
Seems that within current uncertainties MSP possibility can work
Petrovic et al. 1411.2980

But different conclusions in the literature. Open question yet
Cholis et al. 1407.5625, Petrovic et al. 1411.2980, Yuang et al. 1404.2318 Hooper 1305.0830

CR injection burst

Hadronic models

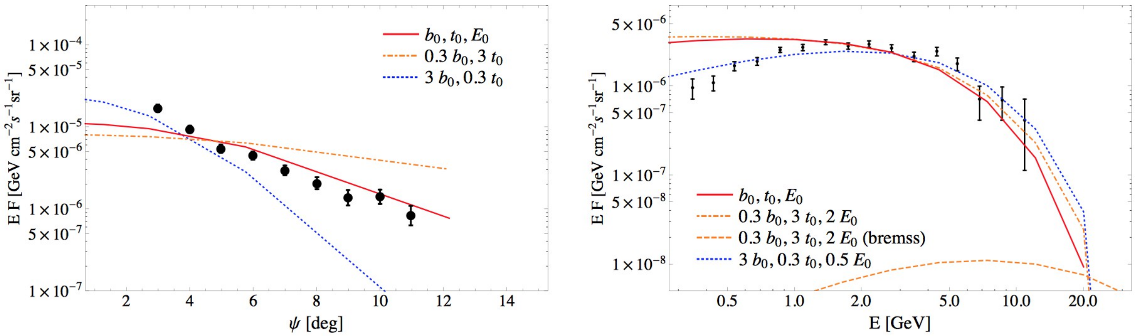
Potential problem: disk-like distribution (emission follows the gas)



Leptonic models

Carlson et al. 1405.7685

Difficult to explain both spectrum and morphology



Petrovic et al. 1405.7928

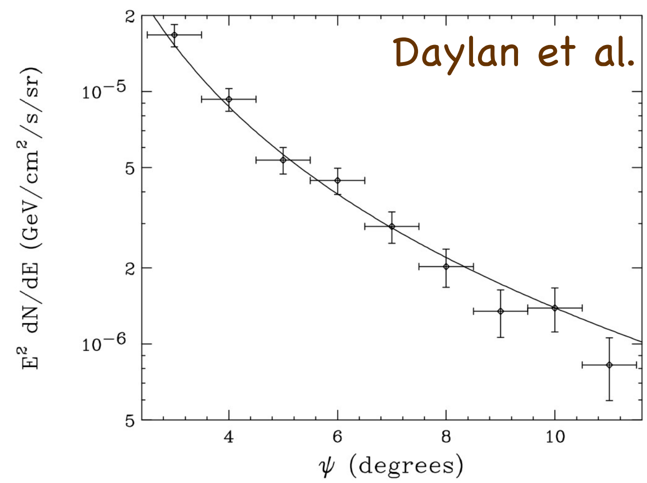
DM interpretation

Emission can be explained by **DM annihilations** with density distribution NFW-like

$$\rho_{\rm gNFW}(r) = \rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left[\frac{1+(r/R_s)^\alpha}{1+(r_\odot/R_s)^\alpha}\right]^{-\frac{(\beta-\gamma)}{\alpha}}$$

with gamma = 1.2 - 1.3
Typical profile from simulations, with adiabatic contraction at the center

Daylan et al. 1402.6703

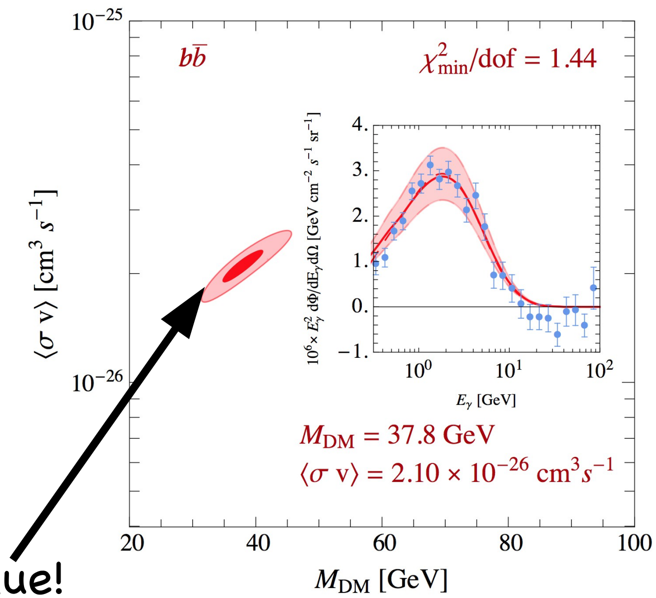


Cirelli,Gaggero,Giesen,MT,Urbano 1407.2173

Uniform spectrum across the excess region

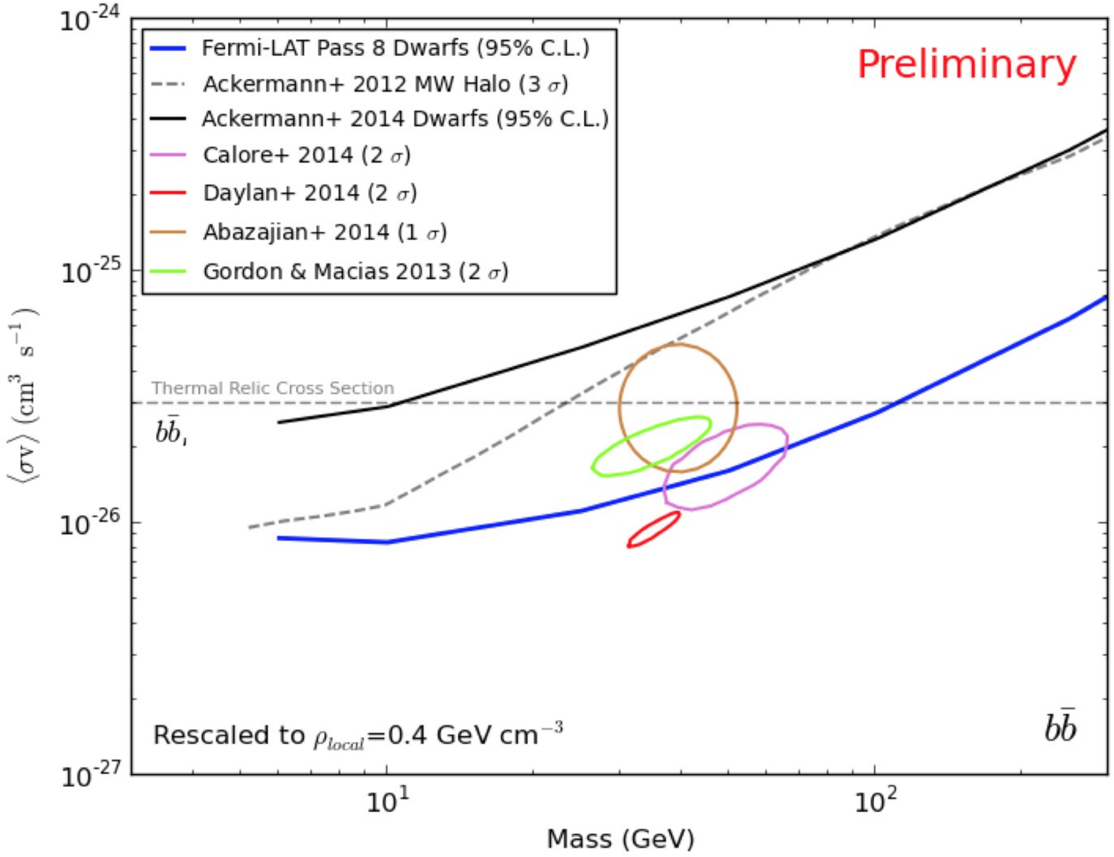
Energy spectrum well fitted by annihilations into hadronic channels, bb (or cc) and DM mass around tens of GeV

Leptonic channels might also work



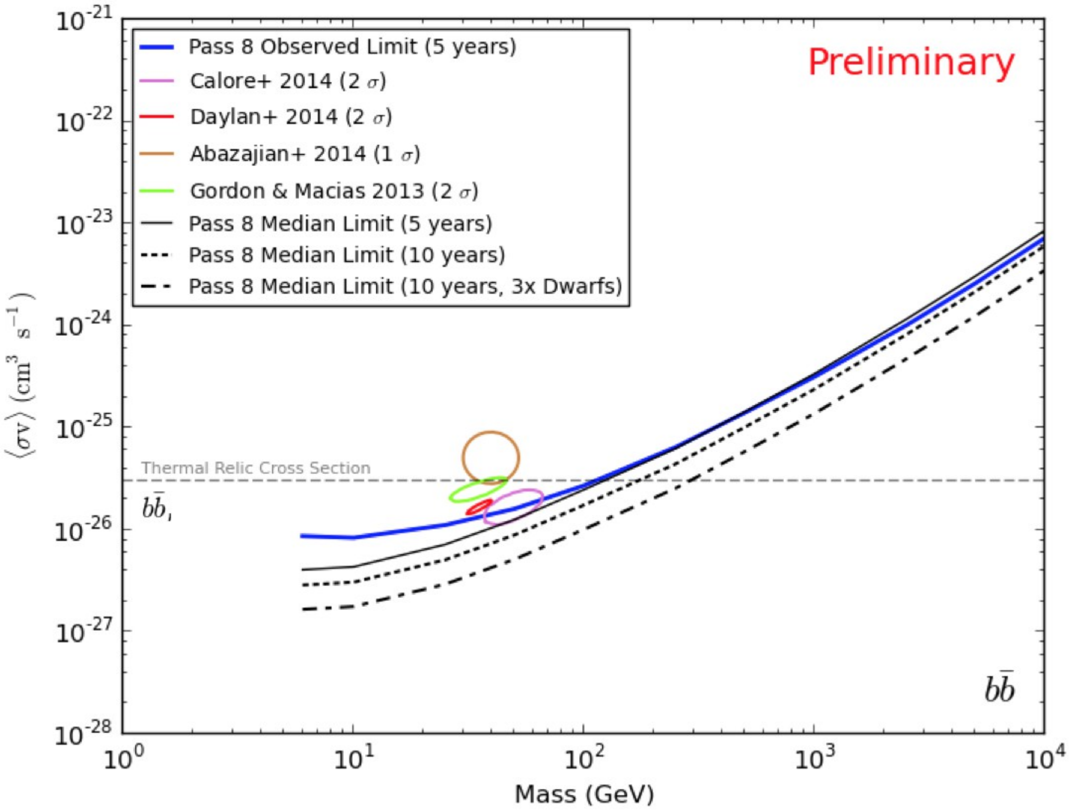
Cross-section close to thermal value!

Dwarf bounds



From Anderson, Fermi Coll., Fermi Symposium 2014

Future dwarf bounds



From Anderson, Fermi Coll., Fermi Symposium 2014

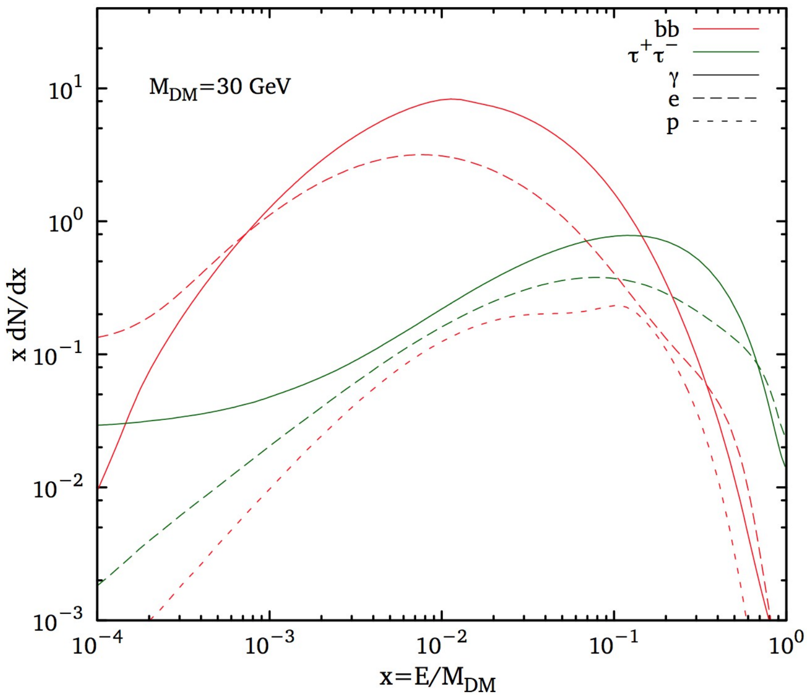
Role of secondary emissions

DM injects significant amount of energetic electrons and, depending on the annihilation channel, anti-protons

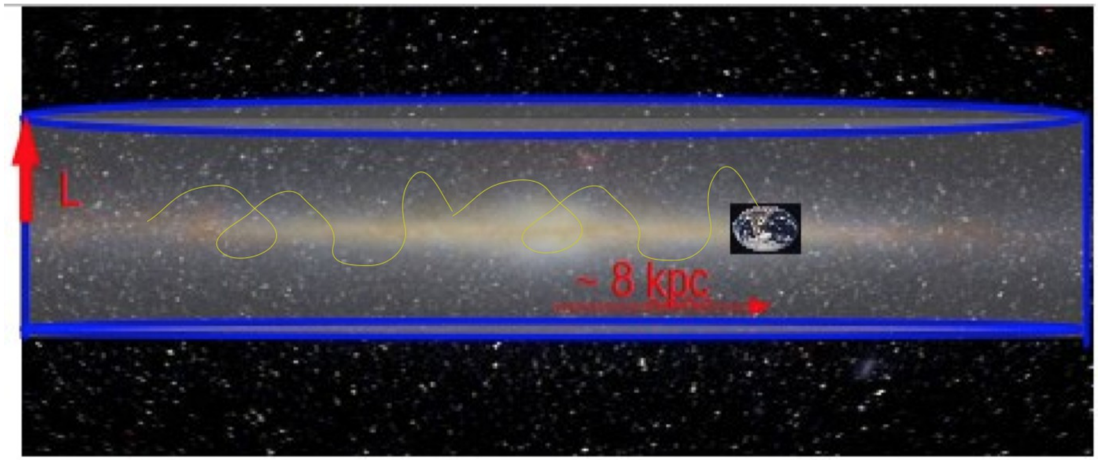
Electrons induce secondary gamma-ray emission through IC and brem

Electrons in magnetic fields → synchroton radiation → radio/micro-wave frequencies

Anti-p fluxes bounded from local CR observations



Propagation of charged particles



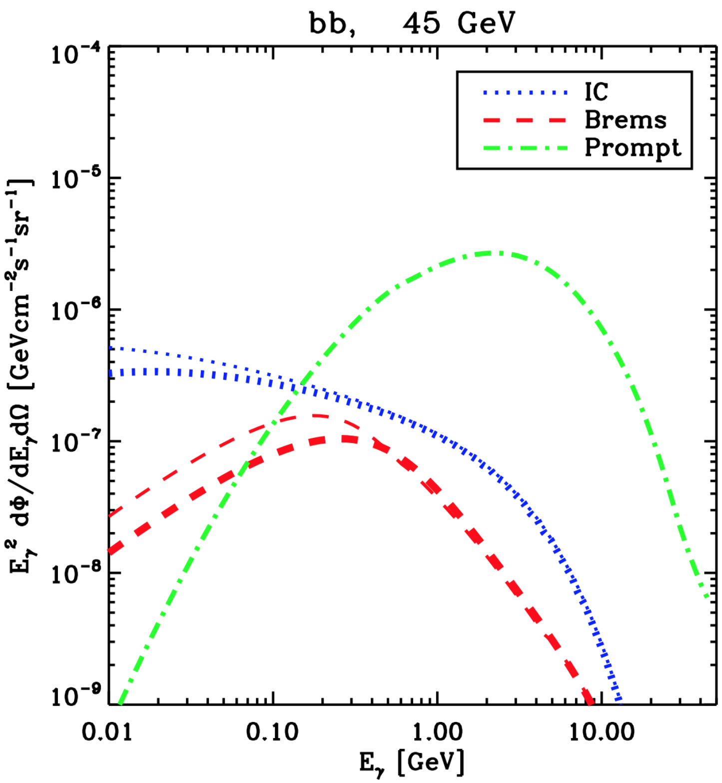
$$\frac{\partial N^i(r,z,p)}{\partial t} = \frac{\partial}{\partial x_i} D_{ij} \frac{\partial N^i}{\partial x_j} + \boldsymbol{v}_c \cdot \boldsymbol{\nabla} N^i - \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{v}_c\right) N^i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N^i}{p^2} + Q(r,z,p)$$

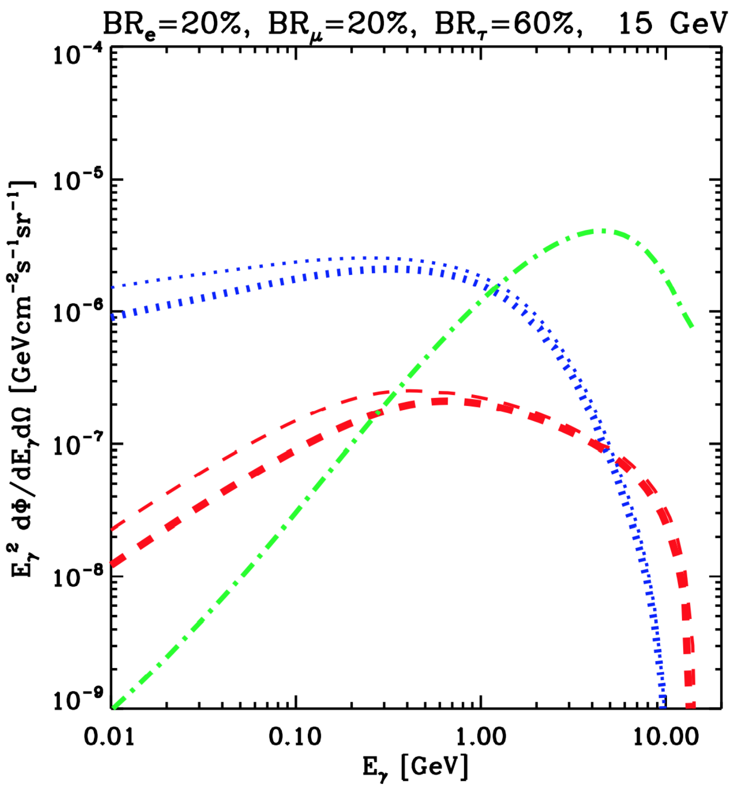
Diffusion coefficient: $D = D_0 \, \beta^\eta \left(\frac{R}{R_0}\right)^\delta e^{|z|/z_t}$

Solve diffusion equation with DRAGON

Gamma spectra from IC/brems

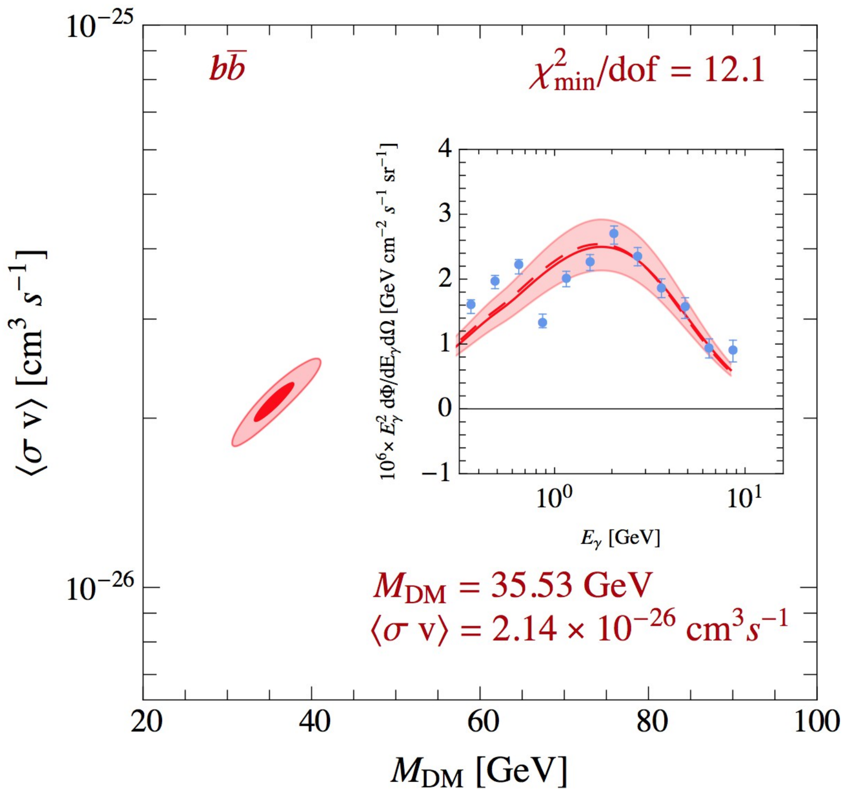
Compute Inverse-Compton and Brems produced by electrons with GAMMASKY
Gas and Interstellar Radiation Field maps as in GALPROP

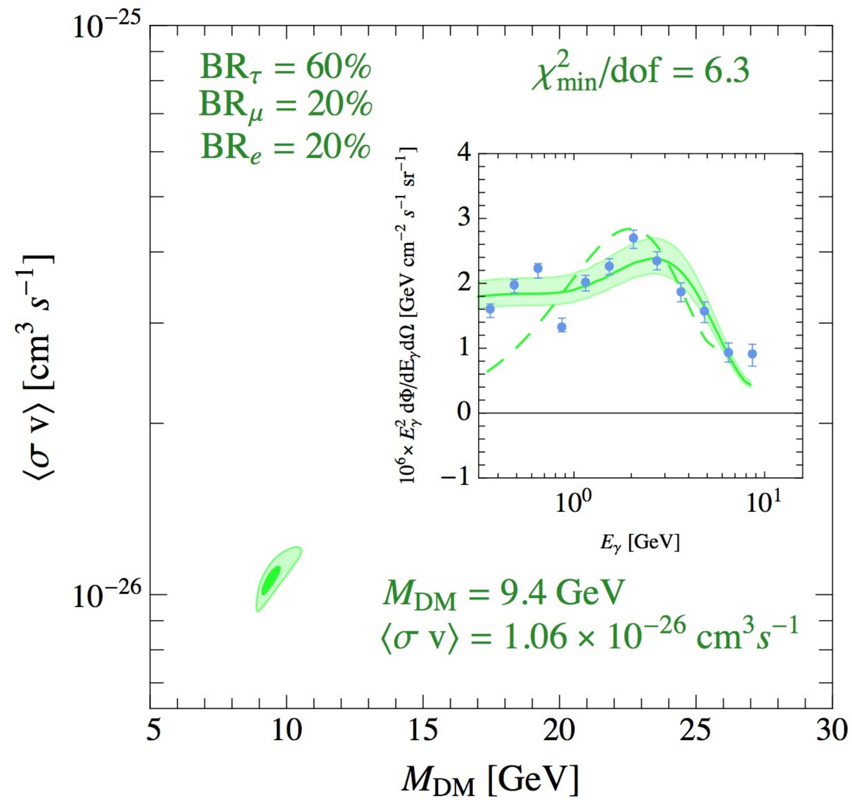




Secondary emissions relevant for leptonic channels
Only marginal role for hadronic channels

Best-fit regions





Including secondary emissions, leptonic channels might be a viable options for GC excess

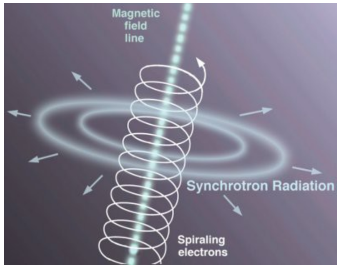
See also Lacroix, Boehm and Silk 1403.1987

Very recently a leptonic interpretation of GC emission proposed in

Abazajian, Canac, Horiuchi, Kaplinghat, Kwa, 1410.6168

Radio bounds

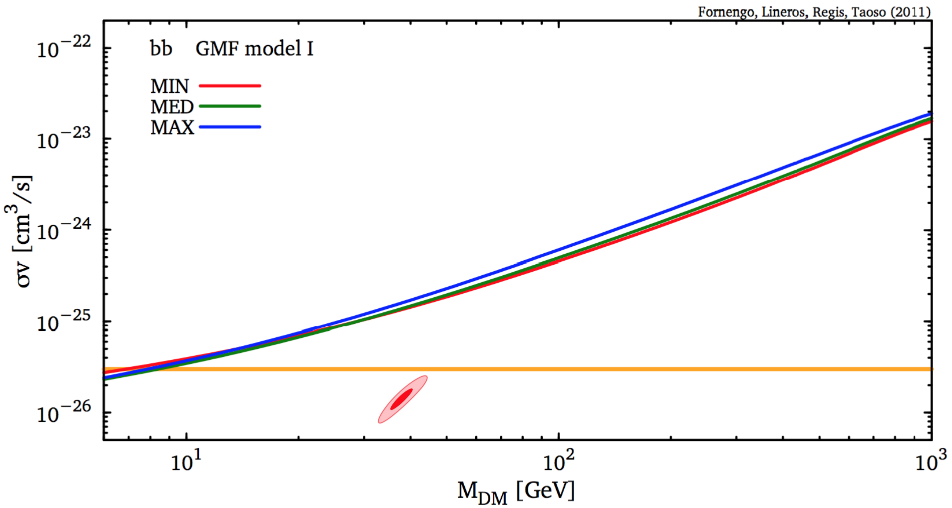
Synchrotron emission falls in radio band for tyical values of the galactic magnetic field



$$\nu \sim 30\ \mathrm{MHz}\ \frac{B}{6\mu G}\left(\frac{E_e}{1GeV}\right)^2$$

Constraints from radio surveys from 22 MHz - 1.4 GHz

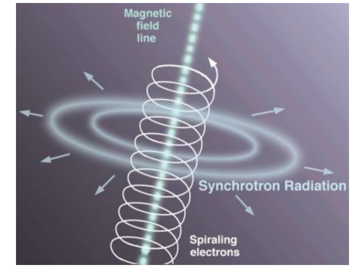
Additional uncertainty wrt gamma: magnetic fields & propagation



Fornengo, Lineros, MT, Regis 1110.4337

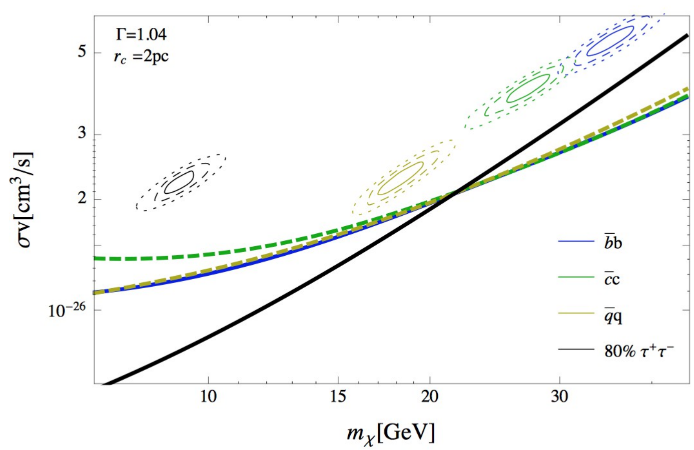
Radio bounds

Synchrotron emission falls in radio band for typical values of galactic magnetic fields



$$\nu \sim 30 \text{ MHz} \frac{B}{6\mu G}\left(\frac{E_e}{1GeV}\right)^2$$

Constraints from Jodrell Bank obs at 408 MHz, 4 arcsec GC region
Tight bounds but very sensitive to ingredients in a small region @ GC
Diffusion, winds, density profile,… ?



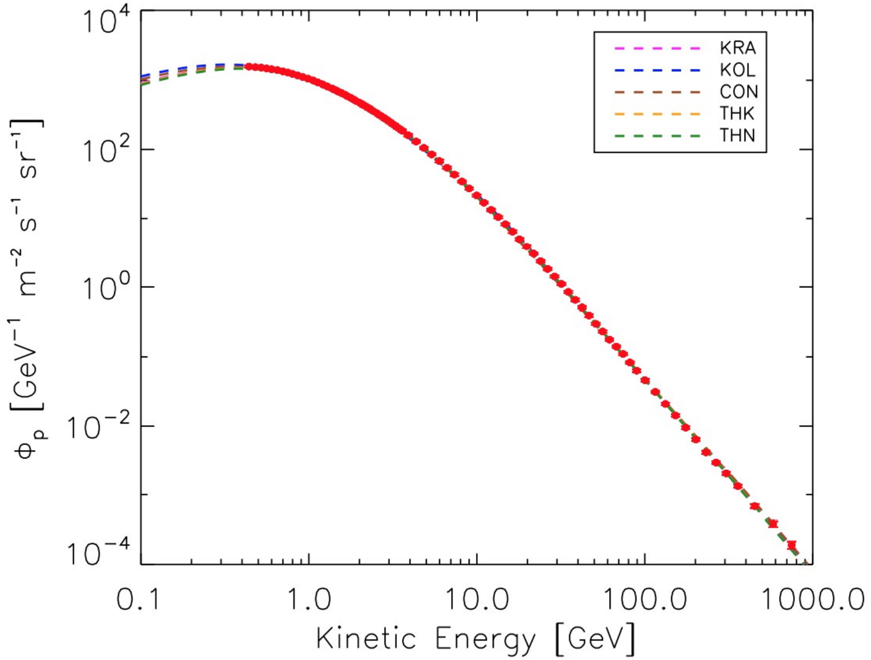
Bringmann et al. 1406.6027

See also Bertone Cirelli Strumia MT et al. 0811.3744, Regis Ullio 0802.0234, Aloisio Blasi Olinto 0402588, …

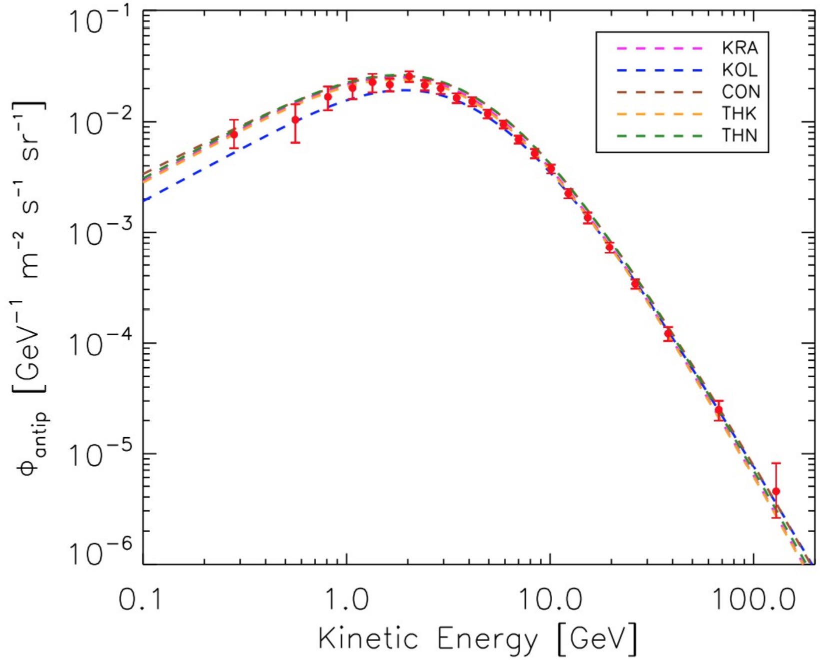
Antiprotons

PAMELA observations vs cosmic-rays propagation models

PROTONS



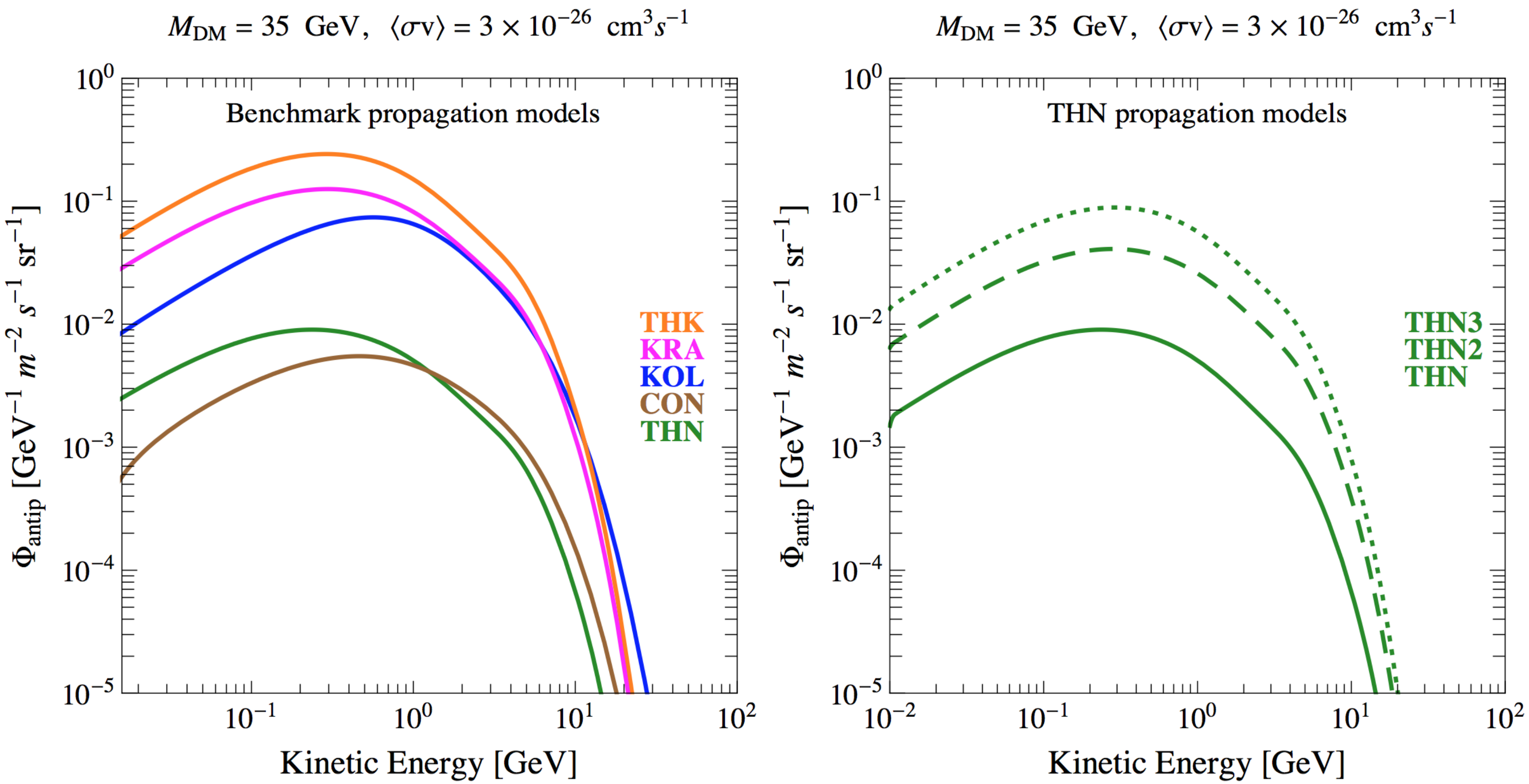
ANTI-PROTONS



Models in good agreement with anti-p data

Use PAMELA DATA + anti-p cosmic-ray background to constrain anti-p from DM

Anti-p from DM



Anti-p flux from DM strongly depends on the propagation model

Cirelli, Gaggero, Giesen, MT, Urbano 1407.2173

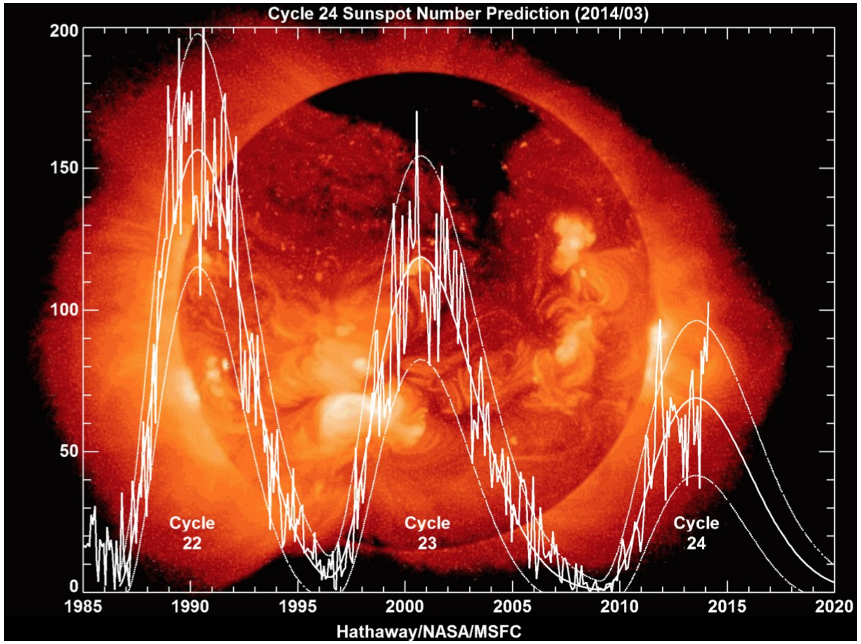
Solar modulation

Effect of solar wind very relevant for

charged particles < 10 GeV

The effect depends on the solar activity

which changes with time



Use force field approximation for solar modulation

$$\frac{d\Phi_{\bar{p}\oplus}}{dK_\oplus} = \frac{p_\oplus^2}{p^2}\frac{d\Phi_{\bar{p}}}{dK}, \qquad K = K_\oplus + |Ze|\phi_F^{\bar{p}}$$

Fisk potential ϕ is a pheno parameter fitted to the data

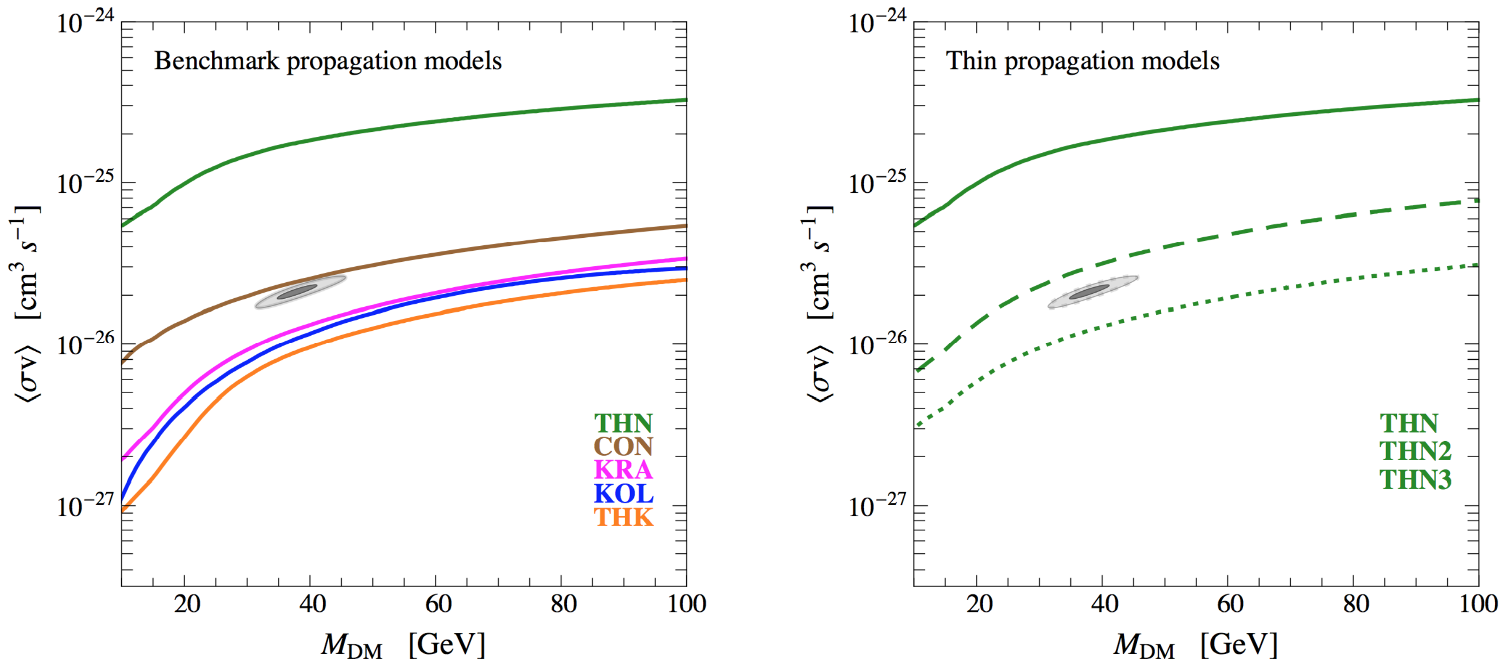
Anti-p constraints on DM

Consider charge-dependent effects

Marginalize over interval of Fisk potential to set the constraints

Interval of ± 50% around Fisk of p from a dedicated analysis based on HELIOPROP

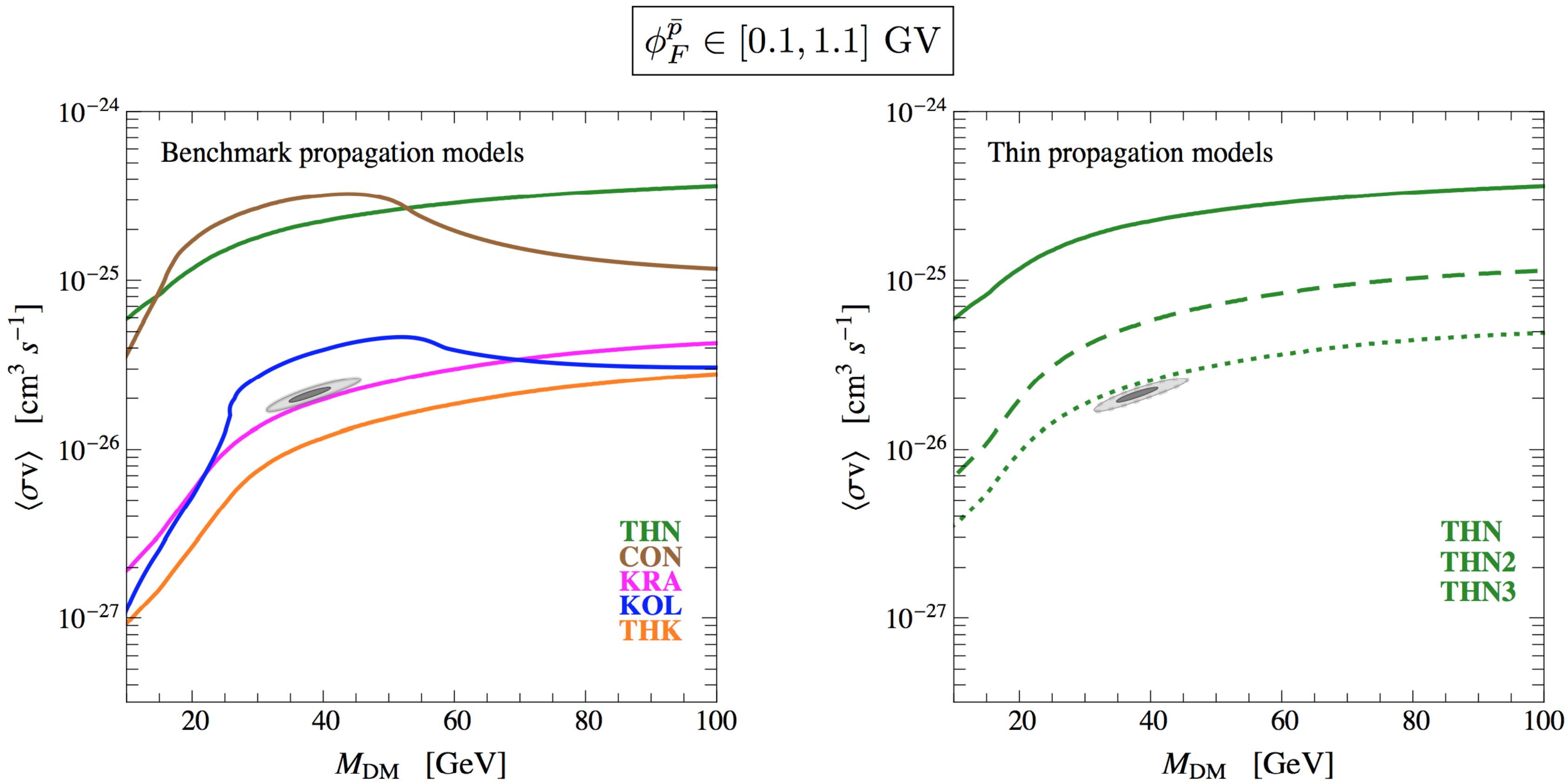
$$\phi_F^{\bar{p}} = \phi_F^{p} \pm 50\%$$



Anti-p constraints on DM

Very conservative range of variation of Fisk potential bracketing extreme observed

Variations of the Fisk potential



Other recent analysis on anti-p bounds & GC excess: Bringmann, Vollmann, Weniger 1406.6027,
Hooper, Linden, Mertsch 1410.1527

Conclusions

New extended source in the GC region on top of astro foregrounds!

Excess seems robust against variations of galactic diffuse emission models
However not all uncertainties have been explored!

Energy spectrum and morphological **properties fit well with expectations from DM** but alternative astrophysical explanations are also viable

DM interpretations **not yet constrained by Dwarf** constraints but future improvements should cover that region of the DM parameter space

Secondary emissions matter, both for spectral properties of the emission and constraints

Anti-p flux from PAMELA allows to set very stringent bounds on DM but
beware of theoretical uncertainties on CRs production and propagation and of the solar modulations

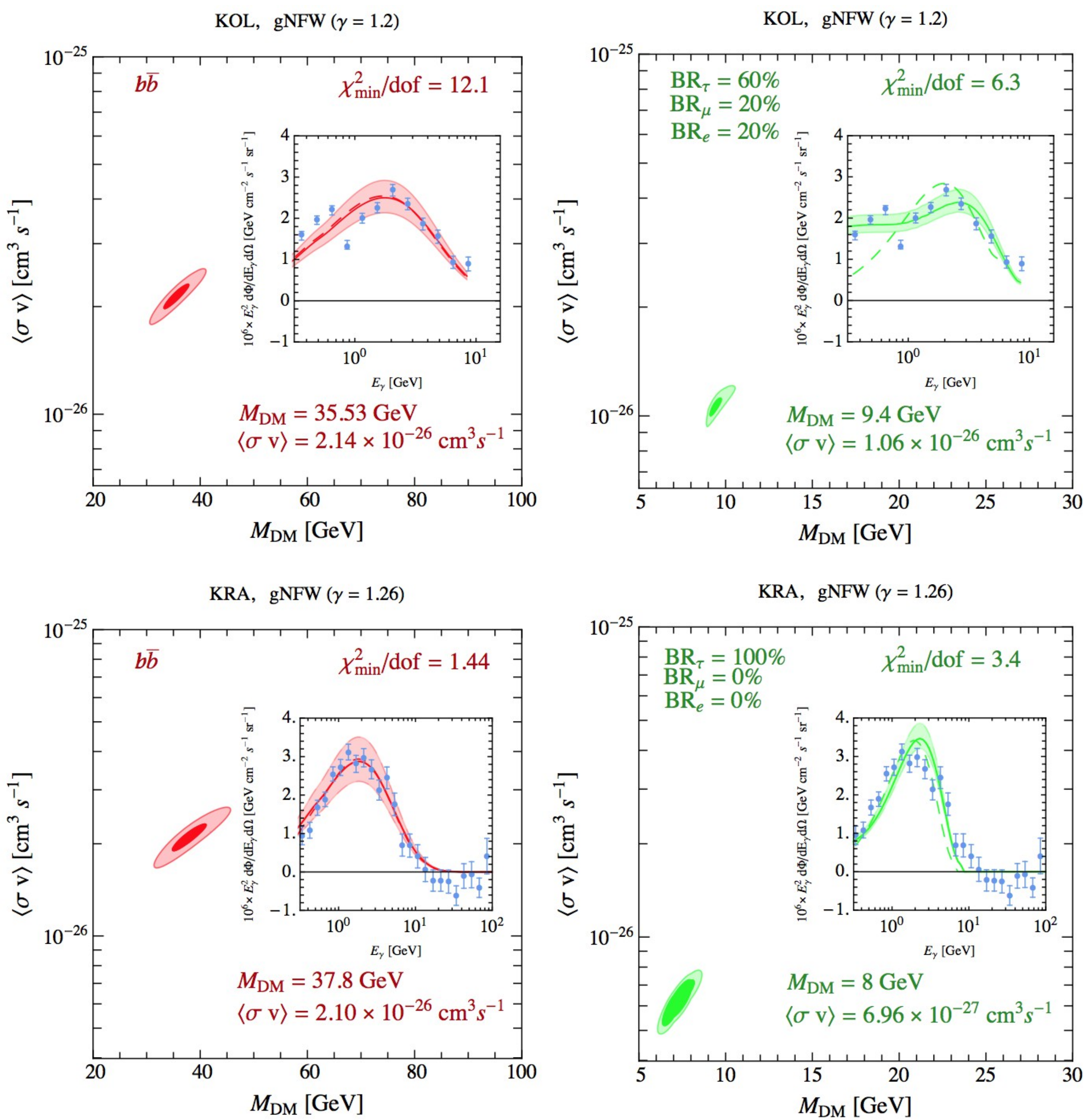
For conservative choices, **anti-p bounds are compatible with the GeV GC excess**

THANKS

Fisk potentials from HELIOPROP runs

polarity	tilt angle	m.f.p. (AU)	δ	ϕ_p	$\phi_{\bar{p}}$	rel. diff.
-1.00	10.00	0.05	0.30	1.18	1.18	0.00%
-1.00	10.00	0.05	0.50	1.18	1.18	0.00%
-1.00	10.00	0.05	1.00	1.12	1.12	0.00%
-1.00	10.00	0.10	0.30	1.06	1.10	3.77%
-1.00	10.00	0.10	0.50	1.02	1.10	7.84%
-1.00	10.00	0.10	1.00	1.02	1.10	7.84%
-1.00	10.00	0.20	0.30	0.78	0.96	23.08%
-1.00	10.00	0.20	0.50	0.74	0.90	21.62%
-1.00	10.00	0.20	1.00	0.60	0.74	23.33%
-1.00	10.00	0.30	0.30	0.60	0.82	36.67%
-1.00	10.00	0.30	0.50	0.54	0.76	40.74%
-1.00	10.00	0.30	1.00	0.46	0.58	26.09%
-1.00	10.00	0.40	0.30	0.36	0.46	27.78%
-1.00	10.00	0.40	1.00	0.48	0.72	50.00%
-1.00	20.00	0.05	0.30	1.46	1.18	-19.18%
-1.00	20.00	0.05	1.00	1.28	1.12	-12.50%
-1.00	20.00	0.40	0.30	0.48	0.72	50.00%
-1.00	20.00	0.40	1.00	0.36	0.46	27.78%
-1.00	40.00	0.05	0.30	1.56	1.18	-24.36%
-1.00	40.00	0.40	0.30	0.50	0.70	40.00%
-1.00	40.00	0.40	1.00	0.38	0.44	15.79%
-1.00	60.00	0.05	0.30	1.50	1.86	24.00%
-1.00	60.00	0.05	1.00	1.18	1.34	13.56%
-1.00	60.00	0.40	0.30	0.50	0.66	32.00%
-1.00	60.00	0.40	1.00	0.40	0.42	5.00%

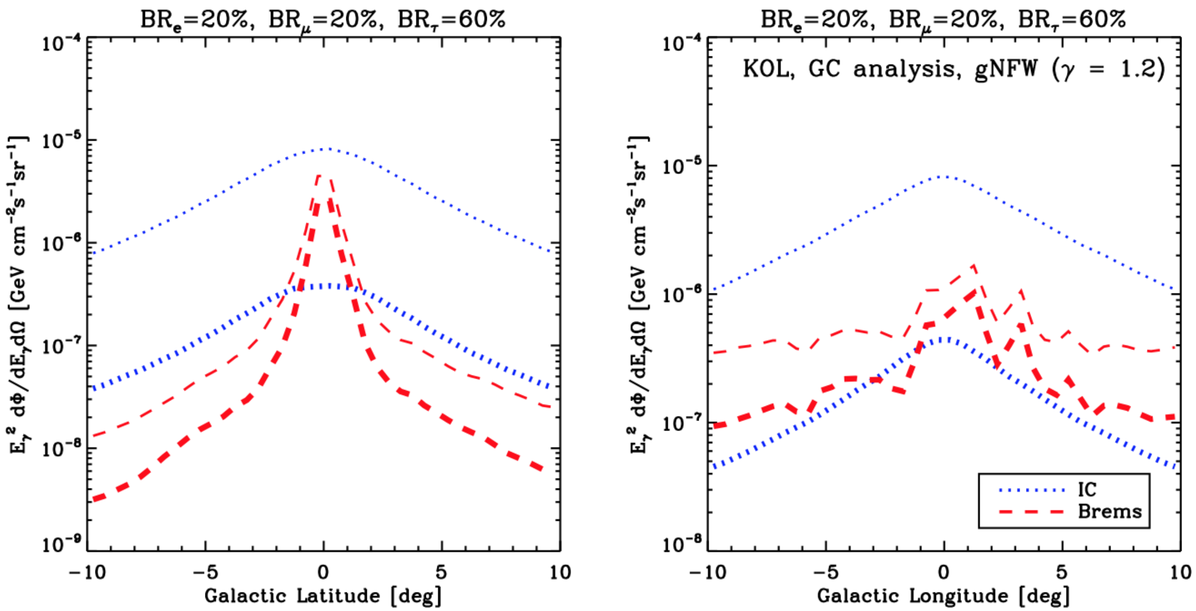
Fits of the GeV excess



IC and Brems emissions

Compute Inverse-Compton and Brems produced by electrons

Gas and Interstellar Radiation Field maps from GALPROP



IC more spherically symmetric

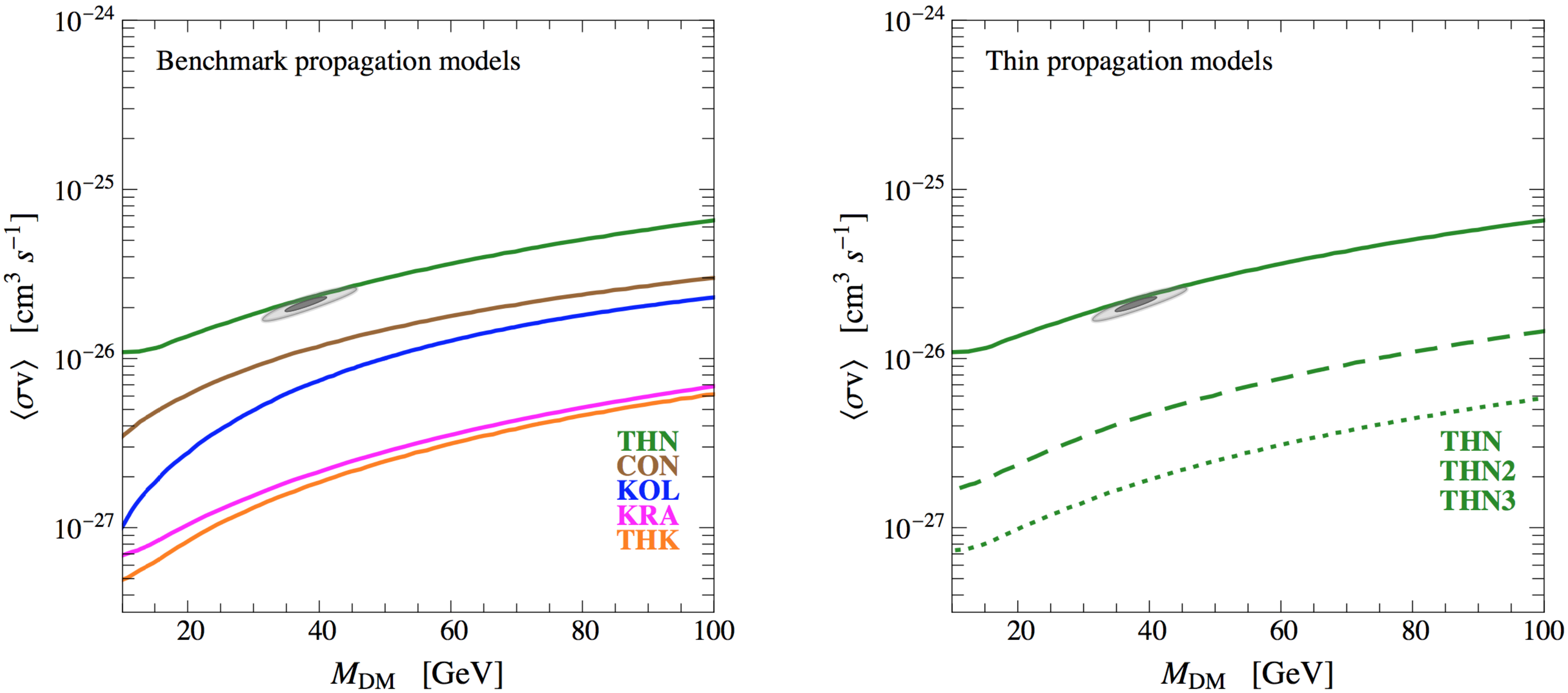
Brems correlated with the gas

Anti-p constraints on DM

Fisk potential determined fitting protons data

Bounds on bb channel

$\phi_F^{\bar{p}} = \phi_F^{p}$ fixed



$$\Phi_{\bar{p}}(M_{\rm DM}, \langle\sigma v\rangle, \phi_F^{\bar{p}}) = \Phi_{\bar{p}}^{\rm BG}(\phi_F^{\bar{p}}) + \Phi_{\bar{p}}^{\rm DM}(M_{\rm DM}, \langle\sigma v\rangle, \phi_F^{\bar{p}})$$

Benchmark models

	KRA	KOL	CON	THK	THN	THN2	THN3
z_t [kpc]	4	4	4	10	0.5	2	3
D_0 $[10^{28}\ \mathrm{cm}^2\,\mathrm{s}^{-1}]$	2.64	4.46	0.97	4.75	0.31	1.35	1.98
δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
v_{A} $[\mathrm{km\,s^{-1}}]$	14.2	36	38.1	14.1	11.6	11.6	11.6
γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
dv_{c}/dz $[\ \mathrm{km\,s^{-1}\,kpc^{-1}}]$	0	0	50	0	0	0	0
ϕ_F^p [GV]	0.650	0.335	0.282	0.687	0.704	0.626	0.623
$\chi^2_{\mathrm{min}}/\mathrm{dof}$ (p in [25])	0.462	0.761	1.602	0.516	0.639	0.343	0.339

Adopt a set of propagation model tuned against protons and B/C data

Span models with thick (10 kpc) – thin (1kpc) diffusion regions

Include models with large re-accelleration and convective winds