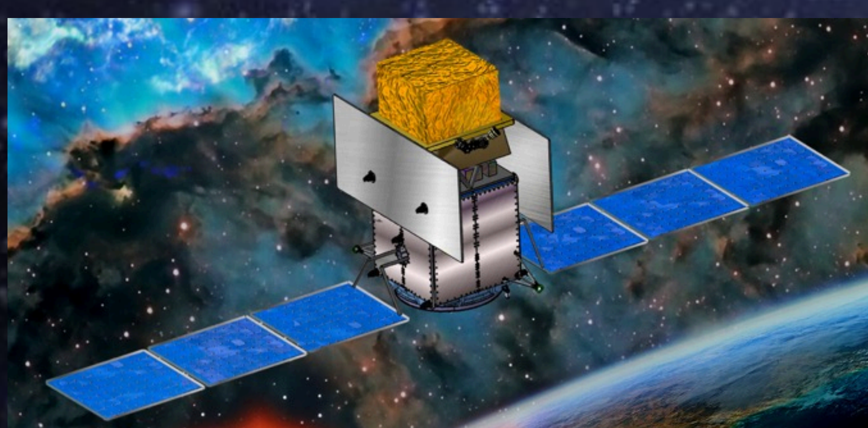
Potential of e-ASTROGAM for the discovery of Dark Matter and new particles



Padova
March 2nd, 2017

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GRAPPA GRavitation AstroParticle Physics Amsterdam
Universiteit van Amsterdam

Outline

- Introduction. The Dark Matter puzzle

- Dark Matter searches at all scales. Interplay with astrophysics.

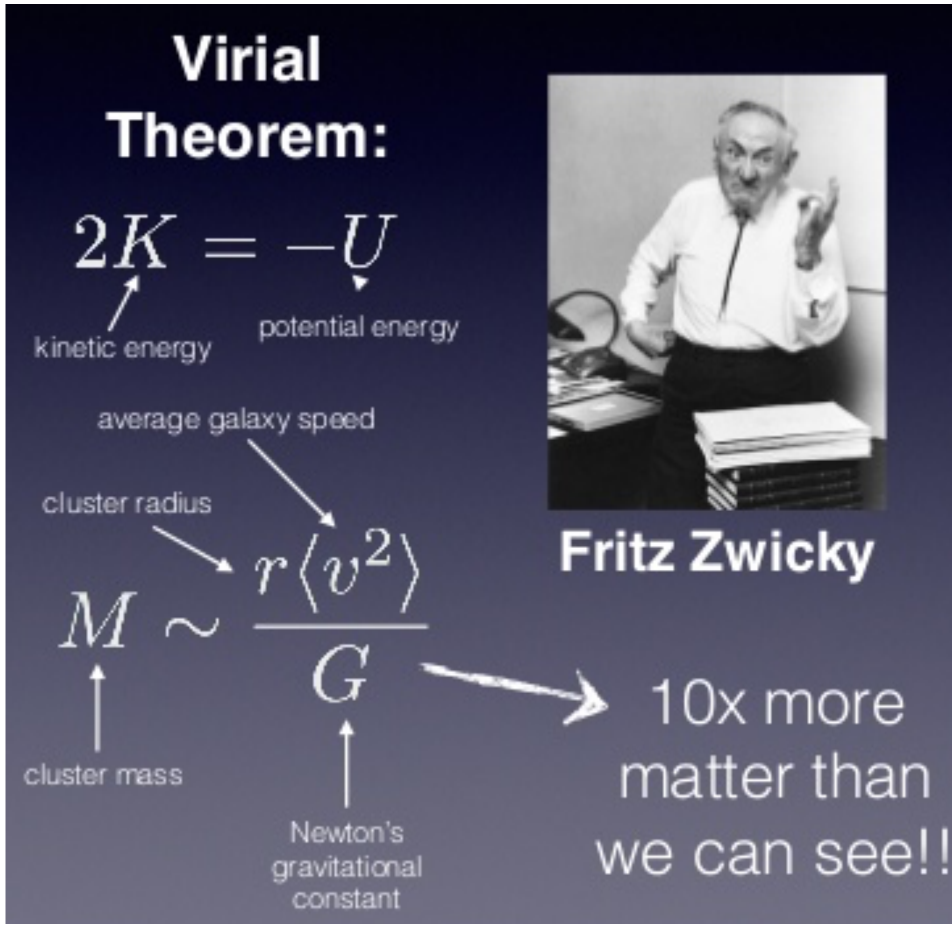
PART 1 - MeV DM - prospects of indirect detection with e-ASTROGAM

☆ MeV DM: annihilation channels, spectral features, the role of secondary emission from in-flight annihilation, bremsstrahlung, inverse Compton scattering.
☆ projected limits for e-ASTROGAM

PART 2 - GeV DM - discussion on the GeV excess claim

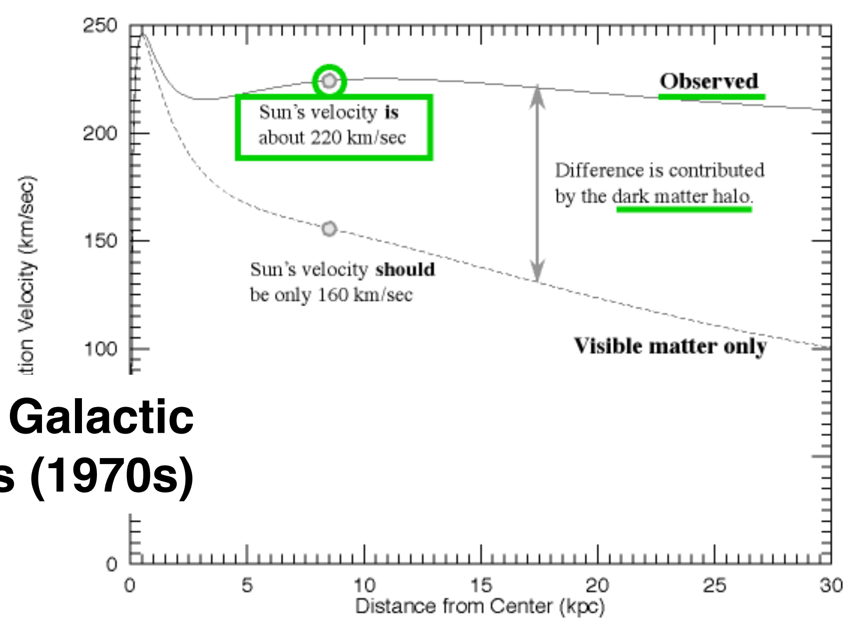
☆ the claim of a GeV excess from the inner Galaxy
☆ limits from the antiproton channel
☆ the role of secondary emission
☆ the crucial role of the background templates

Introduction: The Dark Matter puzzle



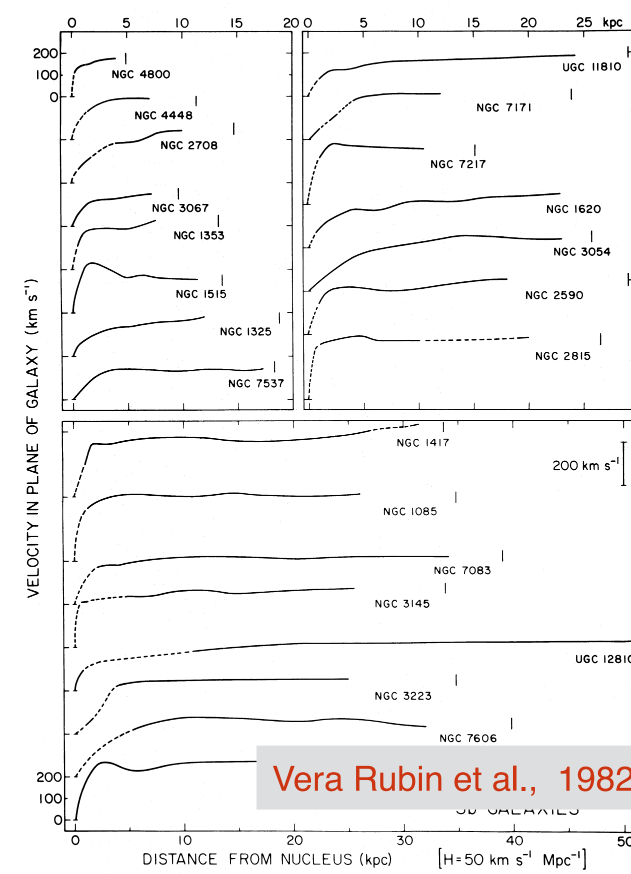
The coma cluster (APOD website)

Dark Matter at Galaxy cluster scales (anomalous mass-to-light ratio, 1930s)



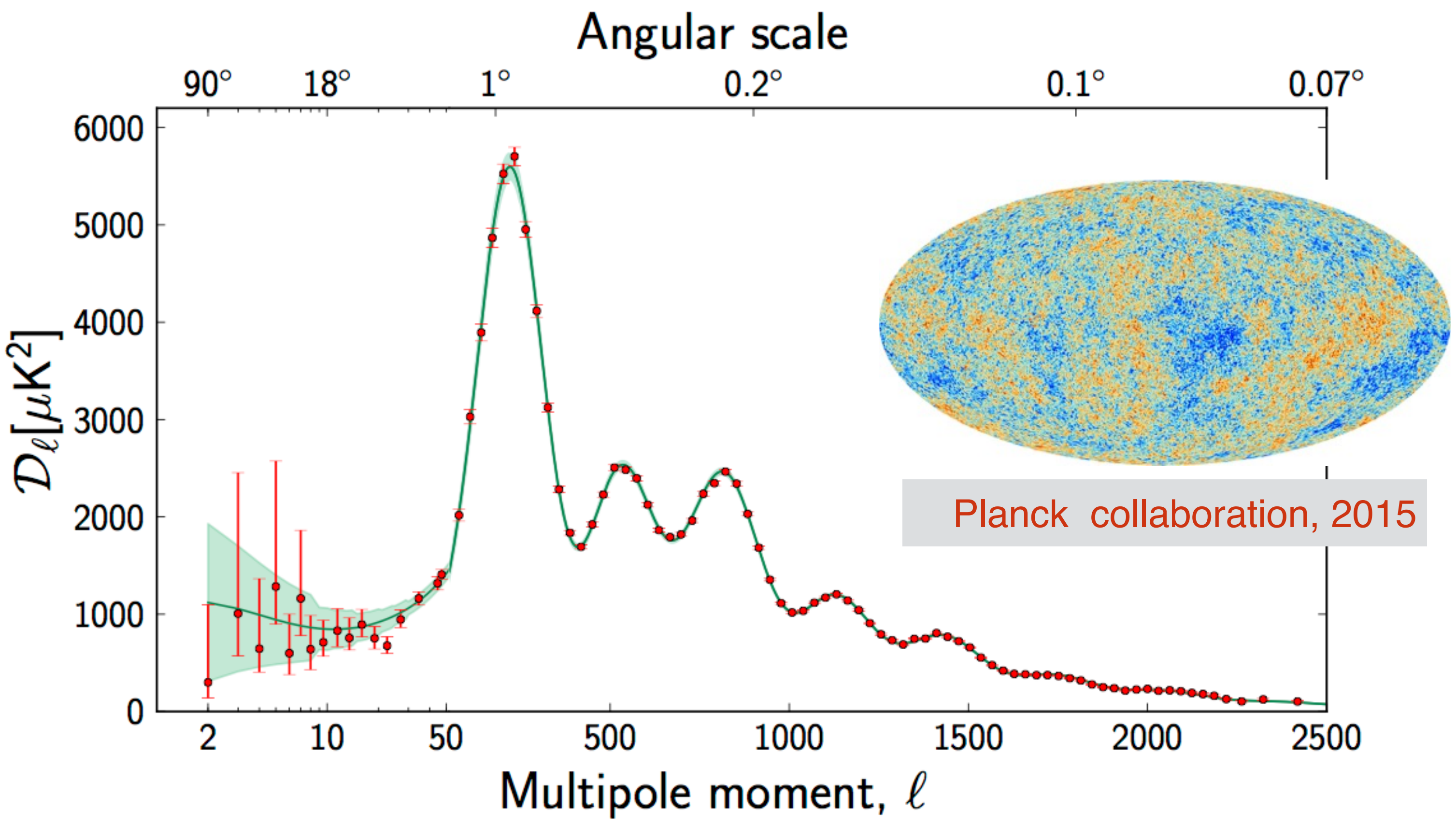
Dark Matter at Galactic scales (1970s)

Vera Rubin (1928-2016)



Vera Rubin et al., 1982

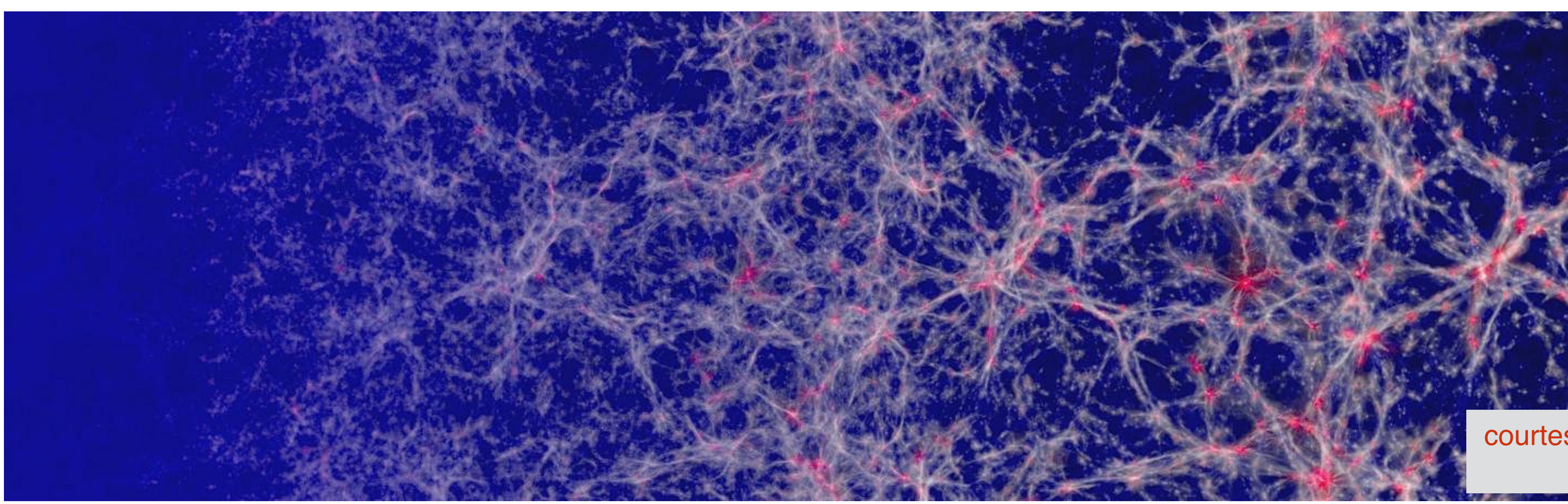
Introduction: The Dark Matter puzzle



Planck collaboration, 2015

Dark Matter at cosmological scales

Dark Matter as a crucial ingredient in structure formation

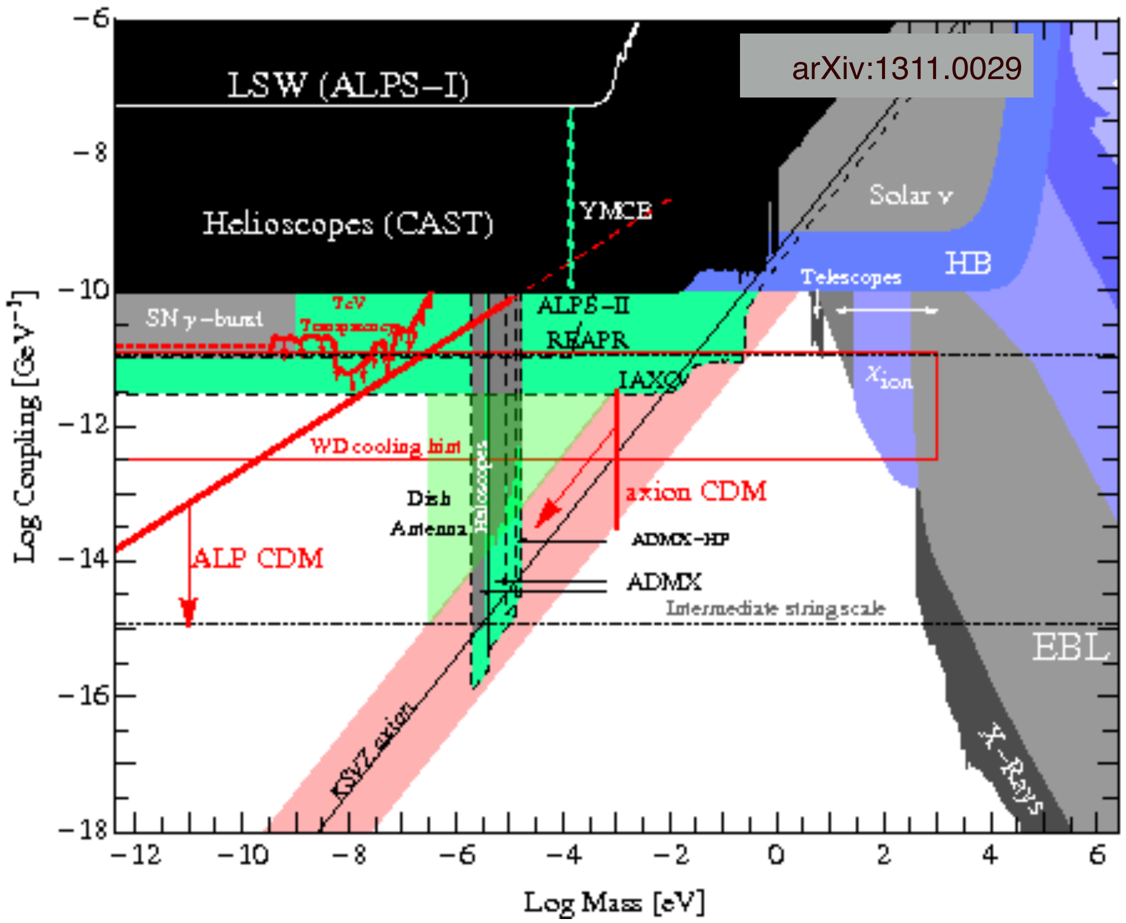


courtesy of the EAGLE collaboration

overview on Dark Matter candidates

10^{3} eV

— Axion-like particles



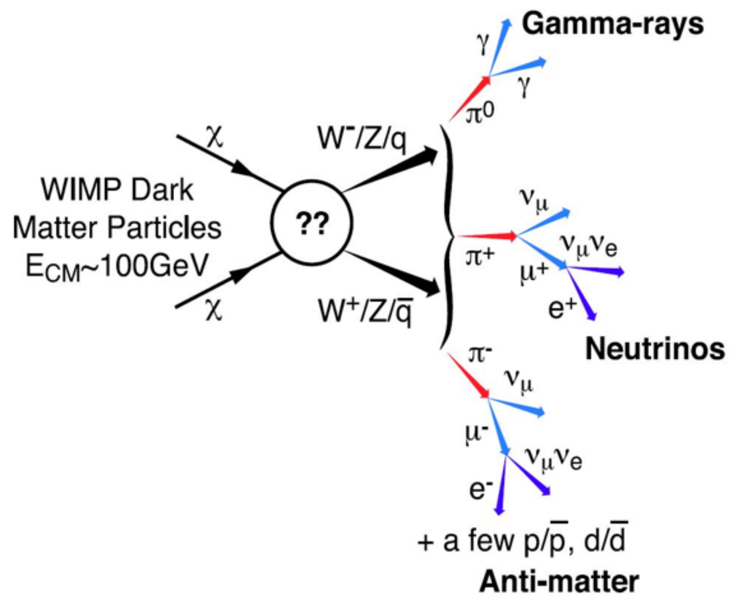
— Fuzzy Dark Matter

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy
[see recent paper: Hui, Ostriker, Tremaine, Witten 2016]

Fornax dSph seen from San Esteban (Chile) - 14Dec2003

10^{-22} eV

overview on Dark Matter candidates



10^{12} eV

10^{9} eV

— Weakly interacting massive particles (WIMPS)
e.g. lightest neutralino in MSSM
[~10 GeV -> ~100 TeV]

- very large parameter space
- **strong limits** from direct detection
- **indirect detection channels**: gamma rays (emission from dwarf spheroidal galaxies? from inner Galaxy? line features?) CR antiprotons, positrons, anti-deuterium, anti-helium; neutrinos from WIMP capture in the Sun

10^{6} eV

10^{3} eV

— Warm dark matter (e.g. sterile neutrinos)

overview on Dark Matter candidates

10^{12} eV

10^{9} eV

10^{6} eV

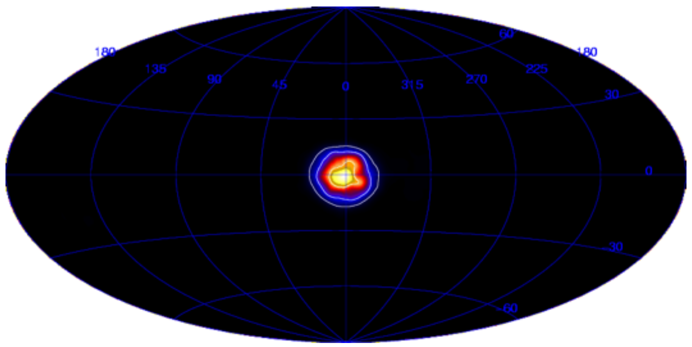
10^{3} eV

— what about Low-mass WIMPs (MeV-GeV)?

- **vanilla WIMPs are not good candidates** because of the (model-dependent) Lee-Weinberg limit:

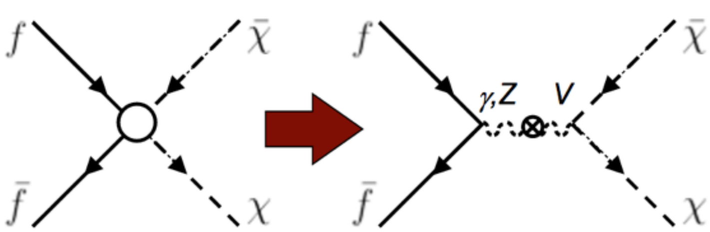
$$\Omega_\chi h^2 \sim 0.1 \frac{10^{-8}}{\mathrm{GeV}^{-2}} \cdot \frac{1}{G_F^2\, m_\chi^2} \sim 0.1 \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2$$

masses lower than ~10 GeV would over-close the Universe
(under the assumption of weak interaction)



- **“vector portal” models**

Boehm&Fayet, Nucl.Phys **B683** (2004)
Boehm et al., PRL **92** (2004)
—> Motivation: explain the 511keV line signal from the Galactic bulge
—> They require M < 7 MeV to avoid overproduction of γ-rays
*—> Strong constraints from CMB and BBN, **now ruled out**: a solid limit is M > 10 MeV*
Wilkinson et al., Phys.Rev. **D94** (2016)

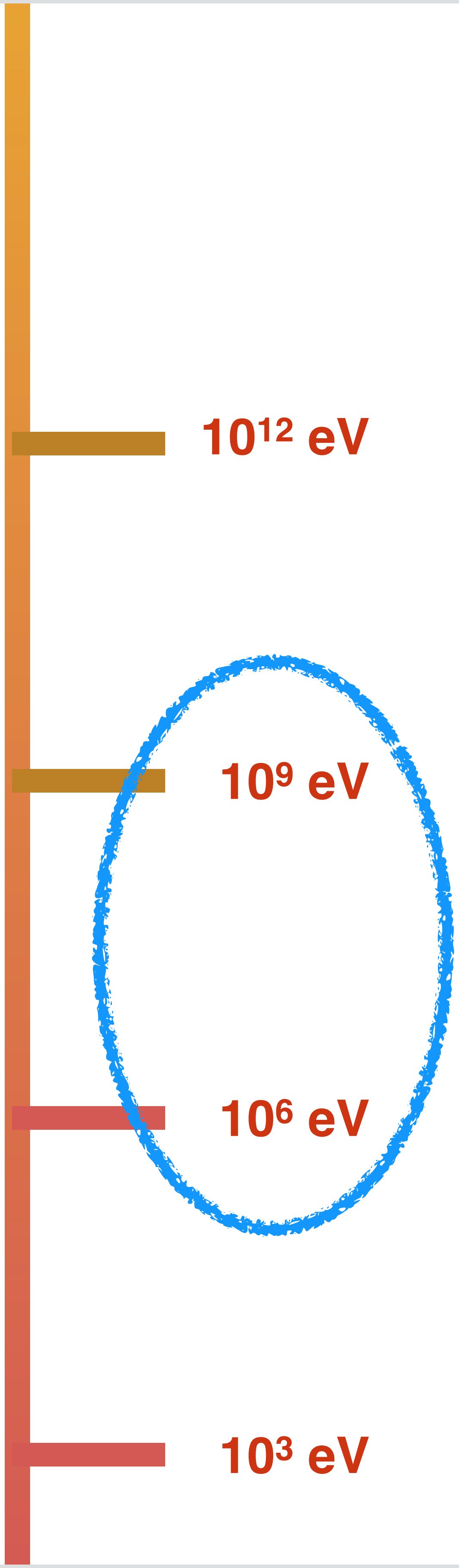


- **currently viable models for MeV DM:**

☆ *some realizations of **secluded, self-interacting DM***
[Pospelov et al., Phys.Lett. **B662** 2008]

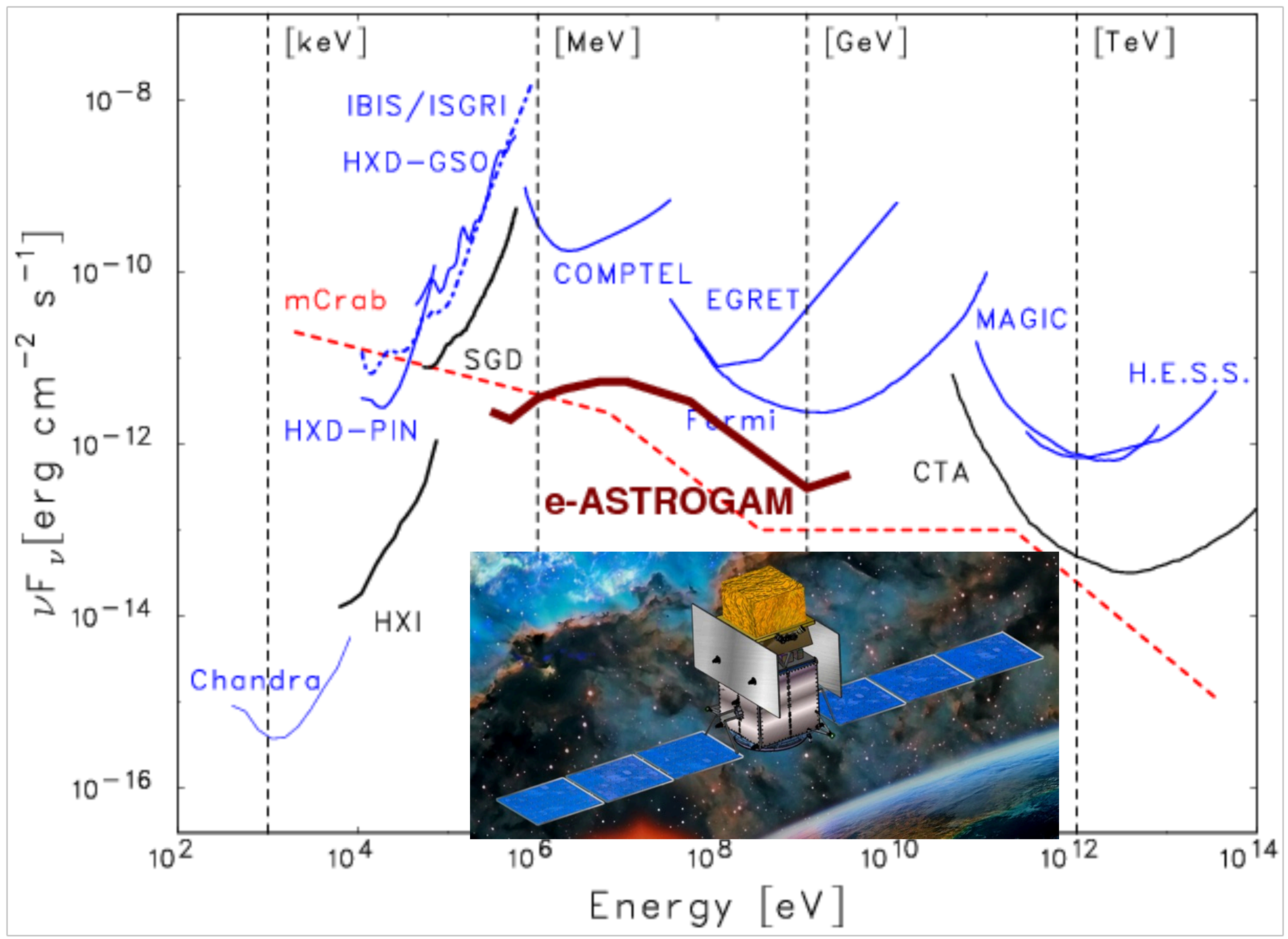
☆ *some realizations of **strongly-interacting DM***
[Hochberg et al., PRL **113**, 2014]

overview on Dark Matter candidates

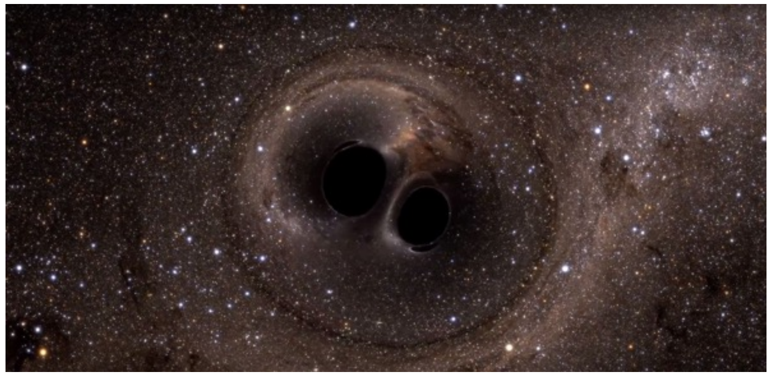


— what about Low-mass WIMPs (MeV-GeV)?

Indirect detection of MeV-GeV DM particles is one of the science goals of e-ASTROGAM



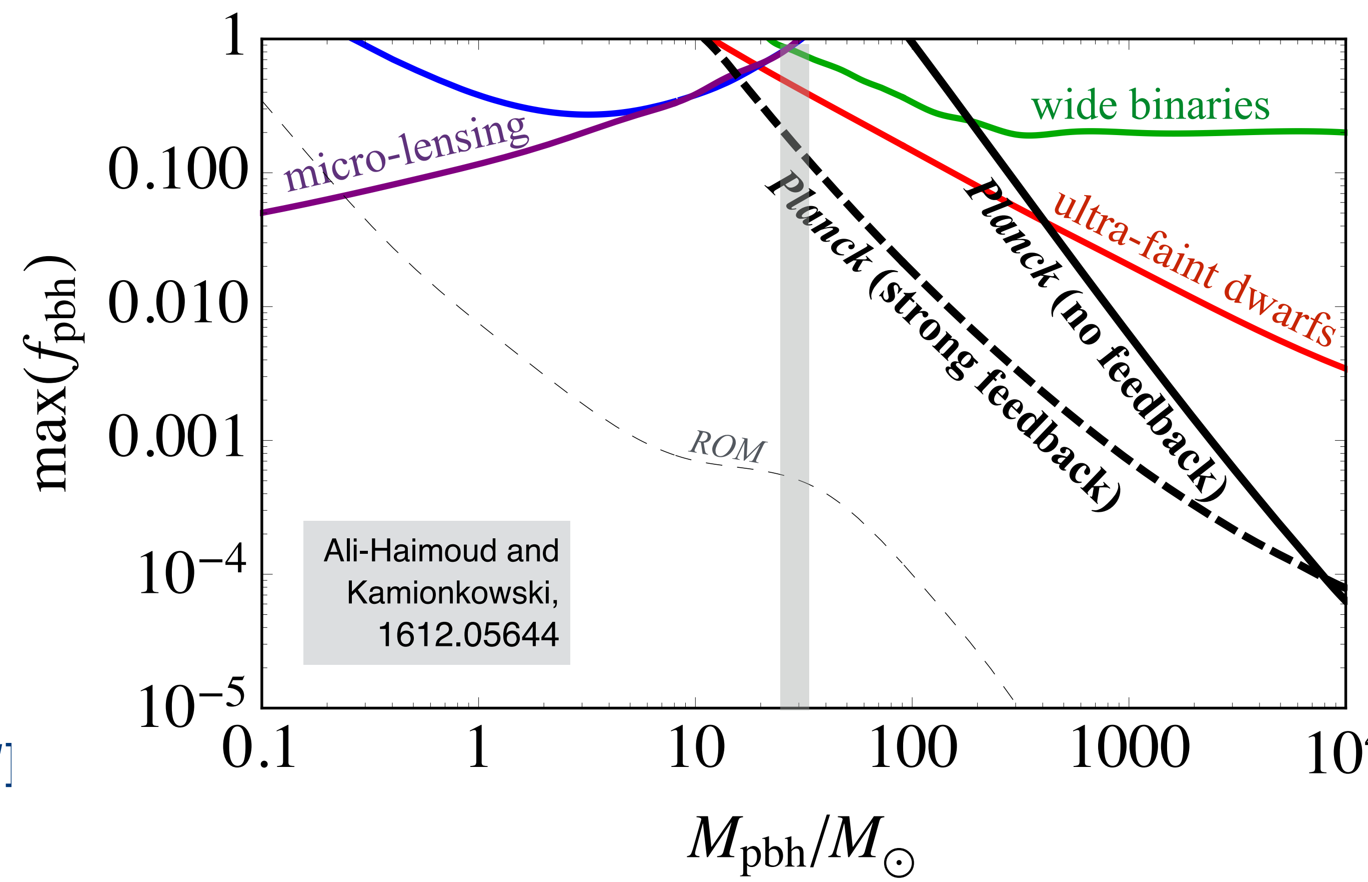
overview on Dark Matter candidates



10^{57} GeV ~ 10^{33} g ~ 1 Msun

— Primordial black holes (PBHs)

[*Zeld'ovich and Novikov 1966, Hawking 1971*]
— large mass range
— should have formed before BBN
— **many constraints** from lensing, wide binaries, Galactic disk stability
— very popular in the 80s, less considered after MACHO project (Alcock 2001)



— WIMPs

1 GeV

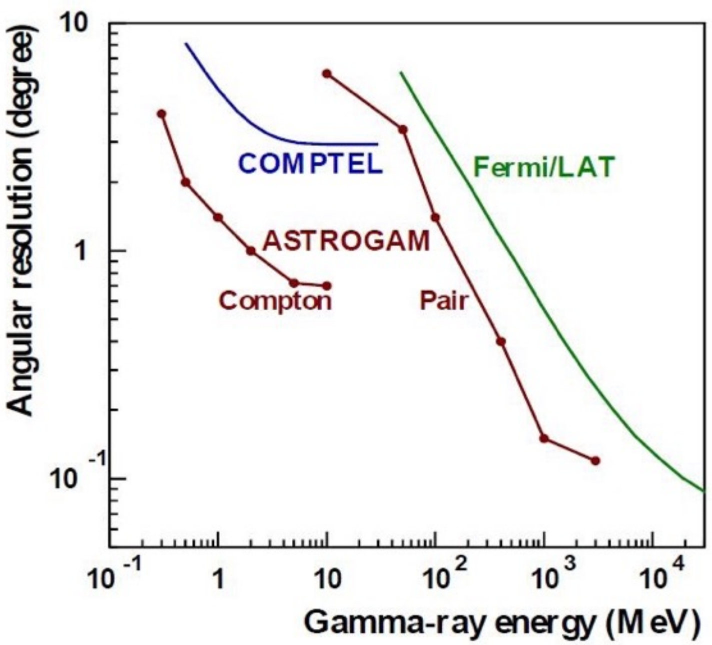
Credit for the BBH system: Bohn et al. (see http://www.black-holes.org/lensing

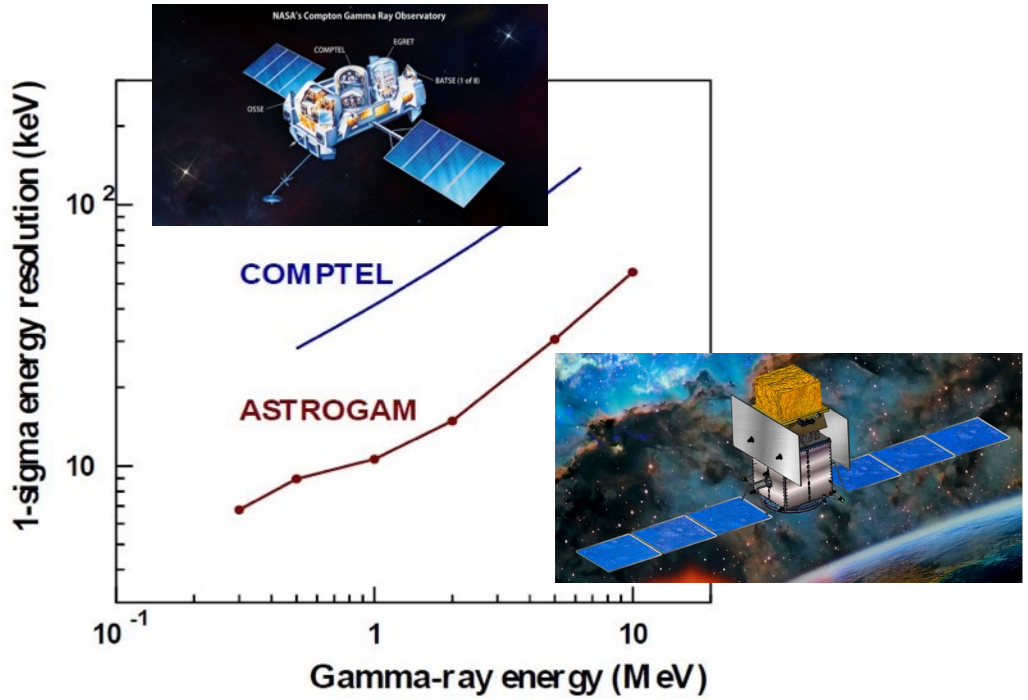
Part 1: indirect detection of MeV DM

A promising strategy to look for Dark Matter in the MeV-GeV domain is the **search for spectral features in the diffuse γ-ray emission**

Let’s see the potential of e-ASTROGAM.

Based on
Richard Bartels, Daniele Gaggero, Christoph Weniger, “Prospects for indirect dark matter searches with MeV photons”, in preparation





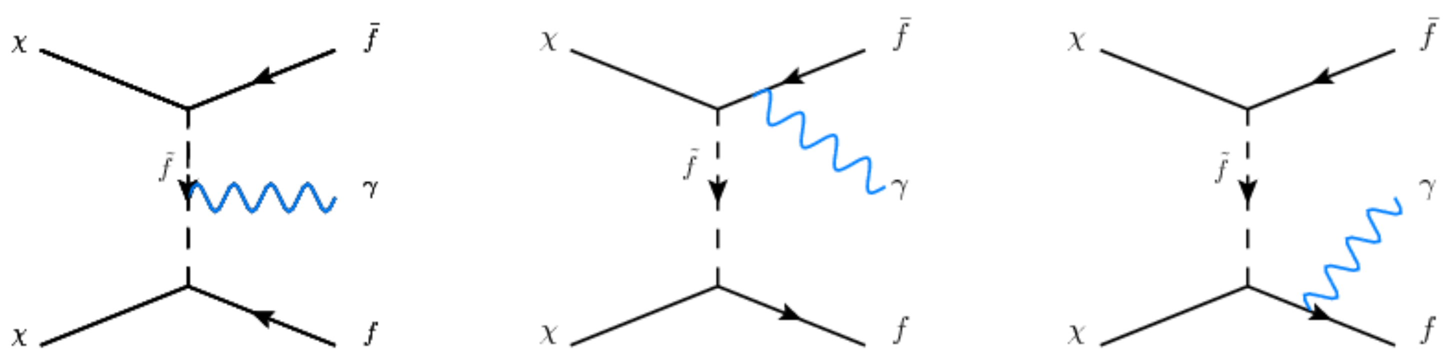
Excellent energy resolution in the Compton domain —> e-ASTROGAM is the ideal instrument for this purpose!

Part 1: indirect detection of MeV DM

A promising strategy to look for Dark Matter in the MeV-GeV domain is the **search for spectral features in the diffuse γ-ray emission**

Origin of gamma-ray radiation from DM annihilation:

1) **Final-state radiation** (e.g. internal bremsstrahlung)

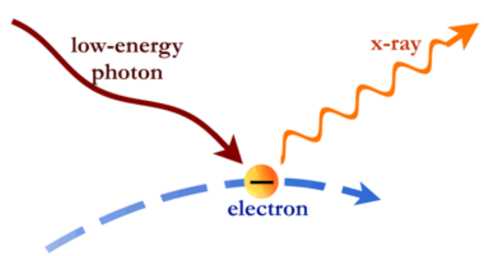


$$\frac{d\Phi}{dE\,d\Omega} = \frac{a\,\langle\sigma v\rangle\,J}{4\pi m_\chi^2}\,\frac{dN_\gamma}{dE_\gamma}$$

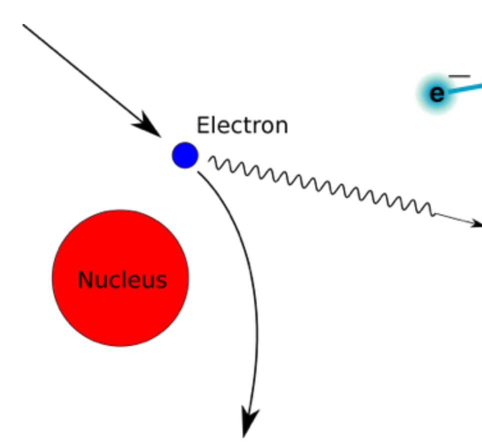
$$J = \int_{\mathrm{l.o.s.}} ds\,\rho^2(r(s,\theta))$$

2) For leptonic channels: **secondary emission** from the electrons and positrons

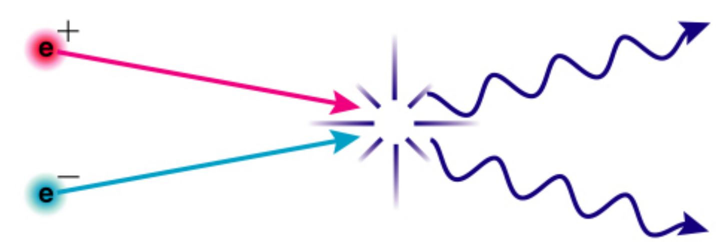
— *Inverse Compton* scattering



— *Bremsstrahlung*



— *In-flight annihilation* of positrons



Part 1: indirect detection of MeV DM

A promising strategy to look for Dark Matter in the MeV-GeV domain is the **search for spectral features in the diffuse γ-ray emission**

Annihilation channels for low-mass DM

$$\boxed{\chi\chi \rightarrow \gamma\gamma}$$

a γ-ray line $\frac{dN_\gamma}{dE} = 2\delta(E - m_\chi)$

$$\boxed{\chi\chi \rightarrow \pi^0\pi^0}$$

a box-like γ-ray spectrum $\frac{dN_\gamma}{dE} = \frac{4}{\Delta E}\Theta(E - E_-)\Theta(E_+ - E)$

$$\boxed{\chi\chi \rightarrow \pi^0\gamma}$$

$$\boxed{\chi\chi \rightarrow e^+e^-}$$

electrons and positrons injected mono-energetically. Significant FSR from internal bremsstrahlung

$$\boxed{\chi\chi \rightarrow \phi\phi,\ \phi \rightarrow e^+e^-}$$

DM annihilates via a mediator. The relative importance of secondary emission is enhanced.

$$\boxed{\chi\chi \rightarrow \mu^+\mu^-}$$

FSR can originate from DM annihilation into muons, or from the subsequent decay of muons

Leptonic channels and the role of secondary radiation

$$\chi\chi \rightarrow e^+e^-$$

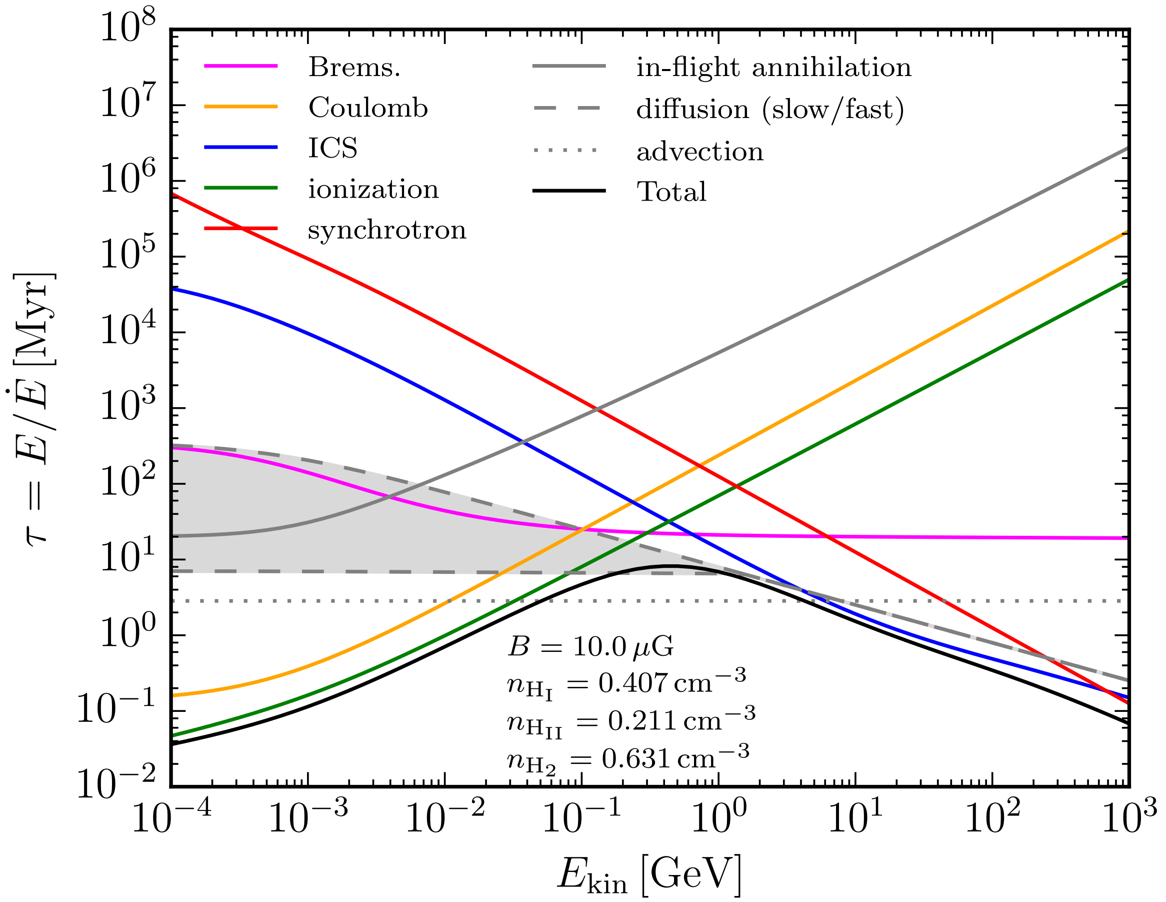
$$\chi\chi \rightarrow \mu^+\mu^-$$

The diffuse γ-ray signal from the inner Galaxy has a strong contribution from *secondary radiation originating from the final-state leptons during their journey through the Galaxy*

Relevant processes to be taken into account for leptonic propagation in the Galaxy:

- ☆ **Diffusion** (due to the interaction of the leptons with the inhomogeneities in the Galactic magnetic field)
- ☆ **Advection**
- ☆ **Coulomb interactions** with the ionized component of the interstellar gas
- ☆ **Ionization** of the neutral component of the interstellar gas
- ☆ **Bremsstrahlung**
- ☆ **inverse Compton scattering** on the diffuse radiation field
- ☆ **Synchrotron emission**
- ☆ **in-flight annihilation** of positrons on the free electrons

R.Bartels et al. 2017



Part 1: MeV DM

Leptonic channels and the role of secondary radiation

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

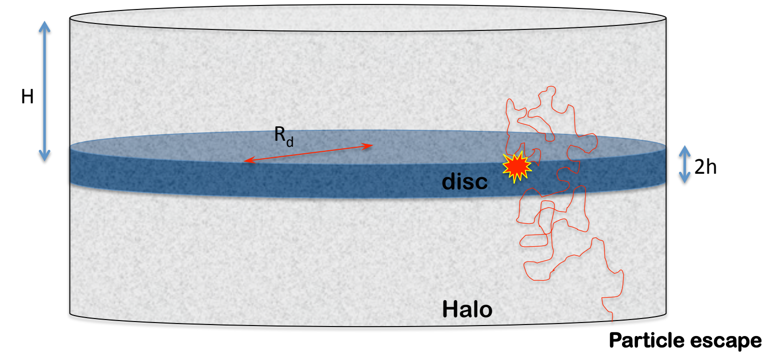
$$\chi\chi \to \mu^+\mu^-$$

The diffuse γ-ray signal from the inner Galaxy has a strong contribution from *secondary radiation originating from the final-state leptons during their journey through the Galaxy*

We model the relevant processes with the numerical packages DRAGON and GammaSky

☆ DRAGON solves the diffusion-loss equation for all cosmic-ray species, either originating from astrophysical sources or from Dark Matter annihilation.

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right) N_i$$



☆ GAMMASKY computes the diffuse gamma rays originating from π^0 decay, inverse Compton scattering, bremsstrahlung

- C. Evoli, D. Gaggero, D. Grasso, L. Maccione, “Cosmic ray nuclei, antiprotons and gamma rays in the galaxy: a new diffusion model” JCAP issue 10 id 018 (2008)
- C. Evoli, D. Gaggero, A. Vittino, G. Di Bernardo, M. Di Mauro, A. Ligorini, P. Ullio, D. Grasso, “CR propagation with DRAGON2: I. numerical solver and astrophysical ingredients” arXiv:1607.07886, JCAP 2017

Part 1: MeV DM

Leptonic channels and the role of secondary radiation

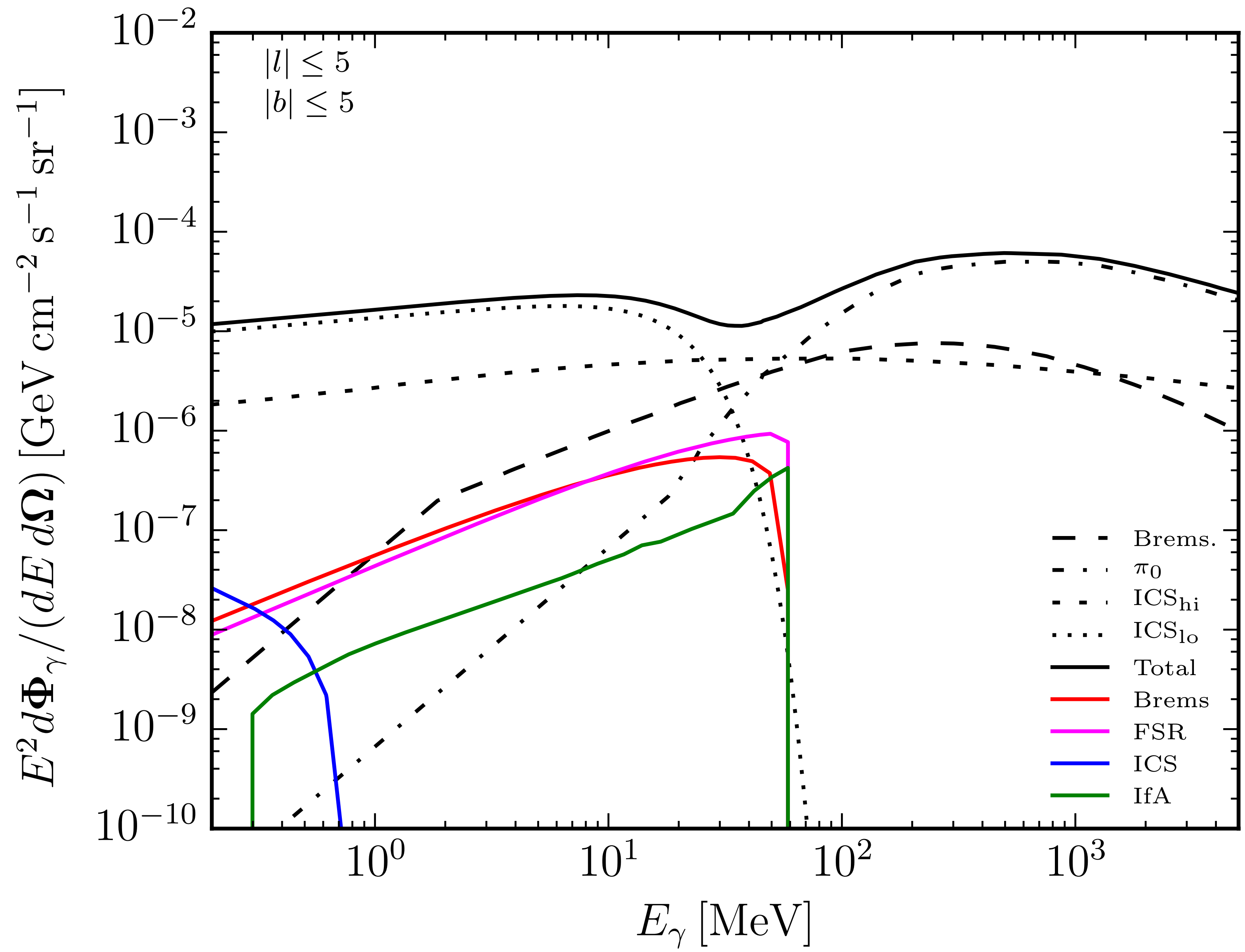
Both final-state radiation and secondary emission contribute to a characteristic spectral feature with a sharp cutoff at the DM particle mass scale

Here we show the γ-ray spectrum resulting from $\chi\chi \to e^+e^-$

<σv> = 10^{-28} cm^3 s^{-1}

ROI: *inner 10°x10°*

the DM signal is decomposed into:
- final-state radiation
- inverse Compton
- bremsstahlung
- in-flight annihilation



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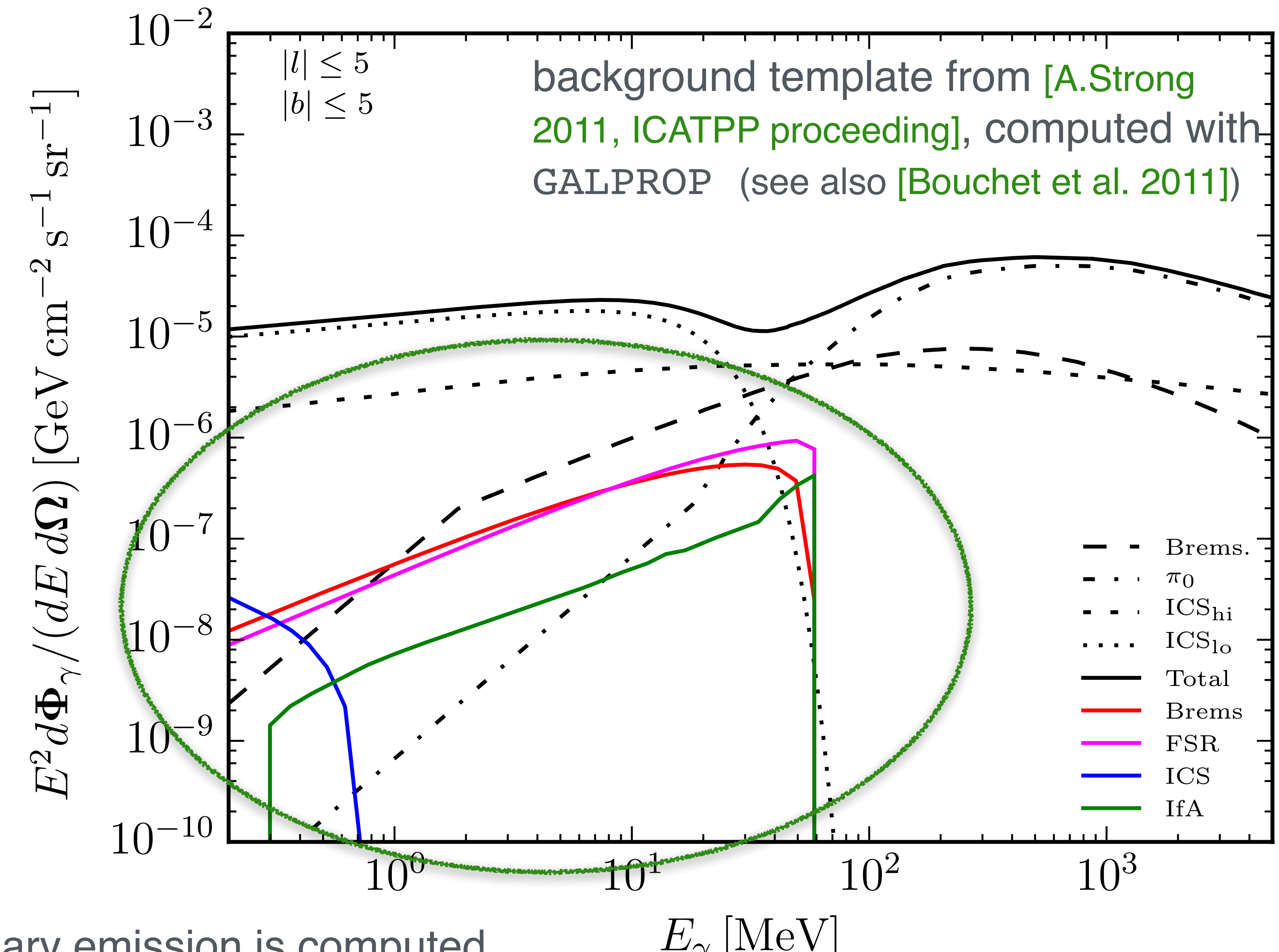
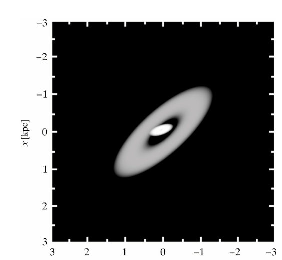


the secondary emission is computed with DRAGON, making use of a detailed 3D model for the gas distribution [K. Ferrière et al., A&A 2007]



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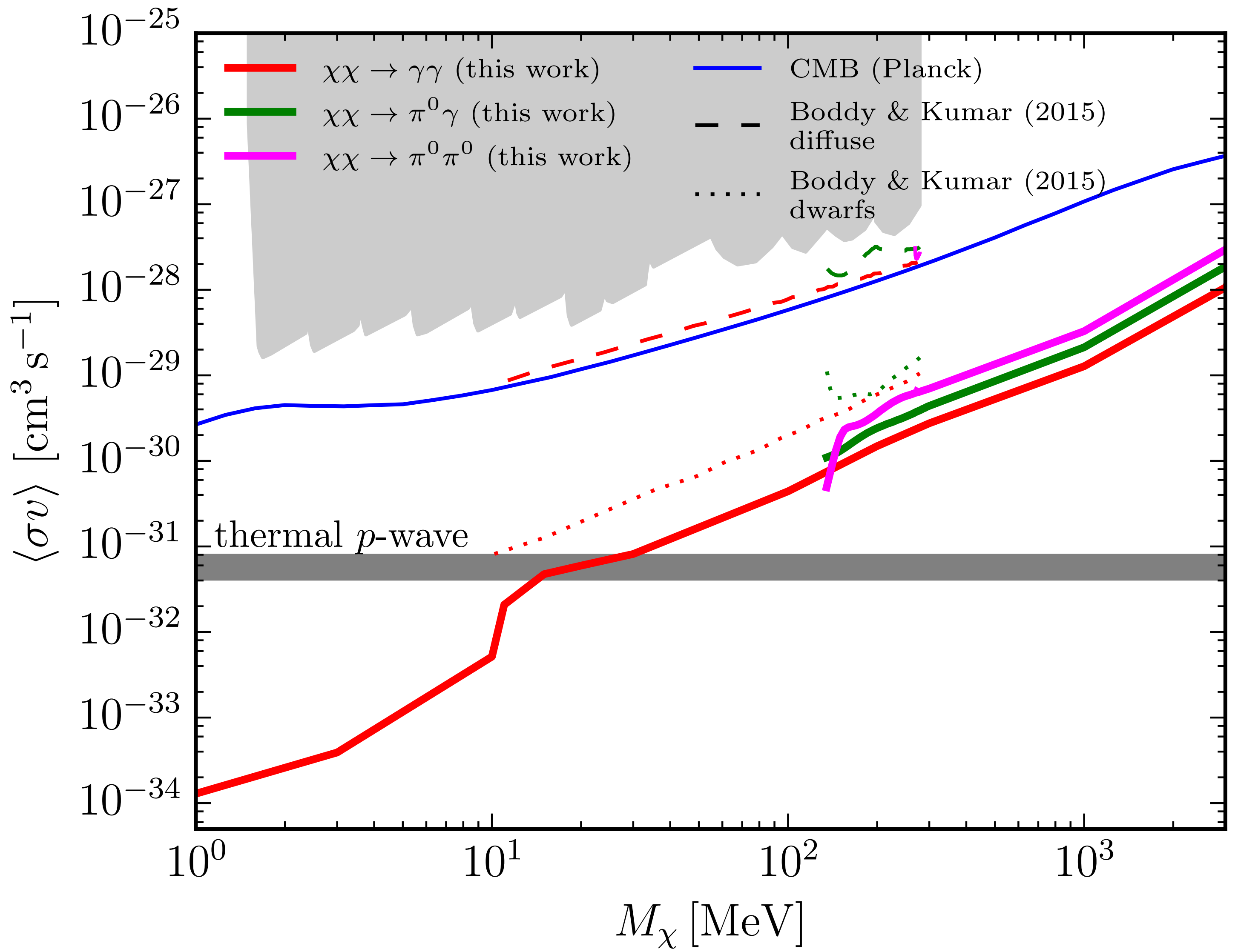
Projected upper limits expected from e-ASTROGAM for γ-ray lines and pions

assuming no signal in the data
computed using the *Fisher Information*
[see talk by C.Weniger]

95% CL limits
1-year of effective full-sky exposure
(5y of pure exposure)
systematics:
☆ **1% small-scale systematic uncertainty**
as found in [A. Albert et al. JCAP **10**(2014)]
☆ *15% large-scale systematic uncertainty*
(correlation length taken as 0.5 dex)

ROI: *inner 10°x10°*

our results are compared to
1) CMB bounds (blue line)
2) γ-ray bounds based on existing COMPTEL and EGRET data with no background subtraction (grey shaded regions)
3) other projected ADEPT bounds with different (more conservative) treatment of background (dashed), and assuming 15% sys. uncertainty (we have 1% for small-scale fluctuations)



we require that the p-wave term sets the relic density and still dominates at the
time of recombination, in order to avoid the CMB constraint from late-time energy injection between the epochs of recombination and reionization

R.Bartels et al. 2017

Projected upper limits expected from e-ASTROGAM for leptonic channels

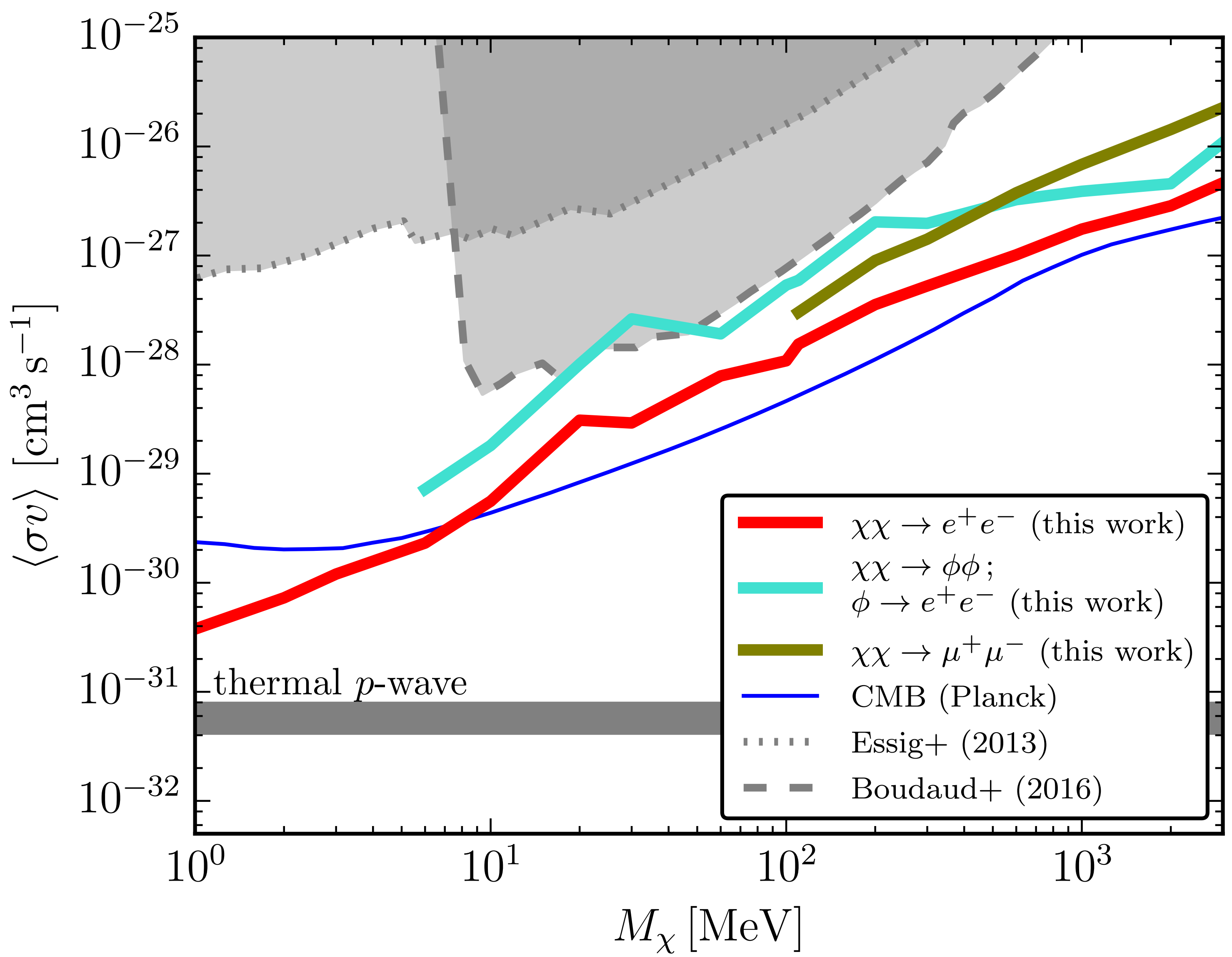
assuming no signal in the data
computed using the *Fisher Information*
[see talk by C.Weniger]

95% CL limits
1-year of effective full-sky exposure
(5y of pure exposure)
systematics:
☆ **1% small-scale systematic uncertainty**
as found in [A. Albert et al. JCAP **10**(2014)]
☆ *15% large-scale systematic uncertainty*
(correlation length taken as 0.5 dex)

ROI: *inner 10°x10°*

our results are compared to

1) CMB bounds (blue line)
2) γ-ray bounds based on existing COMPTEL and EGRET data with no background subtraction, less optimized ROI, and **no secondary emission** considered (grey shaded areas)



we require that the p-wave term sets the relic density and still dominates at the
time of recombination, in order to avoid the CMB constraint from late-time energy injection between the epochs of recombination and reionization

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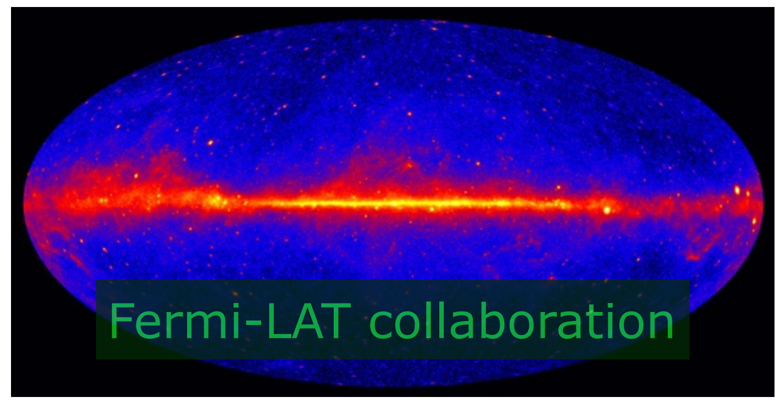
Part 2: The γ-ray inner Galaxy excess

In the 300 MeV - 300 GeV range we have the possibility to study the diffuse gamma-ray emission, and possibly look for signatures of new physics, thanks to the Fermi-LAT maps

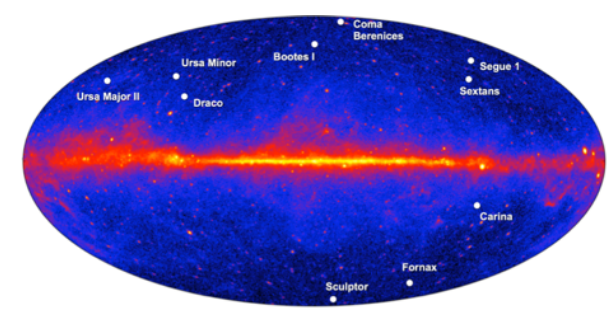
Diffuse emission due to *pion decay, Inverse Compton scattering, bremsstrahlung*



Interesting features relevant for DM searches

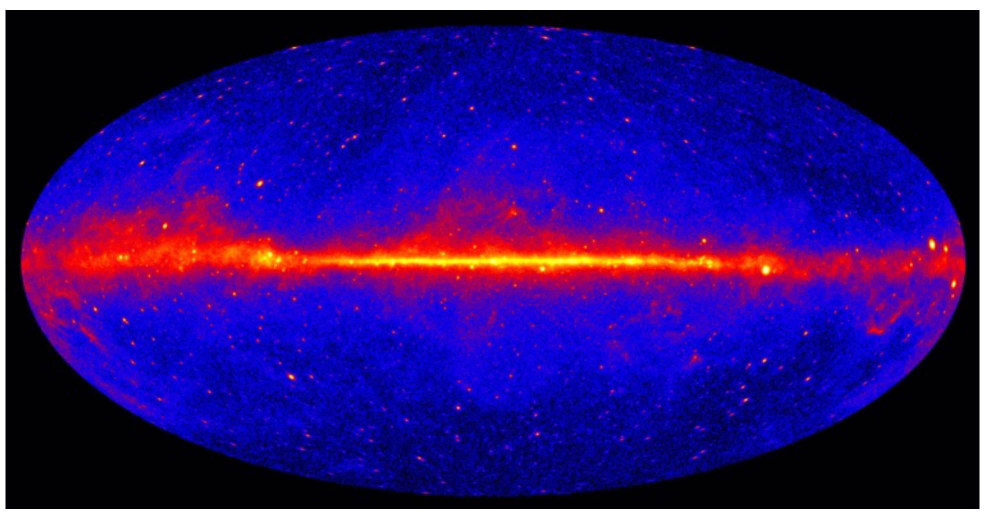
- **gamma-ray line**? *no detection yet*

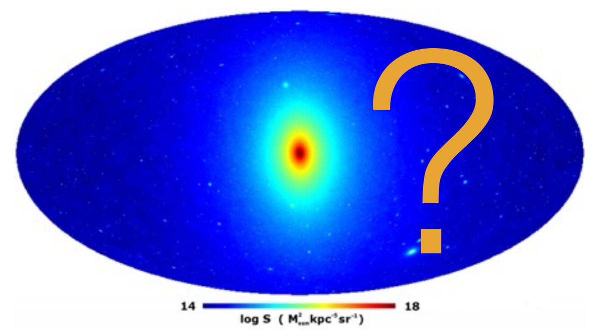
- *significant* gamma-ray emission from **dwarf spheroidal Galaxies**? *no detection yet*

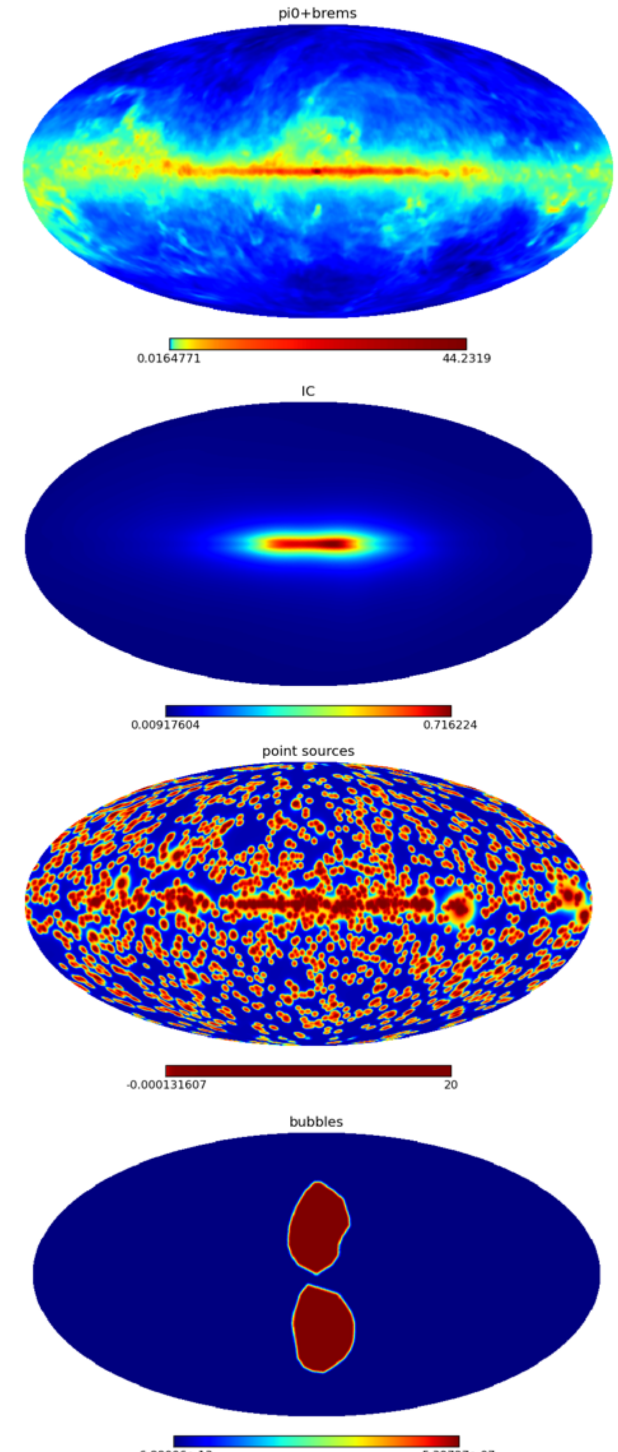


- **gamma-ray excesses** from inner Galaxy? **There's a tentative claim to be discussed**

Does a NFW template improve the fit of the Fermi-LAT data?





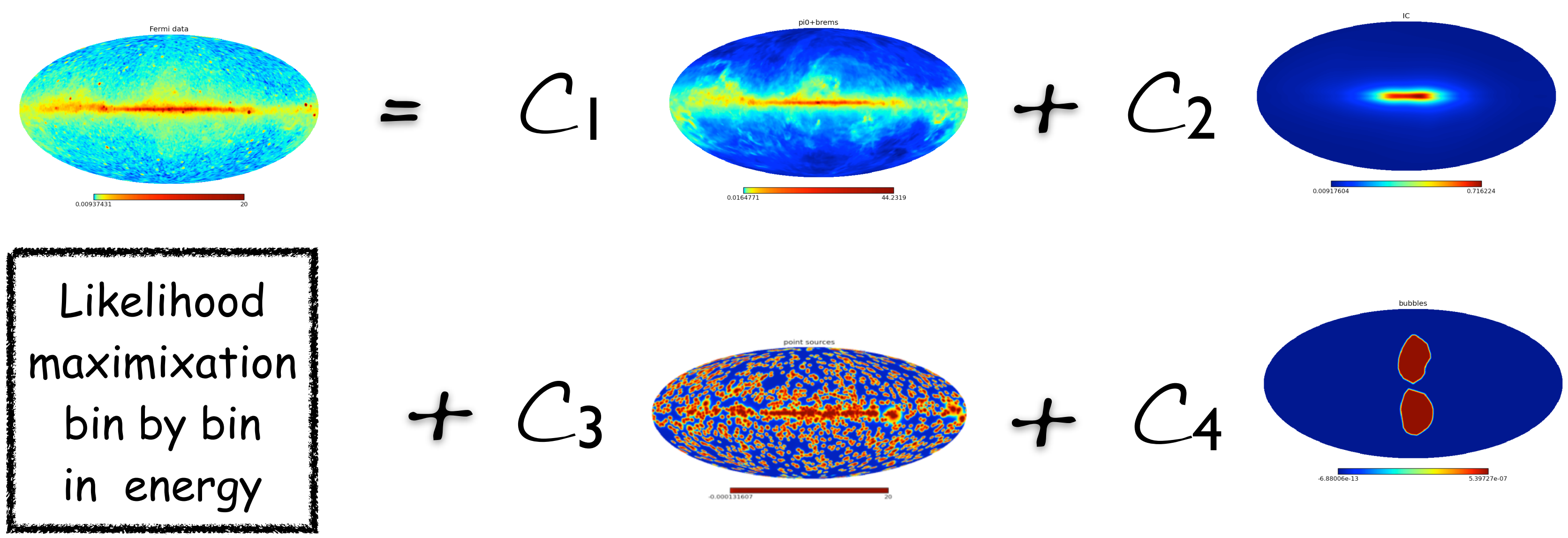


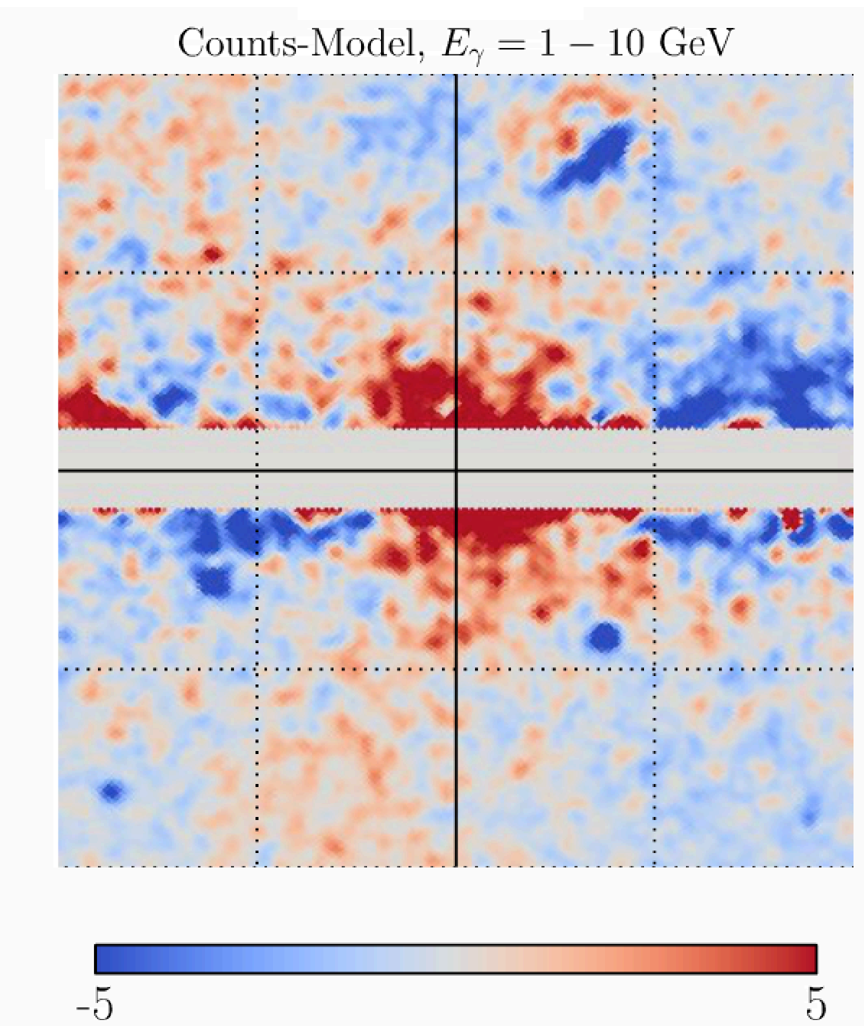
yes, according to a long series of papers

D. Dixon et al. 1998 [arXiv:9803237]; V. Vitale et al. 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; D. Hooper and L. Goodenough, 2010 D. Hooper and T. Linden, 2011; K. N. Abazajian and M. Kaplinghat, 2012 D. Hooper and T. R. Slatyer, 2013; C. Gordon and O. Macias, 2013 T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden; S. Portillo, N. L. Rodd and T. R. Slatyer, 2014 [arXiv:1402.6703]; F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]; F. Calore et al. 2015 [arXiv;1411.4647]

Does a NFW template improve the fit of the Fermi-LAT data?

If you try to model the gamma-ray emission taking into account the diffuse emission from π0 decay, the Inverse Compton emission, and all the other known gamma-ray sources, you end up missing something in the inner Galaxy

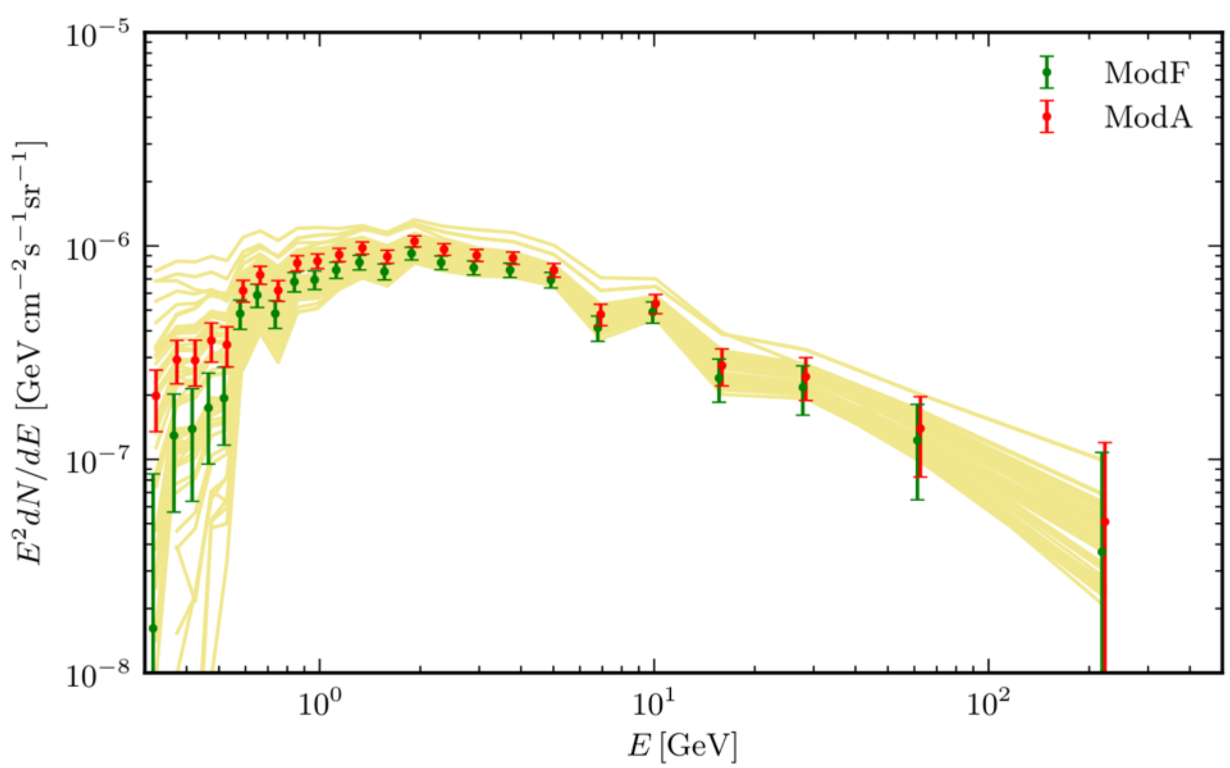




What about the spectrum?

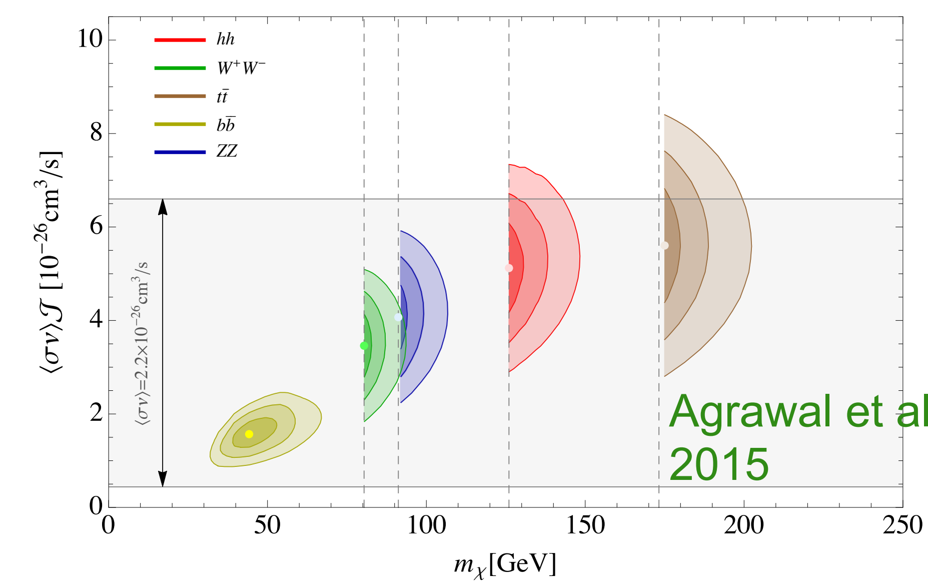
The spectrum of the signal is compatible with 40 GeV DM annihilating to conventional channels, with the reference thermal cross section (or with a larger DM mass, and a different channel, e.g. WW)

A "compelling case of dark matter detection", the evidence for a new class of sources, or maybe a mis-modeling of the background?

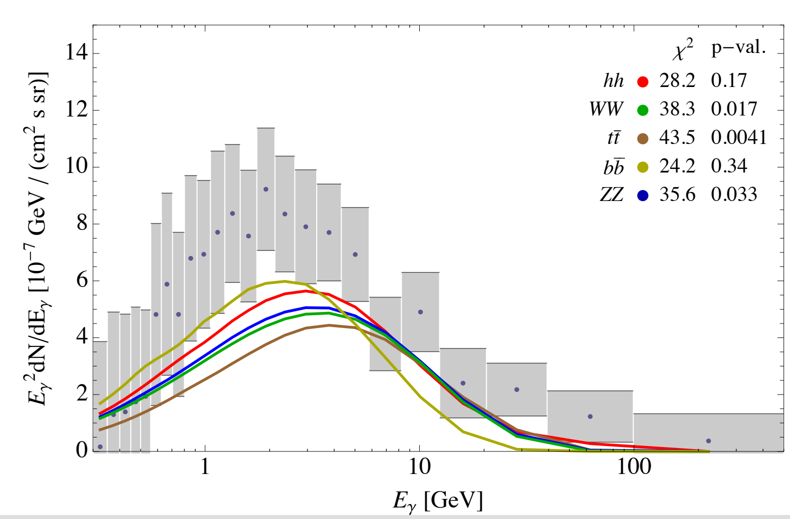


F. Calore, I. Cholis and C. Weniger, JCAP **03** id038 (2015)

F. Calore et al., PRD **91** (2015)



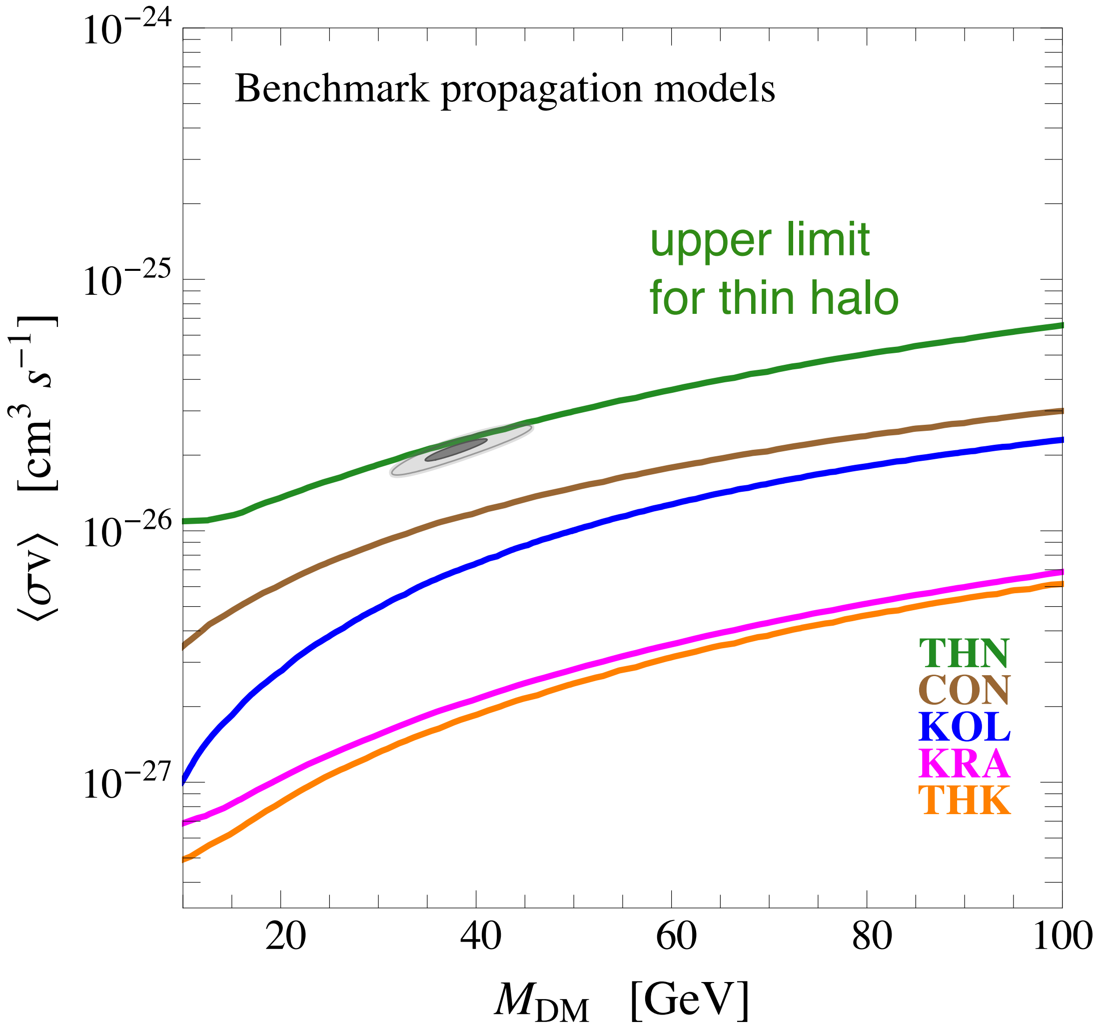
Agrawal et al 2015

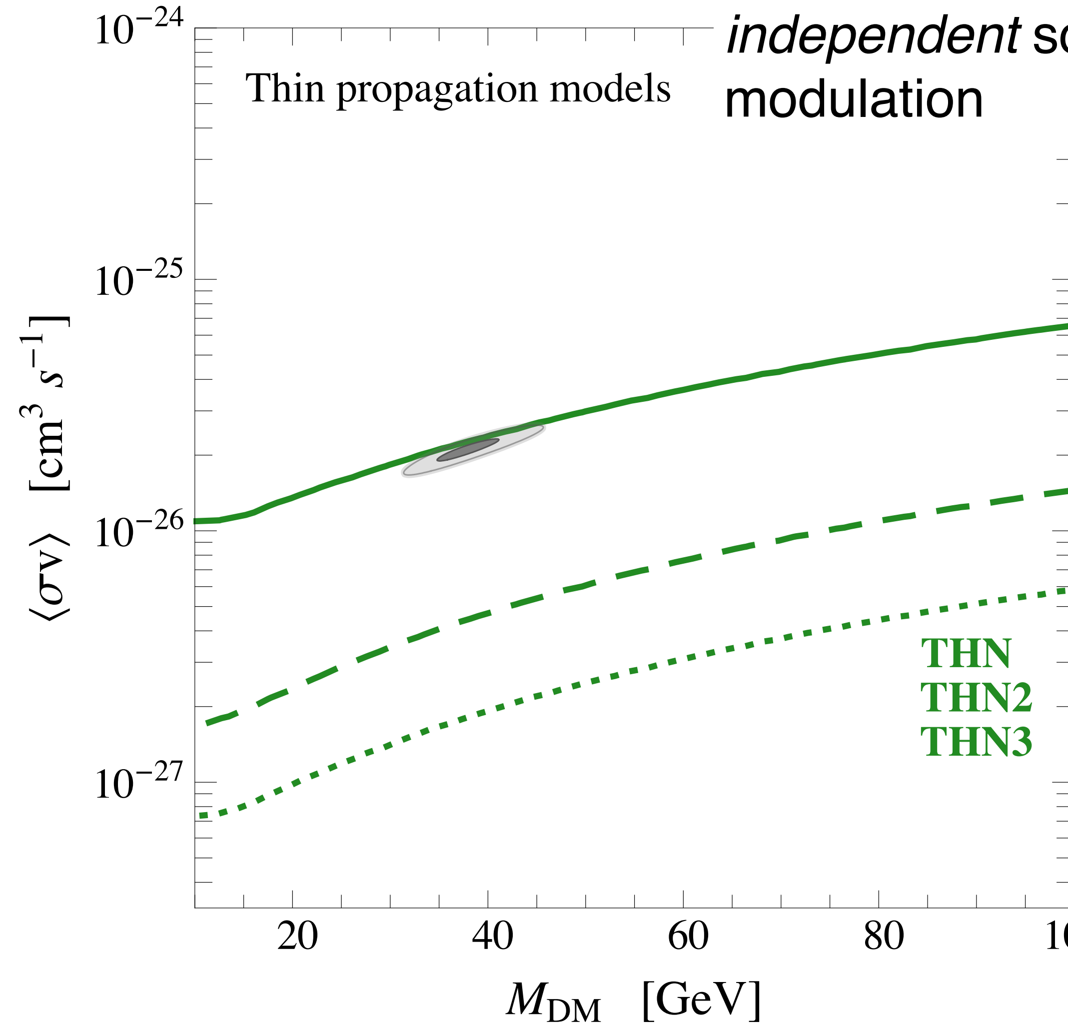


Constraints from other channels — antiprotons

strong tension with antiproton constraints in the case of *charge-independent* solar modulation

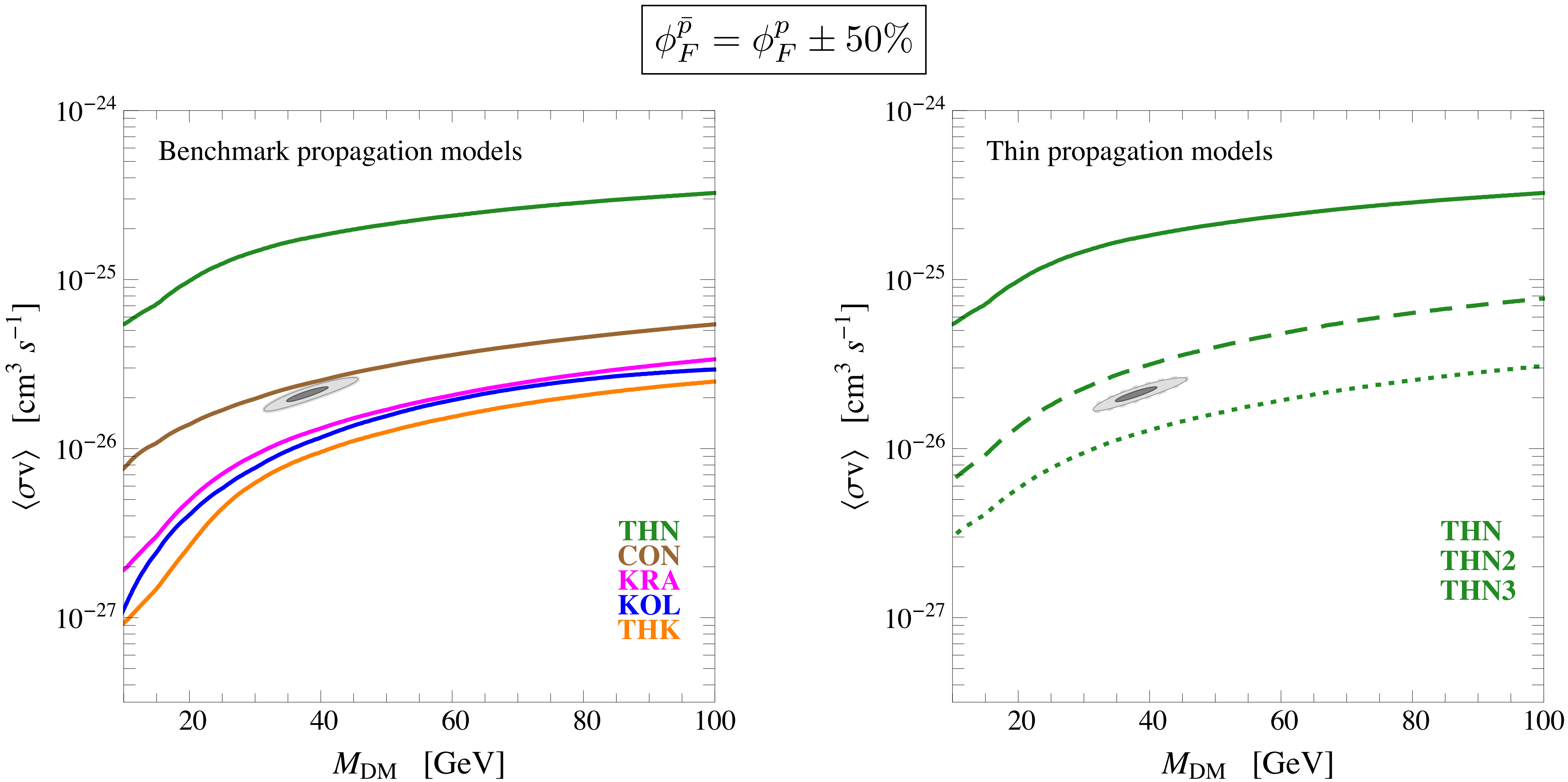
$\phi_F^{\bar{p}} = \phi_F^{p}$ fixed





M. Cirelli, DG, G. Giesen, M. Taoso, A. Urbano, JCAP **12** 2014

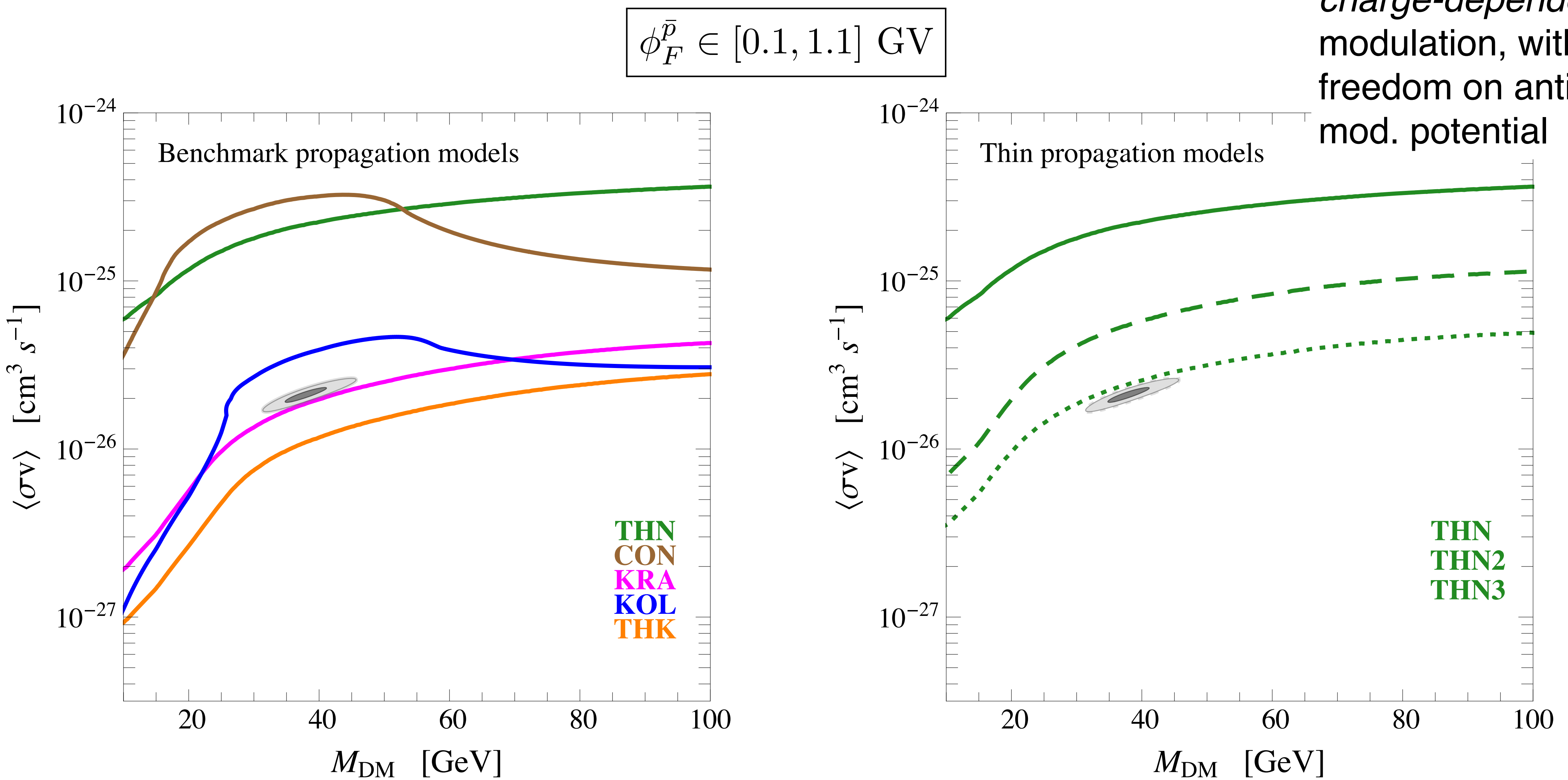
Constraints from other channels — antiprotons



M. Cirelli, DG, G. Giesen, M. Taoso, A. Urbano, JCAP **12** 2014

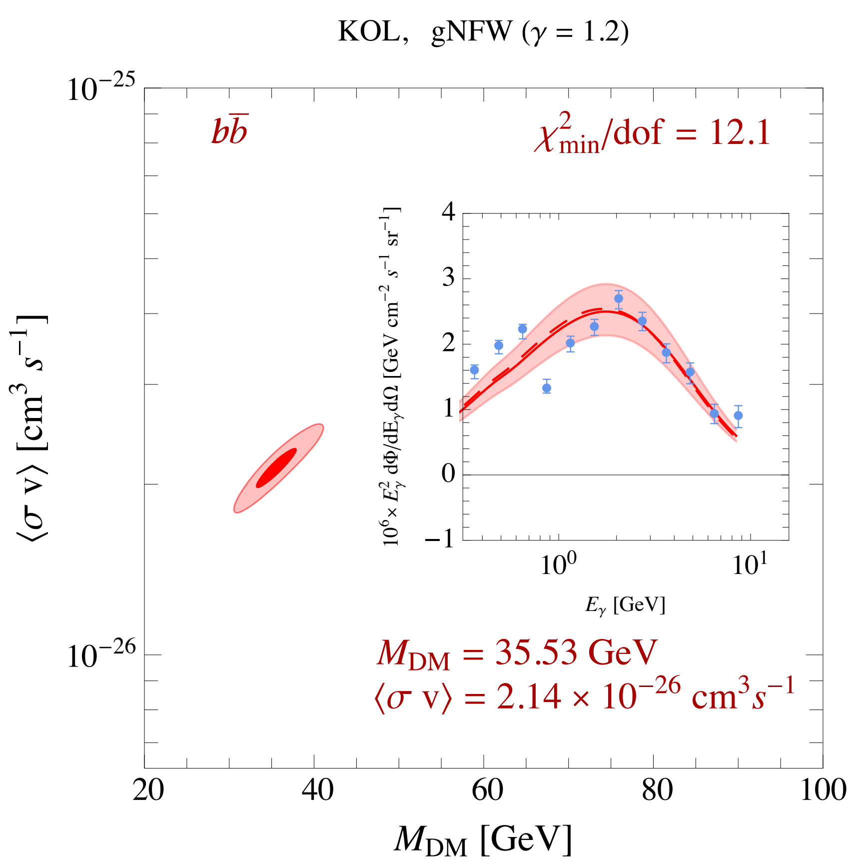
Constraints from other channels — antiprotons

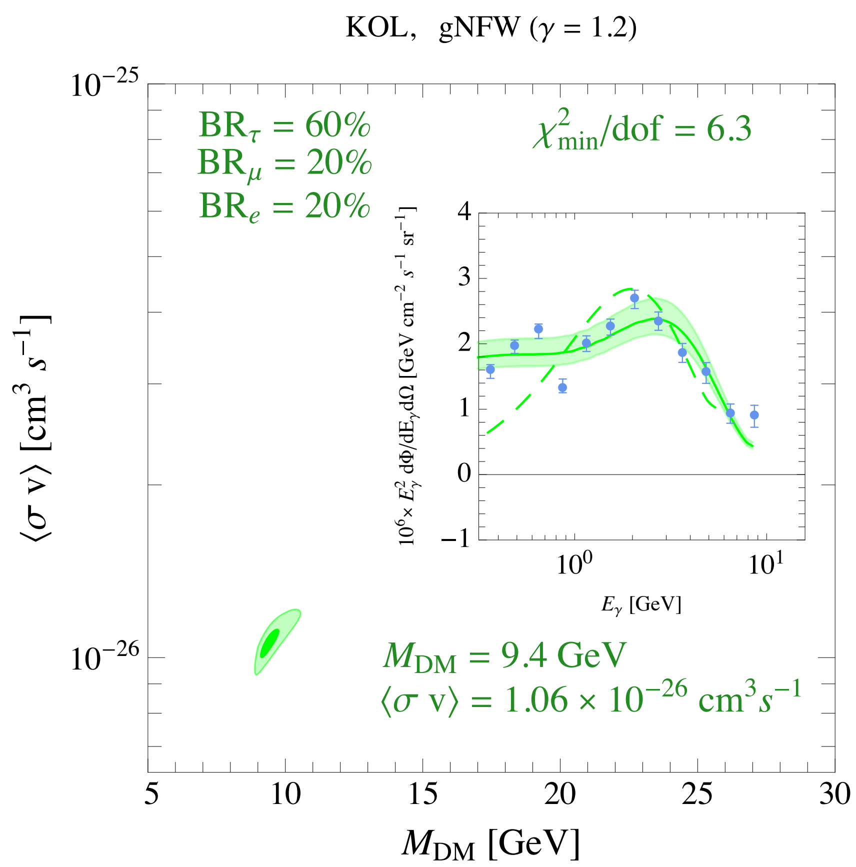
consistent with antiproton constraints in the case of *charge-dependent* solar modulation, with maximal freedom on antiproton mod. potential



M. Cirelli, DG, G. Giesen, M. Taoso, A. Urbano, JCAP **12** 2014

The role of secondaries





M. Cirelli, DG, G. Giesen, M. Taoso, A. Urbano, JCAP **12** 2014

As far as the bb final state is concerned, secondary emissions do not play a significant role.

Considering DM annihilation into leptons, on the contrary, the inclusion of secondary emissions can significantly improve the goodness of the fit

What about millisecond pulsars?

A population of millisecond pulsars can naturally satisfy the requirements on both spectrum and morphology of the GeV excess signal.

A wavelet analysis [*R. Bartels et al. 2015*] based on 7 years of Fermi-LAT data pointed out a clustering of photons compatible with a population of millisecond pulsars, with a statistical significance of 10.0σ.

For plausible values of the luminosity function, this population can explain 100% of the observed excess emission.

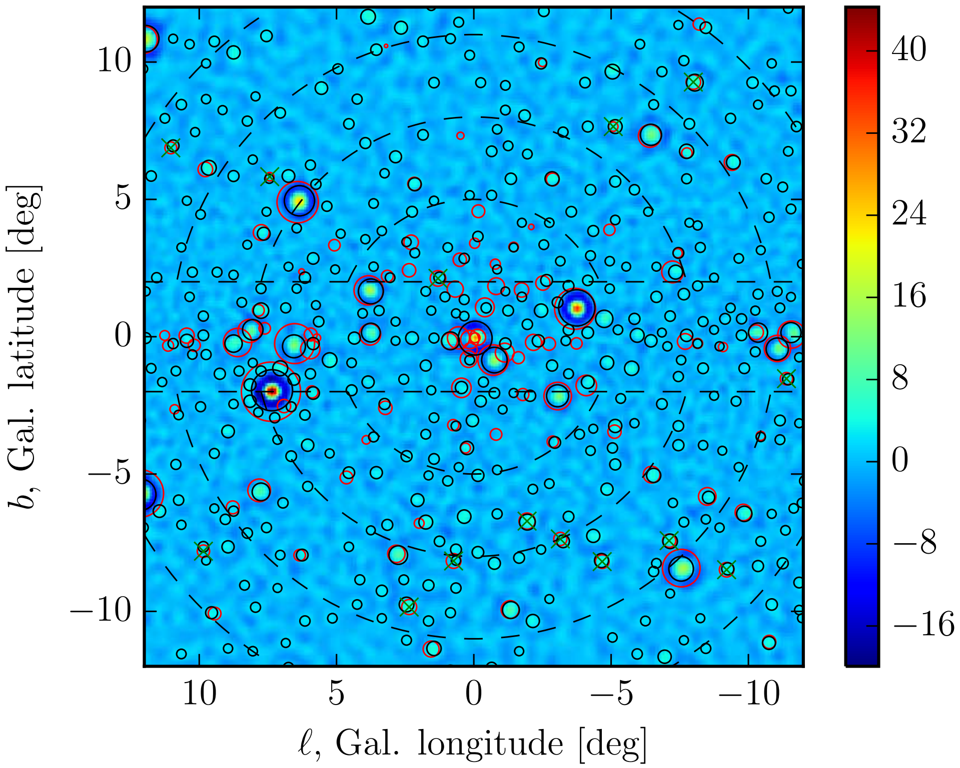
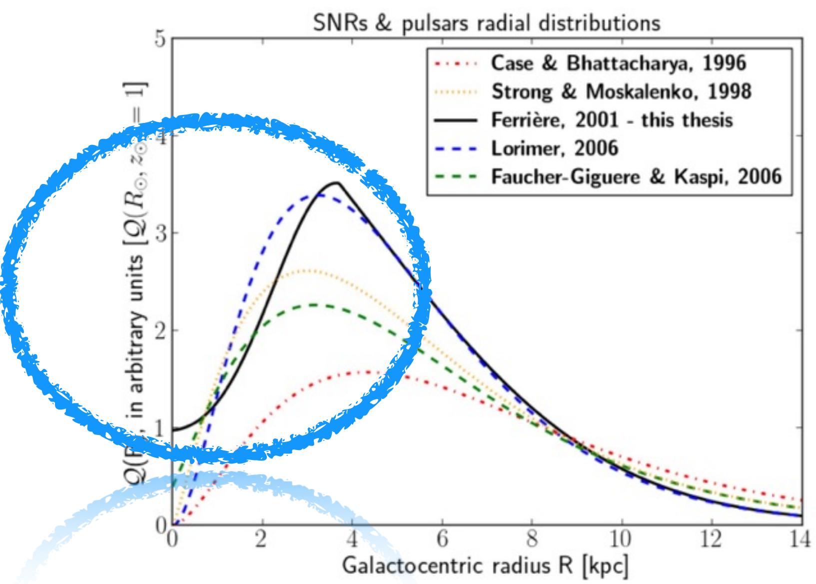


FIG. 1. SNR of the wavelet transform of γ rays with energies in the range 1–4 GeV, $\mathcal{S}(\Omega)$. The black circles show the position of wavelet peaks with $\mathcal{S} \geq 2$; the red circles show the position of third Fermi-LAT catalog (3FGL) sources. In both cases, the circle area scales with the significance of the source detection in that energy range. The dashed lines indicate the regions that we use for the binned likelihood analysis, where latitudes $|b| < 2^\circ$ are excluded because of the strong emission from the Galactic disk. The subset of 3FGL sources that remains unmasked in our analysis is indicated by the green crosses.

R. Bartels, S. Krishnamurthy, C. Weniger, 2015

The role of the astrophysical diffuse background



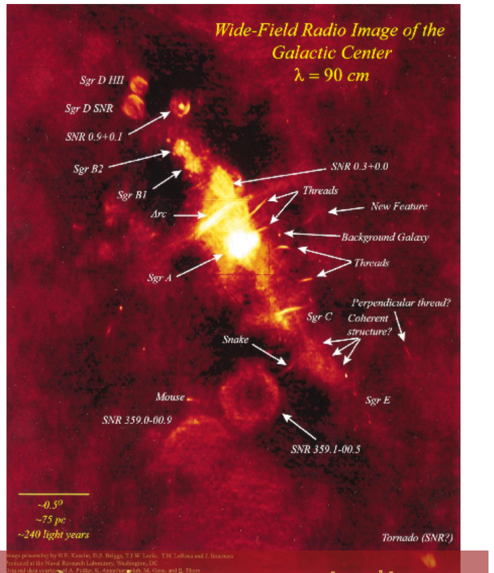
(a) *Radial profile of the distribution functions of the* CRs *sources*

The background models assume no sources in the center… is that reasonable?

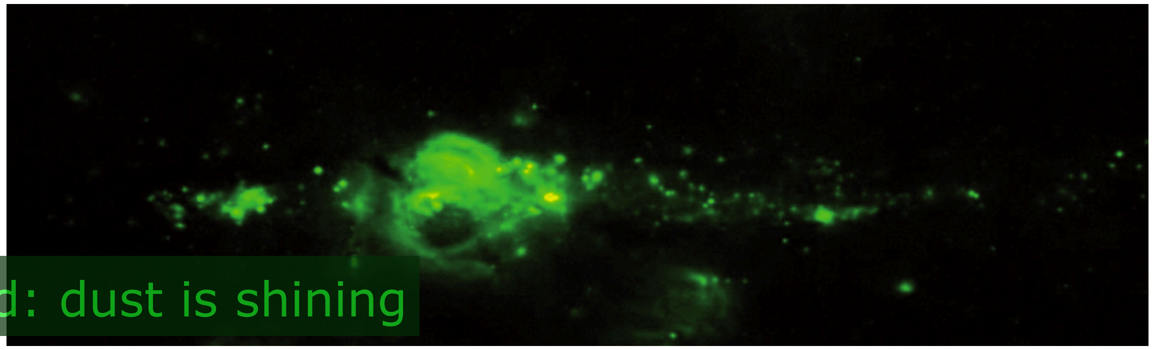
Probably it's not realistic: A very efficient star formation is going on

According to [Figer et al. 2004 ApJ 581 2002] 1% of the total SFR takes place in the inner 2-300 pc

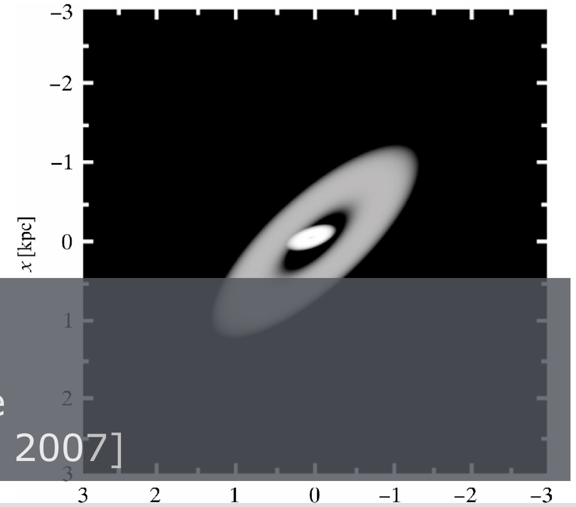
(2 order of magnitude more than the average); see also [Longmore et al. 1208.4256]



Radio (90 cm): electrons spiraling in a higly magnetized environment are shining. Nonthermal filaments, SNRs… [LaRosa et al. ApJ 119 2000]



Infrared: dust is shining

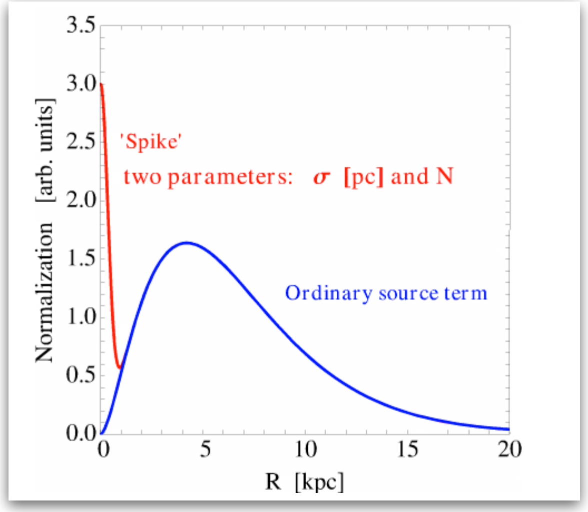


A large reservoir of molecular gas: the Central Molecular Zone [K. Ferrière et al., A&A 2007]

Reabsorbing most of the GC excess

A modified source term in the center, compatible with the astronomical observations, reabsorbs the excess!

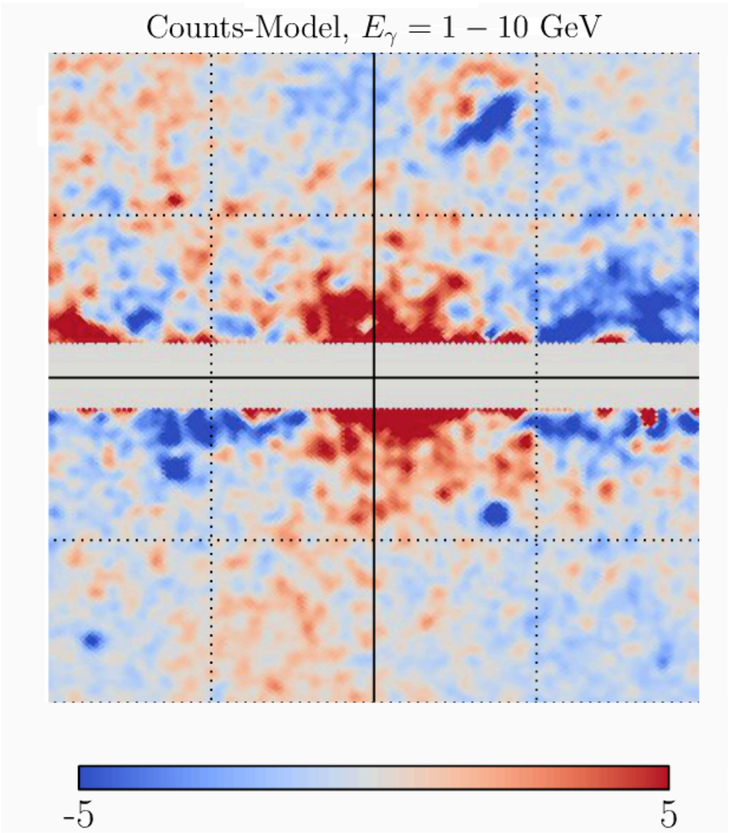
[D. Gaggero et al. 2015]
[E. Carlson and S. Profumo 2016]

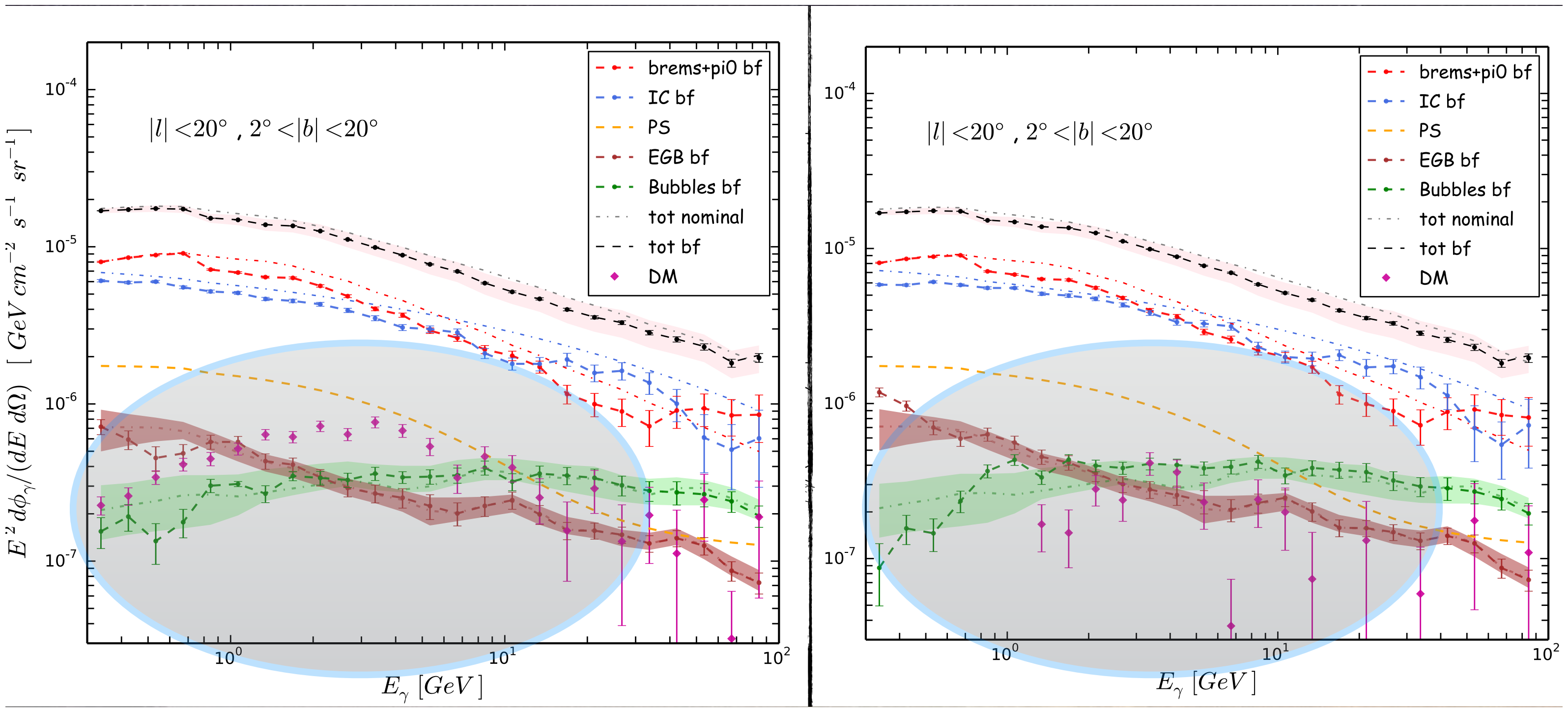


$$Q(x,y,z) = \mathcal{N} \exp\left(-\frac{x^2+y^2+z^2}{\sigma^2}\right)$$

normalization compatibly with star formation rate estimate @ the GC

spike extension roughly matching CMZ one, i.e. O(100) pc





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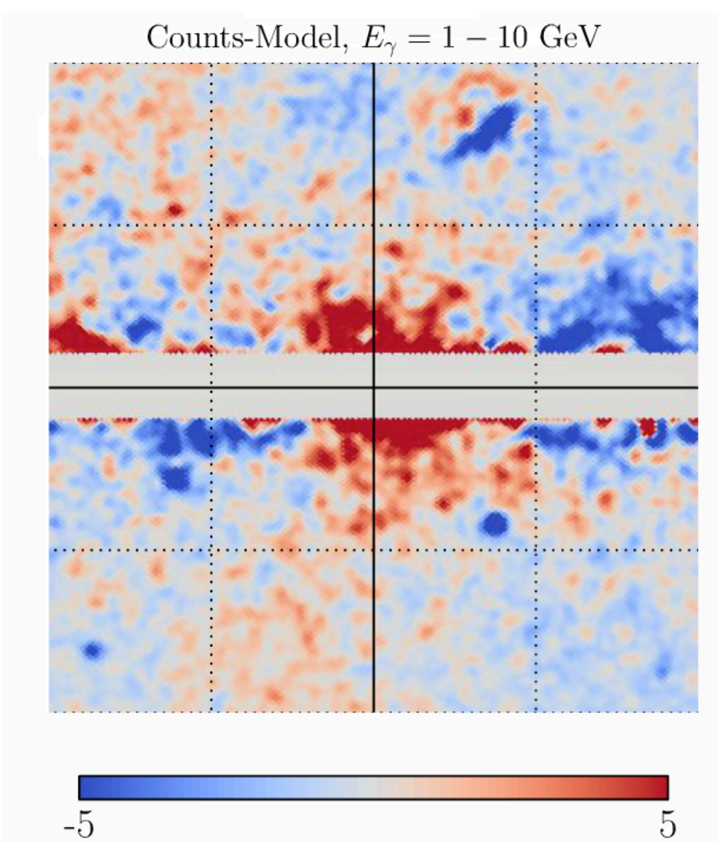

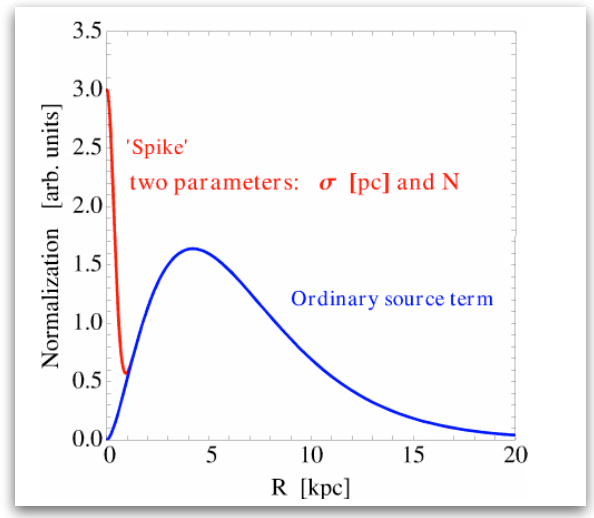

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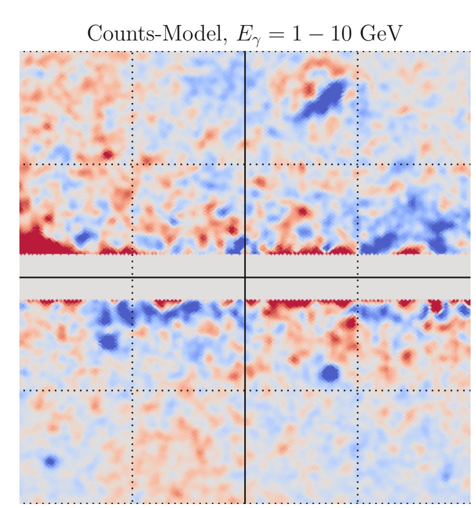
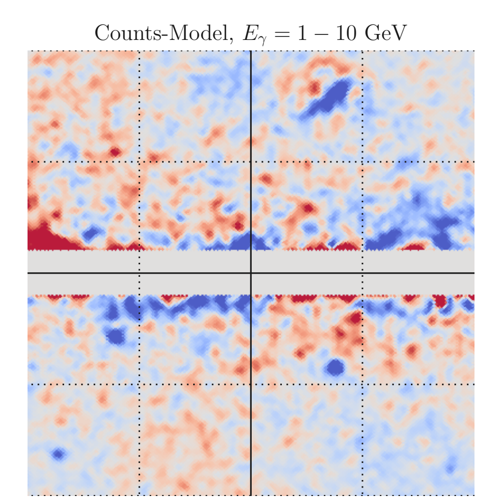
Model+DM



Model+spike

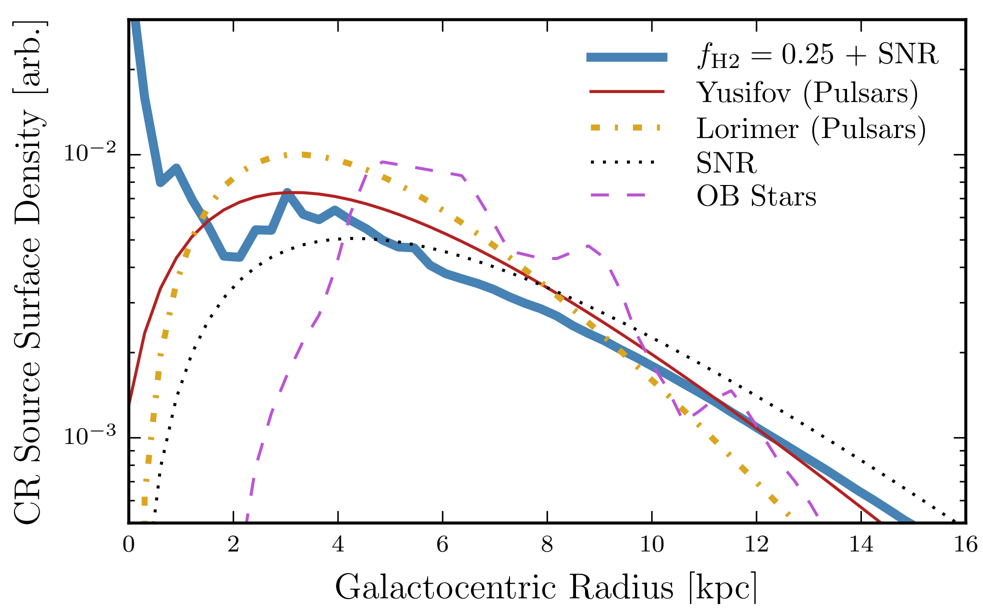


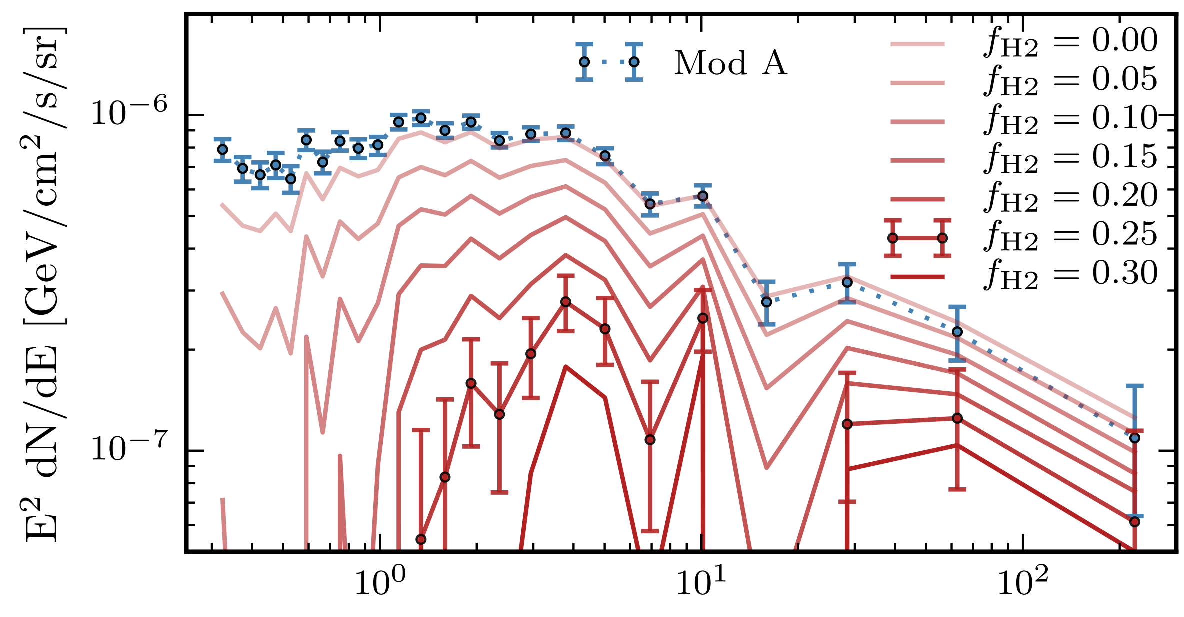
Part 2: The γ-ray inner Galaxy excess

Reabsorbing most of the GC excess

A modified source term in the center, compatible with the astronomical observations, reabsorbs the excess!

[D. Gaggero et al. 2015]
[E. Carlson and S. Profumo 2016]



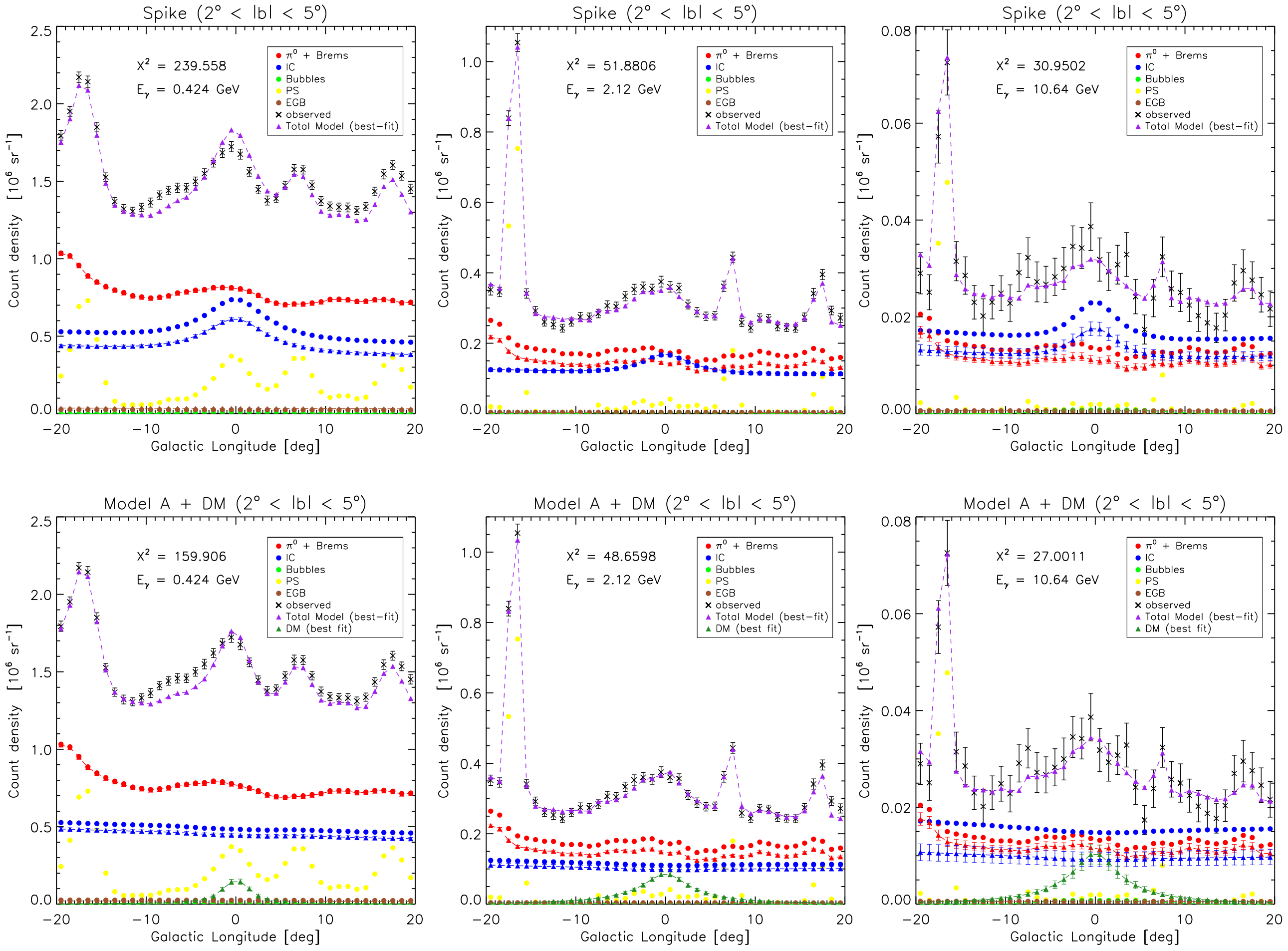


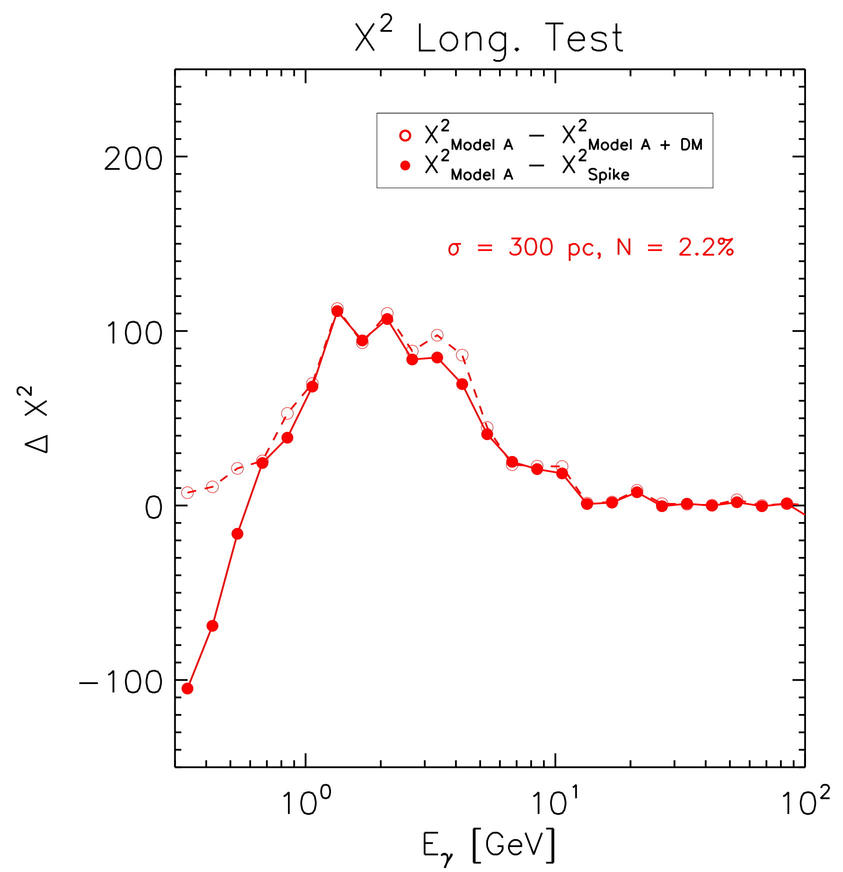
Reabsorbing most of the GC excess

The astrophysical interpretation has problems at low energy

The DM template, applied to the conventional background, with no sources at the center, still provides a better fit

A hybrid scenario may be the solution? enhanced IC background + millisecond pulsar population?





Conclusions

Part 1 — The MeV domain: prospects of detecting a spectral signature of DM annihilation

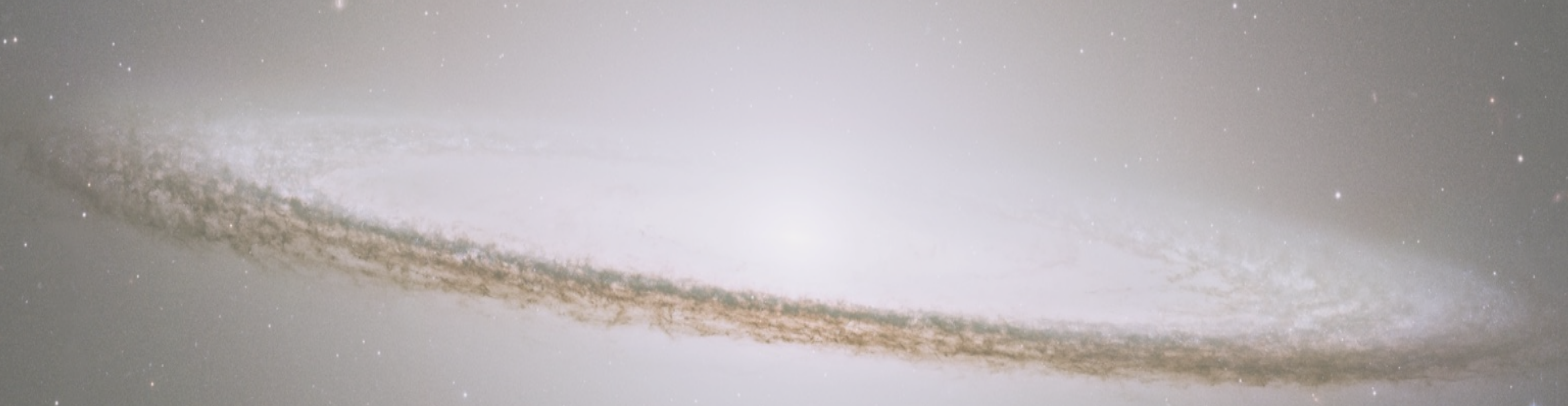
e-ASTROGAM, thanks to its excellent energy resolution in the Compton domain, will have the capability to either detect a spectral signature in the MeV domain connected to DM annihilation, or place stringent upper limits

Part 2 — The GeV domain: discussion about a tentative claim of DM detection at few GeV from the inner Galaxy

Pro DM interpretation: Provides a good fit of the data, compatible with “vanilla” WIMP paradigm

Against DM interpretation: High degeneracy with astrophysical effects. The claim is based on an inadequate IC template.

Thank you for your attention!



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