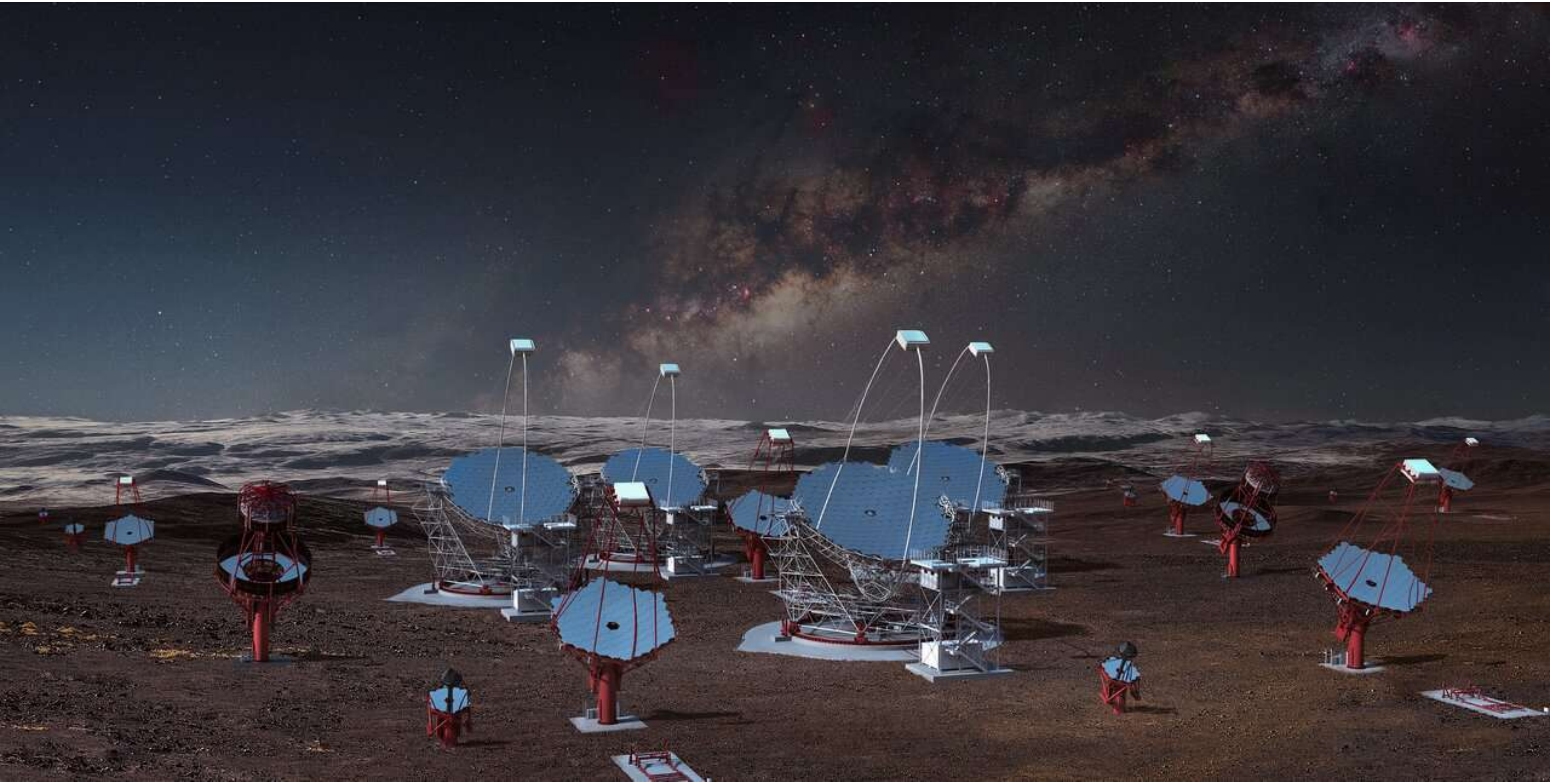


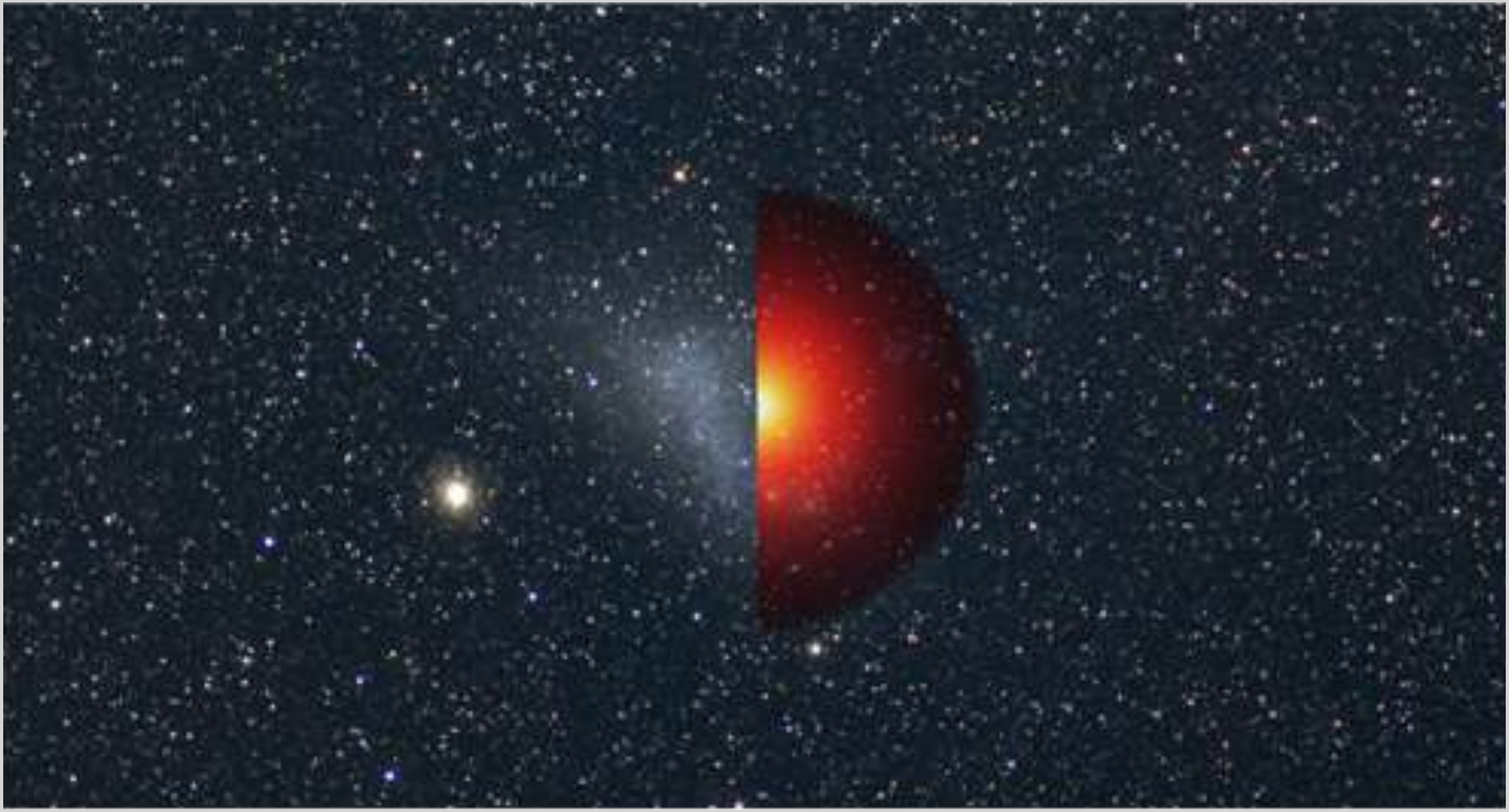
Latin-American School on CTA Science

March 27-31, 2023

São Paulo, Brazil

ICTP-SAIFR/IFT-UNESP

Dark matter - gamma-ray sky and DM searches



Gabrijela Zaharijas

Centre for Astrophysics and Cosmology, University of Nova Gorica

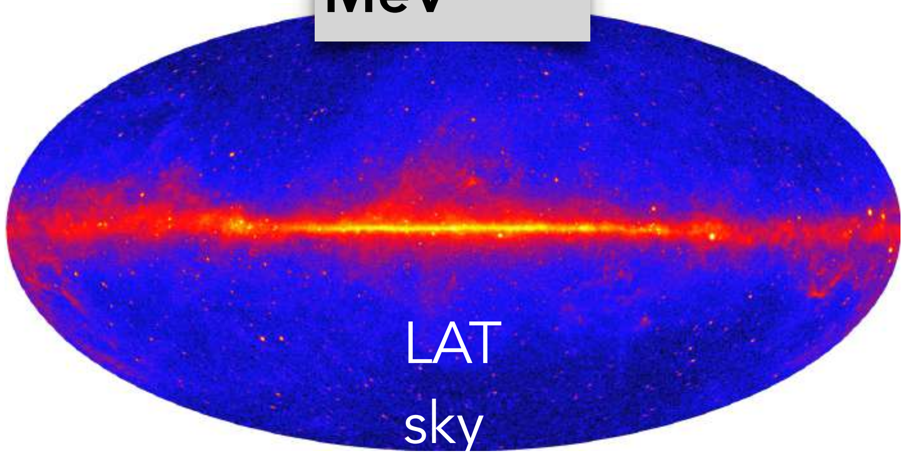
Outline

1. Pre history *a detour*
2. (gravitational) evidence for dark matter
3. DM candidates
4. Experiments
5. Signal & Targets
6. The gamma-ray sky (astro ‘backgrounds’)
7. Data Analysis strategy
8. Examples of search in particular targets (WIMPs)
   - Galactic center
   - dSphs
   - Galaxy clusters

Today

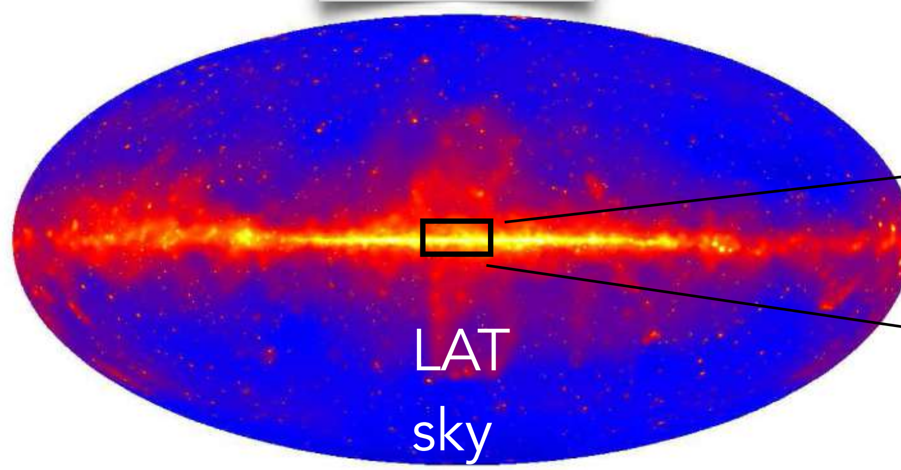
The gamma ray sky

>300 MeV



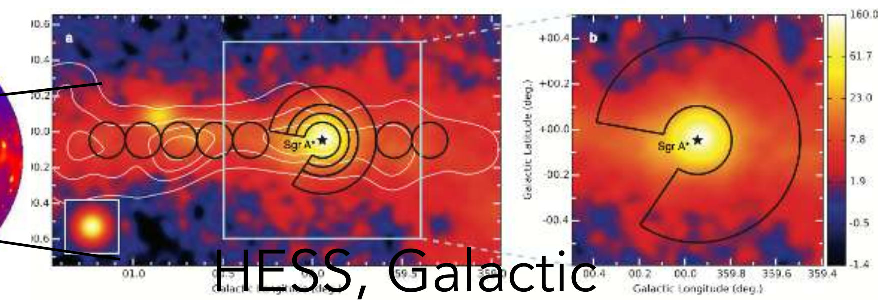
LAT sky

>10 GeV



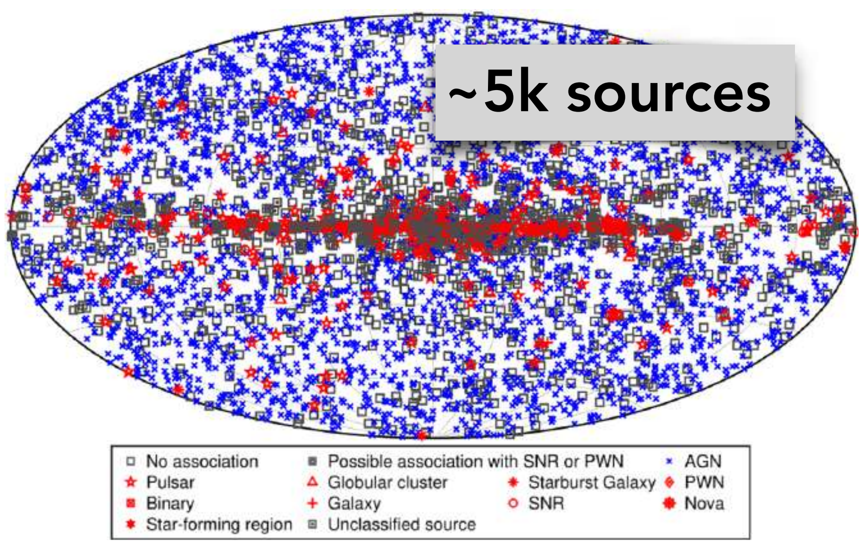
LAT sky

>~100 GeV



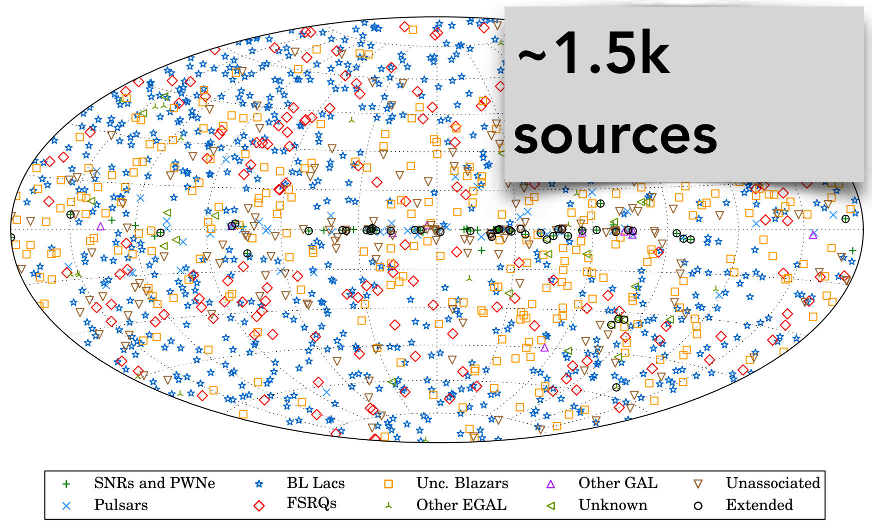
HESS, Galactic center Ridge

~5k sources



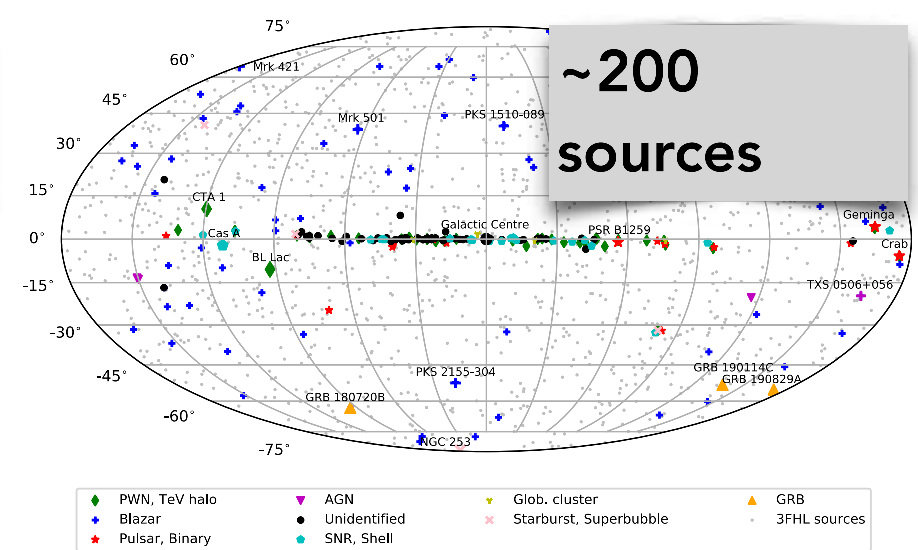
LAT source catalogue, >300 MeV (4FGL)

~1.5k sources



LAT source catalogue, **>10 GeV** (3FHL)

~200 sources

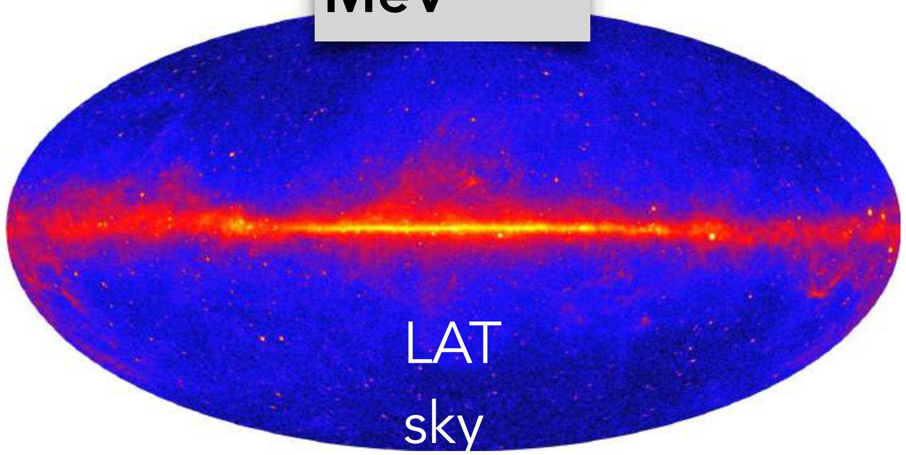


TeVCat, 2019

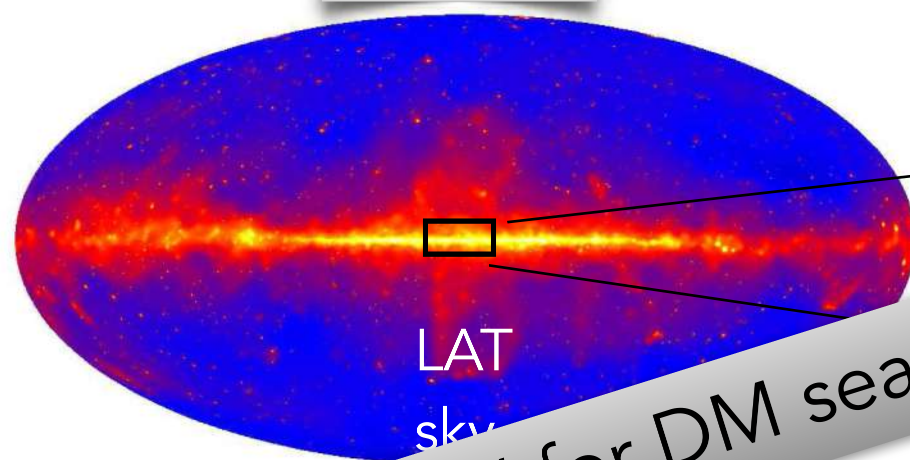
+ o(10-20) PeV sources by LHAASO!

The gamma ray sky

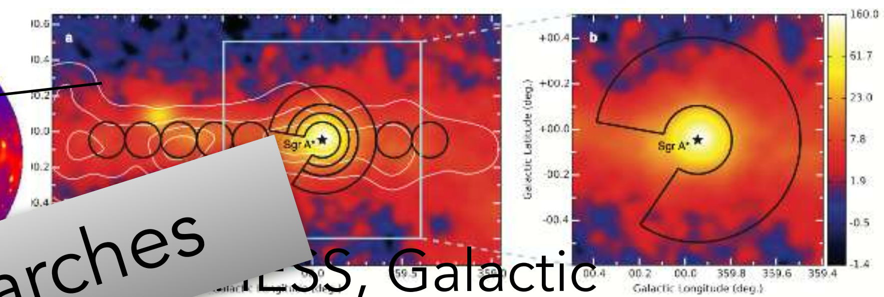
>300 MeV



>10 GeV



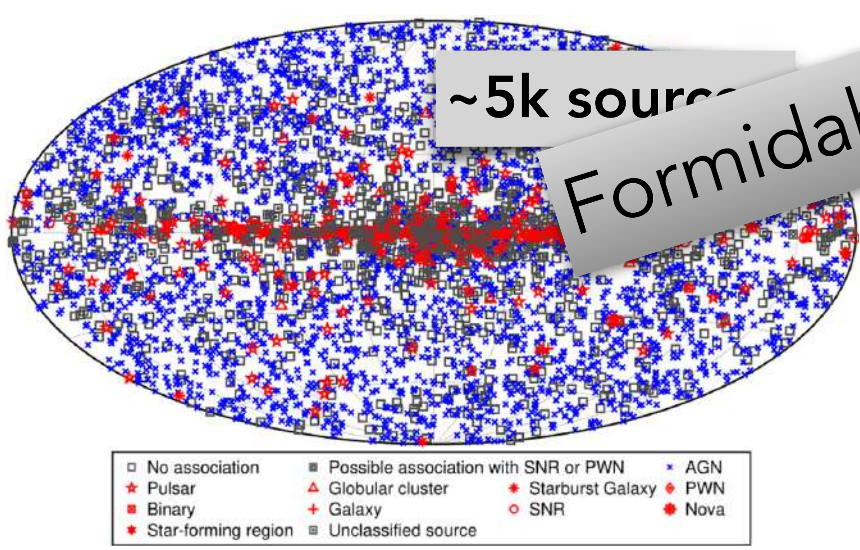
>~100 GeV



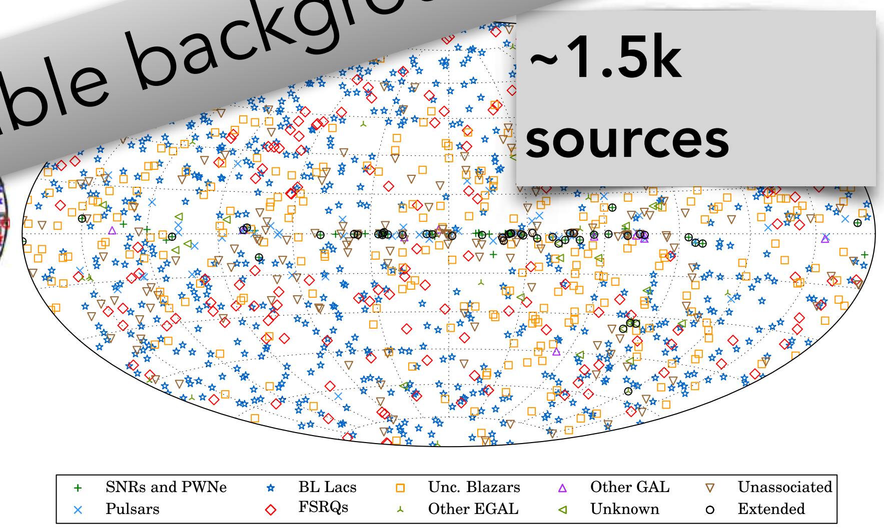
HESS, Galactic center Ridge

Formidable background for DM searches

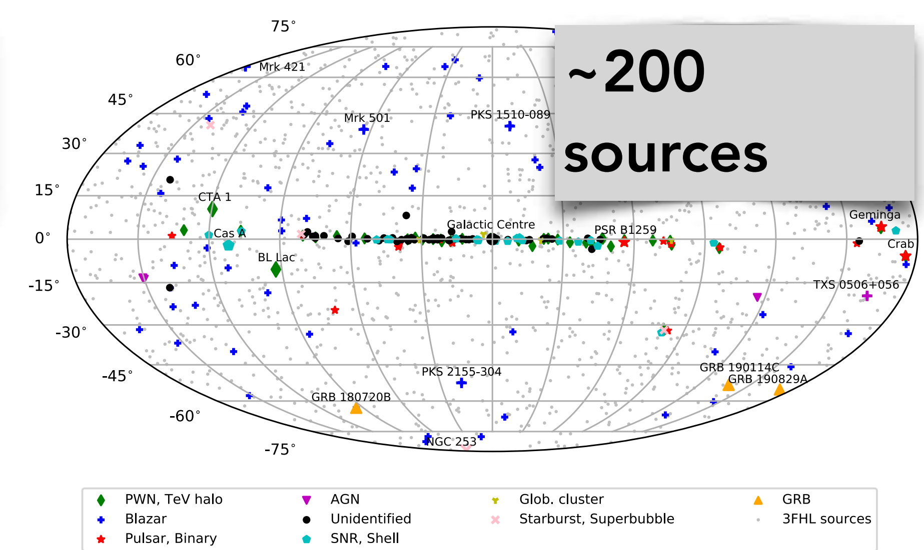
~5k sources



~1.5k sources



~200 sources



LAT source catalogue, >300 MeV (4FGL)

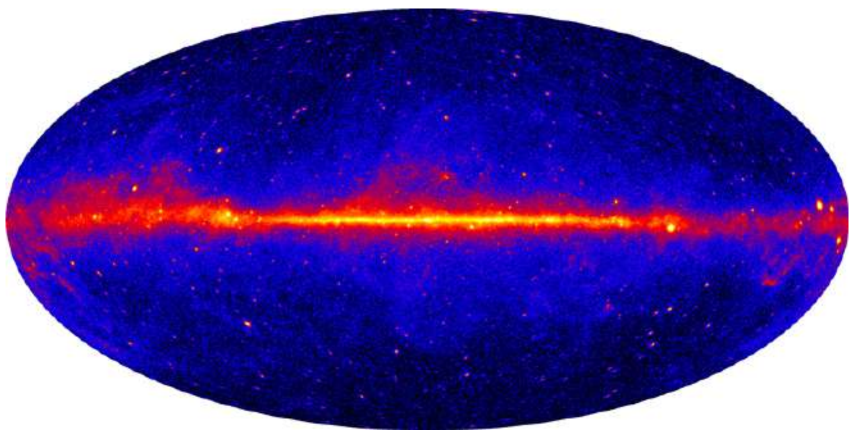
LAT source catalogue, **>10 GeV** (3FHL)

TeVCat, 2019

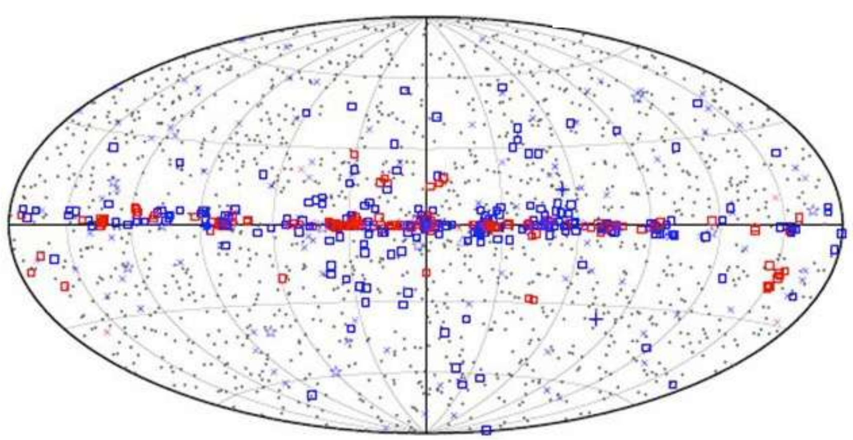
+12 PeV sources by LHAASO!

The Fermi (GeV) sky

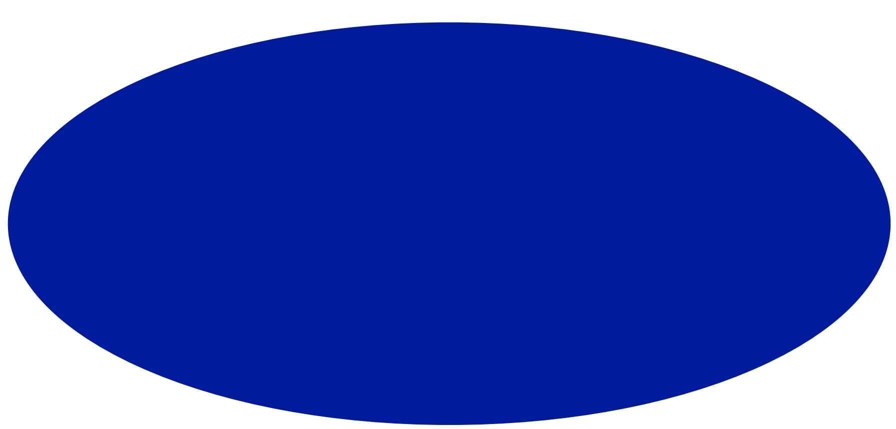
Diffuse emission from our Galaxy



Point sources

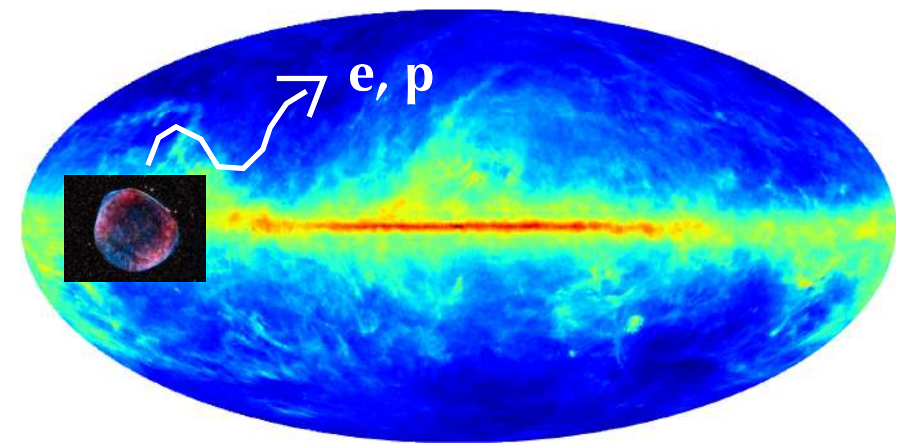


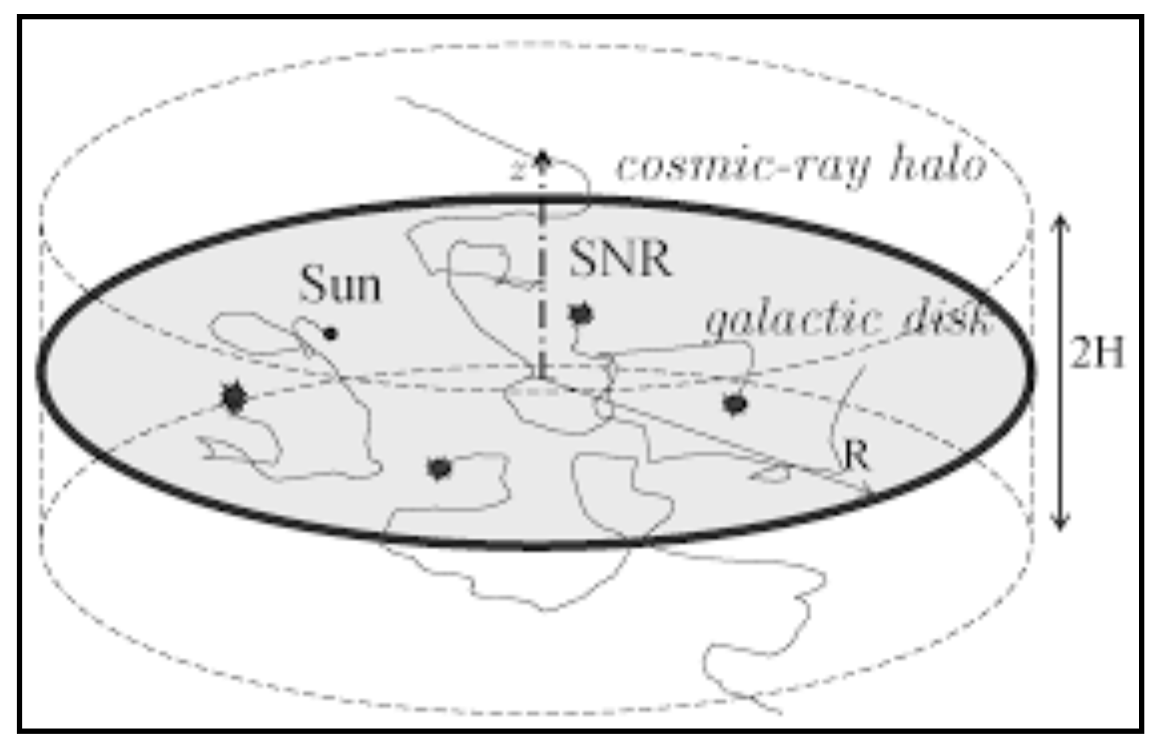
Isotropic emission



90% of the LAT photons!

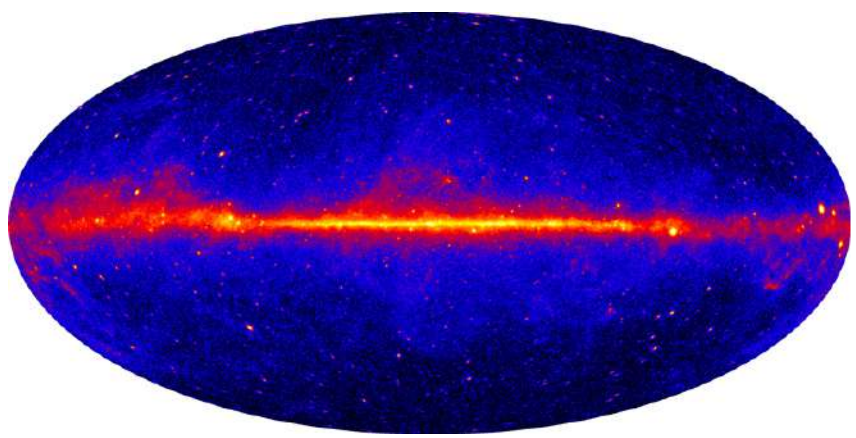
1) ***interstellar emission: cosmic rays*** **trapped in the Galactic magnetic field interact with interstellar medium - *'illuminate' it in gamma rays***



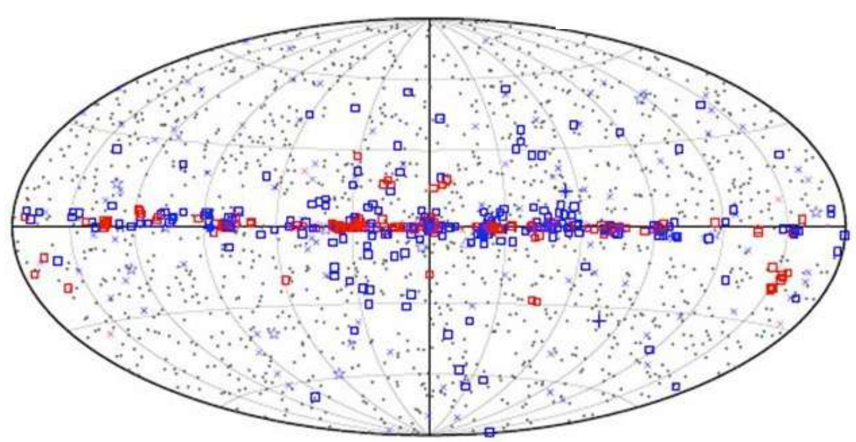


The Fermi (GeV) sky

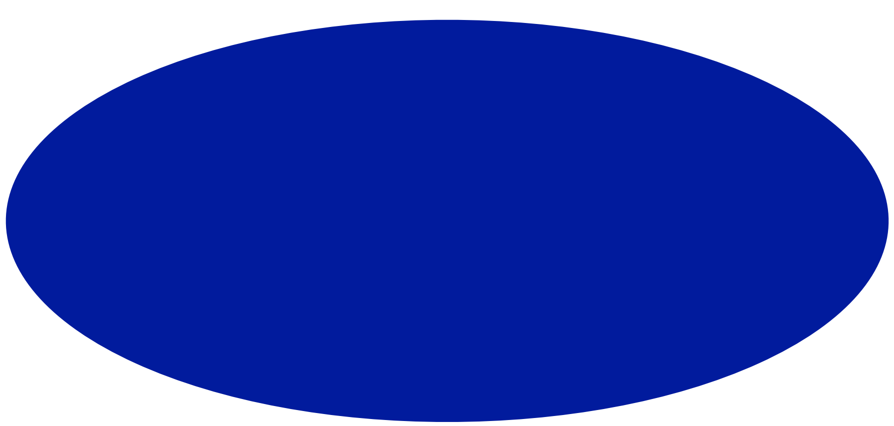
Diffuse emission from our Galaxy



Point sources



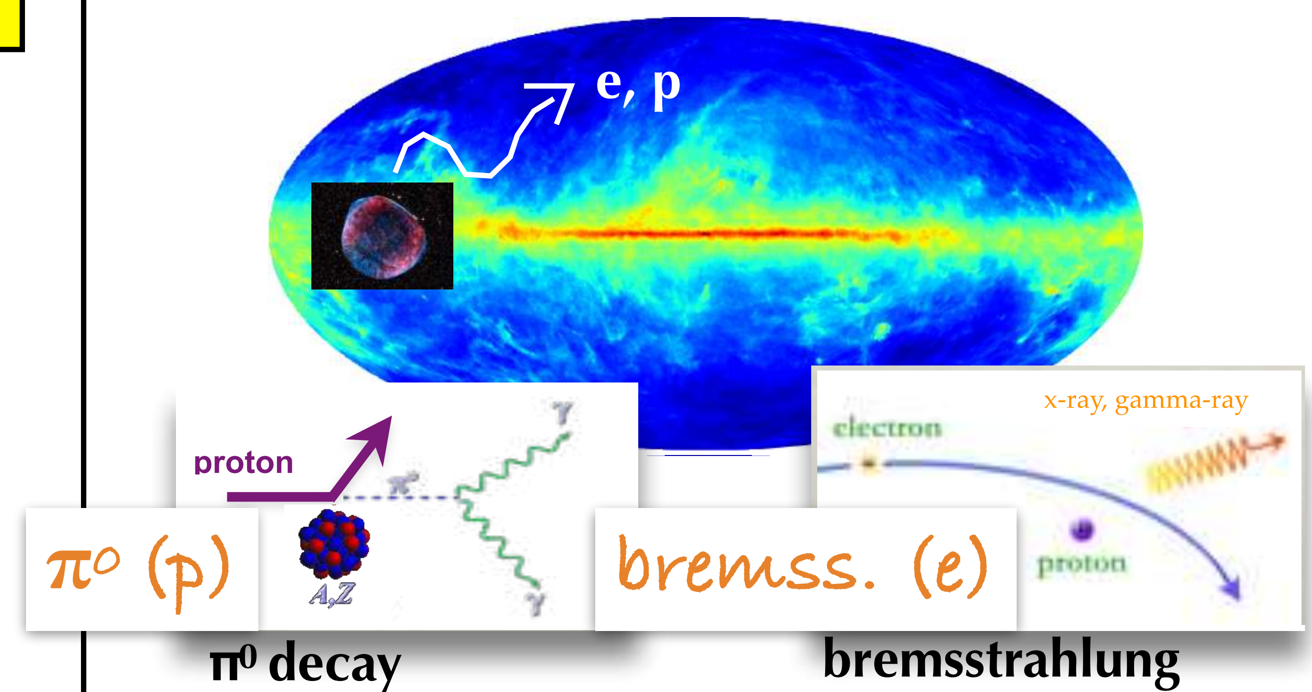
Isotropic emission

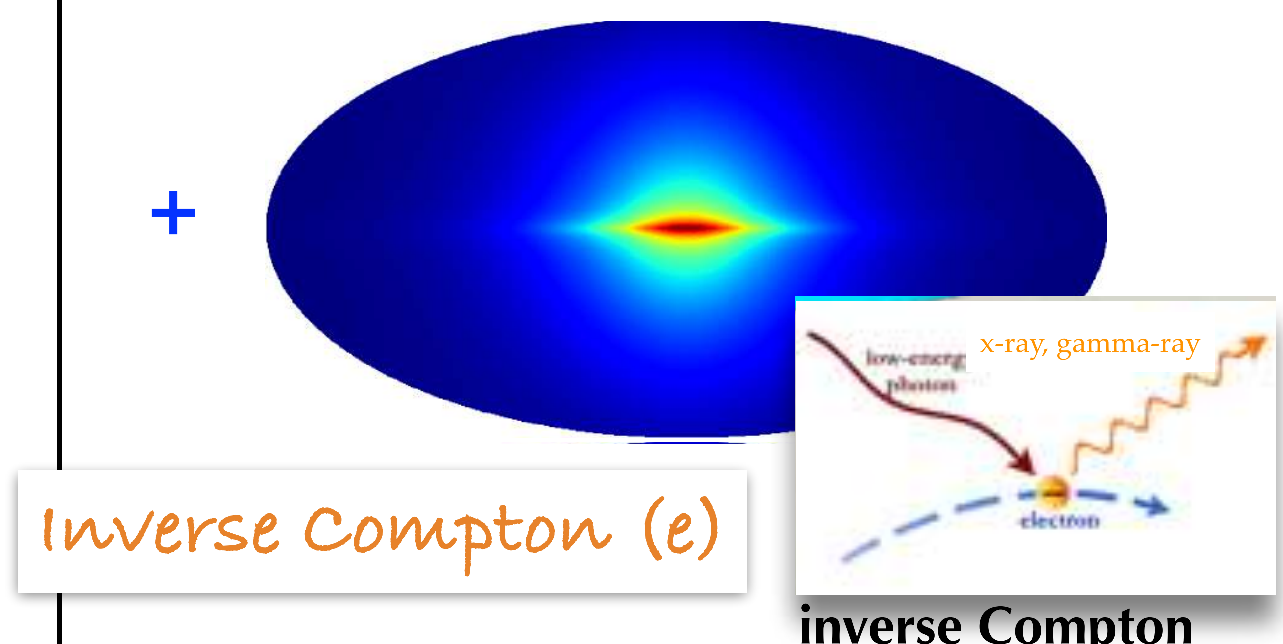


90% of the LAT photons!

1) **cosmic rays**+**interstellar medium**

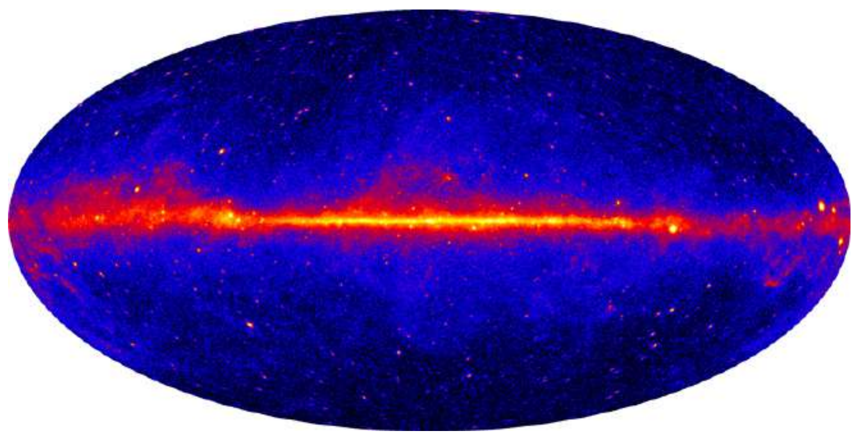
Processes:





The Fermi (GeV) sky

Diffuse emission from our Galaxy



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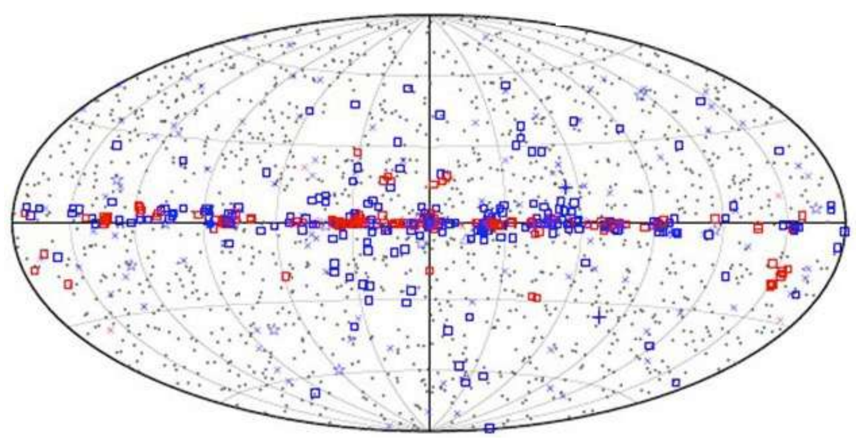
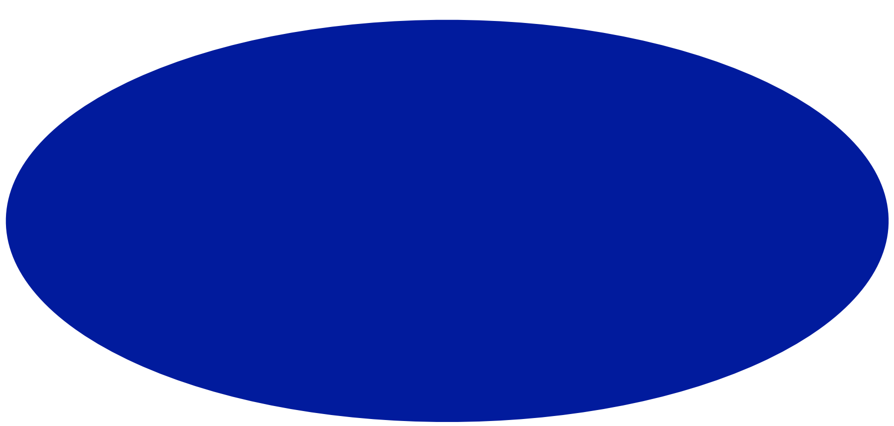


Isotropic emission



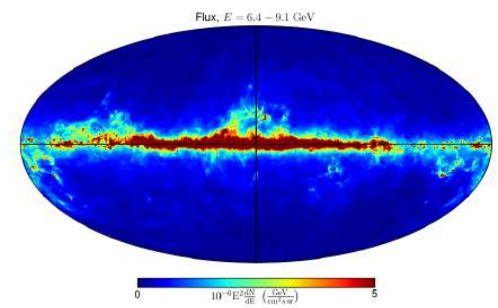
90% of the LAT photons!

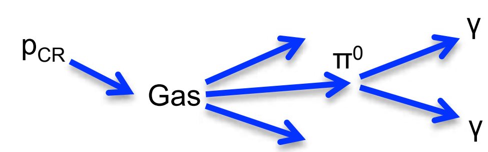
cosmic rays+interstellar medium

— Note: pion and bremsstrahlung emission follow gas distribution

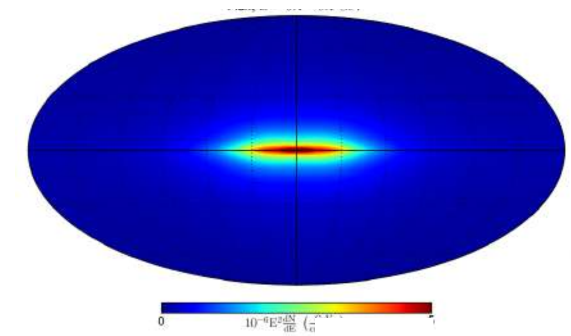
— IC is distributed as interstellar radiation field

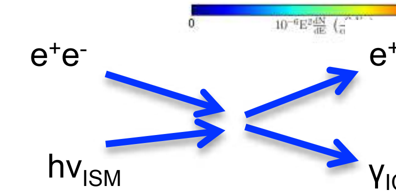
π^0 and bremsstrahlung

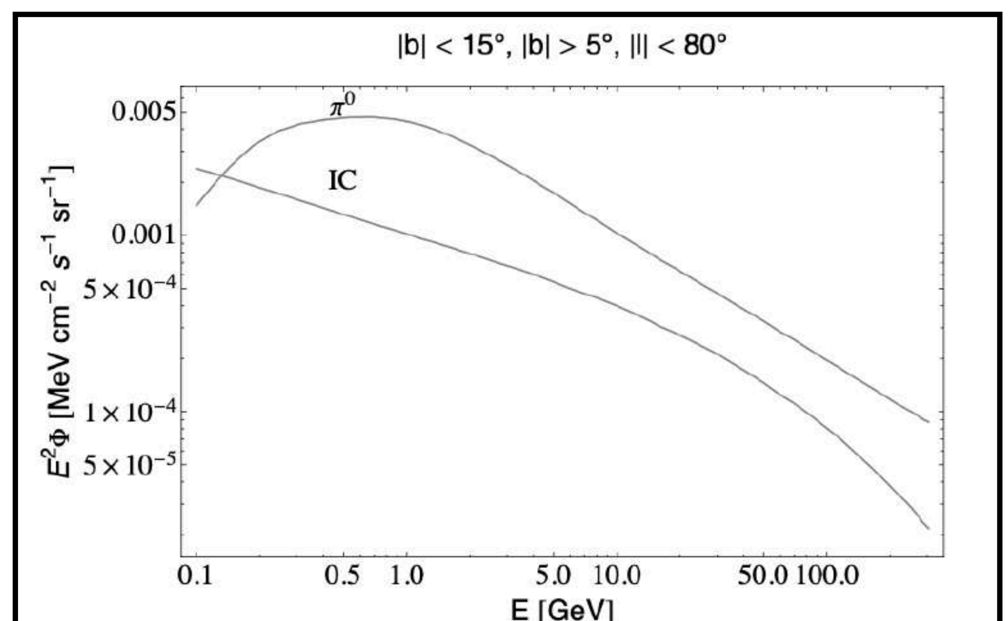




Inverse Compton

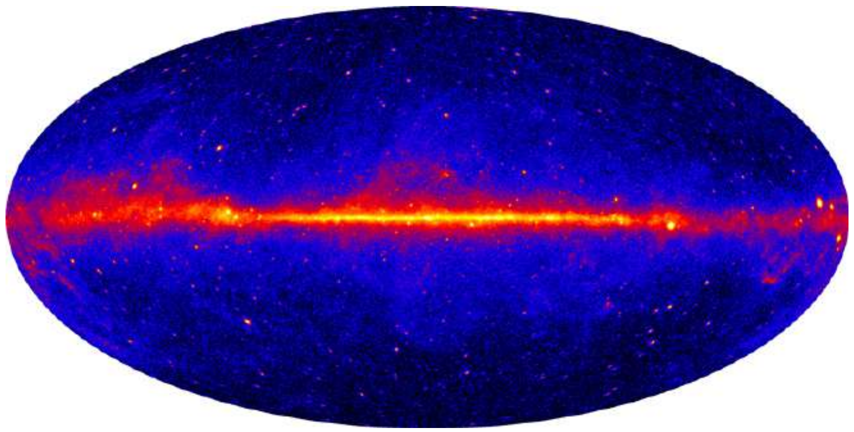




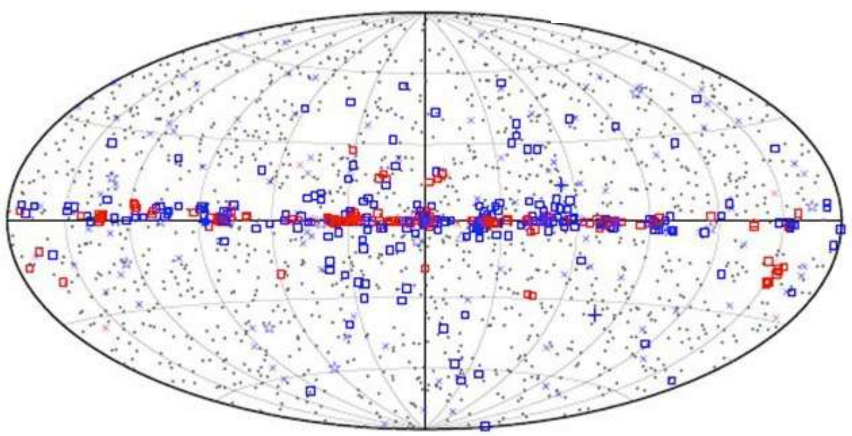


The Fermi (GeV) sky

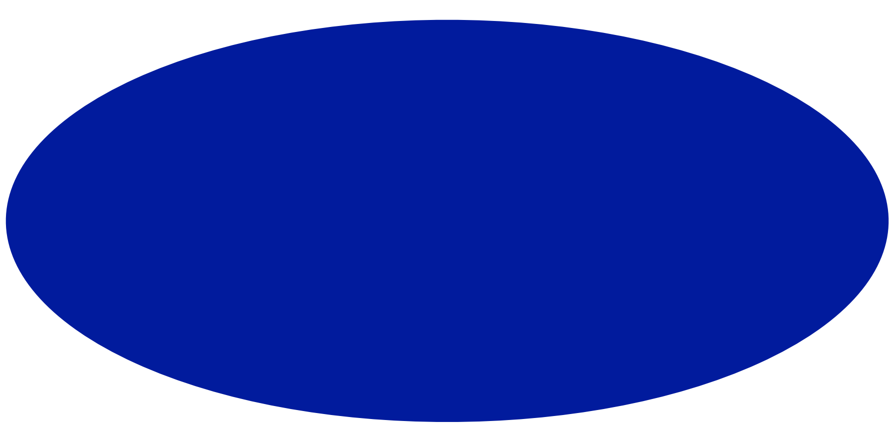
Diffuse emission from our Galaxy



Point sources



Isotropic emission



90% of the LAT photons!

Gamma ray emission described by the *Diffusion Equation*

→Challenges: need to know

— **CR source distribution** from tracers

— **gas density** from atomic transition lines - 3D reconstructions needed

— **Interstellar radiation field** (starlight) for IC

— **Galactic magnetic fields**…

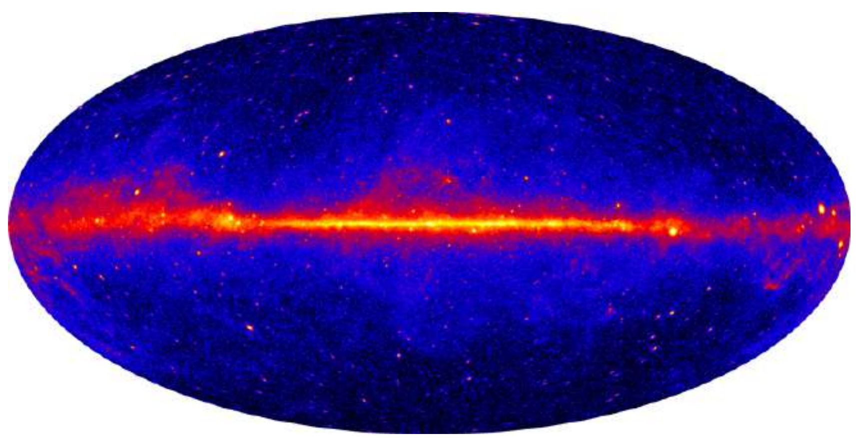
$$
\begin{aligned}
\frac{\partial \psi(\vec{r},p,t)}{\partial t} &= q(\vec{r},p) && \text{sources (SNR, nuclear reactions...)} \\
\text{diffusion} \quad &+ \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi] && \text{convection} \\
\text{diffusive reacceleration} \quad &+ \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right] && \\
\text{E-loss} \quad &- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\,\vec{\nabla}\cdot\vec{V}\psi\right] && \text{convection} \\
\text{fragmentation} \quad &- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d} && \text{radioactive decay}
\end{aligned}
$$

$\psi(\mathbf{r},p,t)$ – *density per total momentum*

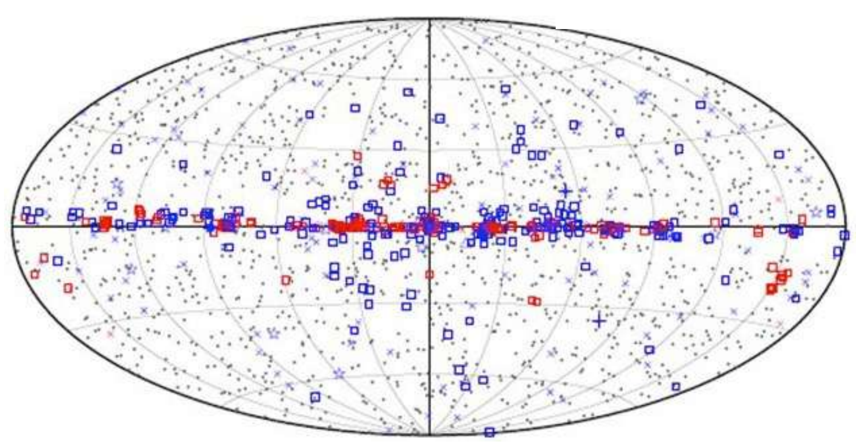
Sophisticated numerical solvers: GALPROP, DRAGON.

The Fermi (GeV) sky

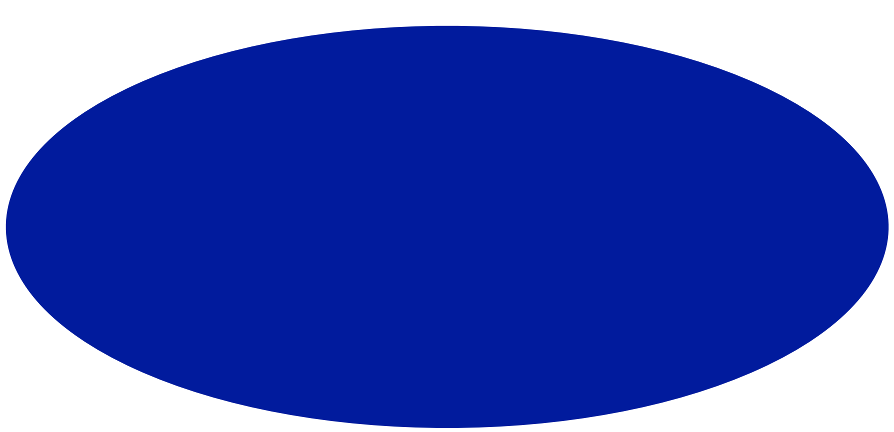
Diffuse emission from our Galaxy



Point sources



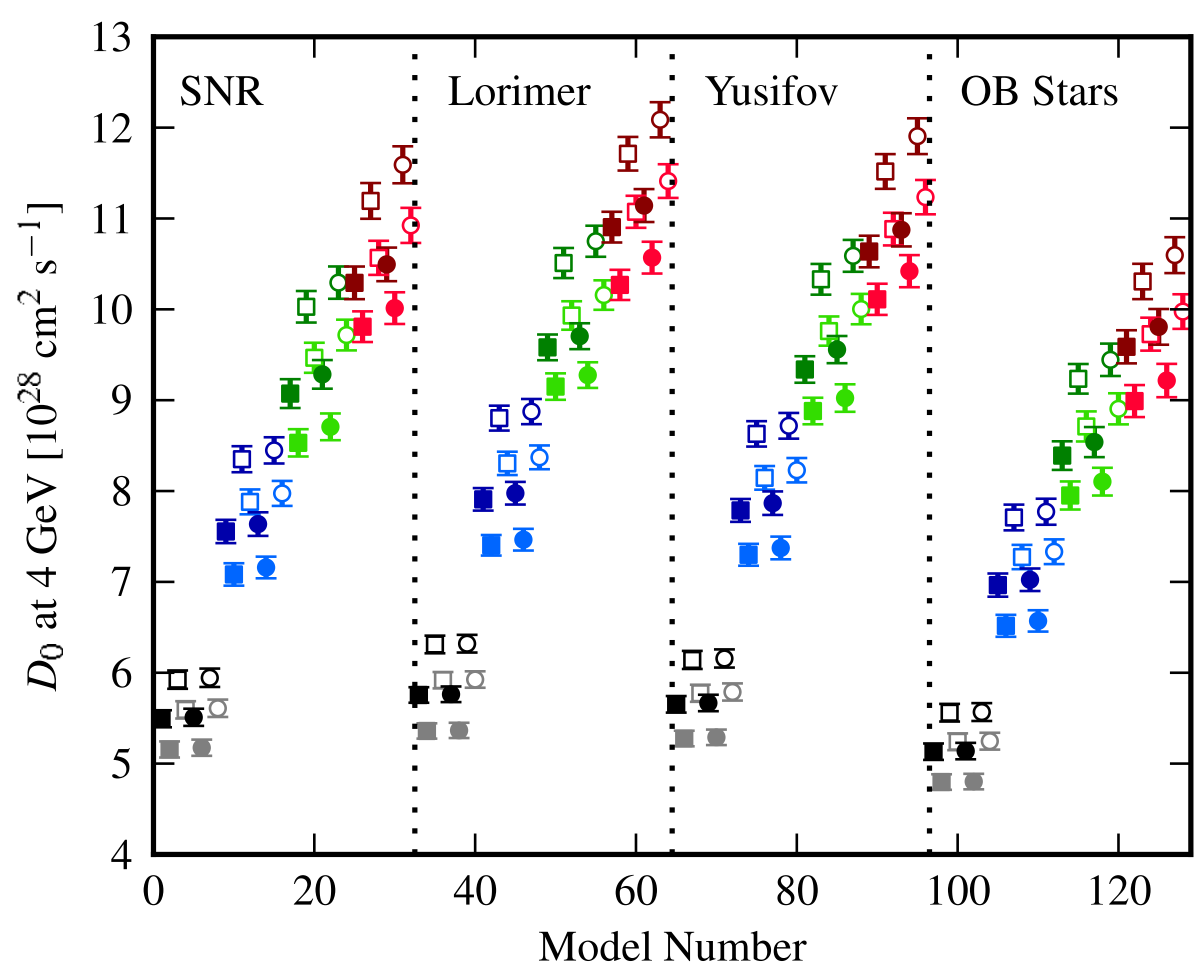
Isotropic emission



90% of the LAT photons!

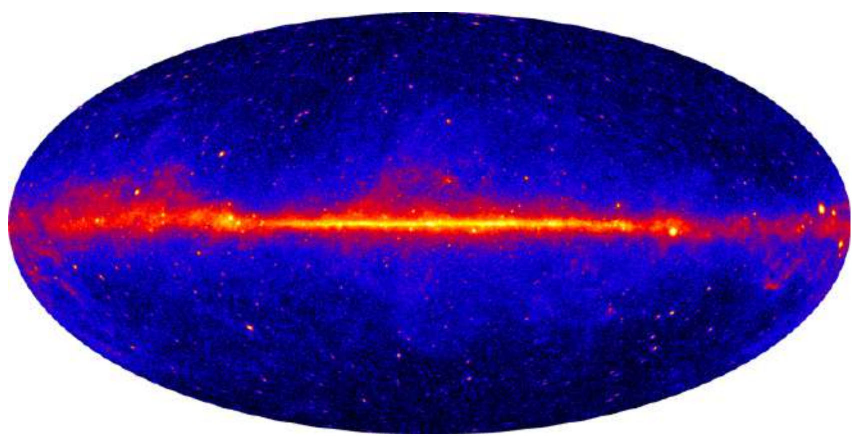
cosmic rays+interstellar medium

— can be used (together with direct CR measurement) to understand 2D properties of CRs and interstellar medium in the Galaxy

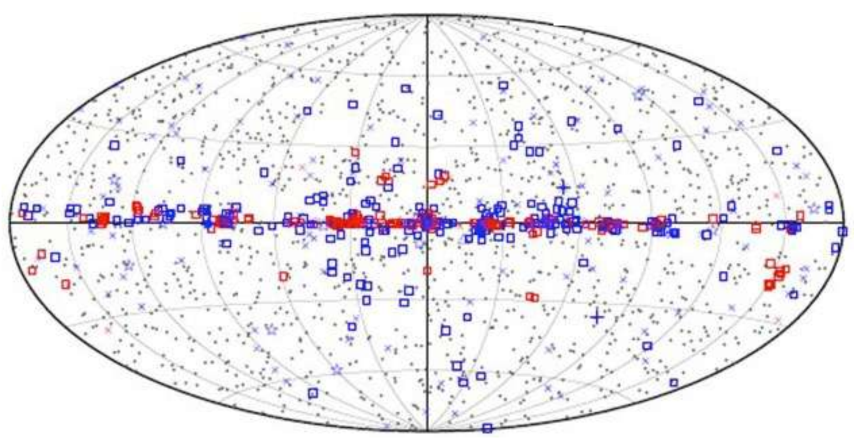


The Fermi (GeV) sky

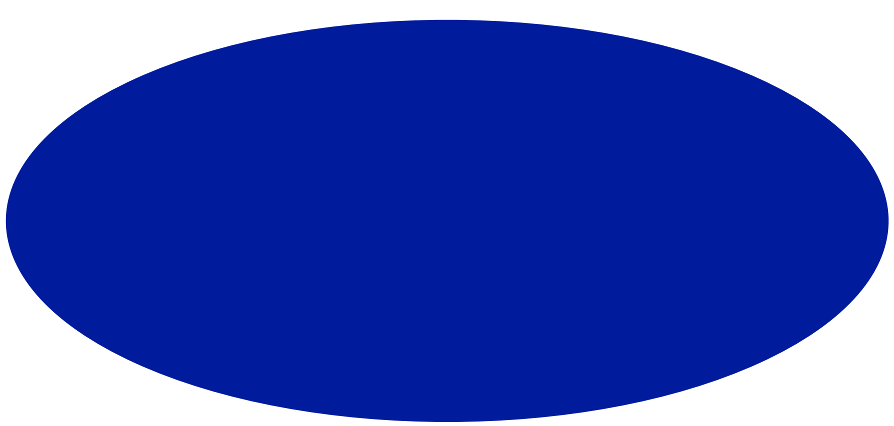
Diffuse emission from our Galaxy



Point sources

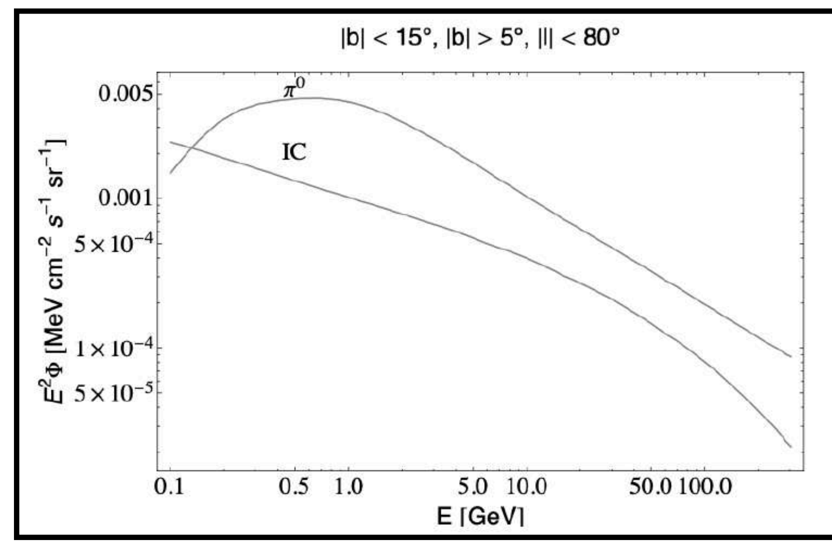


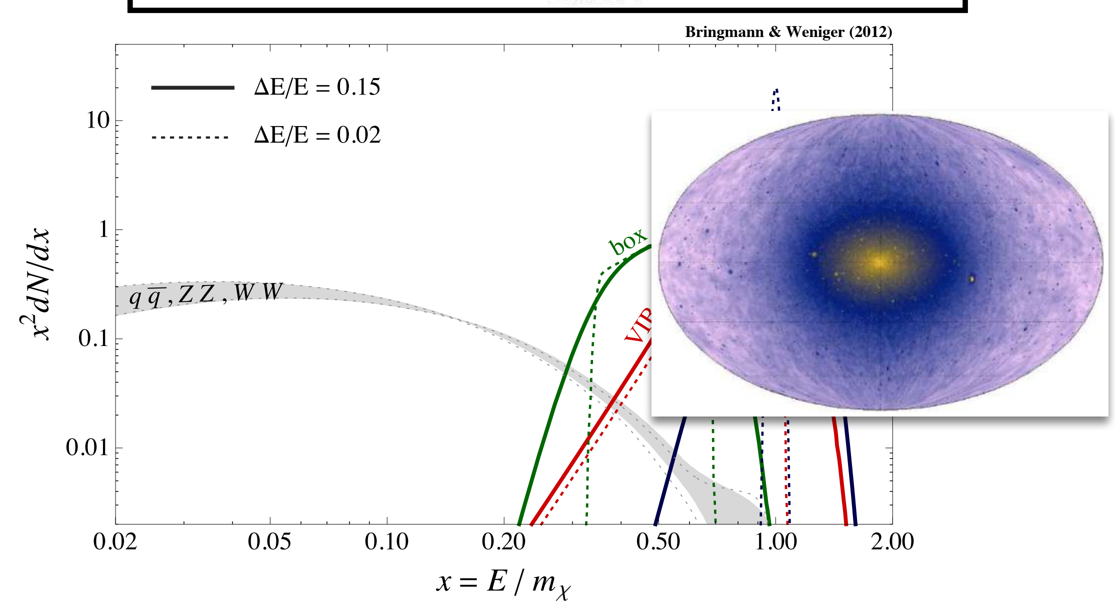
Isotropic emission



90% of the LAT photons!

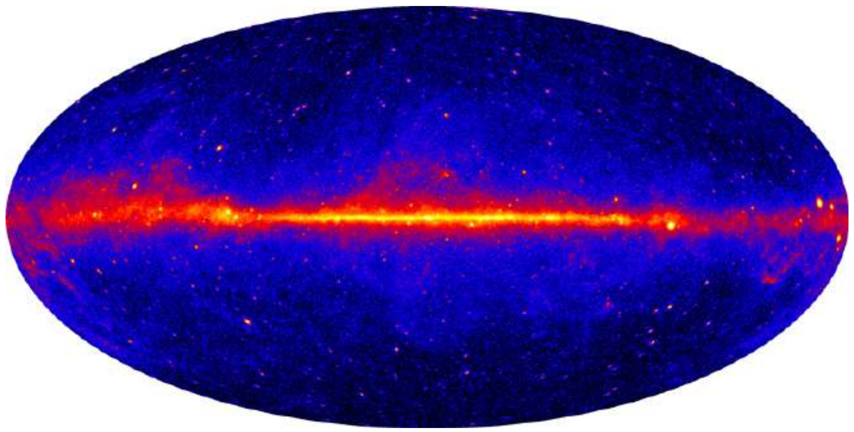
Why important (for DM search):
DM signal often extended and therefore hard to distinguish from extended interstellar emission (know thy enemy)



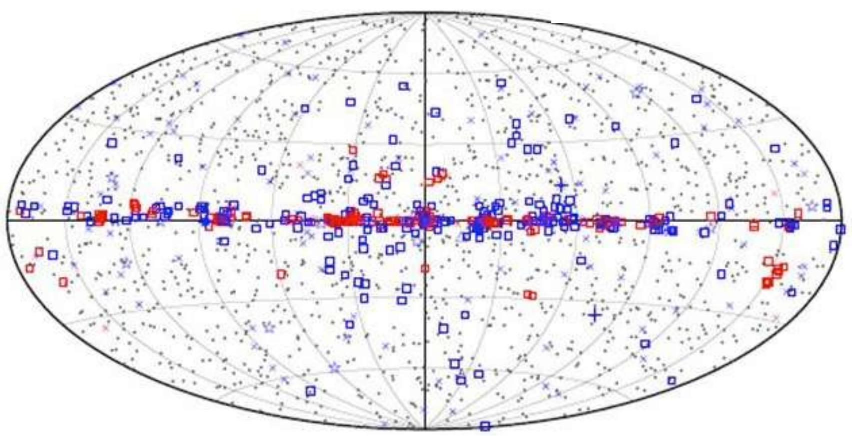


The Fermi sky

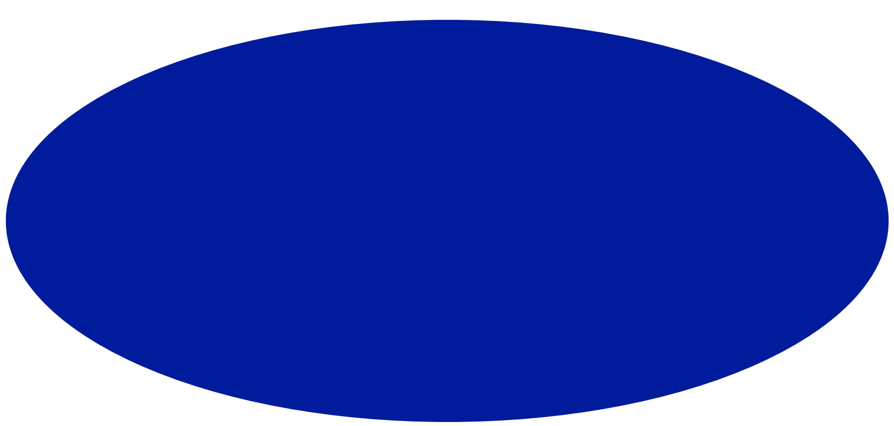
Diffuse emission from our Galaxy



Point sources

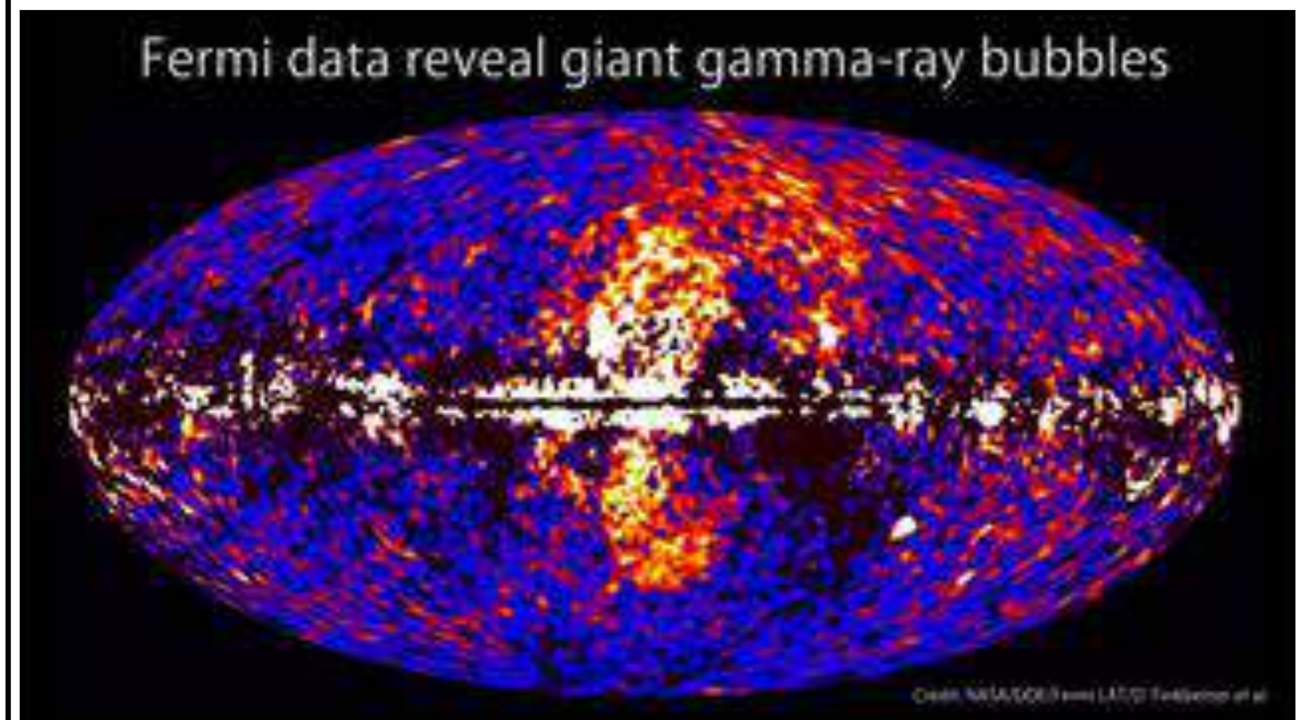


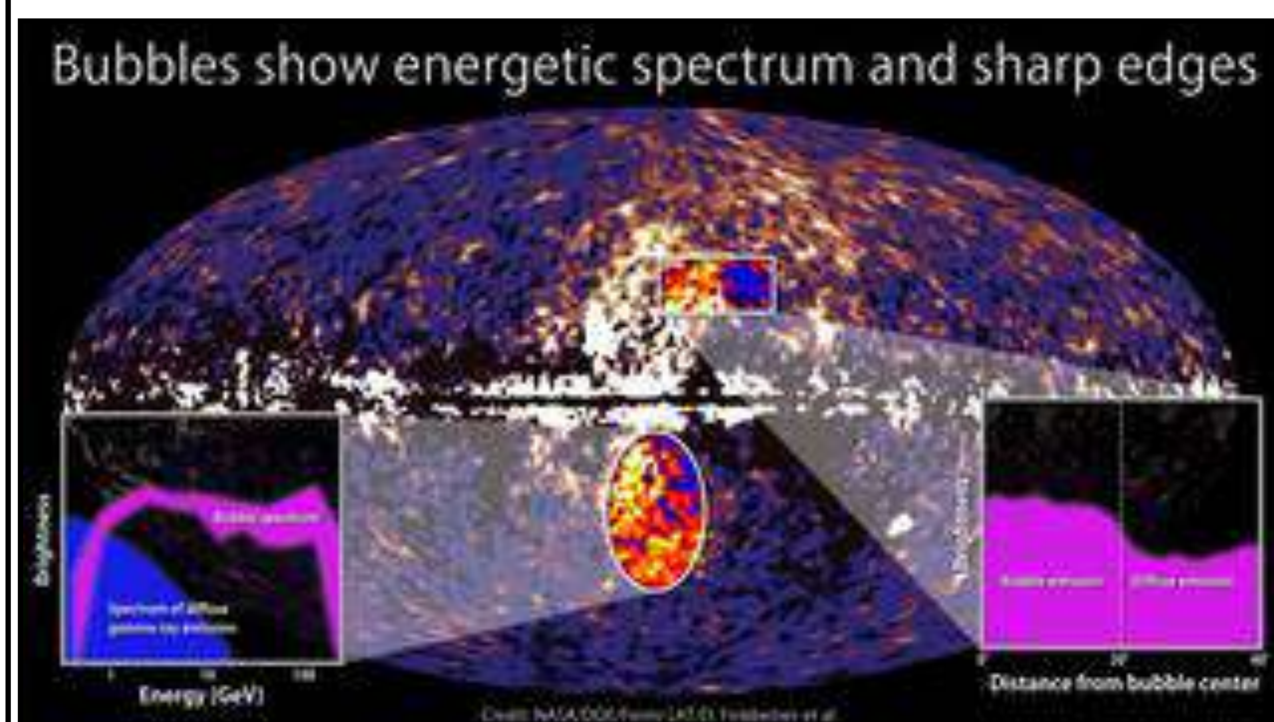
Isotropic emission



90% of the LAT photons!

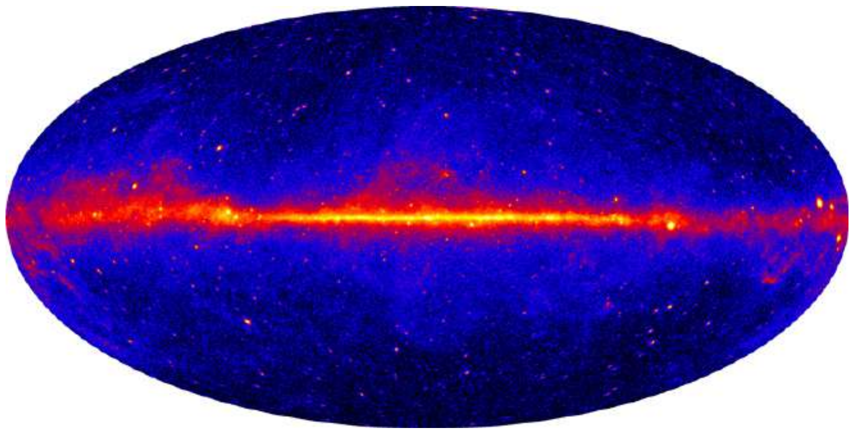
2) **Fermi bubbles**



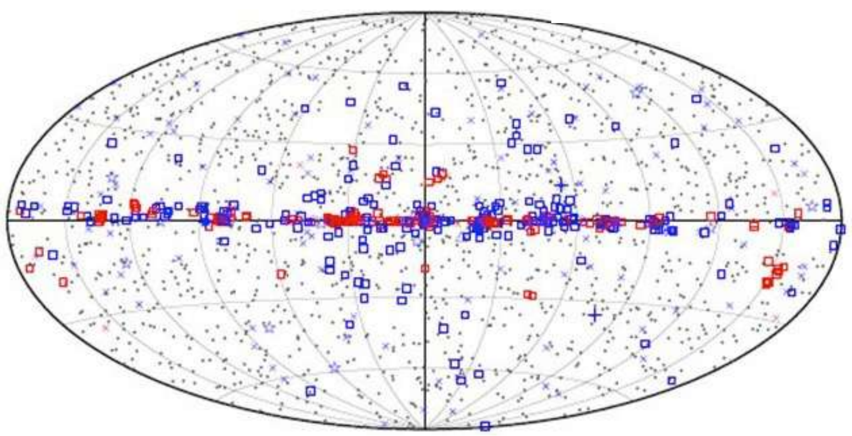


The Fermi sky

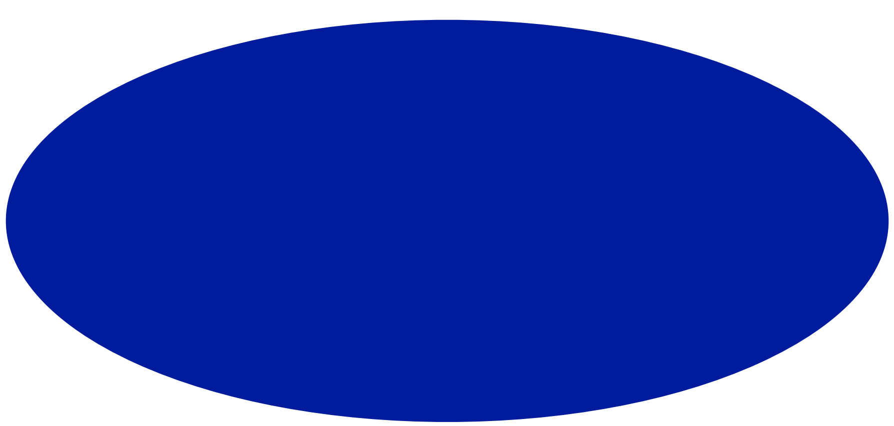
Diffuse emission from our Galaxy



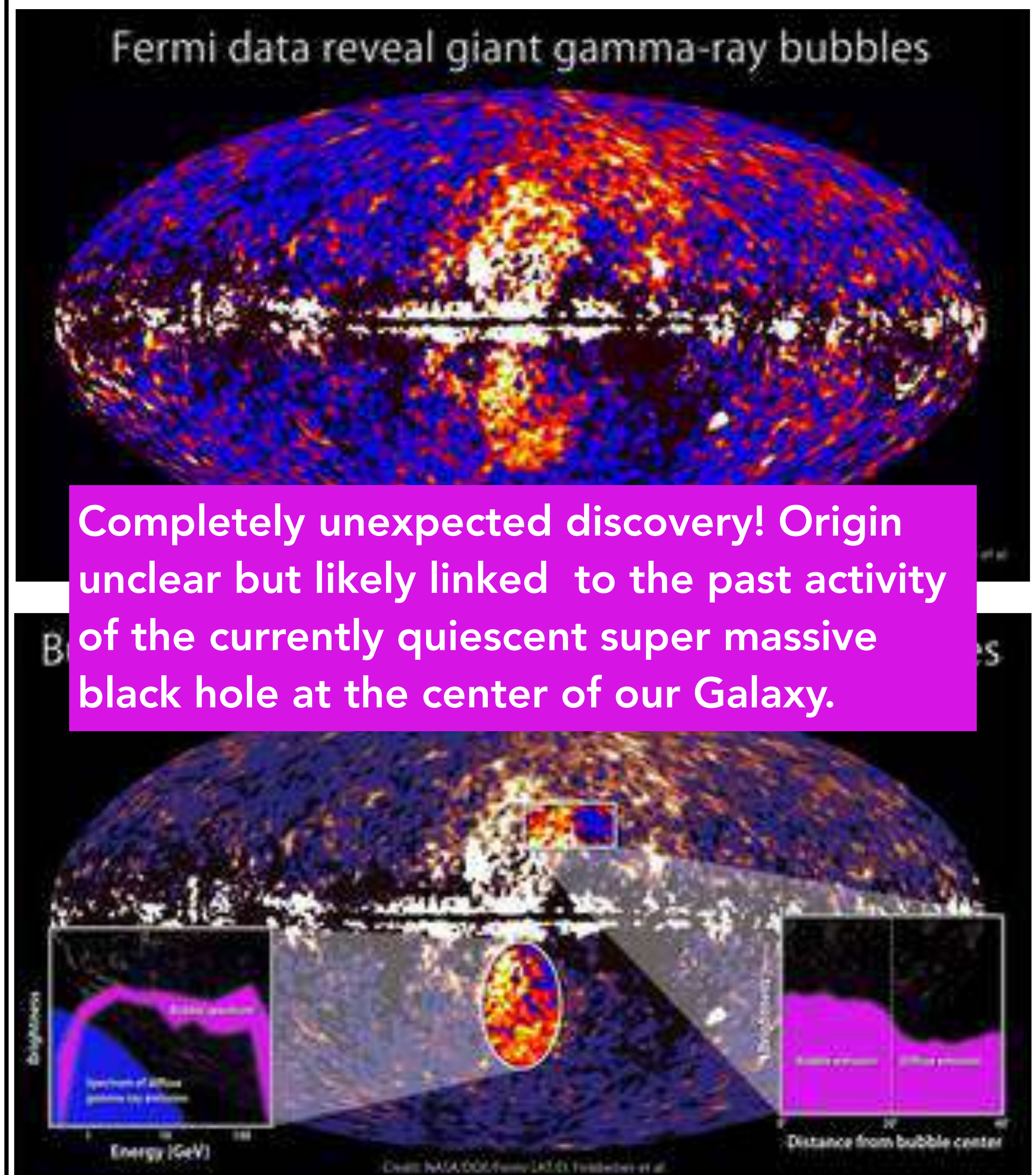
Point sources



Isotropic emission



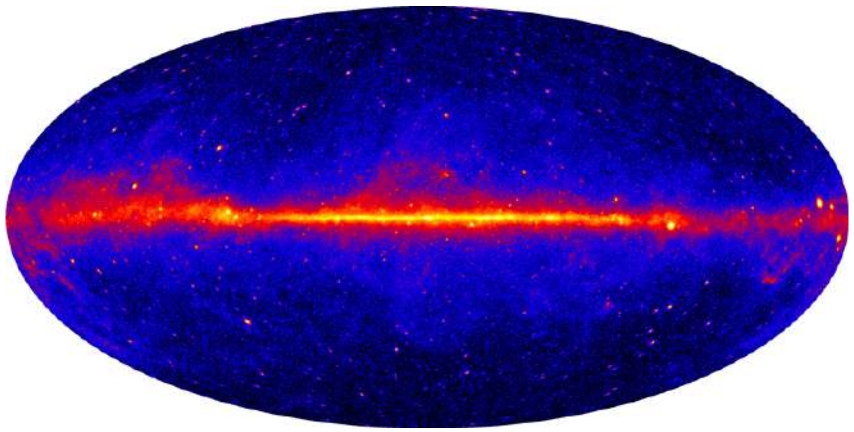
90% of the LAT photons!



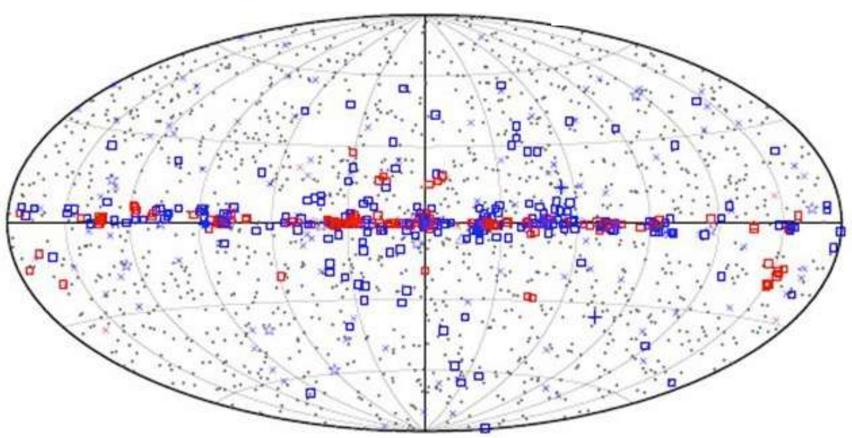
Completely unexpected discovery! Origin unclear but likely linked to the past activity of the currently quiescent super massive black hole at the center of our Galaxy.

The Fermi sky

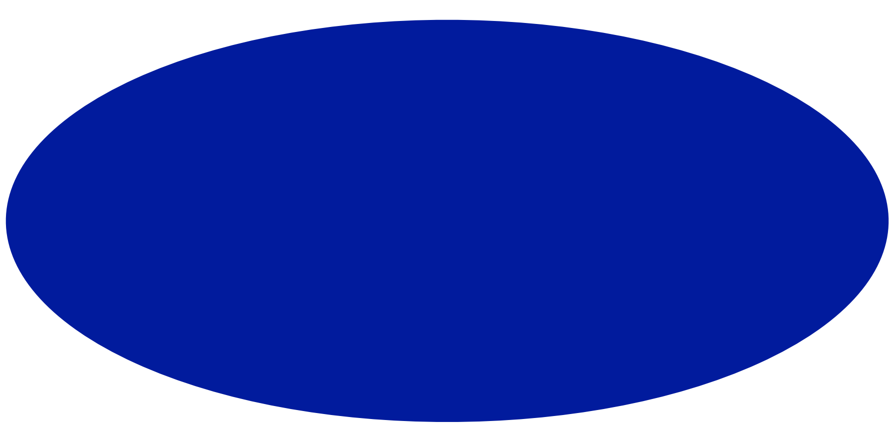
Diffuse emission from our Galaxy



Point sources

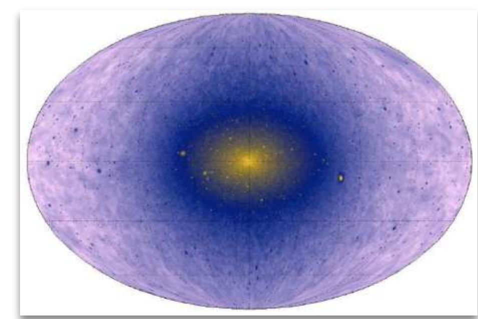


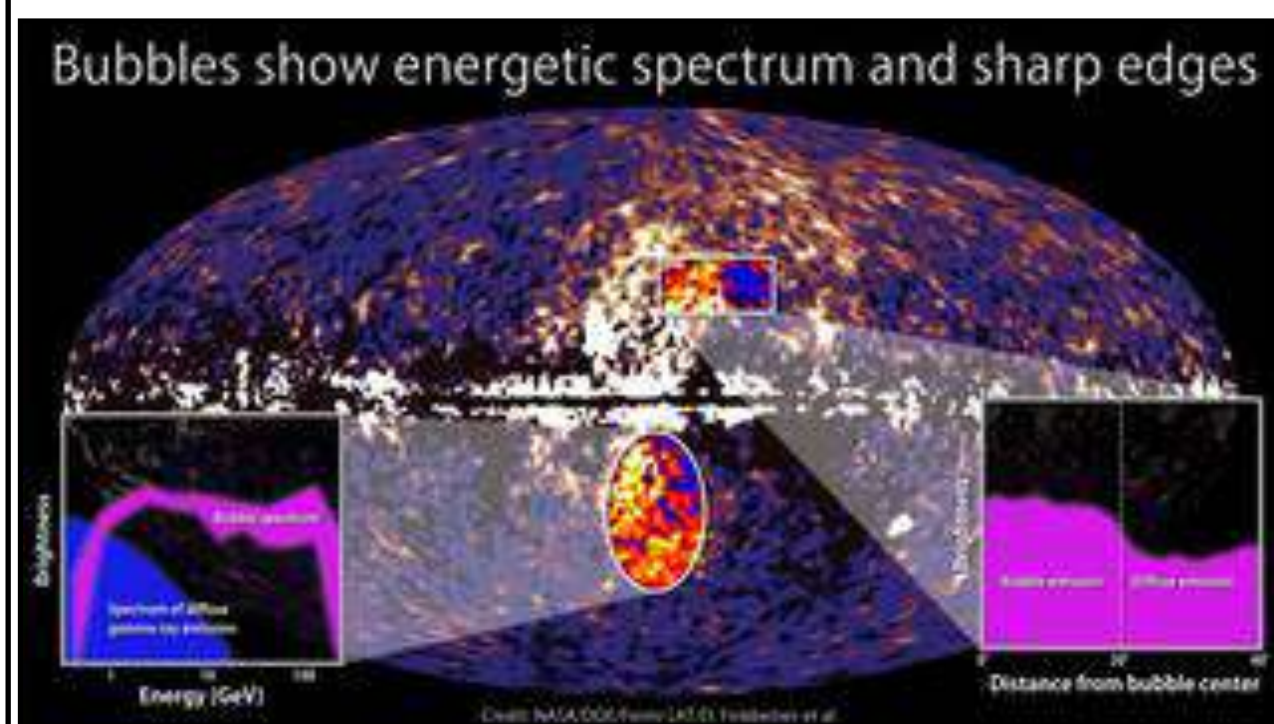
Isotropic emission



90% of the LAT photons!

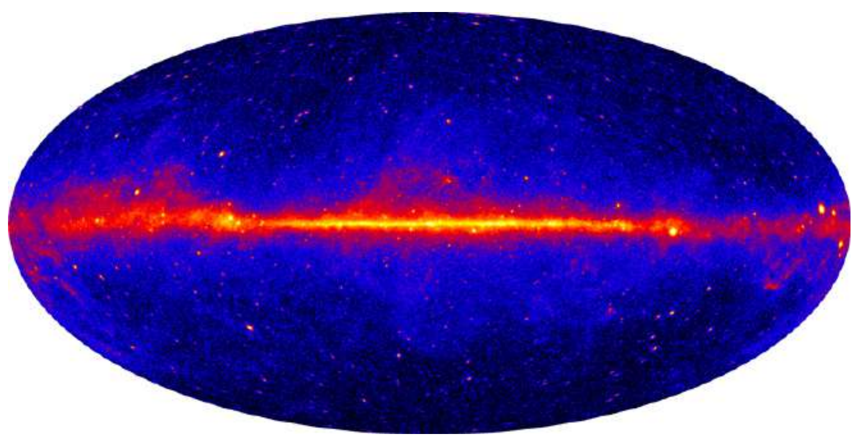
Why important (for DM search):
GC is the place to look for DM
Understanding the origin of the FBs critical for DM search in our Galaxy



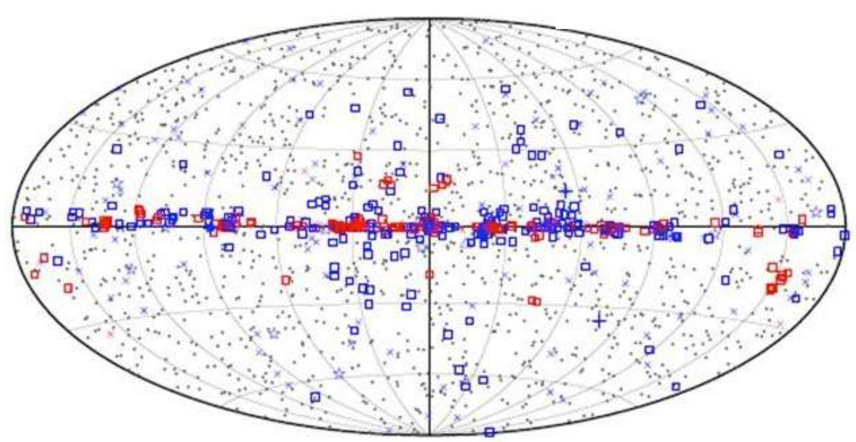


The Fermi sky

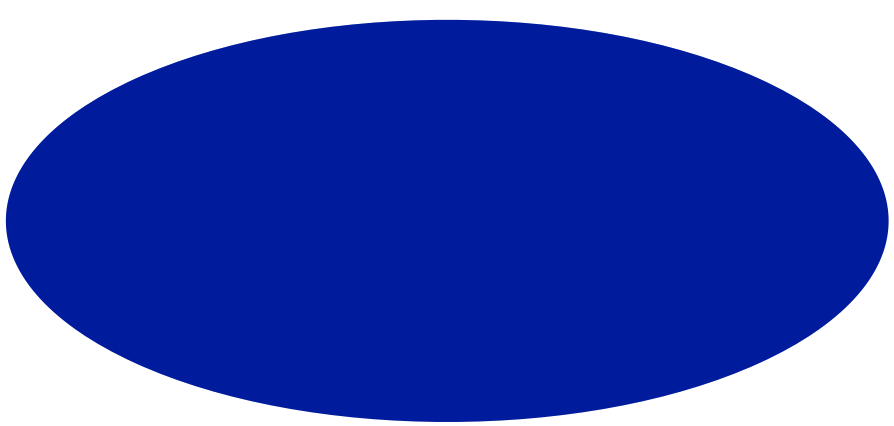
Diffuse emission from our Galaxy



Point sources

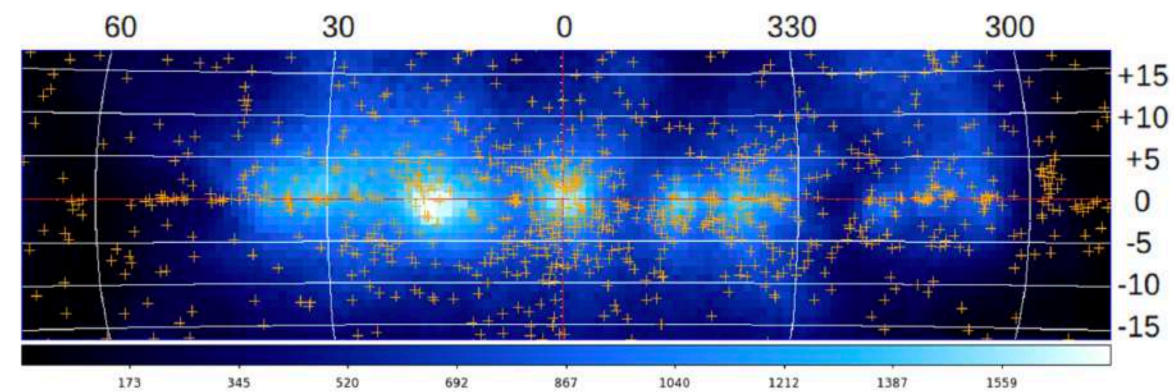


Isotropic emission



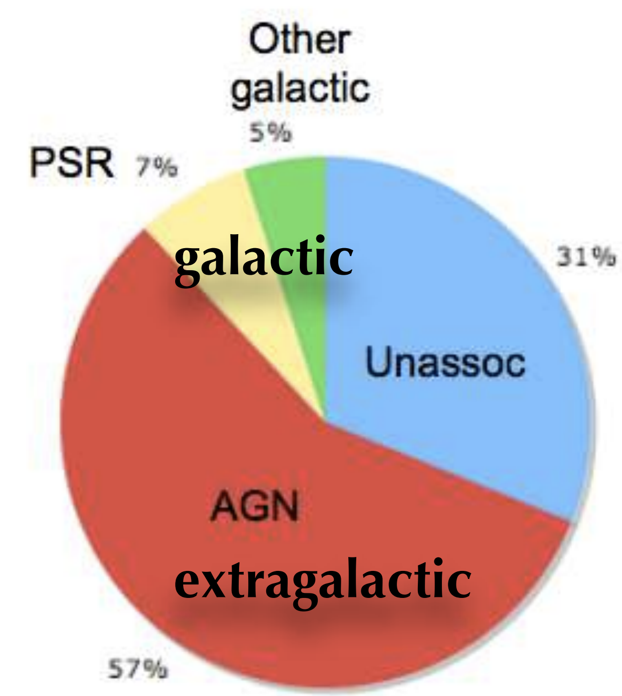
Fermi 4FGL DR3 catalog
>~6.7k sources! In 12y of data taking

Unassociated sources around the GC



[Fermi LAT coll. Astro-ph 2201.11184, ApJS]

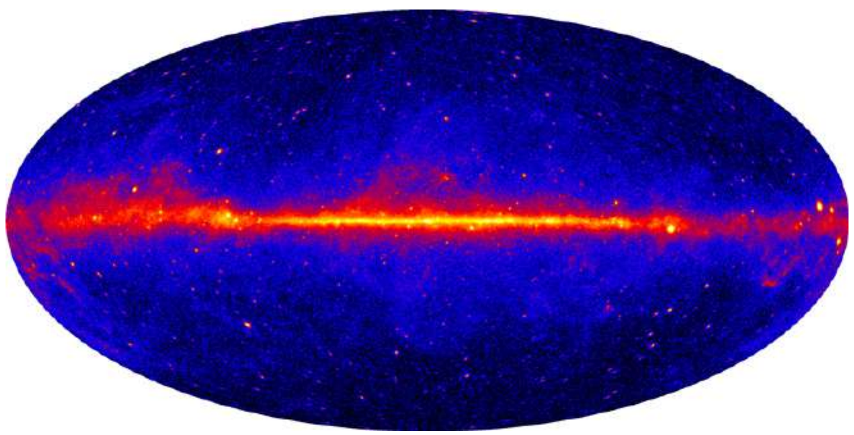
galactic: PSRs, PWNs, SNR, Nova, Globular clusters…



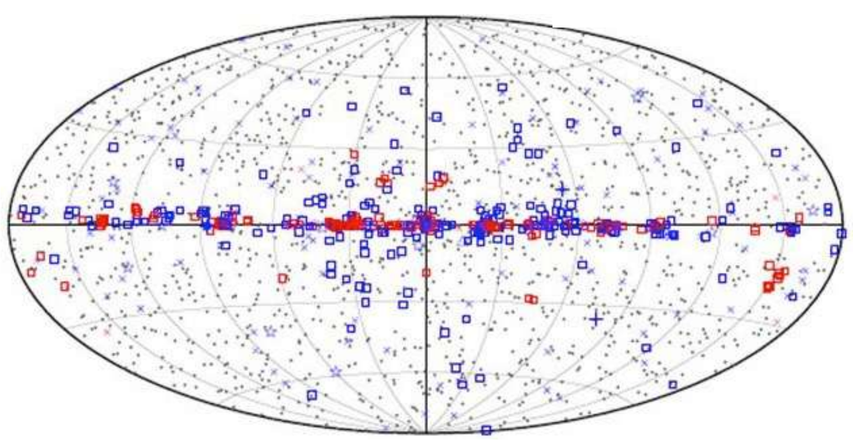
extragalactic: AGNs (BLLacs, FSRQs), star forming galaxies

The Fermi sky

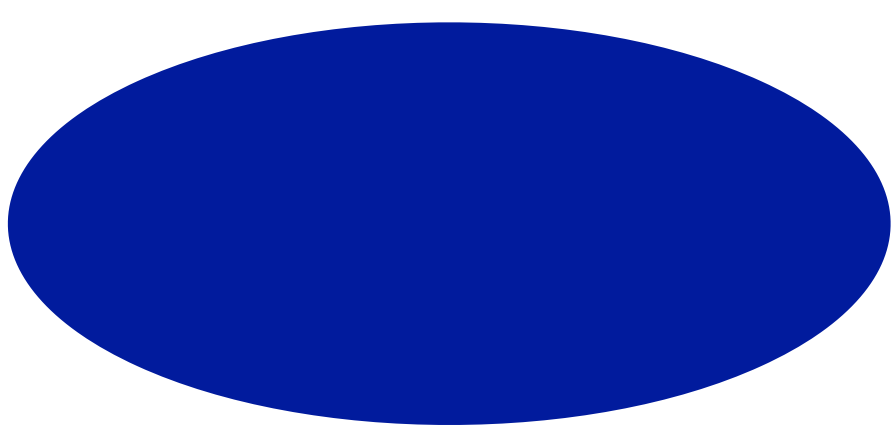
Diffuse emission from our Galaxy



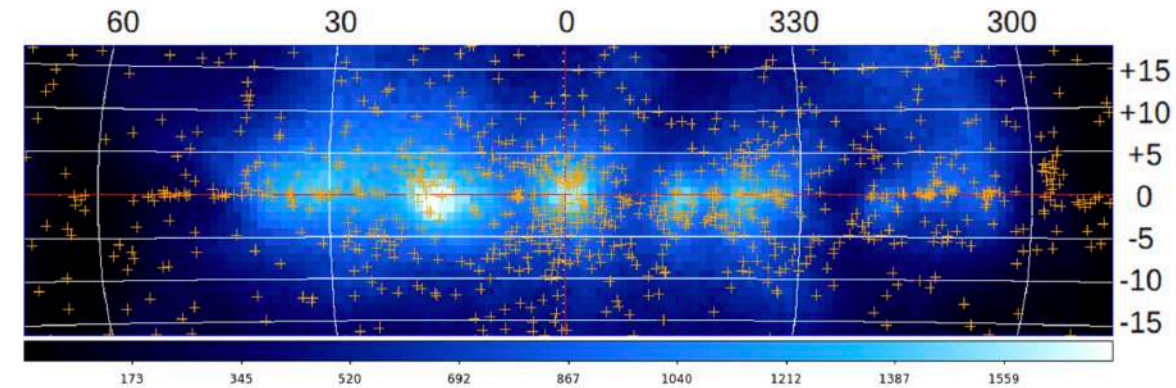
Point sources



Isotropic emission



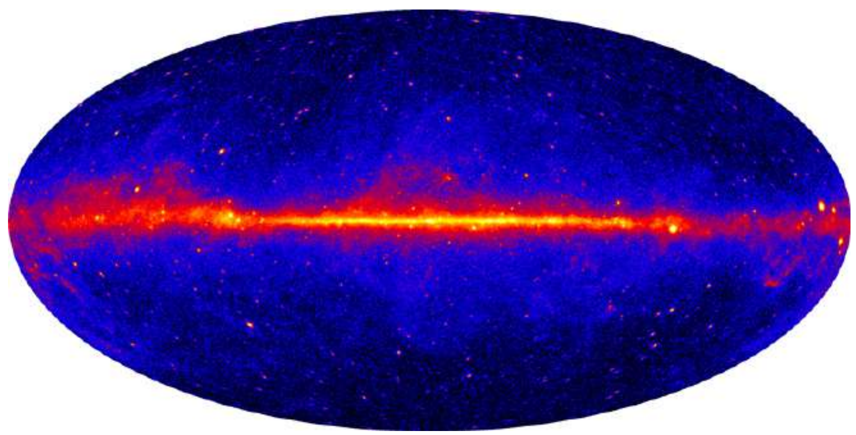
Fermi 4FGL DR2 catalog
>~6000 sources!



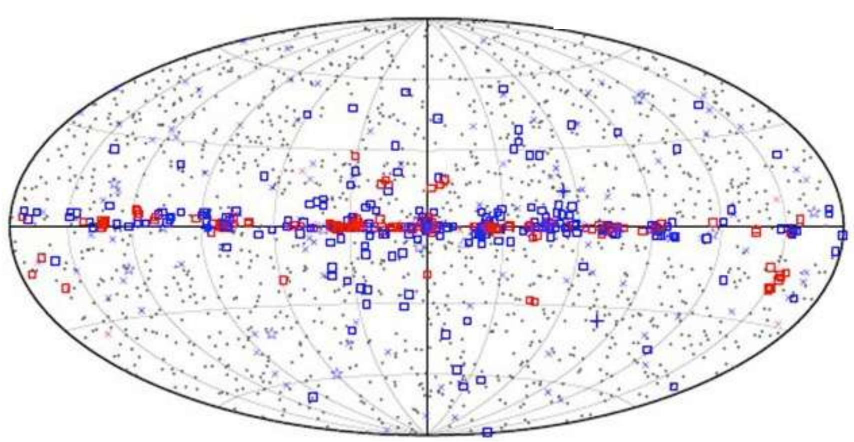
Why important (for DM search):
DM subhalos numerous in the Galaxy - would emit in γ with no counterpart in other wavelength
1/3 of sources unassociated !

The Fermi sky

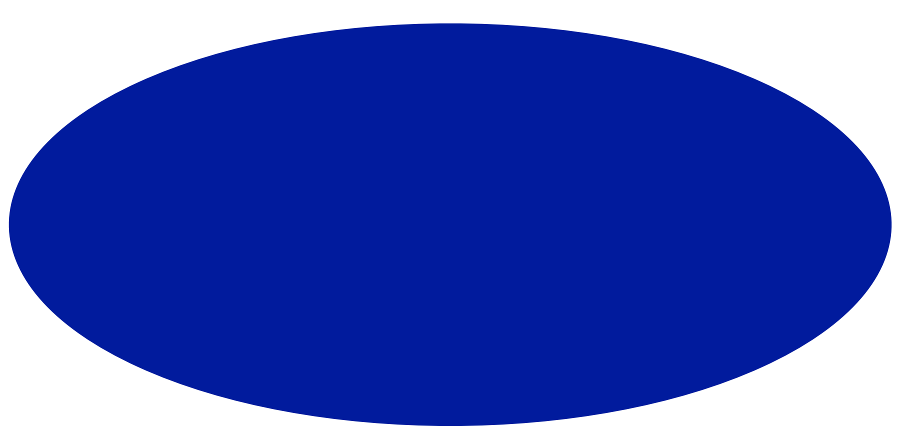
Diffuse emission from our Galaxy



Point sources

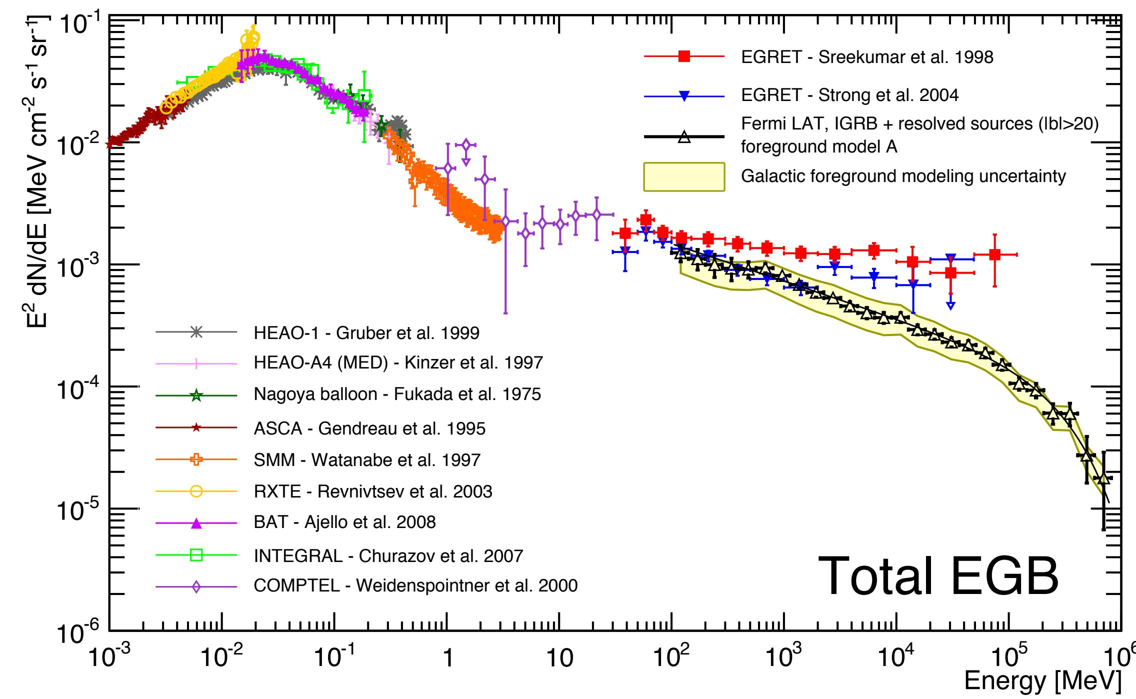


Isotropic emission



dominates at high latitudes

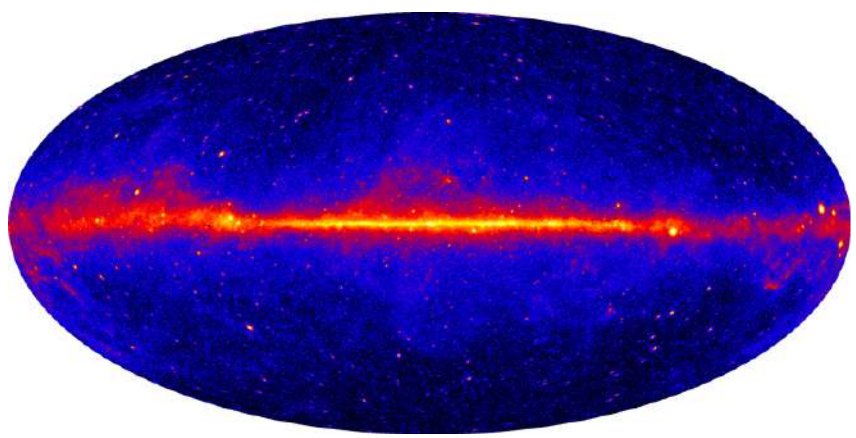
guaranteed contribution: faint (not individually resolved) extragalactic sources



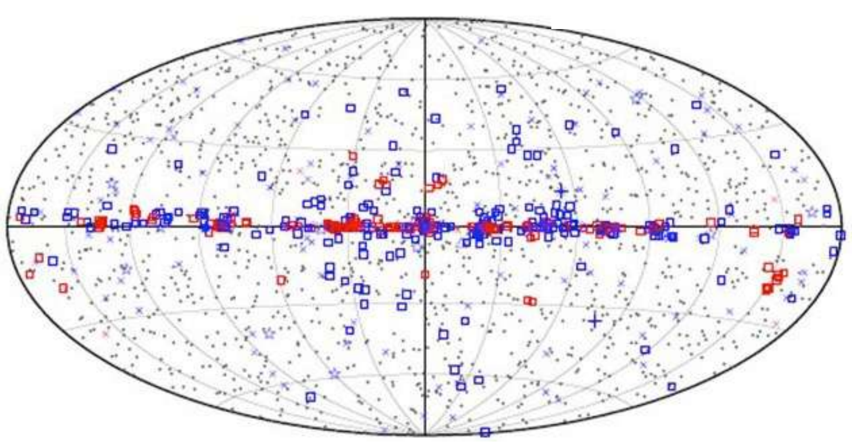
[Ackermann+, ApJ799, 2015)]

The Fermi sky

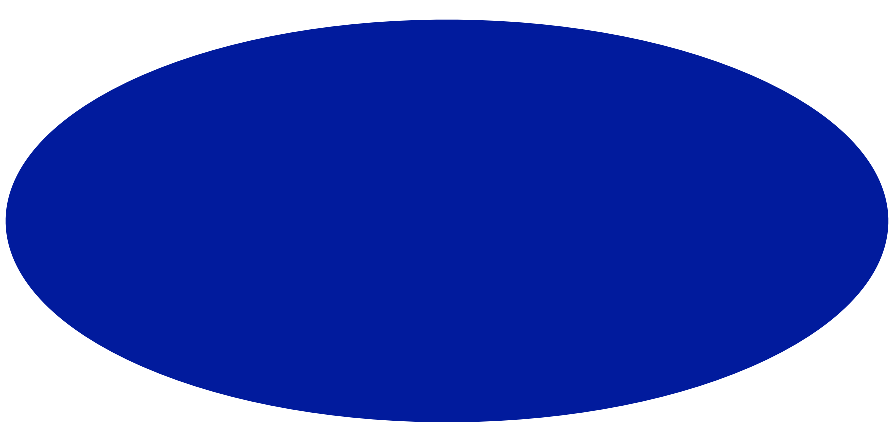
Diffuse emission from our Galaxy



Point sources



Isotropic emission



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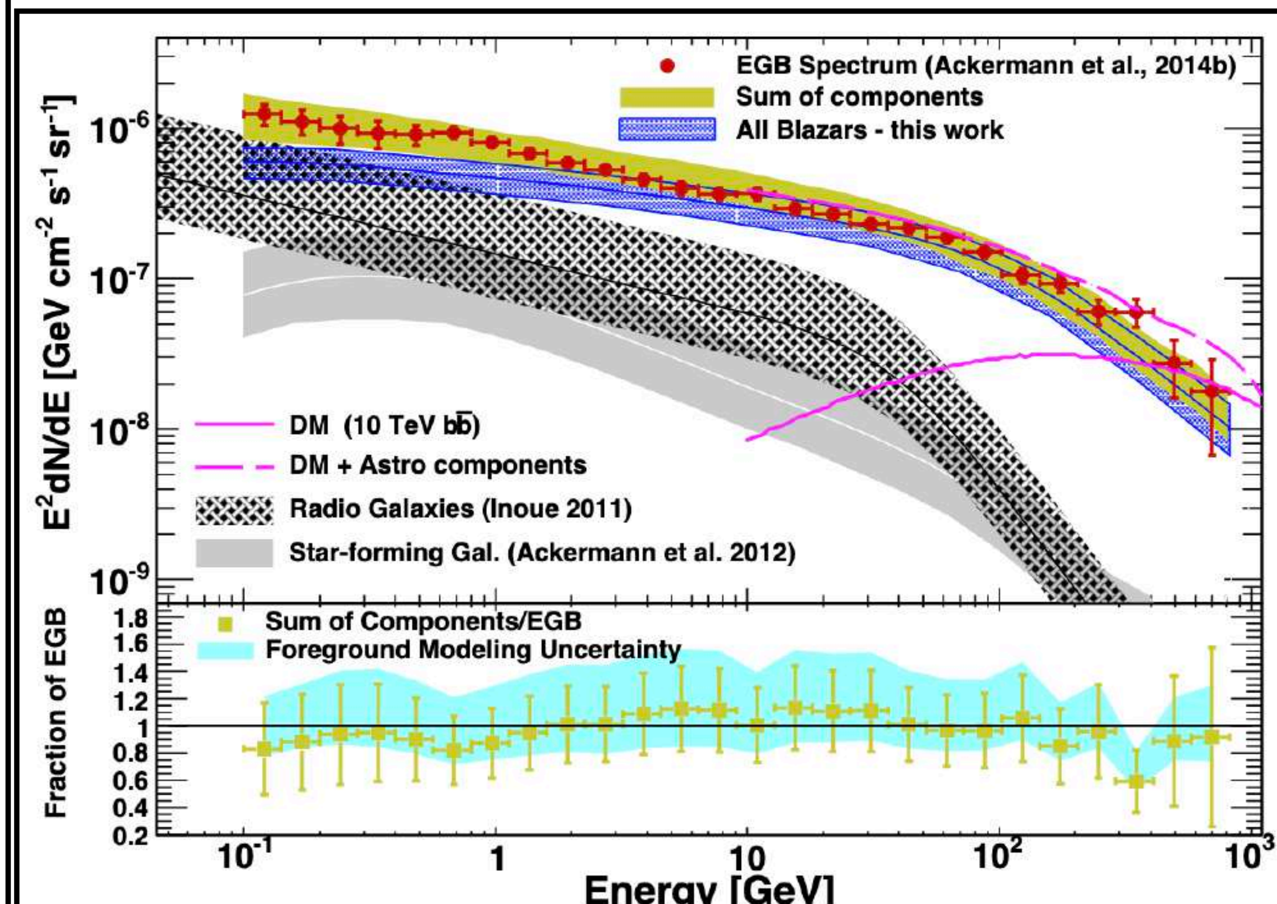
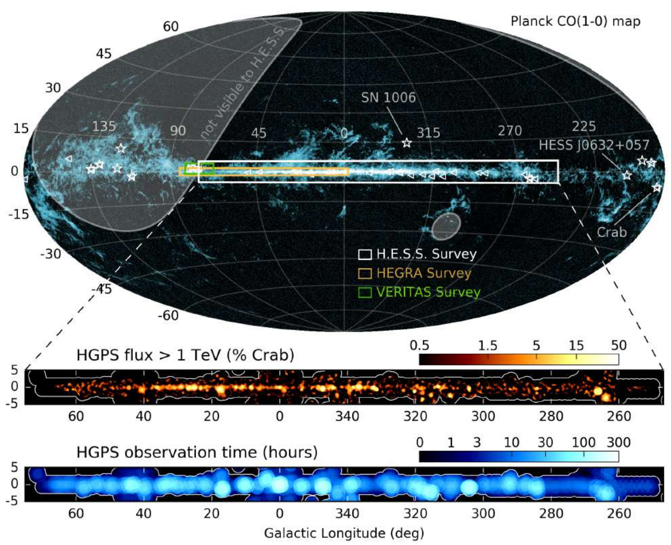


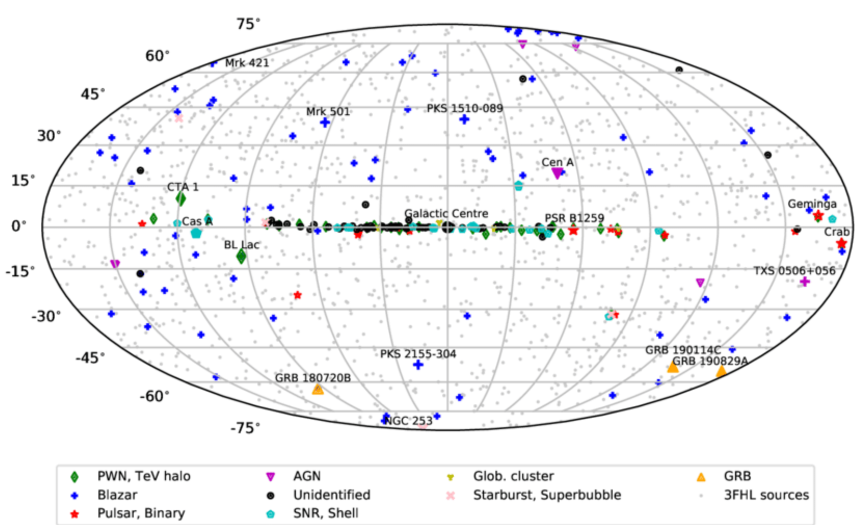
Why important (for DM search):
DM annihilation or decay in all extragalactic halos would contribute to this emission!

The TeV sky

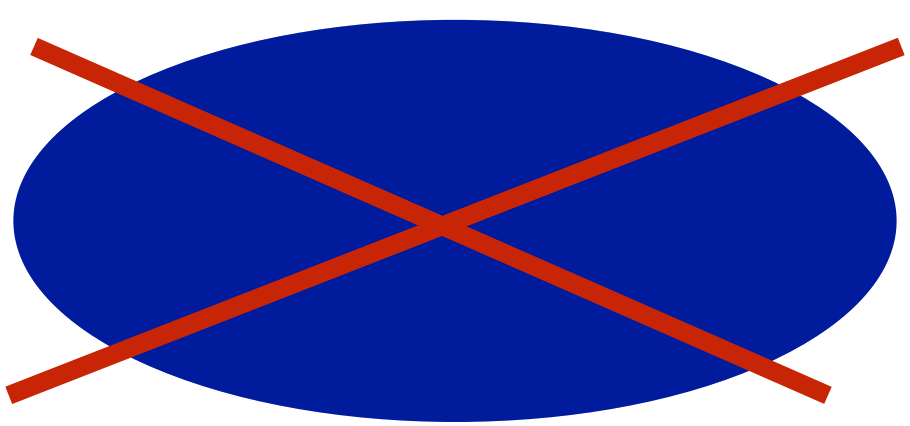
Diffuse emission from our Galaxy



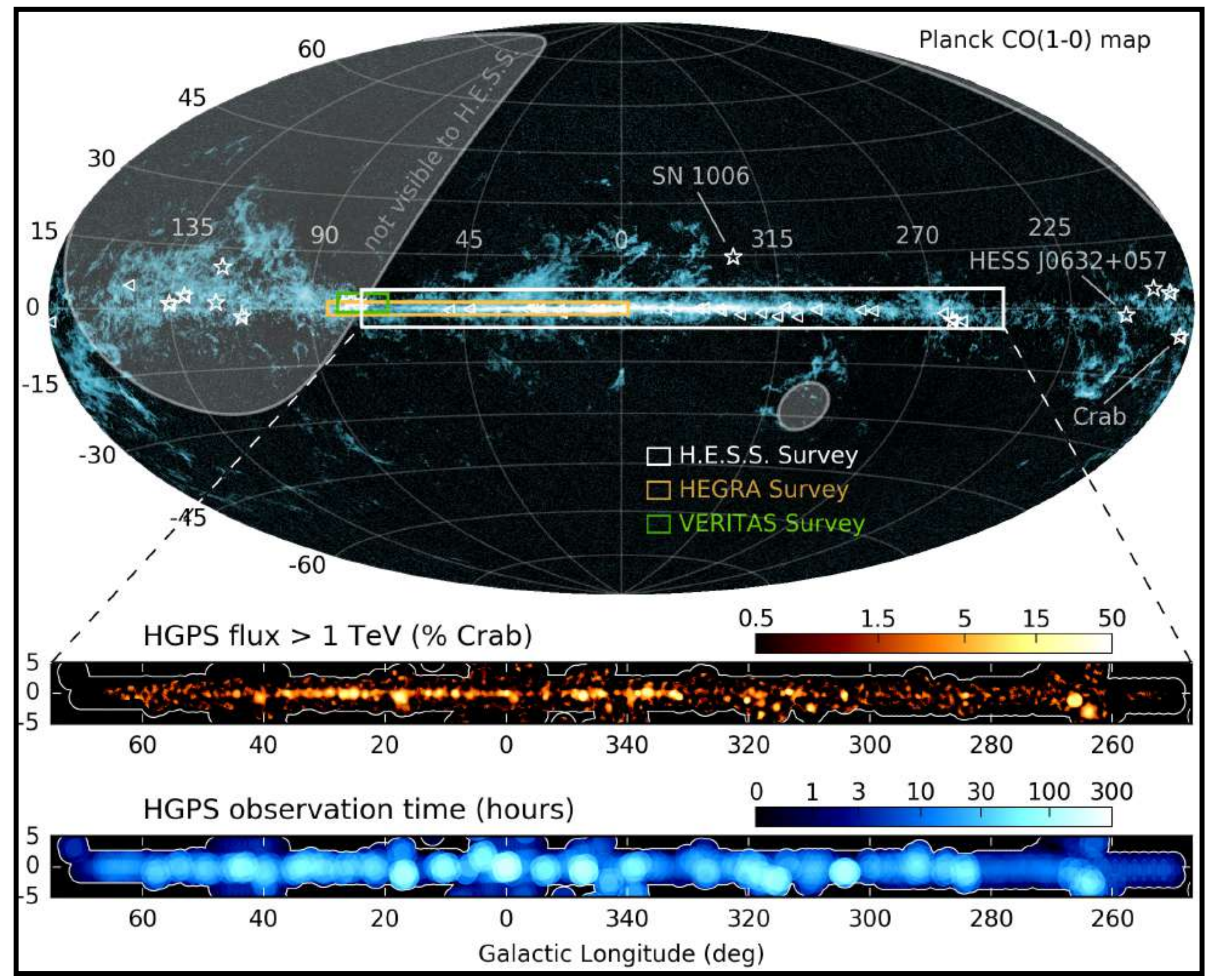
Point sources



Isotropic emission



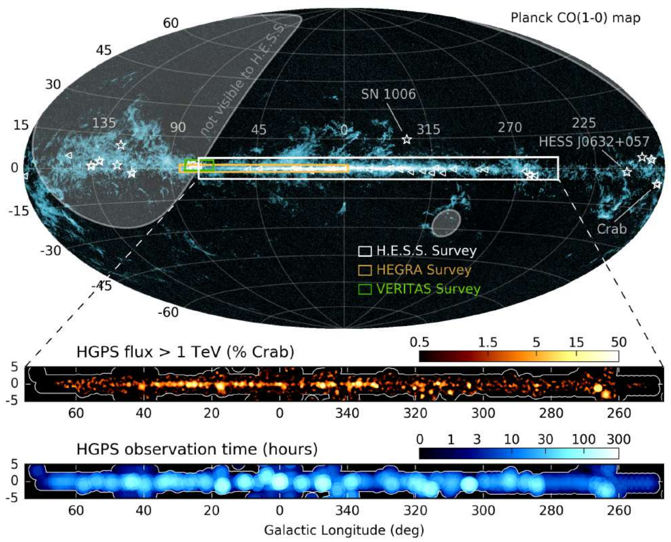
Ground based telescopes performed survey observations of extended regions:



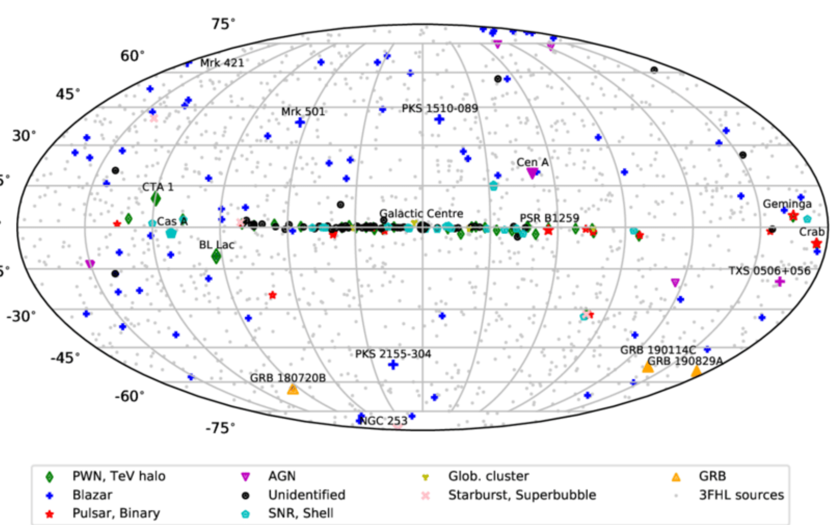
[H.E.S.S. Galactic Plane Survey]

The TeV sky

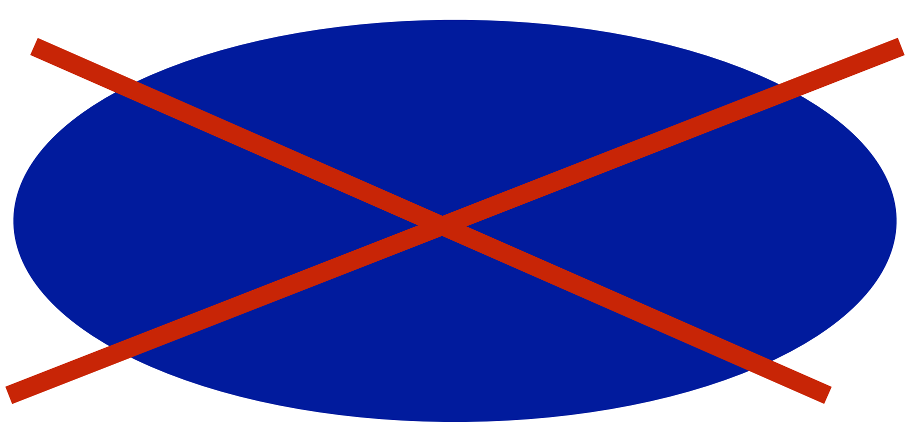
Diffuse emission from our Galaxy



Point sources



Isotropic emission



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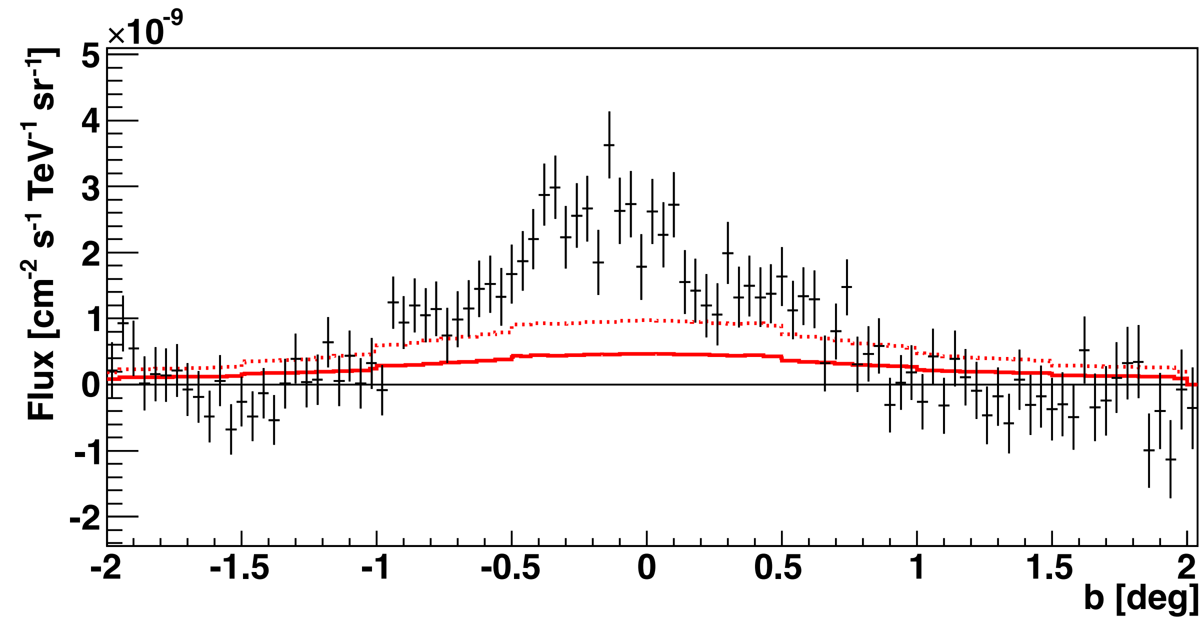
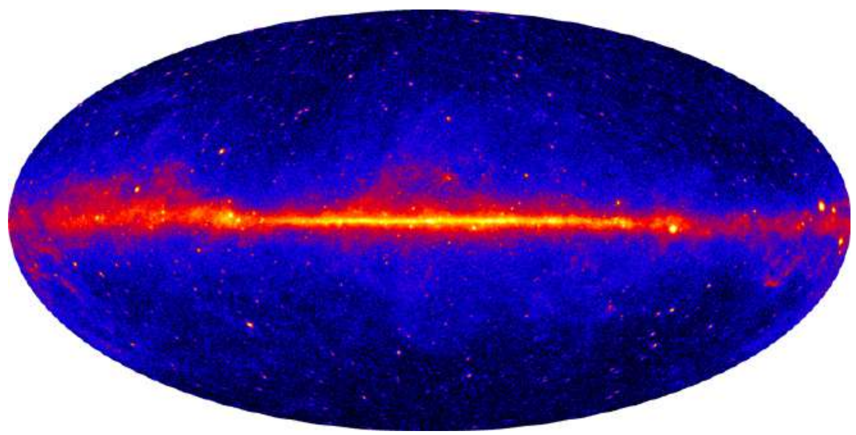


[HESS coll., 2014]

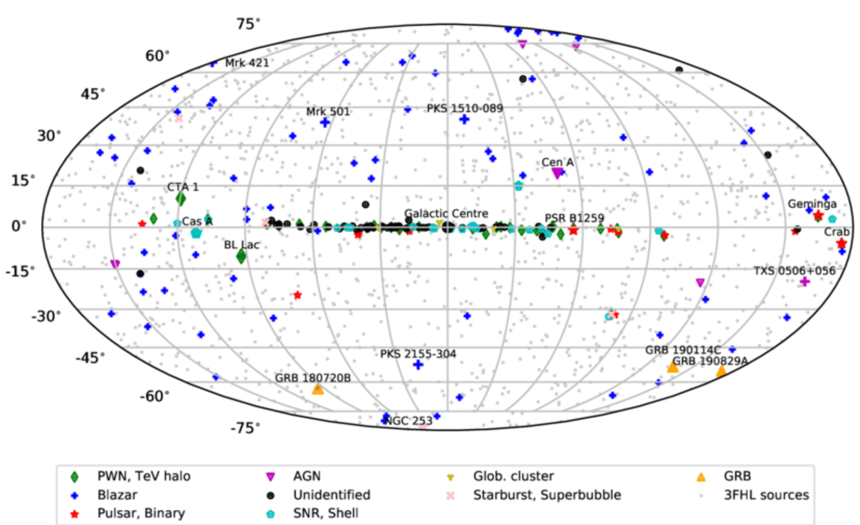
Cumulative diffuse emission detected along the plane

The TeV sky

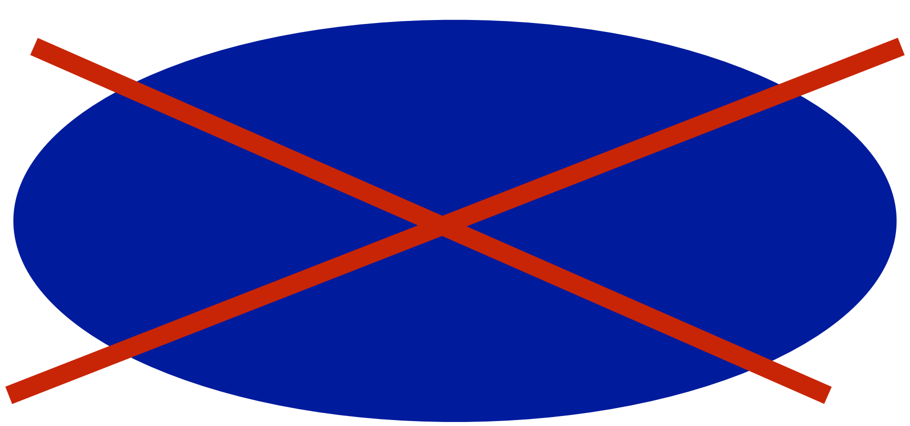
Diffuse emission from our Galaxy



Point sources

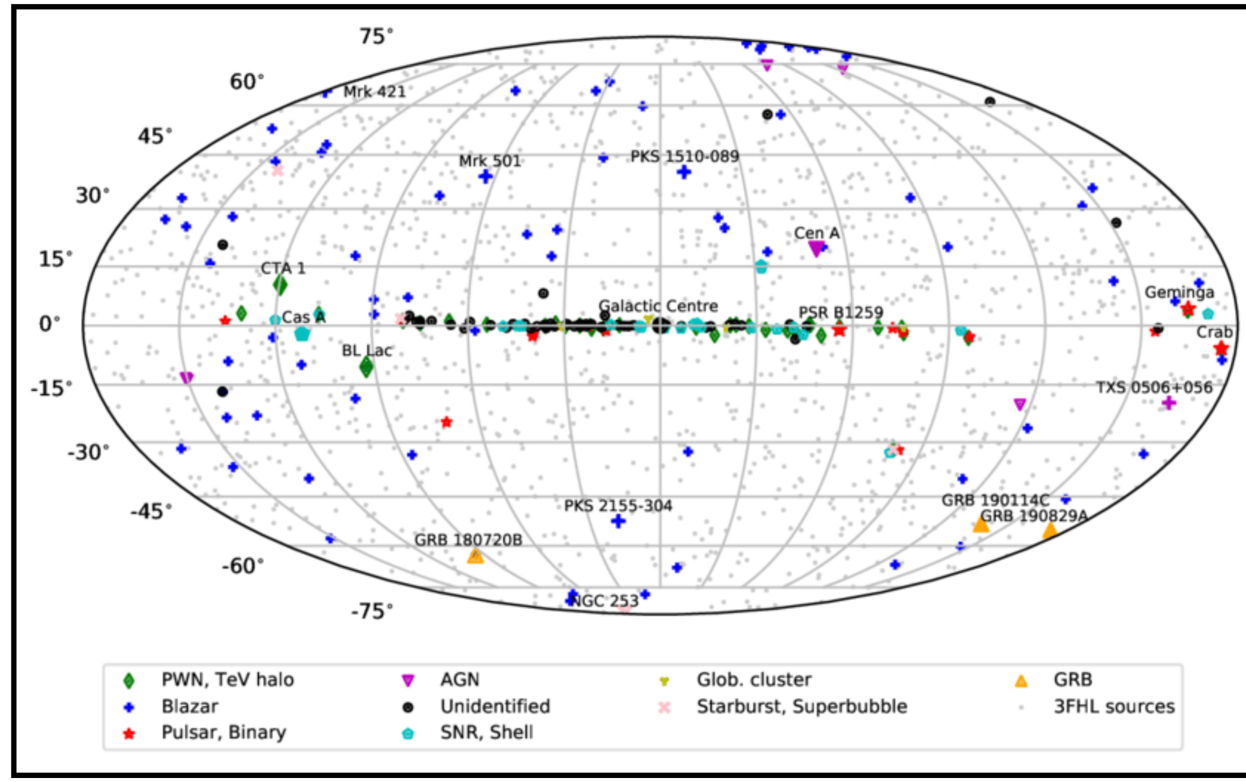


Isotropic emission



Hundreds of sources

Significant portion of galactic sources is extended (PWNs, SNRs etc)



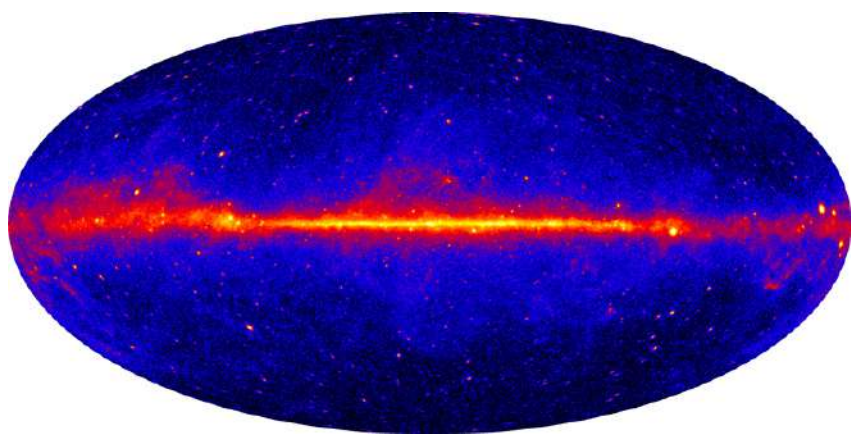
[Hinton & Ruiz-Velasco, 2019]

The TeV sky (mid-2019) overlayed with the 3FHL

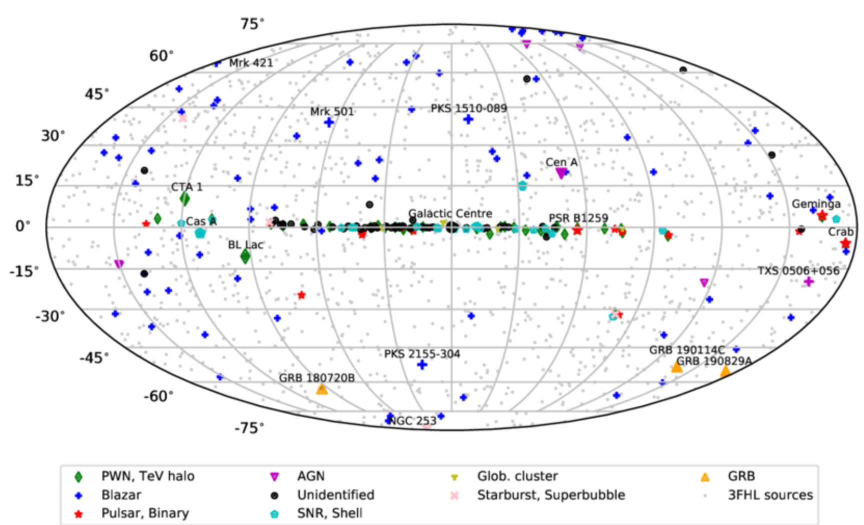
[TeVCat, mid 2019]

The TeV sky

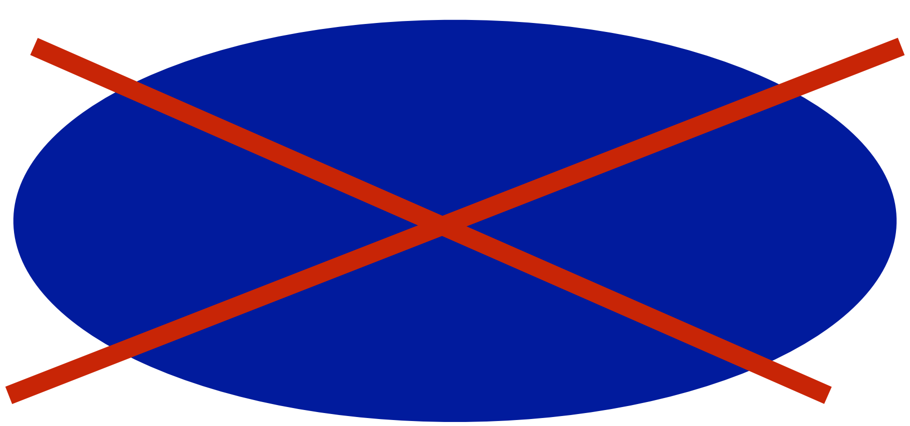
Diffuse emission from our Galaxy



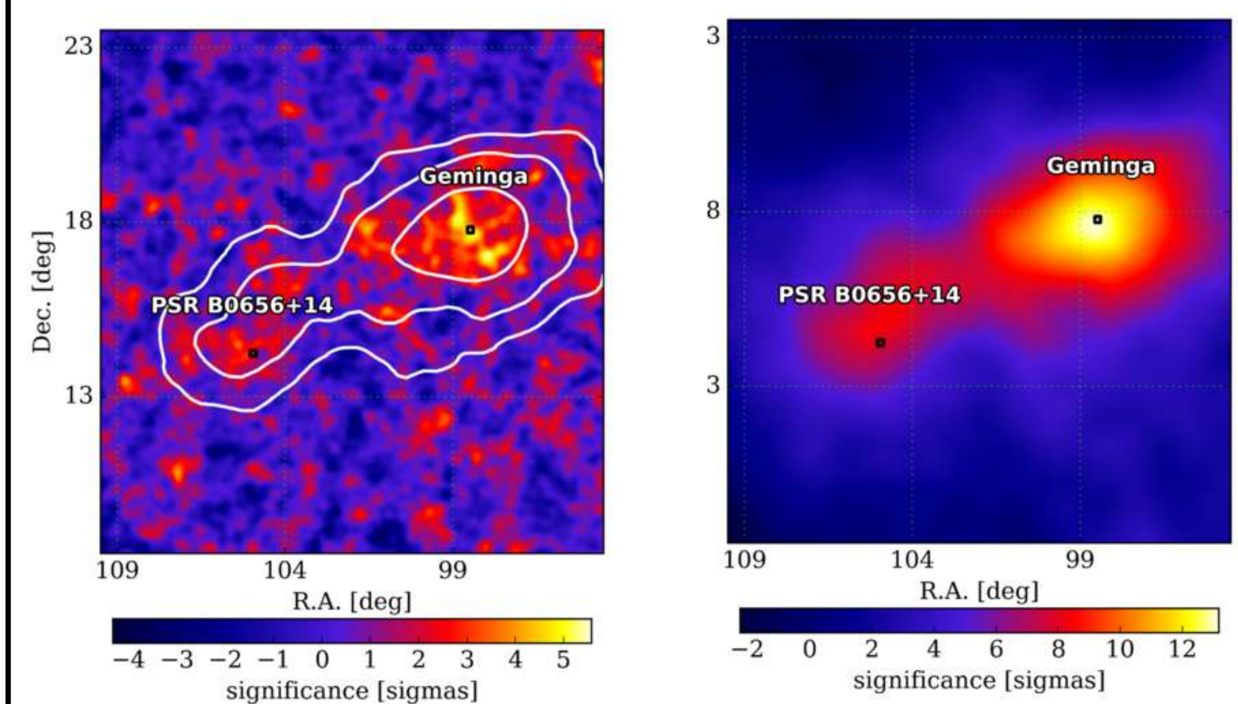
Point sources



Isotropic emission



New kid on the block 'Pulsar halos'



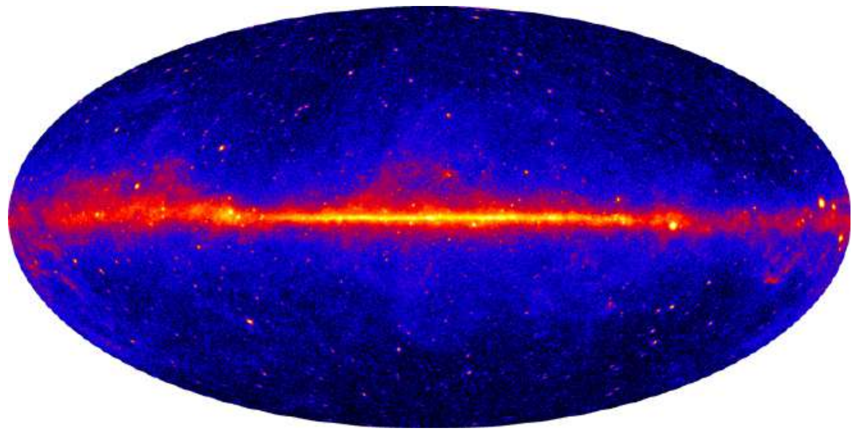
The HAWC Collaboration, *Science* 358, 911 (2017)

New source class: Geminga and Monogem pulsars are surrounded by a spatially extended region (~25 pc) emitting multi - TeV gamma-rays: ***pulsar TeV halos (HAWC)*!**

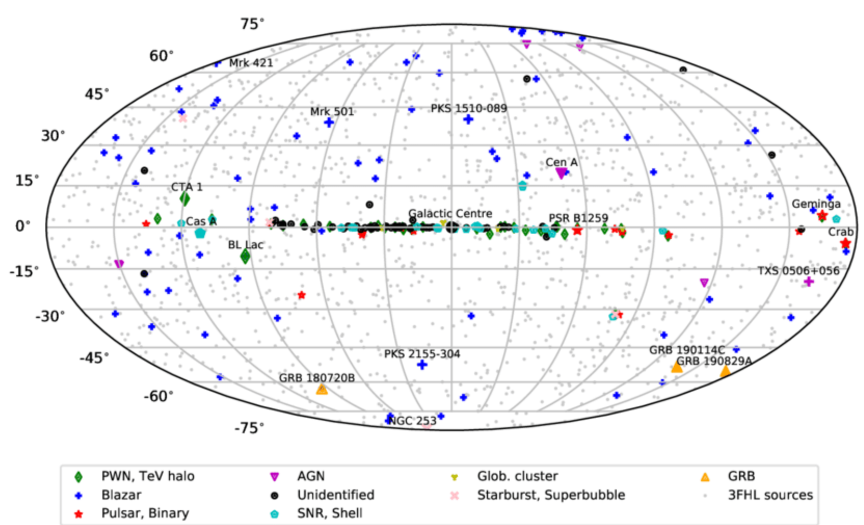
Implied diffusion coefficient TWO ORDERS OF MAGNITUDE lower than the one in the Galaxy.

The TeV sky

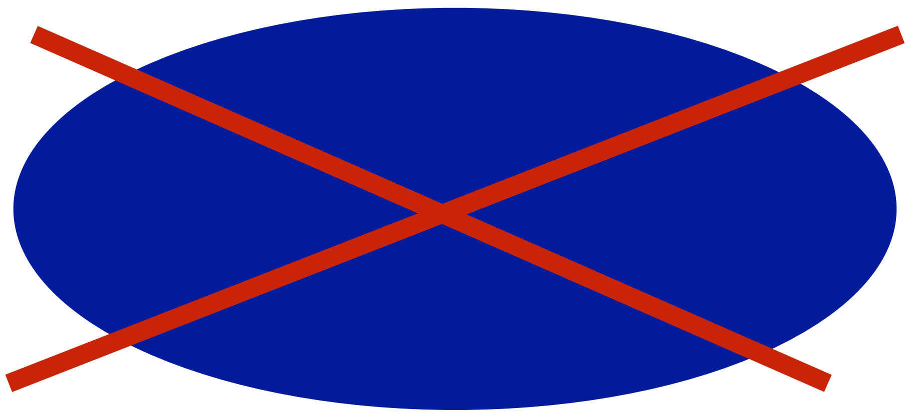
Diffuse emission from our Galaxy



Point sources

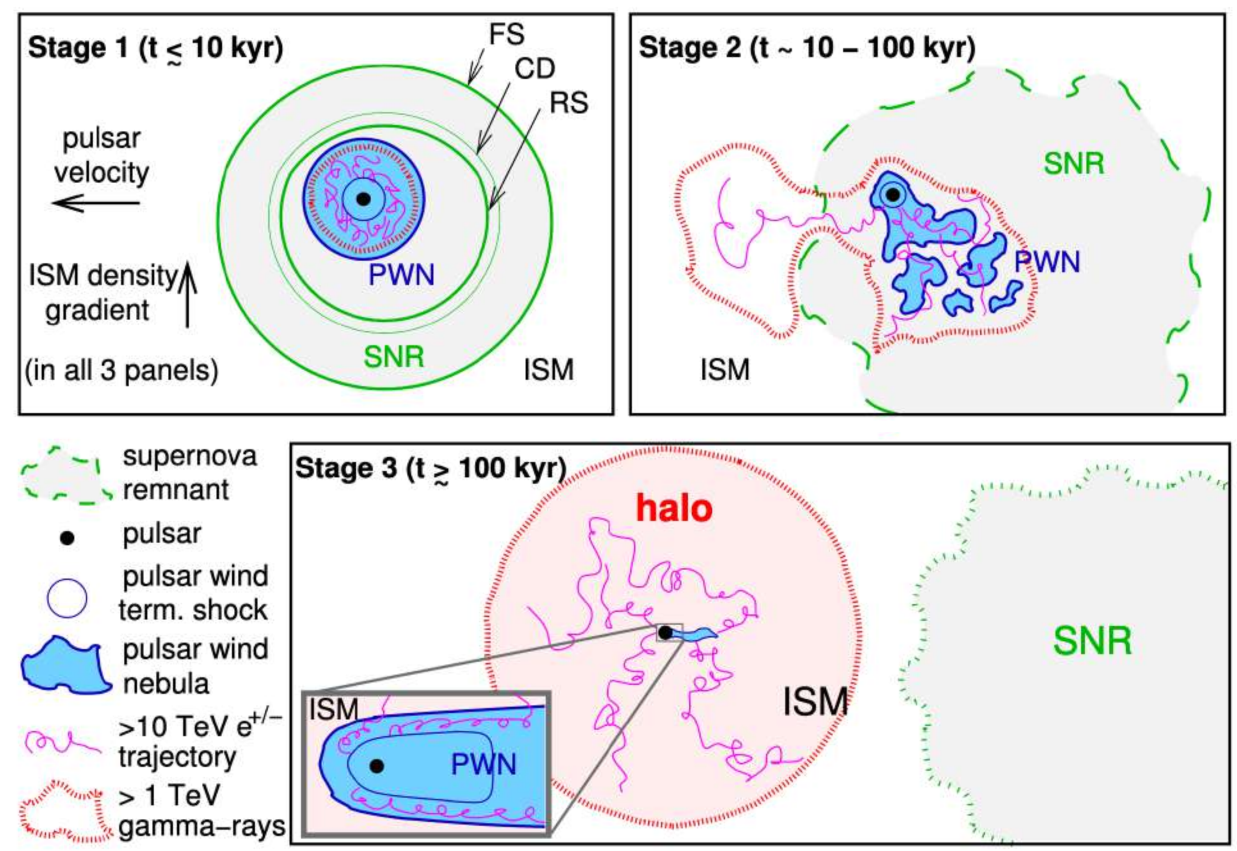


Isotropic emission



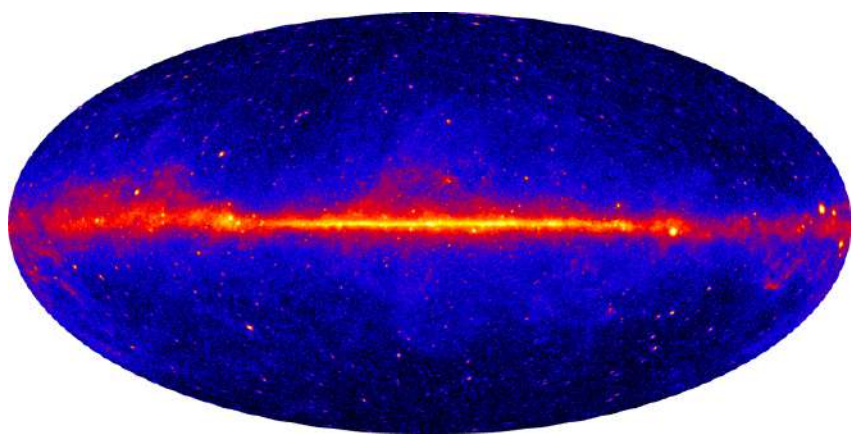
New kid on the block 'Pulsar halos'

G. Giacinti et al.: Halo fraction in TeV-bright pulsar wind nebulae

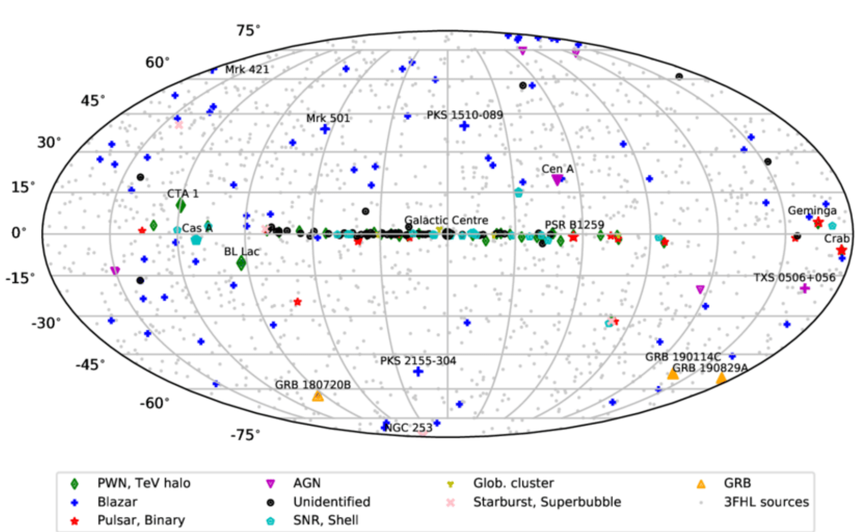


The TeV sky

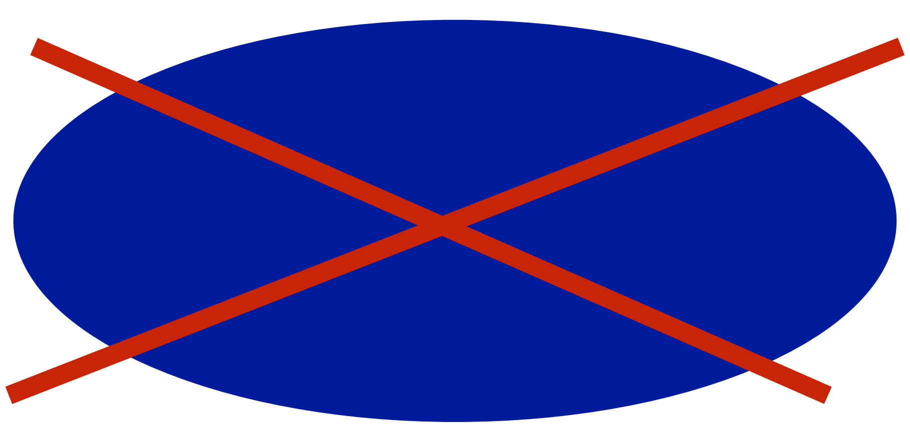
Diffuse emission from our Galaxy



Point sources



Isotropic emission



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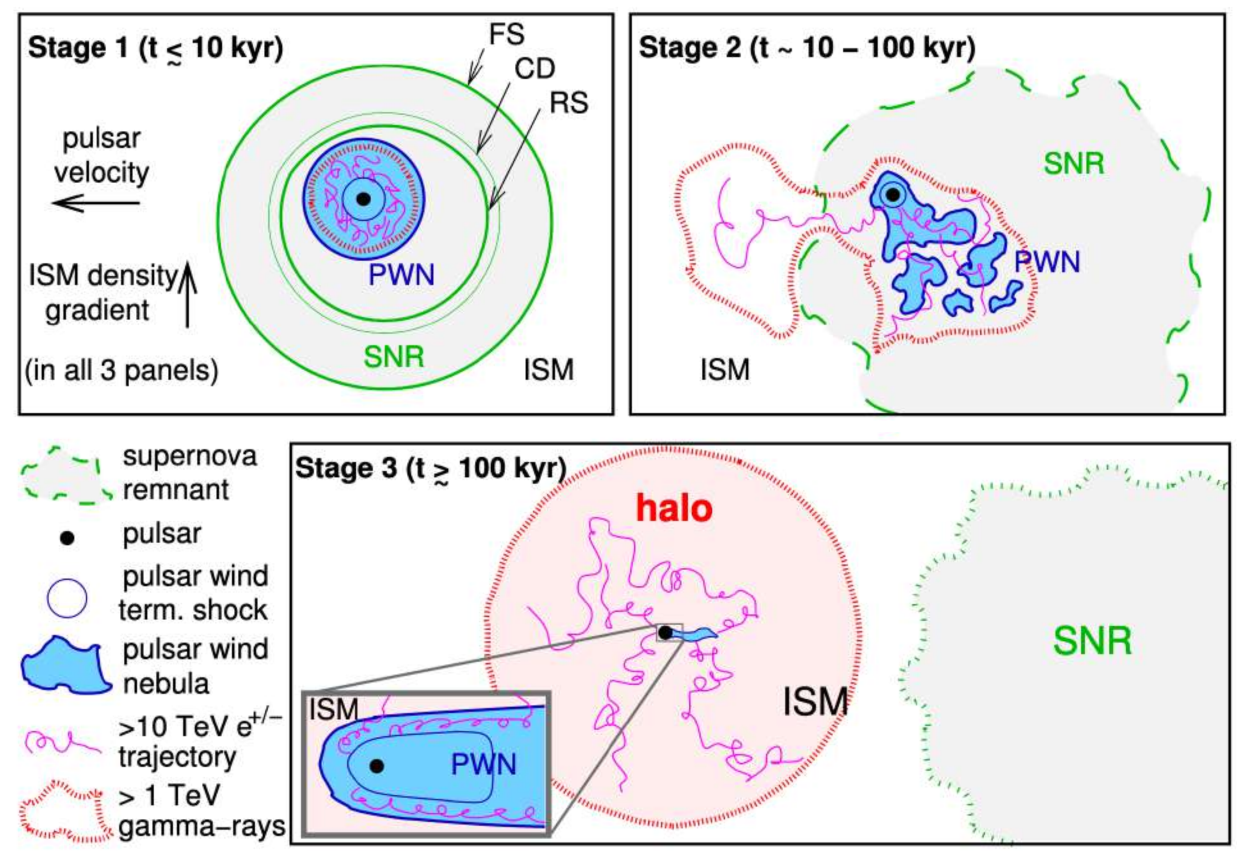


Why Important (for DM search):

1) will tell us about th origin of CR electrons an dtheir propagation in the Galaxy

2) As extended sources an important background for DM search

Outline

1. Pre history *a detour*
2. (gravitational) evidence for dark matter
3. DM candidates
4. Experiments
5. Signal & Targets
6. The gamma-ray sky (astro 'backgrounds')
7. Data Analysis strategy
8. Examples of search in particular targets (WIMPs)
   - Galactic center
   - dSphs
   - Galaxy clusters

Today

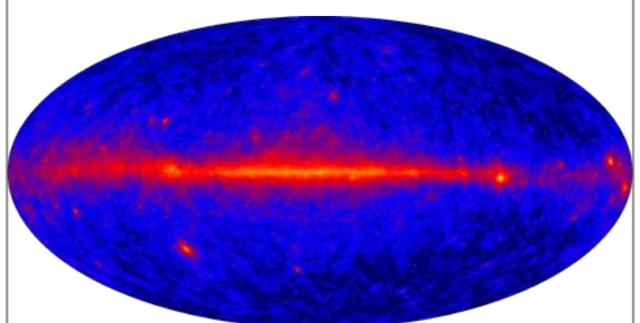
Assembling the cake

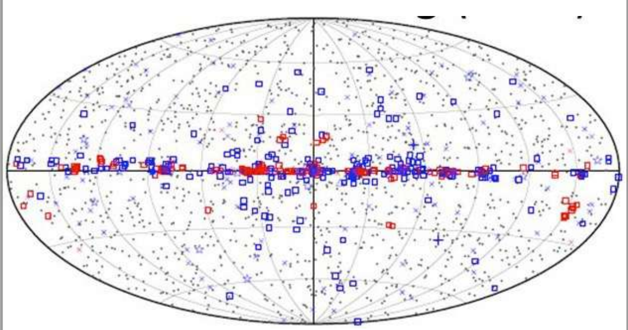
We have the data...

expectations for DM signal

and models for astrophysical backgrounds ...

Gamma rays - analysis techniques - **Fermi LAT**

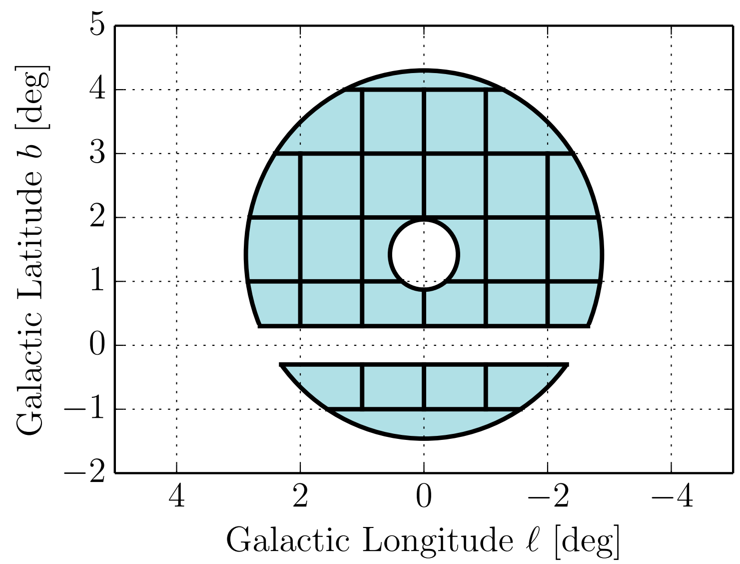




Fermi LAT:

- **Large FoV (whole sky)**
- **Negligible CRs**

Typical: **'Template based' likelihood fitting**



Poisson likelihood:

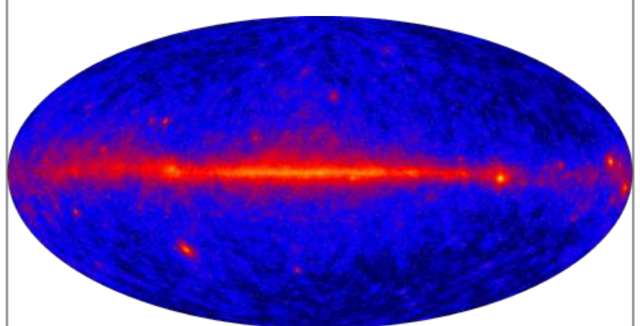
$$\mathcal{L}\left(\boldsymbol{\mu}|\boldsymbol{n}\right) = \prod_{i,j} \frac{{\mu_{ij}}^{n_{ij}}}{n_{ij}!} \exp(-\mu_{ij}).$$

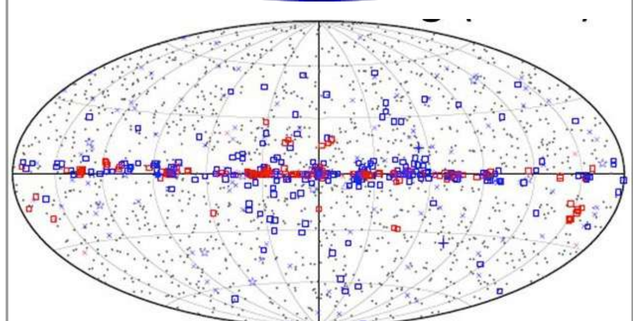
model data

model $\mu_{ij}(A^{\chi}, A_i^X) = A^{\chi}\mu_{ij}^{\chi} + \sum_X A_i^X \mu_{ij}^X$.

DM Astro components

Gamma rays - analysis techniques





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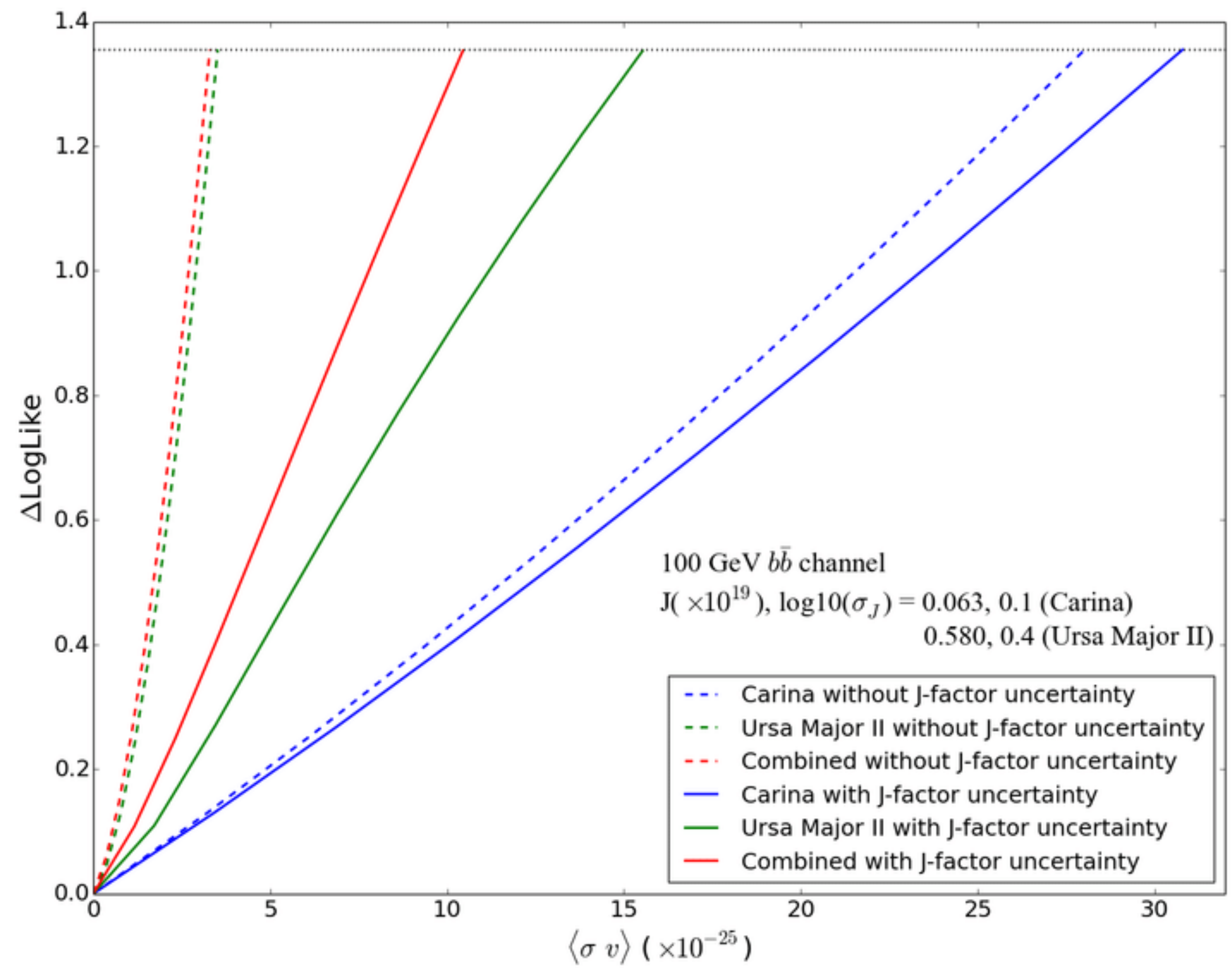
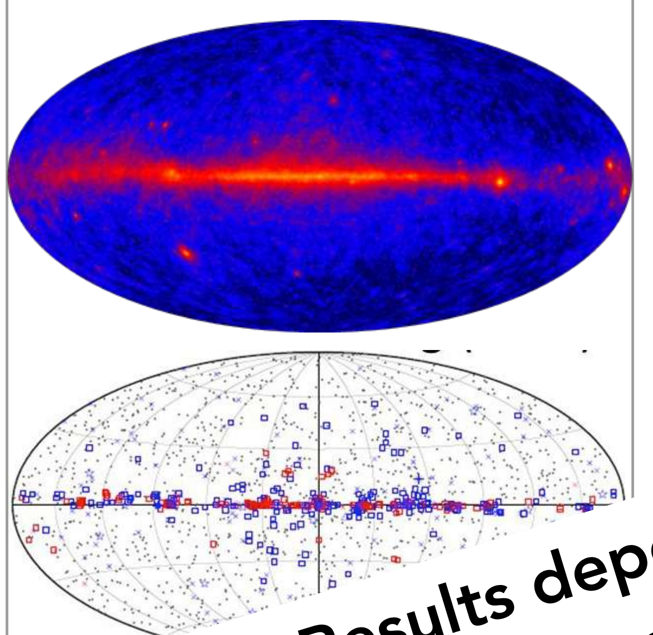
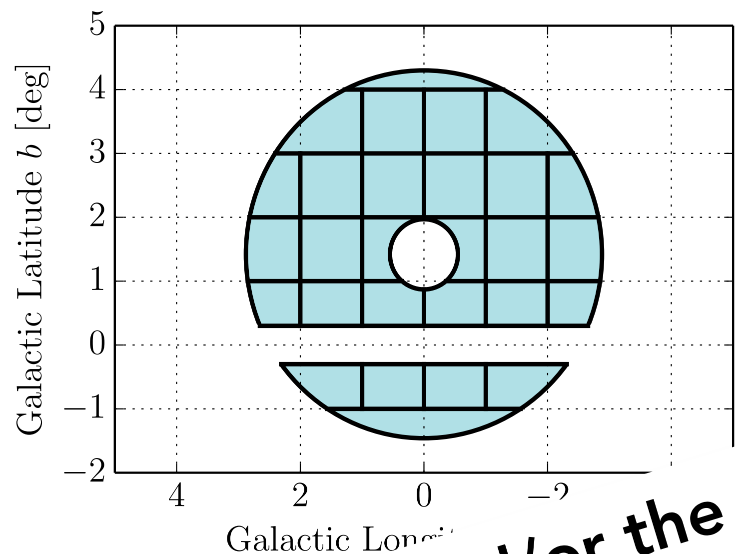


$$\mathrm{TS}(A_\chi) = \min_{\{A_i^X\}} \left(-2 \ln \left[\frac{\mathcal{L}(\boldsymbol{\mu}(A^X, A_i^X) | \boldsymbol{n})}{\mathcal{L}(\hat{\boldsymbol{\mu}} | \boldsymbol{n})} \right] \right)$$

Gamma rays - analysis techniques



Typical: 'Template based' likelihood fitting technique



Poisson likelihood:

$$\mathcal{L}(\boldsymbol{\mu}|\boldsymbol{n}) = \prod \frac{\mu_{ij}{}^{n_{ij}}}{} \quad (-\mu_{ij}).$$

data

- Results depend on input models and/or the amount degrees of freedom - estimate of systematic uncertainties critical

$$\mu_{ij}(A^\chi, A_i^X) = A^\chi \mu_{ij}^\chi + \sum_X A_i^X \mu_{ij}^X .$$

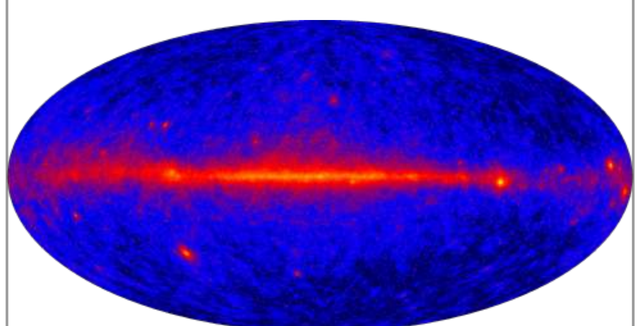
DM

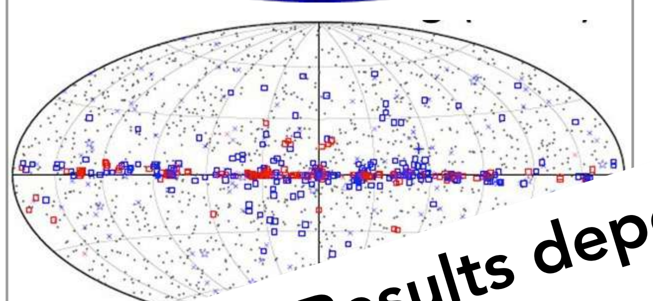
Astro components

Fermi :

- **Large FoV (whole sky)**
- **Negligible CRs**

Gamma rays - analysis techniques

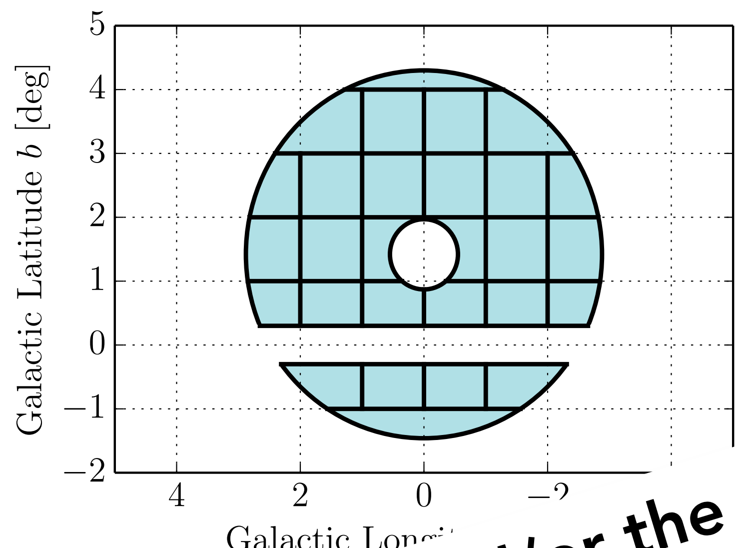




Fermi

- **Large FoV (whole sky)**
- **Negligible CRs**

Typical: 'Template based' likelihood fitting technique



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data

- **Results depend on input models and/or the amount degrees of freedom - estimate of systematic uncertainties critical**

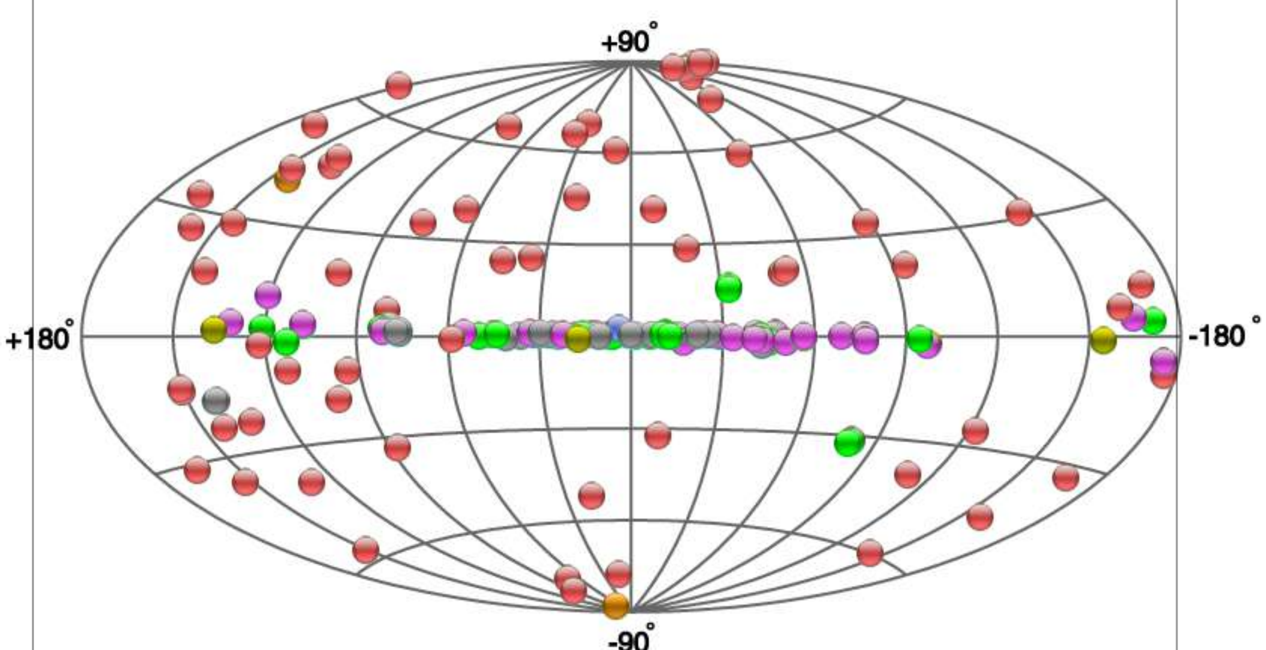
$$\mu_{ij}(A^{\chi}, A_i^X) = A^{\chi}\mu_{ij}^{\chi} + \sum_X A_i^X \mu_{ij}^X \, .$$

'Covariance matrix'

$$\mathcal{L}(\boldsymbol{\mu}|\,\boldsymbol{n}) = \prod_{k=1}^{\mathcal{N}} \frac{\mu_k^{n_k}}{(n_k)!} e^{-\mu_k} \times \exp\left[-\frac{1}{2}\Delta B_k \sum_{l=1}^{\mathcal{N}} \left(K^{-1}\right)_{kl} \Delta B_l\right]$$

ΔBk - perturbations in different background templates, k

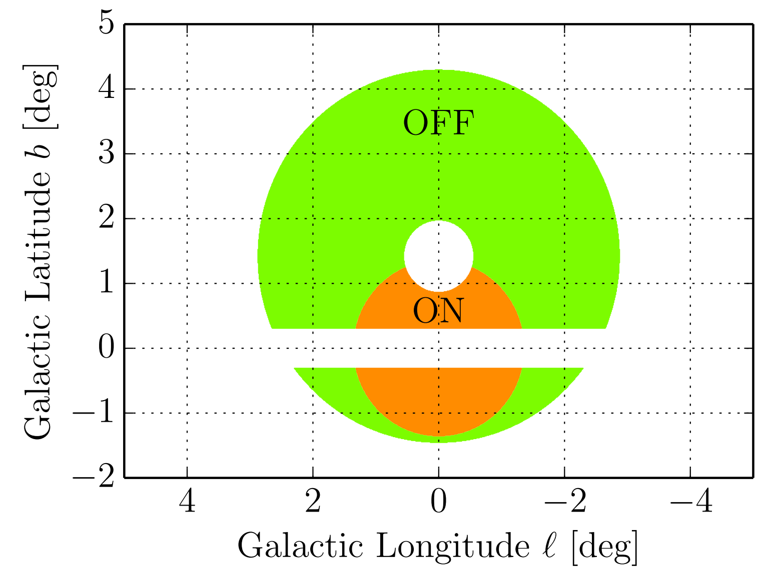
Gamma rays - analysis techniques - **IACTs**



IACTs are pointing telescopes:

- **Small FoV**
- **Significant CR contamination**
- **Better energy and ang resolution**

Traditionally 'ON/OFF' technique

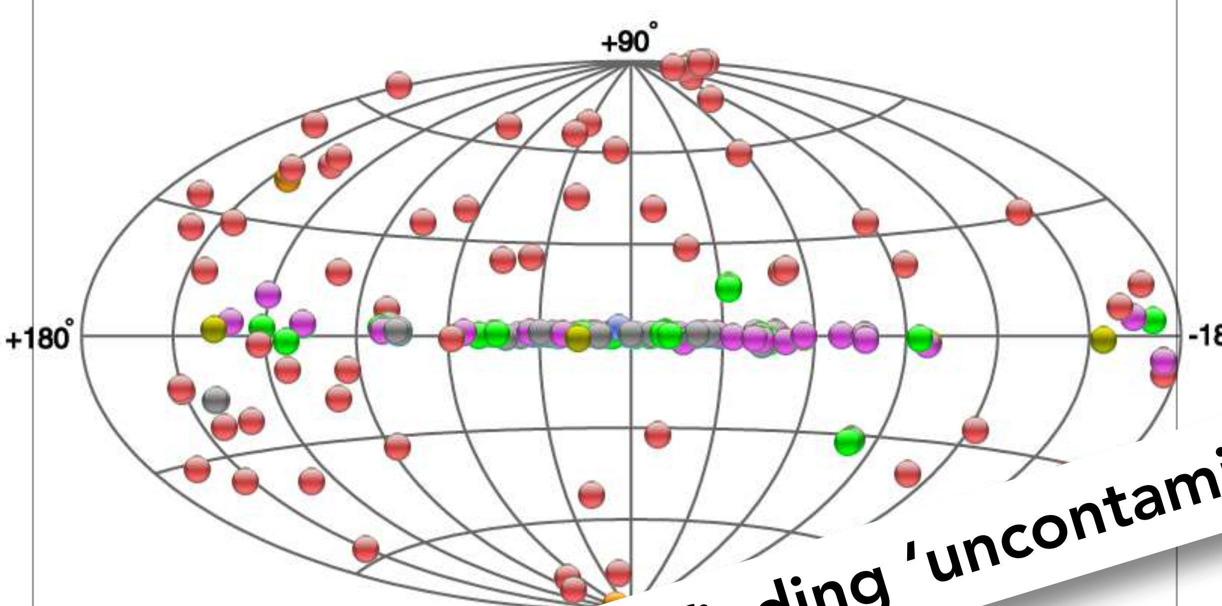


Backgrounds measured, not modelled

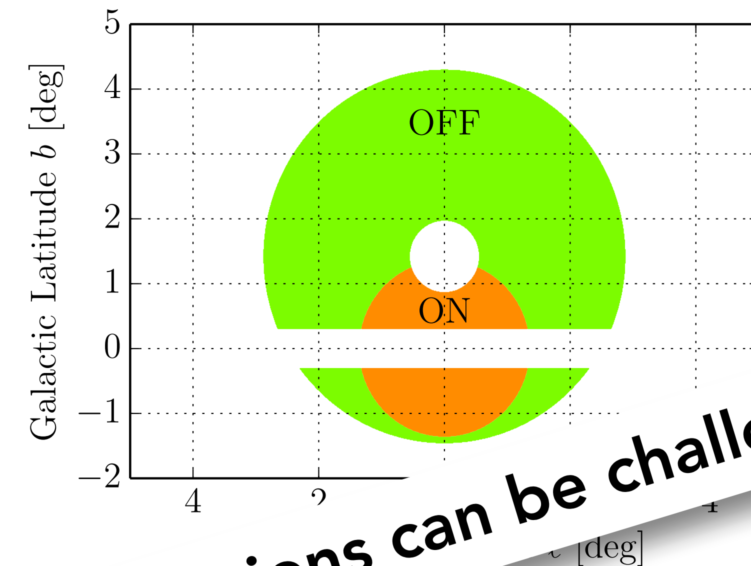
$$\mathcal{L}(M_{\rm DM},\langle\sigma v\rangle) = \prod_{ijk} \mathcal{L}_{ij}\left(\mathbf{N}^{\rm S}_{\mathbf{k}}, \mathbf{N}^{\rm B}_{\mathbf{k}}, \kappa_{\mathbf{k}} \mid \mathbf{N}^{\rm ON}_{\mathbf{k}}, \mathbf{N}^{\rm OFF}_{\mathbf{k}}\right)$$

$$= \prod_{ijk} \frac{\left(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk}\right)^{N^{\rm ON}_{ijk}}}{N^{\rm ON}_{ijk}!} e^{-(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk})} \times \frac{\left(N^{\rm B}_{ijk}\right)^{N^{\rm OFF}_{ijk}}}{N^{\rm OFF}_{ijk}!} e^{-N^{\rm B}_{ijk}}$$

Gamma rays - analysis techniques



Traditionally 'ON/OFF' technique



- However, finding 'uncontaminated' OFF regions can be challenging

...ckgrounds measured not modelled

IACTs are pointing telescopes:

- **Small FoV**
- **Significant CR contamination**
- **Better energy and ang resolution**

$$\mathcal{L}(M_{\rm DM},\langle\sigma v\rangle) = \prod_{ijk} \mathcal{L}_{ij}\left(\mathbf{N}^{\rm S}_{\mathbf{k}}, \mathbf{N}^{\rm B}_{\mathbf{k}}, \kappa_{\mathbf{k}} \mid \mathbf{N}^{\rm ON}_{\mathbf{k}}, \mathbf{N}^{\rm OFF}_{\mathbf{k}}\right)$$

$$= \prod_{ijk} \frac{\left(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk}\right)^{N^{\rm ON}_{ijk}}}{N^{\rm ON}_{ijk}!} e^{-(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk})} \times \frac{\left(N^{\rm B}_{ijk}\right)^{N^{\rm OFF}_{ijk}}}{N^{\rm OFF}_{ijk}!} e^{-N^{\rm B}_{ijk}}$$

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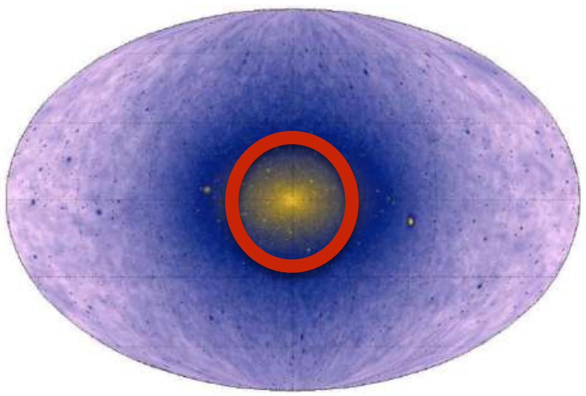
With current telescopes

AND CTA

What strategies (**thermal DM**)?

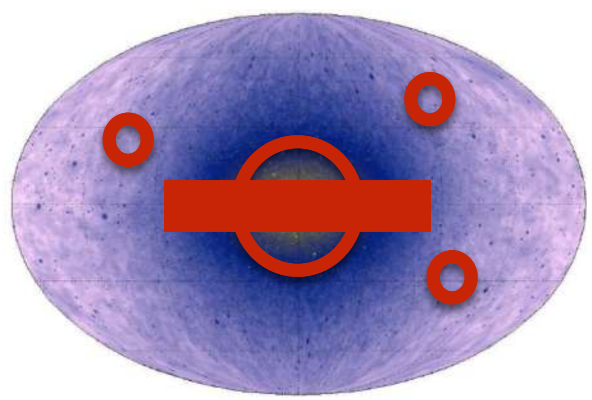
signal strength

GC



[Archaryya et al. JCAP 2020.]

dark subhalos

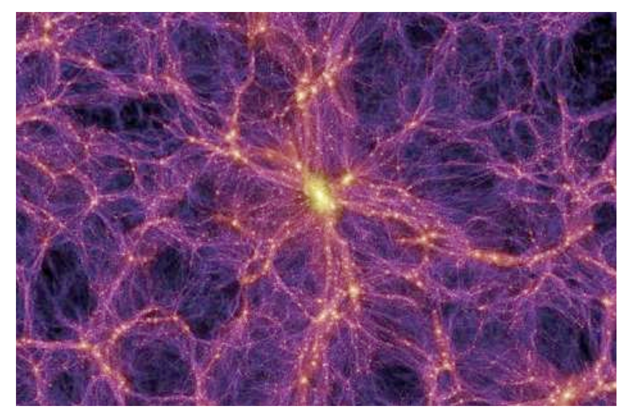


GC halo

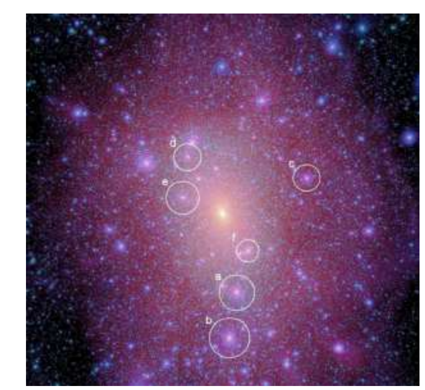
[J. C-B. + Phys.Dark Univ. 32 (2021)]

Extragalactic sources:

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)



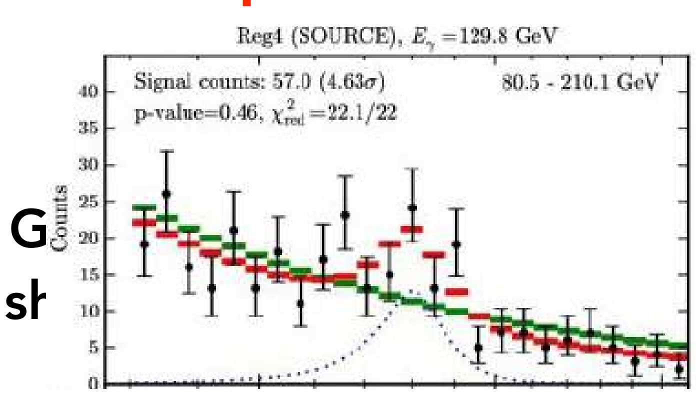
dwarf satellites



Cosmological signal/UEBG:

- Spectral flux
- Auto-correlations
- Cross-correlations w G
  catalogs and cosmic sh

spectral line



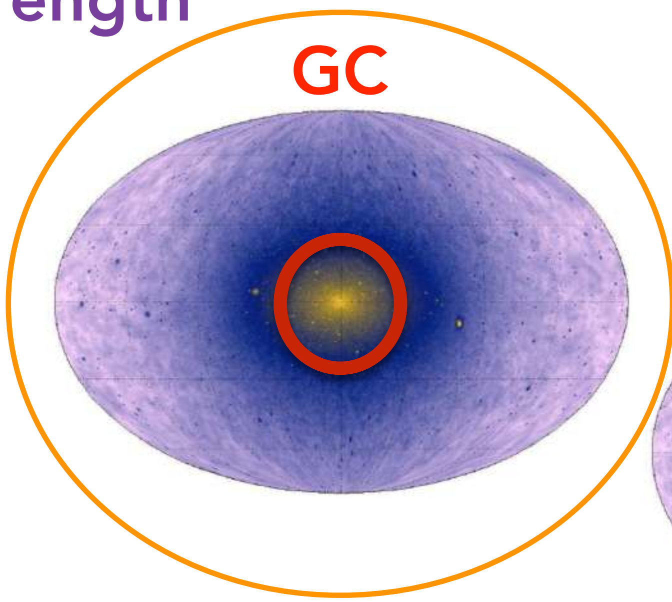
[adapted from: H.-S. Zechlin]

robustness

What strategies (**thermal DM**)?

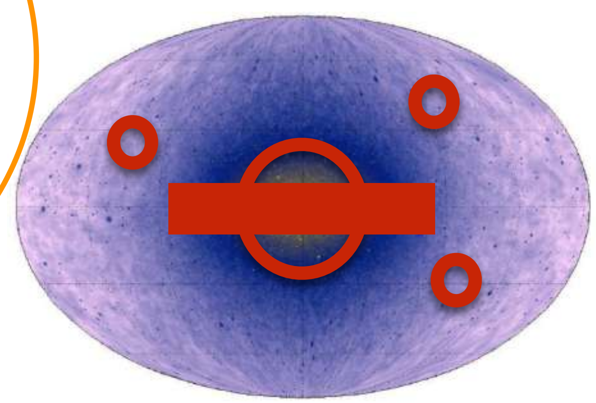
signal strength

GC



[Archaryya et al. JCAP 2020.]

dark subhalos

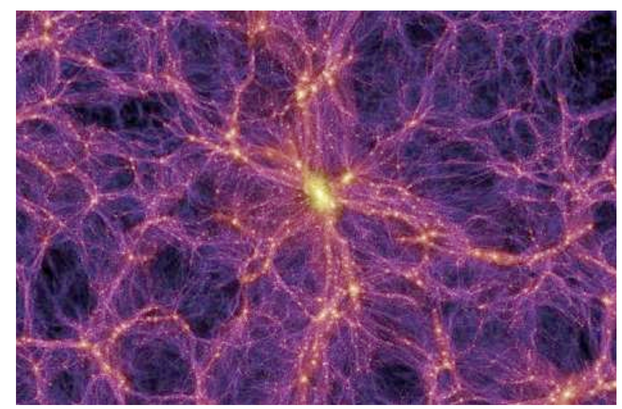


GC halo

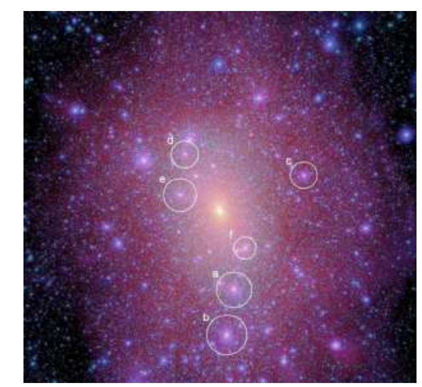
[J. C-B. + Phys.Dark Univ. 32 (2021)]

Extragalactic sources:

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)



dwarf satellites



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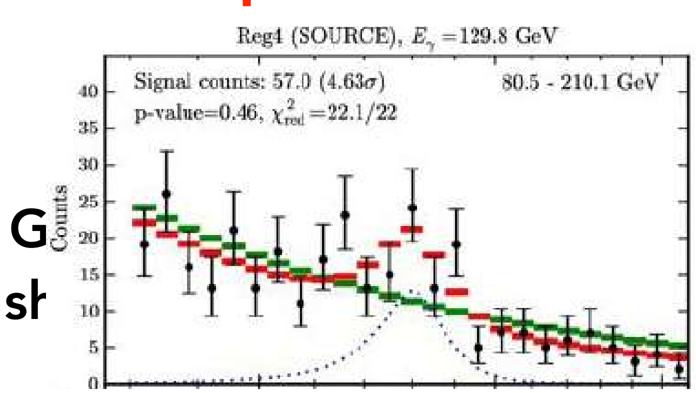
- Auto-correlations
- Cross-correlations w G catalogs and cosmic sh

spectral line



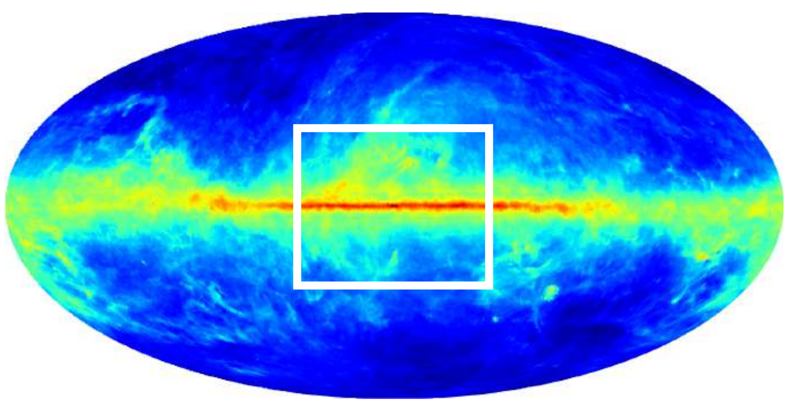
robustness

[adapted from: H.-S. Zechlin]

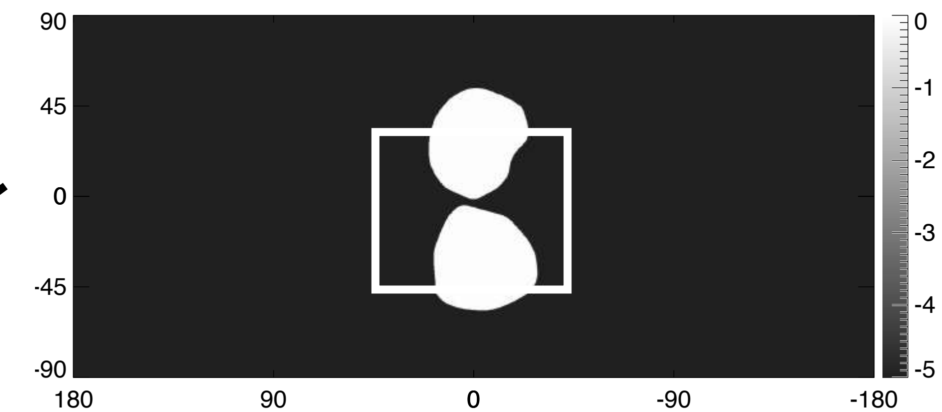
DM @ GC with Fermi LAT

general approach

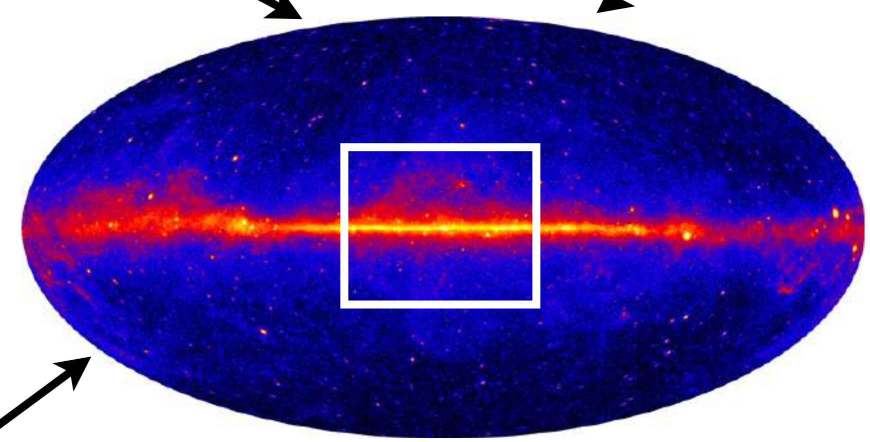
apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs



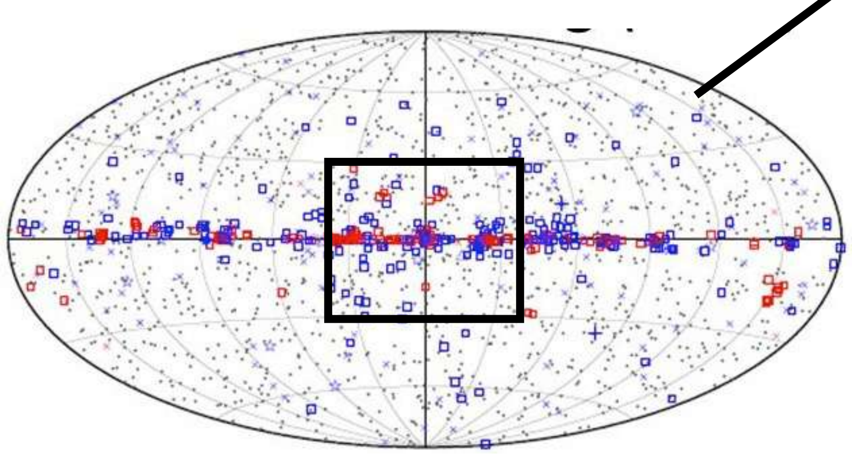
model(s) of the diffuse emission



uniform-brightness template for the Fermi Bubbles



LAT data



point sources from the catalog

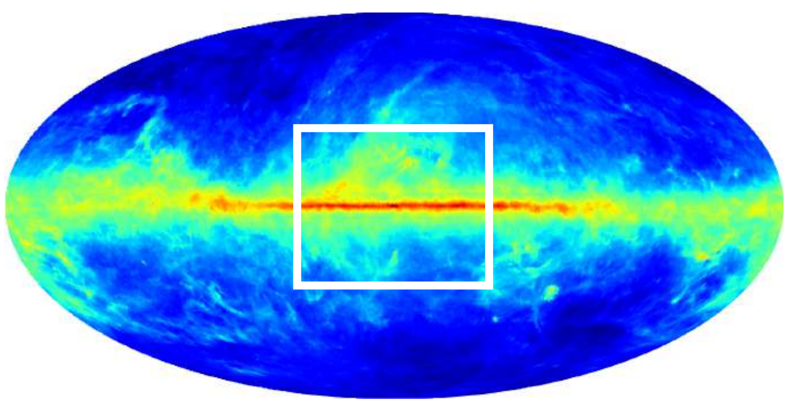
$$\mathcal{L}\left(\boldsymbol{\mu}|\boldsymbol{n}\right) = \prod_{i,j} \frac{{\mu_{ij}}^{n_{ij}}}{n_{ij}!} \exp(-\mu_{ij}).$$

$$\mu_{ij}(A^{\chi}, A_i^X) = A^{\chi}\mu_{ij}^{\chi} + \sum_X A_i^X \mu_{ij}^X \ .$$

DM @ GC with Fermi LAT

general approach

apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs



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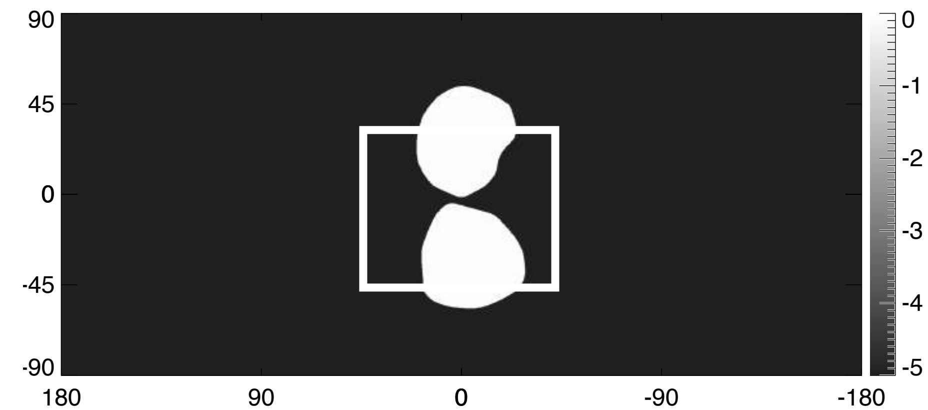

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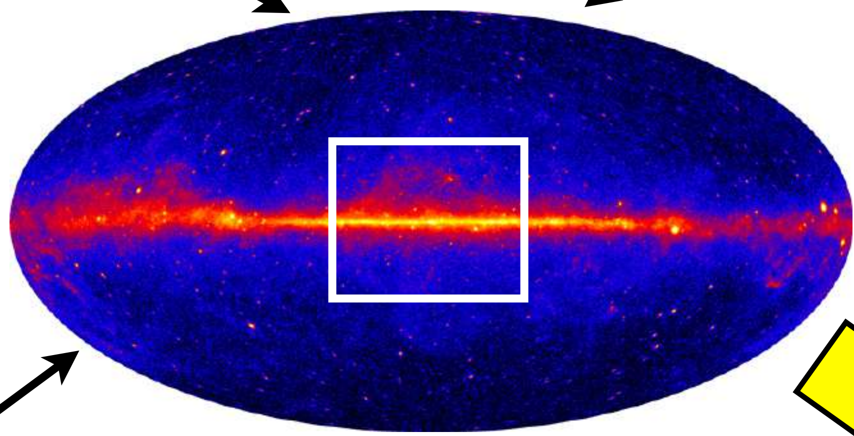
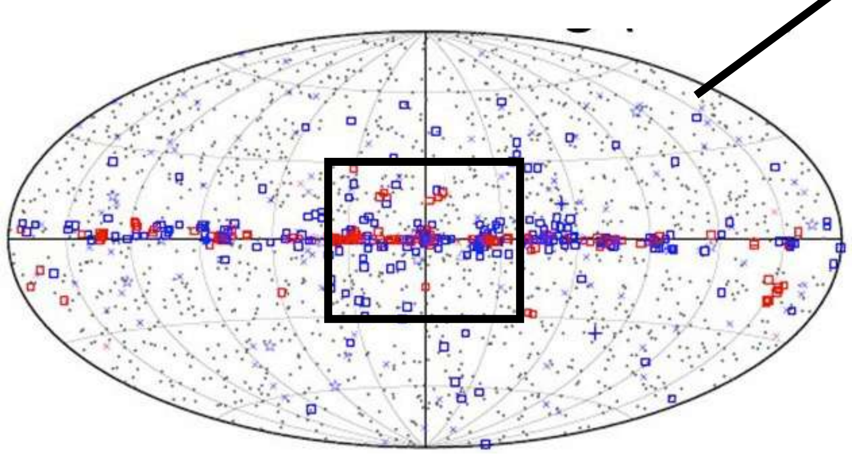


LAT data



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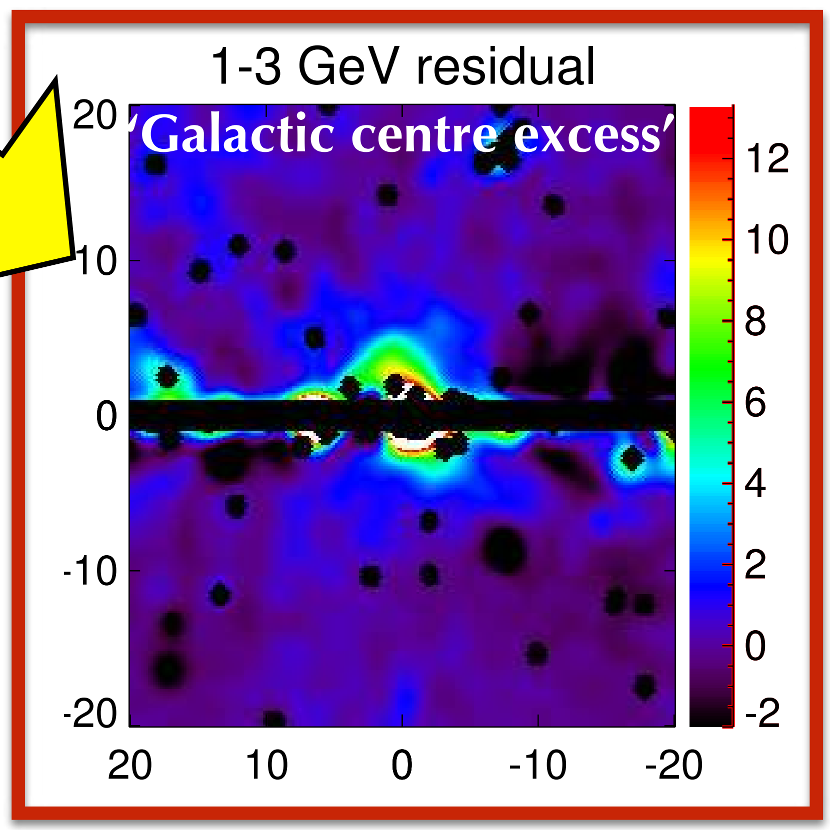
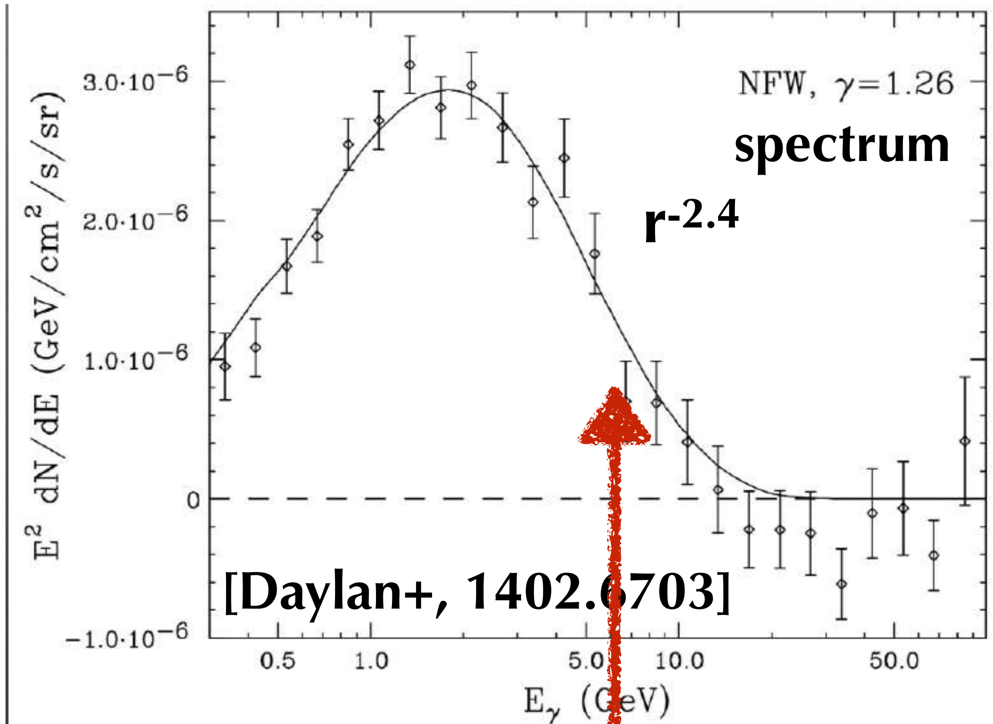
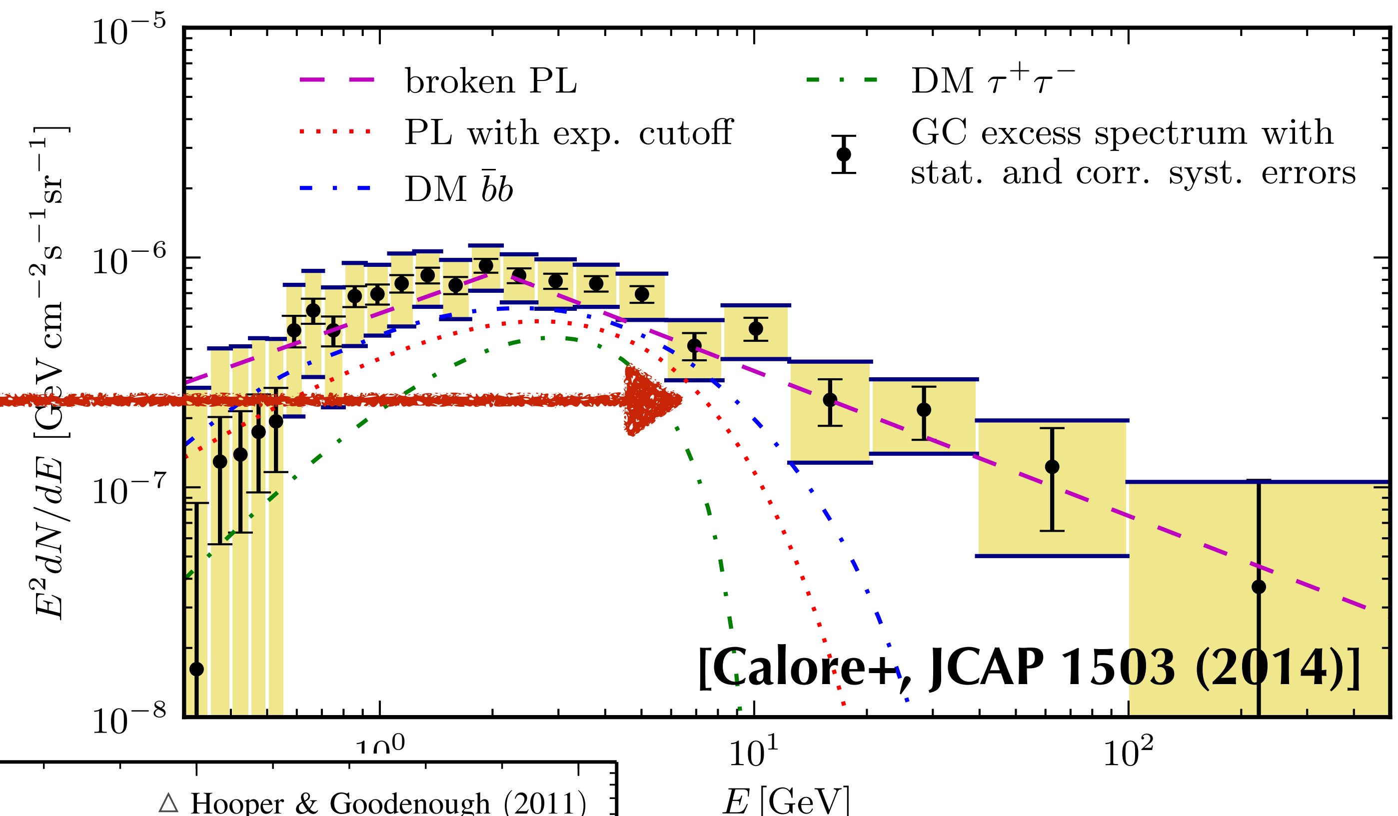


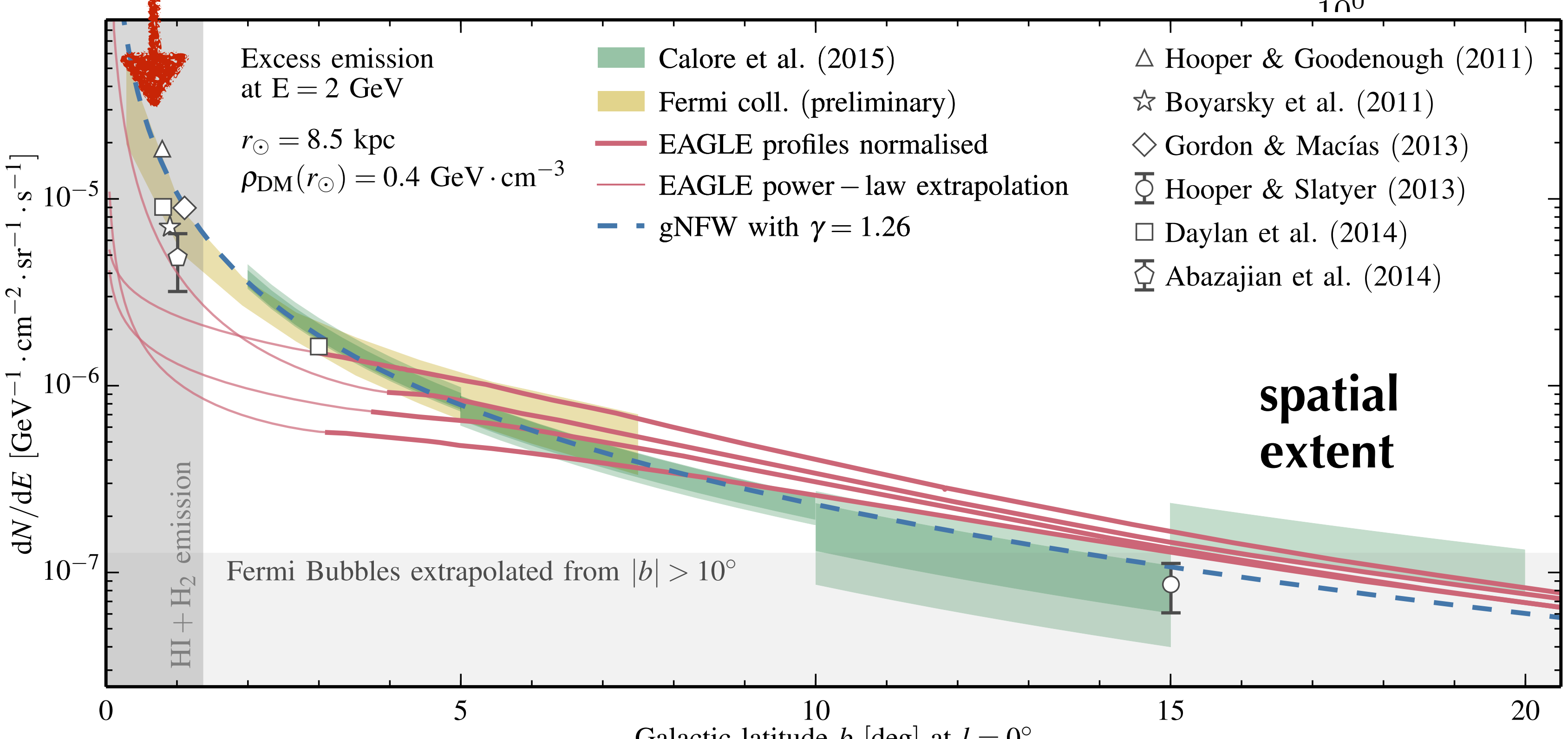
Many works reaching similar results: Vitale & Morseli (2009), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

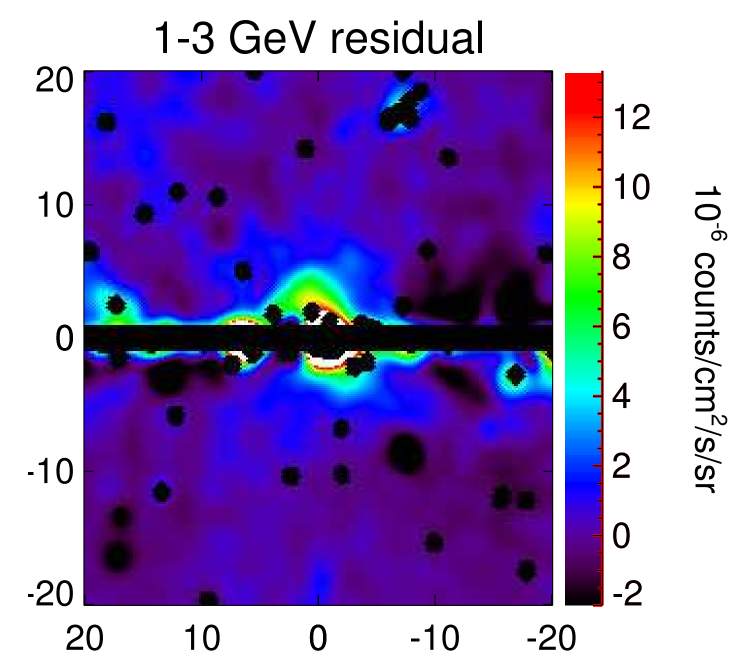


DM spectral fits

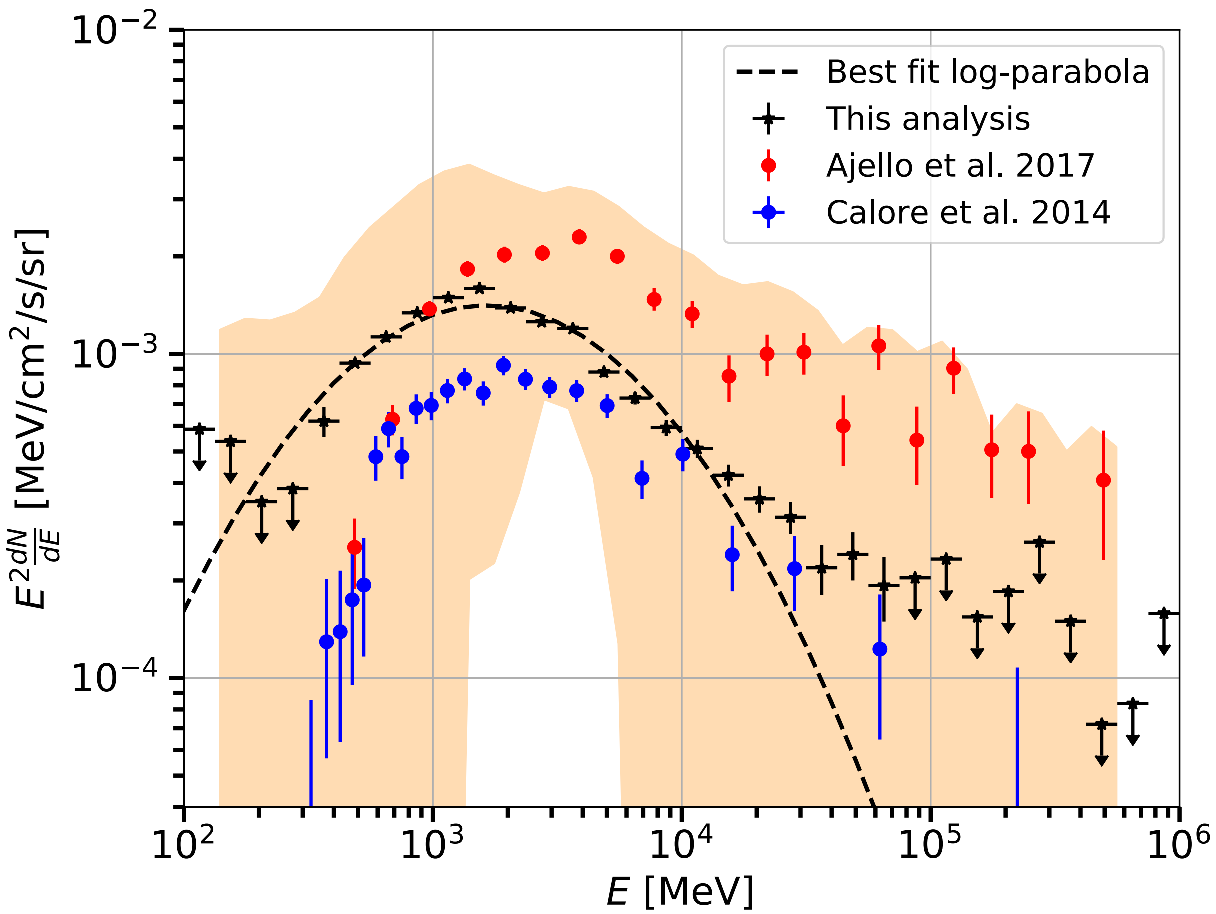


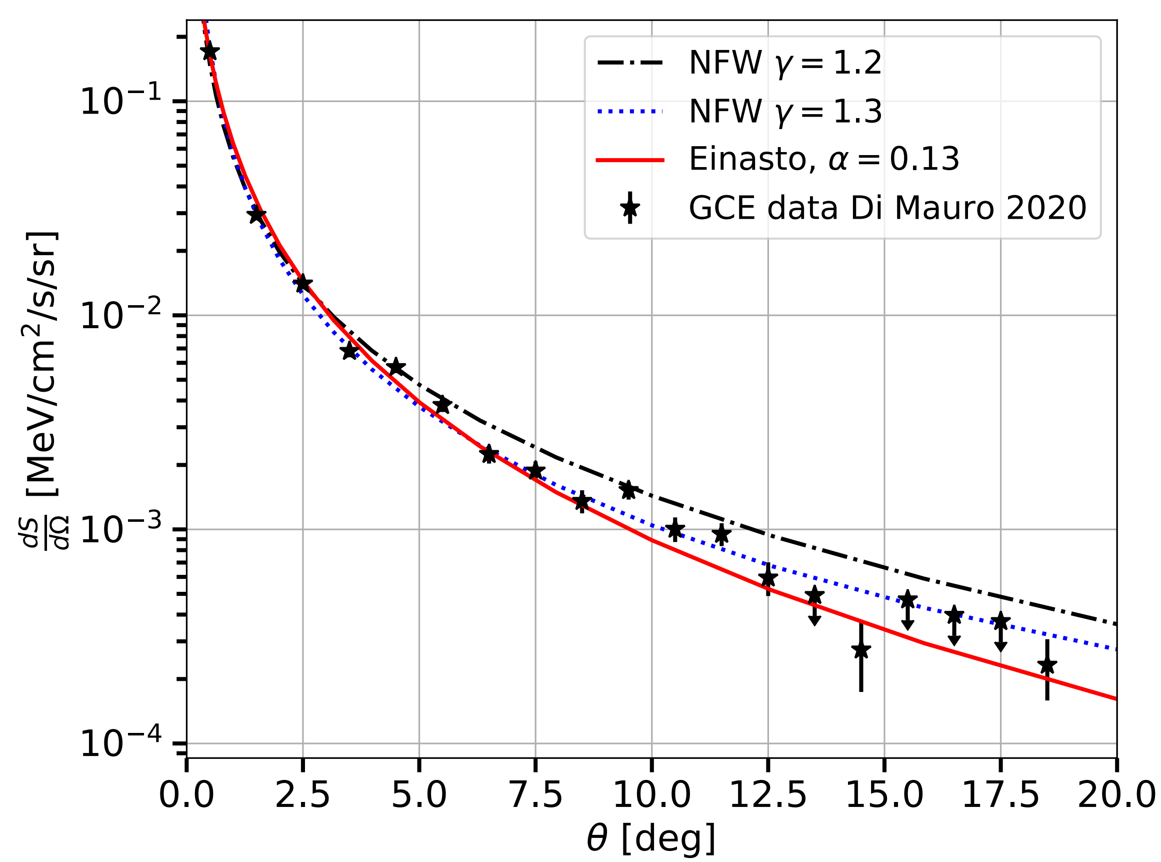
DM morphology





DM @ GC with Fermi LAT





Systematic uncertainty estimates [Ackermann+, ApJ 2017]

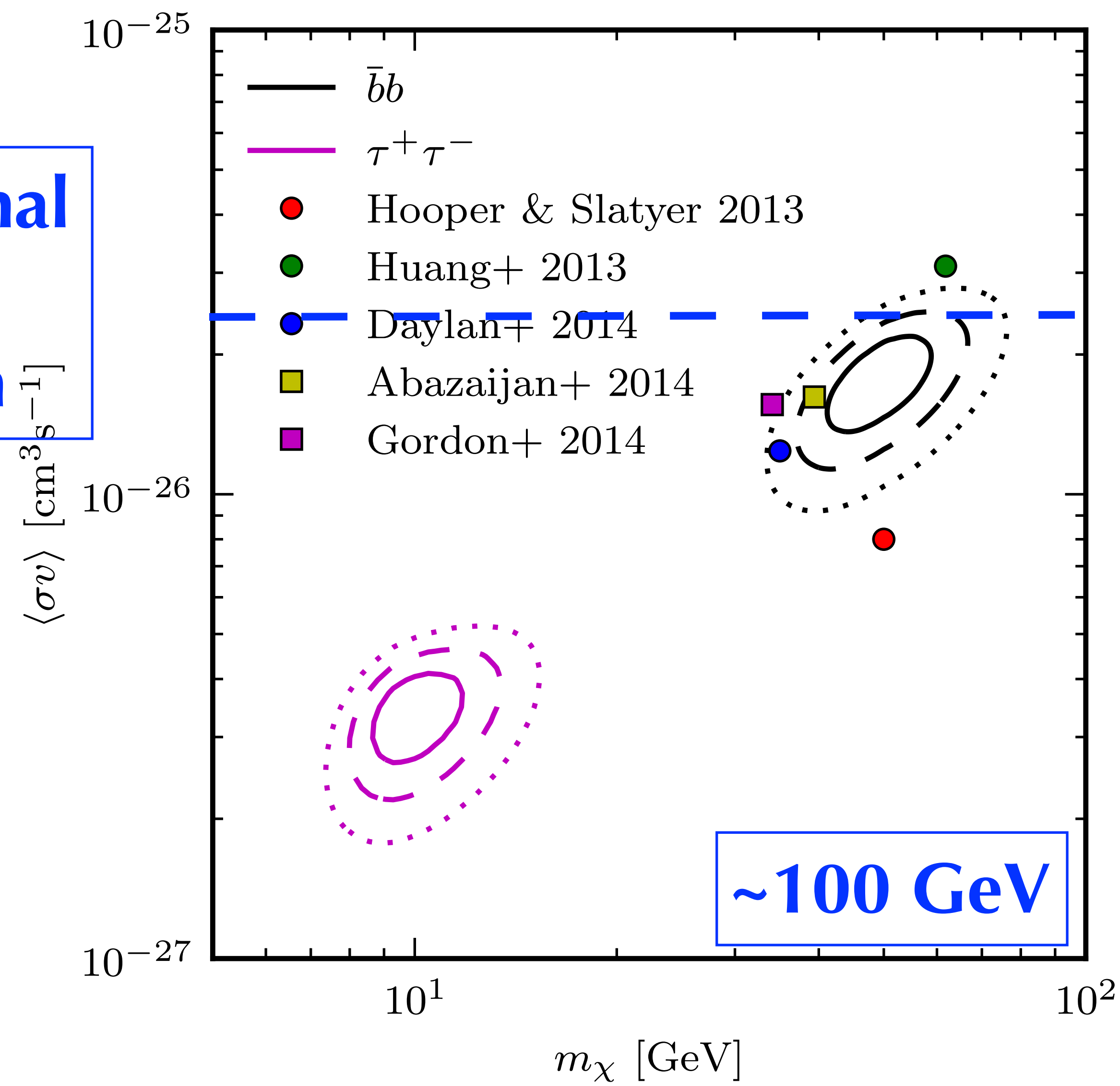
- GALPROP model parameters variations
- Alternative gas maps (softer GCE spectrum < 1GeV)
- Include additional sources of CR electrons near the GC (Gaggero+2015, Carlson+2015 ; GCE reduced)
- data driven template of the Fermi Bubbles

[diMauro+, ApJ 2021]

Could it be dark matter?

Right on the spot where WIMP DM is supposed to be!

~thermal cross section



~100 GeV

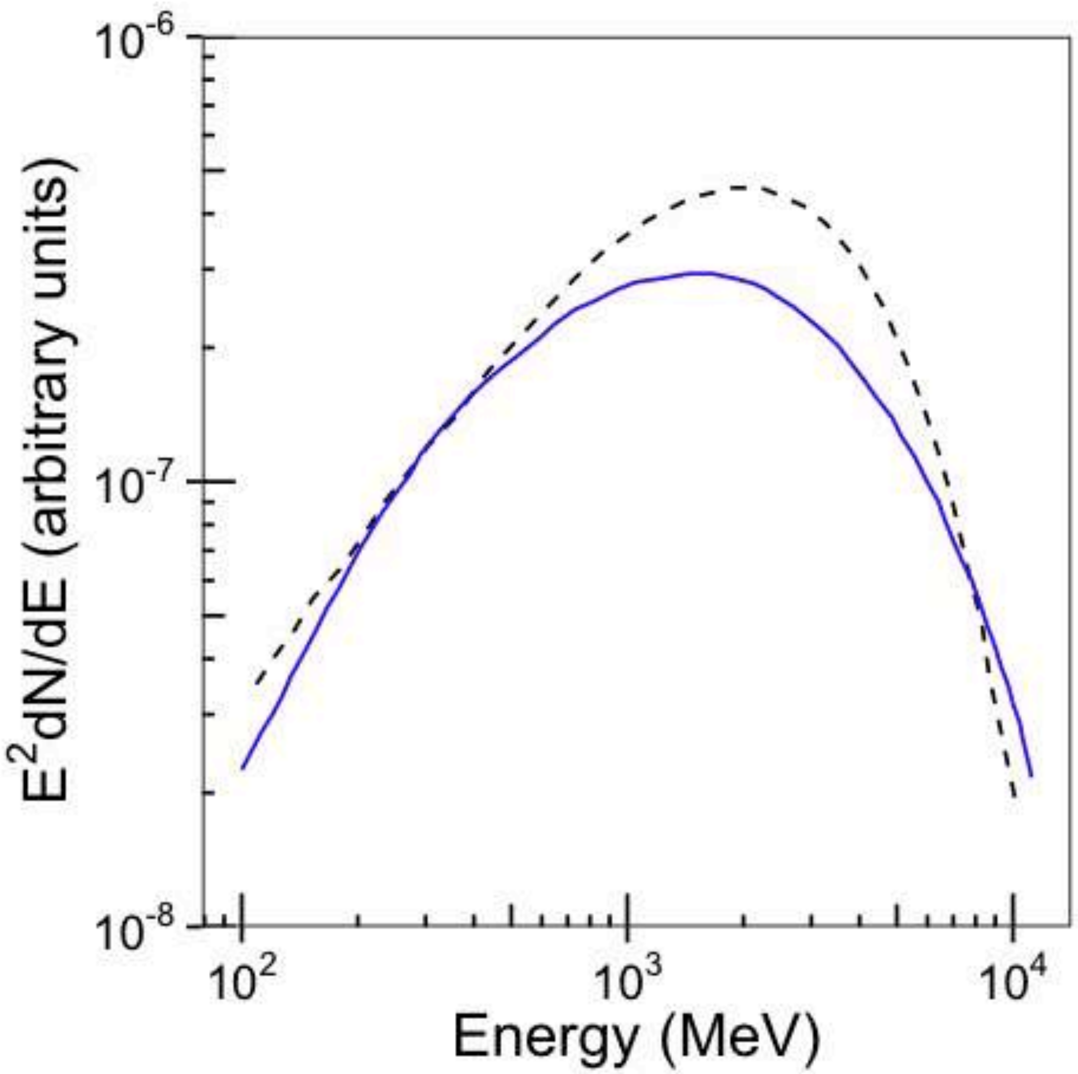
γ

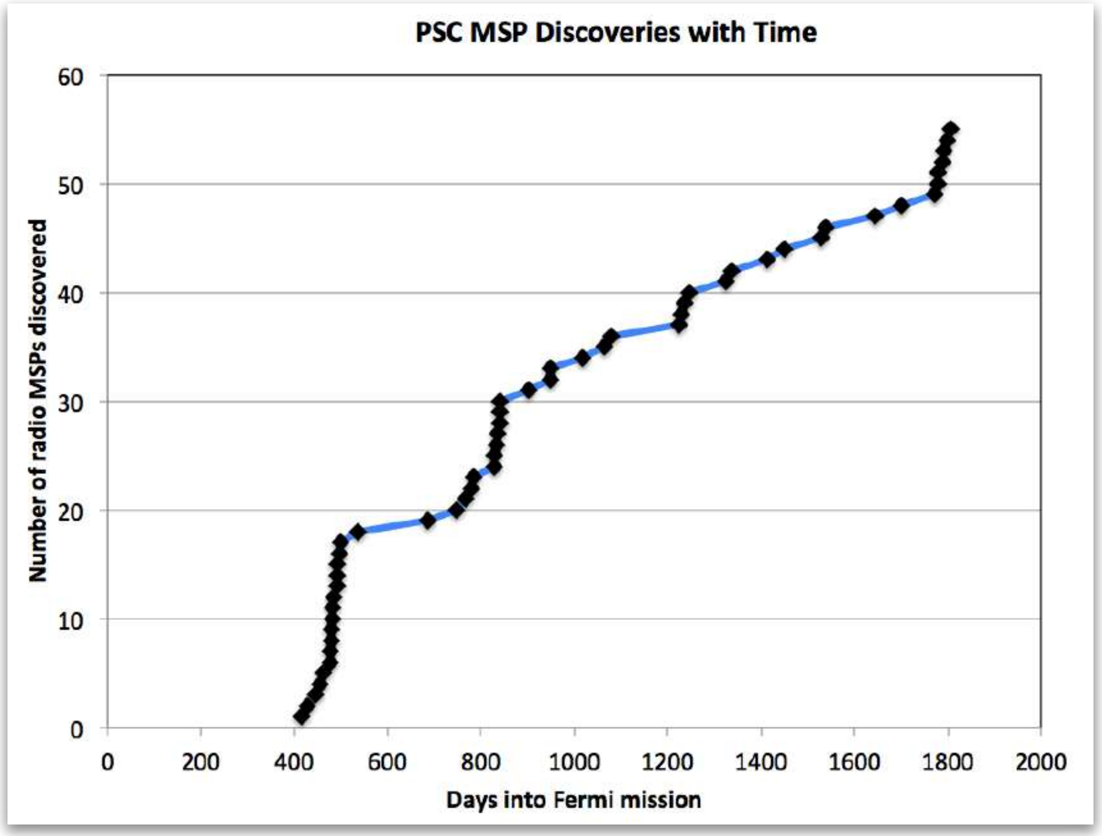
Thermal cross section & <~100 GeV & at the Galactic center

Spatial distribution close to the predicted NFW profiles.

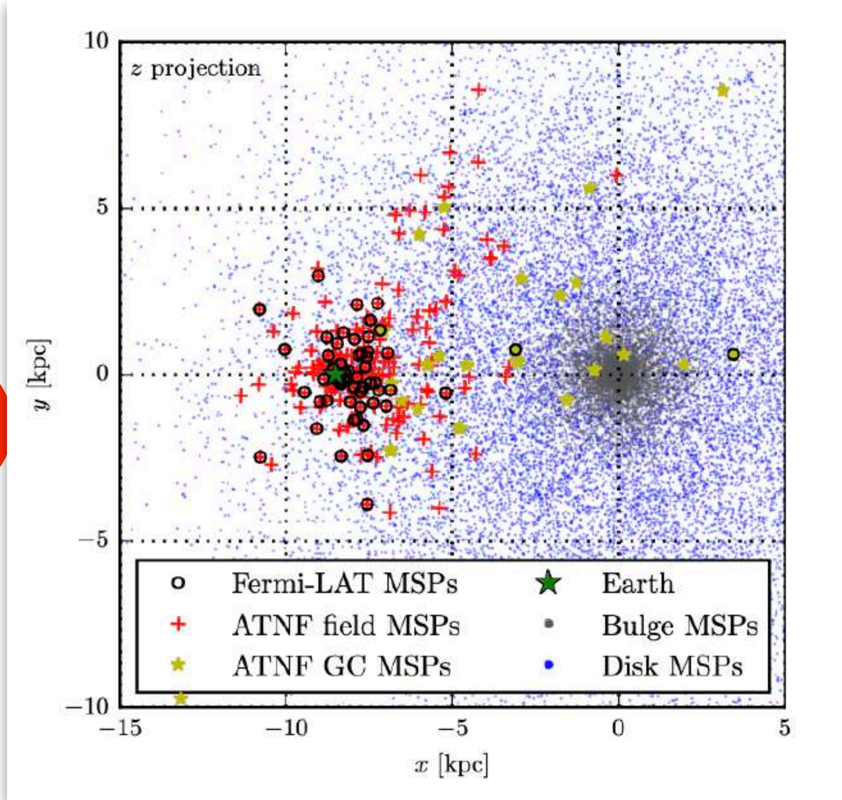
Or…

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)





Baltz et al (2007)



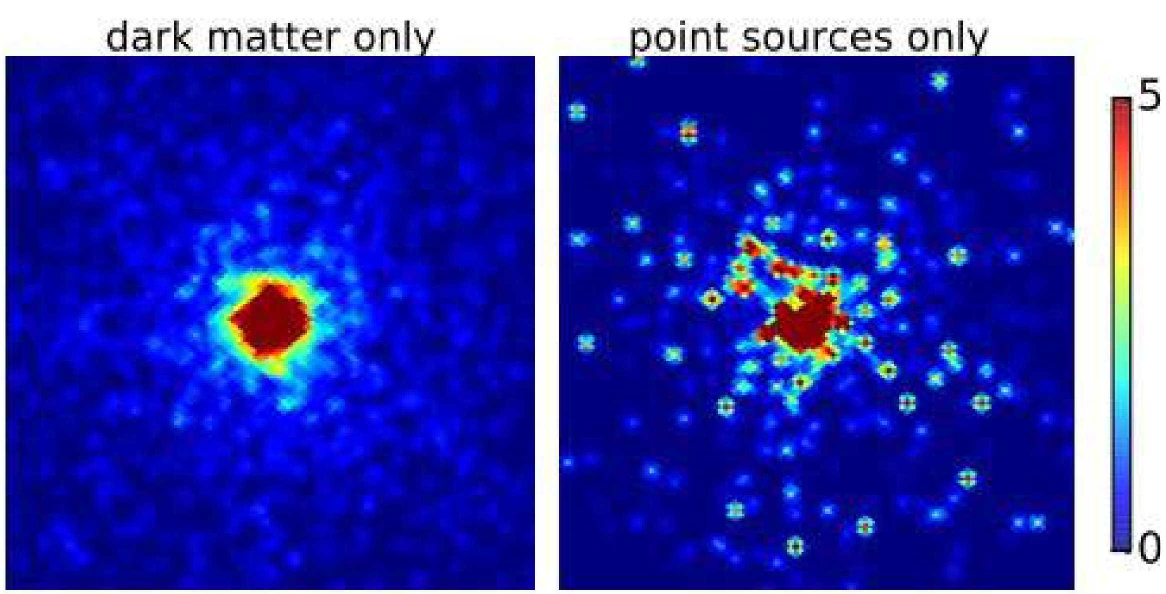
DM @ GC with Fermi LAT

Discovery of the ‘dark matter - like’ excess GCE

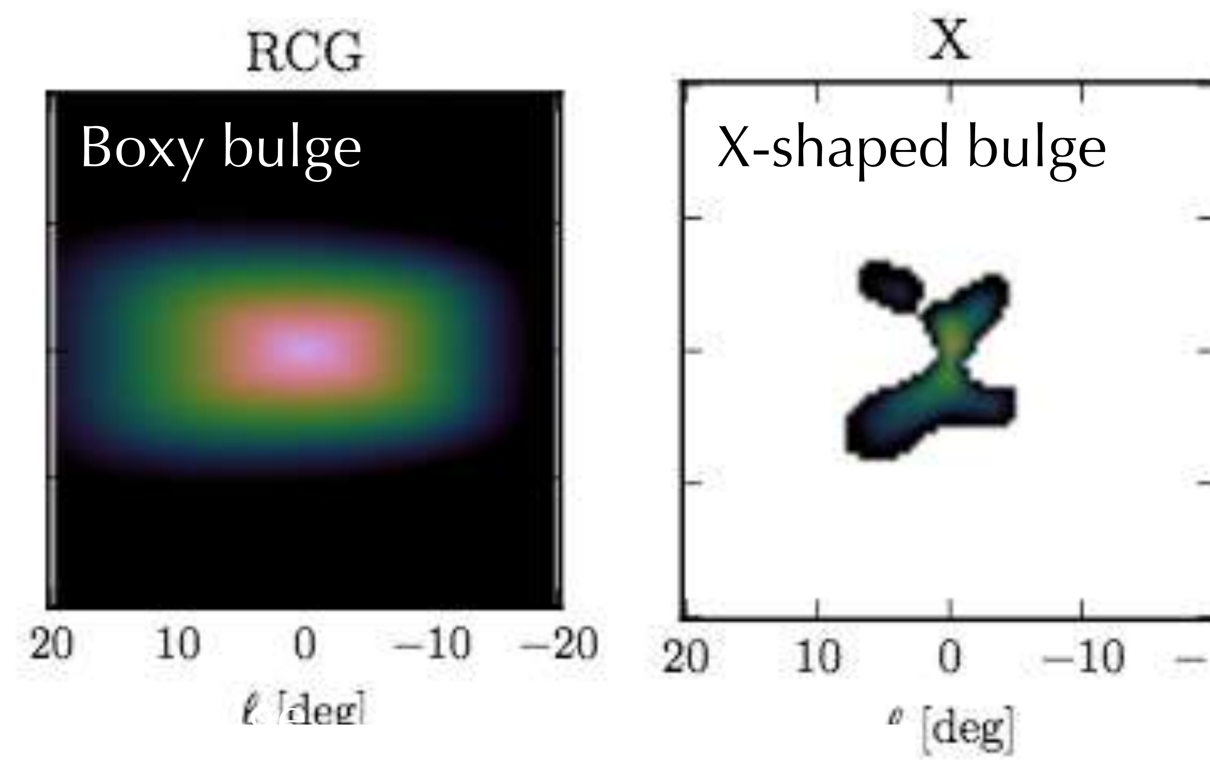
Evidence that the signal is due to pulsar is strengthening:

— **statistical properties of photo counts** suggest that GCE is of a ‘point source’ origin

(Bartels+, PRL (2016), Lee+, PRL (2016))



(Credit: Lee+ 2014)



— evidence of **GCE tracing stellar densities**

(Bartels+, 1711.04778; Macias+, Nature Astronomy (2018))

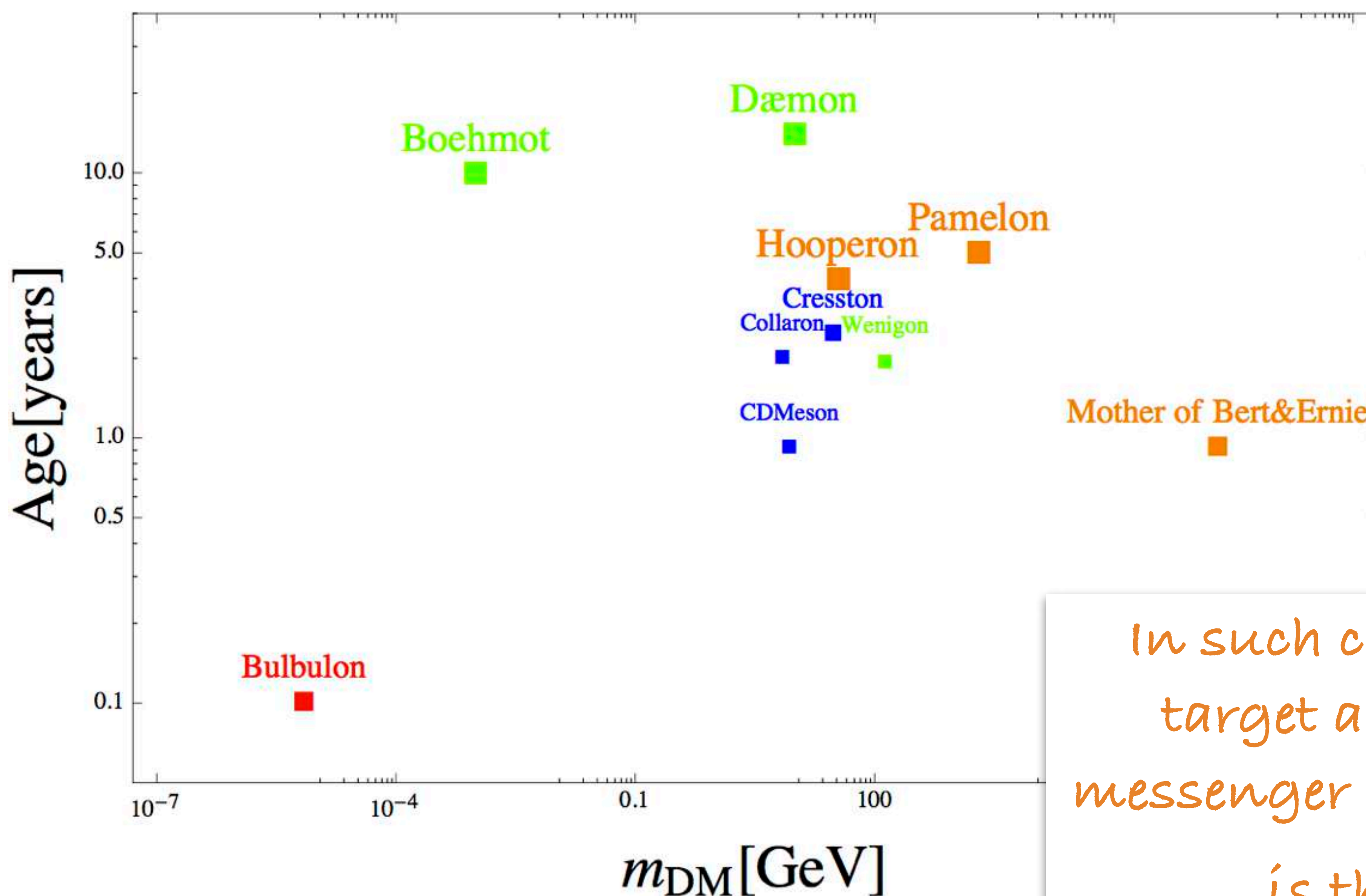
Deep neural networks

— **Machine learning techniques** could also be used

(Caron+, JCAP(2017))

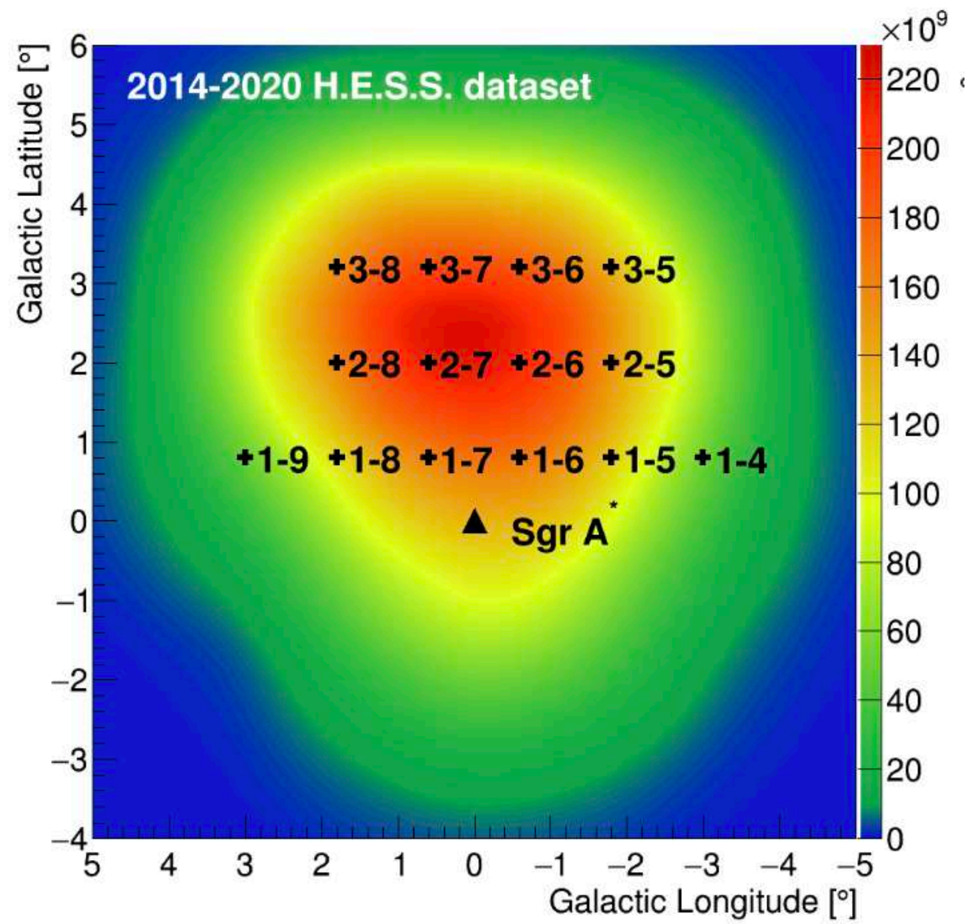
Note of caution

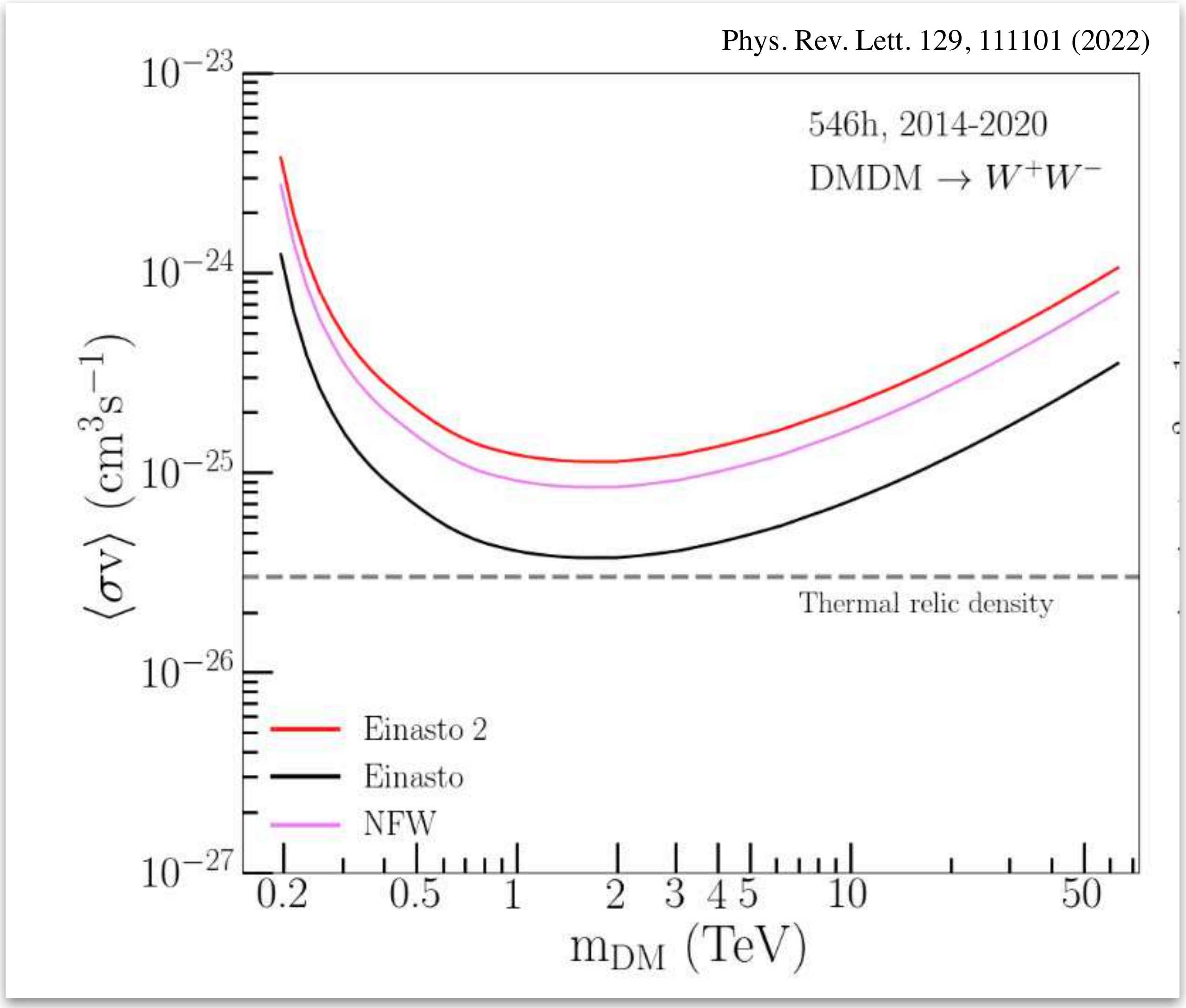
- given the complexity of astrophysical phenomena and experimental challenges it happens relatively often to stumble upon curious **signal hints**.

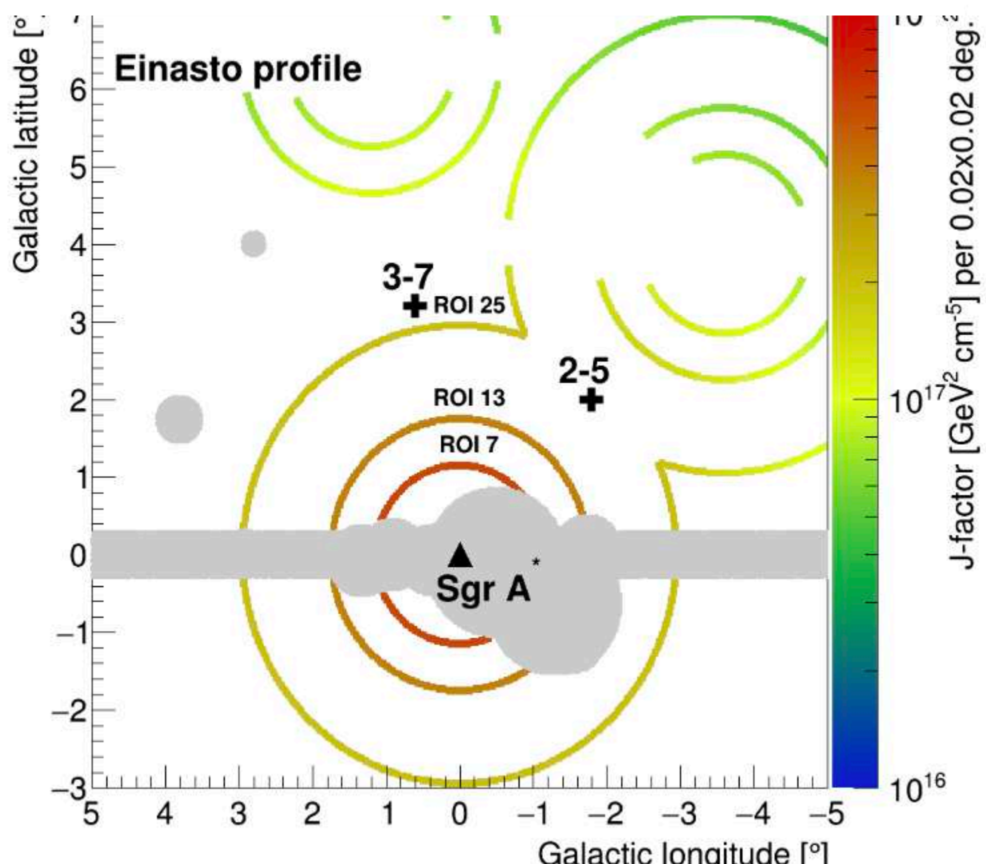


In such cases multi-target and multi-messenger confirmation is the key

DM @ GC with HESS







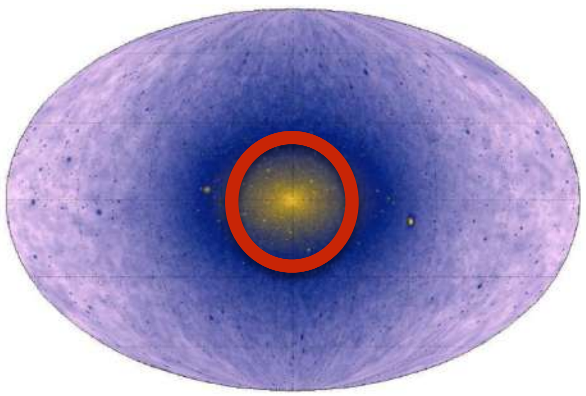
HESS performed an Inner Galaxy survey and derived strong limits. Used ON/OFF techniques.

Limits vanishing for cored DM profiles.

What strategies (**thermal DM**)?

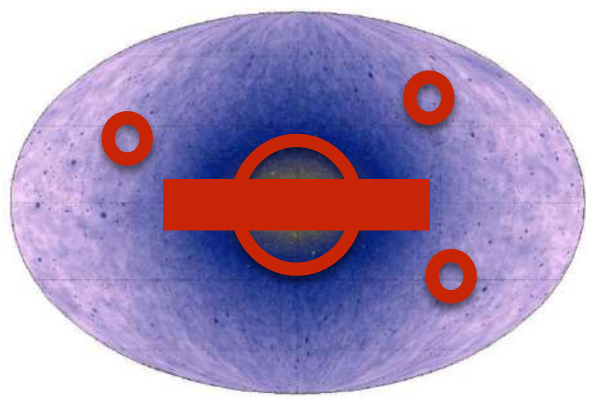
signal strength

GC



[Archaryya et al. JCAP 2020.]

dark subhalos



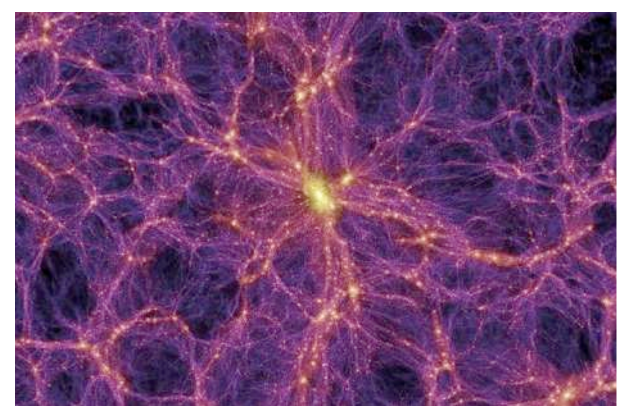
GC halo

[J. C-B. + Phys.Dark Univ. 32 (2021)]

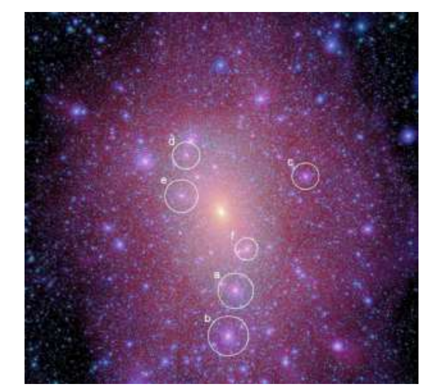
The curious case of Andromeda

Extragalactic sources:

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)



dwarf satellites



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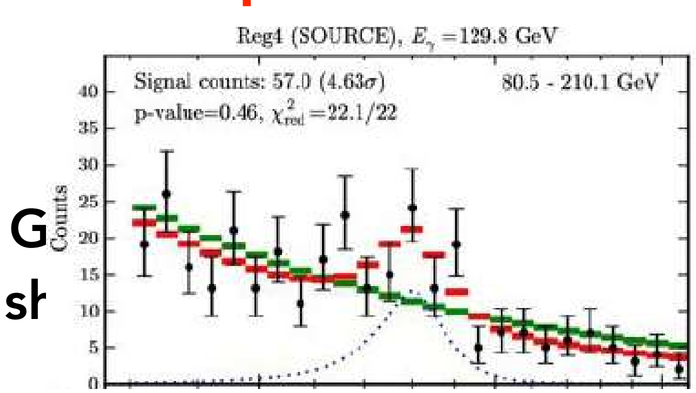
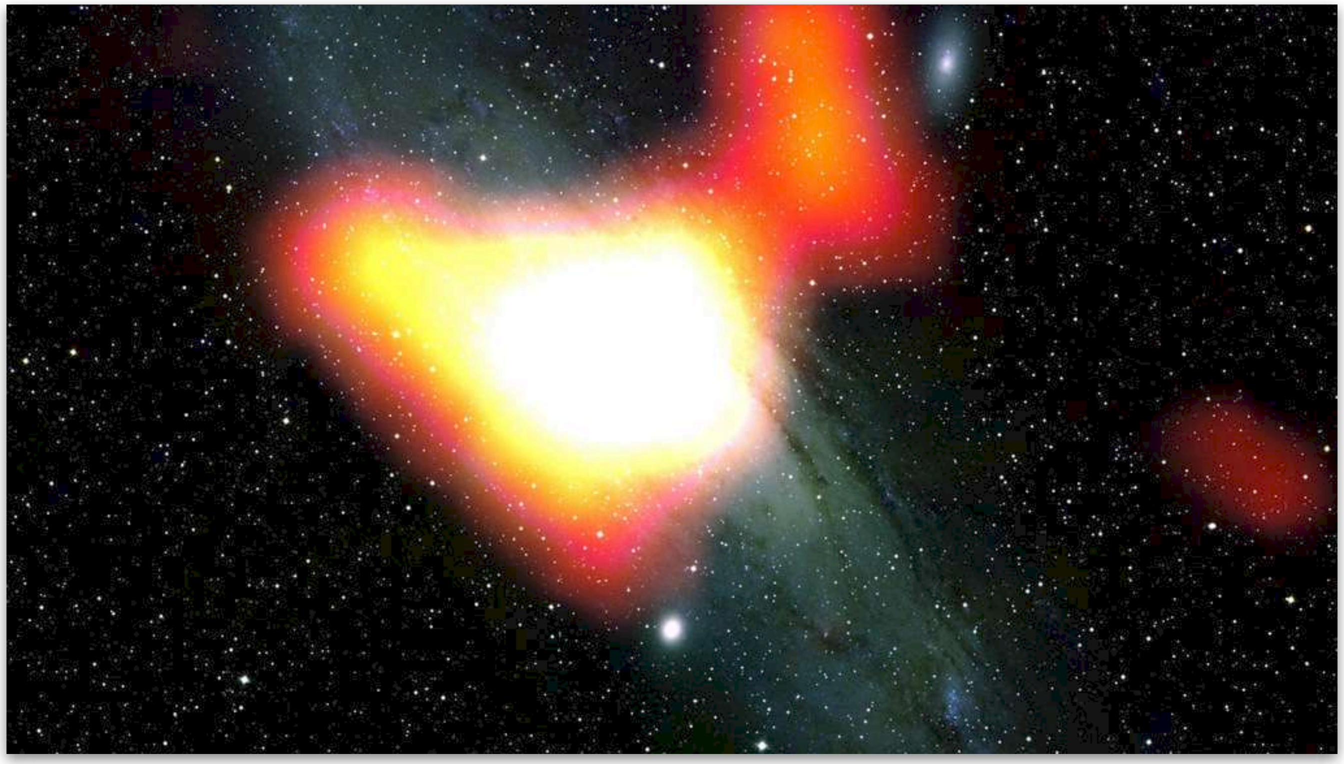
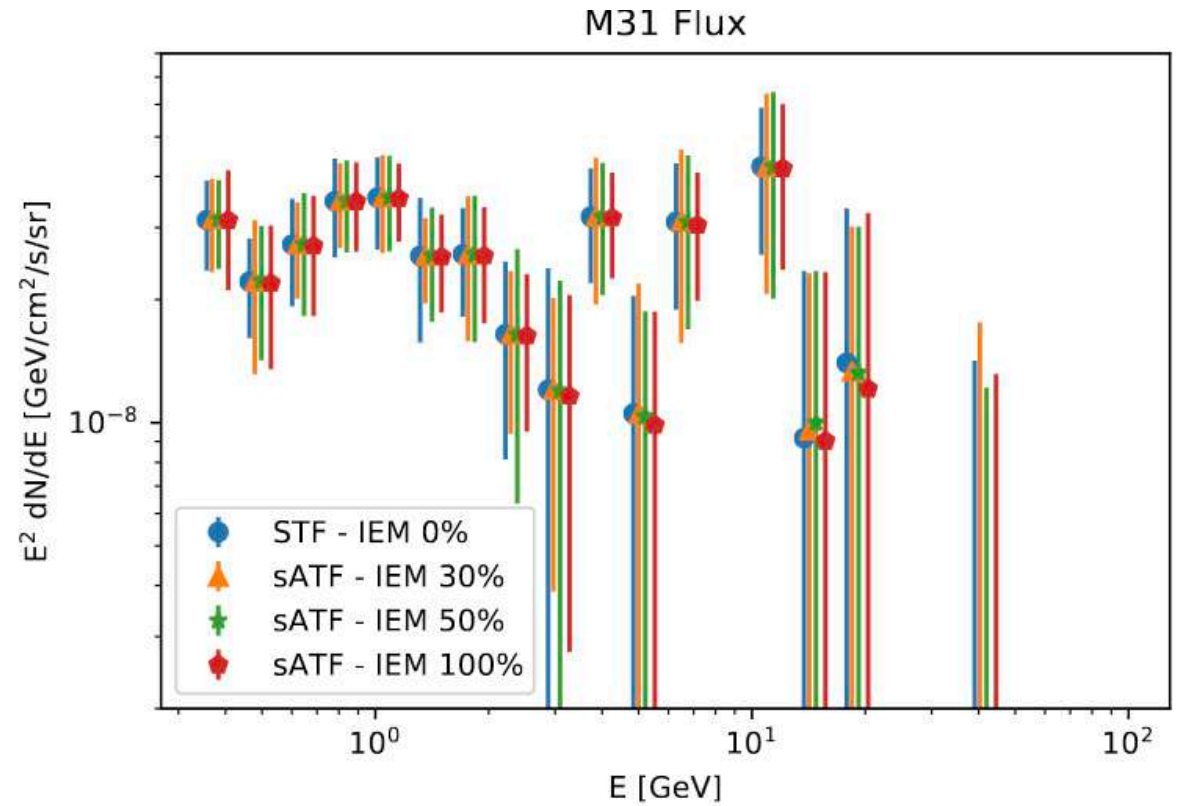


robustness

[adapted from: H.-S. Zechlin]

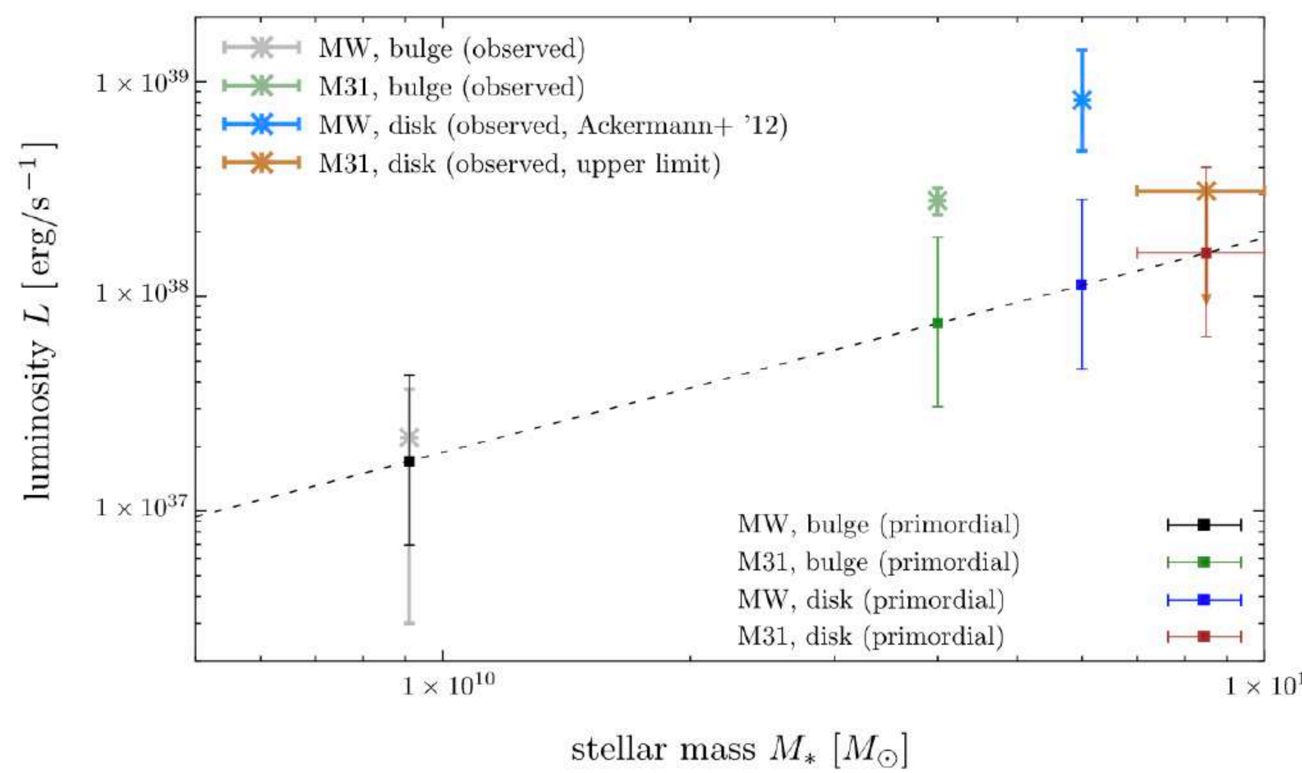
GCE and M31





An extended gamma ray emission (0.4deeg) observed from the Bulge one M31.

Consistent in luminosity and spectra with the GCE (assuming pulsars or DM)

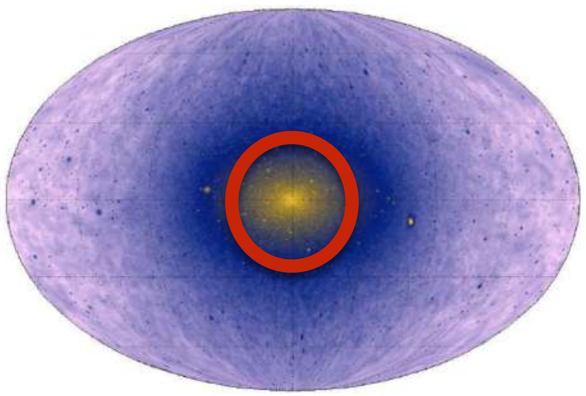


[Eckner, C.+, 1711.05127, Armand, C.+, 2102.06447]

What strategies (**thermal DM**)?

signal strength

GC



[Archaryya et al. JCAP 2020.]

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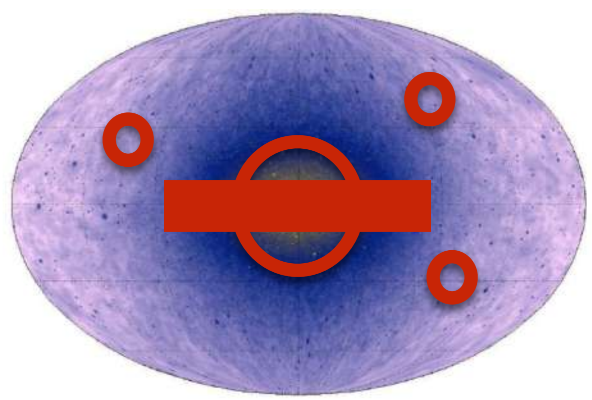

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[J. C-B. + Phys.Dark Univ. 32 (2021)]

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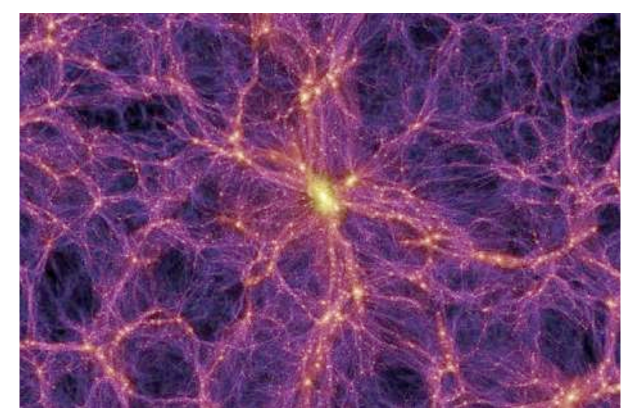

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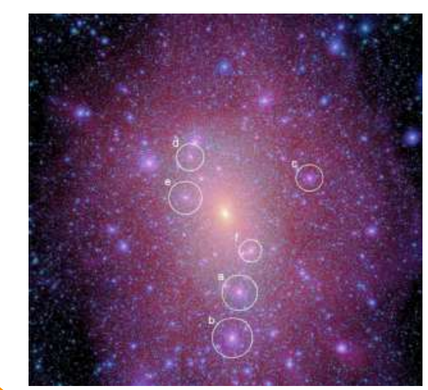

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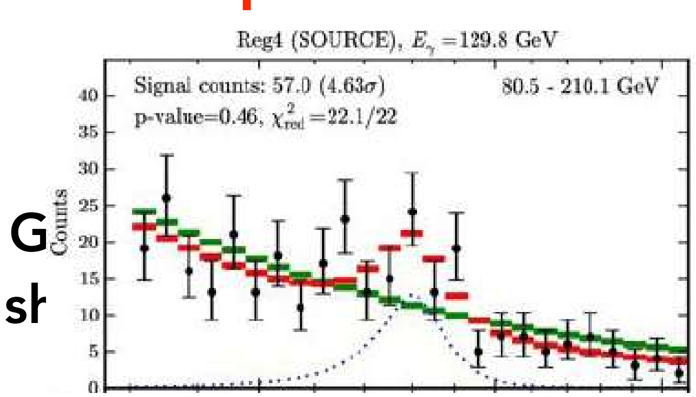
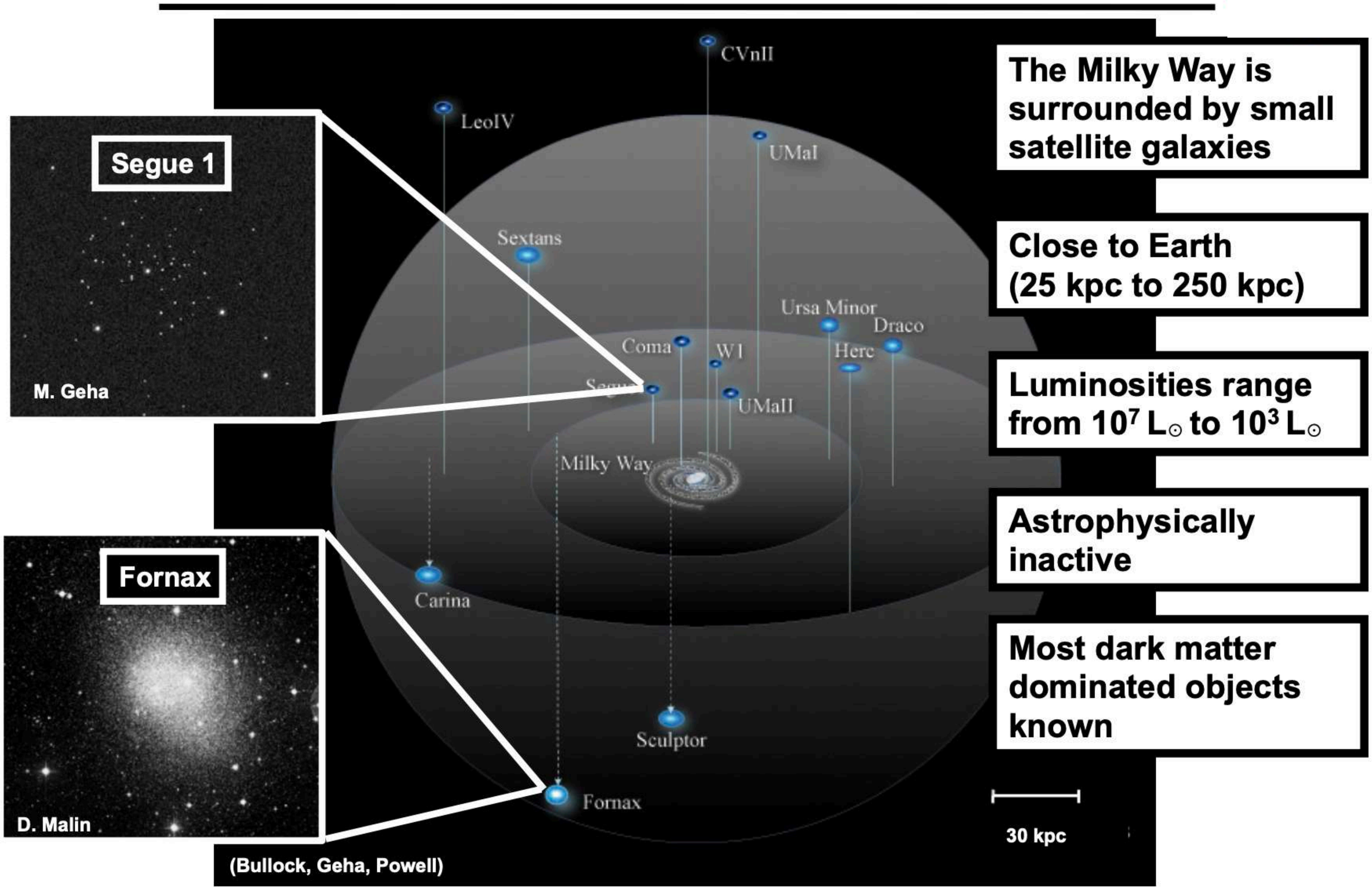


[adapted from: H.-S. Zechlin]

robustness

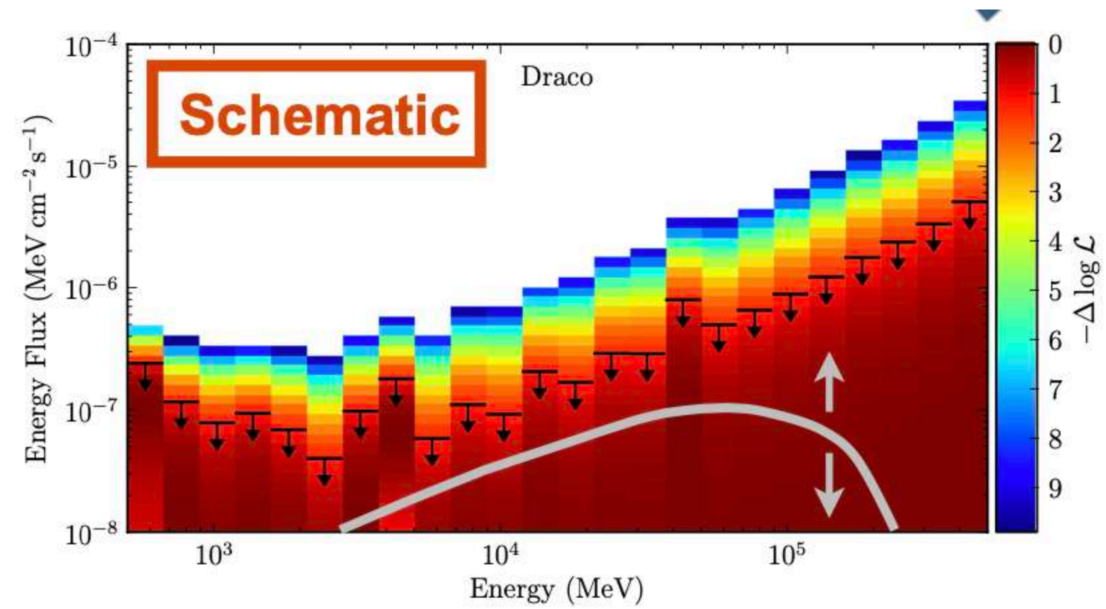
DM @ dSphs with Fermi LAT

For DM interpretation, **multi-target tests** are essential
—> **dwarf spheroidal galaxies!**



DM @ dSphs with Fermi LAT

- **Incorporate statistical uncertainty in the integrated J-factor as a nuisance parameter in the global likelihood fit**
- **Model the spatial distribution of the putative gamma-ray source in accord to the DM profile in the dSphs**
- **Constrain the maximum cross section allowed by the data**
  - **Individually fit each of the 18 dSphs with kinematic J-factors**
  - **Perform a joint likelihood analysis on a subset of 15 spatially independent dSphs**



$$\tilde{\mathcal{L}}_i(\boldsymbol{\mu}, \boldsymbol{\alpha}_i \,|\, \mathcal{D}_i) = \underbrace{\mathcal{L}_i(\boldsymbol{\mu}, \hat{\boldsymbol{\theta}}_i \,|\, \mathcal{D}_i)}_{\text{Global LAT Likelihood}} \underbrace{\times \frac{1}{\ln(10) J_i \sqrt{2\pi}\sigma_i} e^{-(\log_{10}(J_i) - \overline{\log_{10}(J_i)})^2/2\sigma_i^2}}_{\text{Uncertainty in J-factor}}$$

Global LAT Likelihood

Uncertainty in J-factor

$$\underbrace{\tilde{\mathcal{L}}(\boldsymbol{\mu}, \{\boldsymbol{\alpha}_i\} \,|\, \mathcal{D}) = \prod_i \tilde{\mathcal{L}}_i(\boldsymbol{\mu}, \boldsymbol{\alpha}_i \,|\, \mathcal{D}_i)}_{\text{Joint Likelihood}}$$

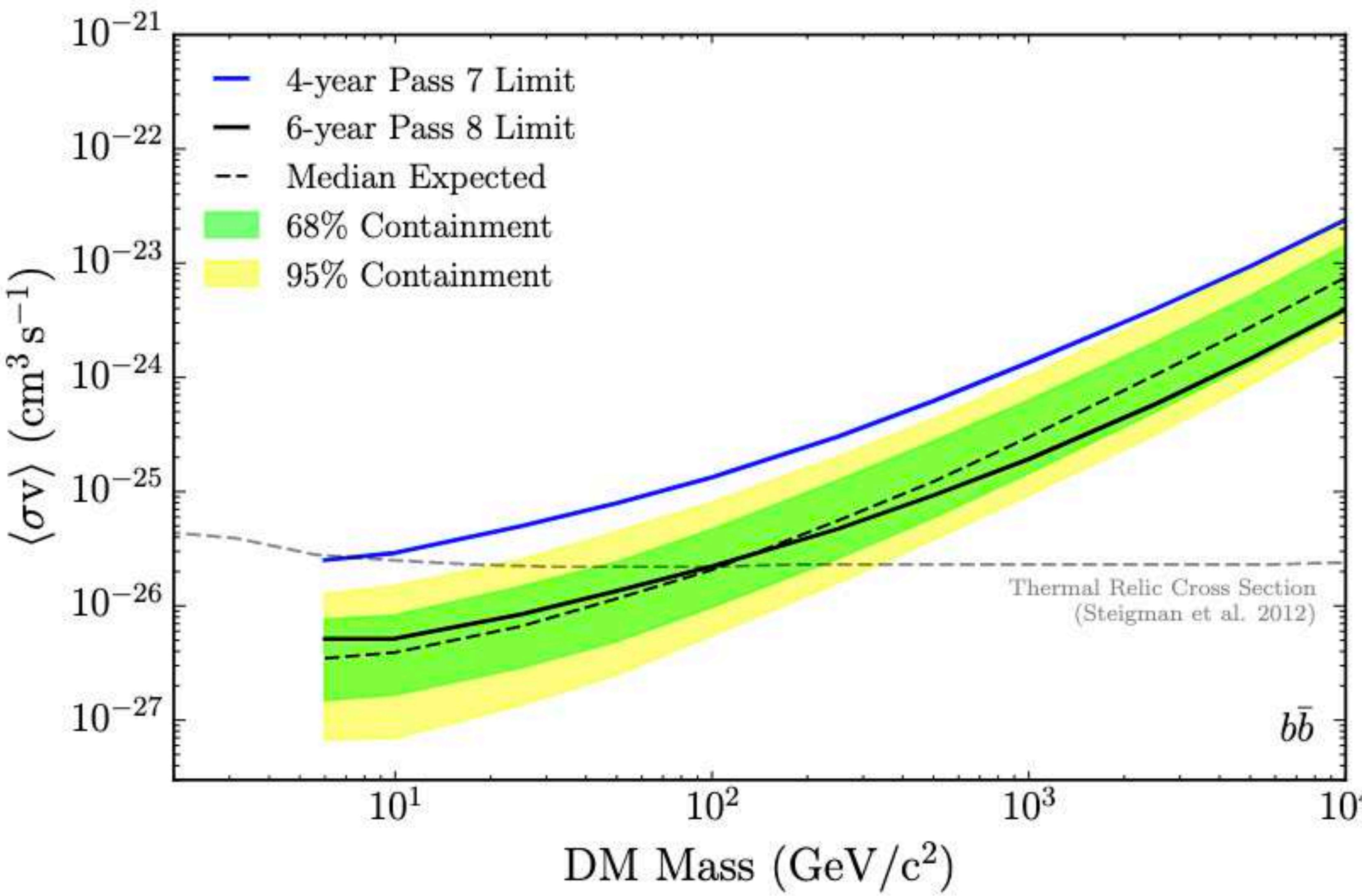
Joint Likelihood

9

DM @ dSphs with Fermi LAT

Using the joint likelihood to combine info from **15 dSphs, taking into account the uncertainties in their DM content —> one of the strongest DM limits to date**

annihilation cross section



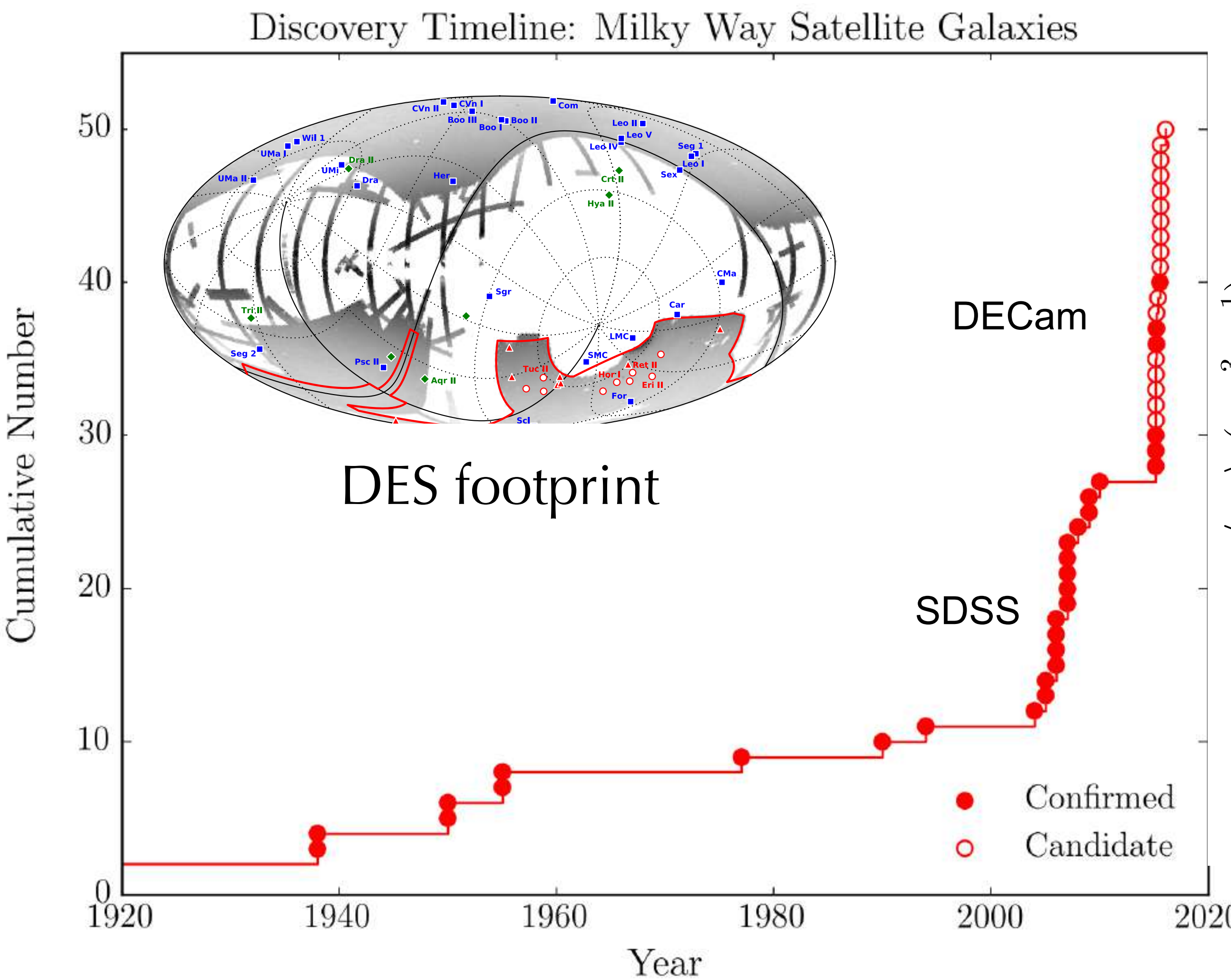
[Ackermann+, 1503.02641]

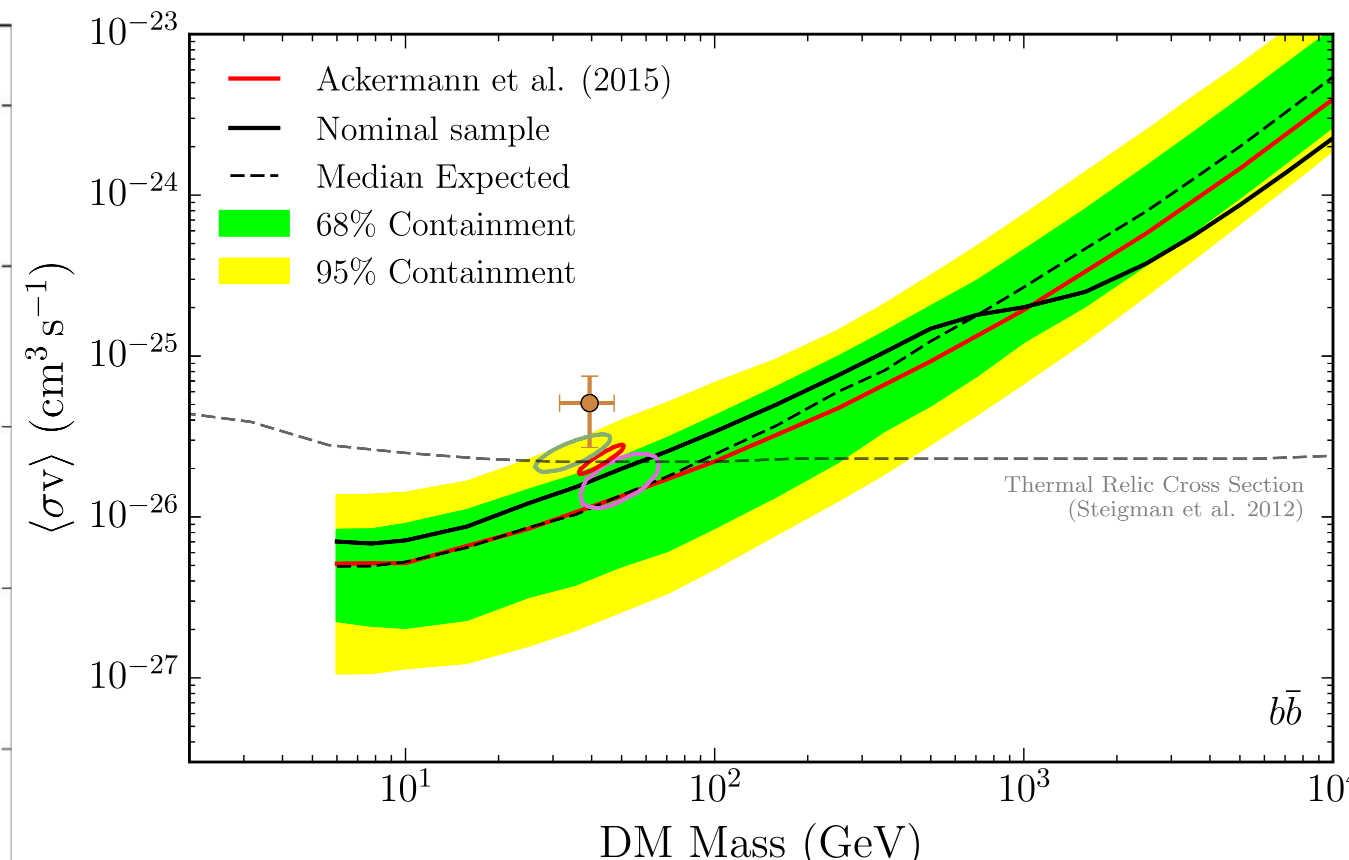
GCE dark matter origin in tension with complementary gamma ray observations

DM @ dSphs with Fermi LAT

More targets coming up!

>45 dSphs, 28 kinematically confirmed + 17 candidates since 2015 (DES, PANSTARSS)





[A. Albert+, (2016)]

LAT data coincident with **four** of the newly discovered targets show a ~**2σ (local) γ-ray emission in excess of the background**, weakening the limits by 1.5x at low masses.

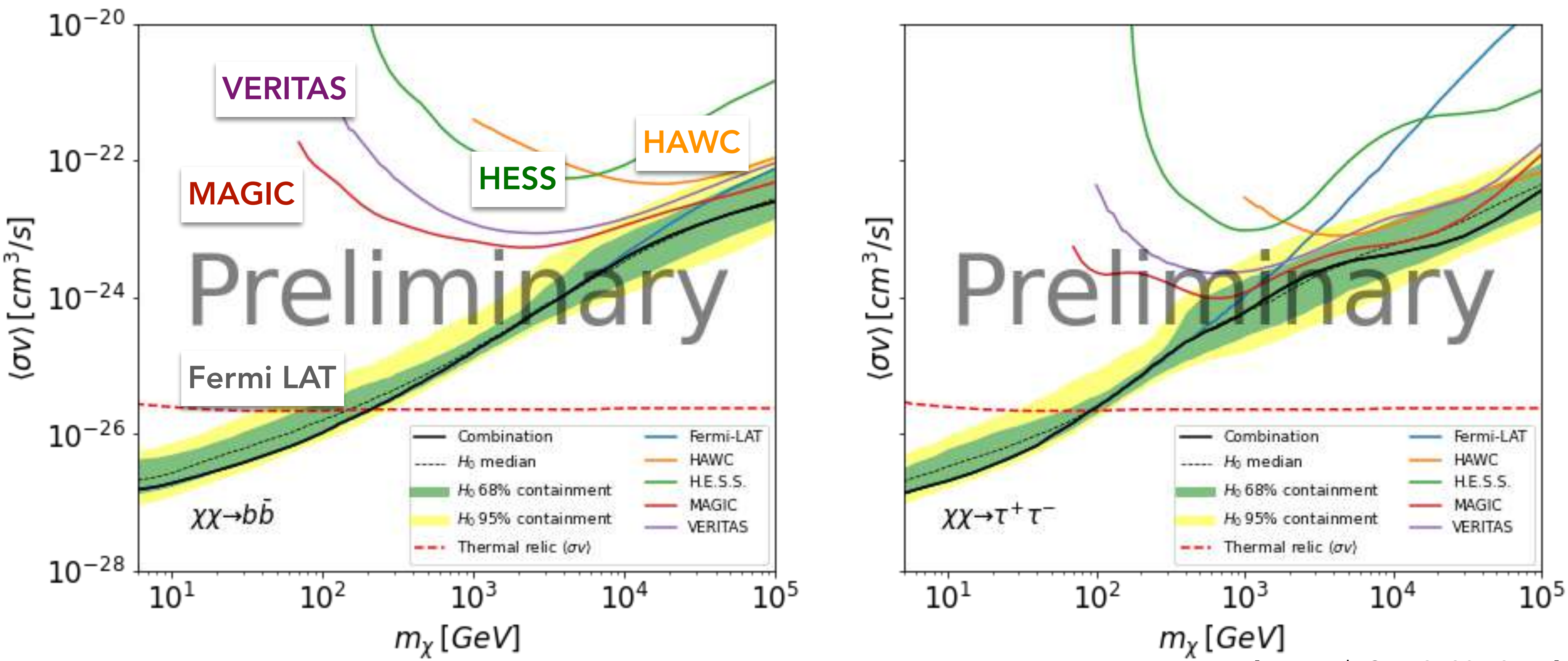
[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]

[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]

DM @ dSphs

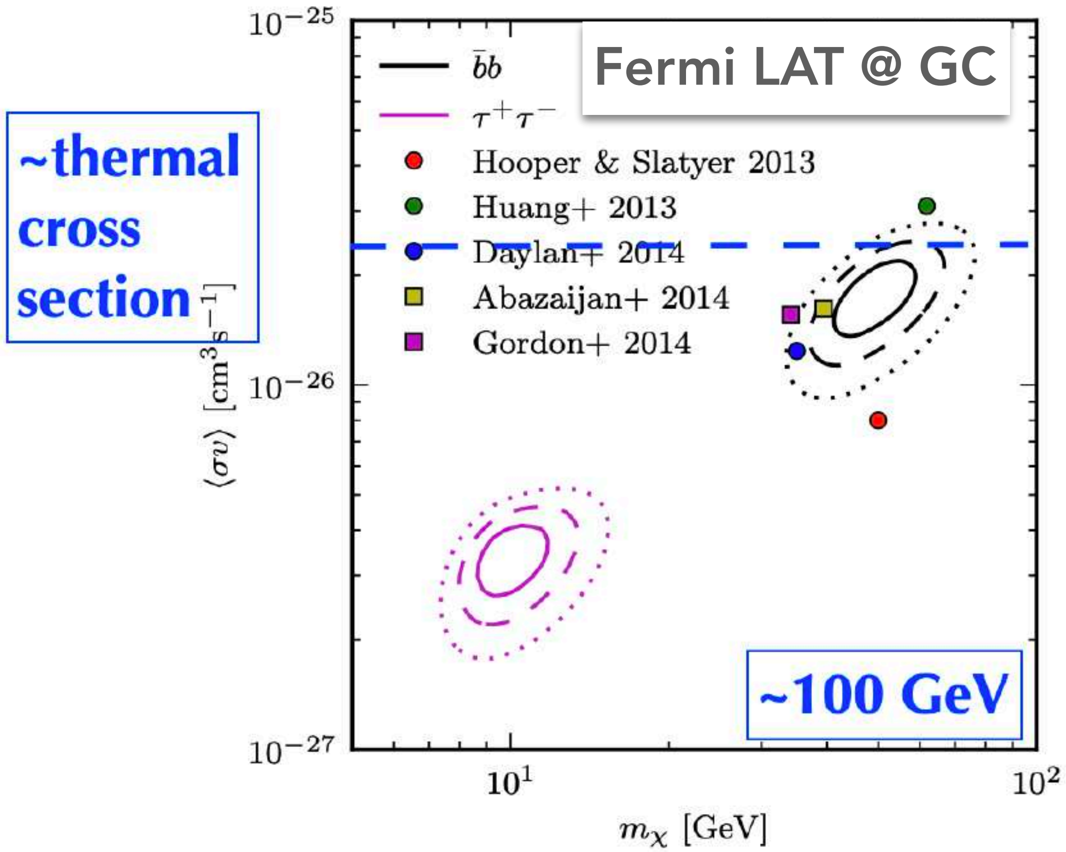
Latest: 20 dSphs and 5 gamma ray telescopes (Fermi LAT. MAGIC, HESS, Veritas, HAWC)

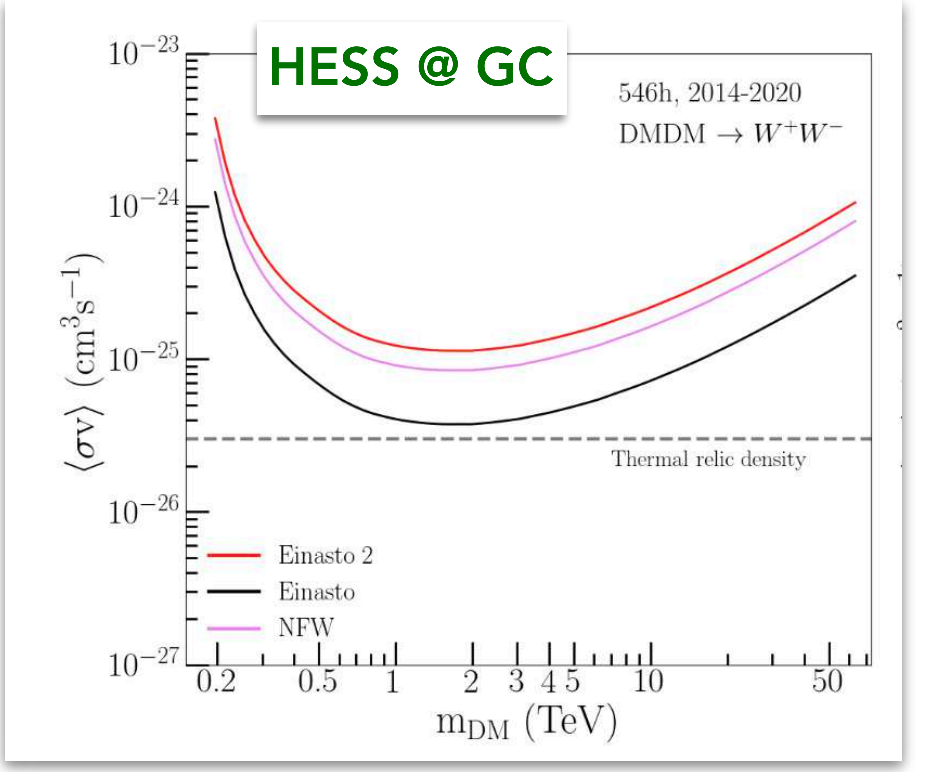
More data + excellent collaboration between experiments!

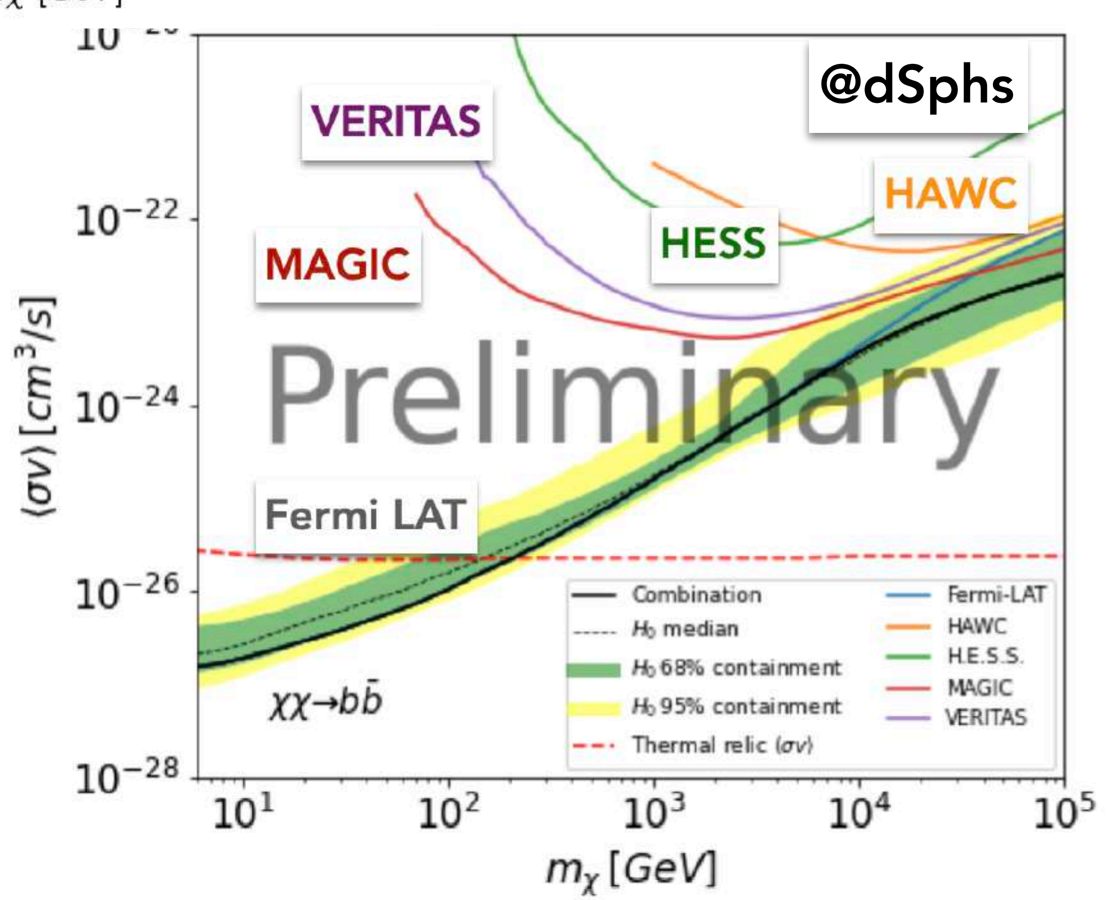


[Armand, C.+, 2108.13646]

Summary - searches in GC and dSPhs

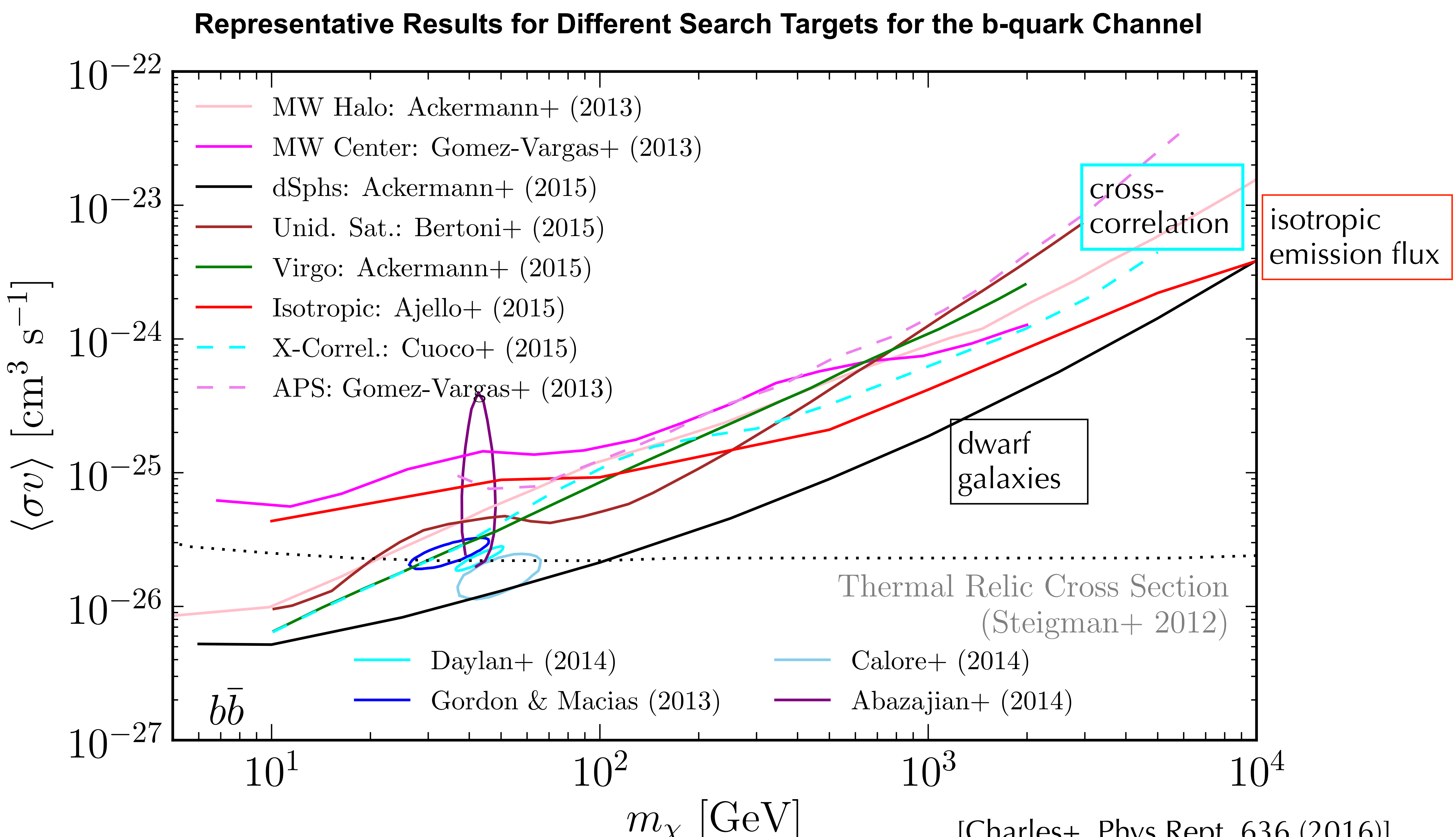






WIMPs - all gamma ray limits (cca 2016)

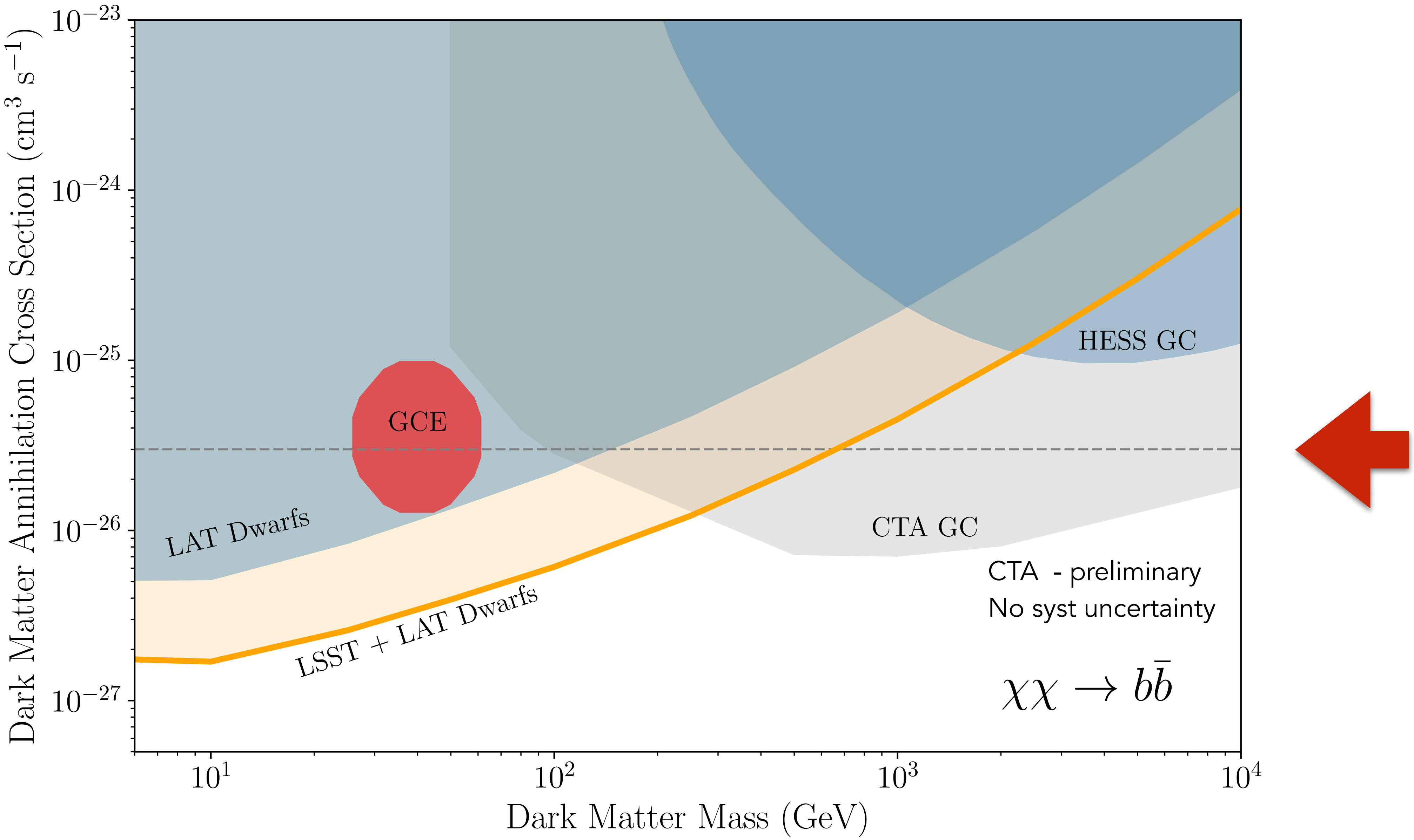
Many analysis approaches



[Charles+, Phys.Rept. 636 (2016)]

Thermal DM and CTA - the big picture

- **CTA unique experiment to test thermal WIMP models in the TeV range!**



[Probing the Fundamental Nature of Dark Matter with the LSST, Drlica-Wagner+, 2019]

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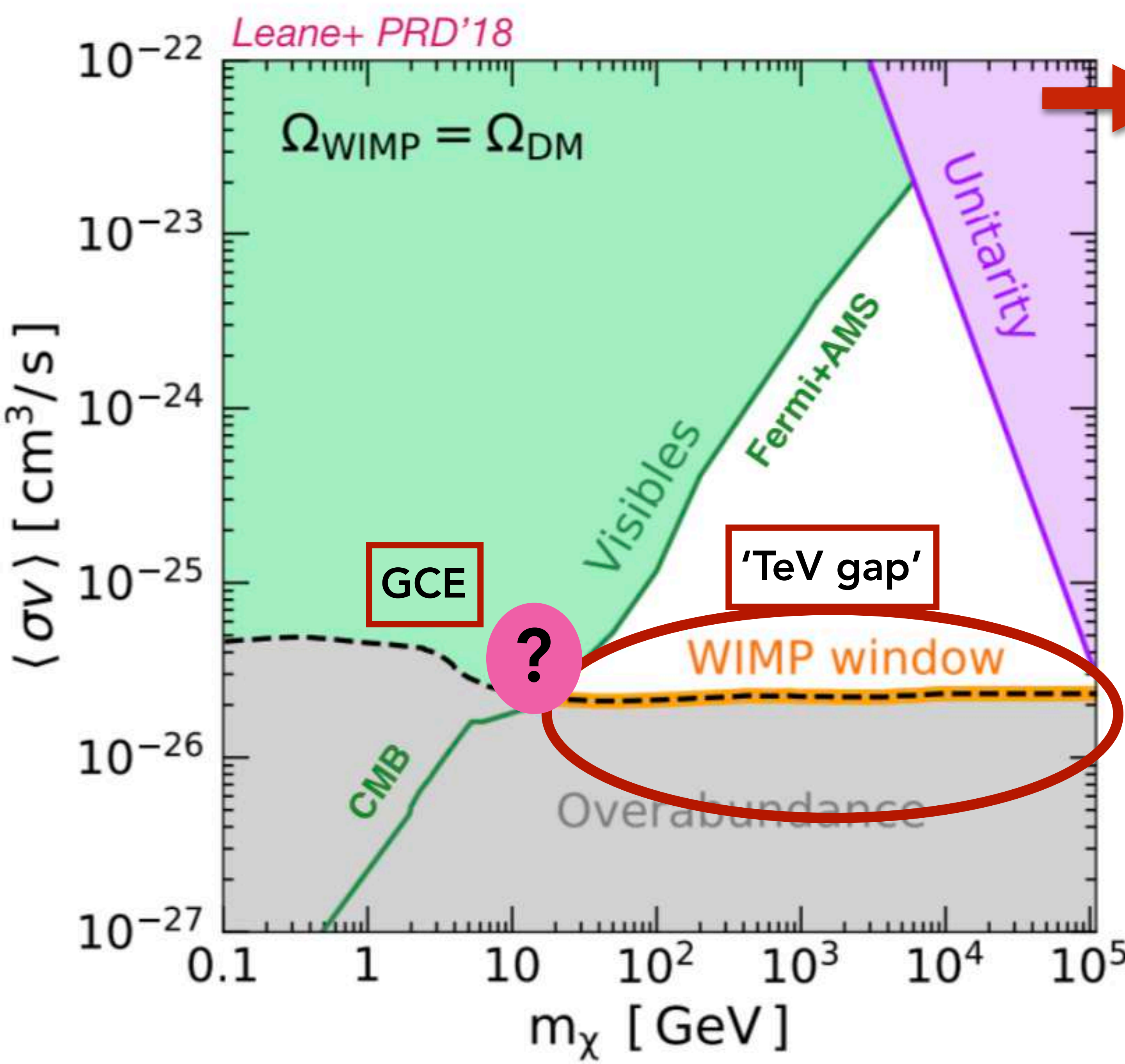
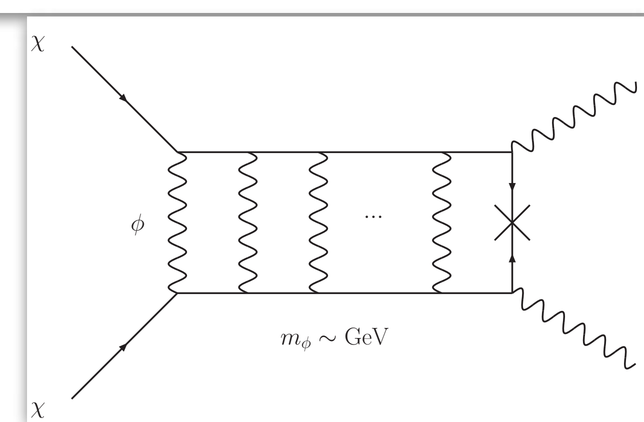
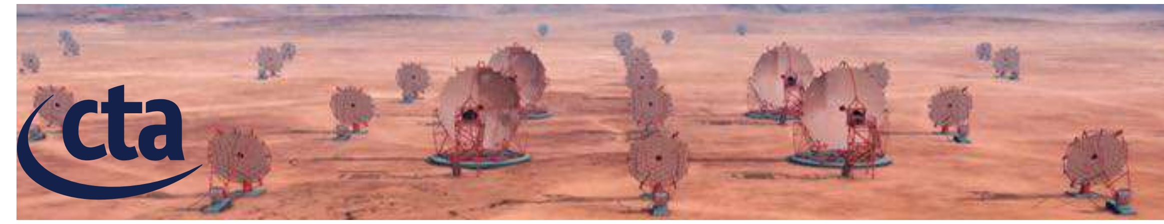


Decaying DM

Note of caution: for multi-TeV DM phenomenology naturally more complex, Z/W exchanges leading to Sommerfield enhancements/bound states etc Unitarity bound (based on s-wave assumption) might not hold either

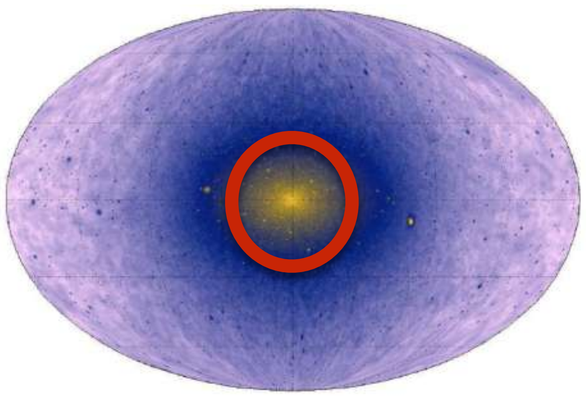


Looking into the **future** - **where to look with CTA**



signal strength

GC

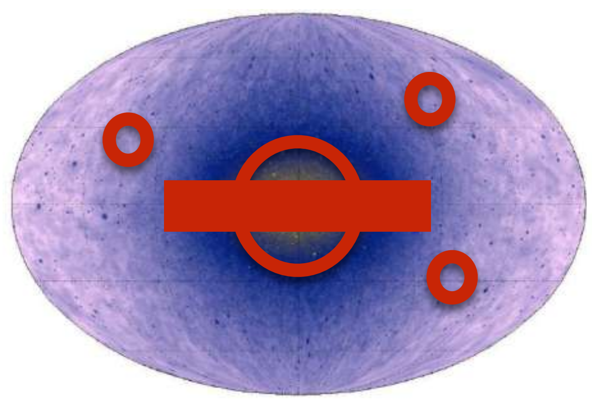


[Archaryya et al. JCAP 2020.]

CTA consortium paper published

CTA non-consortium paper published

dark subhalos



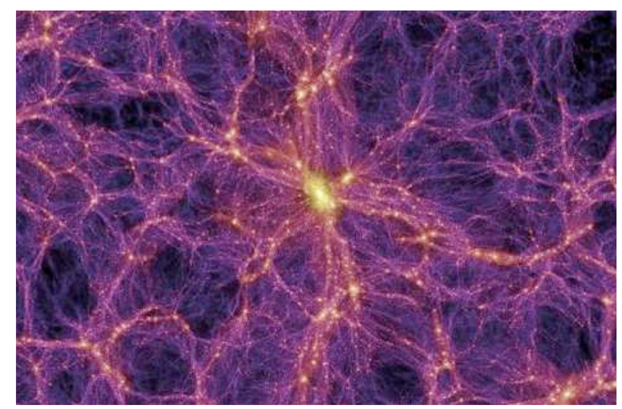
GC halo

[J. C-B. + Phys.Dark Univ. 32 (2021)]

CTA consortium papers being refereed

Extragalactic sources:

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)



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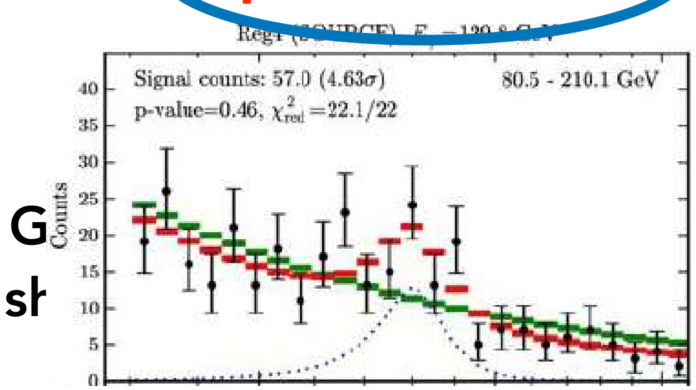
dwarf satellites

Cosmological signal/UEBG:

- Spectral flux
- Auto-correlations
- Cross-correlations w G… catalogs and cosmic sh…

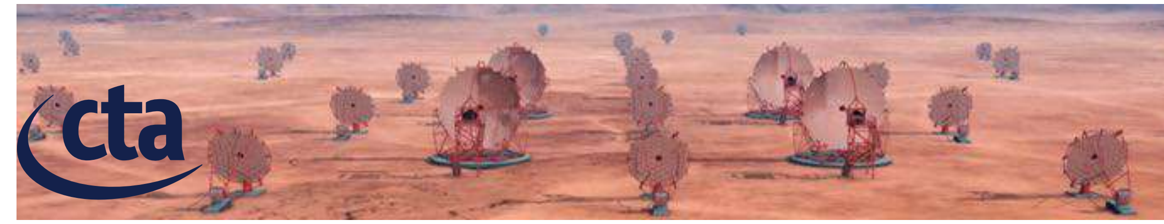
spectral line



robustness

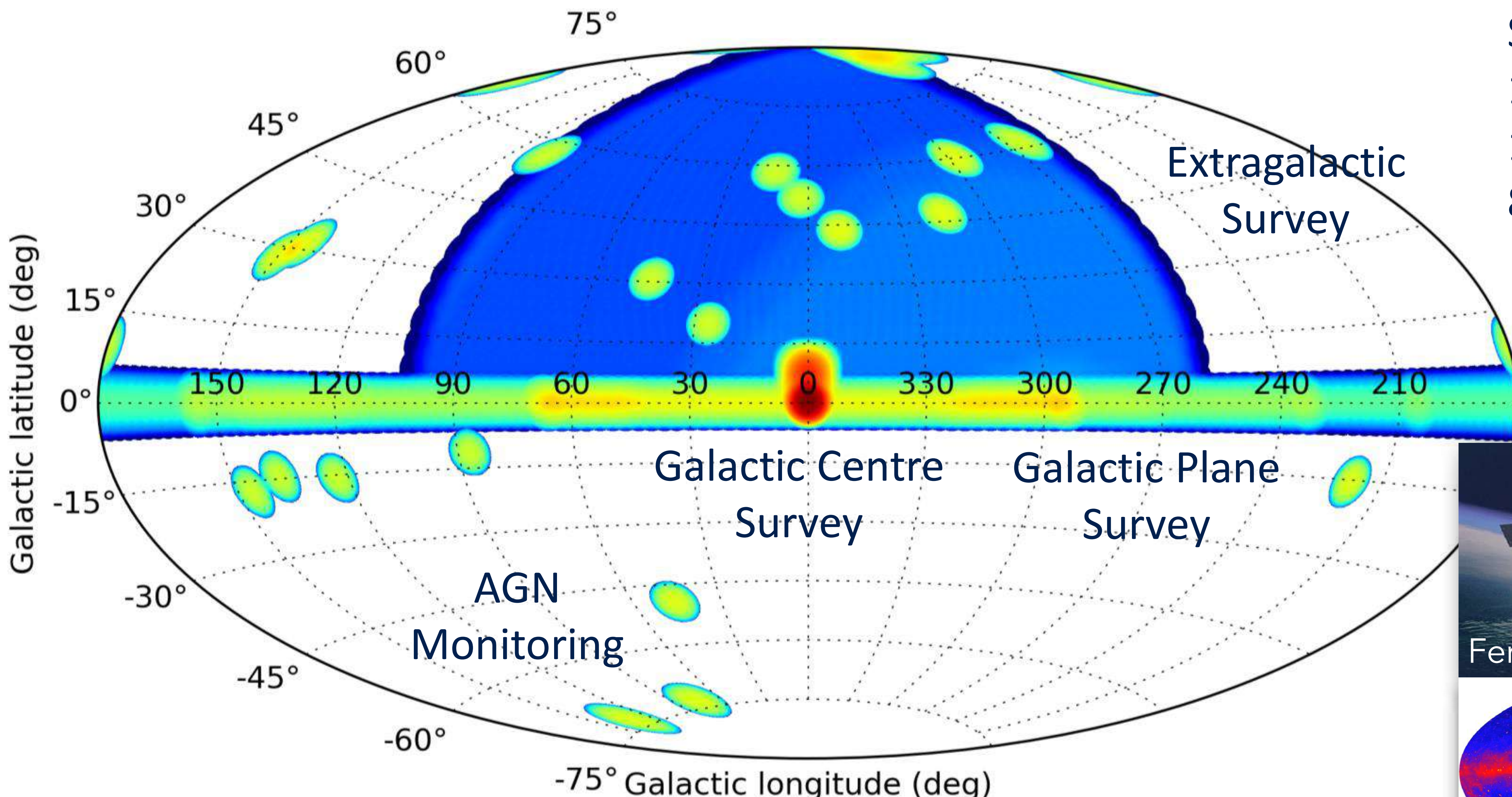
[adapted from: H.-S. Zechlin]

CTA as a whole-sky observatory

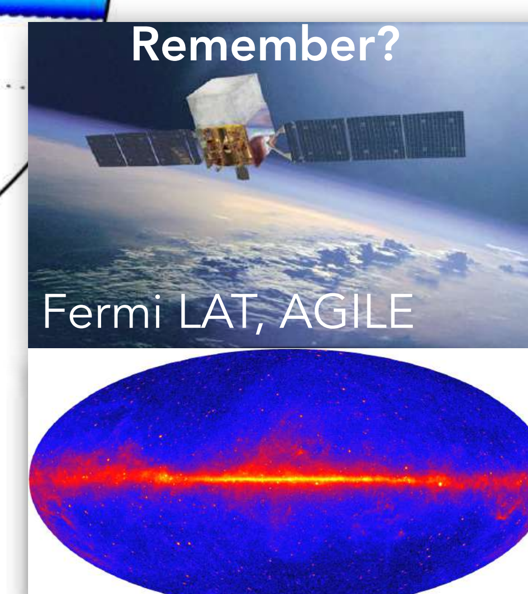


Novel observational strategy: **extended sky surveys**

- **Unbiased view** of the sky
- Bridging the differences with **satellite data**



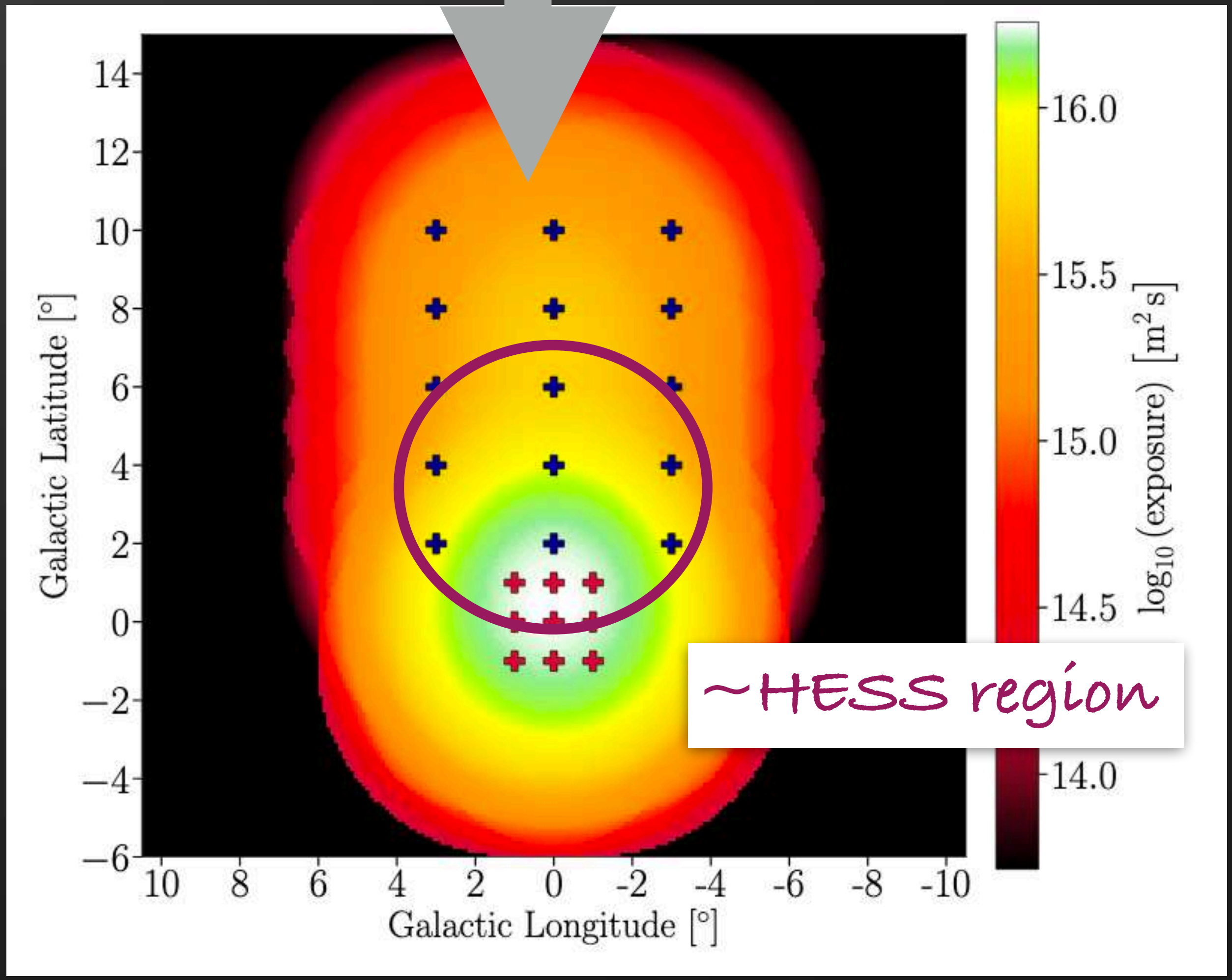
Simulated:
1980 h South
1815 h North
8132 pointings



CTA @ GC

Extended survey: additional 300 hours (relevant for cored DM profiles!)

- **Galactic center survey**: 525 hours over first 10 years
- **Extended survey**: additional 300 hours



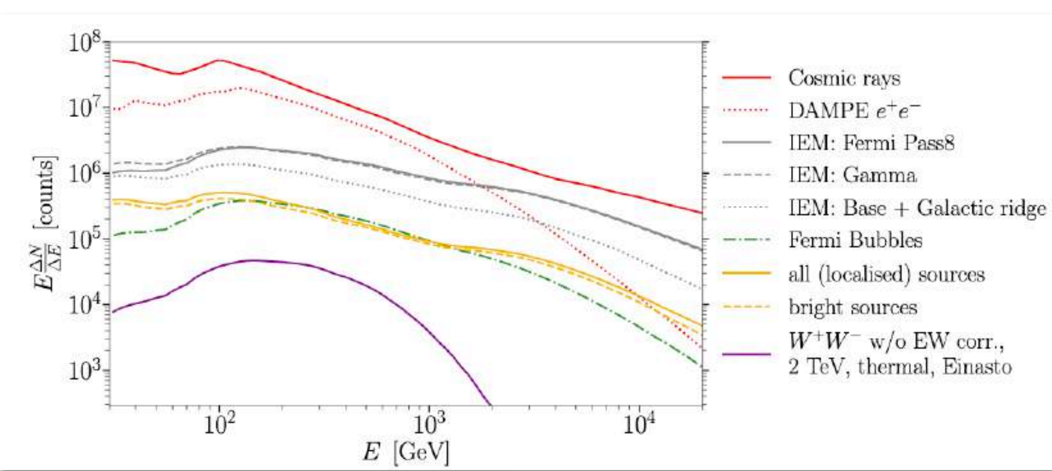
[Archaryya et al. JCAP 2020.]

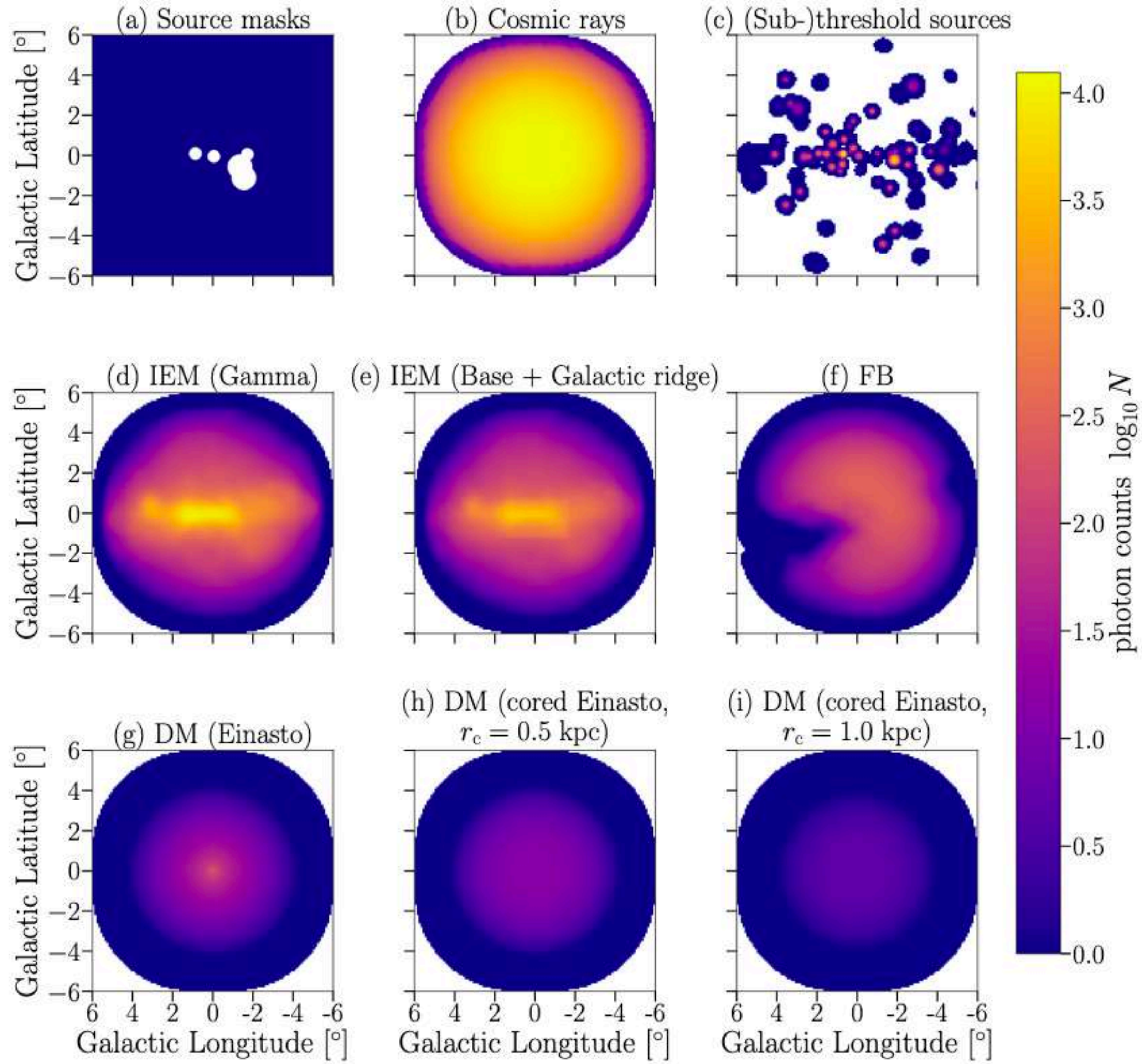
CTA @ GC

CTA analysis techniques

ON/OFF analysis unfeasible for GC (no good OFF region)

—> FULL 3D TEMPLATE ANALYSIS





[Archaryya+, 2020]

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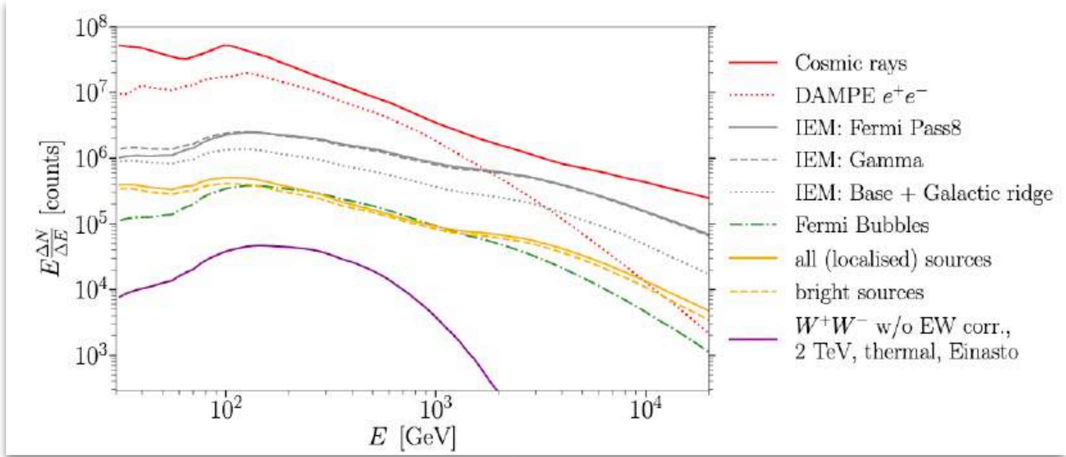

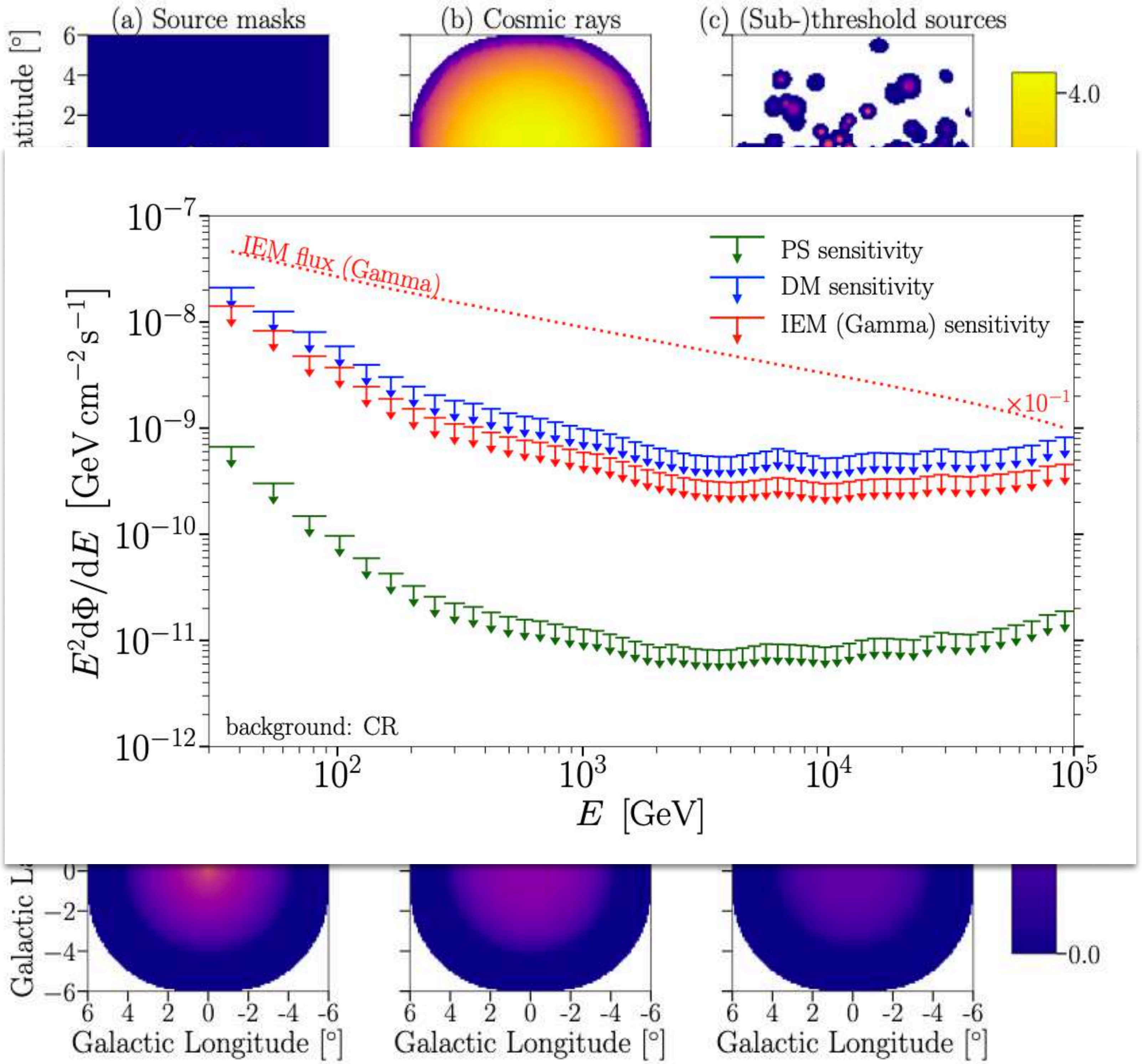

[Archaryya+, 2020]

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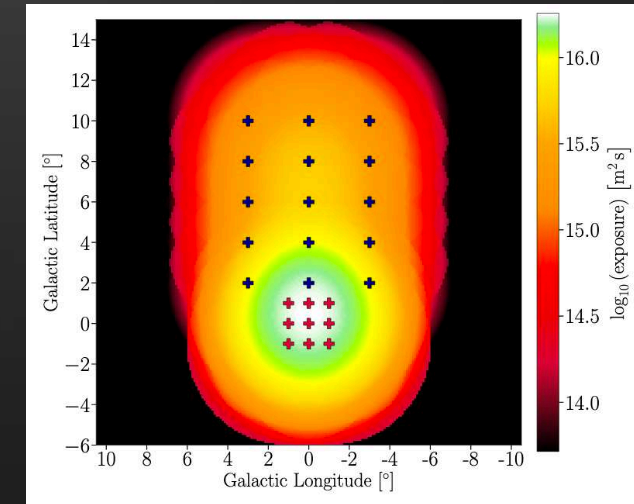
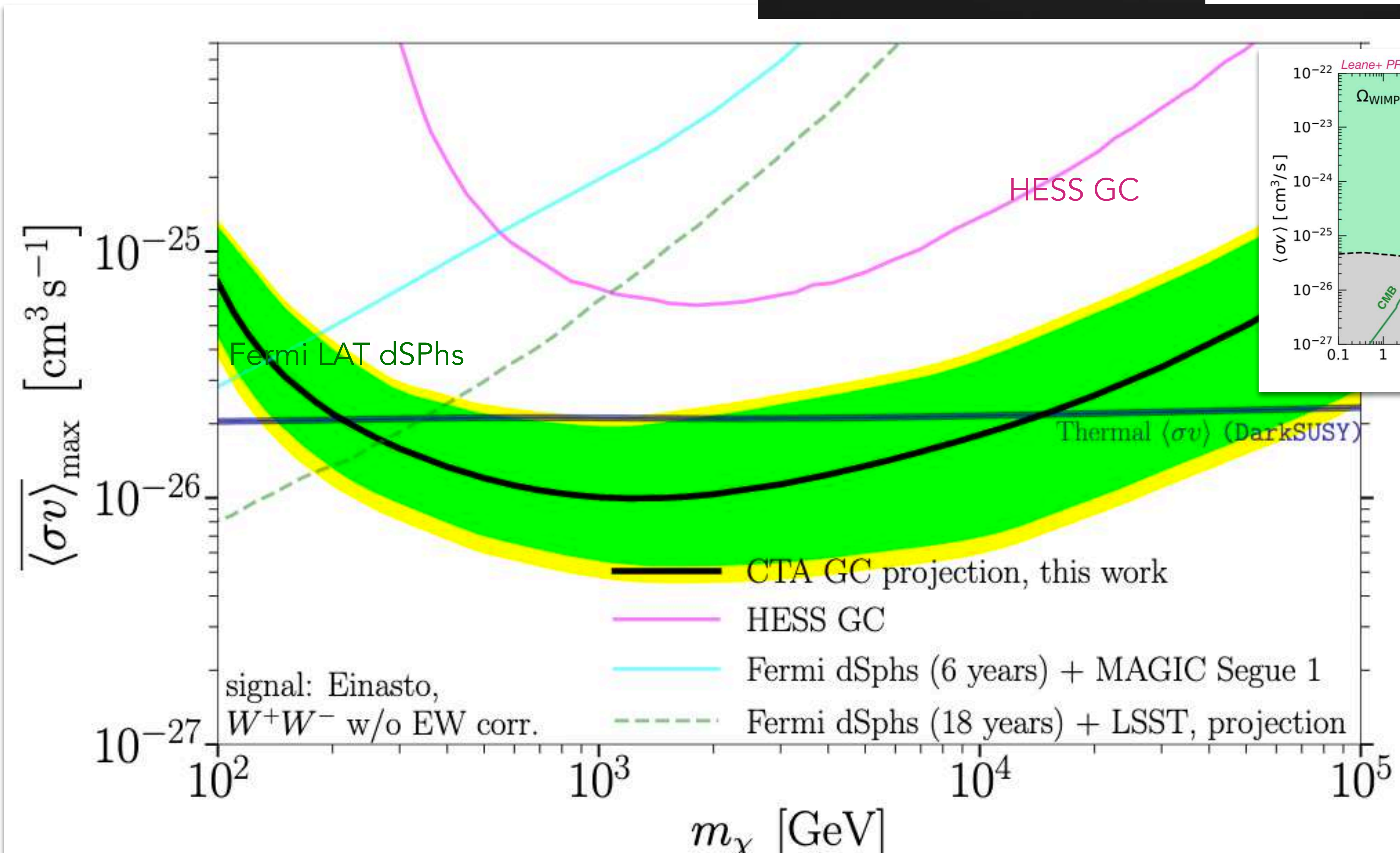
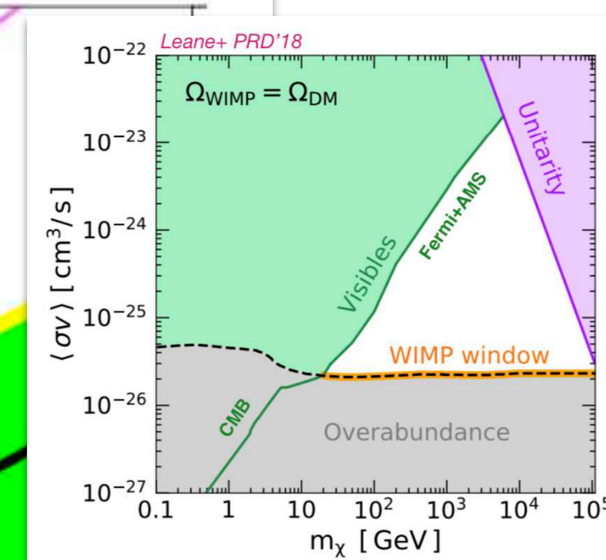


Expected to probe the TeV window





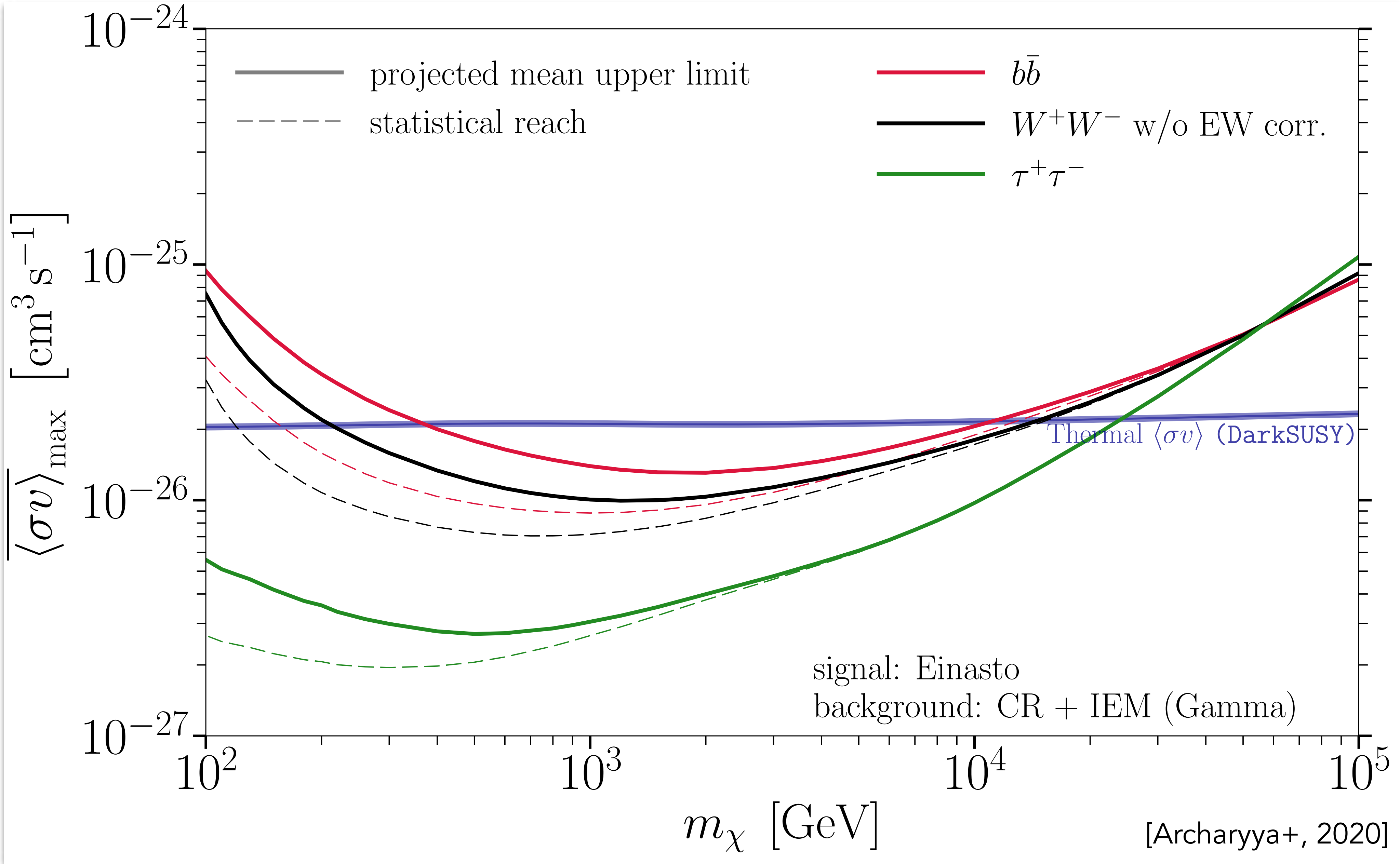
[Archaryya et al. JCAP 2020.]

Galactic center with CTA

Likelihood analysis for sensitivity includes:

- systematic uncertainties
- astro backgrounds

—> CTA expected to probe thermal annihilation cross section between 100s of GeV and tens of TeV



[Archaryya+, 2020]

Decaying DM and CTA?

GAMMA-RAY DM SEARCHES IN CLUSTERS

- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$
- Components:
  - Baryonic Matter
    - Galaxies (~ 3% - 5%)
    - Intra Cluster Medium (~ 15% - 17%)
  - Dark Matter (~80%)

NGC1275 in Perseus Galaxy Cluster

- In terms of DM searches:

Decay

Best possible targets to consider

Annihilation

Competitive compared to other prime targets, considering substructure

[Sánchez-Conde+11]

Caveat

Expected gamma-ray emission from hadronic processes

- No clear detection but some hints claimed

  Ackermann+15 [Fermi-LAT Collab.], Xi+18, Adam+21

[J. Pérez-Romero, IDM 2022]

Decaying DM and CTA?

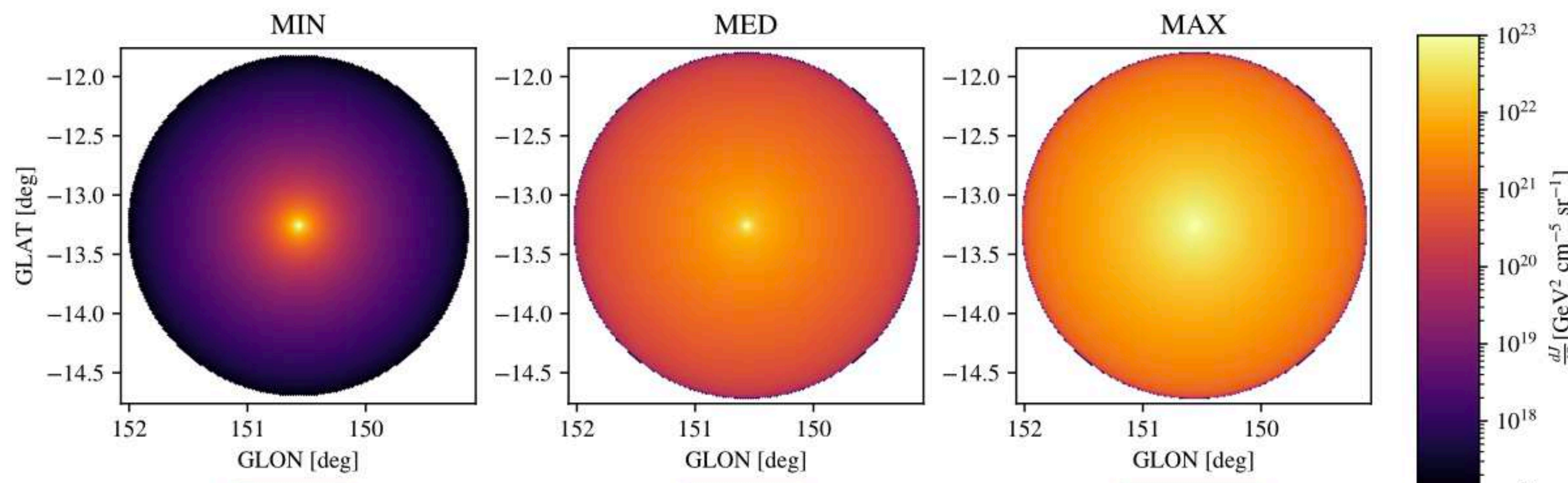
DM-INDUCED EXPECTED SIGNAL

- Applying modelling formalism we obtain:

Annihilation	$\log_{10} J$ [GeV^{2}cm^{-5}]
MIN	17.42
MED	18.43
MAX	19.20
Decay	$\log_{10} D$ [GeV cm^{-2}]
	19.20

Skymaps of the differential J-factor

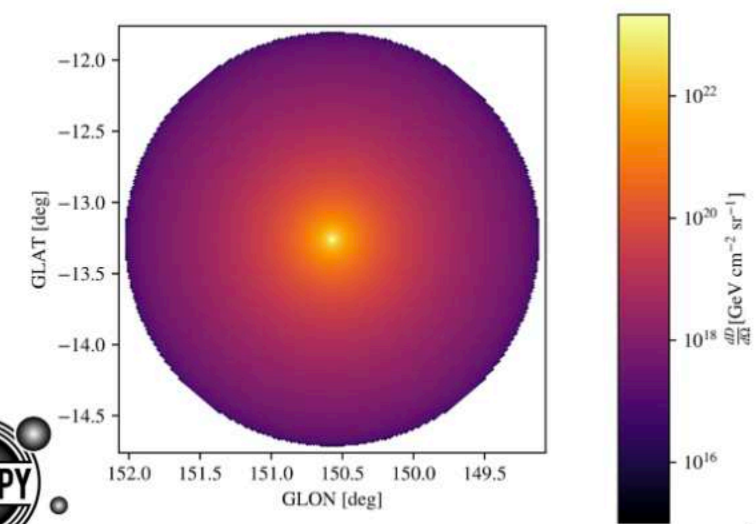
Annihilation



MIN MED MAX

Skymap of the differential D-factor

Decay

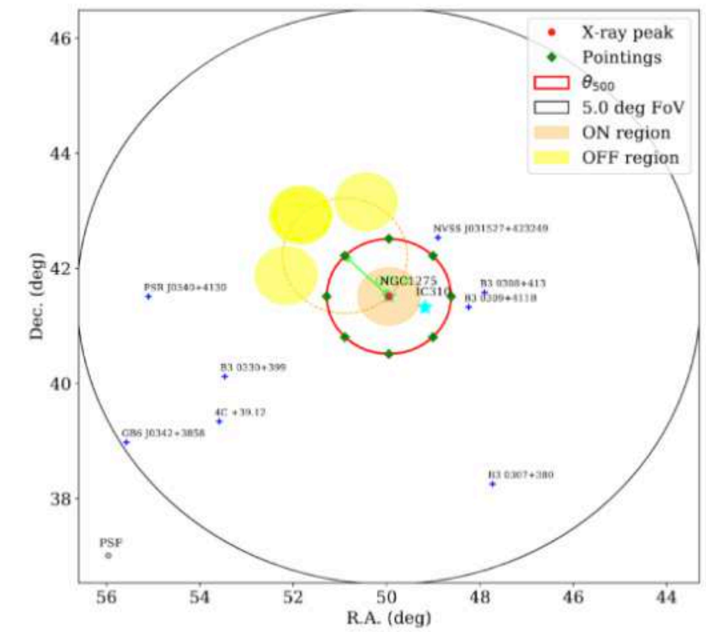


[J. Pérez-Romero, IDM 2022]

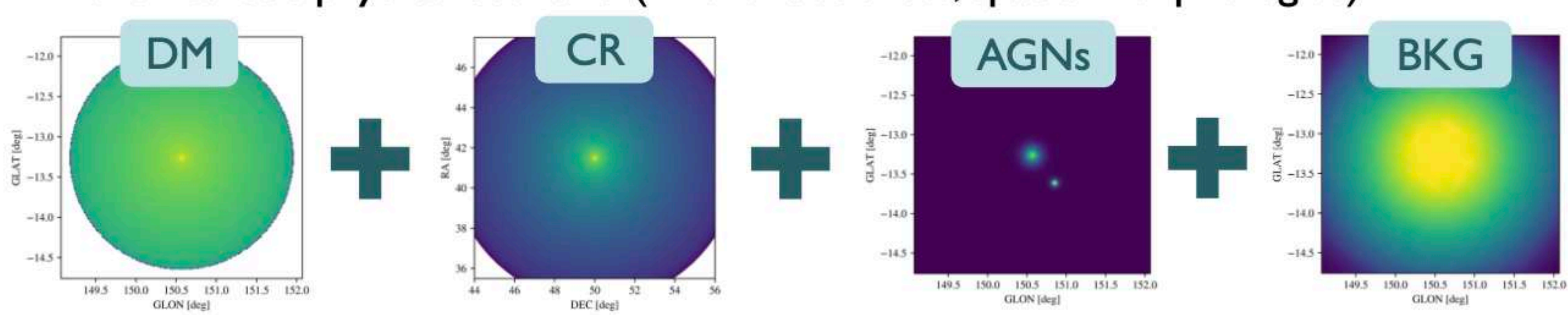
Decaying DM and CTA?

CTA ANALYSIS CONFIGURATIONS

1. First approach - **On/Off Analysis**
   - Lowest level of complexity (only DM + BKG emission, point-like/DM template)
   - More constraining results
   - Allow direct comparisons (historically used in Imaging Air Cherenkov Telescopes (IACTs) as MAGIC)



2. Final analysis goal - **Template fitting**
   - More realistic physical scenario (different sources, spatial morphologies)

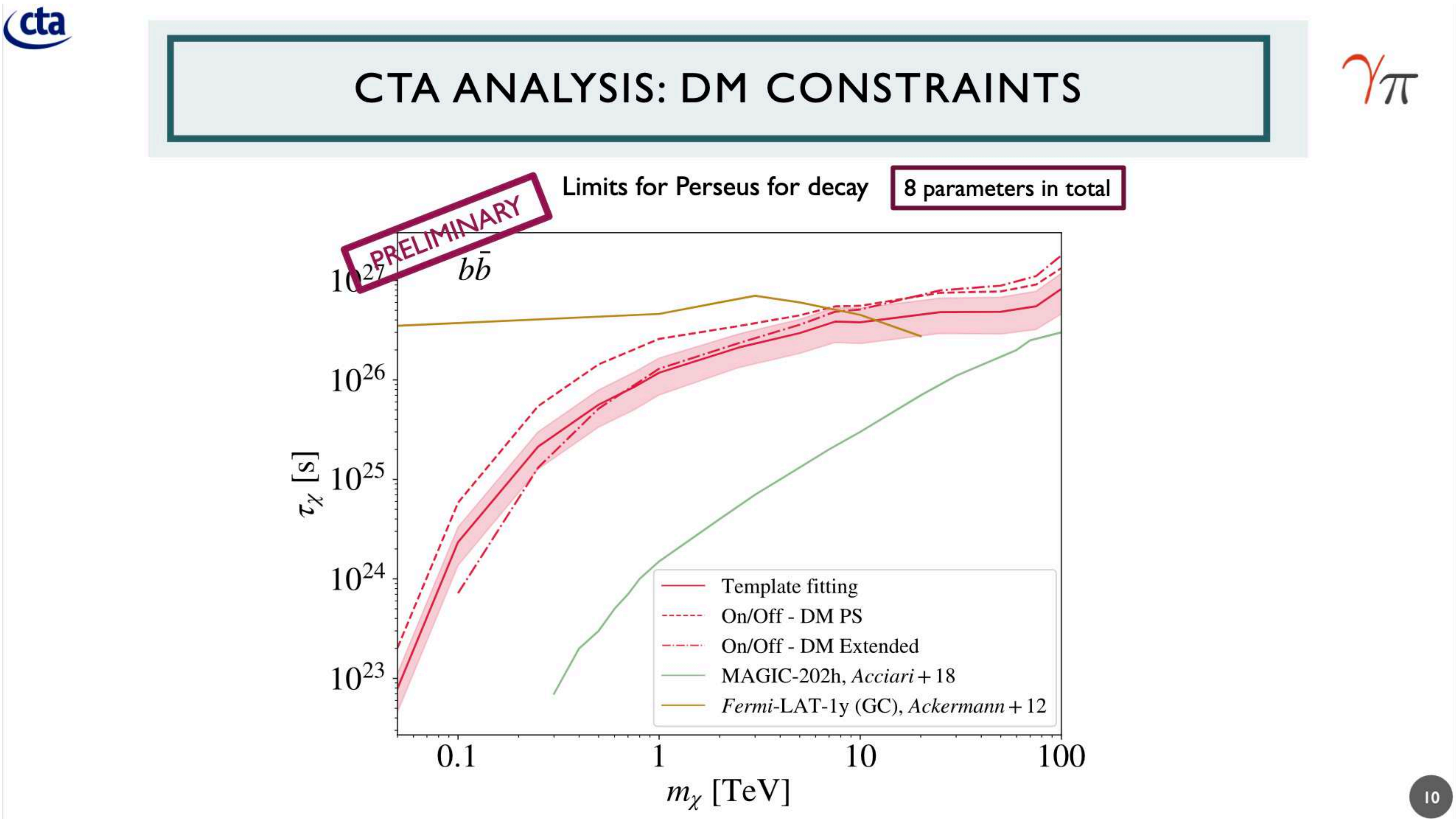


   - Makes it possible to check correlations between components
   - Historically used in *Fermi*-LAT analysis and in state-of-the-art for IACTs (*Acharyya+20* [*CTA Cons.*])

8

[J. Pérez-Romero, IDM 2022]

Decaying DM and CTA?



[J. Pérez-Romero, IDM 2022]

Looking into the **future** - **where to look with CTA**

signal strength

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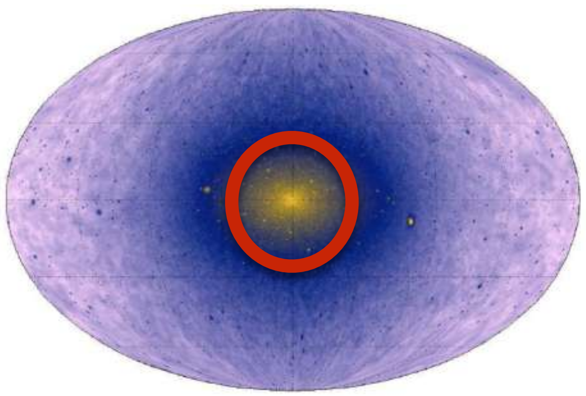

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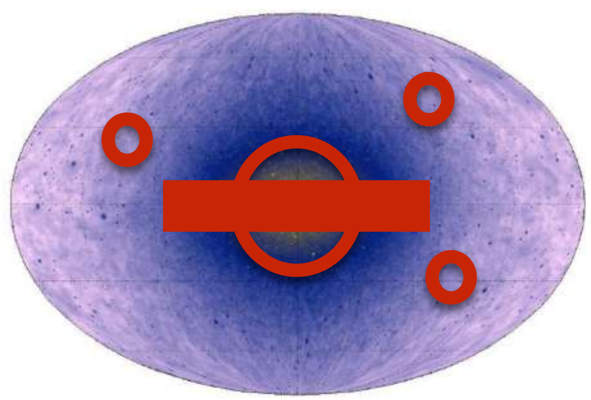

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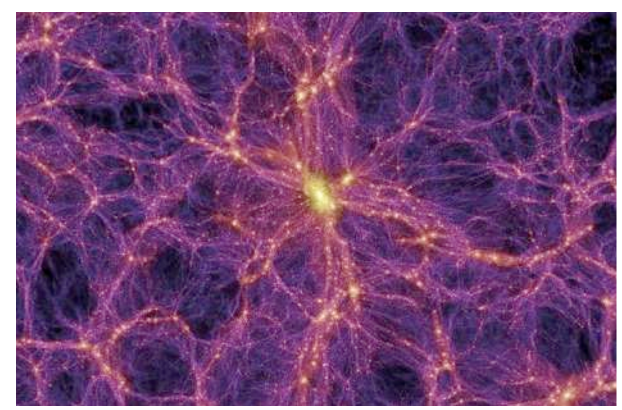

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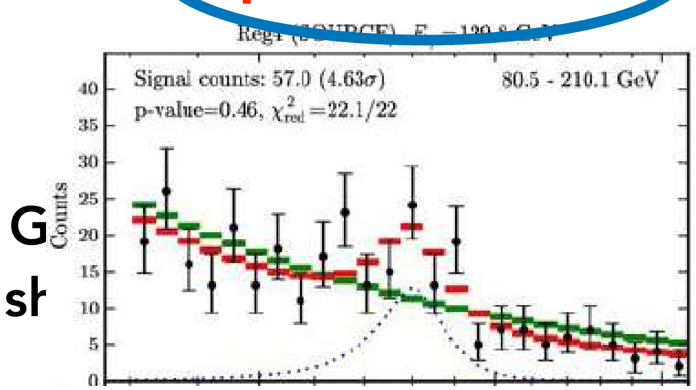

Many more analysis ongoing ... getting ready for the first data!

[adapted from: H.-S. Zechlin]

robustness

Summary

Search for DM is not easy… but a worthy task!

Field is mature and growing + astrophysics is exciting :)

Lots of ideas and well thought strategies that can be applied to variety of systems

"The hardest thing of all is to find a black cat in a dark room, especially if there is no cat."

— Confucius

~40yr search

Summary

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Suggested literature:

— "**Status of Indirect (and Direct) Dark Matter searches**", Marco Cirelli, PoS ICRC2015 (2016) 014, 1511.02031 [astro-ph.HE]

— "**Sensitivity Projections for Dark Matter Searches with the Fermi Large Area Telescope**", E. Charles et al., Phys.Rept. 636 (2016), 1605.02016 [astro-ph.HE]

— **History of dark matter**, Bertone and Hooper, Rev.Mod.Phys. 90 (2018), 1605.04909

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