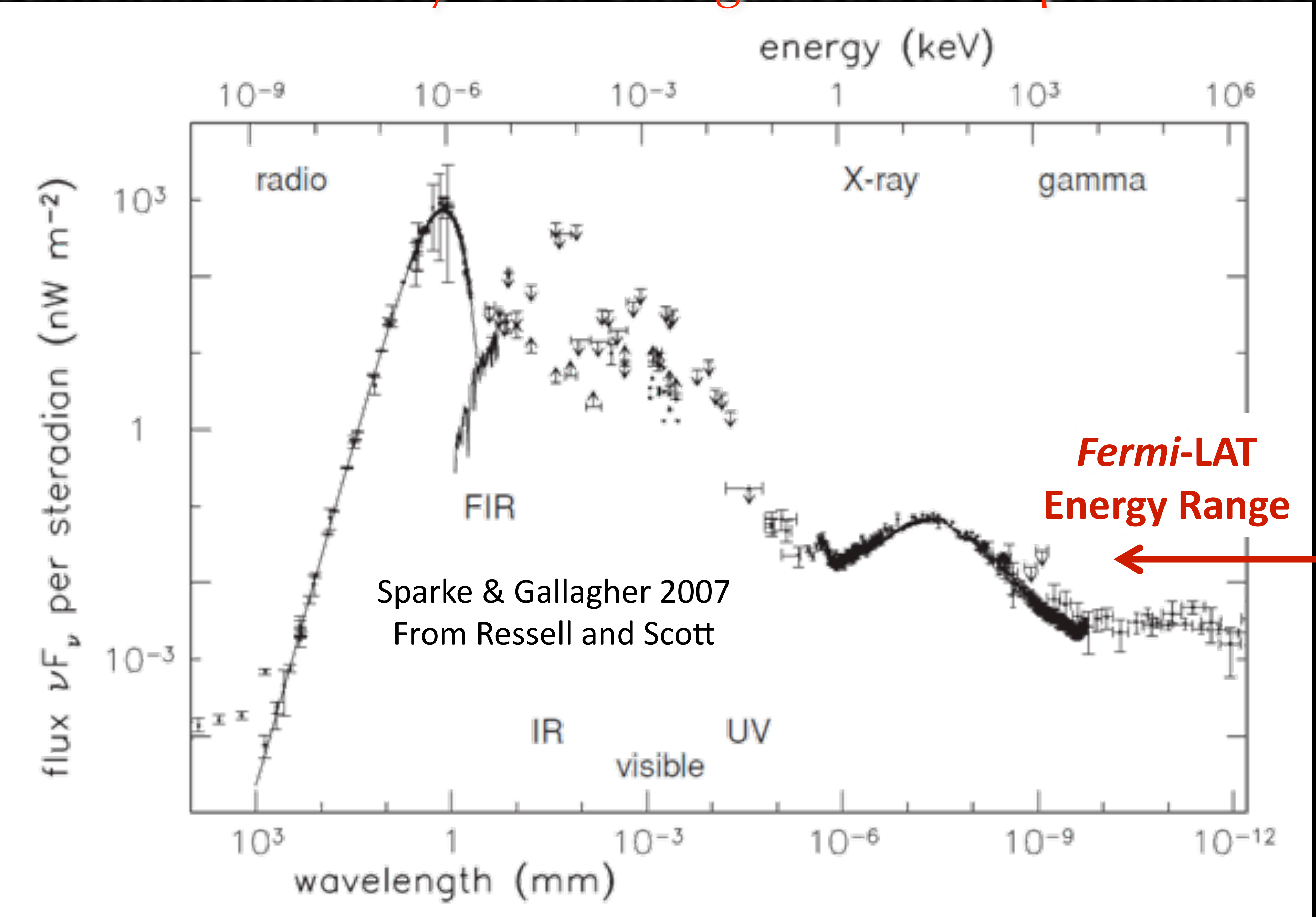
Cosmological dark matter signal

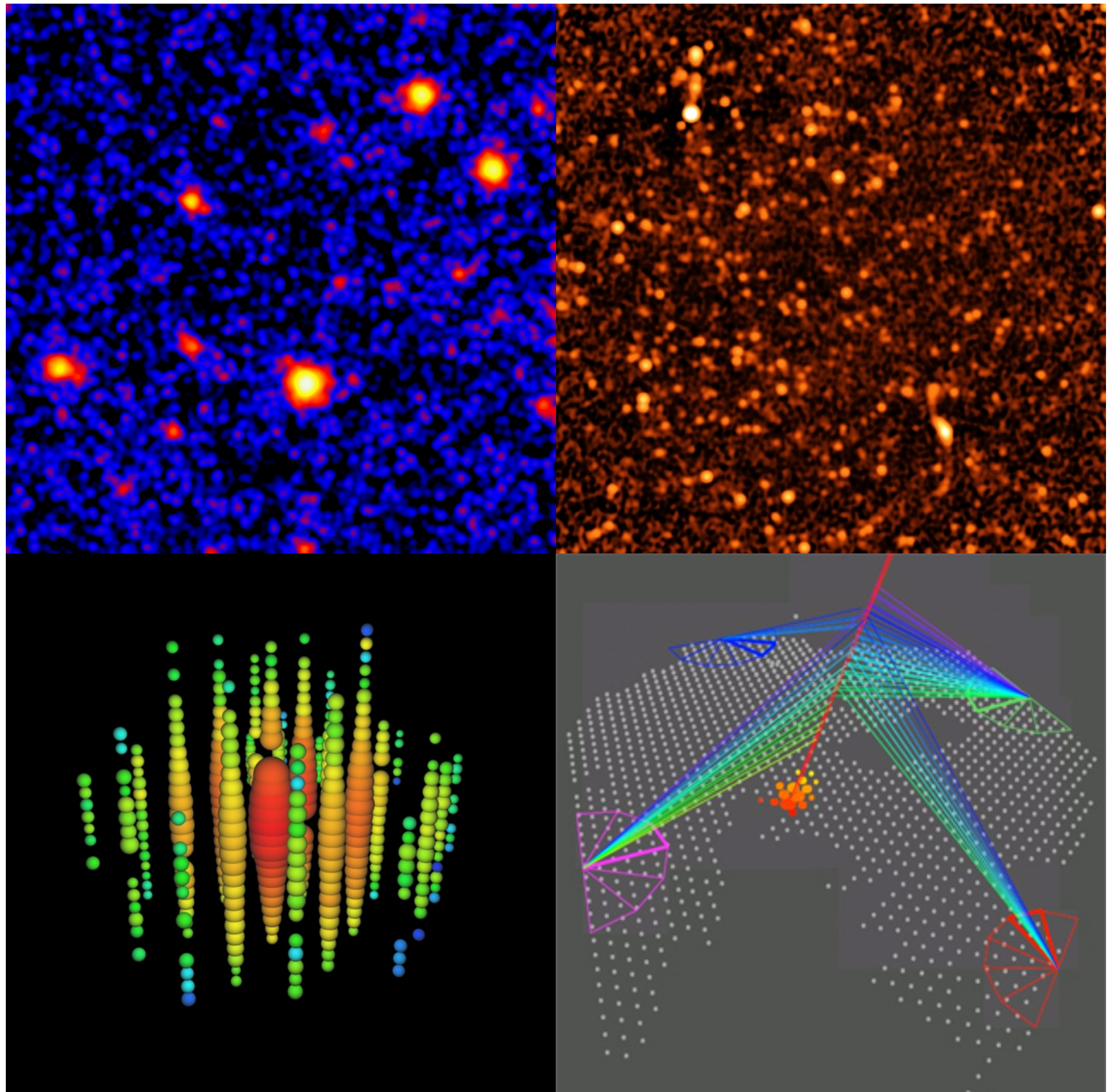
Gabrijela Zaharijas
University of Nova Gorica
Slovenia

Extragalactic background light

cumulative intensity of all extragalactic/isotropic emission



***Fermi*-LAT Energy Range**



The origin of the **extragalactic gamma-ray background** is not definitively established …

nor the **extragalactic radio background** …

nor **high-energy cosmic neutrinos** …

nor **ultra-high-energy cosmic rays** …

[credit: K. Bechtol, APS 2014]

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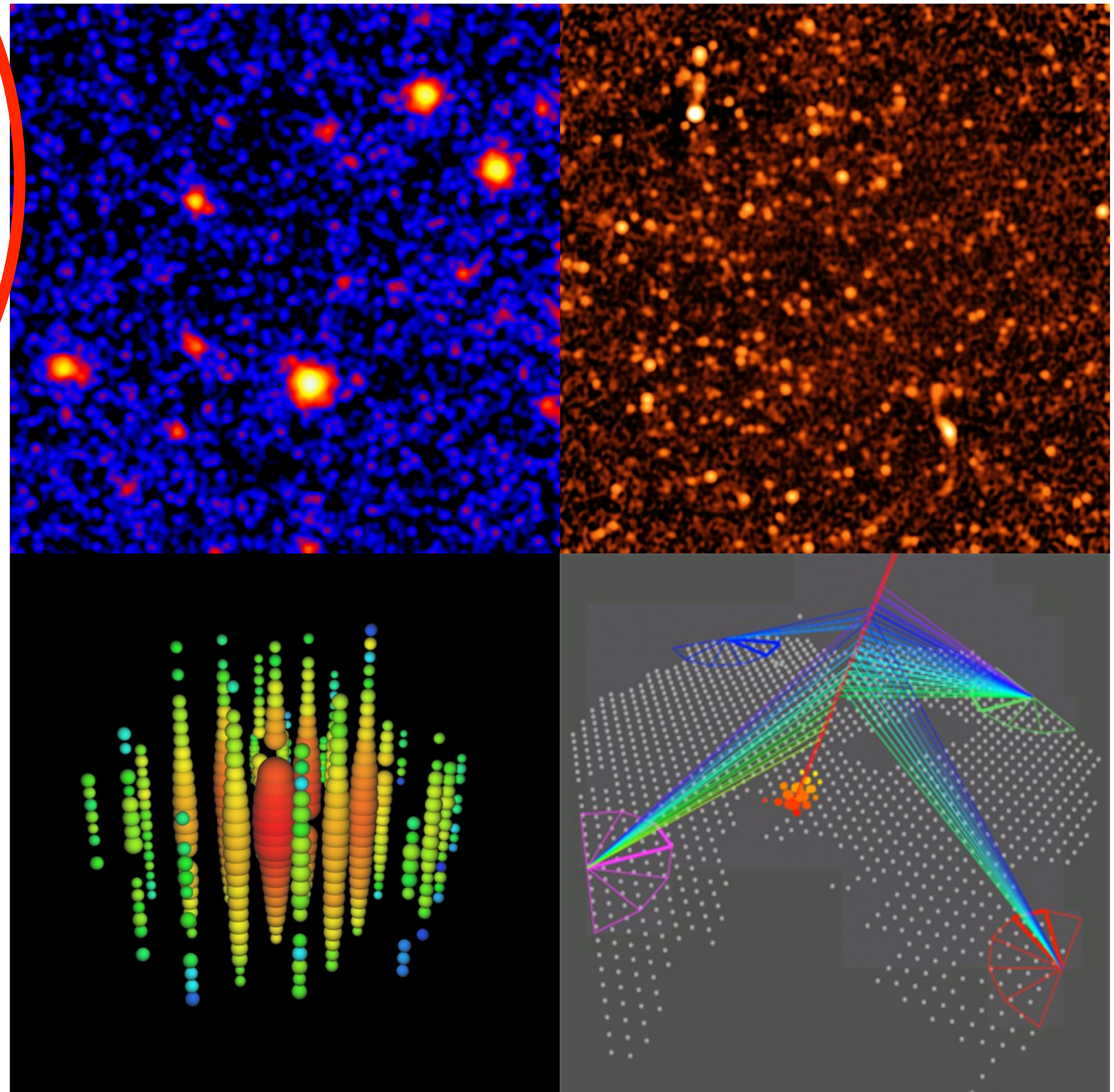


nor the **extragalactic radio background** …

nor **high-energy cosmic neutrinos** …

nor **ultra-high-energy cosmic rays** …

[credit: K. Bechtol, APS 2014]

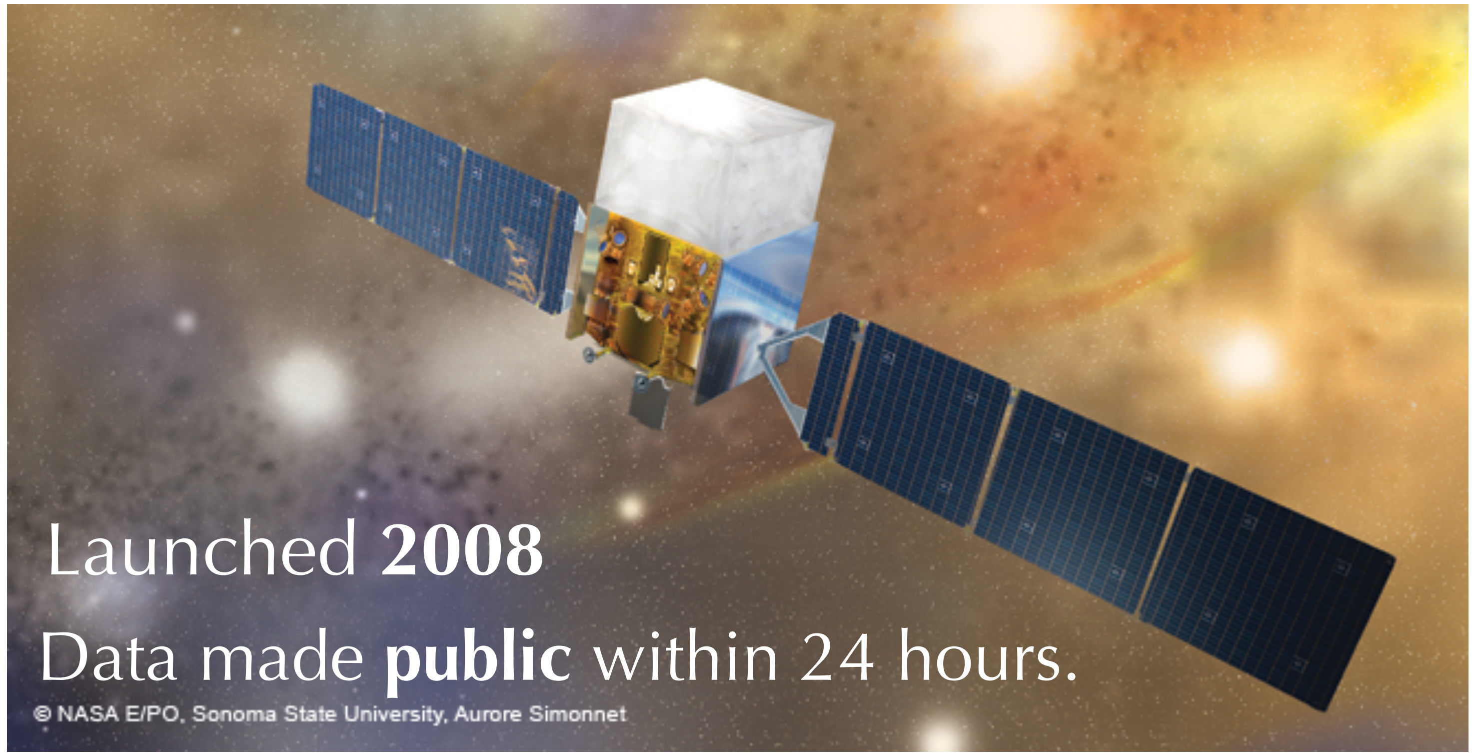
Outline

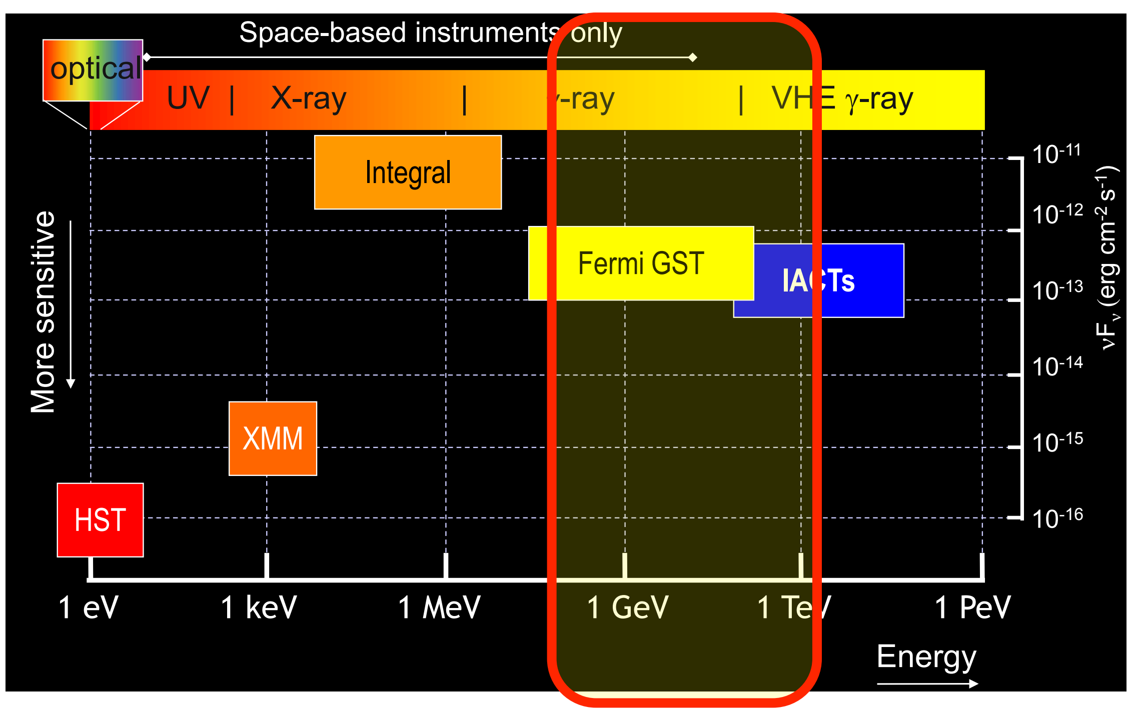
1. How do we measure isotropic gamma ray emission

2. what are the ‘guaranteed’ contributions

3. how do we use his knowledge to test fundamental physics

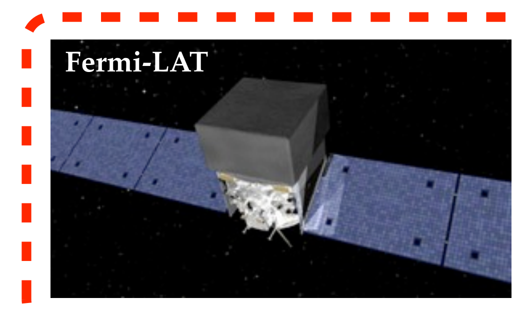
The Fermi LAT



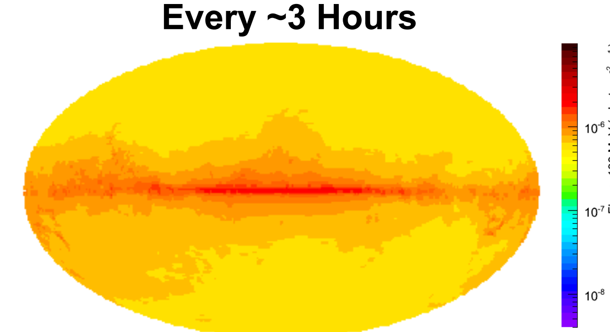


WIMP Mass Range

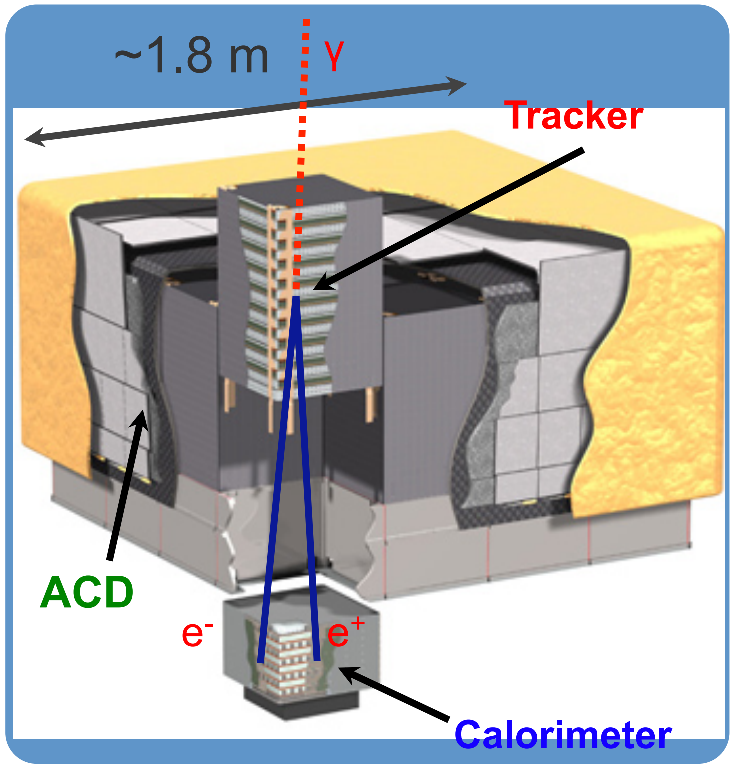
Energy range: 20 MeV to >300 GeV ~M_Z - ideally suited for WIMP search



Every ~3 Hours

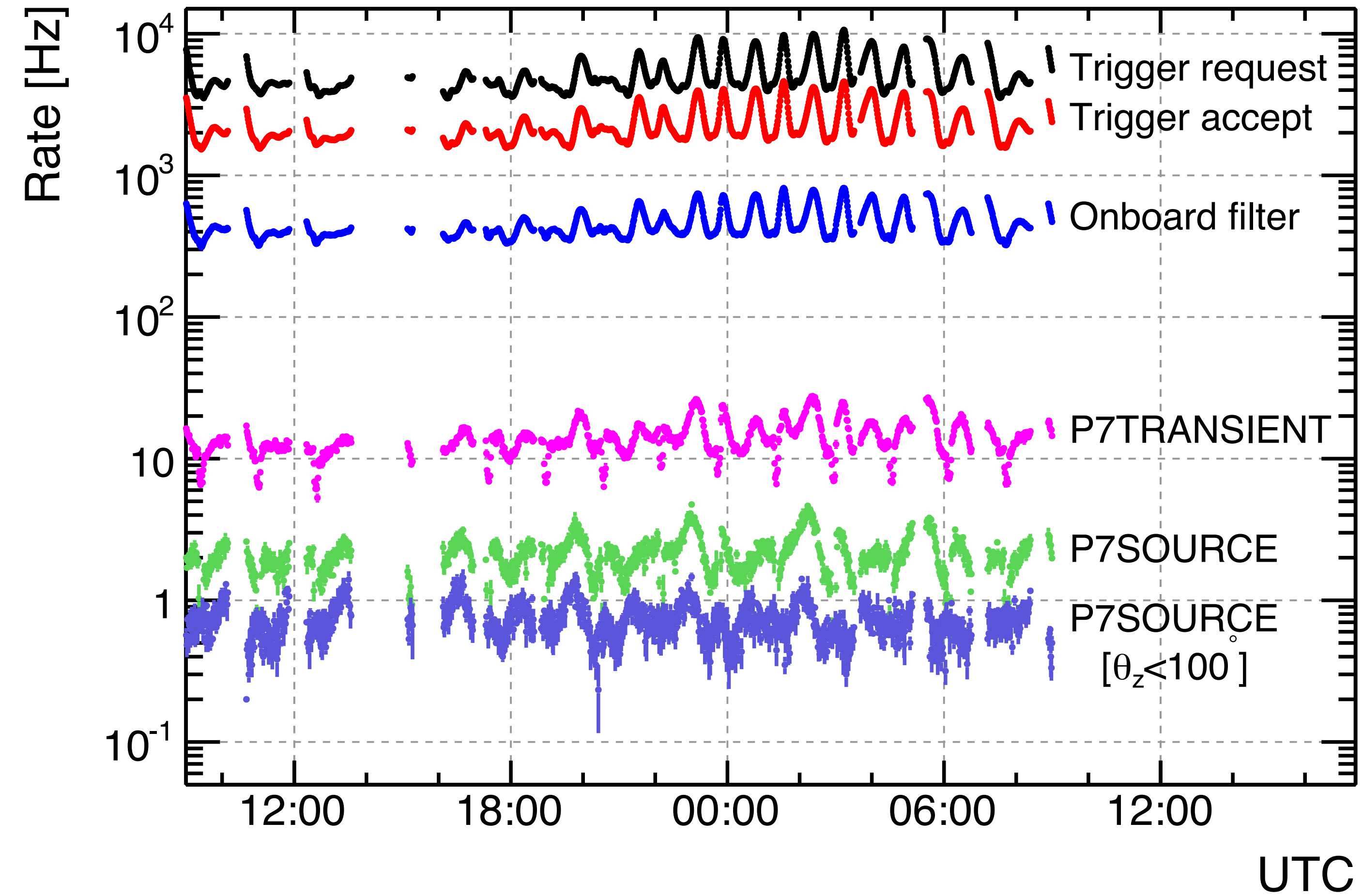


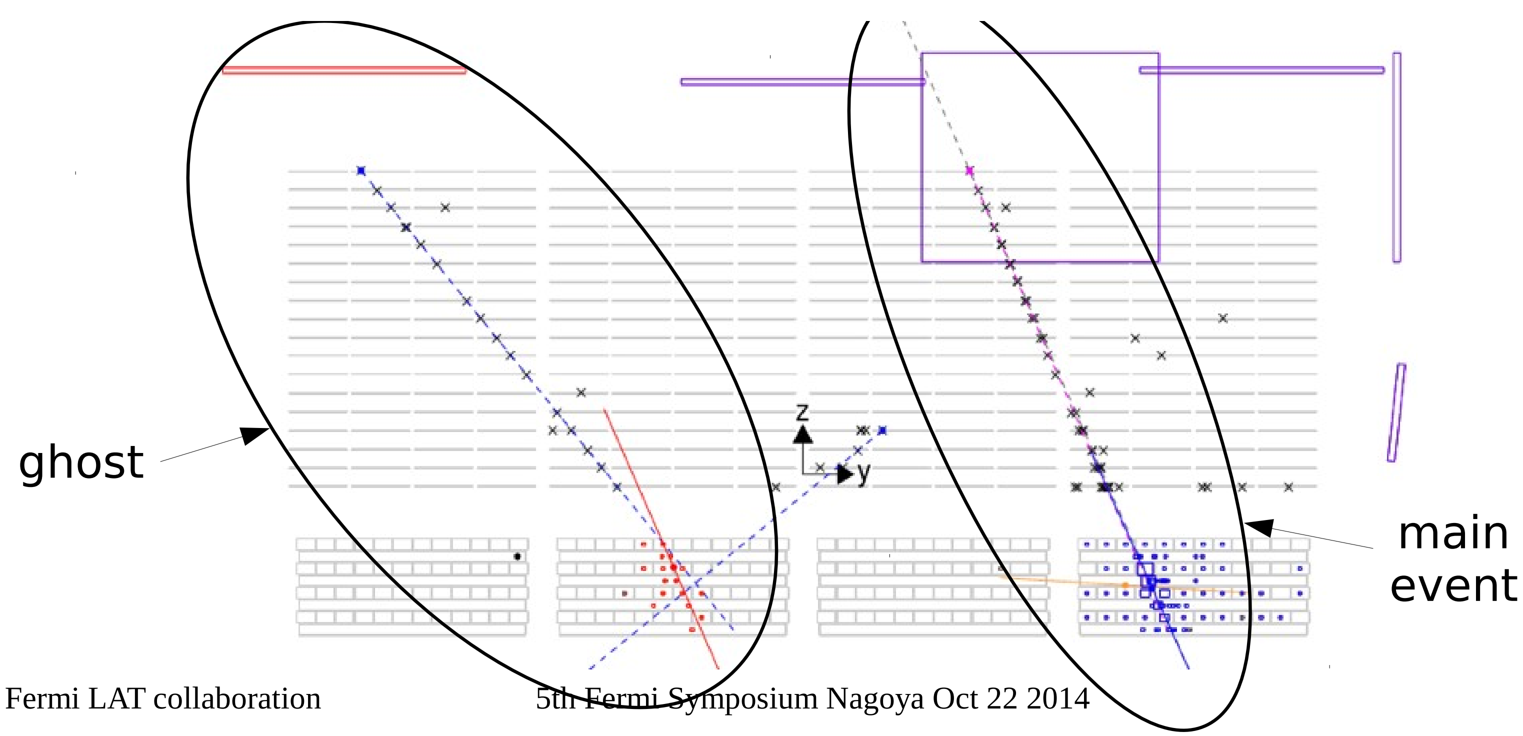
Large field of view: 20% of the sky at any instant!



Atwood et al., ApJ 697, 1071 (2009)

Flux of charged particles is several thousand times larger than the γ-ray flux.

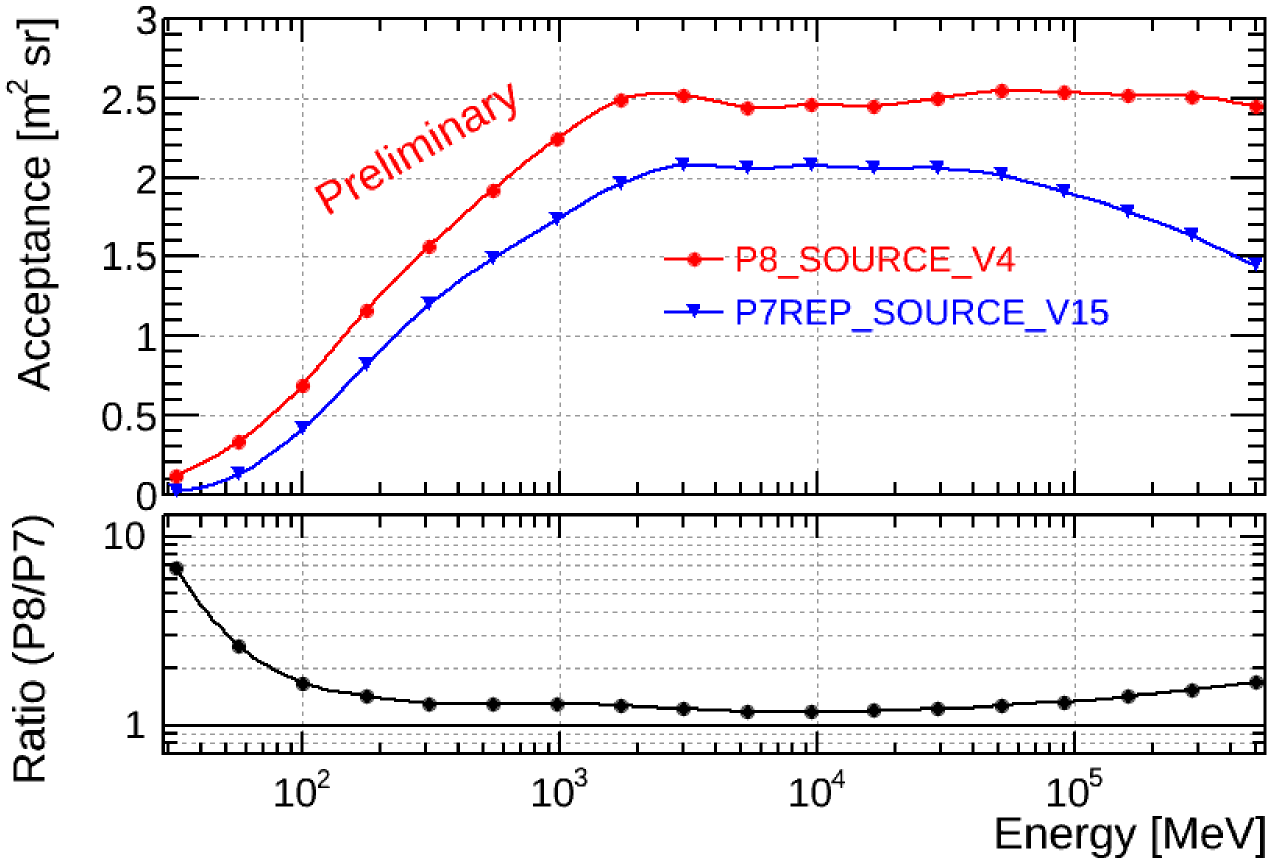


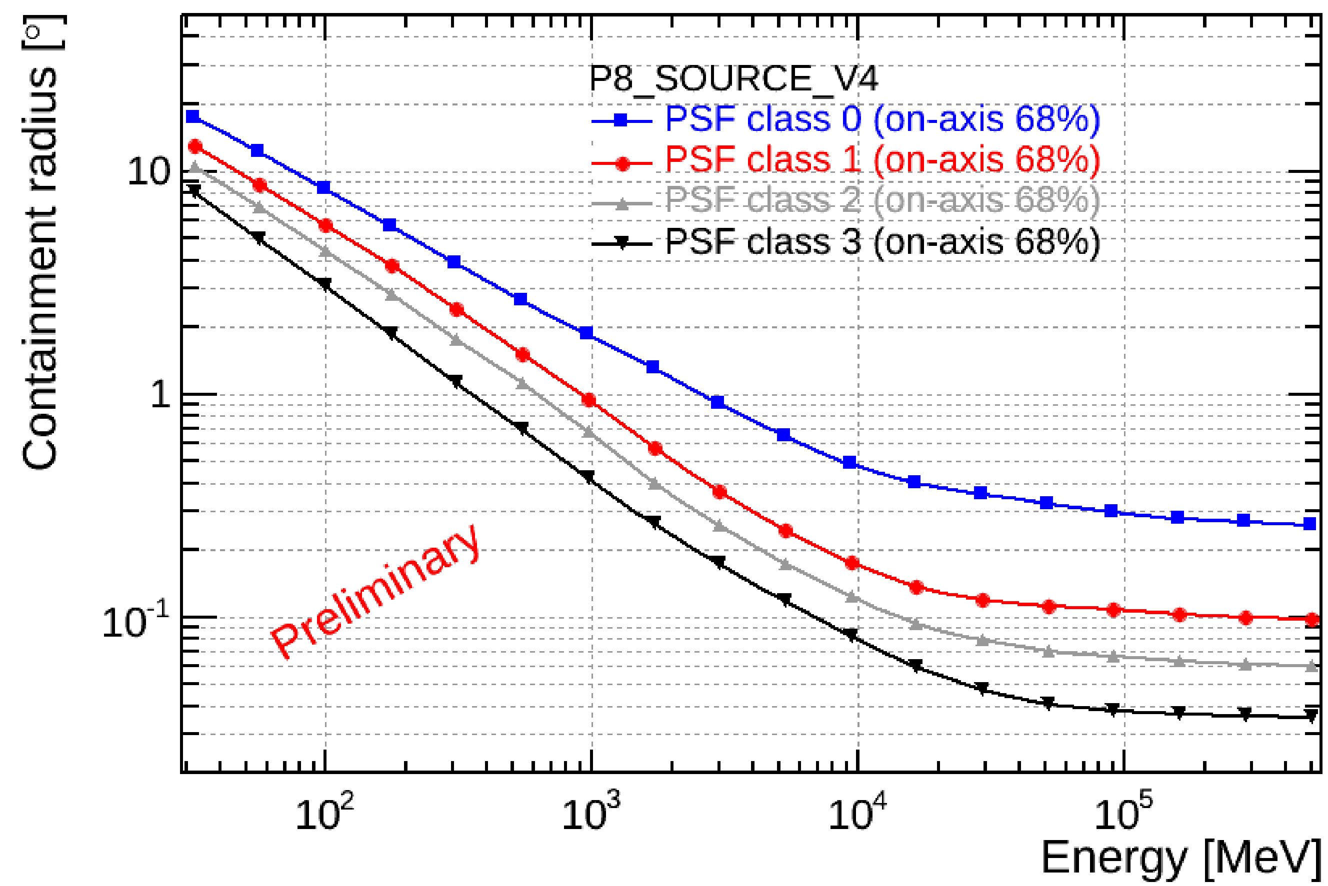


Photon samples are prepared based on **event-by-event analyses**.

Pass 6 -> the event analysis scheme designed prior to launch.
Pass 7 -> accounts for known on-orbit effects based on the real events collected in 2 yrs.
Pass8 - incorporates so far gained experience - deals with issues of ghosts events, incorporates better clustering reconstruction.

Commercial break → Pass 8

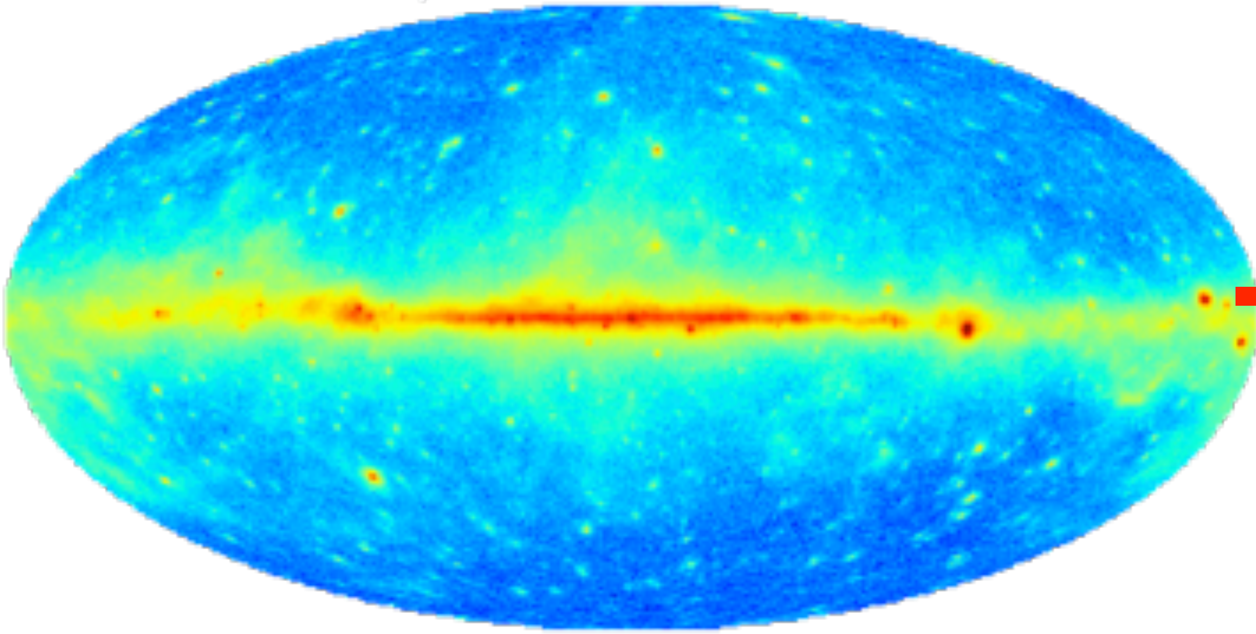




Acceptance ratio >~2 at the edges of energy range
Angular resolution several (~10) times better in the best event class (PSF3) -- lower effective area but narrower PSFs.

The Fermi sky

LAT photons above 300 MeV



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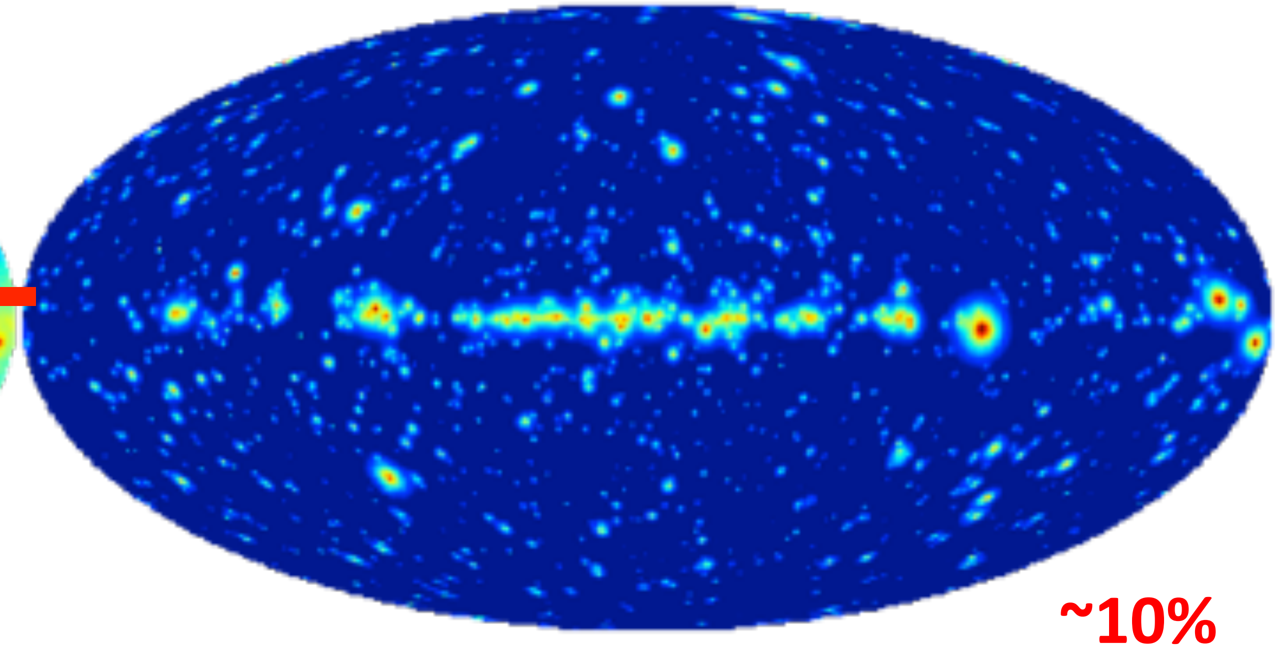
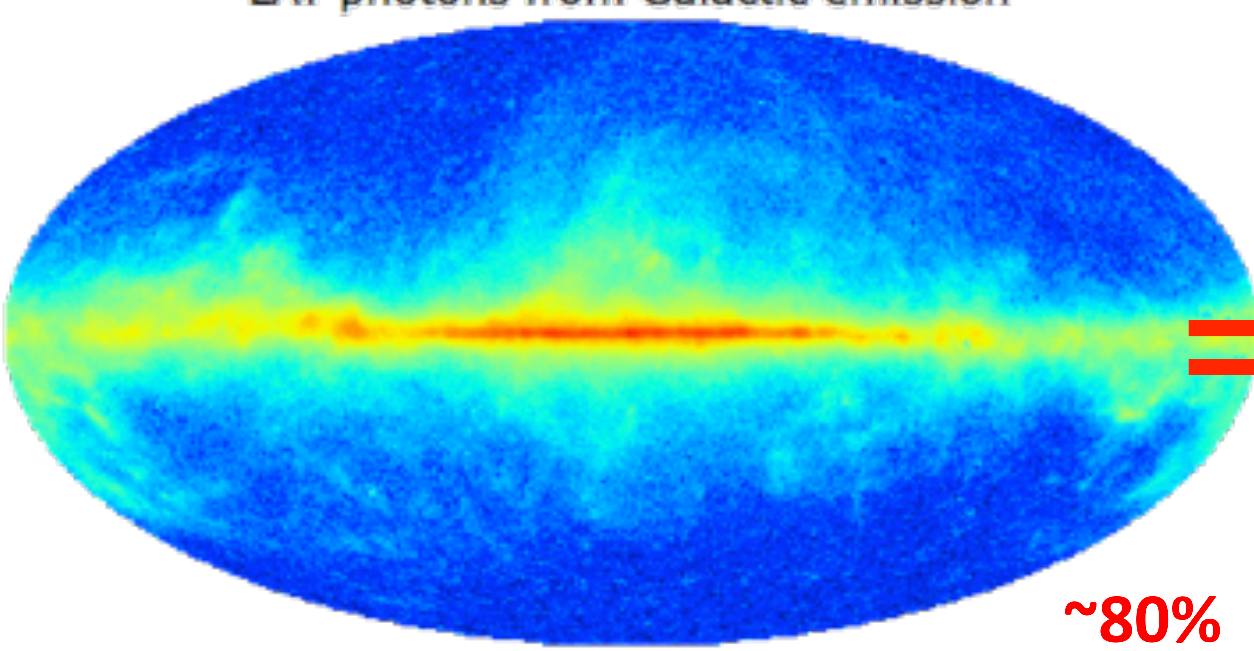
Point Sources



~10%

\- LAT photons from Galactic emission



~80%

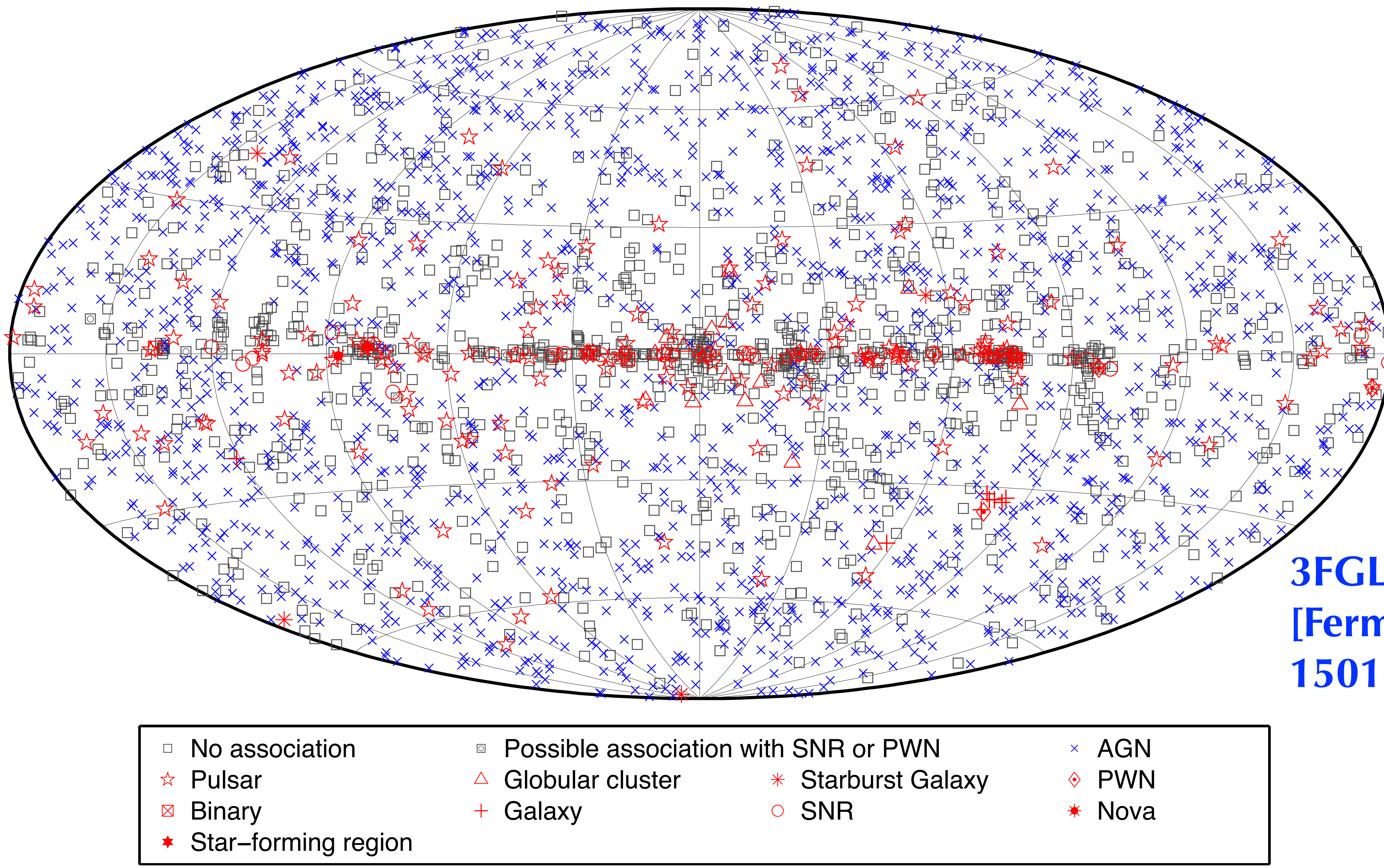
=>

Nearly isotropic all-sky component (includes residual cosmic-ray background)

~10%

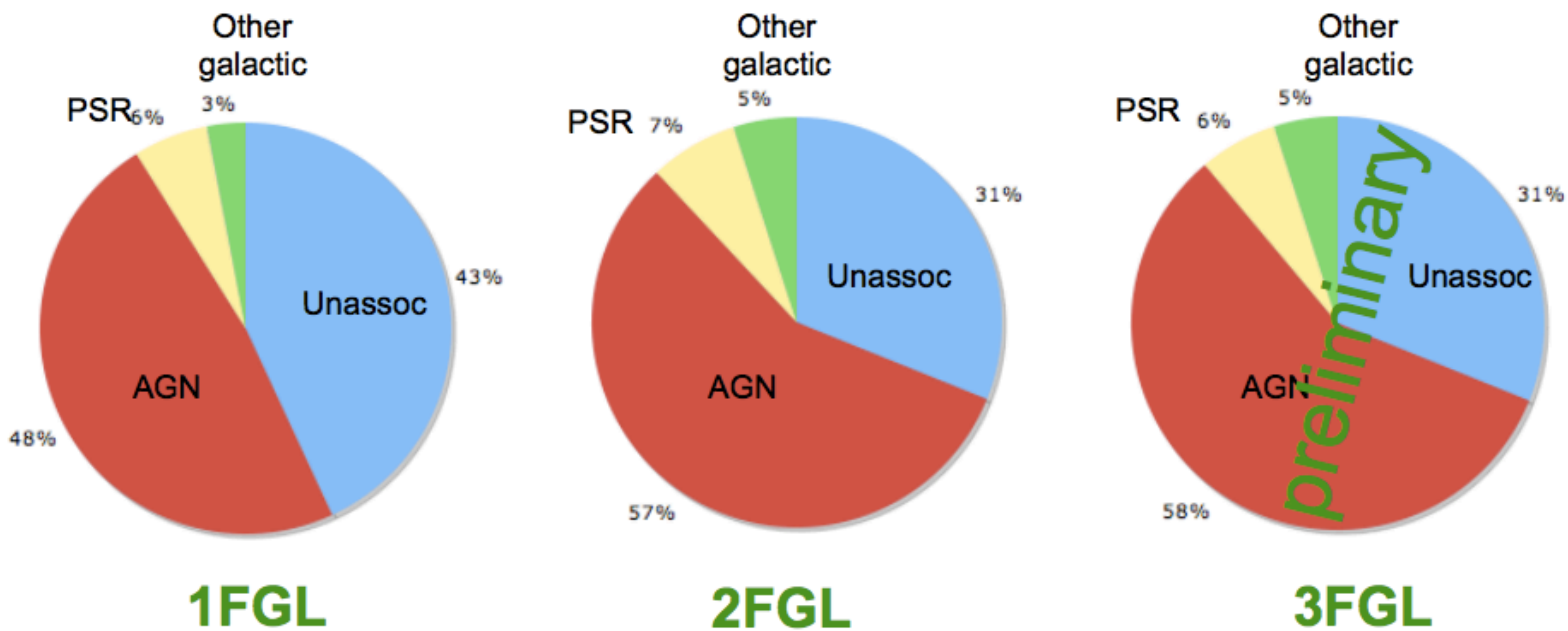
The Fermi sky

Point sources: whole sky coverage + GeV energy range → thousands of point sources (**3033 in 3FGL**)



3FGL [Fermi LAT coll. 1501.02003]

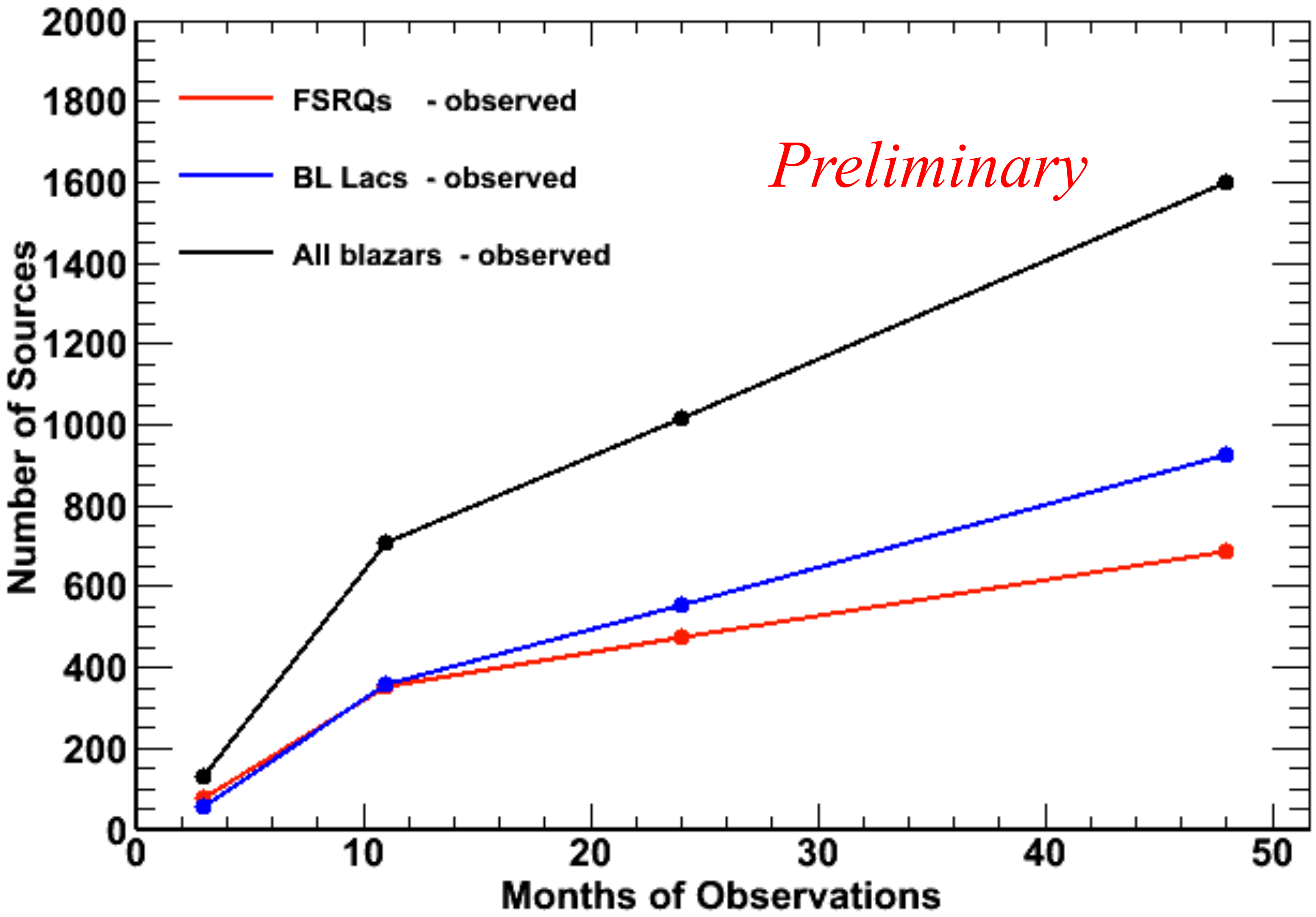
Point sources:

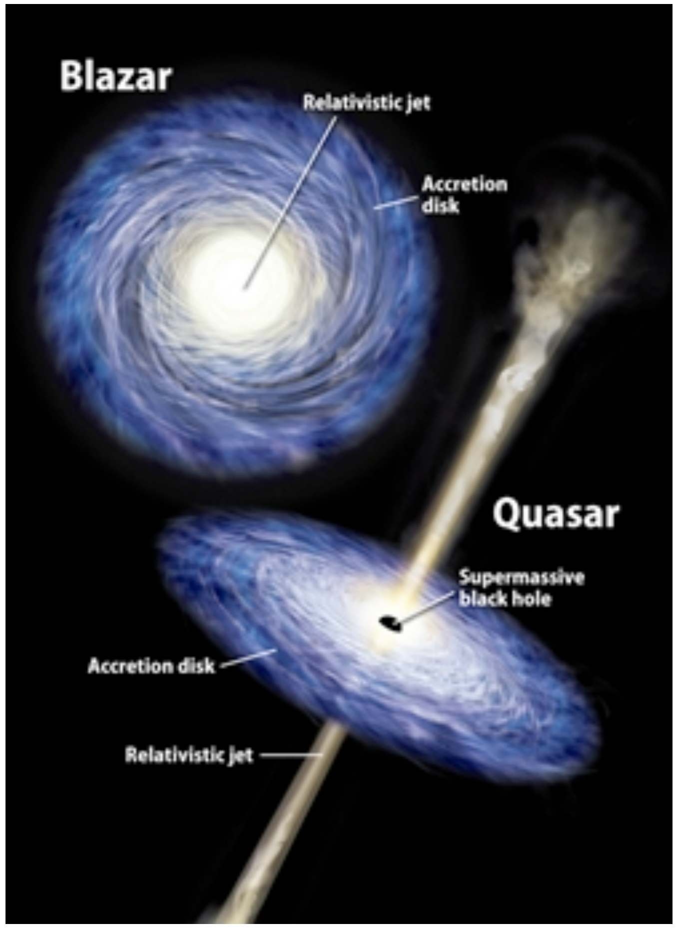


~1400 (11m) ~1800(2 yr) ~3000 (4yr)

better statistics, improved event and gamma ray background analysis and search criteria

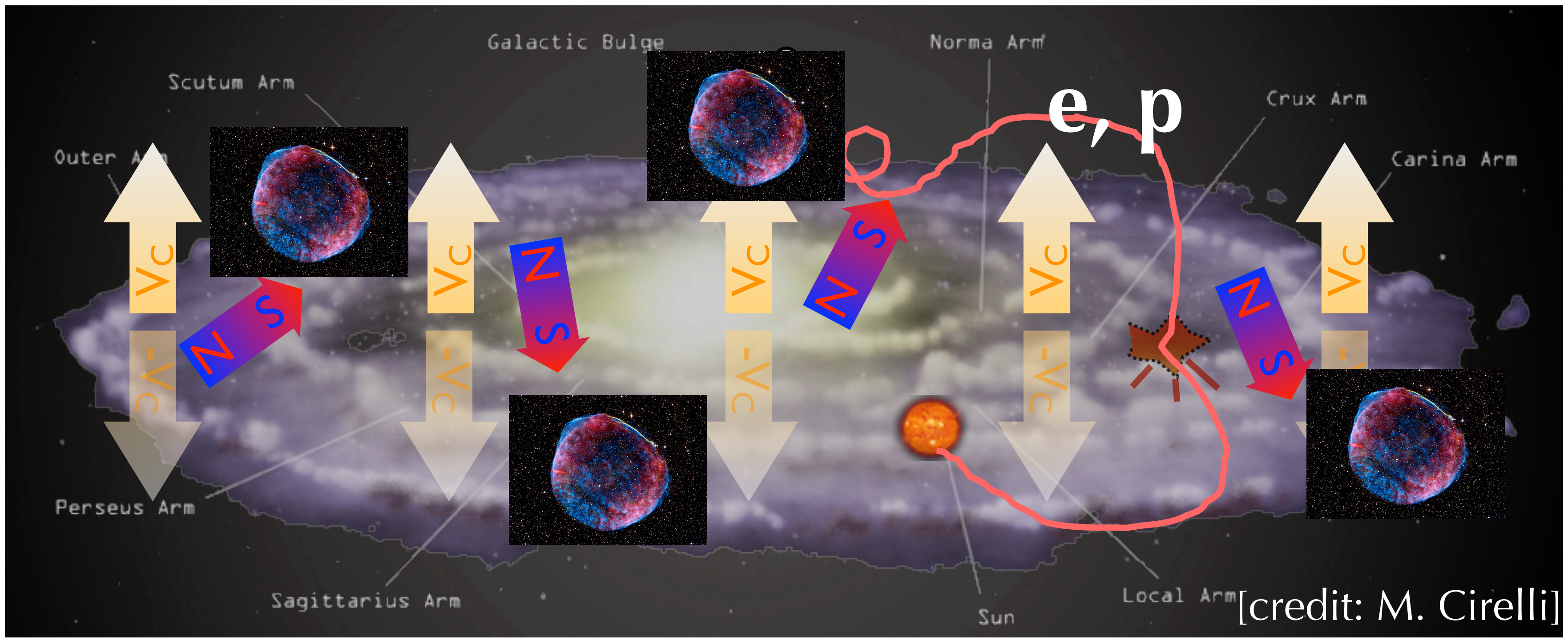
Main extragalactic source class: **blazars! 'superstars of the GeV sky'**
Active Galactic Nuclei (AGN) with a relativistic jet pointing close to our line of sight.





The Fermi sky

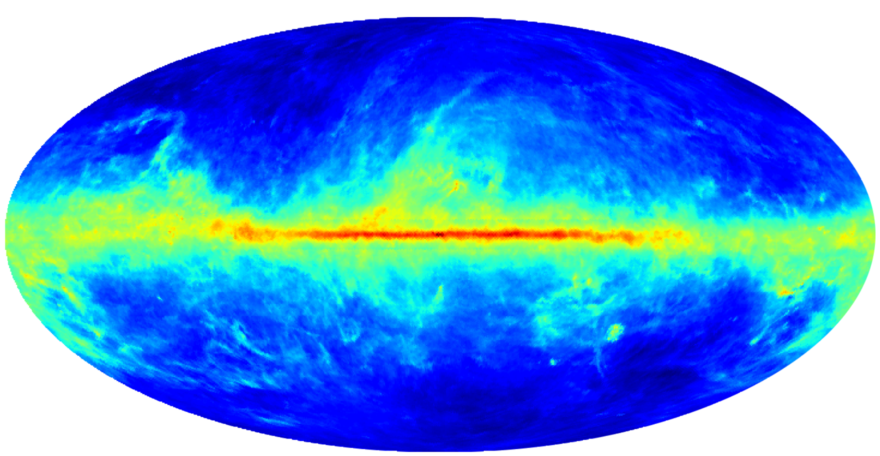
Galactic diffuse emission: 90% of the LAT photons!



cosmic rays + **interstellar medium** → **secondary gamma ray emission**

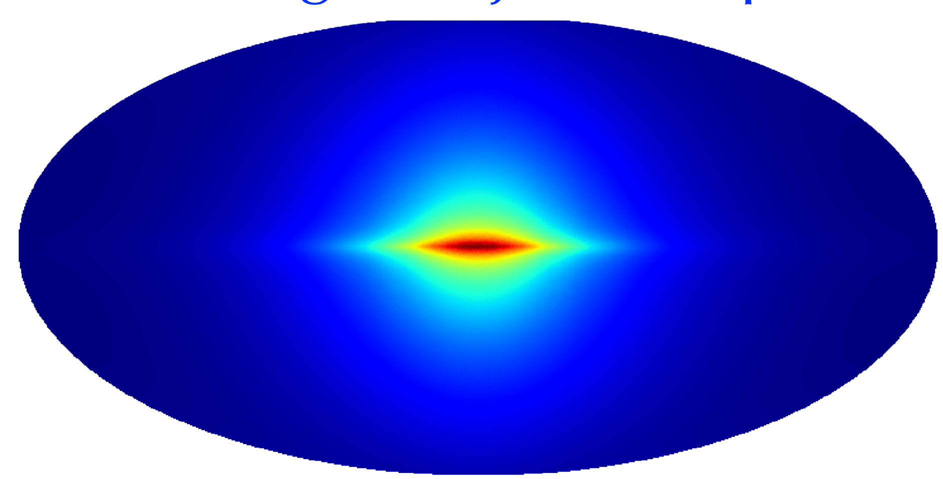
many parameters: distribution of sources, magnetic fields, gas, injection spectra...

~



π^0, **bremss**

+



IC

Isotropic emission - Fermi LAT measurement 100 MeV-820 GeV

Derivation of the isotropic emission in three steps:

1. **define event selection**: customized selection of gamma ray events, at LOW and HIGH energies

2. **template fitting of components of whole sky emission** to determine the spectrum of the isotropic component

3. **subtract additional cosmic ray contamination** detector level simulations

[Ackermann+ (Fermi LAT col.): ApJ (2015), 1410.3696]

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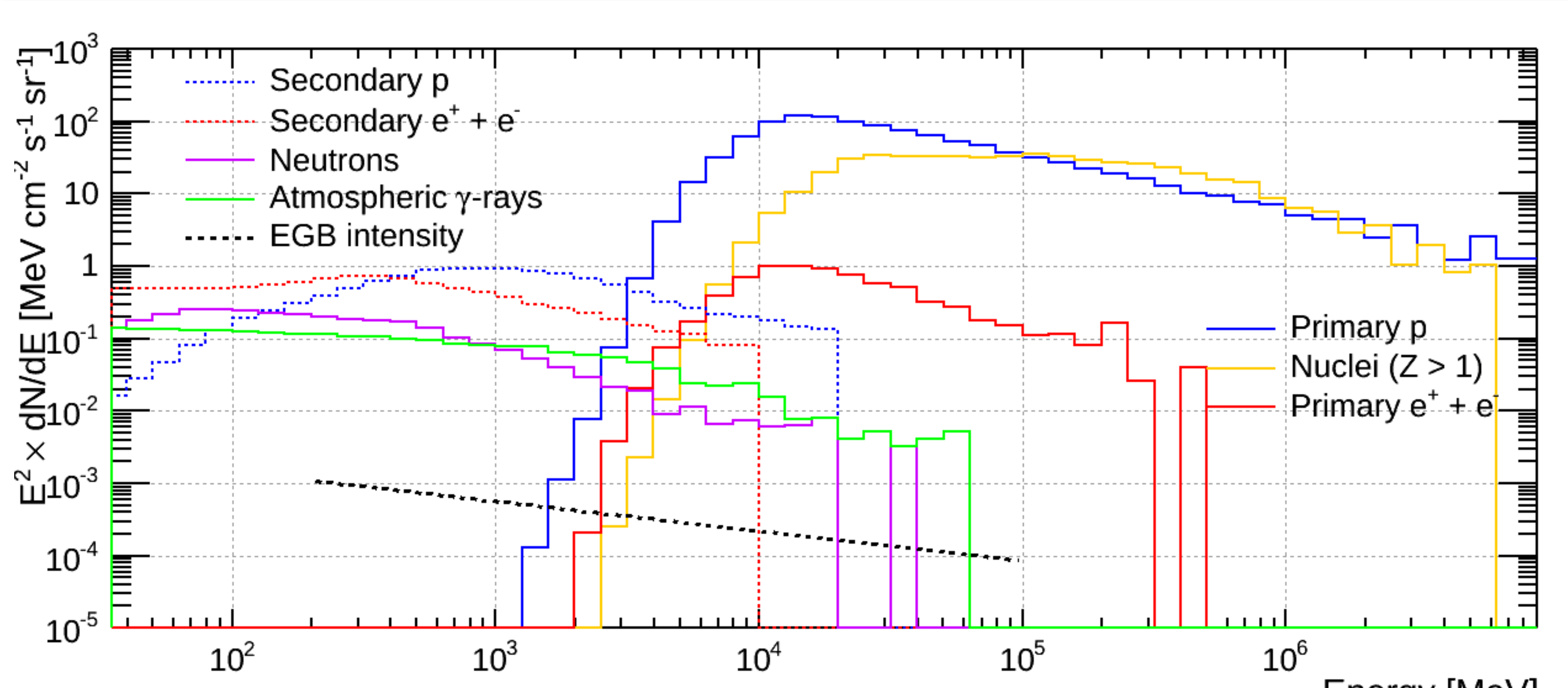
Isotropic emission

50 months LAT data.
The predefined event classes have insufficient CR background (ISOTROPIC!) rejection performance < 400 MeV and > 100 GeV -> **develop custom selection**.



Ackermann et al. 2012, ApJS, 203, 4

Since particle background composition varies significantly over LAT energy range, devise **two custom event selections** optimized for **low-energy (<13 GeV)** and **high-energy (>13 GeV)** IGRB analysis

Isotropic emission

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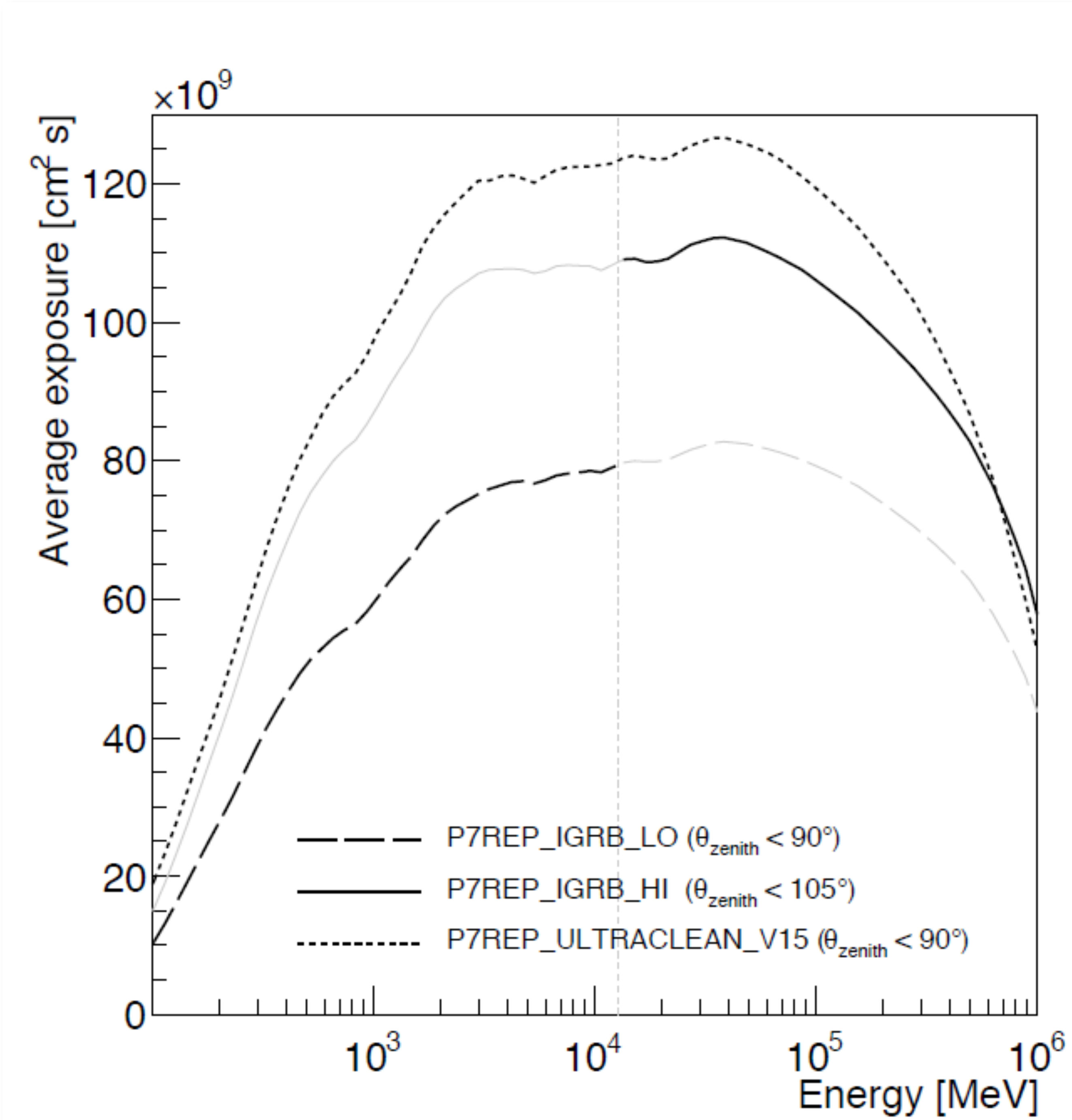

Relative to standard P7 Ultraclean selection, cosmic-ray background rate reduced by factor 3 around 200 MeV (where background rate is highest) and acceptance increased >500 GeV

Isotropic emission - Fermi LAT measurement 100 MeV-820 GeV

Derivation of the isotropic emission in three steps:

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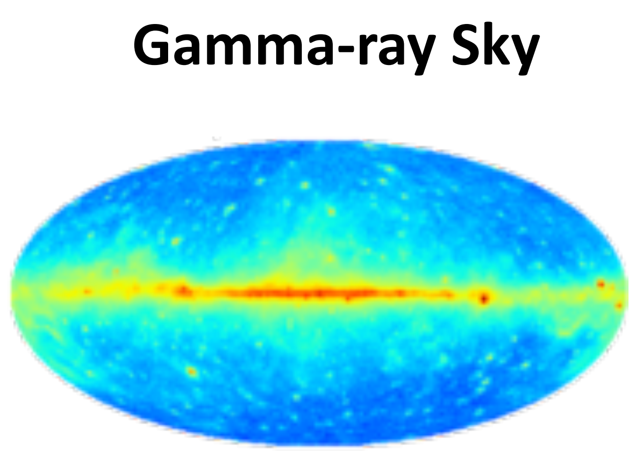
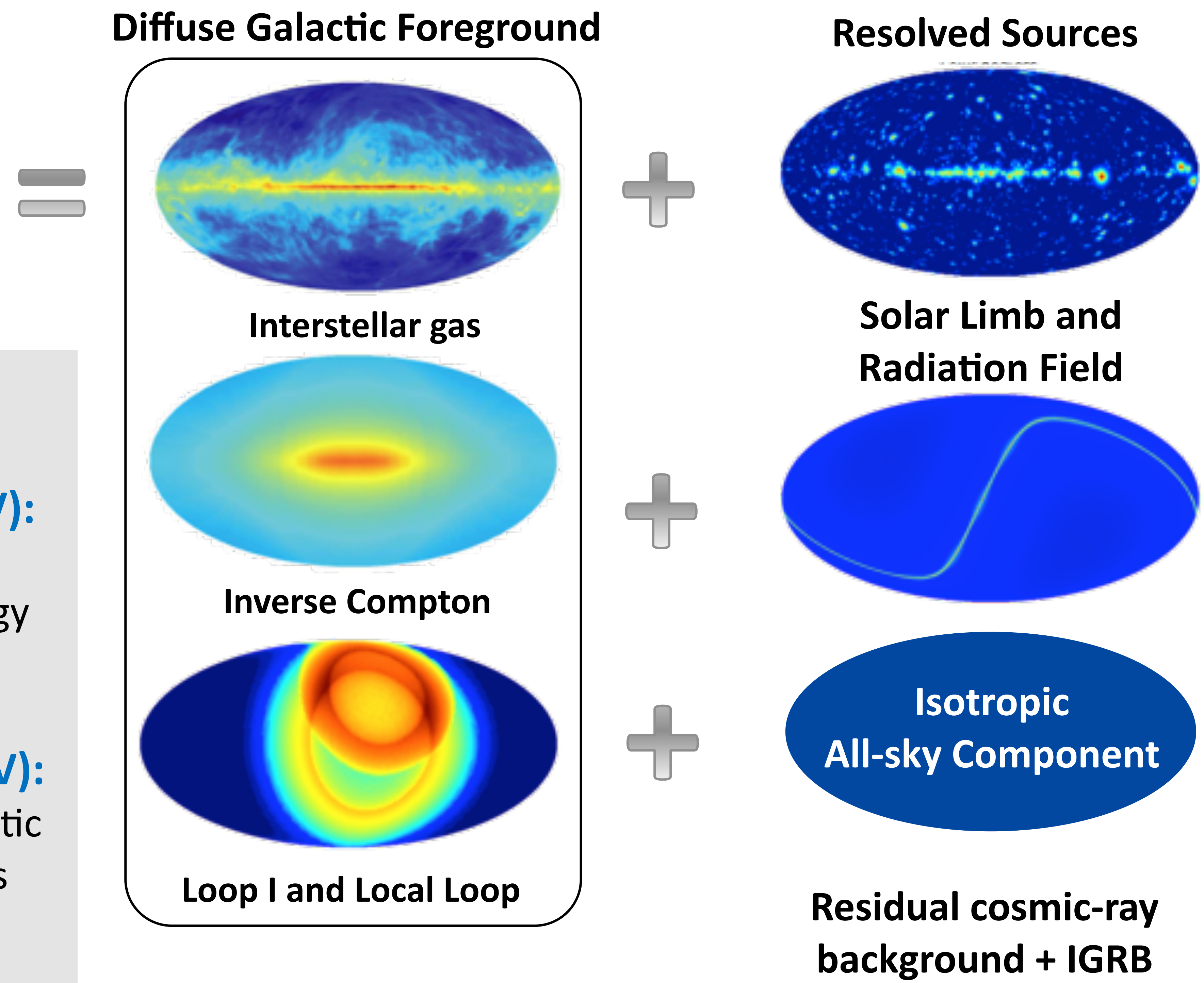
Isotropic emission

step 2: Galactic diffuse emission: Template Fitting Procedure (Maximum Likelihood in each pixel and energy bin)





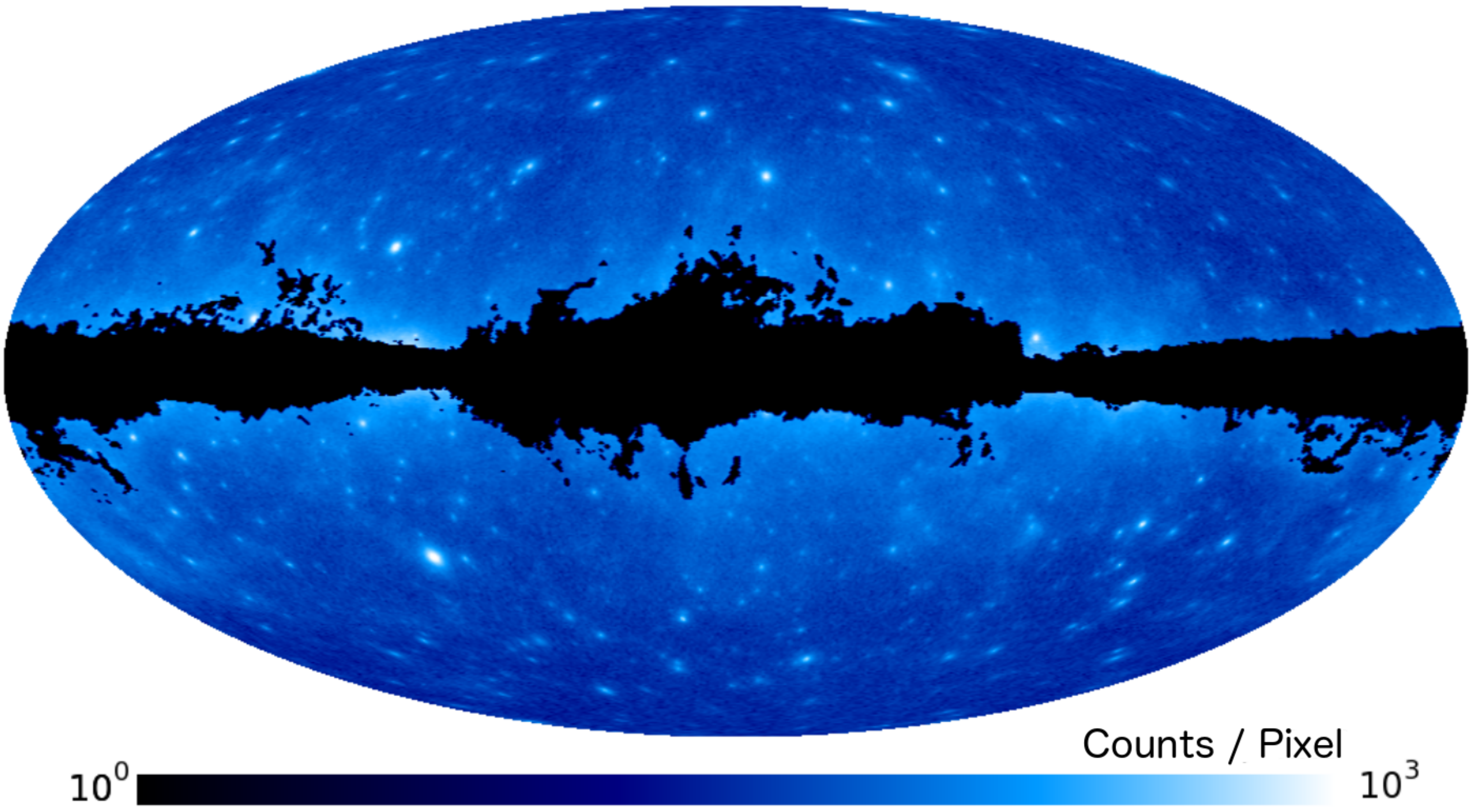
Two Energy Regimes

Low-energy (<13 GeV):
Normalizations fitted separately in each energy bin for all components

High-energy (>13 GeV):
Normalizations of Galactic foreground components set by average fit result from 6 – 51 GeV

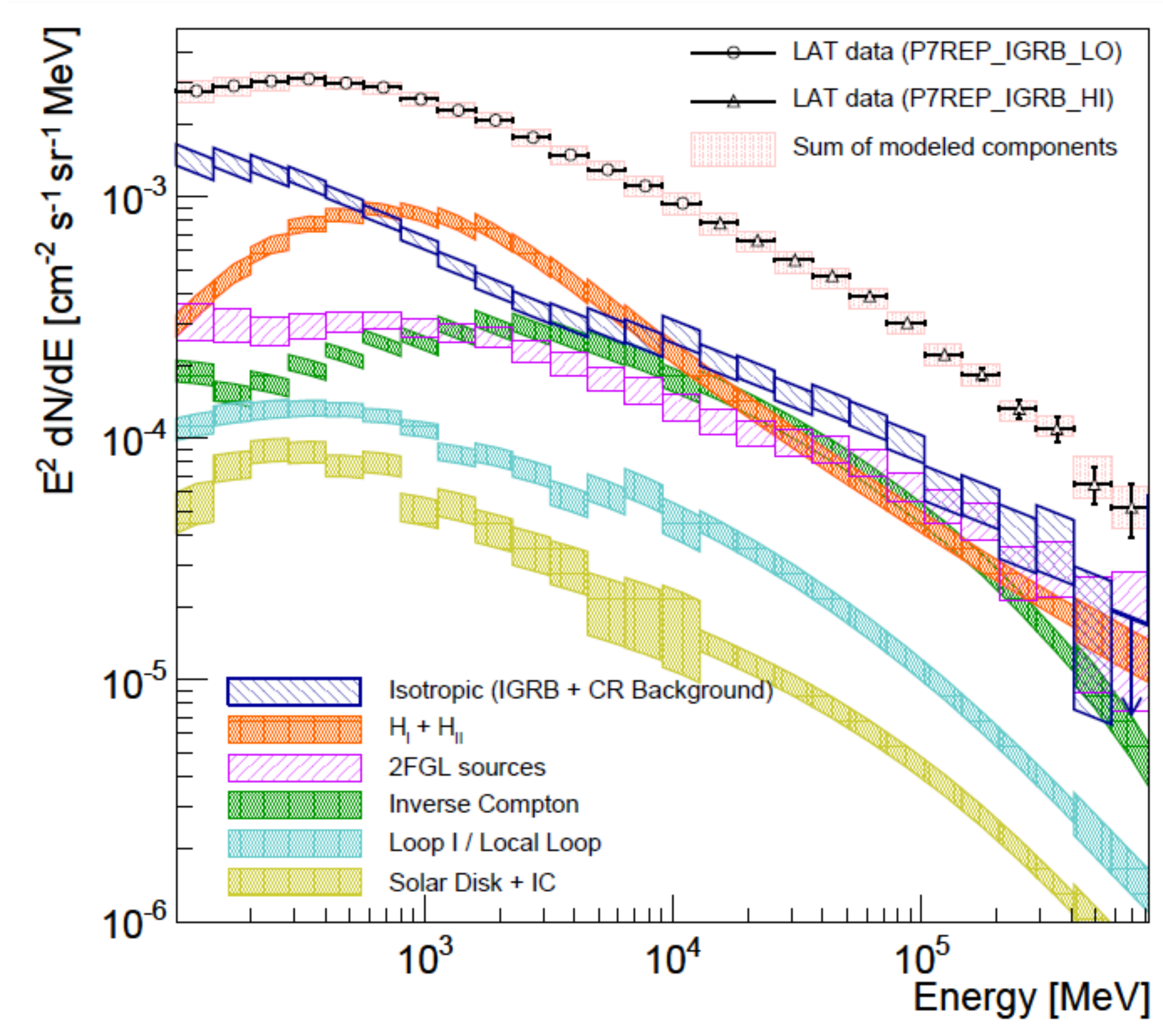
Isotropic emission

the brightest regions (gas emission) mask



Isotropic emission

step 2: Galactic diffuse emission: Template Fitting Results (benchmark GDE model)

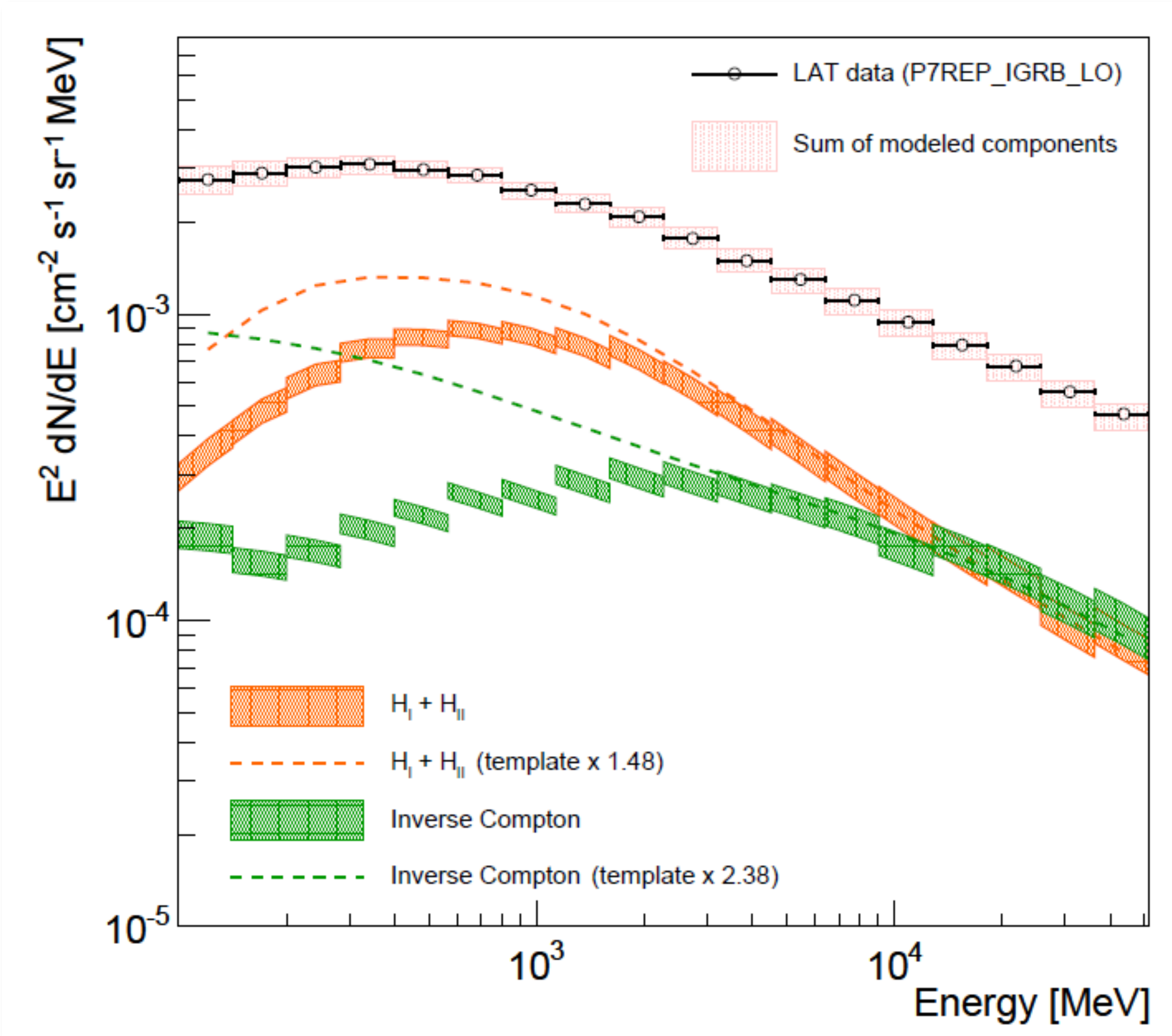


Average intensities at Galactic latitudes |b| > 20 deg attributed to each model component for **baseline Galactic foreground model**

Error bars include statistical uncertainty and systematic uncertainty from LAT effective area parameterization

Isotropic emission

step 2: Galactic diffuse emission: GDE uncertainties



Good agreement between baseline Galactic foreground model spectral shapes and fit to LAT data above few GeV

Bin-by-bin fit can partially compensate for spectral deviations from model, but model over-prediction below 1 GeV may indicate incomplete understanding of cosmic-ray source distribution, interstellar radiation field, etc.

Motivates consideration of alternative Galactic foreground models

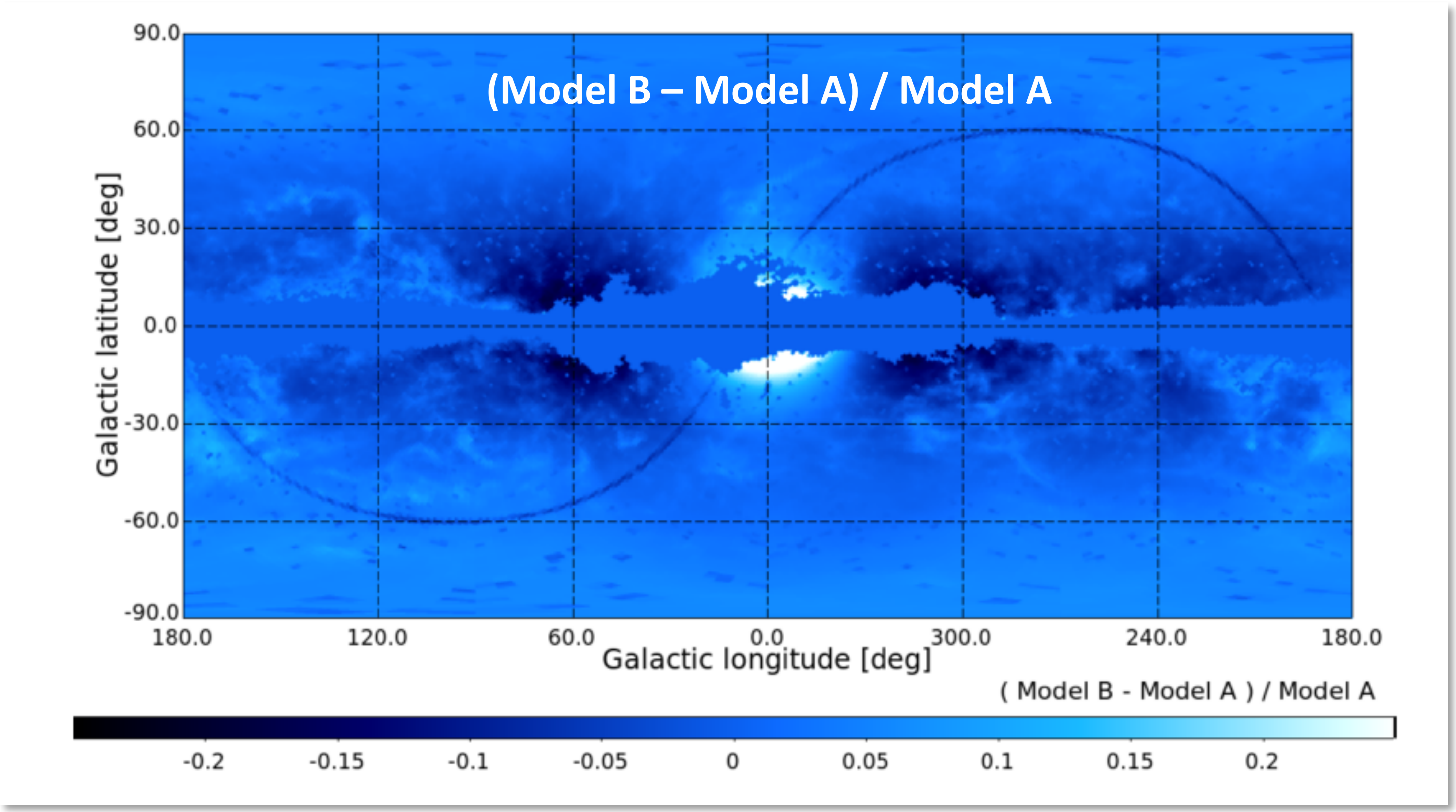
Isotropic emission

step 2: Galactic diffuse emission: GDE uncertainties

Model A (baseline): Similar to models in Ackermann et al. 2012, ApJ, 750, 3

Model B: Add population of electron-only sources near Galactic center

Model C: Vary cosmic-ray diffusion rate with Galactocentric height and radius



Isotropic emission

step 2: Galactic diffuse emission: GDE uncertainties

Test the following variants for baseline Galactic foreground model A

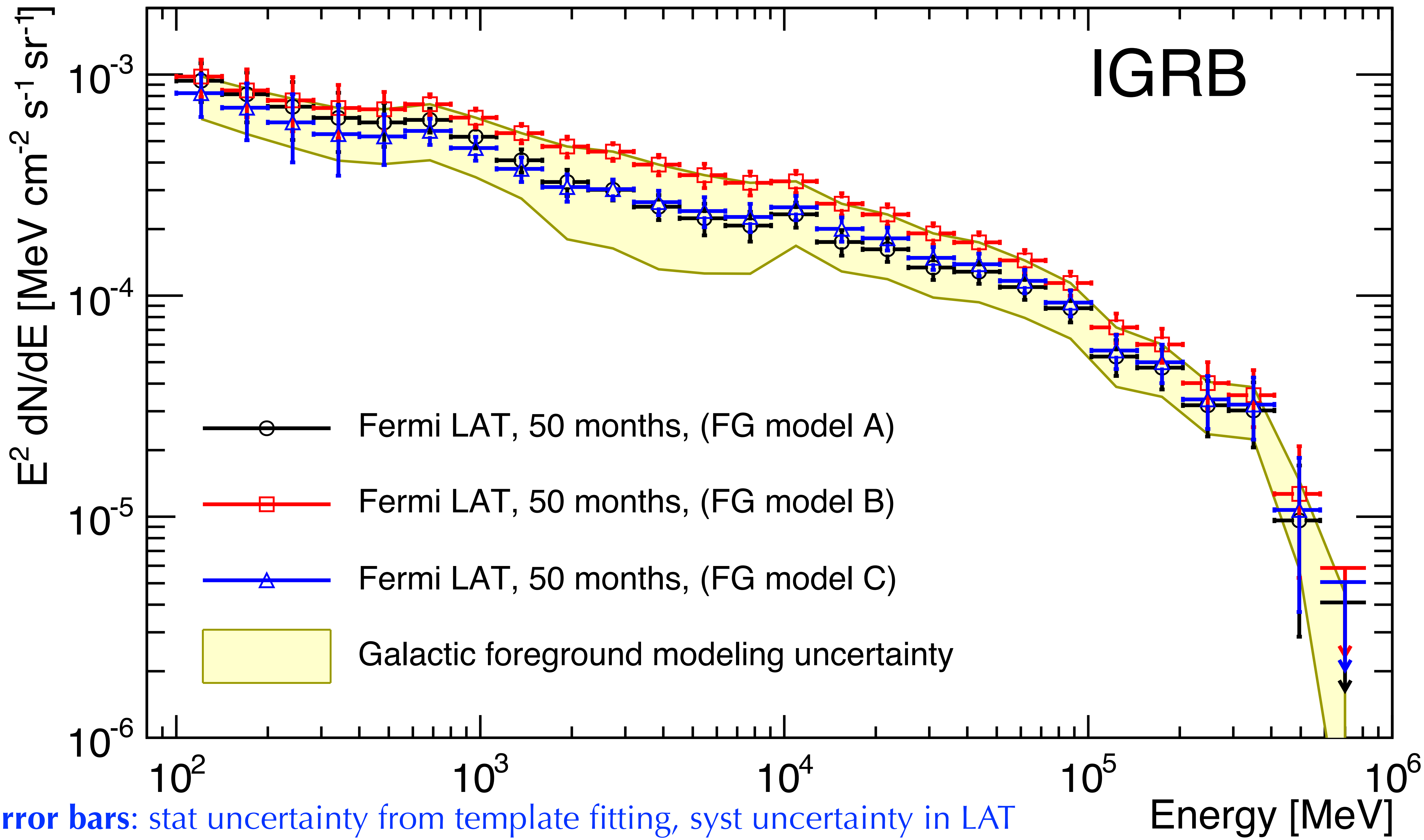
- Increase radiation field in Galactic bulge (×10)
- Lower Galactic random magnetic field strength (from 7 to 3 μG)
- Test plain diffusion model without reacceleration
- Different cosmic-ray source radial distribution (SNRs vs. pulsars)
- Variation in cosmic-ray halo size (4 or 10 kpc vs. 5 kpc)
- Test two different templates for the "*Fermi* Bubbles"
- Vary dust to atomic hydrogen ratio (±10%)

Check consistency of IGRB intensity inferred from distinct regions

- Inner / outer Galactic hemispheres
- North / south Galactic hemispheres

Isotropic emission

and the final result...

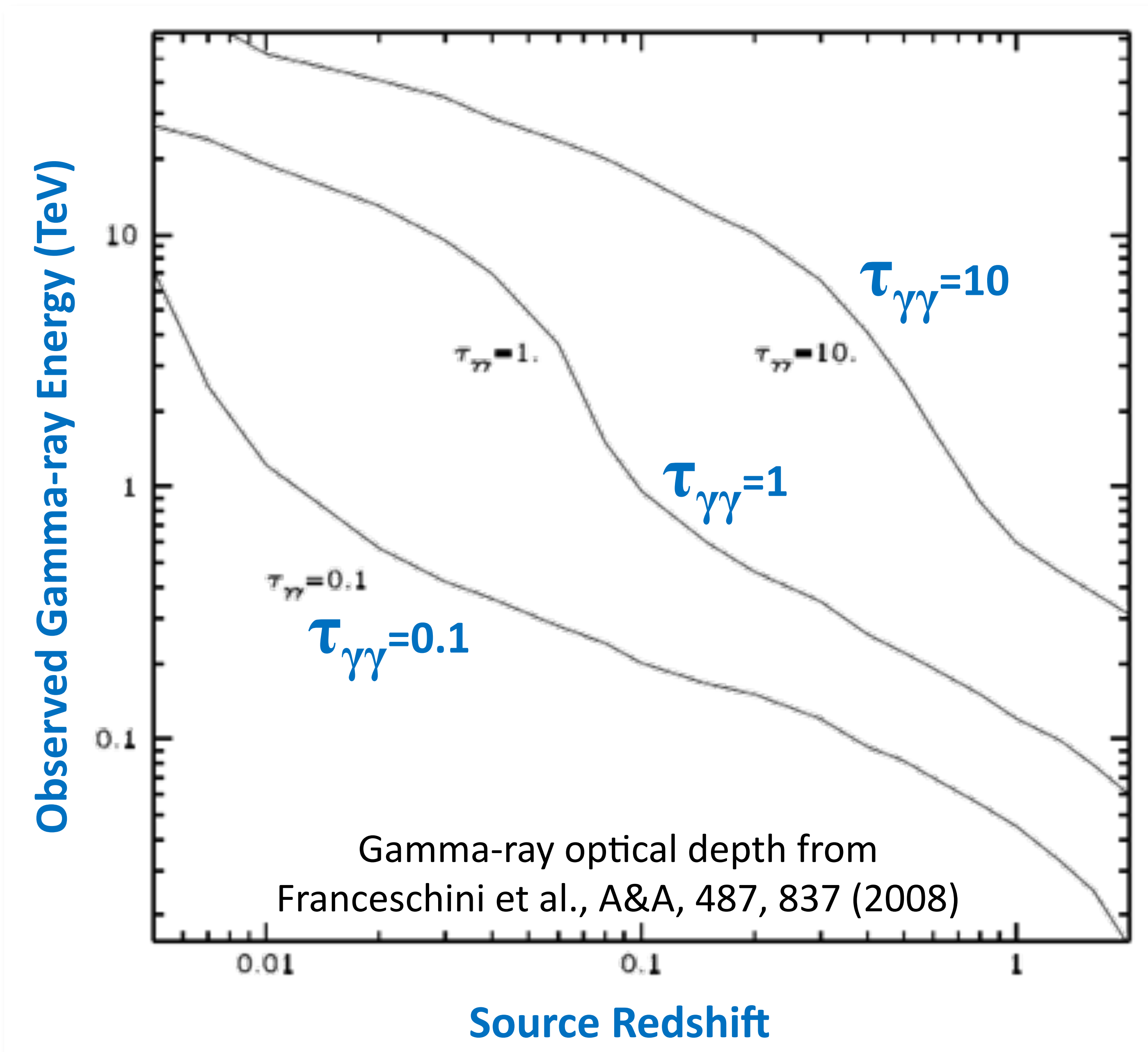


error bars: stat uncertainty from template fitting, syst uncertainty in LAT effective area, and syst uncertainty in residual cosmic-ray background levels

Isotropic emission

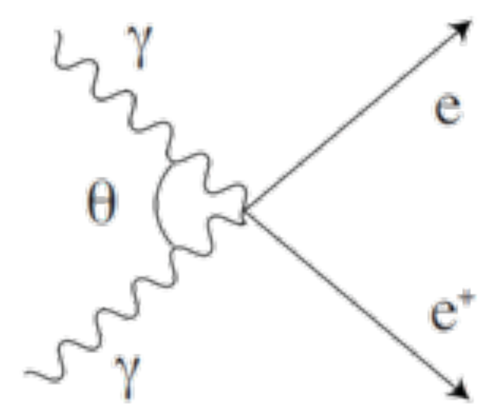
->PL + exp cut-off

EGB spectrum is found compatible with a power law with a photon index of 2.32 (±0.02) that is exponentially cut off at 279(±52) GeV.



Gamma-ray optical depth from
Franceschini et al., A&A, 487, 837 (2008)

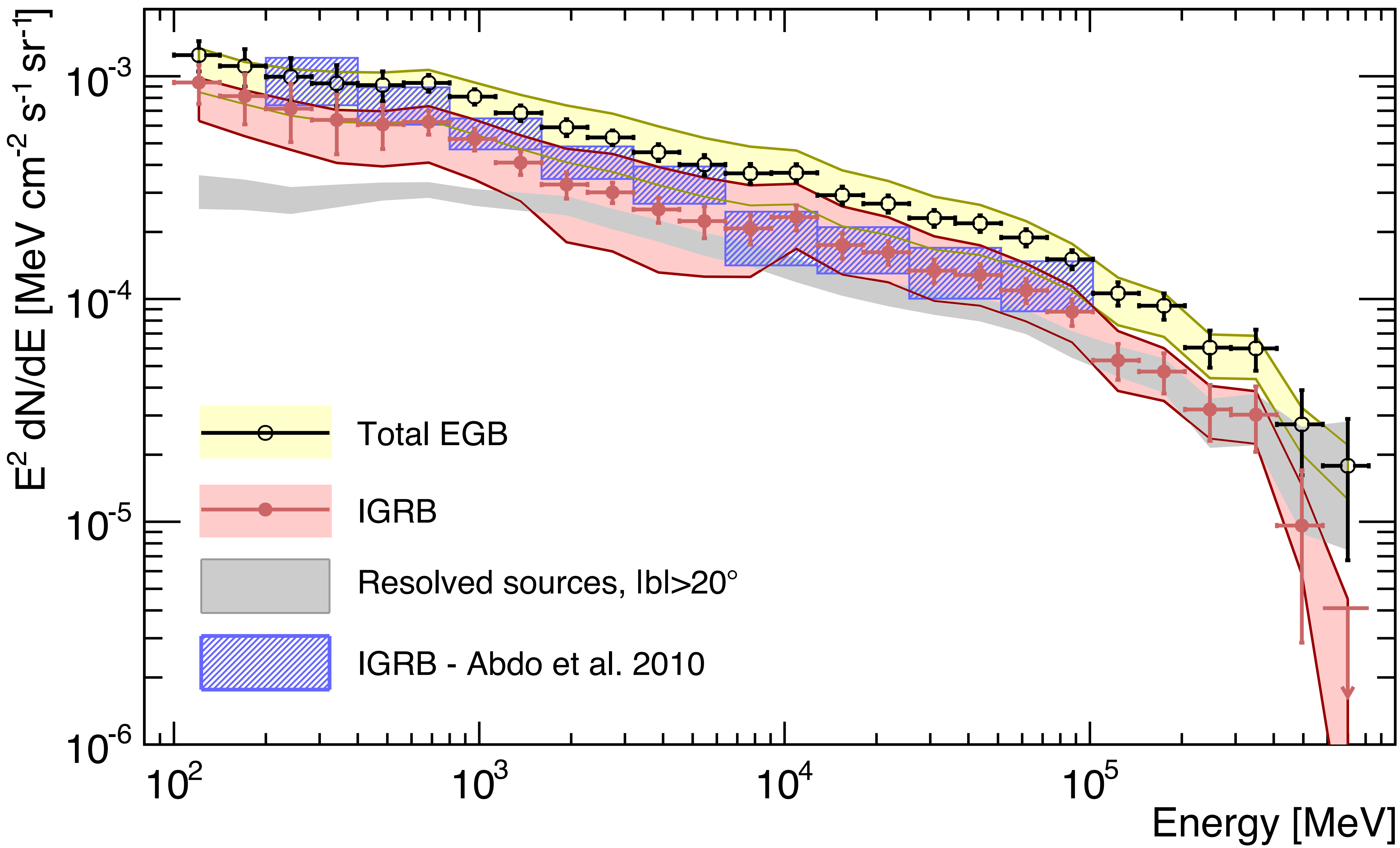
Above ~100 GeV, we expect a gamma-ray horizon due to electron/positron pair production on the IR/ optical/UV extragalactic background light



Isotropic emission

Results

EGB = IGRB + point sources (stays constant in time)



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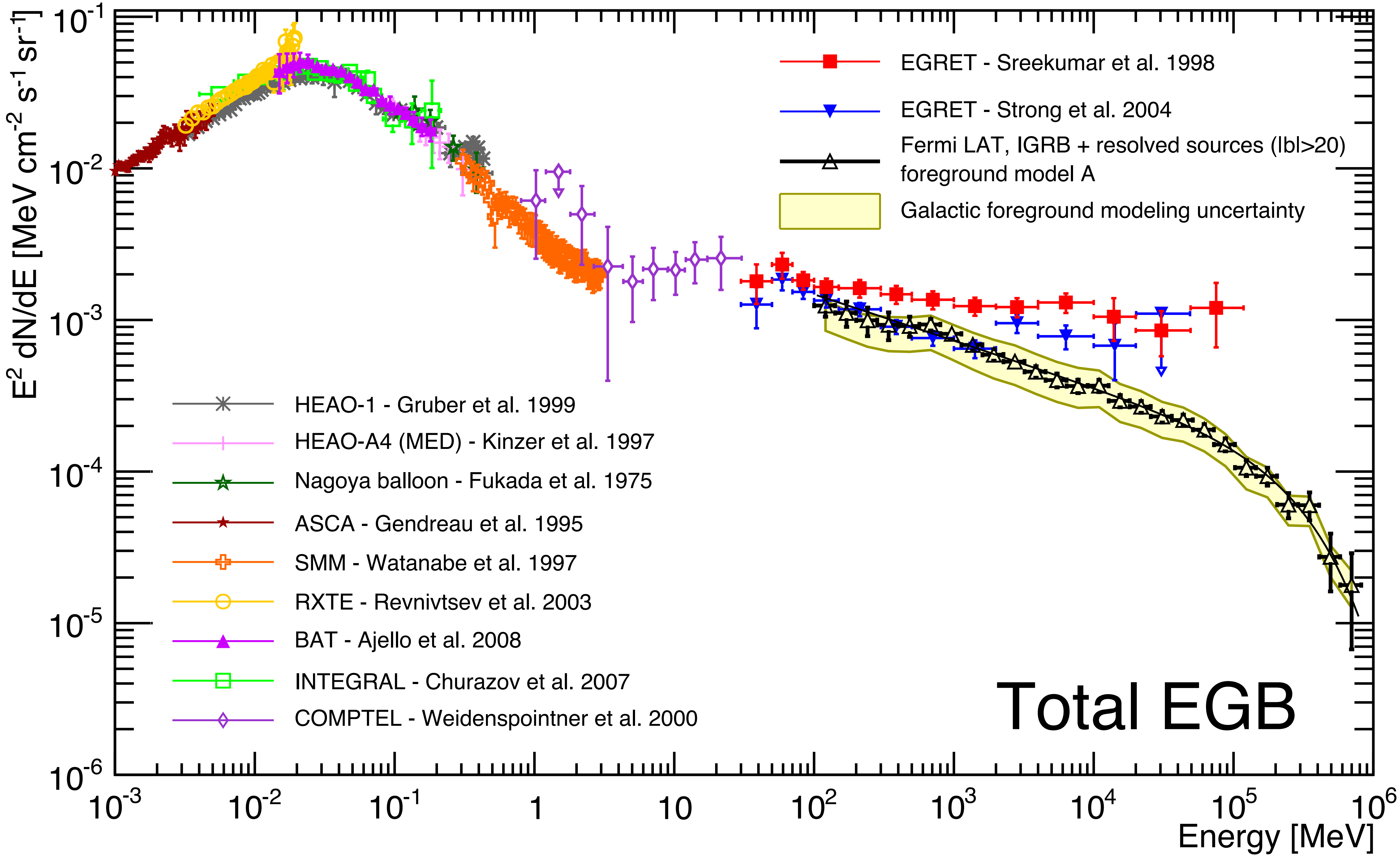
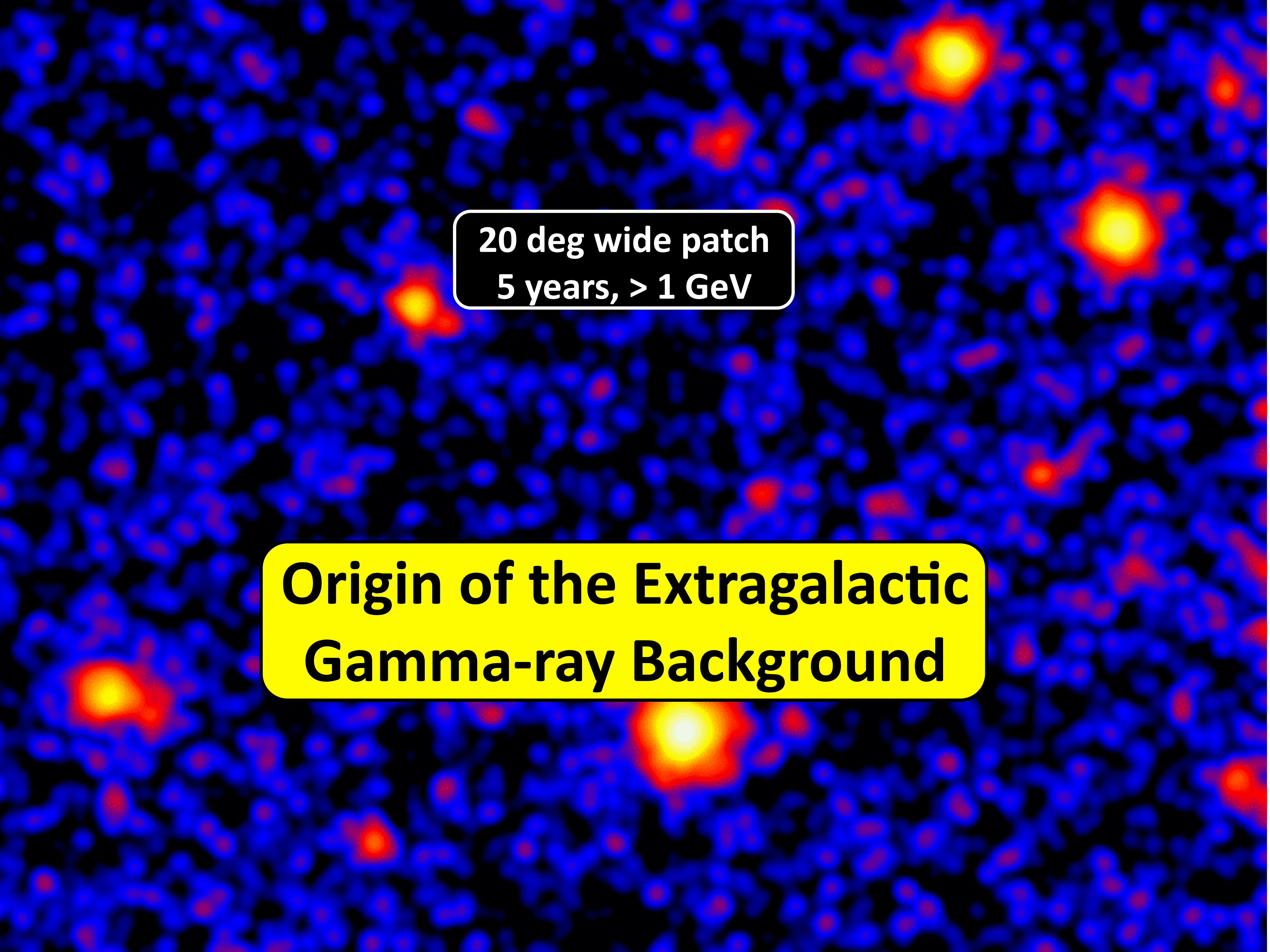
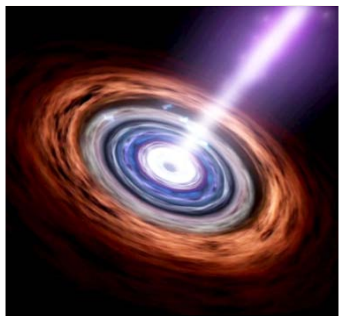


Origin of the Extragalactic Gamma-ray Background



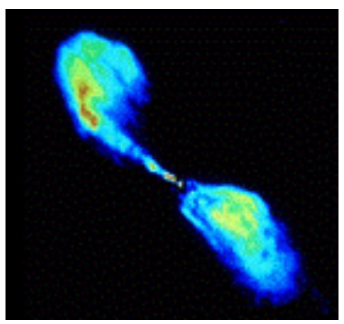
The origin of emission

Undetected sources



Blazars

Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.

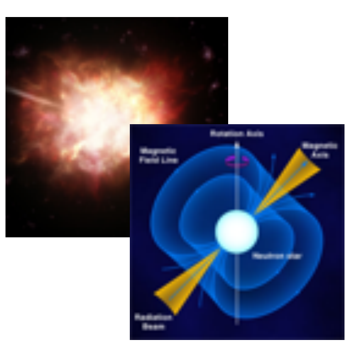


Non-blazar active galaxies

27 sources resolved in 2FGL
~ 25% contribution of radio galaxies to EGB expected. (e.g. Inoue 2011)

Star-forming galaxies

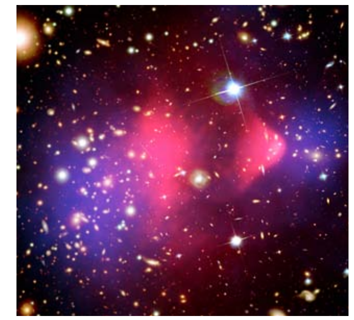
Several galaxies outside the local group resolved by LAT. Significant contribution to EGB expected. (e.g. Pavlidou & Fields, 2002, Ackermann et al. 2012)



GRBs
High-latitude pulsars

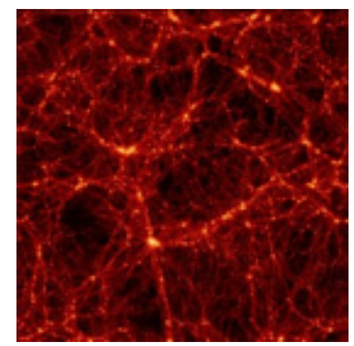
Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

Diffuse processes



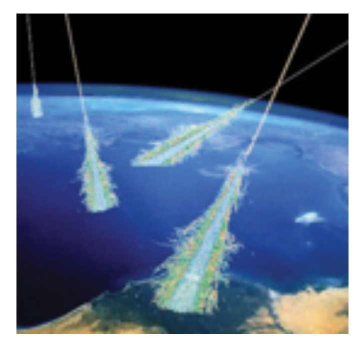
Intergalactic shocks

Widely varying predictions of EGB contribution ranging from 1% to 100% (e.g. Loeb & Waxman 2000, Gabici & Blasi 2003)



Dark matter annihilation

Potential signal dependent on nature of DM, cross-section and structure of DM distribution (e.g. Ullio et al. 2002)



Interactions of UHE cosmic rays with the EBL

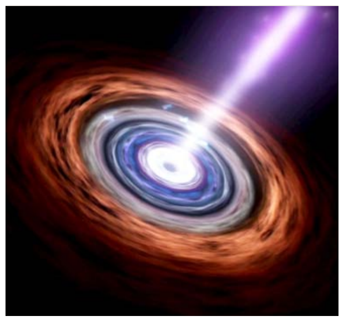
Dependent on evolution of CR sources, predictions varying from 1% to 100 % (e.g. Kalashev et al. 2009)

Extremely large Galactic electron halo (Keshet et al. 2004)

CR interaction in small solar system bodys (Moskalenko & Porter 2009)

The origin of emission

Undetected sources



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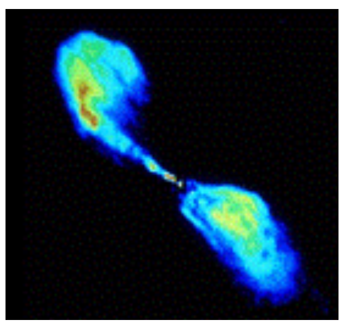

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In- -ks

-ctions of
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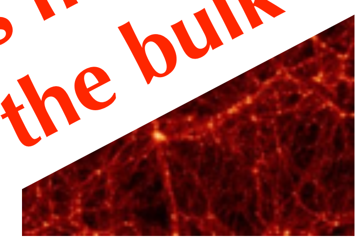

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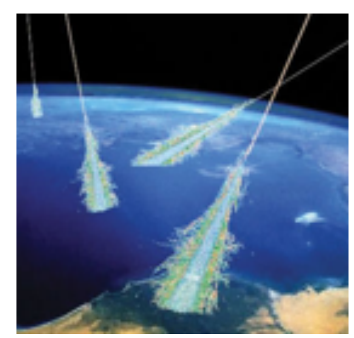

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The Big Questions:

– Which class of source contributes how much to the EGB ?

– Can unresolved sources explain the bulk of the EGB ?

The origin of emission

Many models in the literature:

Blazars: Stecker+93, Padovani+93, Salomon&Stecker94, Chiang&Mukherjee+98, Mukherjee&Chiang99, Muecke&Pohl00, Narumoto&Totani06, Giommi+06, Dermer07,Pavlidou&Venters08, Kneiske&Mannheim08, Bhattacharya et al. 2009, Inoue&Totani 09, Abod et al. 2010, Stecker & Venters 2010 etc
Star forming galaxies: Pavlidou & Fields 2002, Thompson+07, Bhattacharya&Sreekumar09, Makiya+11, Fields+10, Stecker&Venters+11, etc.
Radio galaxies: Stawarz+06, Inoue+08, Inoue11, Massaro&Ajello11, DiMauro13
Milli-second pulsars: Fauchere-Giguere & Loeb10, Siegal-Gaskins+10/ Dermer07

Blazars (AGNs with a jet pointing in our direction) are (by far) the largest population of sources detected by Fermi LAT.

Goal: Revise Blazar contribution to the EGB - derive new models for the luminosity and redshift evolution of the whole blazar class and of its SED

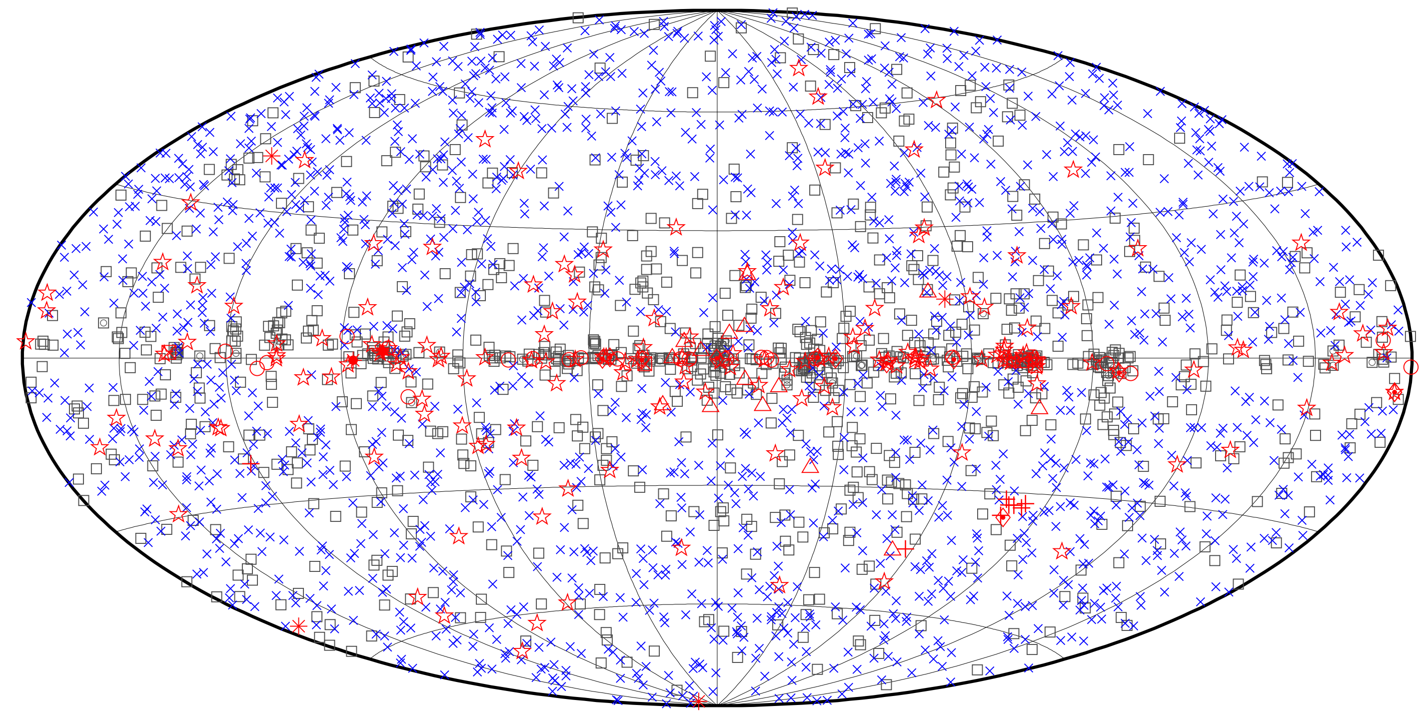
Source sample:

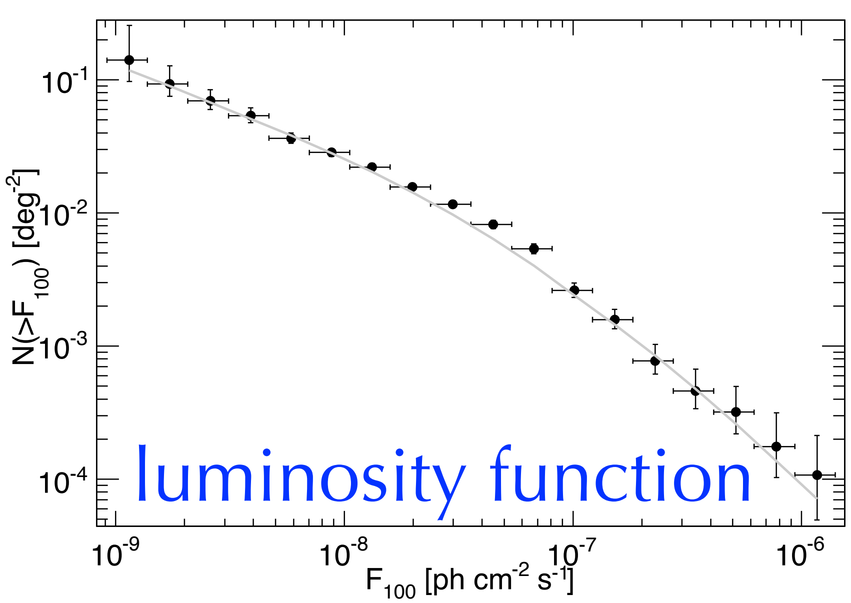
- Start from the sample of 410 blazars (211 BL Lacs / 199 FSRQs - considered together) from Abdo et al. 2010, ApJ 720, 435 for which incompleteness is known
- Sample of ~211 BL Lacs with full redshift information: ~100 with spectroscopic redshifts, ~100 with redshift constraints

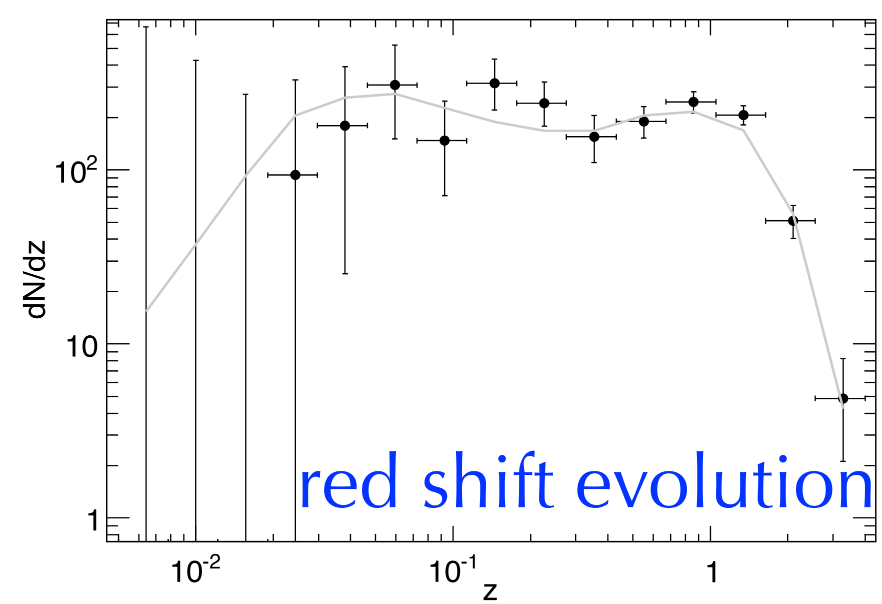
[Ajello+ (w GZ): ApJ lett (2015), 1501.05301]

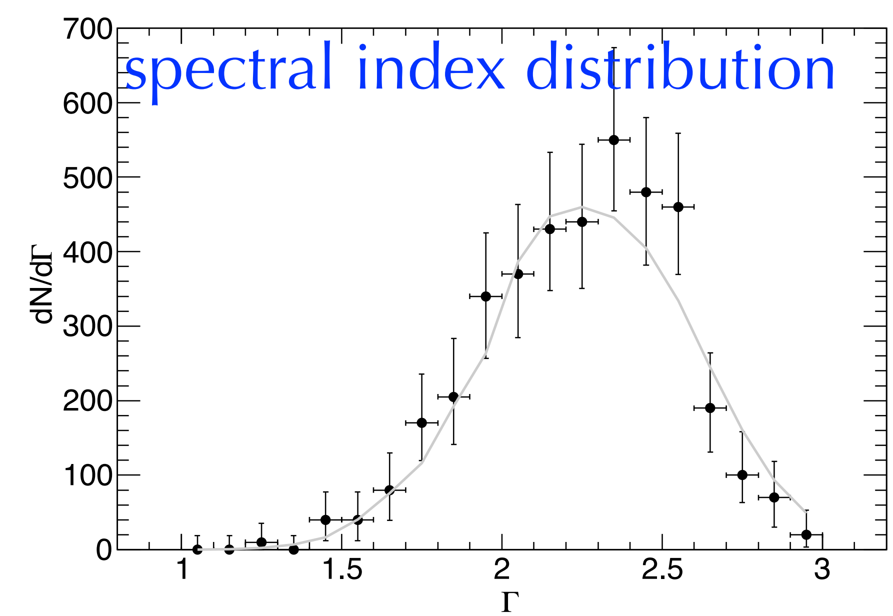
The origin of emission

The idea: based on properties of the resolved blazar population (x)
- luminosity function
- spectra
- red shift evolution



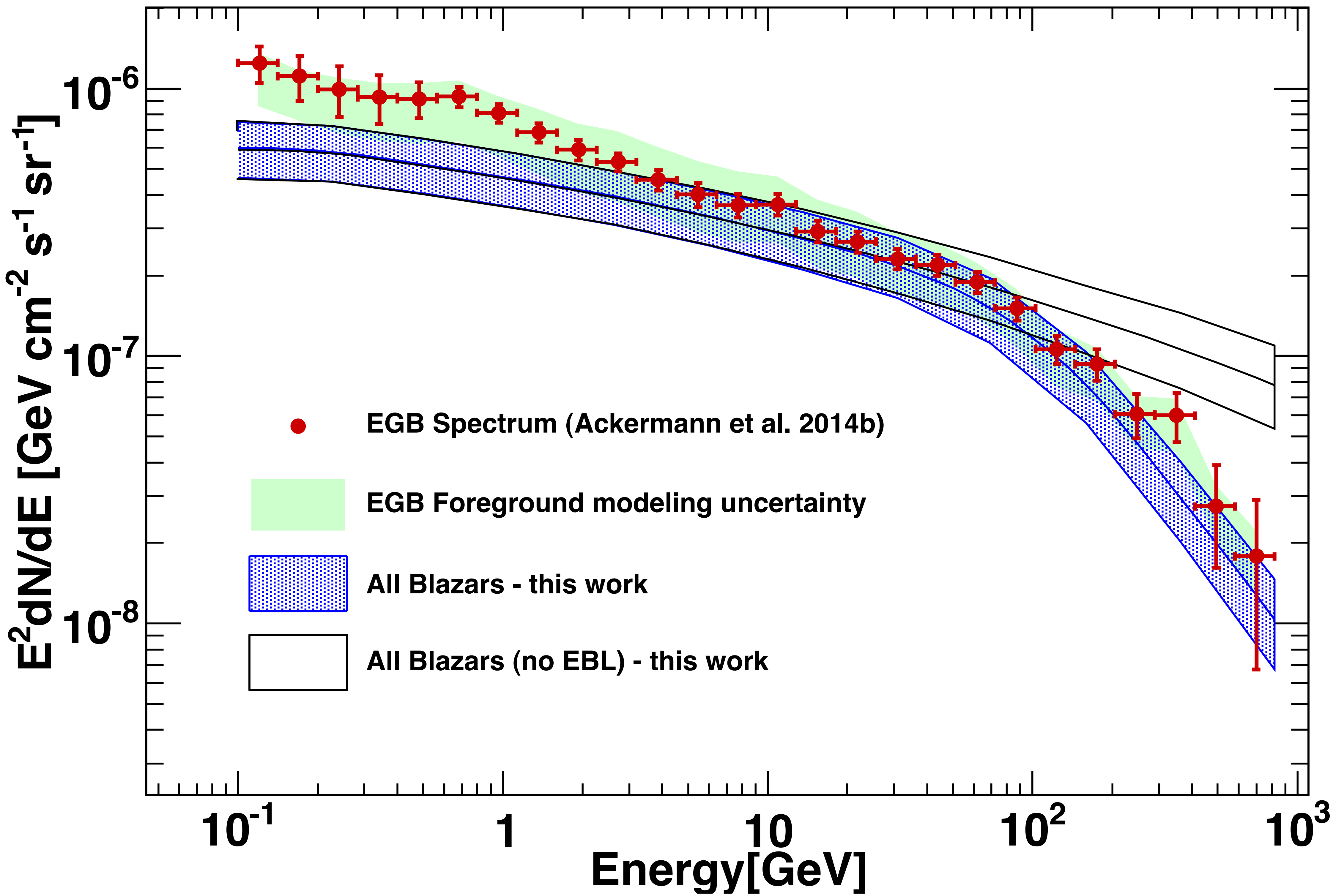






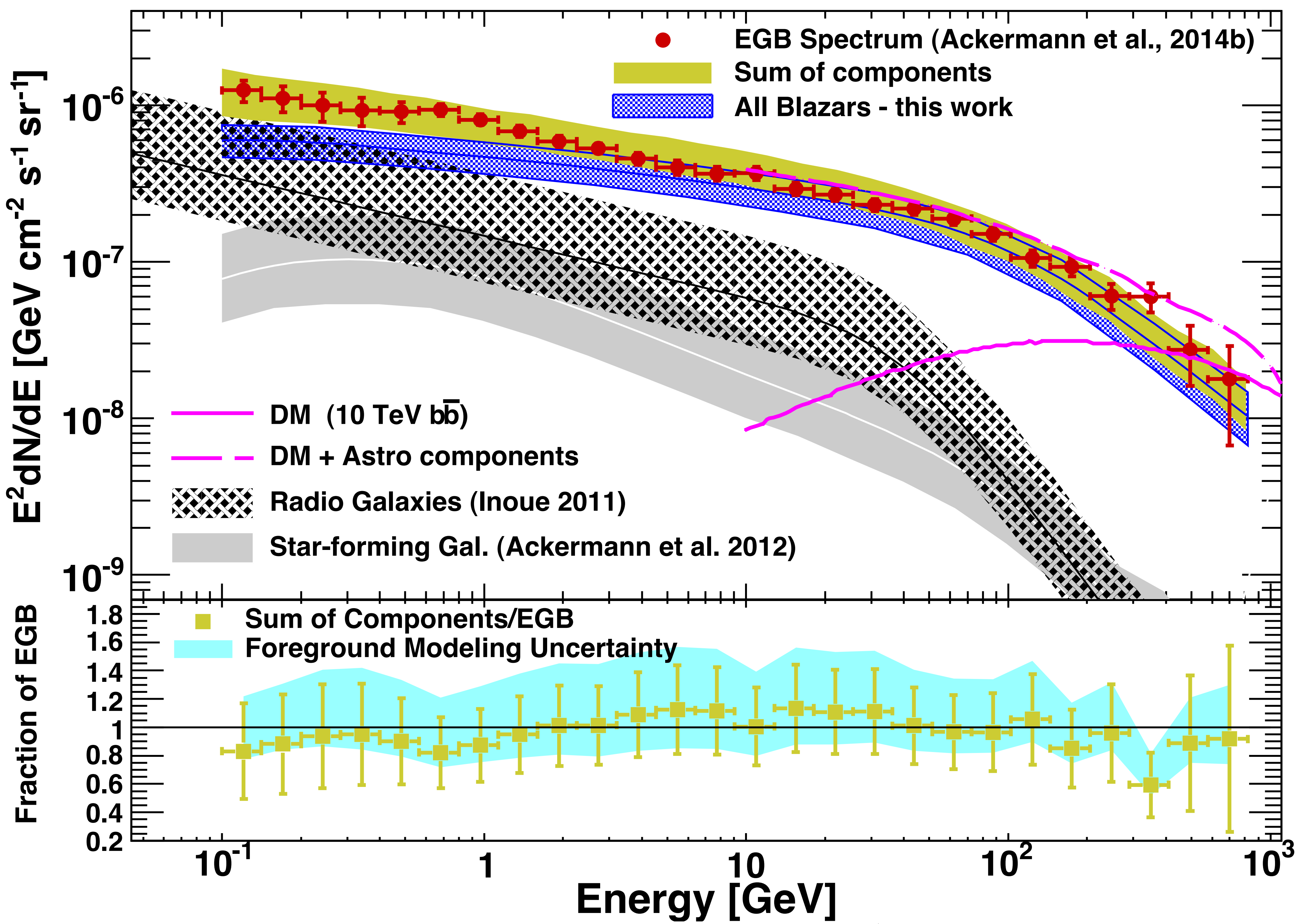
$$F_{EGB}(E_\gamma) = \int_{\Gamma_{\min}=1.0}^{\Gamma_{\max}=3.5} \mathrm{d}\Gamma \int_{z_{\min}=10^{-3}}^{z_{\max}=6} \mathrm{d}z \int_{L_\gamma^{\min}=10^{43}}^{L_\gamma^{\max}=10^{52}} \mathrm{d}L_\gamma \cdot \Phi(L_\gamma, z, \Gamma) \cdot \frac{dN_\gamma}{dE} \cdot \frac{dV}{dz} \;\; [\mathrm{ph\ cm^{-2} s^{-1} sr^{-1} GeV^{-1}}]$$

The origin of emission

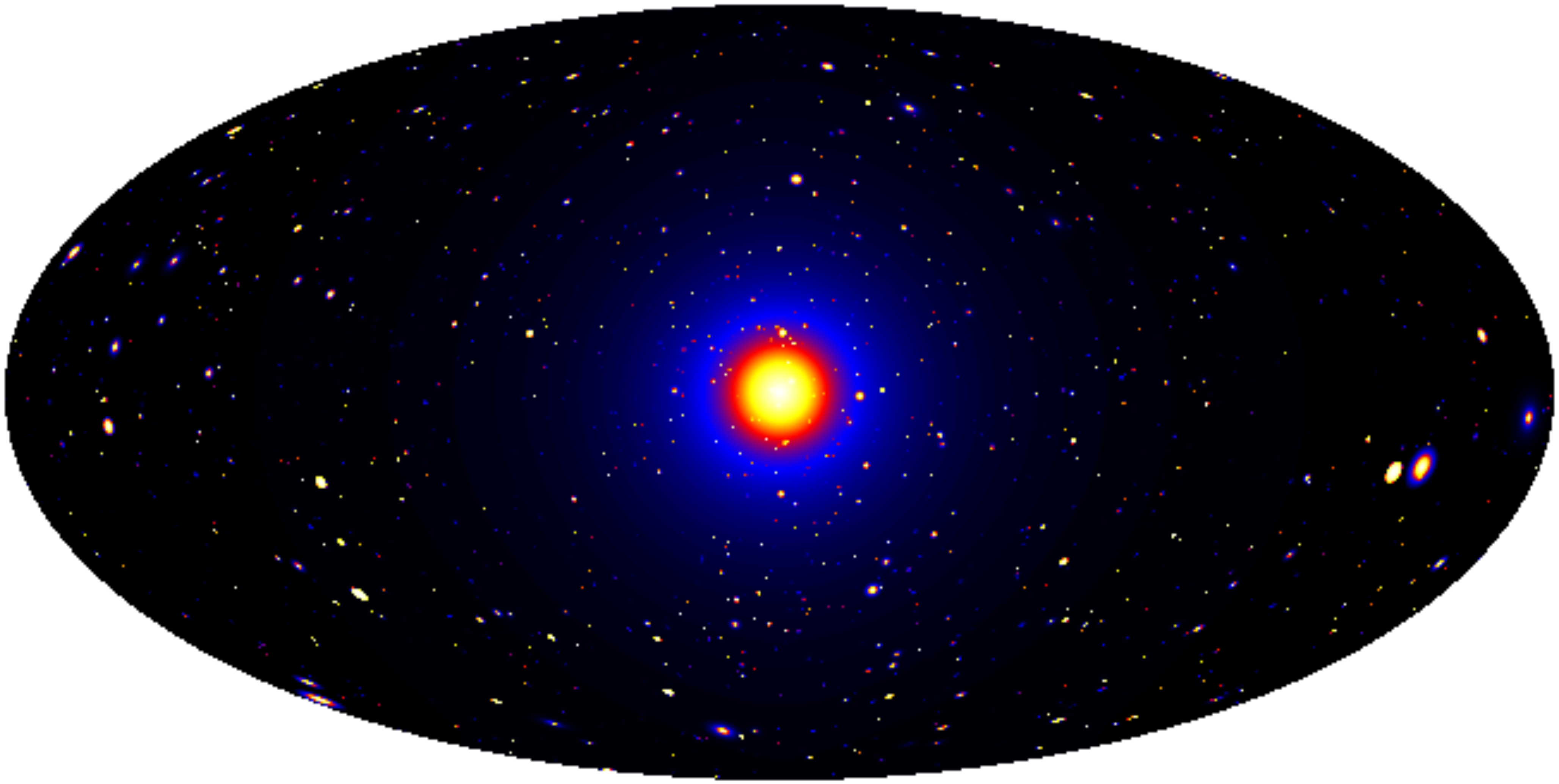


The origin of emission

Together with other contributions the full range of the gamma ray EGB measurement can be explained - limits on additional contributions -> dark matter annihilations



The dark matter-induced gamma-ray sky

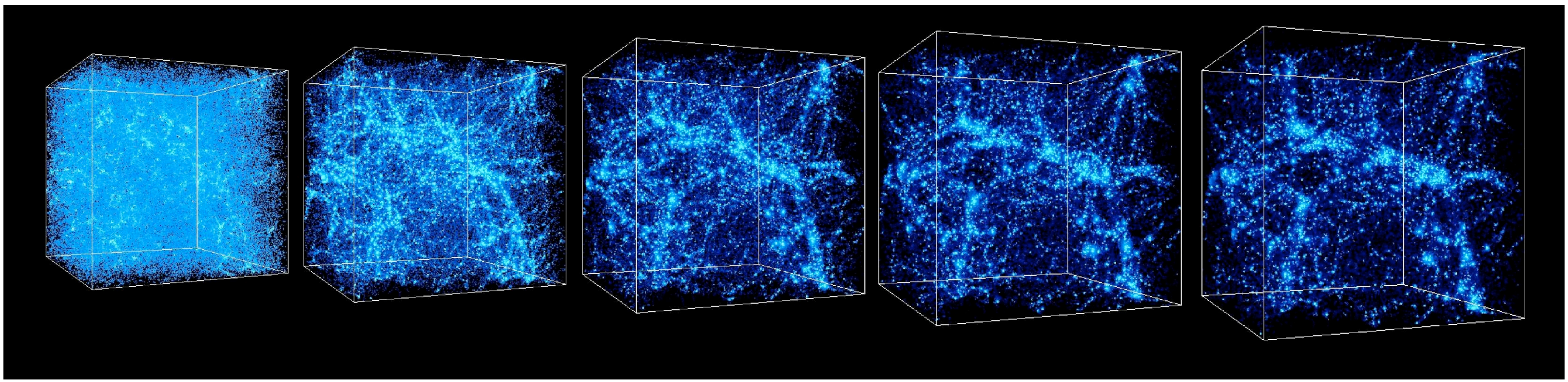


Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Cosmological DM signal

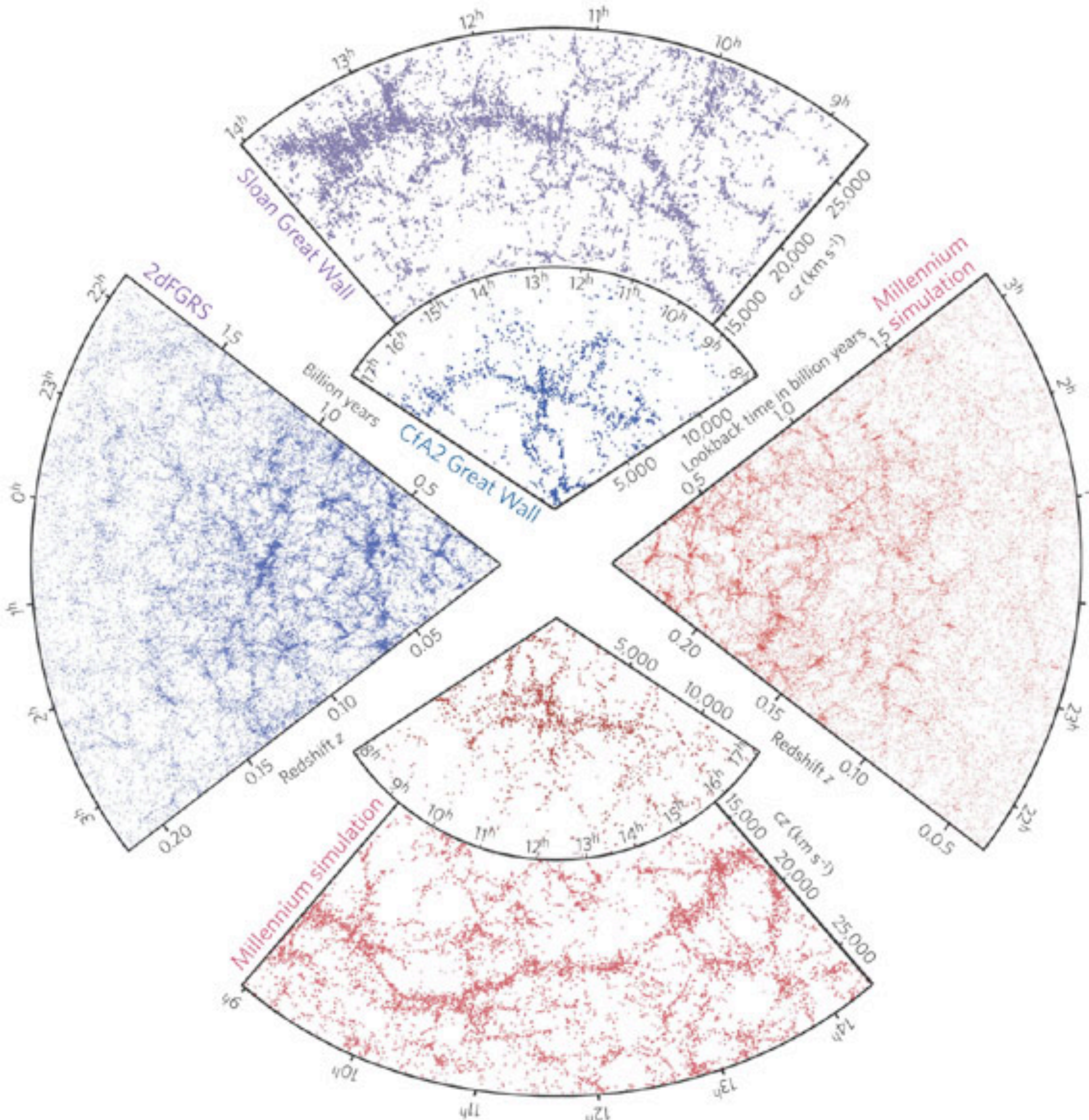
- multiple evidence for dark matter presence in the Universe
- in the ‘Standard model’ of Cosmology

(quantum) overdensities... ... grew to large structures we observe today!

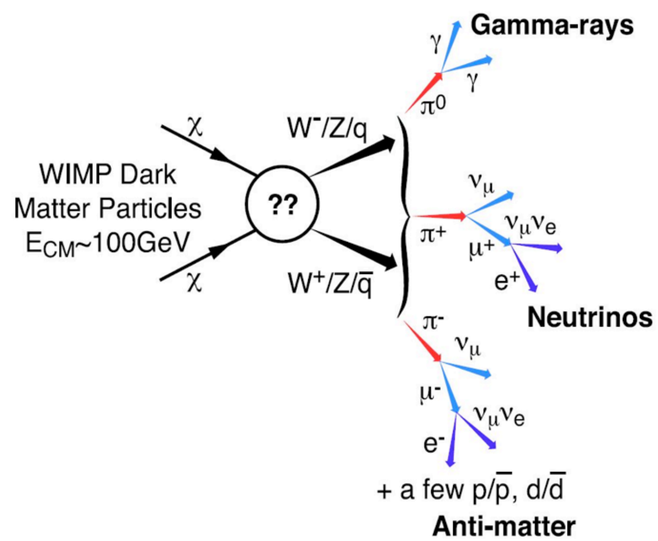


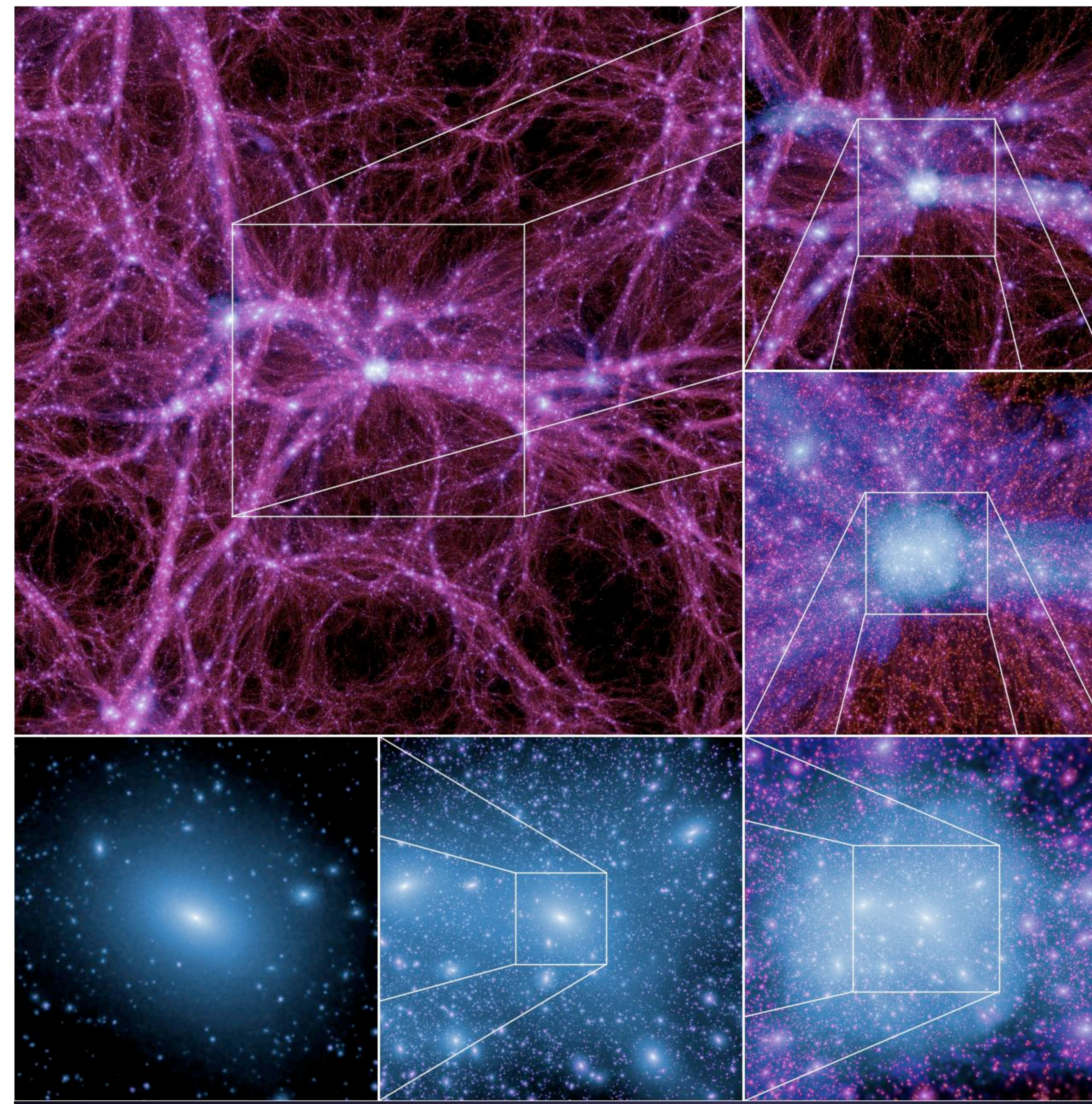
Cosmological DM signal

- N-body simulations of DM clustering have excellent agreement with observations of large scale structures.



Cosmological DM signal





- DM annihilation signal from all DM halos at all redshifts should contribute to the IGRB. WIMPs in the LAT range.
- Gamma-ray attenuation due to the EBL and 'redshifting' effects should make lower redshifts ($z \leq 2$) to contribute the most.
- **Issues:** DM halos and substructure expected at all scales down to a $M_{min} \sim 10^{-6}\ M_{sun}$. (Torsten's work!)
- Currently unmatched by the computer power/resolution of simulations.

Cosmological DM signal

- **Challenges:**

1. What is DM distribution in the sky - which components contribute to isotropic emission?

2. What are DM clustering properties at various (small!) scales -> determines the amplitude of the DM gamma ray signal

3. DM signal WITHIN our Galaxy: could it bias the measurement of the isotropic spectral flux?

Cosmological DM signal

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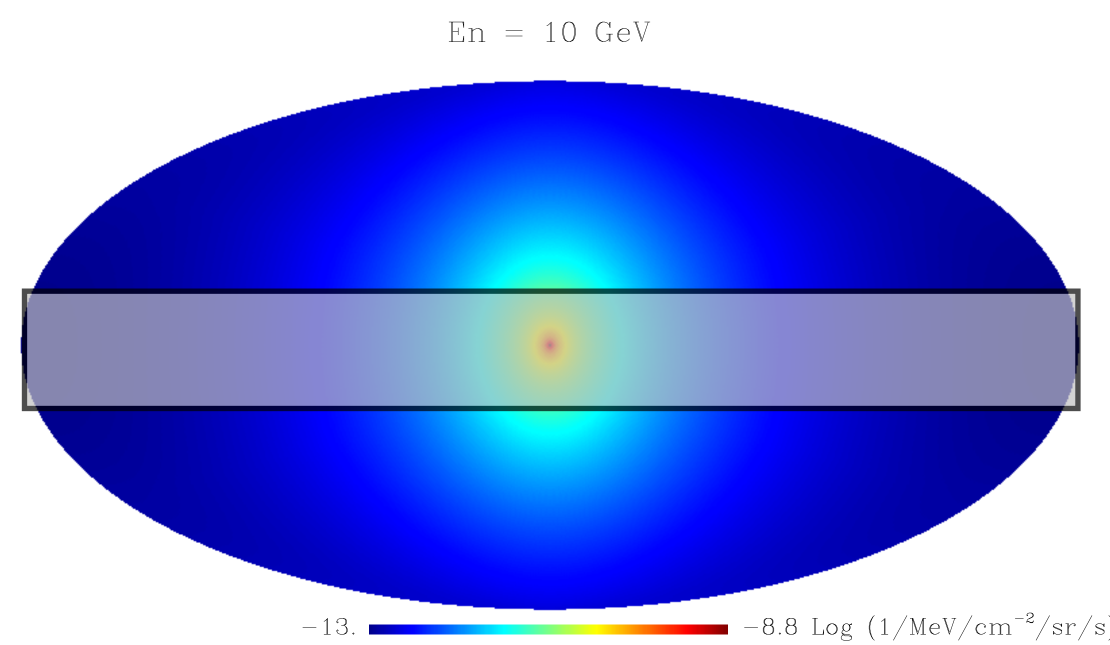
Cosmological DM signal

- **Isotropic vs non isotropic components?**

– Looking from Earth, we see three DM components
  - – smooth DM halo of the Milky Way
  - – Galactic Subhalo population
  - – Cosmological DM

DM annihilation intensity of the smooth DM halo varies more than a factor of 16 for latitudes >20 deg.



$\rho \sim r^{-2}$

b>20deg

Cosmological DM signal

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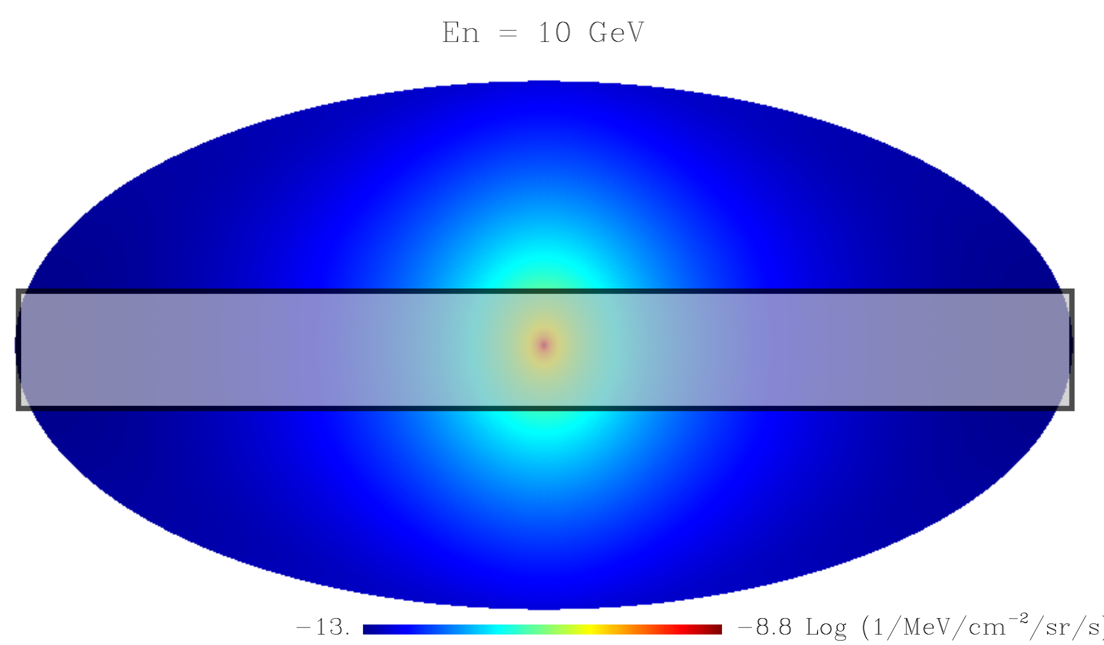
- **– Galactic Subhalo population**
- **– Cosmological DM**



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-> not included in the isotropic DM signal.

Cosmological DM signal

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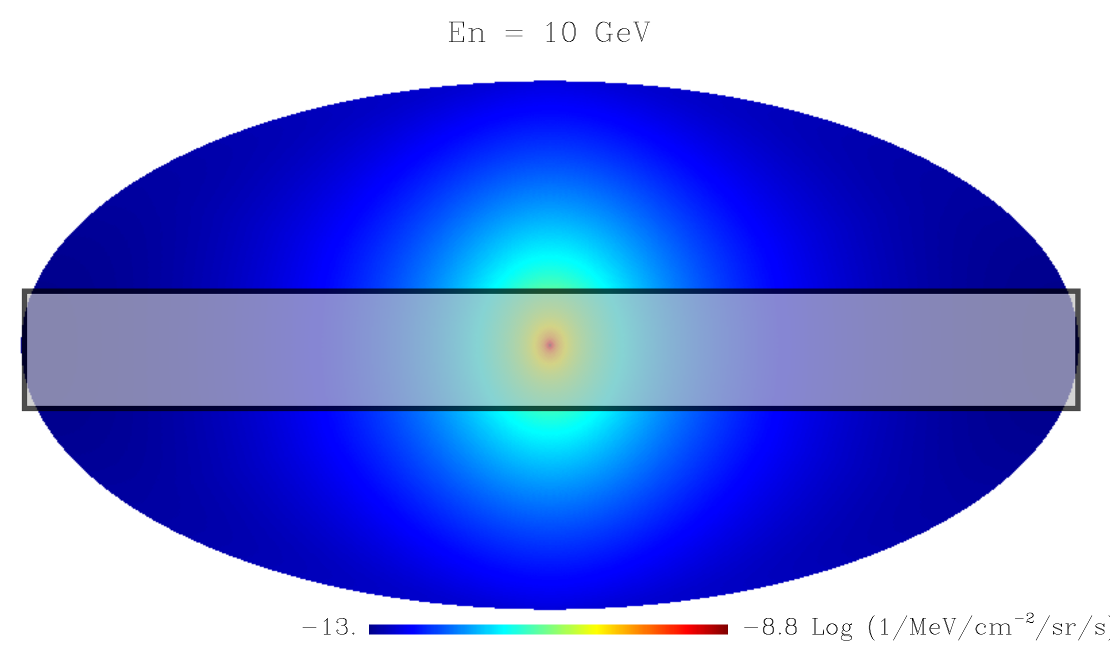

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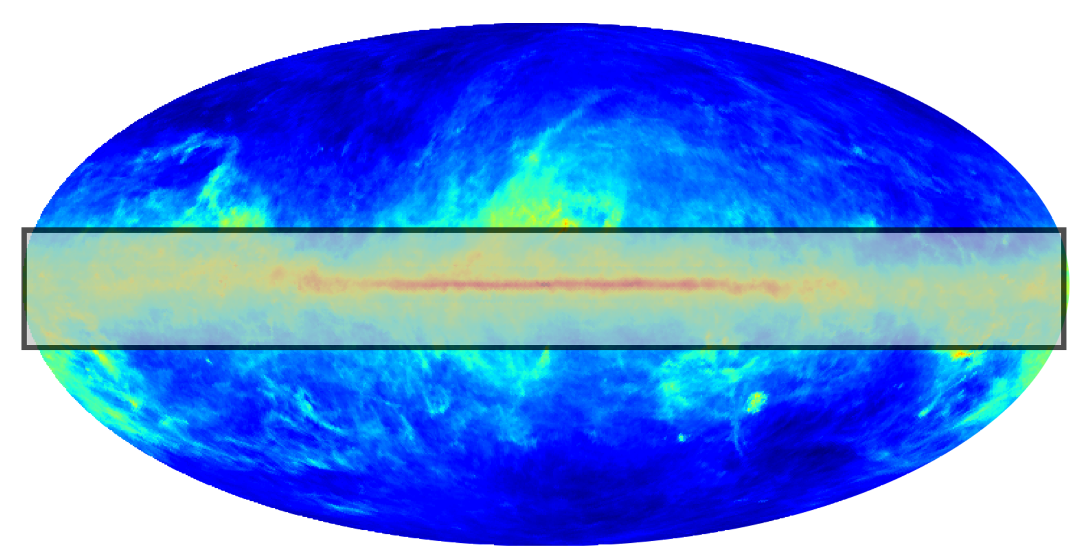
b>20deg

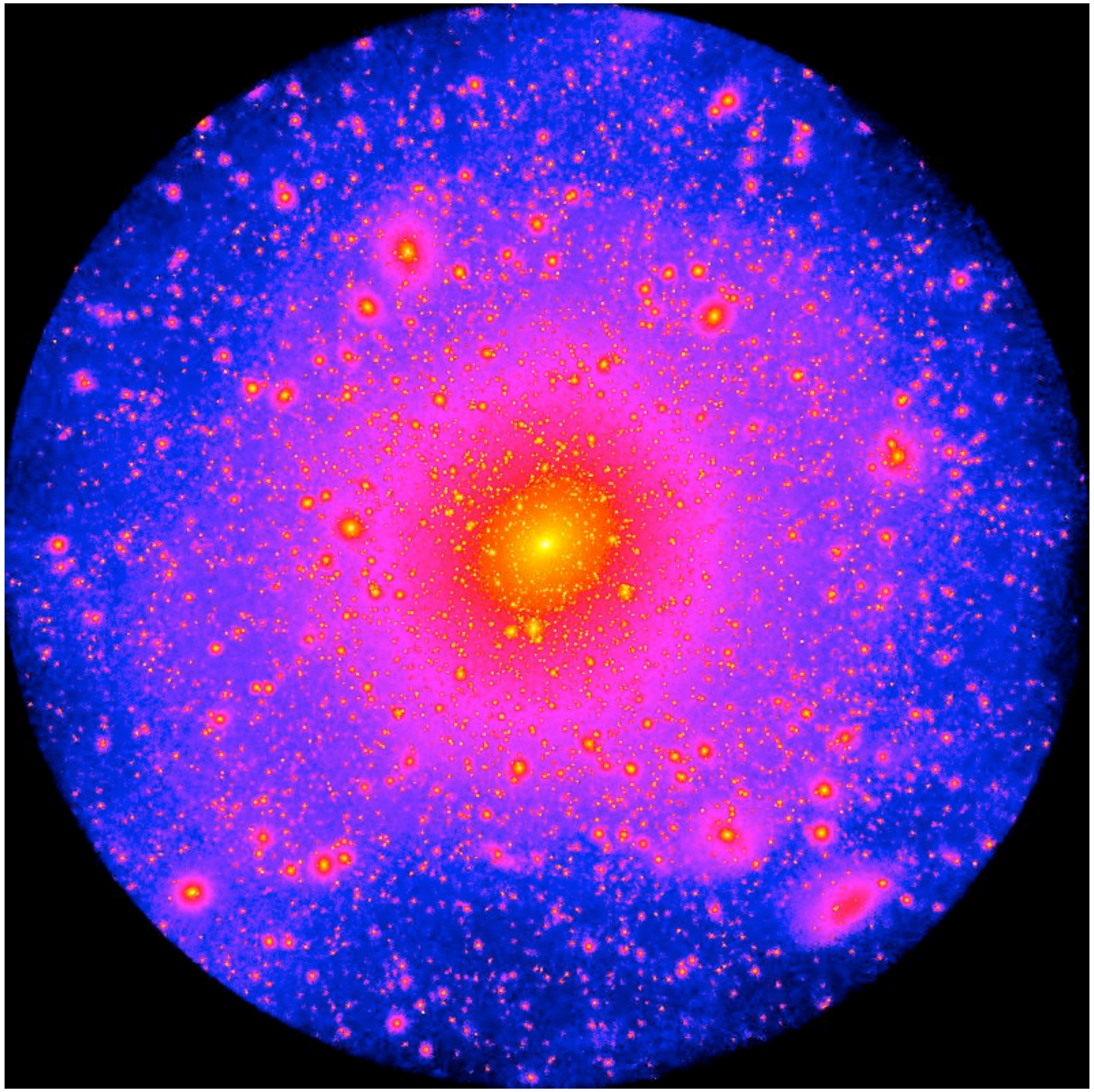


However, it might sufficiently close (in morphology and spectra) to the Galactic diffuse emission (studied).

Cosmological DM signal

- **Isotropic vs non isotropic components?**

– **Looking from Earth, we see three DM components**
  – **smooth DM halo of the Milky Way**
  – **Galactic Subhalo population**
  – **Cosmological DM**



Typically found at large distances from the Milky Way luminous disk!

Depending on the simulation Galactic substructure is expected to be isotropic at the level of ~10% to 20 (80)%.

We include it in our isotropic signal with two choices for the overall magnitude.

Cosmological DM signal

- **Challenges:**

1. What is DM distribution in the sky - which components contribute to isotropic emission?

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3. DM signal WITHIN our Galaxy: could it bias the measurement of the isotropic spectral flux?

Theoretical predictions for the cosmological signal

FLUX from extragalactic DM annihilation

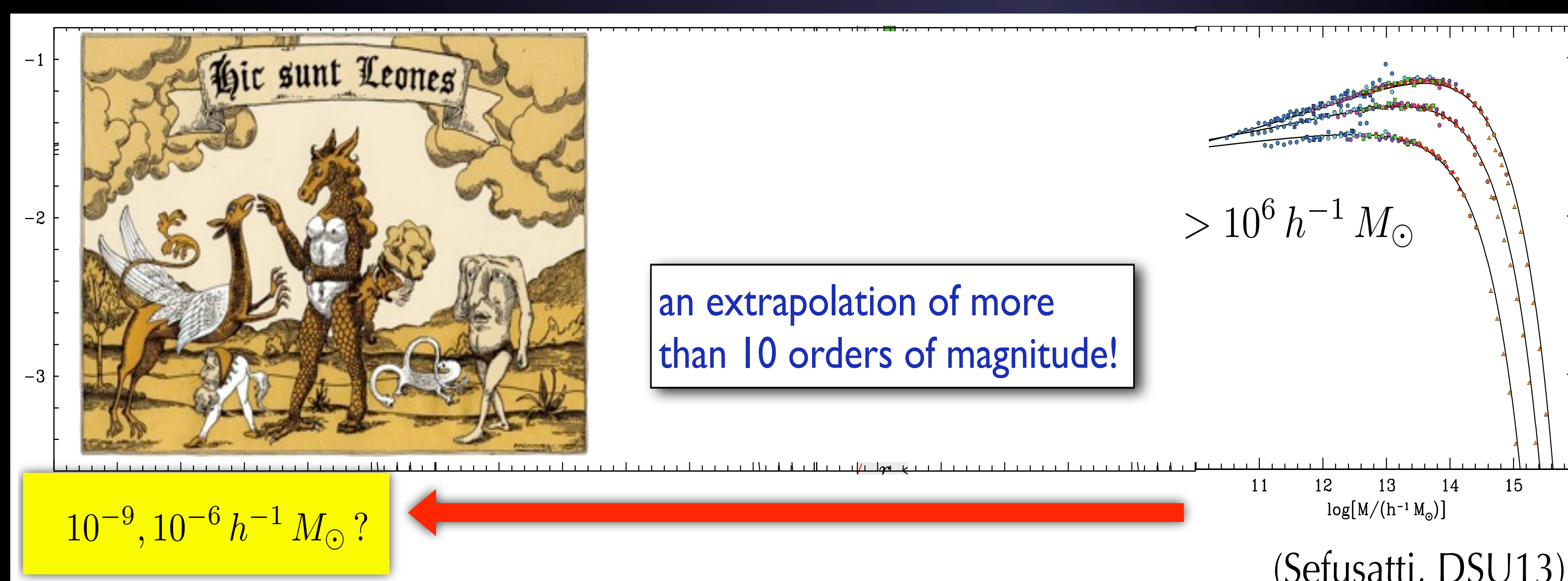
$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z,E_0)}$$

Constant for a particular DM model — **"Flux multiplier"** — **Redshifted DM spectrum** — **EBL (Domínguez+11)**

The **flux multiplier** is a measure of the clumpiness of the DM in the Universe, and is the *main source of theoretical uncertainty* in this game.

Uncertainties in this parameter traditionally huge!

Simulations do not resolve the whole hierarchy of structure formation…



HALO MODEL (I): bAsIcS

Sum of DM annihilations in all halos, at all cosmic epochs.

1) calculation in real space

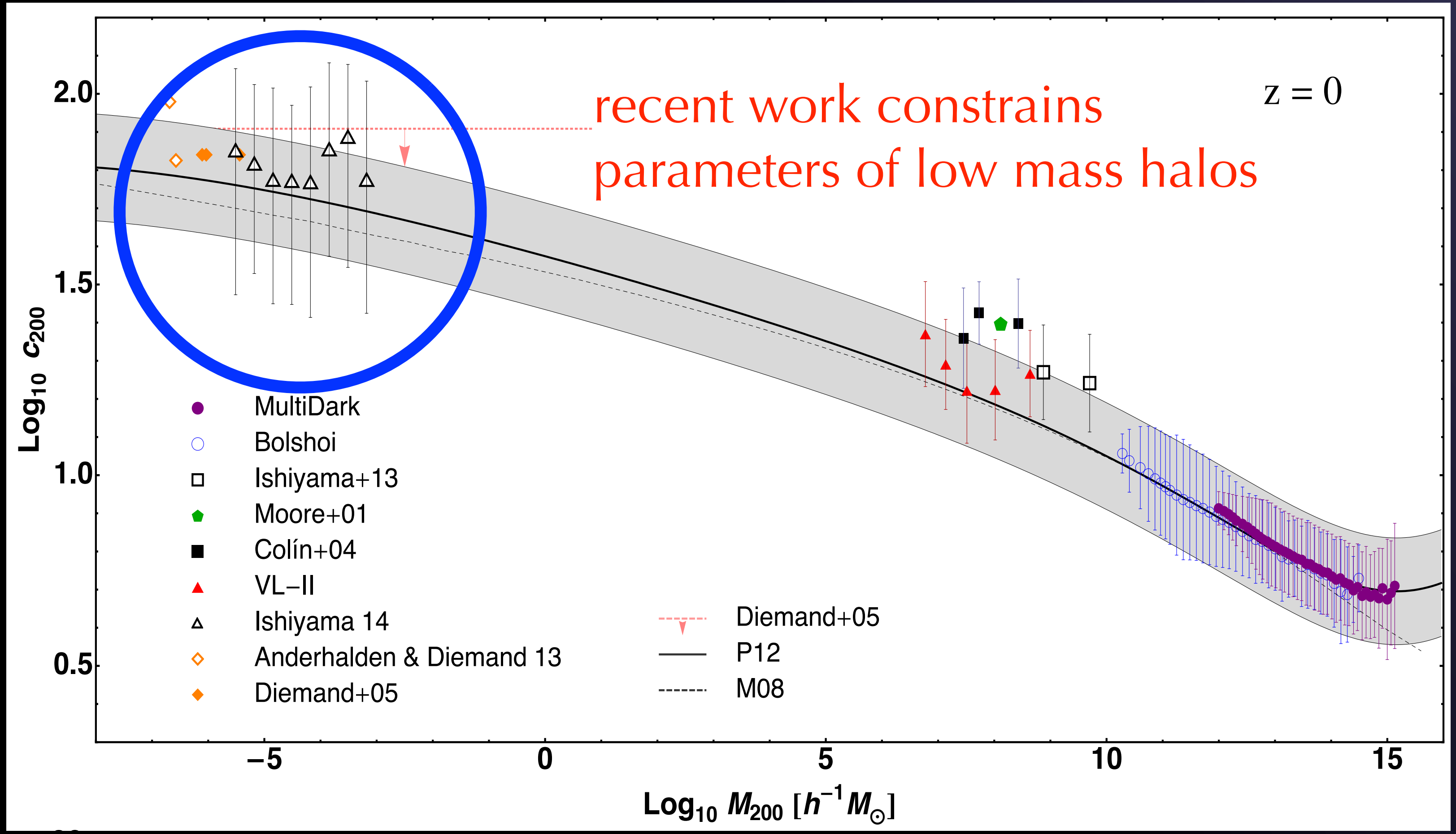
FLUX MULTIPLIER

$$\zeta(z) = \frac{1}{\Omega_{\mathrm{DM}}\rho_c}\int_{M_{\mathrm{min}}} dM \frac{dn}{dM} M \frac{\Delta_v(z)}{3}\langle F(M,z)\rangle$$

Halo mass function — **Halo masses and concentrations**

2) parameters: halo mass function, concentration of halos, their density profiles…

[MASC & Prada, 2014, MNRAS accepted]



Planck cosmology.

Prada+12 concentration-mass model.

NFW DM density profiles

$M_{min} = 10^{-6} M_{sun}$

Tinker+08 HMF, with z=0 parameters as in Prada+12.

POWER SPECTRUM APPROACH

1) calculation in momentum space

FLUX MULTIPLIER

$$\rho(z,\hat{\Omega}) \equiv [1+\delta(z,\hat{\Omega})]\,\bar{\rho}(z) = [1+\delta(z,\hat{\Omega})]\Omega_{\rm DM}\,\rho_c(1+z)^3$$

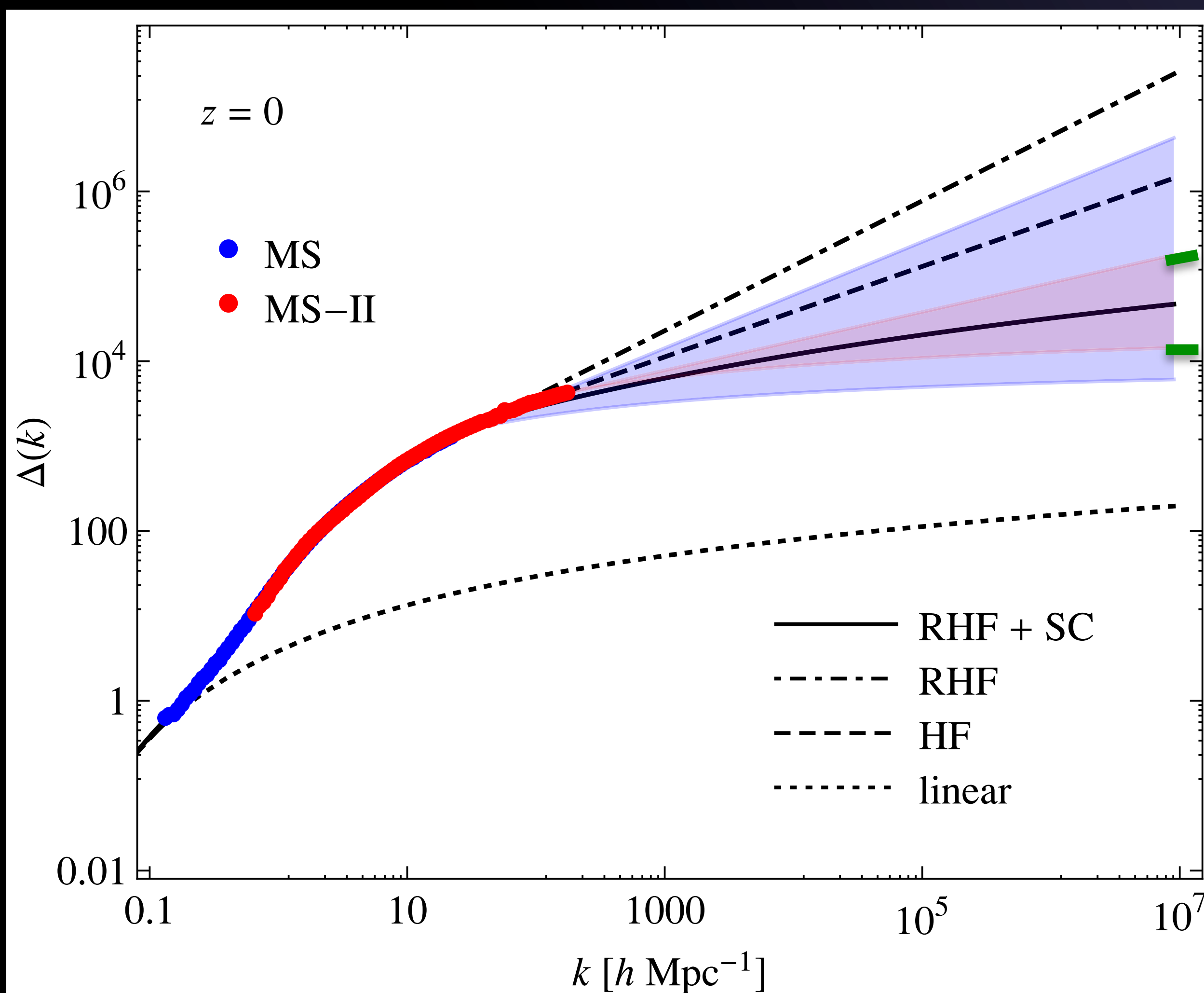
$$\zeta(z) \equiv \langle \delta^2(z) \rangle = \int^{k_{max}} \frac{dk}{k} \frac{k^3 P_{NL}(k,z)}{2\pi^2} \equiv \int^{k_{max}} \frac{dk}{k} \Delta_{NL}(k,z)$$

Integral over the non-linear matter power spectrum, P_{NL}

Adimensional P_{NL}

2) only one parameter

Δ_{NL} is measured in simulations.



Sefusatti, Zaharijas et al., MNRAS (2014)

MAX extrapolation to the lowest scales

MIN extrapolation to the lowest scales

We follow Sefusatti+14, which uses the Millenium simulations (MS and MS-II).

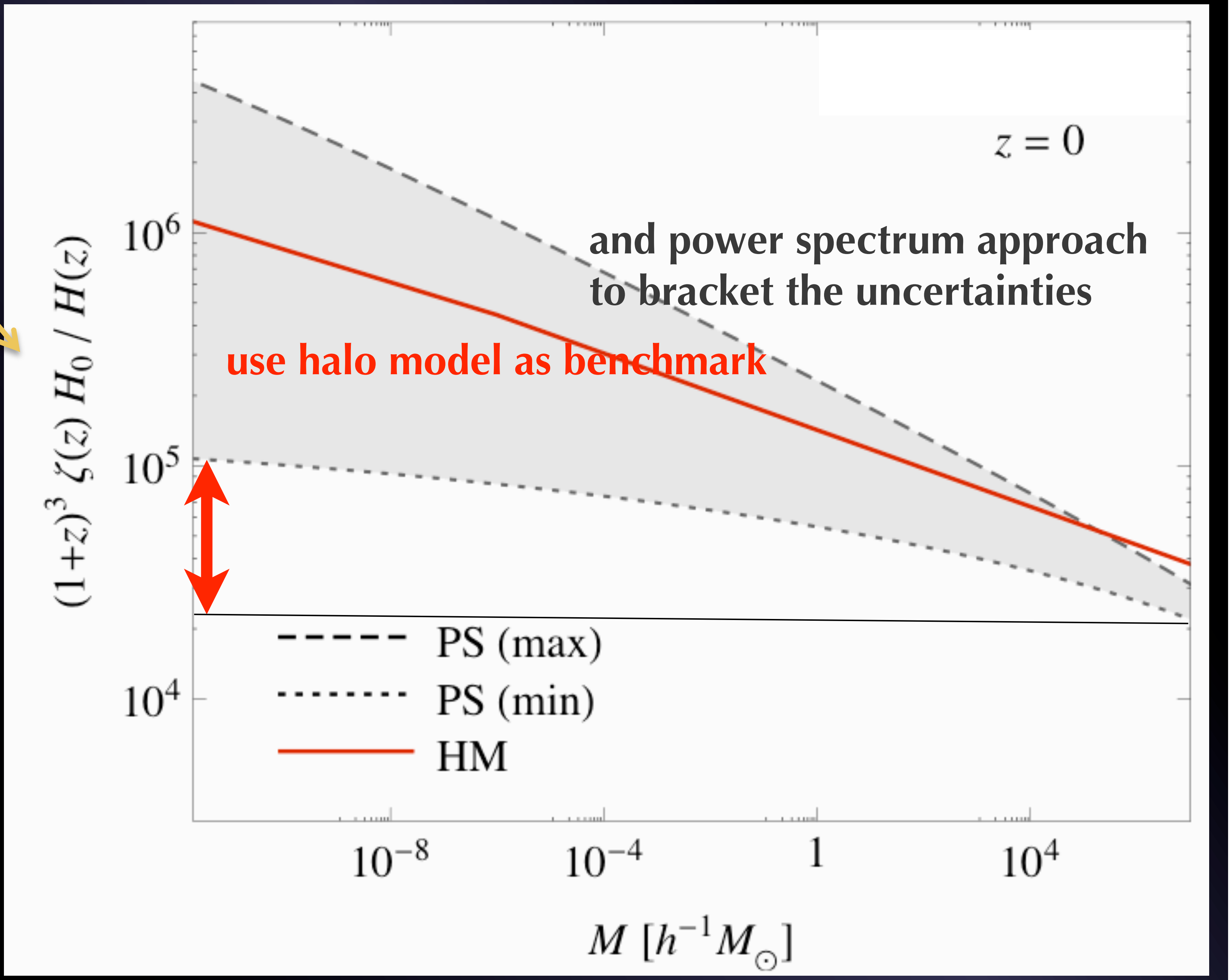
Results scaled to Planck cosmology.

Extrapolation to low masses with MS-II.

Substructure naturally accounted for.

HM vs. PS predictions (II)
dependence on minimum halo mass

Normalized flux multiplier

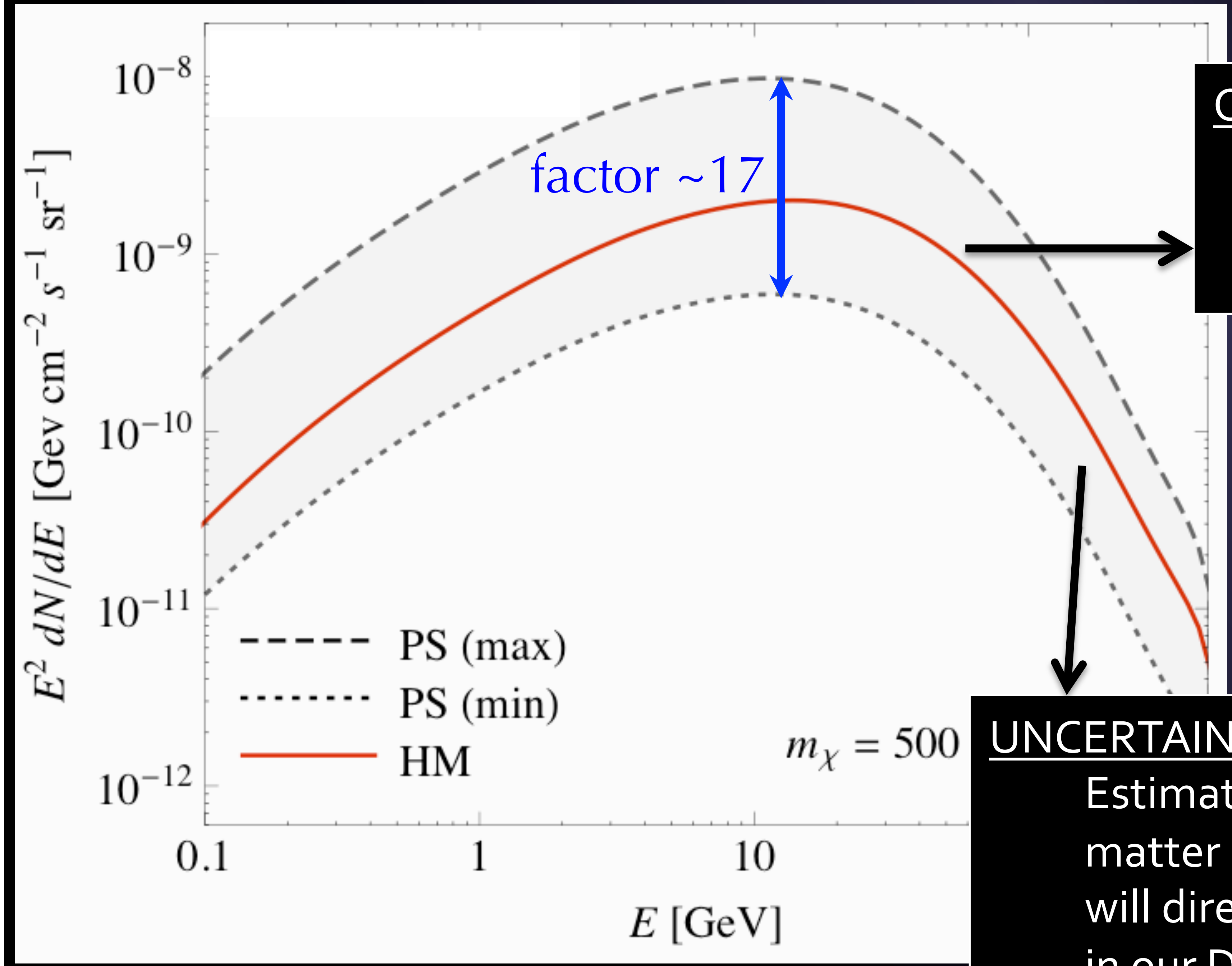


Good agreement except at the highest (probably unrealistic) M_{min} tested

PS-min nearly insensitive to M_{min}. Not true for PS-max.

Comparison at z=0 a fair estimate, since most of the DM signal comes from low z.

HM vs. PS predictions (III)
(example of) DM annihilation fluxes



OUR BENCHMARK MODEL:
calculated in **Halo Model** approach using the most up-to-date parameters.

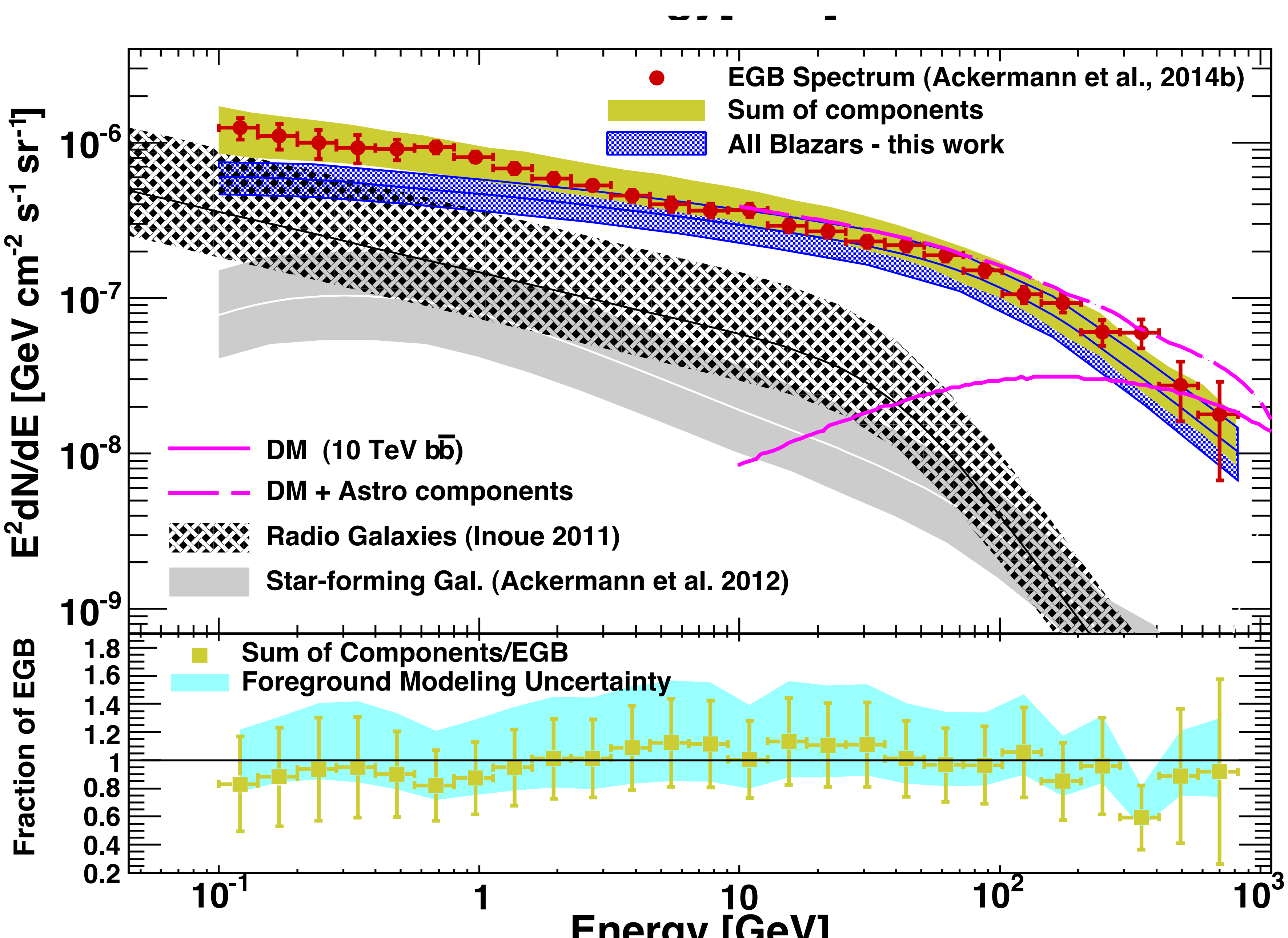
UNCERTAINTY BAND:
Estimated by means of the non-linear matter **Power Spectrum** approach. It will directly translate into uncertainties in our DM limits.

[500 GeV WIMP annihilating to bb quarks]

Limits

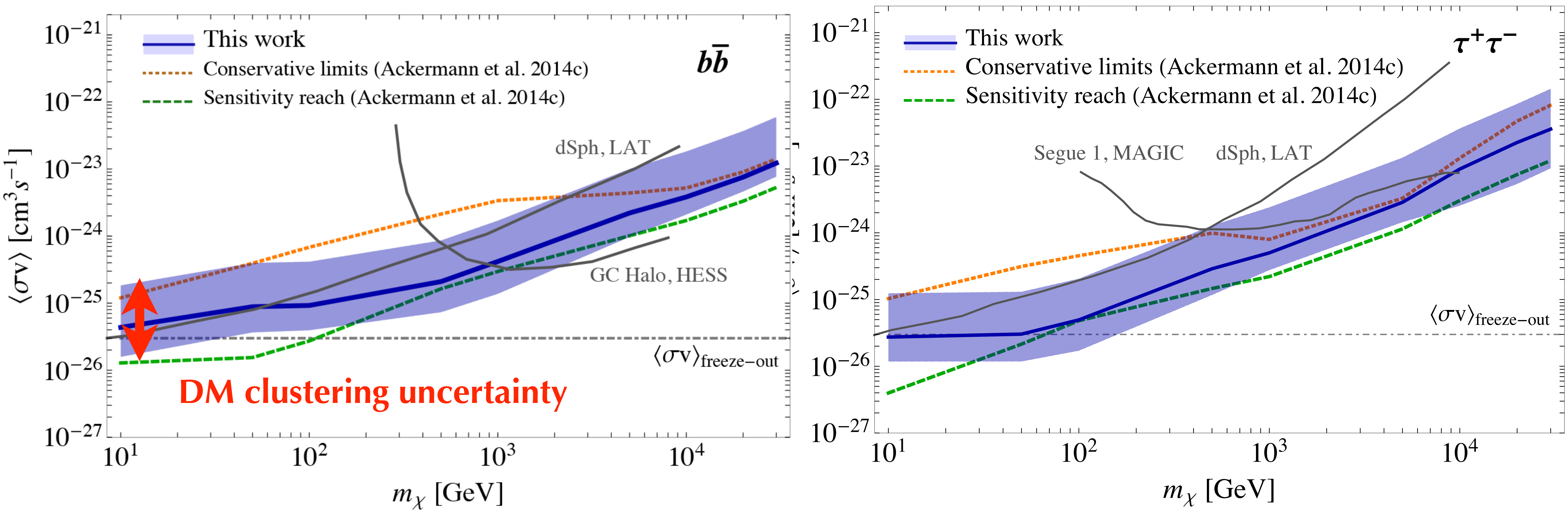
combining all ingredients:

- EGB measurement 0.1-820 GeV
- contribution of unresolved sources
- up to date estimate of DM clustering properties



Limits

Uncertainty in : Galactic diffuse emission models and contribution of unresolved sources taken into account in chi2 procedure



Limits comparable with strongest limits from other targets - probe generic prediction for WIMP models - thermal freeze out cross section.

Other methods to tackle isotropic emission

So far, heads on approach -- the highest statistics (whole sky photons), but little handle to separate different contributions to the overall signal (power law).

- Many isotropic contributions: astro sources, CR contamination,
- confusion with large scale emission from the Milky Way etc

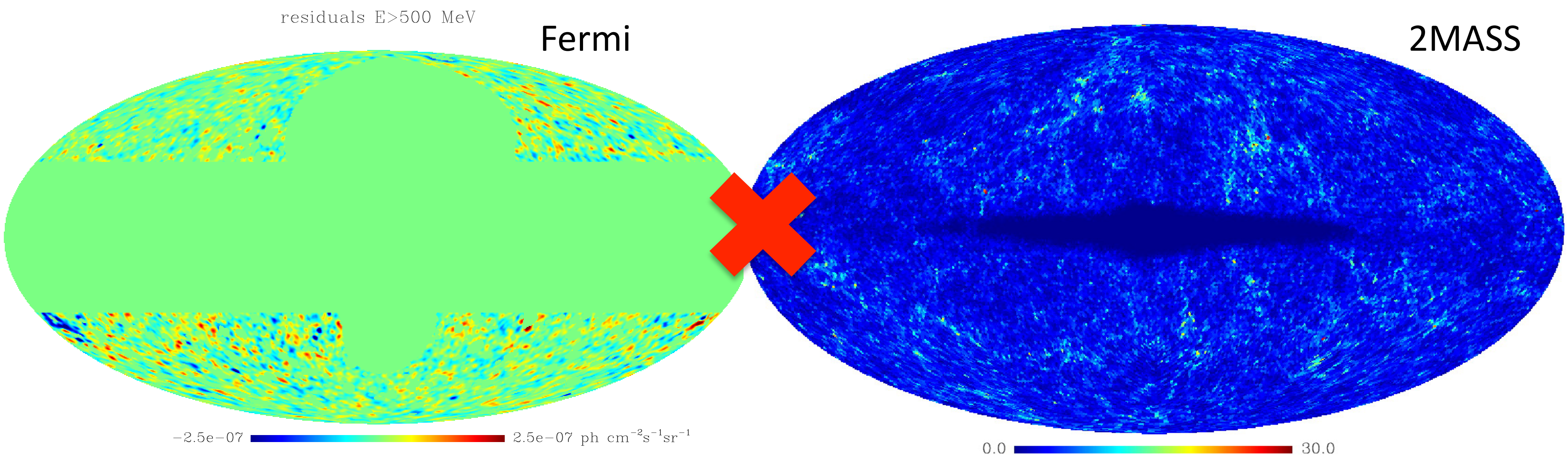
Different approaches:

1D PDF -> use statistical properties of photon counts to distinguish between source populations (Malyshev&Hogg,)

angular anisotropy -> look for two point correlation function (Ackermann+, PRD85 (2012), 1202.2856, ...)

cross correlations -> look for cross correlation between gamma rays and source catalogs (Xia+, MNRAS 2011, 1103.4861...)

cross correlations - cross-correlation analysis between the IGRB and objects that may trace the astrophysical sources of the IGRB



$$\langle \hat{f}_\gamma(z,k)\hat{f}_g^*(z',k')\rangle = (2\pi)^3\delta^3(k+k')P_{\gamma g}(k,z,z'),$$

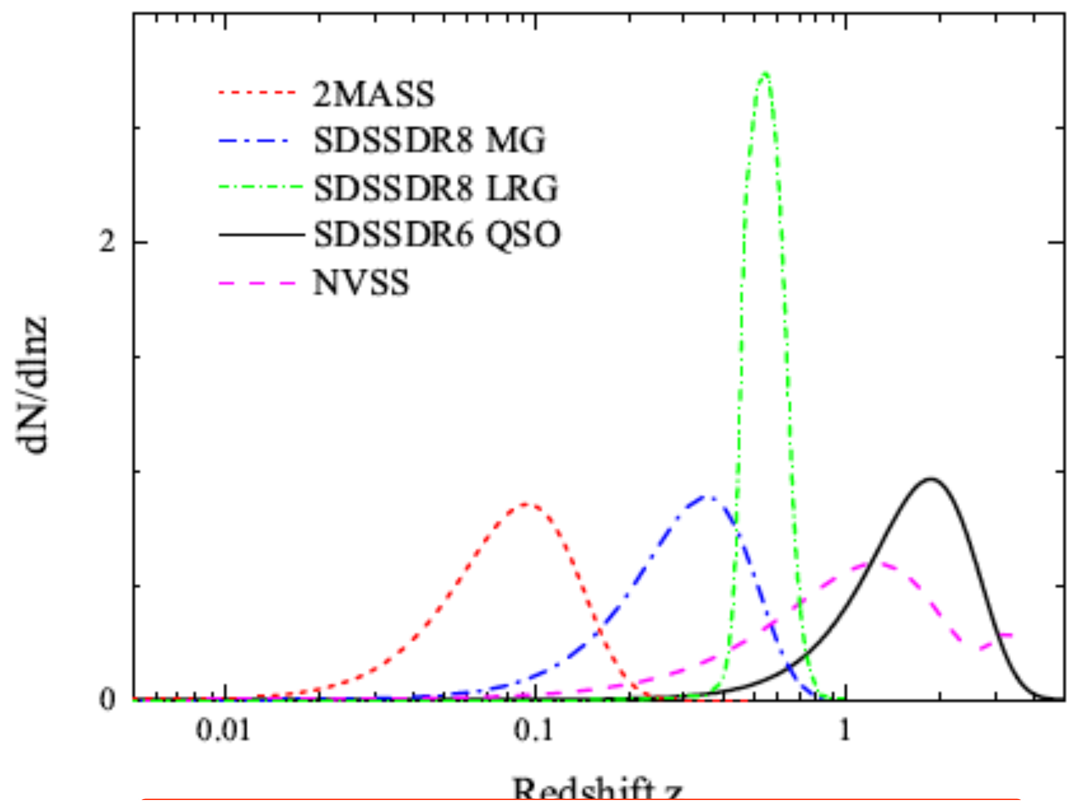
density fields of catalogue sources fg, or gamma ray emitters fγ

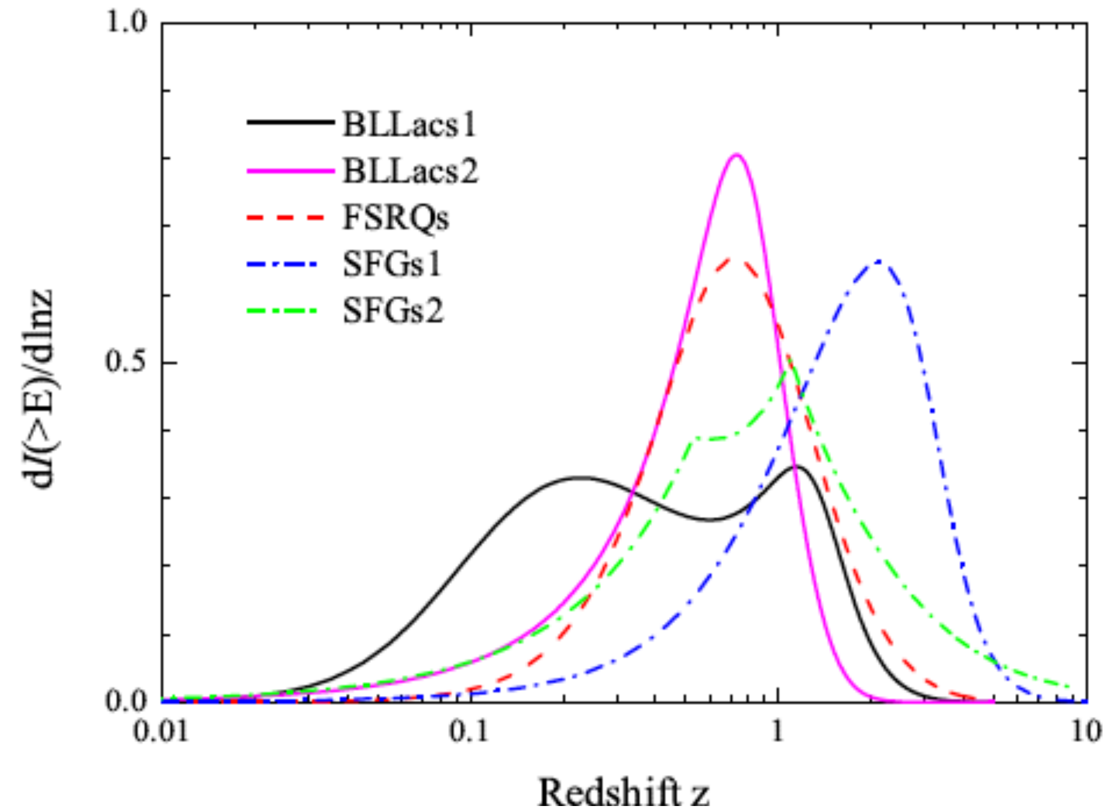
$$C_\ell^{(\gamma g)} = \int \frac{d\chi}{\chi^2} W_\gamma(\chi) W_g(\chi) P_{\gamma g}\left(k=\ell/\chi,\chi\right)$$

cross angular power spectrum, W contribution of objects at different redshifts

[Cuoco+:, 1506.01030; Reggis+, PRL (2015), 1503.05922]

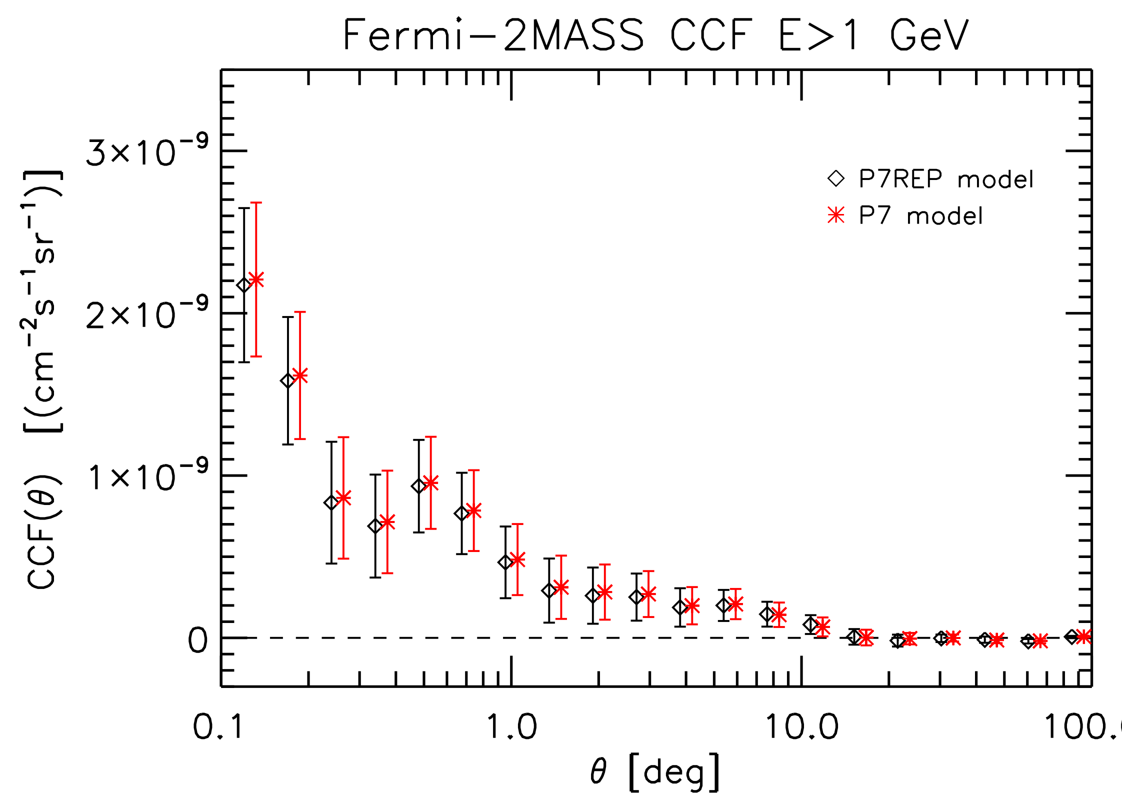
cross correlations - cross-correlation analysis between the IGRB and objects that may trace the astrophysical sources of the IGRB



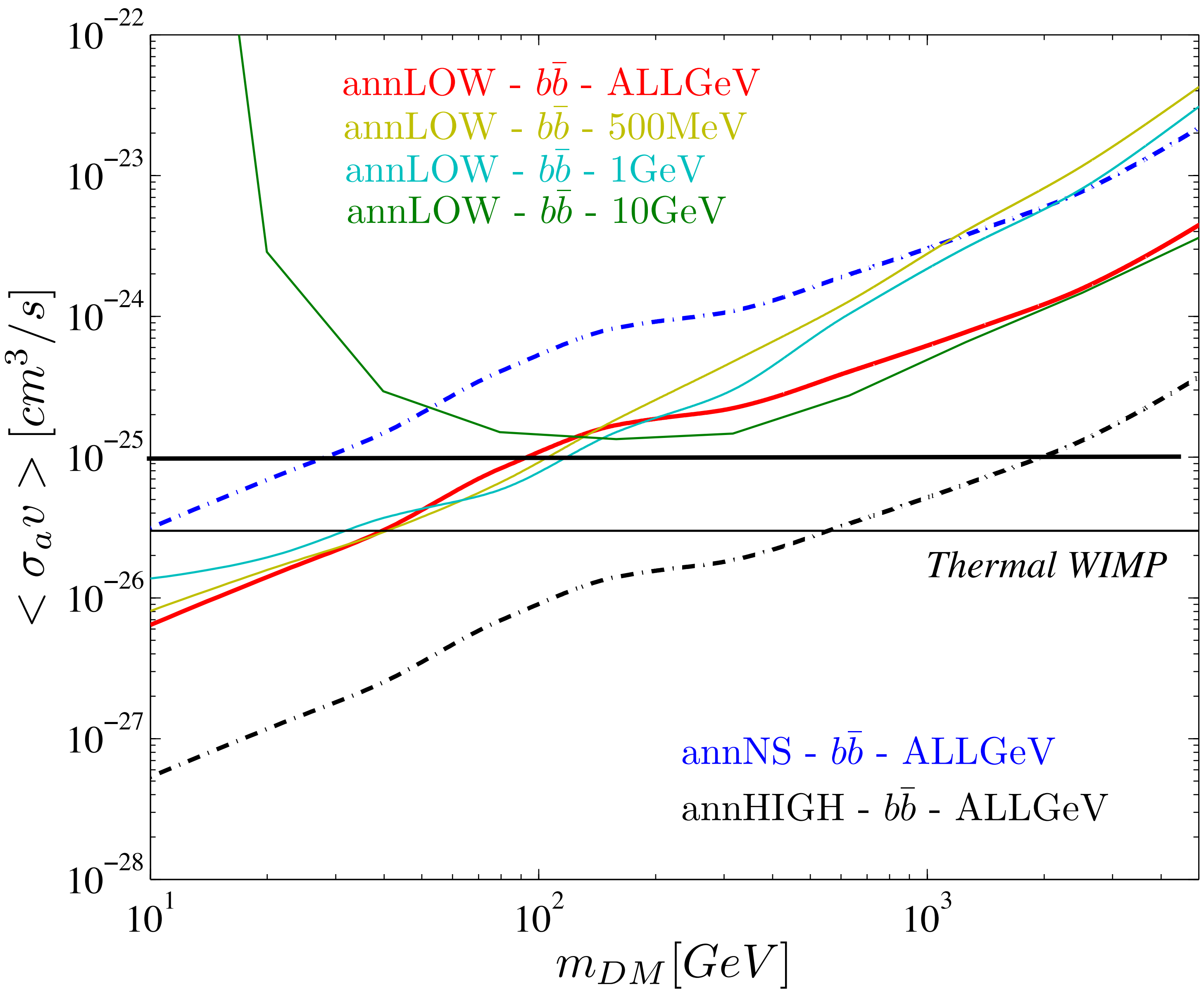


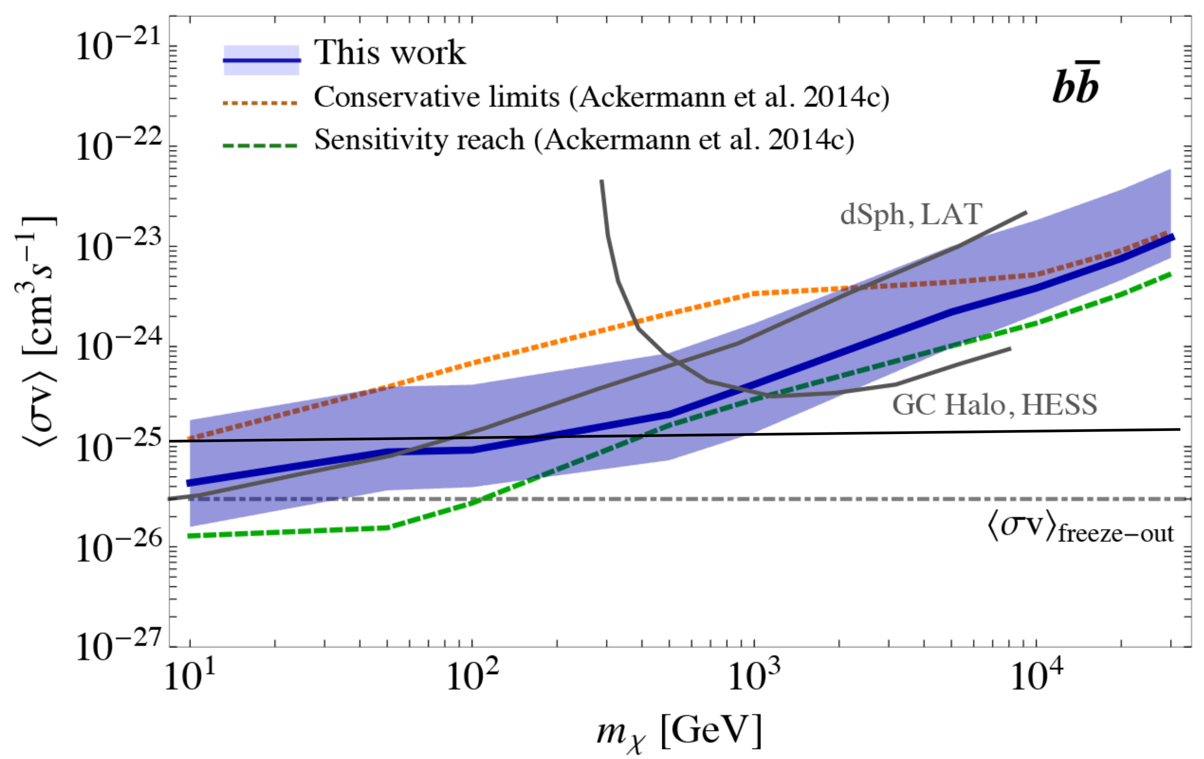
Tomography of the gamma ray sky

cross correlation detected with 2MASS catalogue - favors a model in which the IGRB is mainly produced by SFGs (72^{+23}_{-37} % with 2σ errors).
(at <~10 GeV energies)



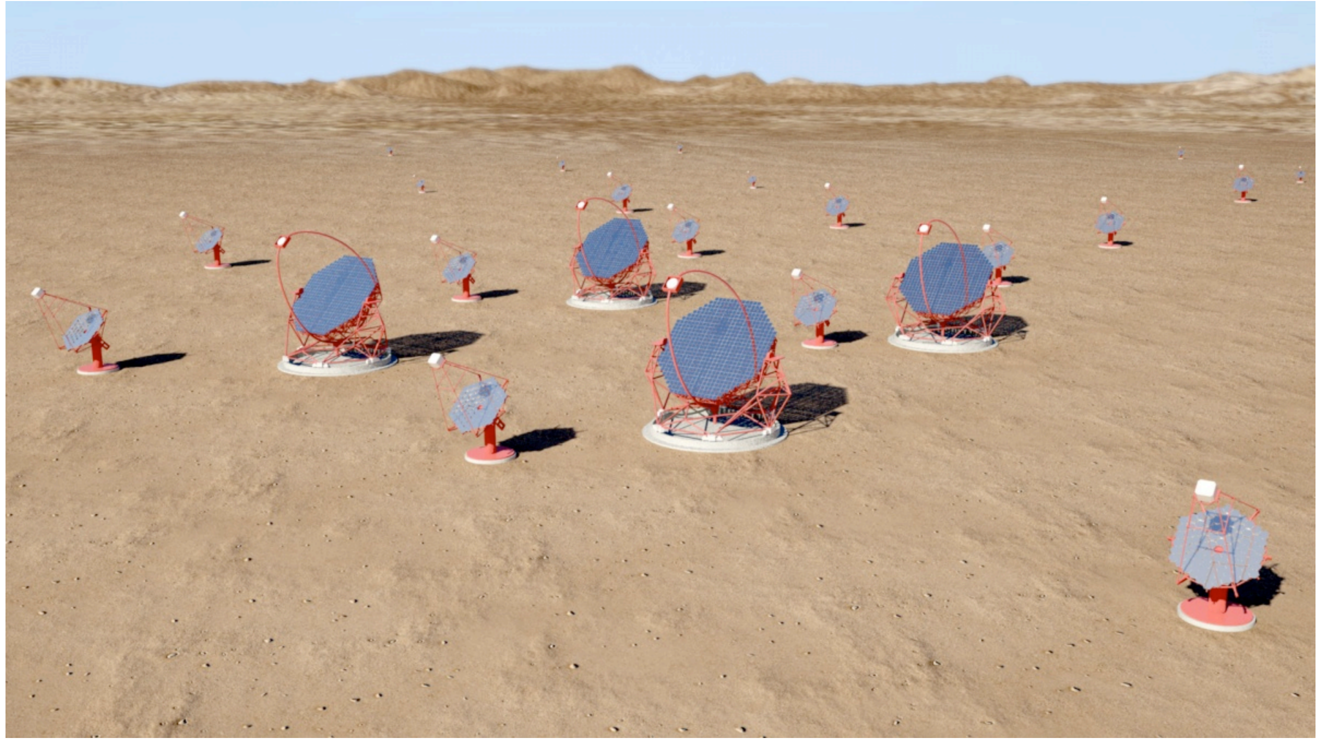
cross correlations - after all source contributions modeled and subtracted, stringent DM limits, specially at ~<100 GeV!
DM clustering still main uncertainty.





Future?

CTA: Entering the construction phase (in ESO Chile and La Palma). gamma rays with energies >~20 GeV, with better angular resolution, 0.07deg.

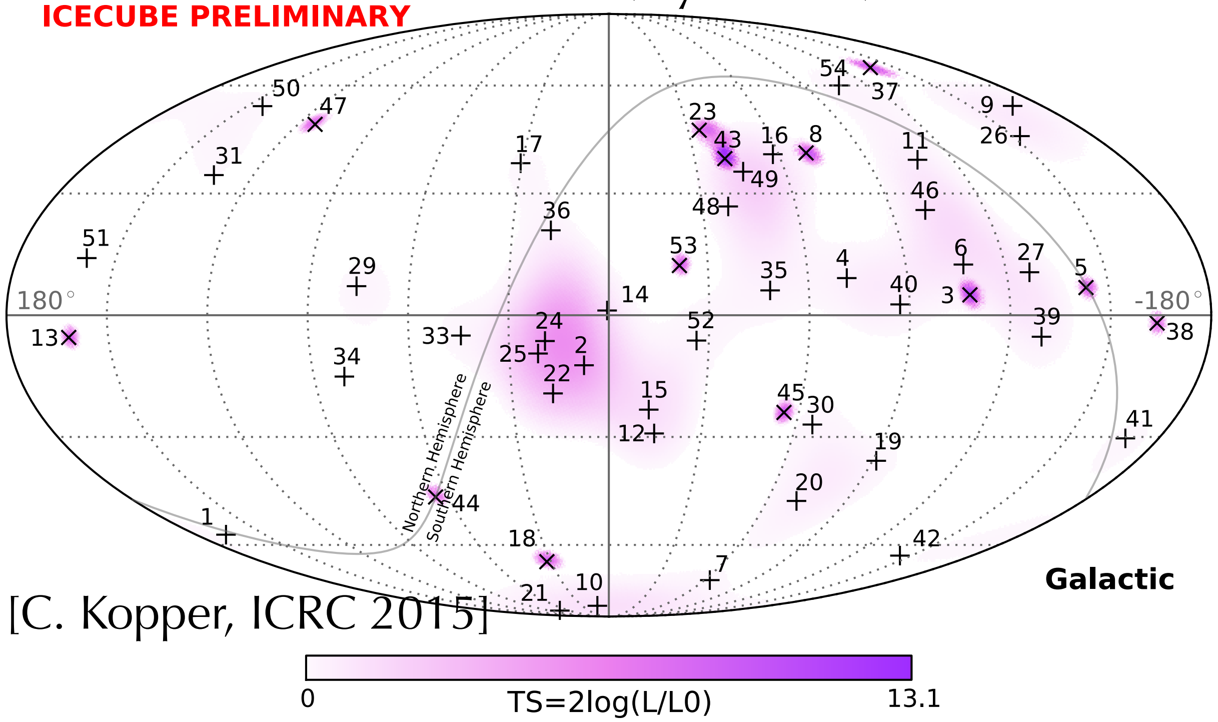


Gamma- 400: approved gamma ray satellite, better angular resolution at >10 GeV, but it might improve also <1 GeV (funding dependent).

PANGU, Gamma-light: several proposals for new satellites in the MeV-<~few GeV range with much better angular resolution.

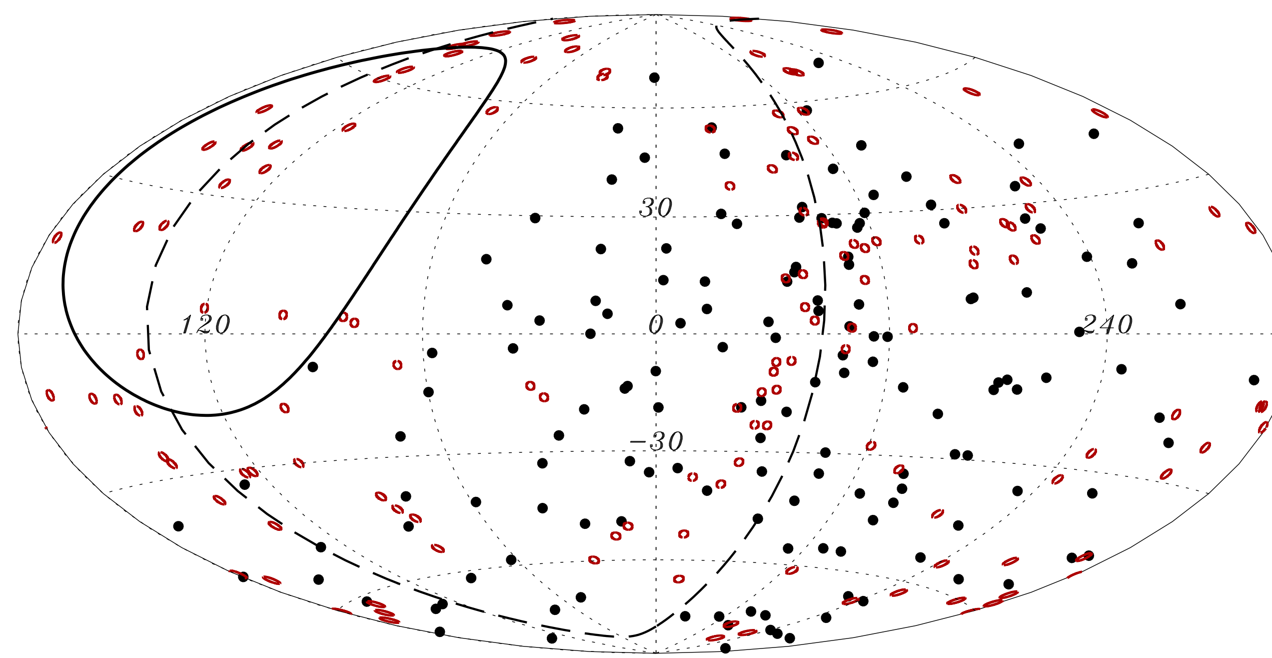
Future?

Ice Cube: 53(+1) events above10 TeV (4yr data)



[C. Kopper, ICRC 2015]

SKA: array of radio telescopes to be built in South Africa and Australia



events with E ≥ 58 EeV (black dots)

Pierre Auger upgrade: ongoing, will be able to tell the composition of the highest energy CRs

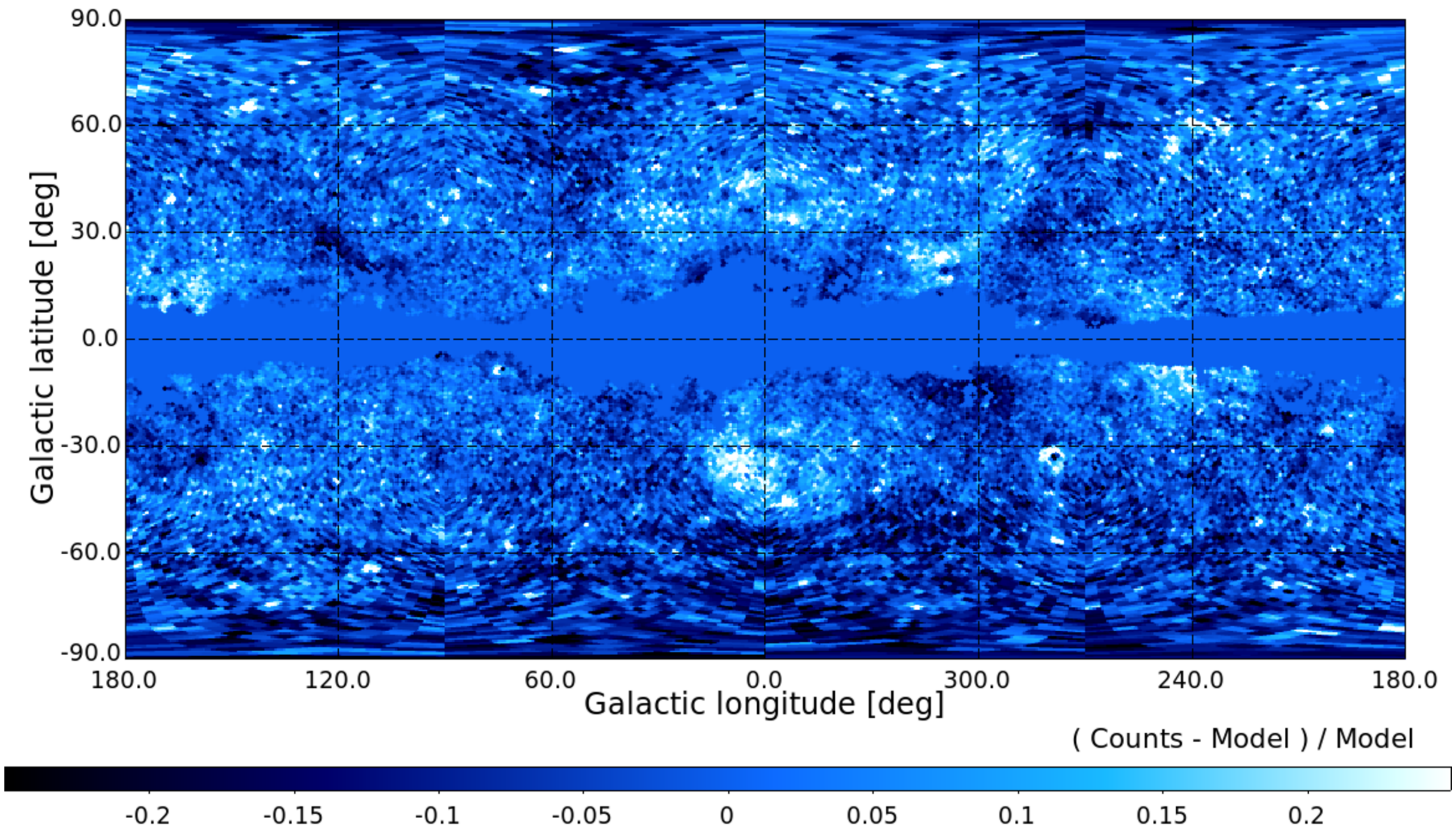
Summary

- More data coming up
- Data analysis getting more sophisticated
- exciting time for high energy astrophysics:
    - expect better understanding of high energy signals,
    - DM sensitivity in the right ballpark, the signal might show up along the way

Extra Slides

Cosmological DM signal

- **Isotropic vs non isotropic components?**
  - **Whole sky residuals of the IGRB measurement are at a <~20% level**
  - **'allowed' level of departure from large scale 'isotropic' DM emission in our analysis.**



[Ackermann+ (Fermi LAT col.): ApJ (2015), 1410.3696]

Cosmological DM signal

- **Challenges:**

1. **What is DM distribution in the sky - which components contribute to isotropic emission?**

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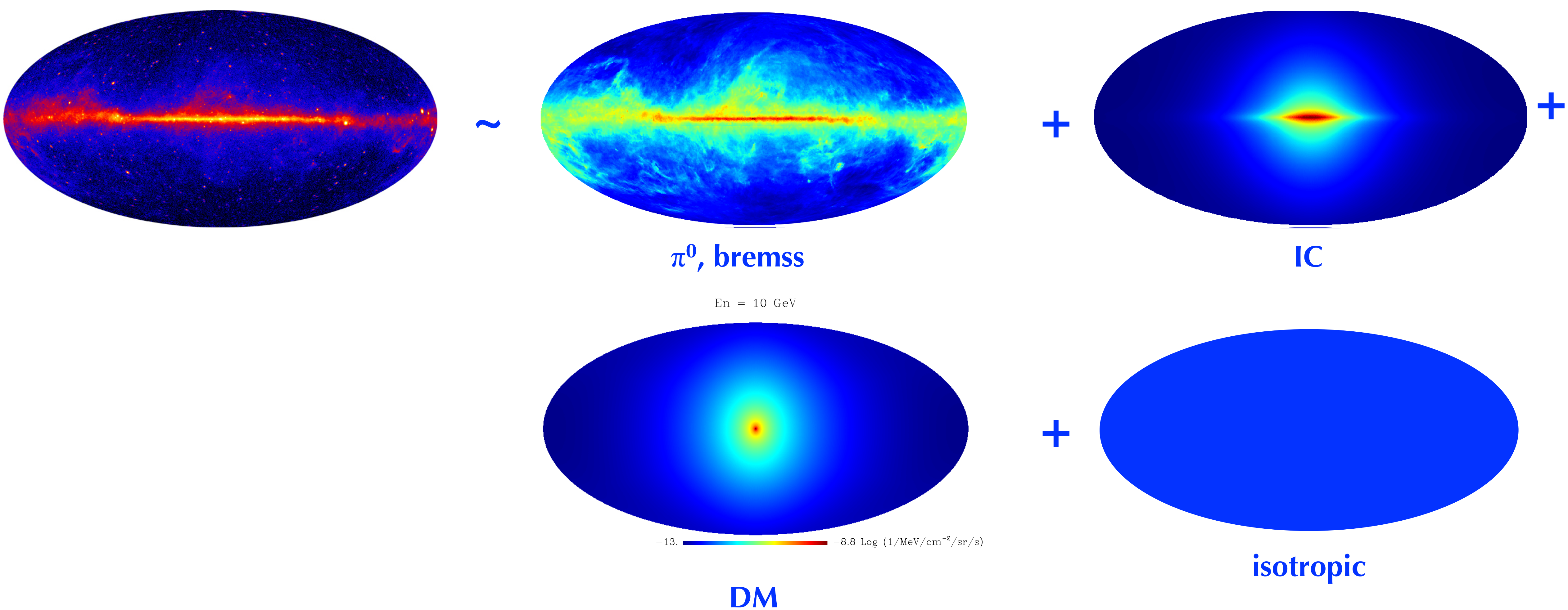
- **Non isotropic components - smooth DM halo**
  - **degenerate in part with the Galactic diffuse emission**
    - **we explored at what level the DM Galactic smooth counterpart of the isotropic signal impacts the derivation of the IGRB spectrum**



We repeated the original fits used to the derive the IGRB, but this time adding DM galactic template (for which *minimal* Galactic DM content is assumed).

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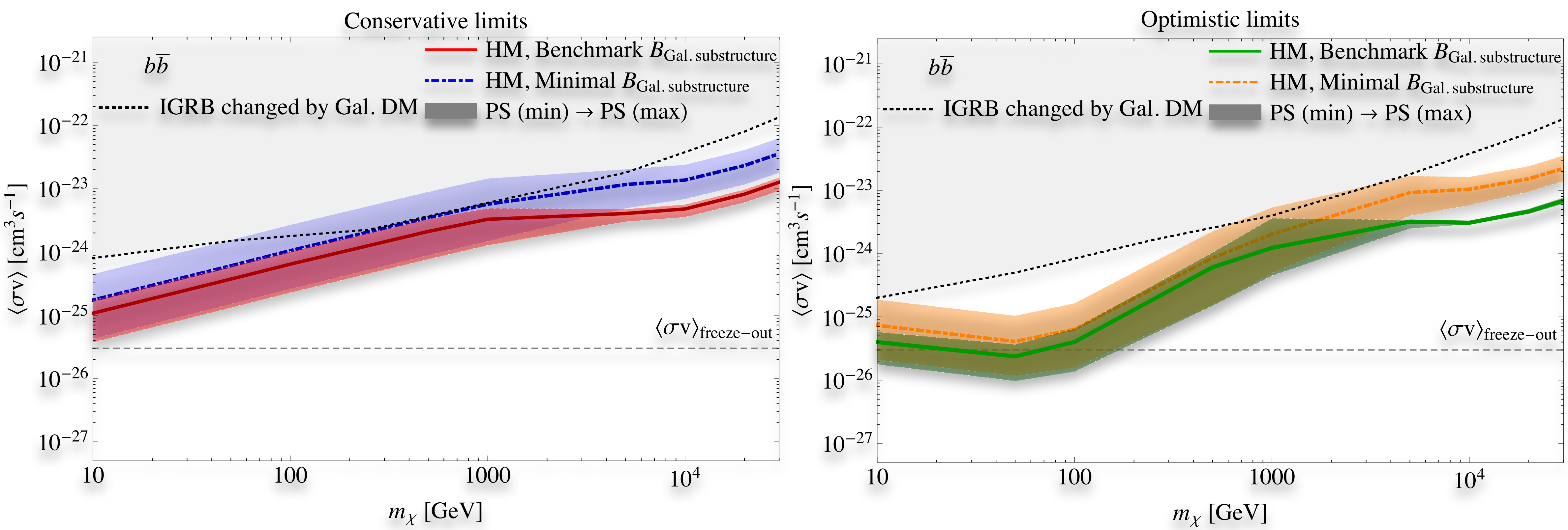
    - **– we explored at what level the DM Galactic smooth counterpart of the isotropic signal impacts the derivation of the IGRB spectrum**



For the cross sections in the gray region DM Galactic smooth signal would significantly alter the IGRB spectrum: 2σ from its syst band (left) or 2σ departure wrt to the IGRB error-bars (right). For most of the exclusion band our procedure is self consistent.

The DM limits in the intersection region are conservative, as IGRB gets lower in the presence of the Galactic smooth component.

-> we do not add high latitude smooth component to the signal as it might have been partially subtracted in the procedure of deriving the IGRB.

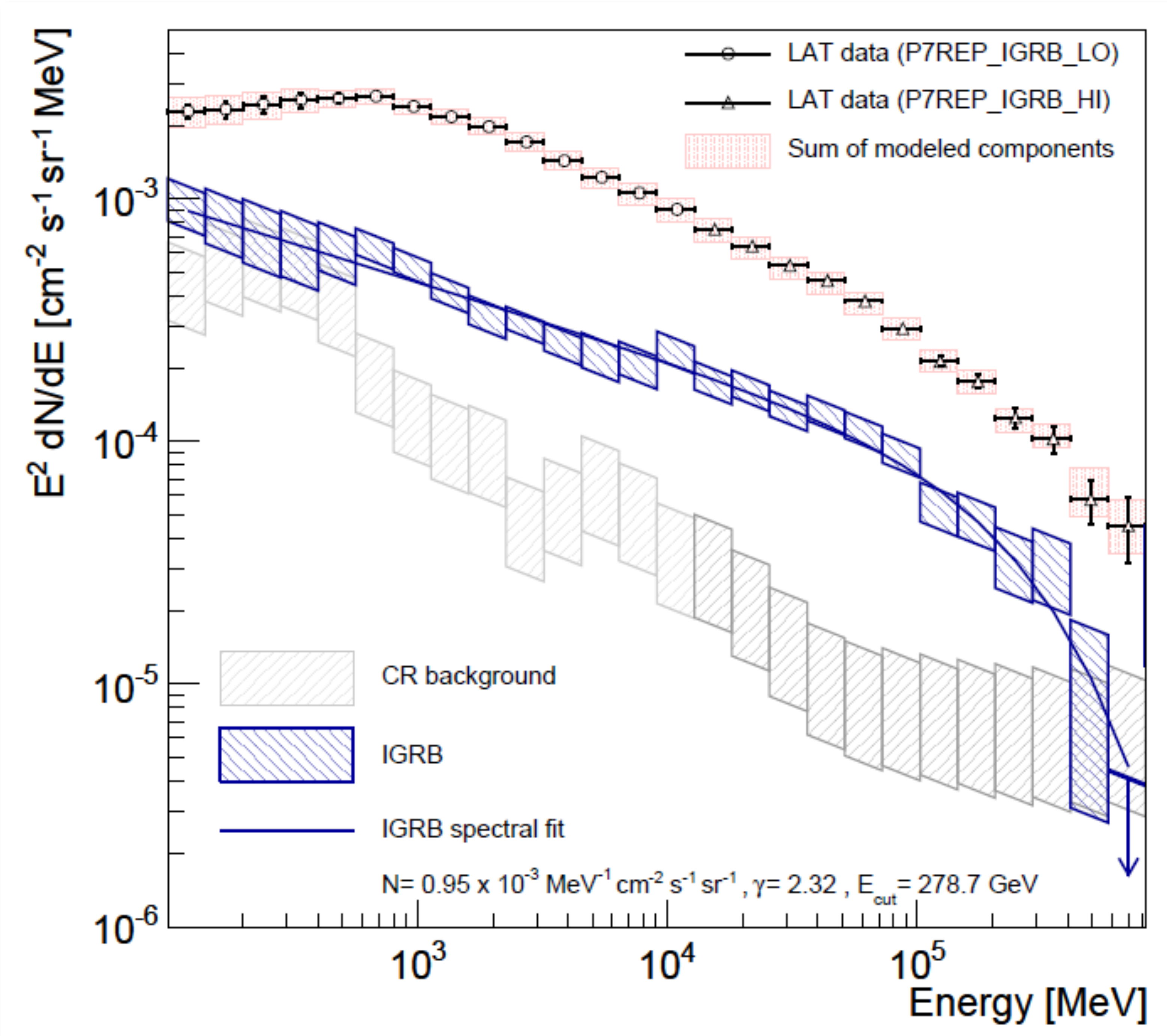
Isotropic emission - Fermi LAT measurement 100 MeV-820 GeV

Derivation of the isotropic emission in three steps:

1. **define event selection**: customized selection of gamma ray events, at LOW and HIGH energies
2. **template fitting of components of whole sky emission** to determine the spectrum of the isotropic component
3. **subtract additional cosmic ray contamination** detector level simulations

Isotropic emission

step 3: subtract remaining CR contamination (extensive detector-level simulations calibrated to the in on-orbit data)



IGRB intensity determined by subtracting residual cosmic-ray background from isotropic component in each energy bin

Uncertainties reflect statistical uncertainty from template fitting, systematic uncertainty in LAT effective area, and systematic uncertainty in residual cosmic-ray background levels

Baseline Galactic foreground model A

Isotropic emission

Results: PL + exp cut-off

$$\frac{dN}{dE} = I_{100}\left(\frac{E}{100\ \mathrm{MeV}}\right)^{-\gamma} \exp\left(\frac{-E}{E_{\mathrm{cut}}}\right)$$

→ Systematic uncertainties dominate over most of energy range, so χ^2 values cannot be easily interpreted in terms of statistical significance

Galactic Foreground Model	I_{100} [$\mathrm{MeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$]	γ	E_{Cut}	$I_{>100}$ [$\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$]	χ^2/ ndof Power Law Exponential Cutoff	χ^2 / ndof Power Law
A	$(0.95 \pm 0.08) \times 10^{-7}$	2.32 ± 0.02	279 ± 52	$(7.2 \pm 0.6) \times 10^{-6}$	13.9 / 23	87.5 / 25
B	$(1.12 \pm 0.08) \times 10^{-7}$	2.28 ± 0.02	206 ± 31	$(8.7 \pm 0.6) \times 10^{-6}$	7.9 / 23	151 / 24
C	$(0.85 \pm 0.08) \times 10^{-7}$	2.30 ± 0.02	269 ± 50	$(6.5 \pm 0.6) \times 10^{-6}$	11.9 / 23	89.1 / 24

Summarizing Galactic foreground systematic studies, fitted normalization of the IGRB varies by +15% / -30% with respect to foreground model A, power law slope varies between 2.28 – 2.34, and cutoff energy varies between 206 – 374 GeV

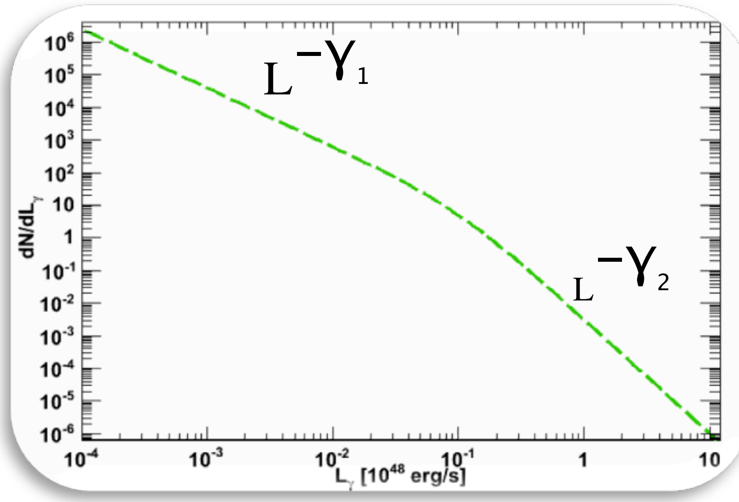
The origin of emission

Luminosity Function

$$\Phi(L_\gamma, z) = \Phi(L_\gamma / e(z), z = 0)$$

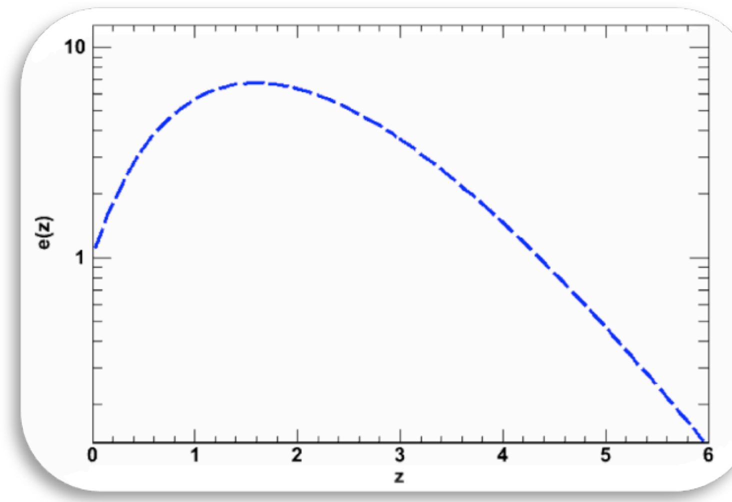
=

Local Luminosity Function



+

Evolutionary Factor



the sources experience both luminosity and density evolution

$$\Phi(L_\gamma, z=0) \propto \left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2}\right]$$

Typical double power law

$$e(z) = (1+z)^k e^{z/\gamma}$$

Evolution in luminosity as a power-law with index k and a cut-off after z_{cut}=-1-kγ

$$k = k_d + \tau(\log L - 46)$$

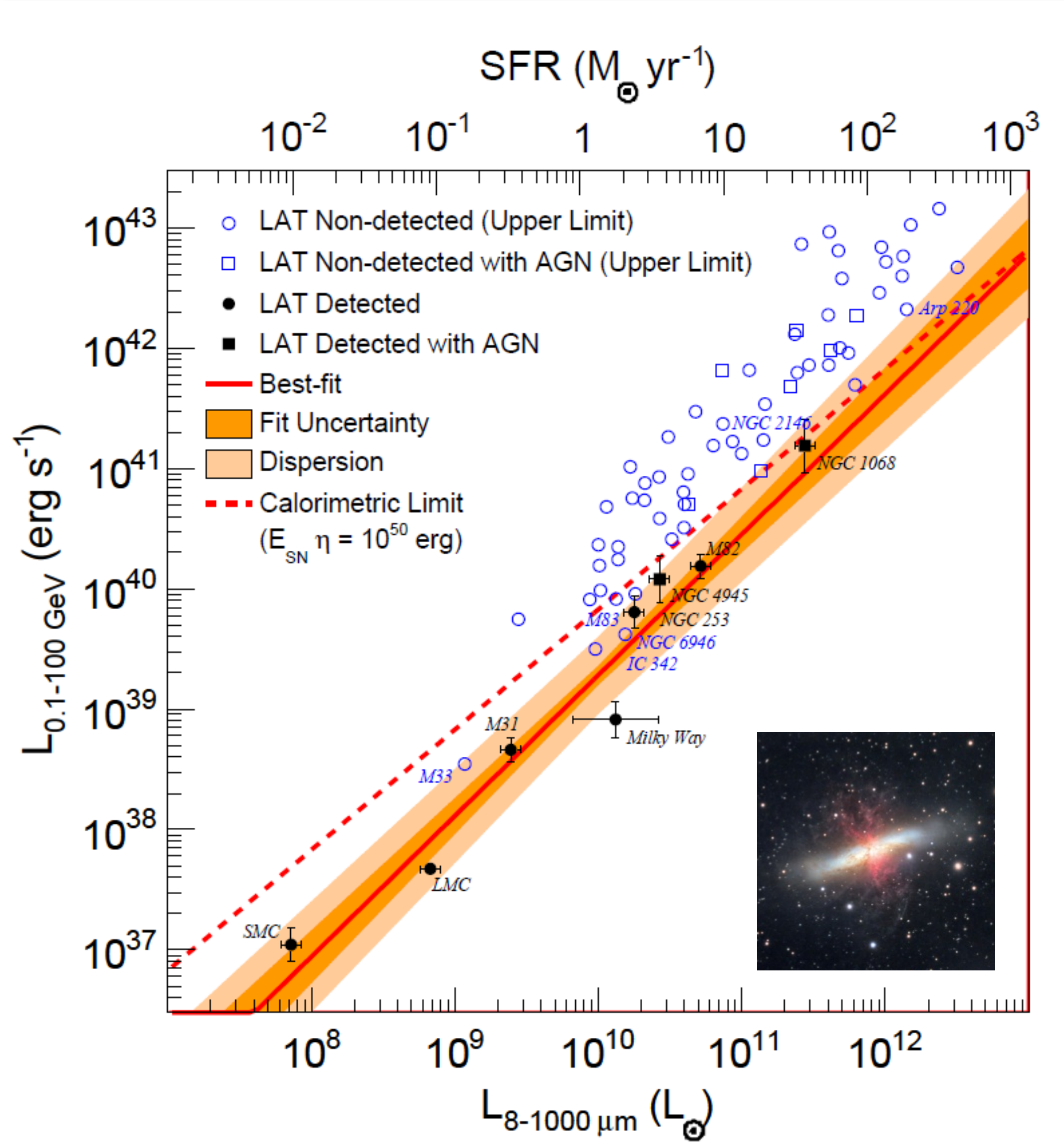
Accounts for the different speeds of evolution

Spectrum:

$$\frac{dN}{dE} = \frac{A}{\left(\frac{E}{E_b}\right)^a + \left(\frac{E}{E_b}\right)^b} * e^{-\tau(E,z)}$$

The origin of emission

Star-forming Galaxies: Multiwavelength Scaling Relations



Cumulative intensity of star-forming galaxies almost entirely unresolved

Contribution to EGB estimated with multiwavelength scaling relations or physical models calibrated in local universe

For example, gamma-ray luminosity of Local Group and nearby starburst galaxies is quasi-linearly correlated with star-formation rate
(traced by total IR luminosity)

Ackermann et al. 2012, ApJ, 755, 16

Isotropic emission

step 2: Galactic diffuse emission: GDE uncertainties

Model A (baseline): Similar to models in Ackermann et al. 2012, ApJ, 750, 3

Model B: Add population of electron-only sources near Galactic center

Model C: Vary cosmic-ray diffusion rate with Galactocentric height and radius