# 8th International Fermi Symposium

# The power of the unresolved

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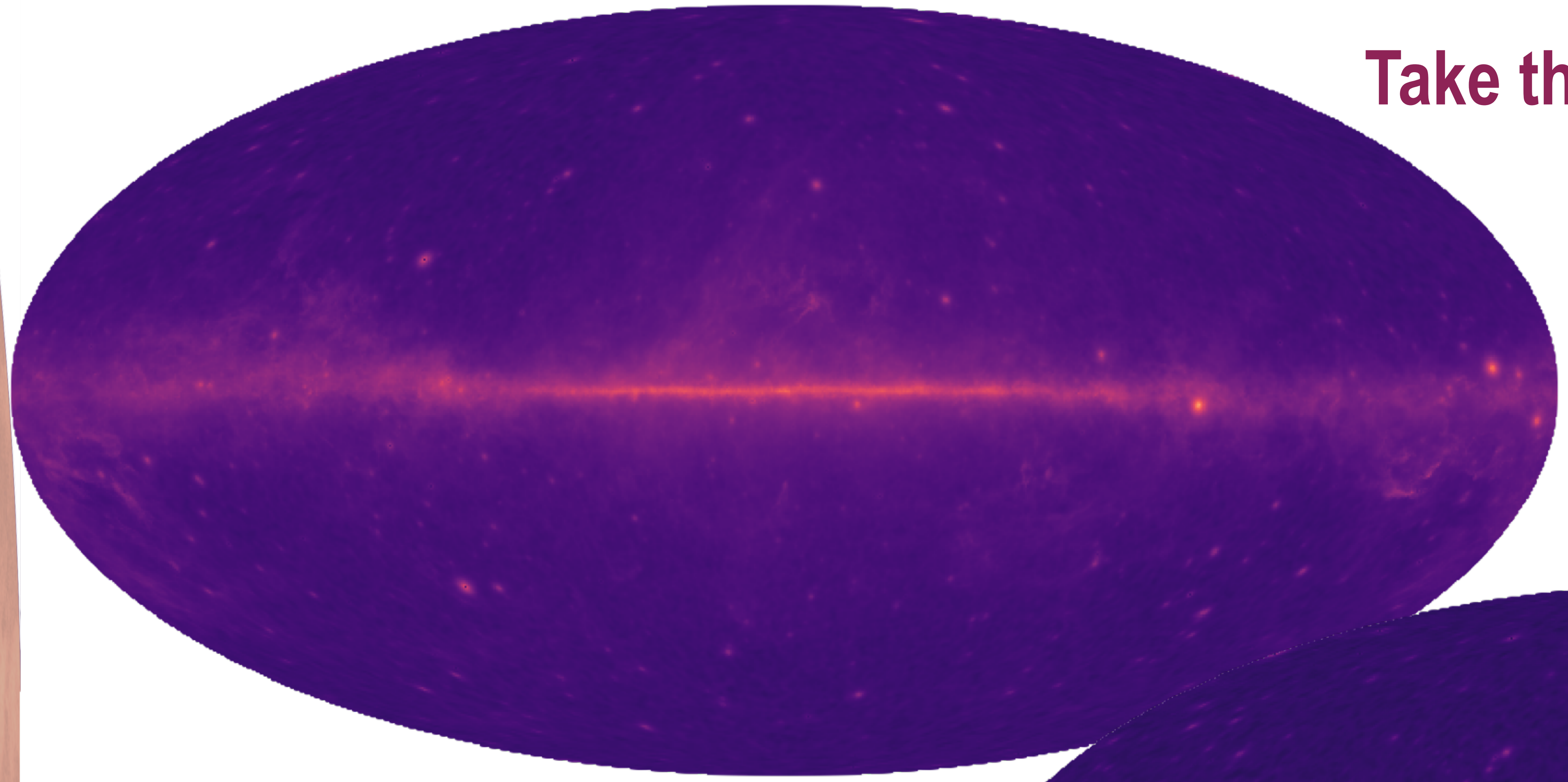
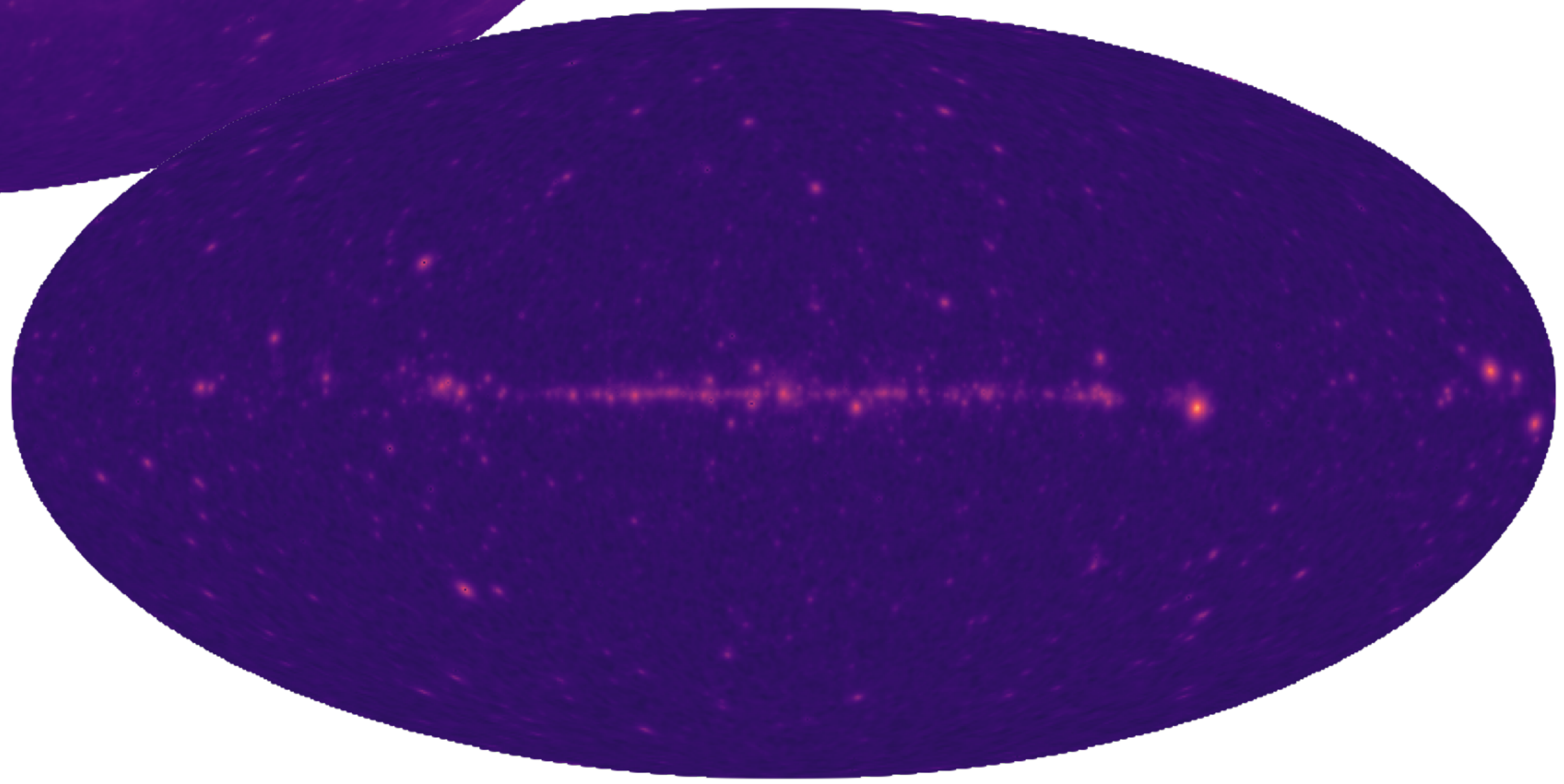
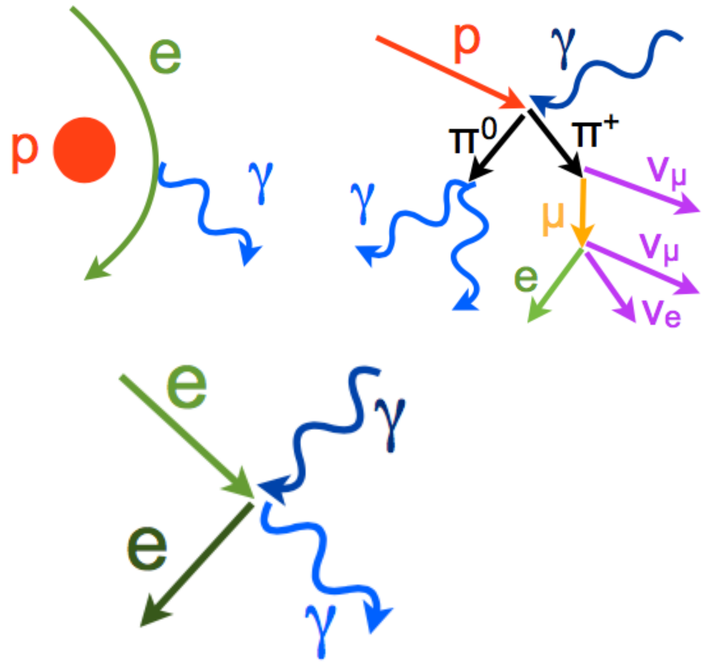
# What Fermi sees



Take the total γ-ray emission

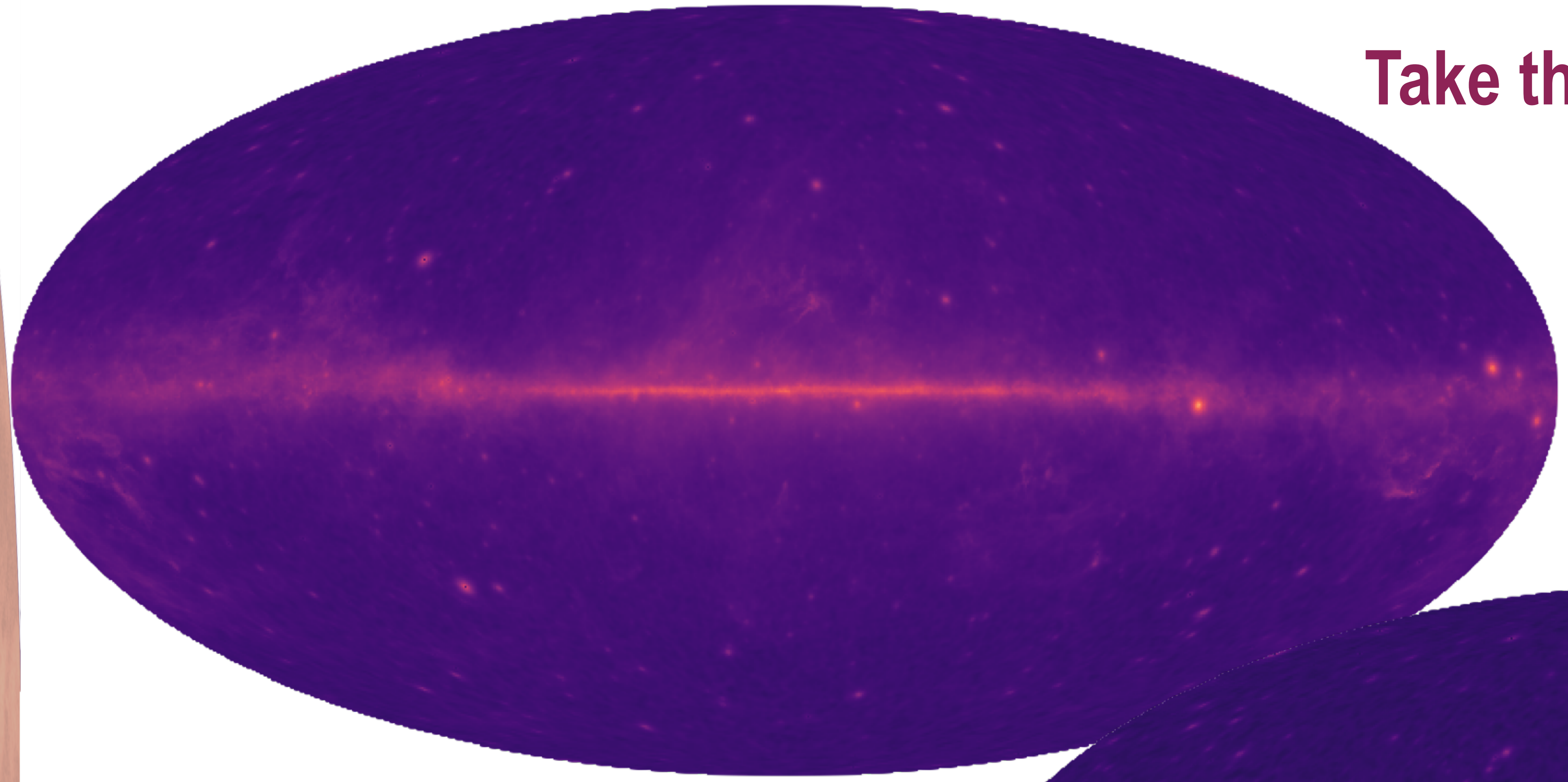
Remove Galactic diffuse emission



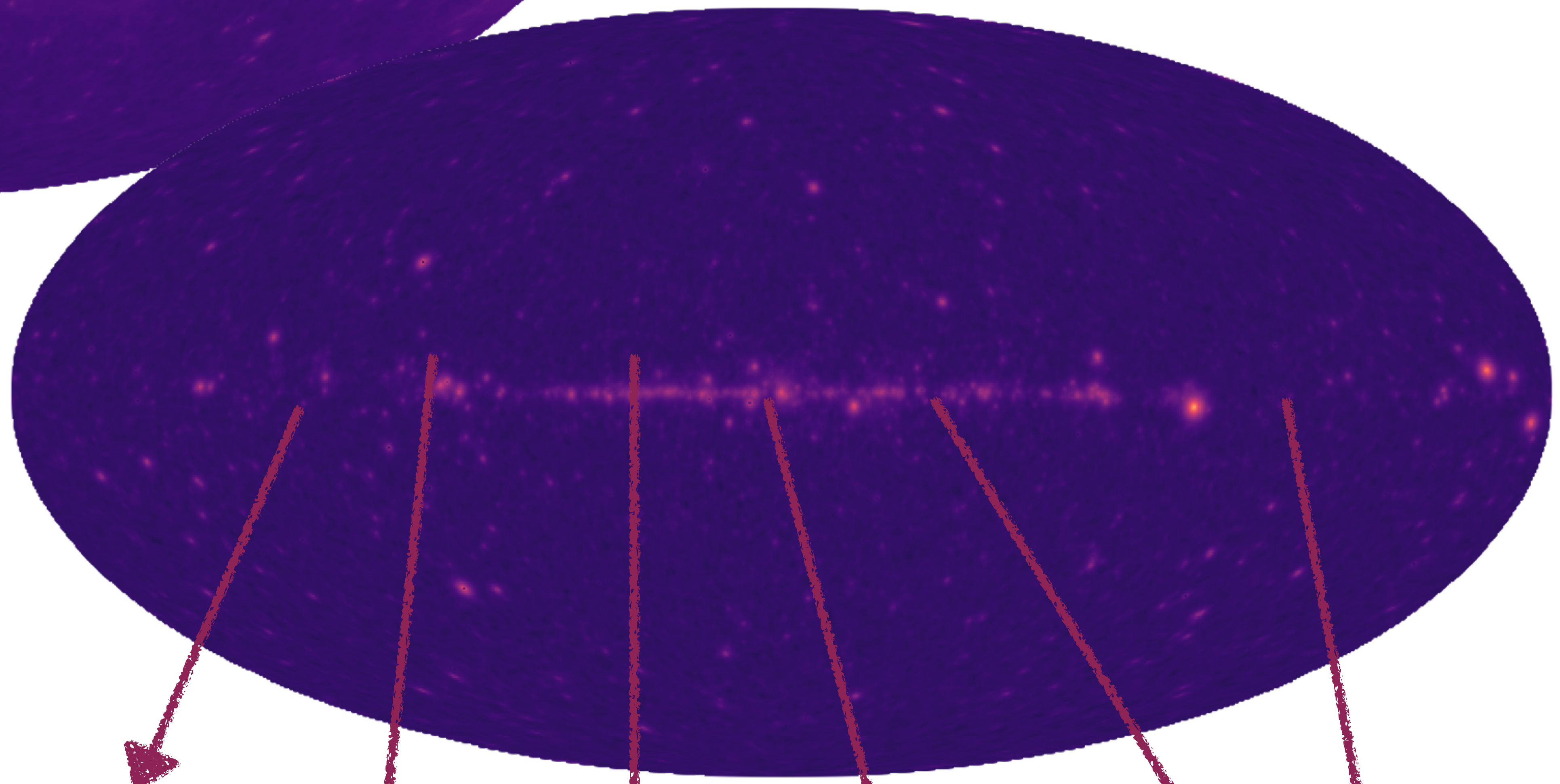


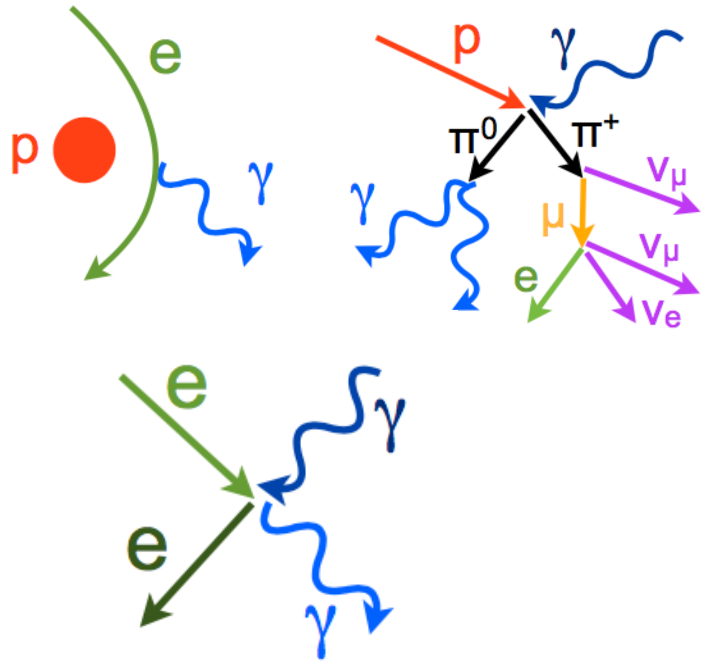
# What Fermi sees

Take the total γ-ray emission



Remove Galactic diffuse emission






Novae, Super Nova Remnants (SNRs)

Star-forming regions

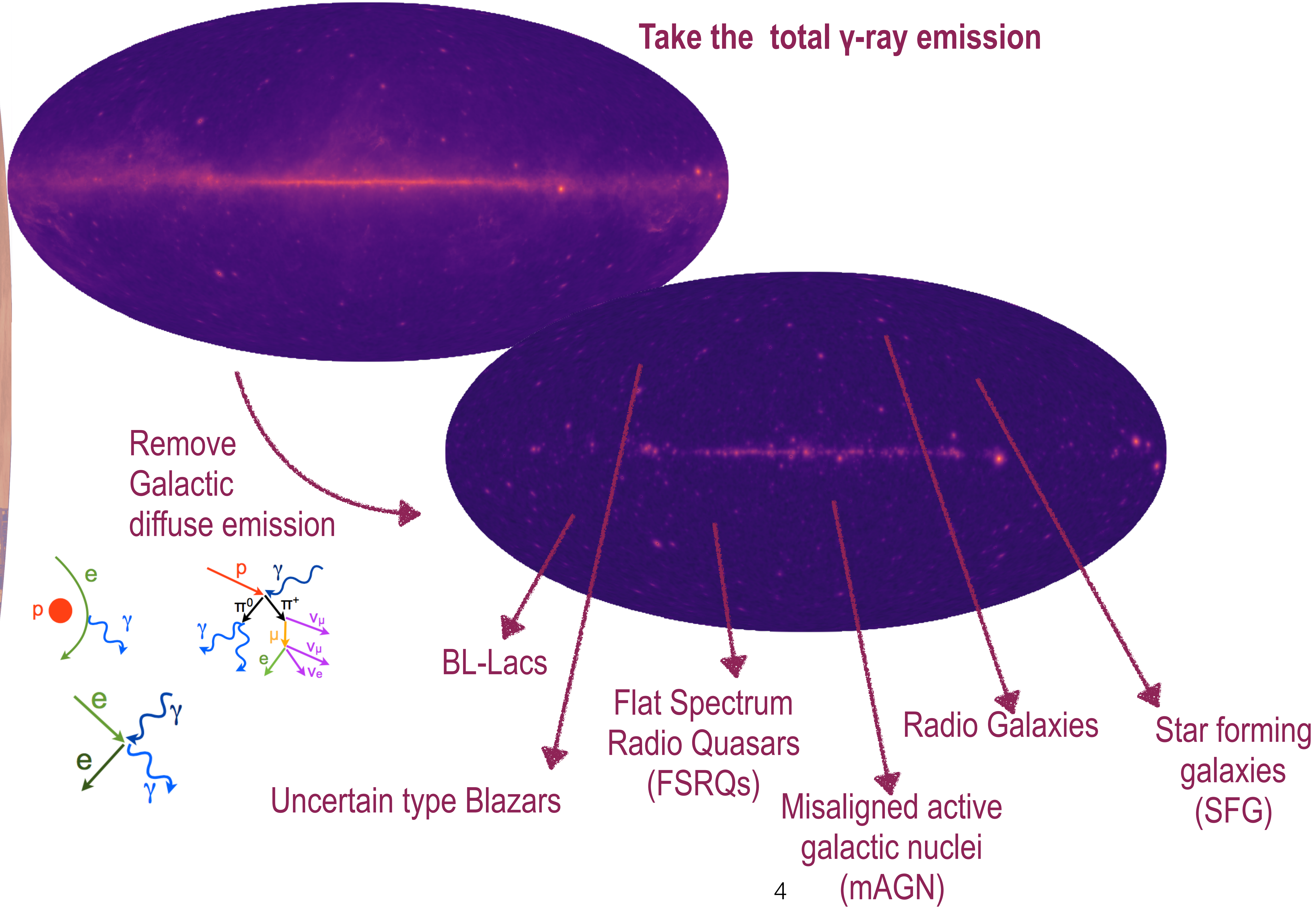
Pulsars

Pulsar wind nebulae (PWN)

Globular clusters

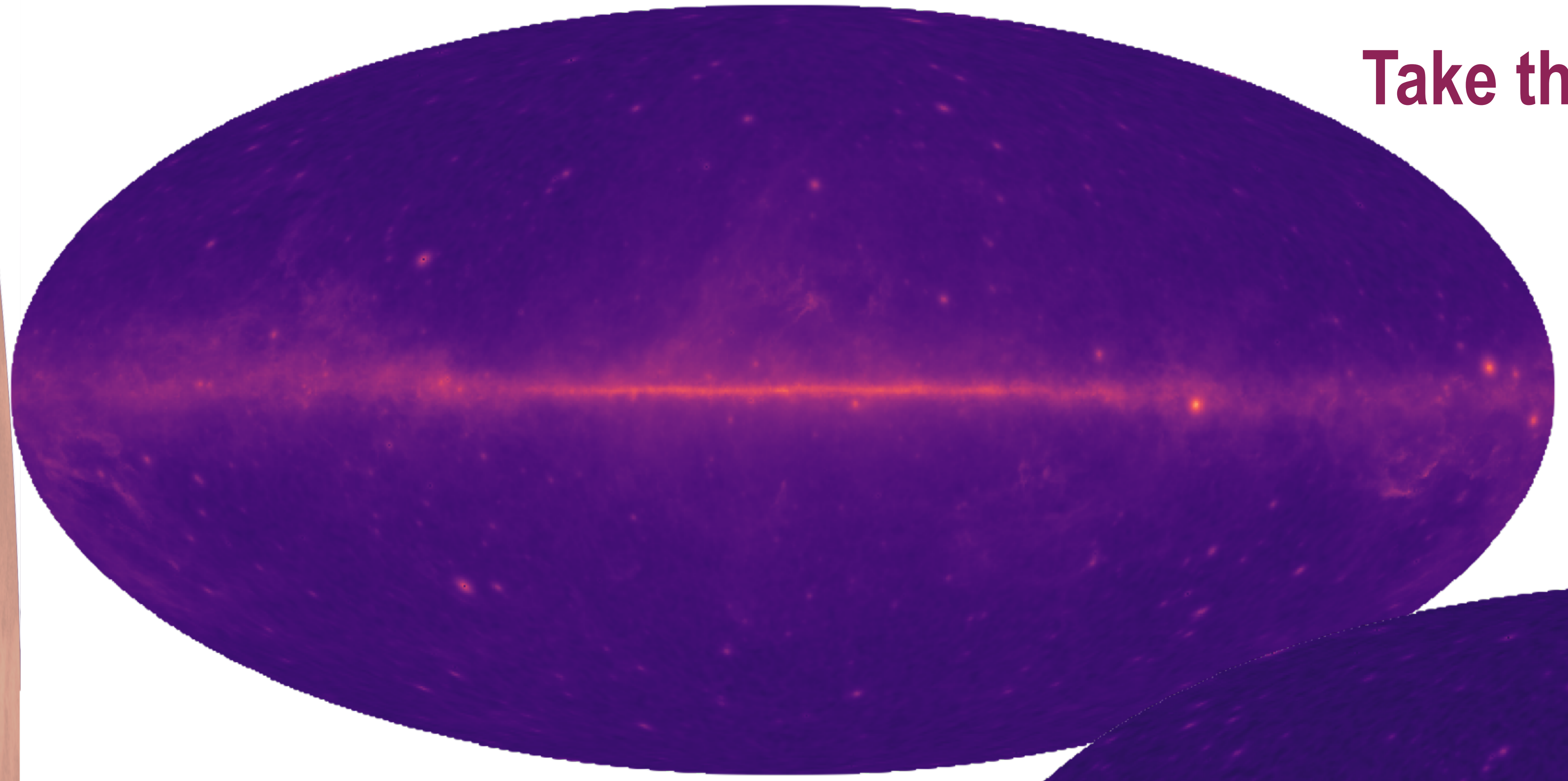
Binary systems

# What Fermi sees

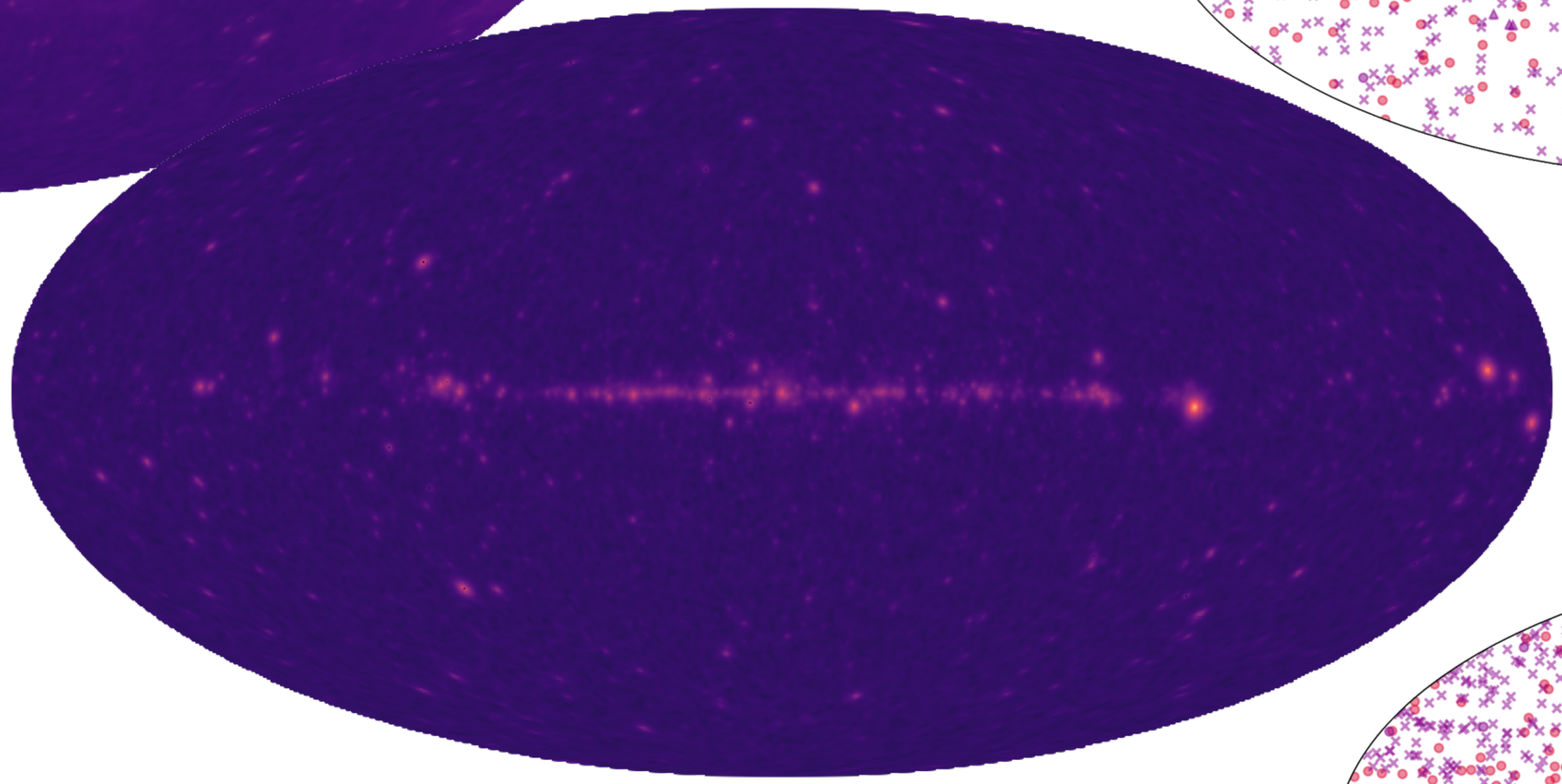


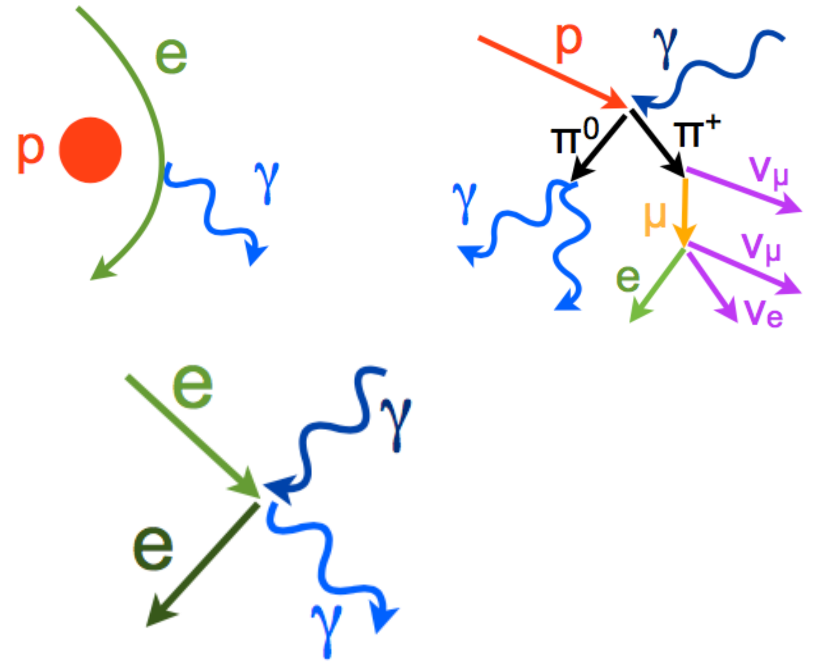
# What Fermi sees

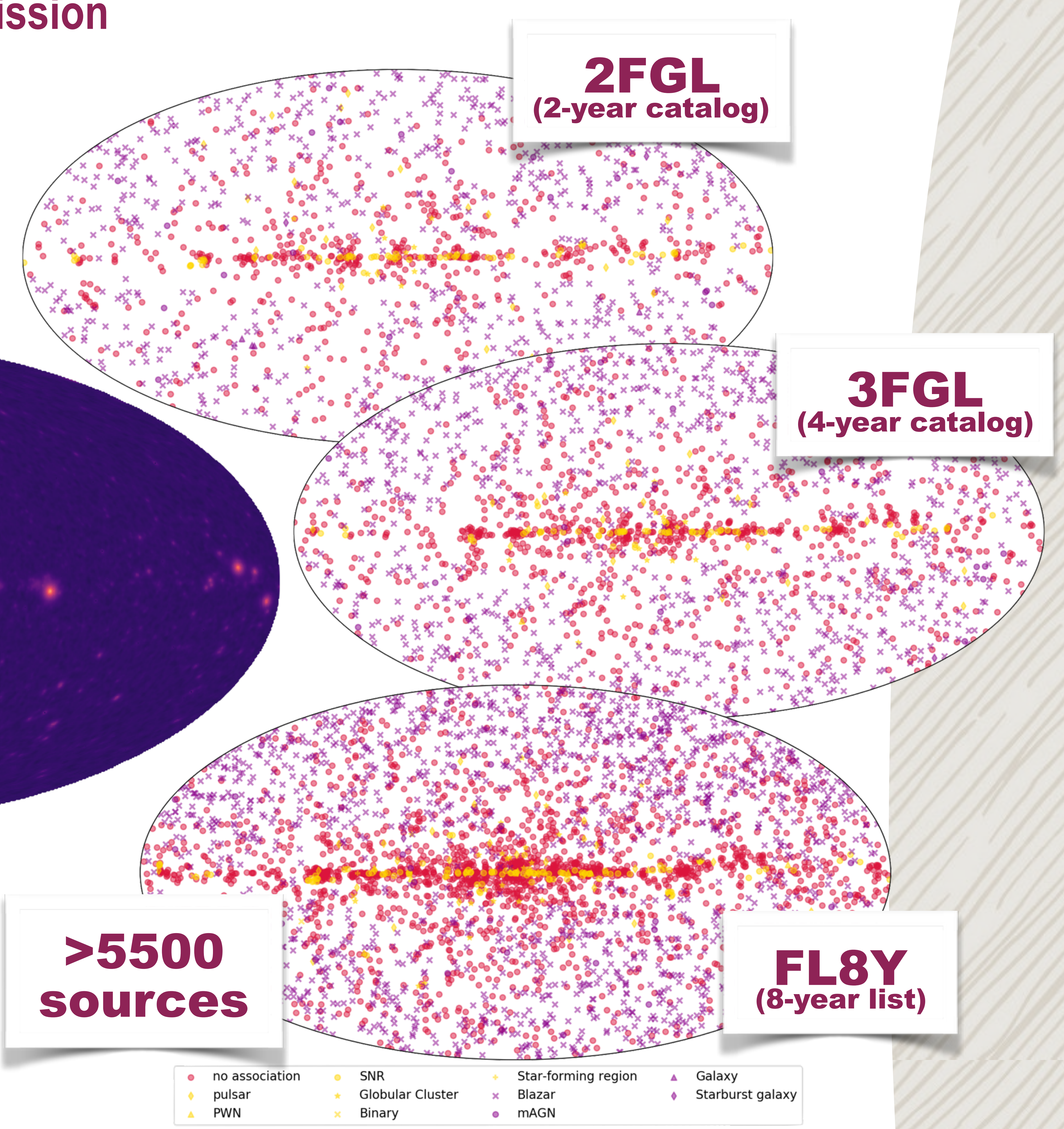
Take the total γ-ray emission



Remove Galactic diffuse emission

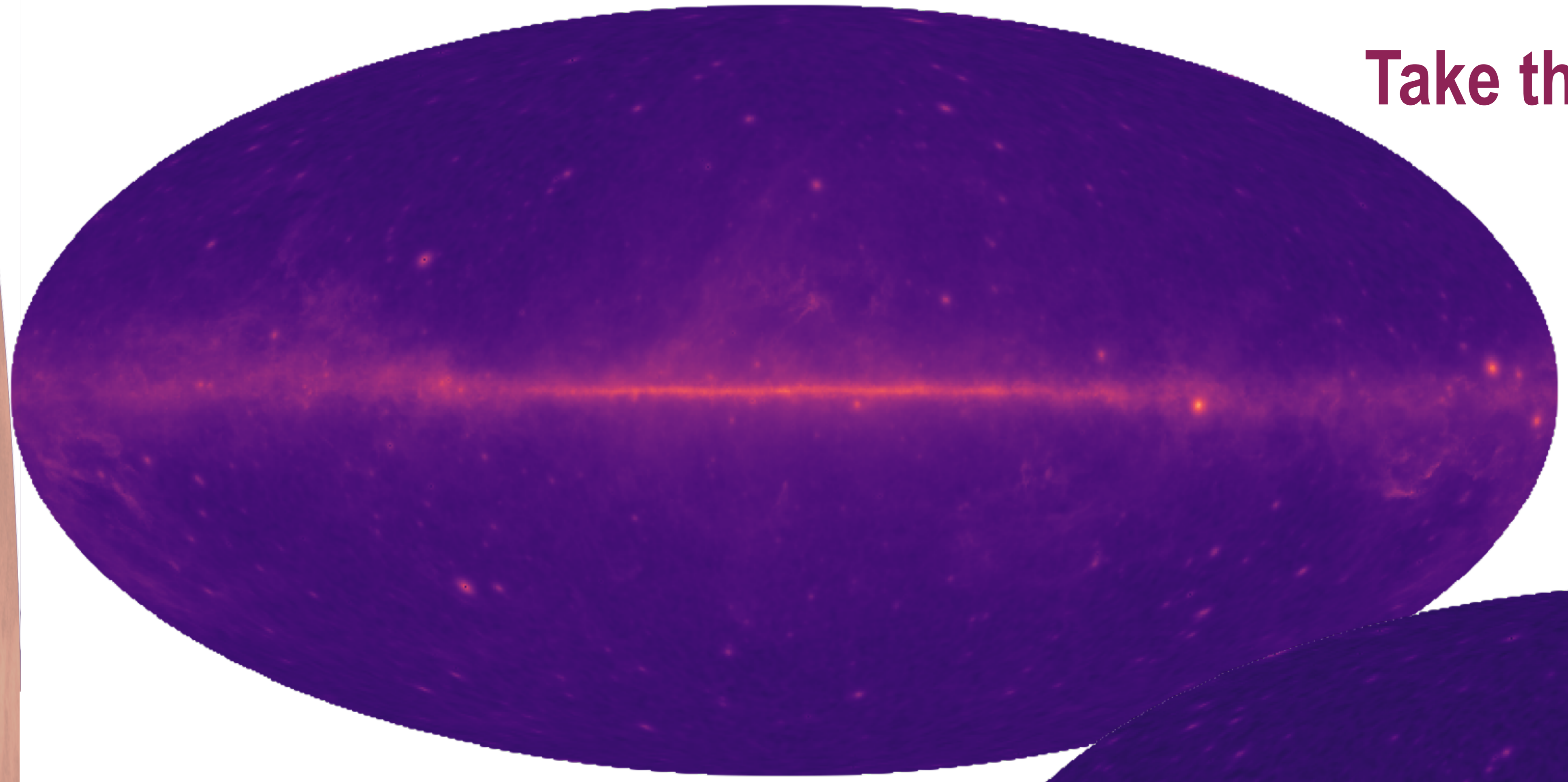




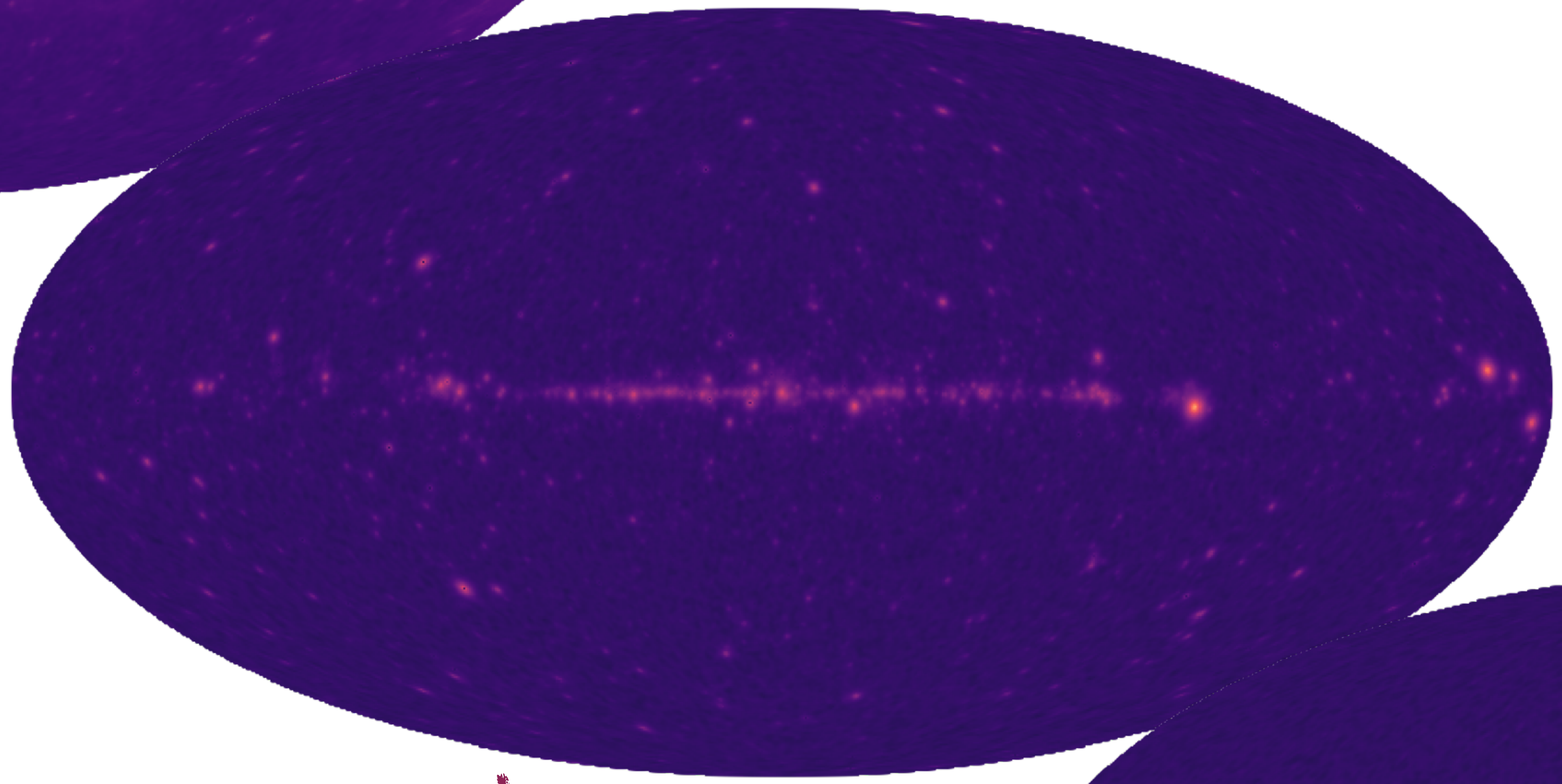



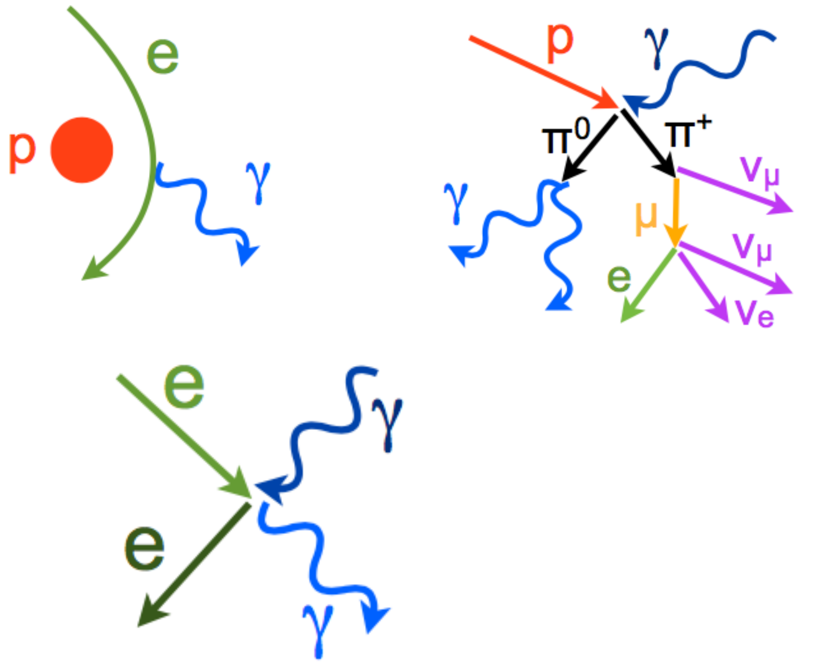
# The UGRB

Take the total γ-ray emission

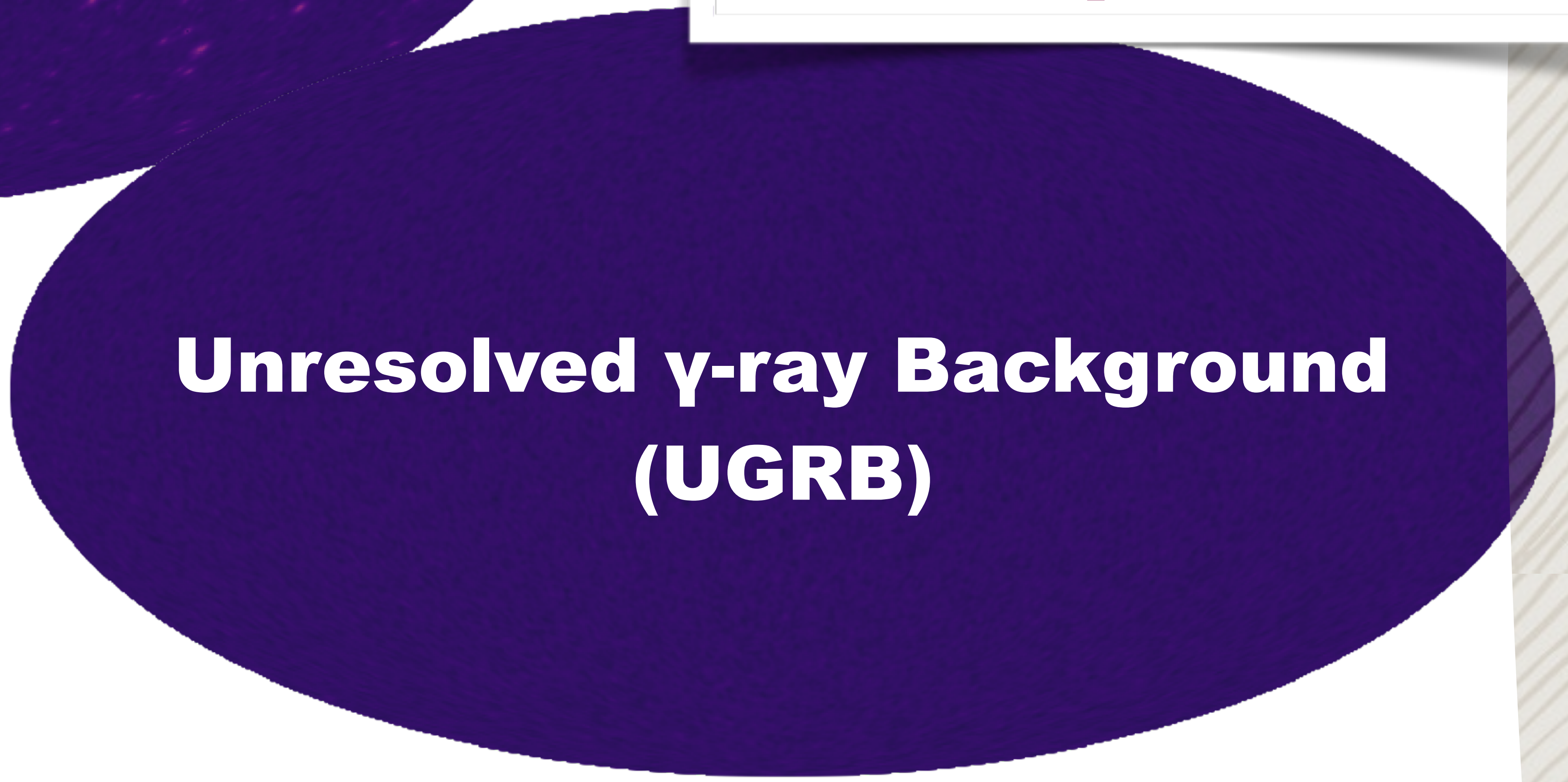


Remove
Galactic
diffuse emission





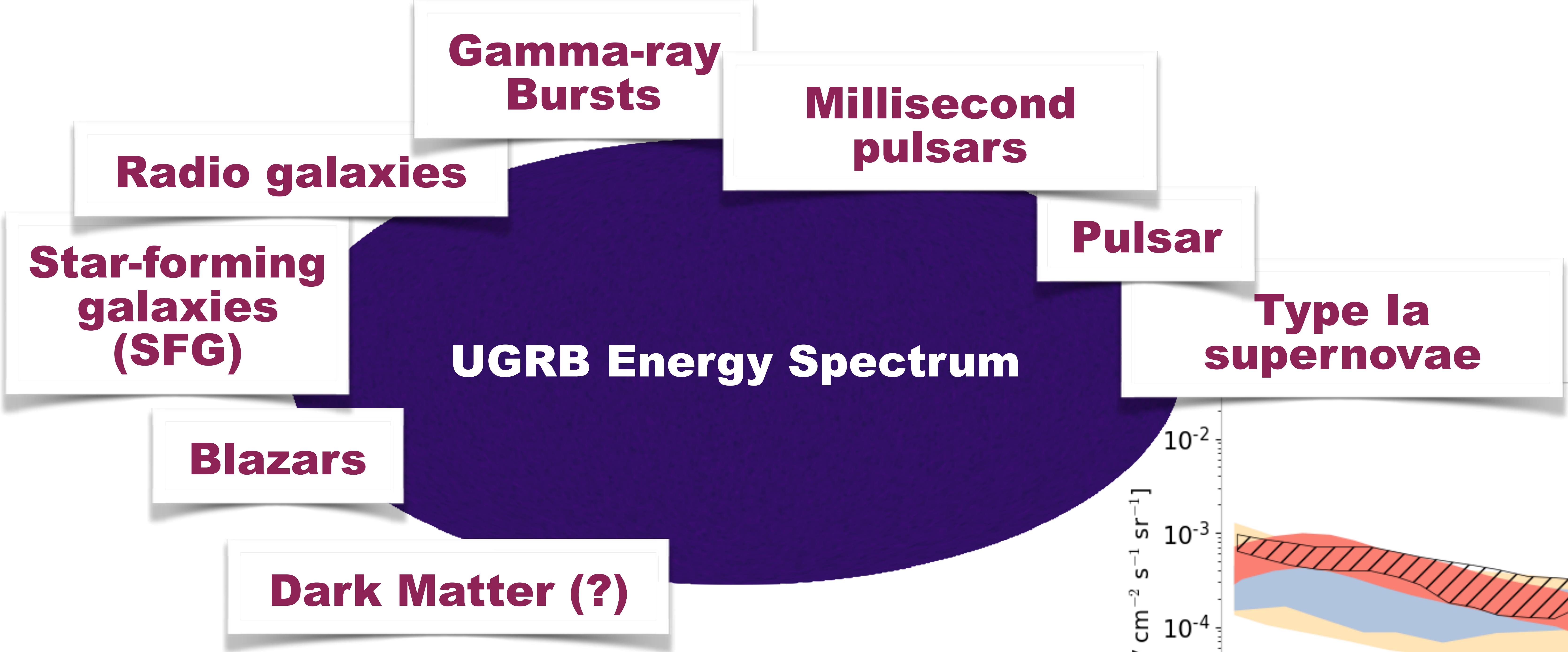

Remove
Resolved sources

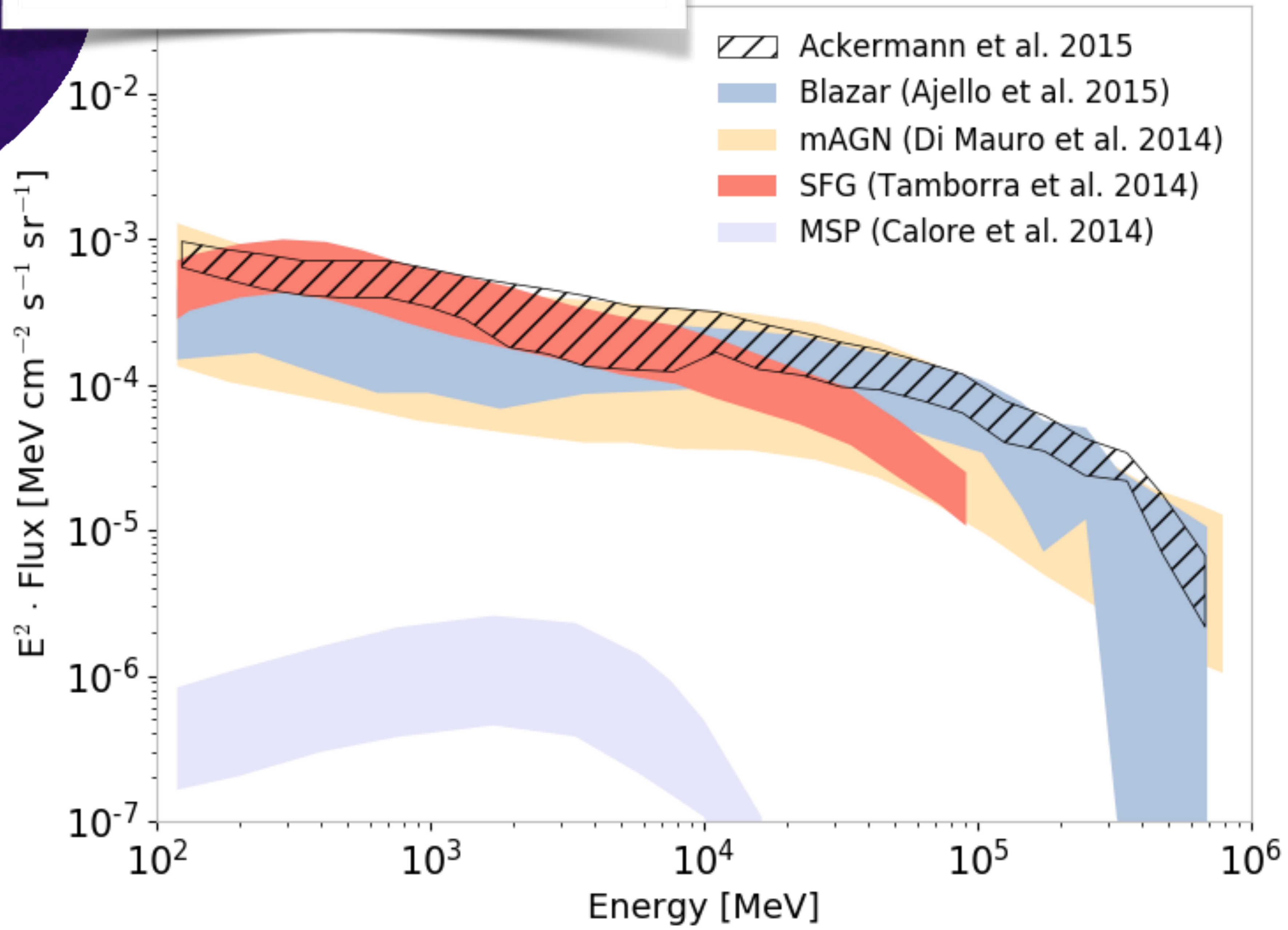



**1) time-dependent component!**

# What contributes to the UGRB intensity

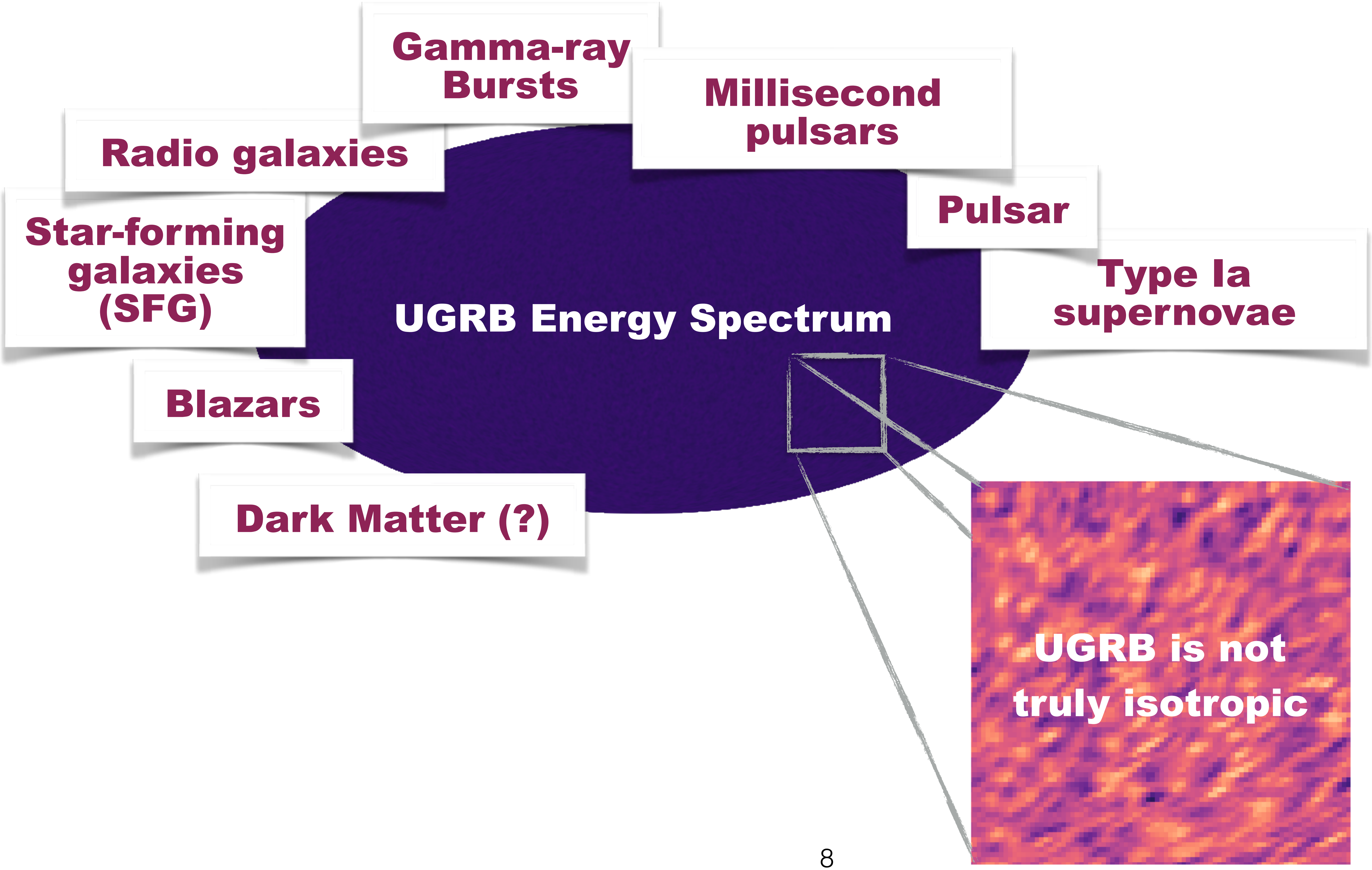
Estimated contribution to the unresolved emission **intensity**:



# Beyond the monopole...

Estimated contribution to the unresolved emission **intensity**:



# Beyond the monopole thanks to Fermi-LAT performances*

Gamma-ray Bursts

Millisecond pulsars

Radio galaxies

Pulsar

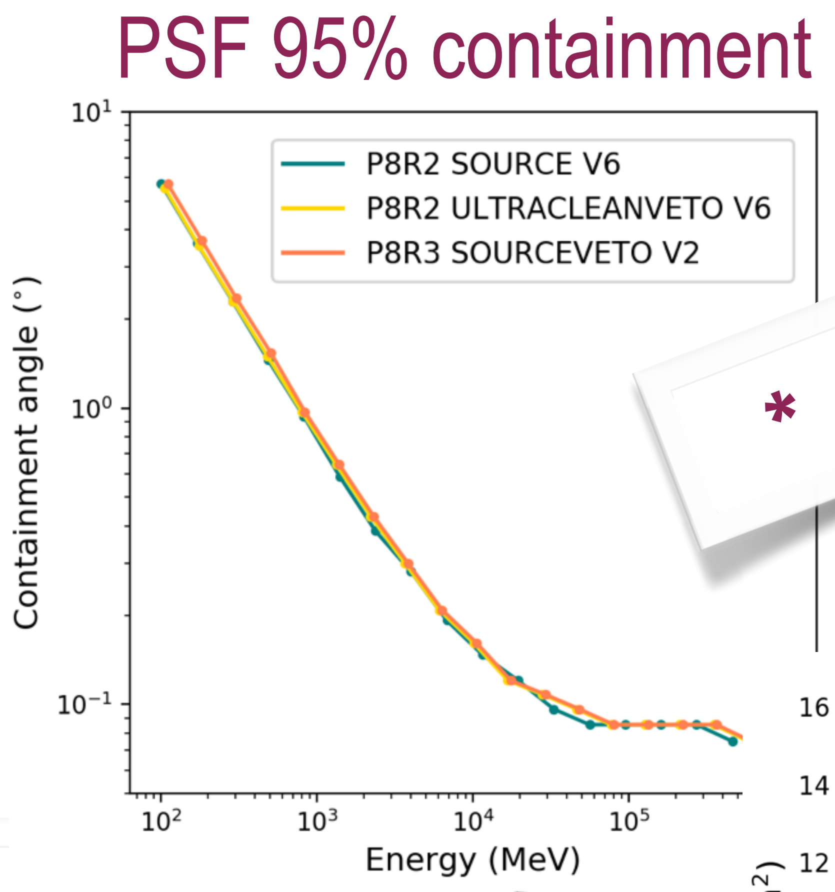
Star-forming galaxies (SFG)

**UGRB Energy Spectrum**

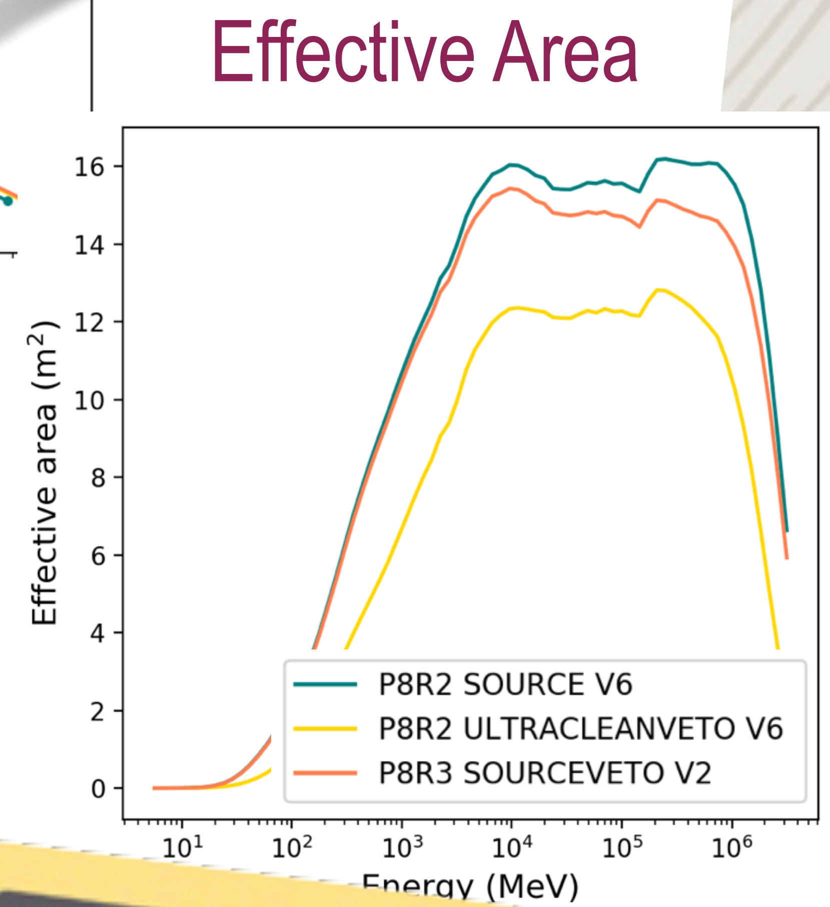
Type Ia supernovae

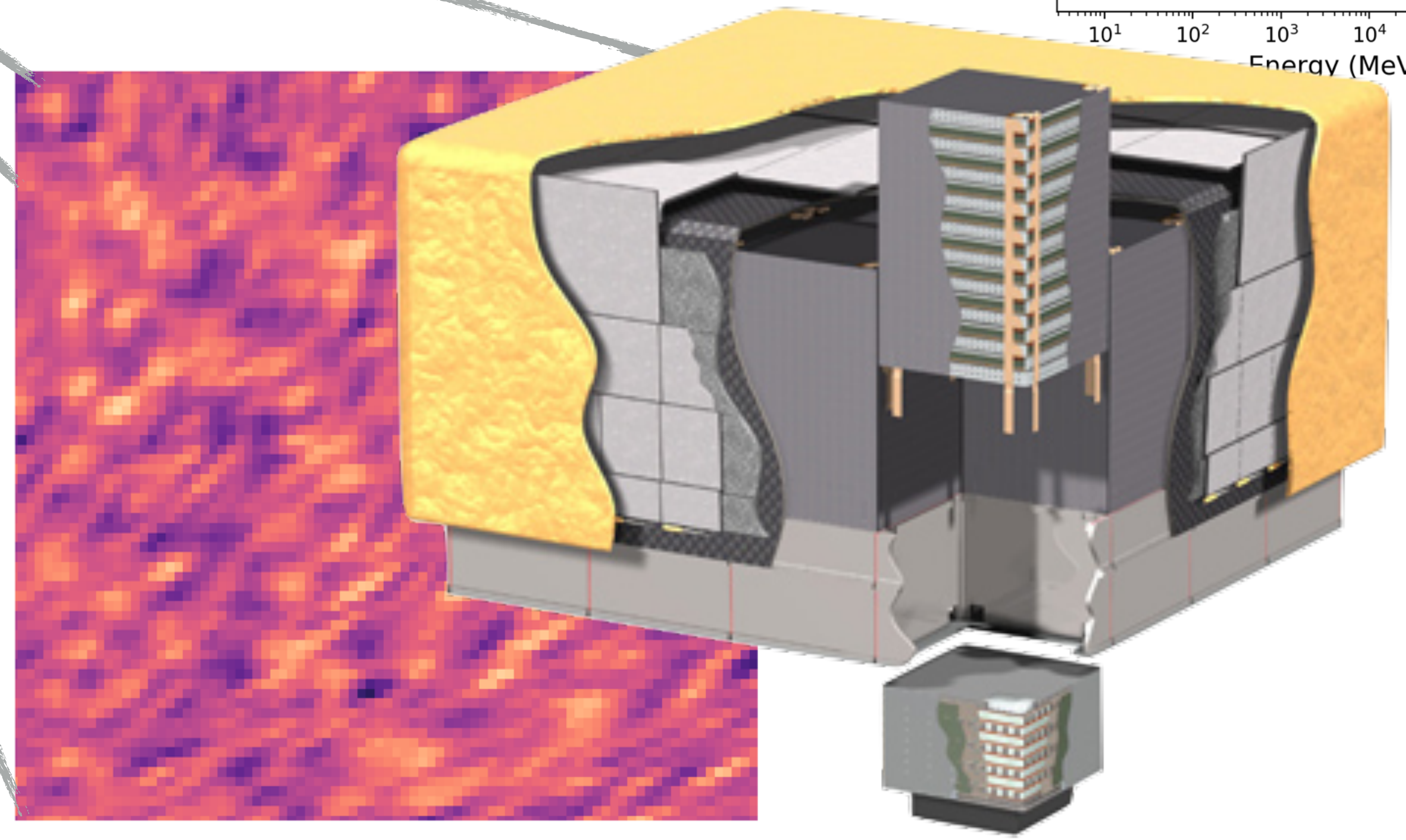
Blazars

Dark Matter (?)



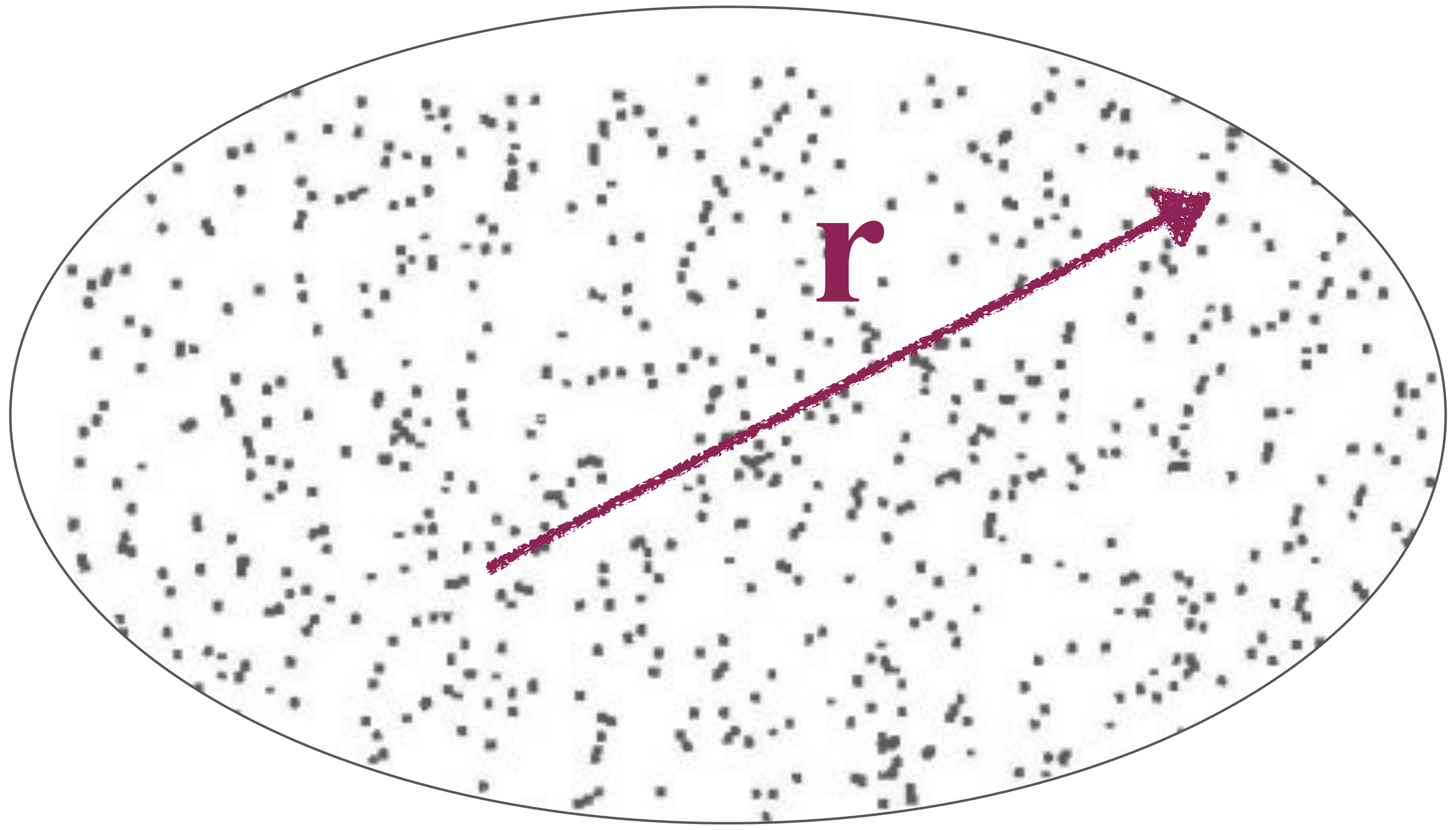

* see poster n.107



# Autocorrelation

**2-point correlation function (ACF)**: the excess probability, above the expectation from a random distribution, of finding an object in a volume dV at a separation r.




$$dP = n\,[1 + \xi(\mathbf{r})]\,dV$$

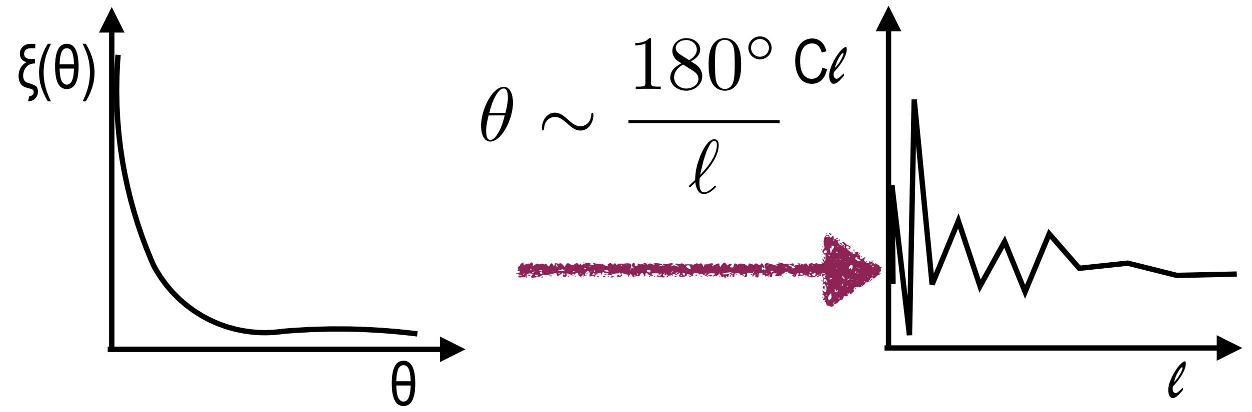
$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\ \delta(\mathbf{x}+\mathbf{r}) \rangle_V$$

n = number density
dV = volume
r = separation

Physical space

Harmonic space

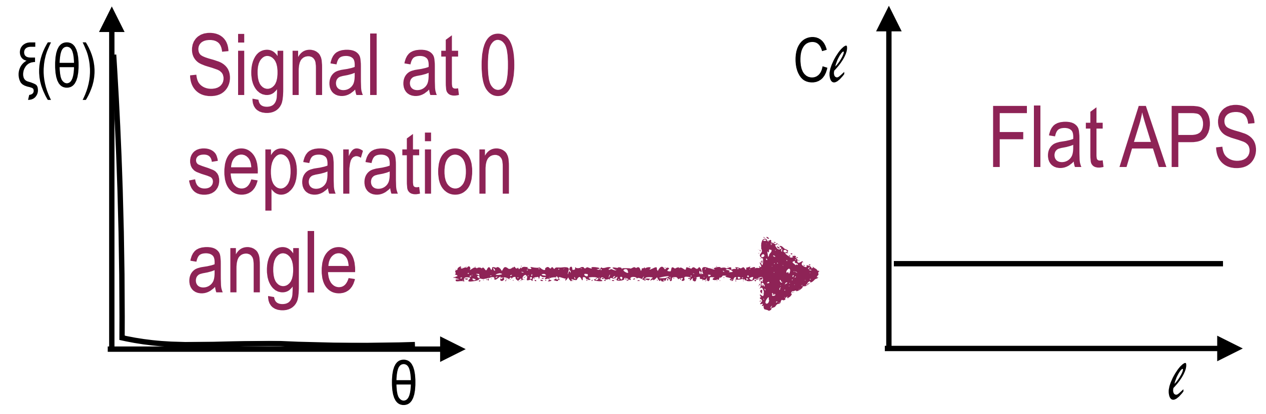
$$\theta \sim \frac{180^\circ}{\ell}$$




For a spherical surface geometry it is convenient to use the Legendre transform: the **angular power spectrum (APS), Cl**:

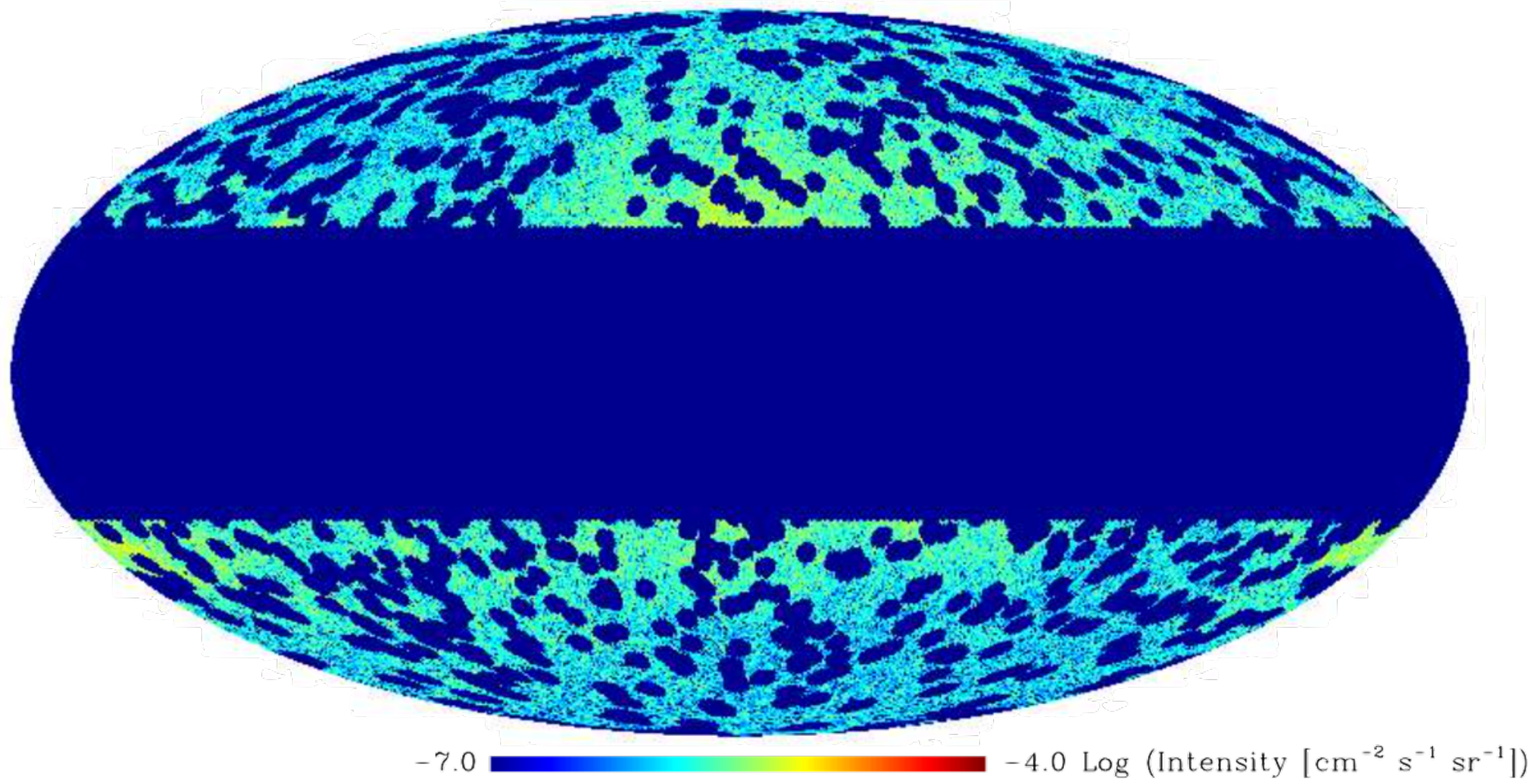
$$\mathrm{ACF}(\theta) = \sum_\ell \frac{2\ell+1}{4\pi} \bar{C}_\ell P_\ell[\cos(\theta)]$$

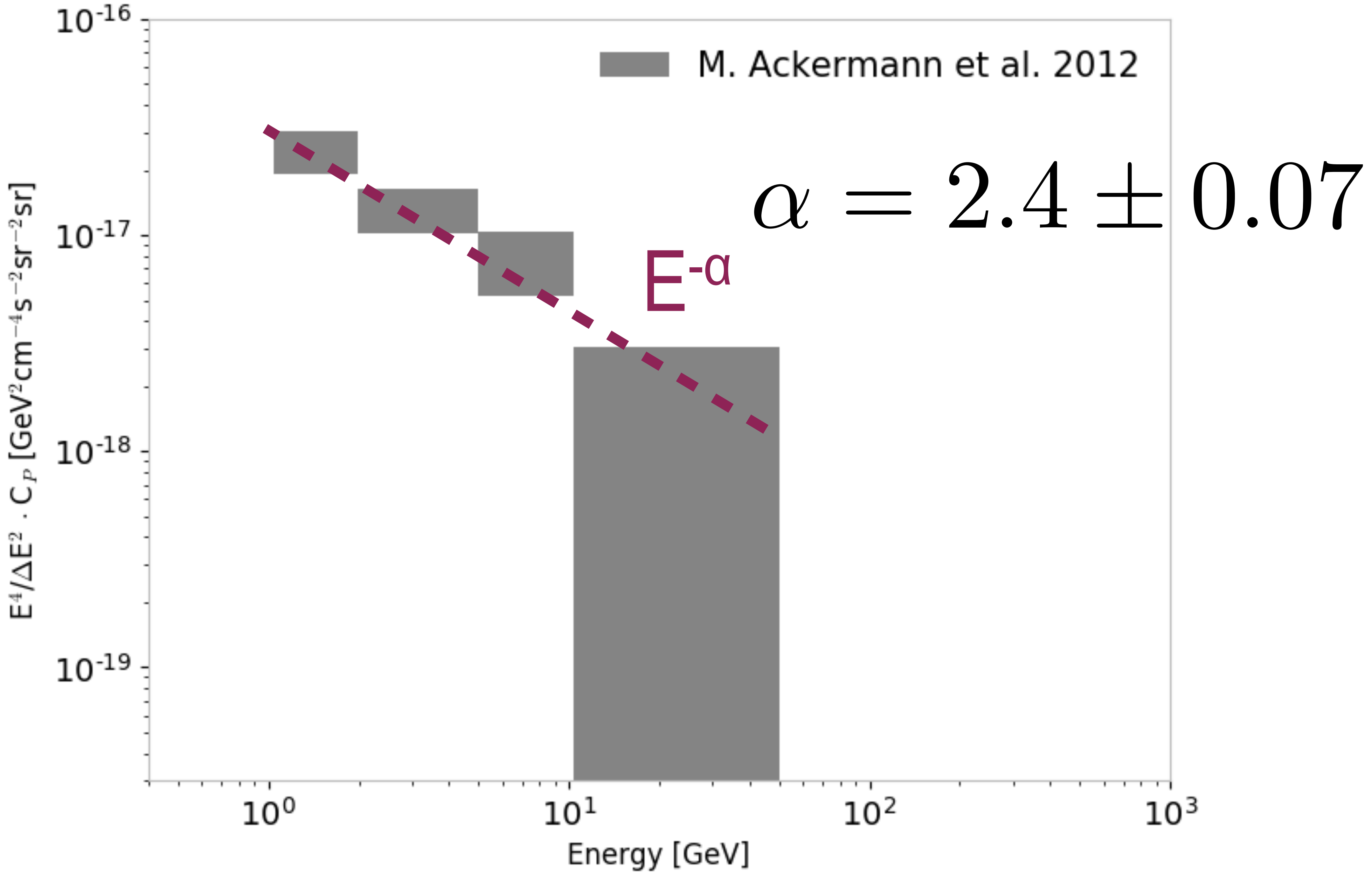
If the anisotropy field is produced by point like-sources:




$C_P$

# Past Measurements - Ackermann et al. 2012




**22 months** (Pass 6)
1-50 GeV (4 bins)
Resolved sources from the **1FGL**

mask correction

APS estimator:

$$C_{\ell,E}^{\text{sig}} = \frac{C_\ell^{\text{raw}}/f_{\text{sky}} - C_N}{W_{\ell,E}^2}$$

White noise correction

PSF correction

$$C_N = \frac{\langle N_{\gamma,pix} \rangle}{\Omega_{pix} \langle A_{pix}^2 \rangle}$$

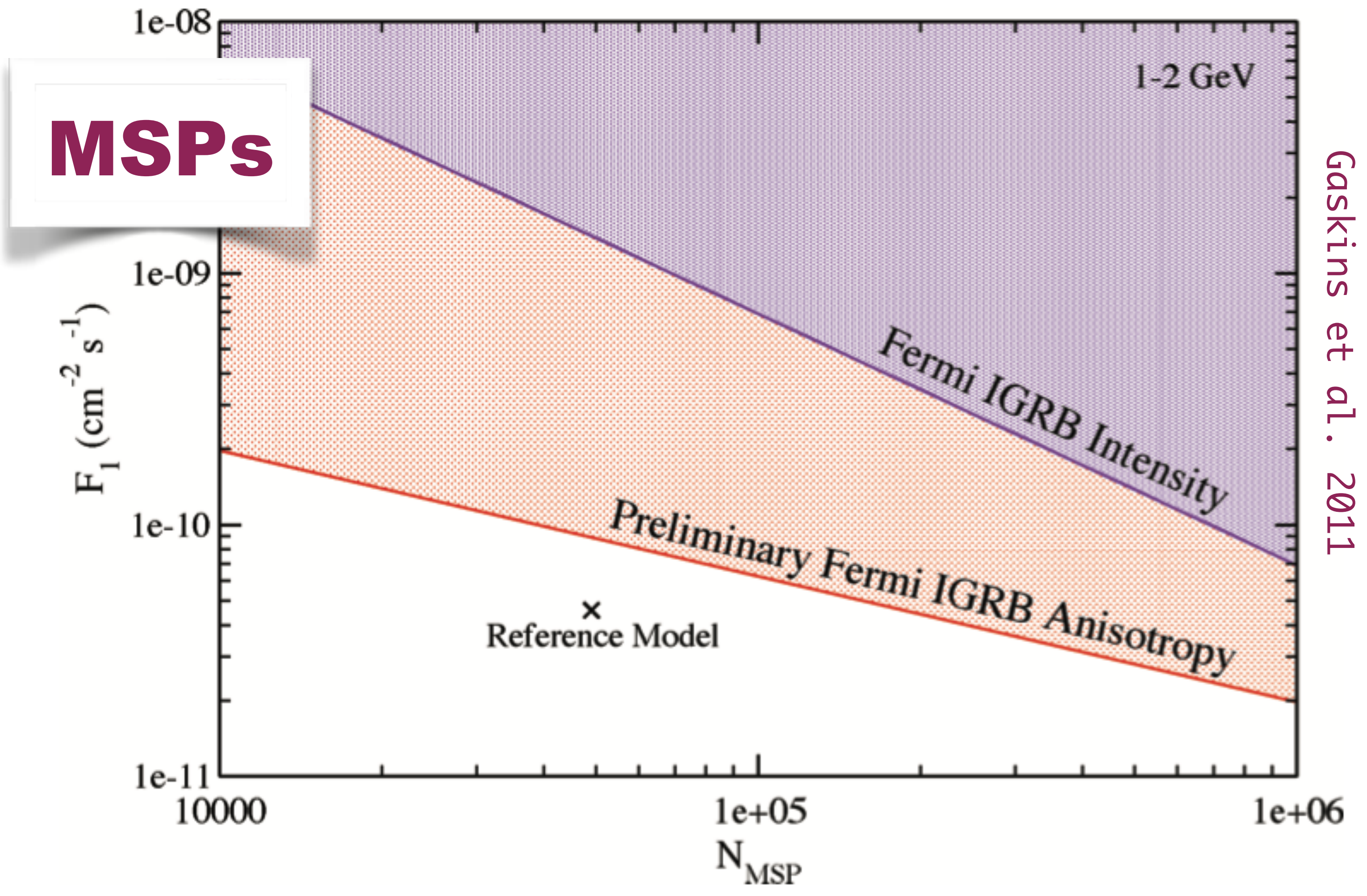
**2) Noise-dominated probe!**

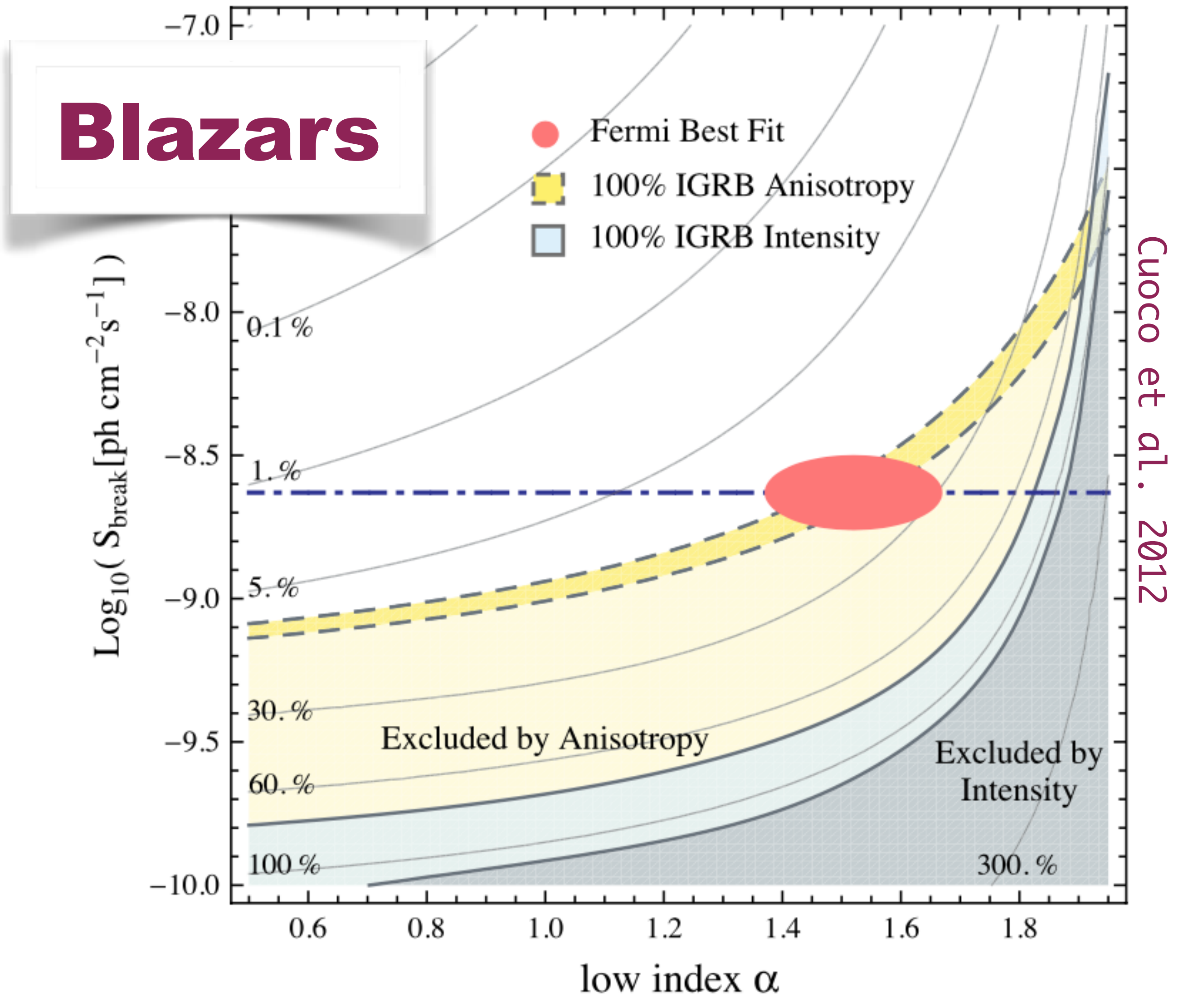
$$W_l^{beam}(E) = 2\pi \int_{\theta_{min}}^{\theta_{max}} P_l(cos\theta) PSF(\theta; E) sin\theta d\theta$$

Ackermann et al. 2012, arXiv:1202.2856v1

# Past Measurements - Ackermann et al. 2012

Autocorrelation to constrain source populations models:




$$I = \int_0^{S_t} S \frac{dN}{dS} dS$$

$$C_P = \int_0^{S_t} S^2 \frac{dN}{dS} dS$$

**Source count distribution**
(the simplest model: broken power law)

- The majority of anisotropy signal: blazars
- blazars contributes to <20% of the UGRB intensity
- the 80% being due to low-intrinsic-anisotropy component

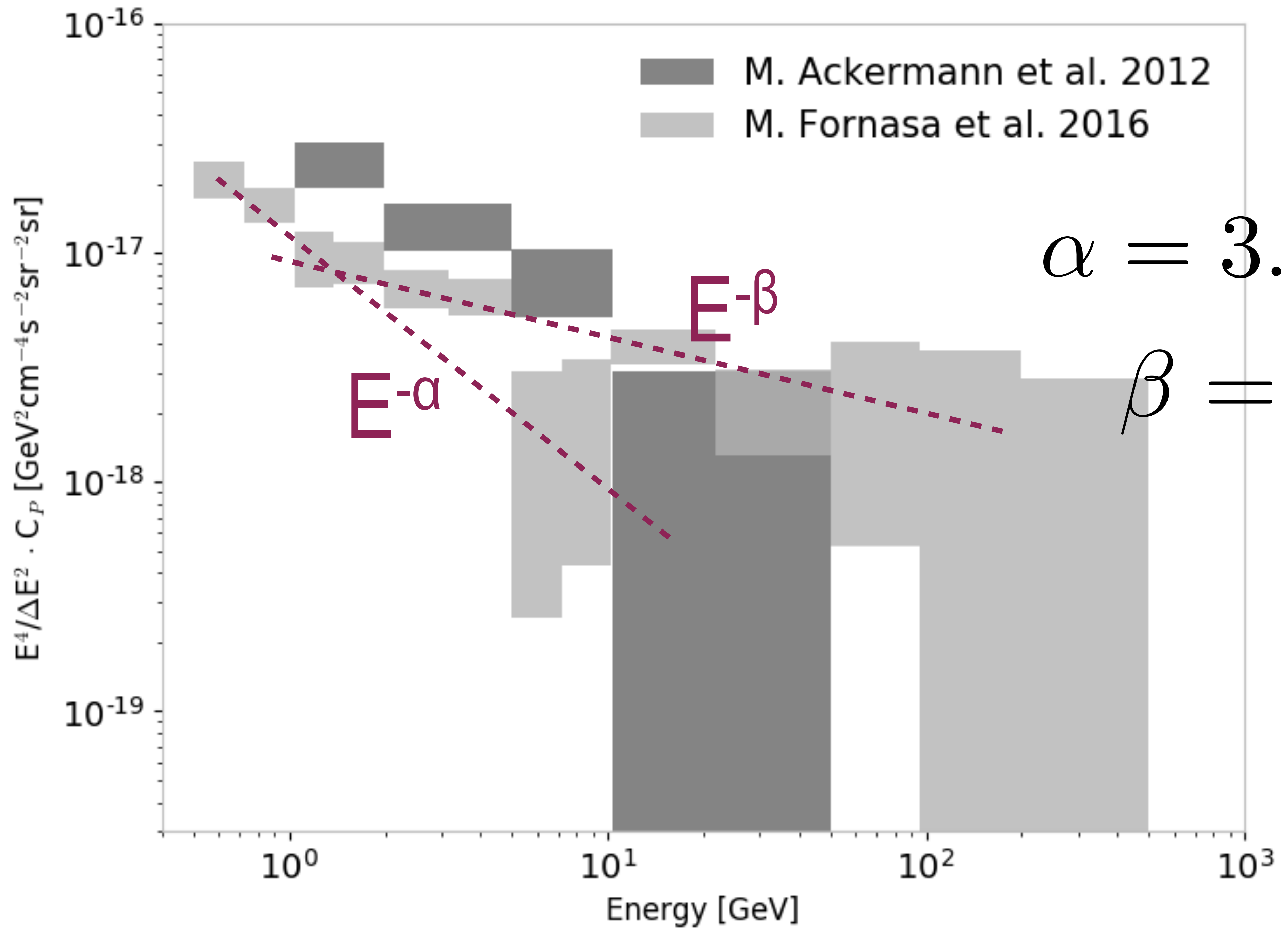
**3) UGRB species do not contribute to intensity and to anisotropy at the same extent!**

Zeclin et al. 2016,arXiv:1605.04256v2
Cuoco et al. 2012, arXiv:1701.06988v1

# Past Measurements - Fornasa et al. 2016

**82 months** (Pass 7)
0.5-500 GeV (13 bins)
Resolved sources from the **3FGL**

**Indications (95% CF) of a double population**

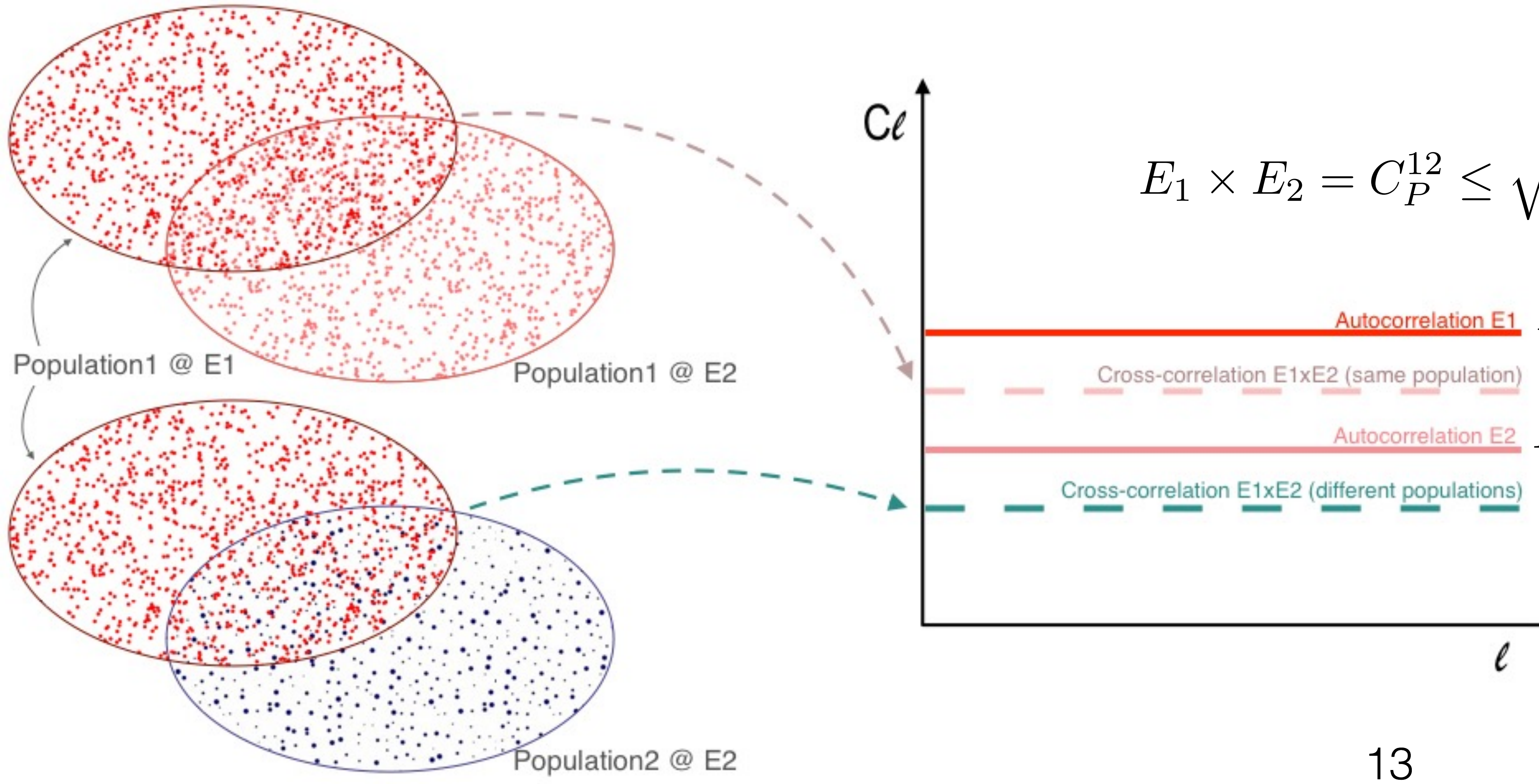



**Very steep!!**

$$\alpha = 3.3 \pm 0.7$$

$$\beta = 2.2 \pm 0.04$$

Cross-correlation between E bins:

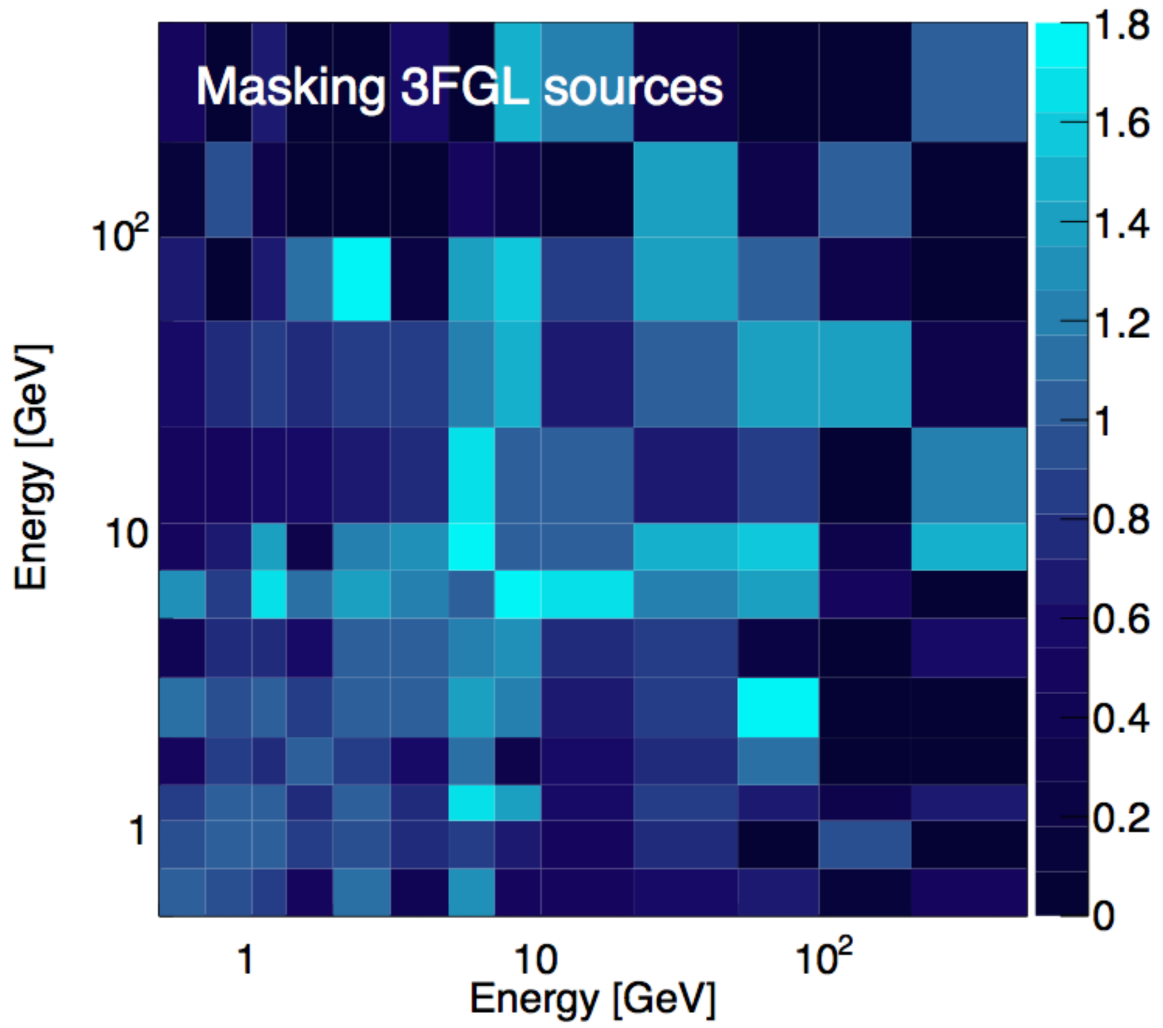



$$E_1 \times E_2 = C_P^{12} \leq \sqrt{C_P^{11} C_P^{22}}$$

$$E_1 \times E_1 = C_P^{11}$$

$$E_2 \times E_2 = C_P^{22}$$

Fornasa et al. (2015)

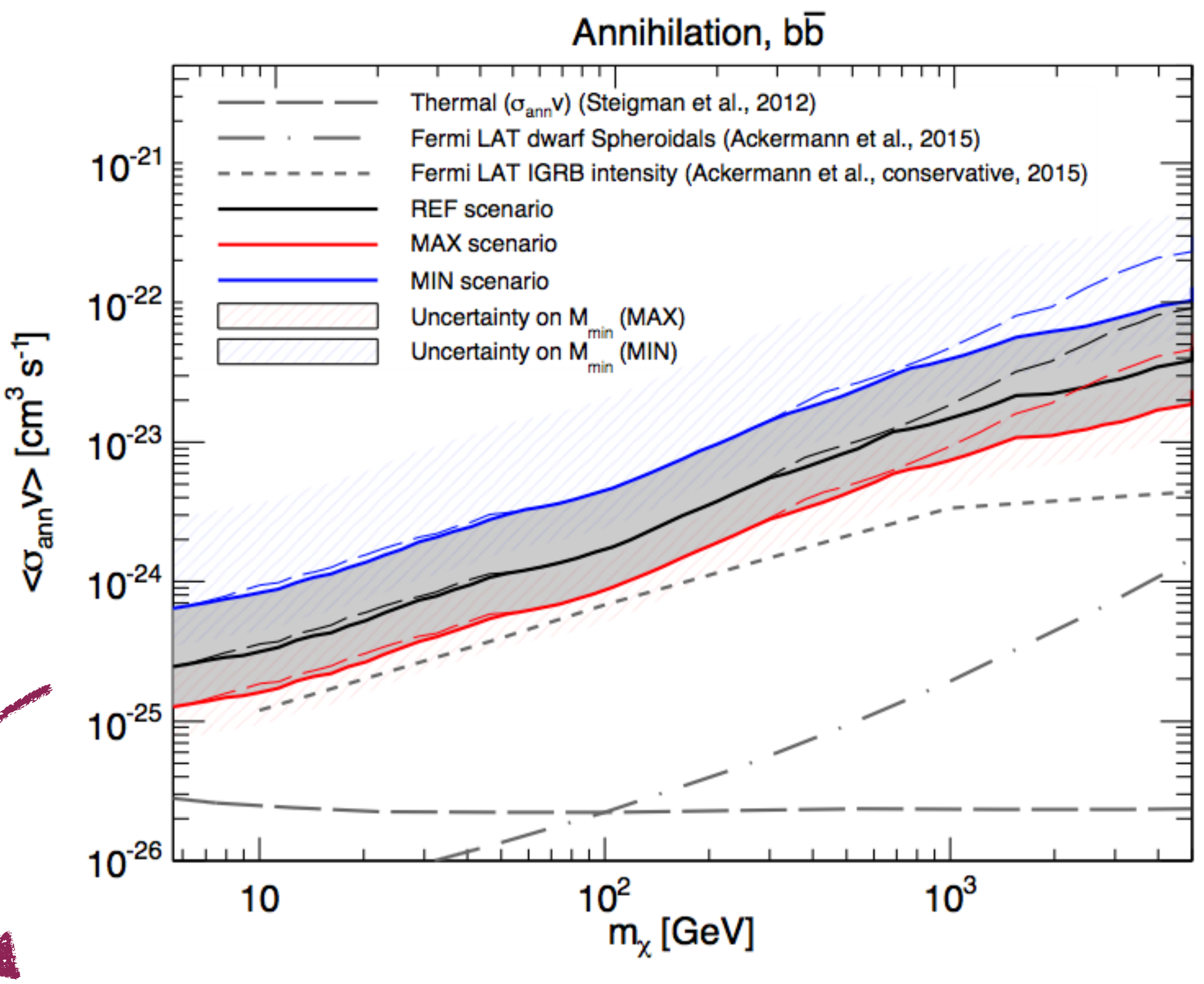


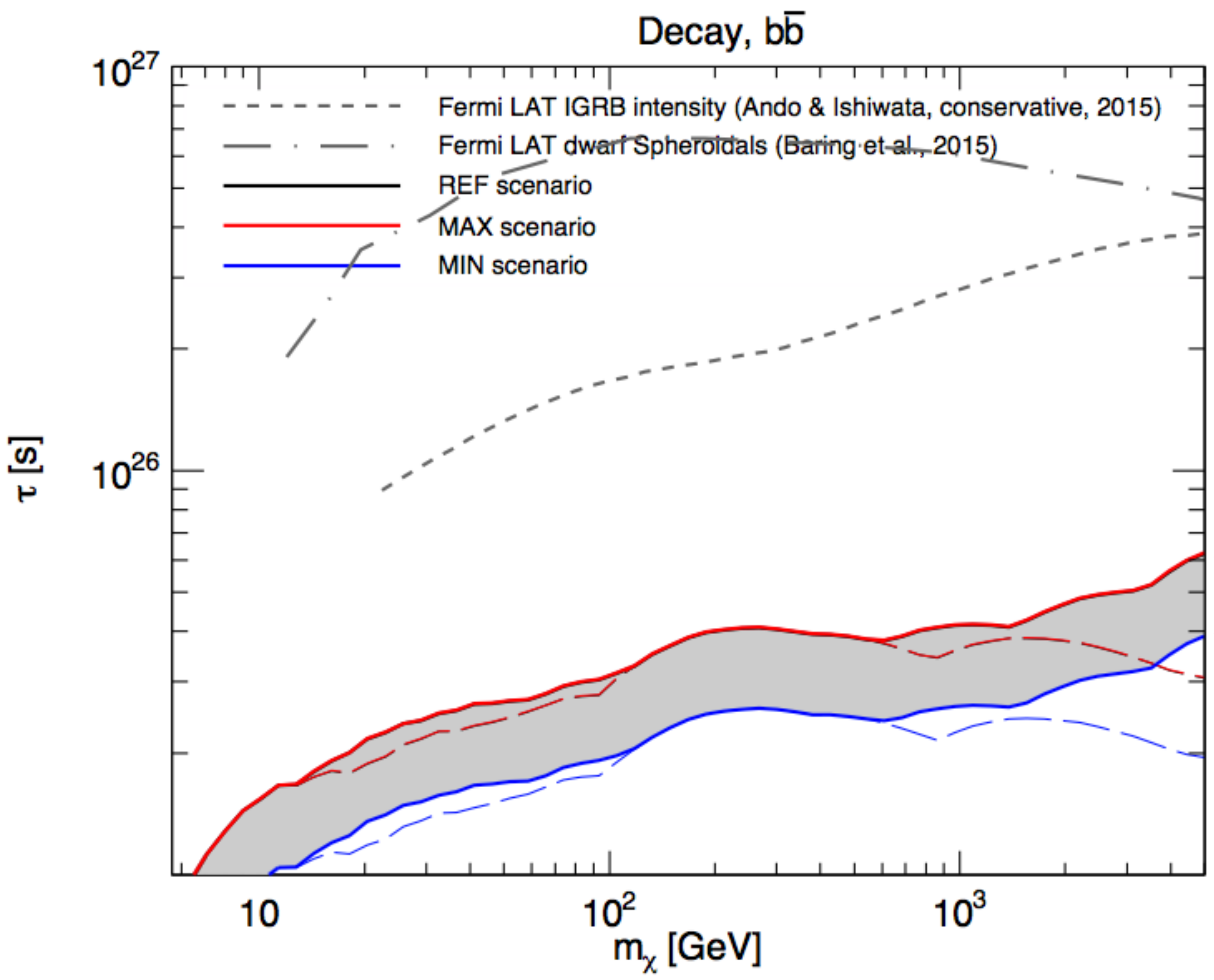

Fornasa et al. 2016, arXiv:1608.07289v2

# Past Measurements - Fornasa et al. 2016

Autocorrelation to constrain WIMP-like DM parameters:

Conservative exclusion limits on annihilating and decaying DM from the new APS measurement by Fornasa et al. 2016




Fornasa et al. (2015)

**Less stringent than UGRB spectrum limit by factor of 2**

Fornasa et al. 2017, arXiv:1608.07289v2

# Current measurement*

* see poster n. 78

** see poster n. 108

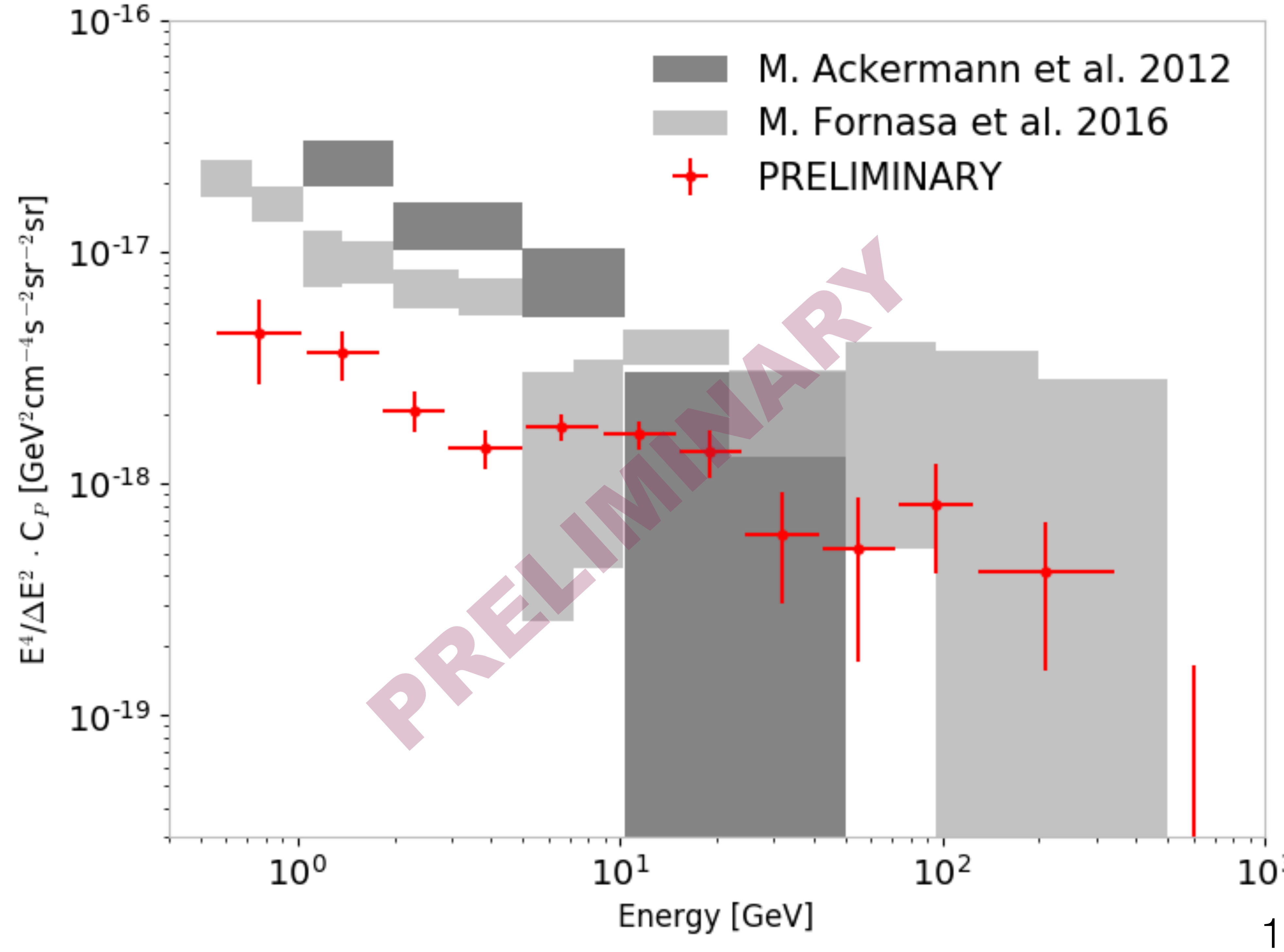
**8 years** (Pass 8 P305)
**SOURCEVETO**** class

0.5-1000 GeV (12 bins)
**FL8Y + 3FHL**

New APS estimator:

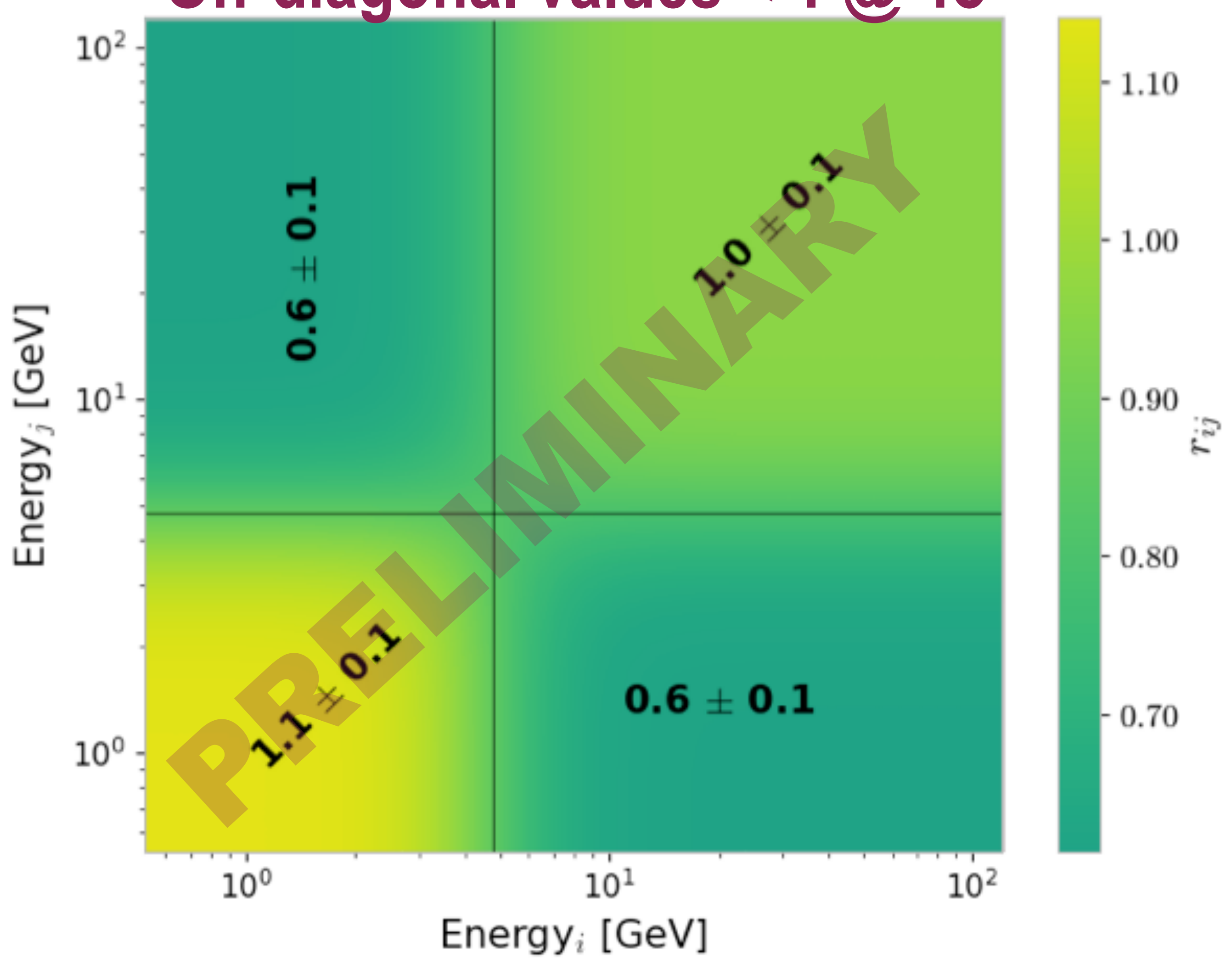
$$C_l^{sig}(l) = \frac{N}{N-1} \sum_{\substack{\alpha,\beta \\ \alpha \neq \beta}} \frac{C_l^{\alpha\beta,PolSpice}(l)}{W_{E_\alpha}(l) W_{E_\beta}(l)}$$

Exploits cross-correlations between adjacent micro energy bins: not affected by noise!




## Double population at 99.98% CL

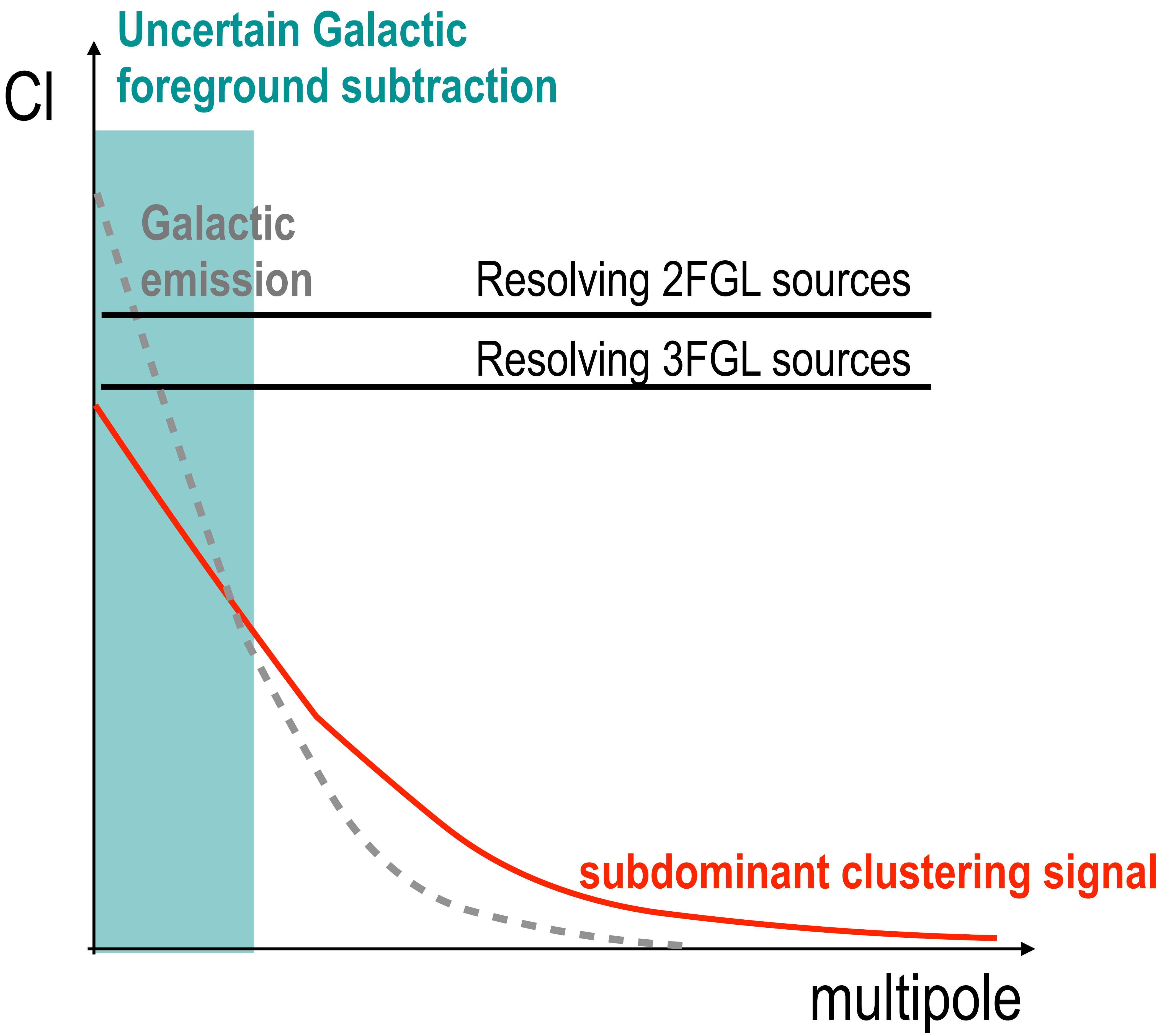
Off-diagonal values < 1 @ 4σ



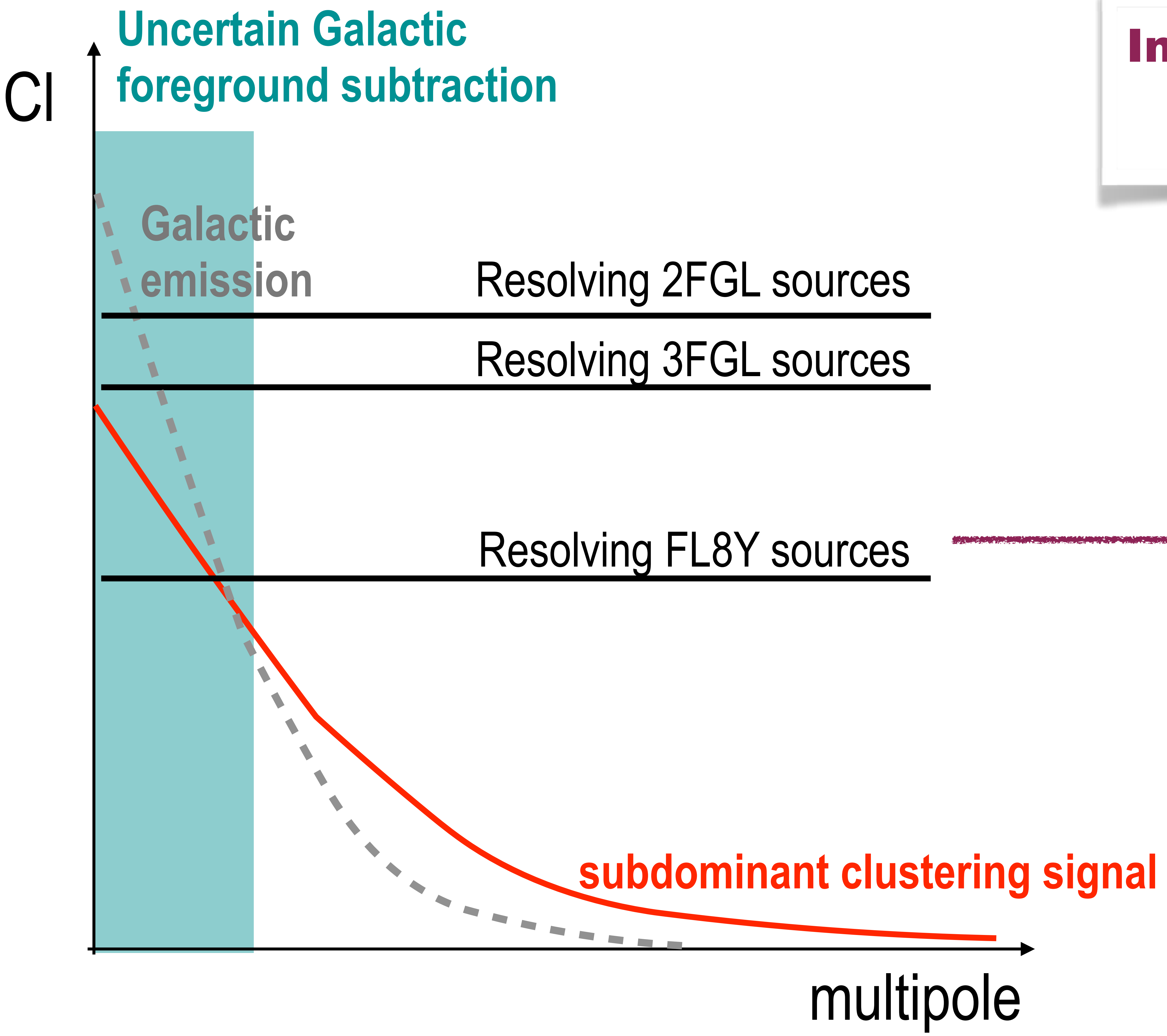

* Submitted to Physical Review

8th International Fermi Symposium
October 14-19, 2018 - Baltimore, MD
- Michela Negro -

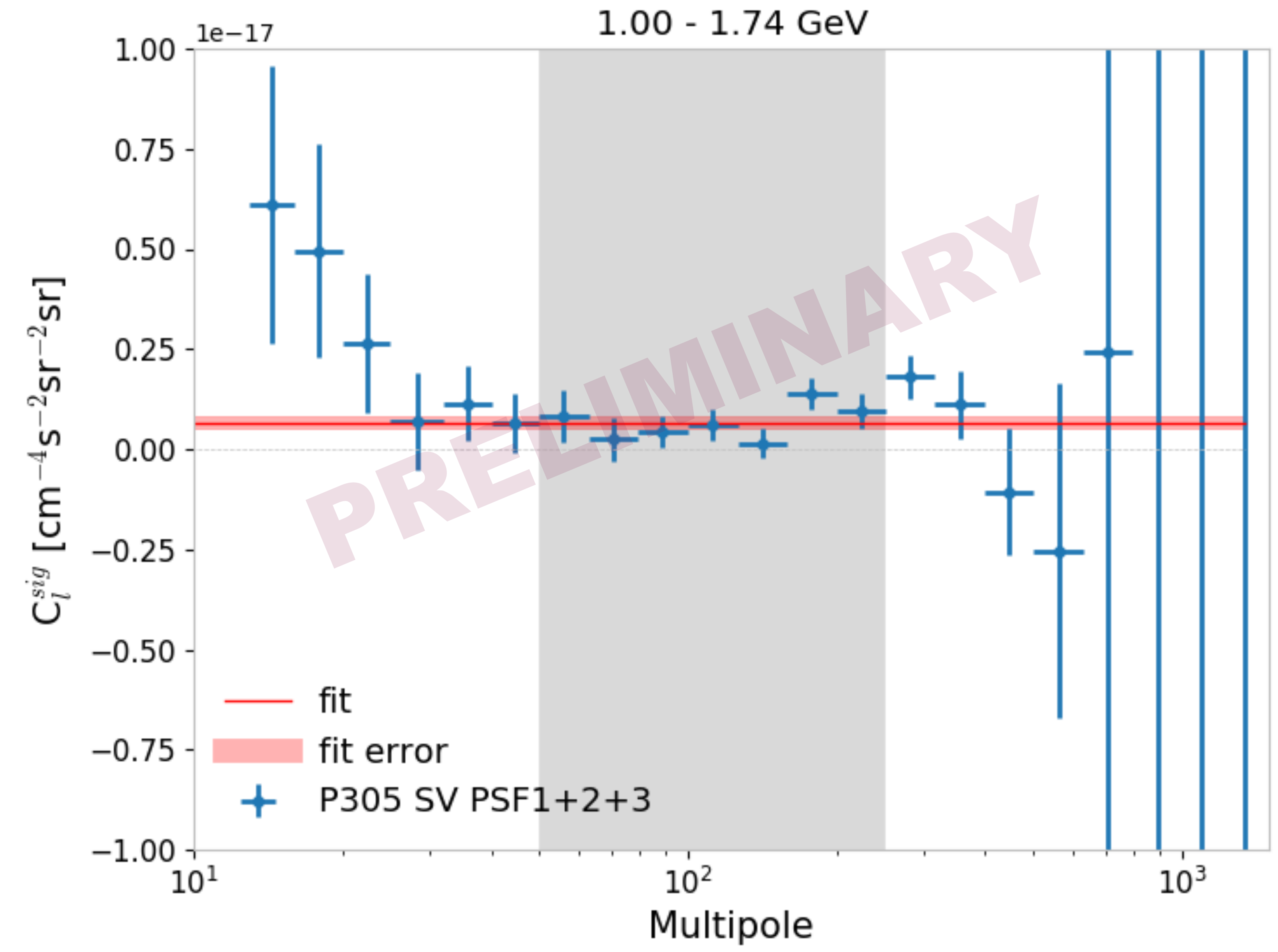
# Future developments - Autocorrelations: beyond the $C_P$



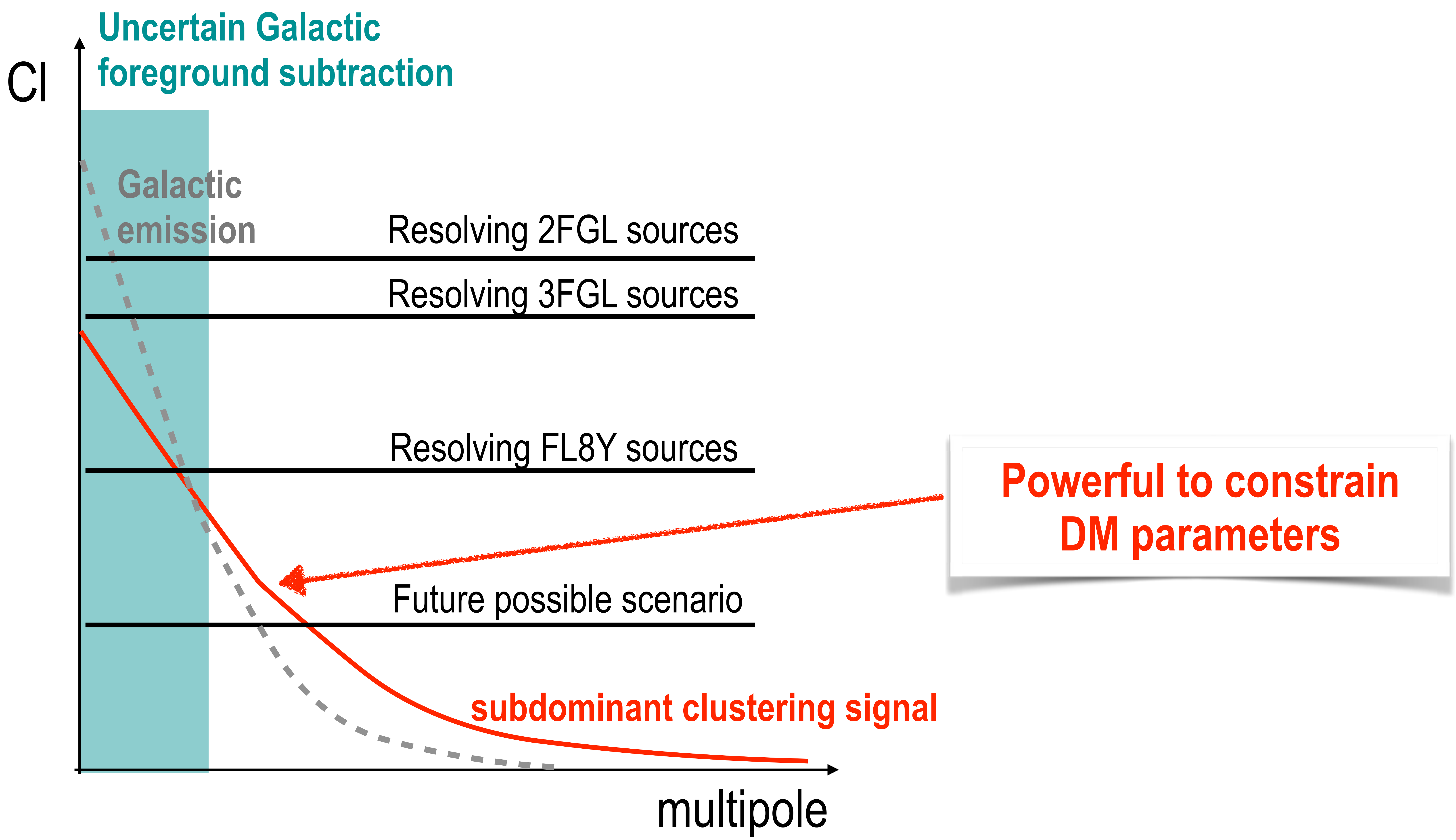
# Future developments - Autocorrelations: beyond the $C_P$



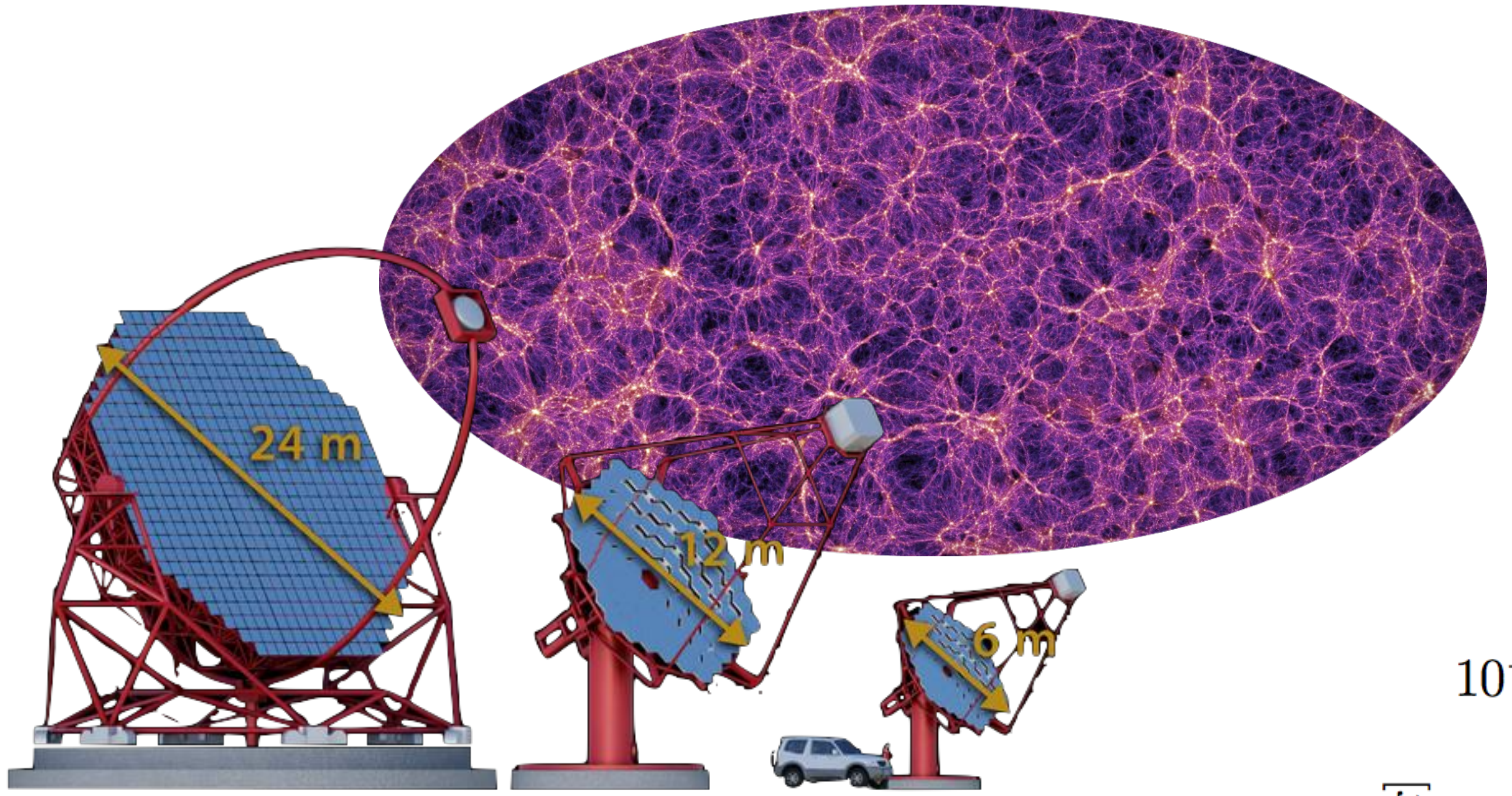

**Imperfect knowledge of Galactic foreground and unresolved signal still dominated by shot noise of point-like sources**

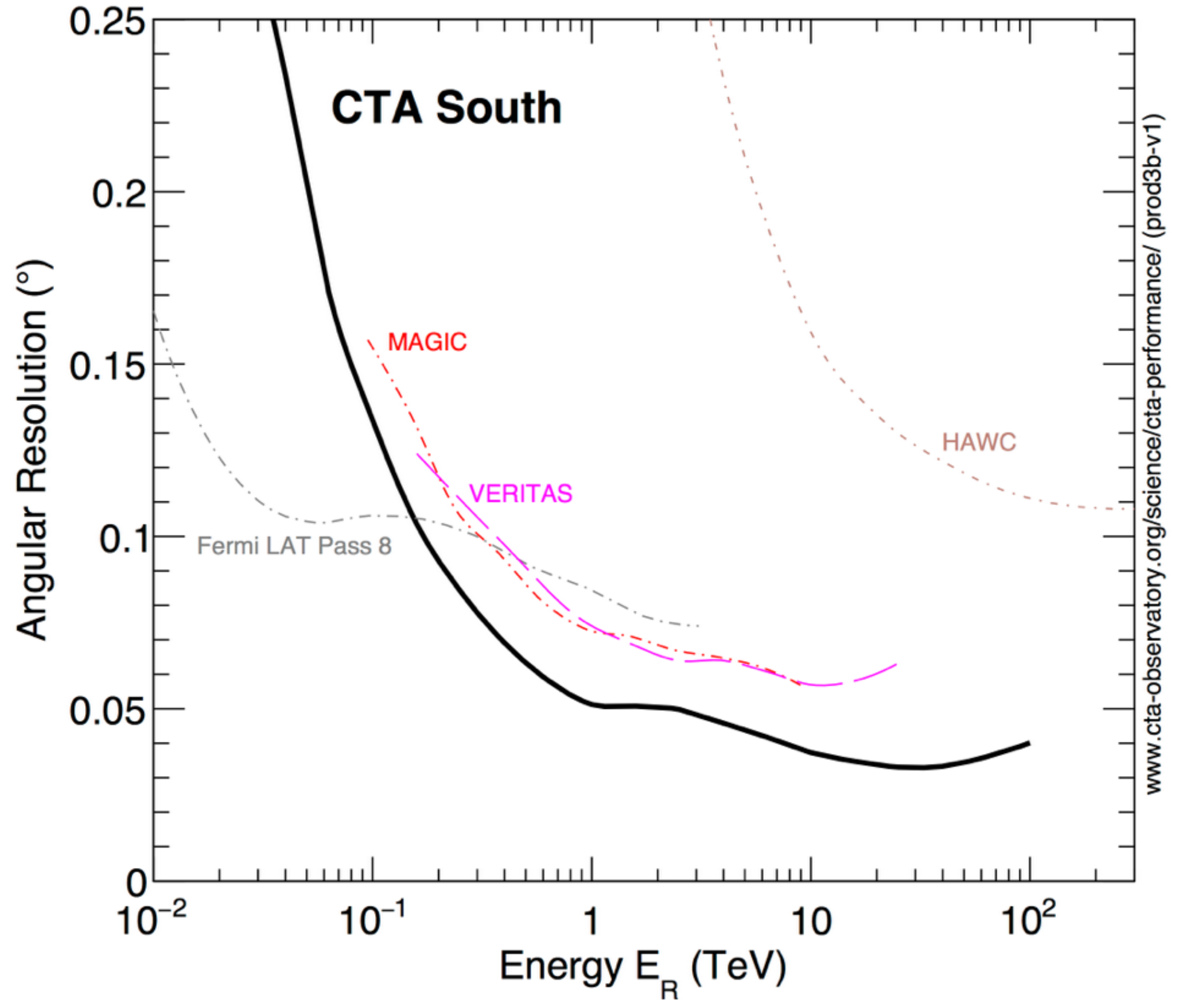


# Future developments - Autocorrelations: beyond the $C_P$



# When CTA will join the effort at TeV energy...

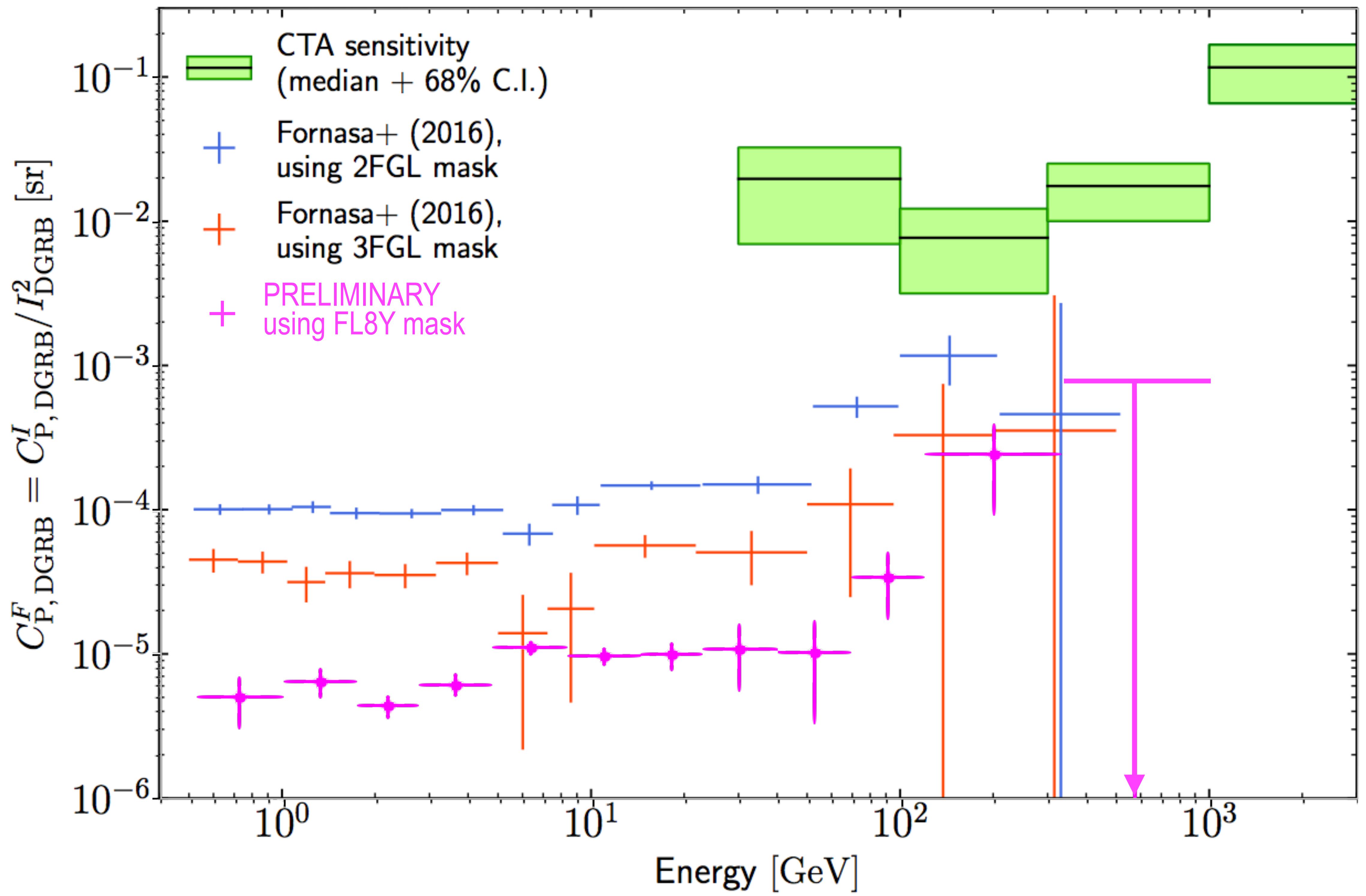



[Hütten & Maier 2018]
Calculation of CTA sensitivity to small-scale anisotropy

Instrumental performance of southern CTA:
- 4 Large-Size Telescopes (LSTs),
- 25 Mid-Size Telescopes (MSTs),
- 70 Small-Size Telescopes (SSTs)

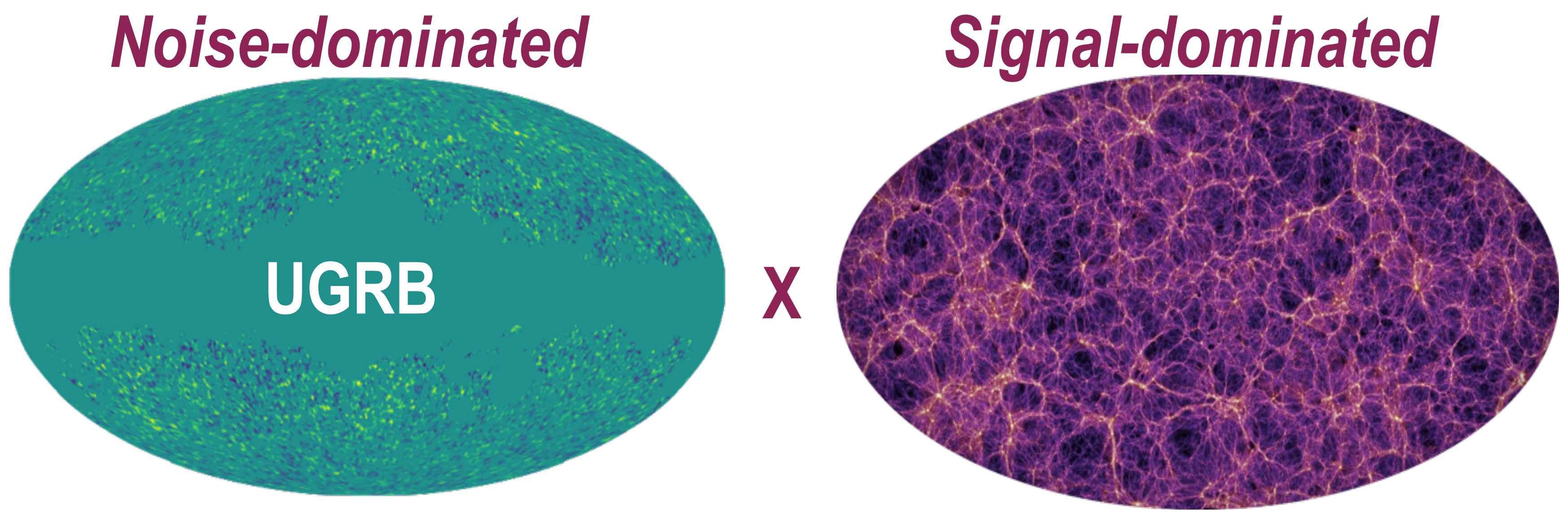
Hütten & Maier 2018



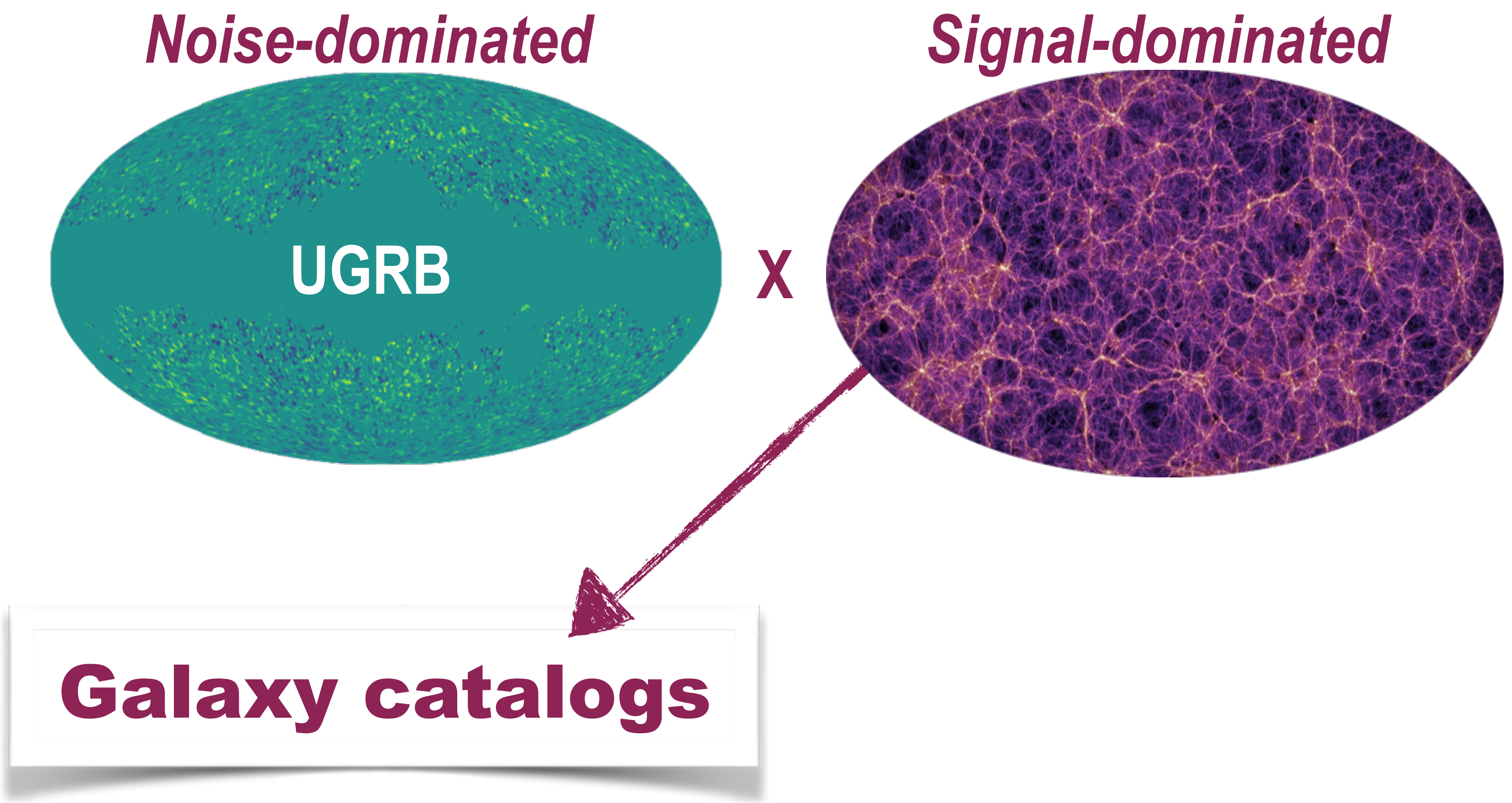

Hütten & Maier 2018, arXiv:1806.01839v1

# UGRB anisotropy characterisation through cross-correlations *

* see talk by Horiuchi (diffuse splinter)

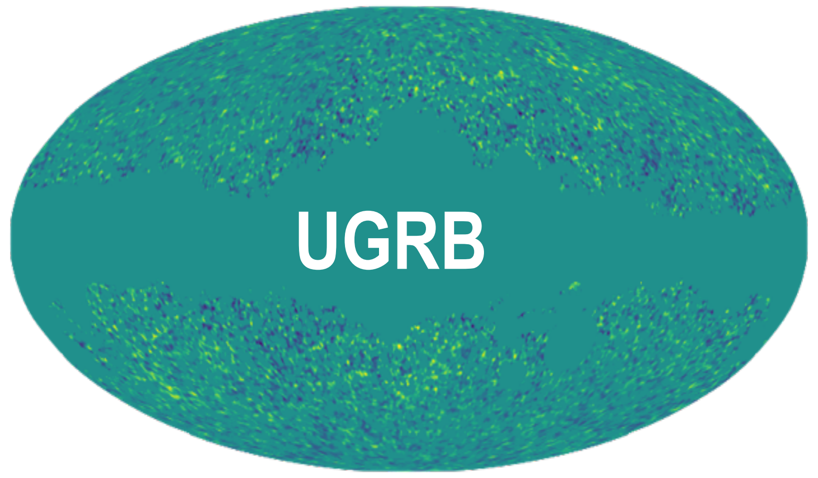


# UGRB anisotropy characterisation through cross-correlations



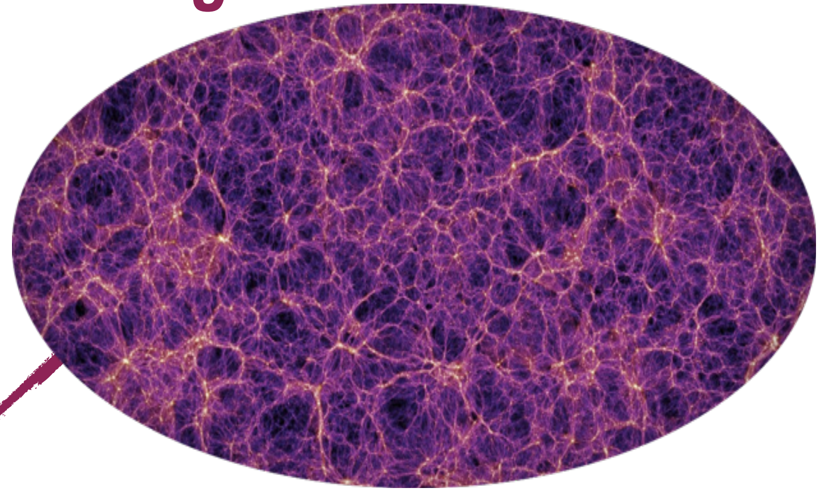
# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated*




X

*Signal-dominated*

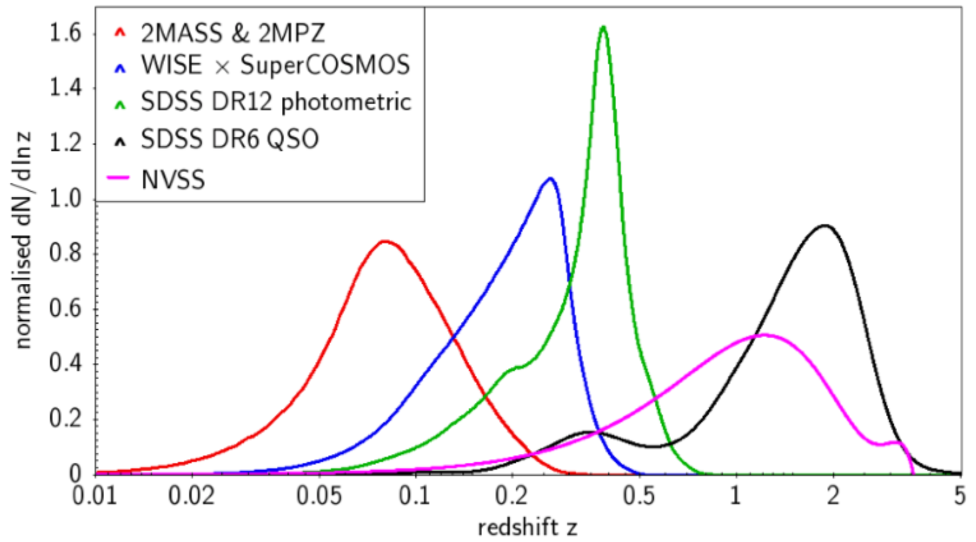


**Galaxy catalogs**

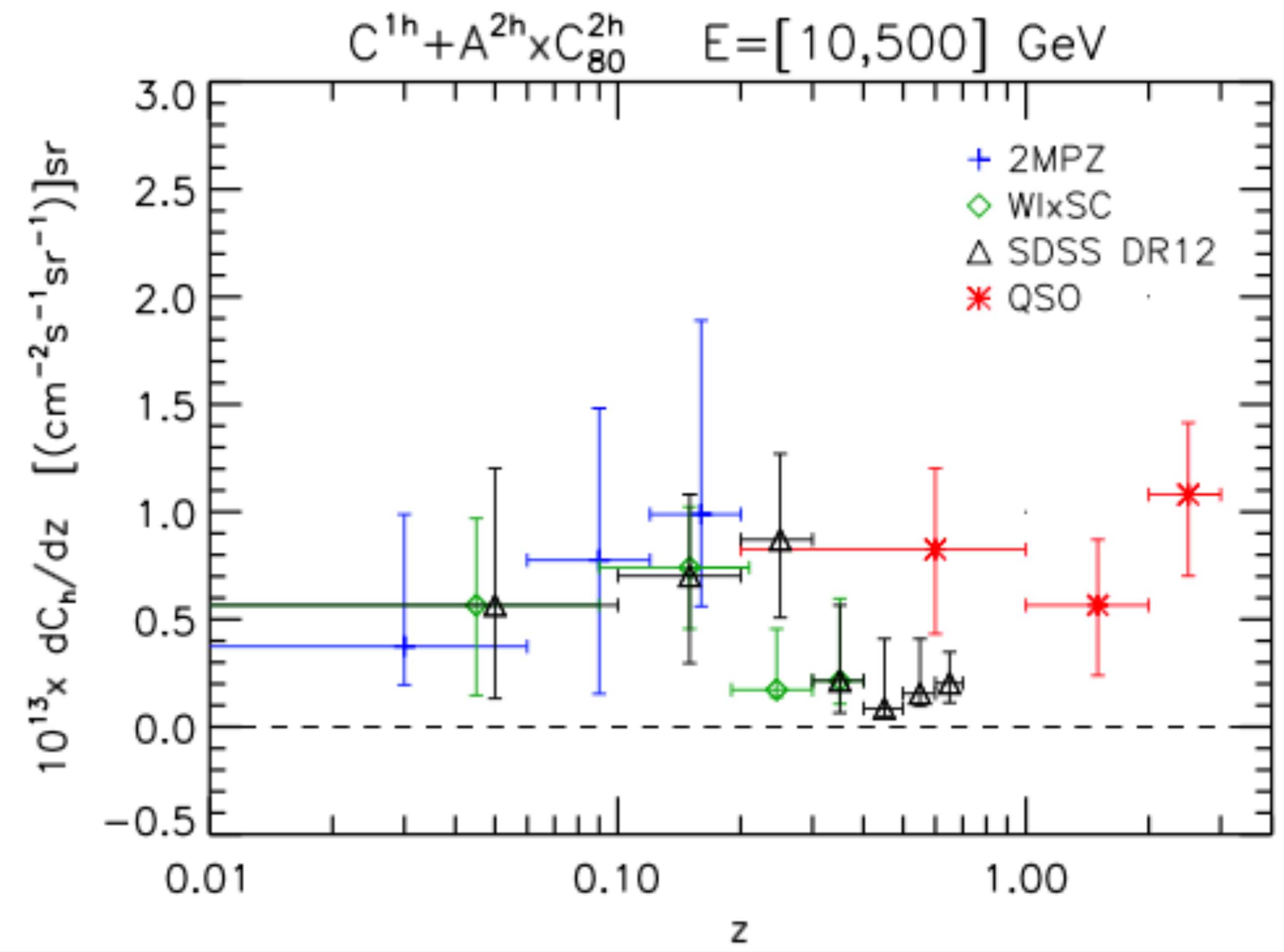
Investigated surveys with **spectral** (E) and **tomographic** (z) approach:

[Cuoco et al. 2017]

- **NVSS**
- **WISExSuperCOSMOS**
- **2MPZ**
- **SDSS DR12**
- **SDSS DR6 QSO**




Cuoco et al. 2017




Cuoco et al. 2017

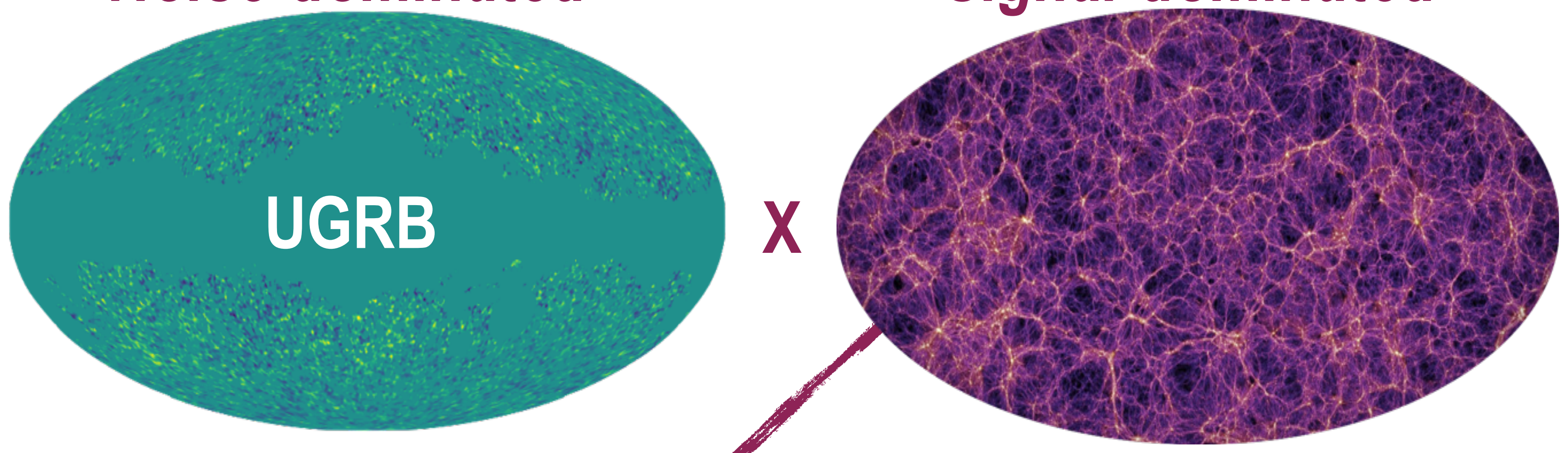
**~Very high significance signal (up to 10 σ for NVSS)**

Signal varies with redshift:
**UGRB produced by different types of sources**

Xia et al. 2011, arXiv:1103.4861v2
Xia et al. 2015, arXiv:1503.05918v1
Cuoco et al. 2017, arXiv:1709.01940v1

# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated* *Signal-dominated*

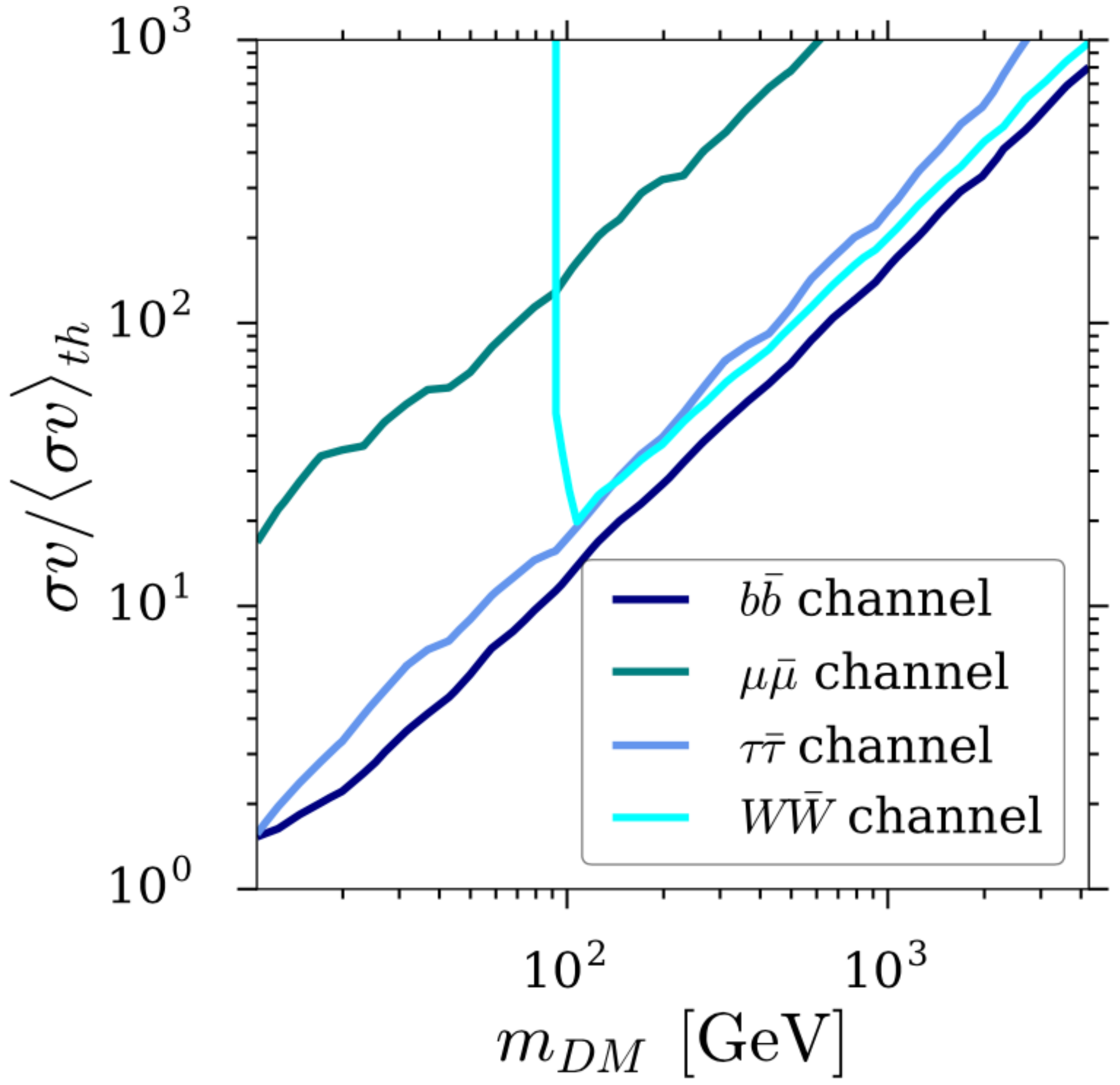



**Galaxy catalogs**

Beyond the **tomographic** approach for **2MPZ** catalog:

[Ammazzalorso et al. 2018 (Arxiv)]

- **redshift slicing (3 bins)**
- **B-band** luminosity slicing:
  **traces the star formation activity**
- **K-band** luminosity slicing:
  **correlates with objects mass**
- **High K - low B** (high masses + low level of star formation)**:**
  **traces DM (WIMP)**

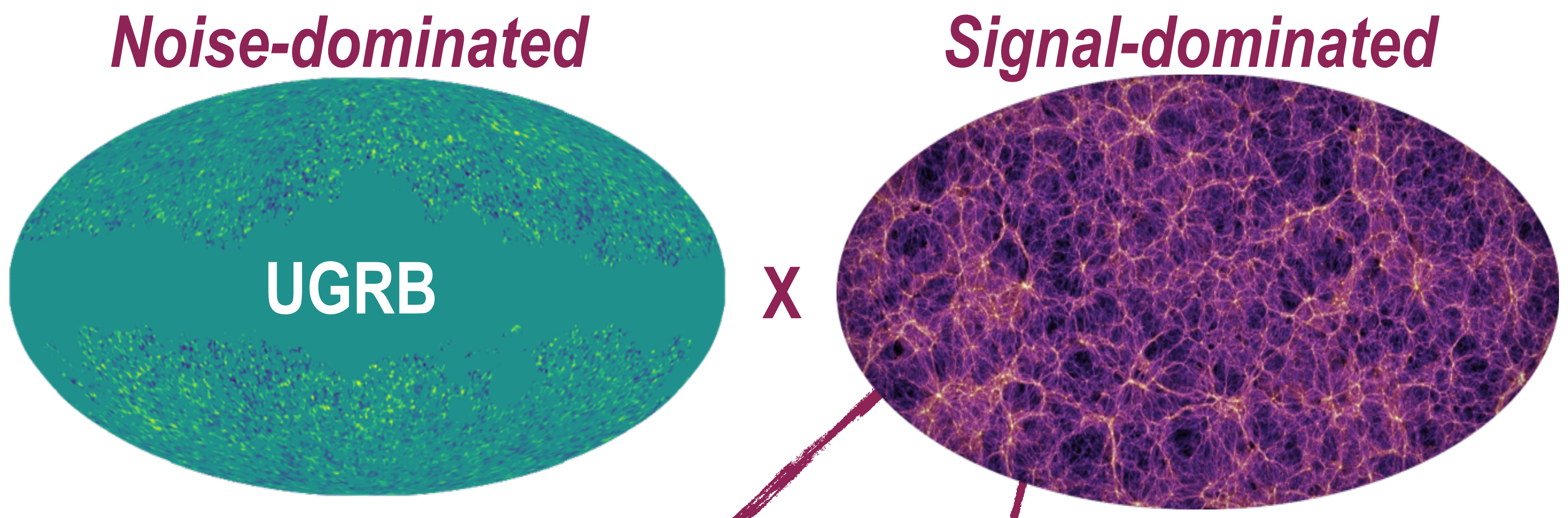



**z < 0.2**

Signal dominated by **mAGNs** emissions + subdominant contribution from **blazars** and **SFGs**

Ammazzalorso et al. 2018, arXiv:1808.09225v1

# UGRB anisotropy characterisation through cross-correlations




**Galaxy catalogs**

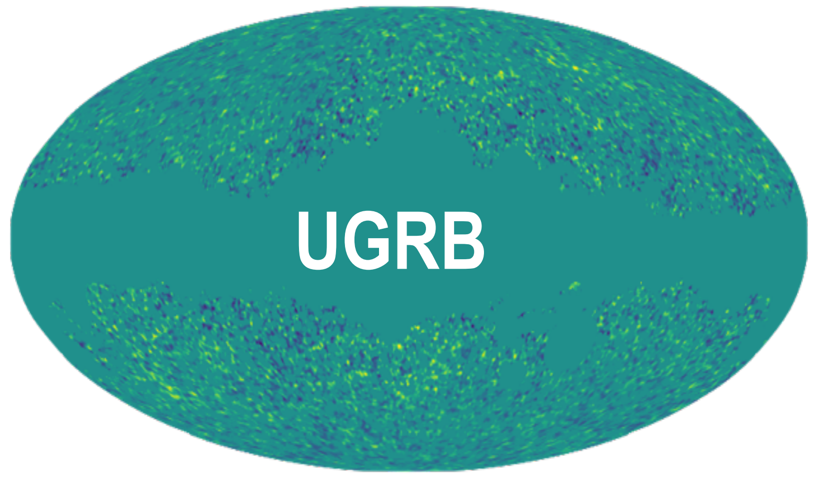
- Different types of sources
- Signal evolves with z
- AGNs +
  blazar + SFG (subdominant)

**Clusters**

Galaxies, hot highly ionized gas, DM, Relativistic CRs

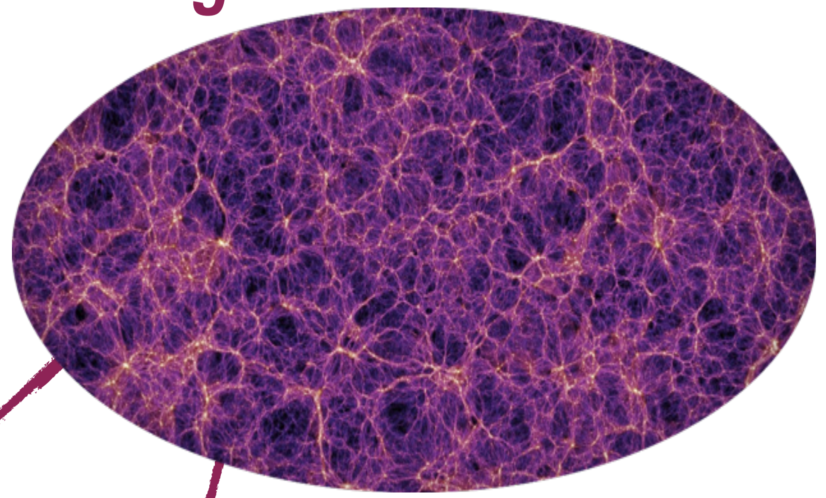
# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated*




x

*Signal-dominated*



**Galaxy catalogs**

- Different types of sources
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  blazar + SFG (subdominant)

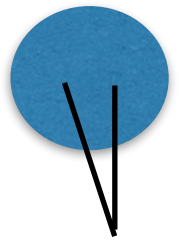
**Clusters**

Galaxies, hot highly ionized gas, DM, Relativistic CRs

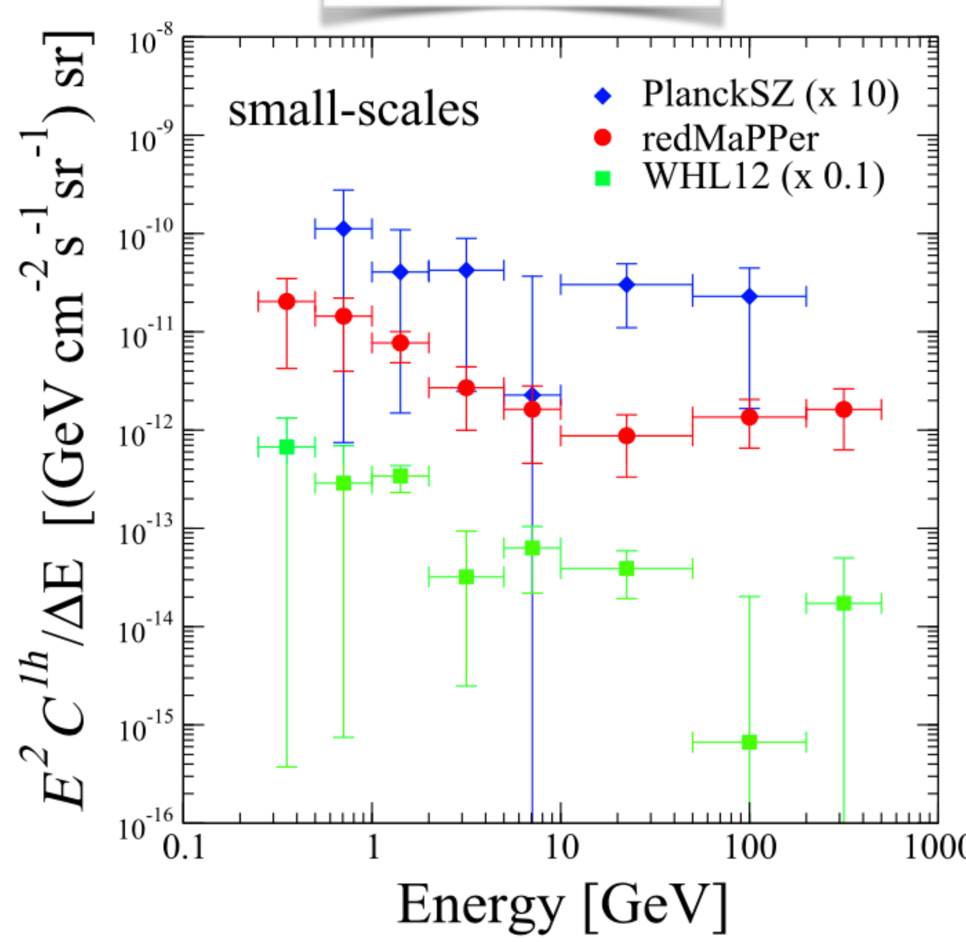
e.g. [Branchini et al. 2017]

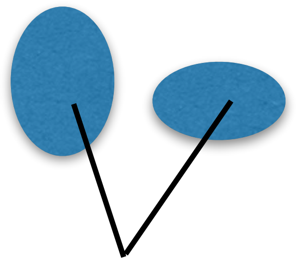
- **WHL12 (158,103 clusters)**
- **redMaPPer (26,350 clusters)**
- **PlanckSZ (1,653 clusters)**

**>3σ signal!**

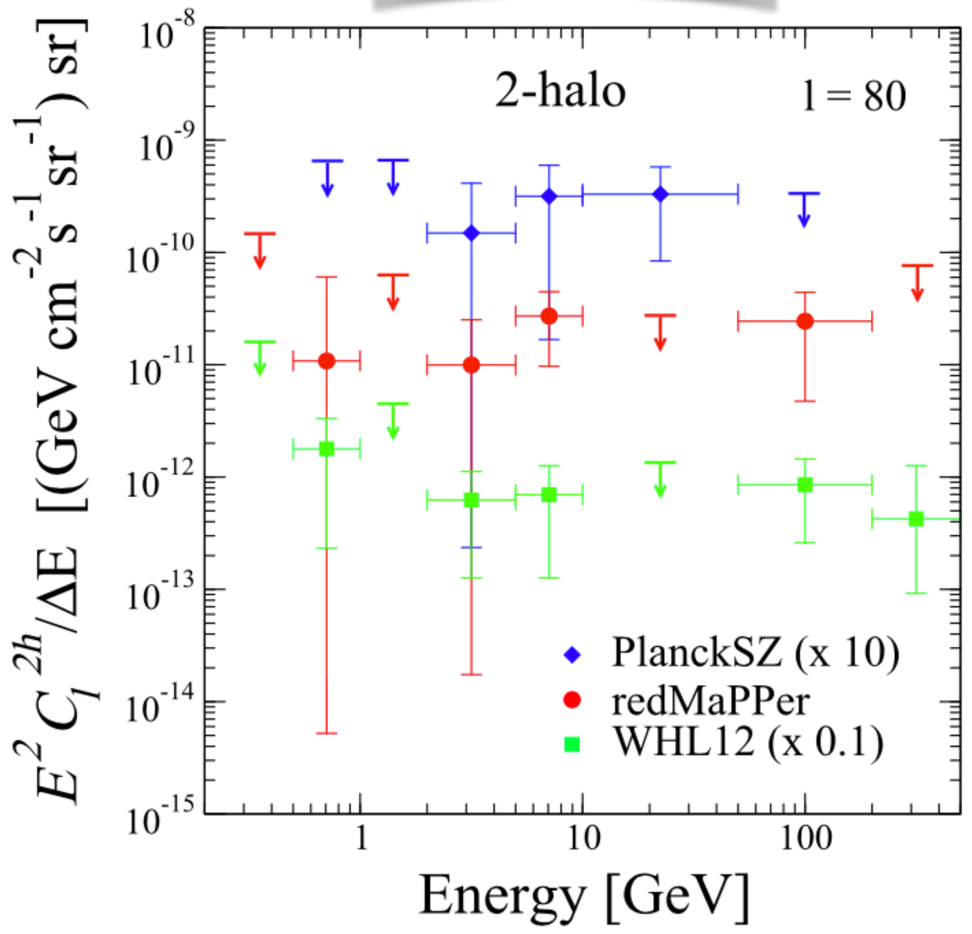


**1-halo term**



**2-halo term**



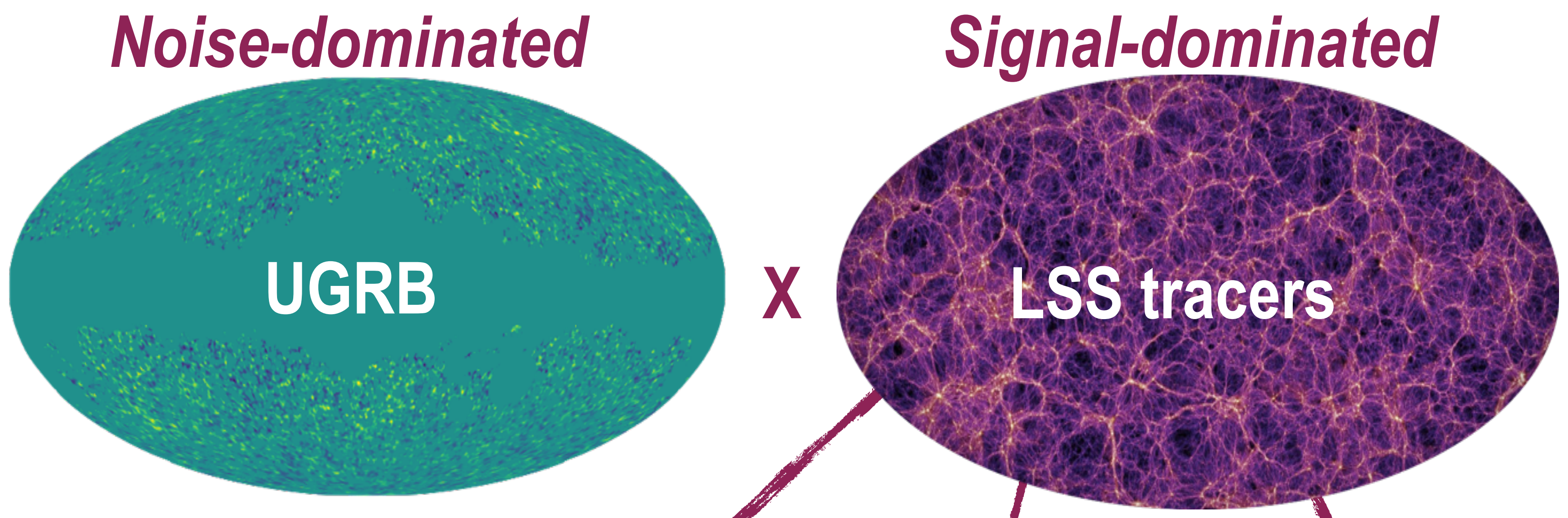

**Small scales:**
hard component (**Blazars?**)
+ soft component
(**mAGN / SFG / …**)

**Large scales:**
hard power law (**Blazars**?)

Constrain the contribution of **Intra-cluster medium** and **DM**

Branchini et al. 2017, arXiv:1612.05788v1

# UGRB anisotropy characterisation through cross-correlations




**Galaxy catalogs**

- Different types of sources
- Signal evolves with z
- AGNs +
  blazar + SFG (subdominant)

**Clusters**

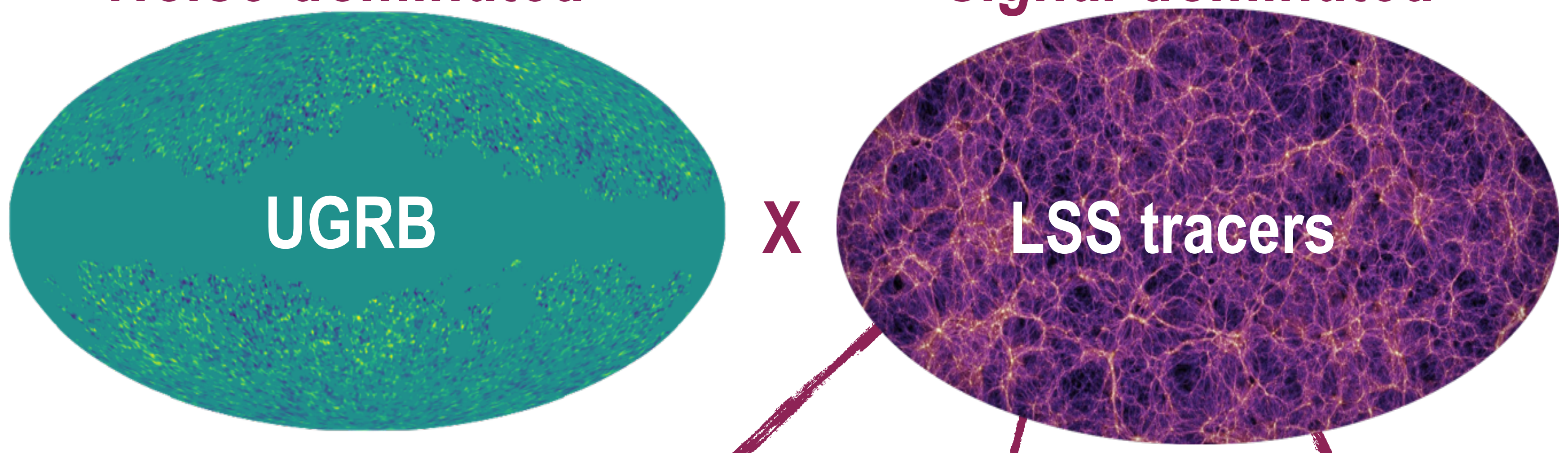
- Large-scale: Blazars-like
- Small-scales: double-component
  - high-energy: Blazars
  - low-energy: SFG/mAGN/…
- Subdominant ICM and annihilating DM

**Cosmic shear**

**Cosmic shear:** statistical measurement of the distortion of images due to the weak lensing

# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated* *Signal-dominated*

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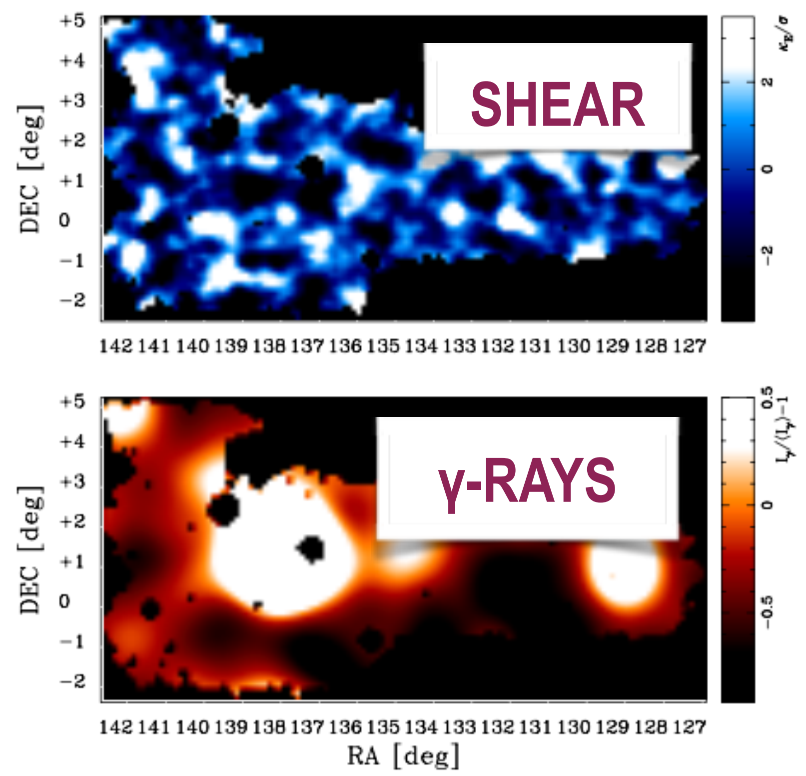
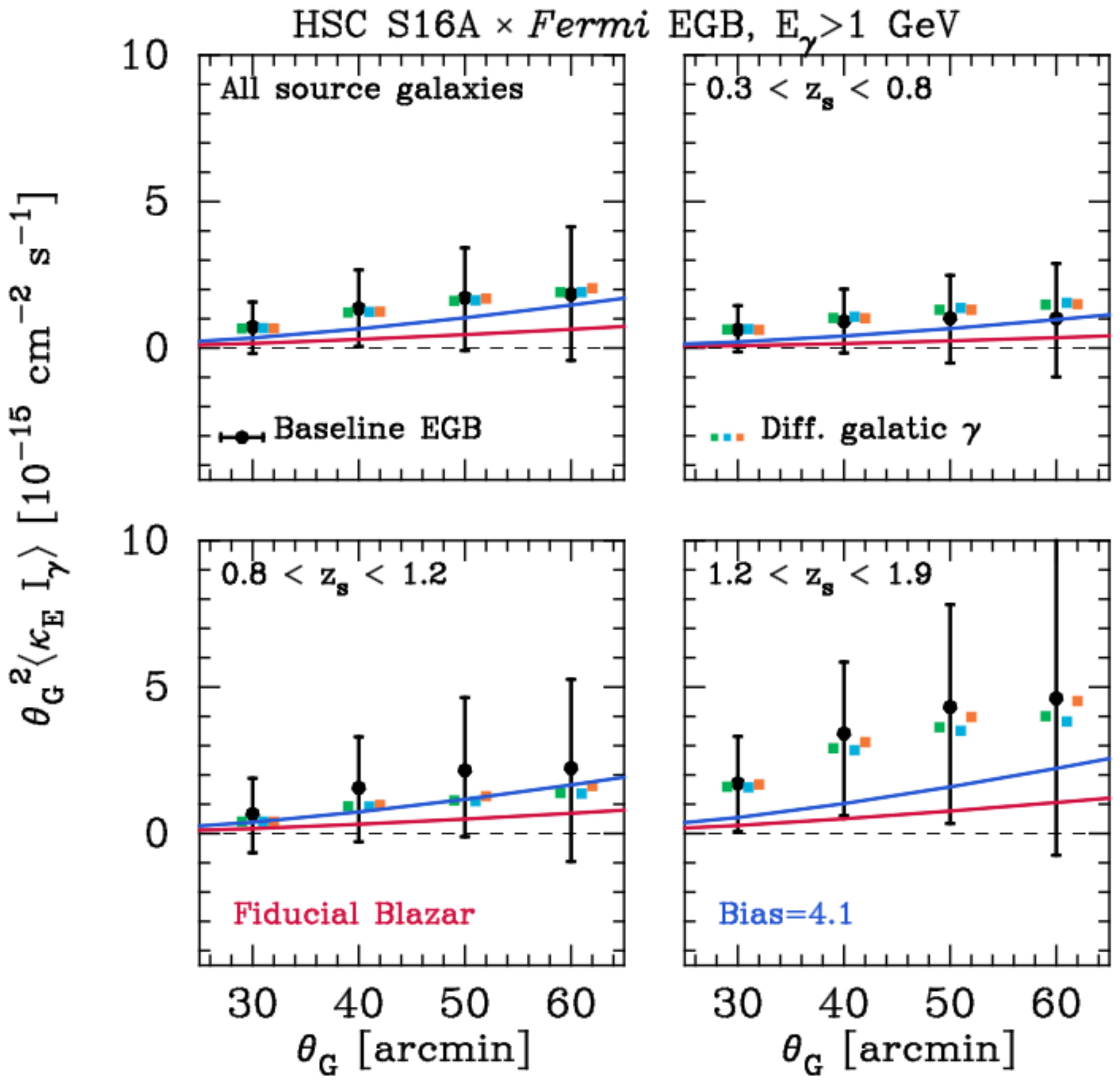
## Cosmic sh

Investigated surveys with **spectral** and **tomographic** approach (proposed by Camera et al. 2013/2015):

- **CFHTLenS + RCSLenS + KiDs** [Troster et al. 2017]
- **Subaru Hyper Suprime-Cam** [Shirasaki et al. 2018]




Shirasaki et al.



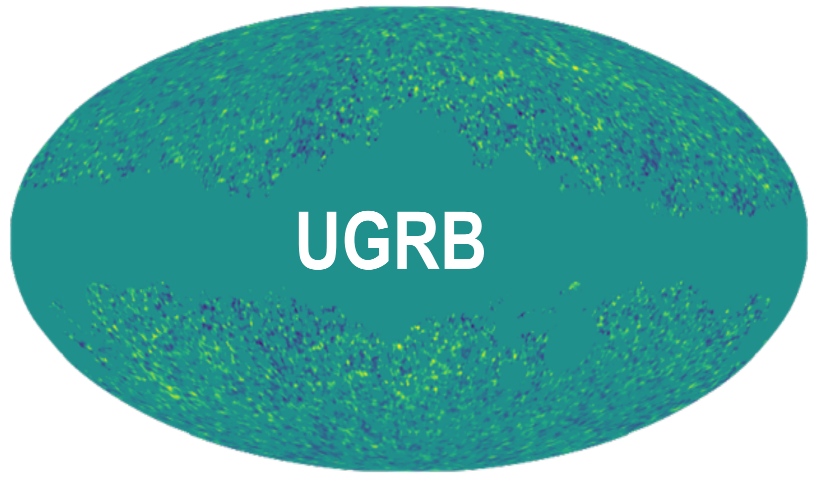

Shirasaki et al. 2018

**no signal detected!**

Hashimoto et al. 2018, arXiv:1805.08139v1
Troster et al. 2017, arXiv:1611.03554v2
Shirasaki et al. 2018, arXiv:1802.10257v2
Camera et al. 2013, arXiv:1212.5018v2
Camera et al. 2015, arXiv:1411.4651v2

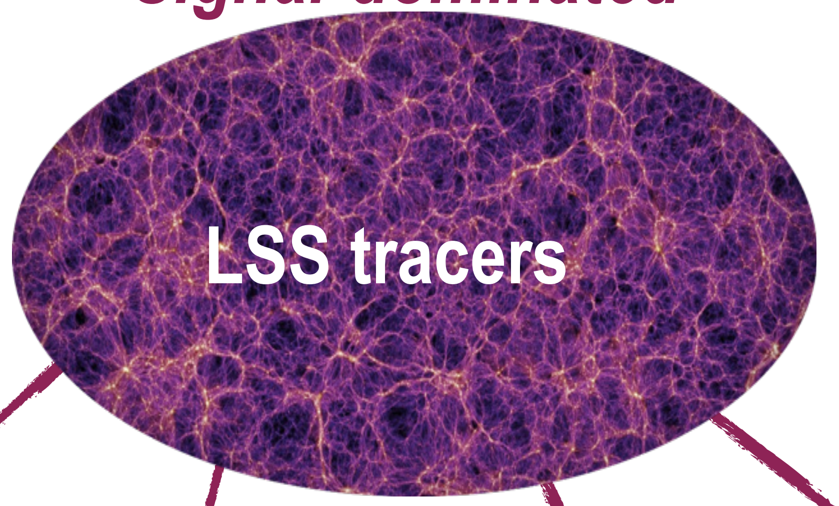
# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated*




x

*Signal-dominated*

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**Cosmic shear**

No signal

**CMB**

**Signature of the Integrated Sache-Wolfe effect.**

[Xia et al. 2011]:
Searched for signature of ISW in cross-correlation between WMAP7-CMB and 21-mo γ-ray data

**CMB lensing**

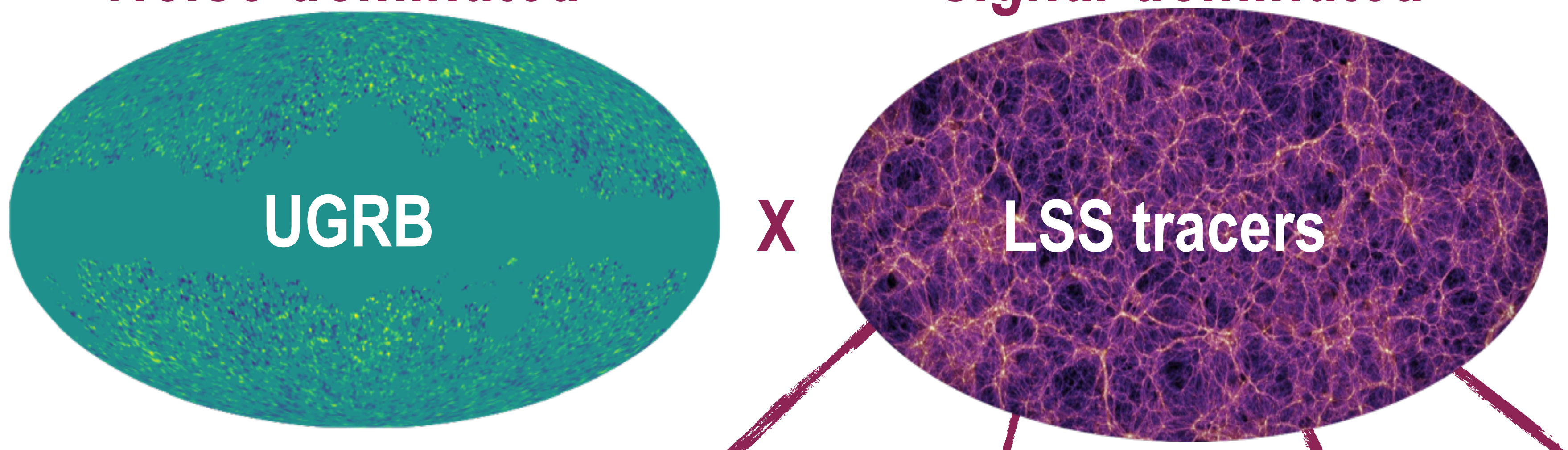
**Lensed CMB map as LSS tracer**

[Fornengo et al. 2015]:
Cross-correlation of Lensing potential of the CMB and γ-ray field to investigate the LSS

Fornengo et al. 2015, arXiv:1410.4997v2
Sachs, R.K. and Wolfe 1967, ApJ, 147, 73
Xia et al. 2011, arXiv:1103.4861v2

# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated* *Signal-dominated*




**Galaxy catalogs**

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- Subdominant ICM and annihilating DM

**Cosmic shear**

No signal

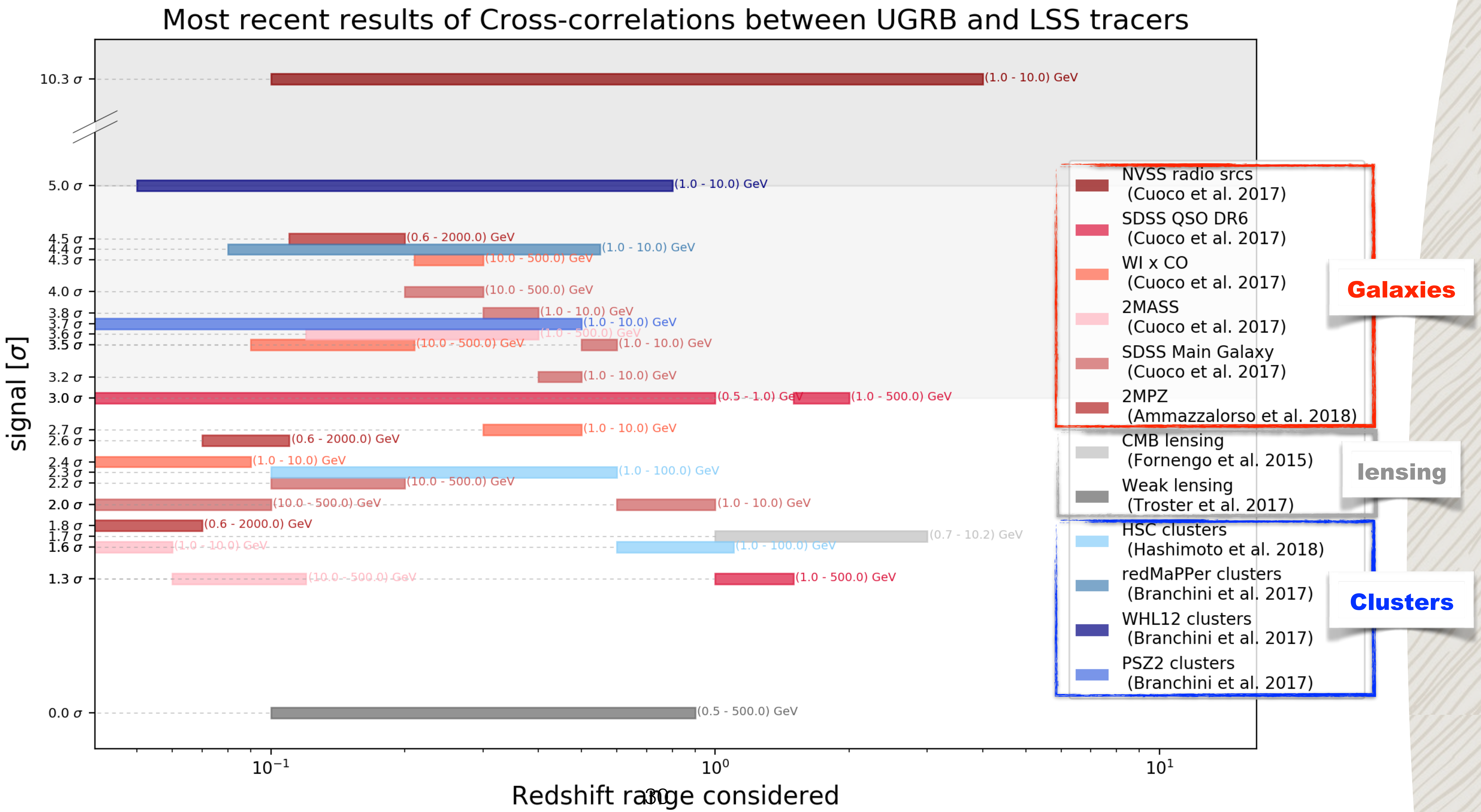
**CMB**

No signal

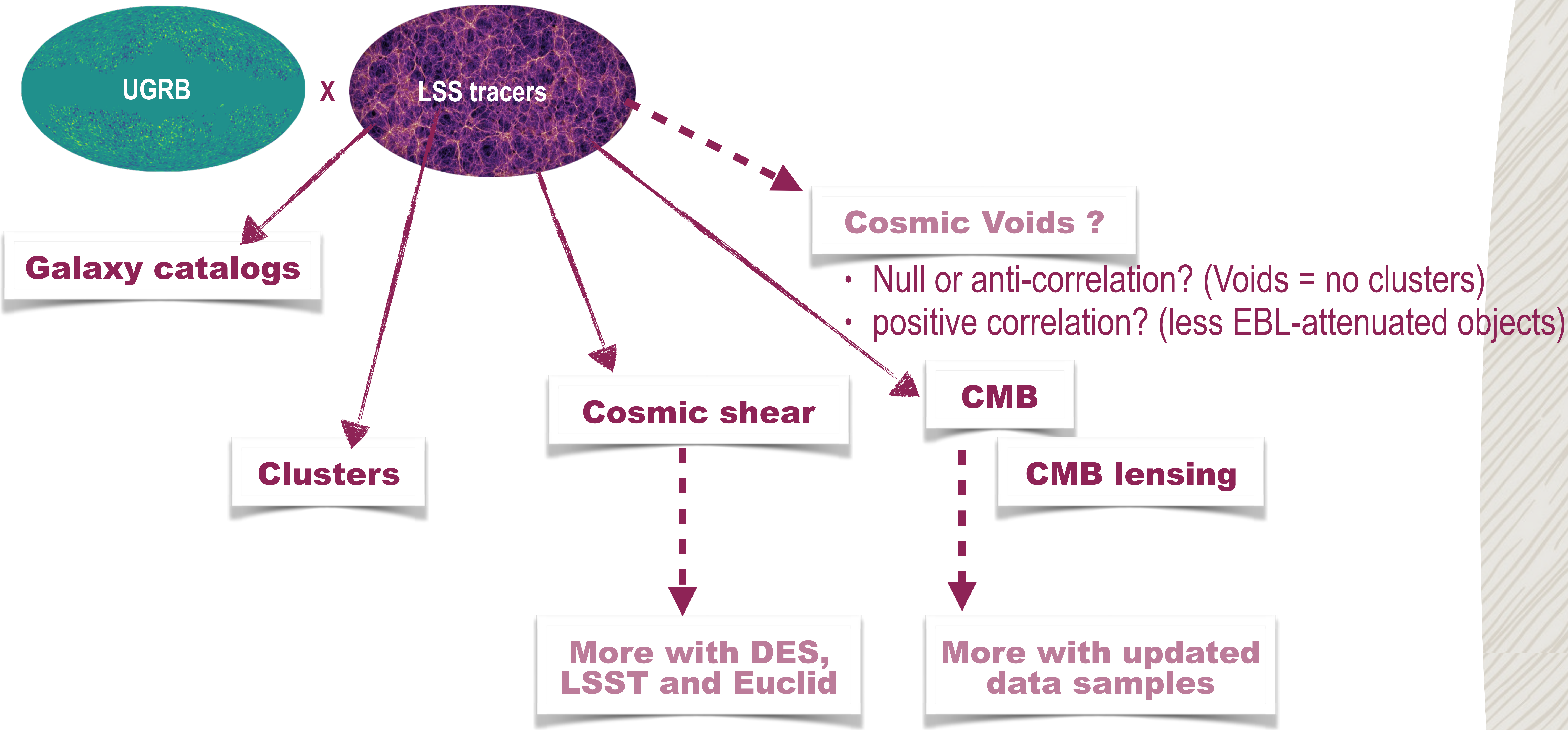
**CMB lensing**

weak signal (~2 sigma)

# UGRB anisotropy characterisation through cross-correlations

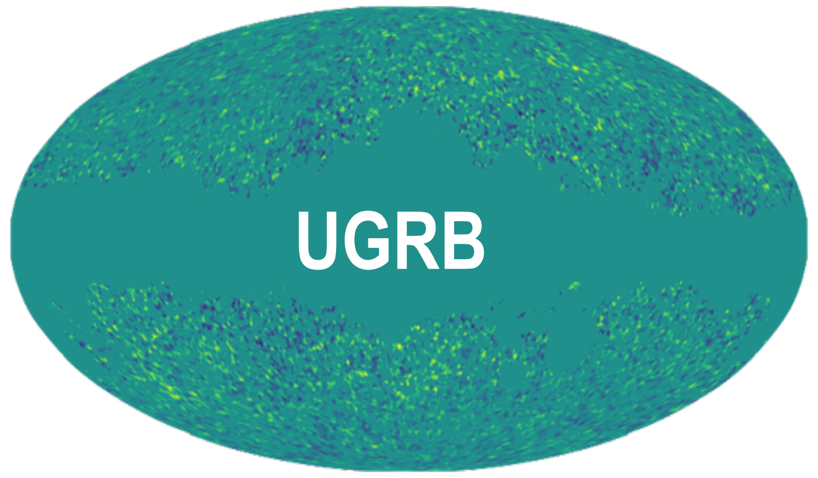


# Future developments of Cross-correlations

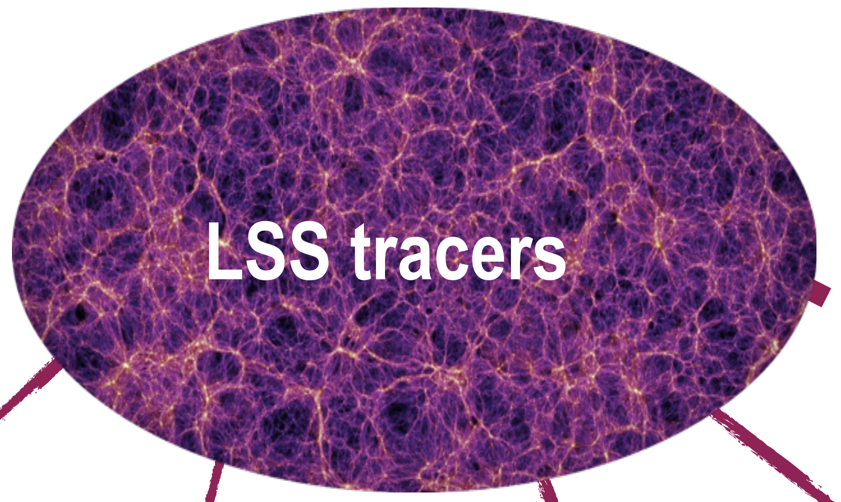


# Future developments - Cross-correlations and multi-messanger

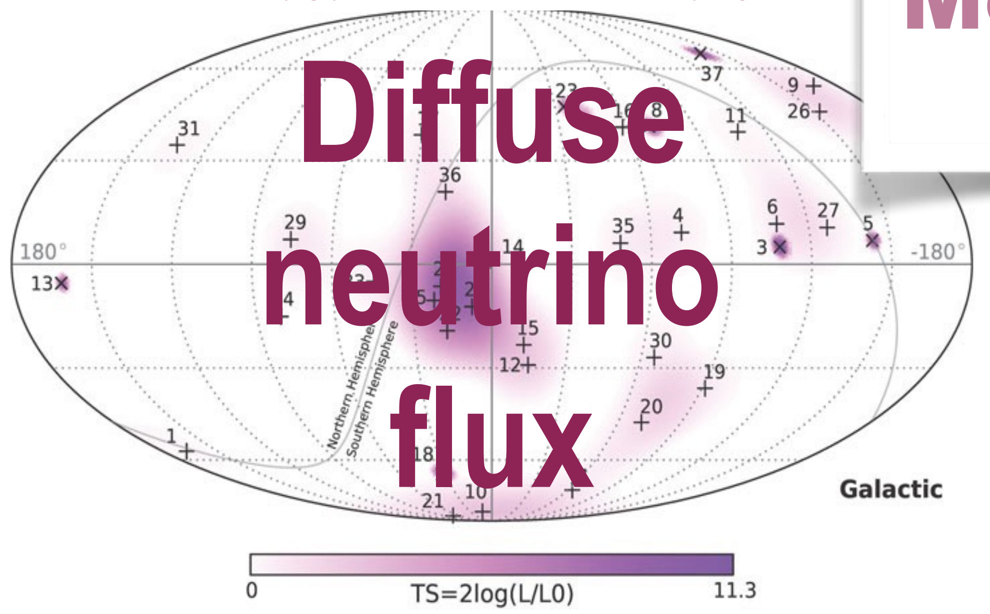
X




X




M.G. Aartsen et al.2014




**More with IceCube Upgrade***

**Even more with IceCube-Gen2 ***

**Galaxy catalogs**

**Clusters**

**Cosmic shear**

**More with DES, LSST and Euclid**

**Cosmic Voids ?**

- Null or anti-correlation? (Voids = no clusters)
- positive correlation? (less EBL-attenuated objects)

**CMB**

**CMB lensing**

**More with updated data samples**

* https://icecube.wisc.edu/news/view/605

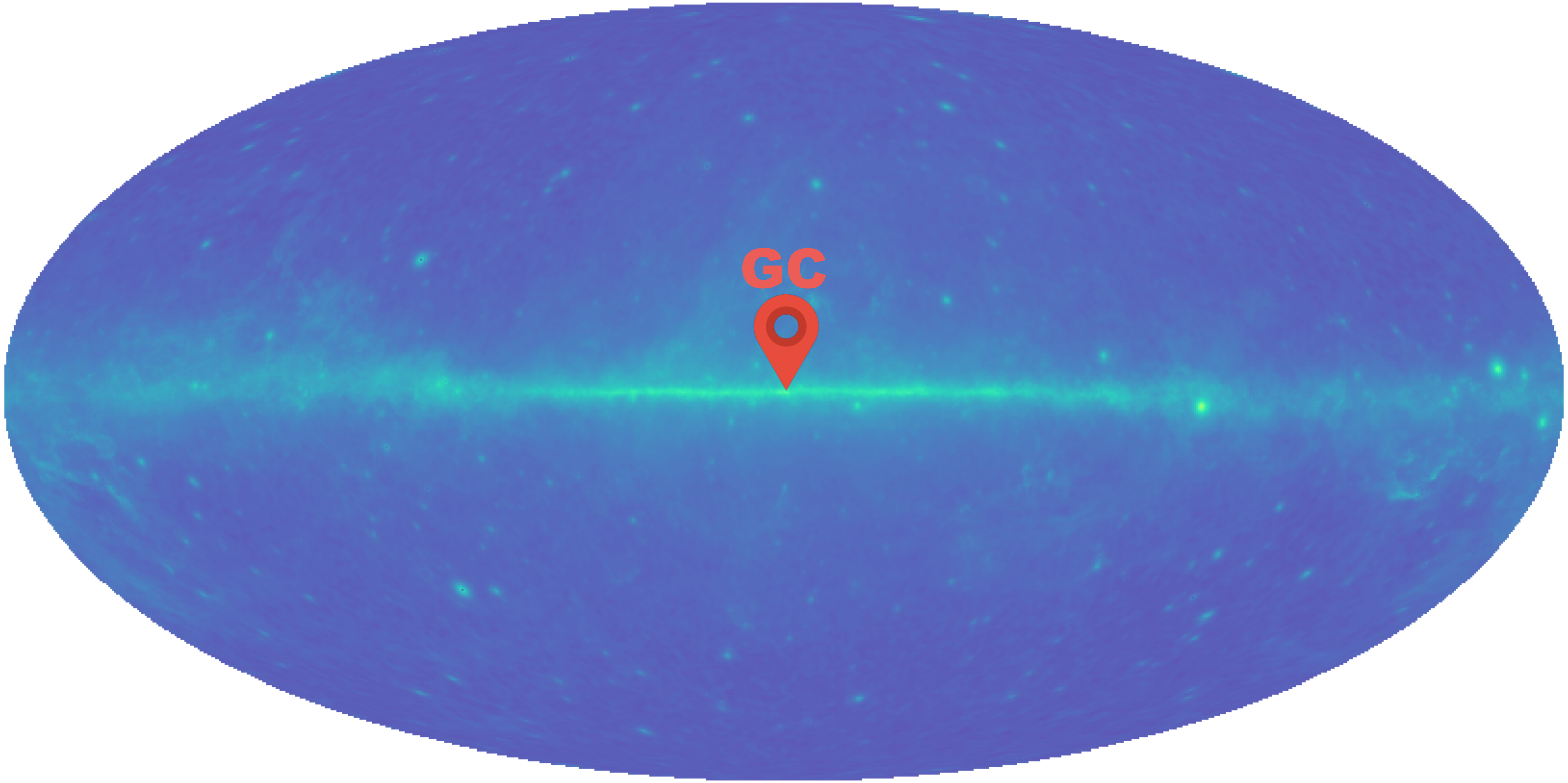
# Summary

| | | *Fermi*'s contribution | Future prospects | Link to other (future) experiments |
|---|---|---|---|---|
| UGRB Anisotropy | Autocorrelation | Direct contribution: provides the measurement<br><br>spin-off:<br>• to exclude/constrain source populations models<br>• set DM limits<br>• unveil unresolved origin | • Unveiling the origin of low-energy component<br>• Detection of subdominant clustering signal in gamma-rays | |
| | | | Understand the nature of the high-energy exponential cut-off | **Čerenkov telescopes (e.g. CTA)** |
| | Cross-correlation | Direct contribution: provides the measurement of the UGRB<br><br>spin-off:<br>• to constrain subdominant ICM and annihilating DM signal<br>• to characterise the γ-ray unresolved emission<br>• high-energy cosmology | • Update UGRB-CMB cross-correlation: ISW effect<br>• Cross-correlation with cosmic voids | **Plank** |
| | | | Update UGRB-weak lensing cross-correlation: constrain DM limits | **DES, LSST, Euclid** |
| | | | Multimessenger Astrophysics: UGRB/EGB-Neutrinos | **IceCube (Upgrade)** |

# Conclusion


Fermi's future
is bright!
(but we could even deal with a
less-bright one very well :) )

# Conclusion



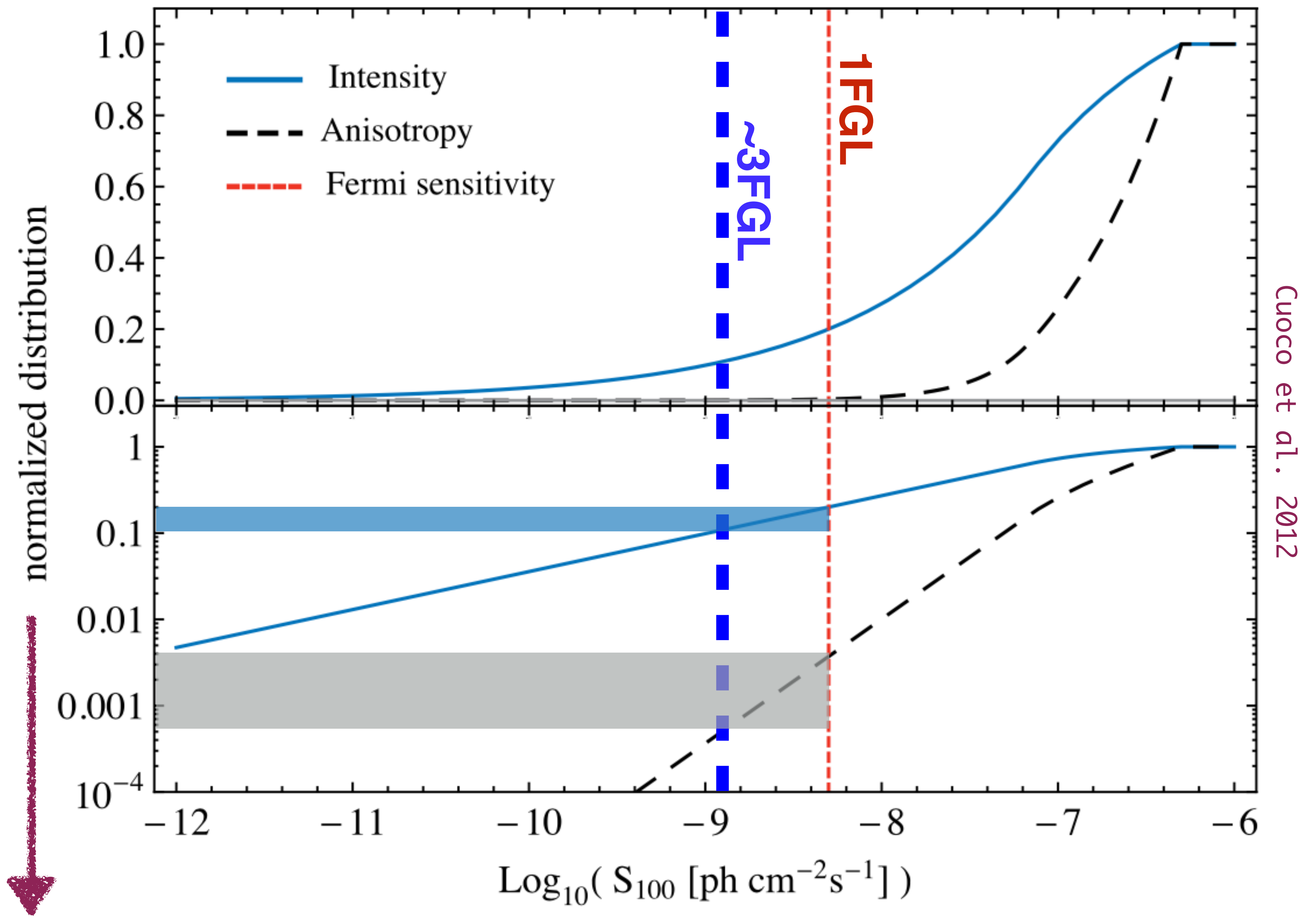
# 8th International Fermi Symposium

# Backup

**Michela Negro**
University and INFN of Torino
michela.negro@to.infn.it

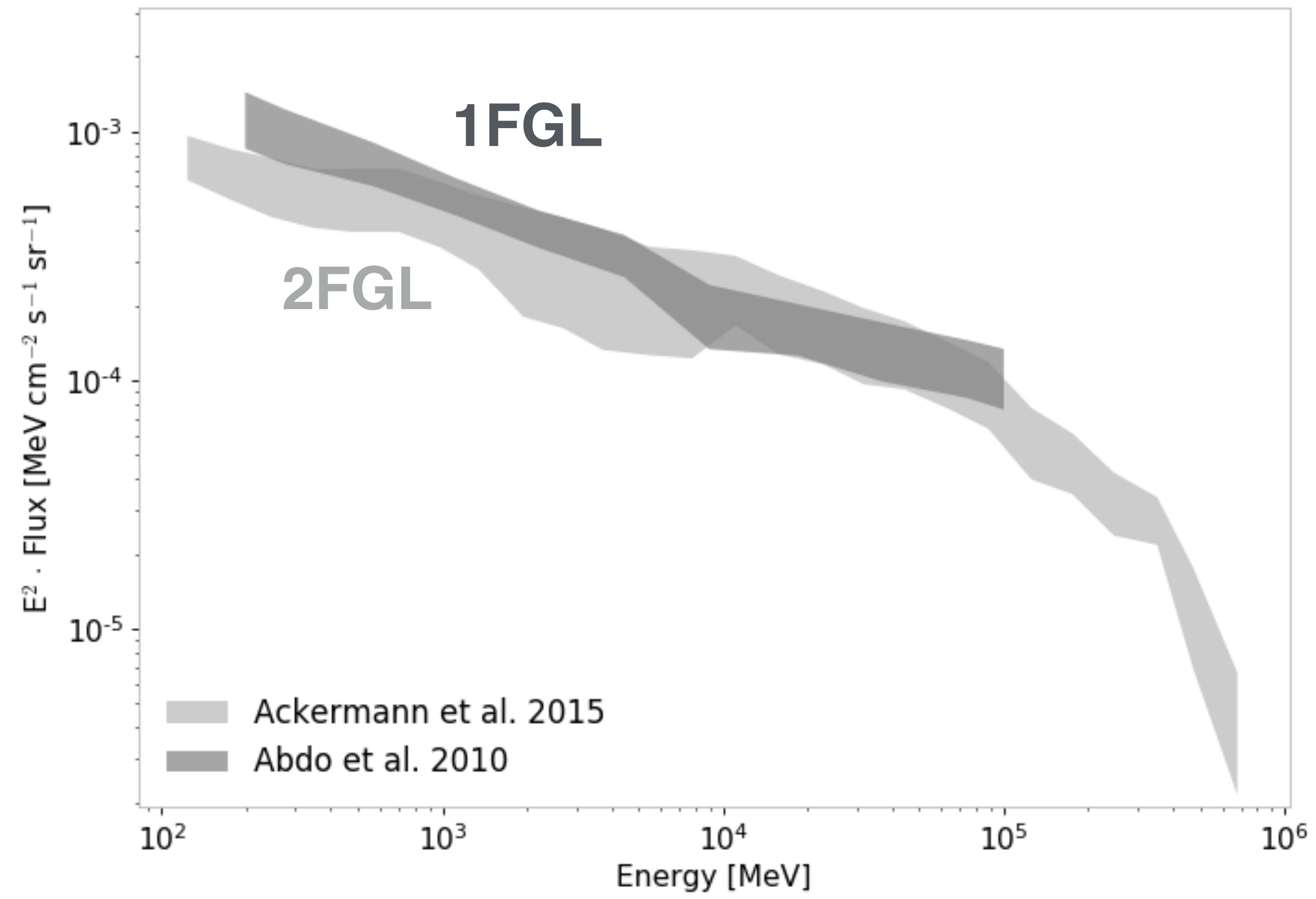
# Intensity and anisotropy energy spectra

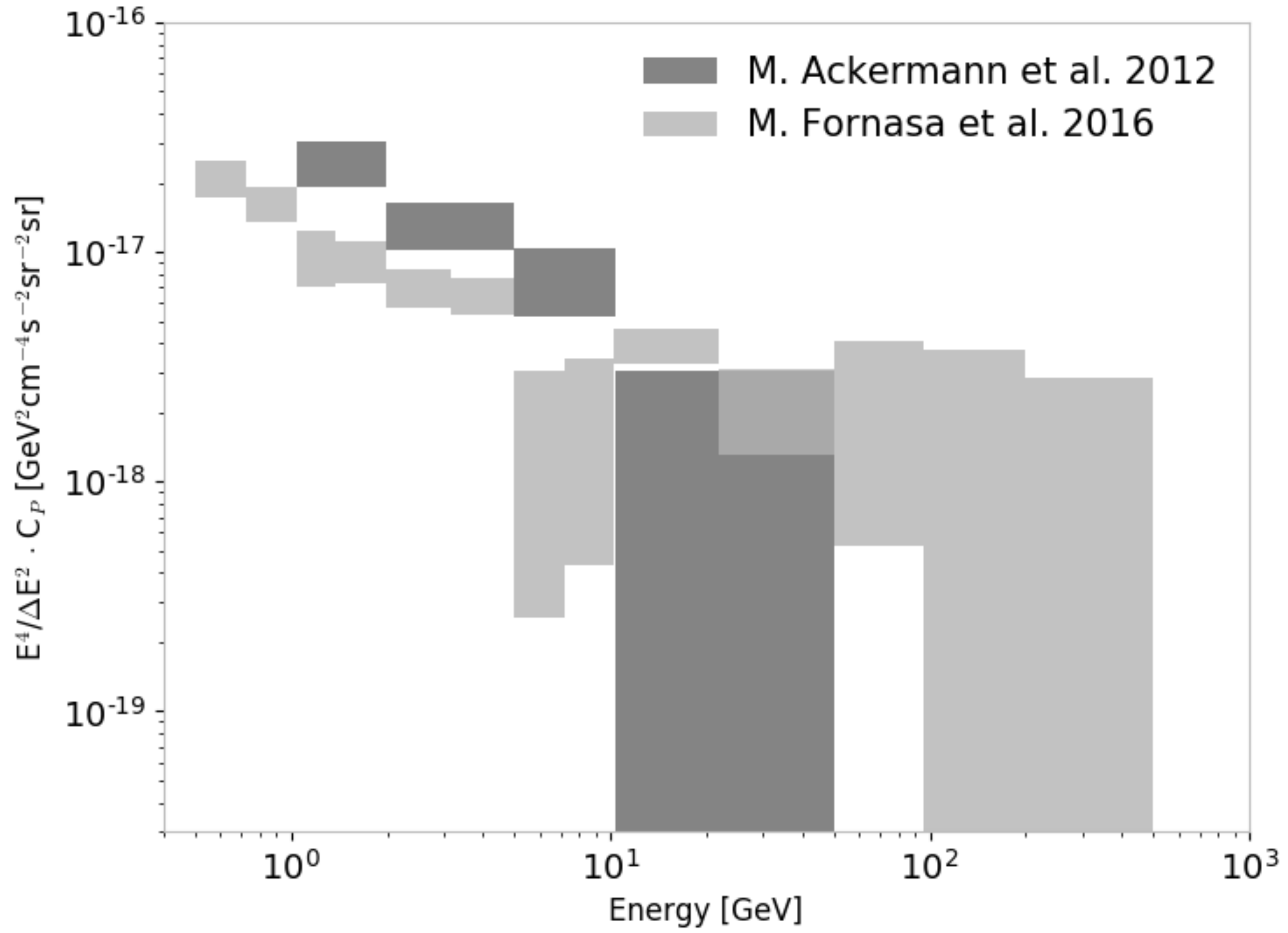
… as complementary observables of the UGRB:




Cumulative contribution of blazar to the Intensity and to anisotropy as a function of source intensity

The anisotropy from unresolved sources is more strongly dependent on the sensitivity limit: improved point source sensitivity have a more notable impact on the measured IGRB anisotropy.



# Past Measurements - Fornasa et al. 2016

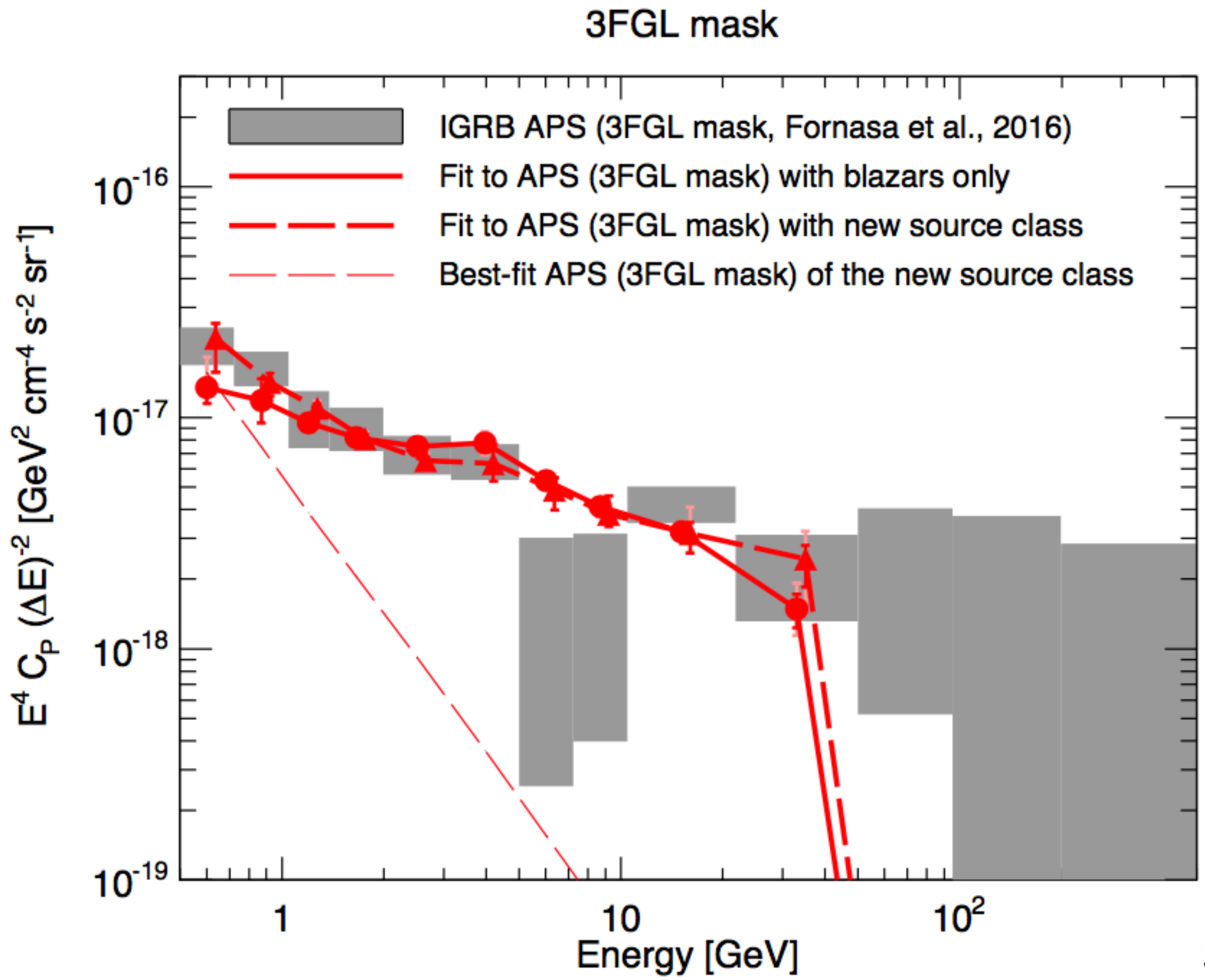
Autocorrelation to investigate the UGRB composition:

**Blazars** VS **Blazars+new-population:**

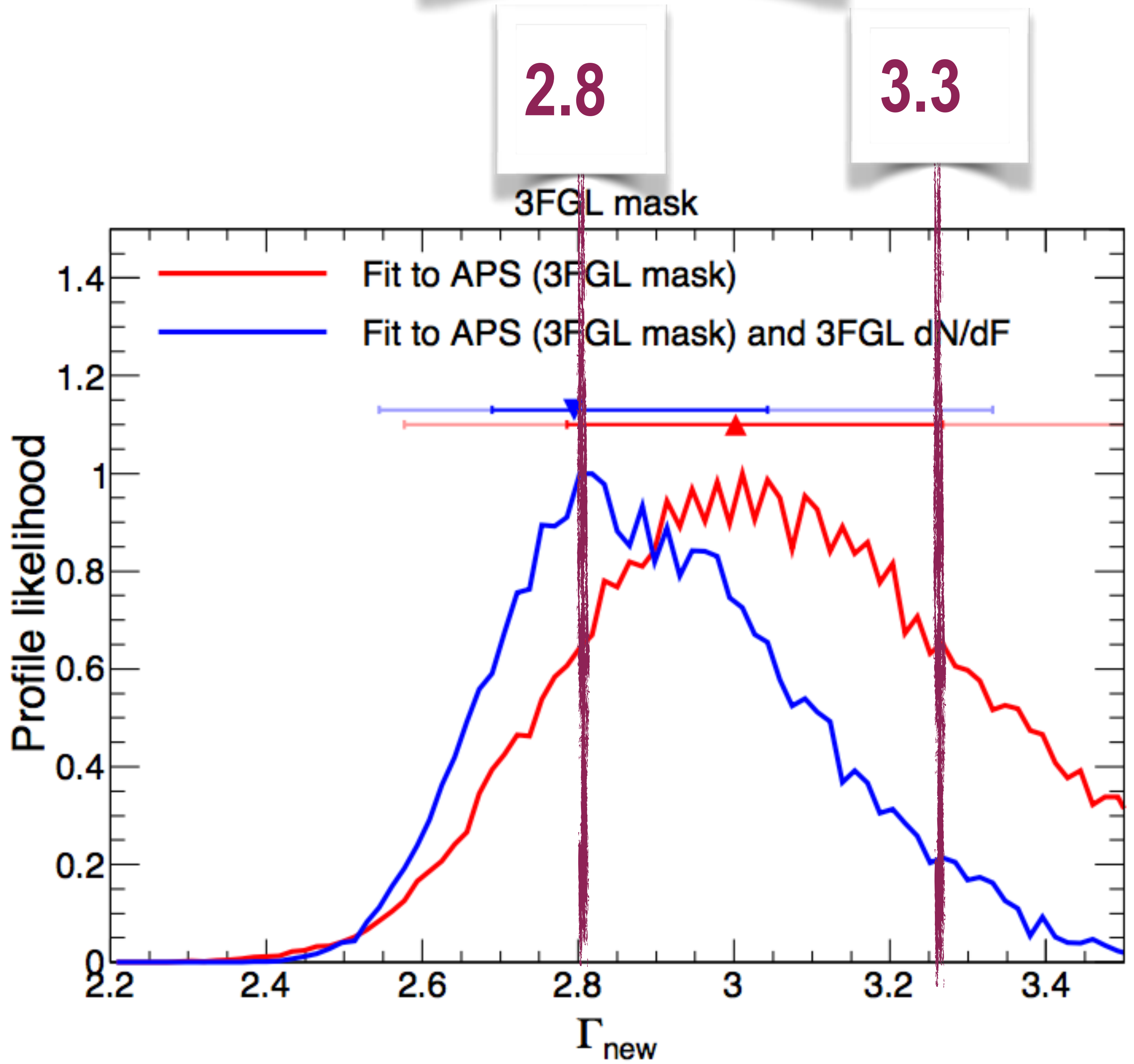
[Abdo et al. 2017]

**Preferred @ 5 σ !**

**Very steep!!**




Ando et al. (2017)




Ando et al. (2017)

Ando et al. 2017, arXiv:1701.06988v1

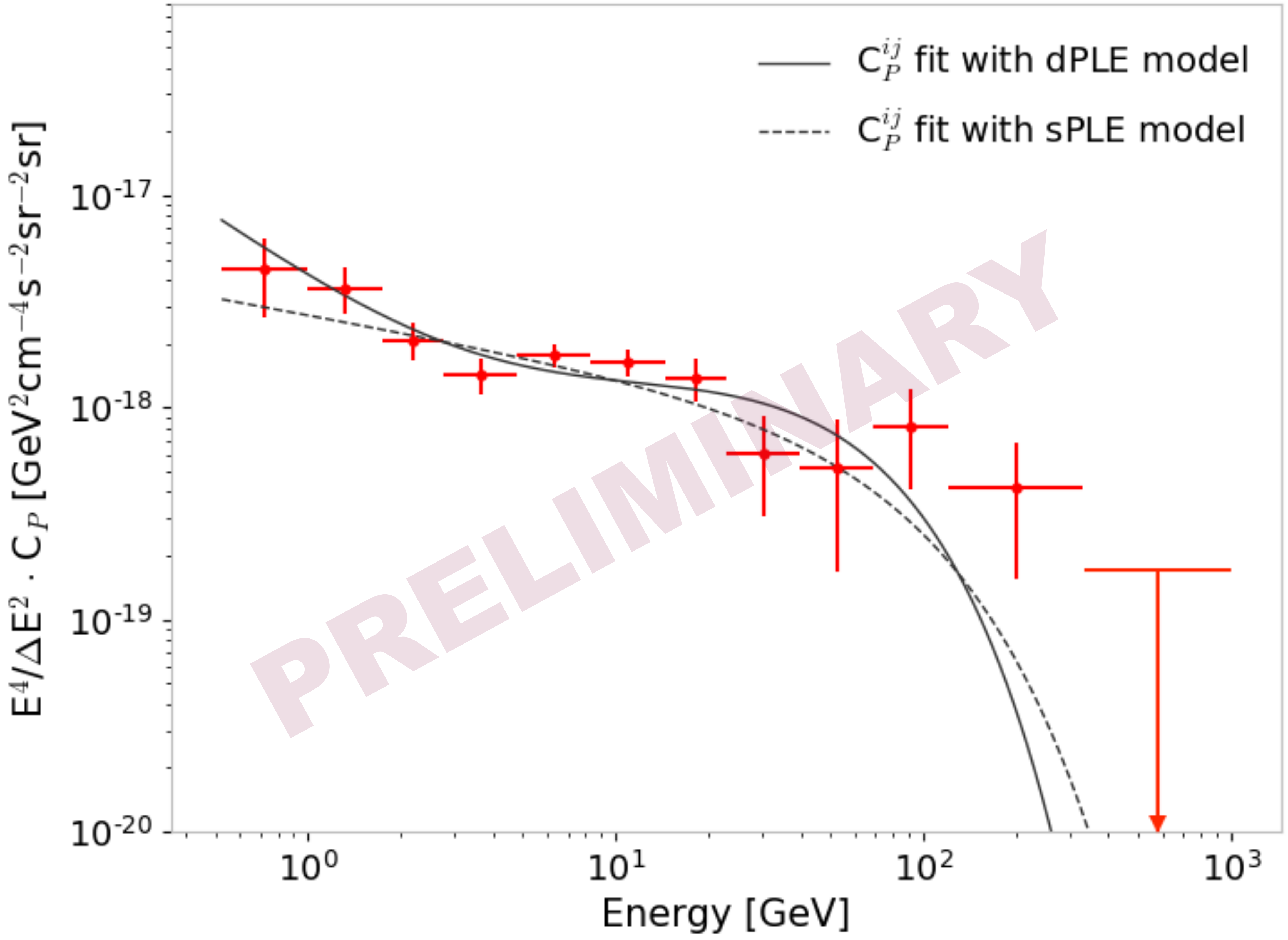
# Fenomenological models

**sPLE** $N_1 \times (E_i E_j)^{-\alpha} e^{\left(-\frac{E_i+E_j}{E_{\rm cut}}\right)}$

**dPLE** $\left[N_1 \times (E_i E_j)^{-\alpha} + N_2 \times (E_i E_j)^{-\beta}\right] e^{\left(-\frac{E_i+E_j}{E_{\rm cut}}\right)}$

**sPLE is excluded at 99.8% CL**

(estimation from $\Delta\chi^2$ distribution evaluated with MC)

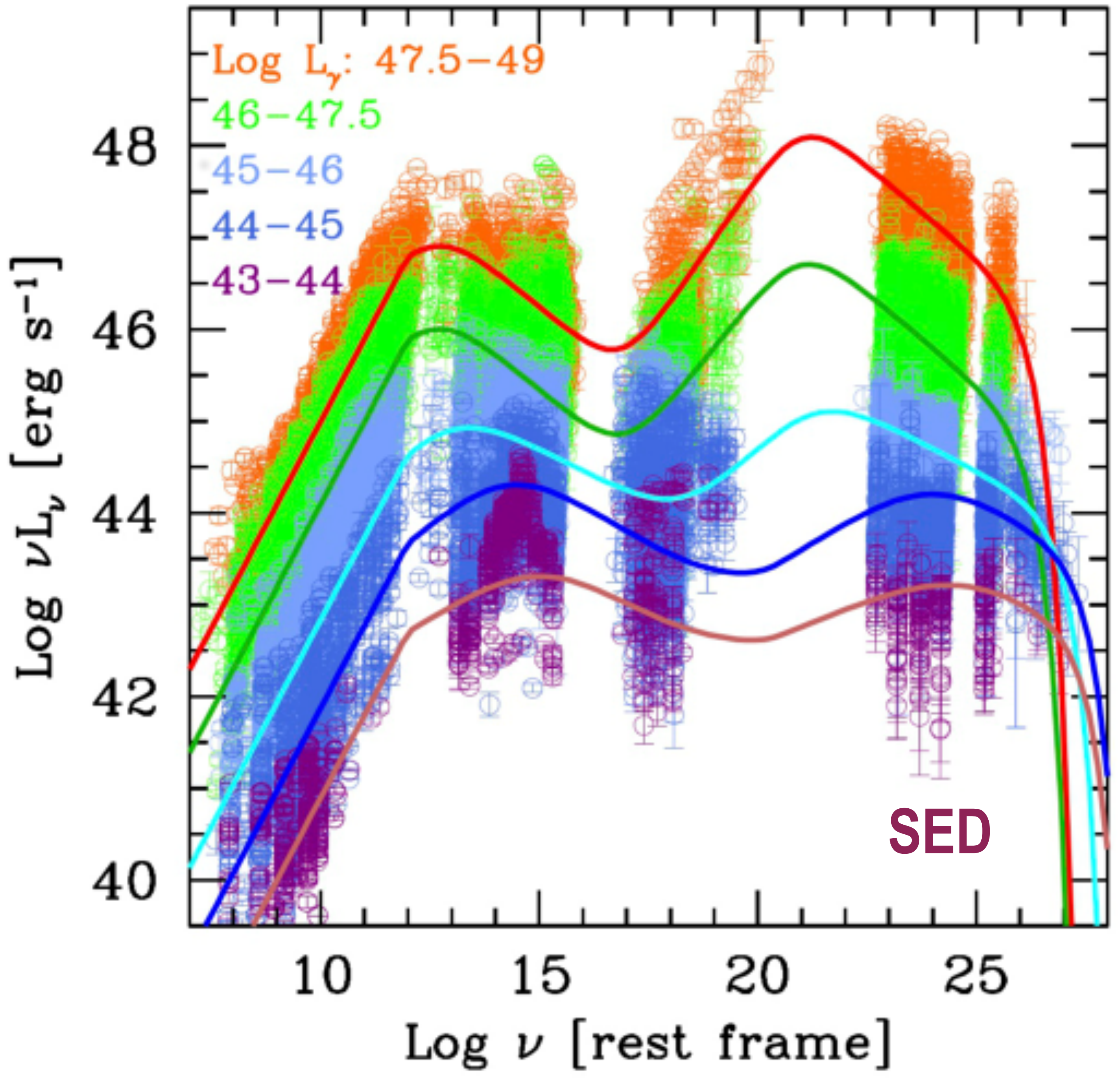


8th International Fermi Symposium
October 14-19, 2018 - Baltimore, MD
- Michela Negro -

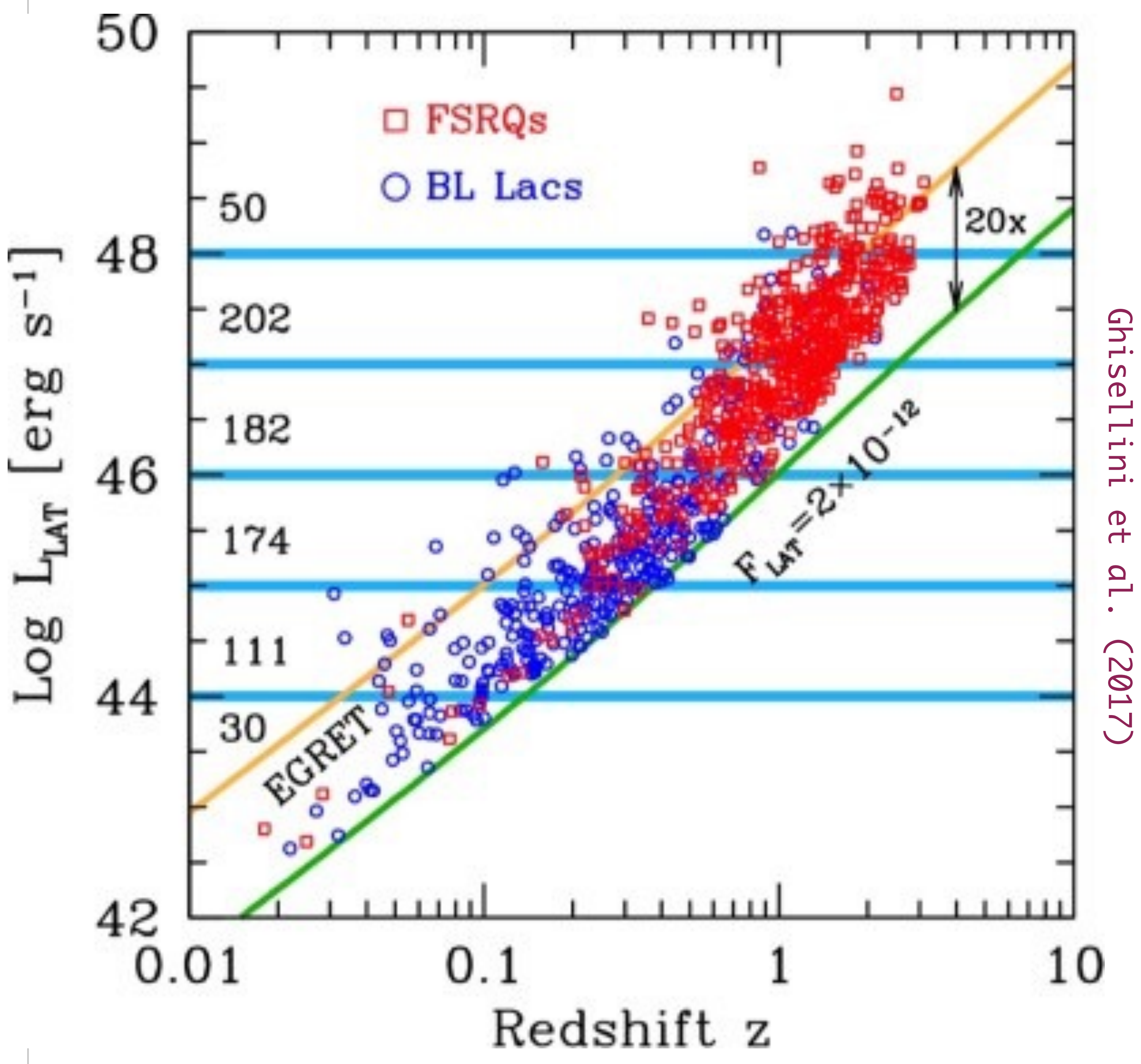
# Two populations

Observations:
- the less luminous the harder
- less luminous are usually BL-Lacs
- Observed BL-Lacs and FSRQs have different z distributions

**Unresolved blazars:**
- **harder spectra than resolved ones**
- **likely BL-Lac type**




Ghisellini et al. (2017)

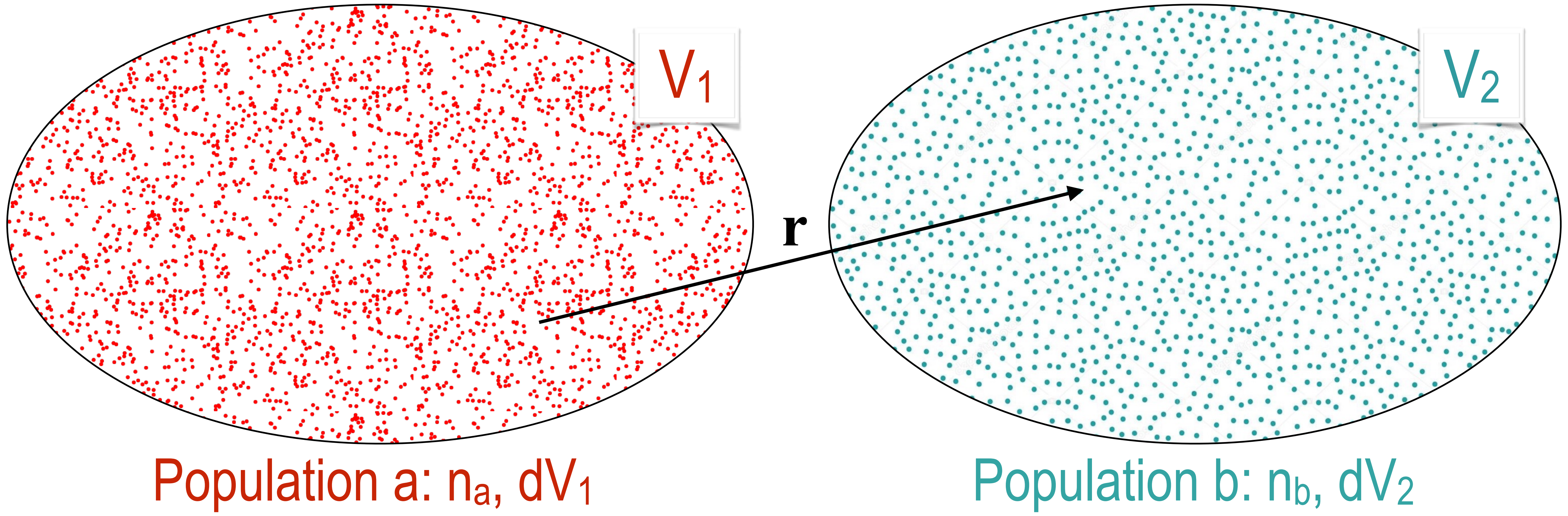



Ghisellini et al. (2017)

Ghisellini et al. 2017
Padovani et al....

# UGRB anisotropy characterisation through cross-correlations *

* see talk by Shunsaku Horiuchi




***2-point cross-correlation function (CCF)***:

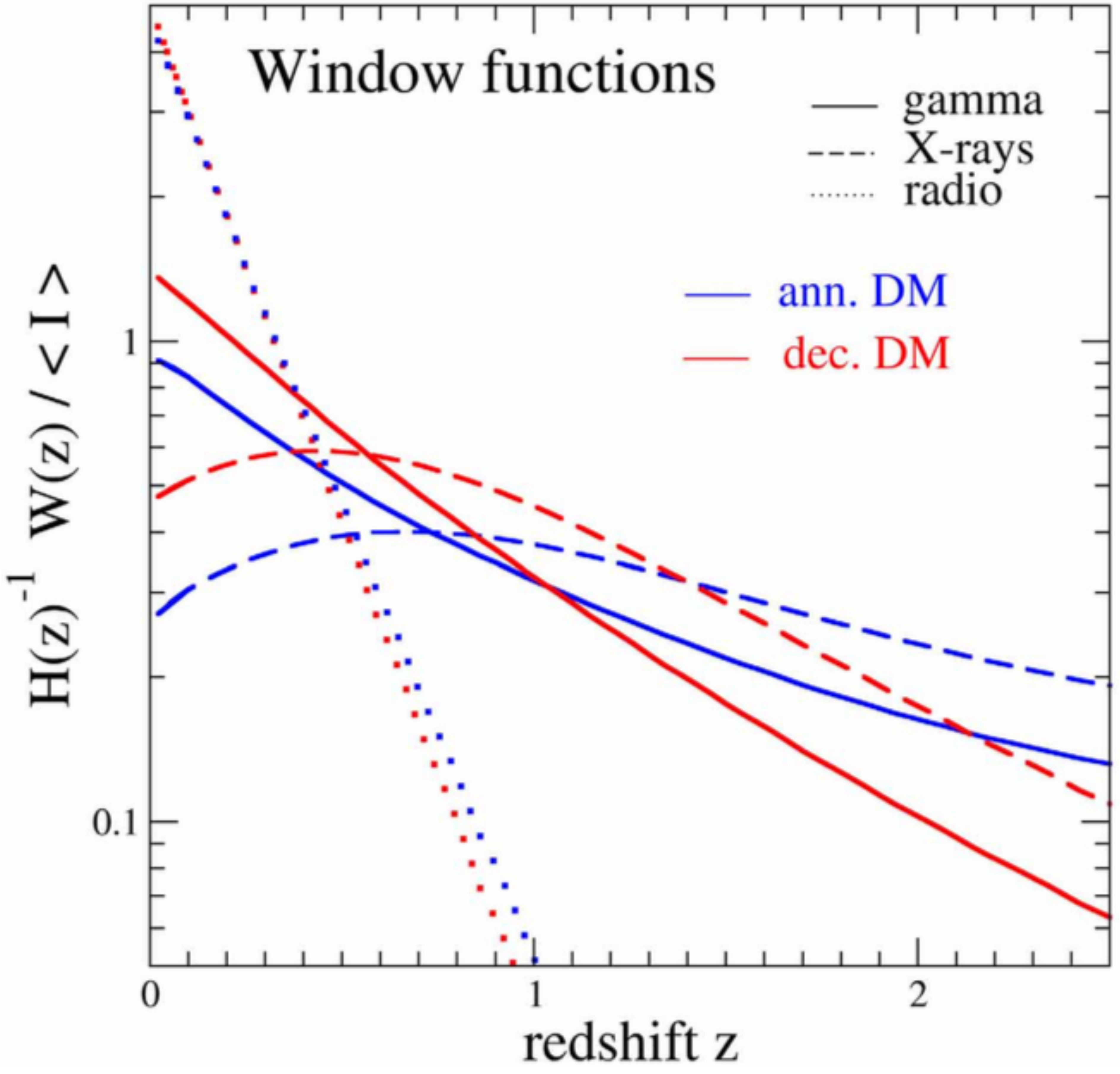
$$dP = n_a n_b \left[1 + \xi_{ab}(\mathbf{r})\right] dV_1 dV_2$$

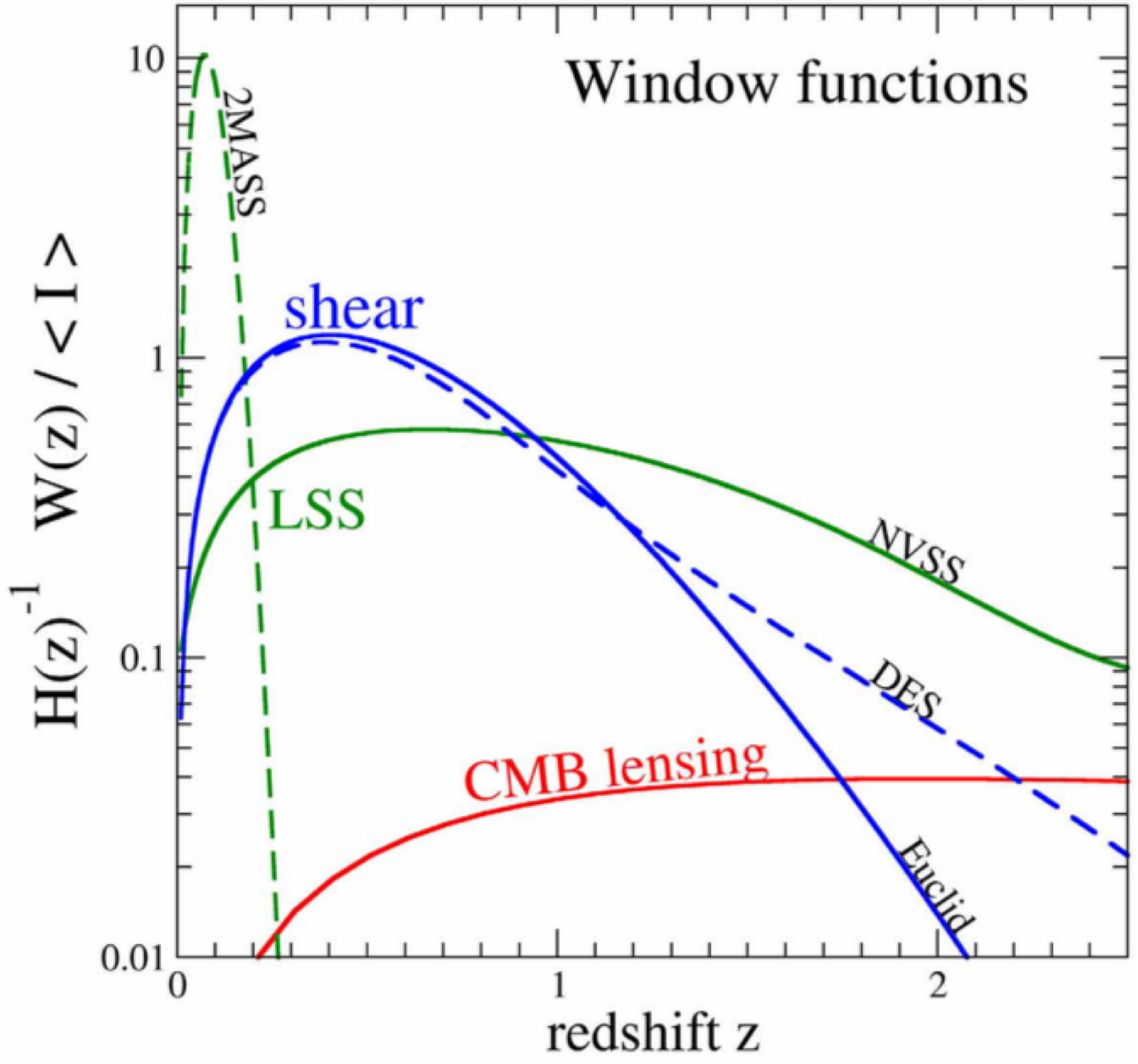
$$\xi_{ab}(\mathbf{r}) = \langle \delta_a(\mathbf{x})\ \delta_b(\mathbf{x}+\mathbf{r}) \rangle$$

***Cross-correlation angular power spectrum***:

$$\mathrm{CCF}^{(ab)}(\theta) = \sum_\ell \frac{2\ell+1}{4\pi} \bar{C}_\ell^{(ab)} P_\ell[\cos(\theta)]$$

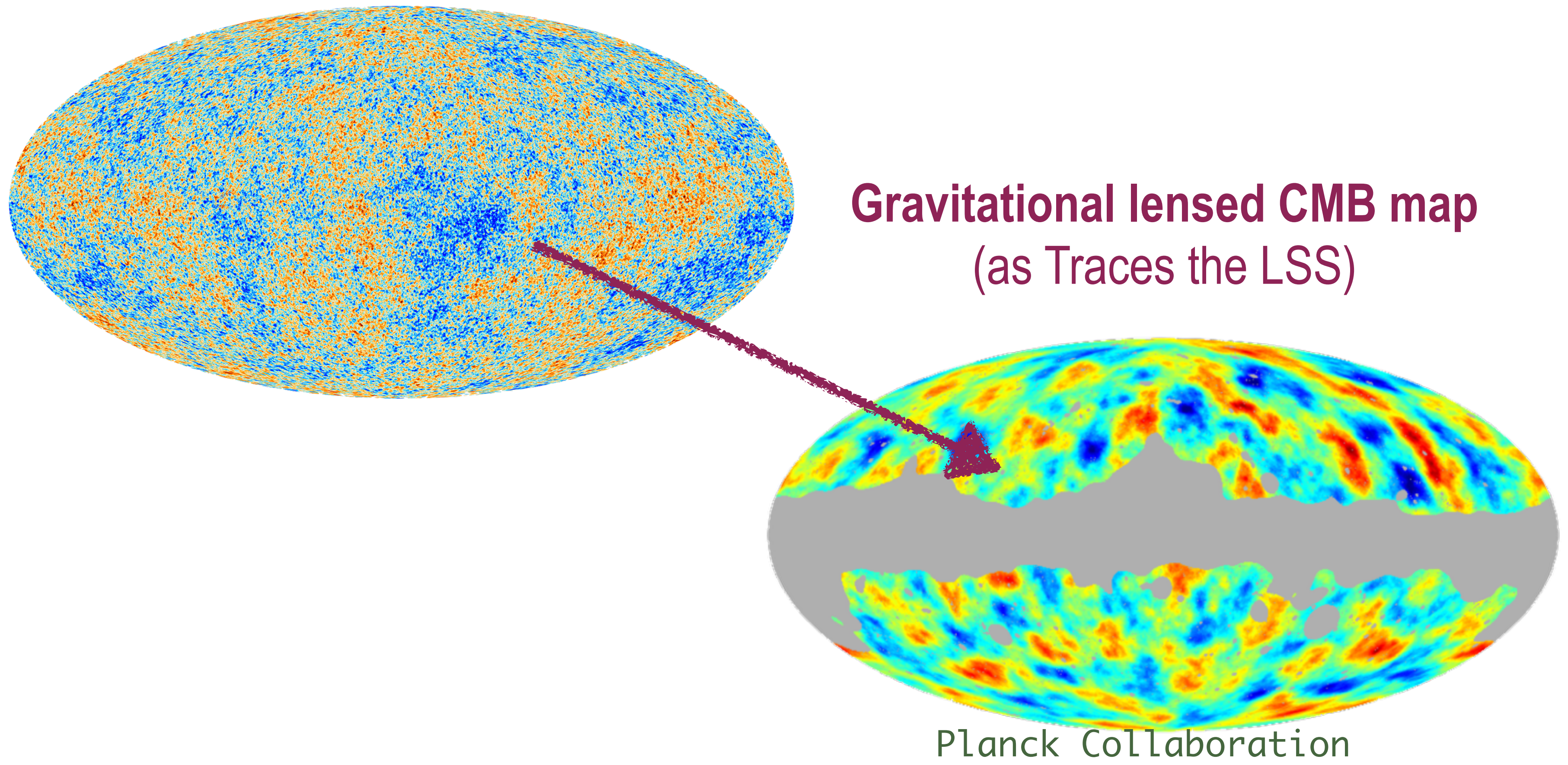
# How to choose a good probe



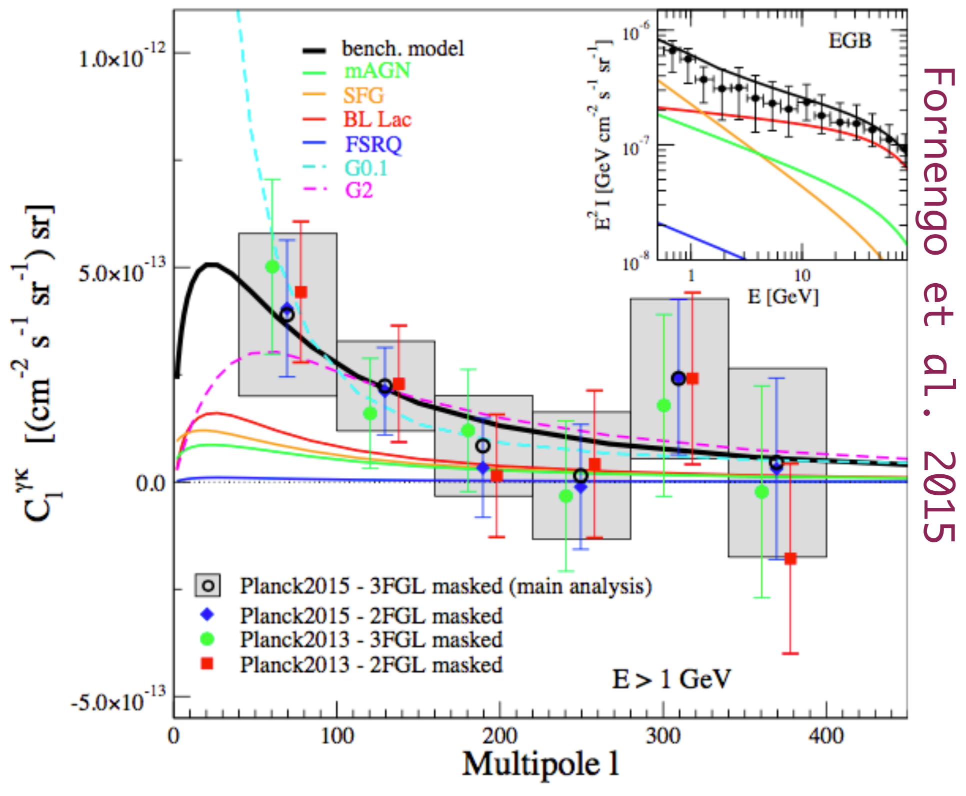



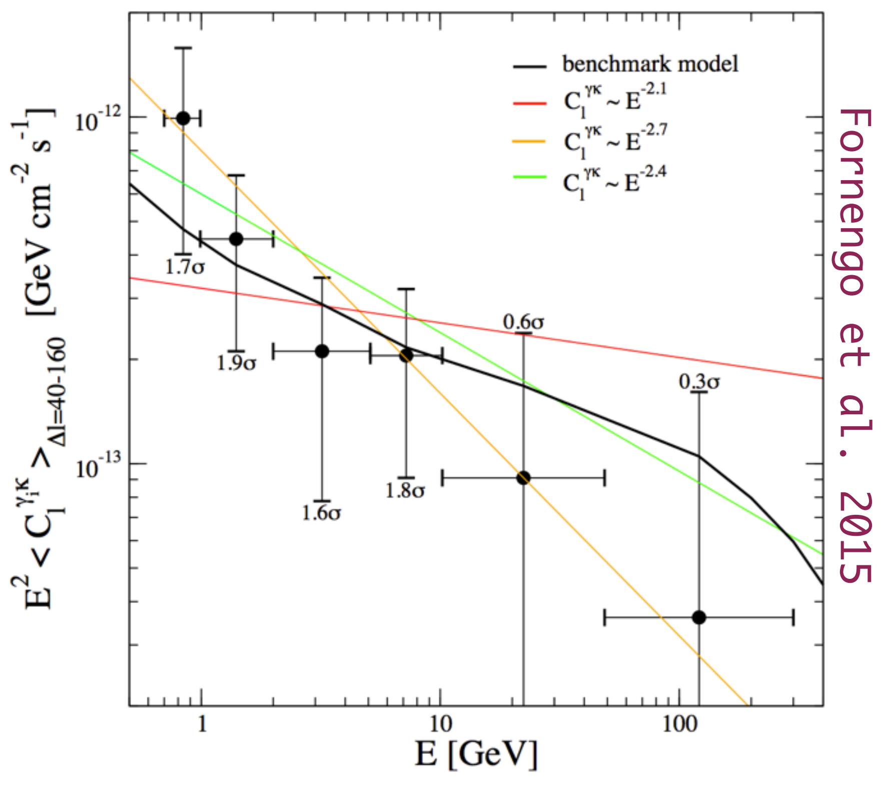
# UGRB anisotropy characterisation through cross-correlations: CMB / CMB lensing

**[Fornengo et al. 2015]:**
Cross-correlation of Lensing potential of the CMB and γ-ray field to investigate the LSS




**Gravitational lensed CMB map**
(as Traces the LSS)



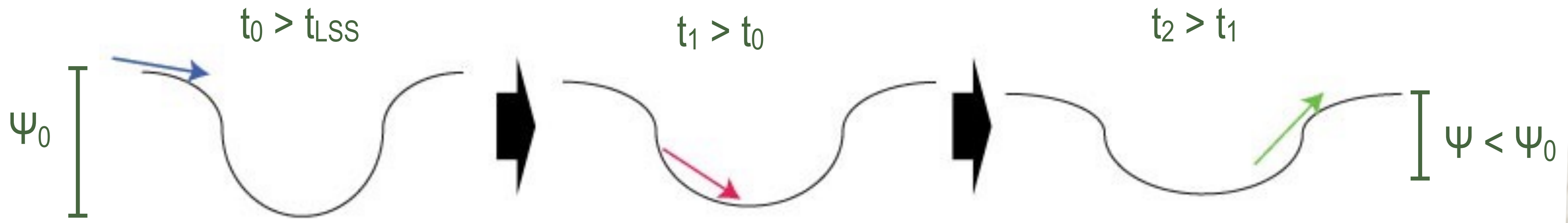

**~2σ limit**

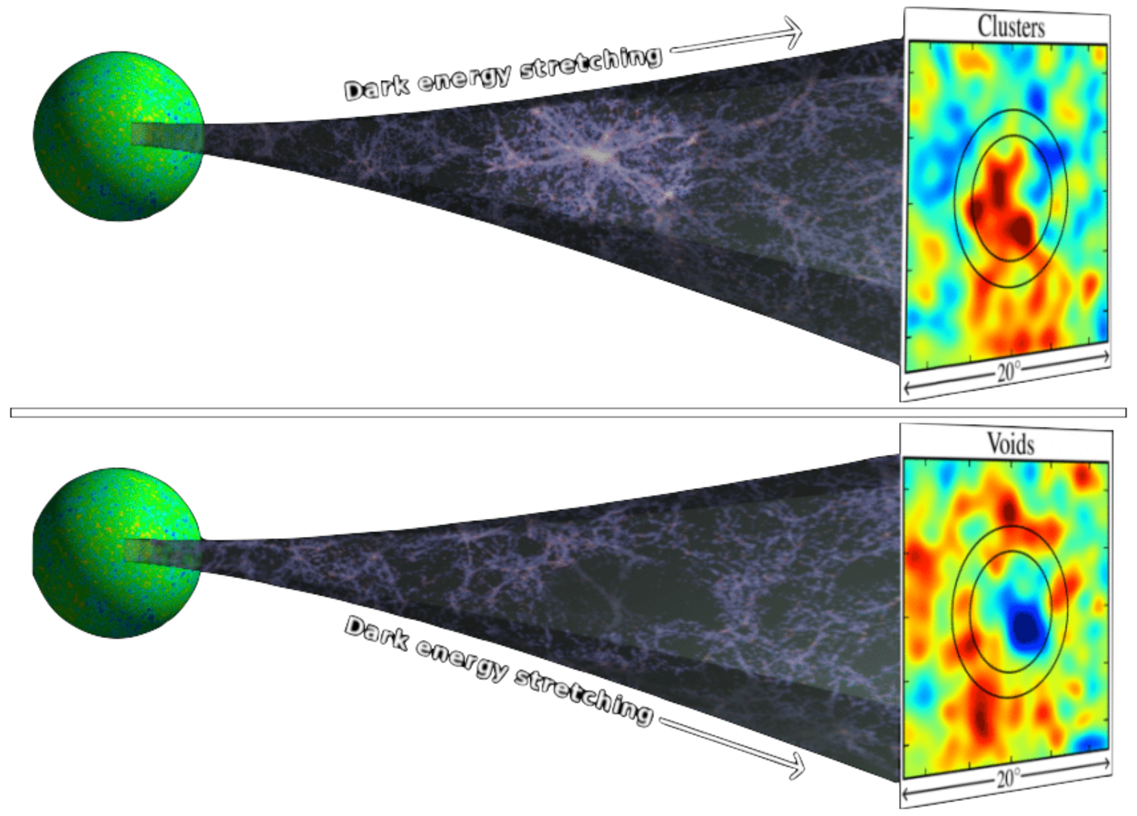
**[Xia et al. 2011]:**
Searched for signature of ISW in cross-correlation between WMAP7-CMB and **21-mo γ-ray data**

**Sachs-Wolfe effect**:
contributes to Cosmic Microwave Background (CMB) anisotropy:
photons from the CMB are gravitationally redshifted

**INTEGRATED SACHS-WOLFE EFFECT (ISW)**
(between last scattering surface and Earth)

When the Universe is dark energy dominated
potential wells or hills evolve significantly

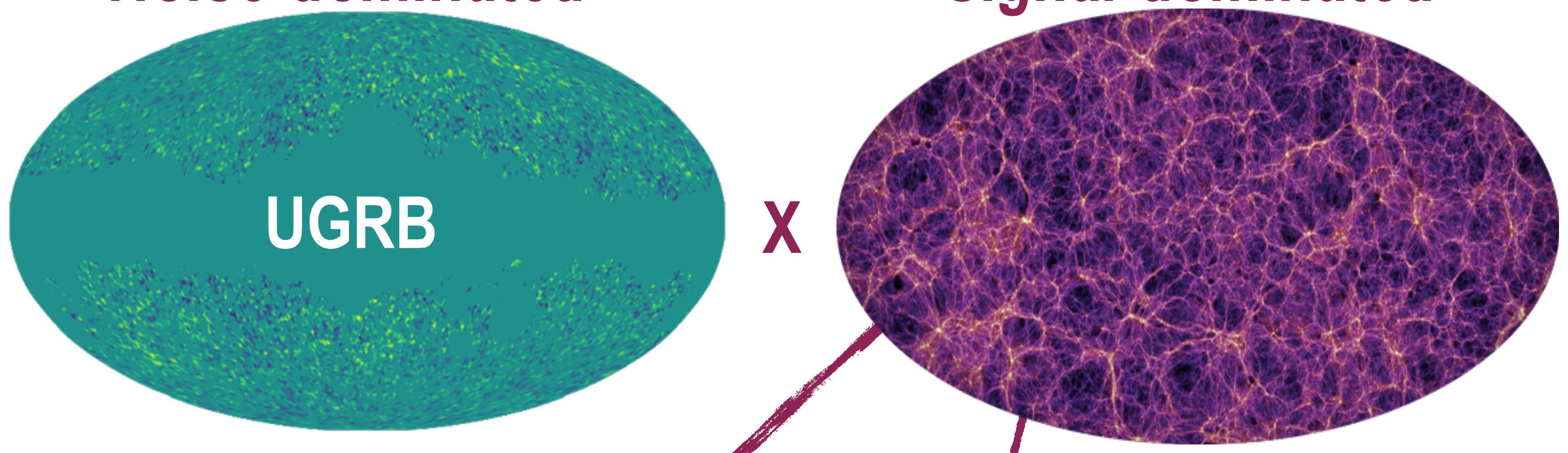



**No signal detected**

# UGRB anisotropy characterisation through cross-correlations

*Noise-dominated* *Signal-dominated*




**Galaxy catalogs**

- Different types of sources
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- AGNs +
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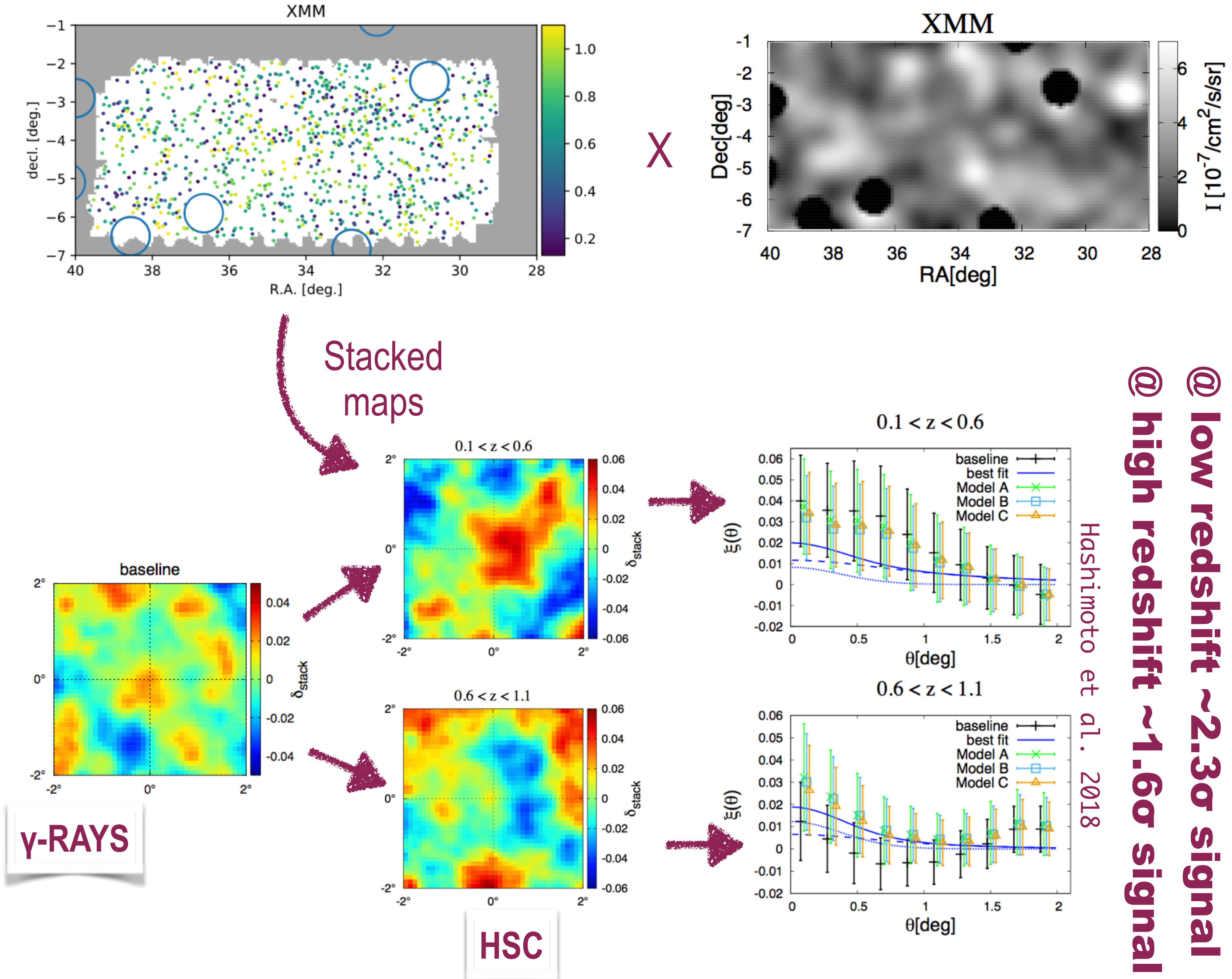
**Clusters**

Galaxies, hot highly ionized gas, DM, Relativistic CRs

[Hashimoto et al. 2018]

- **Subaru Hyper Suprime-Cam (HSC) (4,948 clusters)**




**@ low redshift ~2.3σ signal**
**@ high redshift ~1.6σ signal**

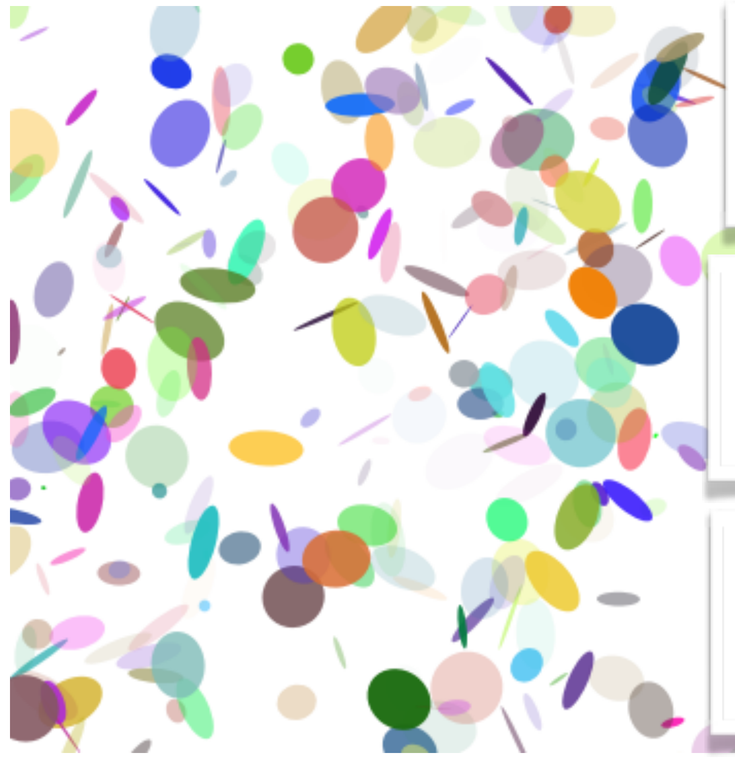
- Compatible with emission from the AGNs along the LSS: Constrain the contribution of **Intra-cluster medium** and **DM annihilation**



Hashimoto et al. 2018, arXiv:1805.08139v1

# UGRB anisotropy characterisation through cross-correlations: weak lensing

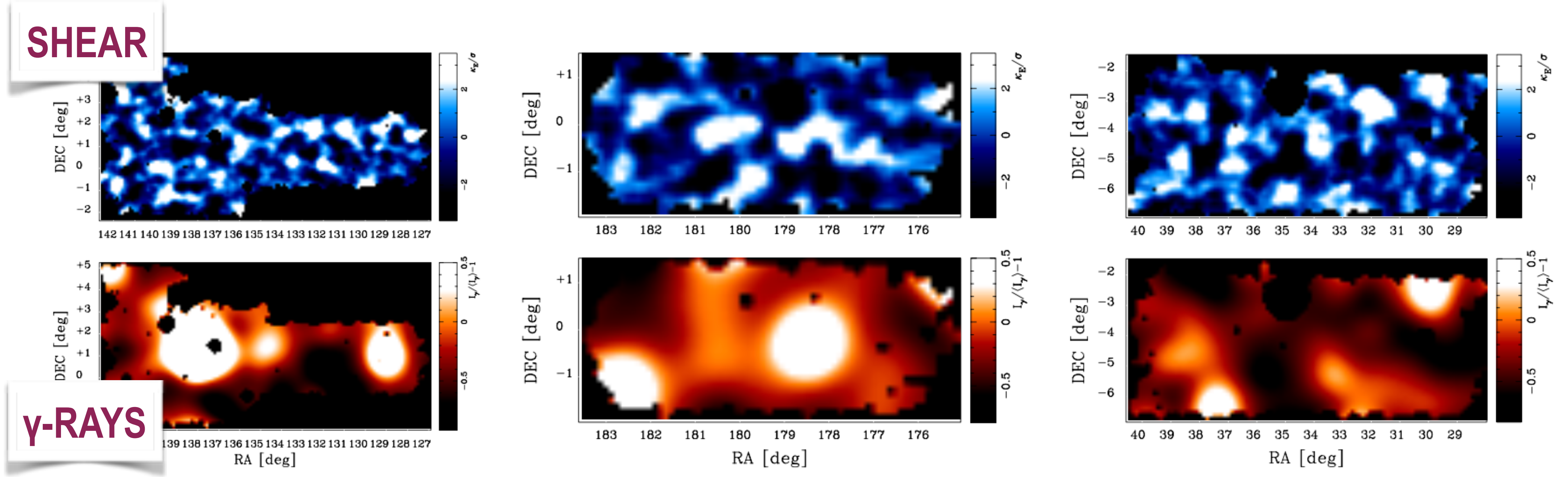
It is possible to produce cosmic shear maps to cross-correlate with gamma-ray maps



1) Hp: galaxies are intrinsically randomly oriented

2) Measure the net ellipticity exceeding the Poisson Noise

3) Infer the strength of the tidal gravitational field




Shirasaki et al. 2018

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  [Troster et al. 2017]
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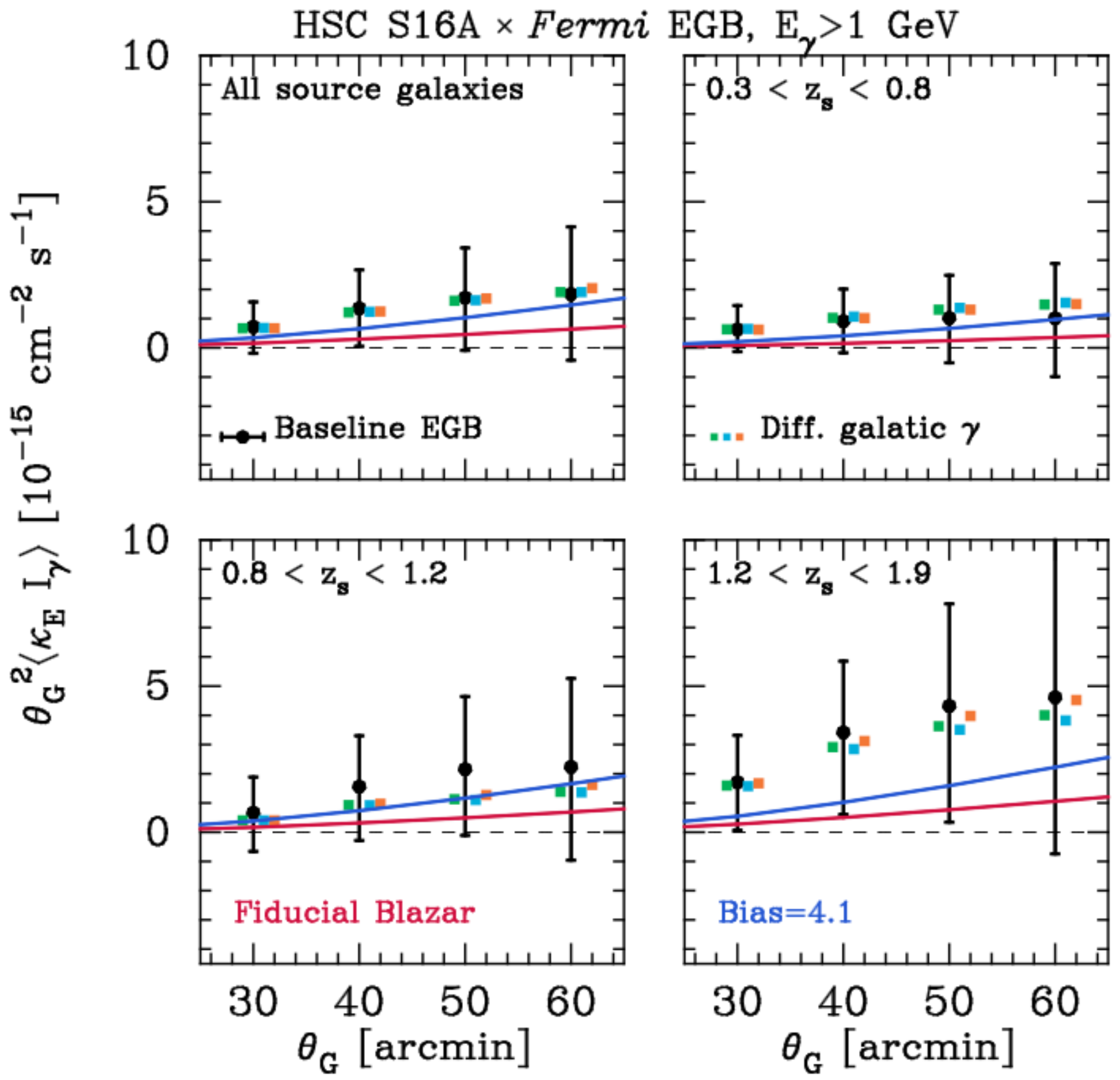
  [Shirasaki et al. 2018]

HSCS16A x Fermi-LAT

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Shirasaki et al. 2018, arXiv:1802.10257v2
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