Unveiling the unresolved gamma-ray Background

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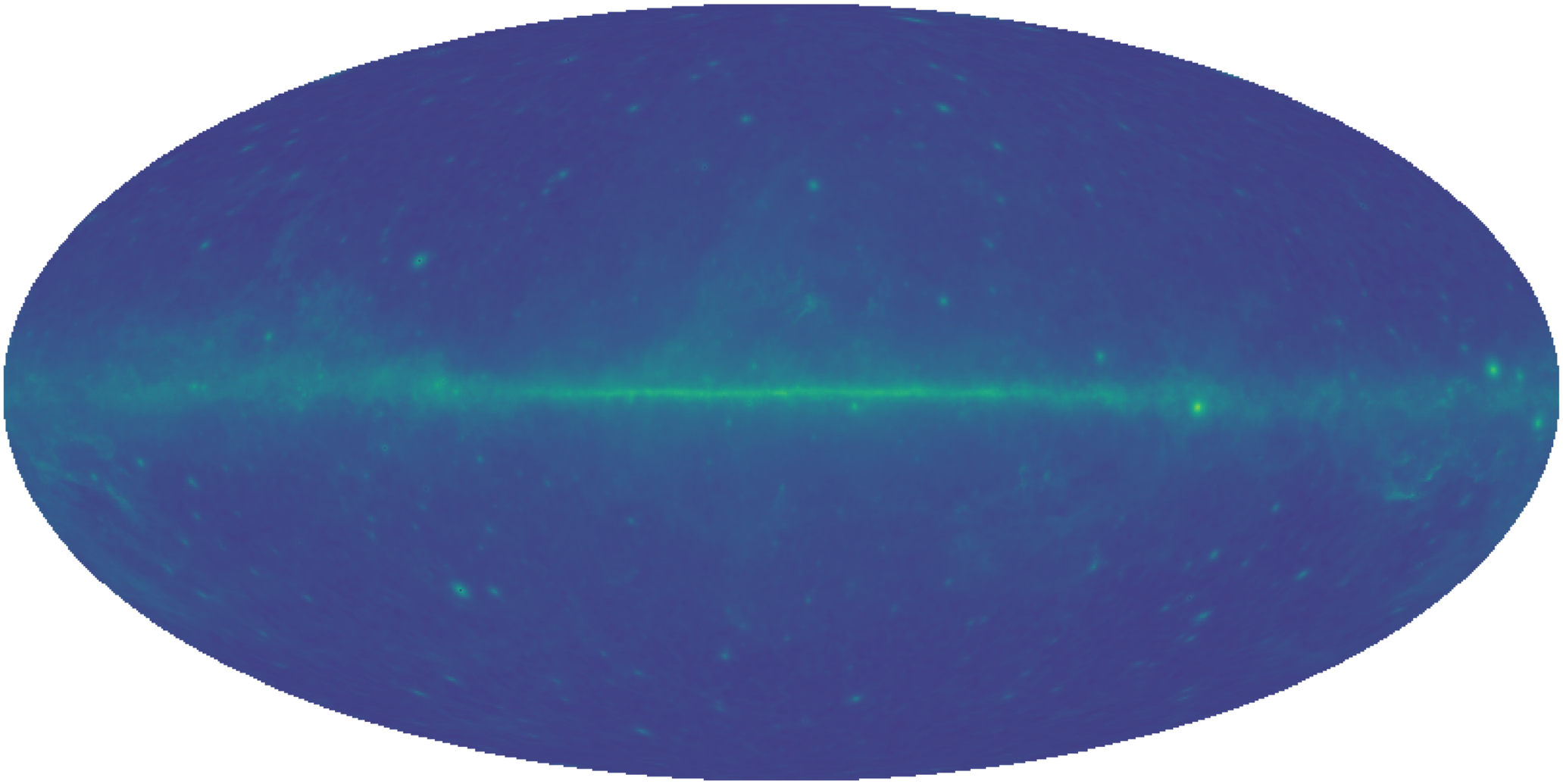
Outline

Unresolved Gamma-Ray Background (UGRB)

Definition of the UGRB

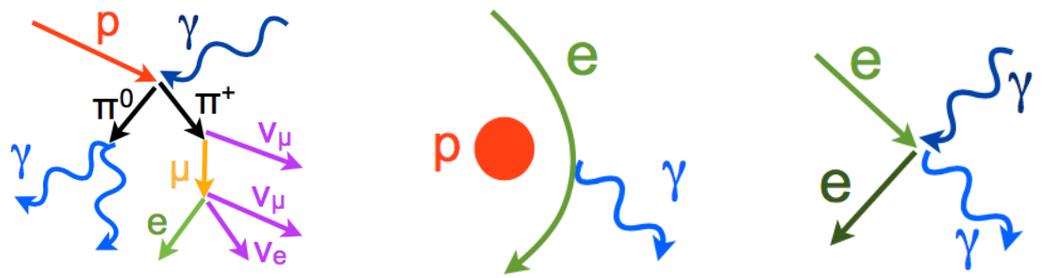
- What we resolve -

Let's start from the total γ-ray emission



~80% Galactic diffuse emission

CRs interact with the interstellar radiation field



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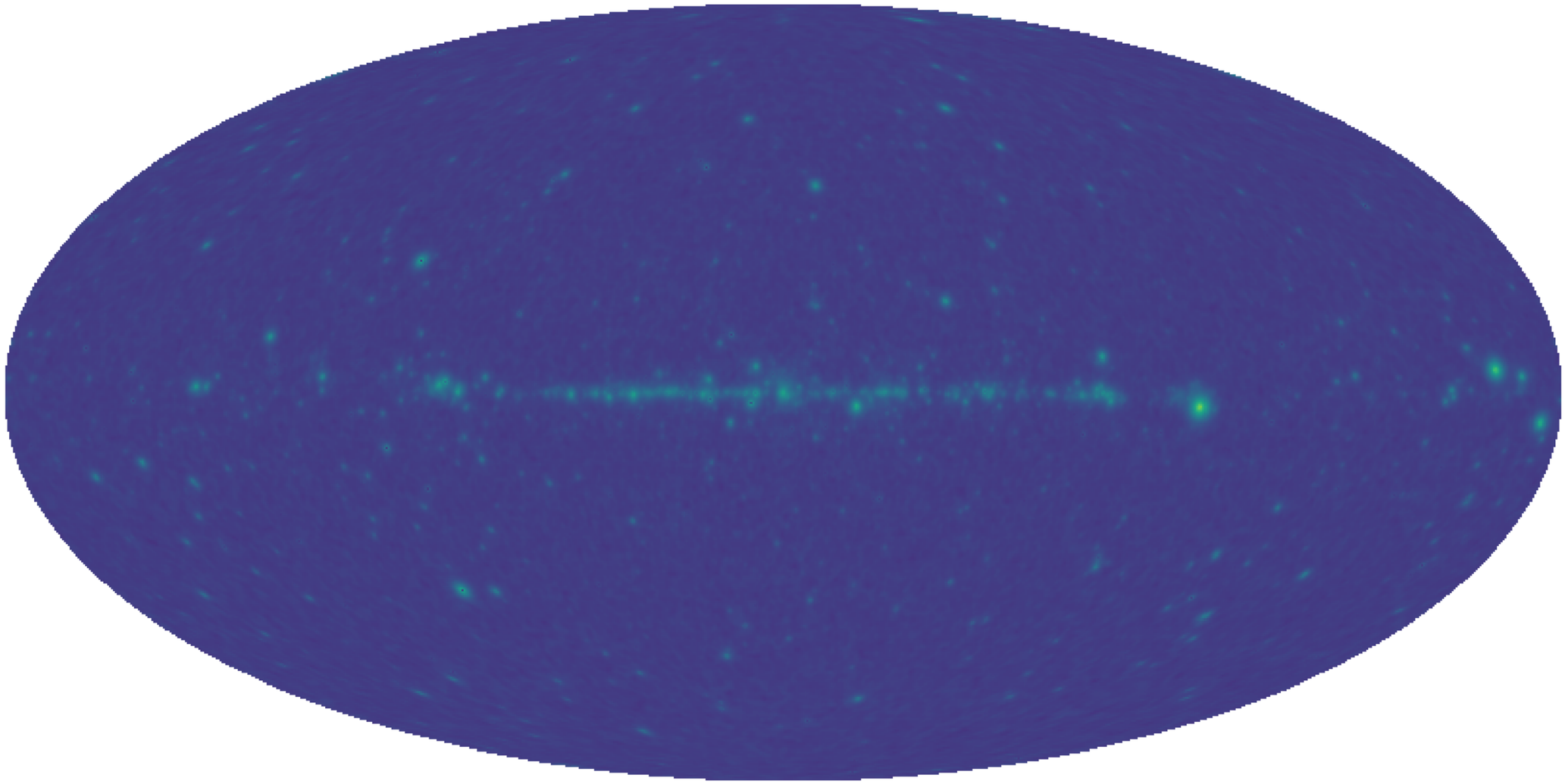
Definition of the UGRB

- What we resolve -

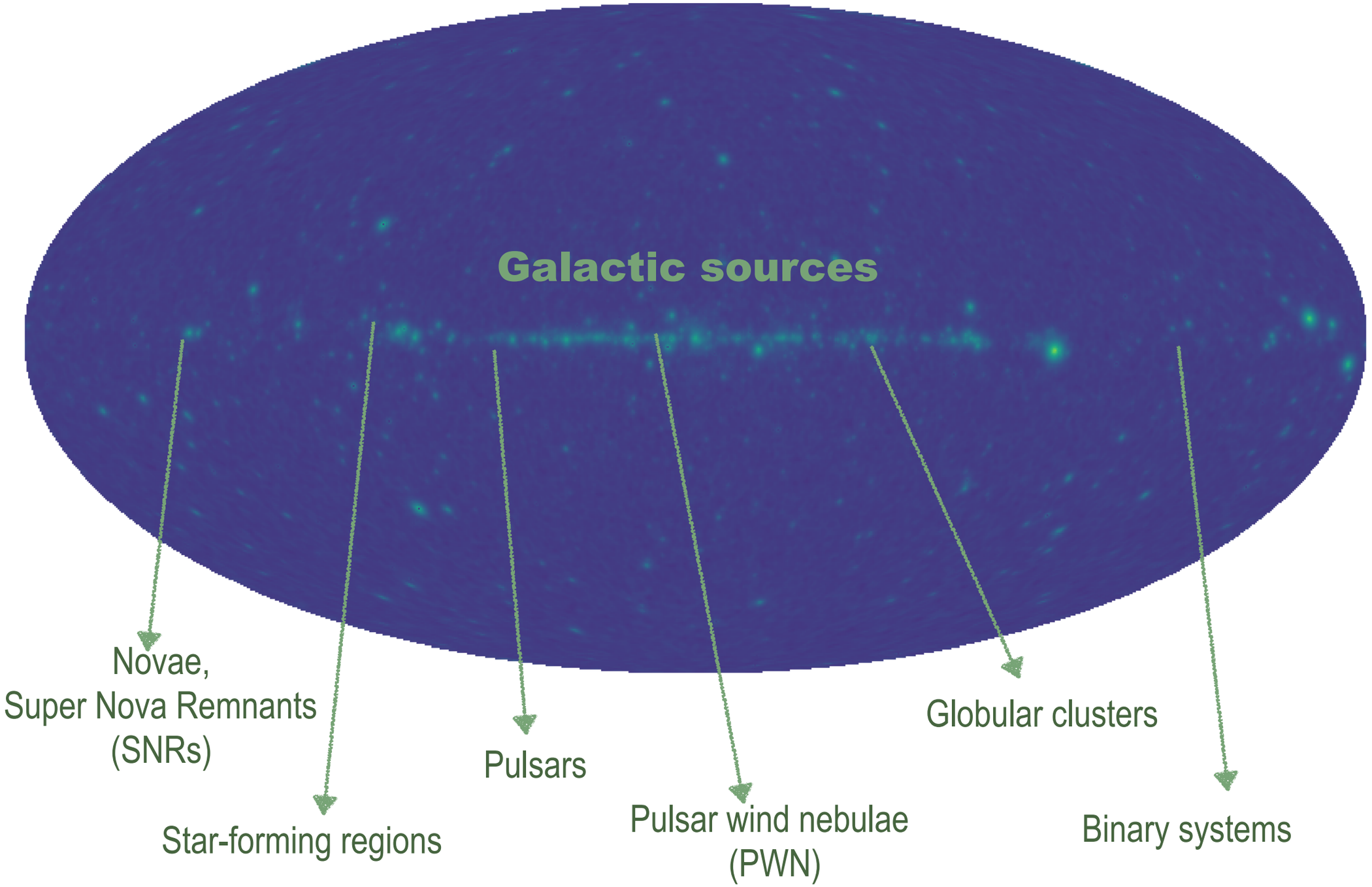
Let's switch off the Galaxy… Contribution of point sources



Definition of the UGRB

- What we resolve -

Contribution of point sources:



Definition of the UGRB

- What we resolve -

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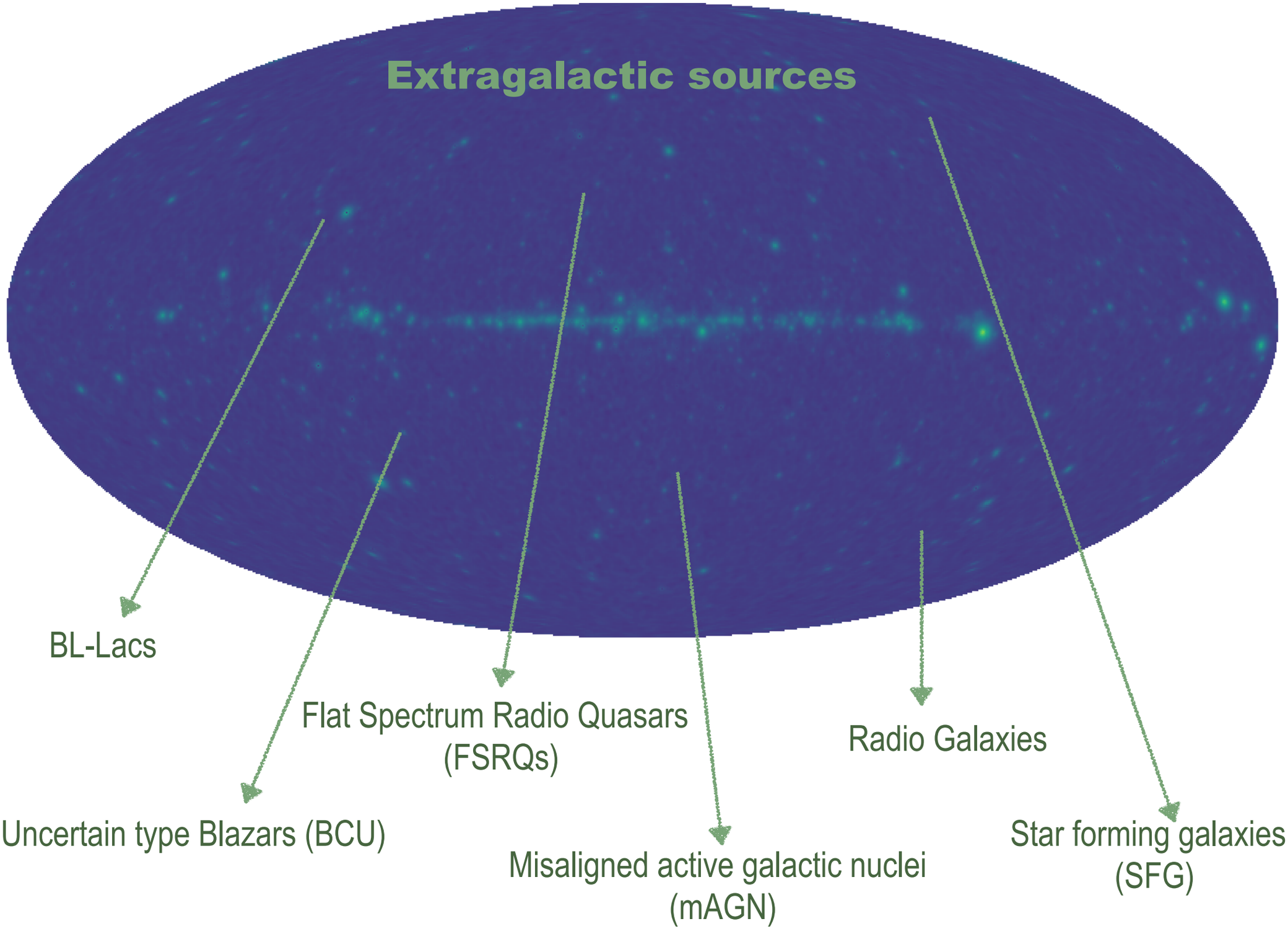
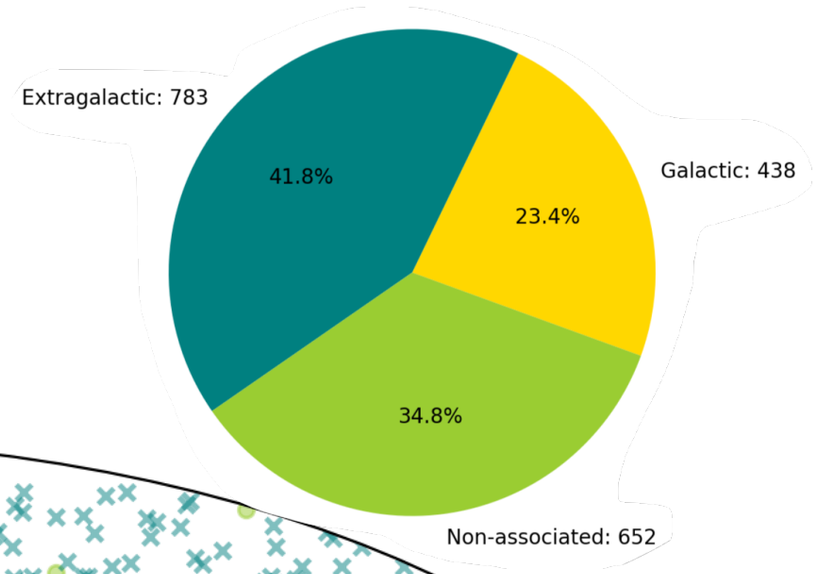
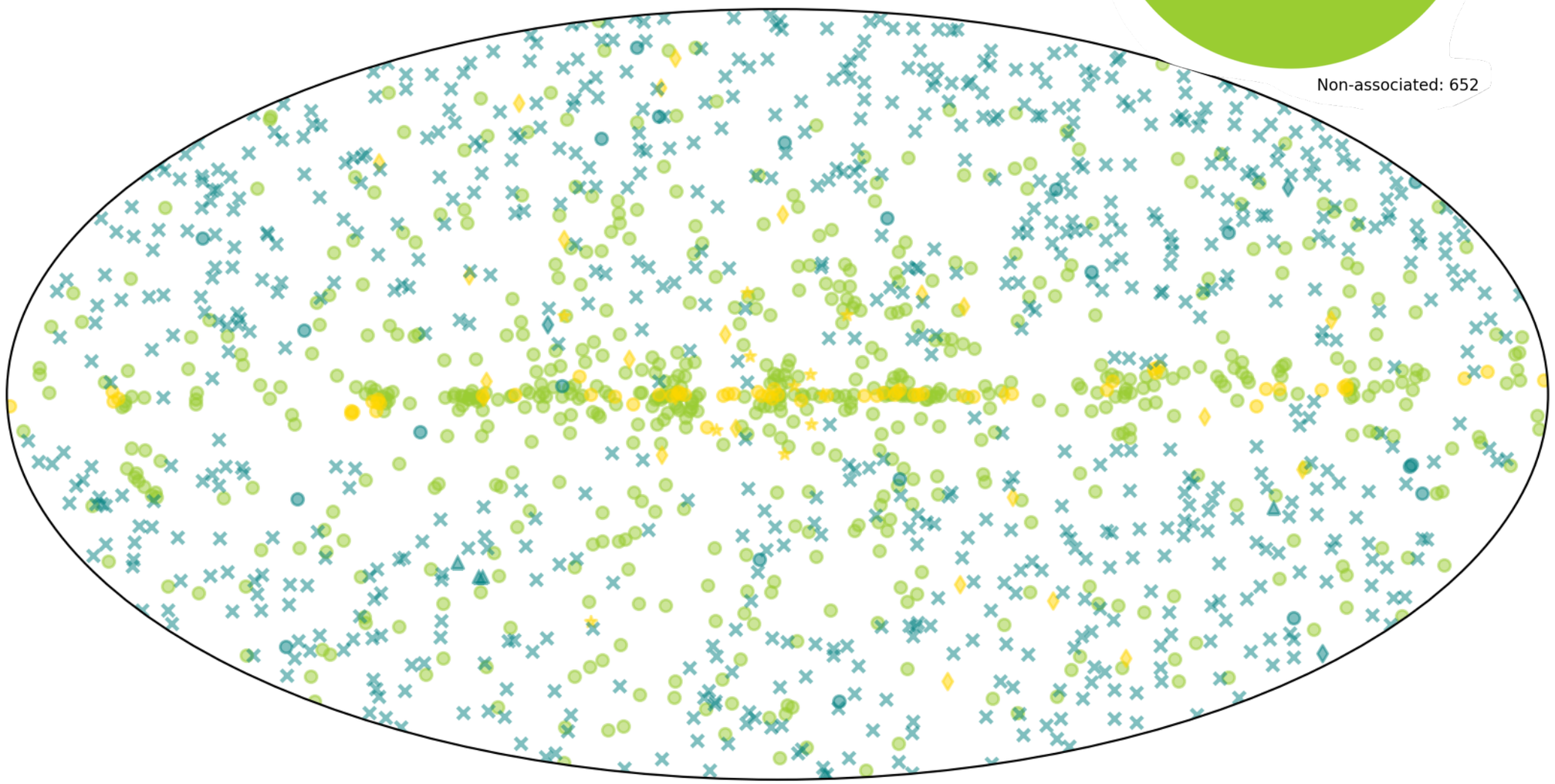


A time-dependent component

Fermi 2-year catalog: **2FGL**

1863 sources

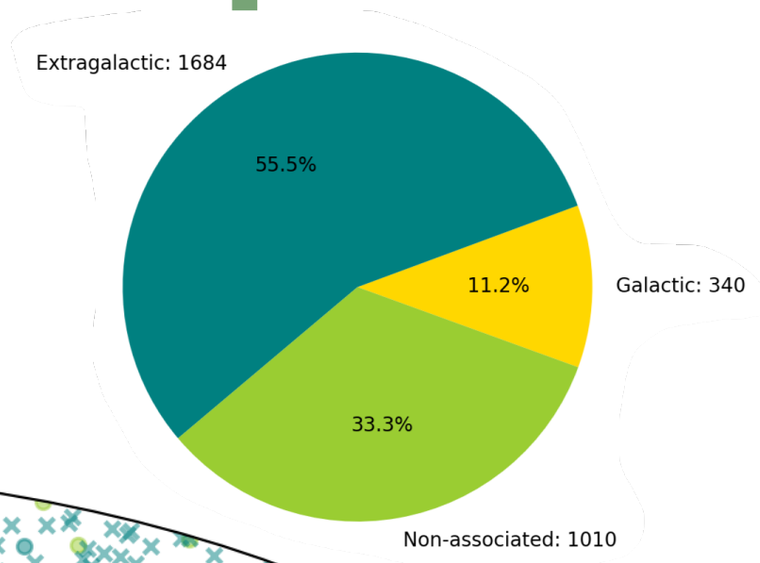


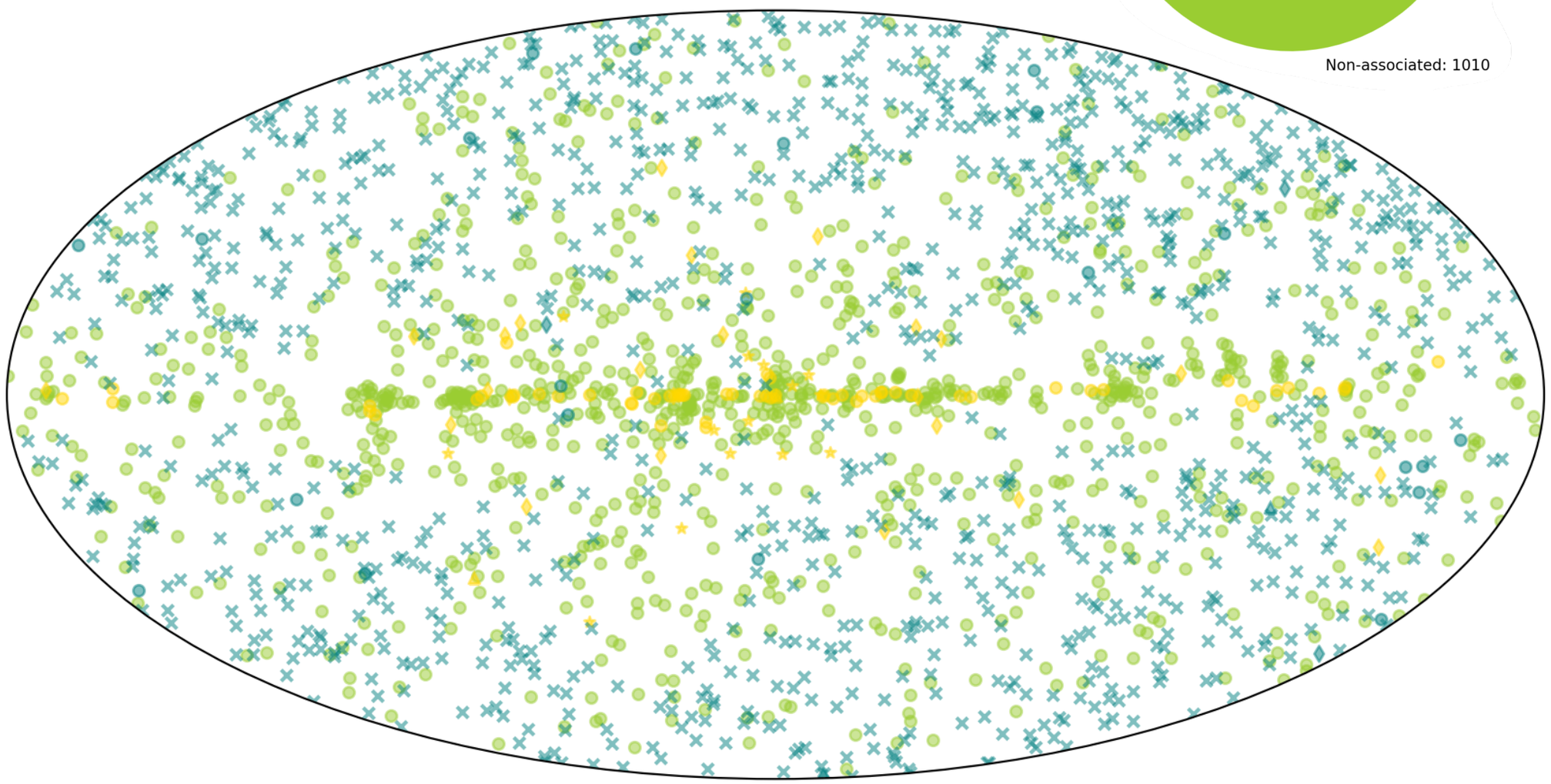


A time-dependent component

Fermi 4-year catalog: **3FGL**

3033 sources

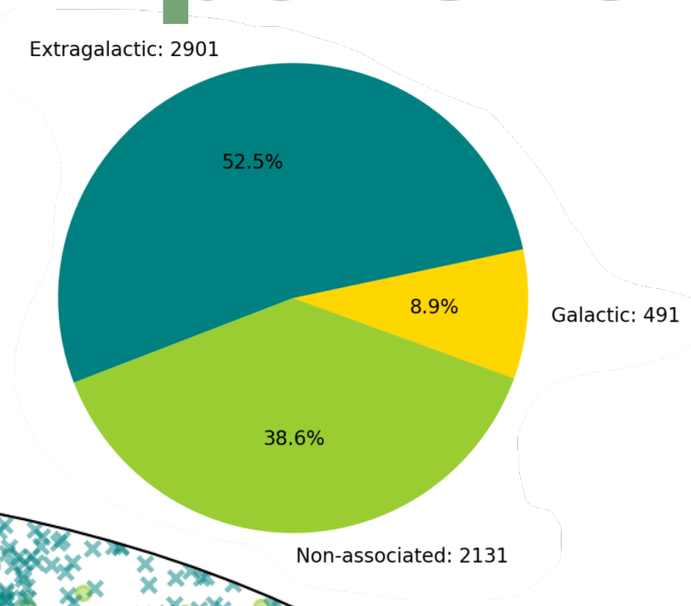


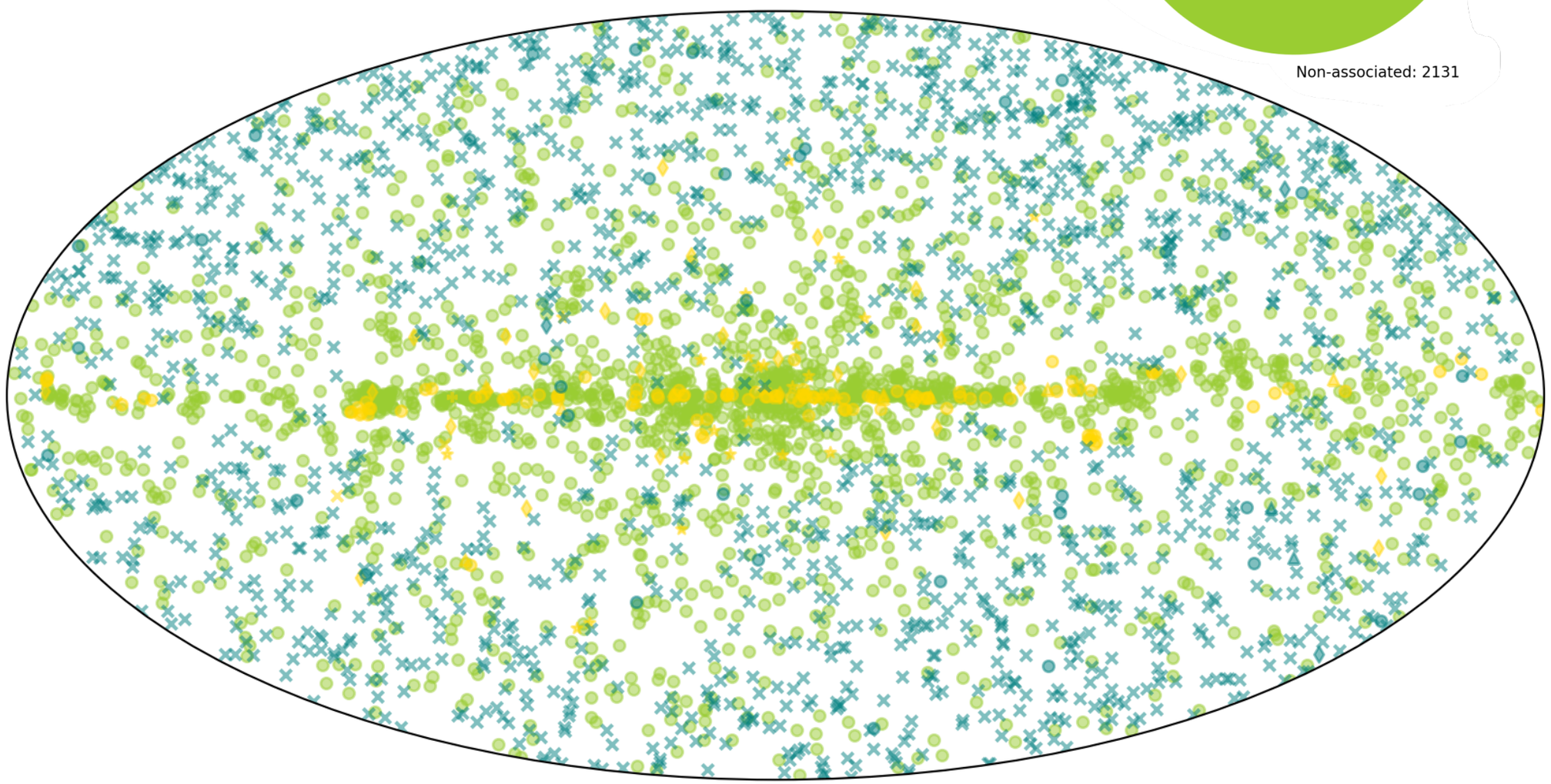


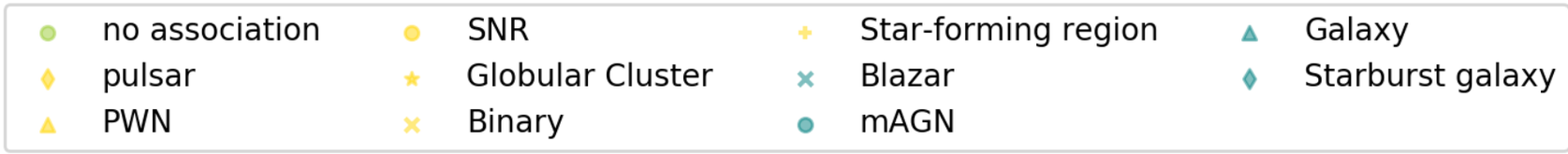
A time-dependent component

Fermi 8-year src list: **FL8Y**

5524 sources

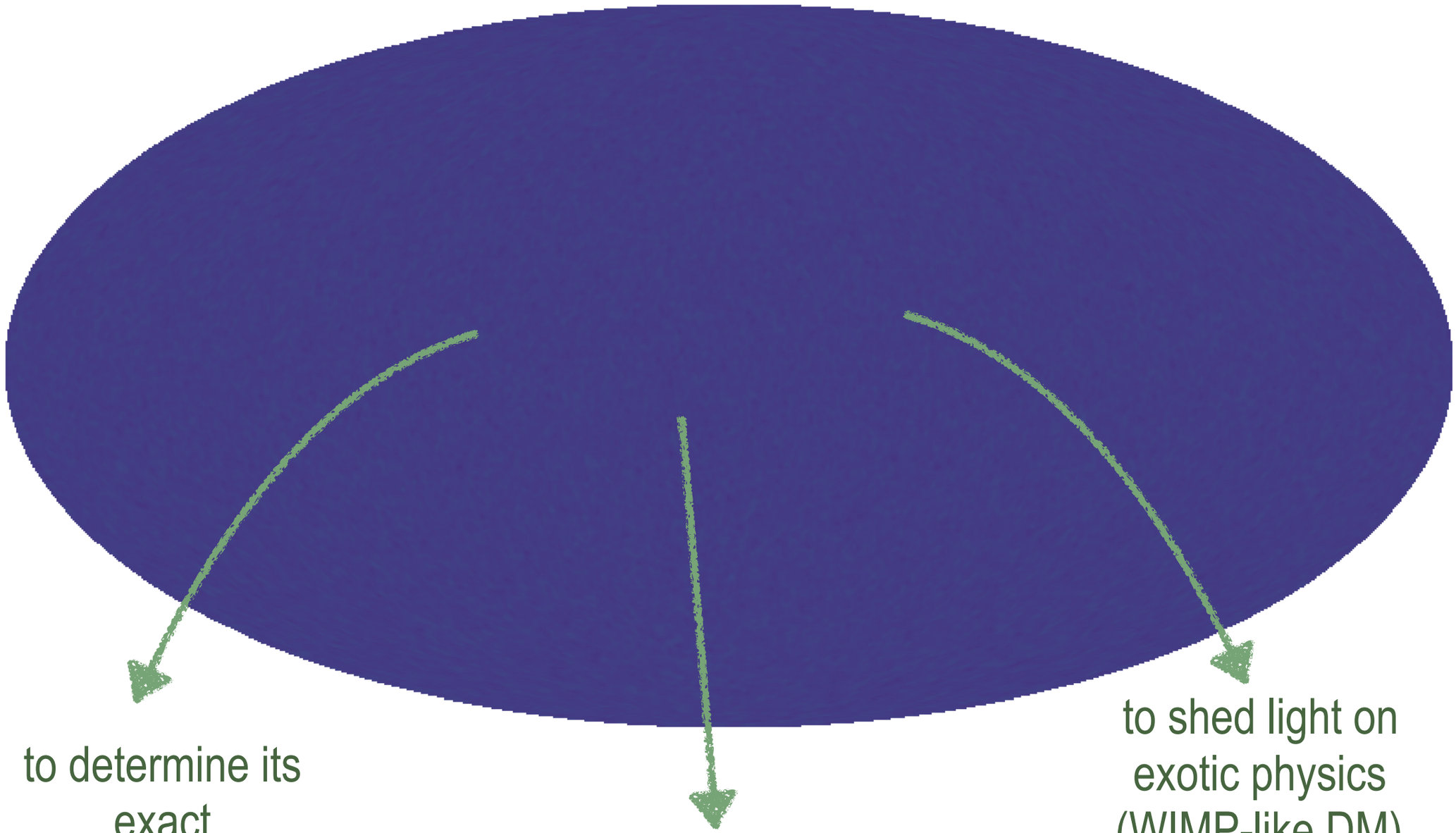






The UGRB
- Why -

Let's switch off the resolved point-like sources….



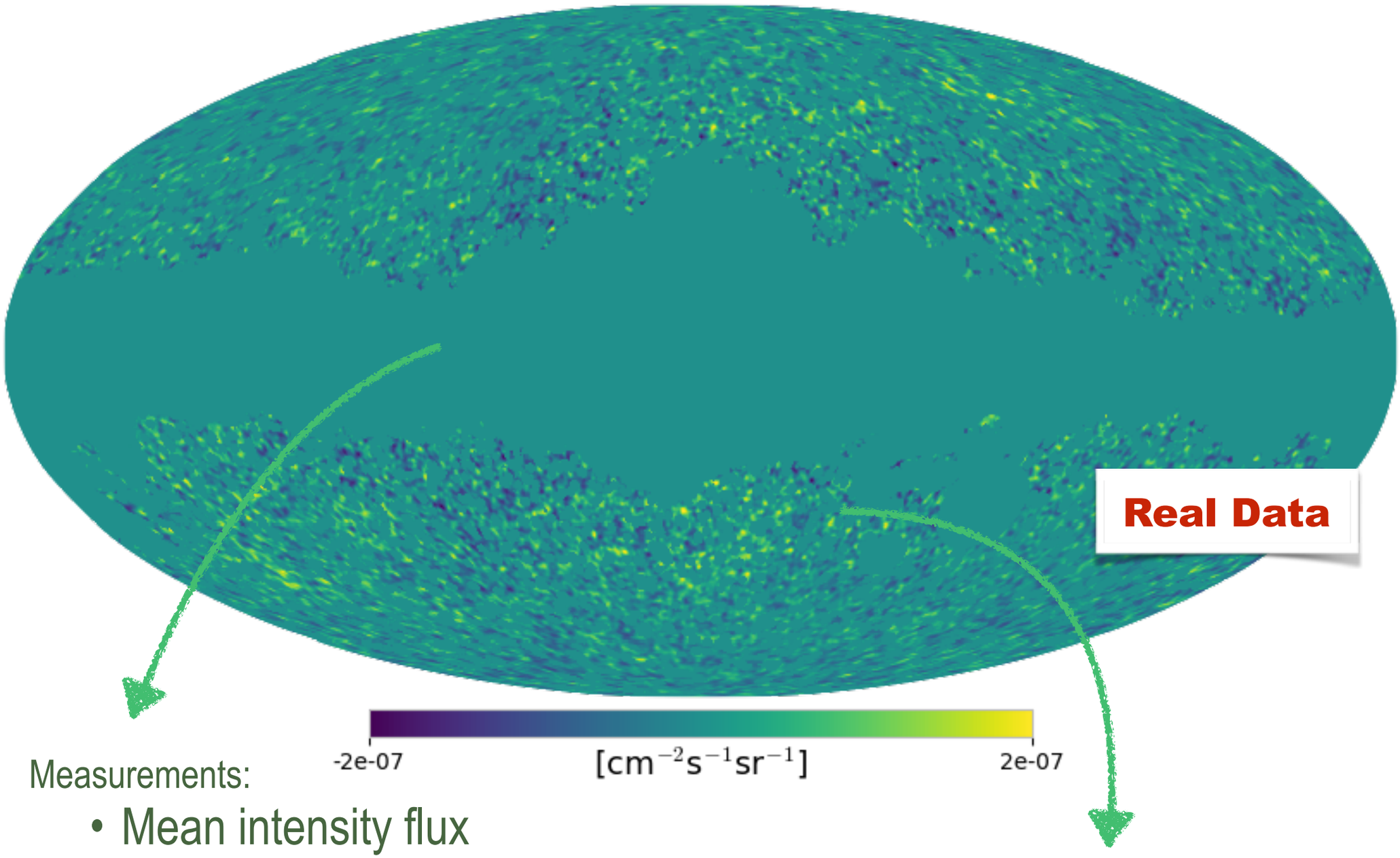
to determine its exact composition

to constrain the faint end of the luminosity functions

to shed light on exotic physics (WIMP-like DM)

The UGRB

- How to study -



Measurements:

- Mean intensity flux
- Intensity fluctuations amplitude
- Photon statistics

Characterization:

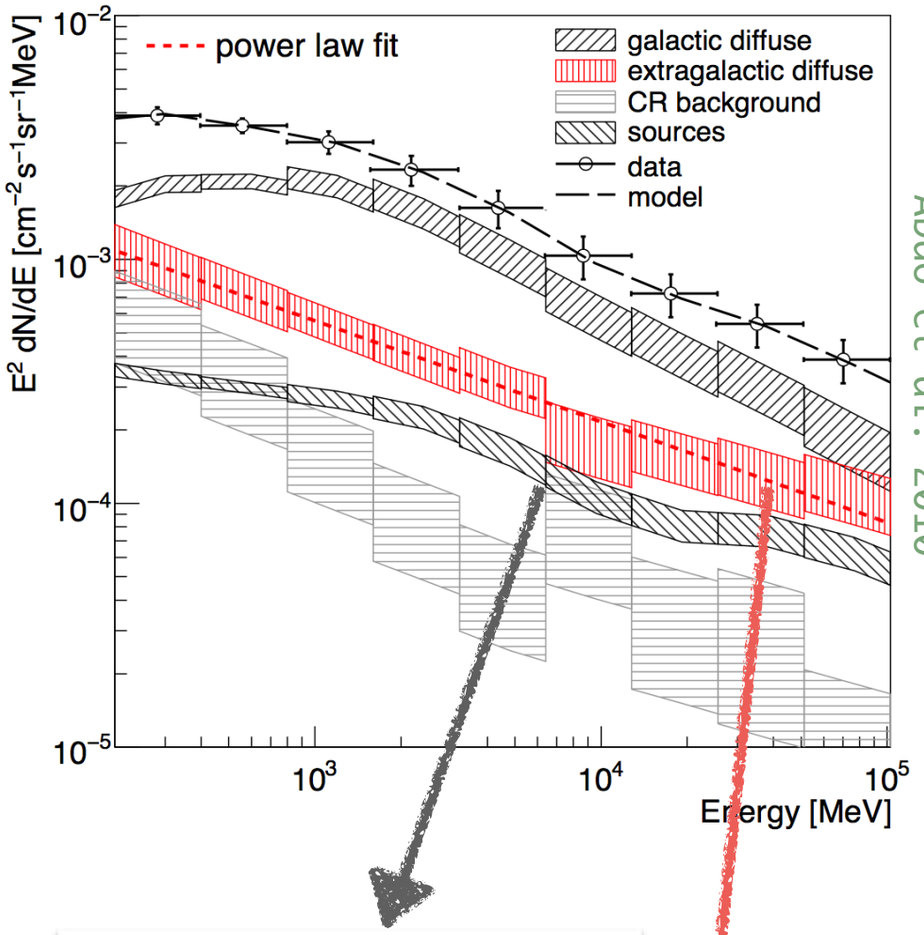
- Cross-correlation technique

UGRB measurements

Abdo et al. 2010, arXiv:1002.3603v1
Ackermann et al. 2014, arXiv:1410.3696v1

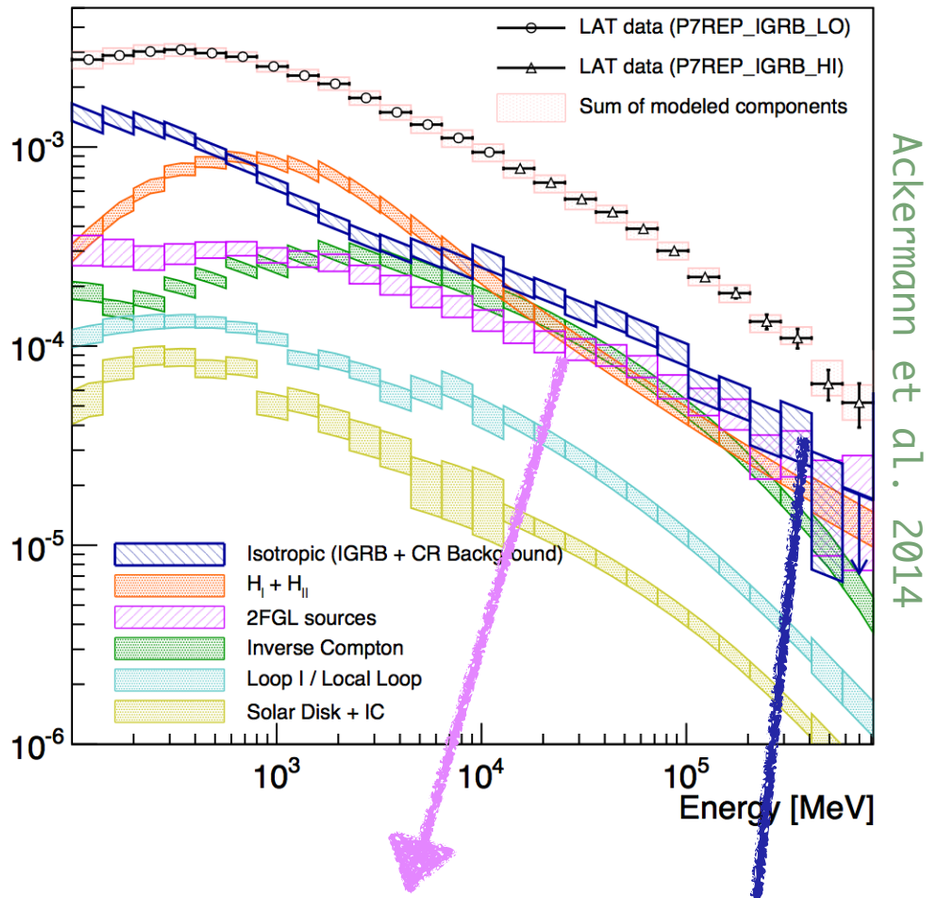
UGRB measurements

- The Intensity Spectrum -



Internal 9-months src list

UGRB @ 10 months

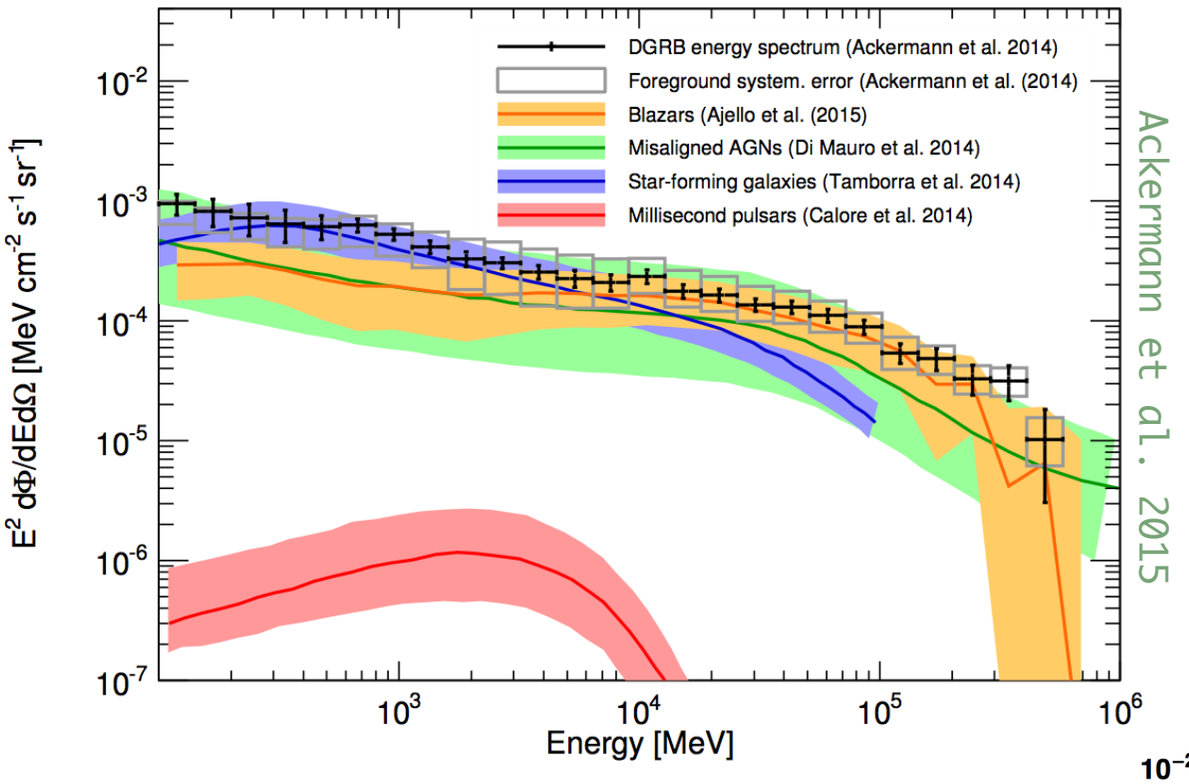


2FGL catalog

UGRB @ 50 months

UGRB measurements

- The Intensity Spectrum -



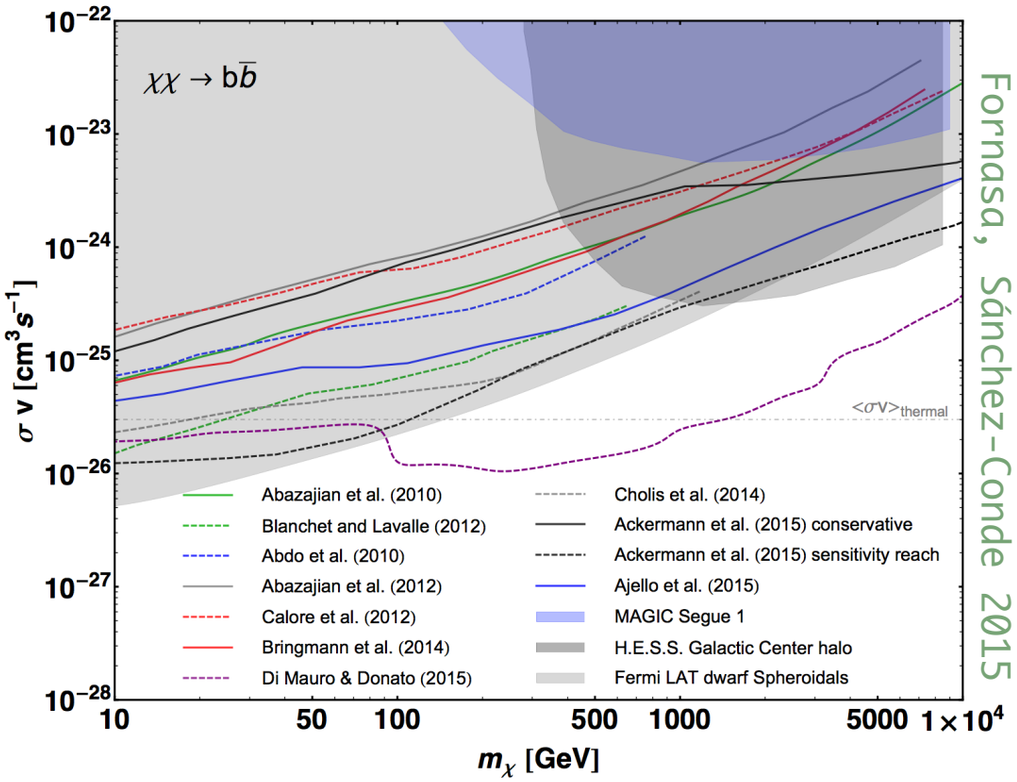
$$I = \int_0^{S_{th}} S \frac{dN}{dS} dS$$

source detection threshold

characteristic of a population (inferred from resolved part)

UGRB astrophysical contributors:

- Blazars
- mAGNs
- SFGs
- MS Pulsars



Not much space left for DM: upper limits

Ackermann et al. 2015, arXiv:1410.3696

UGRB measurements

- The photon count PDF -

Statistical tool: ***1-point photon count probability distribution function (1pPDF)***

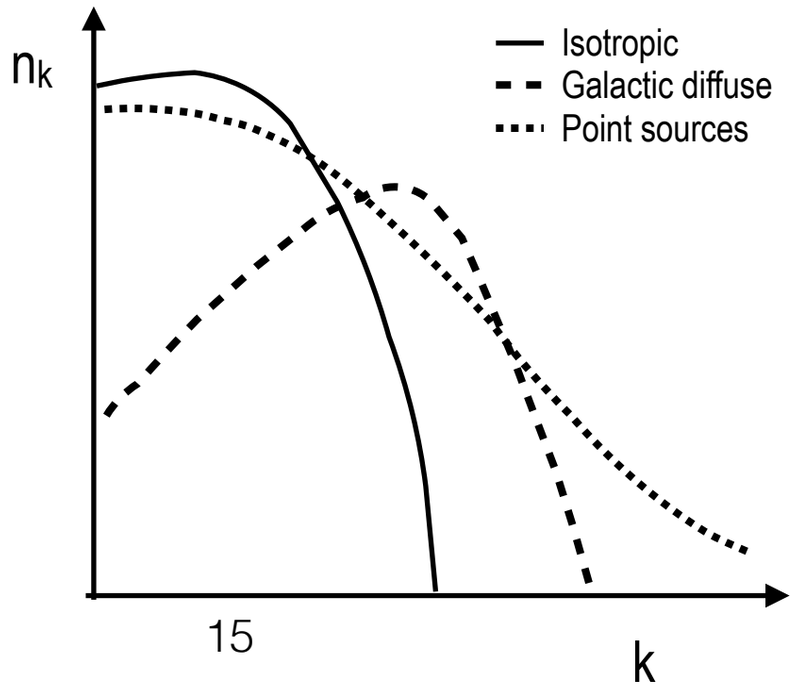
Probability of counting κ photons in a certain pixel: $p_\kappa = \frac{n_\kappa}{N_{pix}}$ num. of pixels with k photons

A possible method to calculate p_k: generating function P(t) $P(t) = \sum_{\kappa=0}^{\infty} p_\kappa t^\kappa$

Discriminate a **Poisson** PDF from a **non-Poissonian** PDF:

Diffuse or SFG-like
(numerous and faint objects)

AGN-like
(rare and bright objects)



UGRB measurements

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Point sources generating function:

$$S(t) = \exp\left[\sum_{m=1}^{\infty}(x_m t^m - x_m)\right]$$

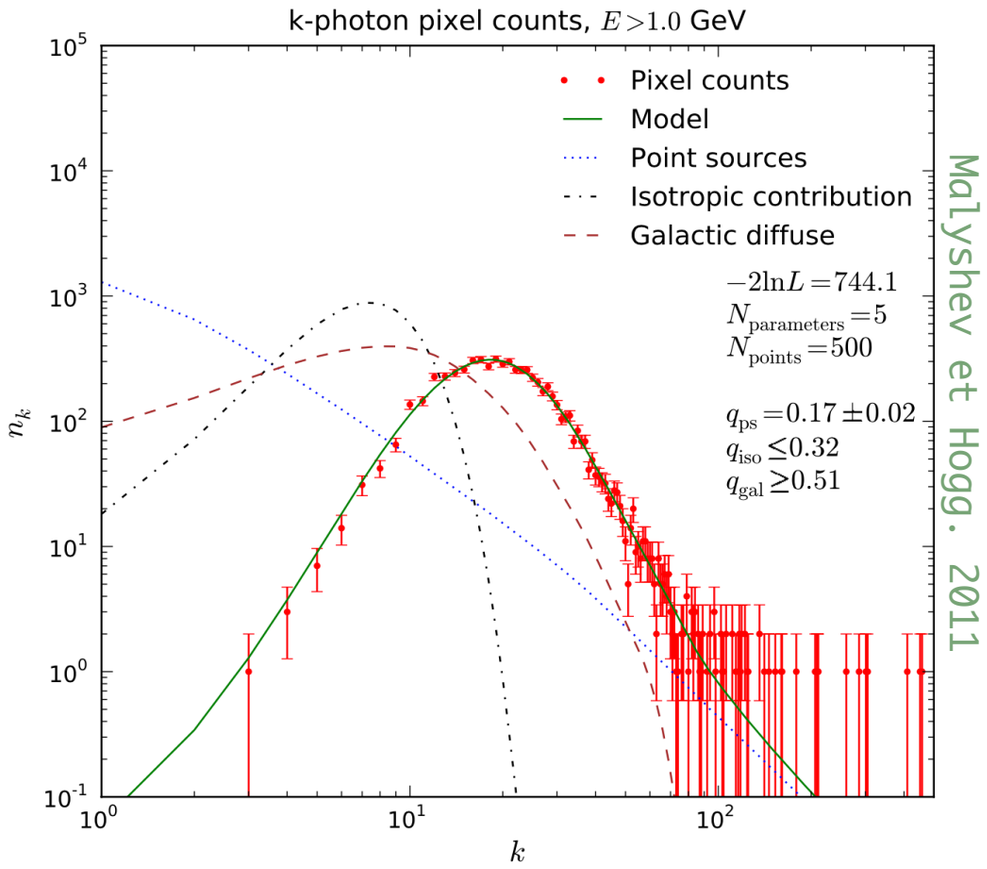
Galactic diffuse generating function:

$$G(t) = \frac{1}{N_{pix}}\sum_{p=1}^{N_{pix}} \exp\left(x_{p,Gal}t - x_{p,Gal}\right)$$

Isotropic generating function:

$$I(t) = \exp\left(x_{iso}t - x_{iso}\right)$$

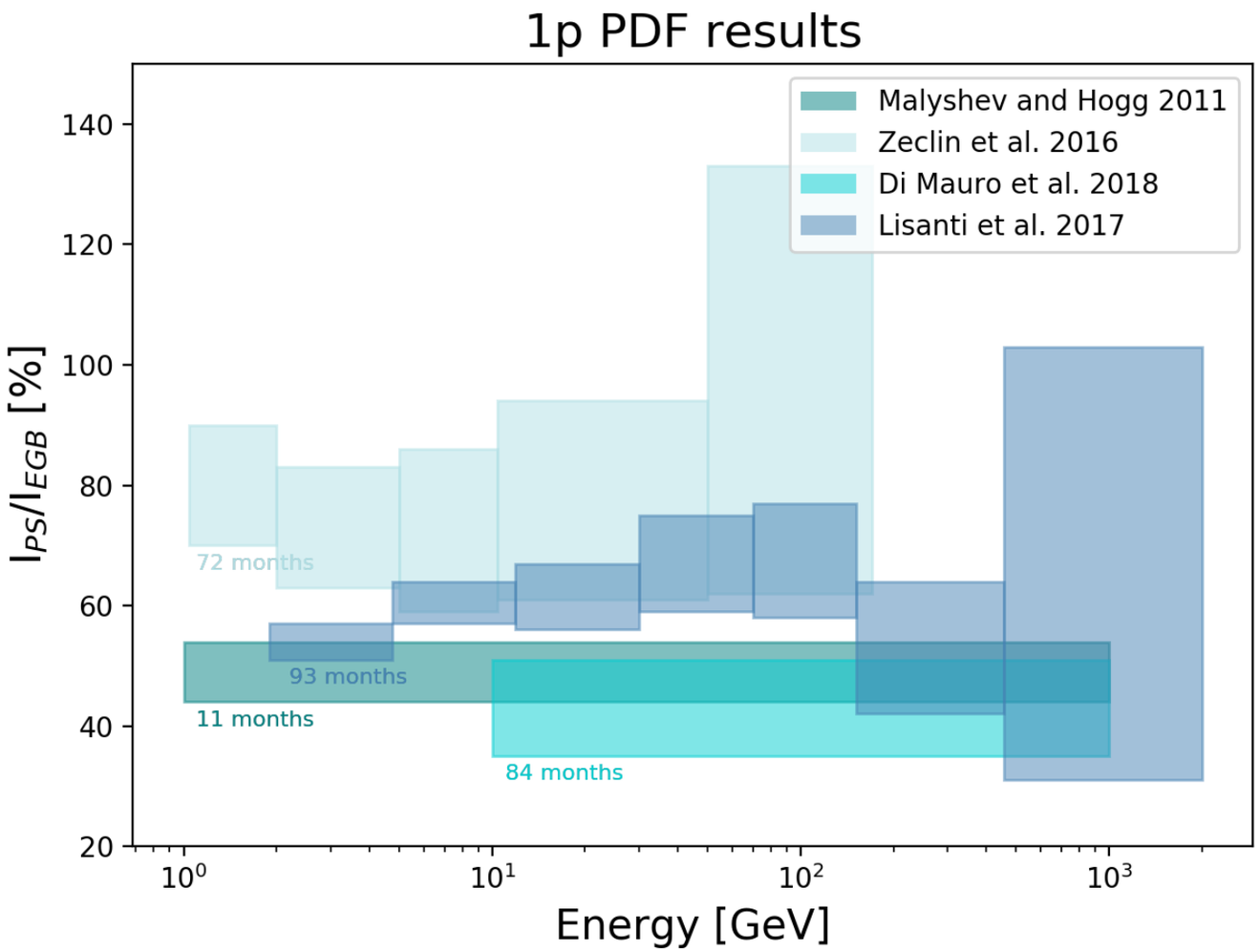
Total: $P(t) = S(t)G(t)I(t)$



UGRB measurements

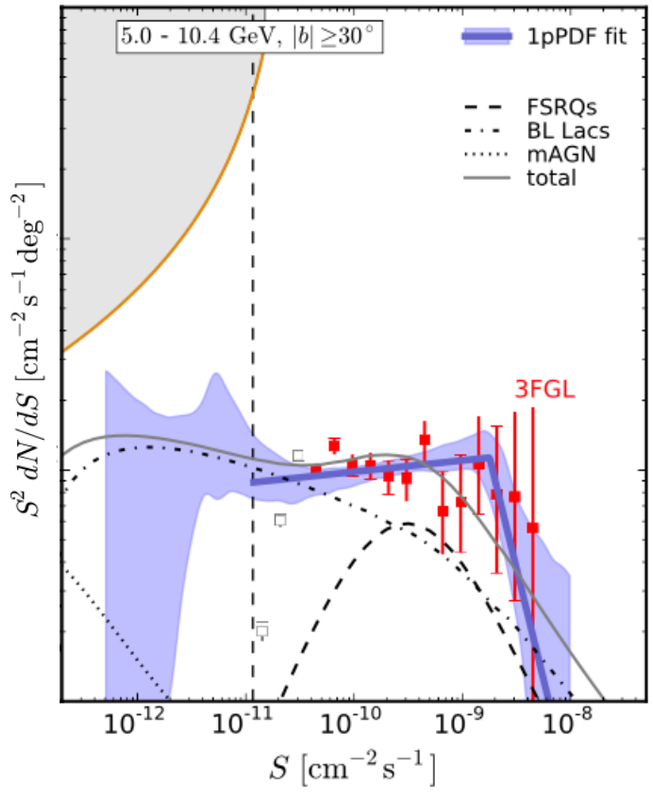
- The photon count PDF -

Point sources contribution to the total EGB intensity:



$$x_m = \frac{\Omega_{pix}}{4\pi} \int_0^\infty dS \frac{dN}{dS}(S) \frac{S^m}{m!} \mathrm{e}^{-S}$$

Zechlin et al. 2016



Unresolved point sources contribution:

$$N_{unres} = \int_0^{S_{th}} \frac{dN}{dS} dS$$

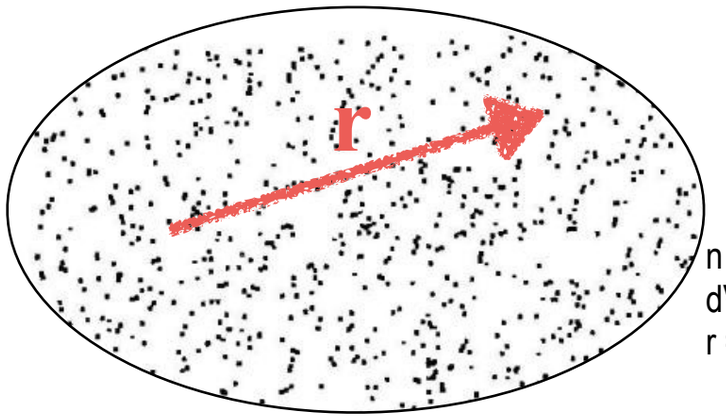
source detection threshold: catalog-dependent

characteristic of a population (inferred from resolved part)

UGRB measurements

- The Anisotropy Spectrum -

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*.



n = number density
dV = volume
r = separation

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

e.g: ξ = 0 for a random field

In terms of density fluctuation at the position **x:** $\delta(\mathbf{x}) = \frac{n(\mathbf{x})}{\langle n \rangle} - 1$

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

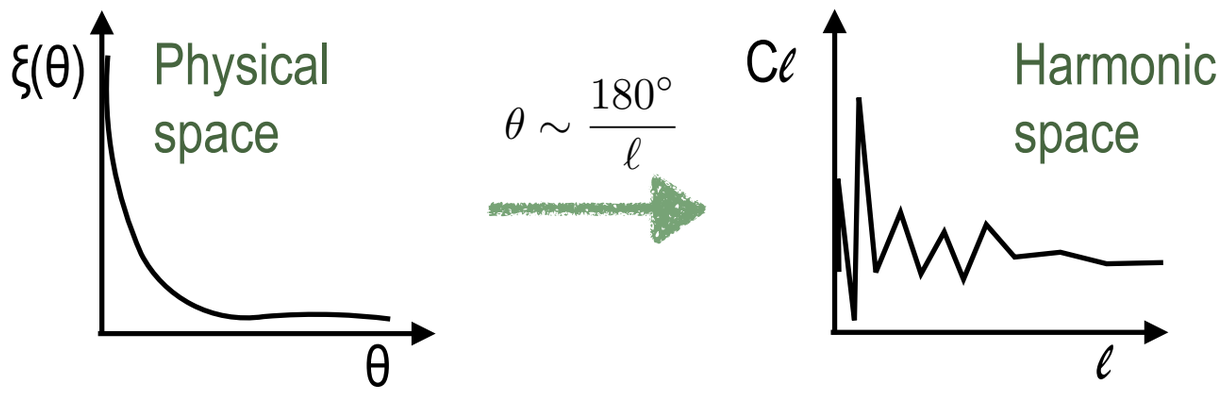
For a spherical surface geometry it is convenient to use the Legendre transform: the ***angular power spectrum (APS), C_l:***

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

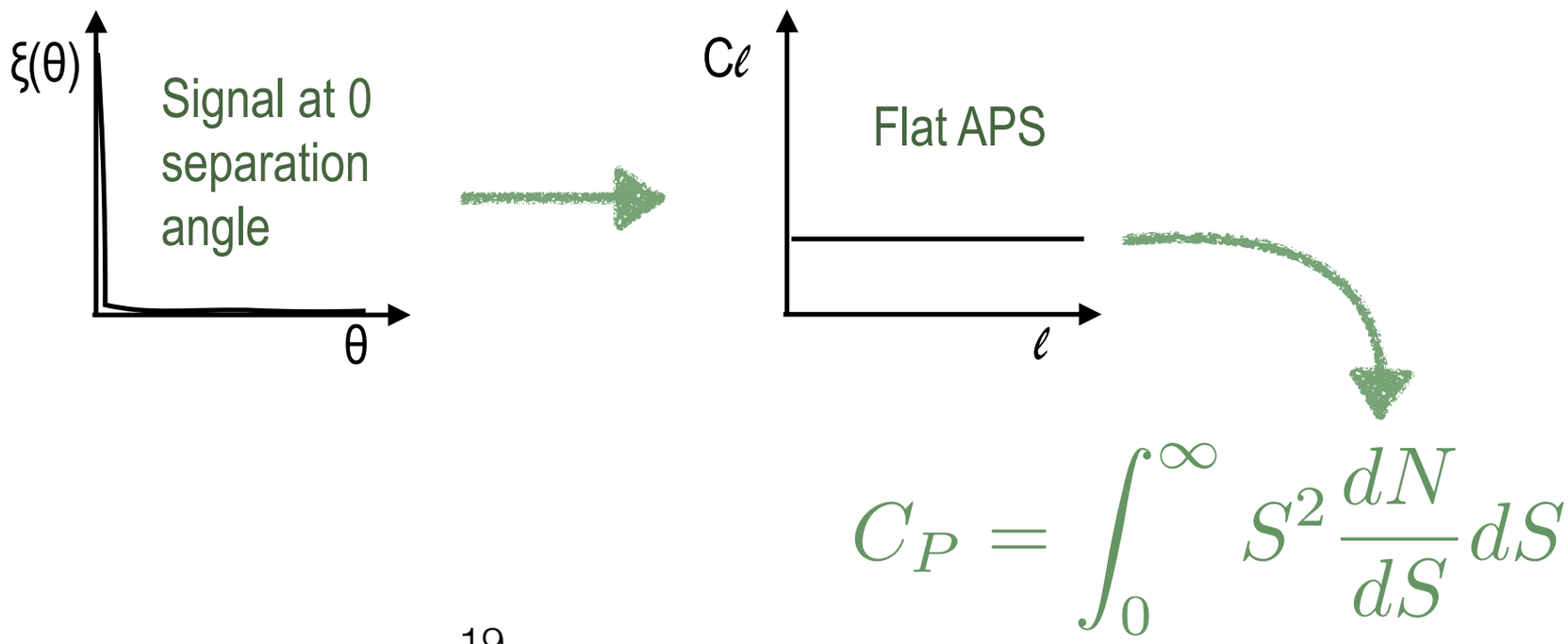
UGRB measurements

- The Anisotropy Spectrum -

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



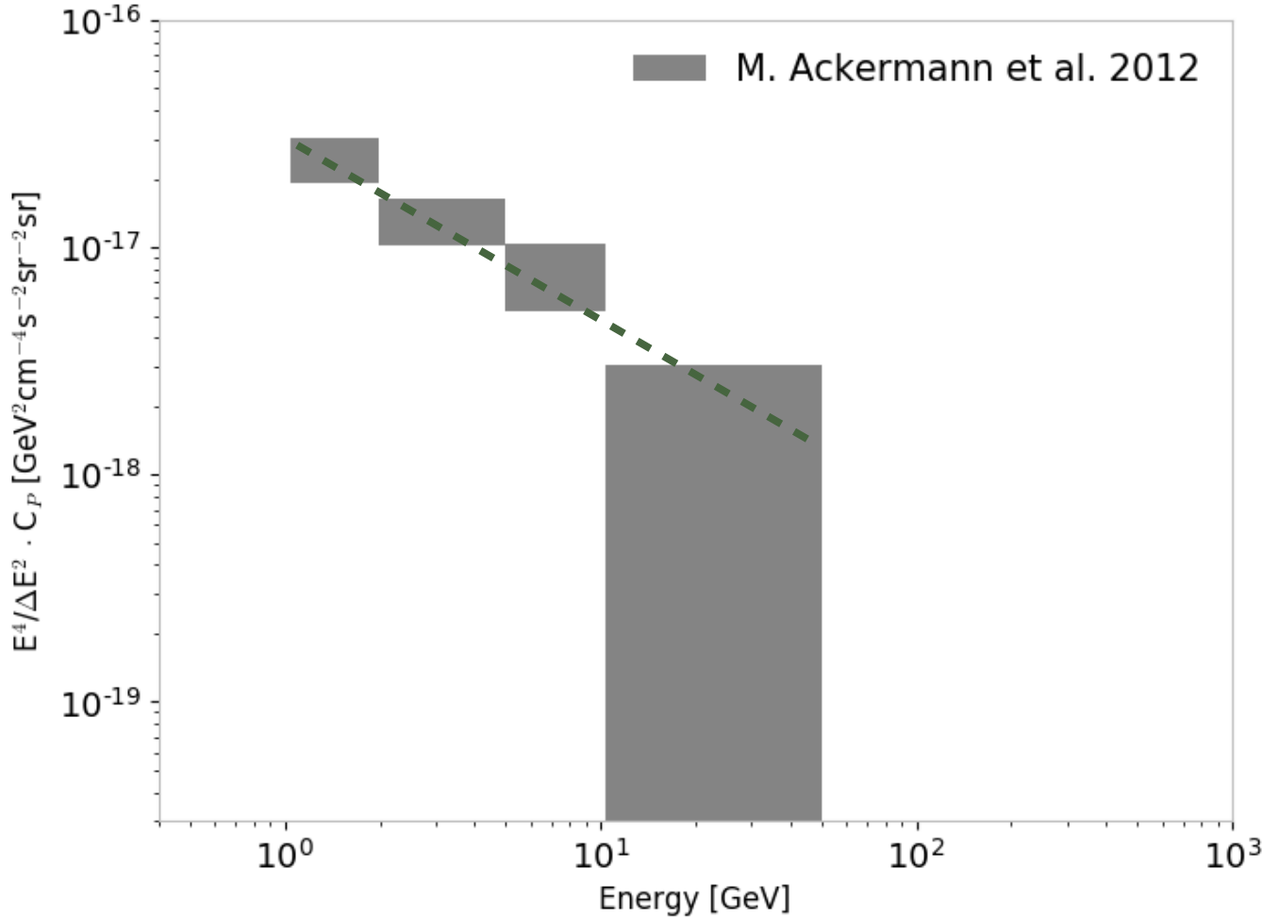
If the anisotropy field is produced by point like-sources:



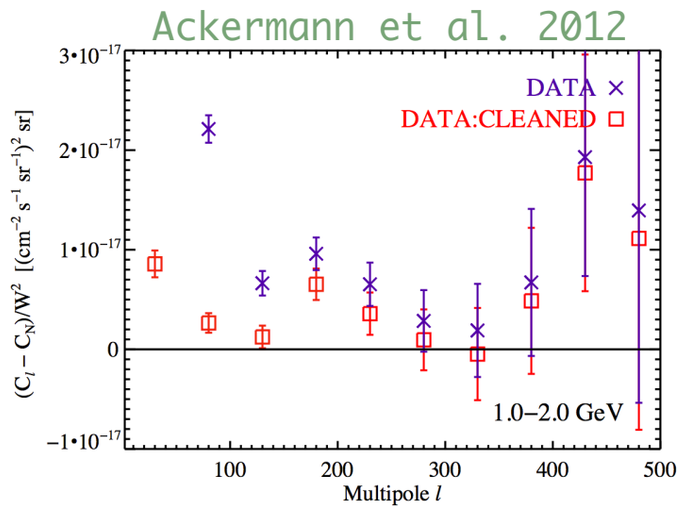
$$C_P = \int_0^\infty S^2 \frac{dN}{dS} dS$$

UGRB measurements

- The Anisotropy Spectrum -



22 months (Pass 6)
1-50 GeV (4 bins)
2FGL mask (plus |b|<30)
$155 < \ell < 504$



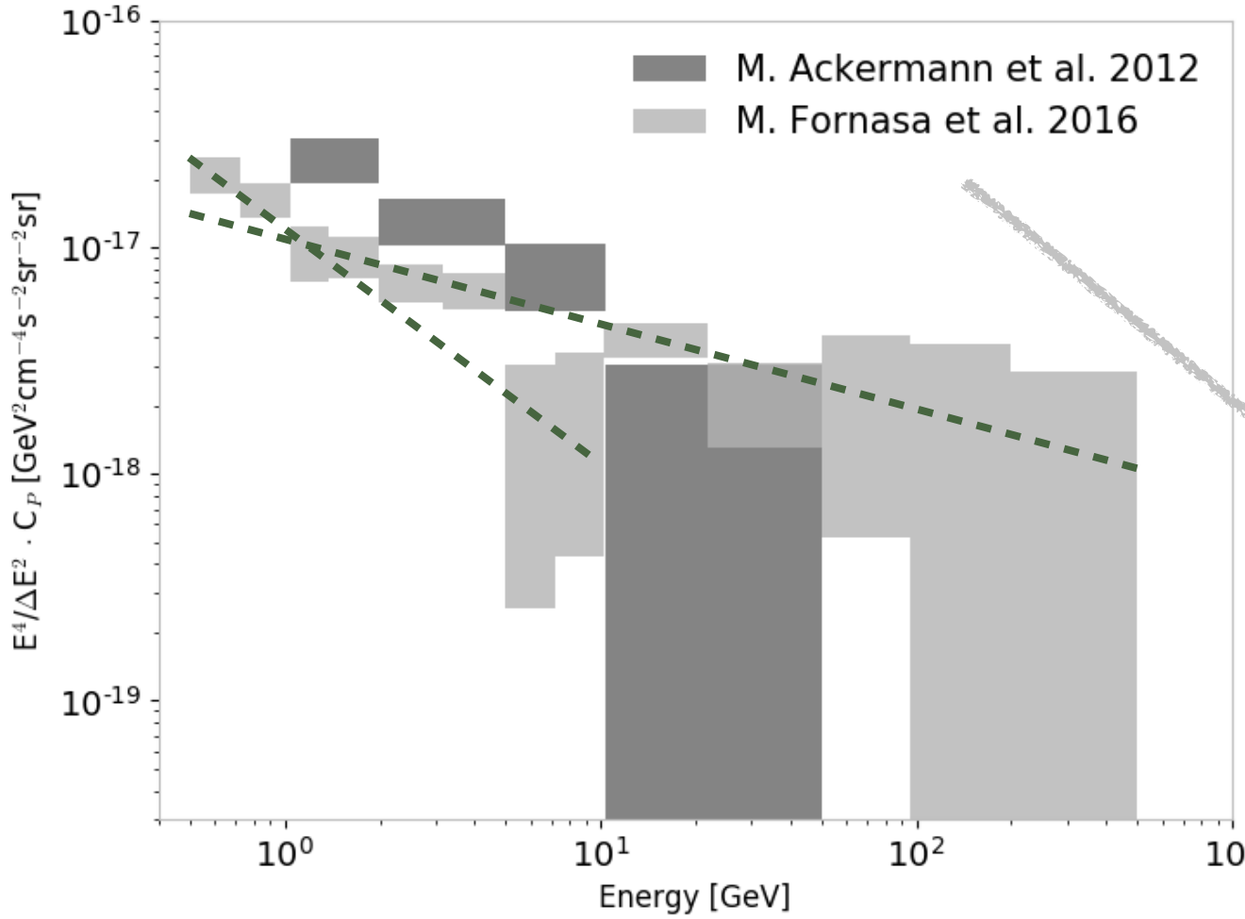
Single power-law with index $\Gamma = 2.40 \pm 0.07$

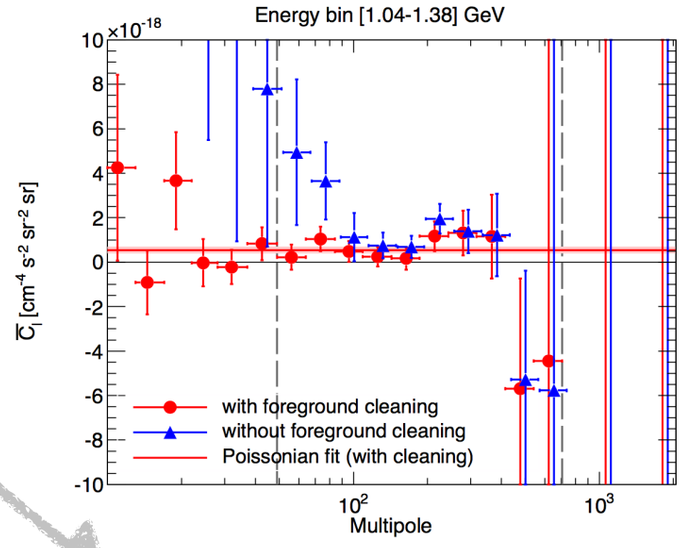
One or more populations of point-like sources can contribute

Ackermann et al. 2012, arXiv:1202.2856v1
Fornasa et al. 2016, arXiv:1608.07289v2
Ando et al. 2017, arXiv:1701.06988v1

UGRB measurements

- The Anisotropy Spectrum -



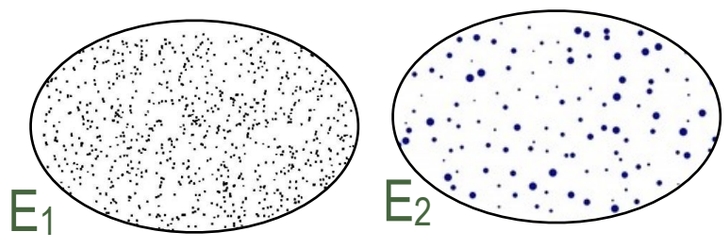


Fornasa et al. 2016

82 months (Pass 7)
0.5-500 GeV (13 bins)
3FGL mask (plus |b|<30)
$50 < \ell < 700$

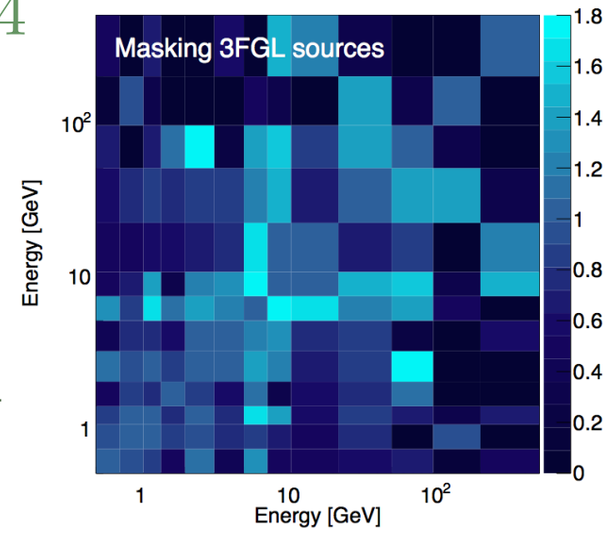
Two power laws: $\alpha = 3.27 \pm 0.7$ $\beta = 2.24 \pm 0.04$

Hints of two populations contributing: cross-correlations between energy bins



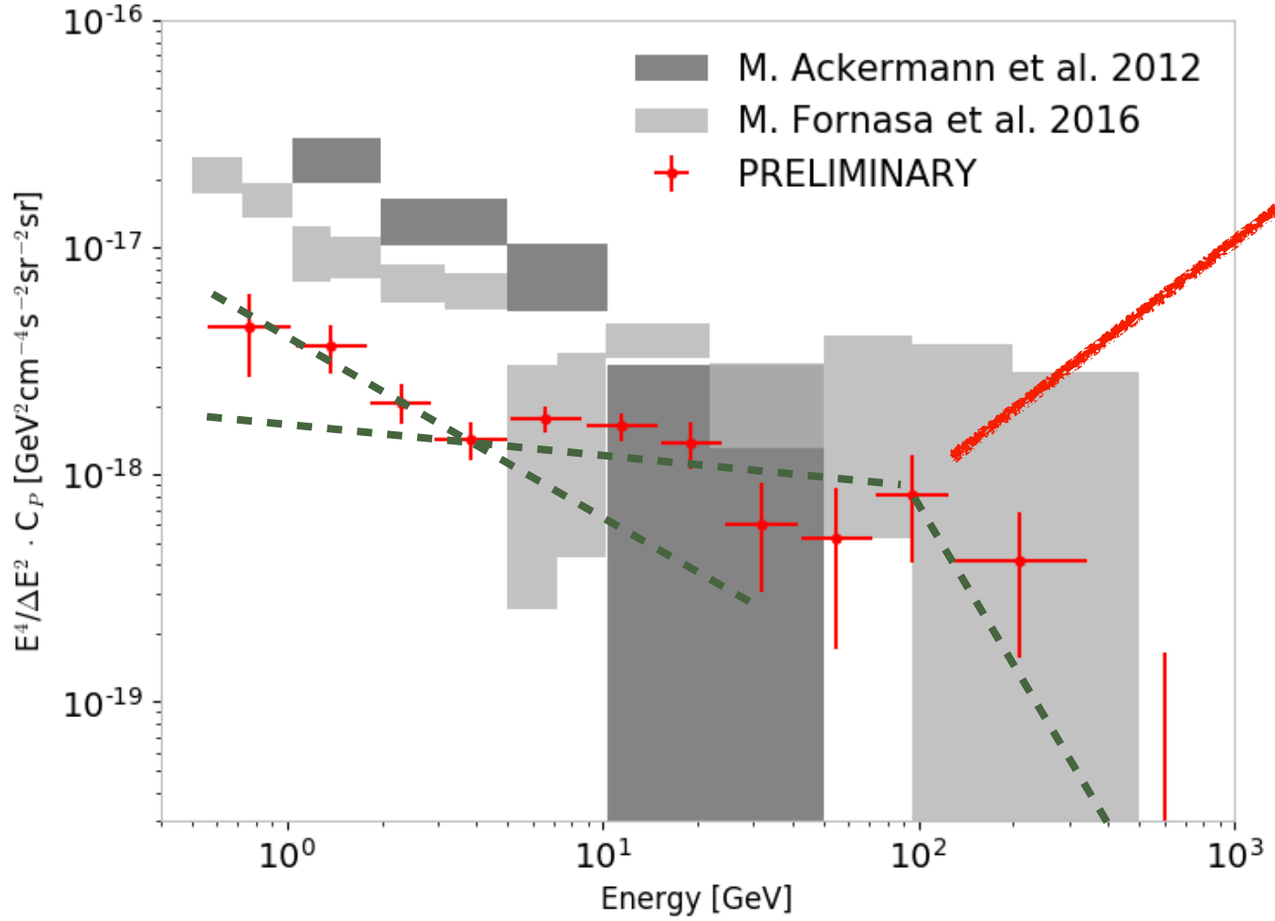
$$E_1 \times E_1 \rightarrow C_P^{11}$$
$$E_2 \times E_2 \rightarrow C_P^{22}$$
$$E_1 \times E_2 \rightarrow C_P^{12} \leq \sqrt{C_P^{11} C_P^{22}}$$

Fornasa et al. 2016

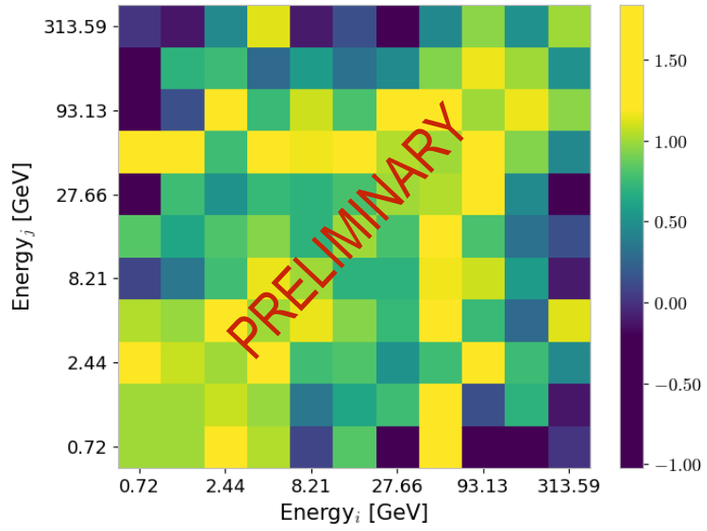


UGRB measurements

- The Anisotropy Spectrum -



8 years (Pass 8)
0.5-1000 GeV (12 bins)
FL8Y + **3FHL** mask (+ GP mask)
$50 < \ell < \ell_{max}$ **(E)**

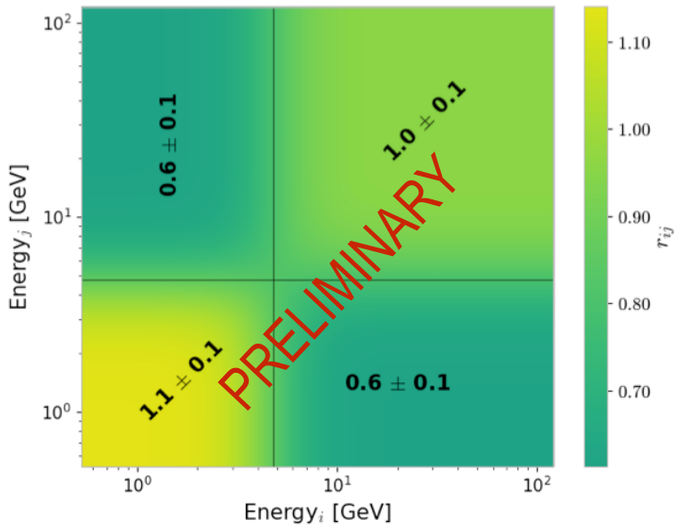


Two power laws + cutoff:

$$\alpha = 2.51 \pm 0.16 \quad \beta = 1.82 \pm 0.12$$

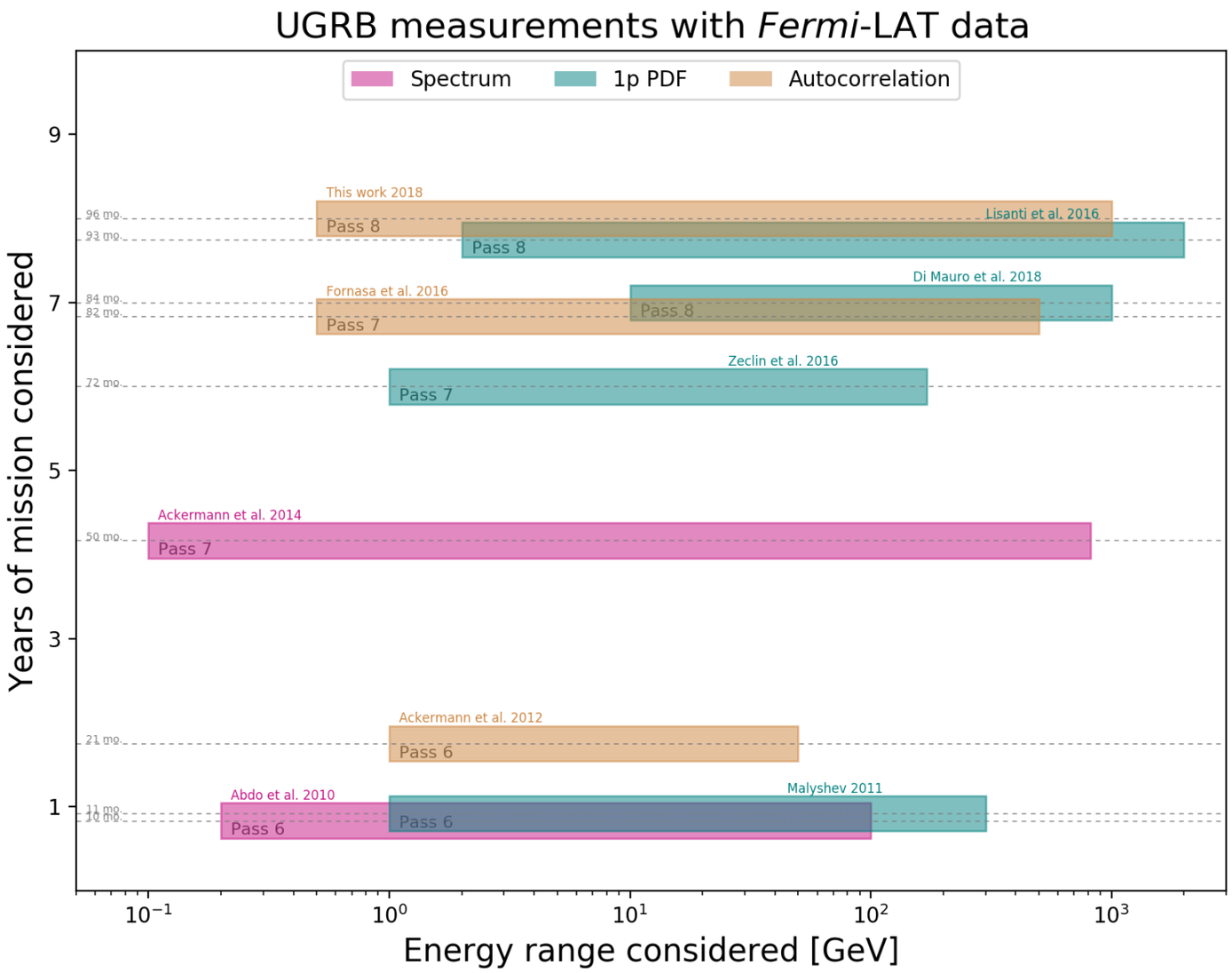
Low energy component: **mAGN / SFG / ?**

High energy component: **~100% Blazars**



UGRB measurements

- Towards a joint interpretation -



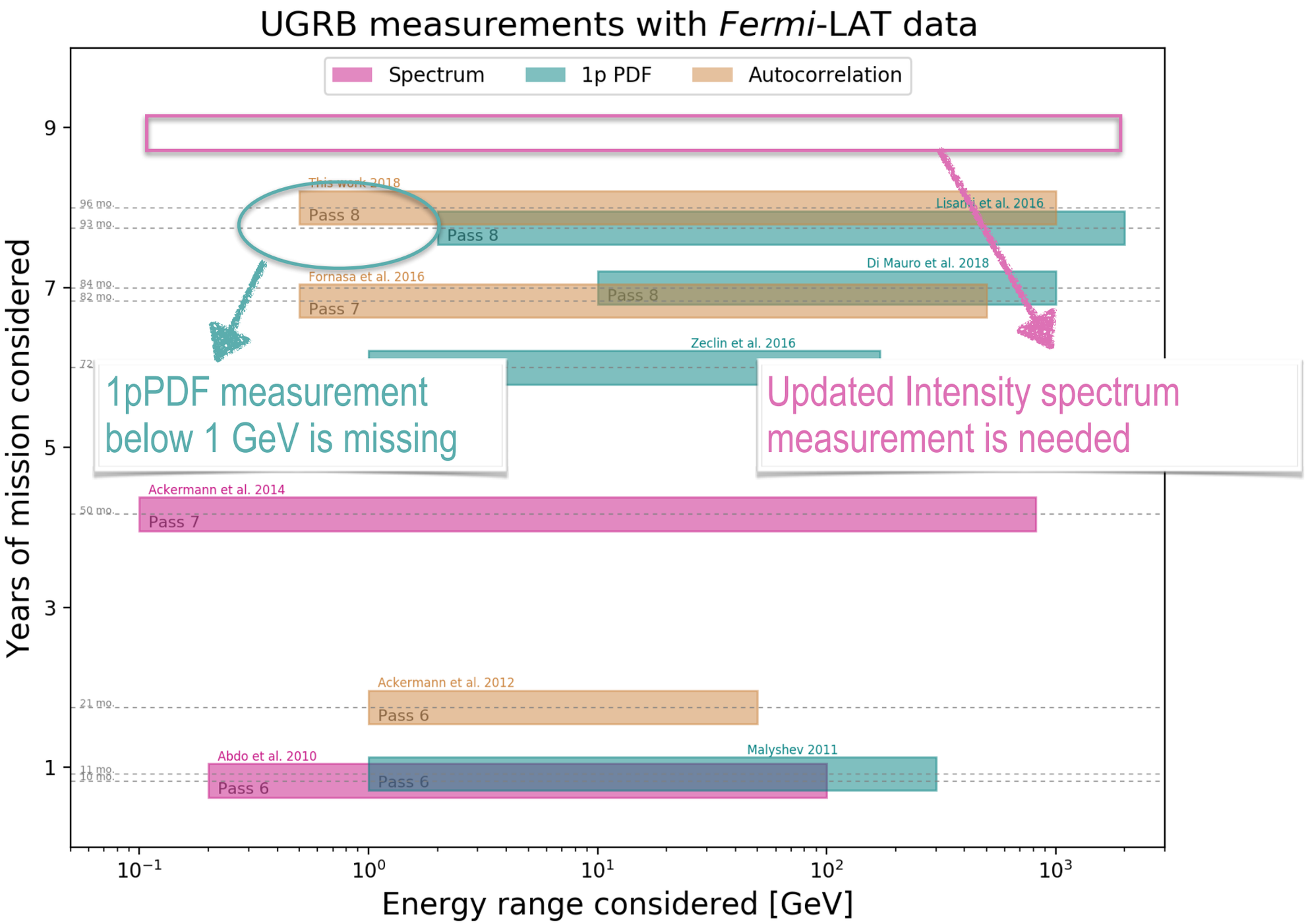
$$N = \int_0^{S_{th}} \frac{dN}{dS} dS$$

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

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

UGRB measurements

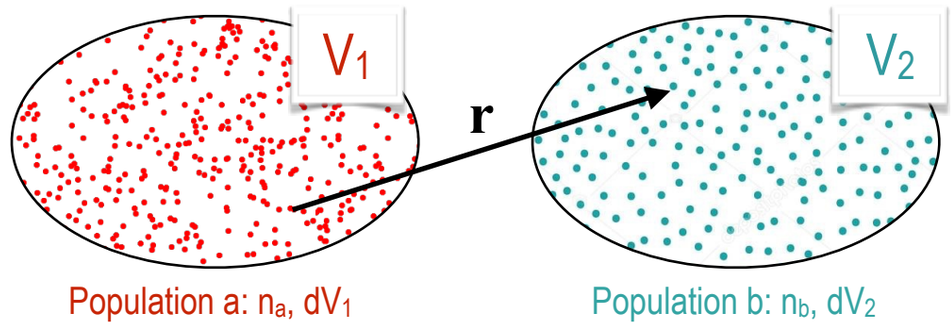
- Towards a joint interpretation -



UGRB characterisation via cross-correlation

UGRB characterisation

Cross-correlation with with independent probes



2-point cross-correlation function (CCF):

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

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

Cross-correlation angular power spectrum:

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

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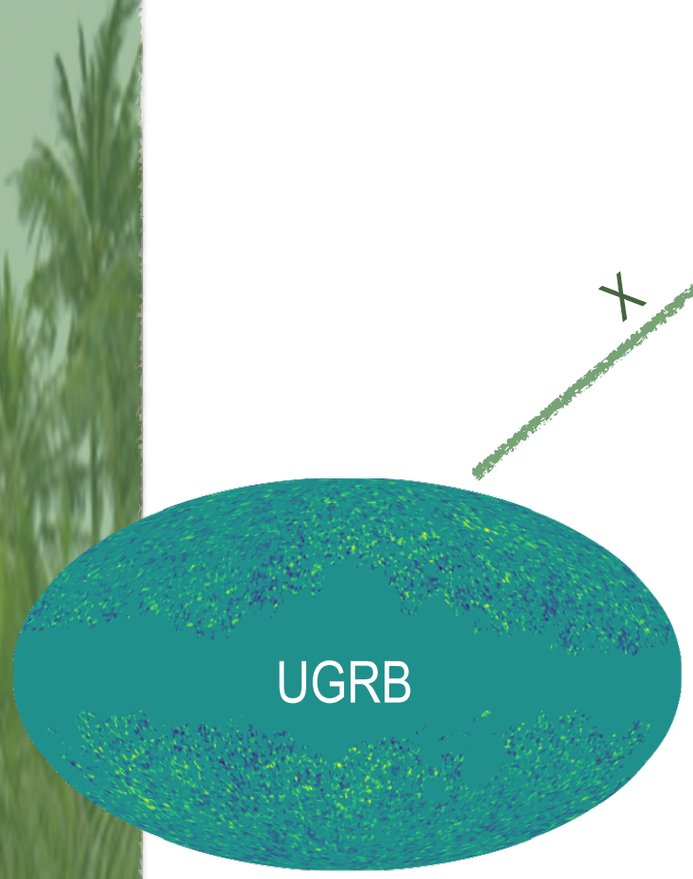
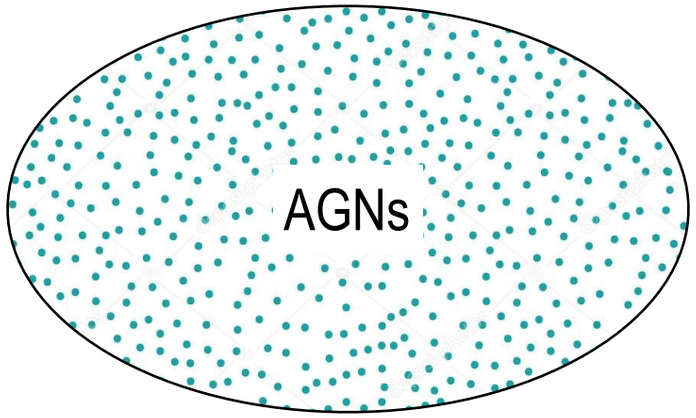
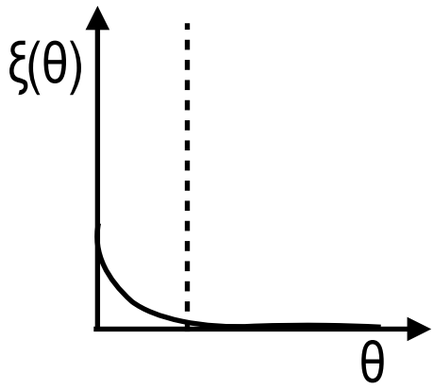
UGRB characterisation

- UGRB X galaxy catalogs -

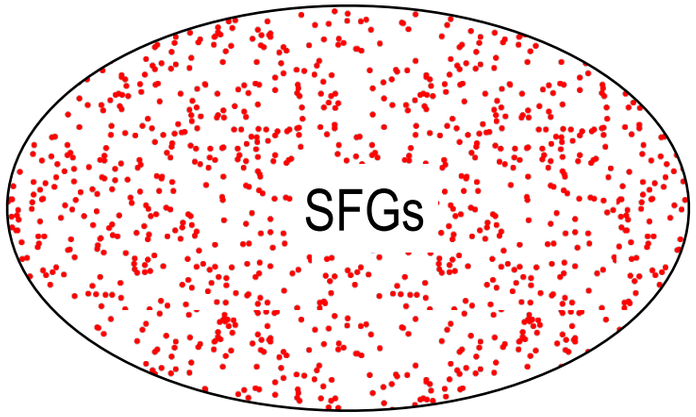


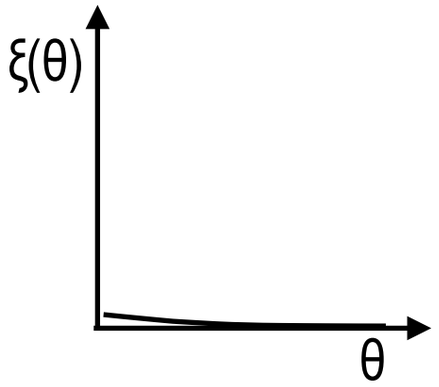
X



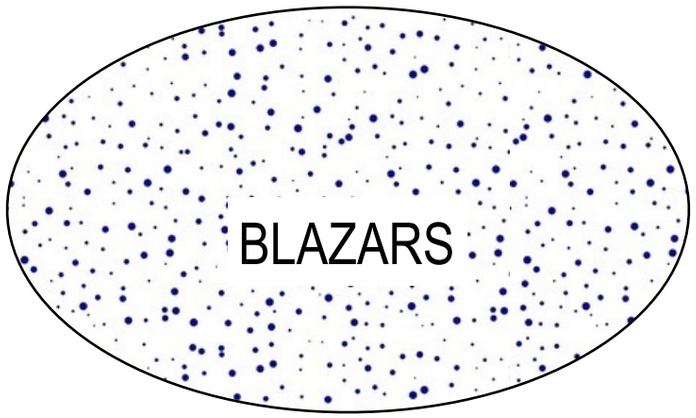


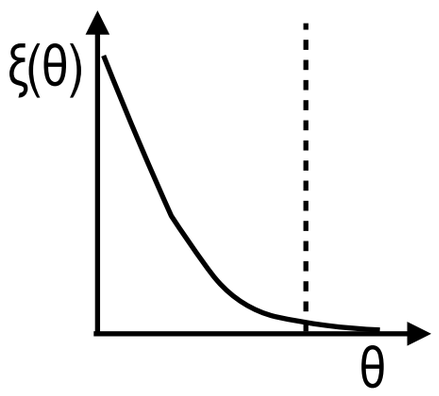
X





X





2018

Quy Nhon

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

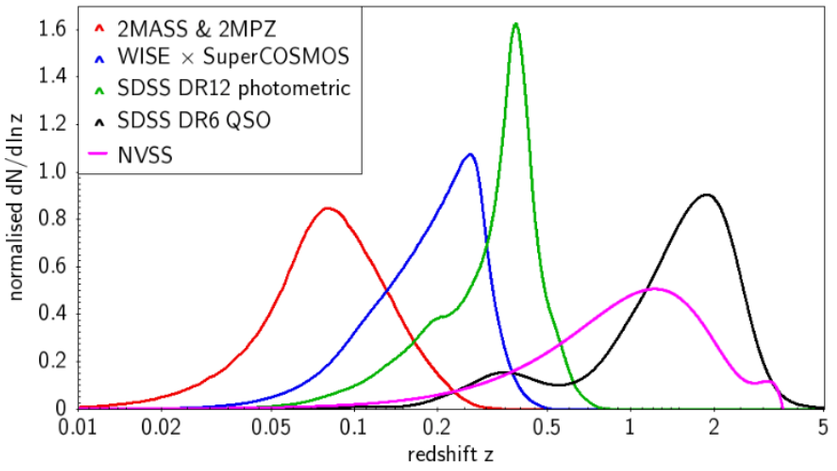
UGRB characterisation

- UGRB X galaxy catalogs -

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

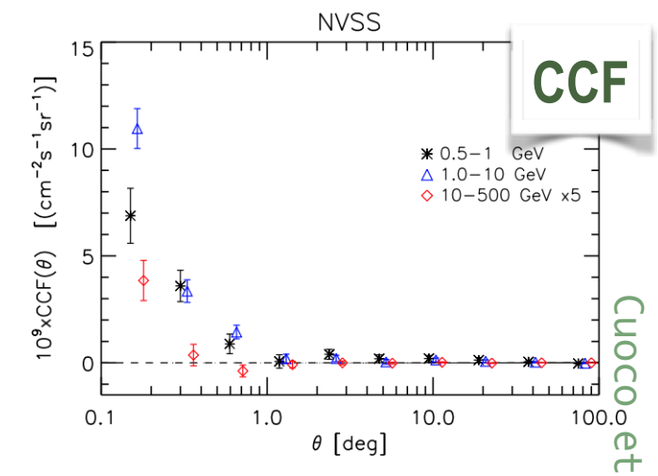
[Cuoco et al. 2017]

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



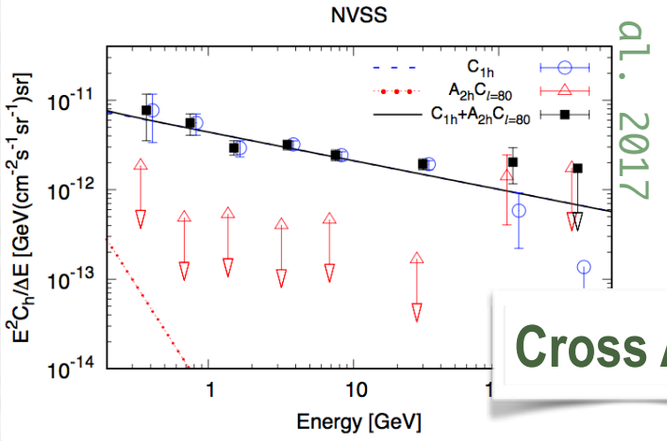
Cuoco et al. 2017

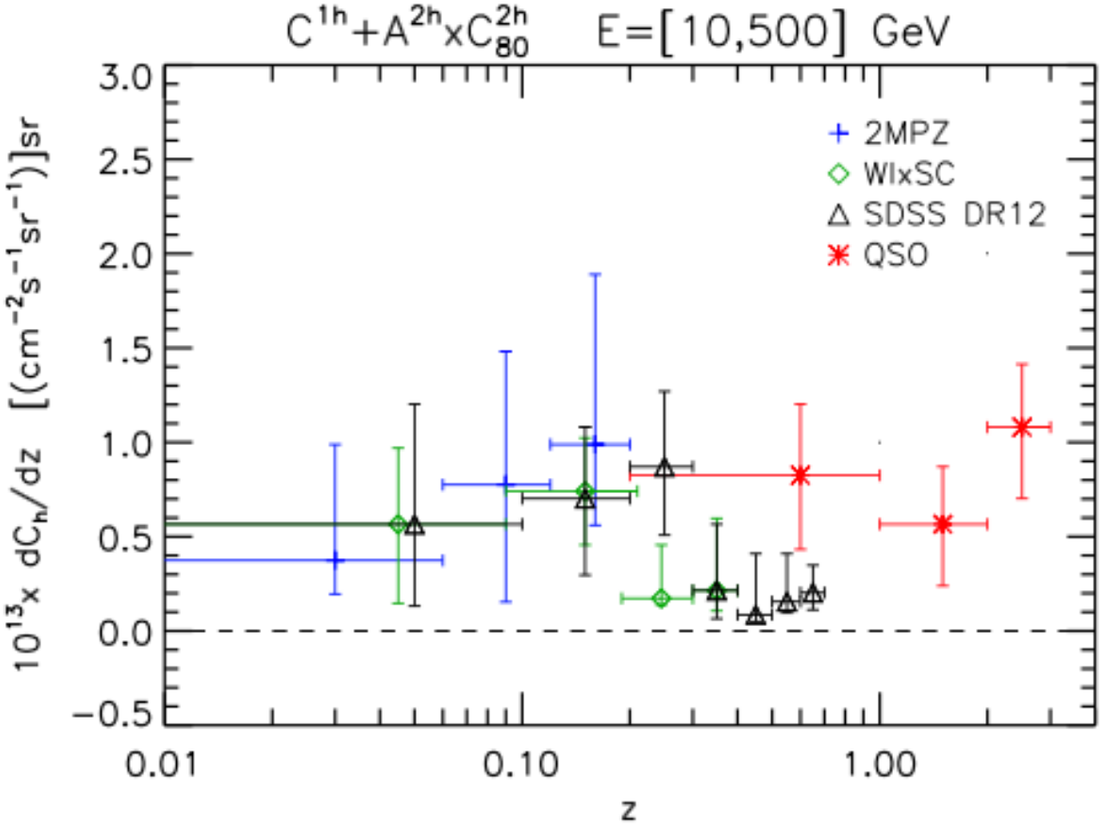
CCF



Cuoco et al. 2017

Cross APS



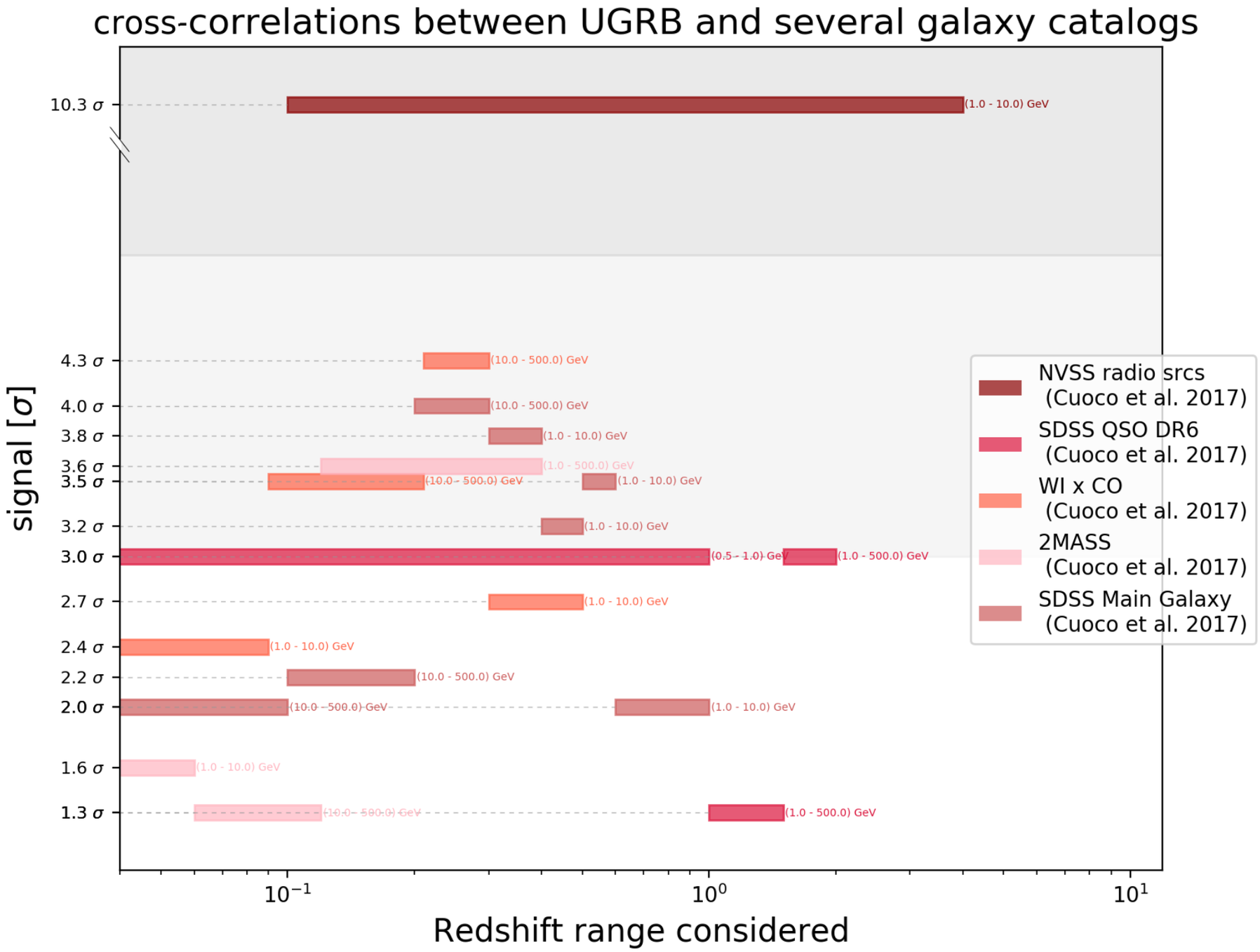


Cuoco et al. 2017

Cuoco et al. 2017, arXiv:1709.01940v1

UGRB characterisation

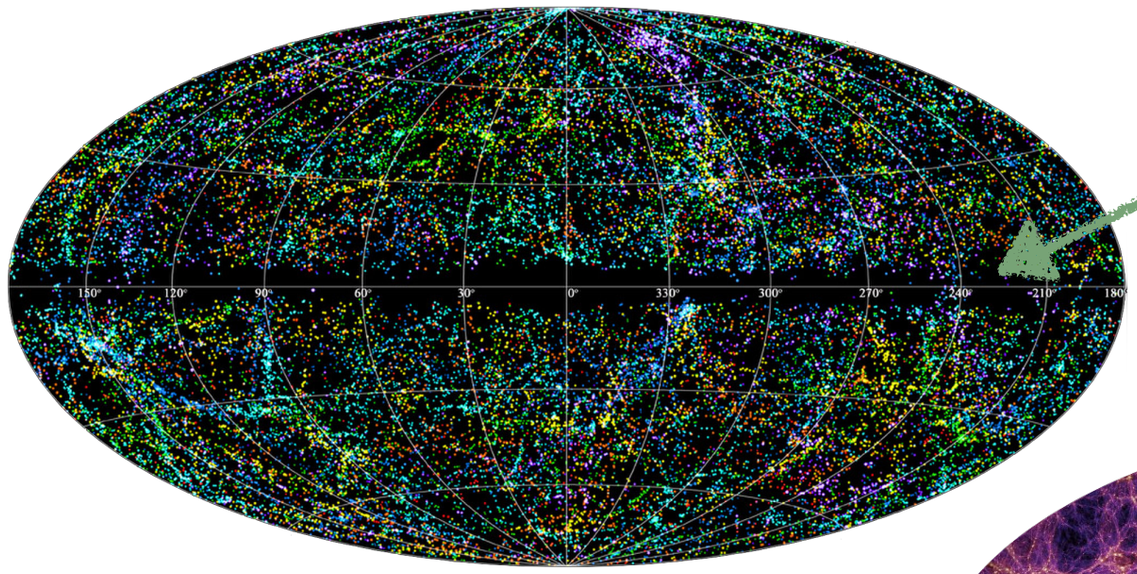
- UGRB X galaxy catalogs -



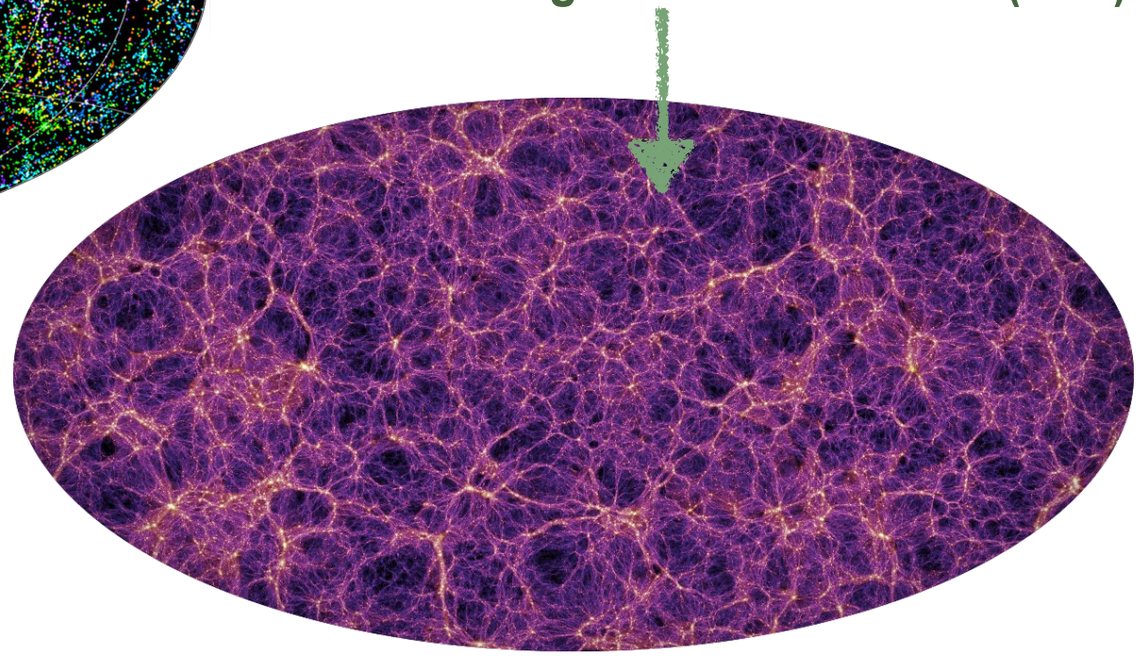
Signal significantly varies with energy and redshift: **UGRB produced by different types of sources**

UGRB characterisation

- UGRB X galaxy clusters -



Galaxy clusters are produced by hierarchical structure formation:
tracers of Large Scale Structures (LSS)



What's inside clusters?

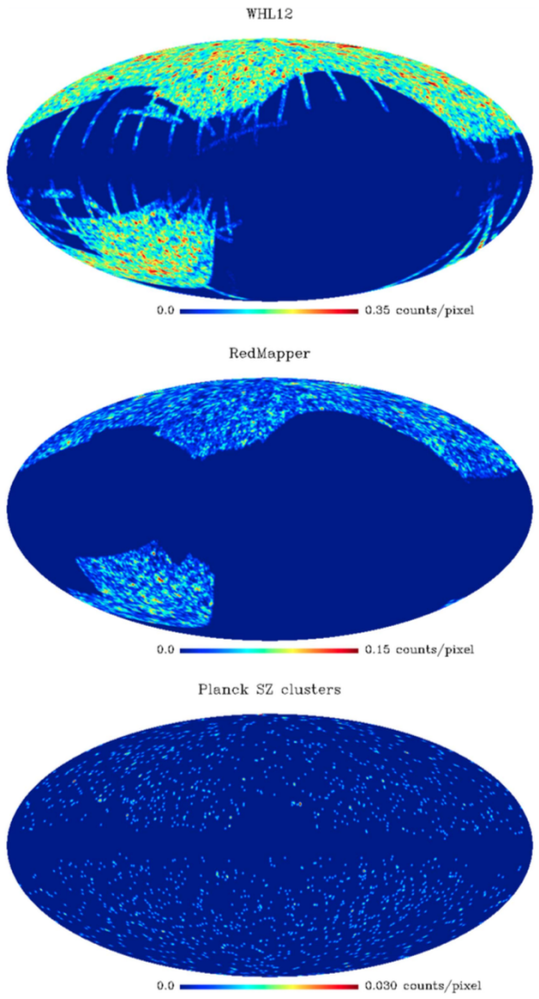
- Galaxies
- Hot highly ionized gas
- DM
- Relativistic CRs

→ **production of γ-rays!**

Cross-correlation signal between **Galaxy clusters** and **γ-rays** is expected**!**

UGRB characterisation

- UGRB X galaxy clusters -



Branchini et al. 2017

>3σ signal!
(up to 5σ)

Investigated surveys with **spectral** and **tomographic** approach:

[Branchini et al. 2017]

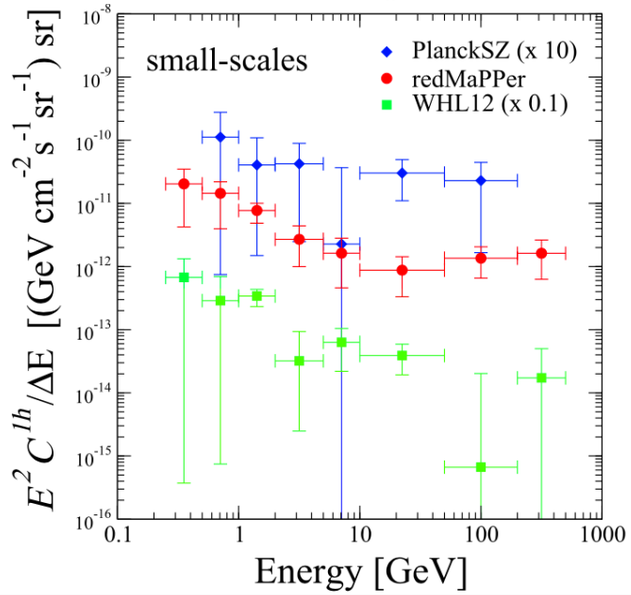
- **WHL12**
- **redMaPPer**
- **PlanckSZ**

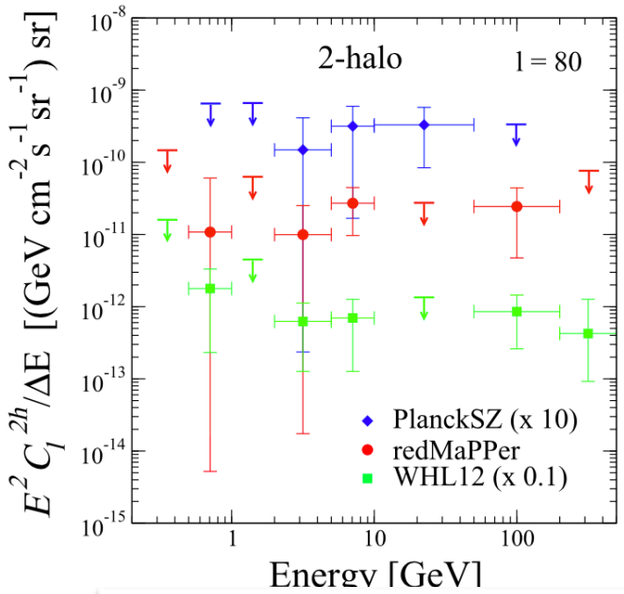
Phenomenological model:

$$\bar{C}_\ell^{(\gamma c)} = C^{1h} + A^{2h} C_\ell^{2h}$$

1-halo term: spacial correlation within a single halo

2-halo term: halo-halo clustering



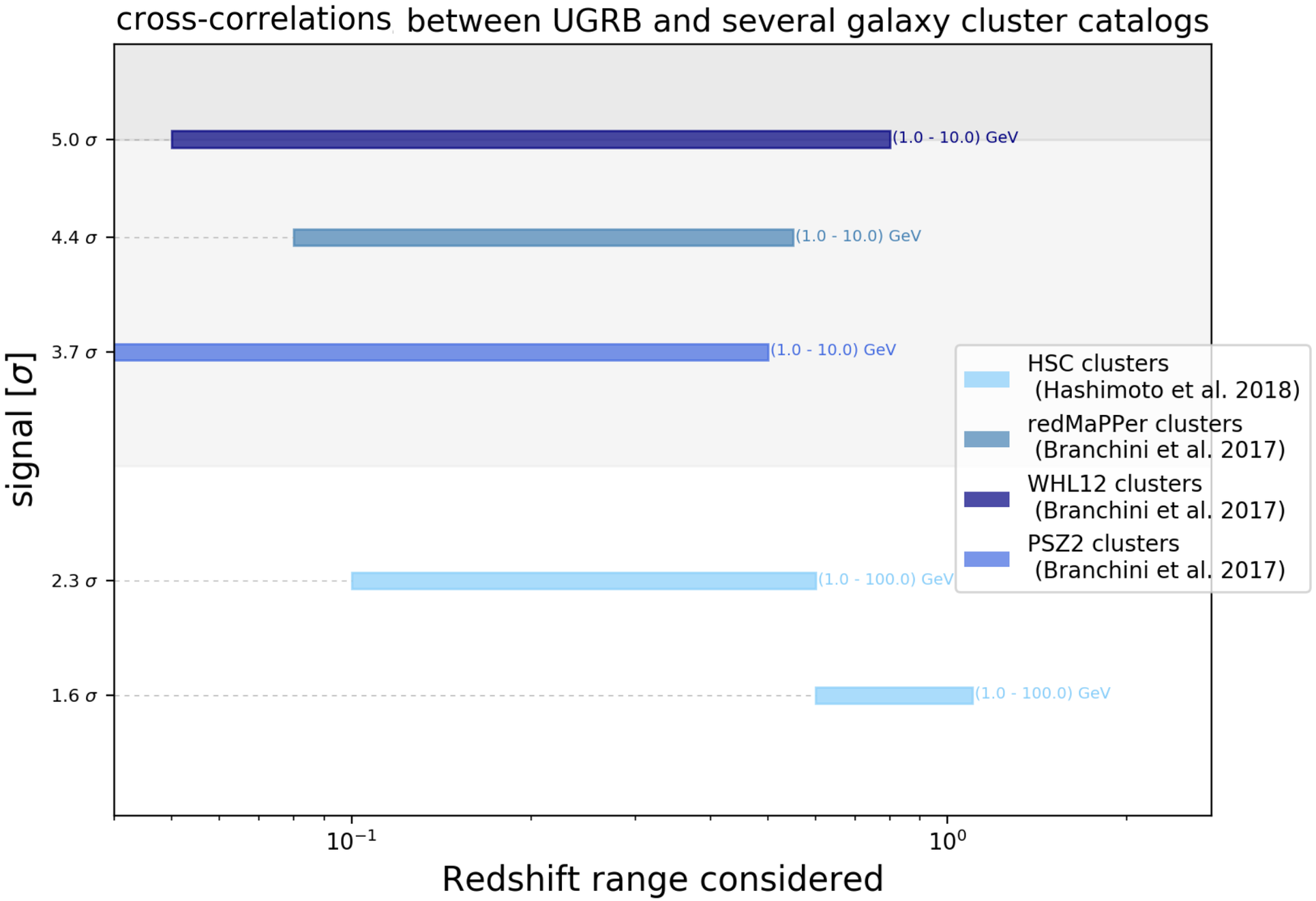


Small scales:
hard+soft component, mAGN / SFG / ?

Large scales:
hard power law, Blazars ?

UGRB characterisation

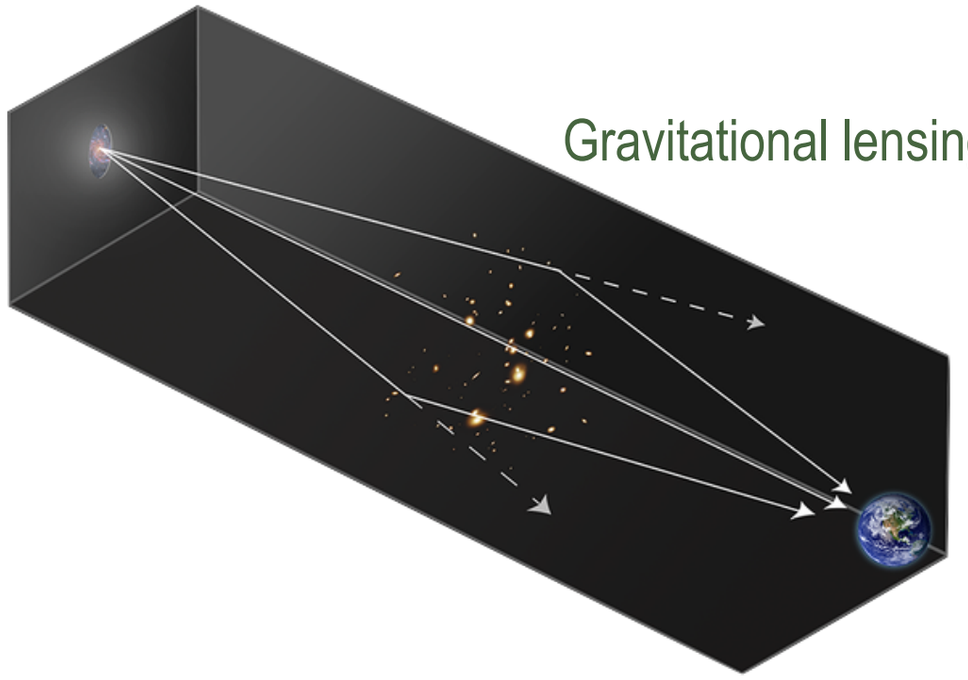
- UGRB X galaxy clusters -



Hashimoto et al. 2018, arXiv:1805.08139v1

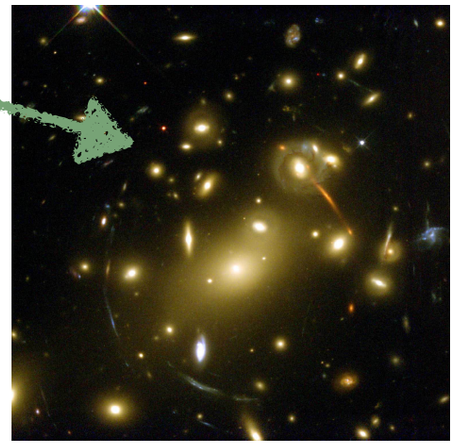
UGRB characterisation

- UGRB X cosmic shear -



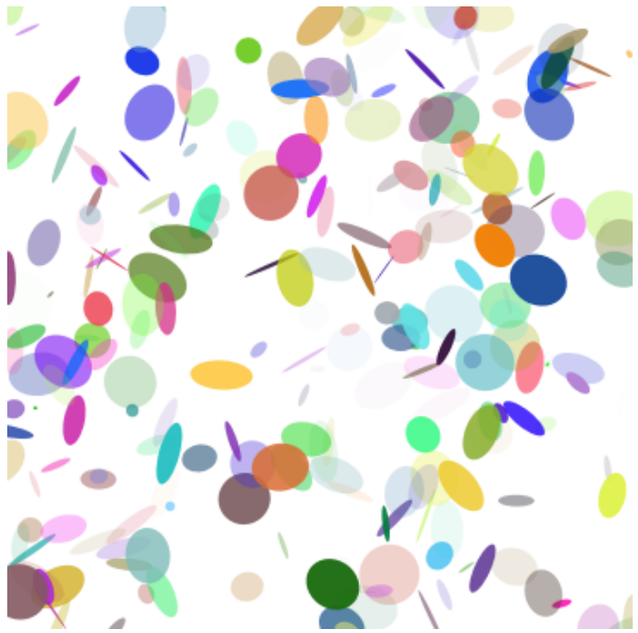
Gravitational lensing:

- **STRONG**
- **WEAK**



- Small effects: magnifications and distortions
- Tracer of the mass distribution at large scales

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



Hp: galaxies are intrinsically randomly oriented

↓

Measure the net ellipticity exceeding the Poisson Noise

↓

Infer the strength of the tidal gravitational field

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

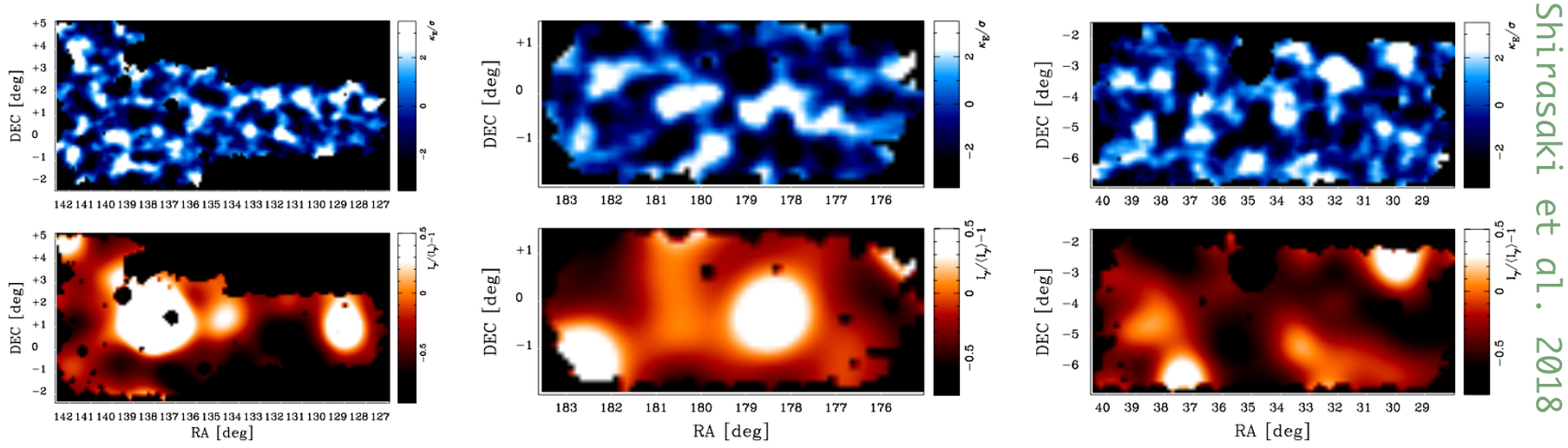
UGRB characterisation

- UGRB X cosmic shear -

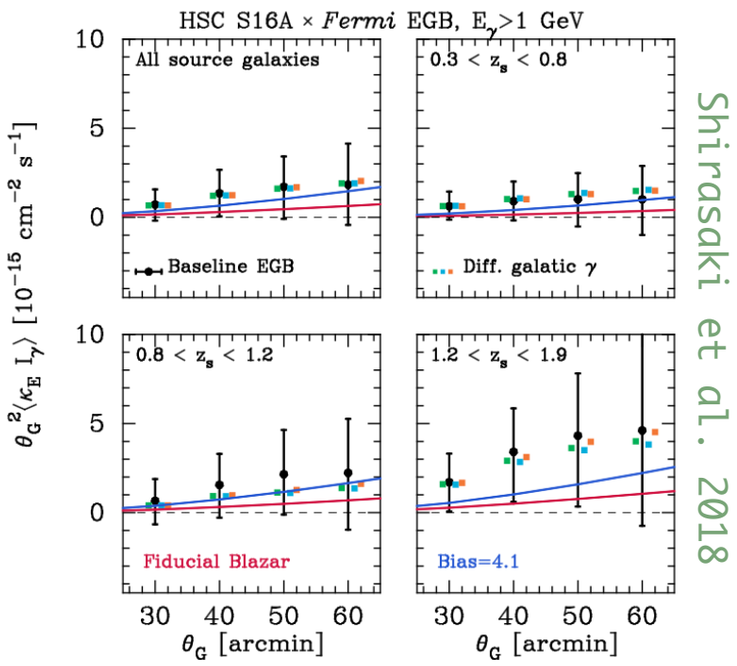
It is possible to produce cosmic shear maps to cross-correlate with gamma-ray maps

SHEAR

γ-RAYS



HSCS16A x Fermi-LAT



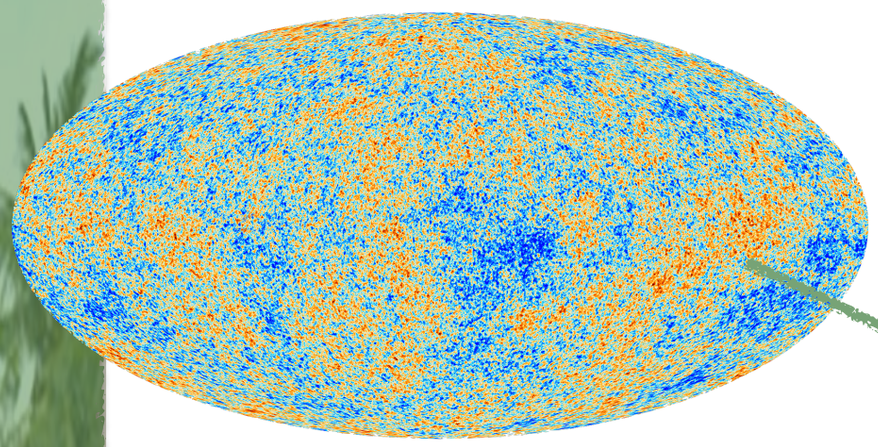
Investigated surveys with **spectral** and **tomographic** approach (proposed by Camera et al. 2013/2015):

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

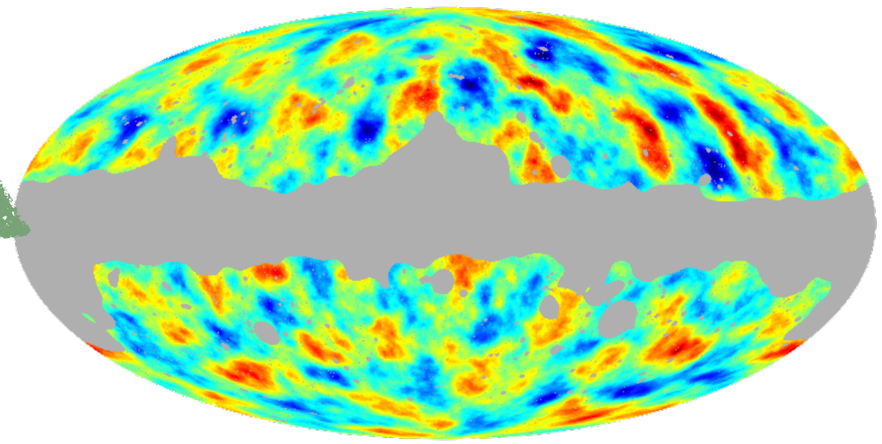
Until now: no signal detected!

UGRB characterisation

- UGRB X CMB lensing potential -

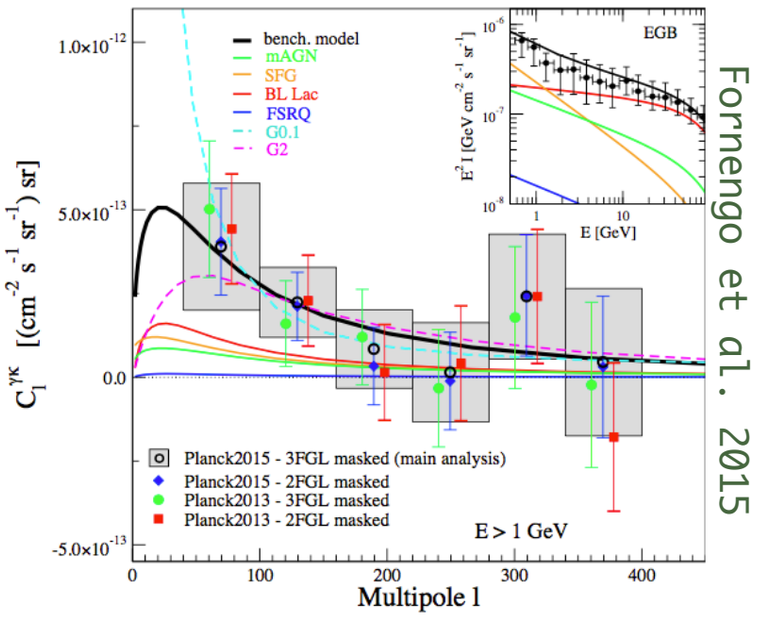


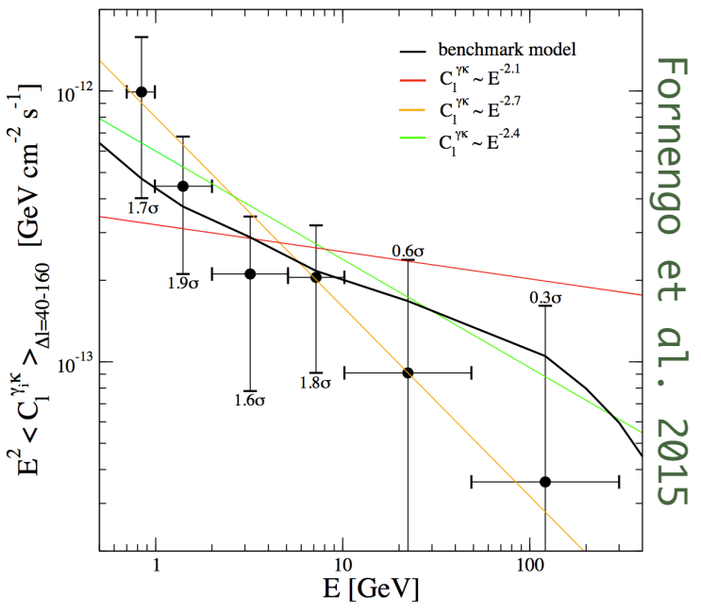
Gravitational lensed CMB map
(as Traces the LSS)



Planck Collaboration

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

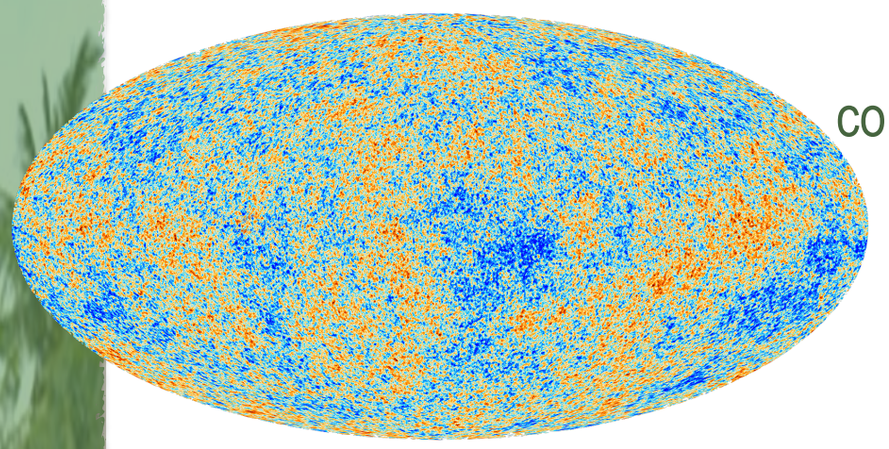




~2σ limit

UGRB characterisation

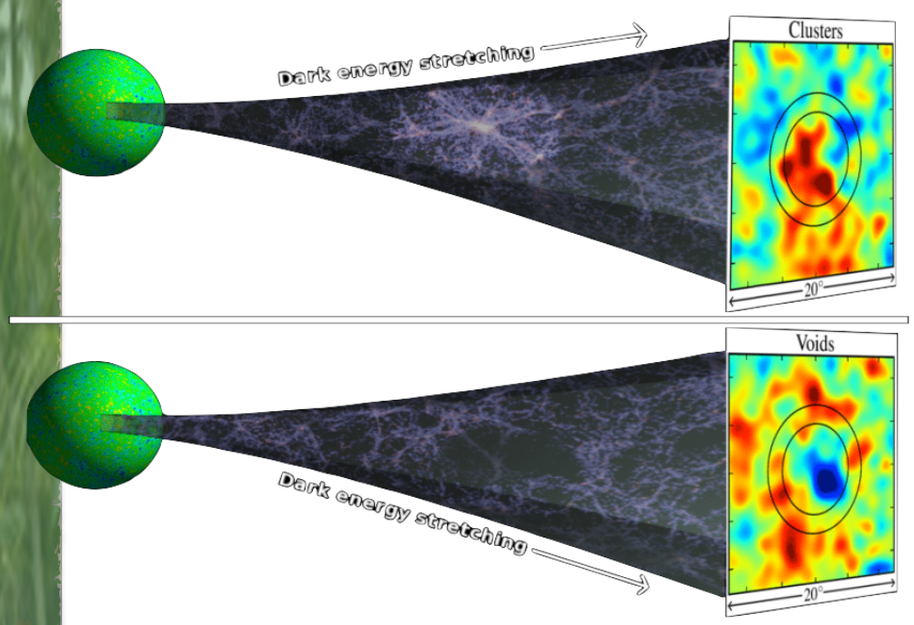
- UGRB X CMB -



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

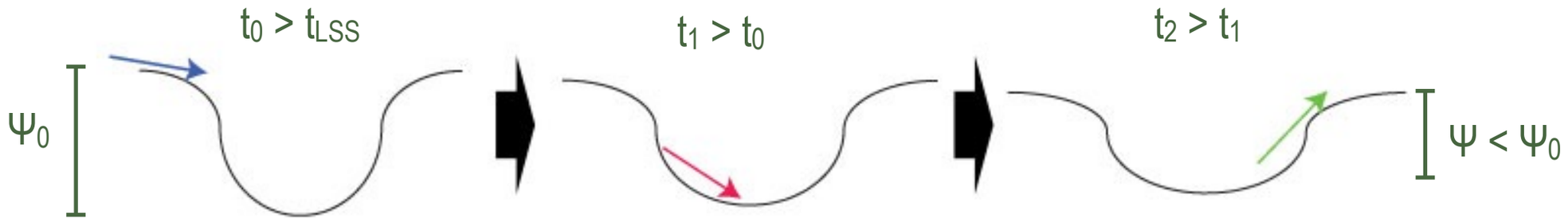
INTEGRATED SACHS-WOLFE EFFECT (ISW)
(between last scattering surface and Earth)

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



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

... but no signal detected!

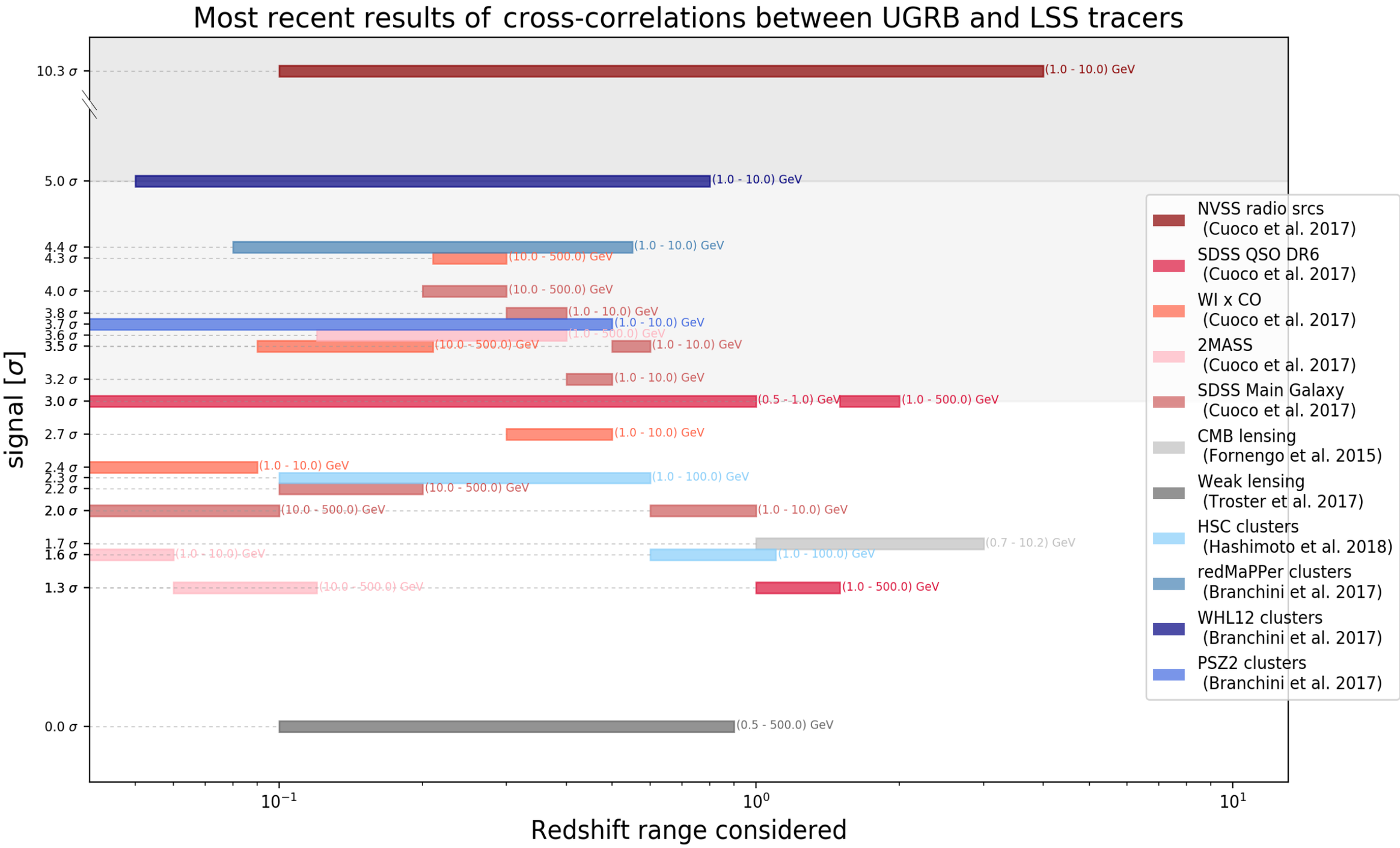


interesting to update this measurement!

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

2018 Quy Nhon

UGRB characterisation



Summary

Unresolved Gamma-Ray Background (UGRB)

To unveil its exact composition

To study source population properties below the instrumental detection threshold

Important to keep its estimation up-to-date

To give limits on mass and cross-section of DM (as a WIMP)

Measurements:

Intensity spectrum **(should be updated)**
Autocorrelation anisotropy **(new results public soon)**
Photon count PDF **(interesting to extend below 1 GeV)**

Characterisation via cross-correlations:

with galaxy catalogs **(strong signal)**
with galaxy clusters **(strong signal)**
with weak lensing of cosmic shear **(no signal)**
with lensing of the CMB **(weak signal)**
with CMB **(no signal, should be updated)**

Beyond the resolved components

Time and analysis-dependent

Mostly extragalactic

Likely unresolved point sources (astrophysical or exotic)

THANK YOU FOR YOUR ATTENTION!

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Back up

Michela Negro
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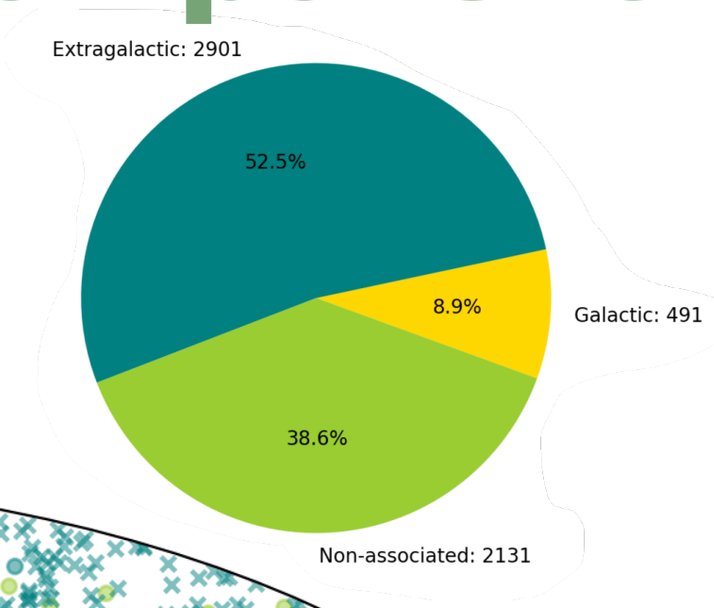
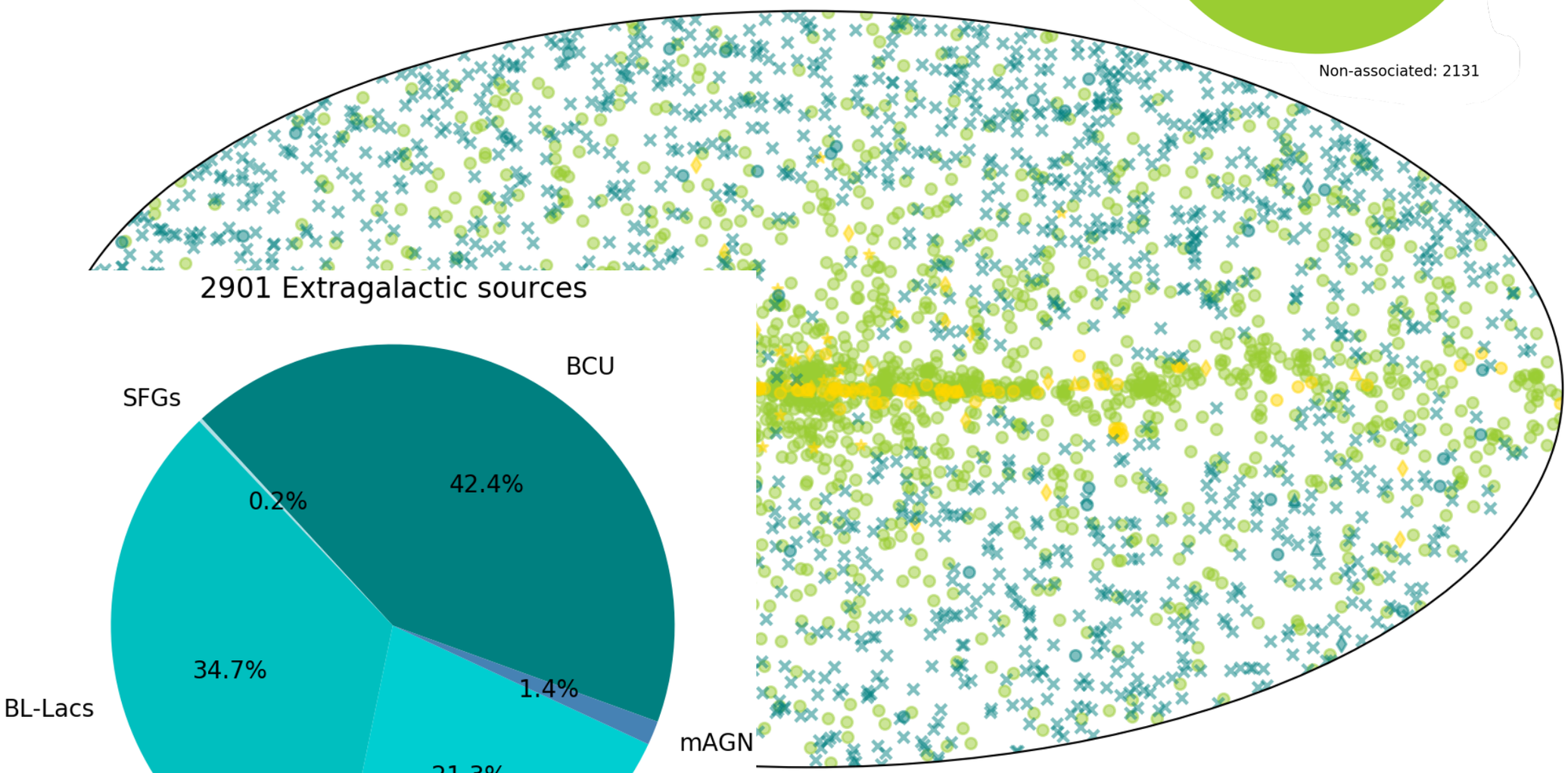
A time-dependent component

Fermi 8-year src list: **FL8Y**

5524 sources

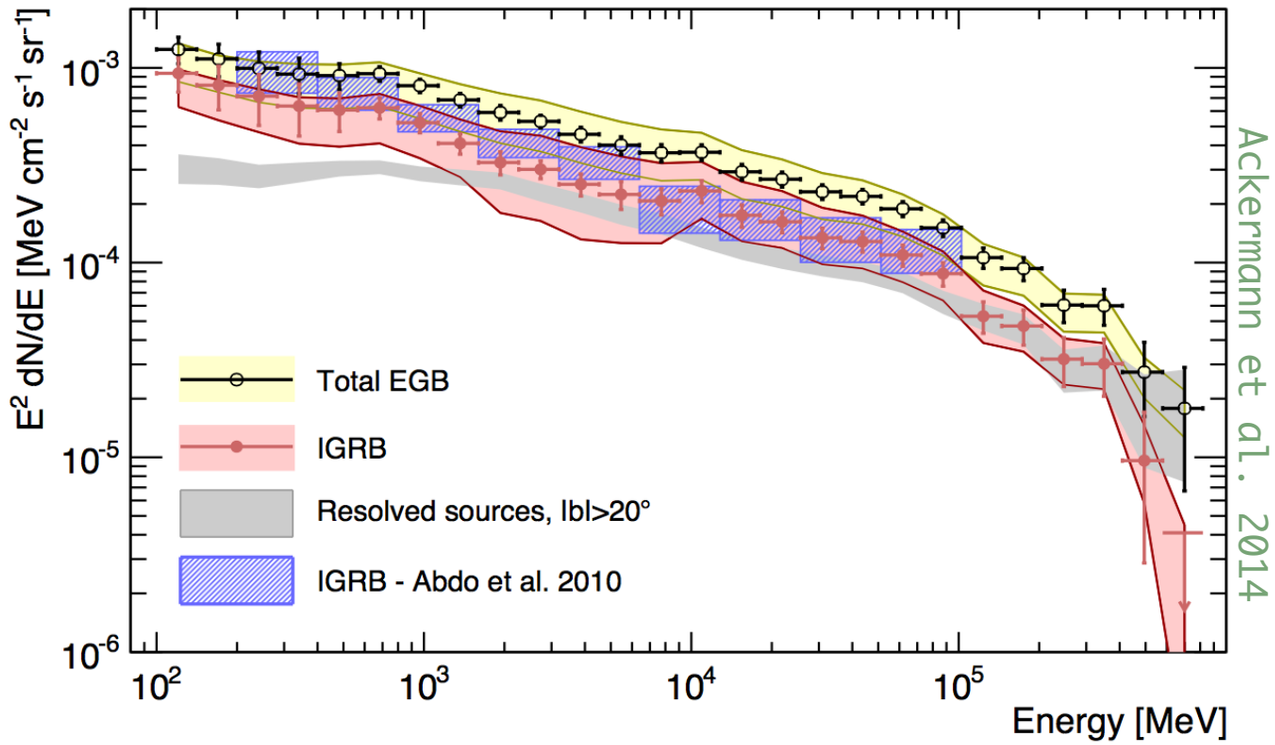




Abdo et al. 2010, arXiv:1002.3603v1
Ackermann et al. 2014, arXiv:1410.3696v1
Fornasa and Sánchez-Conde 2015, arXiv:1502.02866v2

UGRB measurements

- The Intensity Spectrum -



Can be interpreted as the cumulative contribution of different population of γ-ray emitters

The generic differential flux expected from unresolved objects of a certain population:

Fornasa and Sánchez-Conde 2015

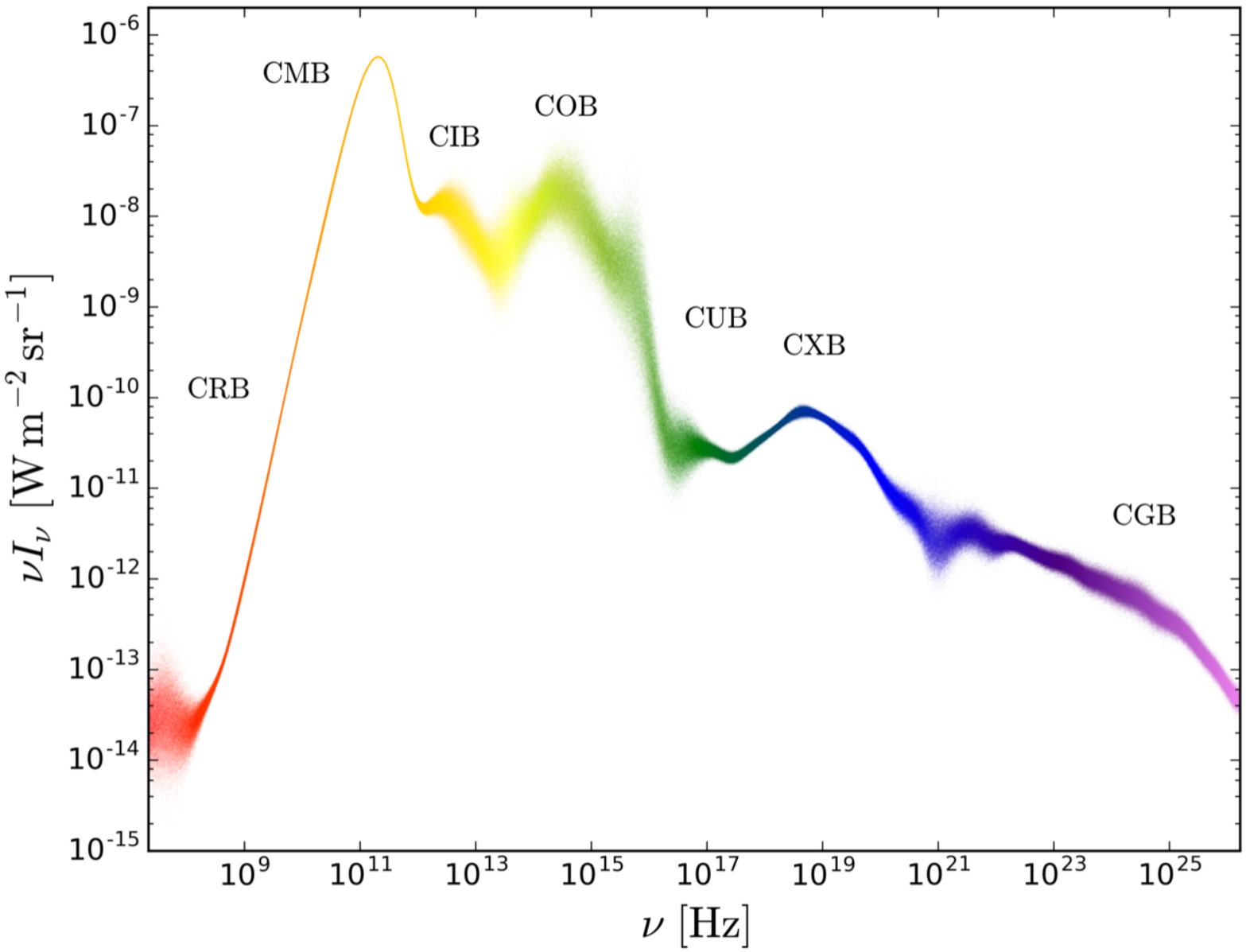
$$\frac{d\Phi}{dEd\Omega} = \int_{z_{max}}^{z_{min}} dz \int_{Y_{max}}^{Y_{min}} dY \int_{\Gamma_{max}}^{\Gamma_{min}} d\Gamma \frac{dN}{dV\,dY\,d\Gamma}(z,Y,\Gamma) \frac{dV}{dz d\Omega} F_{E_0}(z,Y,\Gamma) \left(1 - \frac{\Omega(z,Y,\Gamma)}{\Omega_{max}}\right) e^{-\tau_{EBL}(E_0,z)}$$

- redshift
- Measurable quantity characterising a source population
- characterizes the energy spectrum
- comoving number density
- comoving volume
- gamma-ray flux @ E_0 of the source
- sky coverage
- Selects only unresolved
- EBL cutoff

UGRB measurements

- The Intensity Spectrum -

UGRB spectrum in a wider frame



R. Hill et al. 2018

Michela Negro - VHEPU 2018

Hill et al. 2018, arXiv:1802.03694v1

2018

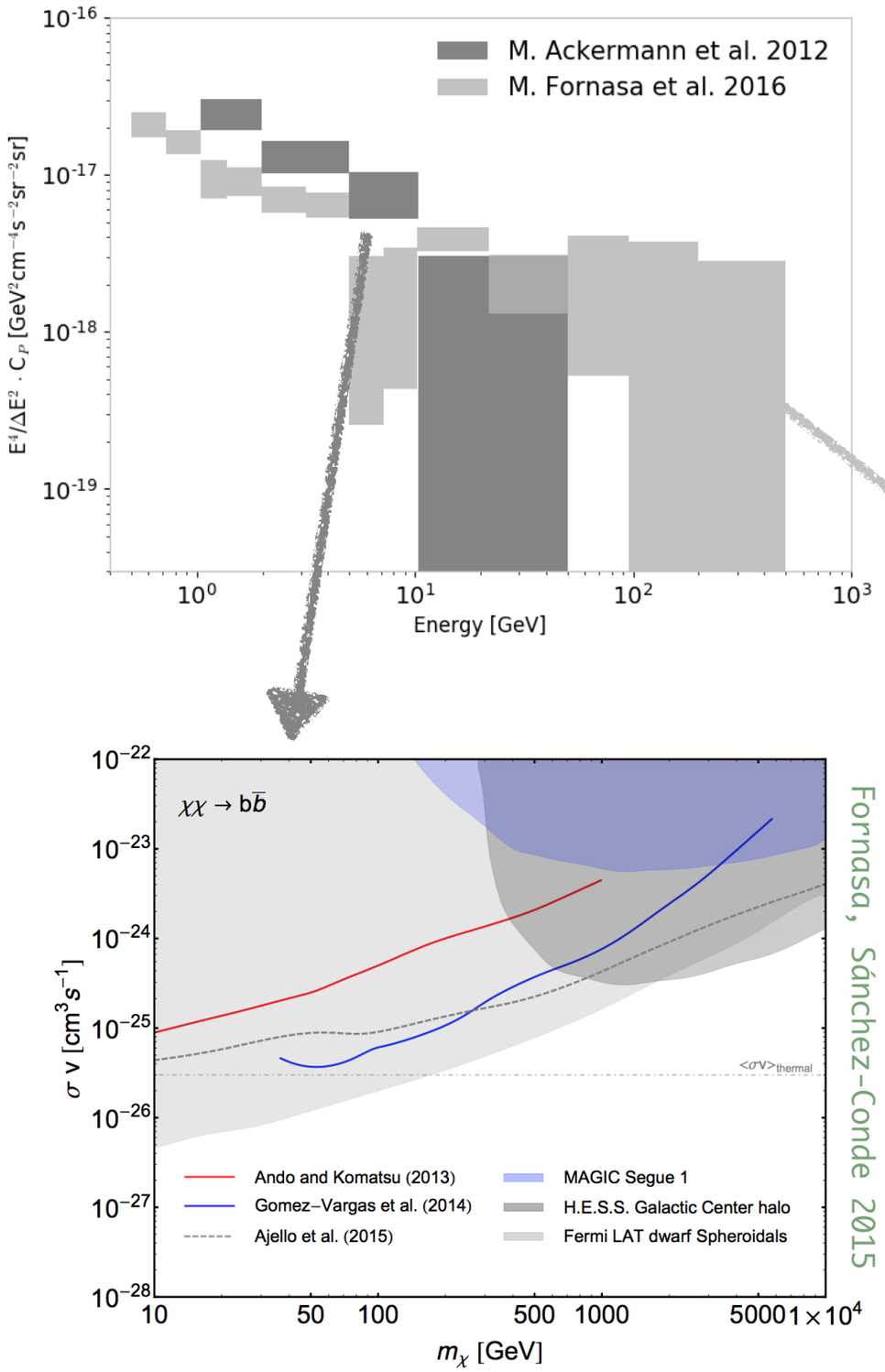
Quy Nhon

Michela Negro - VHEPU 2018

Hill et al. 2018, arXiv:1802.03694v1

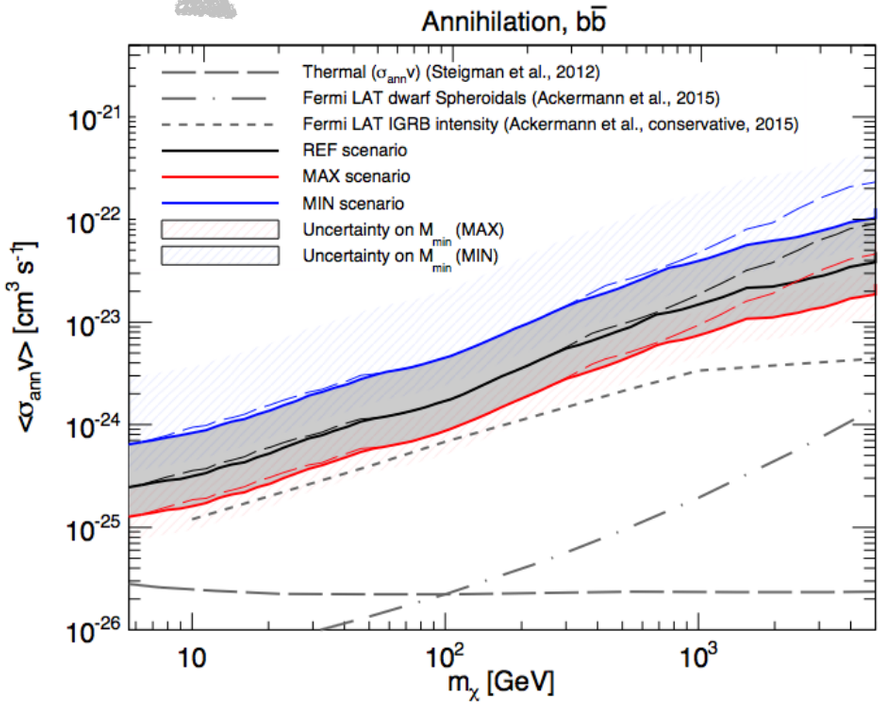
UGRB measurements

- The Anisotropy Spectrum -



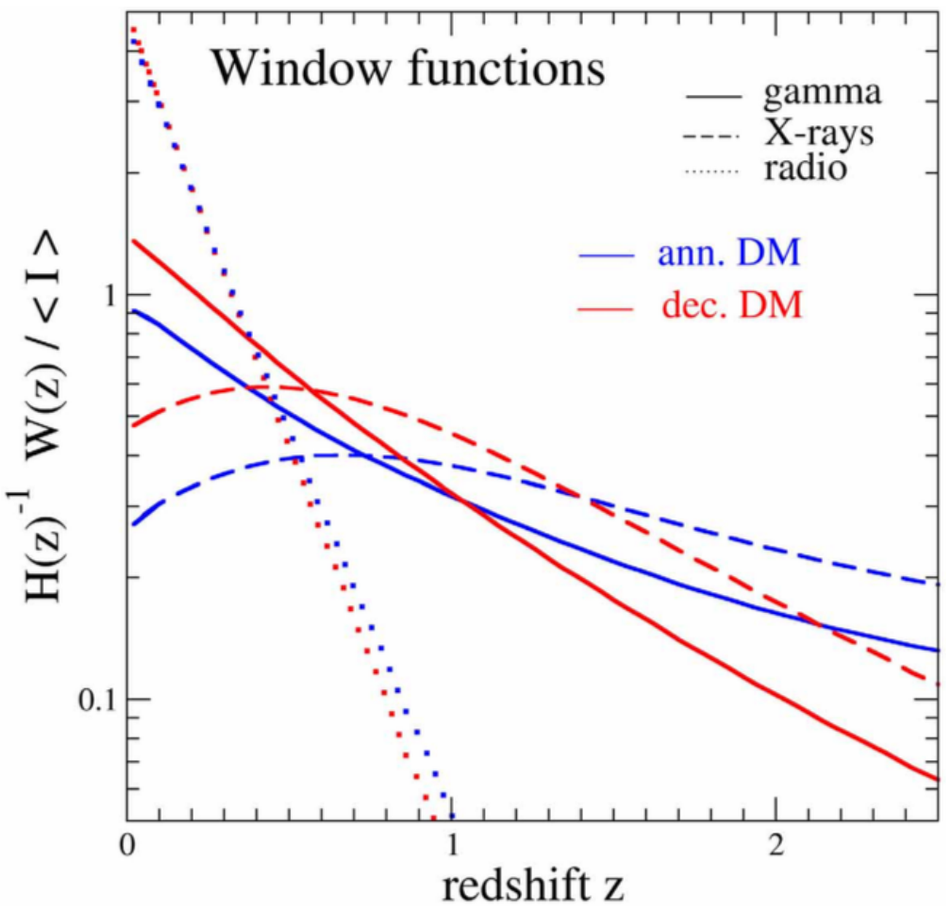
Fornasa, Sánchez-Conde 2015

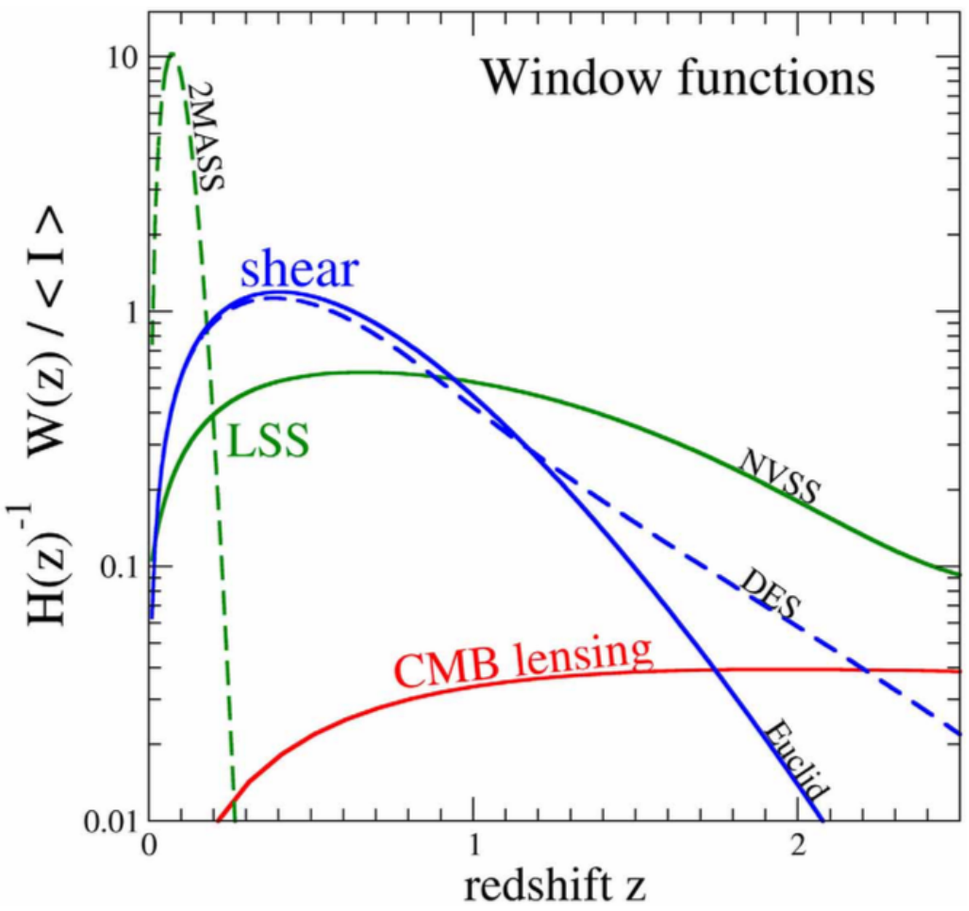
DM limits from autocorrelation



UGRB measurements

- Cross-correlations -





$$W(\chi) = \frac{3}{2} H_0{}^2 \Omega_{\rm m} [1 + z(\chi)] \chi \, \frac{\chi_* - \chi}{\chi_*}$$

CMB lensing

$$W(E, z) = \frac{\langle g_S(z) \rangle}{4\pi (1+z)} \, e^{-\tau[E(1+z),\, z]}.$$

Astrophysical sources

$$W(E, z) = \frac{1}{4\pi} \frac{\Omega_{\rm DM} \rho_c}{m_\chi \tau_d} \frac{dN_d[E(1+z)]}{dE} e^{-\tau[E(1+z),\, z]}$$

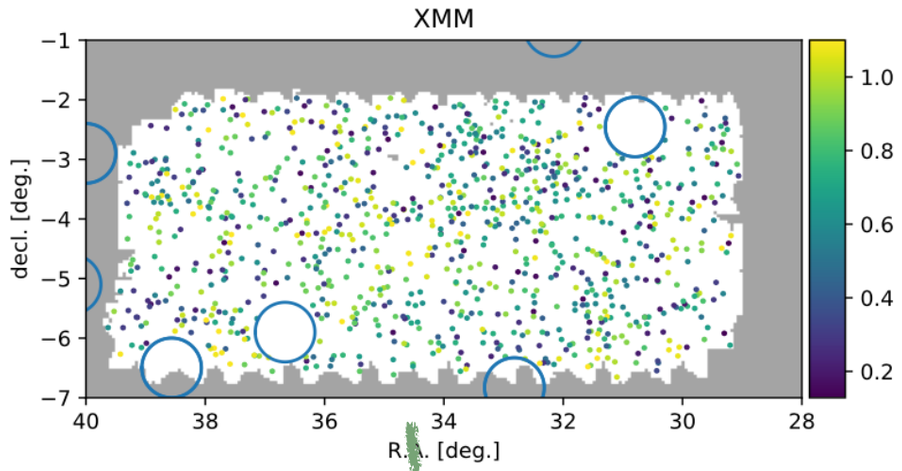
Decaying DM

Hashimoto et al. 2018, arXiv:1805.08139v1

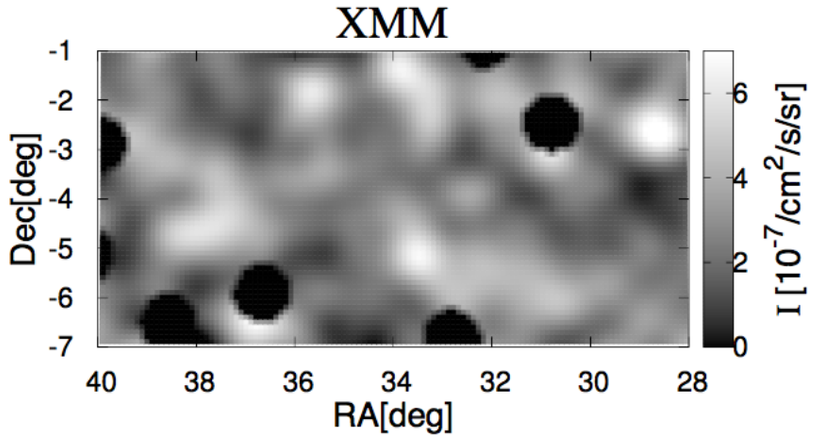
UGRB characterisation

- UGRB X galaxy clusters -

- **Subaru Hyper Suprime-Cam (HSC)** [Hashimoto et al. 2018]

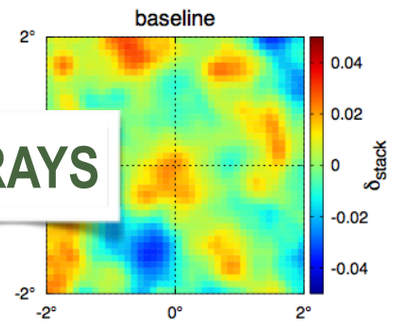


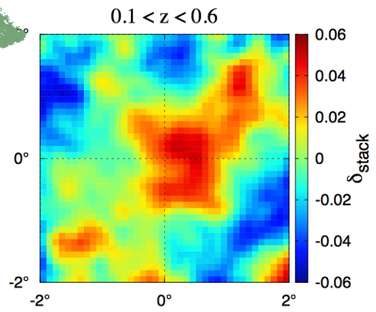
X

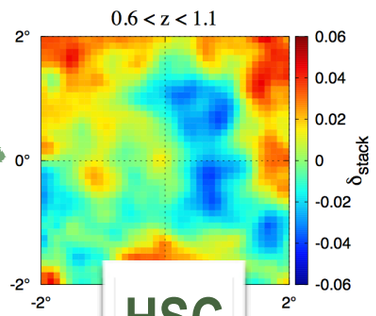


Stacked maps

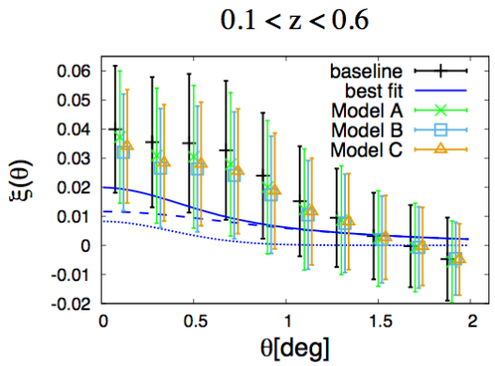
γ-RAYS

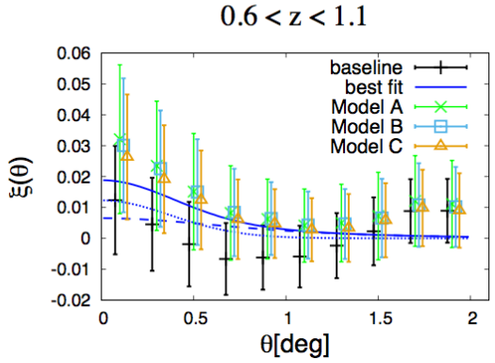






HSC





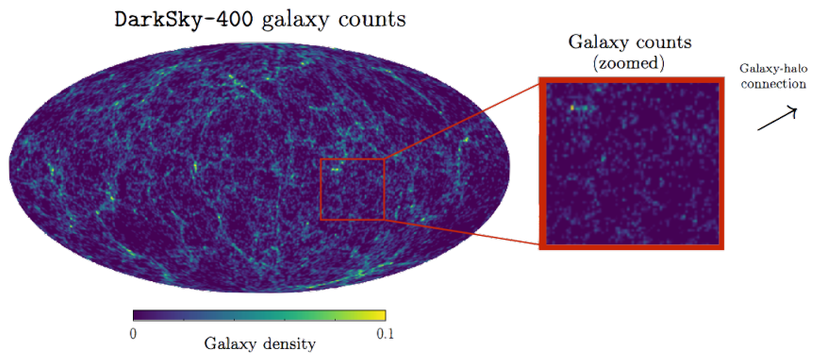
Hashimoto et al. 2018

~2σ signal!

UGRB characterisation

- UGRB X galaxy clusters -

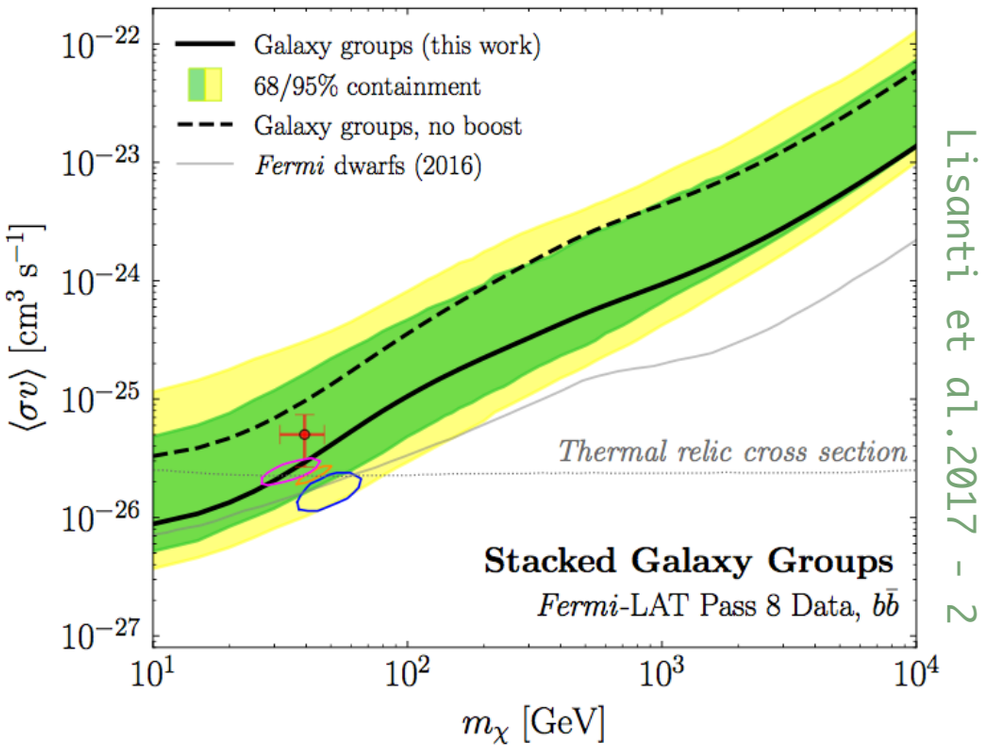
- **Cross with galaxy groups to constrain DM properties** [Lisanti et al. 2017]
  List of the brightest extragalactic dark matter targets in the nearby Universe (z 0.03)



Lisanti et al.2017 - 1

Name	$\log_{10} J$ [GeV^2 cm^{-5} sr]
NGC4472/Virgo	19.11±0.35
NGC0253	18.76±0.37
NGC3031	18.58±0.36
NGC4696/Centaurus	18.33±0.35
NGC1399	18.30±0.37

Top 5 halos



Lisanti et al.2017 - 2

Some references

- Intensity spectrum [1, 2]
- Autocorrelations anisotropy [9, 10]
- photon count Probability Distribution Function (PDF) [3 - 8]
- Cross-correlation with:
  - galaxy catalogs [11-18]
  - galaxy clusters [19-21]
  - weak lensing of cosmic shear [22-26]
  - lensing of the CMB [27]

[1] Abdo et al. (Fermi-LAT) 2010
[2] Ackermann et al. (Fermi-LAT) 2014

[3] D. Malyshev and D. W. Hogg, Astrophys.J. 738, 181418 (2011)
[4] M. R. Feyereisen et al., JCAP 9, 027420 (2015)
[5] H.-S. Zechlin et al. 225, 18 (2016).
[6] M. Lisanti et al. Astrophys.J. 832, 117 (2016)
[7] H.-S. Zechlin et al., Astrophys.J.Lett. 826, L31 (2016)
[8] M. Di Mauro et al., Astrophys. J. 856, 106432 (2018)

[9] Ackermann et al. (Fermi-LAT) 2012
[10] Fornasa et al. 2016

[11] J.-Q. Xia,et al., Mon.Not.Roy.Astron.Soc. 416, 2247 (2011)
[12] S. Ando et al. Phys. Rev. D 90, 023514 (2014)
[13] J.-Q. Xia, et al. 217, 15 (2015).
[14] M. Regis et al Phys. Rev. Lett. 114, 241301 (2015)
[15] A. Cuoco et al. Astrophys.J.Suppl. 221, 29 (2015)
[16] S. Ando, JCAP 10, 061 (2014)
[17] M. Shirasaki et al. Phys. Rev. D 92, 123540 (2015)
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