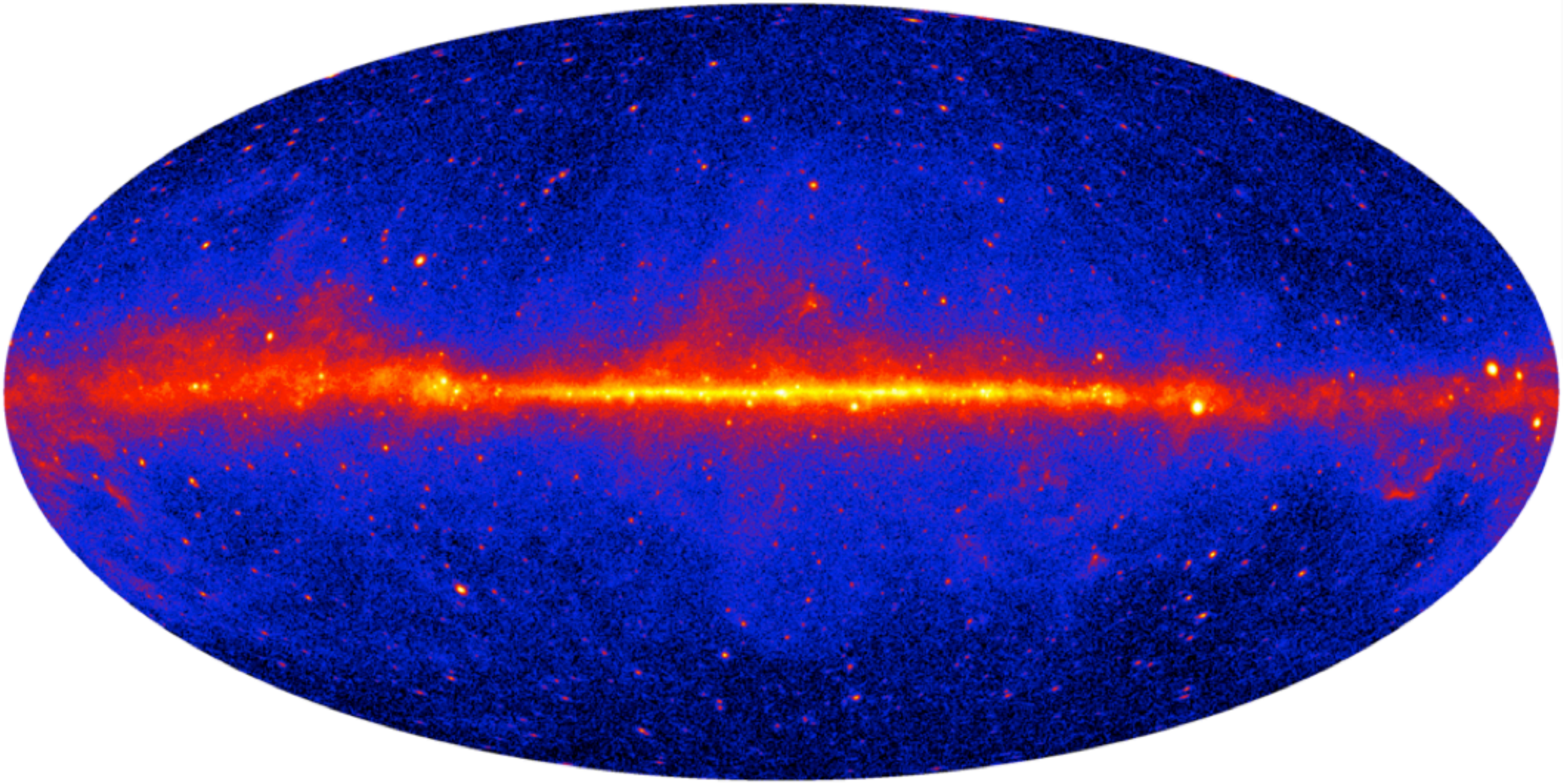
The Fermi-LAT view of the Extragalactic Sky

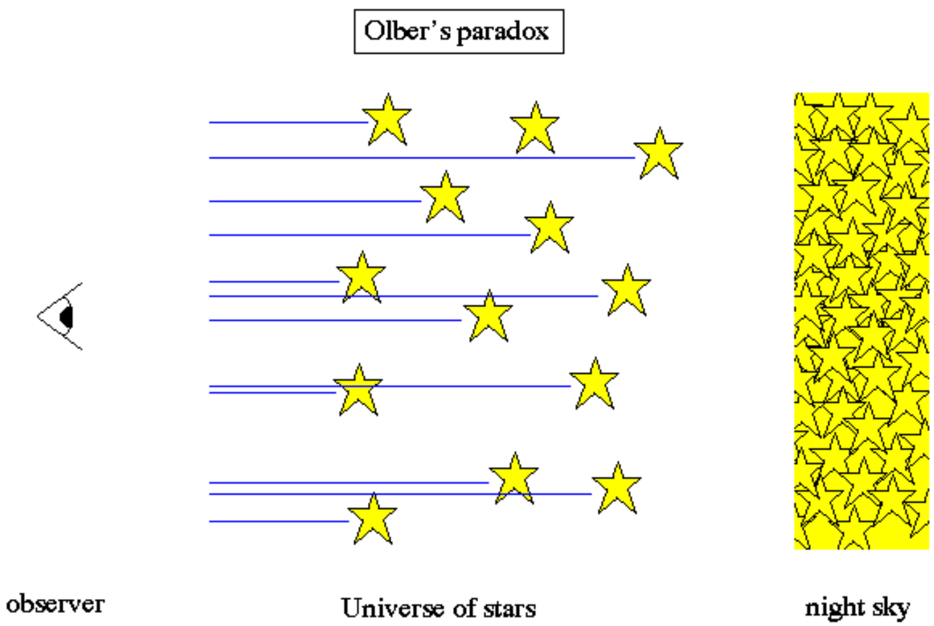


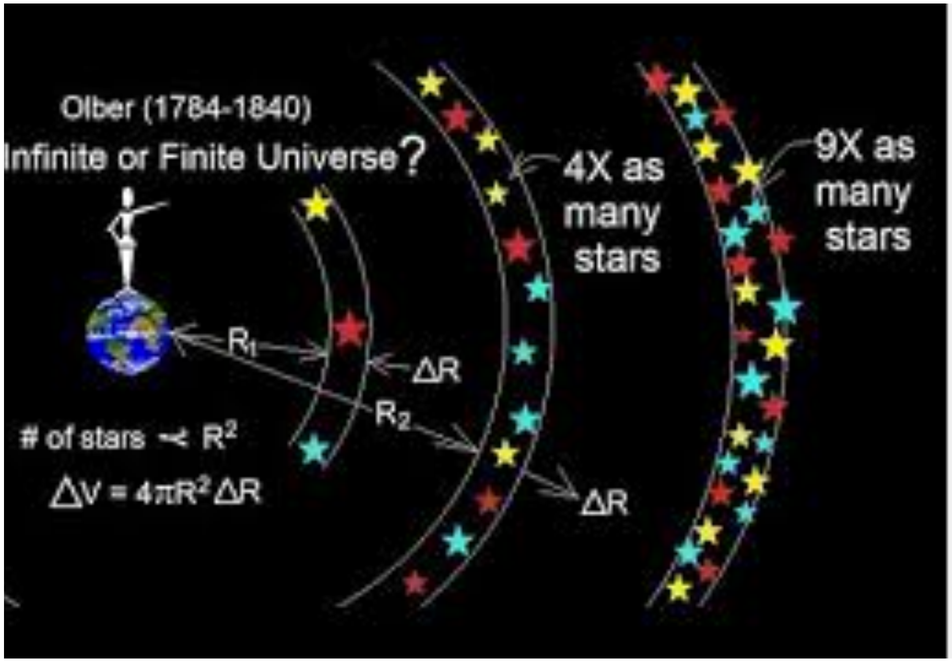
Marco Ajello [Clemson Univ.]
on behalf of the Fermi-LAT Collaboration

2015: the International Year of Light

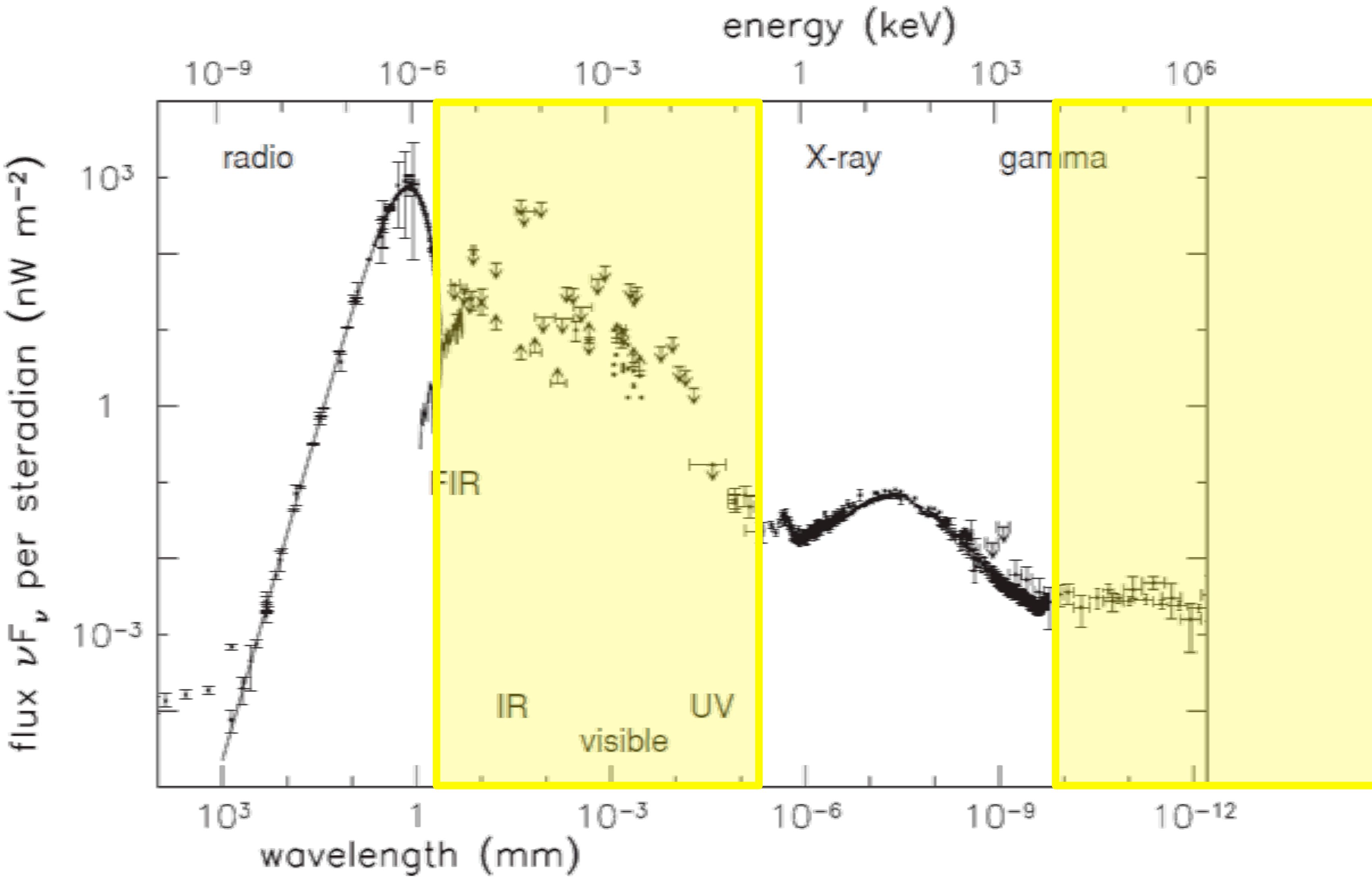
Olbers' Paradox

- If stars are infinite and the Universe is infinite, why is the night sky dark ?

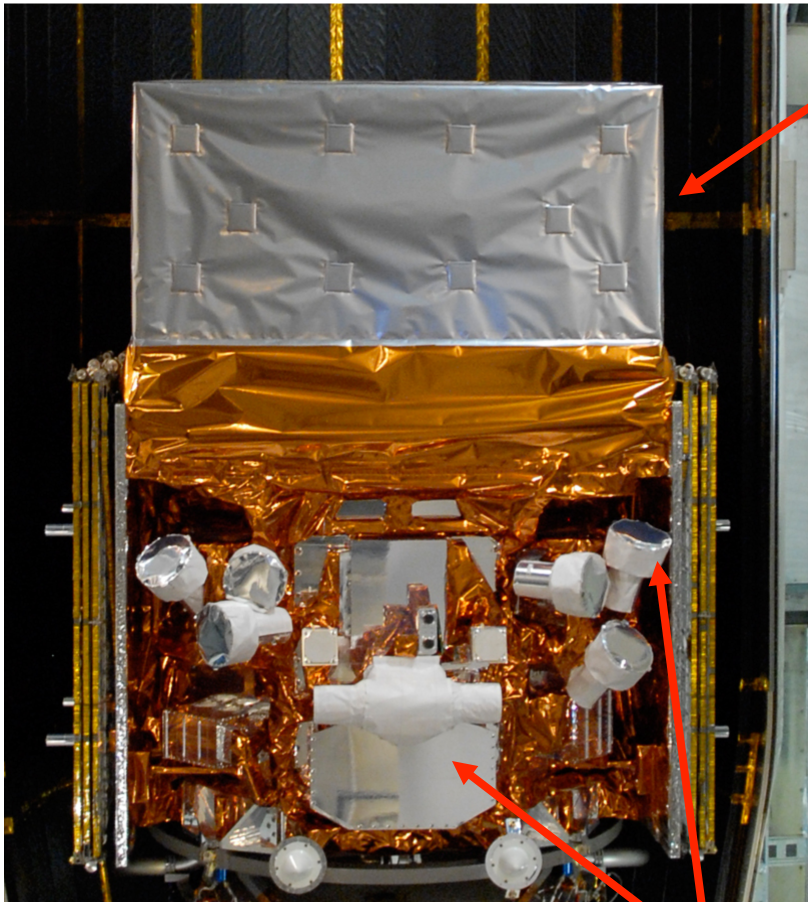




Cosmic Backgrounds

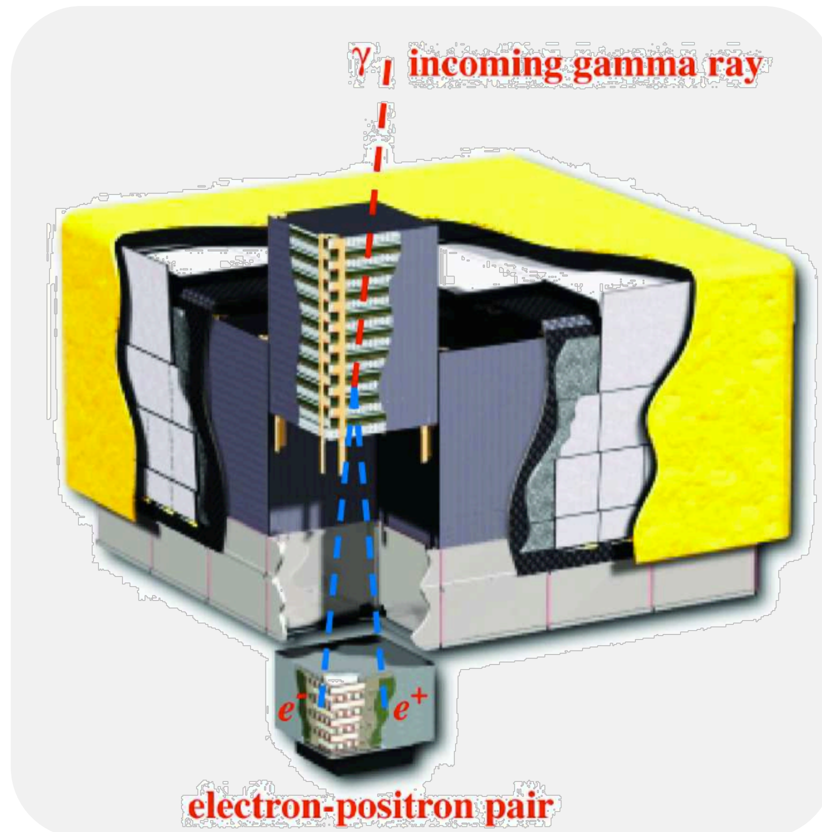


Fermi: Bigger, Sharper, Faster



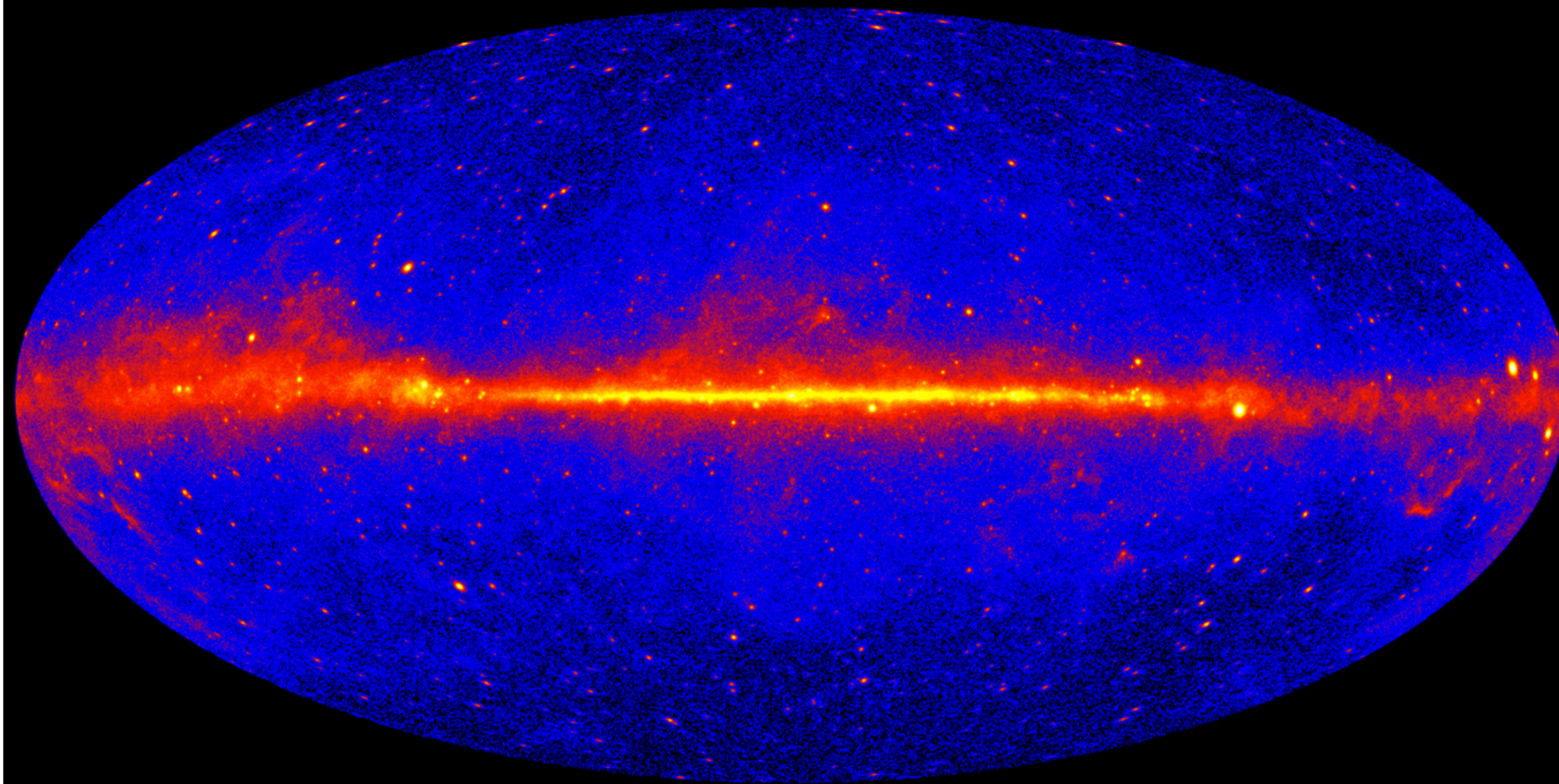
Large Area Telescope (LAT):

- 30 MeV - > >500 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)



Gamma-ray Burst Monitor (GBM)

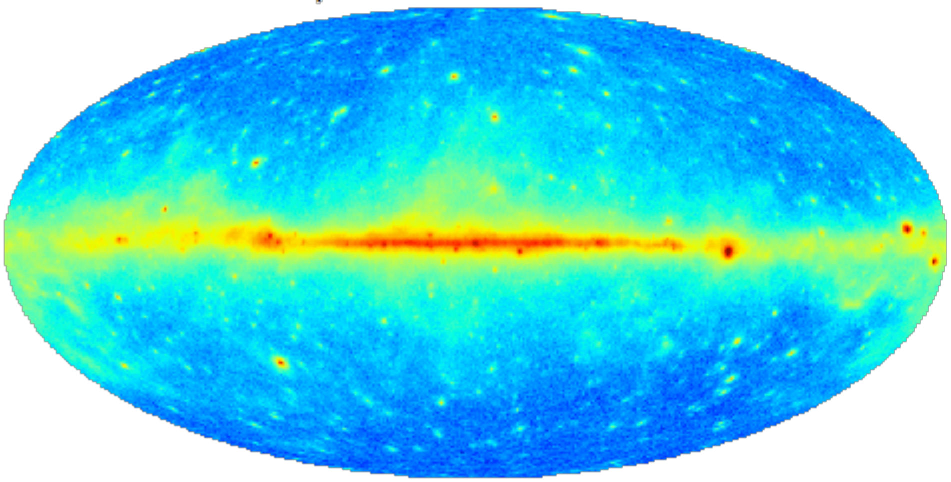
- 8 keV - 40 MeV
- views entire unocculted sky



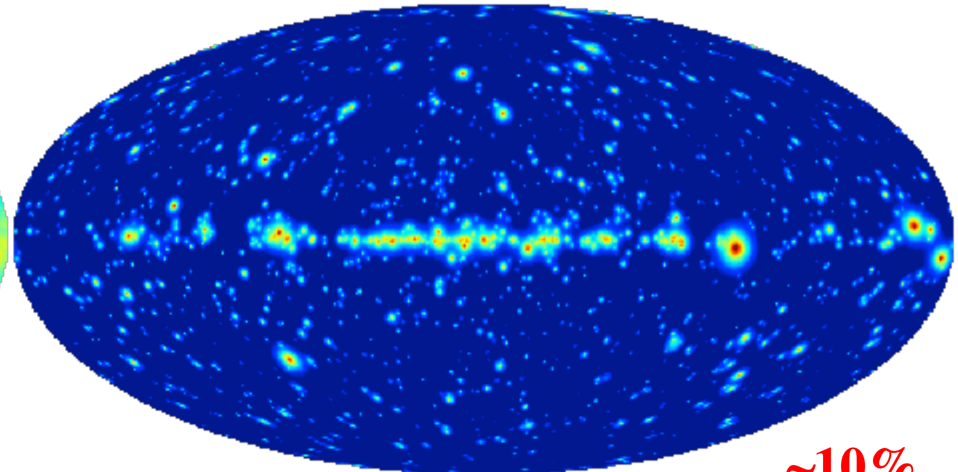
Marco Ajello

The Gamma-ray Sky as Seen by *Fermi*

LAT photons above 300 MeV

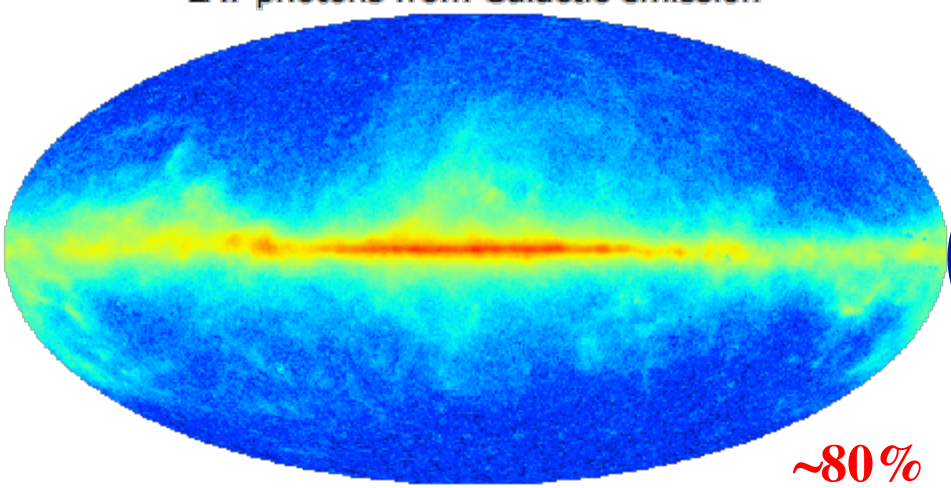


Point Sources



~10%

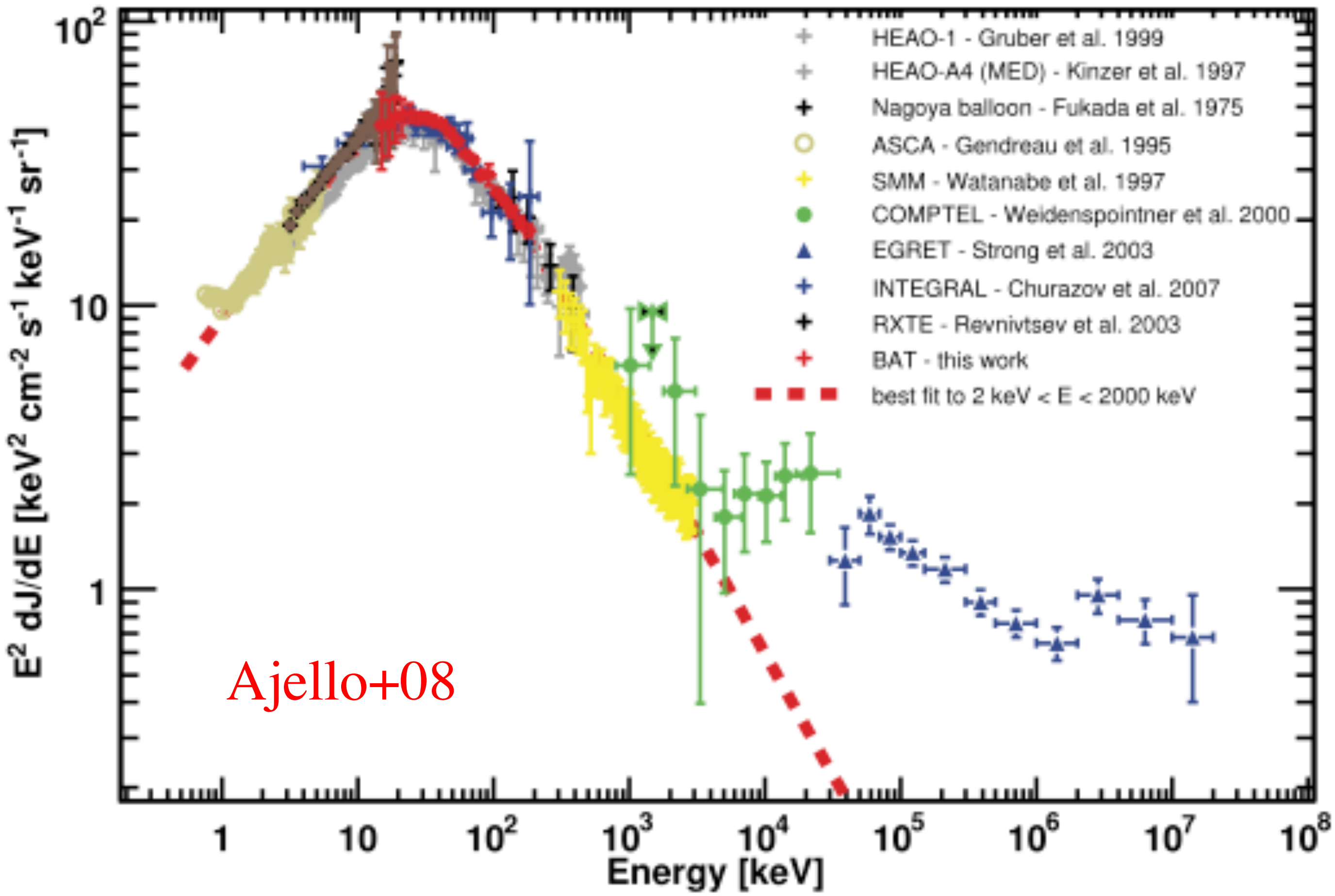
LAT photons from Galactic emission

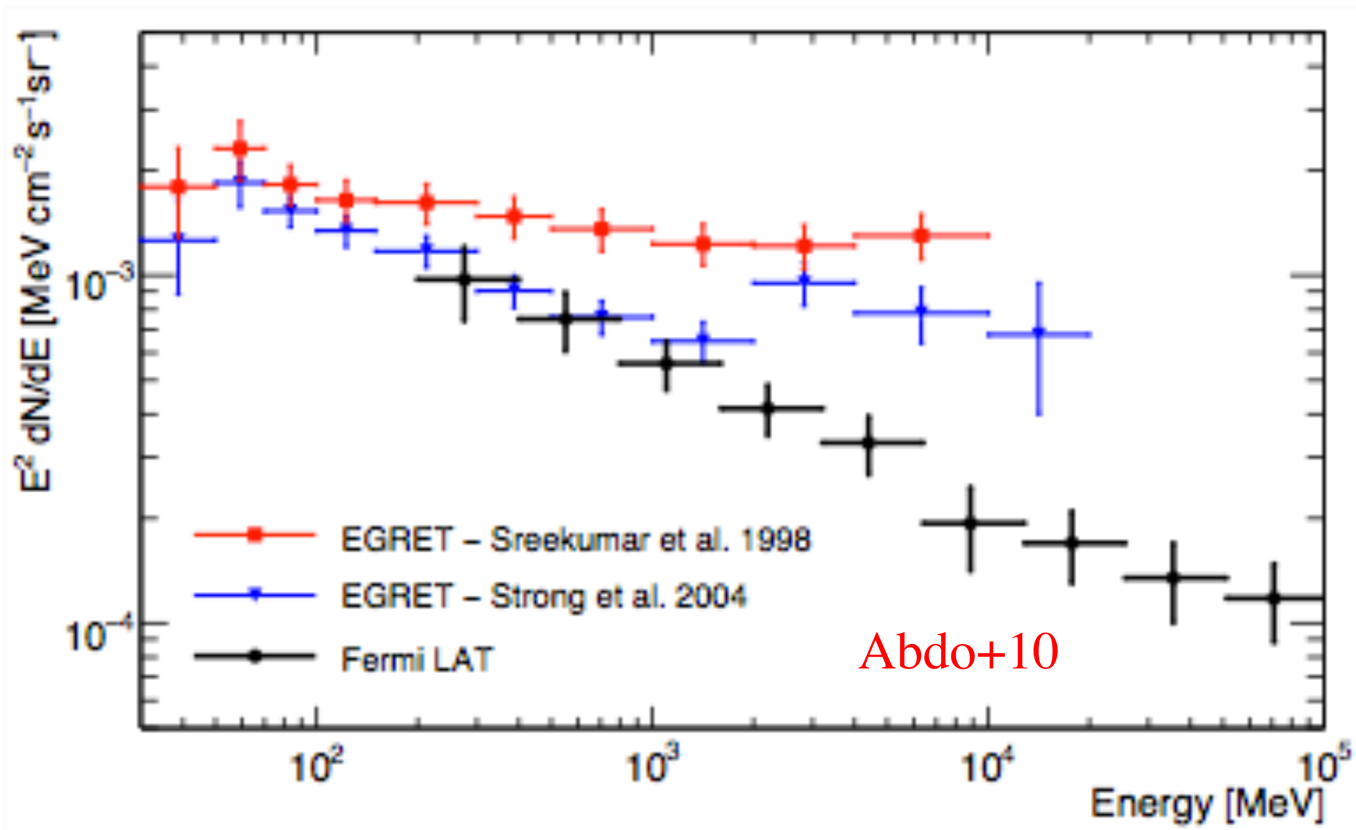


~80%

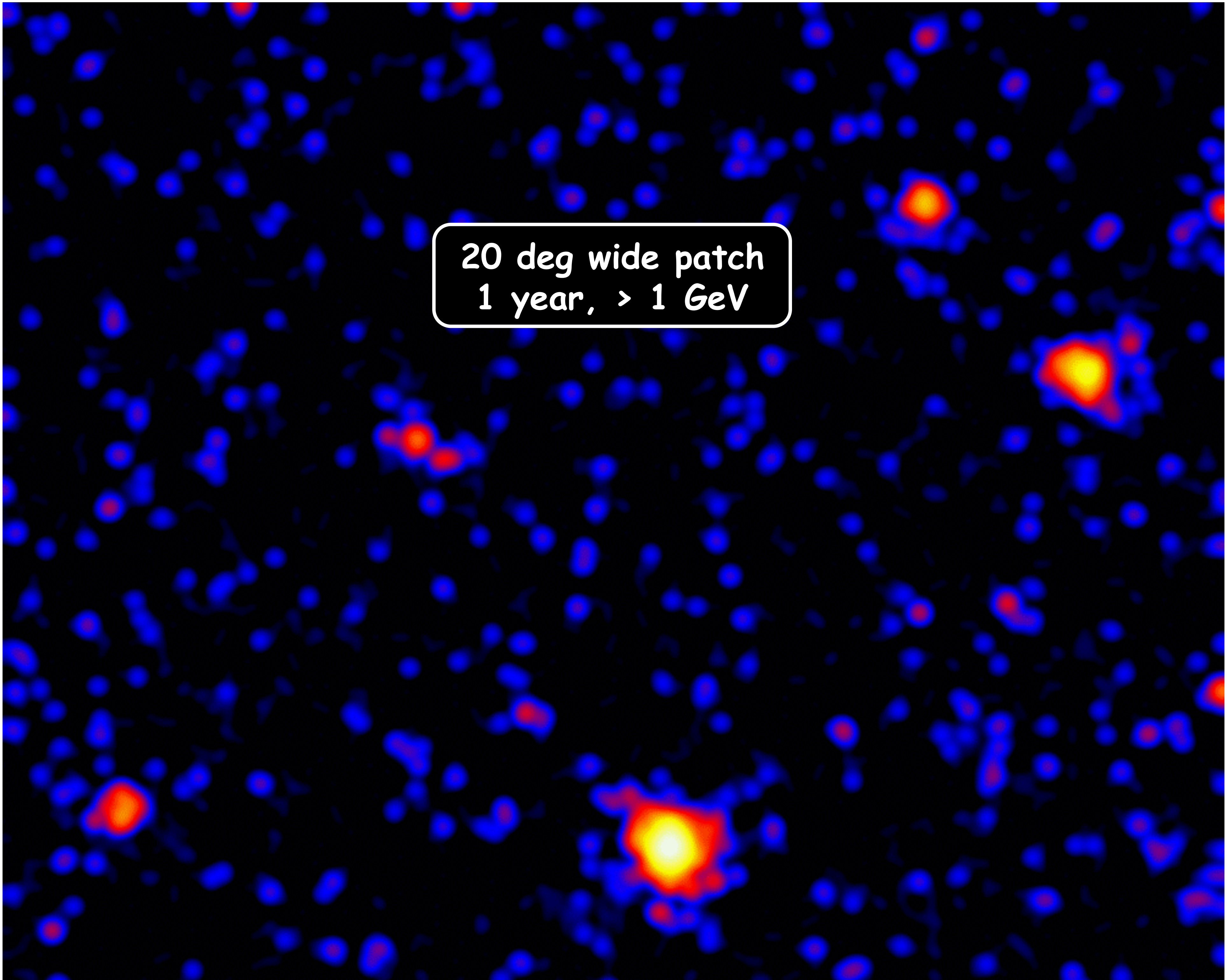
**Nearly isotropic
all-sky component
(includes residual
cosmic-ray background)**

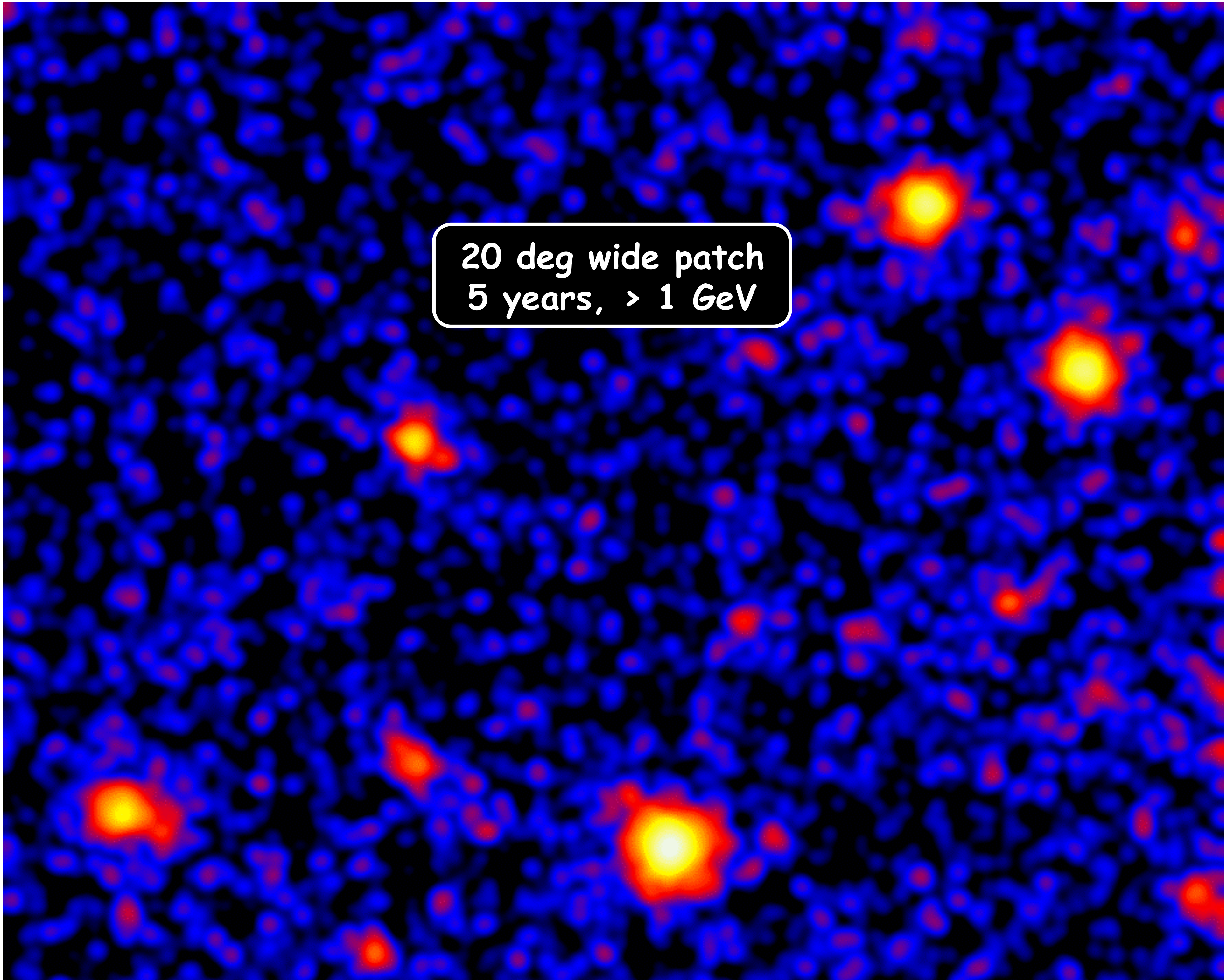
~10%


HEAO-1 - Gruber et al. 1999
HEAO-A4 (MED) - Kinzer et al. 1997
Nagoya balloon - Fukada et al. 1975
ASCA - Gendreau et al. 1995
SMM - Watanabe et al. 1997
COMPTEL - Weidenspointner et al. 2000
EGRET - Strong et al. 2003
INTEGRAL - Churazov et al. 2007
RXTE - Revnivtsev et al. 2003
BAT - this work
best fit to 2 keV < E < 2000 keV
Ajello+08
E^2 dJ/dE [keV^2 cm^{-2} s^{-1} keV^{-1} sr^{-1}]
Energy [keV]

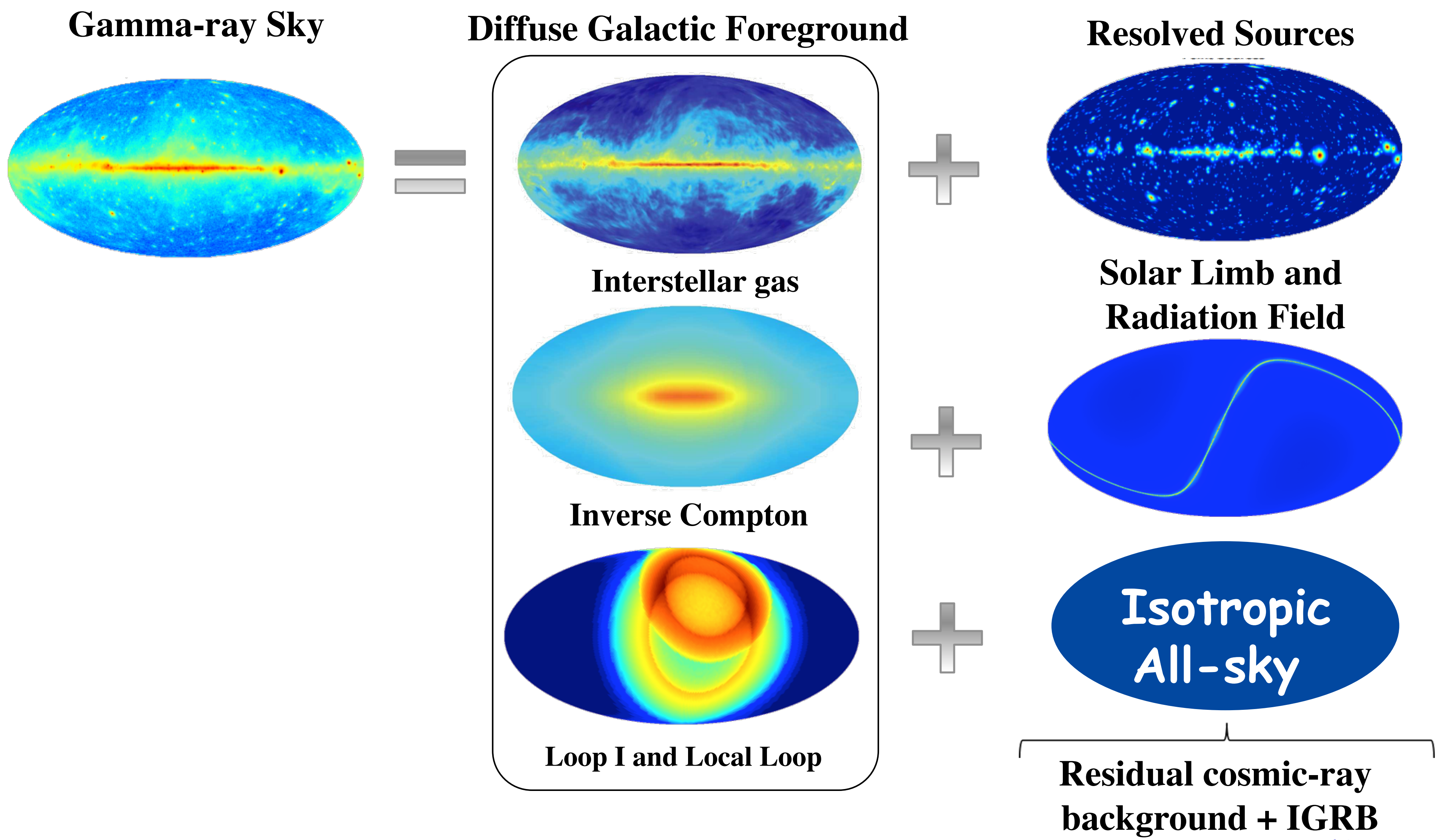


E^2 dN/dE [MeV cm^{-2}s^{-1}sr^{-1}]
10^{-3}
10^{-4}
EGRET – Sreekumar et al. 1998
EGRET – Strong et al. 2004
Fermi LAT
Abdo+10
10^2
10^3
10^4
10^5
Energy [MeV]


20 deg wide patch
1 year, > 1 GeV

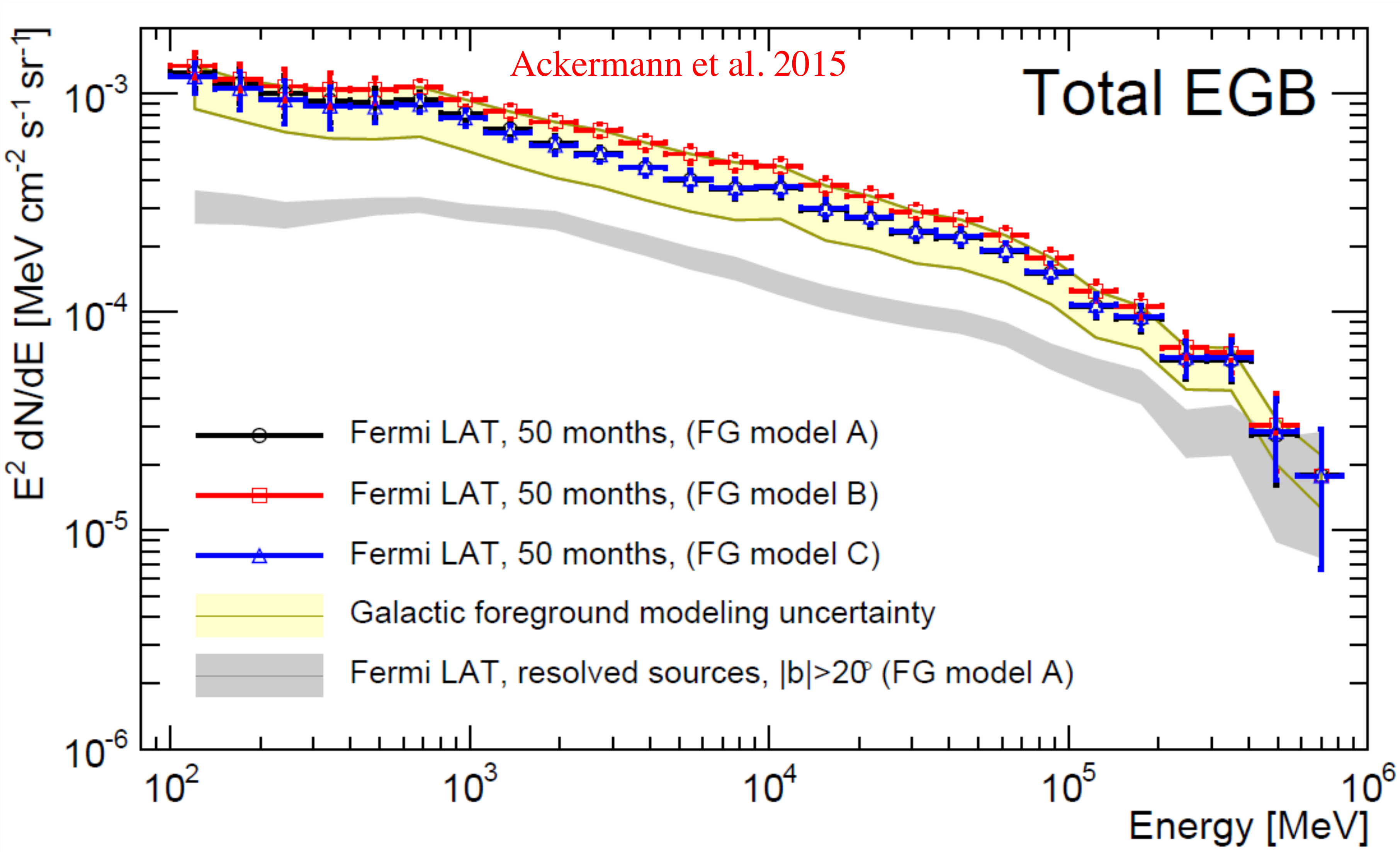

20 deg wide patch
5 years, > 1 GeV

Template Fitting Procedure (Maximum Likelihood)

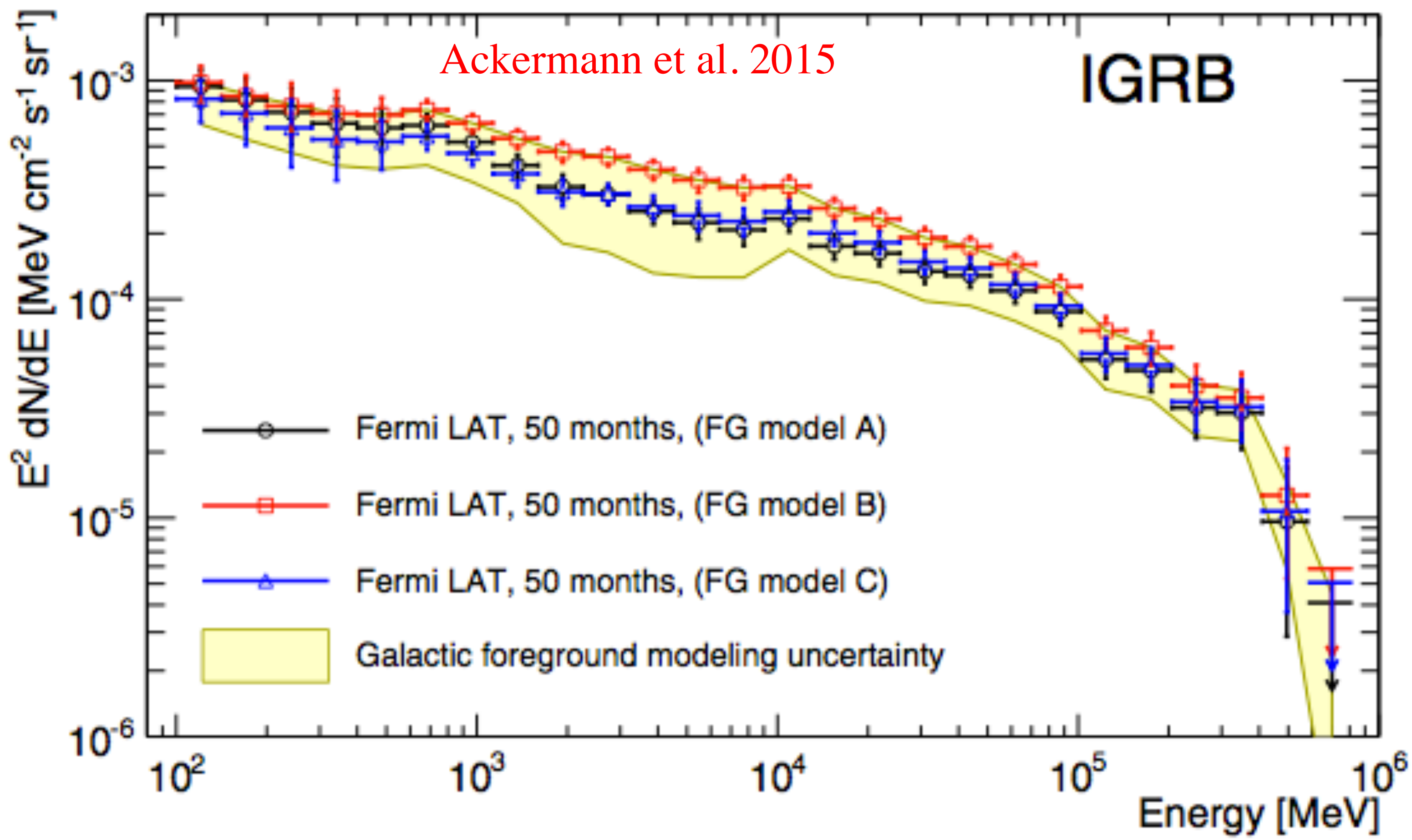


Total Extragalactic Gamma-ray Background

Systematic uncertainty from Galactic foreground represented by yellow band

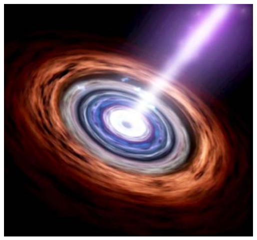


Isotropic Gamma-ray Background

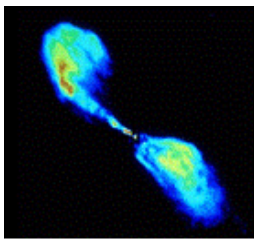


EGB: Why is it important ?

Undetected sources

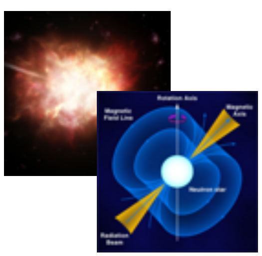


[Blazars]
Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.



[Non-blazar active galaxies]
27 sources resolved in 2FGL
~ 25% contribution of radio galaxies to EGB expected. (e.g. Inoue 2011)

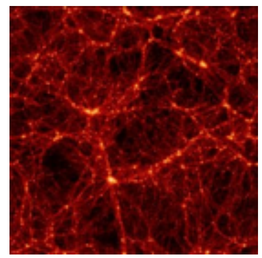
[Star-forming galaxies]
Several galaxies outside the local group resolved by LAT. Significant contribution to EGB expected. (e.g. Pavlidou & Fields, 2002, Ackermann et al. 2012)



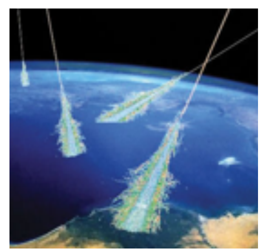
[GRBs]
[High-latitude pulsars]
Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

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)



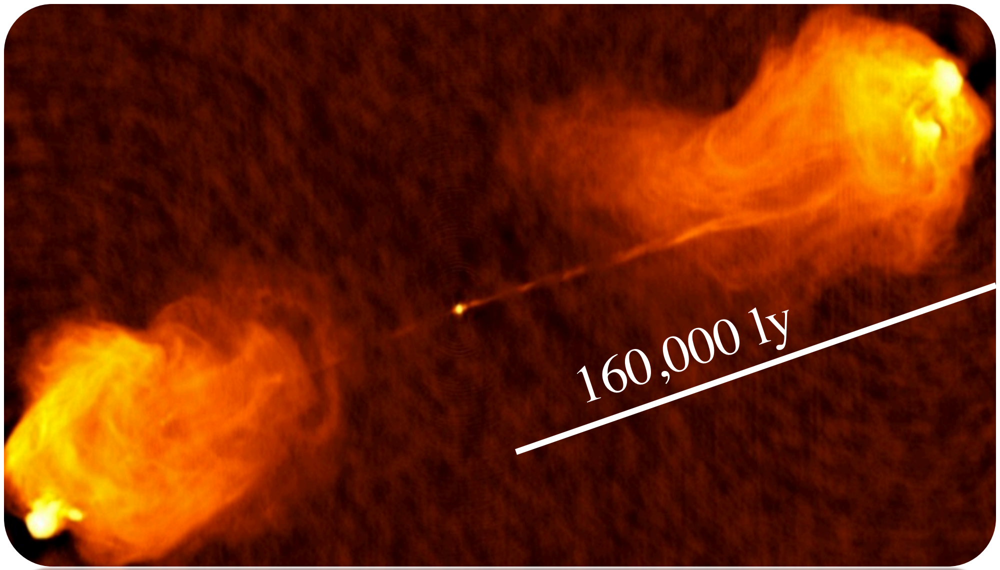
[Interactions of UHE cosmic rays with the EBL]
Dependent on evolution of CR sources, predictions varying from 1% to 100 % (e.g. Kalashev et al. 2009)

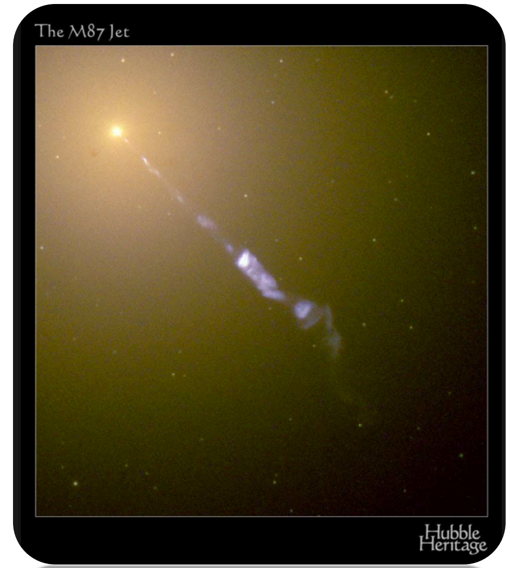
[Extremely large Galactic electron halo] (Keshet et al. 2004)

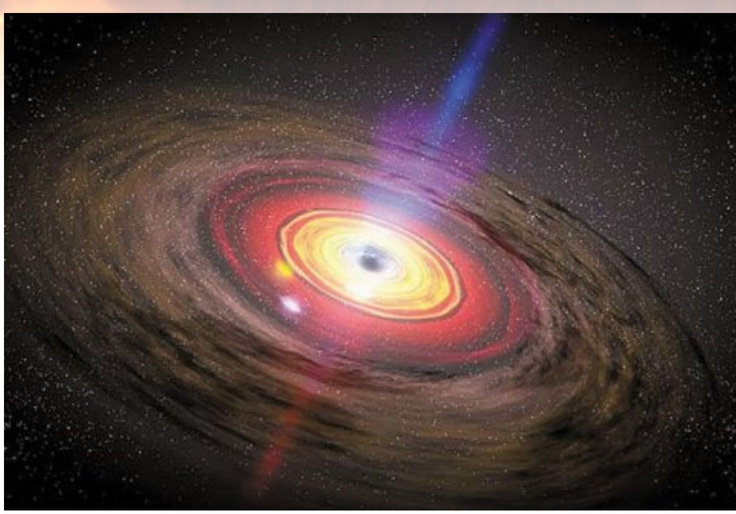
[CR interaction in small solar system bodys] (Moskalenko & Porter 2009)

Blazar Jets

Contain particles accelerated to near speed of light



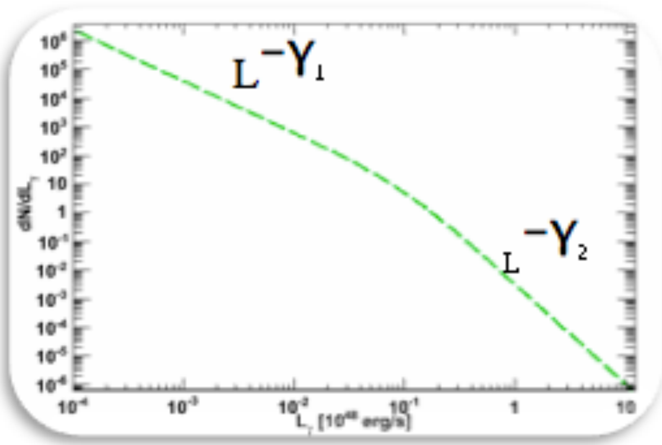




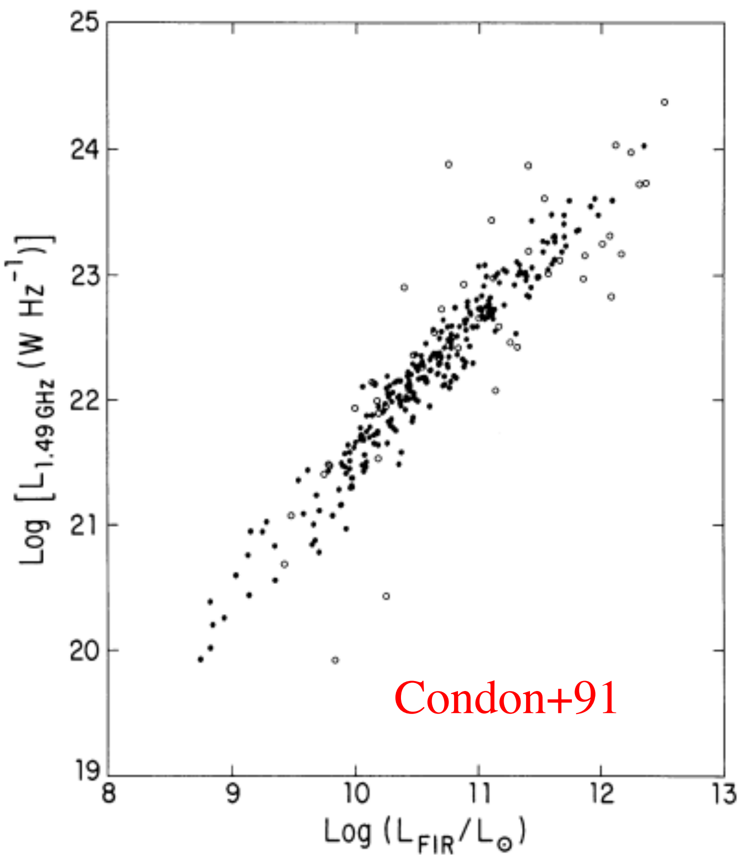
Integrated Emission from Point Sources

- Derive a Luminosity function
  - Fairly Universal

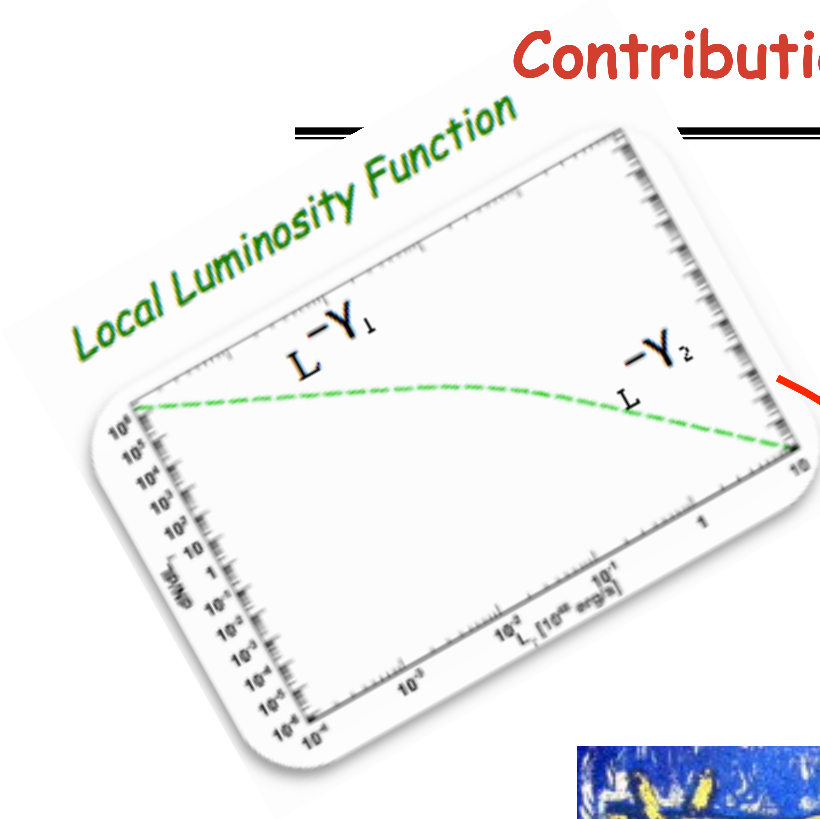
Local Luminosity Function

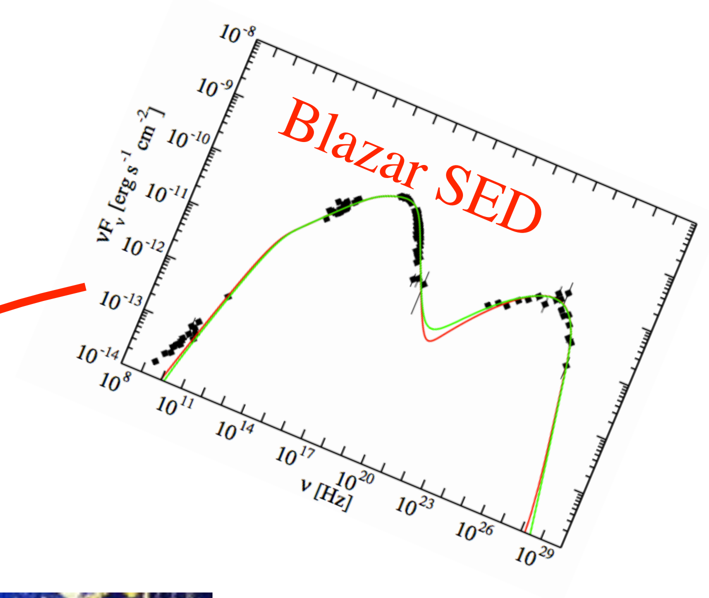


- Use a luminosity function of from another band (e.g. radio)
- Derive a correlation from g-rays to that band (e.g. radio)



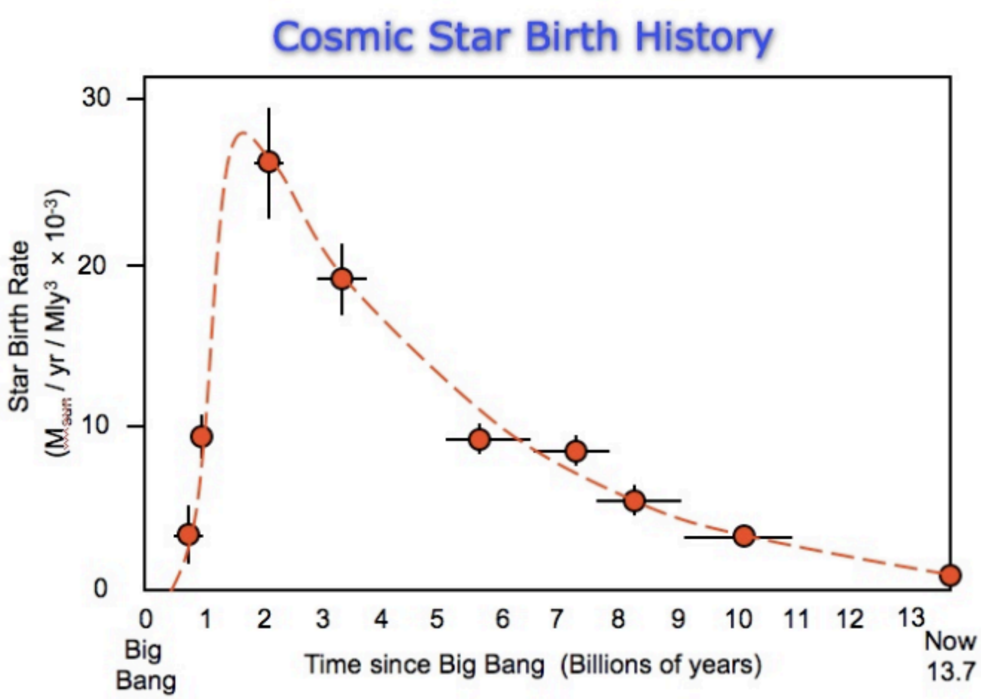
Contribution of Sources to the EGB

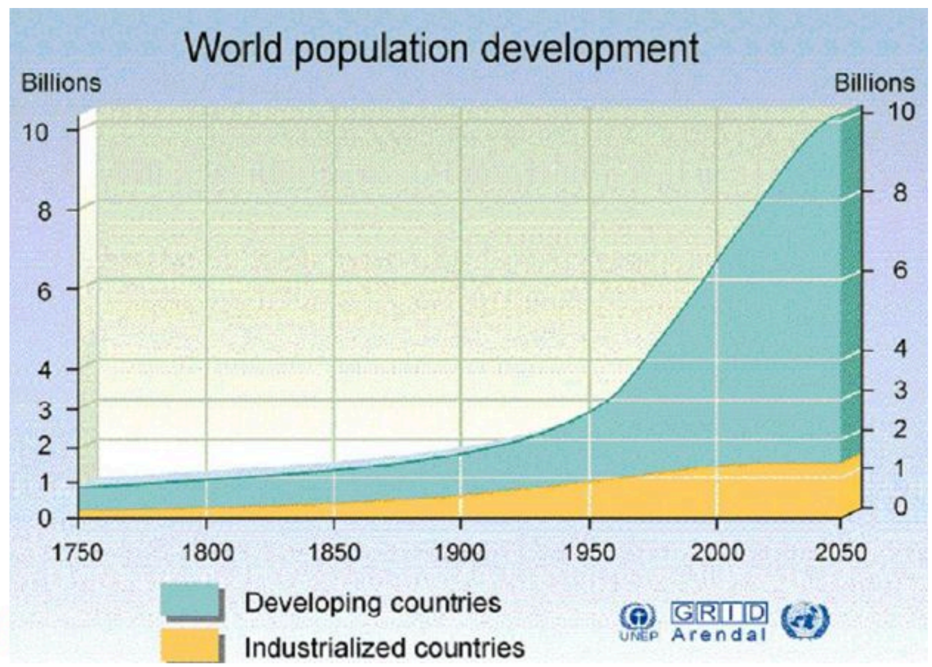




Evolution

- Most things depend on the availability of gas/fuel
- Stars are formed out of gas, galaxies are made of gas, stars and DM
- Black holes feed on gas

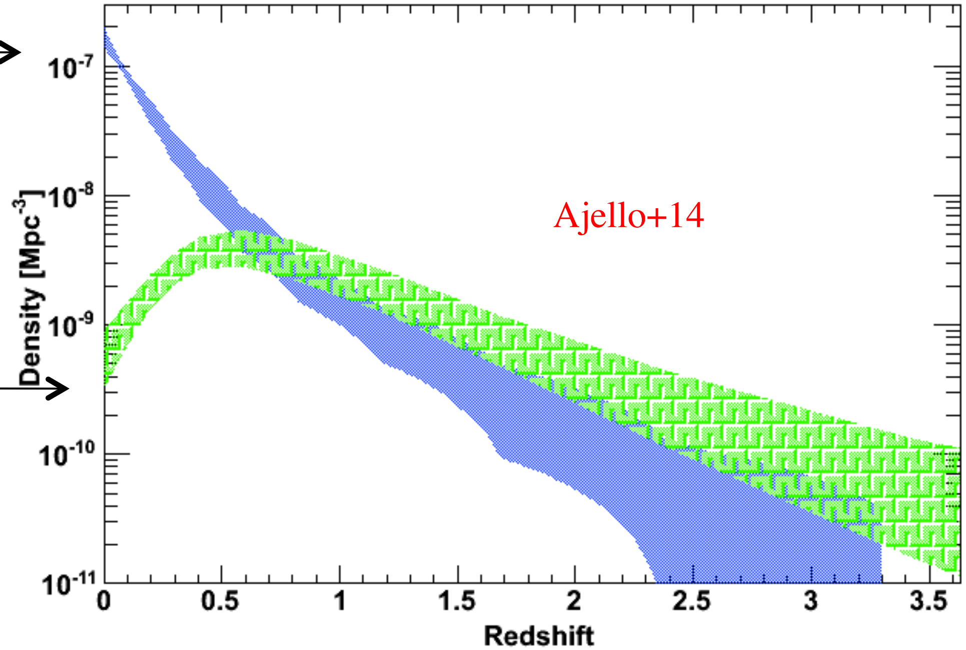




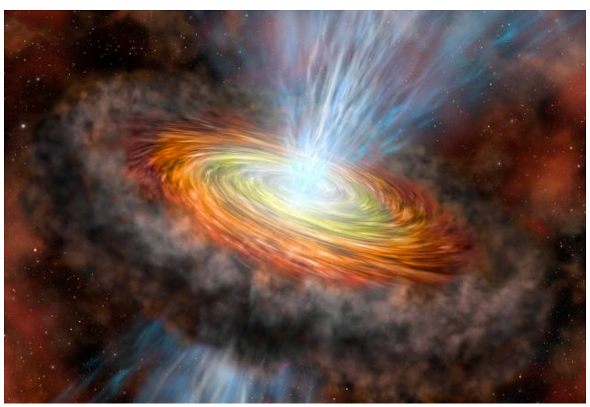
Evolution of Blazars

BL Lacs

Flat spectrum radio quasars (FSRQs)

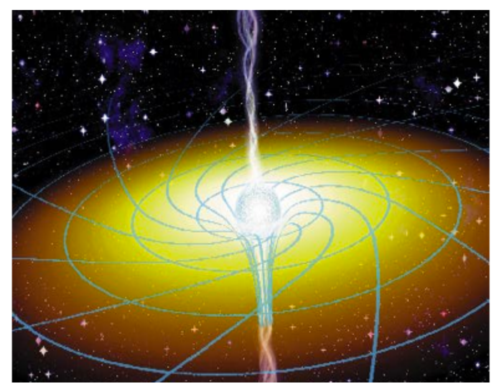


Black hole spun up by accretion



Rotational energy is conserved over time

Energy is extracted



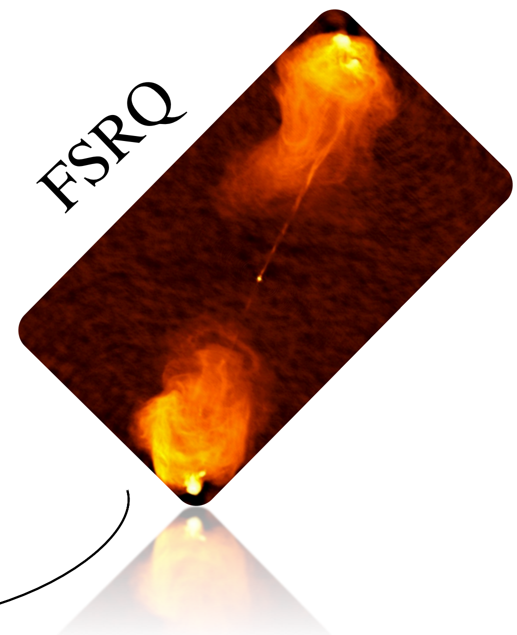
FSRQ

BL Lac

Genetic Link

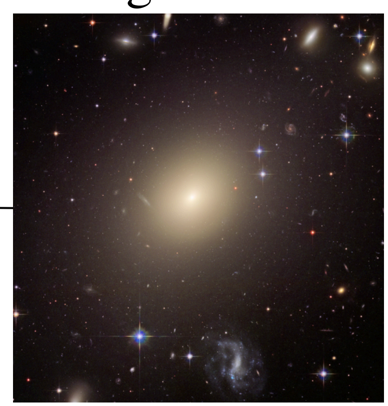
Merging

FSRQ

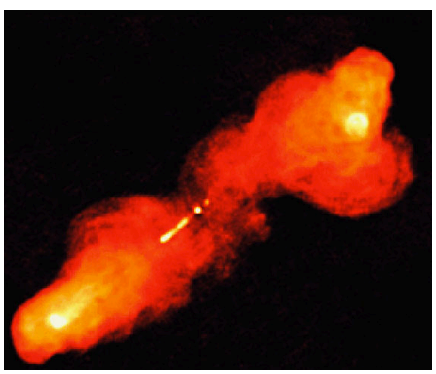


Cavaliere & D'Elia 2002
Böttcher & Dermer 2002

Gas poor elliptical galaxies



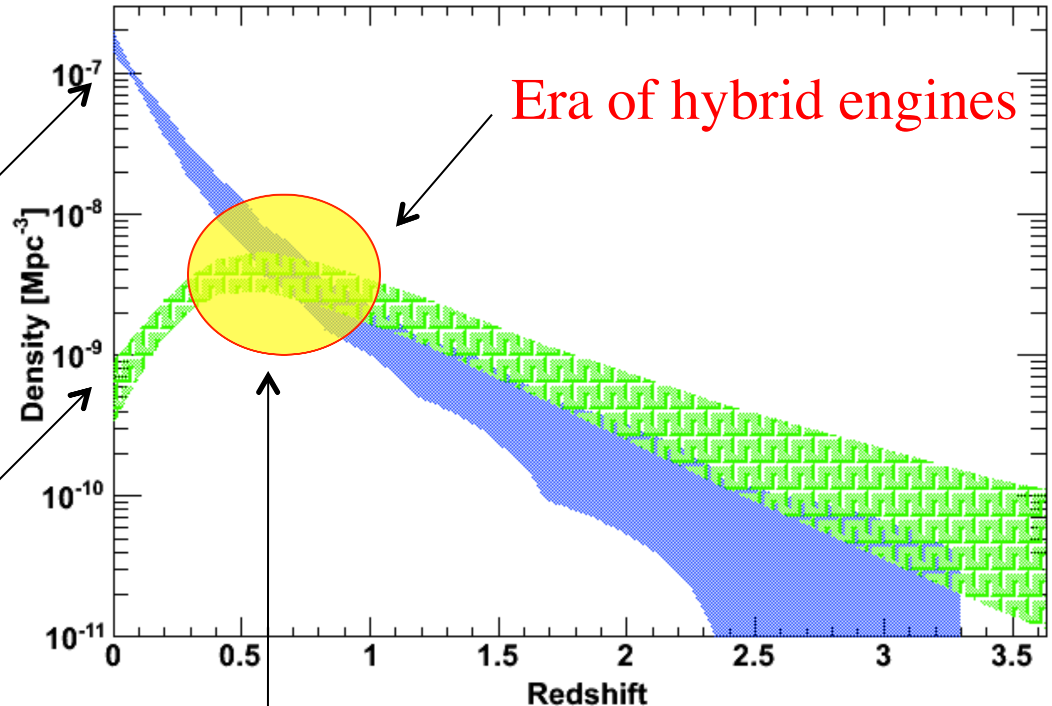
BL Lac

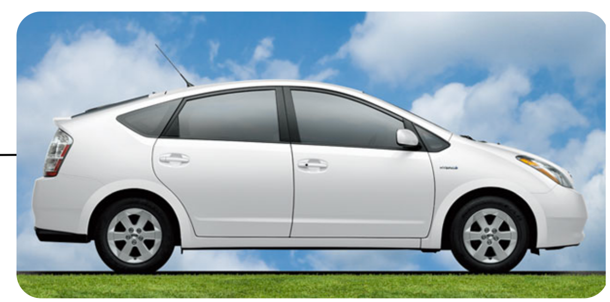


Evolution of Blazars

Electric engines (BL Lacs)

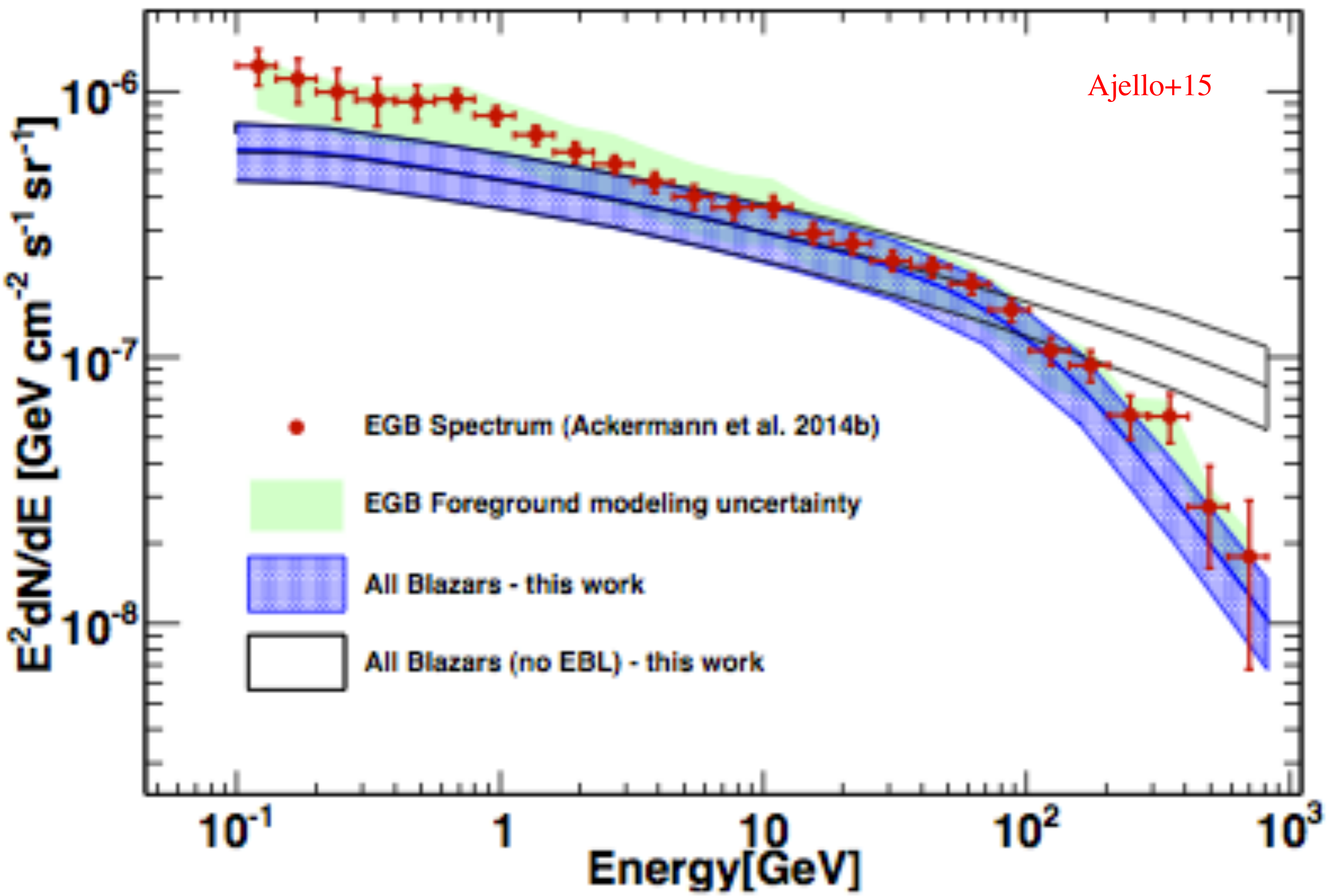
Gas-fueled engines (FSRQs)



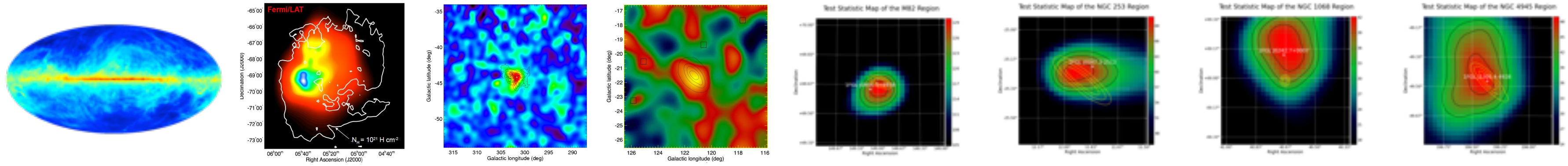


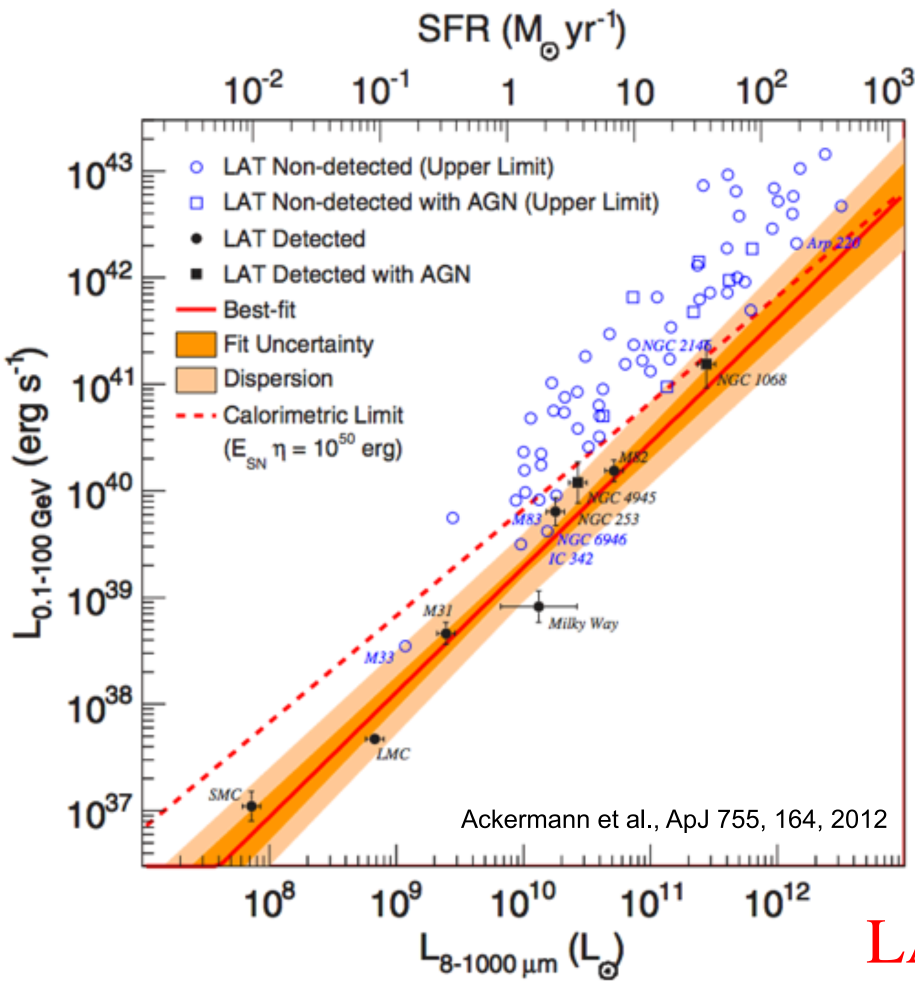
Results

- Blazars contribute a grand-total of $(5\text{-}7)\times10^{-6}$ ph cm^{-2} s^{-1} sr^{-1}
  1. Blazars produce ~50% of the EGB
  2. Blazars + EBL are responsible for the cut-off of the EGB spectrum
  3. In good agreement with Di Mauro & Donato 2015



Star forming galaxies

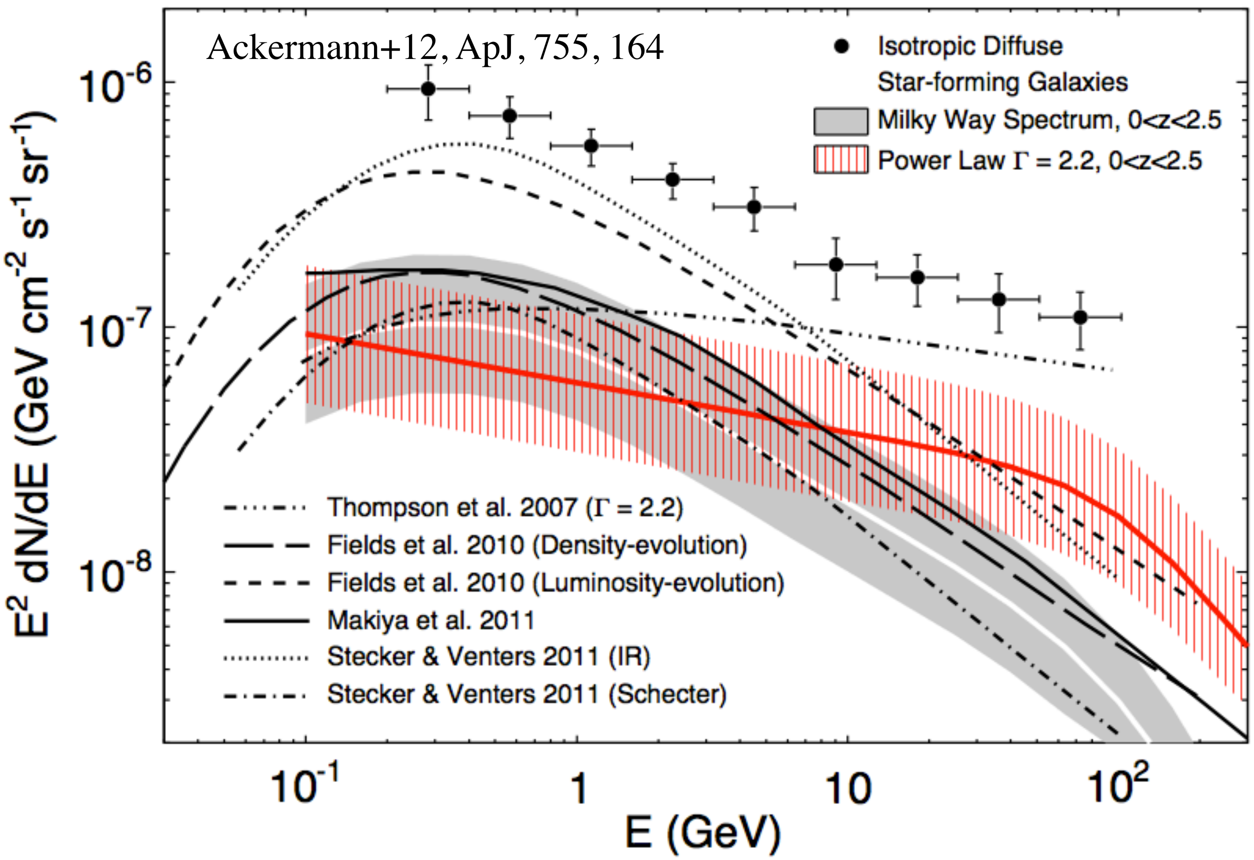




- 8 galaxies detected by the LAT
- Almost linear correlation between gamma-ray luminosity and tracers of star formation
  - bolometric infrared luminosity
  - 1.4 GHz radio continuum emission
- Detection + upper limits can be used to constrain correlation
- Use gamma-ray / IR luminosity correlation to calculate EGB contribution based on IR luminosity function of galaxies.

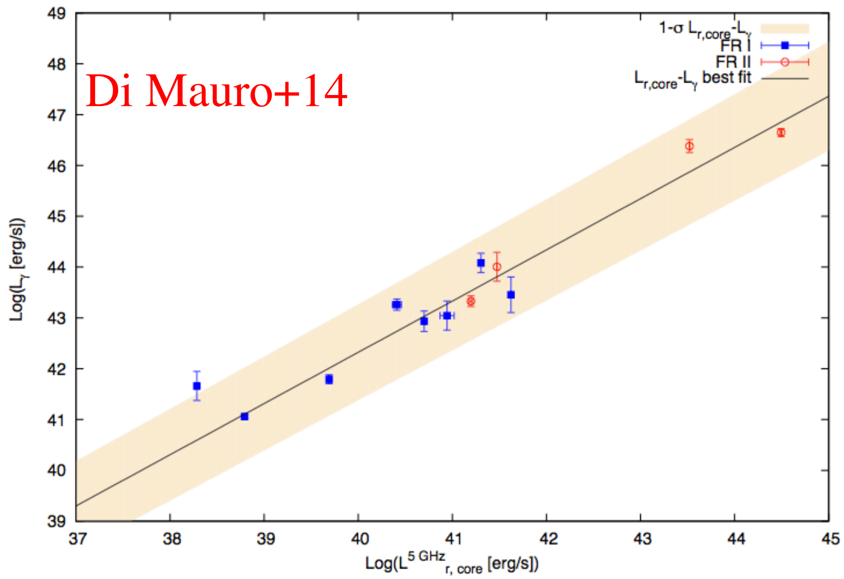
LAT detects all famous C-Thick AGN

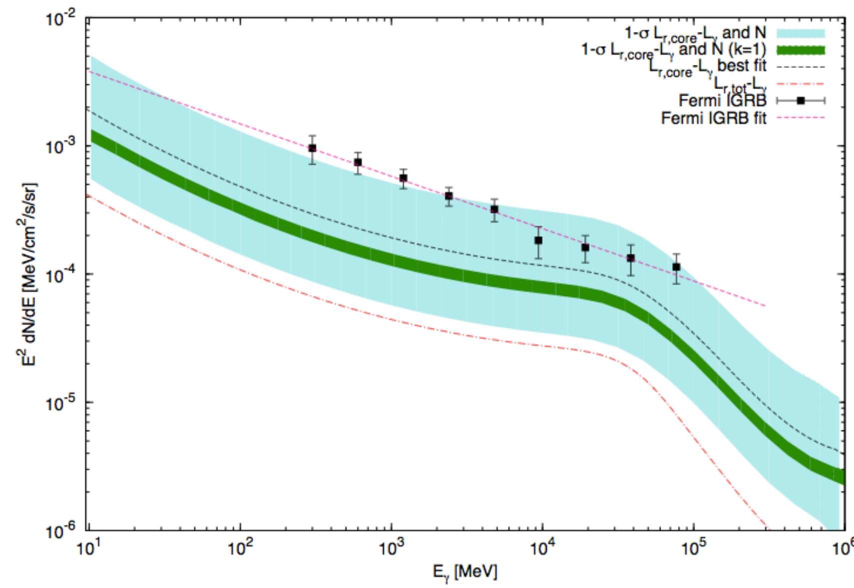
Star forming Galaxies



- Star-forming galaxies contribute 13%(±9%) of the IGRB

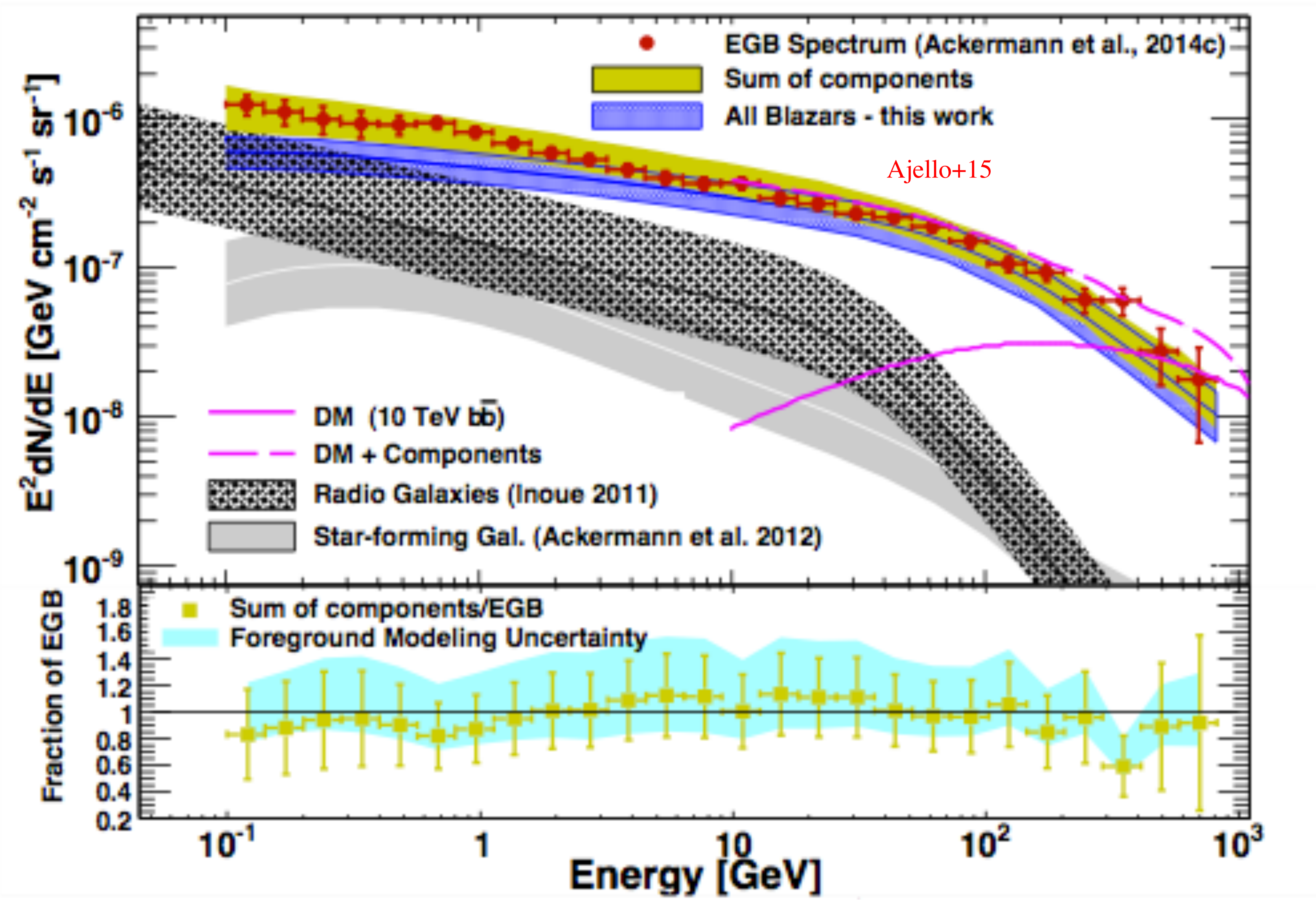
Radio Galaxies





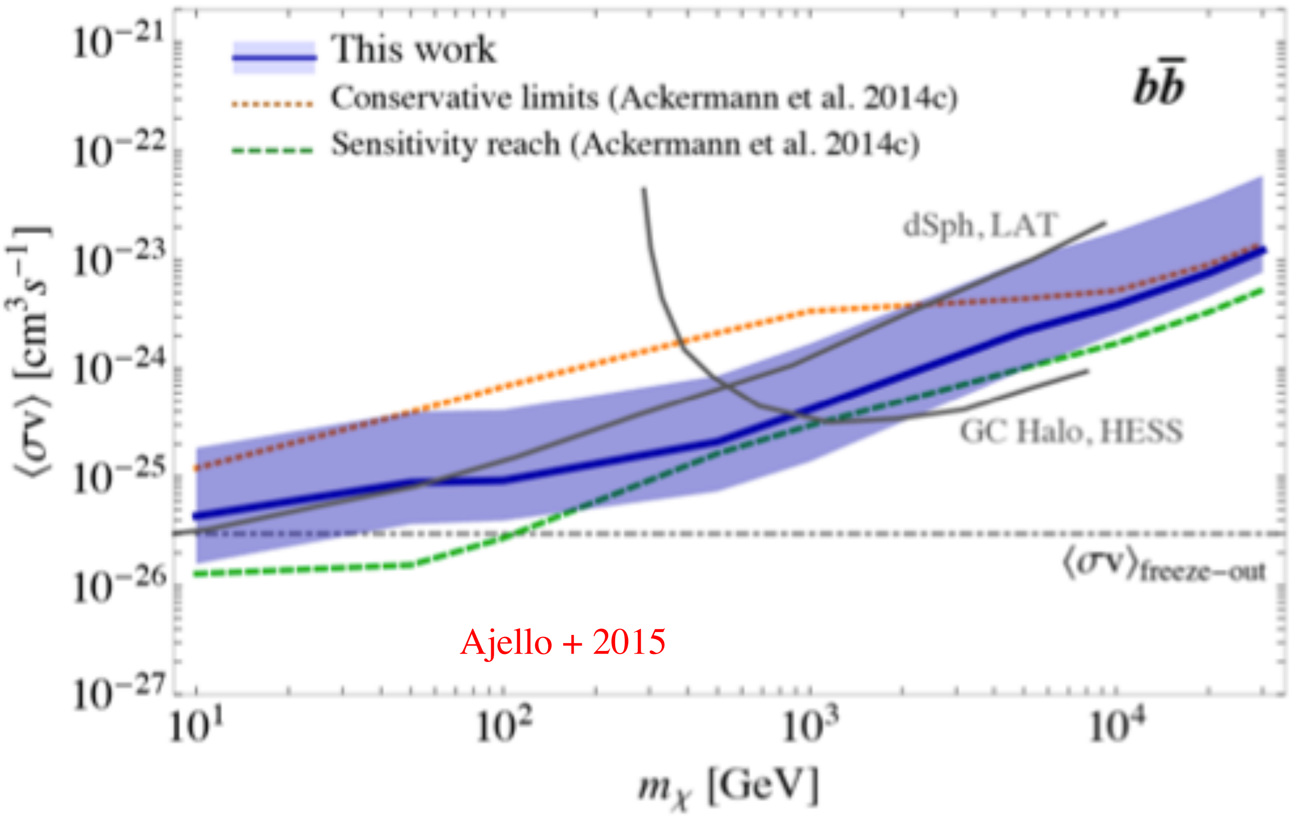
- *Fermi* has detected 15 radio galaxies (Abdo+10, ApJ 720, 912 and Nolan+12, ApJS, 199, 31)
- A correlation exists between the g-ray and the core luminosity
- Using the Willott+01 Luminosity Function, the contribution to the IGRB is: 25% (+58%/-16%)

Summing Everything Up

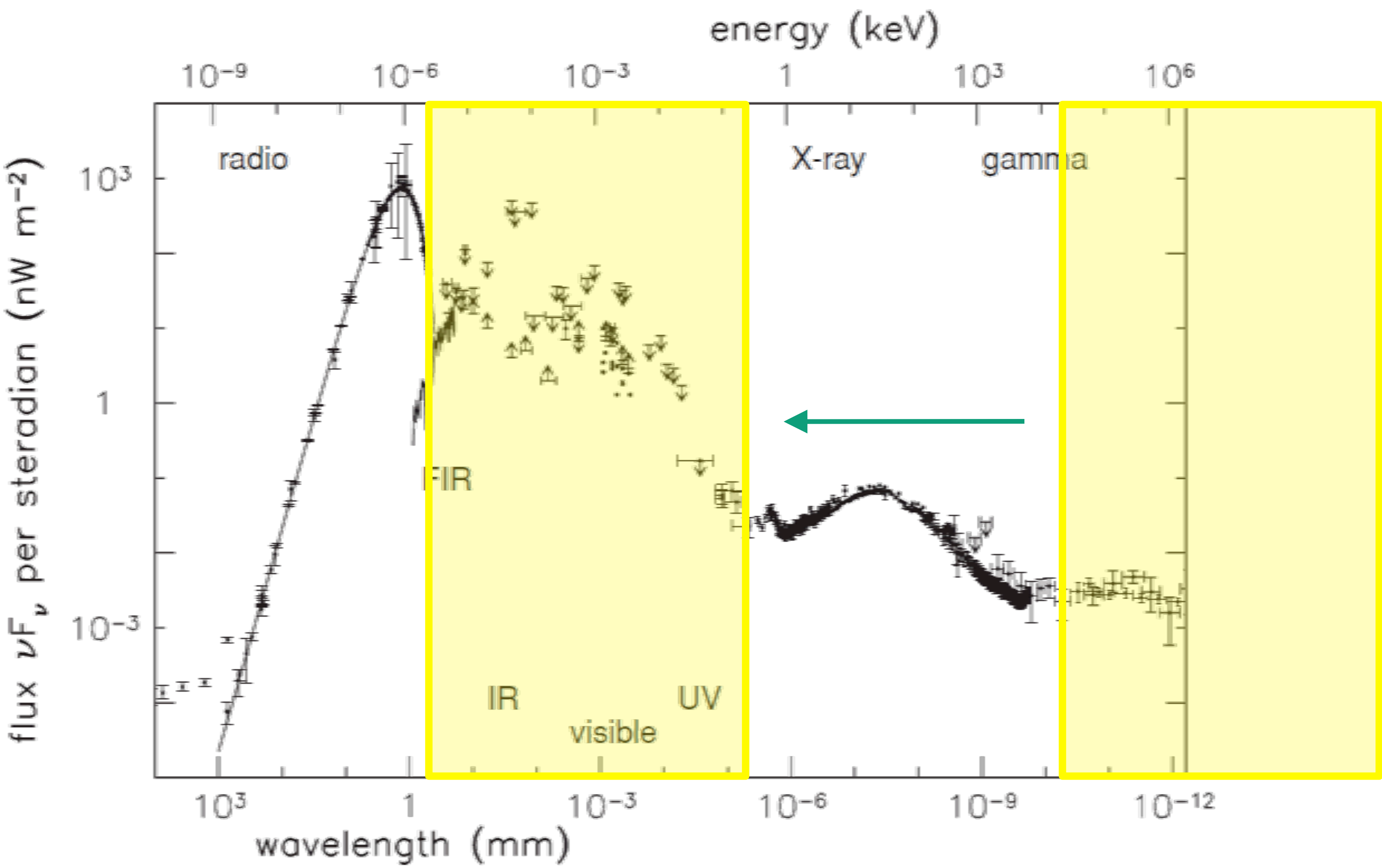


Dark Matter Limits

- DM limits reach higher masses due to the high-energy reach (820 GeV) of the EGB measurement
- Decreasing the uncertainties on source contributions can improve the limits by a factor of 5



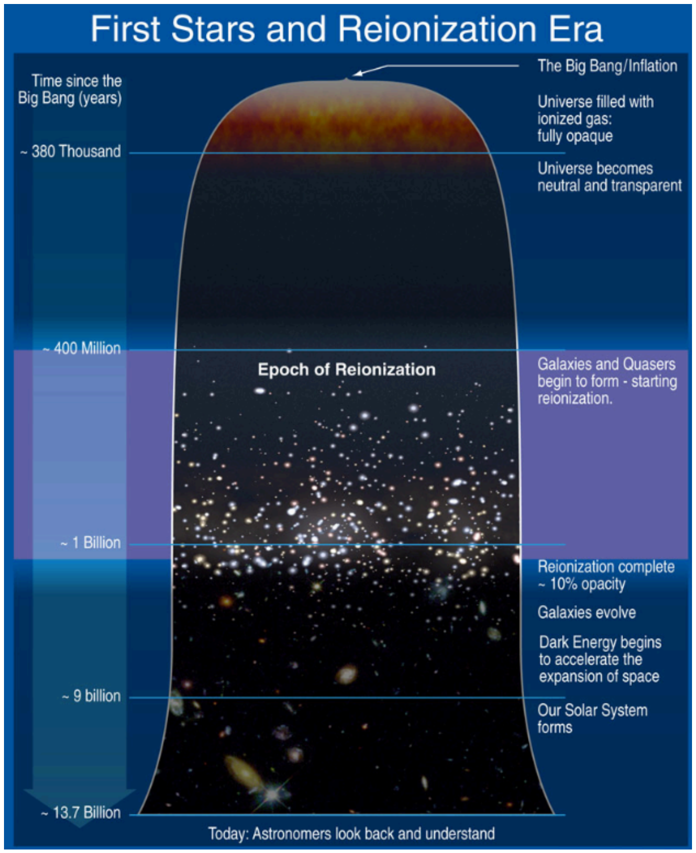
Cosmic Backgrounds

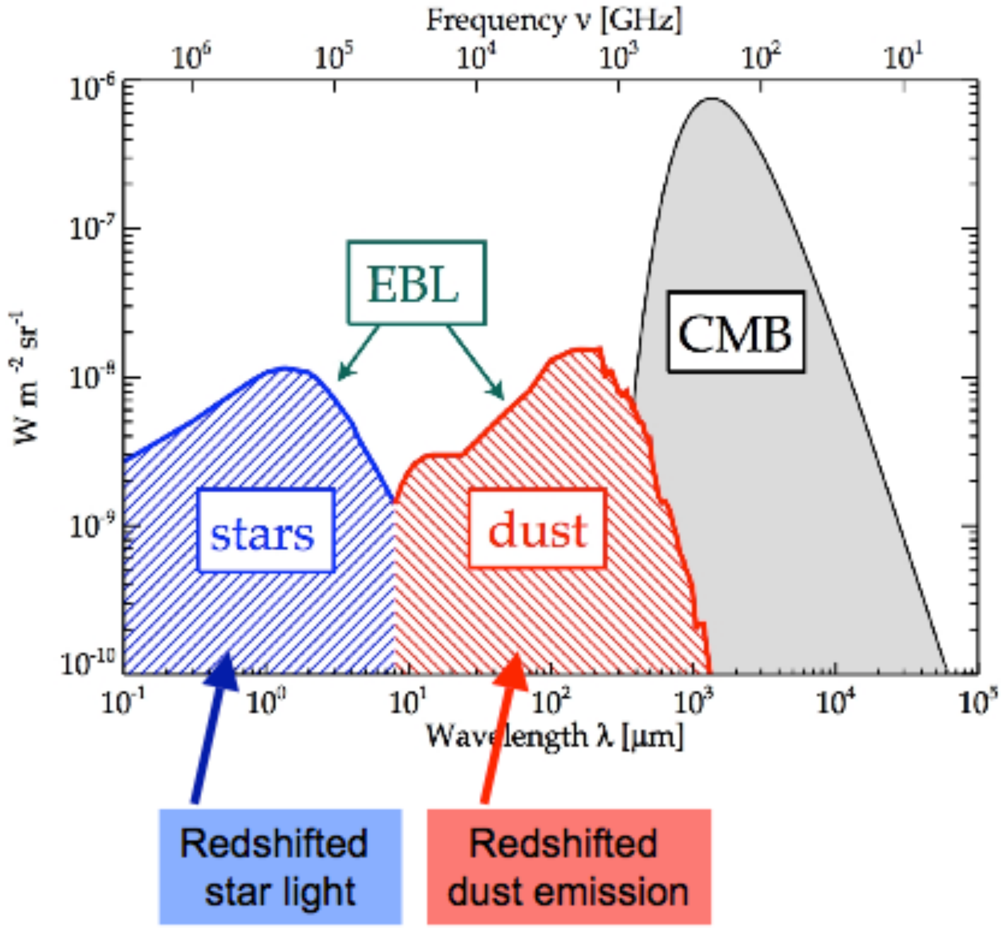


Dominguez, Primack & Bell
2015, *Scientific American*

Marco Ajello

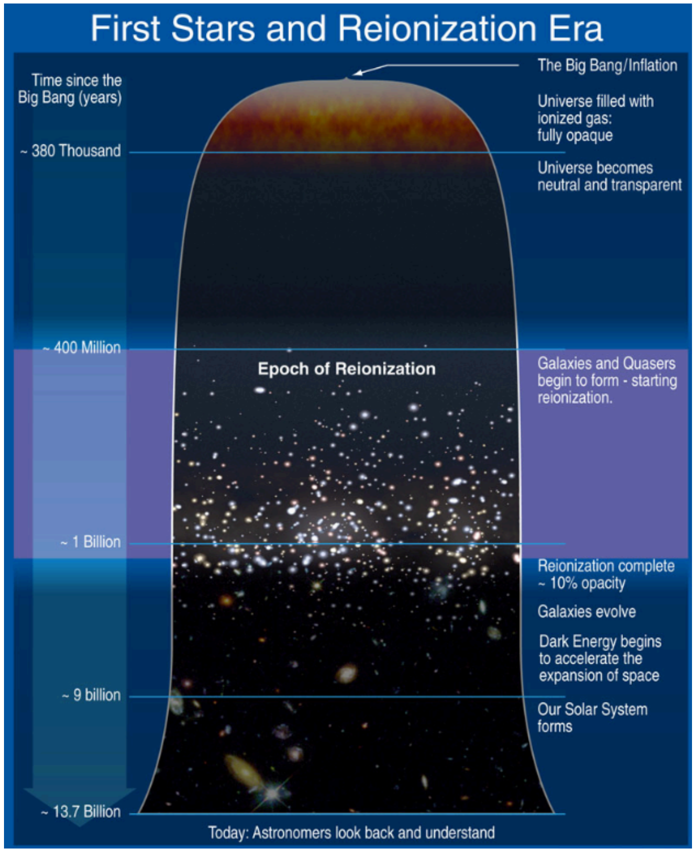
The Extragalactic Background Light

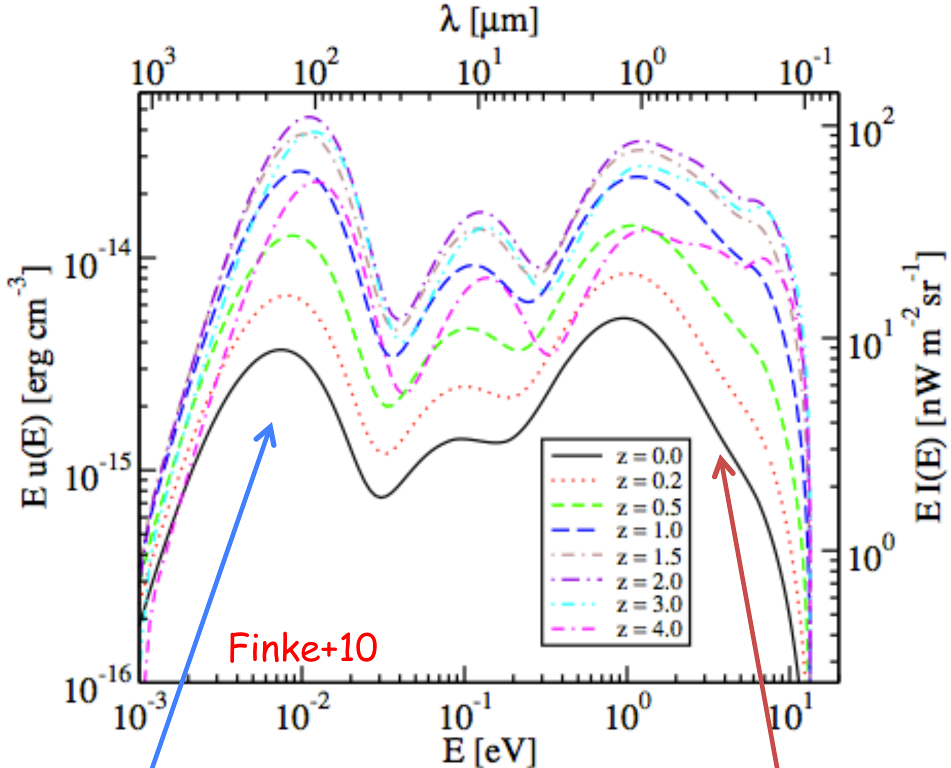




- ->constraints on galaxy evolution, star formation activity, dust extinction processes
- ->understanding cosmic structure formation and evolution

The Extragalactic Background Light





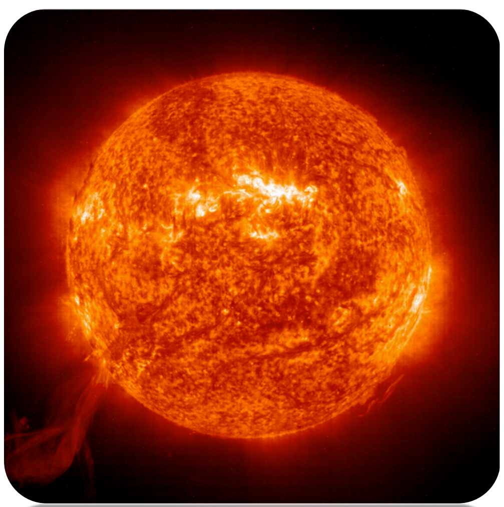
Light emitted by stars

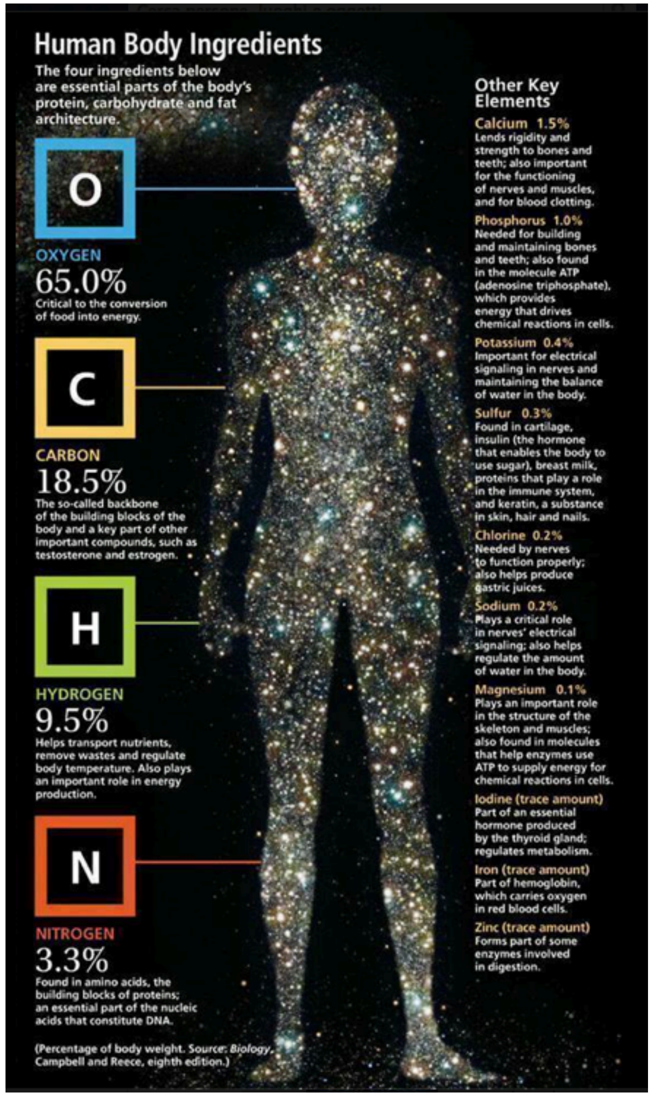
star light reprocessed by dust

- ->constraints on galaxy evolution, star formation activity, dust extinction processes
- ->understanding cosmic structure formation and evolution

Stars

- Stars: fundamental blocks of the Universe
- They bring light (everywhere)
  - The Earth ecosystem depends on sun light
  - Life might depend on light/stars
- They create and disperse elements

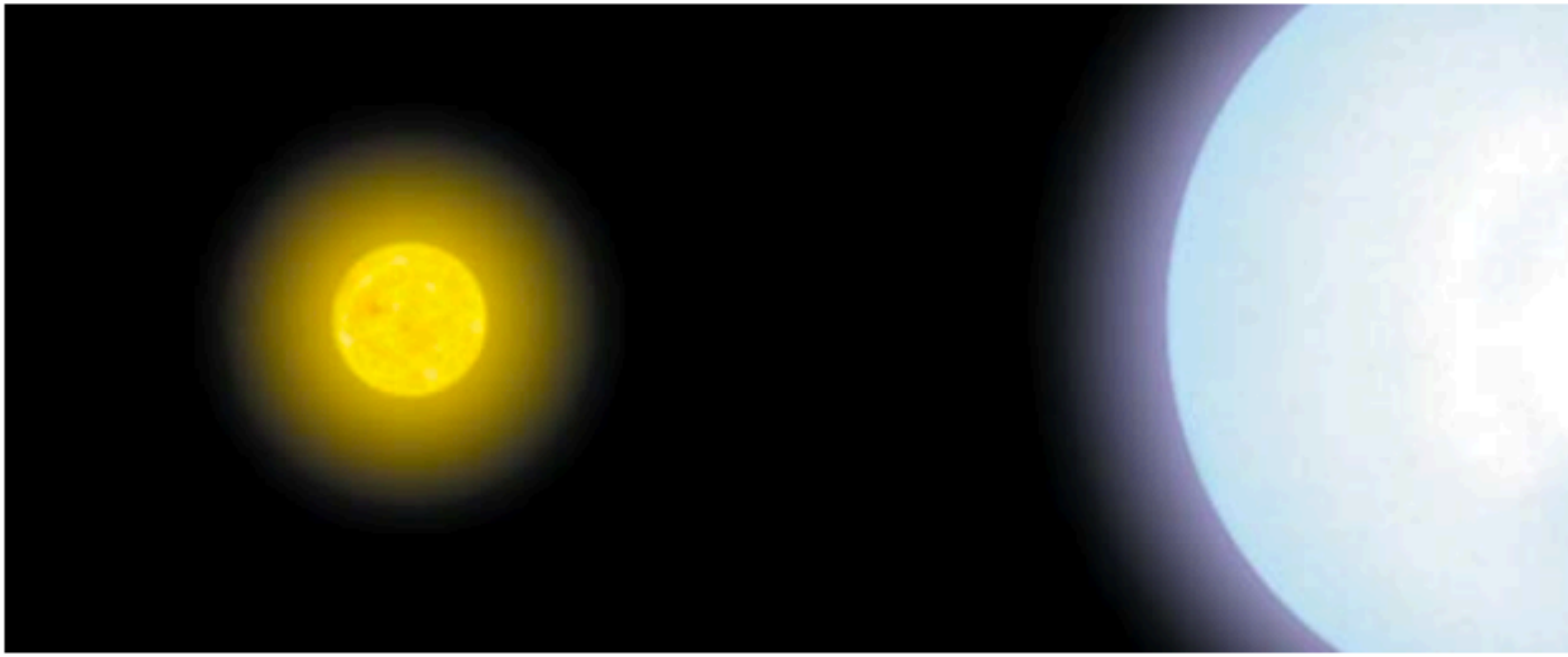




STAR STATS

COMPARING CHARACTERISTICS

Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.



SUN

MASS: **1.989×10^{30} kilograms**

RADIUS: **696,000 kilometers**

LUMINOSITY: **3.85×10^{23} kilowatts**

SURFACE TEMPERATURE: **5,780 kelvins**

LIFETIME: **10 billion years**

FIRST STARS

MASS: **100 to 1,000 solar masses**

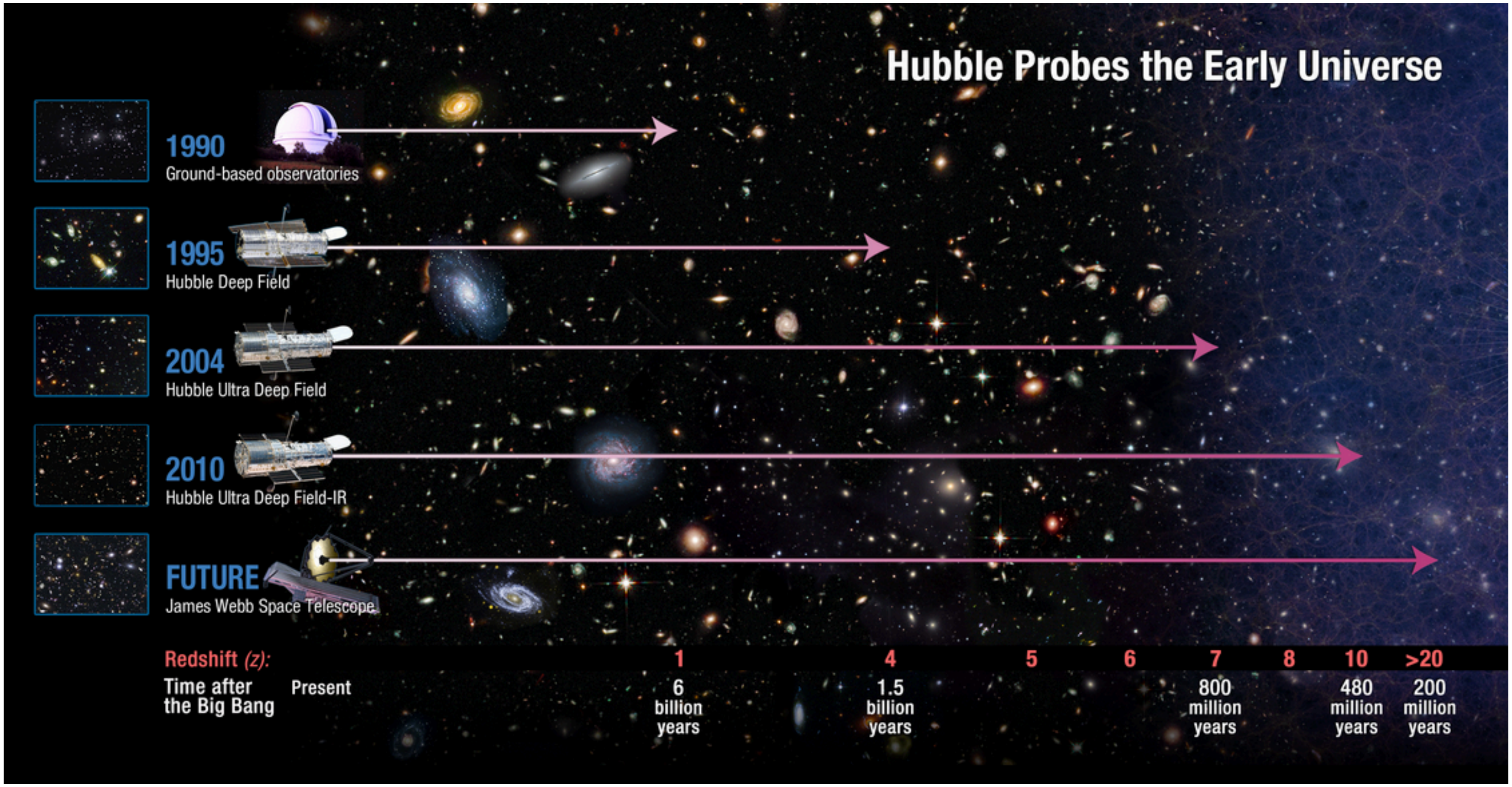
RADIUS: **4 to 14 solar radii**

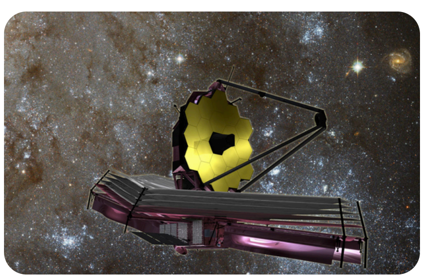
LUMINOSITY: **1 million to 30 million solar units**

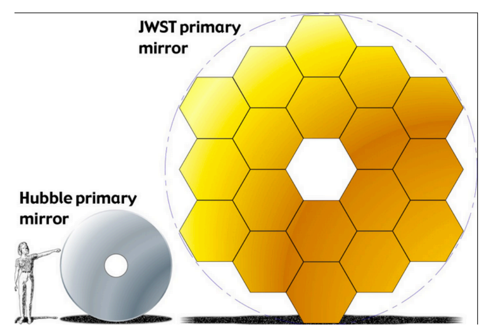
SURFACE TEMPERATURE: **100,000 to 110,000 kelvins**

LIFETIME: **3 million years**

James Webb Telescope





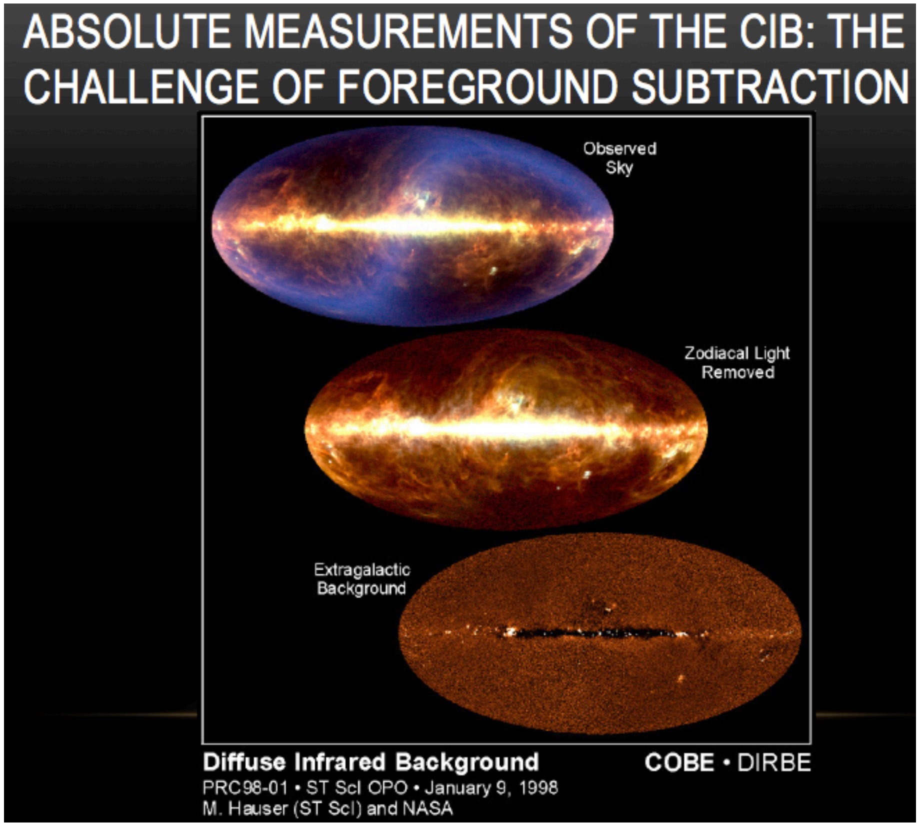


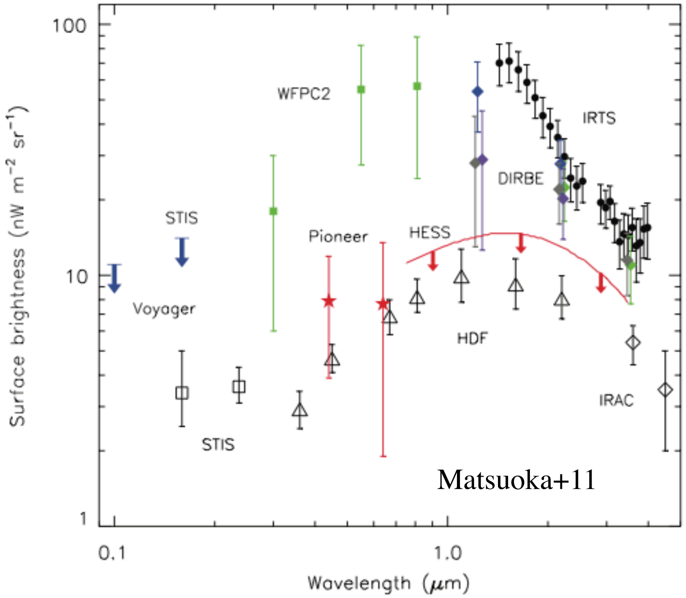
All the Light There Ever Was

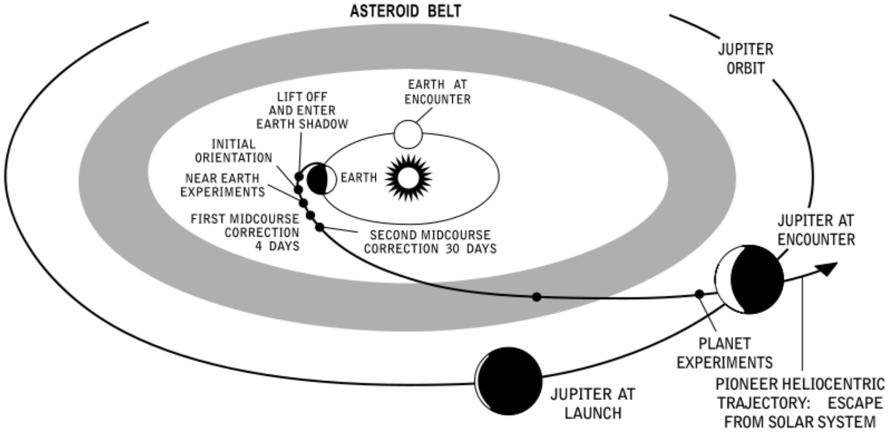
Marco Ajello

Direct Measurements of the EBL

1. Absolute measurements are challenging
2. Intense foregrounds: zodiacal light, stellar and inter-stellar emission in our Galaxy
3. Solution: use spacecrafts outside the solar system

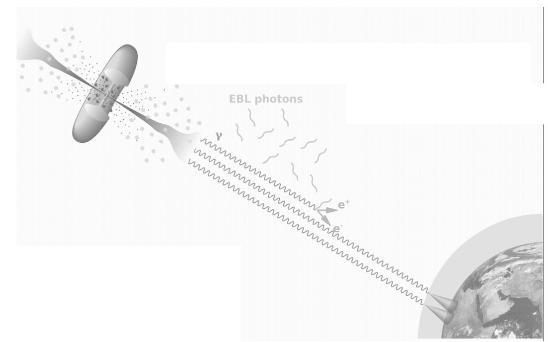




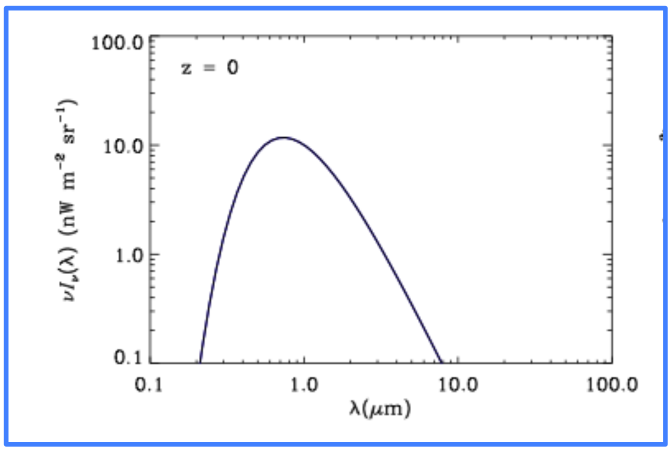


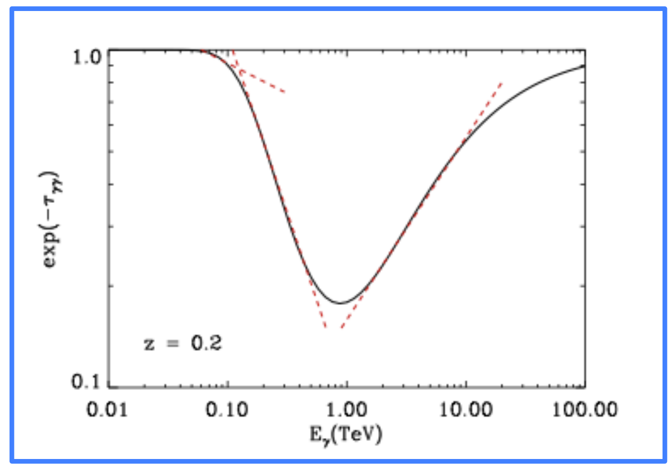
Background gamma-ray sources

- 2 Photons convert into an electron-positron pair if :
  - $E_\gamma \times E_{EBL} \geq 2(m_e c^2)^2$



- Photons of 100 GeV convert with 5eV photons (UV)
- Photons of 1 TeV convert with 0.3 eV photons (IR)





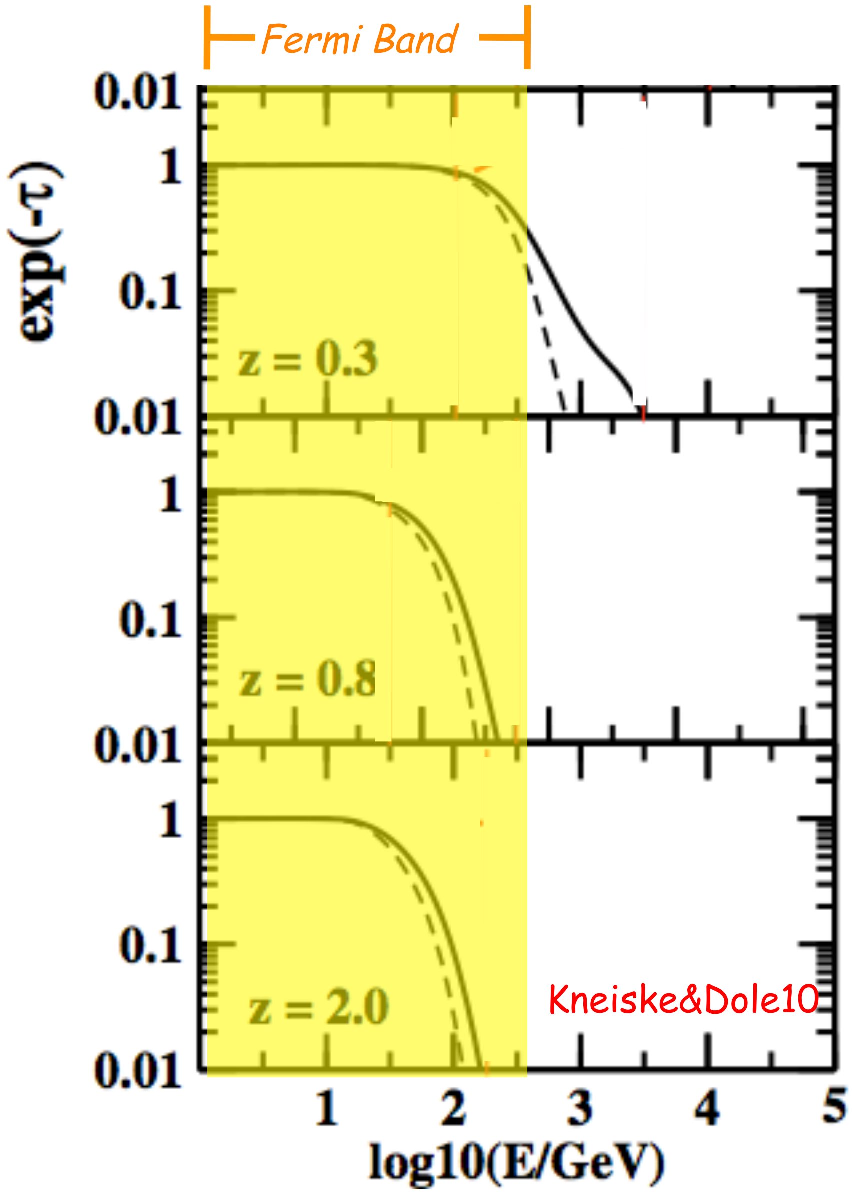
Intrinsic spectrum is attenuated

$$\frac{dN_{obs}}{dE} = \frac{dN_{int}}{dE} \times e^{-\tau_\gamma(E,z)}$$

Optical Depth

$$\tau_\gamma = \int_0^z d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{thr}}^{\infty} d\epsilon' \frac{dn_{bkg}}{d\epsilon} \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$

Expected Attenuation due to the EBL



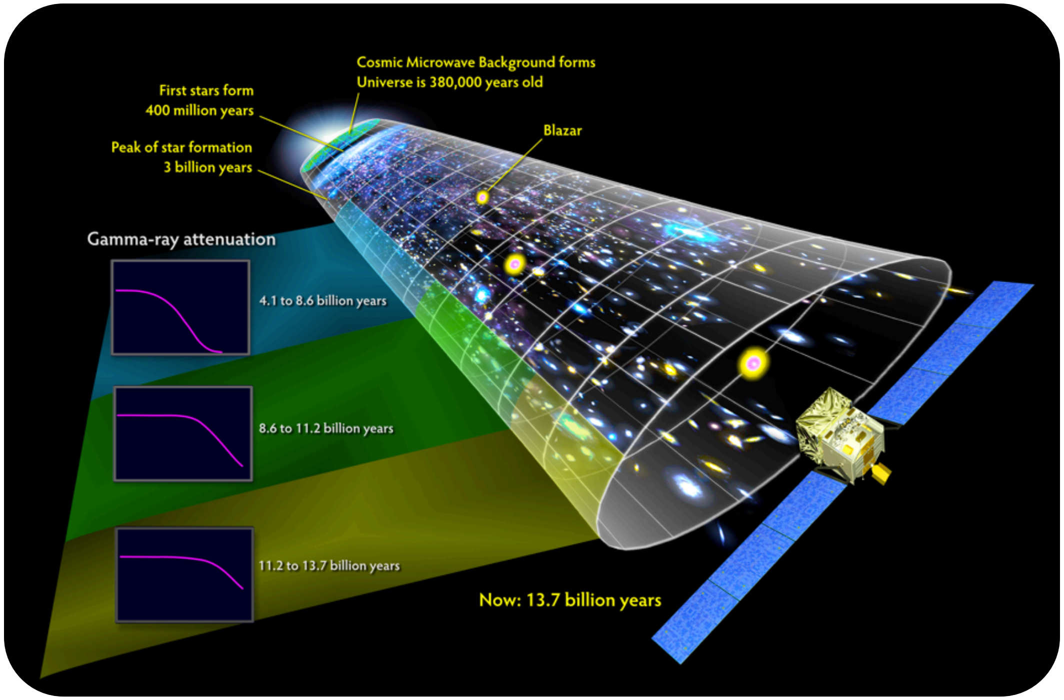
Most models predict an attenuation of >99% at z~1

The EBL leaves a unique redshift/energy dependent attenuation in the spectra of blazars

Analysis Procedure

- Most agnostic approach
  - Assume nothing about blazars' spectra
  - Look for a coherent attenuation which should be in ALL of them at a given Energy for a given redshift

- Fermi detected enough BL Lacs to make a measurement at 3 different epochs

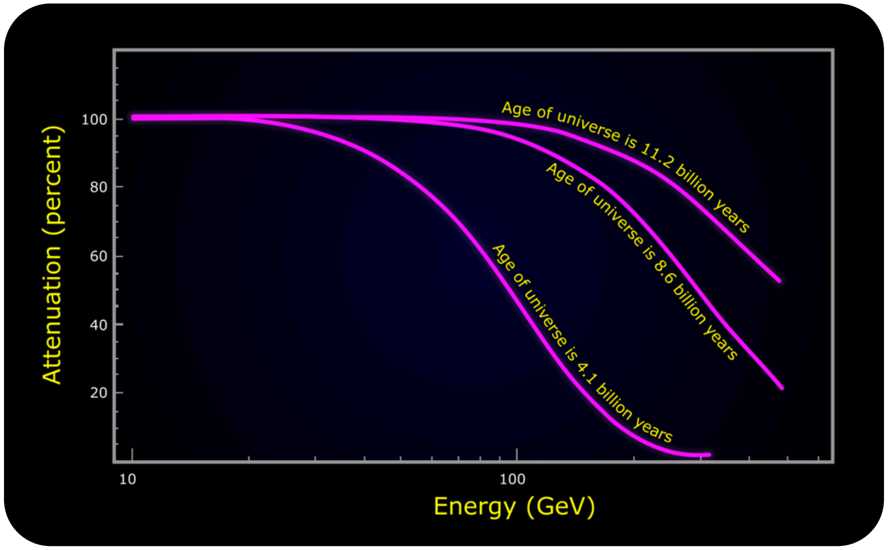


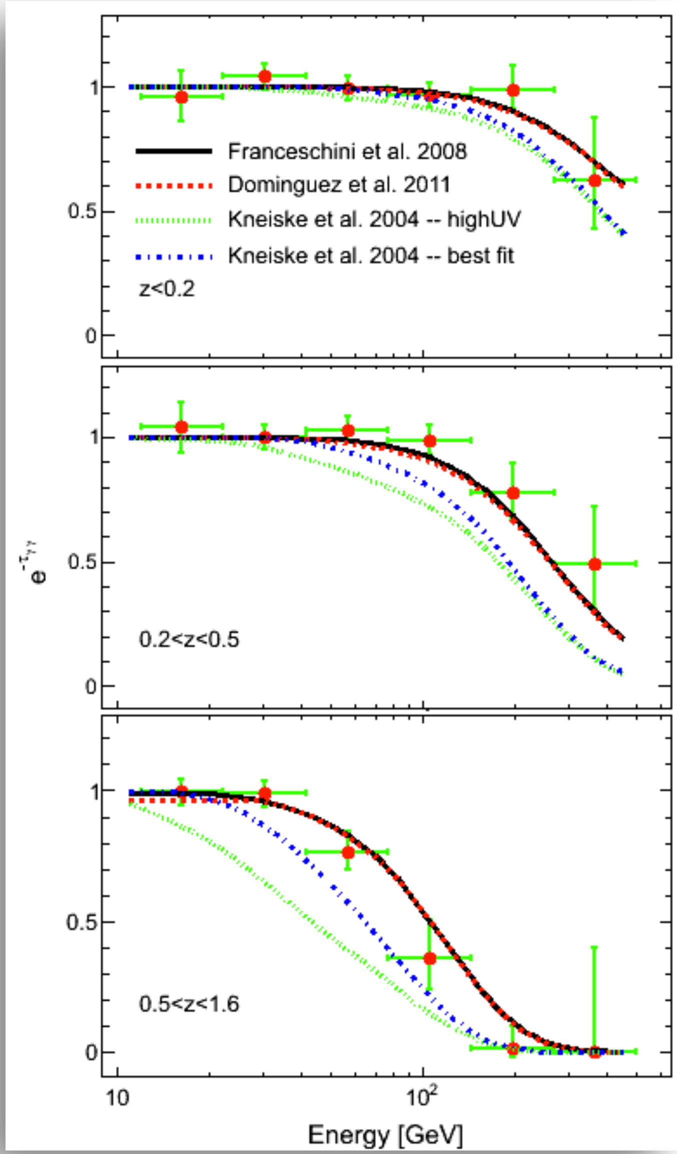
Success! EBL Attenuation detected

- First EBL detection (~6σ)
  (LAT-collaboration, 2012,Science, 338, 1190)

- The cut-off moves in z and Energy exactly as expected for EBL absorption

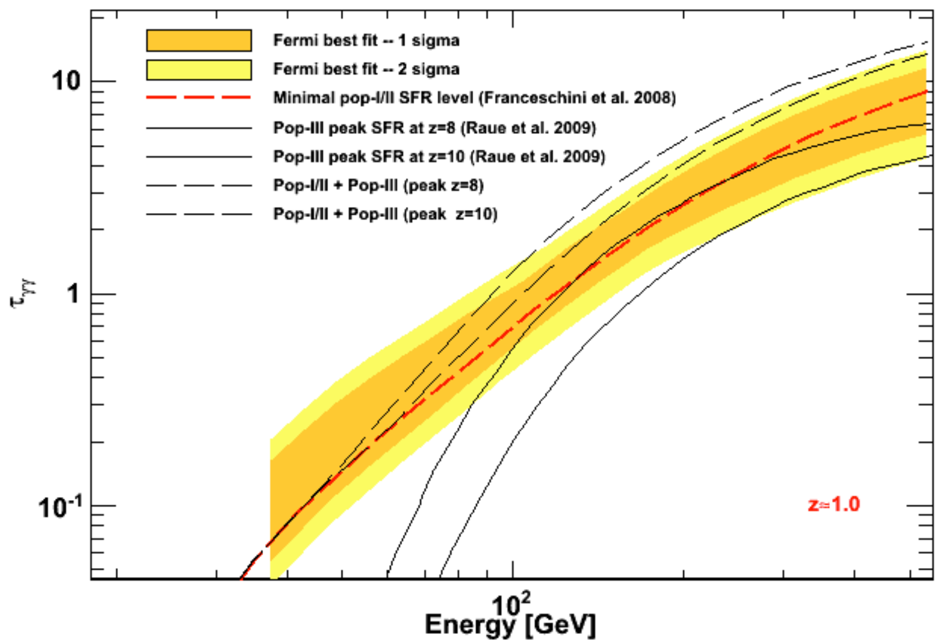
- EBL density at the lowest level: i.e. the amount of light that causes the absorption = amount of light from the galaxies we see

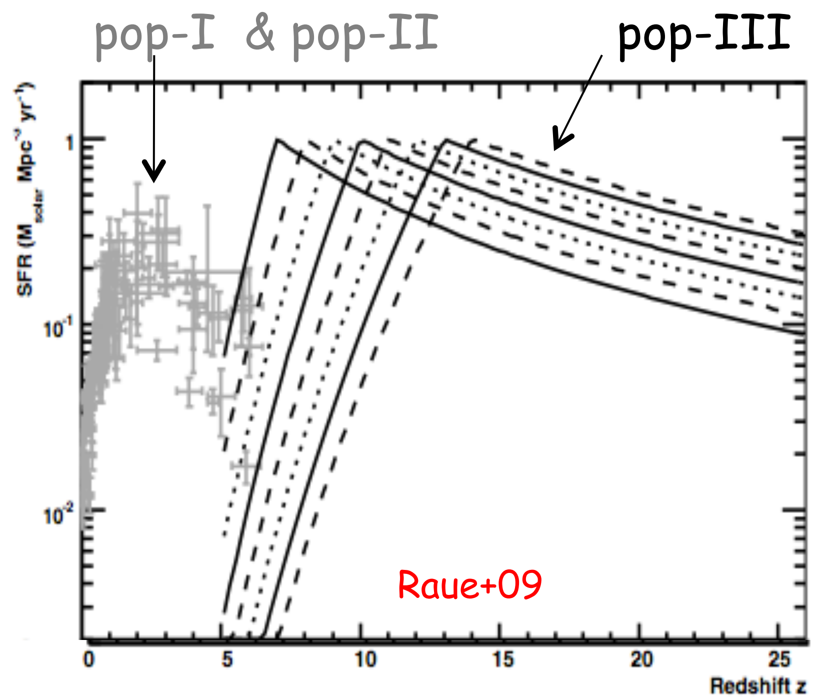




Stellar Archeology

- Light of Pop-III stars increase the opacity w.r.t the one of pop-I and II





- Extremely large contr. of pop-III stars ruled out by Aharonian+06

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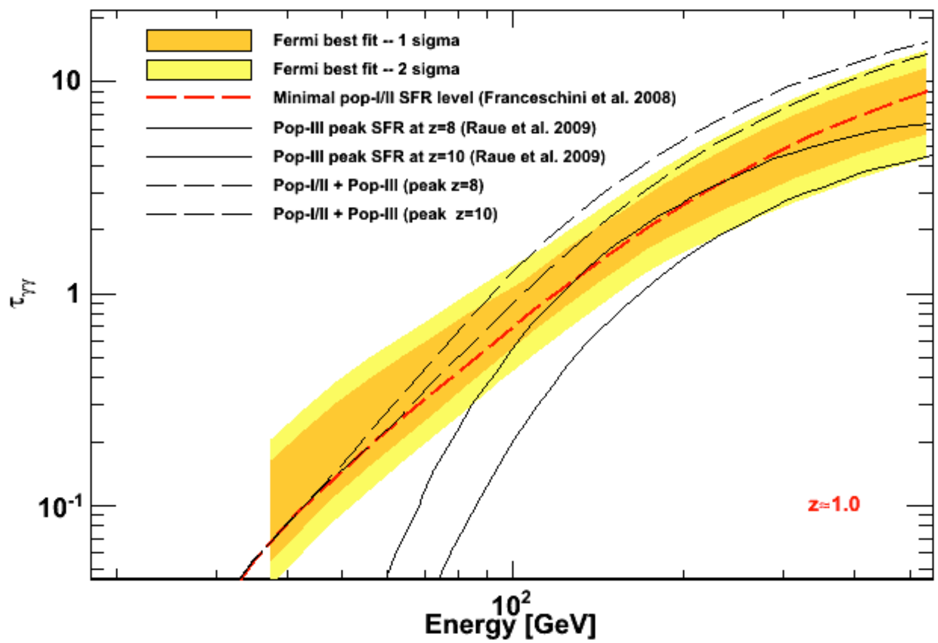
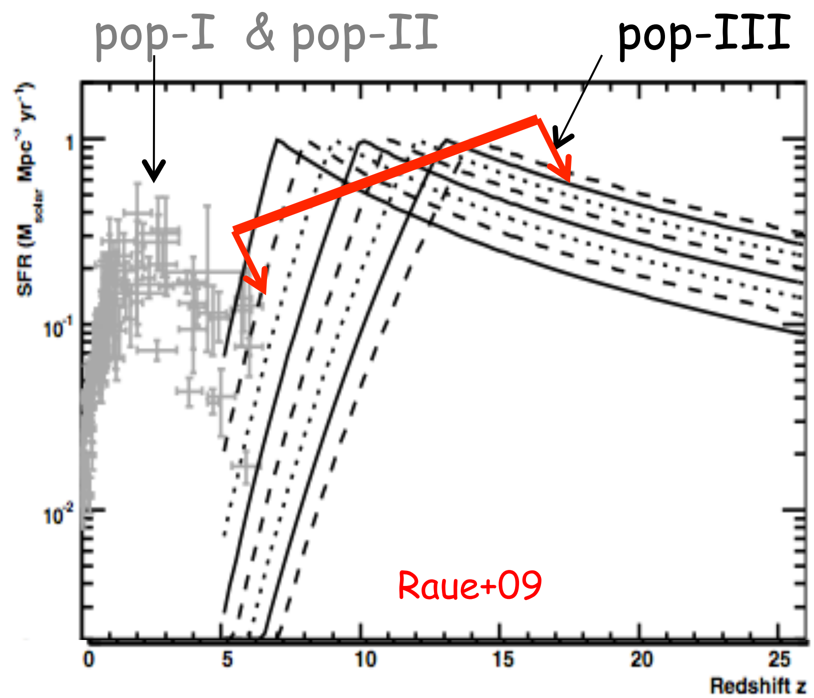
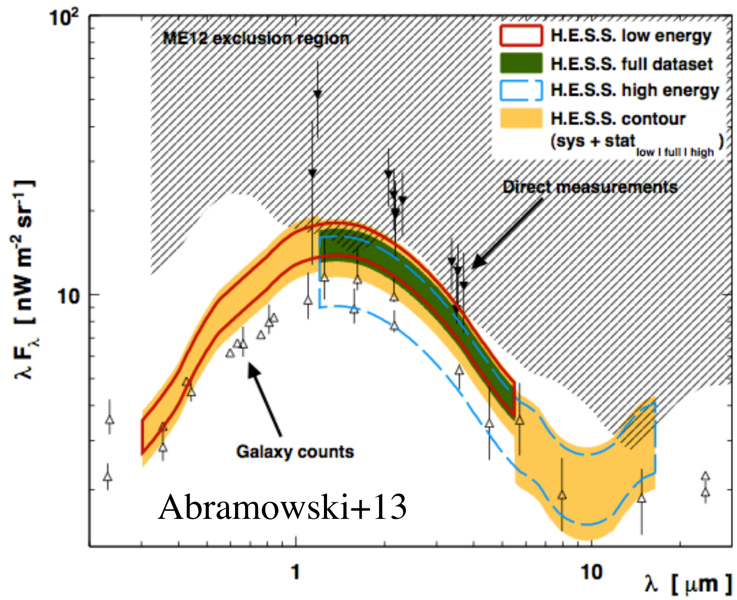


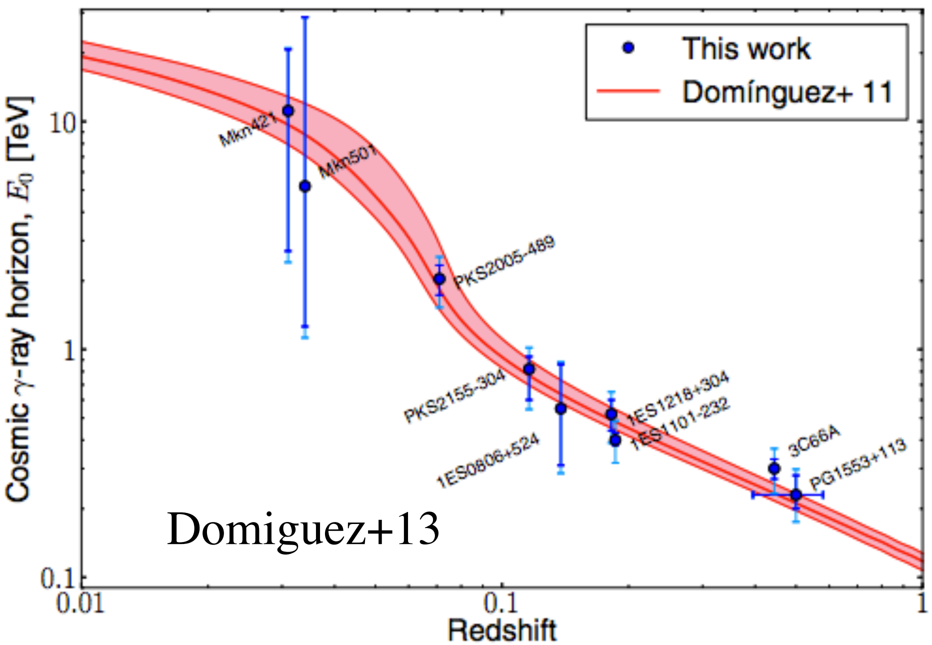


- Extremely large contr. of pop-III stars ruled out by Aharonian+06
- Our measurement constrains the peak SFR of massive stars to be z>10 and have <0.5M_{sun} yr^{-1} Mpc^{-3}

Other gamma-ray Measurements

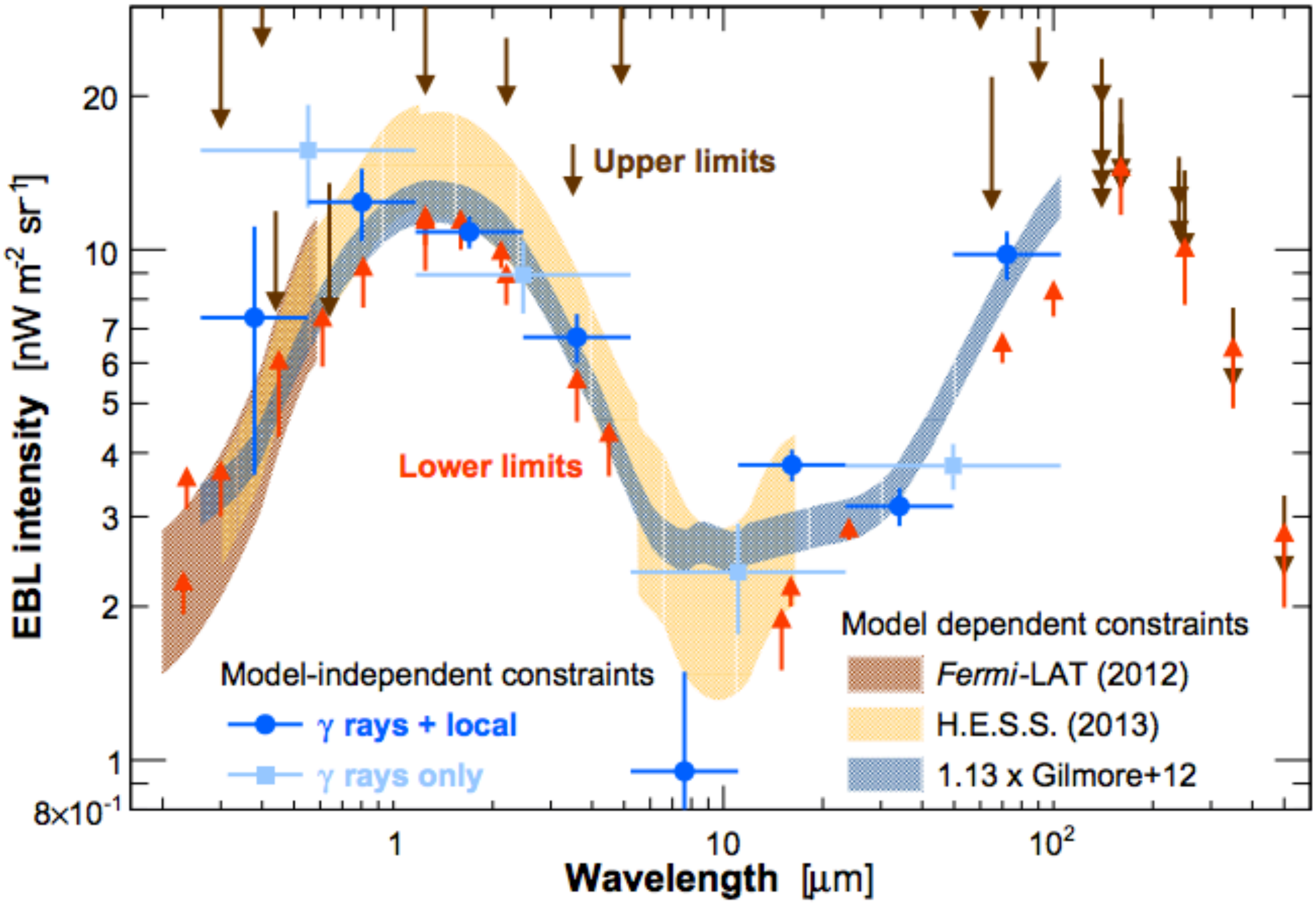
Similar technique applied to 7 bright TeV blazars yields a compatible level of the EBL (sampling the z~0 NIR EBL)





Spectral modeling of 15 TeV blazars allows to measure the cosmic gamma-ray horizon (Dominguez+13)

Up-to-date Status

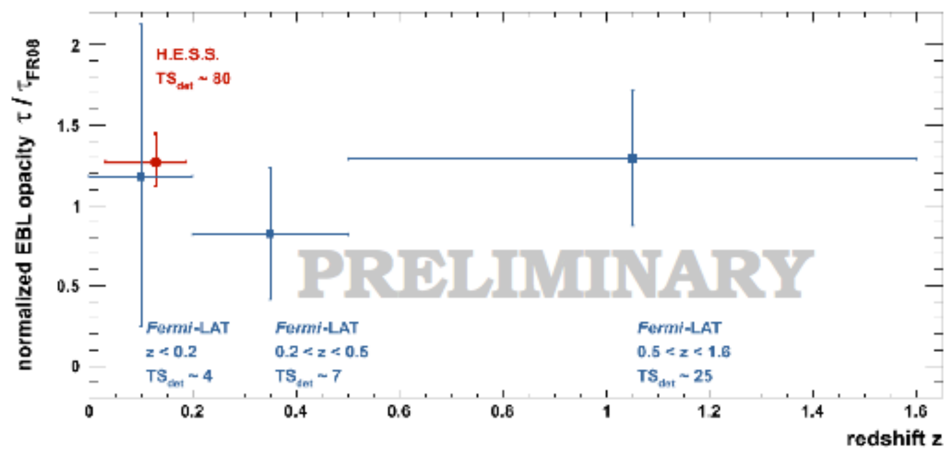


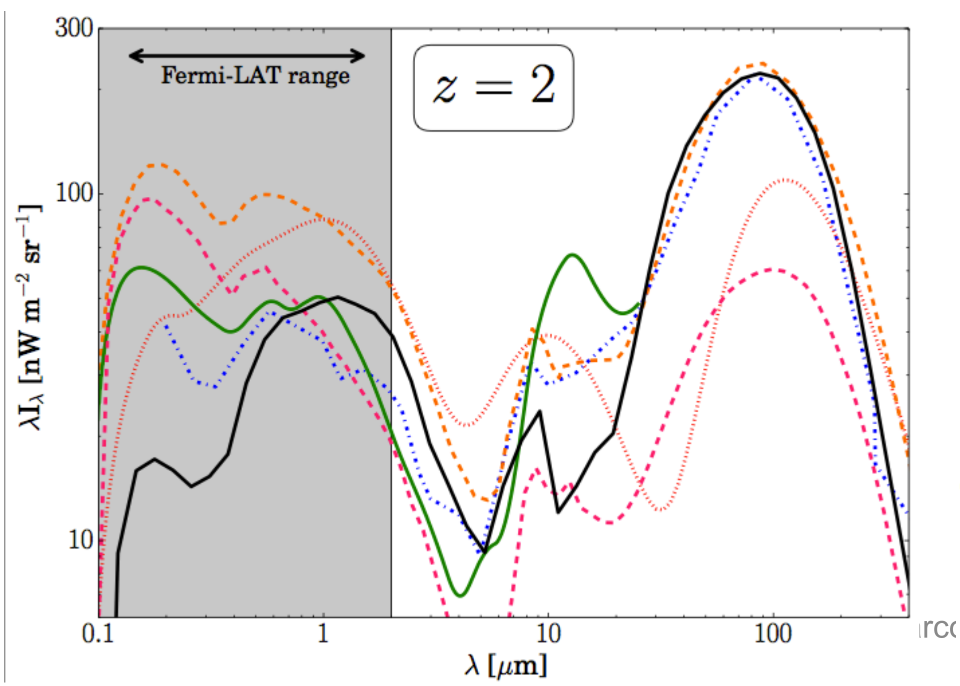
Biteau & Williams 2015

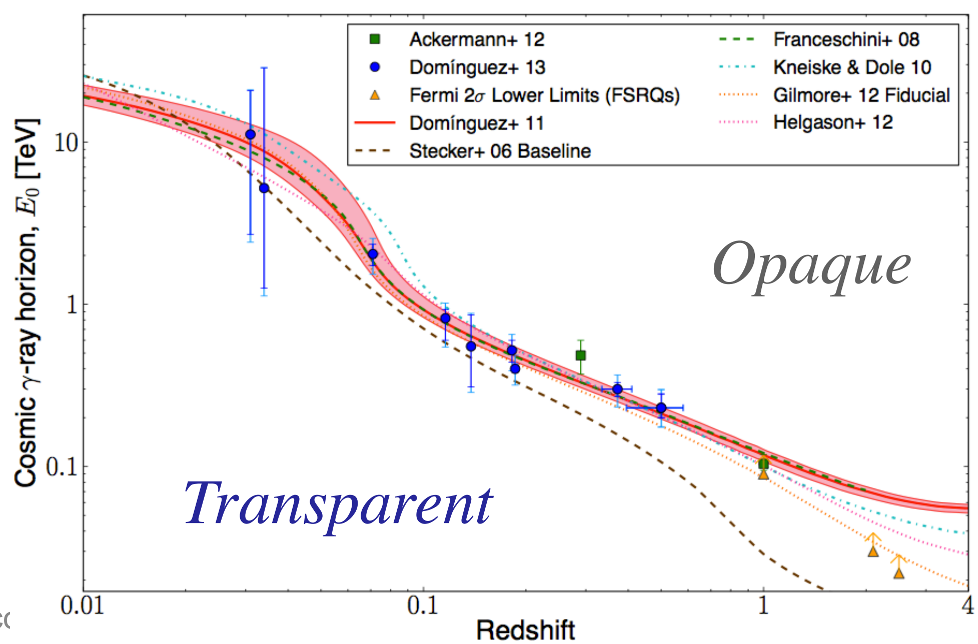
EBL and *Fermi*

- *Fermi*-LAT is the only instrument that can probe above z>0.5 !

- GRBs and FSRQs can be used to probe the EBL evolution up to z~4.3

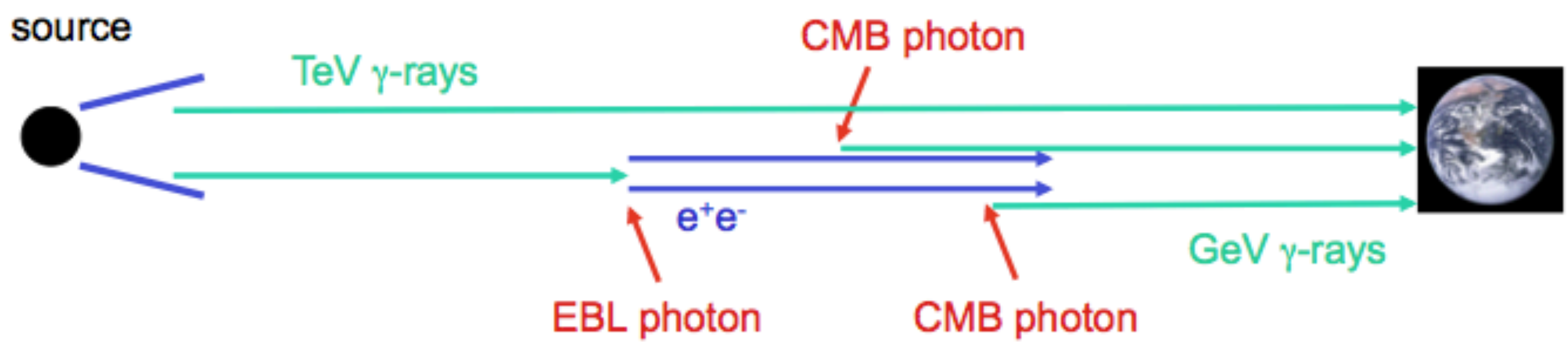






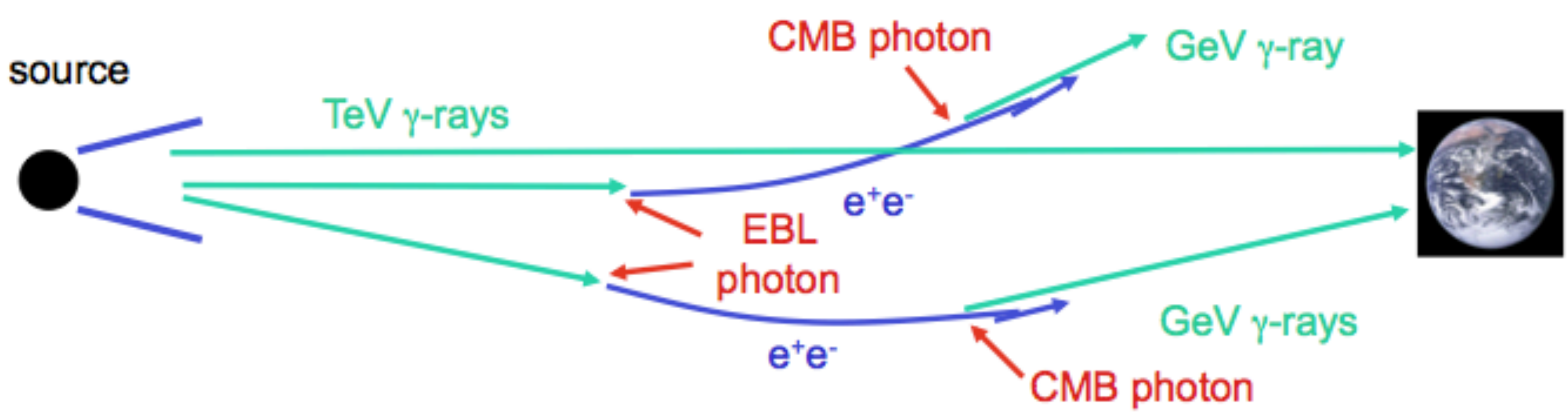
Intergalactic Magnetic Field

No Intergalactic Magnetic Field



GeV γ-rays delayed due to slower e+e- speed

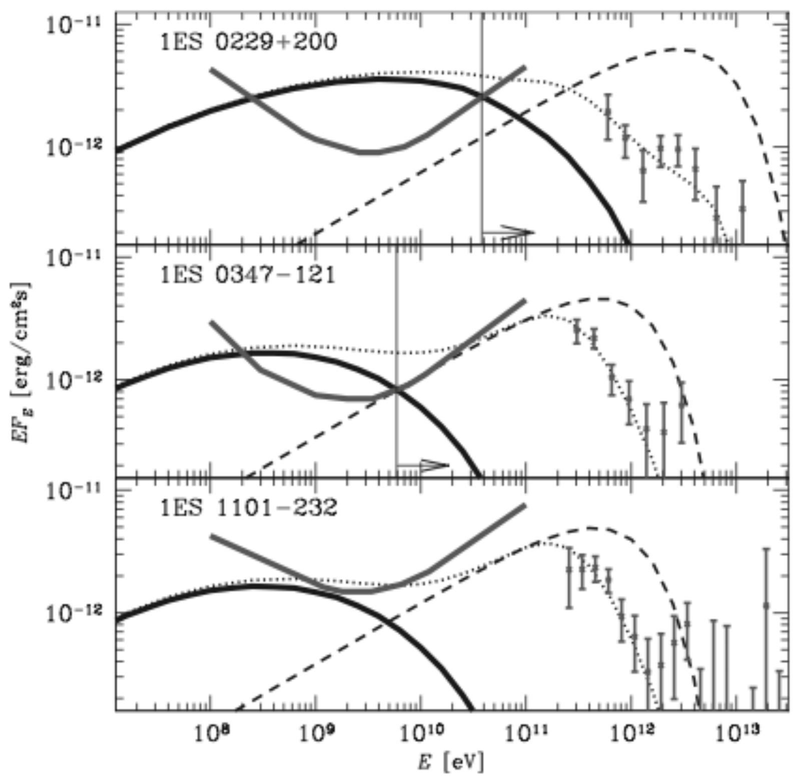
Non-zero Intergalactic Magnetic Field

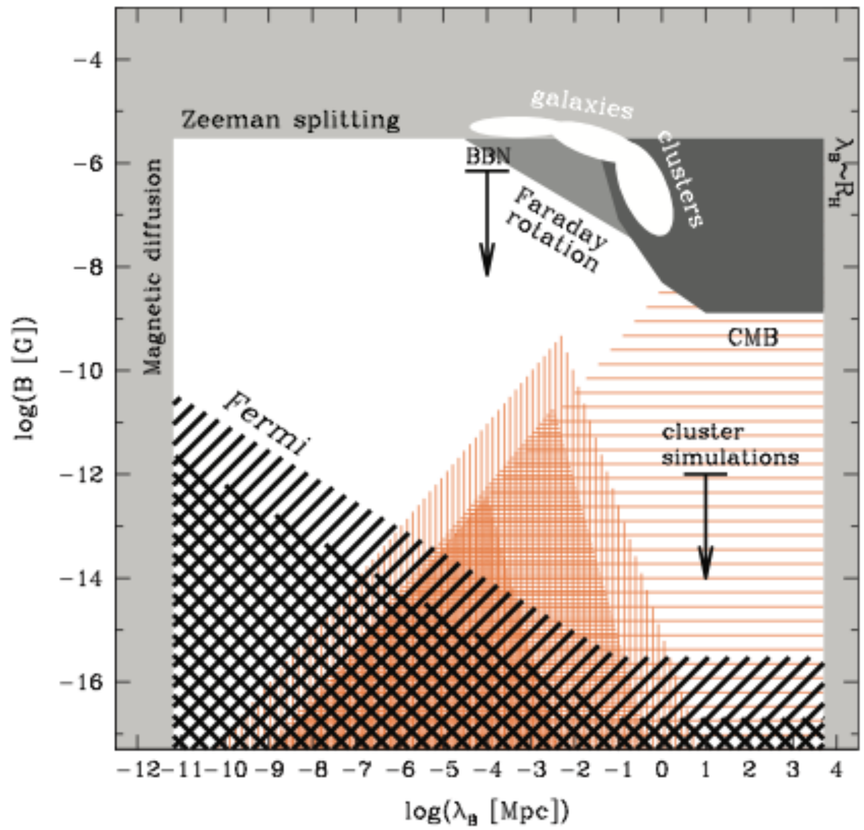


GeV γ-rays delayed due to slower e+e- speed and greater distance traveled

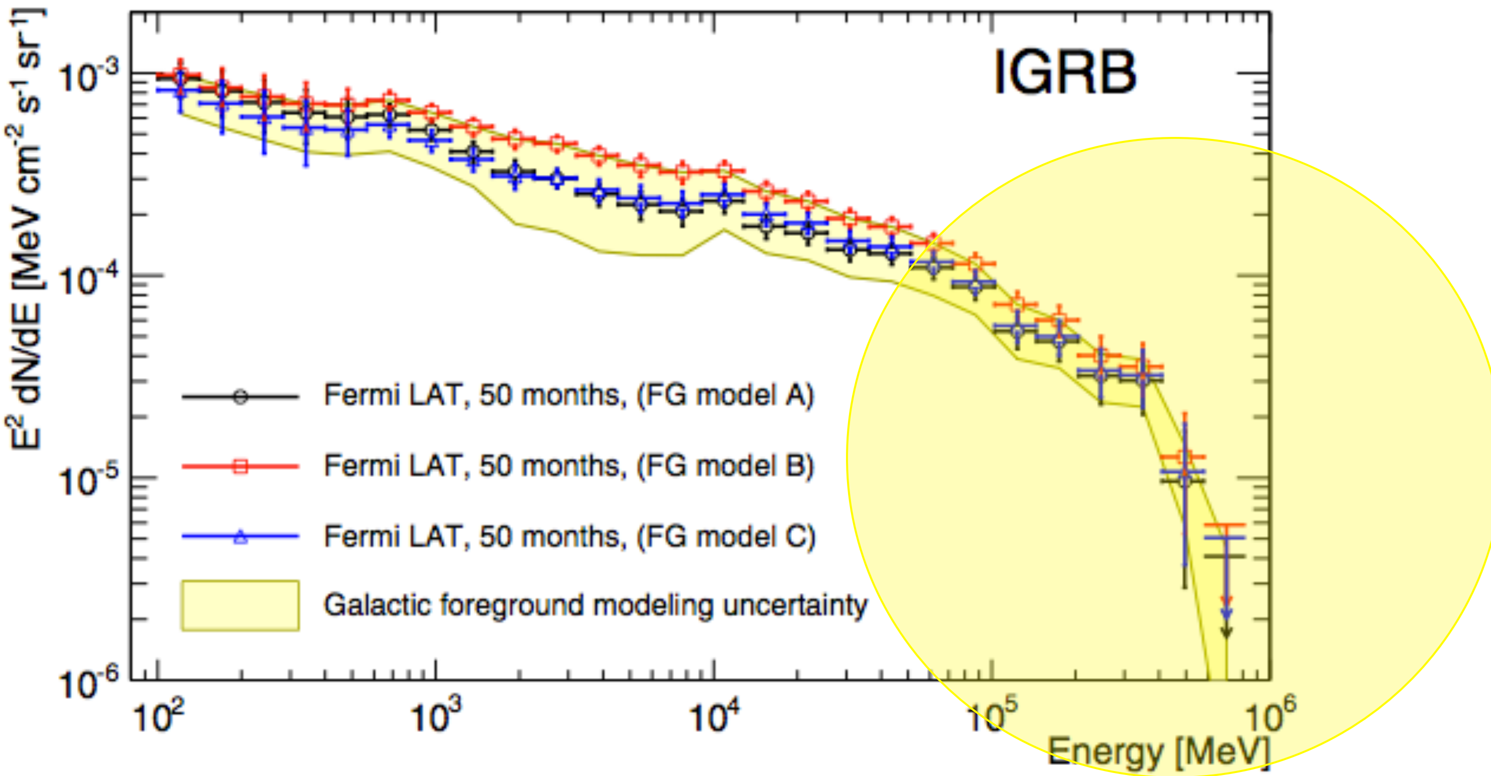
IGMF Bounds

- Evidence for strong magnetic fields from lack of reprocessed cascade emission (Neronov+10, Science)





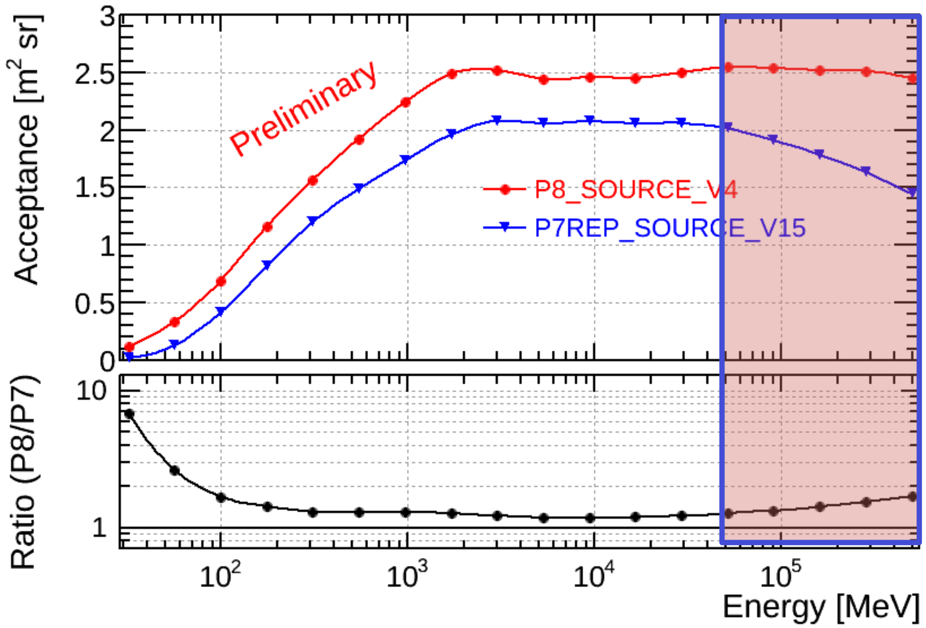
Interesting Energy range

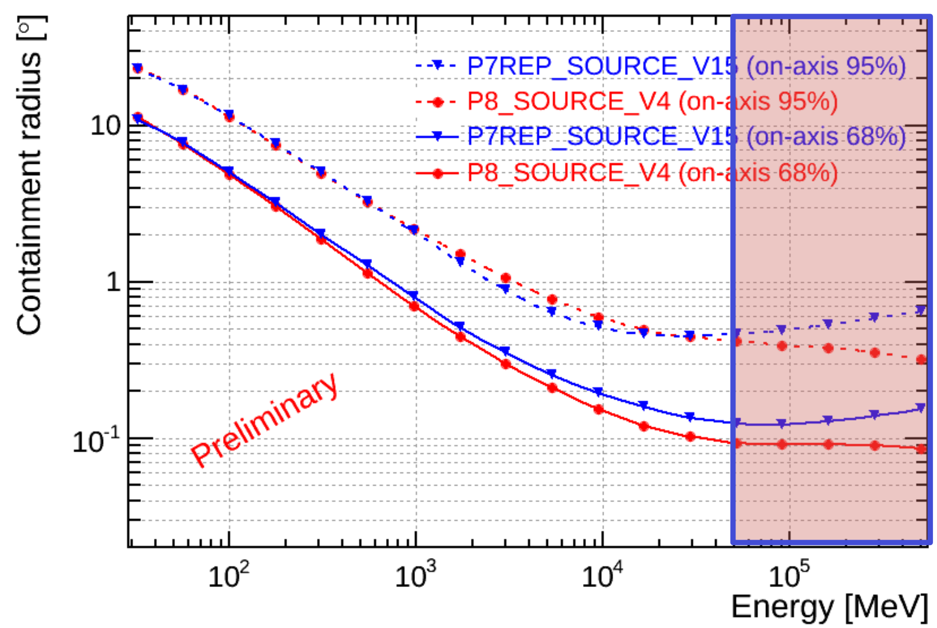


- Above 10-50 GeV:
  - PSF of Fermi-LAT becomes extremely good
  - EBL and IGMF are be very important
  - Cherenkov telescopes are more sensitive but much smaller field of view

Happy 7^{th} Birthday !!

Pass 8





- *Large Progress Expected at >50 GeV:*
  1. **Improve PSF and Acceptance (factor of 0.5-2 in P8)**
  2. **Low background and <u>good</u> (constant) PSF (0.1 deg at 68%)**
  3. **All-sky exposure**

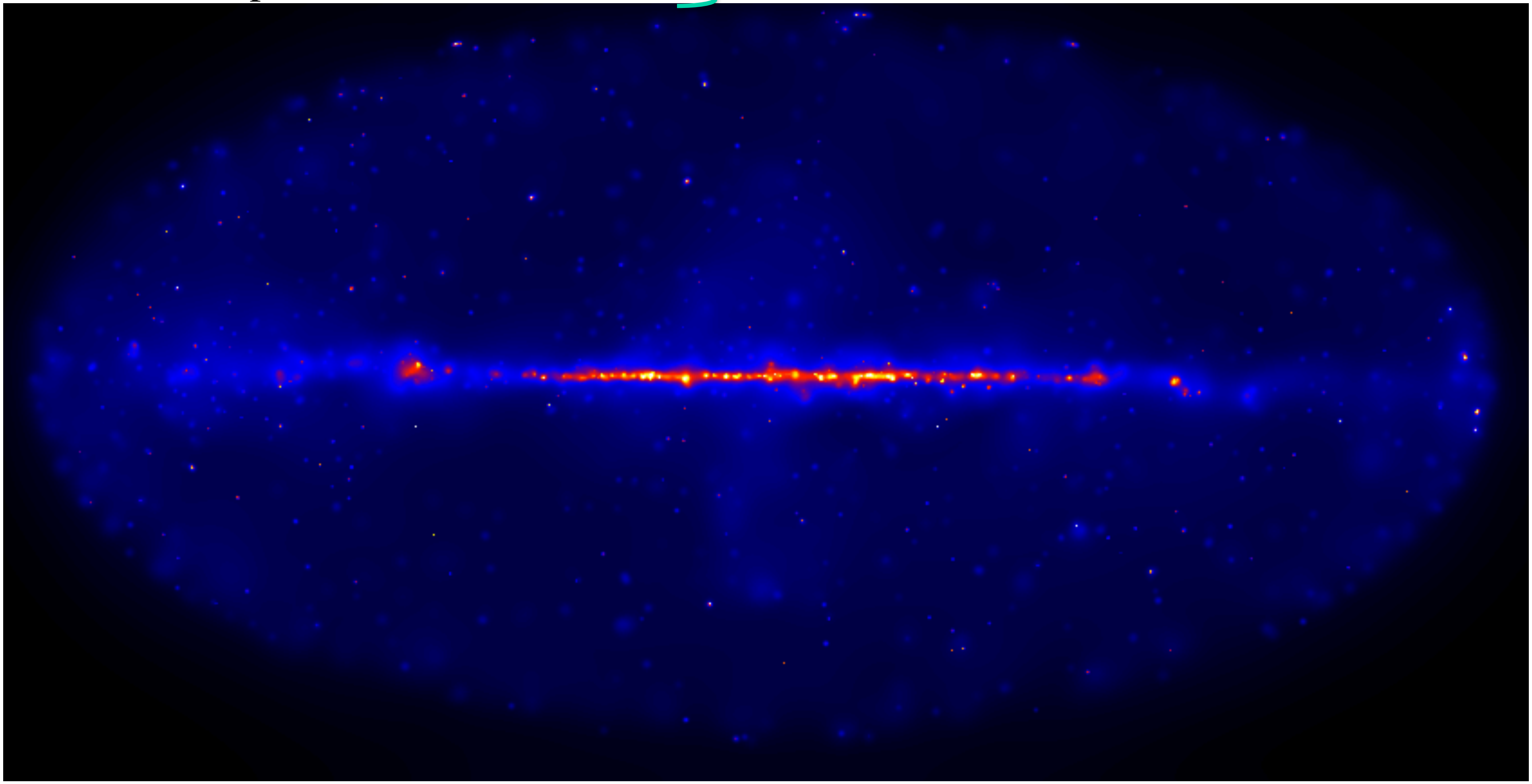
- *Catalog of sources detected at >50 GeV*
  - **Allows study of the EBL, EGB, Galactic plane etc.**
  - **Continues our effort to characterize sources at high energies**
  - **Connects well to ACTs, HAWC and the upcoming CTA**

2FHL Catalog

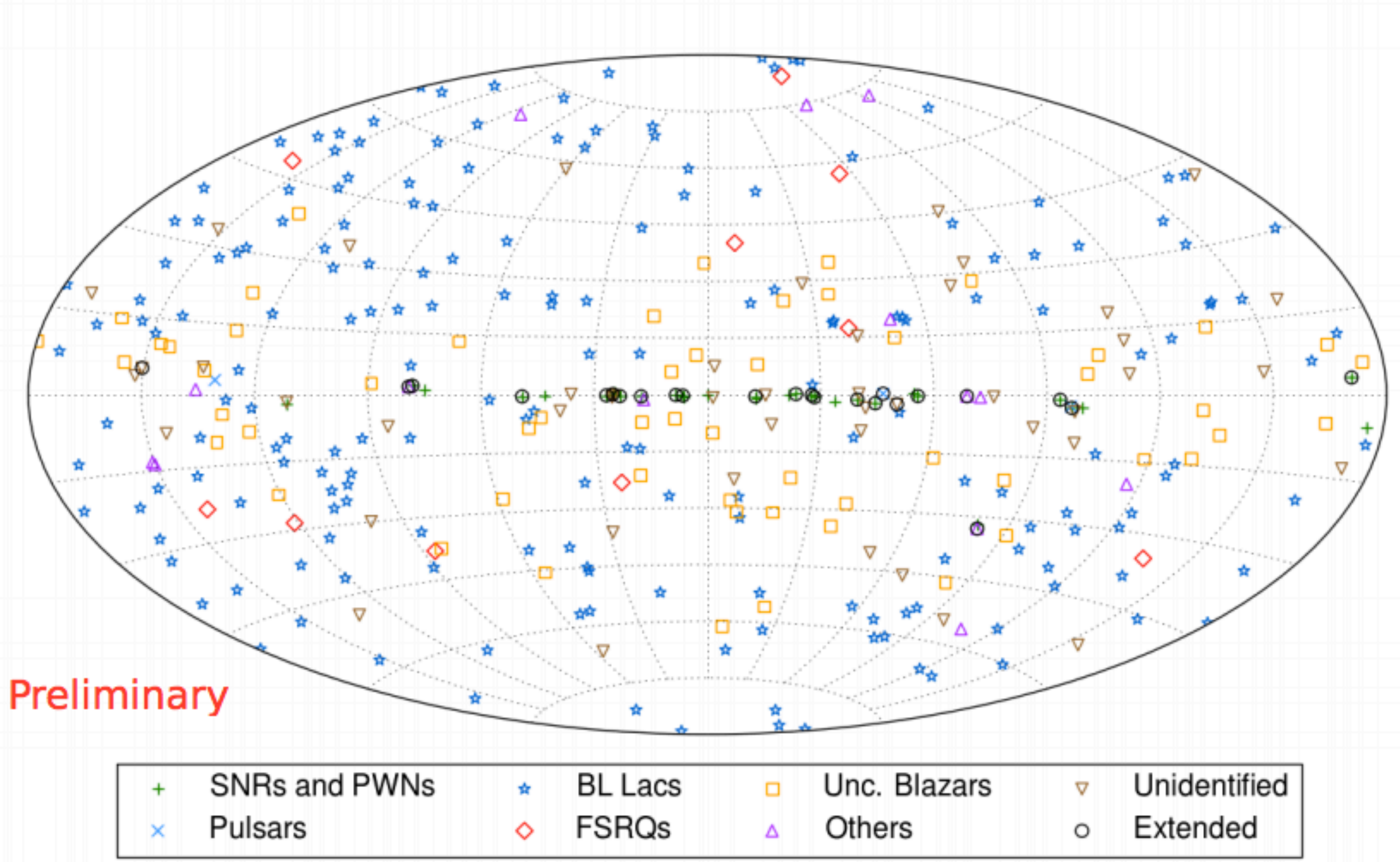
~6.5 years of P8 data (50 GeV – 2 TeV)

61,000 photons E > 50 GeV
25,000 photons E > 100 GeV
3,000 photons E > 500 GeV

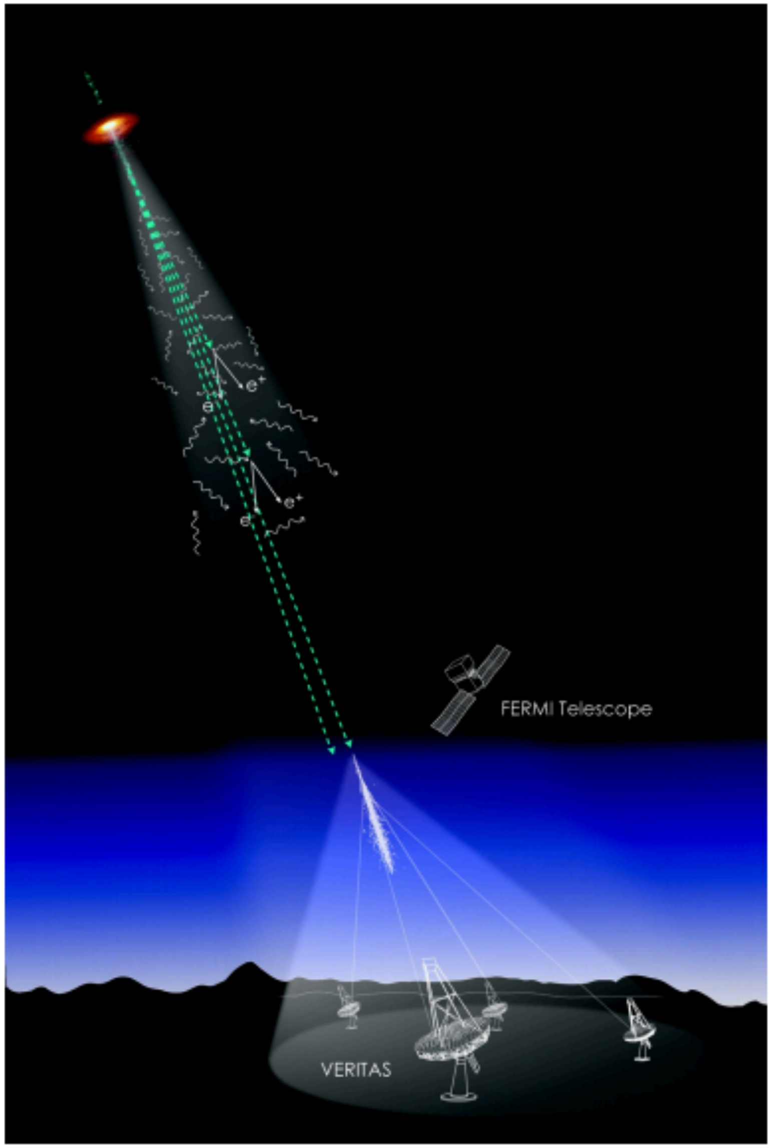
~1.5 photon every deg^2



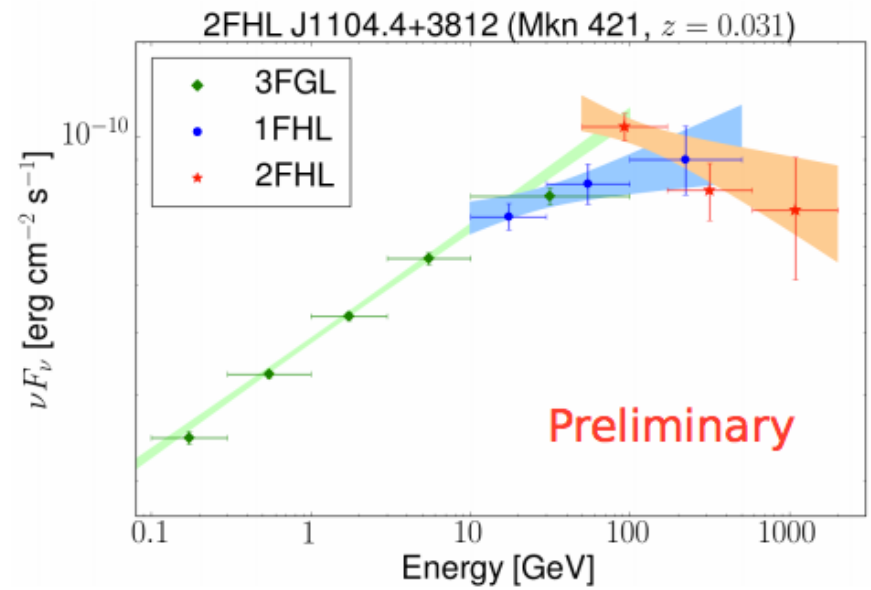
Source Associations

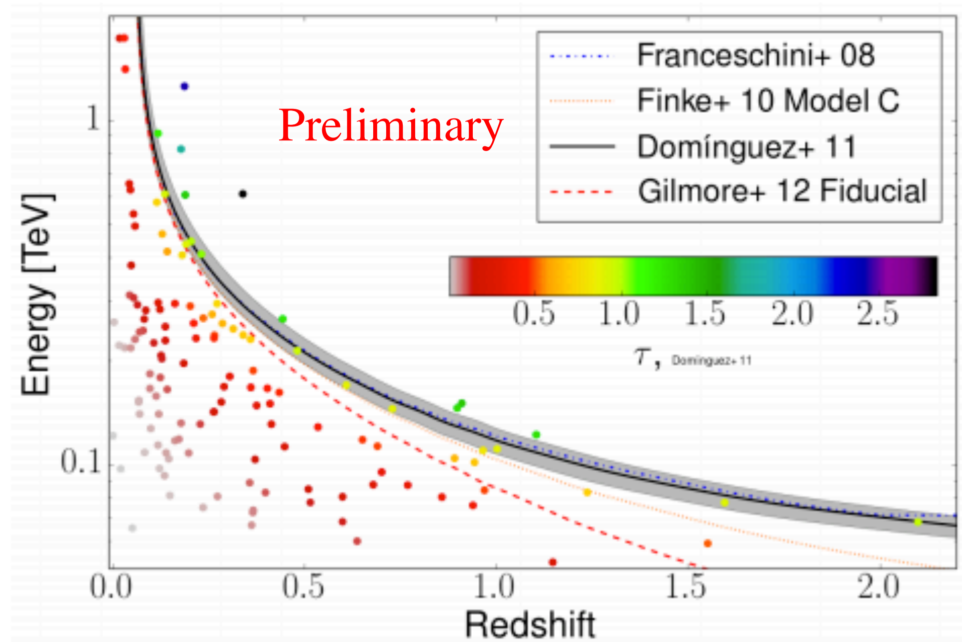


2FHL: Extragalactic Background Light



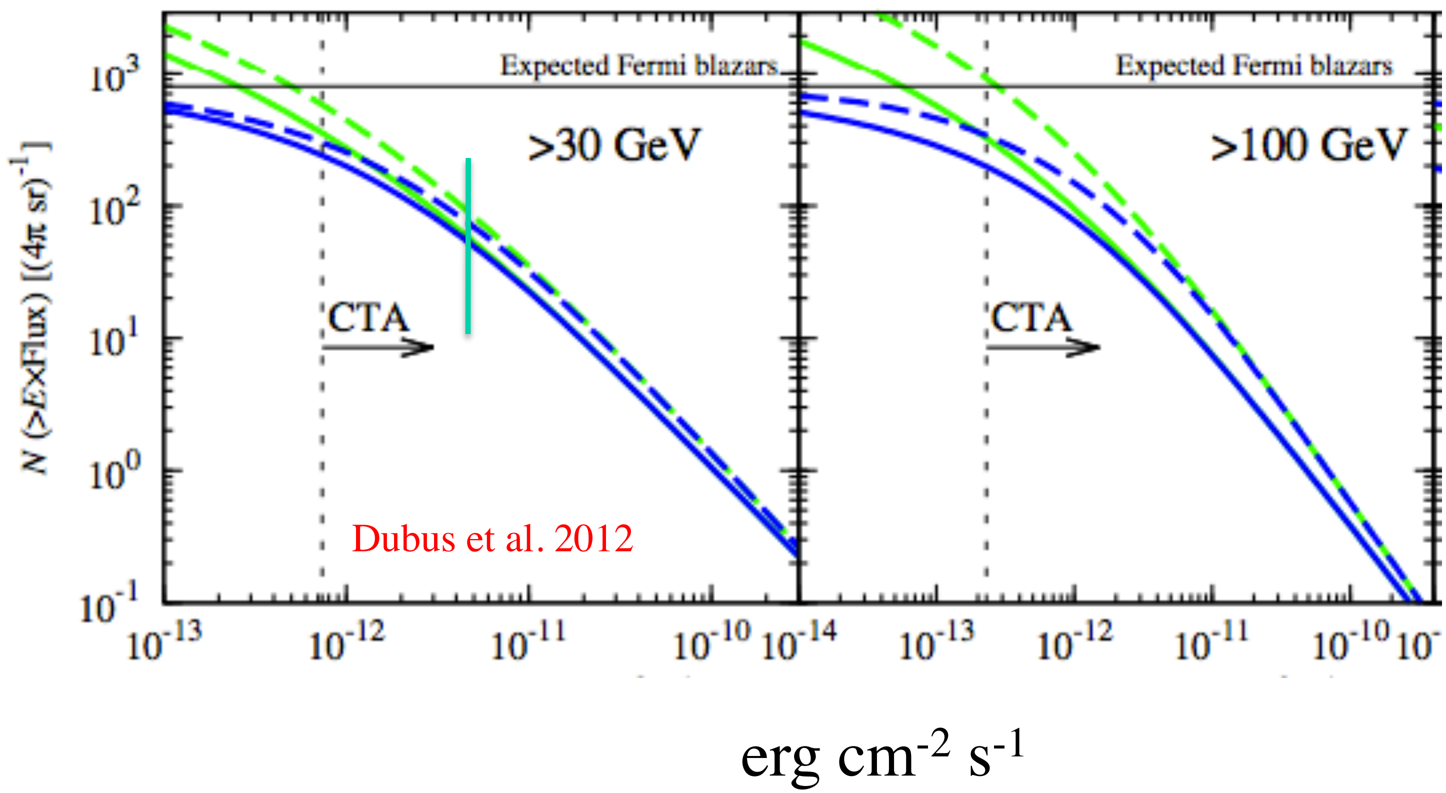
Credit: Nina McCurdy & Joel R. Primack/UC-HiPACC





VHE Surveys

- One of the goal of CTAs is to perform deep surveys of the extragalactic sky
- *Guess What ?* Fermi has already done that !



The End

- *Fermi*-LAT is providing a wealth of results on extragalactic astrophysics and Cosmology: *EGB, EBL, IGMF*

- We are far from have exploited them all: the LAT keeps improving and acquiring exposure time

- *Data are public*, so *Join the Fun!*