Extragalactic Background Light, Hubble constant and Intergalactic Magnetic Fields with Imaging Atmospheric Cherenkov Telescopes: status and perspectives.

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ICRR, University of Tokyo and
Max Planck Institute for Physics, Munich

Cosmology in Miramare, Aug 28 - Sep 2, 2023, Trieste Italy

Observational Cosmology with IACTs

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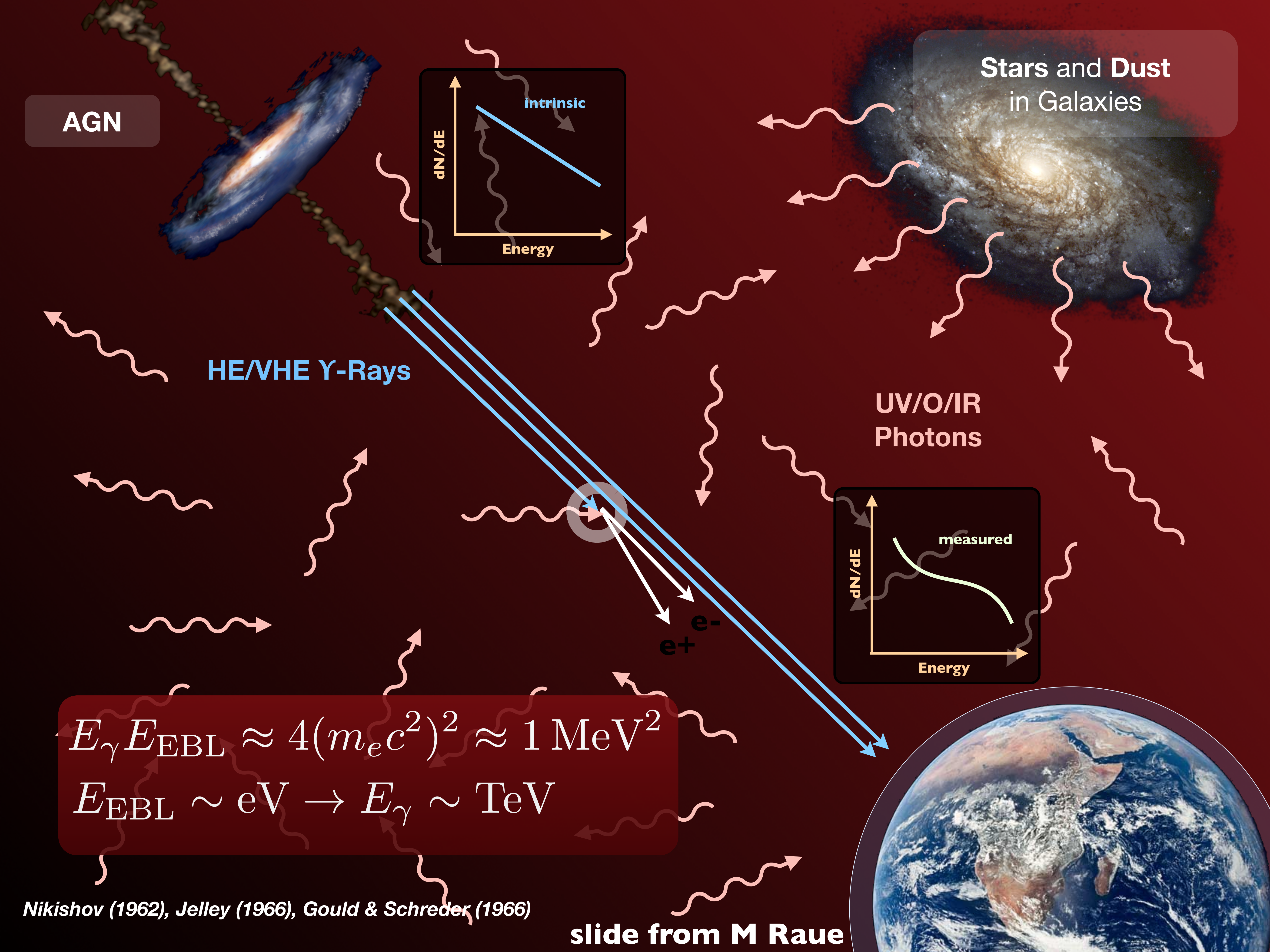
- Extragalactic Background Light
- How can gamma rays contribute to observational cosmology?
- Status of the field
- CTA: program towards observational cosmology


AGN
intrinsic
dN/dE
Energy
Stars and Dust in Galaxies
HE/VHE Ɣ-Rays
UV/O/IR Photons
measured
dN/dE
Energy
e-
e+
$E_\gamma E_{\rm EBL} \approx 4(m_e c^2)^2 \approx 1\,{\rm MeV}^2$
$E_{\rm EBL} \sim {\rm eV} \rightarrow E_\gamma \sim {\rm TeV}$
Nikishov (1962), Jelley (1966), Gould & Schreder (1966)
slide from M Raue

Extragalactic Background Light

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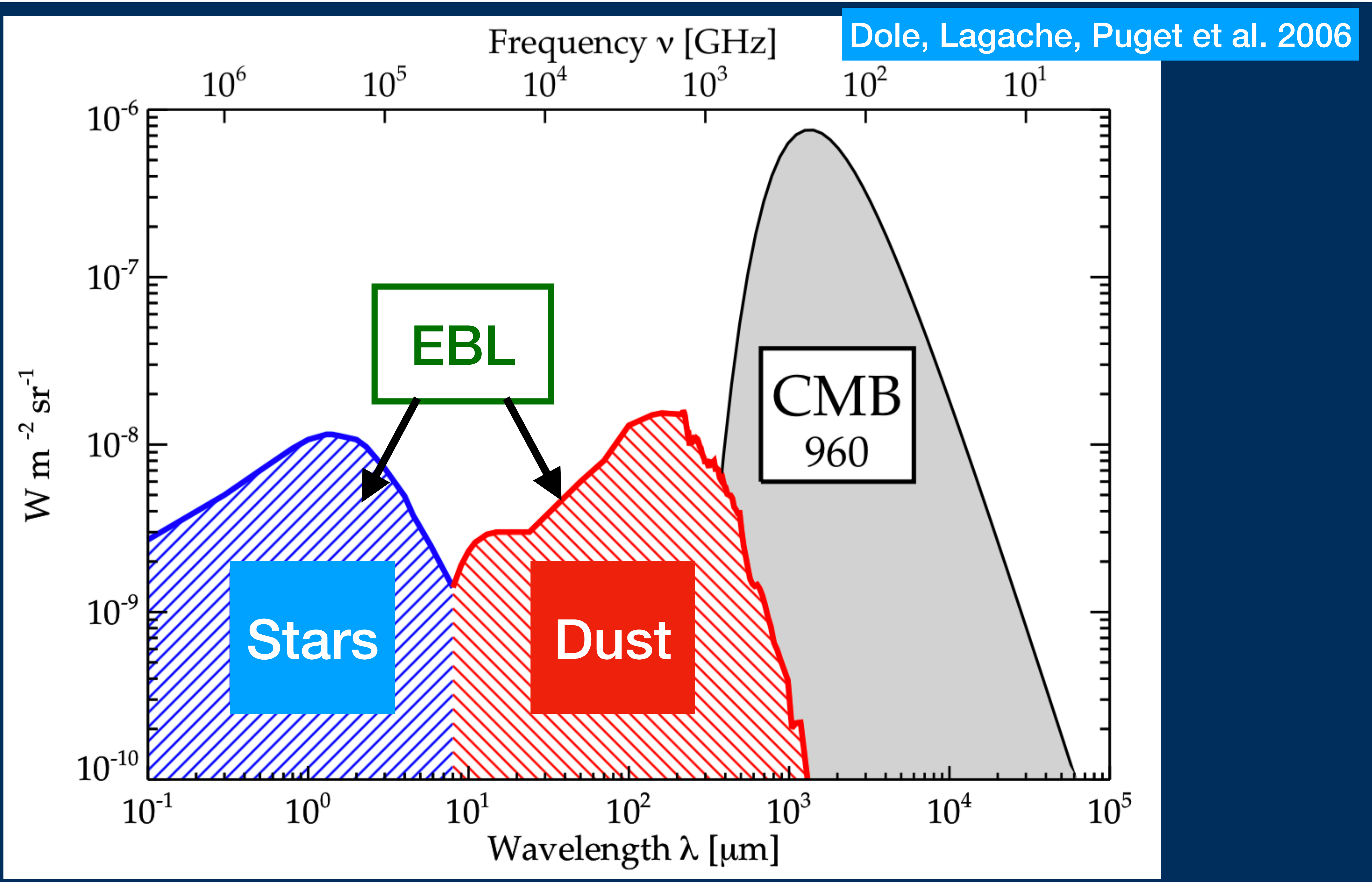
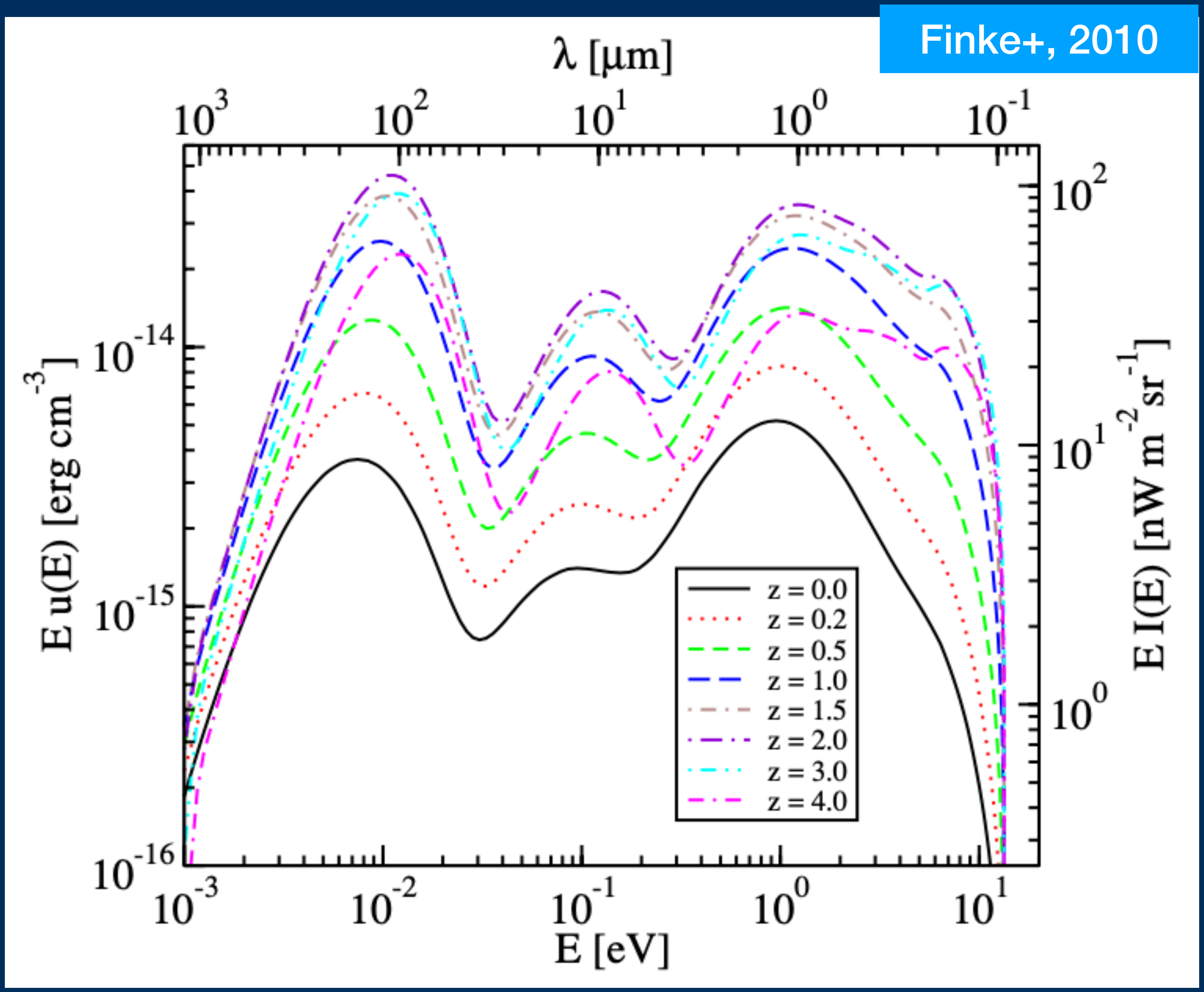


Extragalactic Background Light

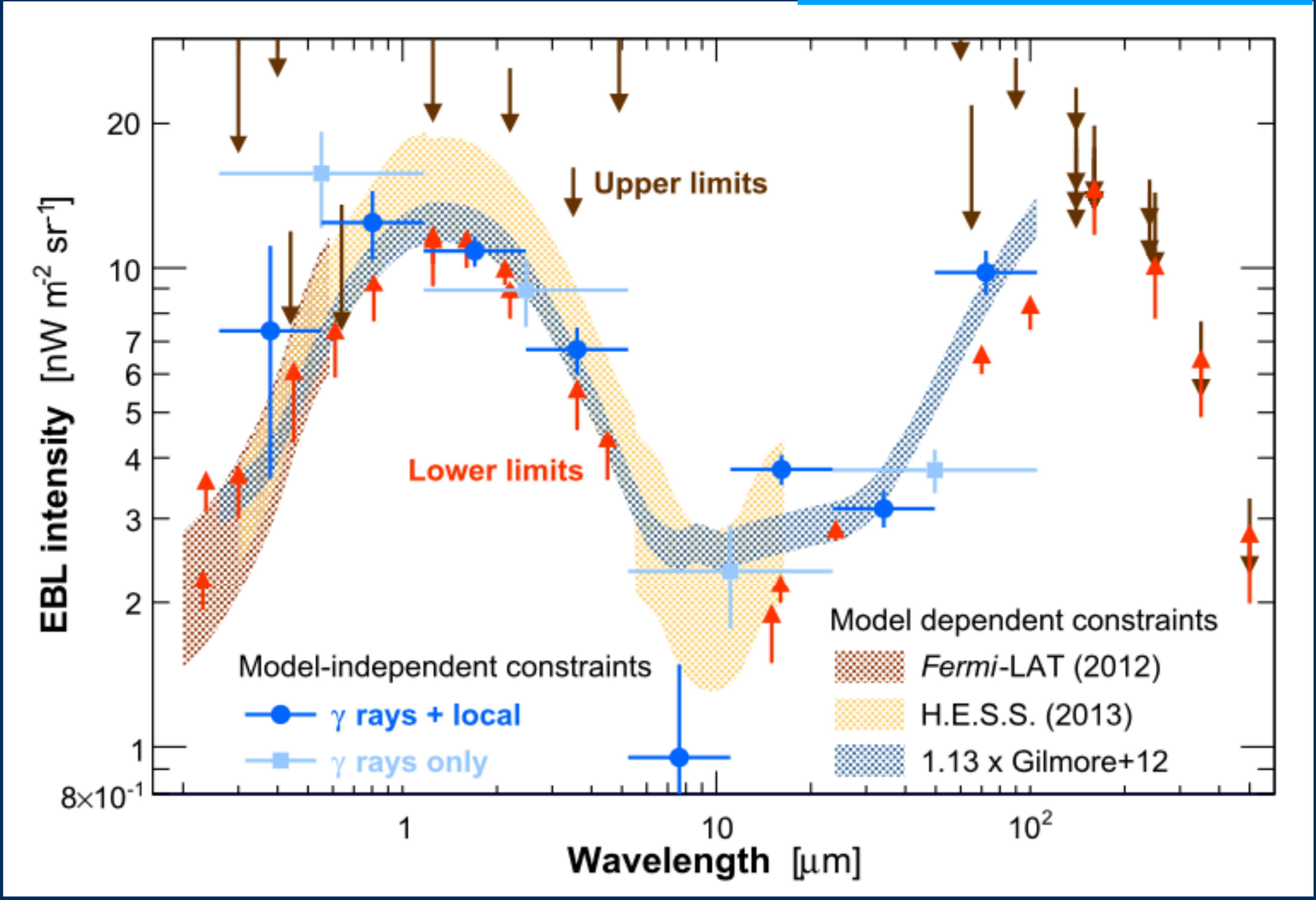
- Building up the EBL
- The EBL evolution is a consequence of the star and galaxy evolution of the universe, including the AGN feedback
- The EBL evolution beyond z=2 is quite uncertain



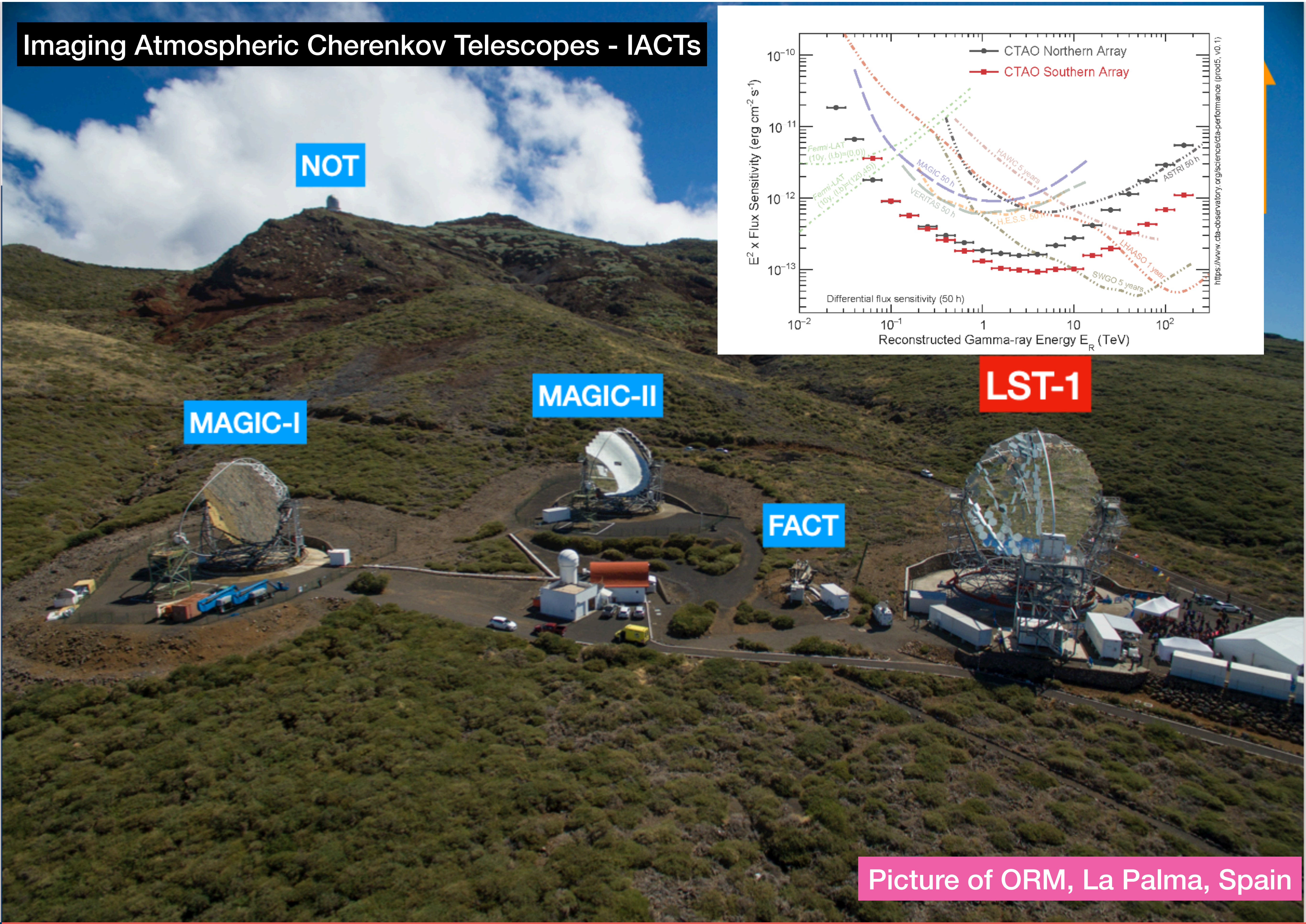
EBL direct measurements

Biteau&Williams, 2015

- Direct measurements are hindered by uncertainties in Zodiacal model and in other systematical effects
- Robust low limits are derived from galaxy counts



Imaging Atmospheric Cherenkov Telescopes - IACTs



Imprint of EBL to gamma-ray spectra

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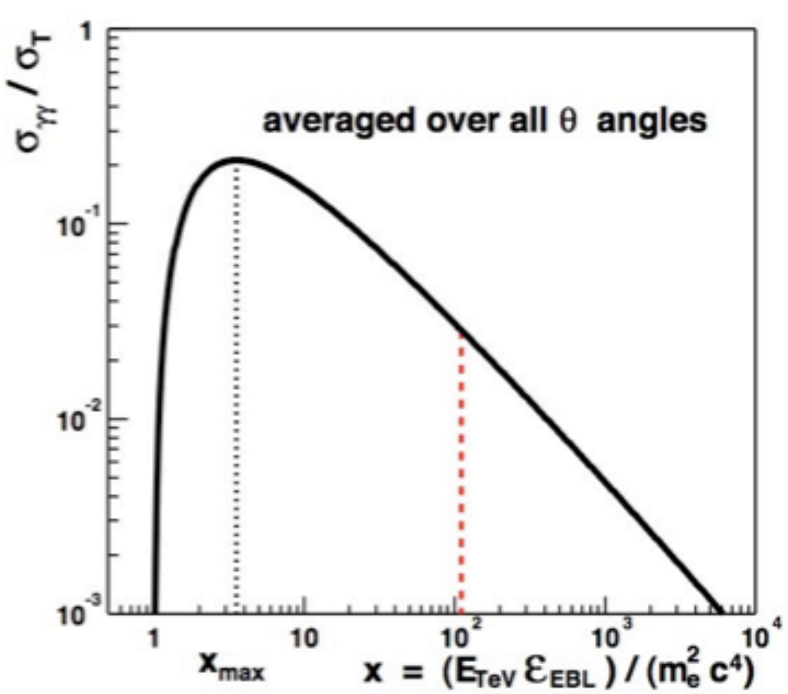
- Cross section of pair production:
  - peaks at ~4*Ethreshold
  - Delta function approximation is not precise

$$\sigma_{\gamma\gamma}(E,\epsilon,\theta) \;=\; \frac{3\,\sigma_T}{16}(1-\beta^2)\left[2\beta\,(\beta^2-2)+(3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right]$$

$$\text{with } \beta \;:=\; \left(1-\frac{2\,m_e^2\,c^4}{E\,\epsilon\,(1-\cos\theta)}\right)^{1/2}$$



Attenuation of gamma-ray flux is calculated by integrating over number density of EBL, angles between photons, and distance to the source. The attenuation is sensitive to the EBL density.

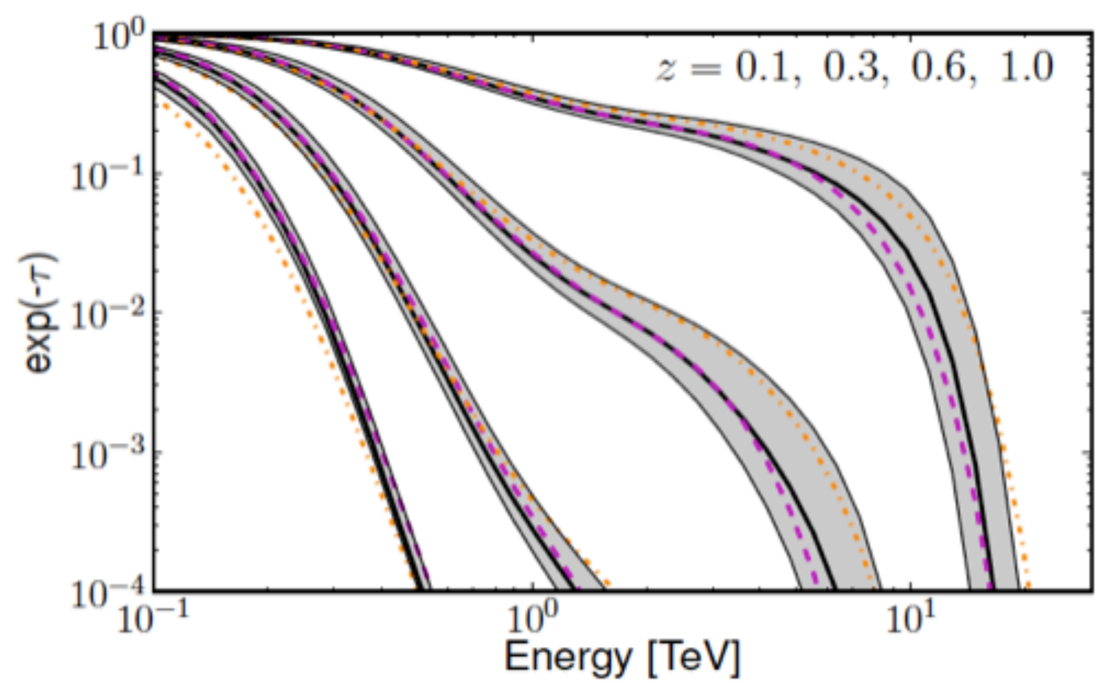
$$\tau(E_\gamma, z) \;=\; \int_0^z d\ell(z') \int_{-1}^{1} d\mu \, \frac{1-\mu}{2} \int_{\epsilon'_{th}}^{\infty} d\epsilon' \, n(\epsilon', z')\, \sigma_{\gamma\gamma}(\epsilon', E', \mu)$$

$$\mu \;:=\; \cos\theta$$

$$n(\epsilon) \;:=\; \text{EBL energy density}$$

$$d\ell(z) \;:=\; \text{distance element}$$

Observed flux = Emitted flux x exp(-τ)



Plot from Dominguez et al., MNRAS 410, 2556 (2011)

How can we derive EBL from gamma-ray measurements?

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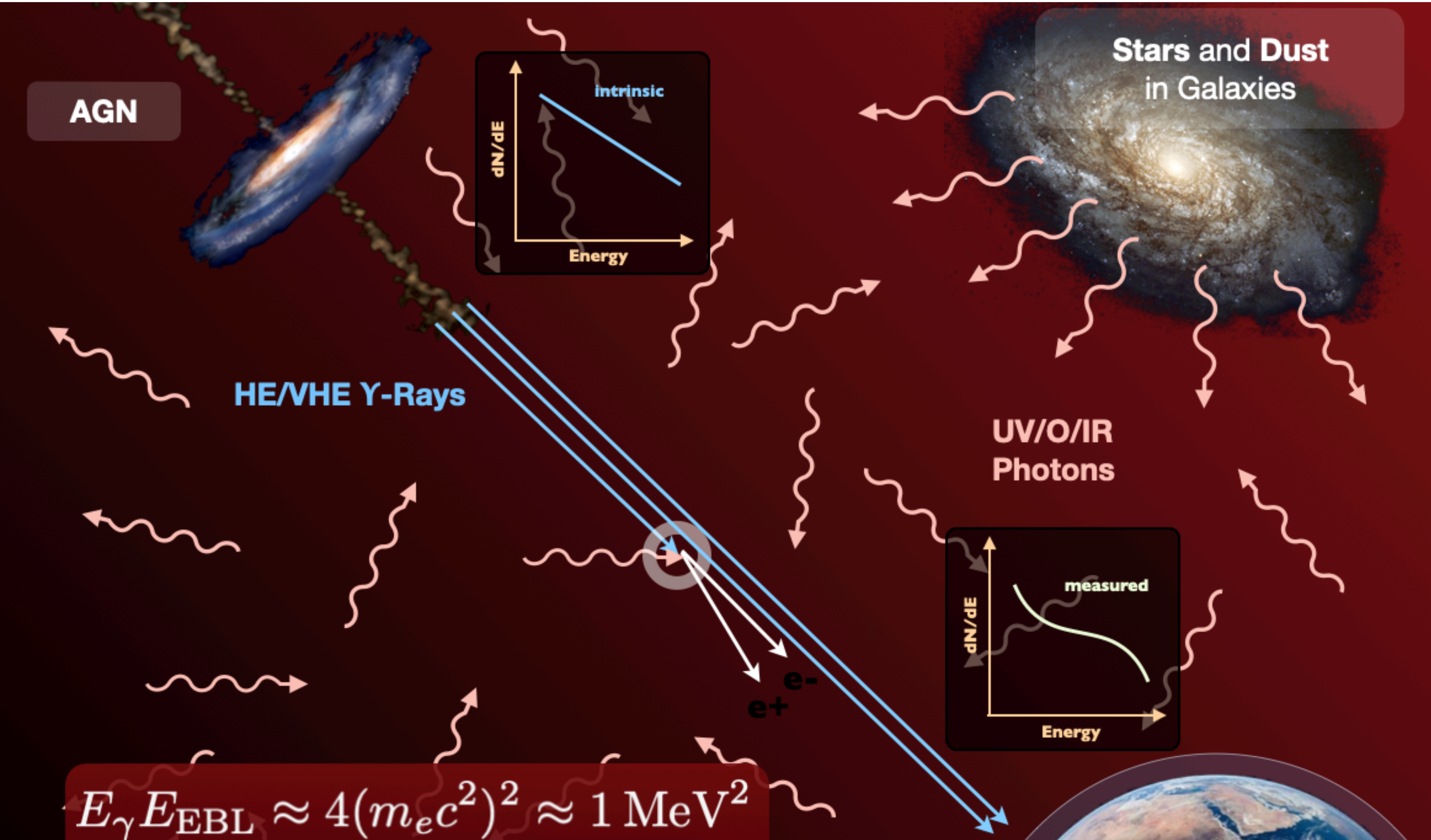

$$E_\gamma E_{\rm EBL} \approx 4(m_e c^2)^2 \approx 1\,{\rm MeV}^2$$

Imprint of EBL to gamma-ray spectra

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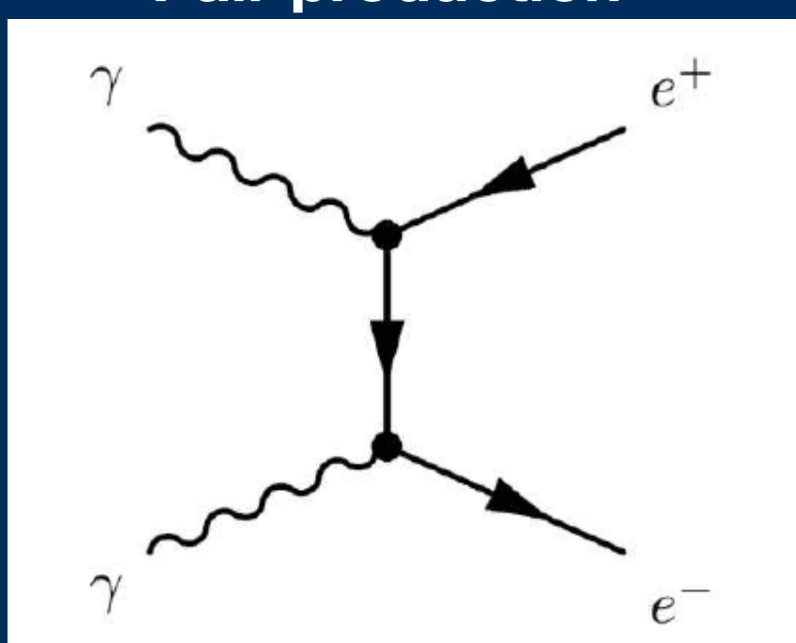
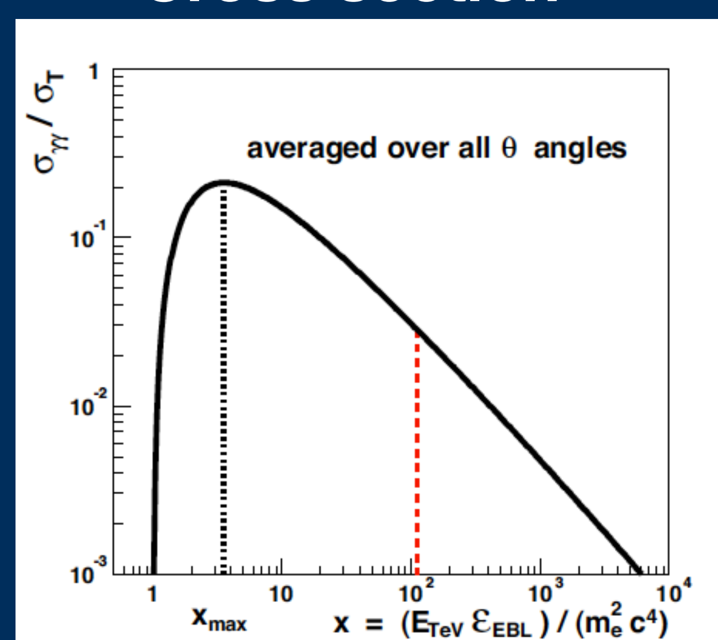
- Two photons can produce electron-positron pair when their energy is large enough
- Threshold: $$E_1 E_2 \geq \frac{2(mc^2)^2}{1 - \cos\Theta}$$
- Cross-section: $$\sigma_{\gamma\gamma}(E, \epsilon, \theta) = \frac{3\,\sigma_{\mathrm{T}}}{16}\,(1-\beta^2)\left[2\beta\,(\beta^2-2) + (3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right]$$

$$\text{with } \beta := \left(1 - \frac{2\,m_e^2\,c^4}{E\,\epsilon\,(1-\cos\theta)}\right)^{1/2}$$

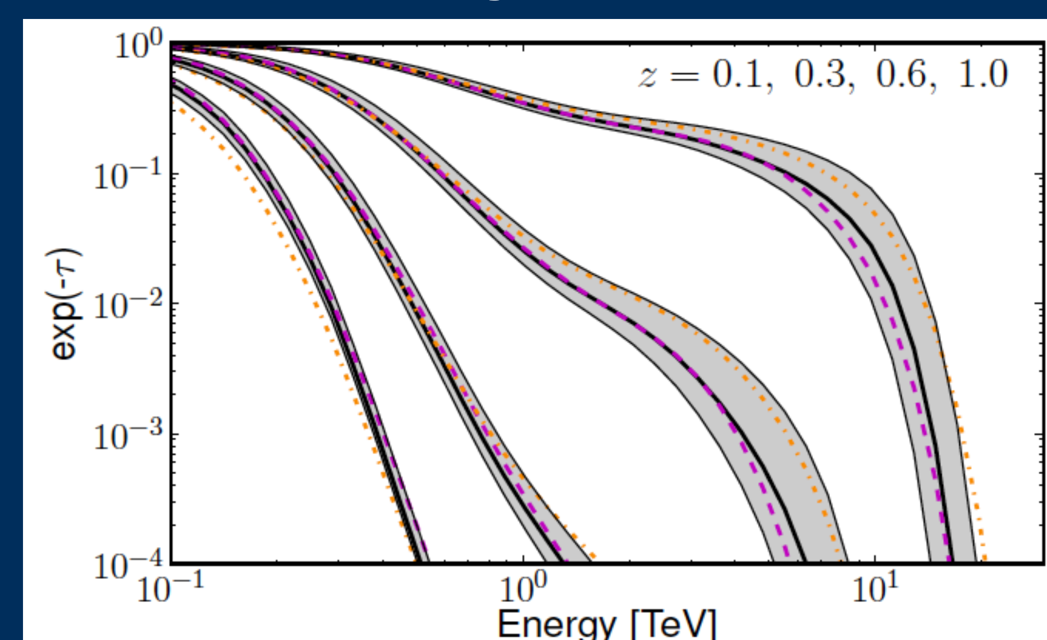
Pair production



Cross section



Gamma-ray attenuation



Dominguez+ 2011

Example of the method

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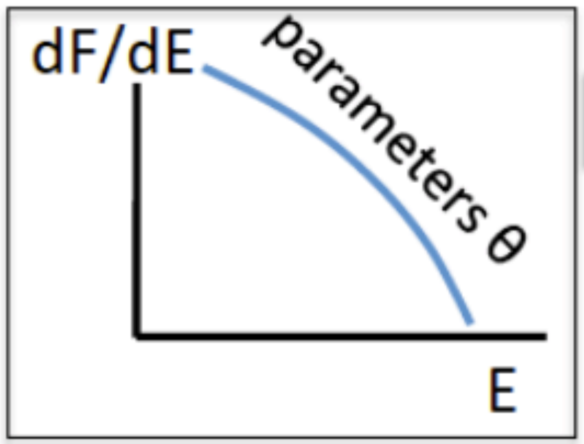
Spectrum

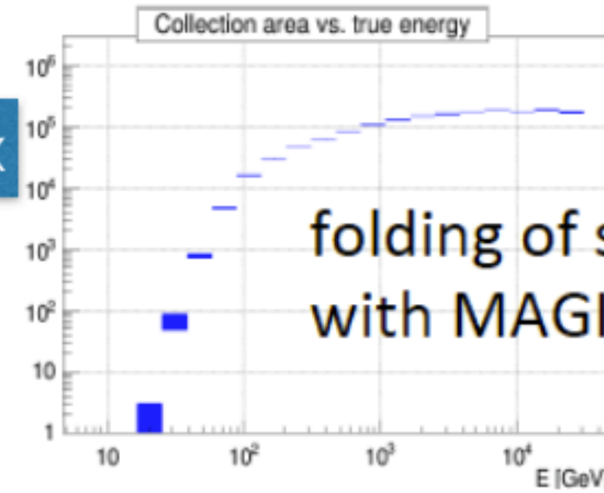


x

EBL model

x

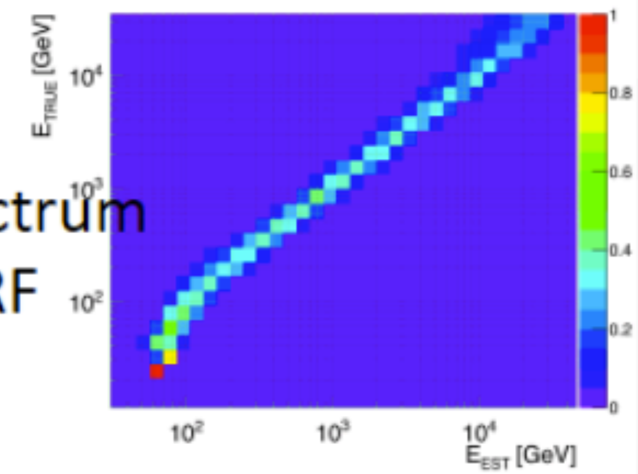
Effective Area



folding of spectrum
with MAGIC IRF

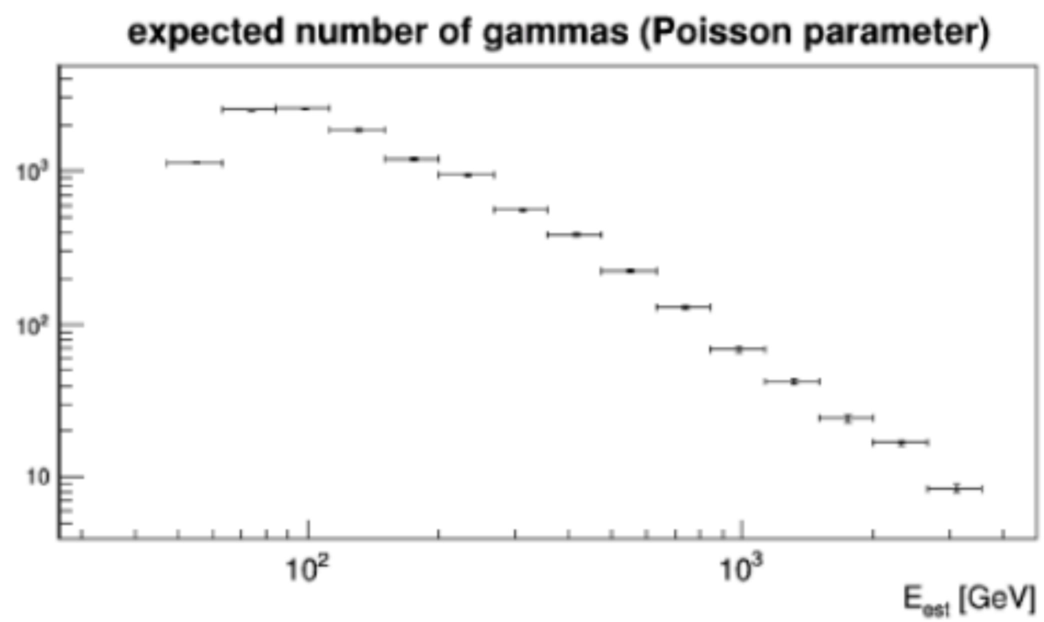
x

Energy migration matrix



x

Eff. time



Convolution of assumed intrinsic spectrum, assumed EBL and telescope response function gives us an expected distribution of gammas.
This is compared with the measured distribution.

- Result of maximization: spectral parameters
- EBL treated as scalable density with a single parameter

(same as done in e.g. Ackermann et al (Fermi-LAT), Science 338, 1190 (2012), Abramowski et al. (HESS), A&A 550, A4 (2013))

Example of the method

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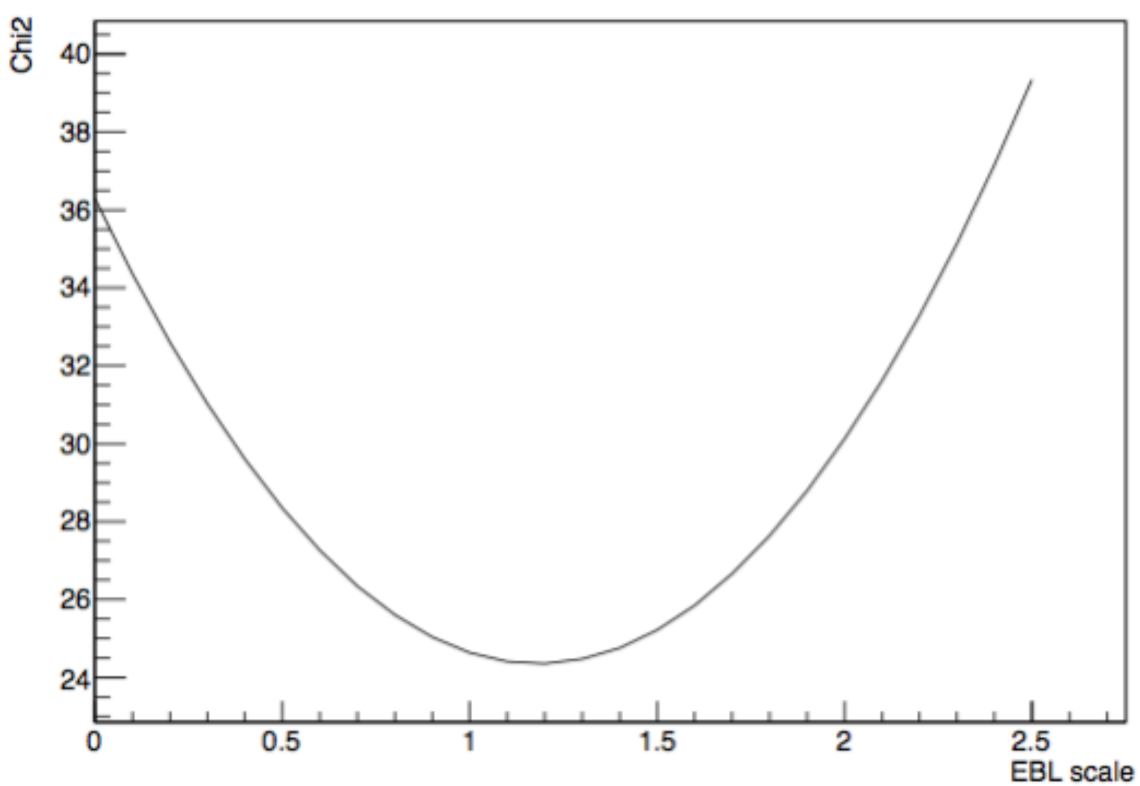
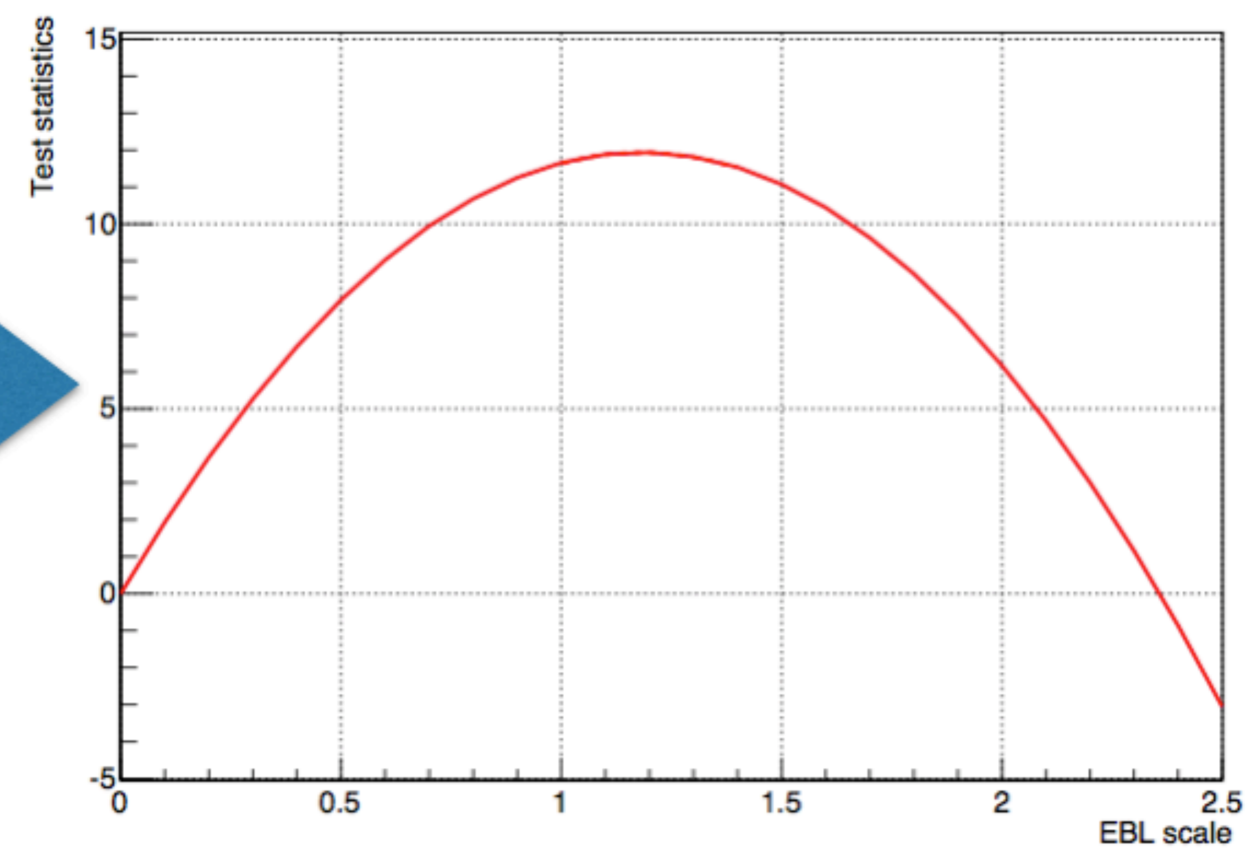
Fit χ^2 vs. EBL density scale



TS $\equiv$ χ^2 (EBL=0) - χ^2 (EBL scale)



- Scan of EBL scaling parameters and compare with EBL=0 case
- Assume different intrinsic smooth parametrizations (Power-Law (PL), Log-parabola (LP), PL with exp. cutoff, LP with exp cutoff). Noted that PL has too strong assumptions, used LP instead.

Example of the results

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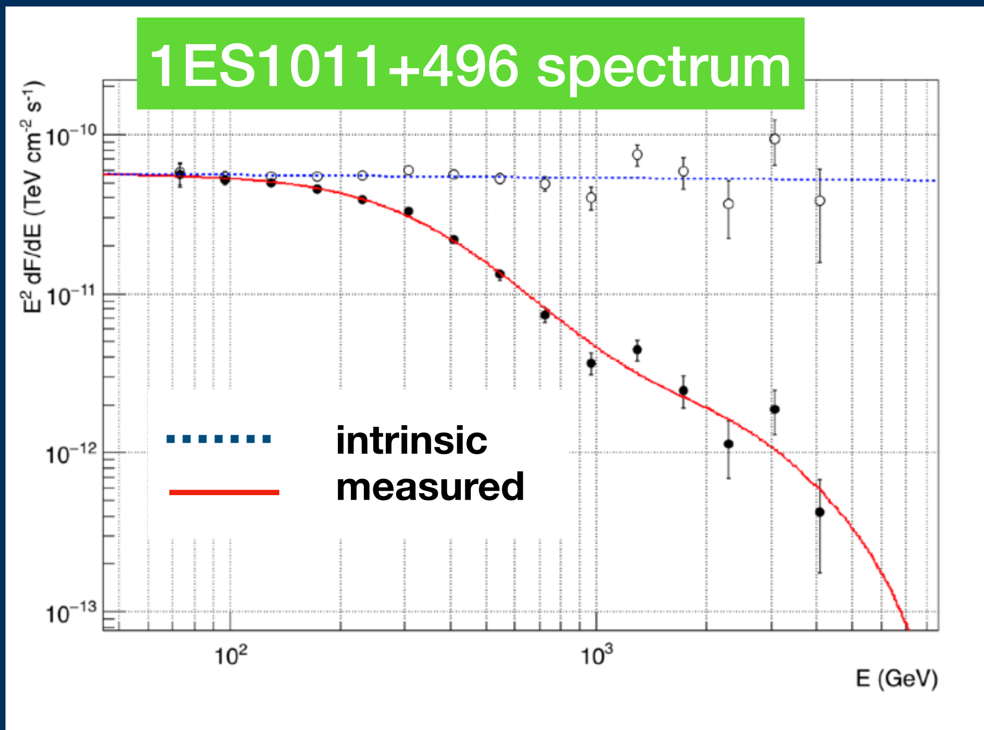
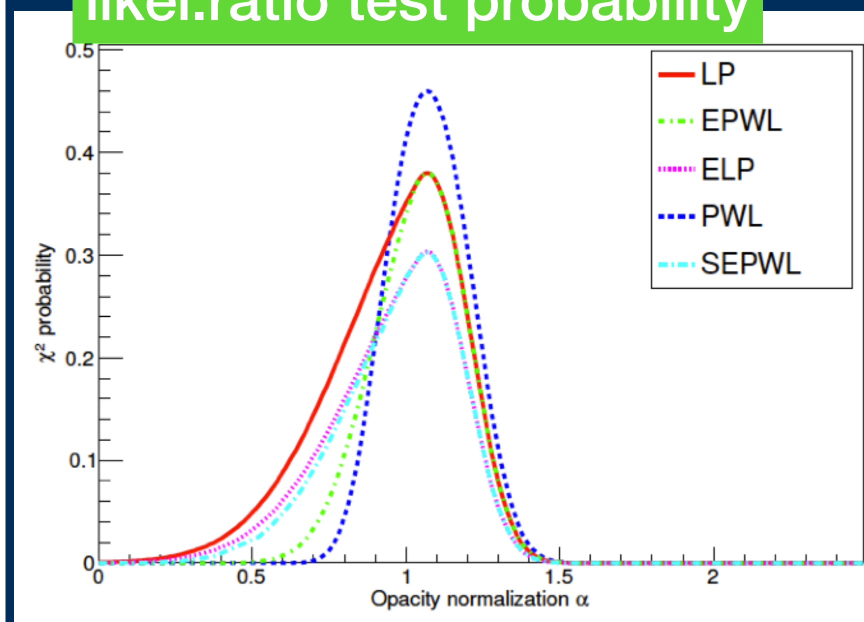
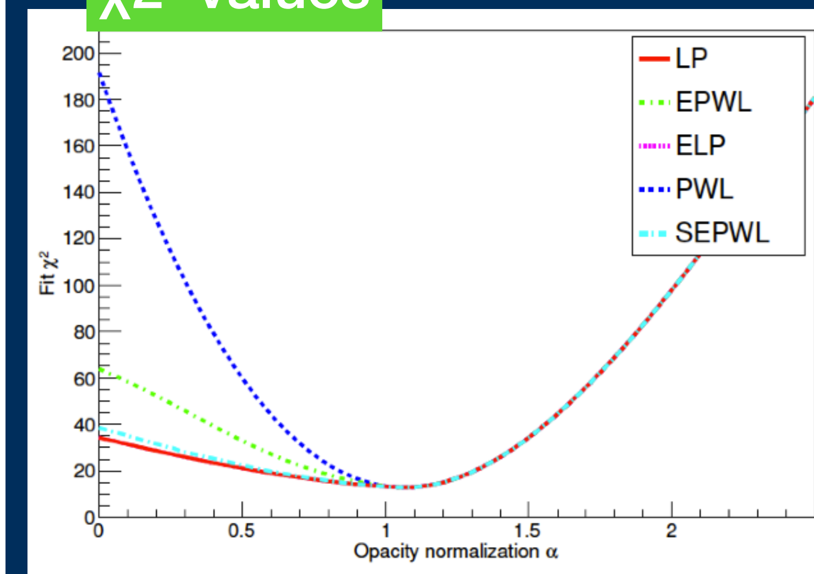
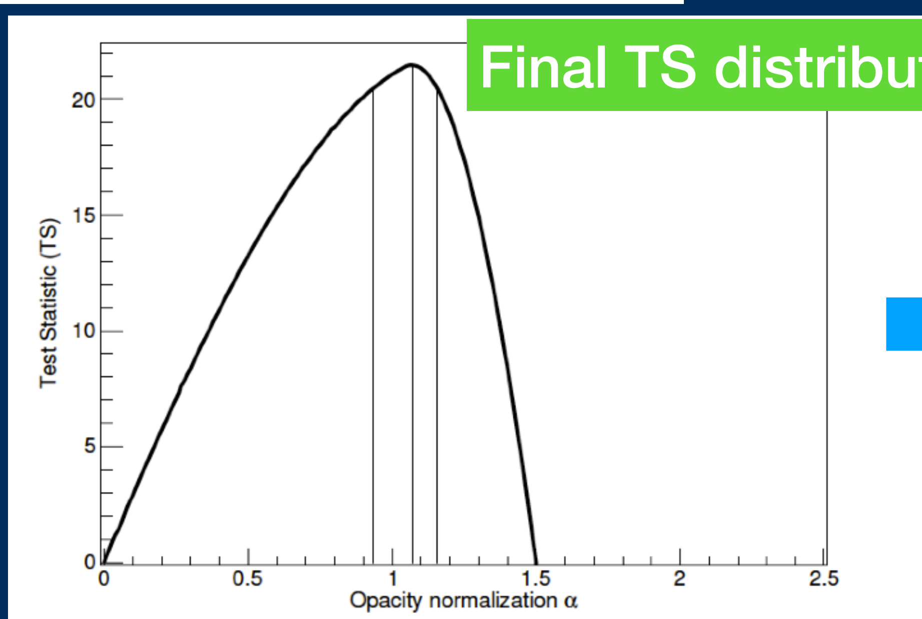
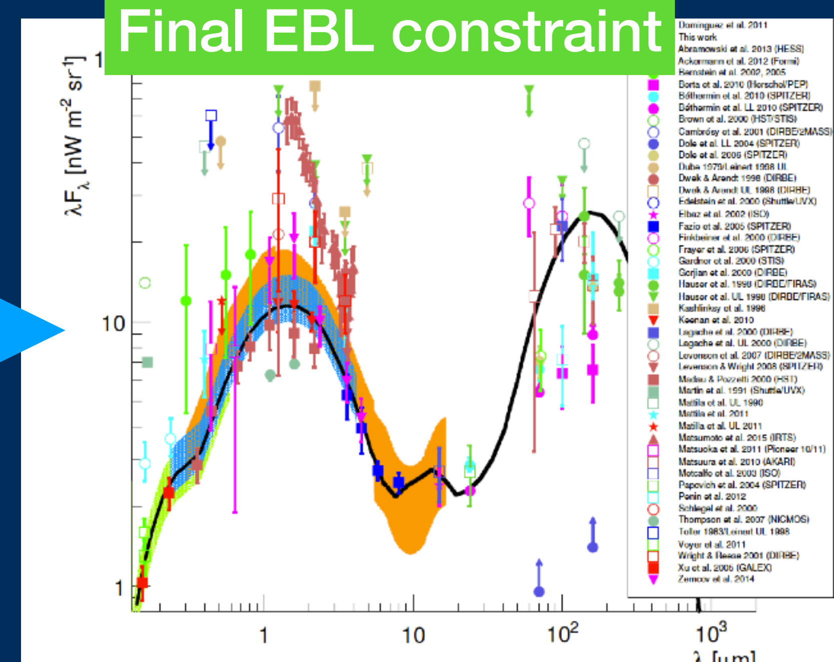
Ahnen et al. (MAGIC), A&A, 590, 24 (2016)





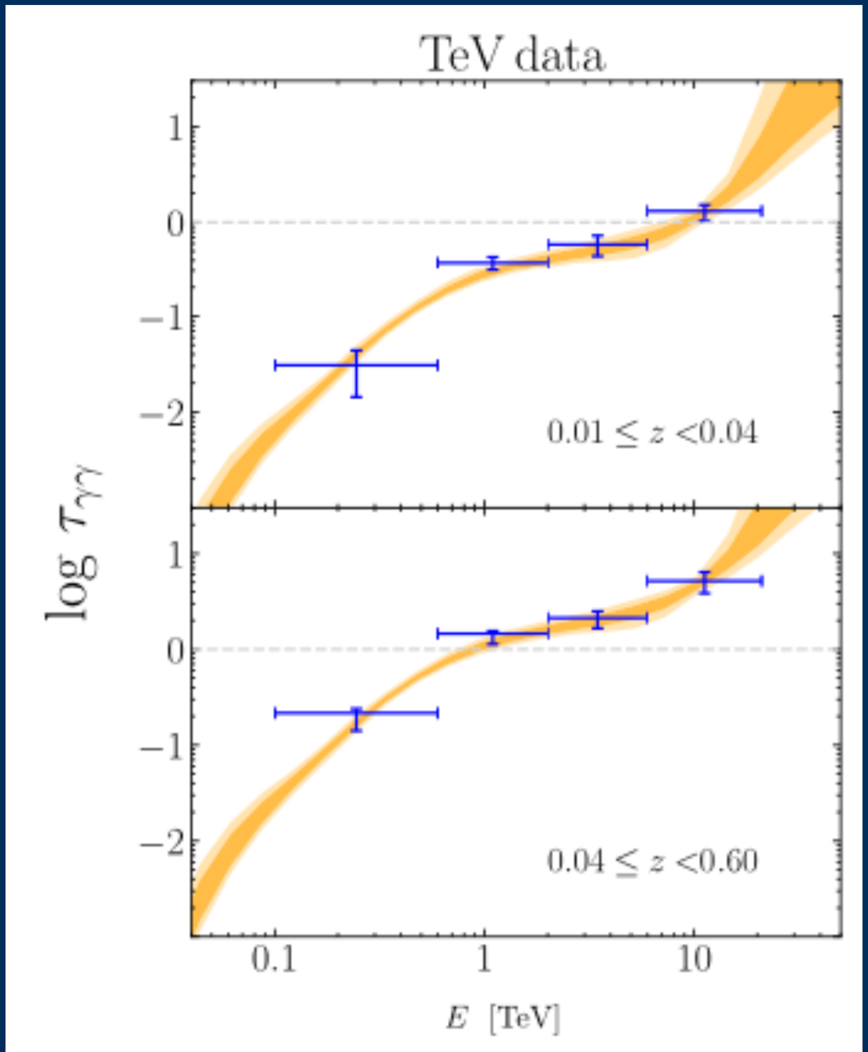


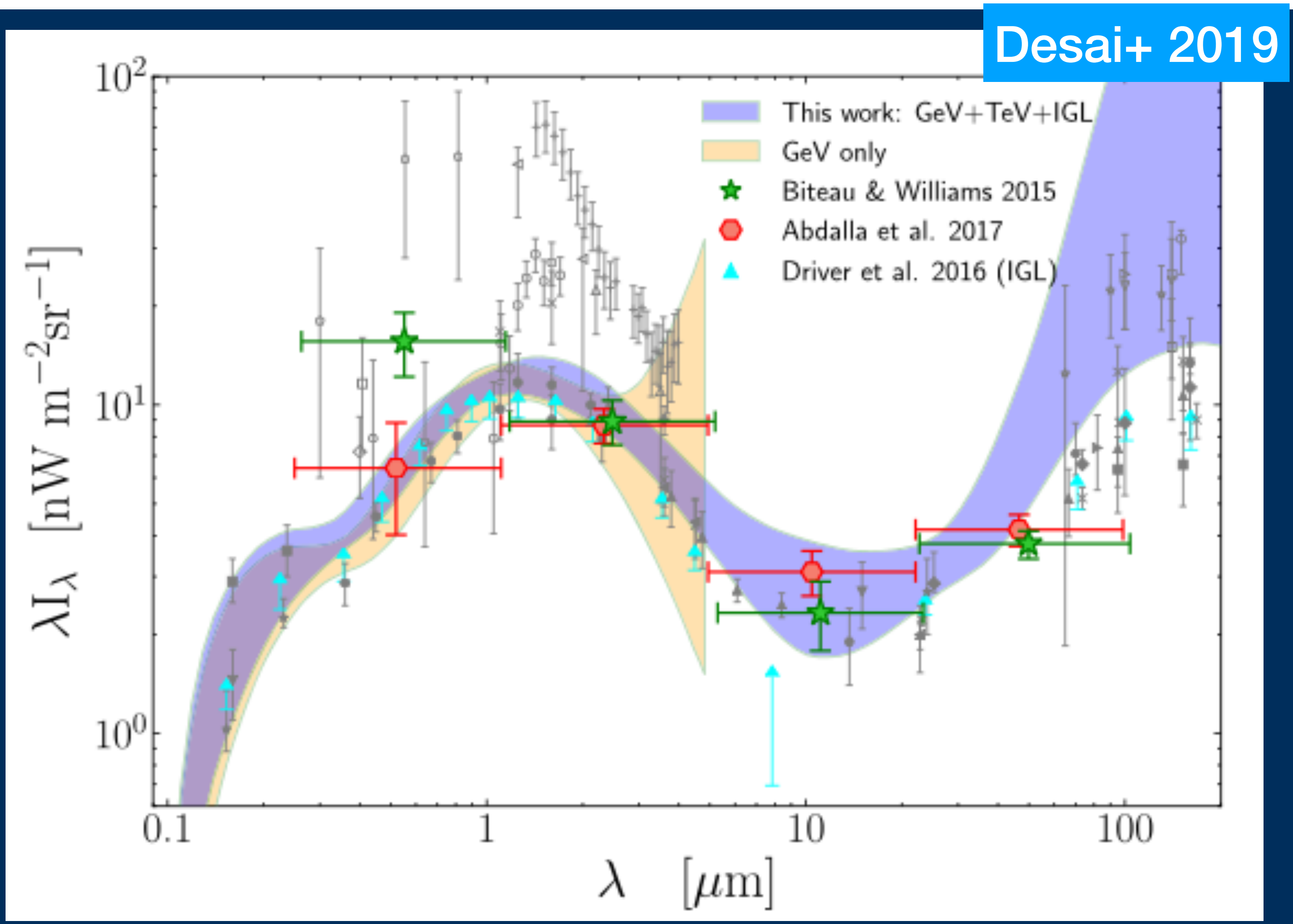




EBL normalization: $\alpha_0 = 1.07\ ^{+0.24}_{-0.20}$ (for Dominguez+2011 model)

indirect EBL measurements

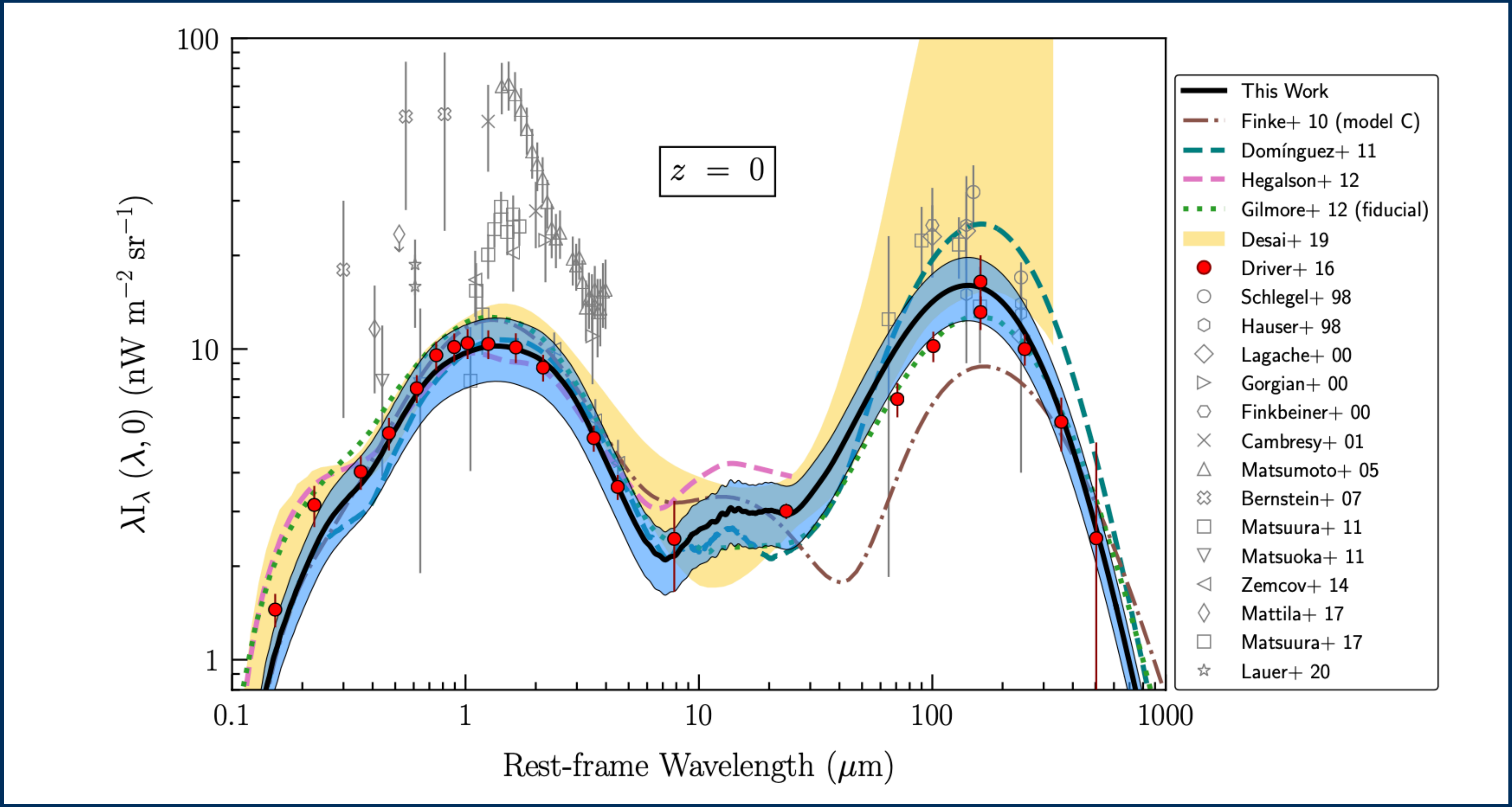




- Precise EBL measurements in optical - Near IR
- Close to lower limits from galaxy counts, i.e. no much(*) room for exotic EBL contributions or axions. Does not mean these are excluded though.
- (*) Not much means 1-2nW m^{-2} sr^{-1} in optical - Near IR, which means this extra EBL must be explained / found

EBL model (example)

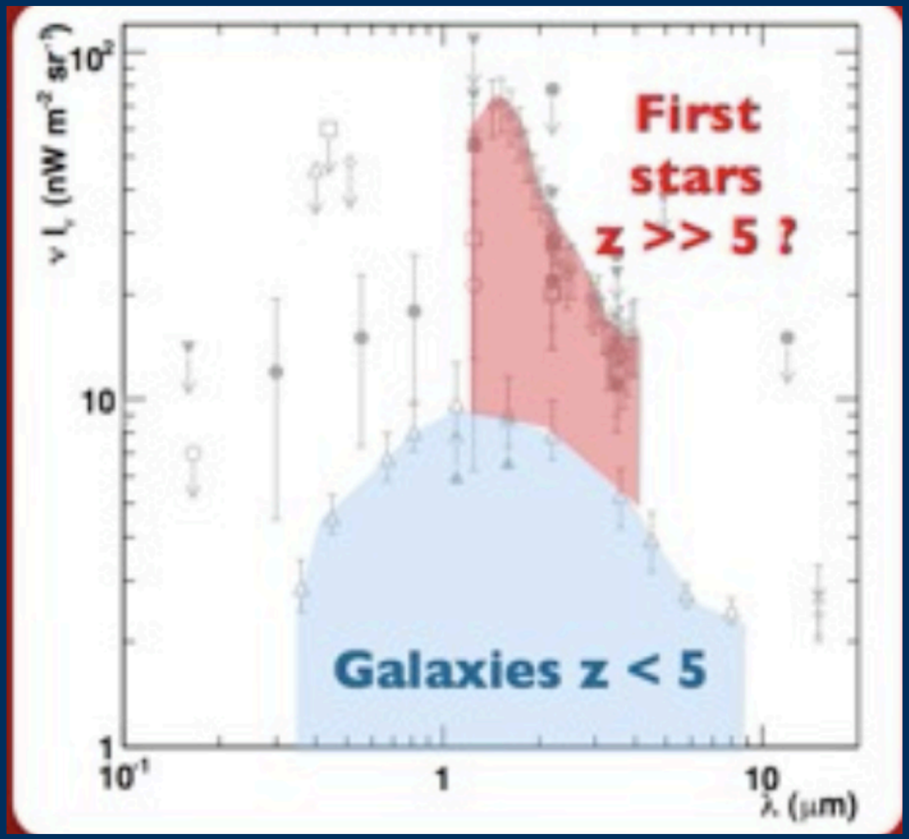
- Saldana-Lopez et al. 2021 shows current best modeling using data from resolved galaxies

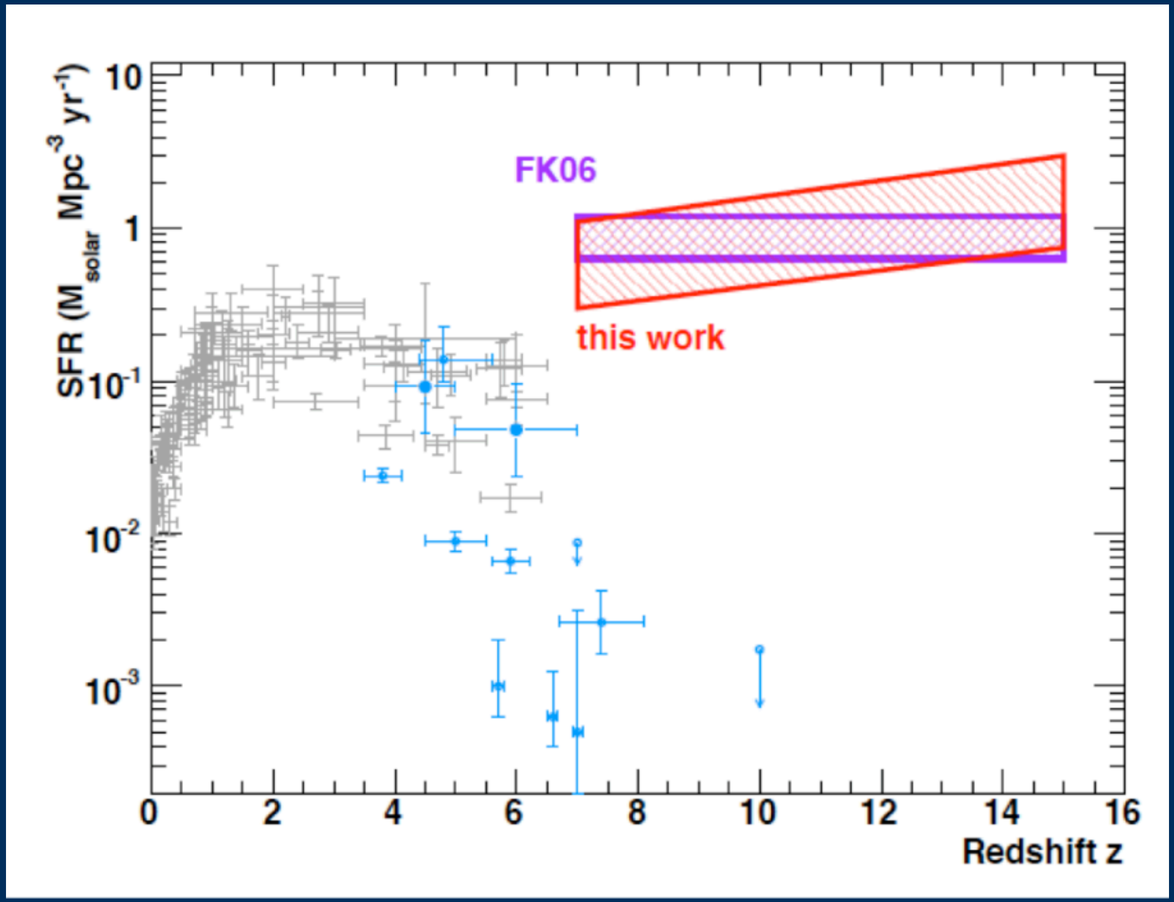


Indirect limits from "extra" EBL

Limits on Population-III stars

- used the recent EBL limits to derive constraints on the Population-III stars
- account for the time evolution of the emissivity of a stellar population
- results:
  - Zero metallicity stars: peak Star Formation Rate of 0.6 - 3 $M_\odot$ / year (for z = 7 - 14)
  - Low metallicity stars: peak Star Formation Rate of 0.3 - 1.5 $M_\odot$ / year (for z = 7 - 14)



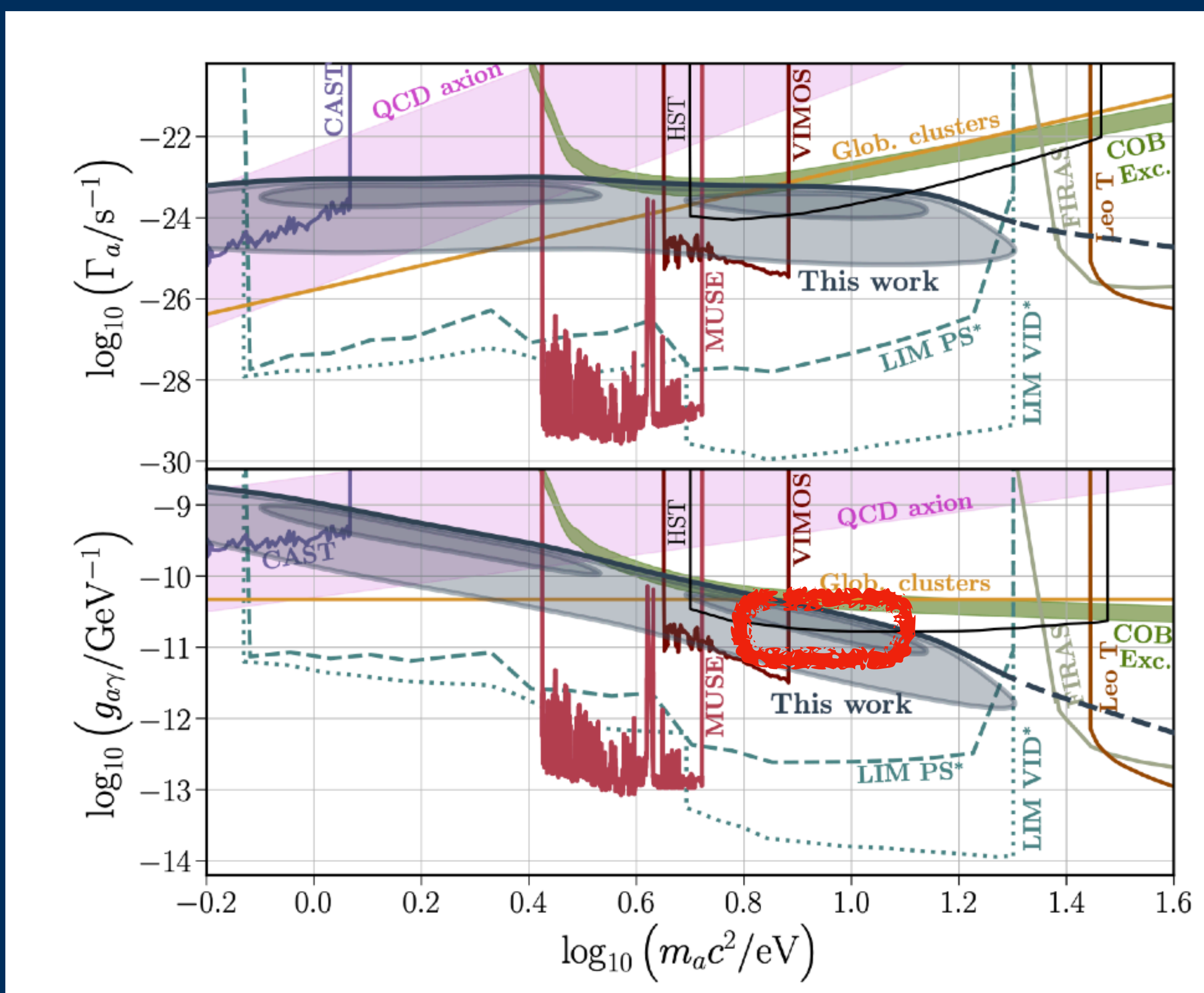


Raue, Kneiske & DM, A&A (2009), 498, 25-35, arXiv:0806.2574

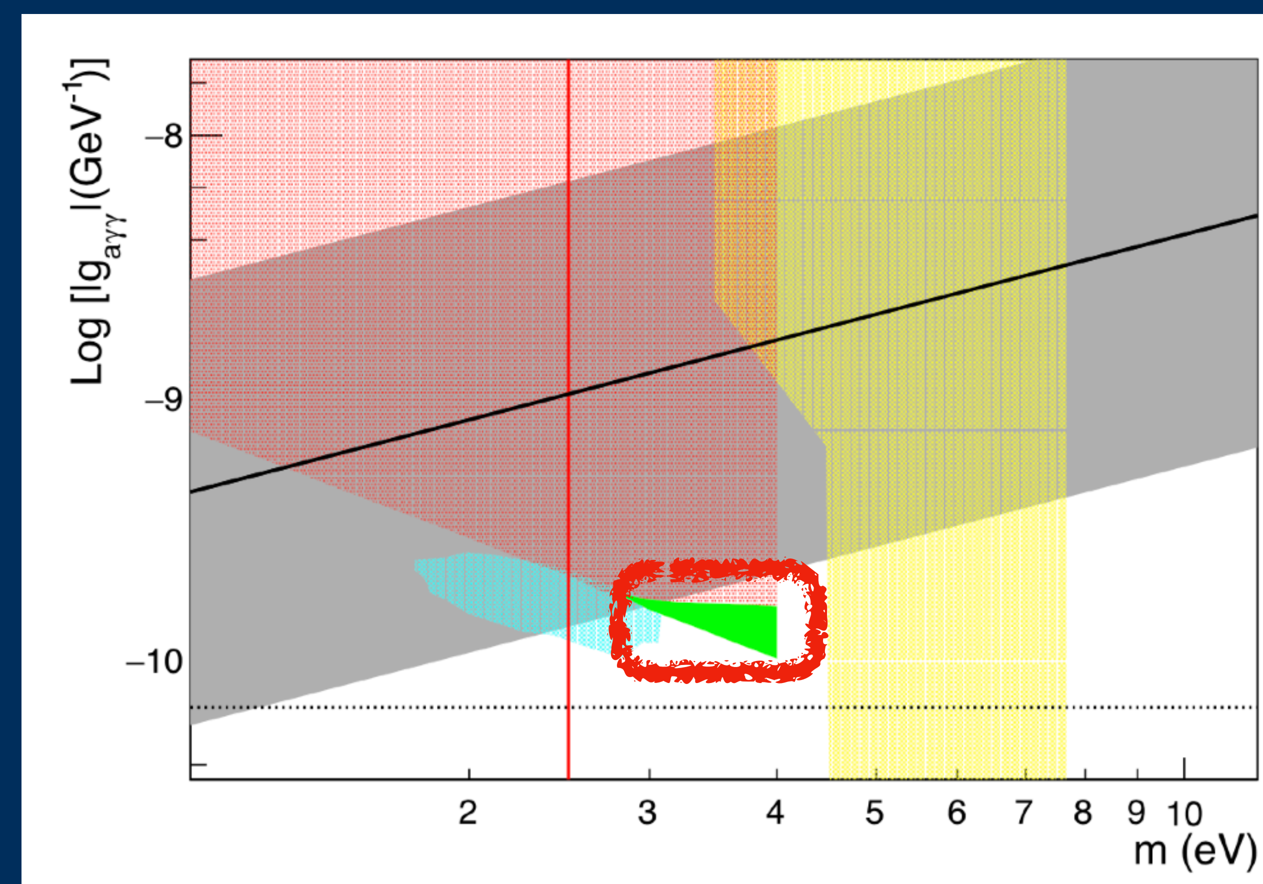
Indirect limits from “extra” EBL

Limits on Axion-like Particles (dark matter candidate)

- Bernal et al 2023 find the best fit around $m_a c^2$~ 8 eV



- Mankuzhiyil et al 2023 find the best match around $m_a c^2$~ 3-4 eV



New direct EBL measurements

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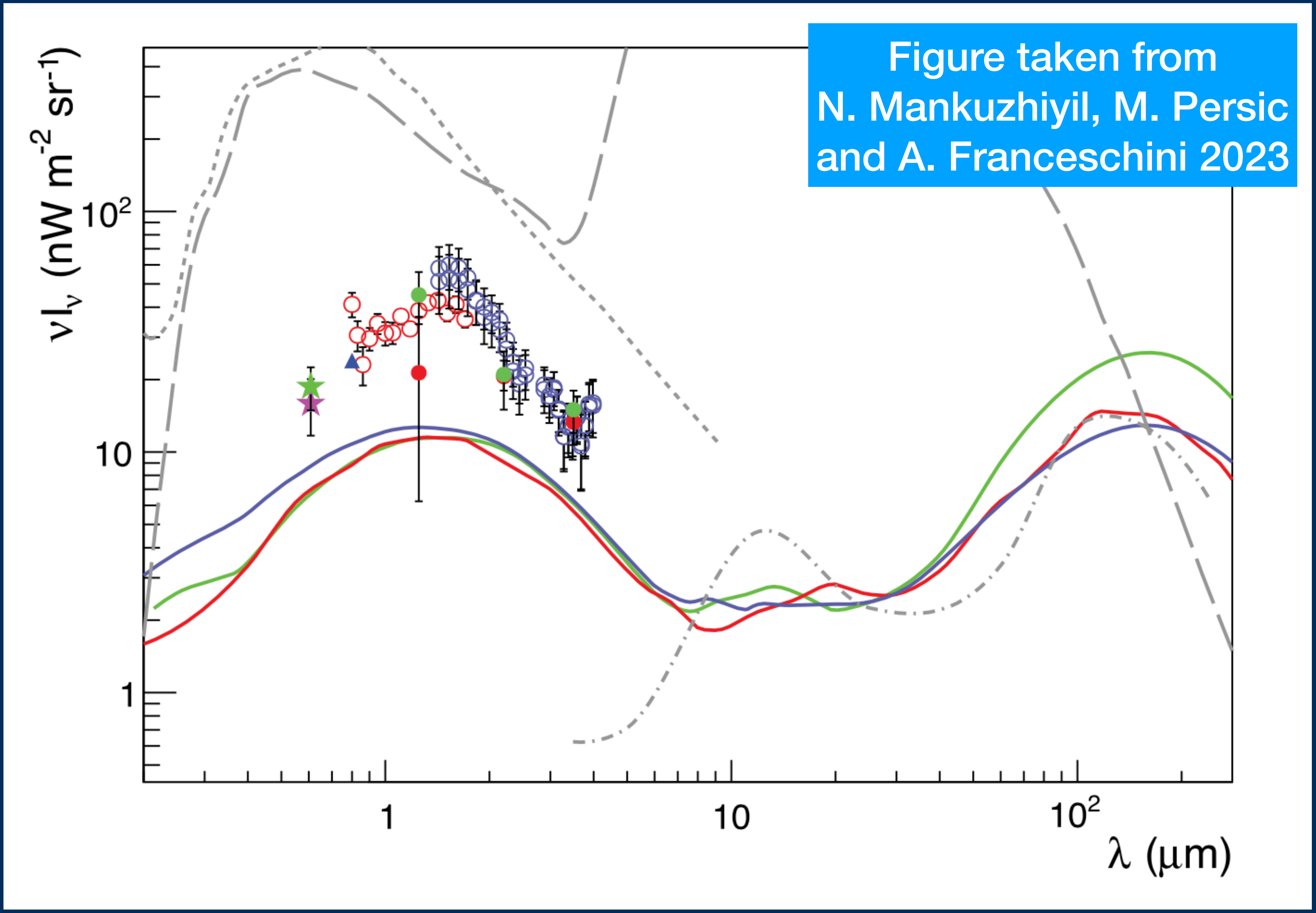
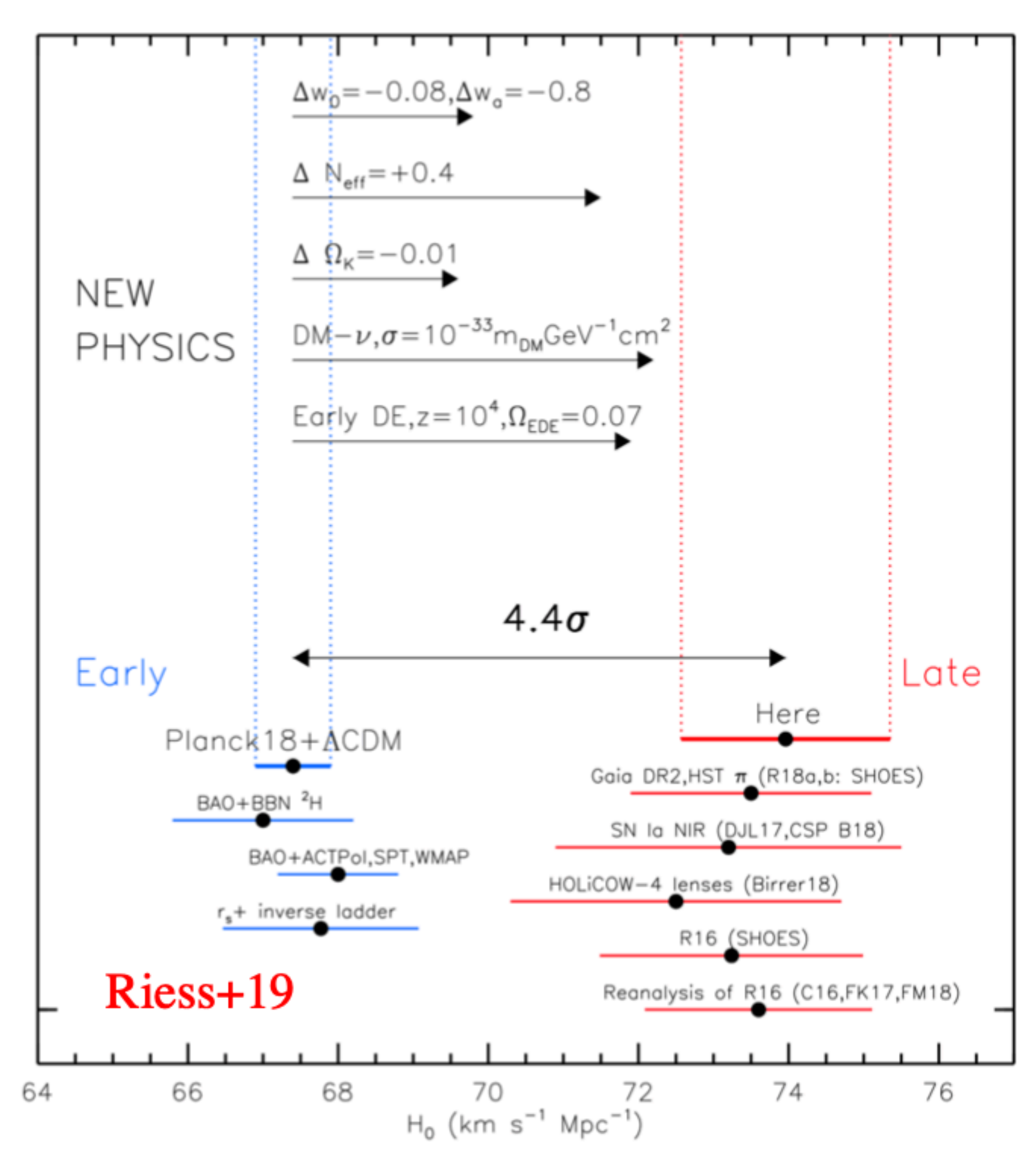
- still significantly and consistently higher than the indirect limits and the EBL level from galaxy counts (i.e. light from resolved sources)

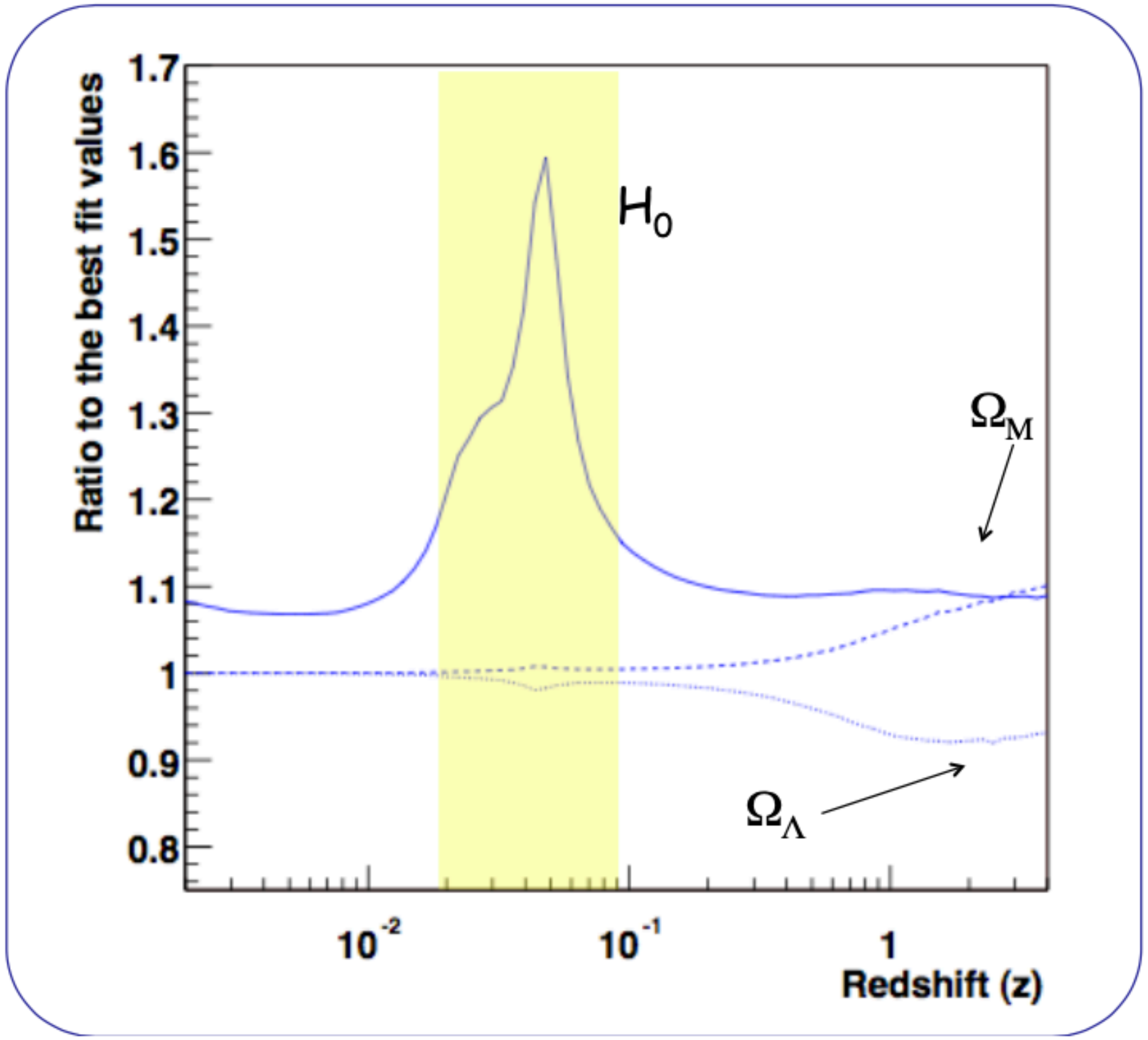


- Open red circles: CIBER (Matsuura et al. 2017)
- Open blue circles: IRTS renalaysis (Matsumoto et al. 2015)
- Filled blue triangle: lower limit from the Hubble XDF (Matsumoto & Tsumuro 2019)
- Filled red circle: DIRBE (Levenson, Wright & Johnson 2007)
- Filled green circle: DIRBE (Sano et al. 2020)
- filled red and green stars: New Horizon (Lauer et al. 2021).

Cosmological constants measurements



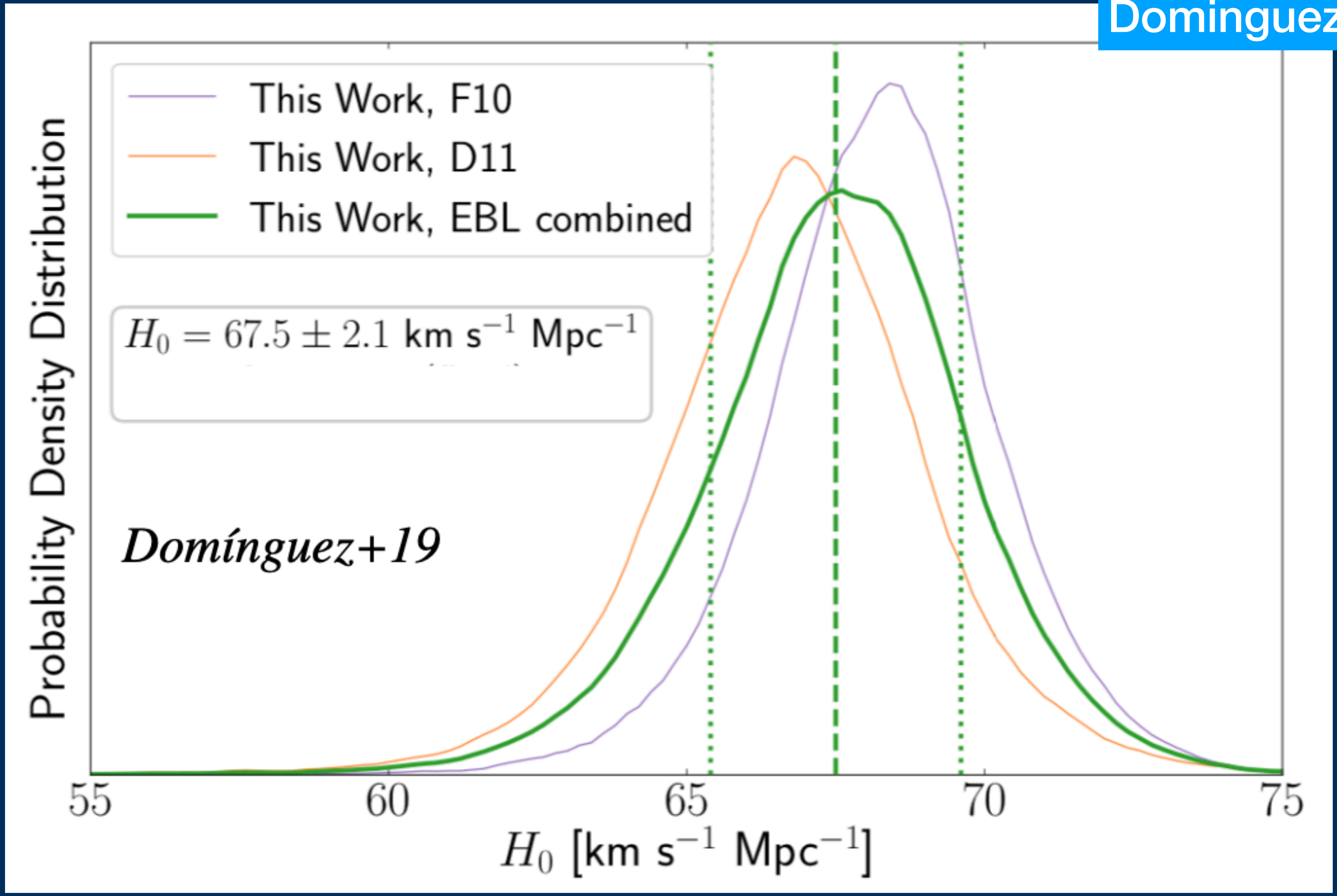
$$\tau_\gamma = \int_0^z d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{\rm thr}}^{\infty} d\epsilon' \frac{dn_{\rm bkg}}{d\epsilon} \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$



- Gamma rays from AGNs at z=0.02-0.1 probe Hubble constant

Cosmological constants measurements

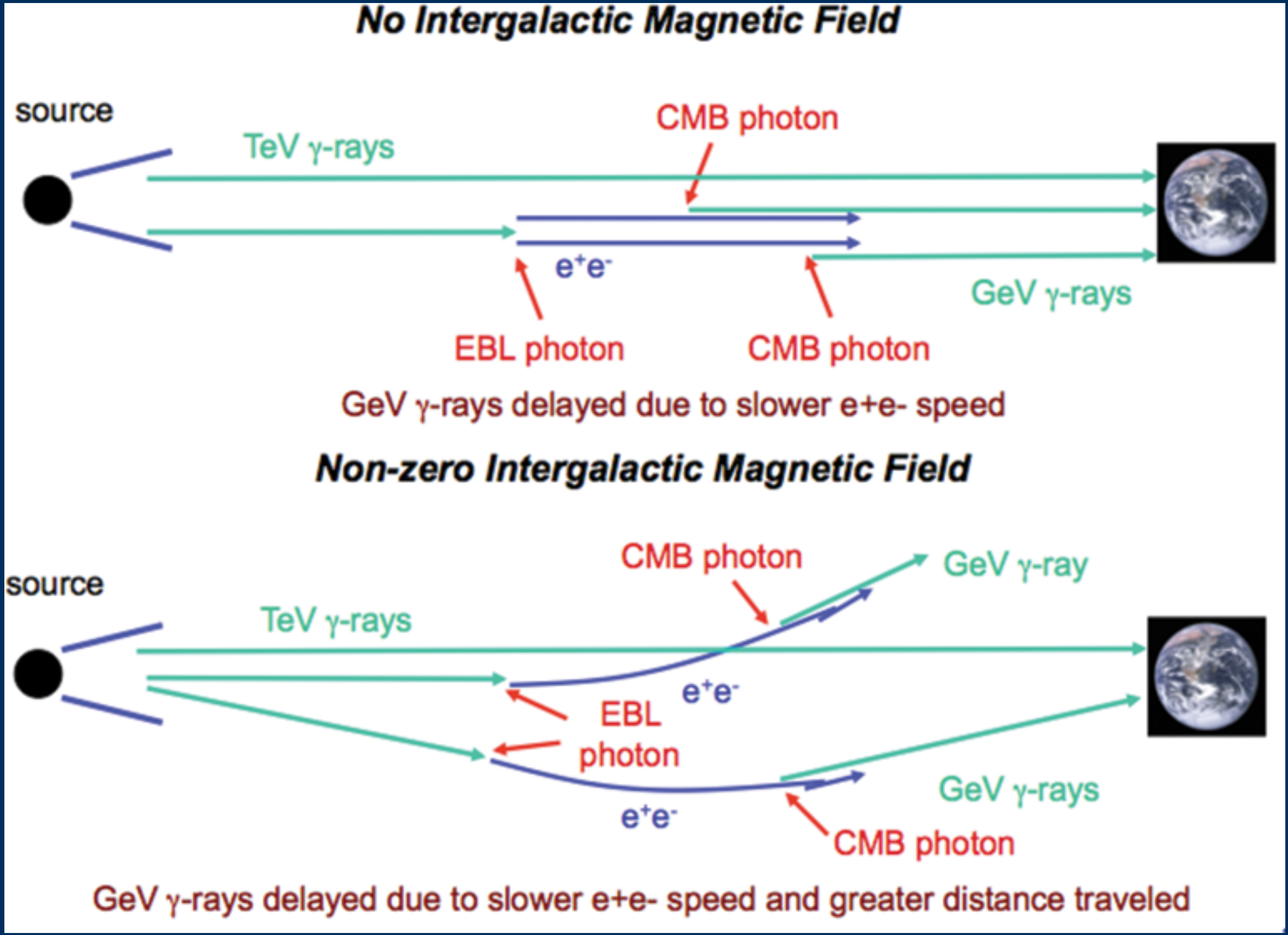
Dominguez+2019



- Even with a limited set of gamma-ray blazars, the Hubble constant can be constrained within 3-5%

Intergalactic Magnetic Field

- Electron-positron pairs (created due to EBL absorption of primary γ rays) can start a cascades through Inverse Compton (IC) scattering of CMB photons
- Secondary γ rays may create a halo around the source and/or a delayed γ-ray signal
- The idea is disputed. Electron-Positron pairs may loose their energy in heating of plasma, and not through IC cascades (e.g. Broderick et al. 2012)



Intergalactic Magnetic Field

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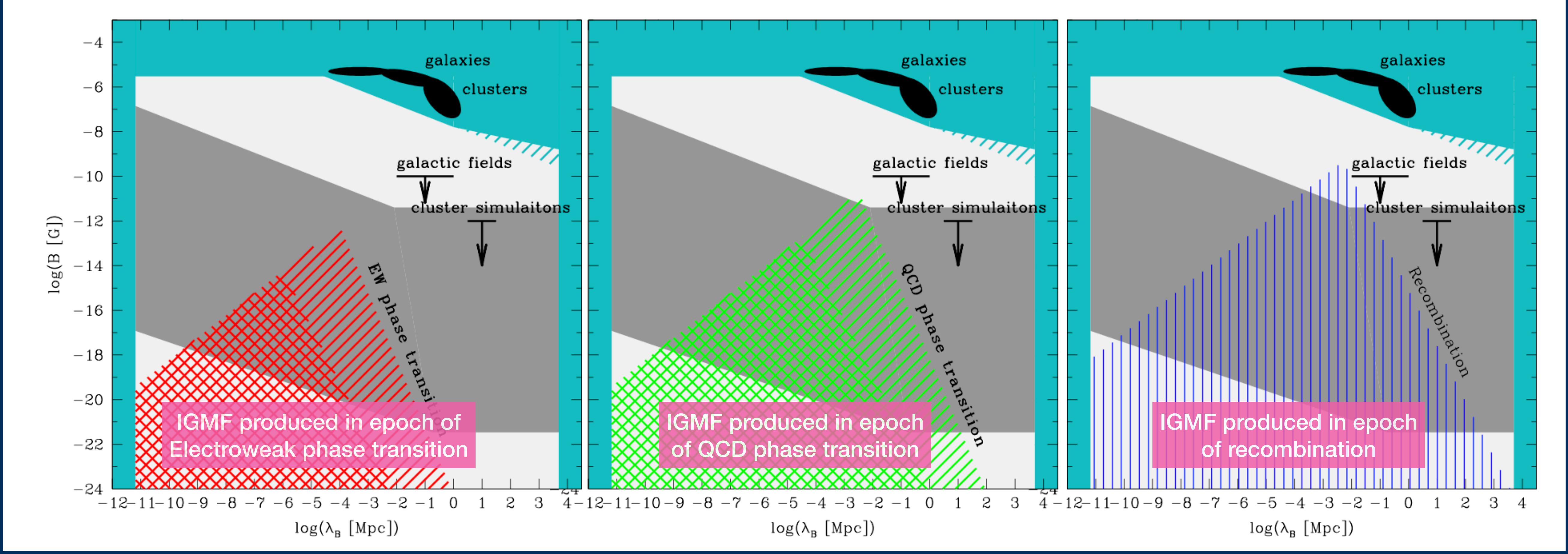
- Strength and correlation length of IGMF are unknown
- Gamma rays can probe a large part of the parameter space when looking for secondary gamma-ray emission in halos around point like sources and/or a delayed secondary emission



Neronov&Semikoz 2009

Intergalactic Magnetic Field

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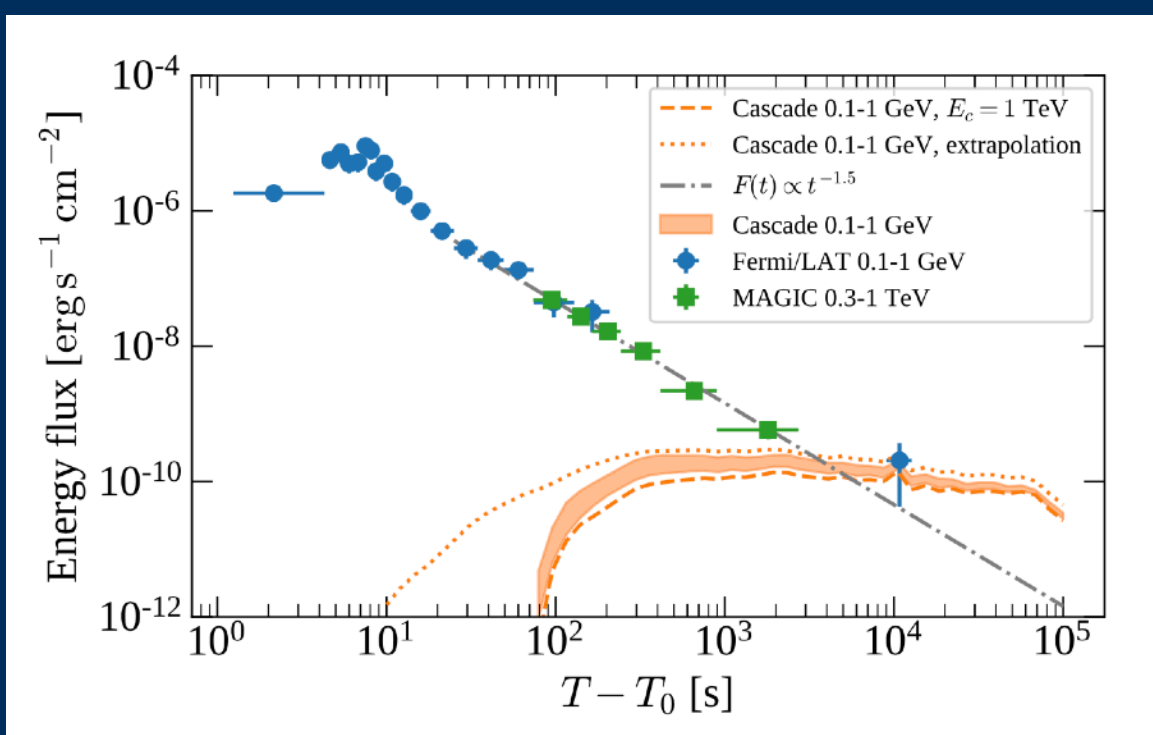
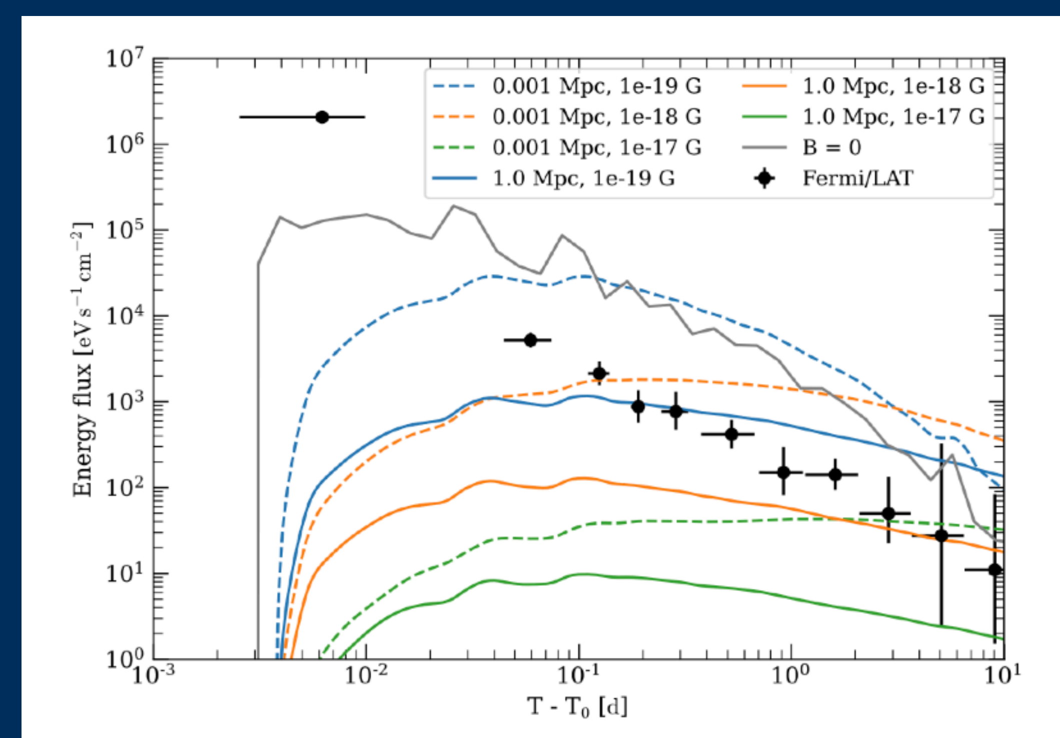
- Using data from Fermi-LAT and MAGIC on GRB190114A
- If all late flux is from cascade emission (secondaries), B-field is very weak, $B < 10^{-21}$ G

- Using data from LHAASO and Fermi-LAT on GRB221009A
- Non-detection of halo signal in Fermi-LAT puts a lower limit on the B-field towards the GRB, $B > 10^{-19}$ G for $l = 1$ MPc



Vovk 2023



Vovk et al 2023

Cherenkov Telescope Array

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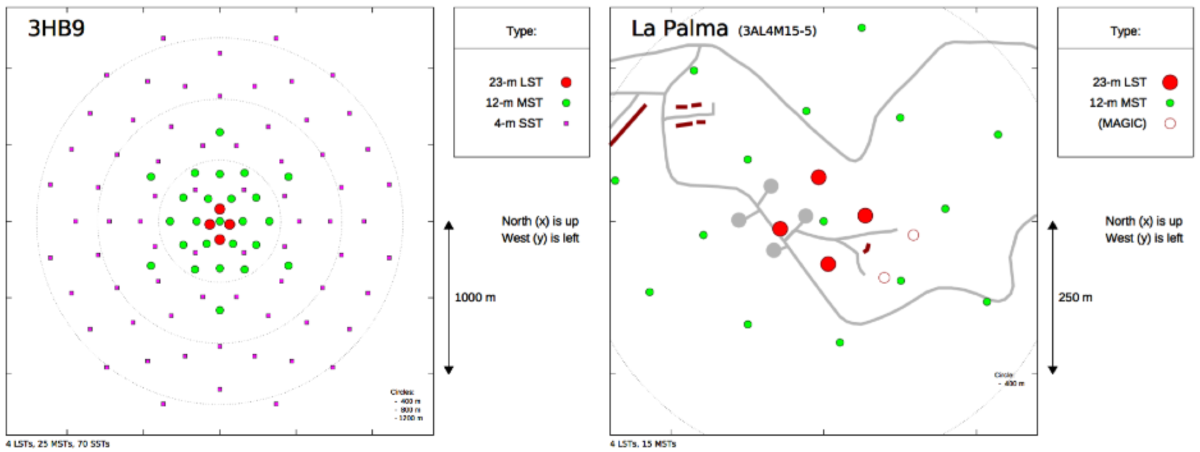


South:
4 LST
25 MST
70 SST

Alpha South:
0 LST
14 MST
50 SST

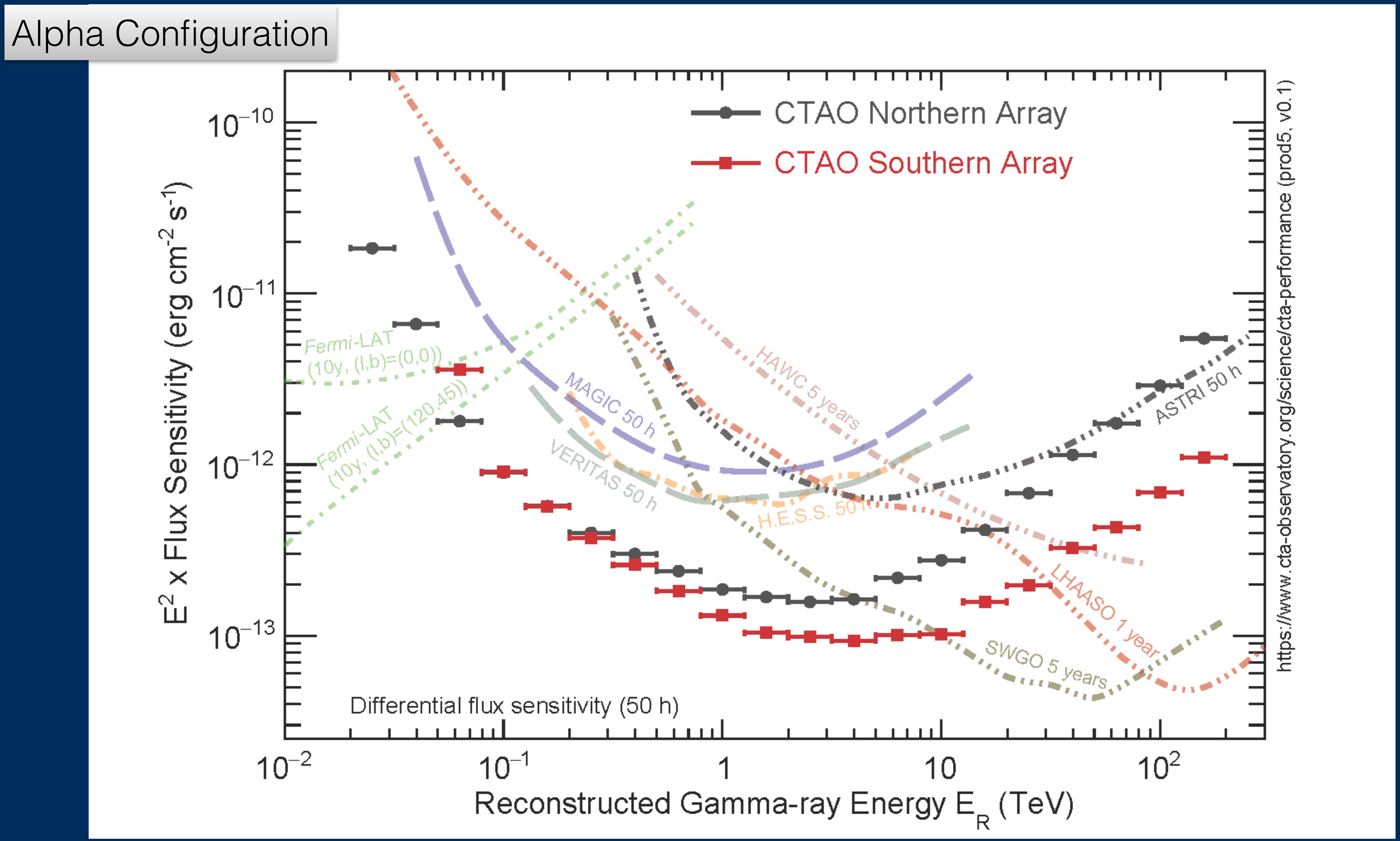
North:
4 LST
15 MST

Alpha North:
4 LST
9 MST

CTA Key Factors:

- Full sky coverage, 2 sites
- Survey capability
- Order of magnitude better sensitivity
- Extended energy coverage (20 GeV - 300 TeV)
- Much improved energy and angular resolutions

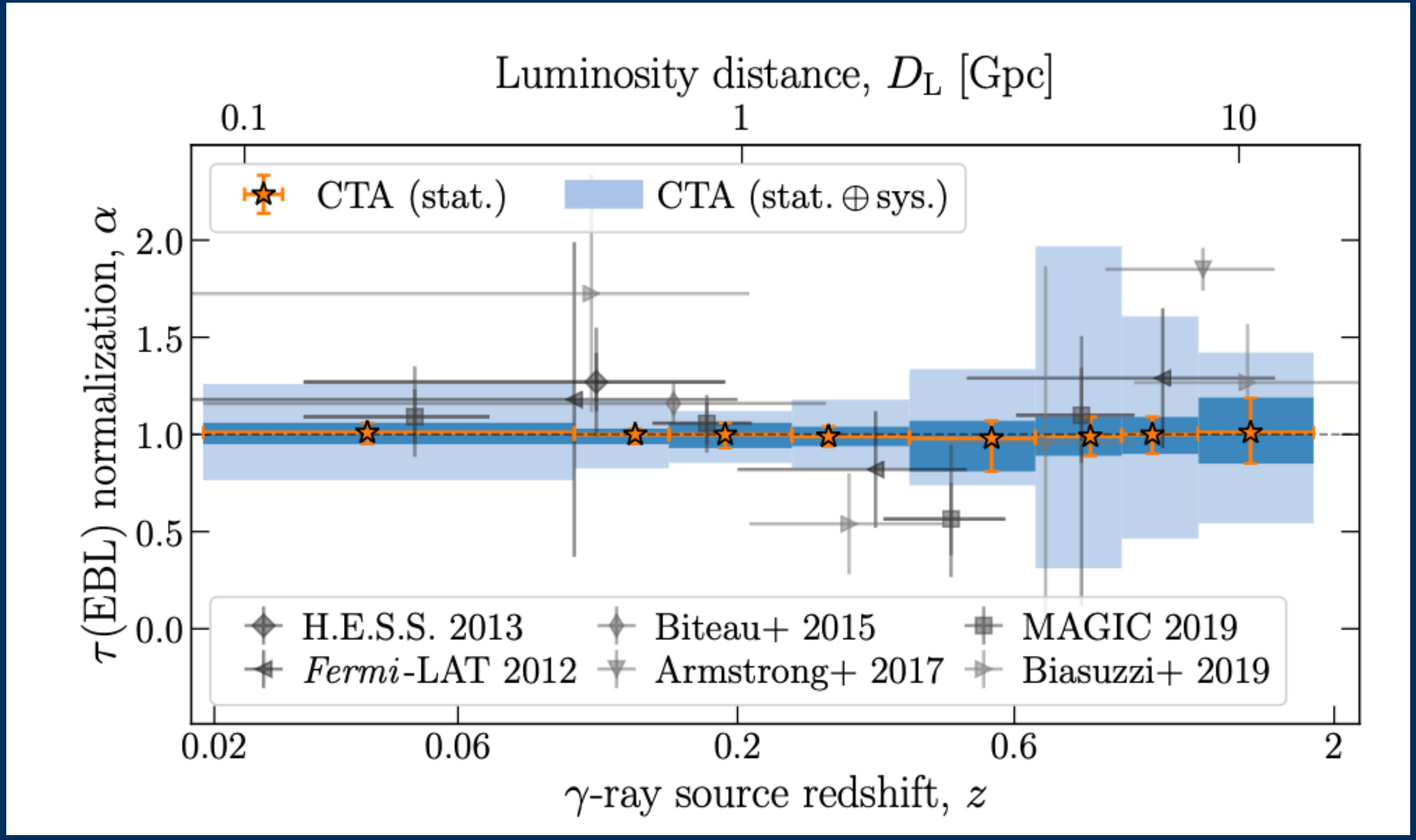
CTA's flux sensitivity compared

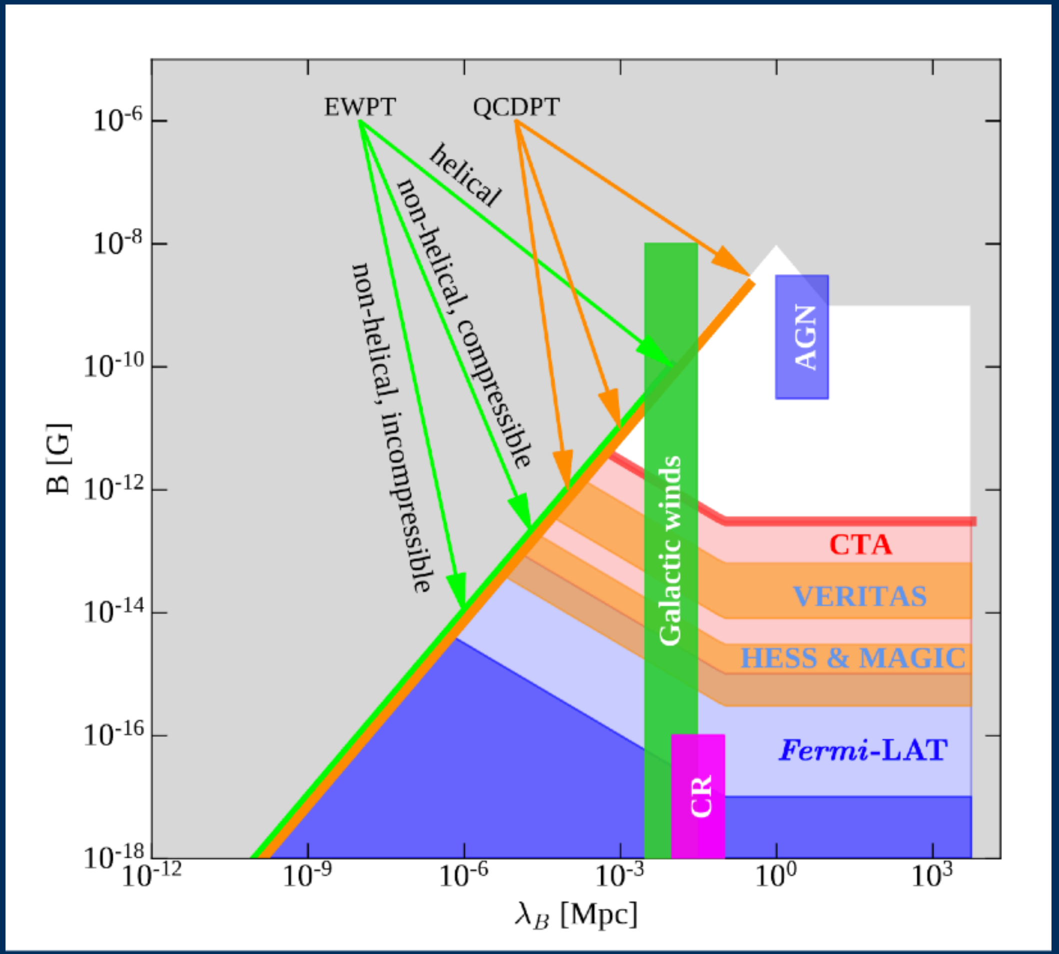


What do we expect from CTA?

CTA consortium, 2021
arXiv:2010.01349

- EBL evolution can be resolved up to z=2 using many gamma-ray sources
- IGMF might be detected if it is in the "right" corner of the parameter space and if the plasma instabilities are not dominating over IC scattering



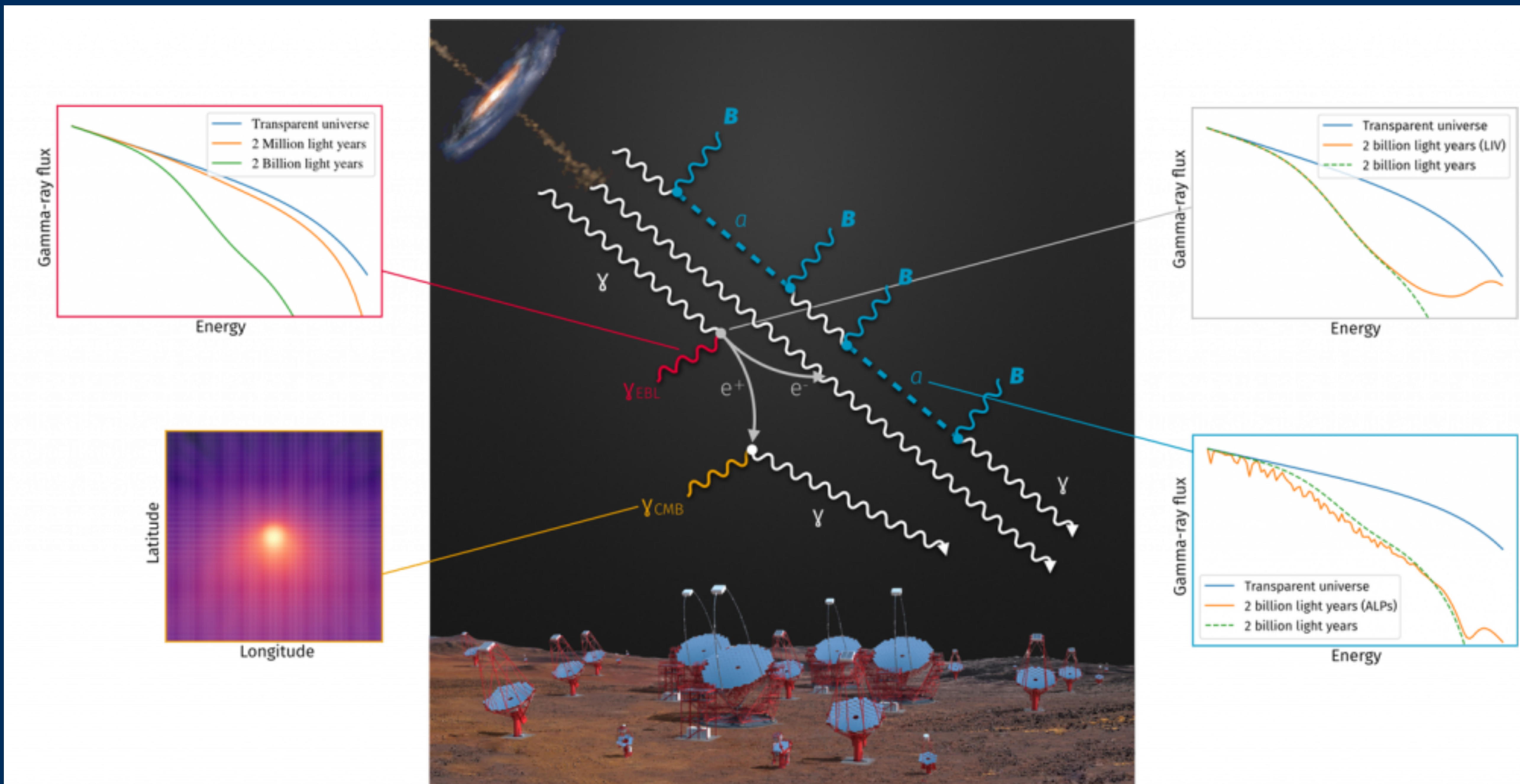


Summary / Outlook

- EBL at z=0 constrained with the IACTs to be on the level of galaxy counts, not much room for extra contributions
- EBL models built using data from measured galaxies are compatible with the EBL resolved with gamma rays
- No clear signs of exotic physics (e.g. signatures of dark stars or axion-like particles). Not excluded either.
- Hubble constant measurements become more robust, currently favouring $H_0 \sim 68$ km s^{-1} Mpc^{-1}
- IGMF signature might be possible to detect
- ***CTA: EBL evolution will be resolved up to z=2 and cosmological constraints will become robust***

backup

Intergalactic Magnetic Field



Relevant Key Science Projects

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- Active Galaxy KSP
  - **Fermi-LAT based non-HBL survey (30 sources)**
  - **Deep observation of radio galaxies (2 sources)**
  - **EBL/IGMF selected survey (50 sources)**
  - **Longterm monitoring of bright blazars (20 brightest)**
  - **Snapshot program to catch flares (100 sources)**
  - **Target of Opportunity program**
- Gamma Ray Bursts
  - **Fast automatic reaction**
  - **Slewing speed <20s to any point in sky with LSTs**
  - **Potential to detect GRBs at z=2 and beyond!**
- Extragalactic Survey
  - **25% of the sky with 6mCrab sensitivity**
  - **~1000h (2-3 years with full array)**
  - **Detect new sources and new source classes**

What do we expect from CTA?

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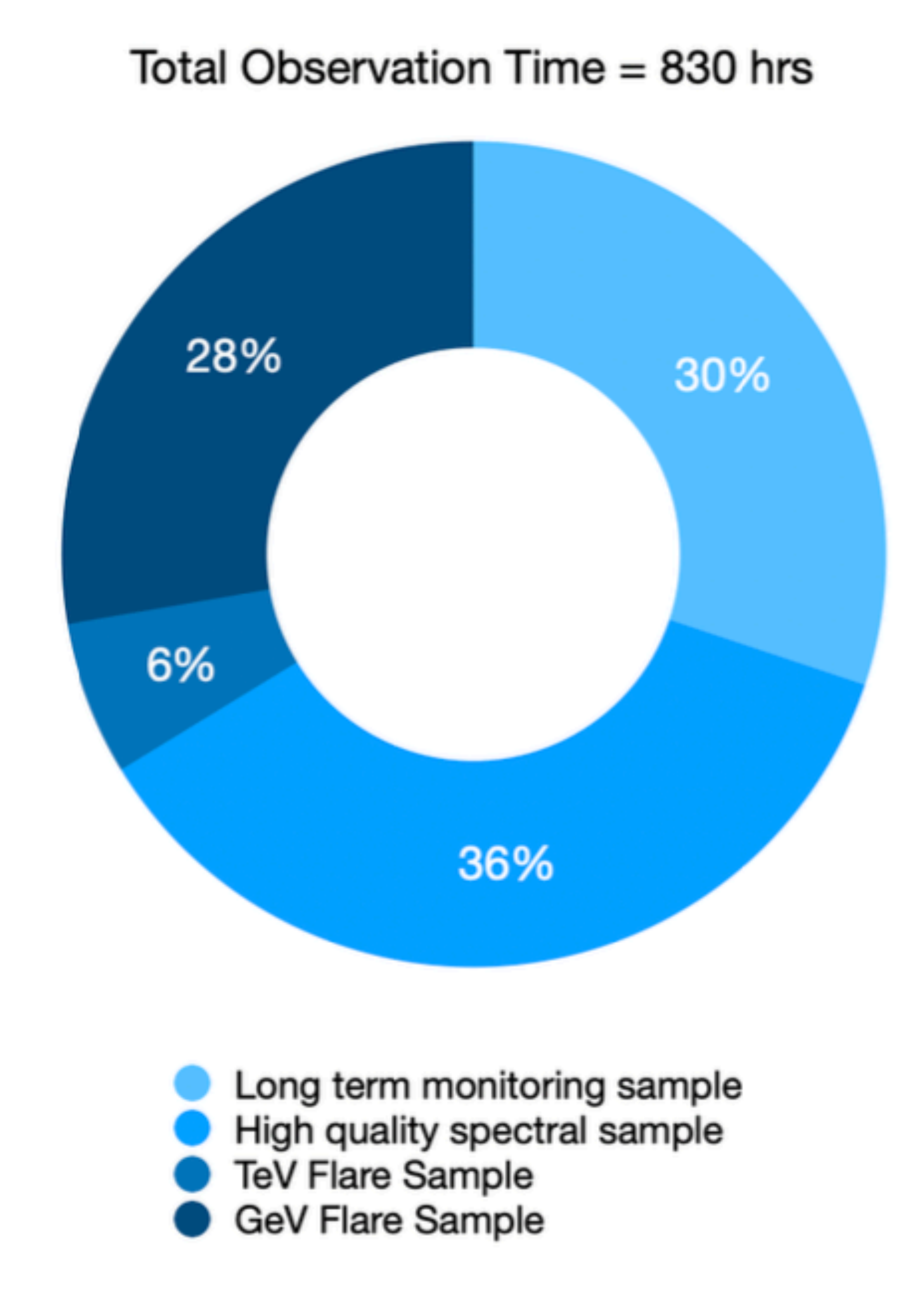
CTA consortium, 2021
arXiv:2010.01349

- We studied EBL resolution with CTA by simulating Fermi-LAT sources with $\tau>1$
- Spectral extrapolation with an intrinsic cut-off depending on redshift (de-redenning) and source type.
- Simulated steady sources + GeV flaring sources + TeV flaring sources
- Used Dominguez+2011 for EBL model test.

Source class	FSRQ	LBL	IBL	HBL	XHBL
E'_{cut} (TeV)	0.1	0.1	0.1	1	10



What do we expect from CTA?

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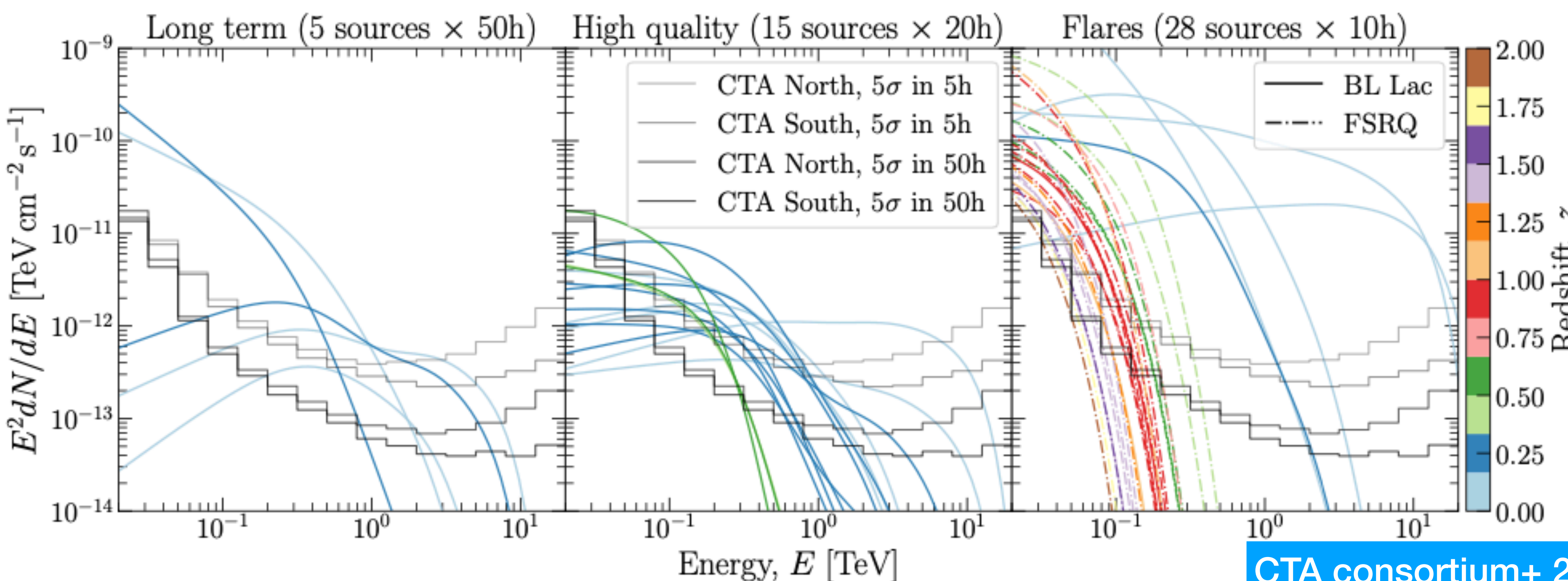
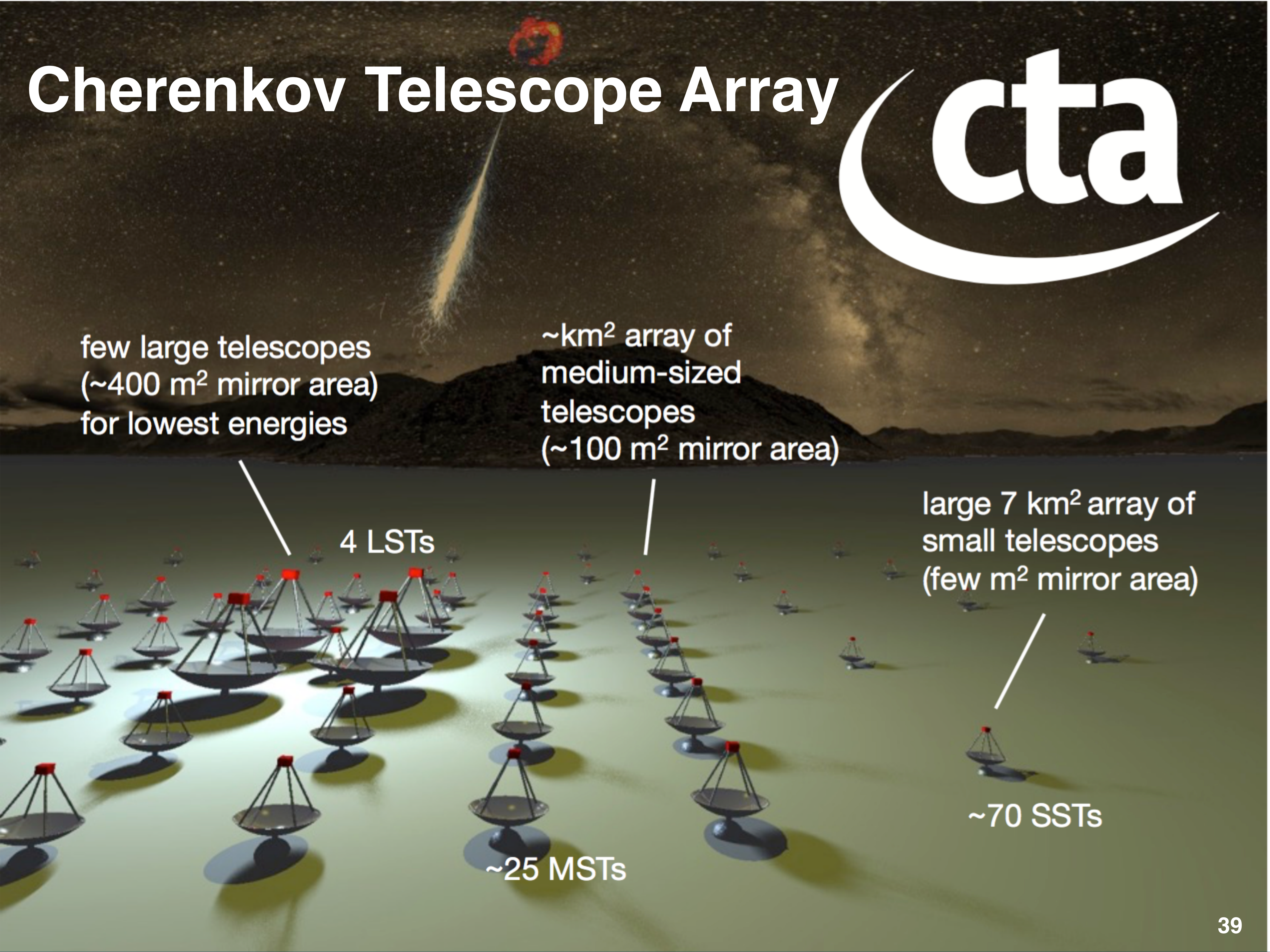


CTA consortium+ 2021
arXiv:2010.01349

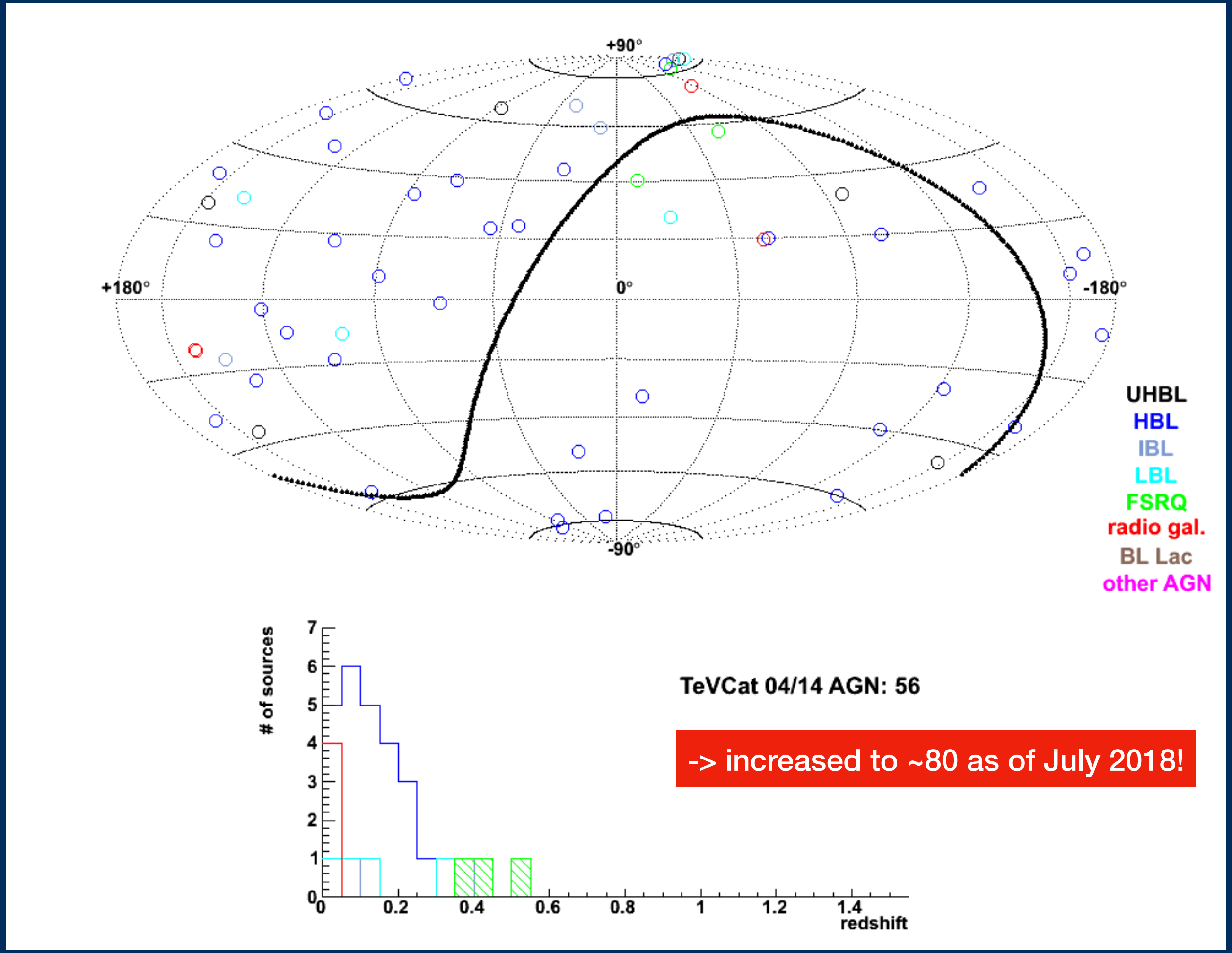
- various CTA Key Science Projects would lead AGN spectra with unprecedented quality and energy range. Also GRBs will contribute!
- within 3-5 years, CTA will be able to characterise EBL up to redshift of z=2

Cherenkov Telescope Array

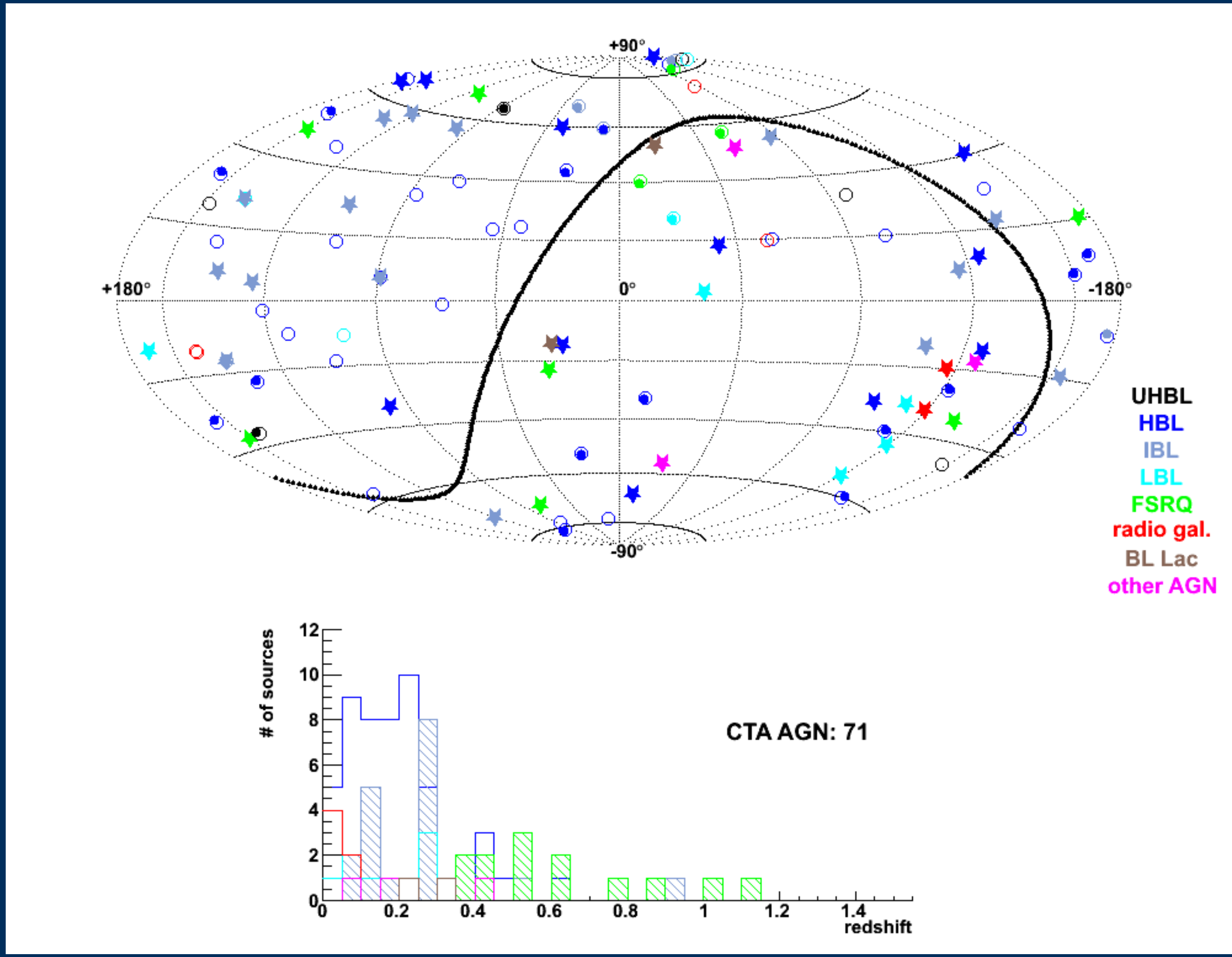


Relevant Key Science Projects

TeV extragalactic Sky
as of Apr 2014



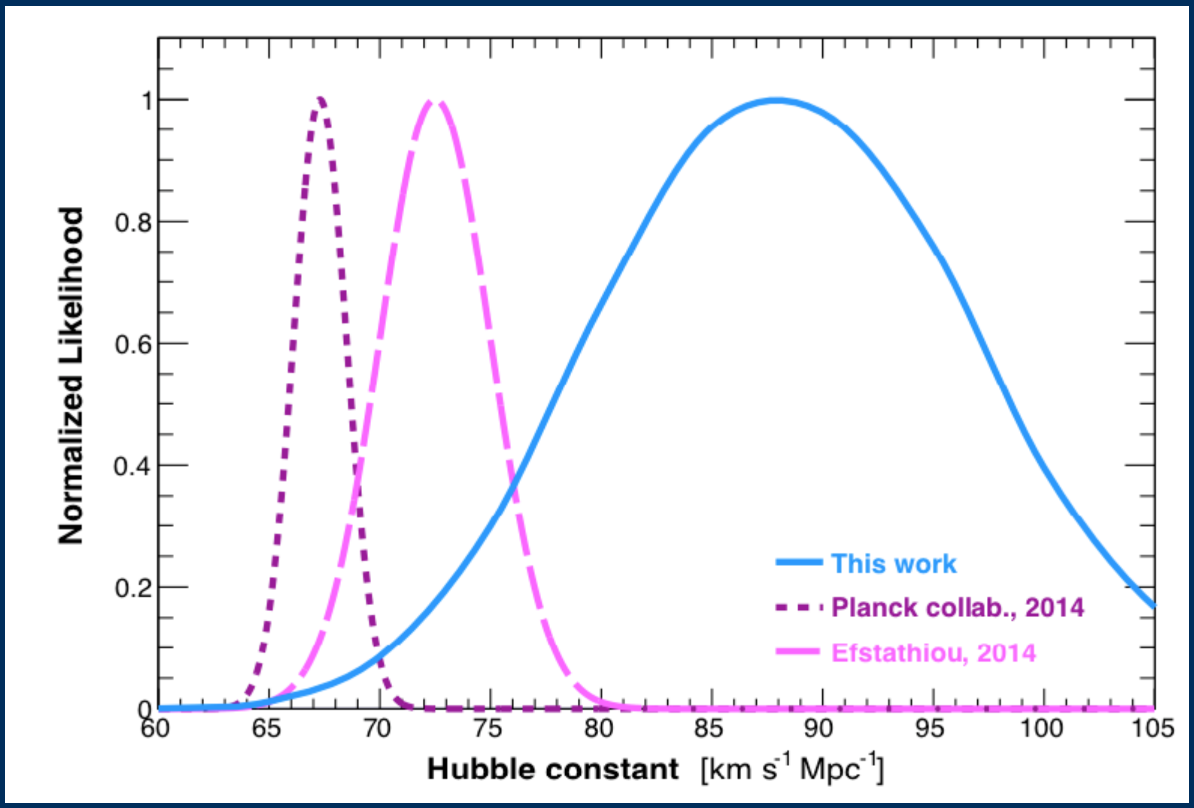
CTA ExGal Sky after 3 years,
no flaring activity included



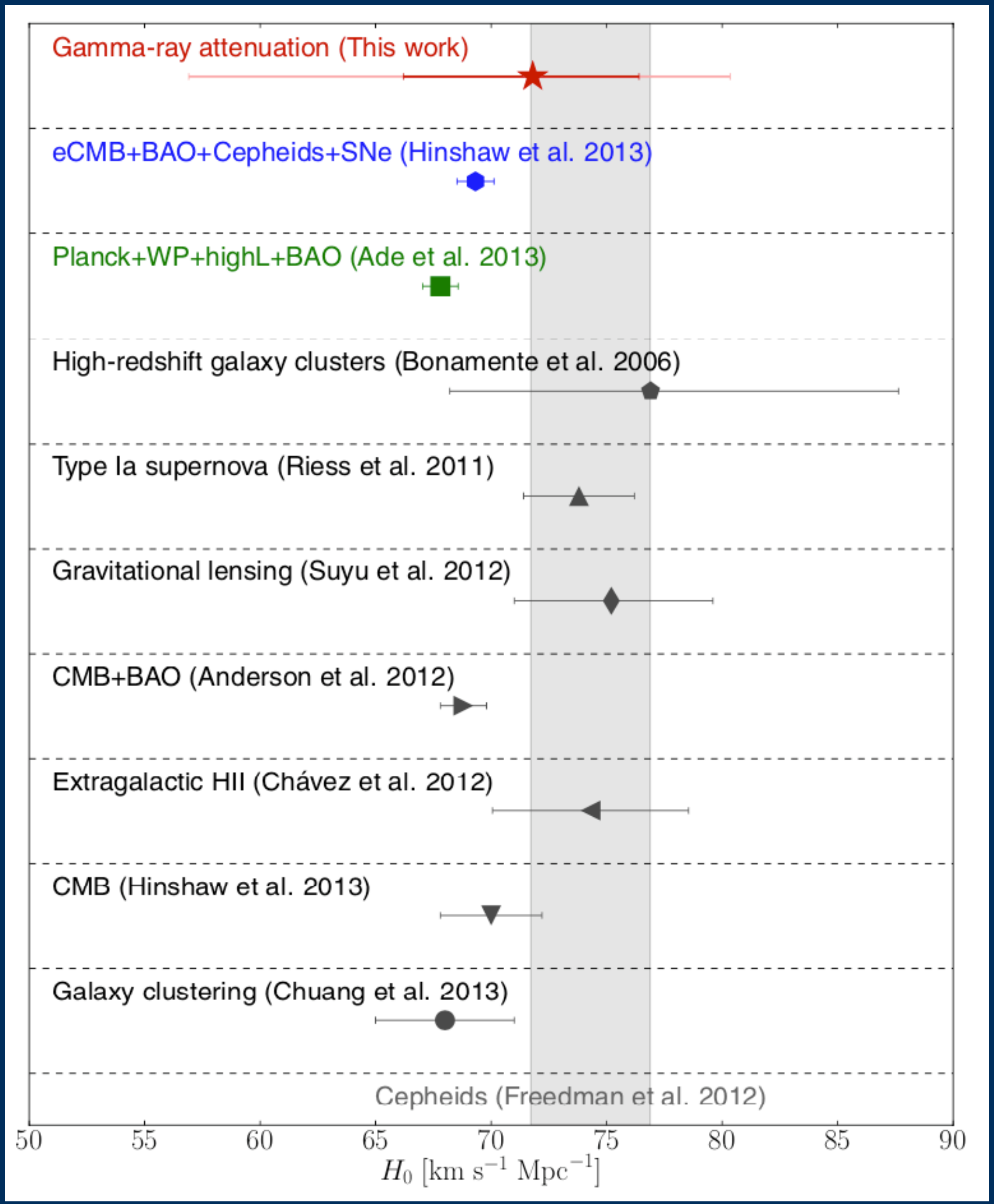
~50 new extragalactic sources in 2-3 years without ToO

Hubble constant

Biteau & Williams 2015



Dominguez & Prada 2013



- The estimations on this slide are using available data, pre CTA era
- With a solid EBL knowledge (<10% uncertainty) will determine Hubble constant with better than 5% uncertainty and reduced systematics