Extra-galactic background light (EBL)

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In cooperation with:
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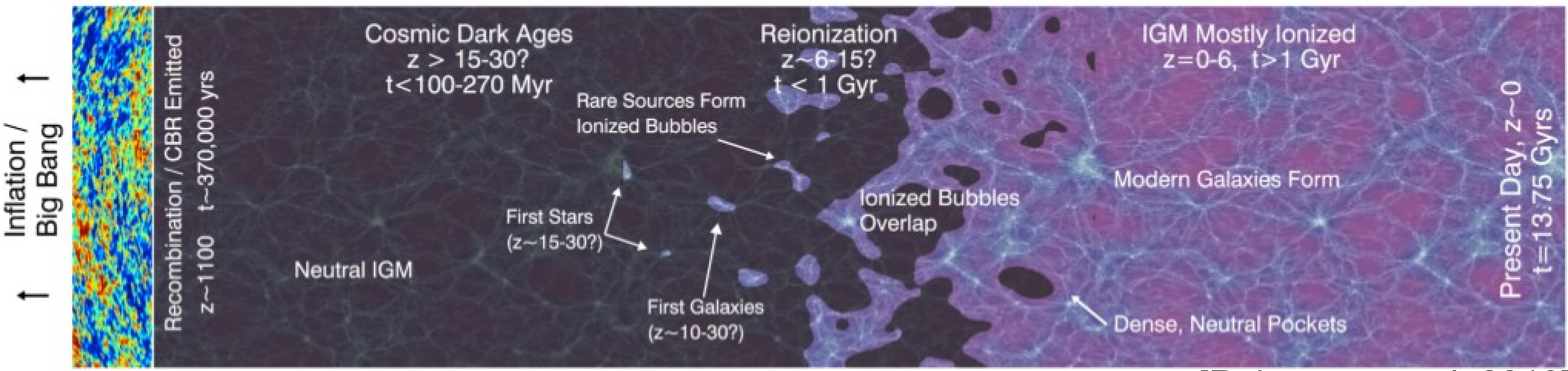
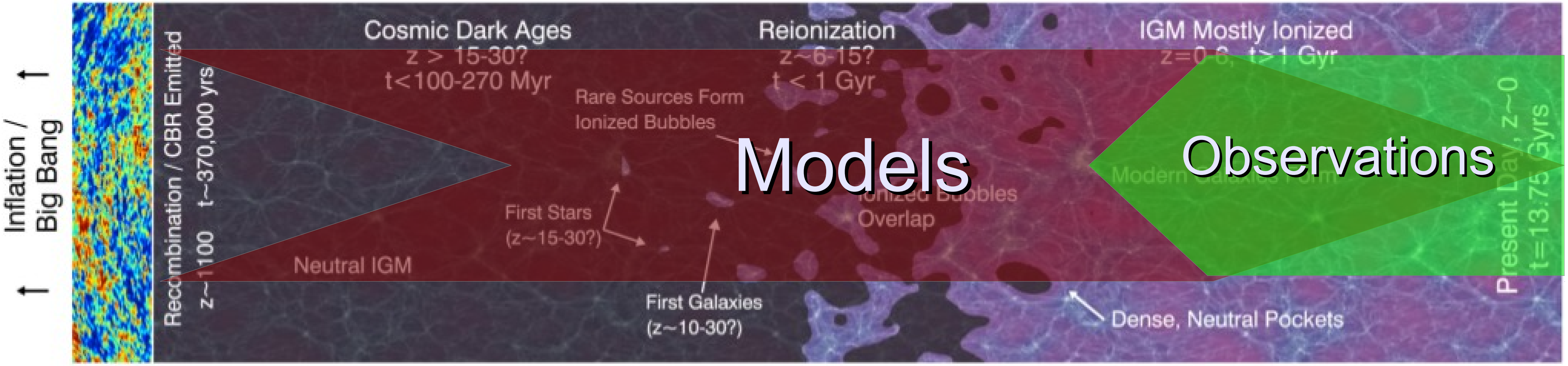


[Robertson et al. 2010]

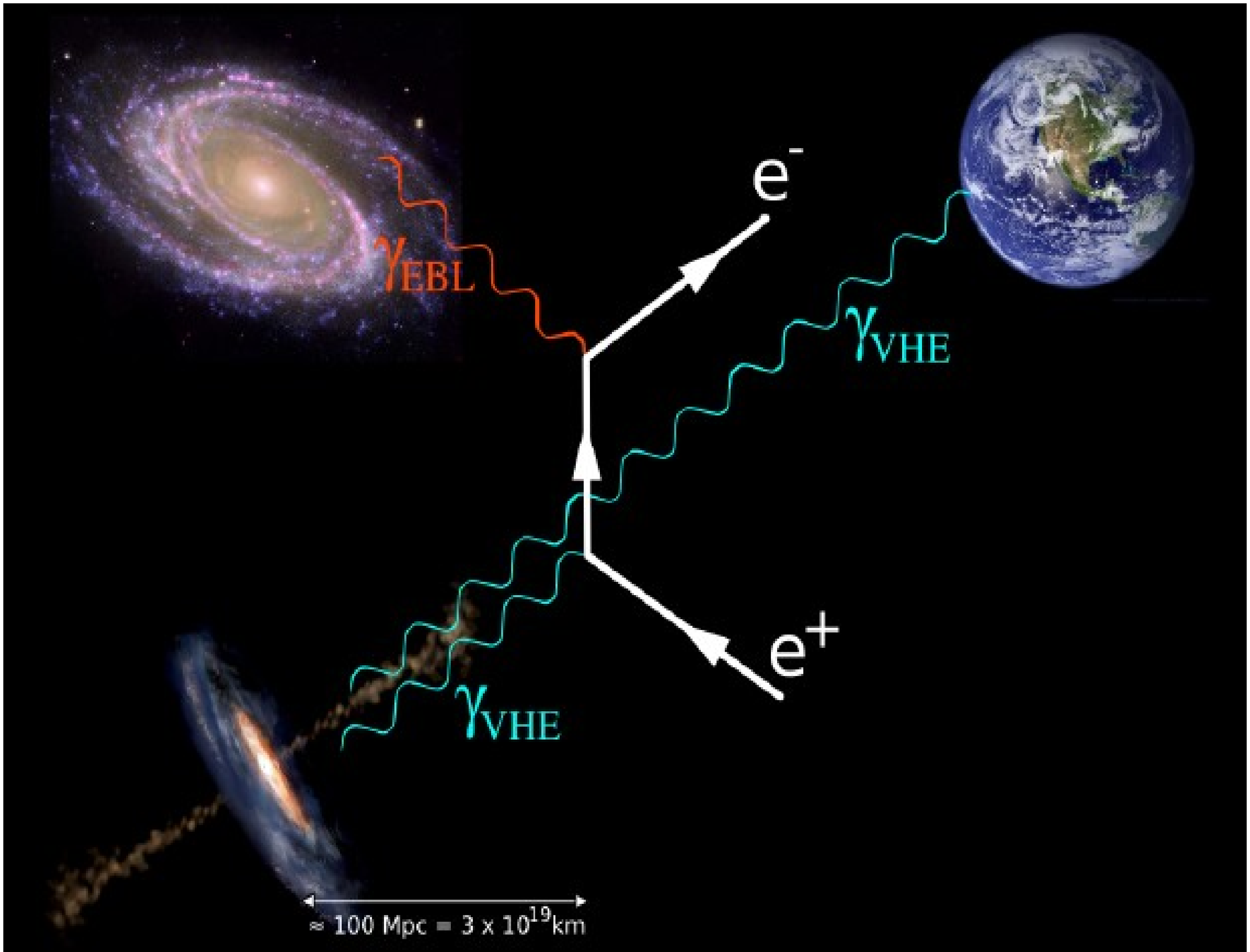
How many stars have been shining in the Universe?
Answer can be given by very-high energy gamma-ray observations!

Outline: EBL



The EBL has not been unambiguously detected, yet!

Outline: VHE (E>100 GeV & EBL)



Ingredients of an EBL model

The simplest type of model (Dwek et al. 1998, Kneiske et al. 2002)

$$P_\nu(z) = \nu I_\nu(z) = \nu \frac{c}{4\pi} \int_z^{z_m} \mathcal{E}_{\nu'}(z') \left| \frac{dt'}{dz'} \right| dz'$$

EBL

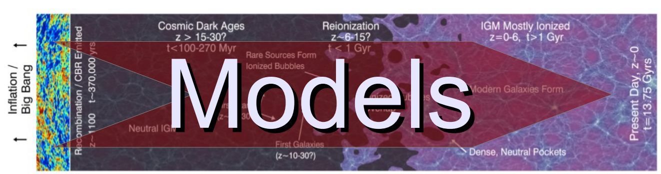
$$\mathcal{E}_\nu(z) = \int_z^{z_m} L_\nu(t(z) - t(z')) \dot{\rho}_*(z') \left| \frac{dt'}{dz'} \right| dz'$$

Emissivity

Stellar population spectra (SPS)

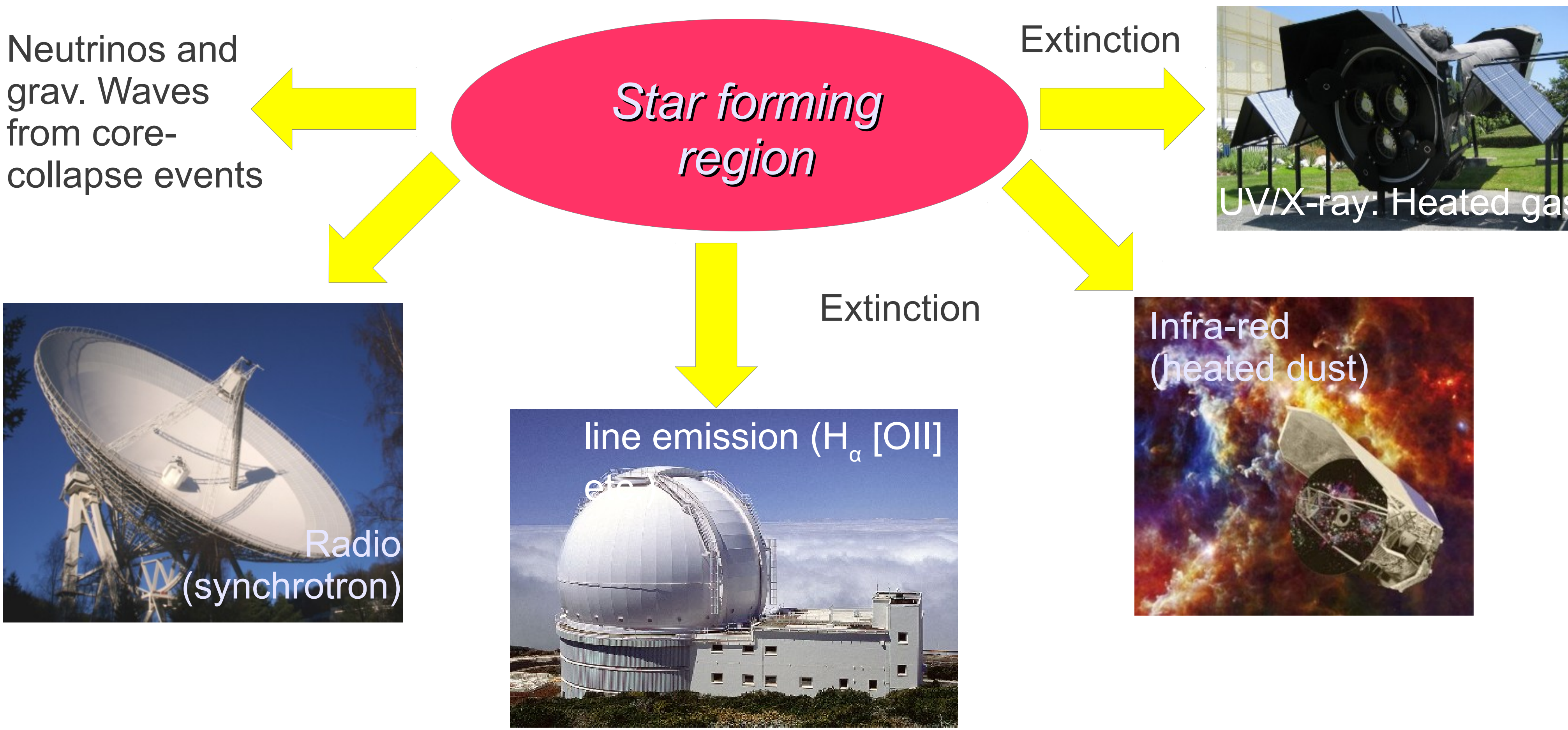
Star formation rate density (SFRD)

[Raue 2012]



Star formation rate history

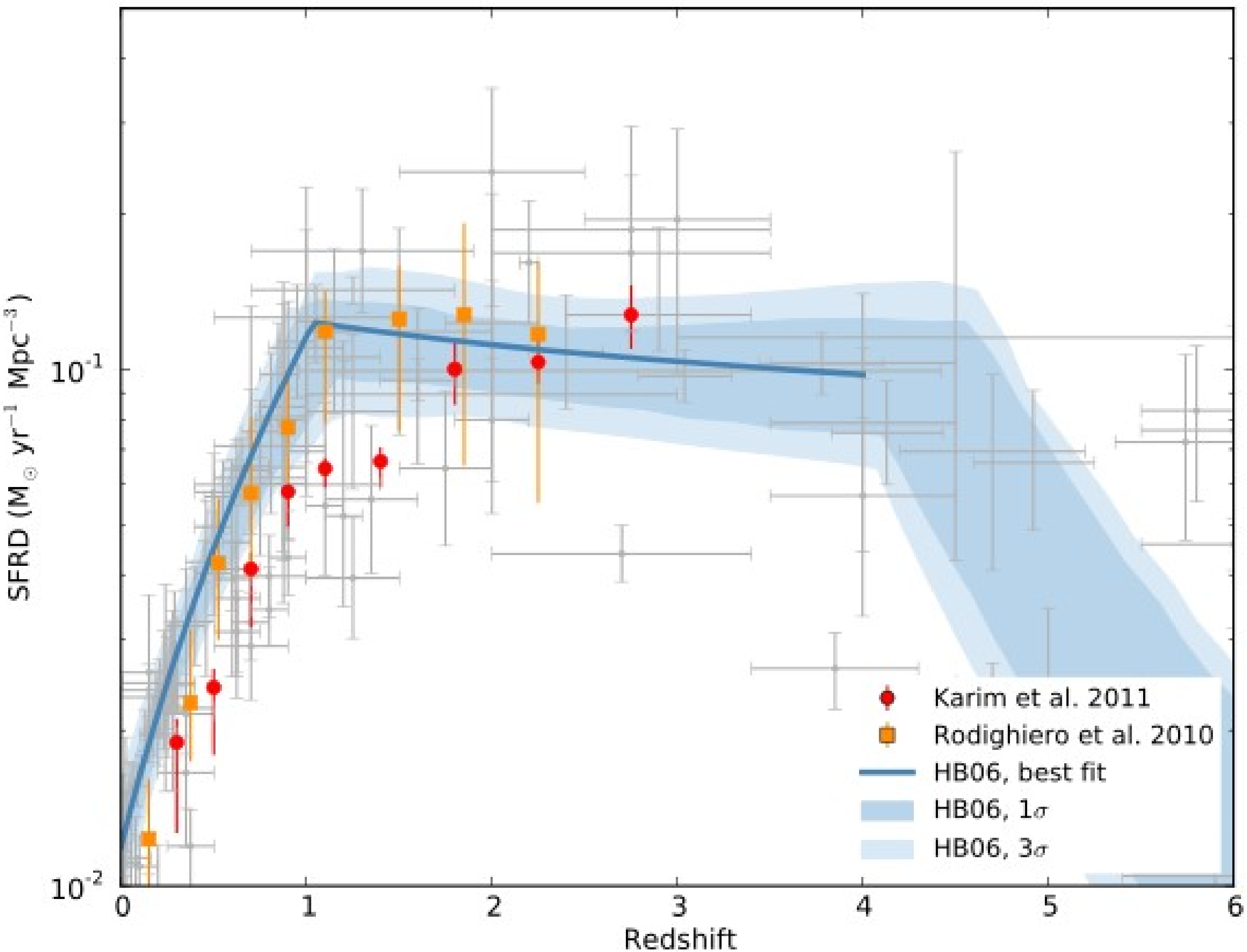
- Tracers of star formation → related to supernova-activity!



Star formation rate history

- Tr
  su

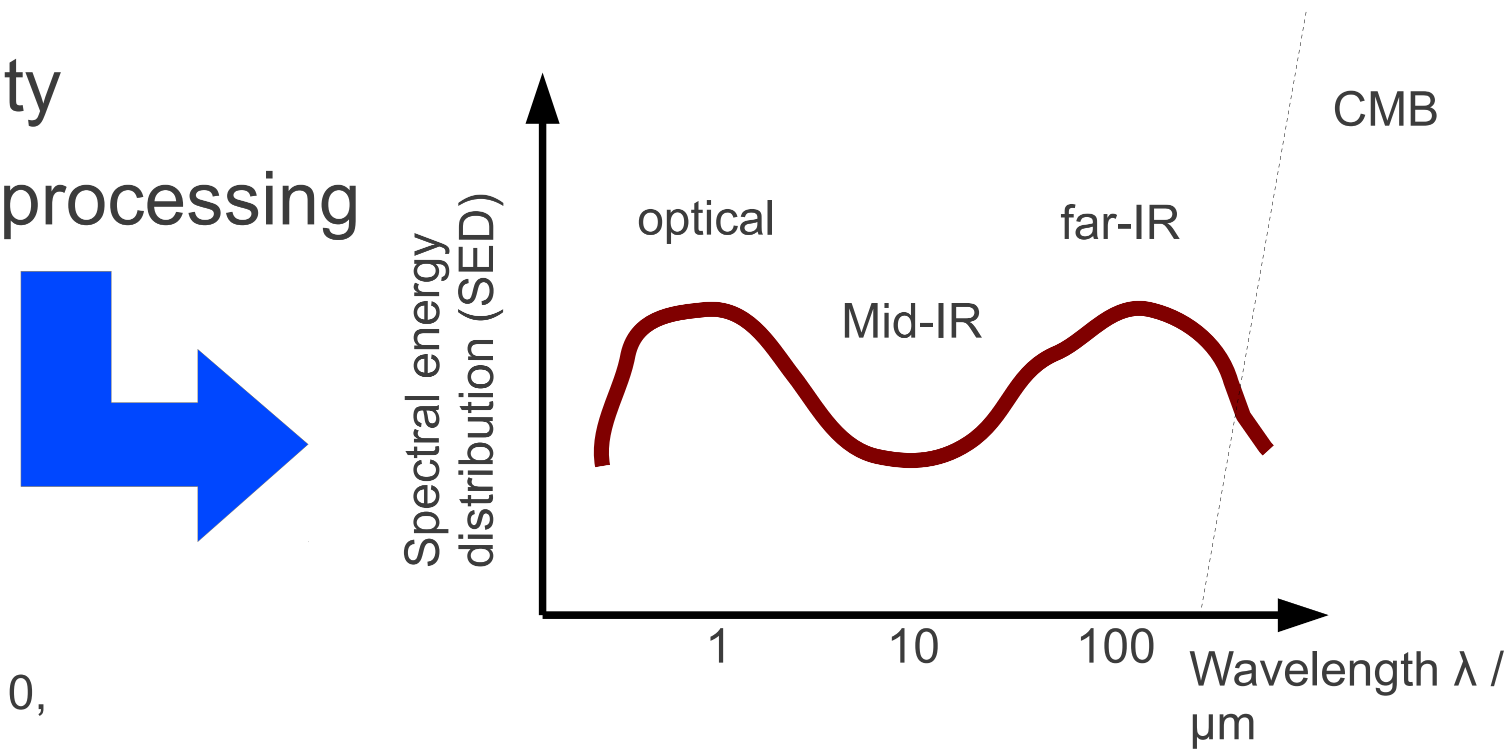
Neutrinos
grav. Wa
from core
collapse



[Hopkins & Beacom 2006]

Stellar population Spectra

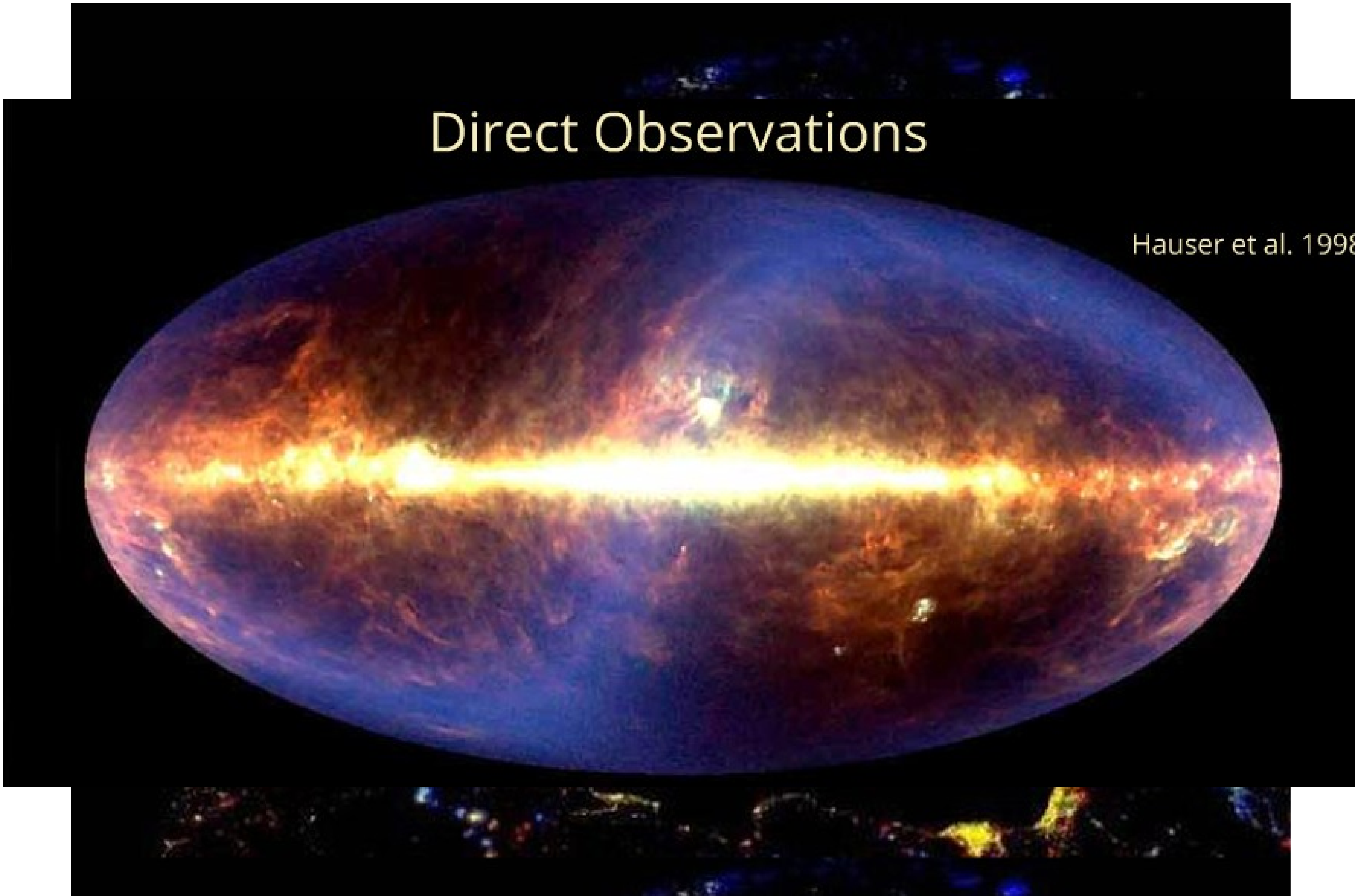
- Stellar models: Bruzual&Charlot (2003), Starburst99 (Leitherer et al. 1999, 2010)
- Parameters:
  - Initial mass function
  - Metallicity
  - Dust re-processing



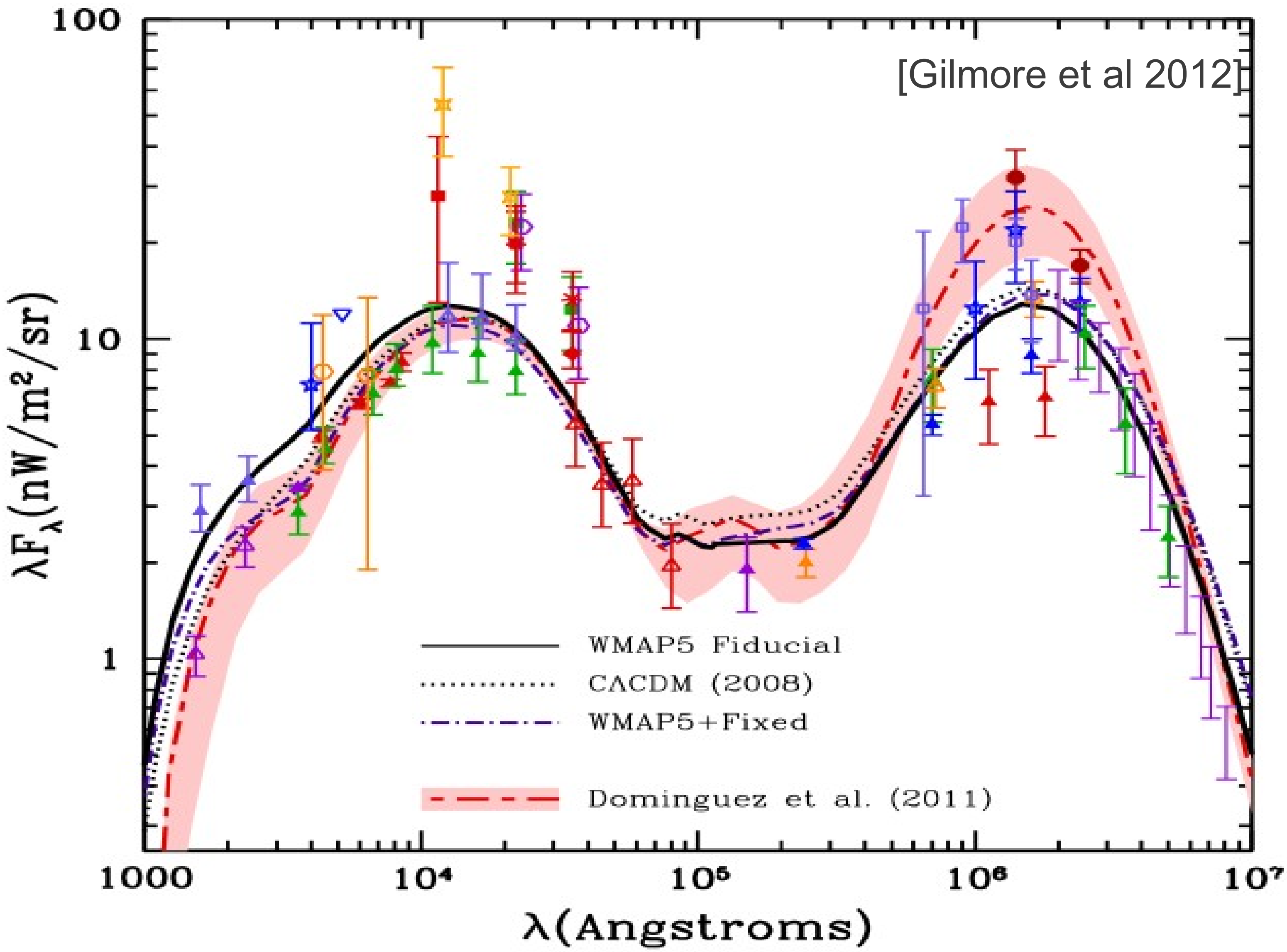
More models:
Franceschini et al. 2010,
Dominguez et al. 2011

Contact with observations

Contact with observations

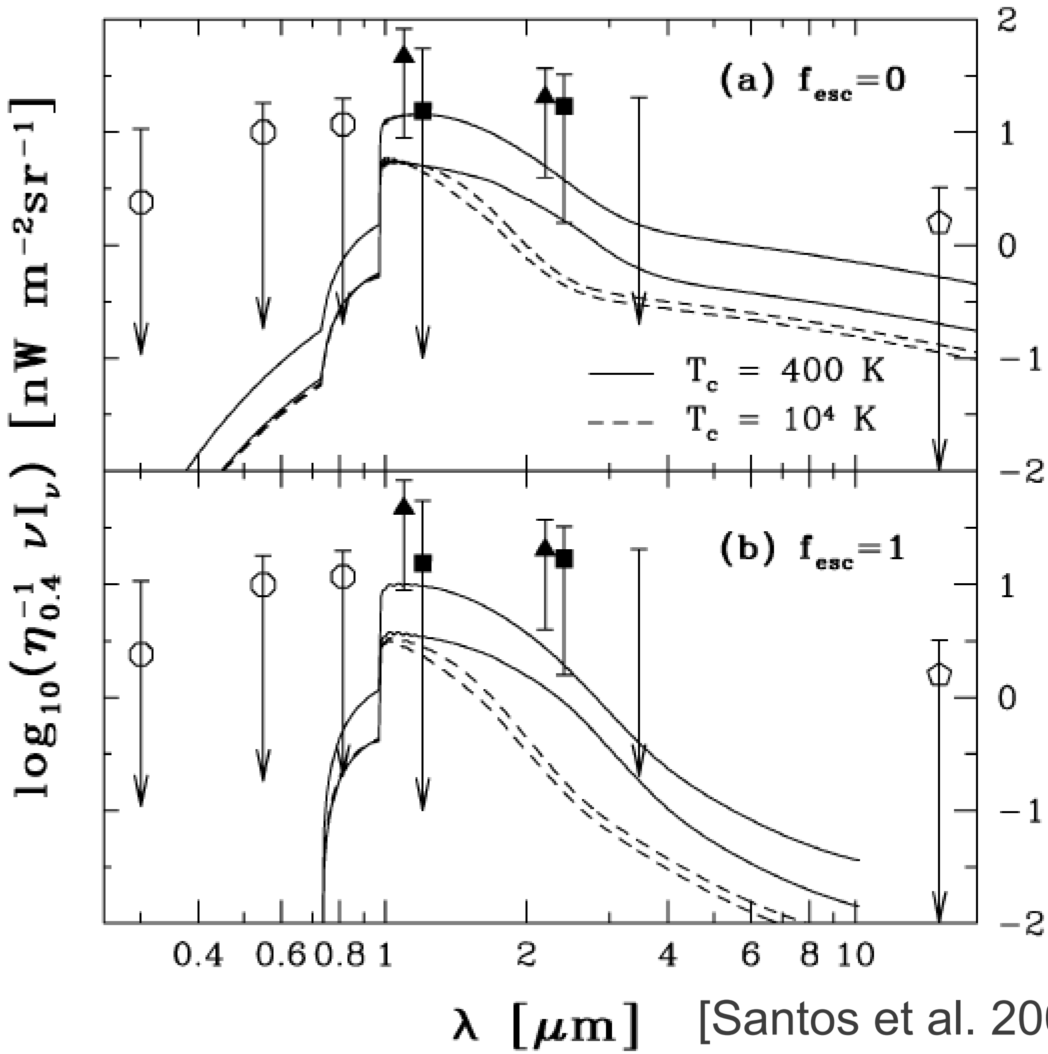


Contact with observations



Comment: Additional sources of photons

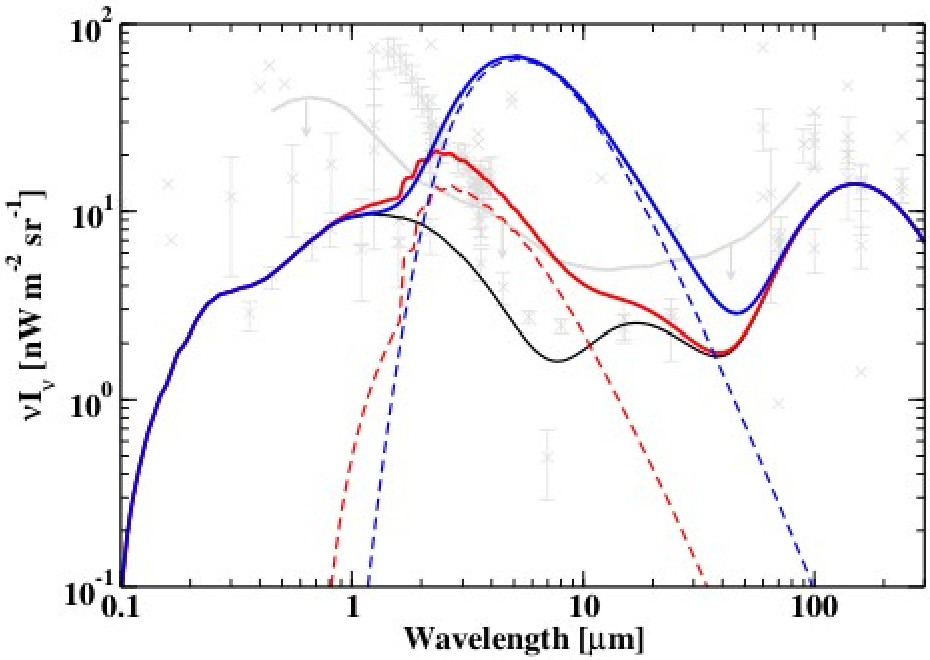
- Population III stars [Santos et al. 2002,Fernandez&Komatsu 2006, Raue et al. 2006, Gilmore 2012]



[Santos et al. 2002]

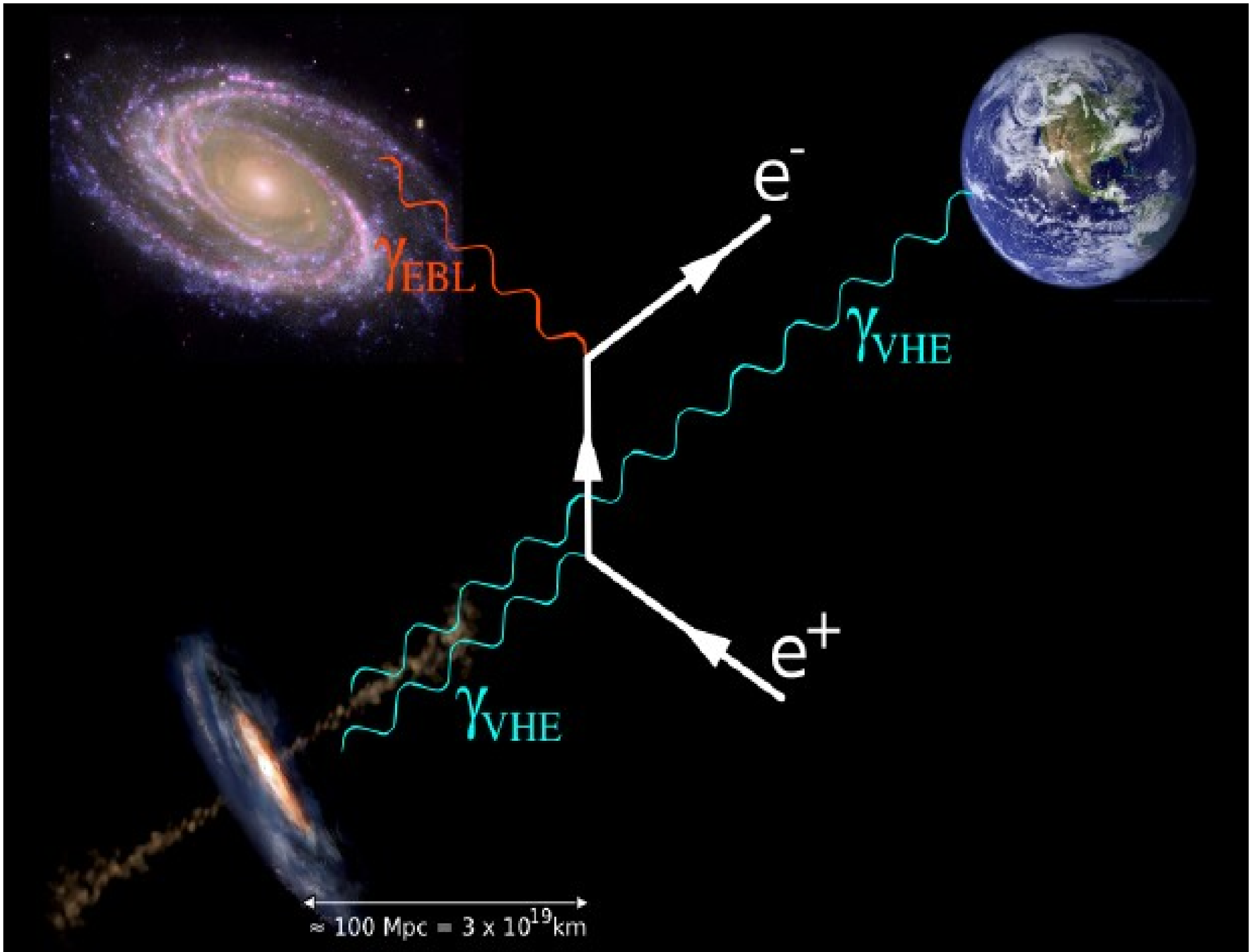
Additional sources of photons

- Dark matter powered stars (Pre-Pop III) [Spolyar et al. 2008] could contribute to the EBL [Maurer et al. 2012]



$$(\nu I_\nu)_{\max} = 2 \times 10^{-5}\ \mathrm{nW\ m^{-2}\ sr^{-1}} \times \left(\frac{\Delta t_{\mathrm{DS}}}{10^7\ \mathrm{years}}\right) \times \left(\frac{\mathrm{SFR_{Norm}}}{10^{-5}}\right) \times \left(\frac{\mathrm{LMR}}{10^3\ \mathrm{L_\odot/M_\odot}}\right) \times \left(\frac{z_{\min}}{10}\right)^{-2.5}$$

EBL and very-high energy gamma-ray propagation



[Nikishov 1962, Jelley 1966,Gould&Schréder 1966]

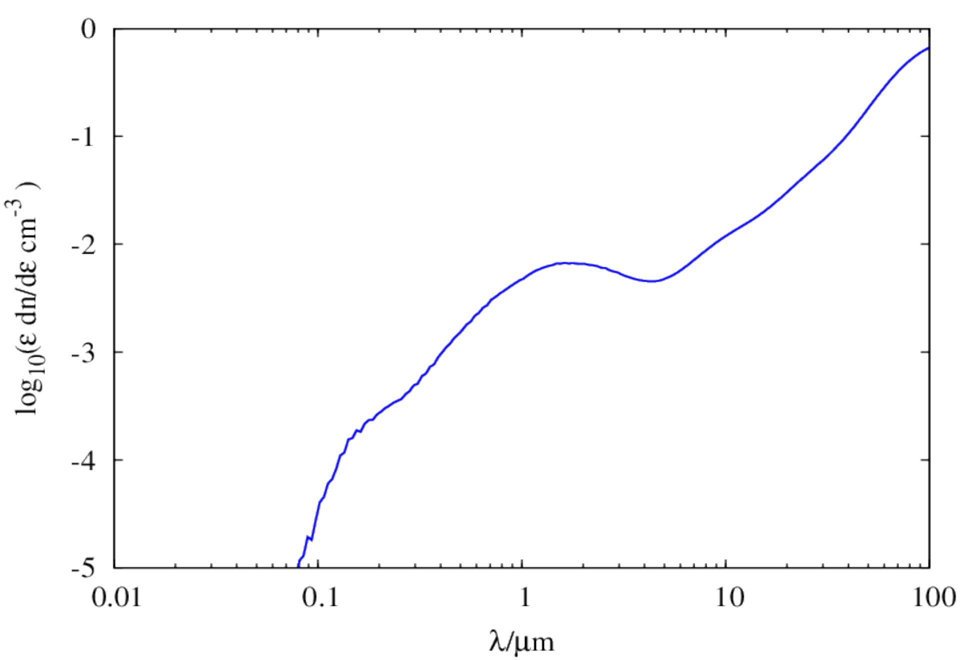
Pair-production → absorption+ reprocessing of gamma-rays

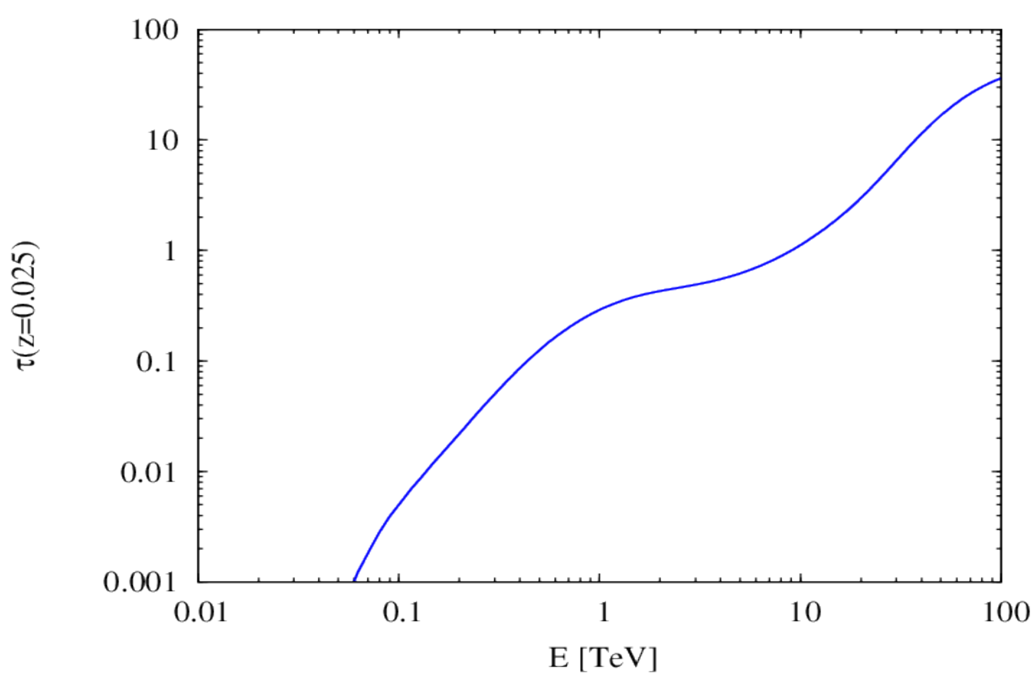
Photon density of EBL
En(0.8eV,z=0)~10^{-2} cm^{-3}

$$\tau_\gamma(E,z_0)=\int_0^{z_0} d\ell(z)\int_{-1}^{+1} d\mu\frac{1-\mu}{2}\int_{\epsilon_{\rm thr}}^{\infty} d\epsilon' n_{\rm EBL}(\epsilon',z)\sigma_{\gamma\gamma}(E,\epsilon',\mu)$$

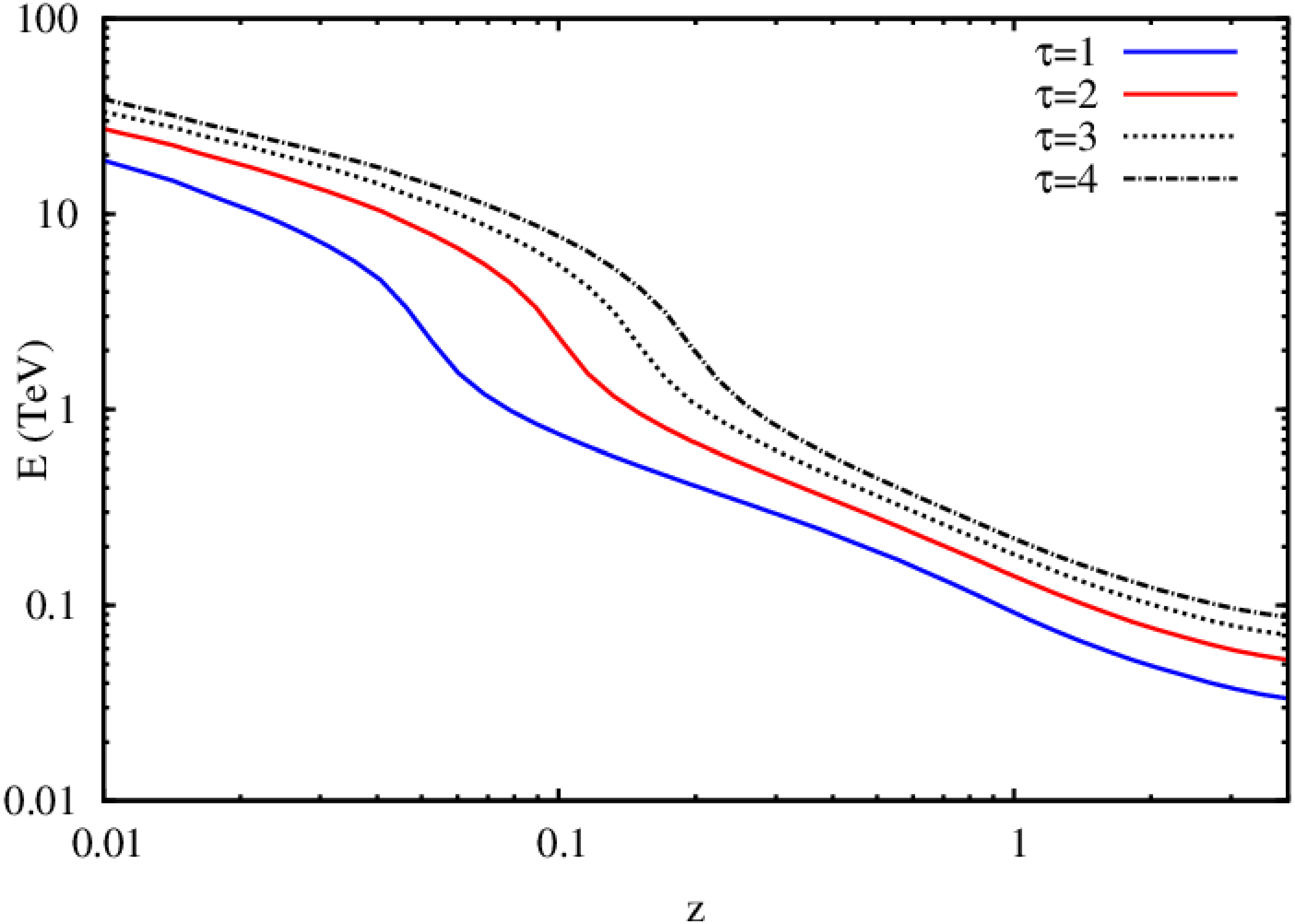
$$\frac{dN_{\rm obs}}{dE}=\frac{dN_{\rm int}}{dE}\times\exp\left[-\tau_\gamma(E,z_0)\right]$$

Pair production cross
Section peaks at
λ=1.2 μm (E/TeV)
~σ_T~6×10^{-25} cm^2





Pair-production → absorption+ reprocessing of gamma-rays



Pair-production → absorption+ reprocessing of gamma-rays

Pair production ↔ Inverse Compton scattering

↓

Down-conversion of gamma-rays → optically thin regime

↓ B-field

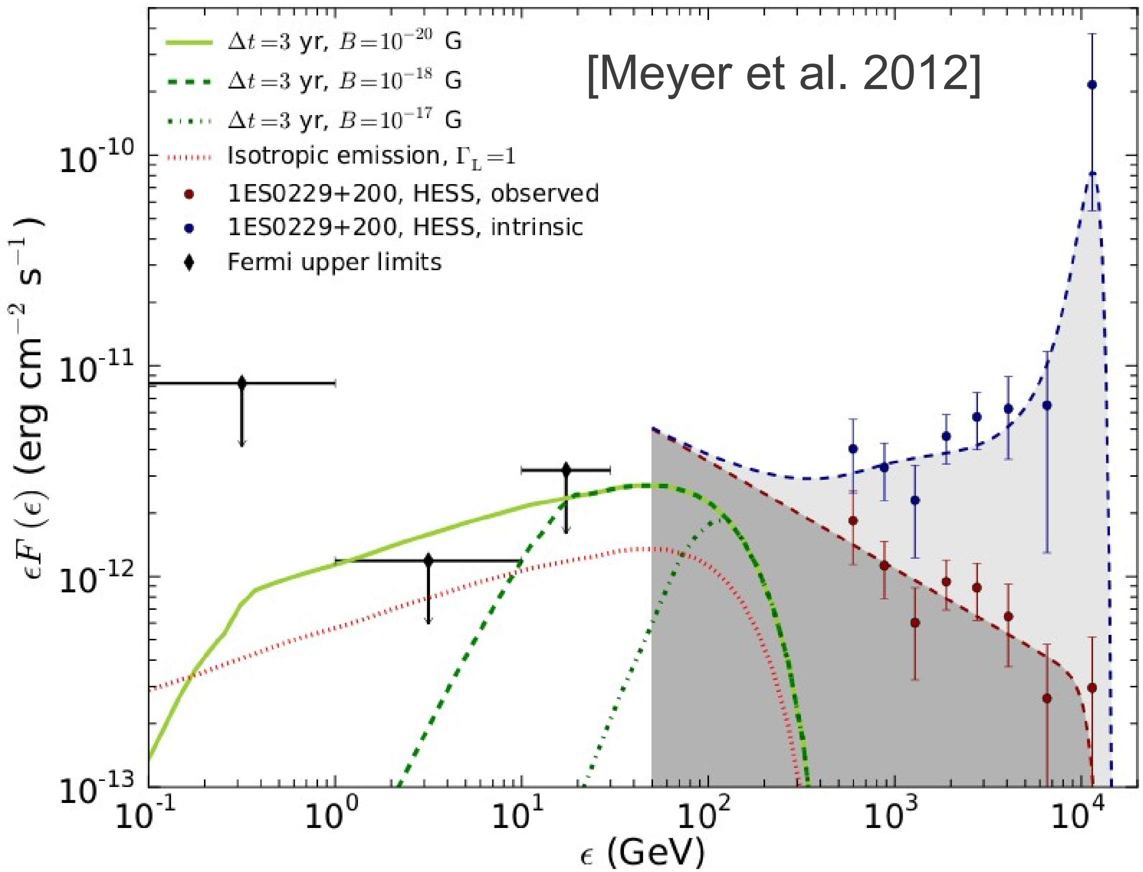
Scatters electrons out of line of sight

Pair-production → absorption+ reprocessing of gamma-rays

Pair production ↔ Inverse Compton scattering

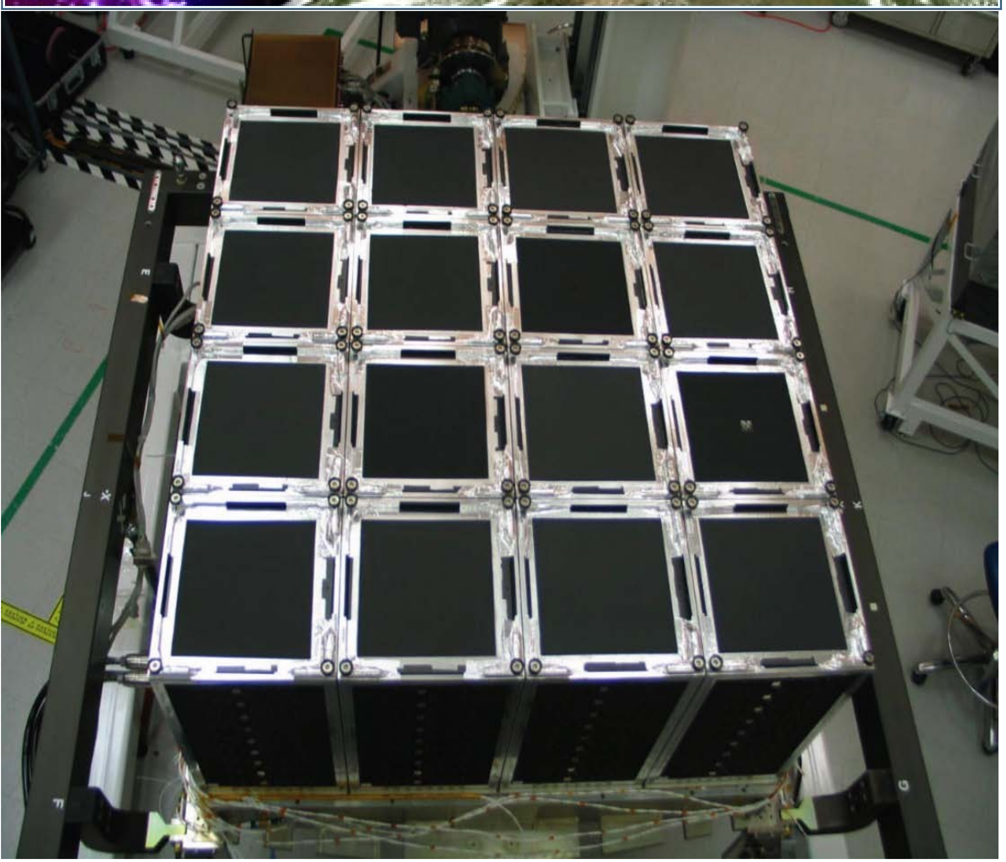
[Neronov &Vovk 2010, Dermer et al. 2011].

Down-conversion of gamma-rays → optically thin regime

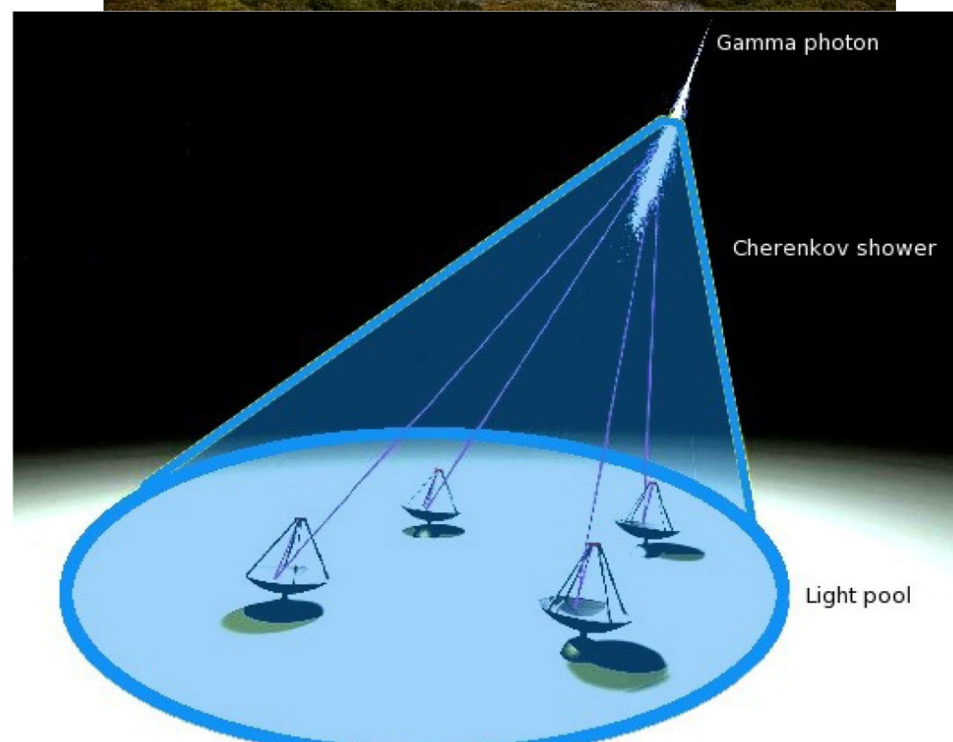


Gamma-ray telescopes

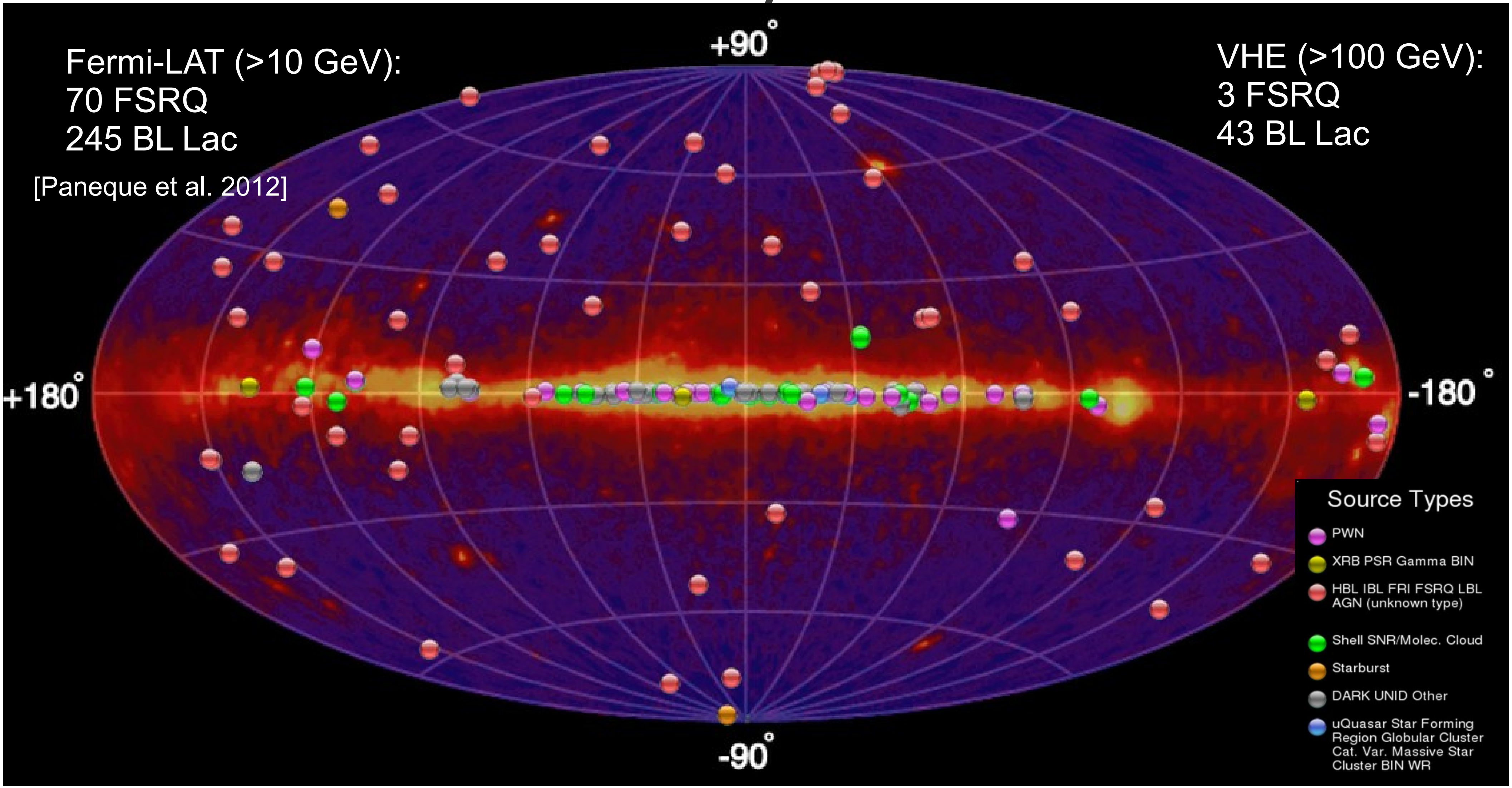
100 MeV – 500 GeV, all-sky pair-production telescope (AΩ~4 m² srad)



50 GeV-50 TeV, air shower detector (AΩ~10^3 m² srad)



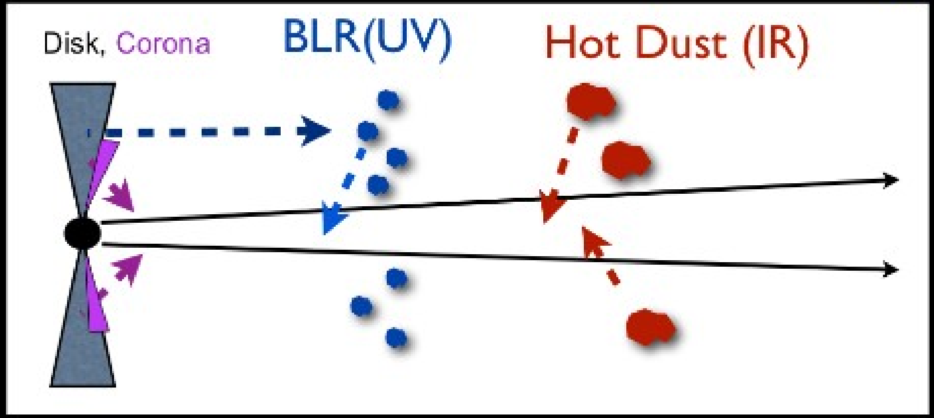
Extra-galactic sources of HE (E>10 GeV) and VHE (>100 GeV) gamma-rays



TeVCat.uchicago.edu

Gamma-rays from Active Galactic Nuclei

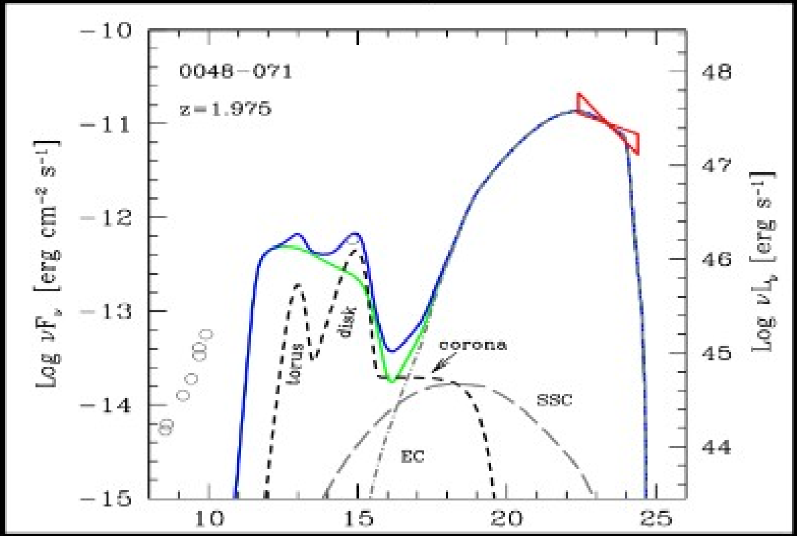
Emission mechanisms: Inverse compton (SSC, EC) and proton synchrotron



Blazars={Flat-Spectrum Radio-Quasars, BL Lac type objects}

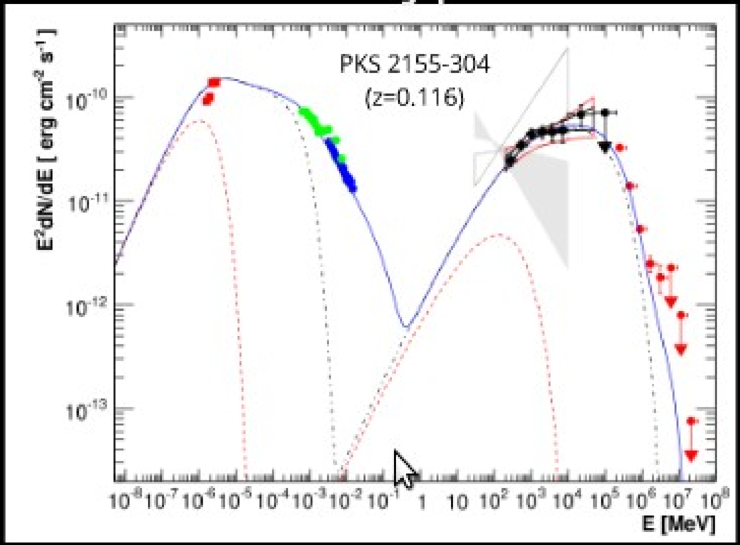
At GeV-energies: FSRQ dominate
At TeV-energies: BL Lacs dominate

FSRQ



Ghisellini et al. 2009

BL Lac type

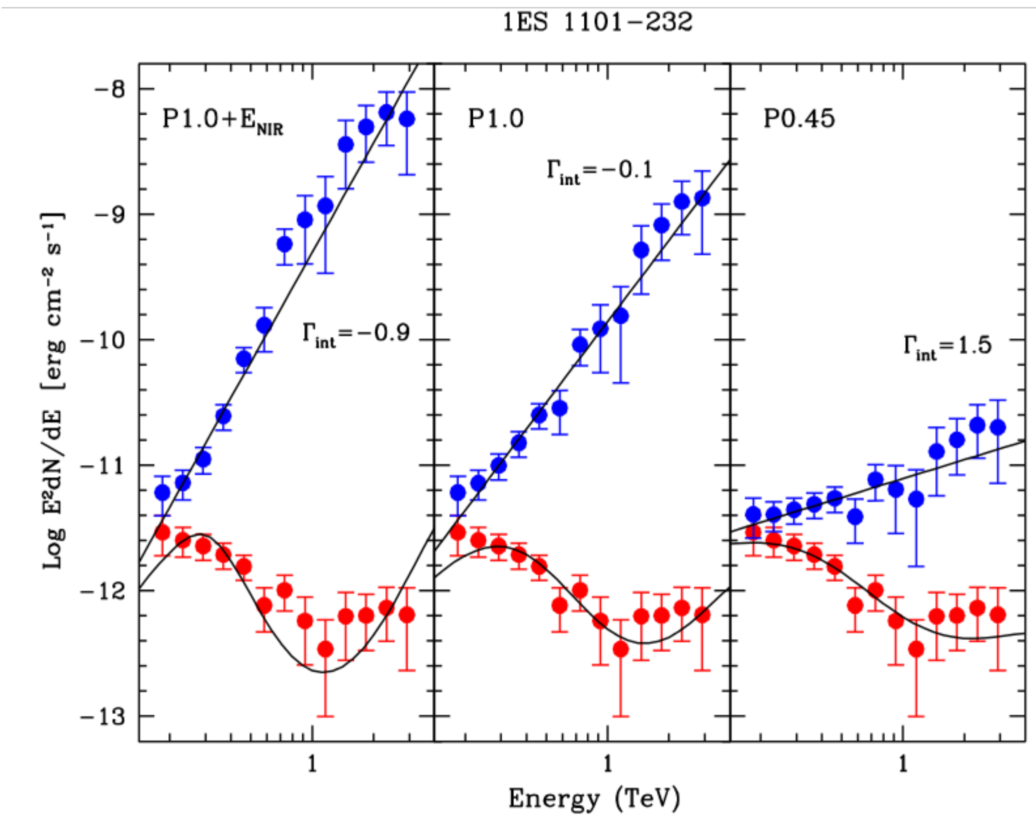


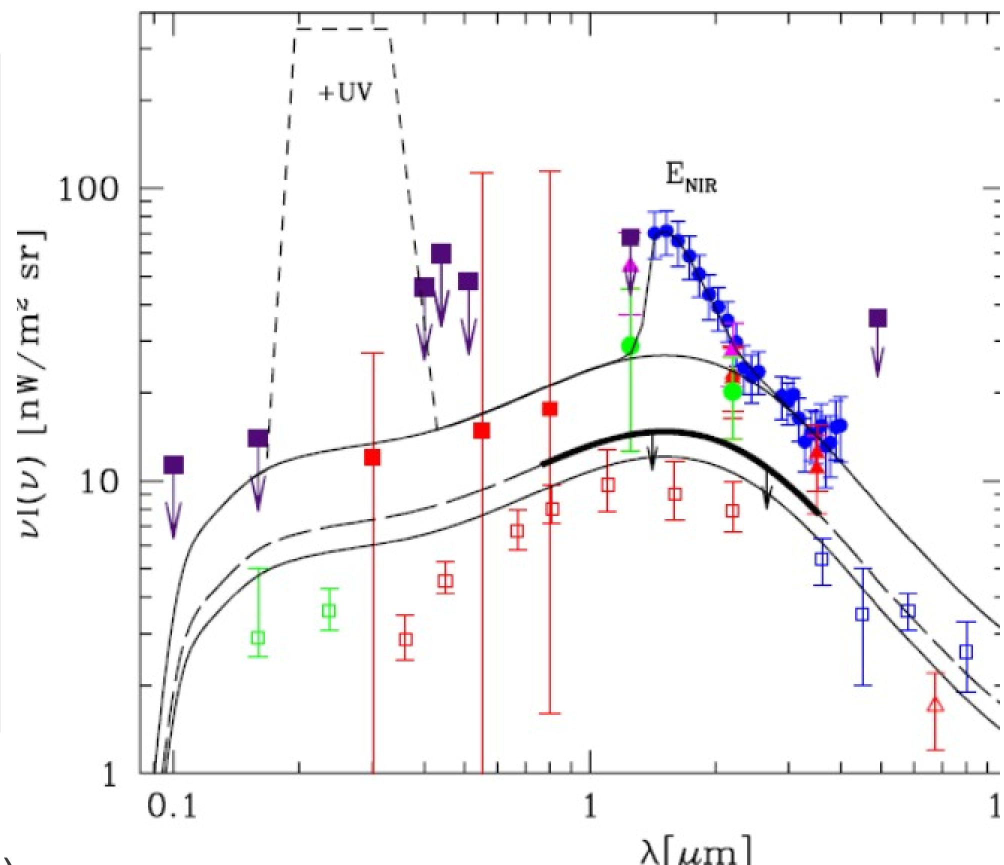
H.E.S.S. Coll [0903.2924]

More about Blazar sequence [Meyer 2011, Finke 2012]

VHE blazars and the EBL

- Limits for a fixed EBL-shape:



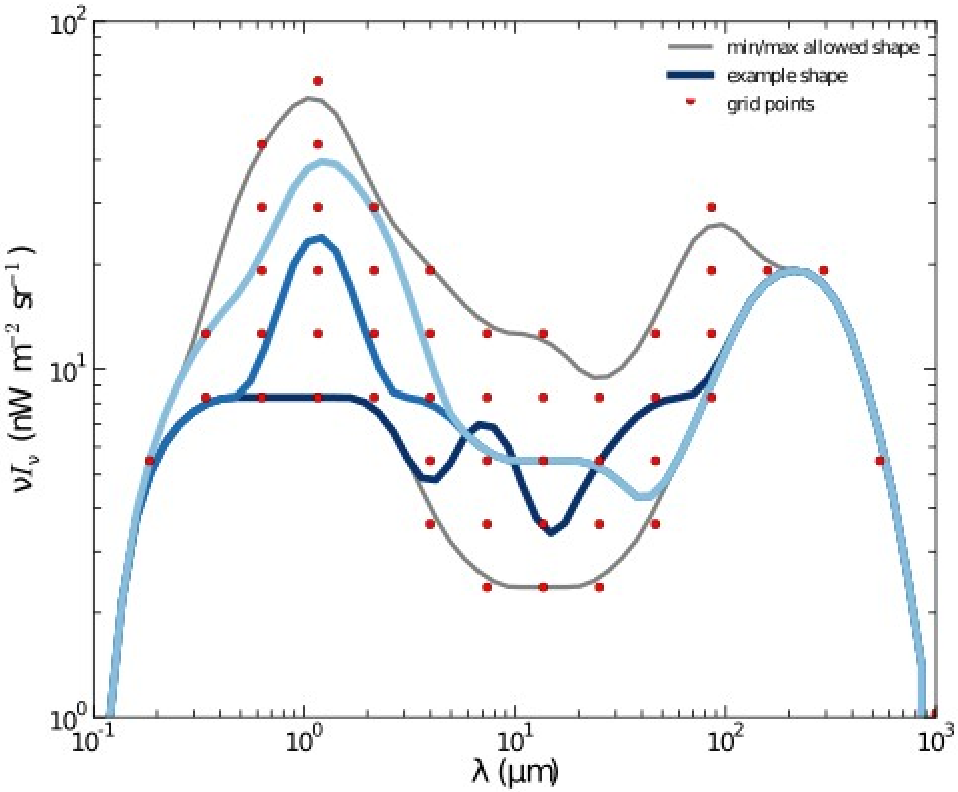


HESS collaboration, Nature (2006)

VHE blazars and the EBL

- Limits for a „free“ shape of the EBL-SED

[Meyer et al. 2012]



EBL at z=0

- Evolution in z (up to z=0.7) with n_{EBL}~$(1+z)^{3-f}$, f=1.2
- Compute optical depth for 1 920 000 shapes of the EBL (splines)
- Collect measured VHE spectra of all available objects
- Combine spectra with Fermi-LAT measurements when available
- Apply correction
- Fit intrinsic spectrum to a series of model spectra until an acceptable fit is achieved

Assumptions on the intrinsic spectrum of VHE Blazars

- If any assumption is not fulfilled, the EBL-shape is discarded:
  - Concavity of the intrinsic spectrum
    - Fermi-LAT spectrum+extrapolation (*VHE-HEIndex*)

      $$\Gamma + \sigma_{\mathrm{stat}} + \sigma_{\mathrm{sys}} < \Gamma_{\mathrm{HE}} - \sigma_{\mathrm{HE,\,stat}}$$

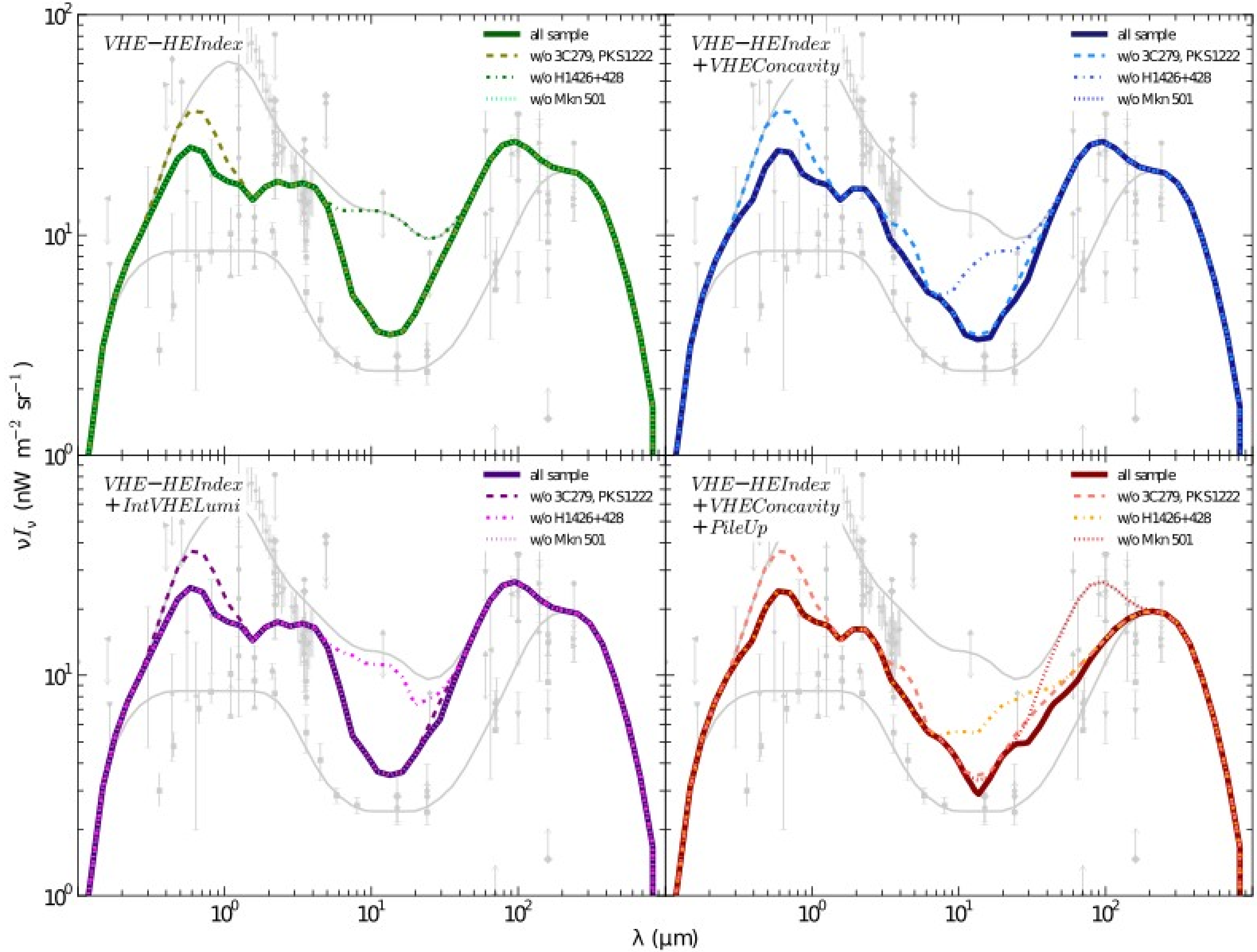
    - No super-exponential pile-up at VHE (Pileup)
    - (Double)Broken power-law not convex (*VHEConcavity)*:

      $$\Gamma_1 - \sigma_1 \leqslant \Gamma_2 + \sigma_2$$
      $$\textit{and} \quad \Gamma_2 - \sigma_2 \leqslant \Gamma_3 + \sigma_3 \text{ (DBPL)}$$

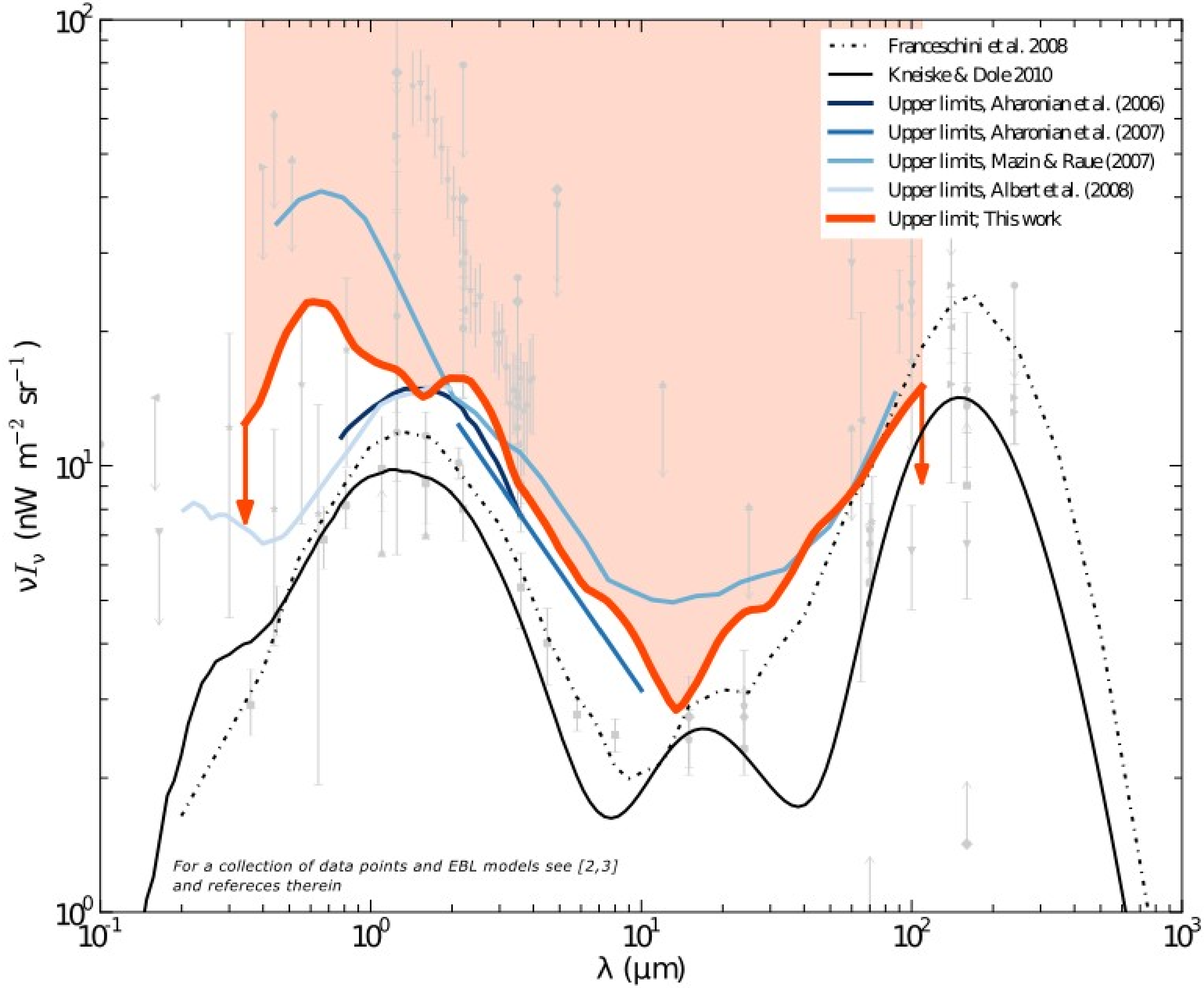
    - Reprocessed cascade emission does not exceed Fermi-LAT measurement (IntVHELumi)

      $$F_{\mathrm{cascade}}(E_{\mathrm{meas}}) > F_{\mathrm{meas}}^{\mathrm{Fermi}} + 2\sigma$$

Results: upper limit=envelope of allowed EBL-shapes

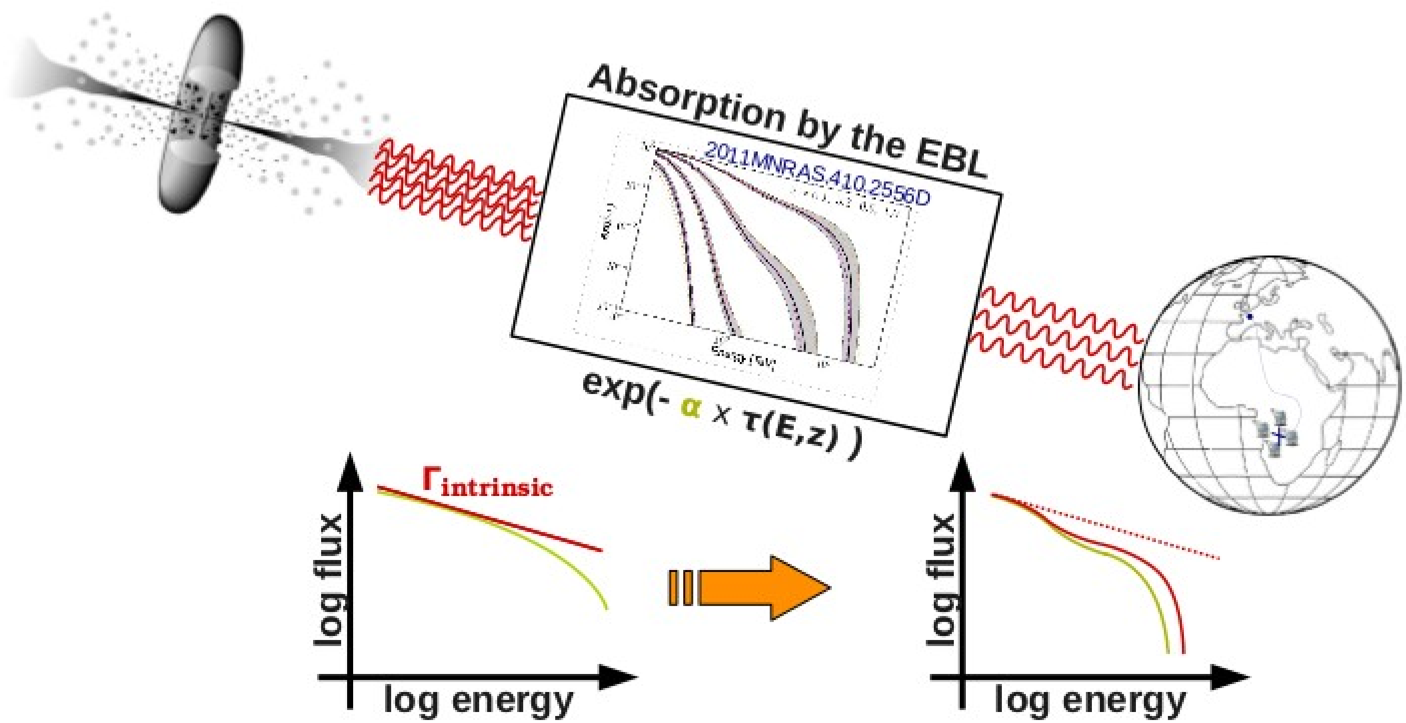


Comparison with other limits



So far: Limits on the EBL
Now: Measurement of the EBL!

Biteau (HESS coll.) 2012,
HESS coll. Subm. 2012



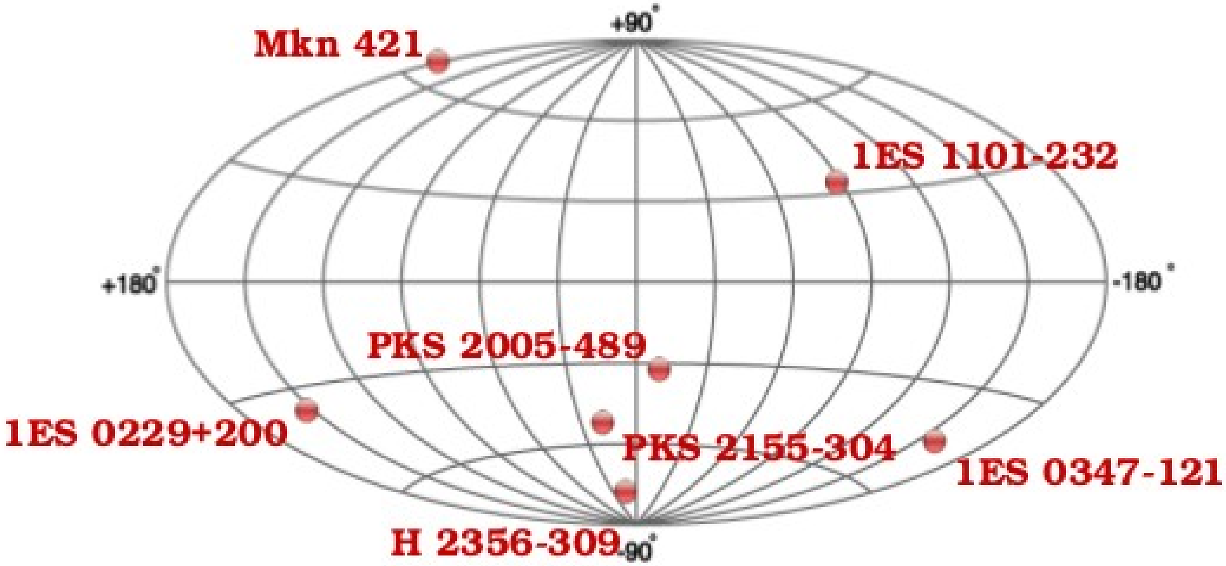
So far
- **Power law spectrum (no curvature)**
- **$\Gamma_{intrinsic} > 1.5$ or $\Gamma_{intrinsic} > \Gamma_{Fermi\text{-}LAT}$**

→ **Upper limit on the EBL density**

This work
- **Curvature allowed, free parameters**
- **Parametrization of the EBL optical depth via a scaling factor α**
- **Fit of a large VHE data set**

→ **Measurement of the EBL density**

Data-set: Observations with H.E.S.S.



PKS 2005−489 at VHE: four years of monitoring with HESS and simultaneous multi-wavelength observations

Discovery of VHE γ-rays from the distant BL Lacertae 1ES 0347-121*

New constraints on the mid-IR EBL from the HESS discovery of VHE γ-rays from 1ES 0229+200

Source	z	N_γ	$E_{\min} - E_{\max}$ [TeV]
Mrk 421 (*1*)	0.031	3381	0.95 – 41
Mrk 421 (*2*)	0.031	5548	0.95 – 37
Mrk 421 (*3*)	0.031	5156	0.95 – 45
PKS 2005-489 (*1*)	0.071	1540	0.16 – 37
PKS 2005-489 (*2*)	0.071	910	0.18 – 25
PKS 2155-304 (*2008*)	0.116	5279	0.13 – 19
PKS 2155-304 (*1*)	0.116	3499	0.13 – 5.7
PKS 2155-304 (*2*)	0.116	3470	0.13 – 9.3
PKS 2155-304 (*3*)	0.116	9555	0.13 – 14
PKS 2155-304 (*4*)	0.116	4606	0.18 – 4.6
PKS 2155-304 (*5*)	0.116	11901	0.13 – 5.7
PKS 2155-304 (*6*)	0.116	6494	0.15 – 5.7
PKS 2155-304 (*7*)	0.116	8253	0.20 – 7.6
1ES 0229+200	0.14	670	0.29 – 25
H 2356-309	0.165	1642	0.11 – 34
1ES 1101-232	0.186	1268	0.12 – 23
1ES 0347-121	0.188	604	0.13 – 11

Data sets on highly significant sources were divided and sorted by flux level

75 000 γ-rays from the seven brightest blazars, with 0.03 < z < 0.19, collected during 400 hours with H.E.S.S.

[Biteau (HESS coll.) 2012]

Spectral fits

$$\phi_z(E) = \phi^{\alpha}_{\text{int}}(E) \times \exp(-\alpha \times \tau(E, z, n))$$

Aim : Fit of the scaling factor α combining data sets

Hypotheses :

- **Template EBL model : Franceschini et al., 2008, A&A, 487, 837**
  Extragalactic optical-infrared background radiation, its time evolution and the cosmic photon-photon opacity,
- **Intrinsic spectrum described with :**

Name	Abbrev.	Function
Power law	PWL	$\phi_0(E/E_0)^{-\Gamma}$
Log parabola	LP	$\phi_0(E/E_0)^{-a-b\log(E/E_0)}$
Exponential cut-off power law	EPWL	$\phi_0(E/E_0)^{-\Gamma}\exp(-E/E_{\text{cut}})$
Exponential cut-off log parabola	ELP	$\phi_0(E/E_0)^{-a-b\log(E/E_0)}\exp(-E/E_{\text{cut}})$
Super exponential cut-off power law	SEPWL	$\phi_0(E/E_0)^{-\Gamma}\exp(-(E/E_{\text{cut}})^{\gamma})$

Method :

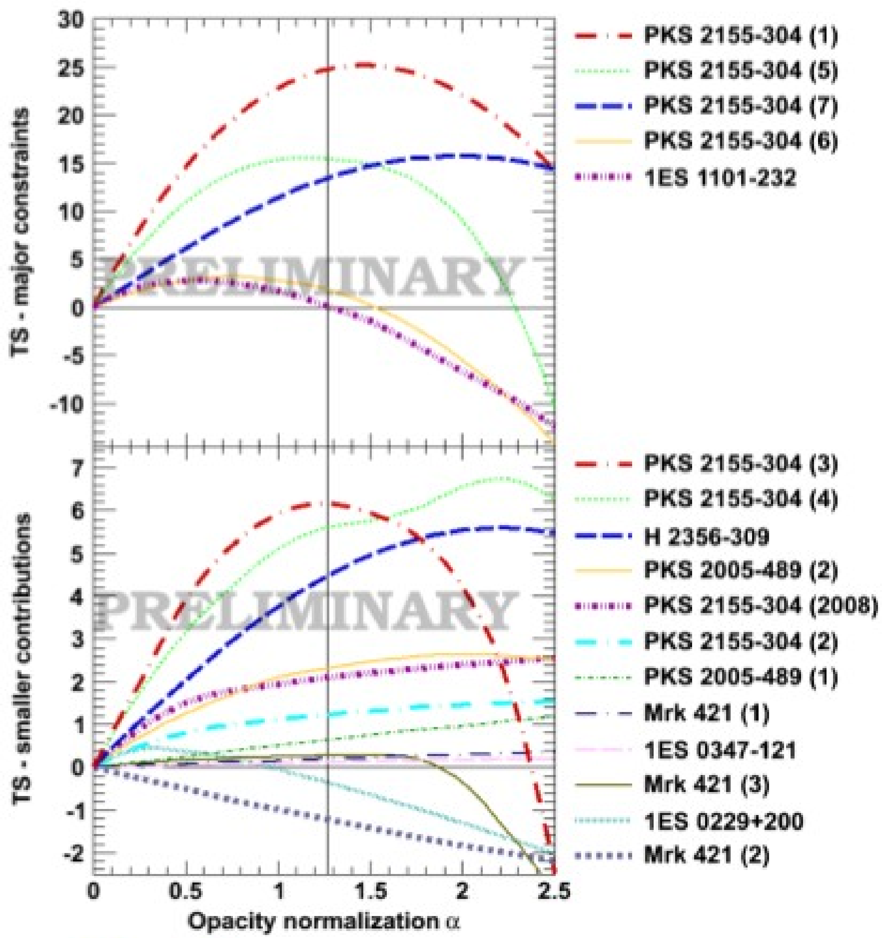
- **Likelihood profiles for each {data set, spectral model}**
- **Selection of the spectral model with the largest χ^2 probability**

[Biteau (HESS coll.) 2012]

Stacking of likelihood profiles

Null hypothesis : no EBL, i.e. α=0

$$\mathrm{TS} = 2\log\left[\mathcal{L}(\alpha)/\mathcal{L}(\alpha=0)\right]$$



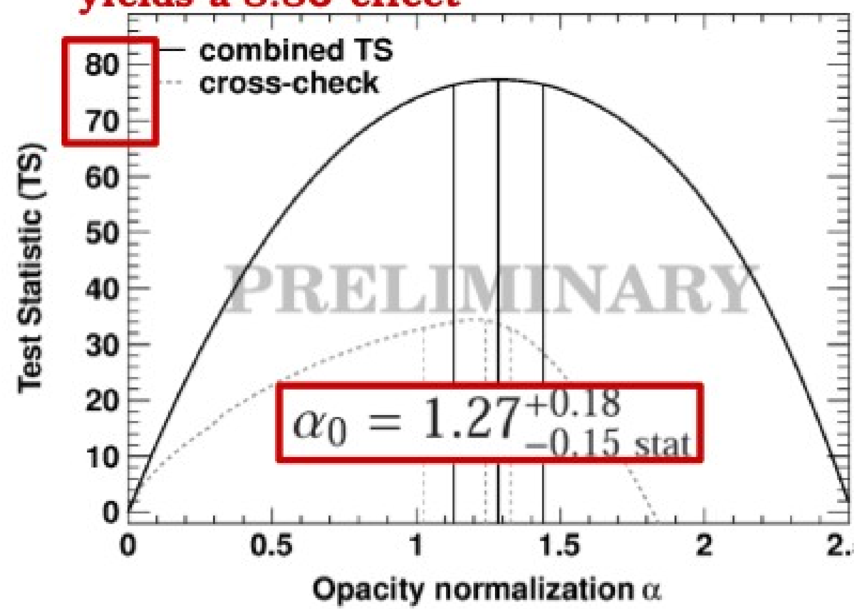
No outlier

No significant variation over redshift

combining the individual TS

$$\mathrm{TS} = \sum_i 2\log\left[\mathcal{L}_i(\alpha)/\mathcal{L}_i(\alpha=0)\right]$$

yields a 8.8σ effect

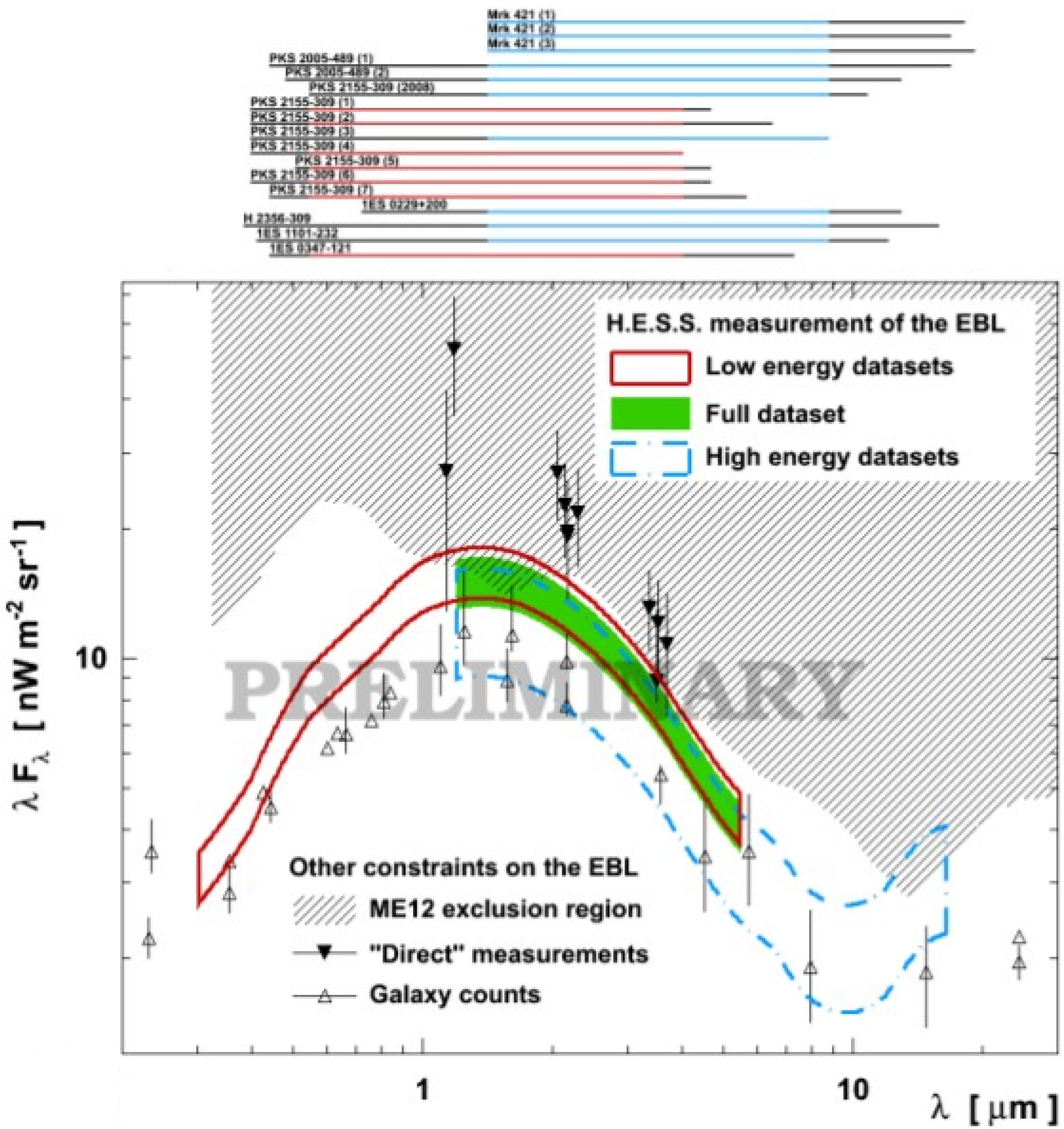


Sources of systematics	Estimated systematics
Analysis chain	0.21
Intrinsic model	0.10
EBL model	0.02
Energy scale	0.05
Total	**0.24**

Full study of the systematics

[Biteau (HESS coll.) 2012]

Measured EBL!



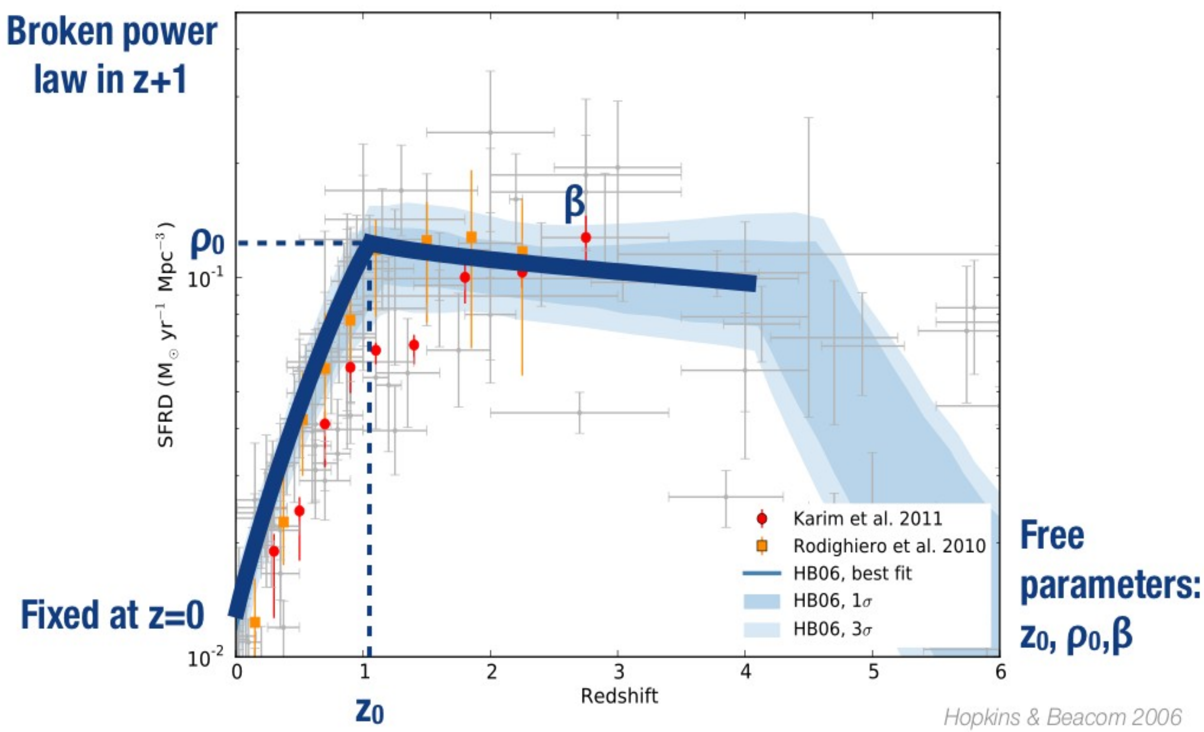
First significant detection of an EBL-consistent red-shift dependent common absorption feature in VHE energy spectra at the level of 9 standard deviations!.

Good agreement with upper and lower bounds (not per construction!)

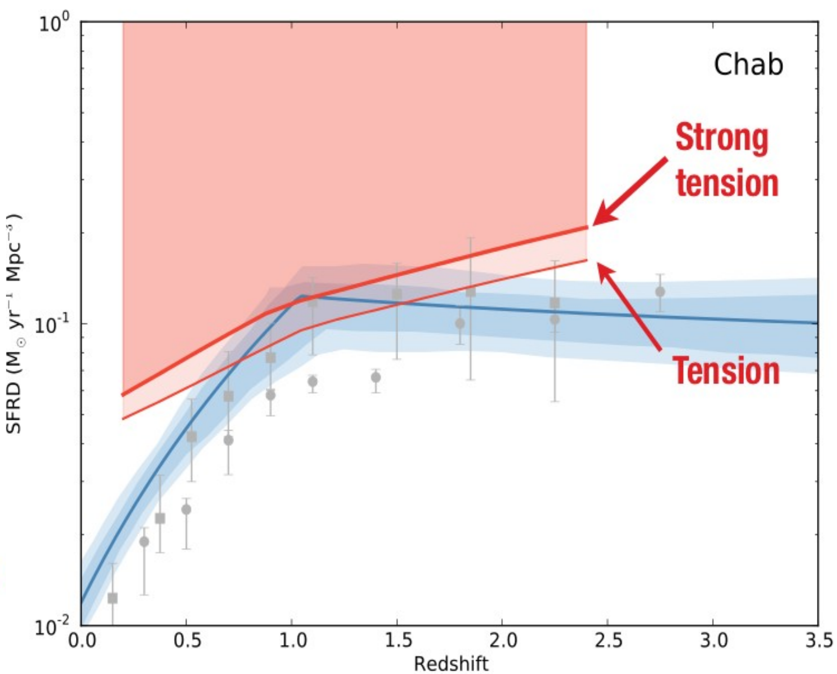
[Biteau (HESS coll.) 2012]

Constraining the star-formation rate

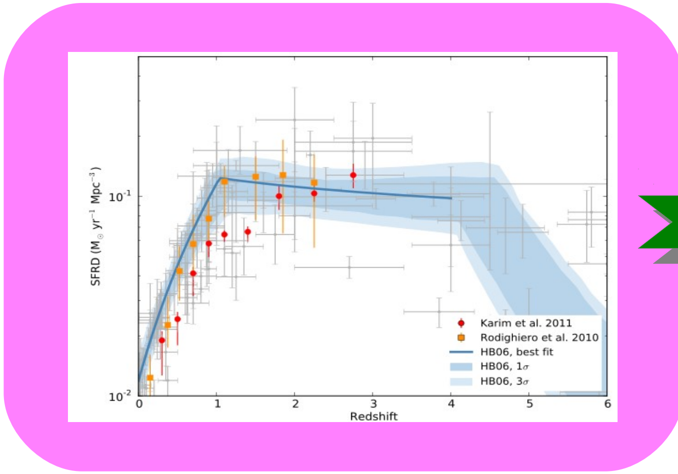
- Using the EBL-limits [Meyer et al. 2012] ⟶ get a (model dependent) handle on the SFR history [Raue et al. 2012]

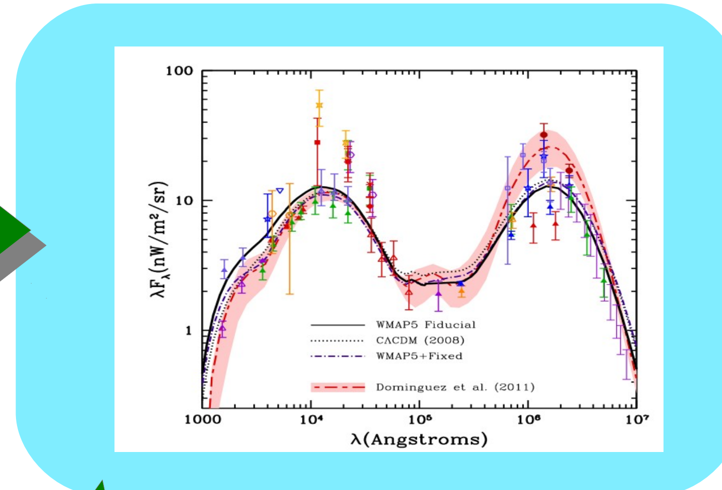


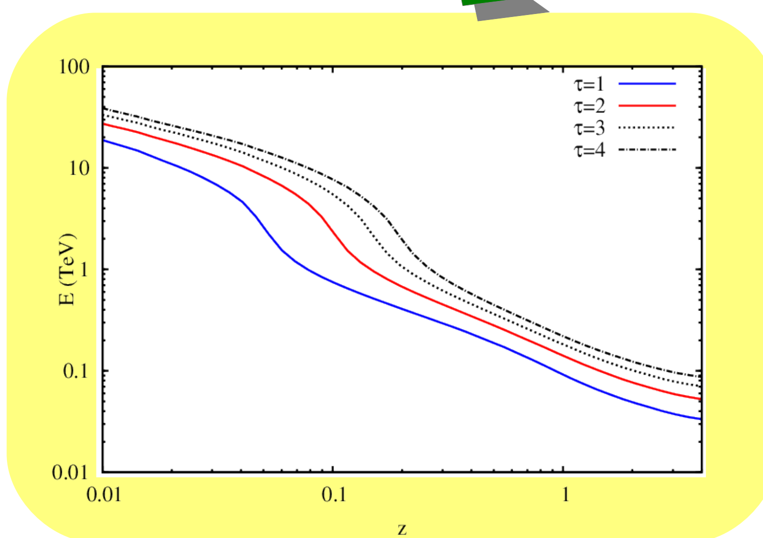
Hopkins & Beacom 2006



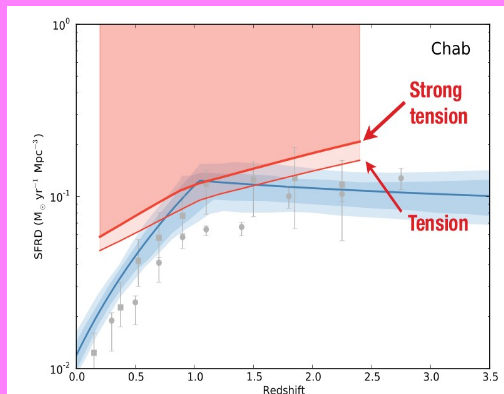
The SFR-EBL-VHE connection..

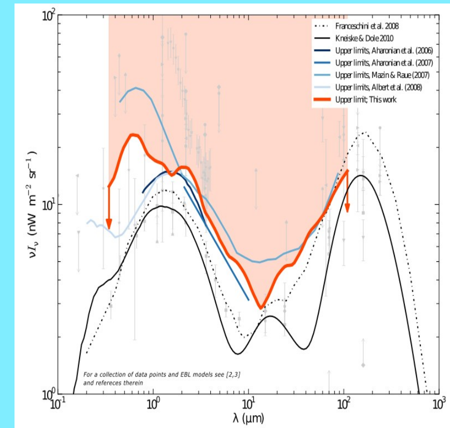


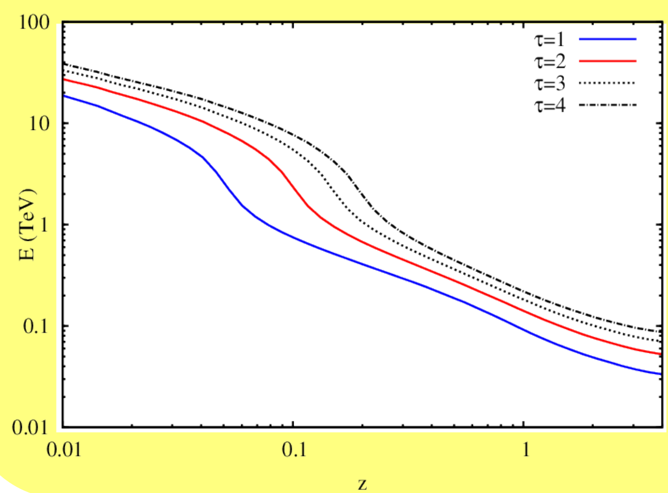




The SFR-EBL-VHE connection..







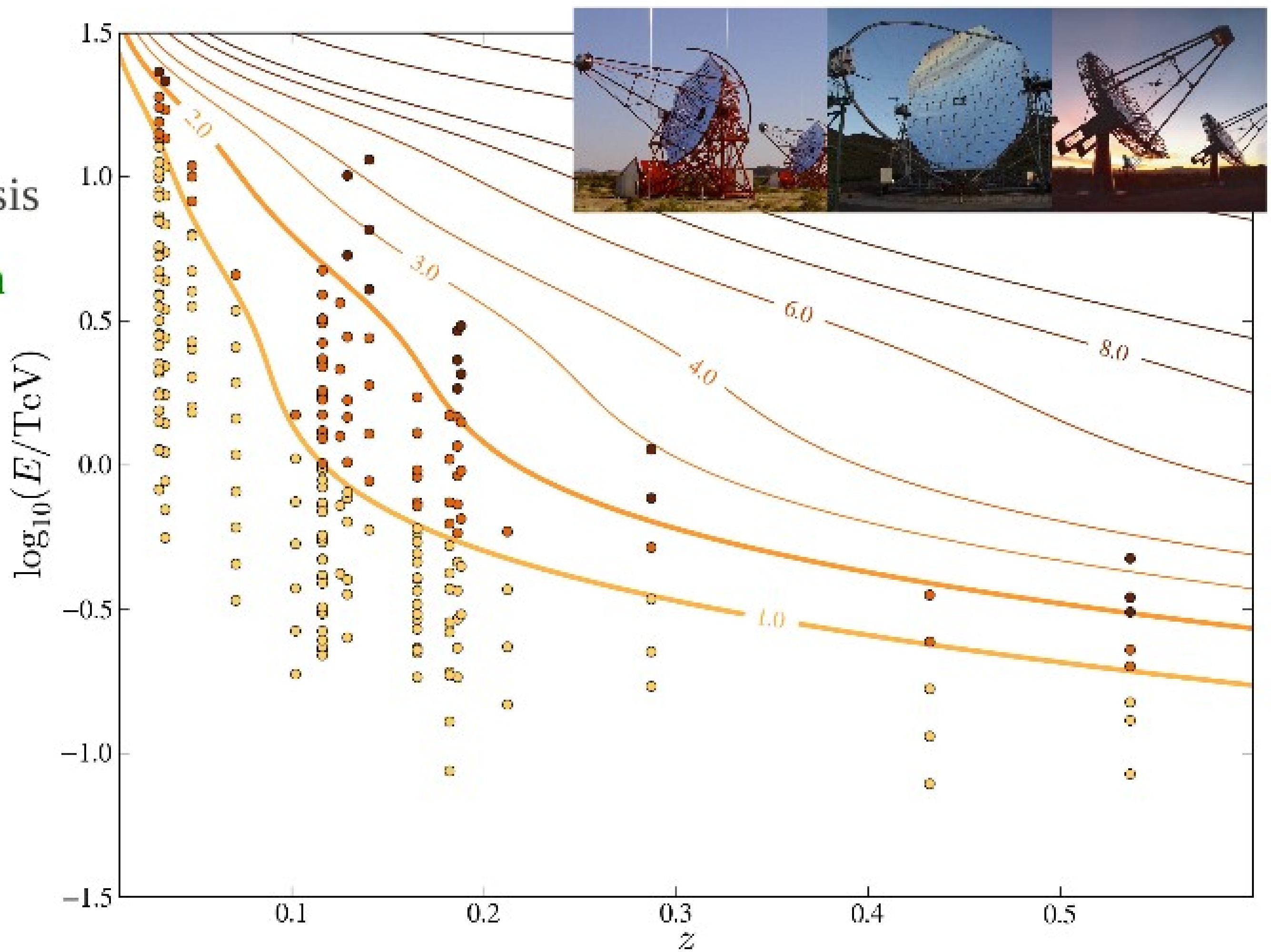

Large Tau
SUPER
SIZE
Dirty
Laundry

A closer look at the tail of the energy spectra

[DH et al. 2012]
Slides from Meyer,
Patras-WS 2012

Under the Assumption of a „minimum“ EBL (=lower limit)

- Features expected to be small → statistical analysis
- In total: **50 AGN spectra**
- **28** spectra with **1 ≤ τ < 2** (*optically thin sample*)
- **9** spectra with **2 ≤ τ** (*optically thick sample*)



[Dieter Horns & MM, *JCAP* (2012), vol. 02 pp 33, arXiv: 1201.4711]

Compare optically thin and optically thick sample

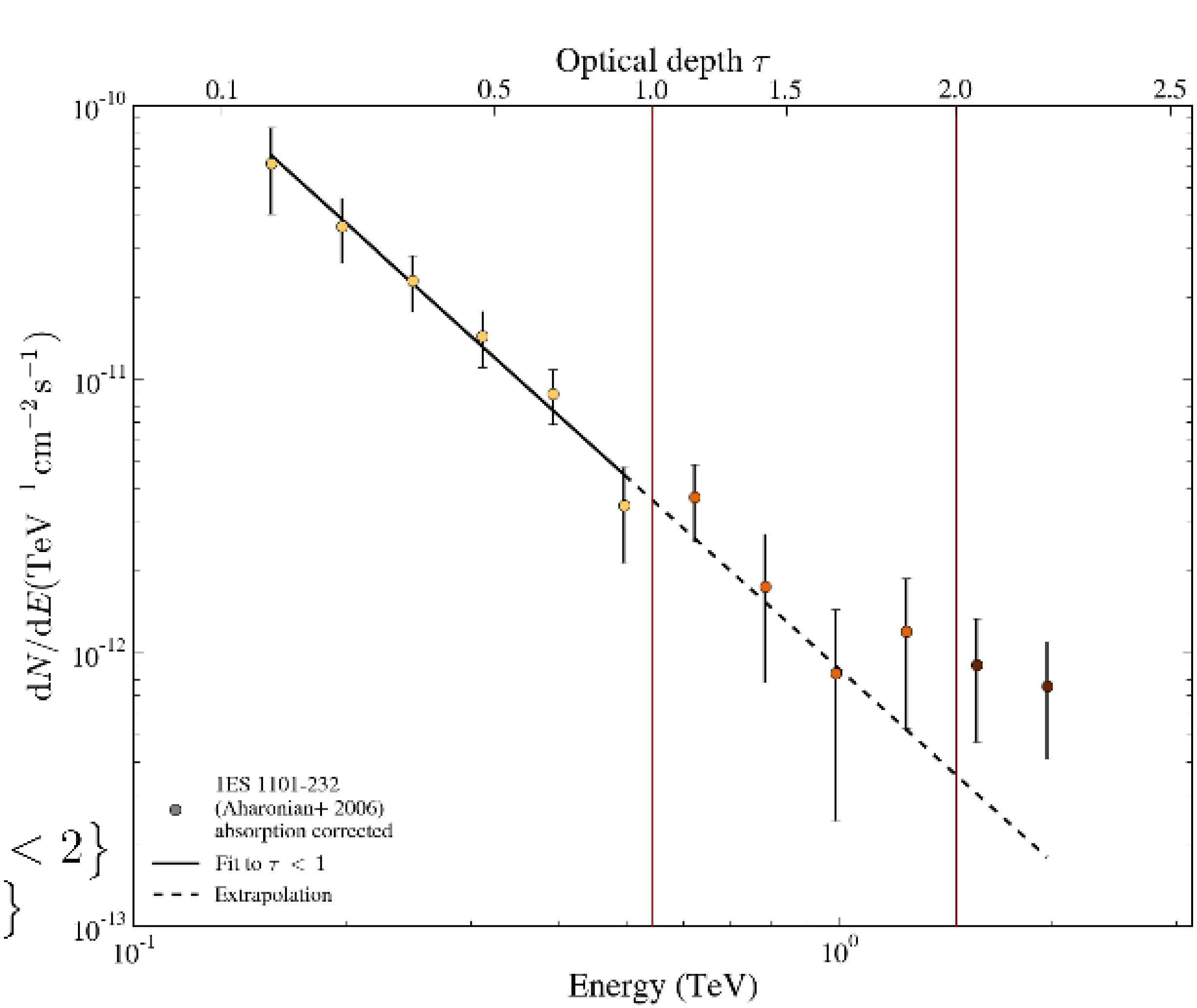
- Fit data **up to τ < 1**
- Extrapolate fit
- Calculate ratio

$$R_i = \frac{f_i^{\rm int} - f_i^{\rm ext}}{f_i^{\rm int} + f_i^{\rm ext}}$$

$f_i^{\rm int}$: intrinsic flux
$f_i^{\rm ext}$: extrapolated flux

- Compare distributions with **Kolmogorov-Smirnov** (KS) test

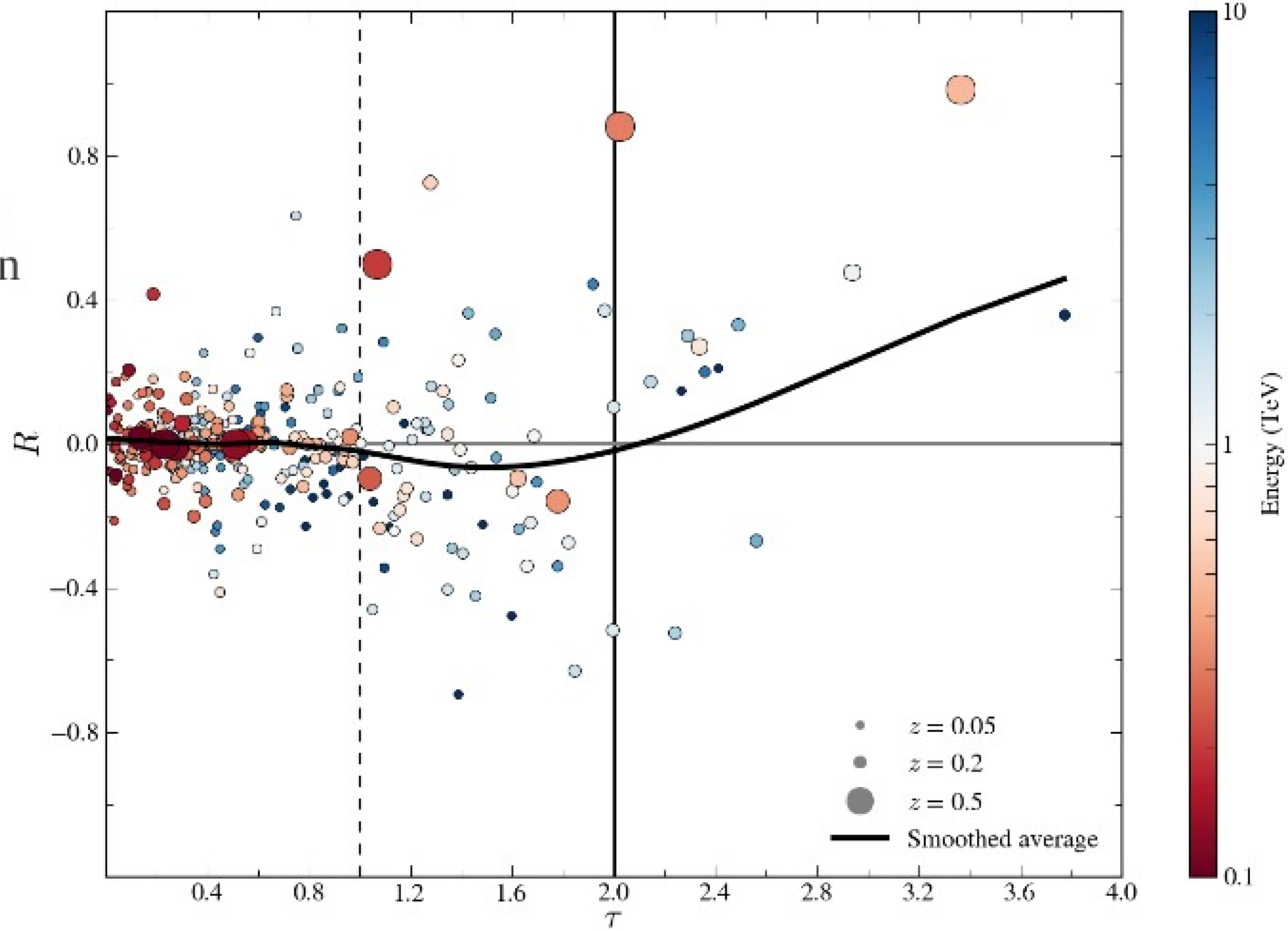
$$\begin{aligned} \mathcal{S}_{\rm thin} &= \left\{R_i^{\rm int} | 1 \leq \tau_\gamma(E_i, z) < 2\right\} \\ \mathcal{S}_{\rm thick} &= \left\{R_j^{\rm int} | 2 \leq \tau_\gamma(E_j, z)\right\} \end{aligned}$$



Compare optically thin and optically thick sample

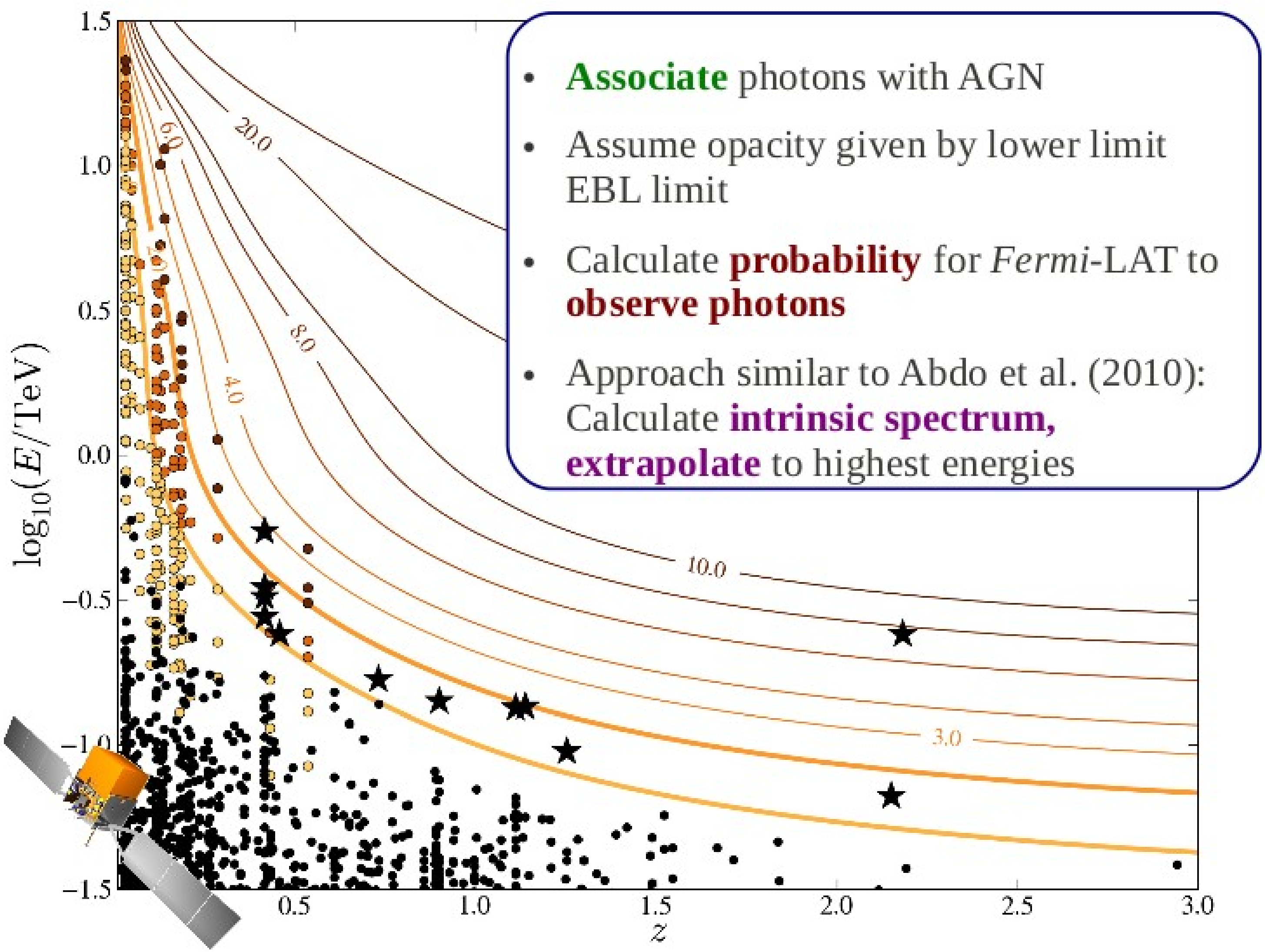
- Samples **not drawn** from same underlying probability distribution files with probability ***P* = 4.2σ**
- Systematics checked:
  - excluded individual spectra
  - excluded highest energy spectral point
  - shift of 15% in energy

  cannot account for effect



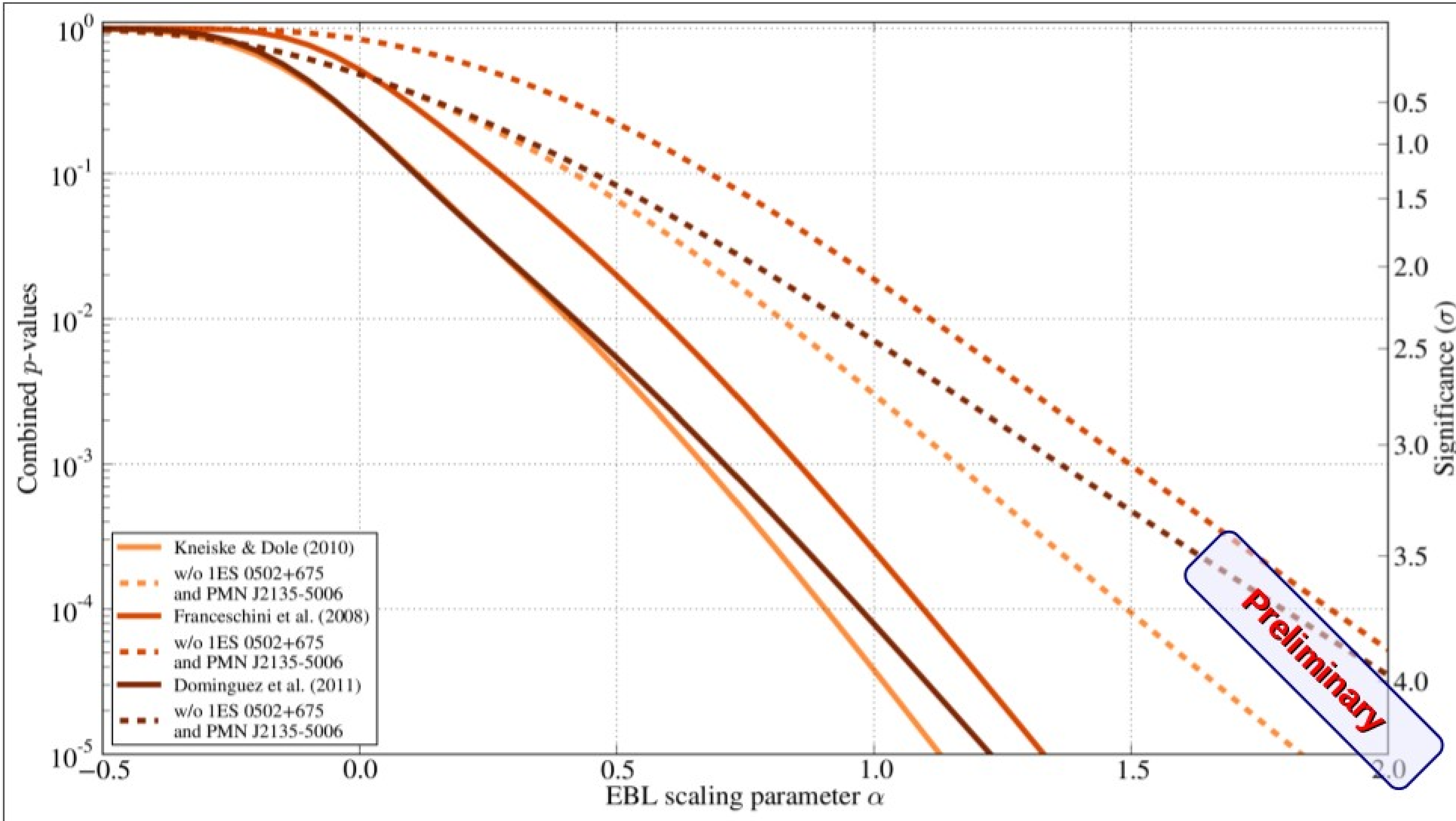
Further analysis of optically thick data with Fermi-LAT

[Meyer et al. In prep]



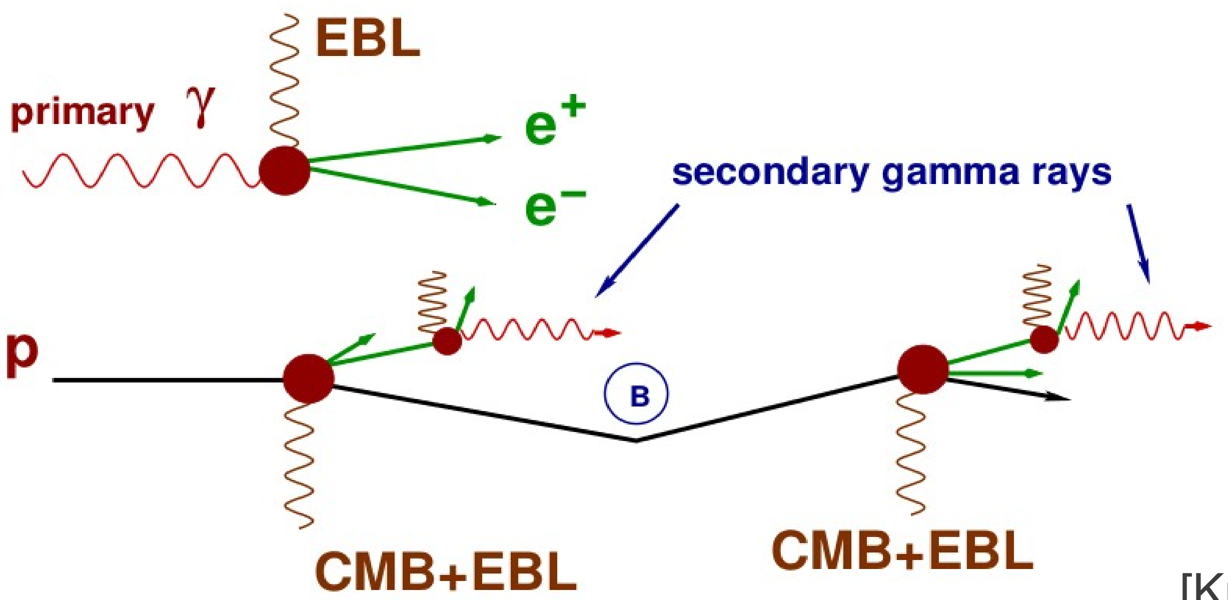
- **Associate** photons with AGN
- Assume opacity given by lower limit EBL limit
- Calculate **probability** for *Fermi*-LAT to **observe photons**
- Approach similar to Abdo et al. (2010): Calculate **intrinsic spectrum, extrapolate** to highest energies

Tension with VHE-measurement of EBL?



Explanations?

- Systematics: Largely excluded (energy shift, bias on last point)
- Physics explanation:
  - VHE Cascading (Kusenko et al. 2010a, 2010b, 2011a, 2011b, 2012a, 2012b). Variability? Spectral Fit?



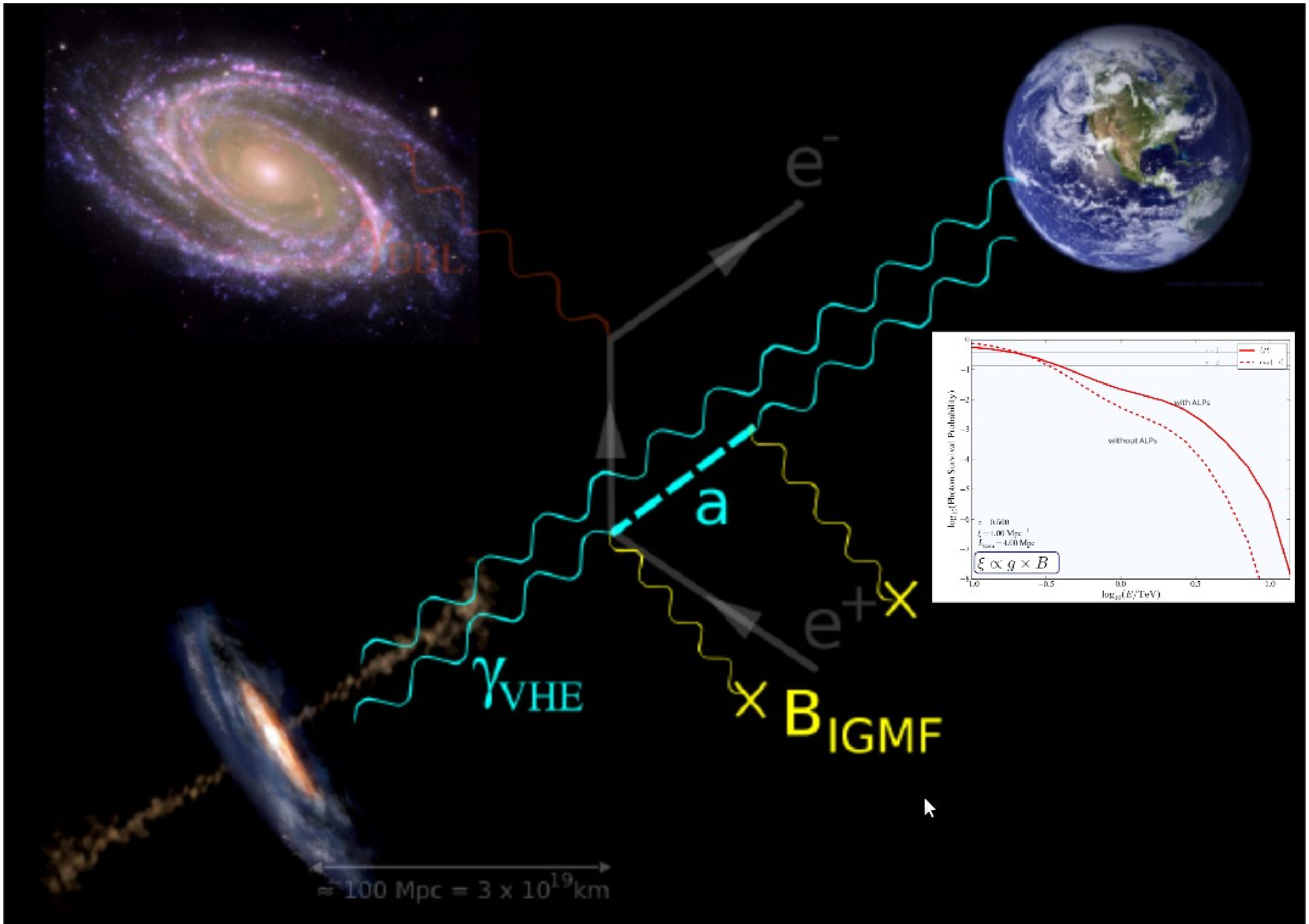
[Kusenko 2012]

Exotic explanations

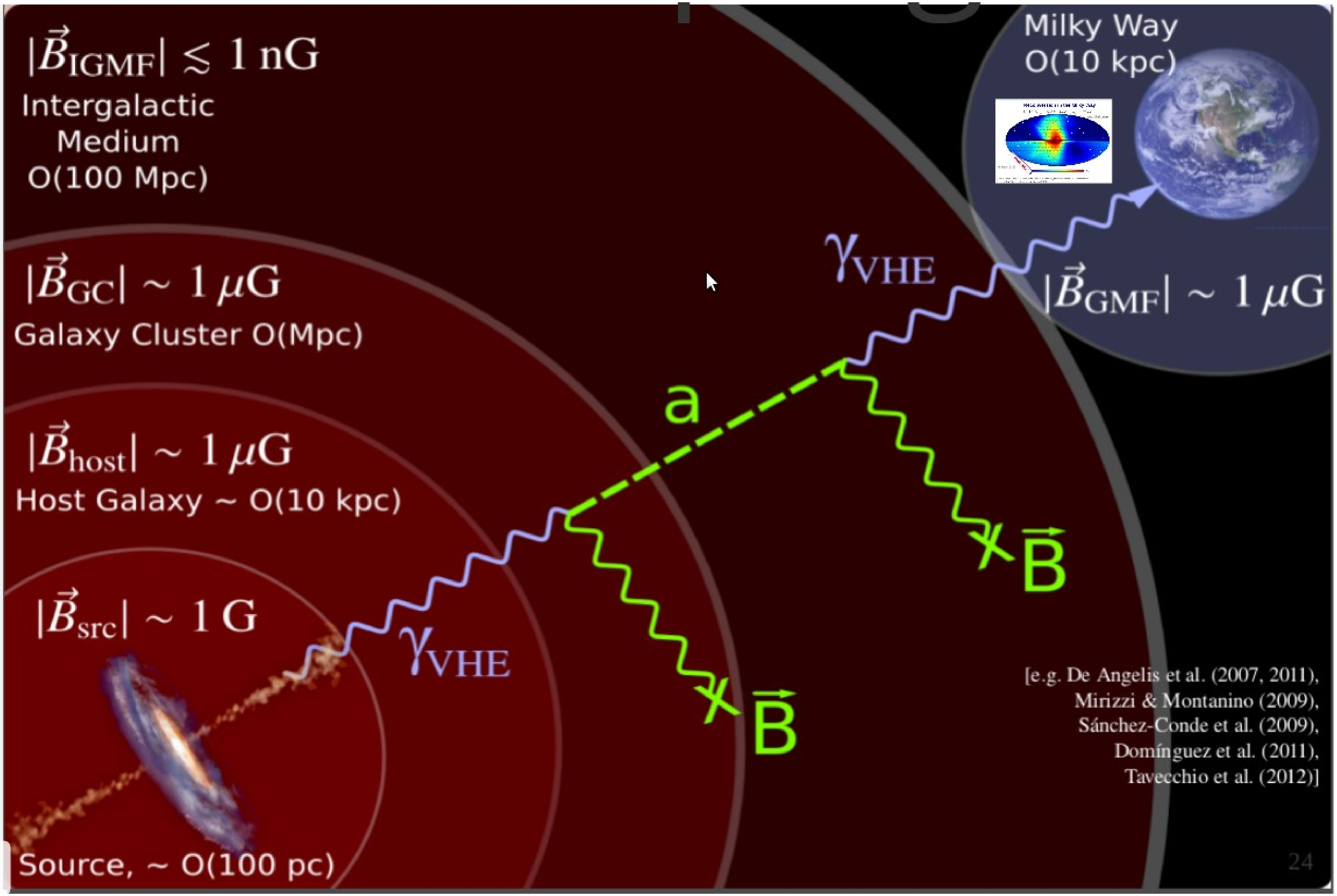
- Lorentz invariance violation (conflict with limits on UHECR propagation [Galaverni & Sigl 2008], observed effect is tau-dependent and not energy dependent
- Light (neV) Axion-like (0^-)particle with $g_{ag} \sim 10^{-11}$ GeV^{-1}

  could explain the observations,
  and could wash the dirty laundry.

Modified propagation

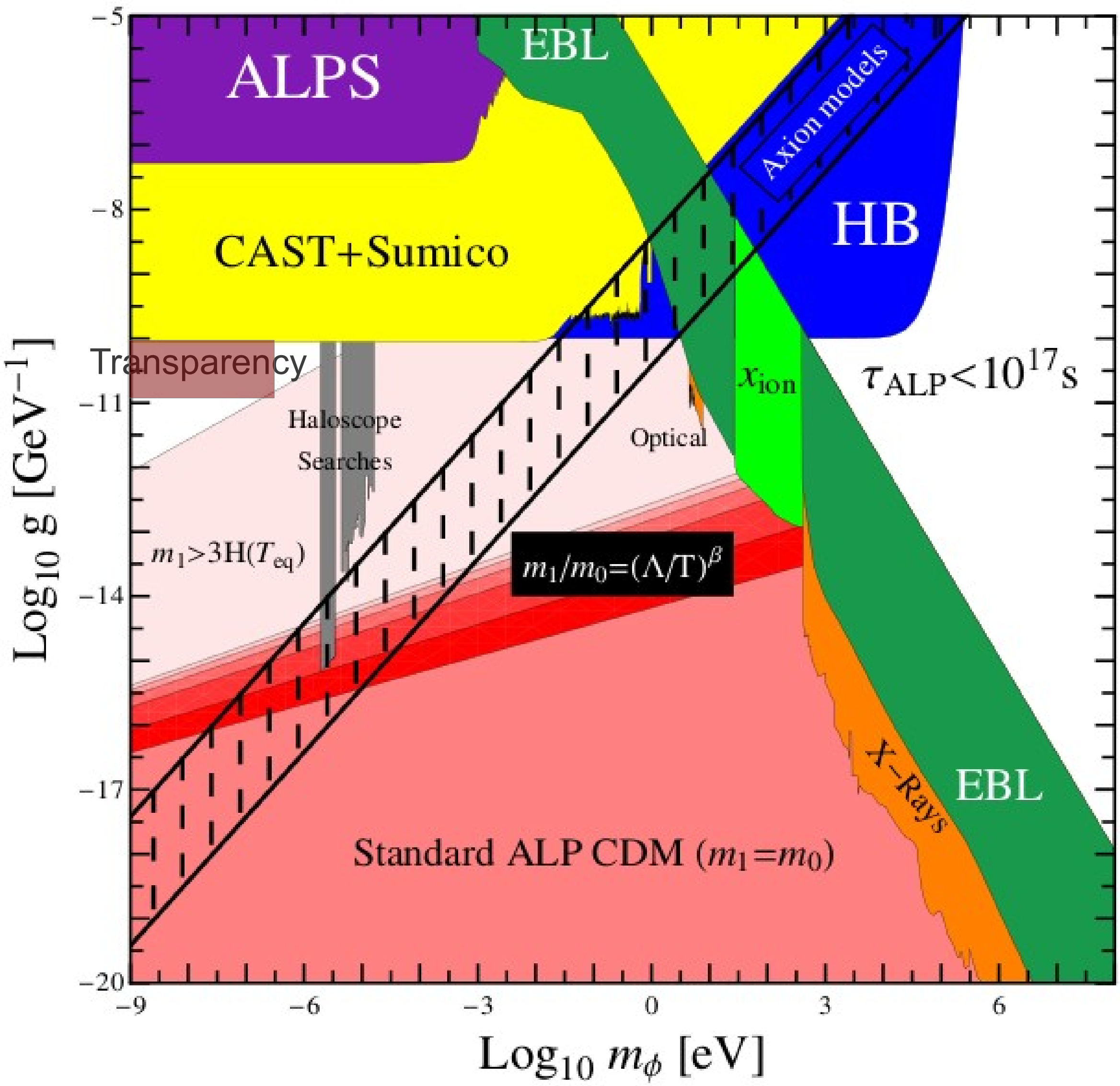


More complicated scenarios



[DH et al. 2012b]

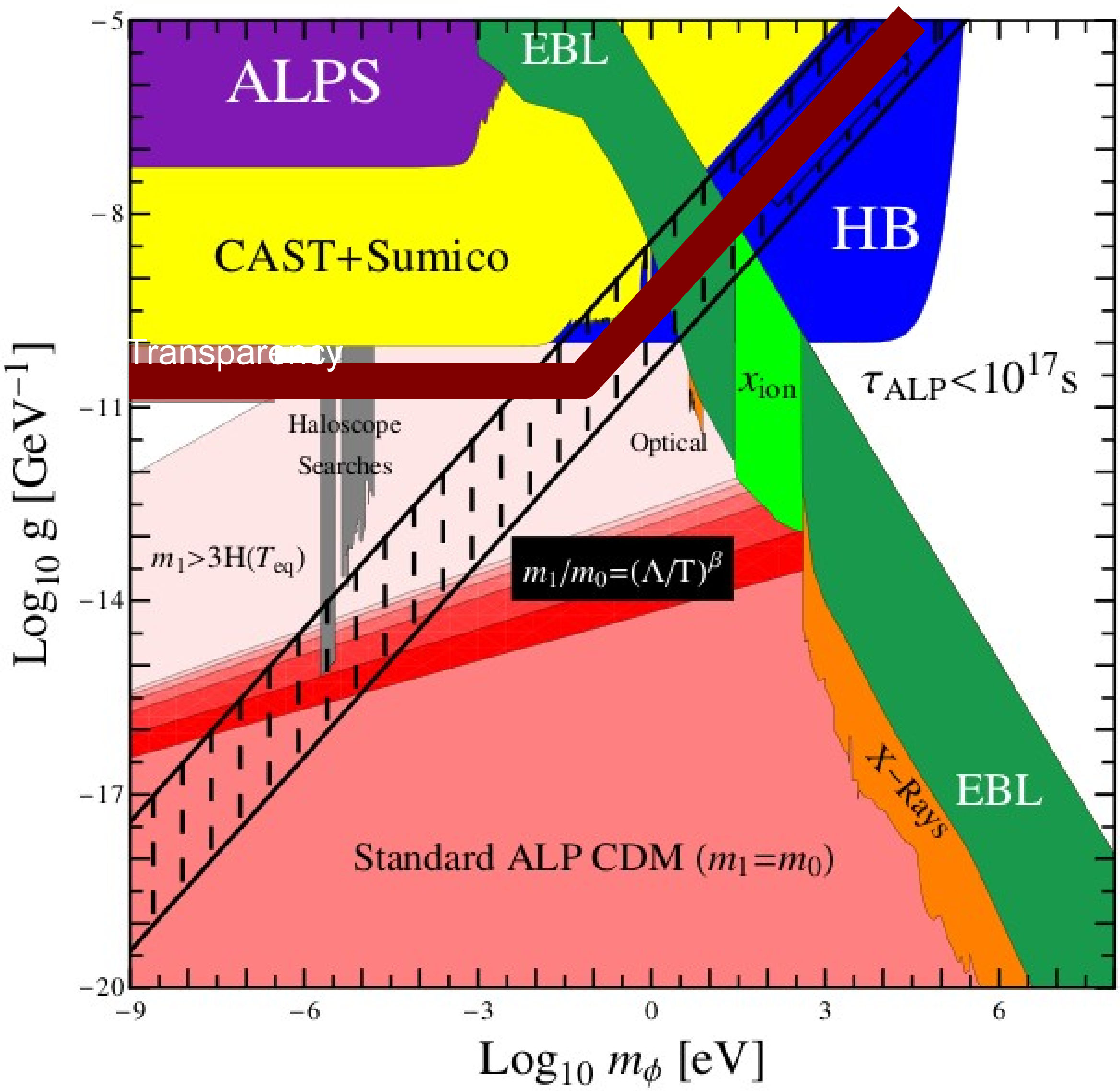
An interesting corner in the ALPS parameter space



[Arias et al. 1202]

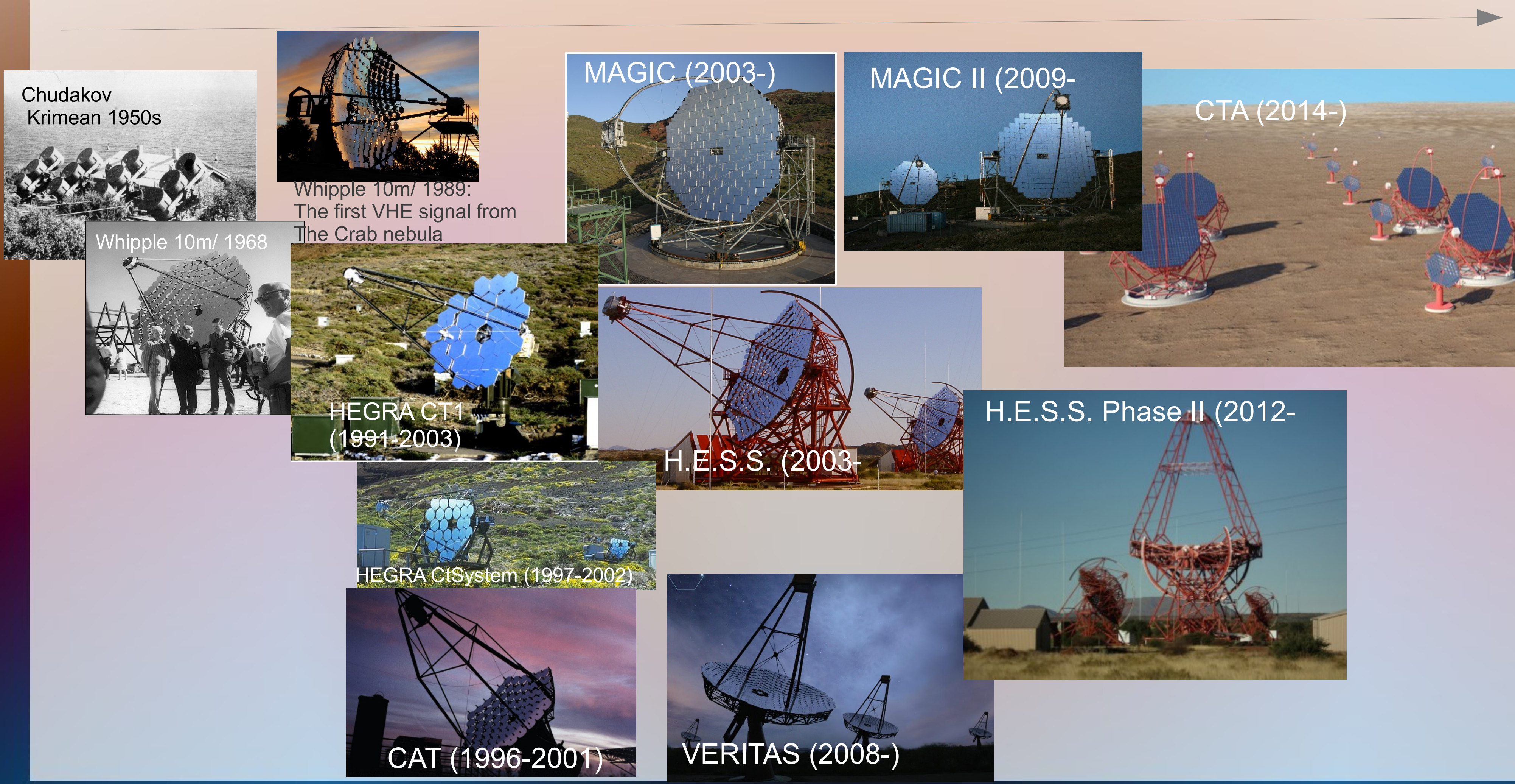
An interesting corner in the ALPS parameter space

~ 1.5 M€
+ Helium..



[Arias et al. 1202]

The evolution of Gamma-ray telescopes



Summary

- EBL models are converging towards the minimum level set by resolved sources
- Conversely, there is not much room for additional sources for the EBL (e.g. Pop III, dark stars)
- VHE observations constrain the EBL from above
- VHE observations can be used to constrain the Star formation history (complementary to traditional tracers of SFR)
- New result: 8.8 sigma evidence for absorption feature in VHE spectra found
- Indications for anomalous transparency at optical depth > 2