Probing the IGMF and fundamental physics with gamma-ray propagation

Manuel Meyer axion-alp-dm.github.io @me_manu

Manuel Meyer
mey@sdu.dk

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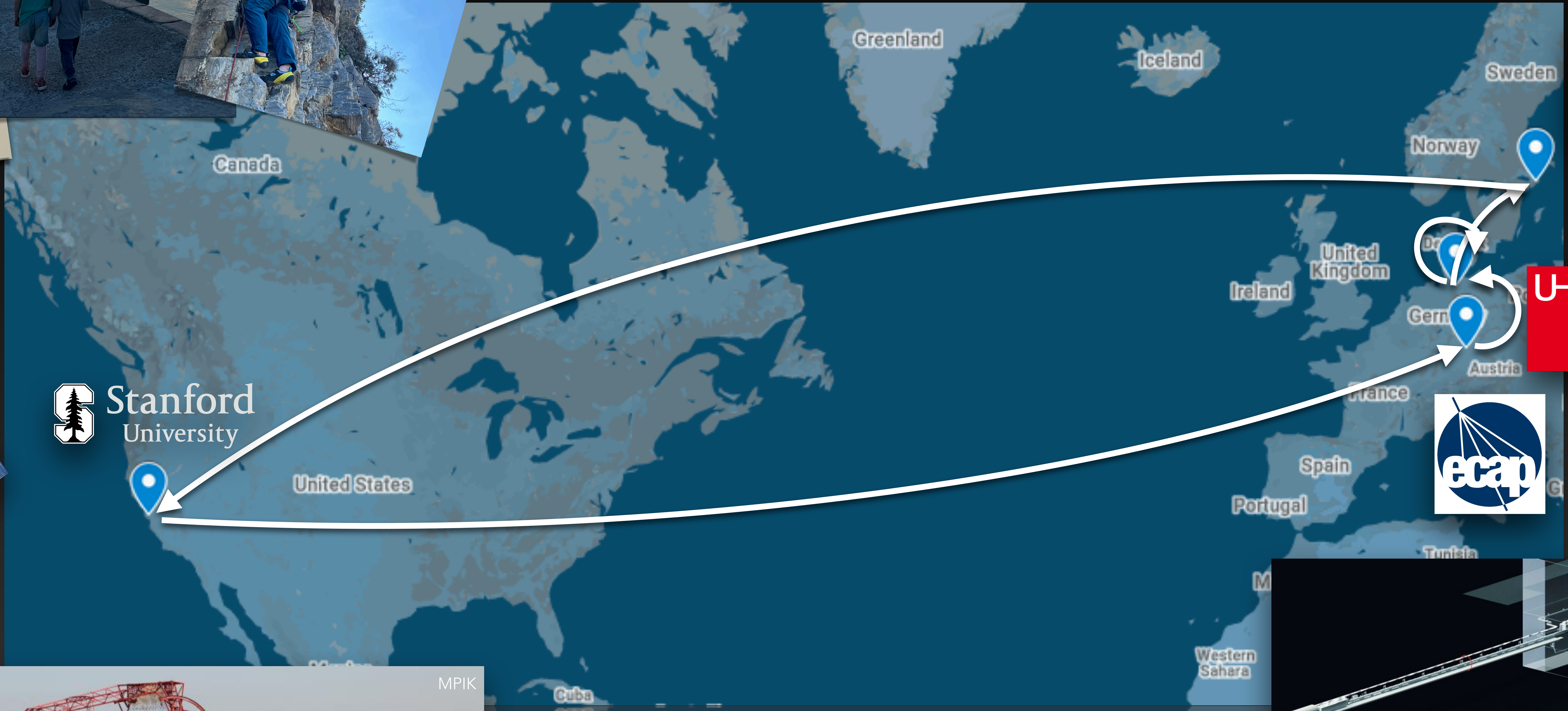
February 13, 2025

About me



Stanford University

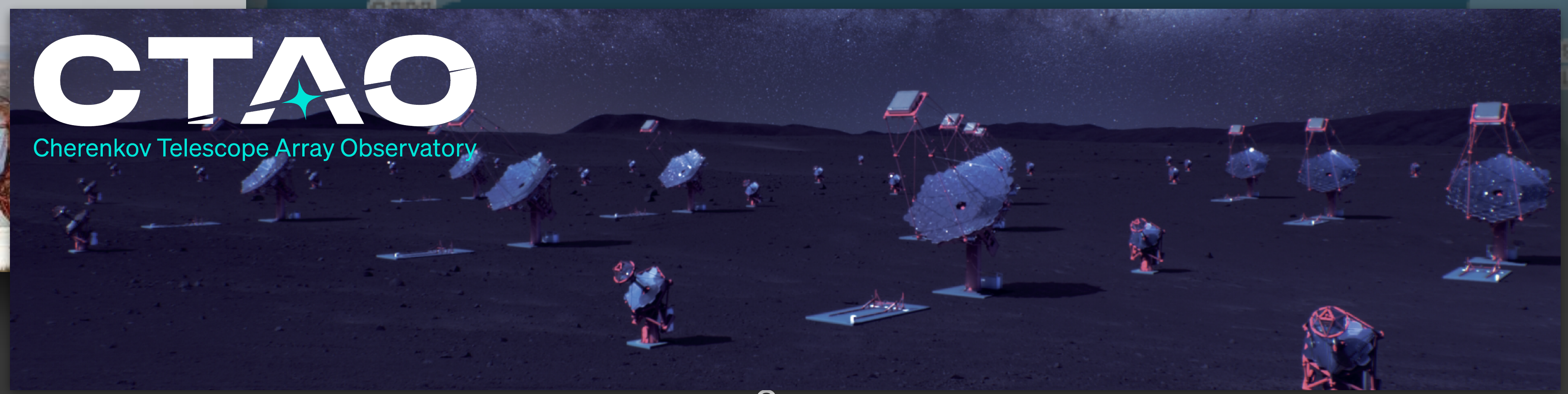
UNIVERSITET STOCKHOLMS

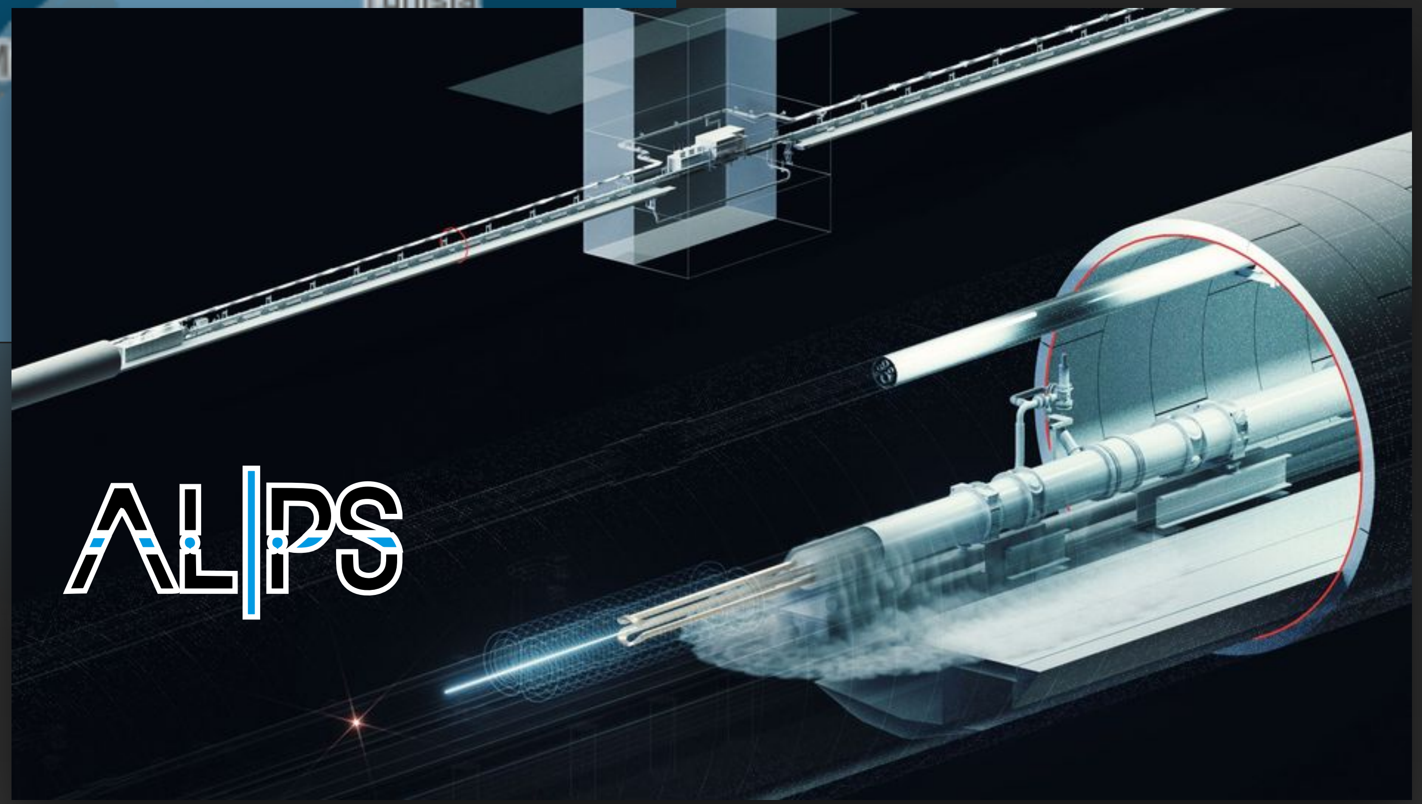
SDU

UH

ecap

Fermi
Gamma-ray
Space Telescope





Recently: experimental work on cryogenic single photon detectors

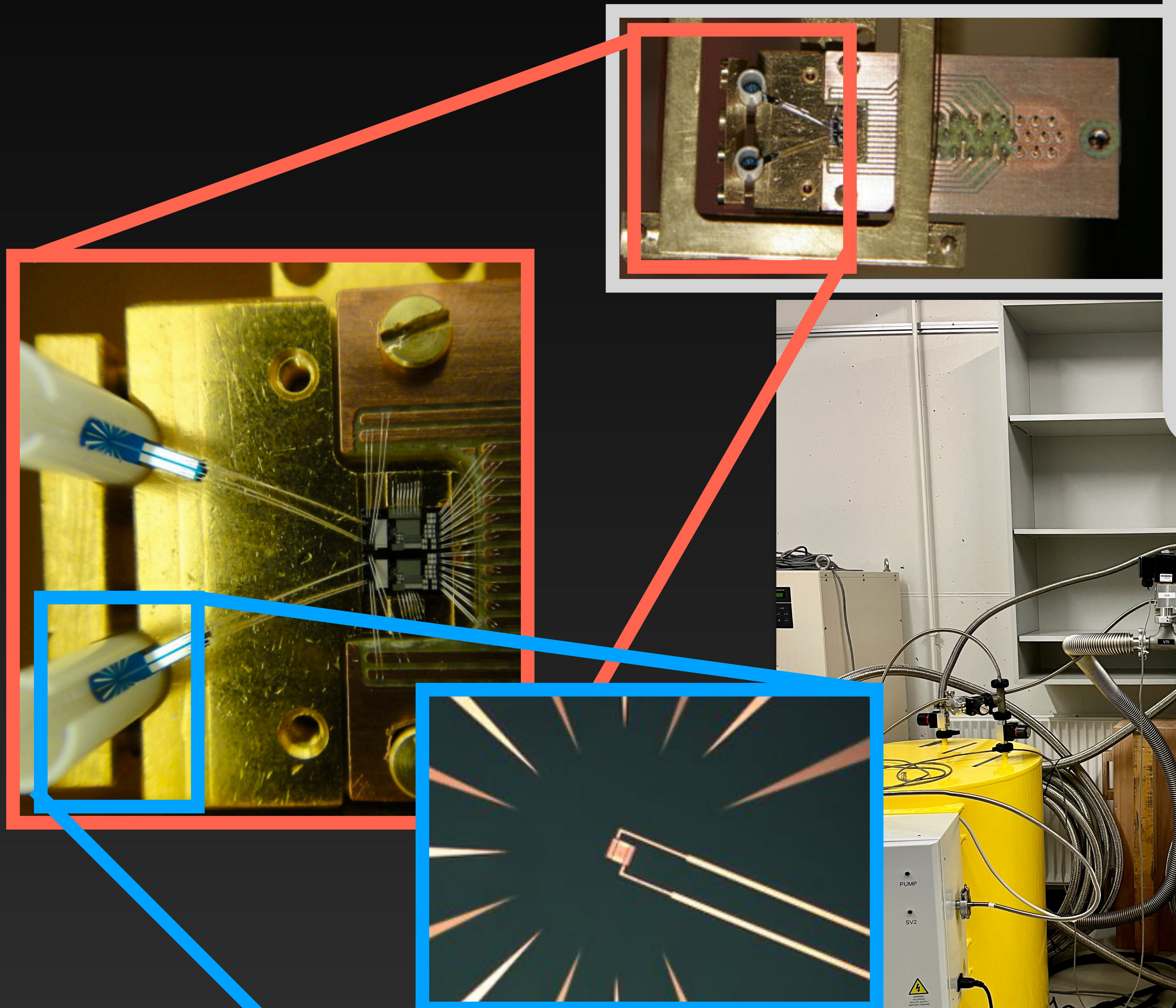
Axel Lindner (DESY) ALPS II Spokesperson

Friederike Januschek TES team lead at DESY

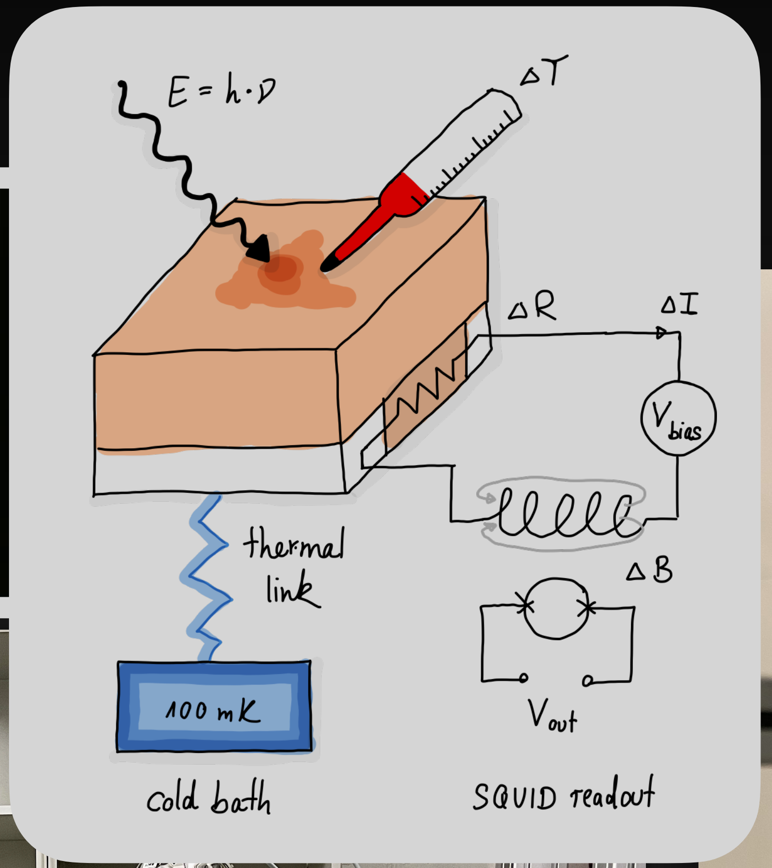
PhD student Christina Schwemmbauer (DESY)

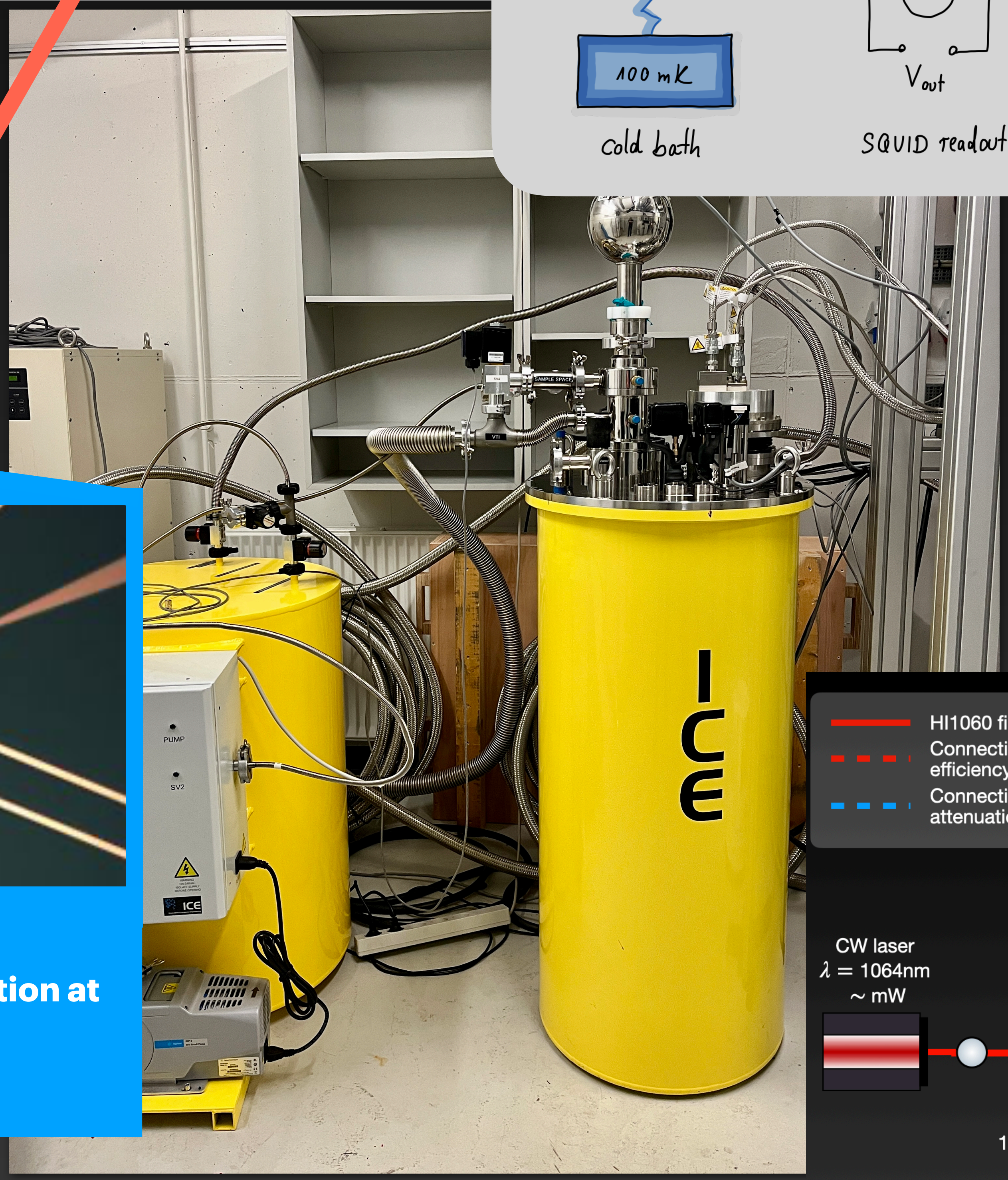
HSU post doc José Alejandro Rubiera Gimeno

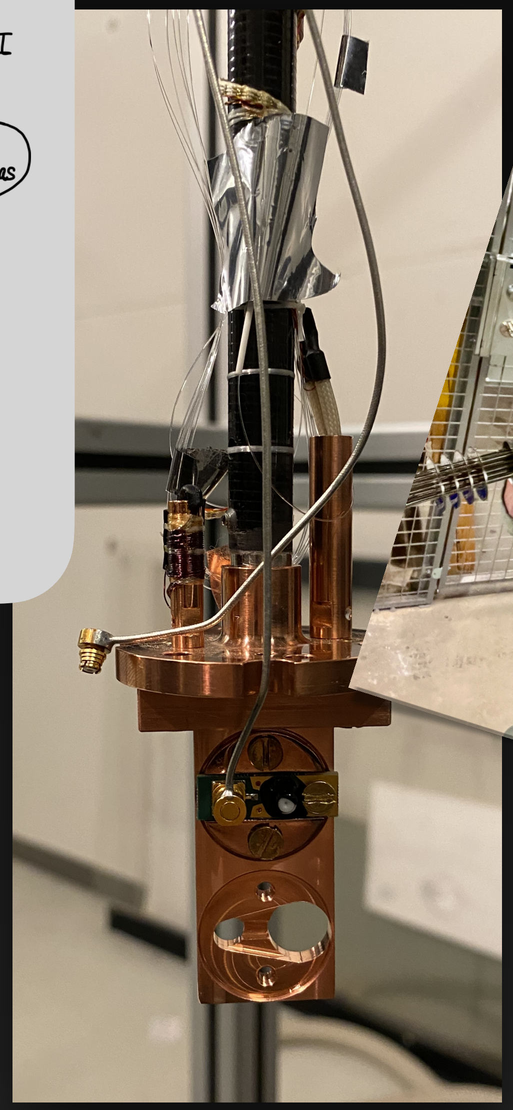
UHH (now HSU) and SDU Post docs Gulden Othman Elmeri Rivasto

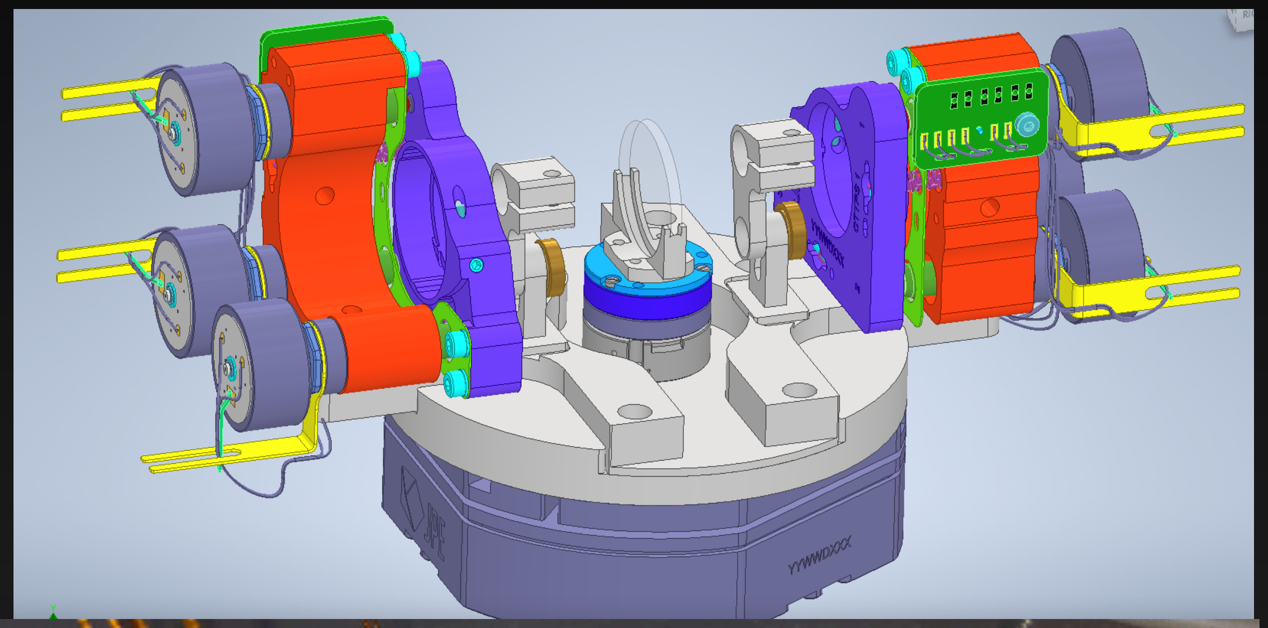


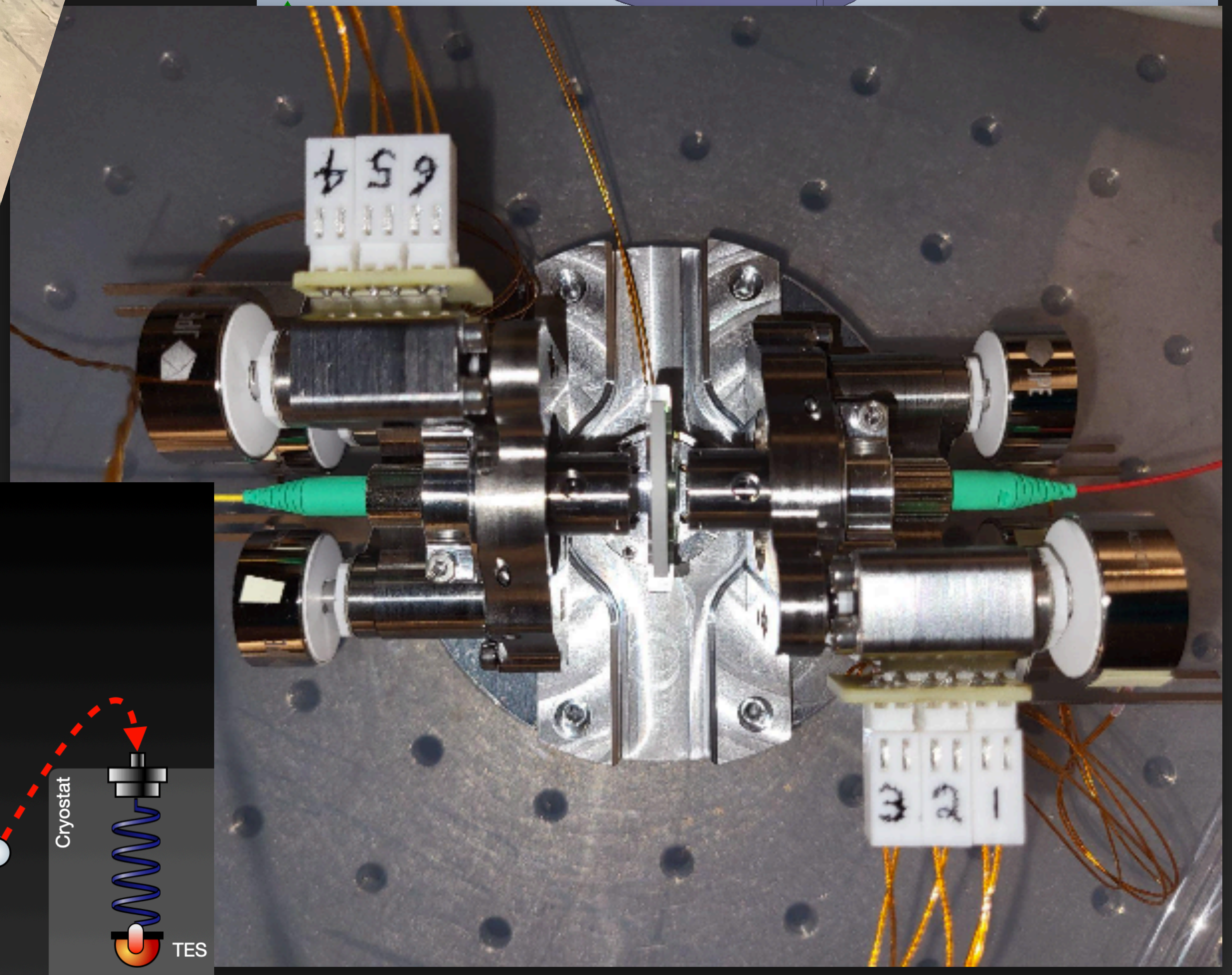
Tungsten microchip, superconducting transition at $T_C \sim 140$ mK
(25 µm x 25 µm x 20nm)

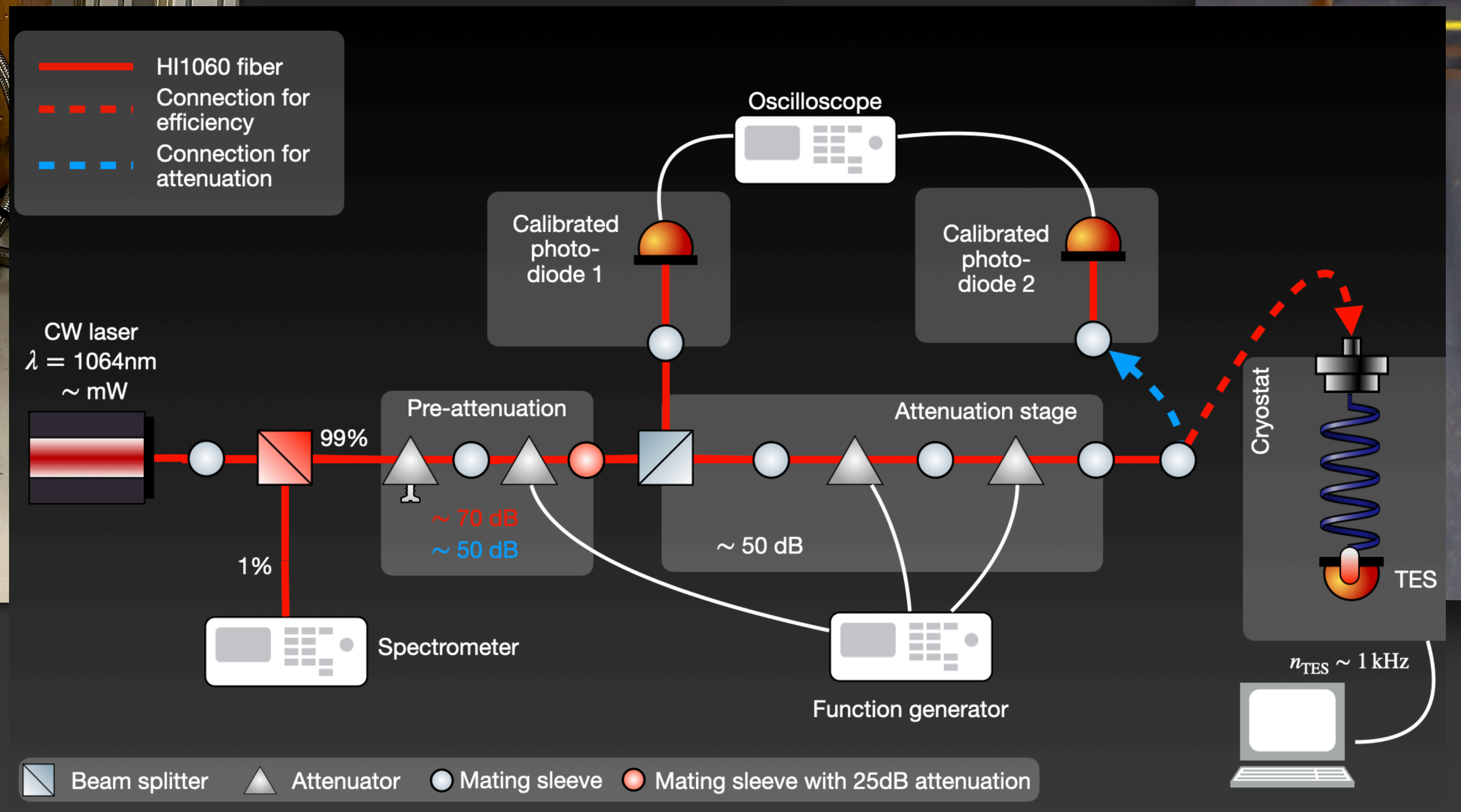


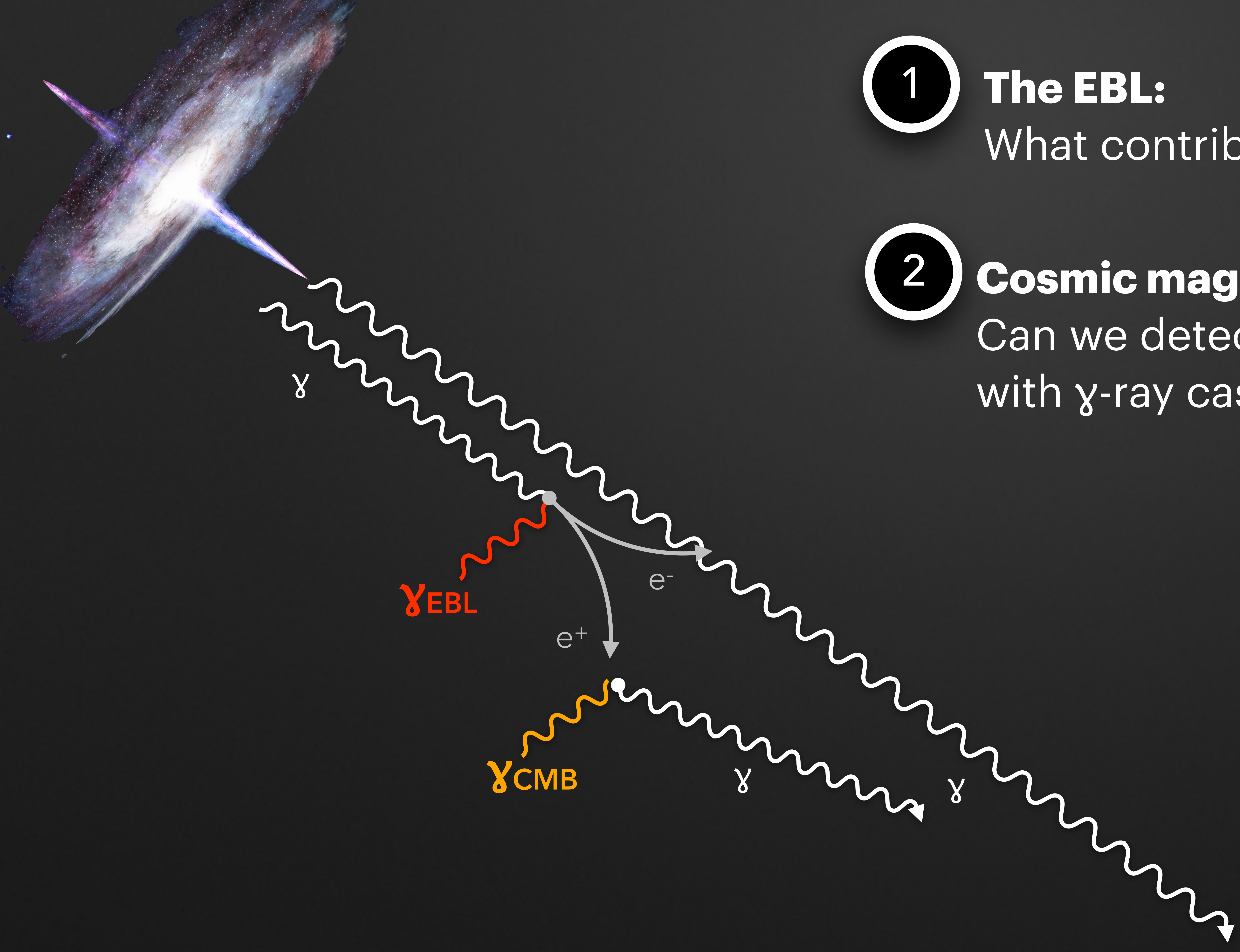






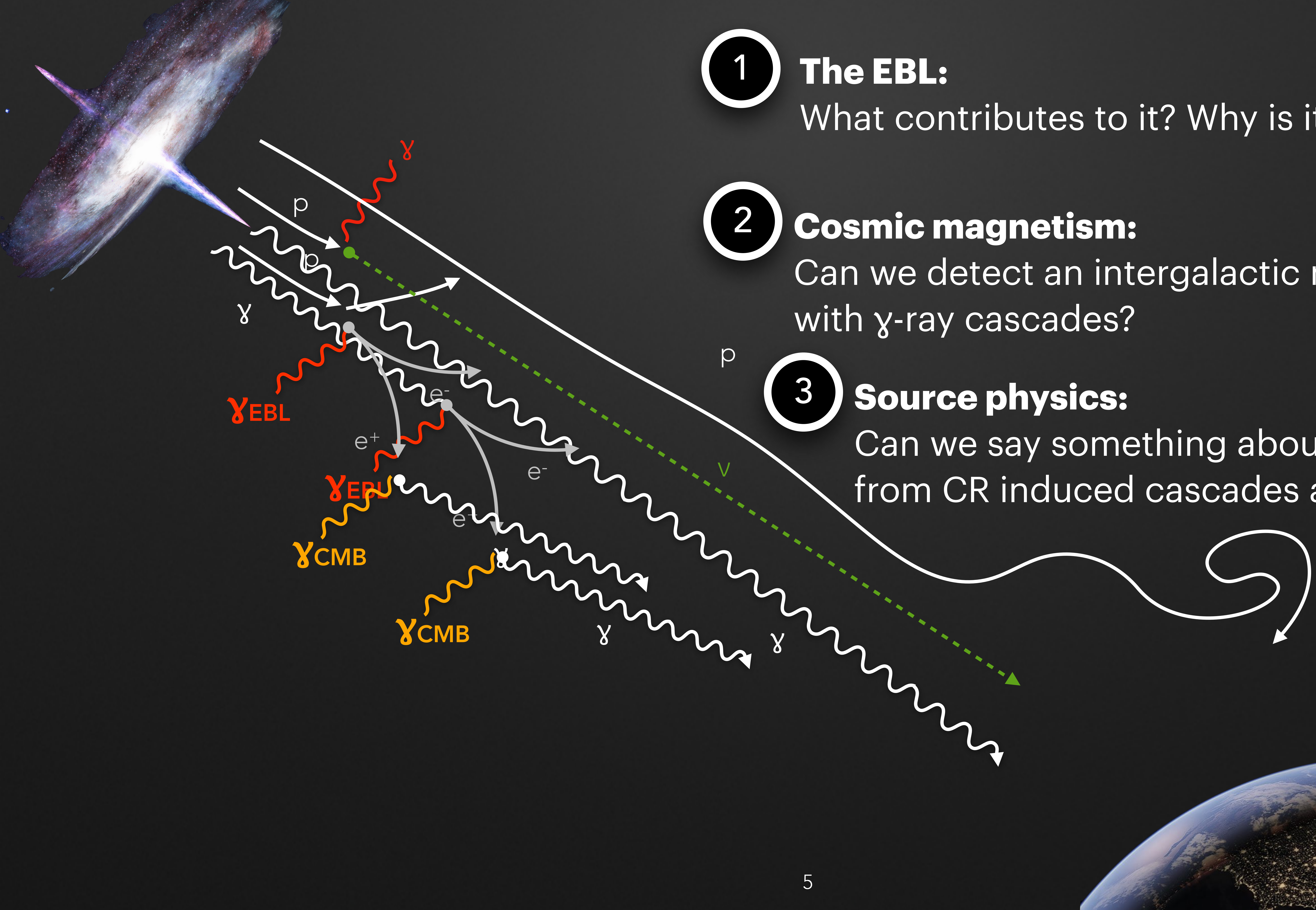






1. **The EBL:**
   What contributes to it? Why is it still uncertain?

2. **Cosmic magnetism:**
   Can we detect an intergalactic magnetic field with γ-ray cascades?



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What contributes to it? Why is it still uncertain?

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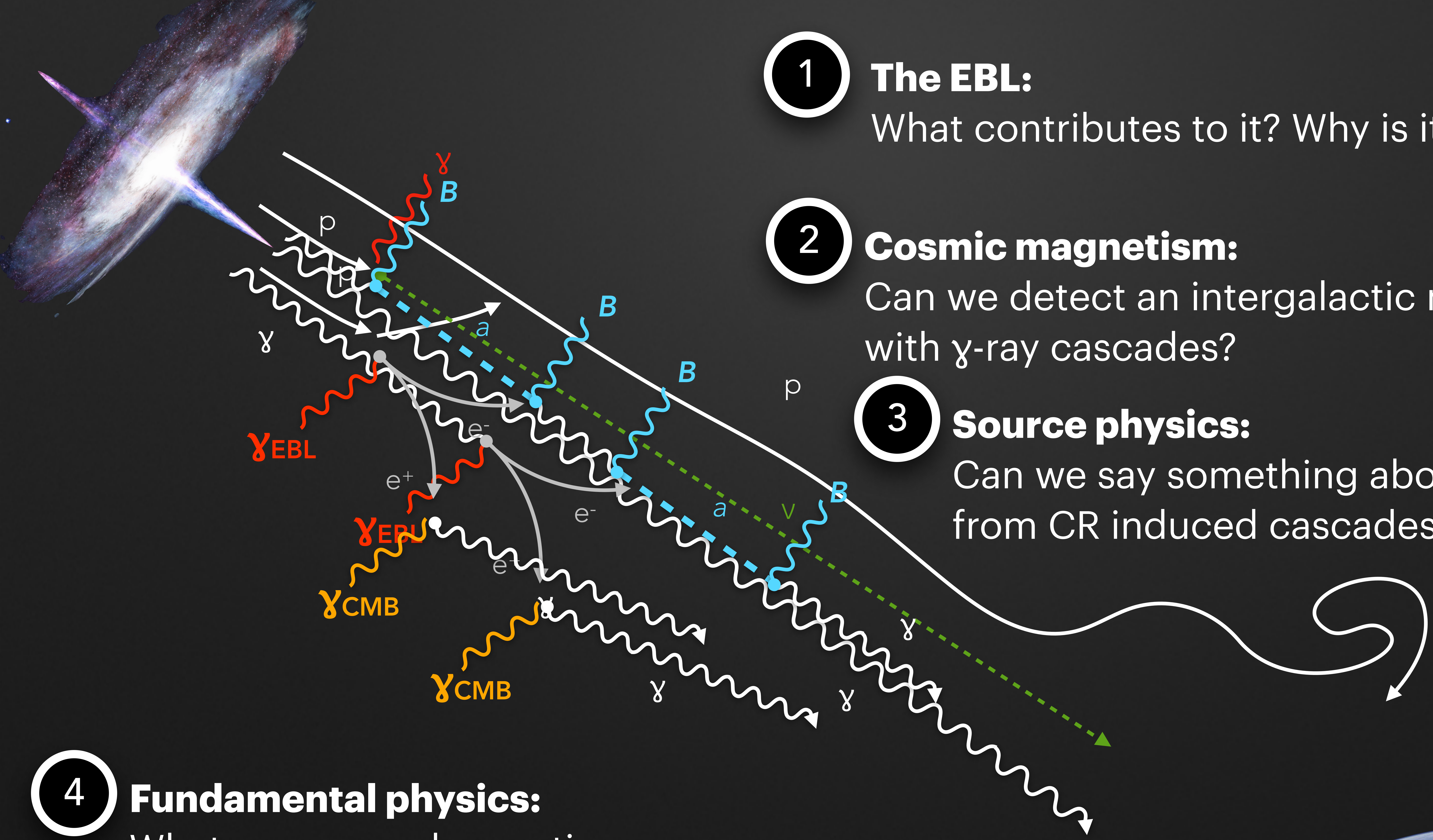
Can we say something about CR acceleration from CR induced cascades and neutrinos?



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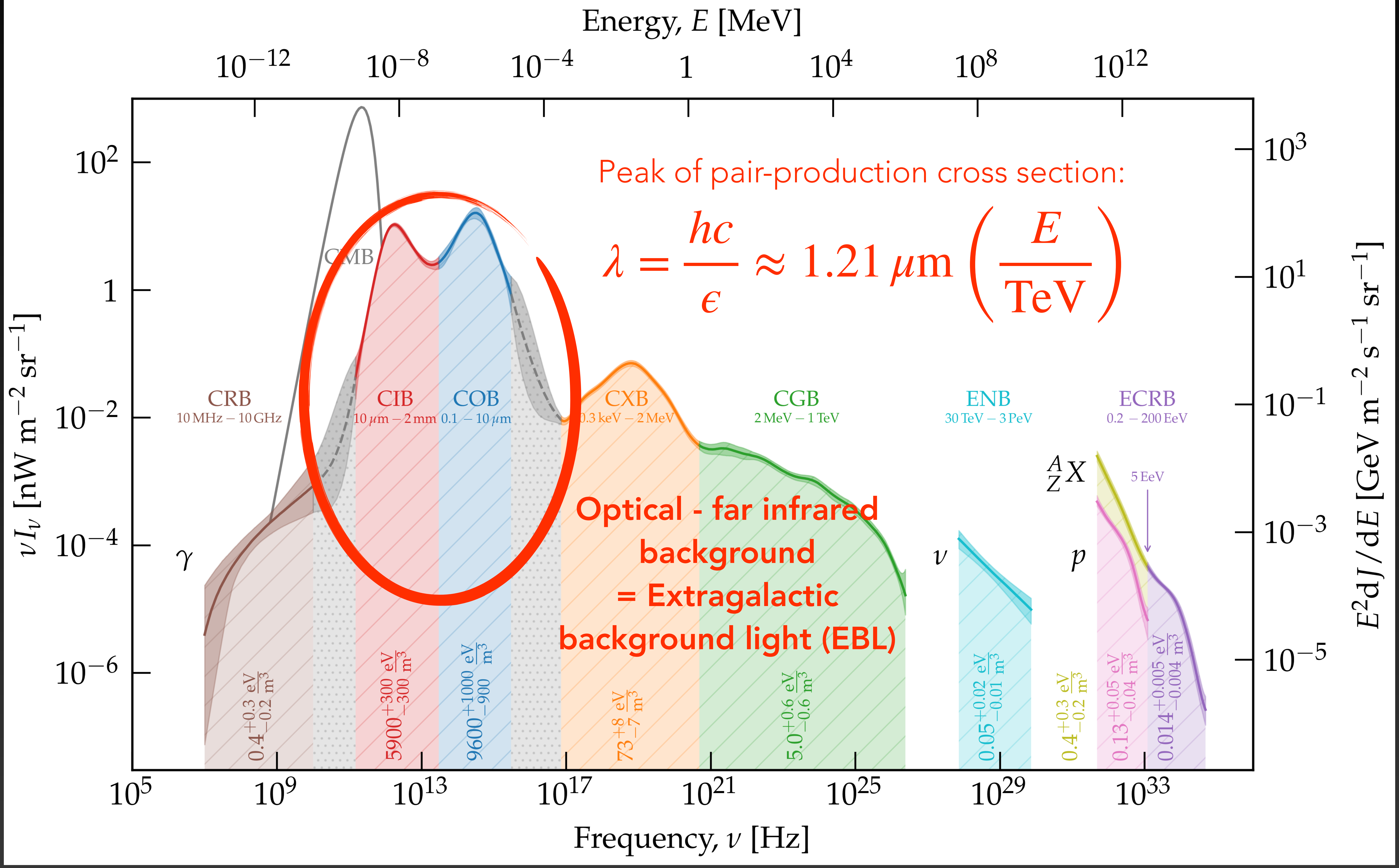
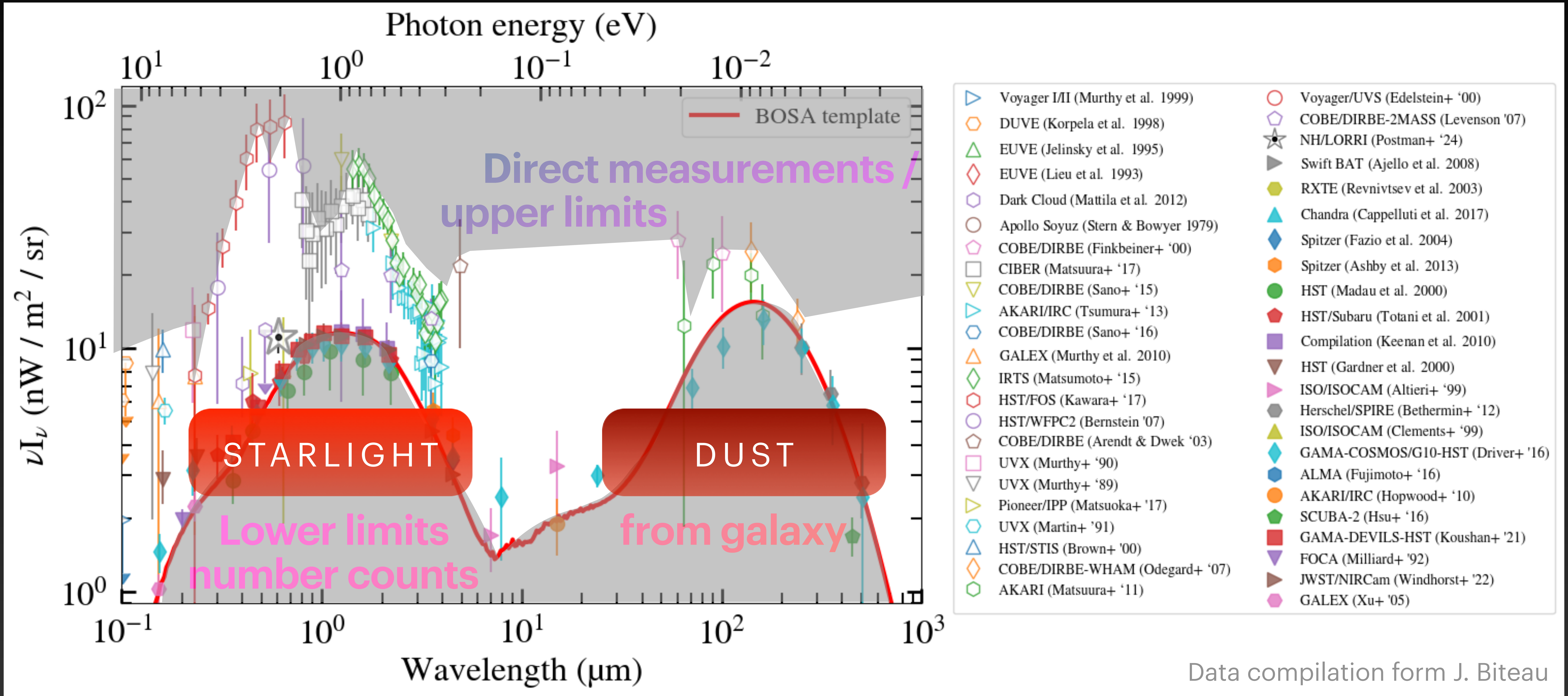
4 **Fundamental physics:**
What can γ-ray observations tell us about axions?

Background radiation fields



EBL Measurements



Data compilation form J. Biteau

$$\nu I_\nu(\lambda, z) = \frac{c^2}{4\pi\lambda} \int_z^{z_{\max}} \mathcal{E}_{\nu'}\left(\lambda \frac{1+z}{1+z'}, z'\right) \left|\frac{dt}{dz'}\right| dz'$$

[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013]

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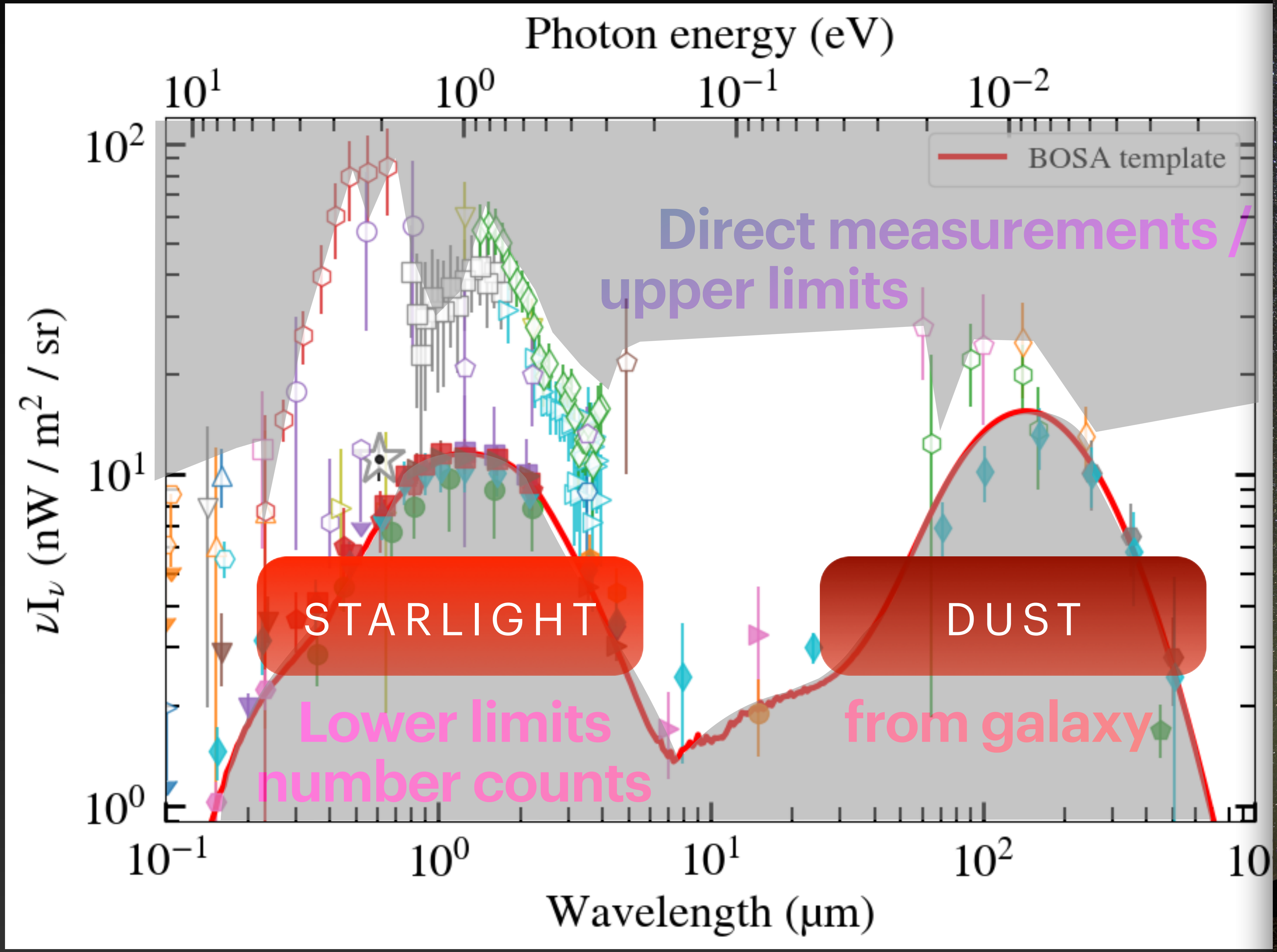

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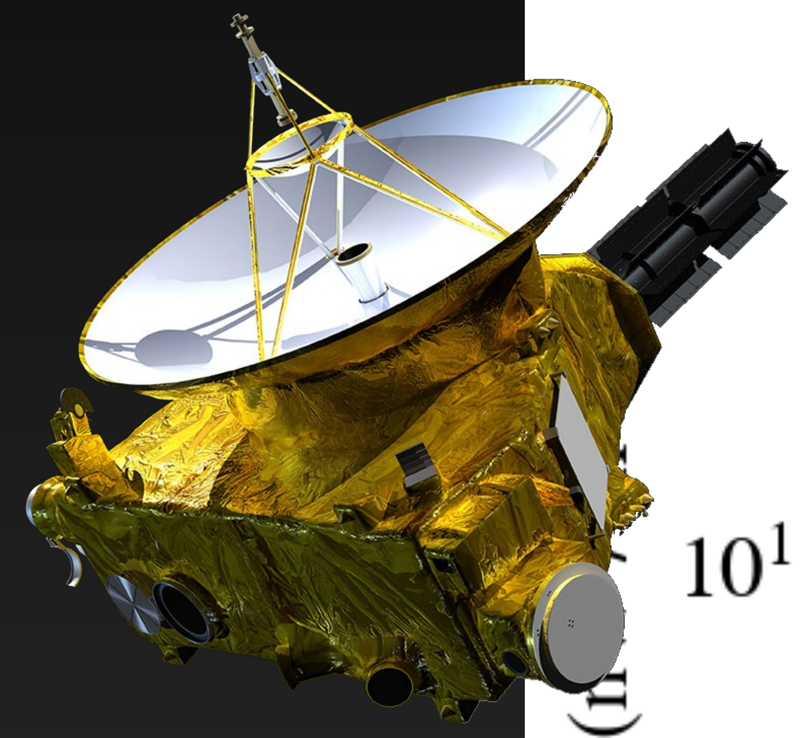
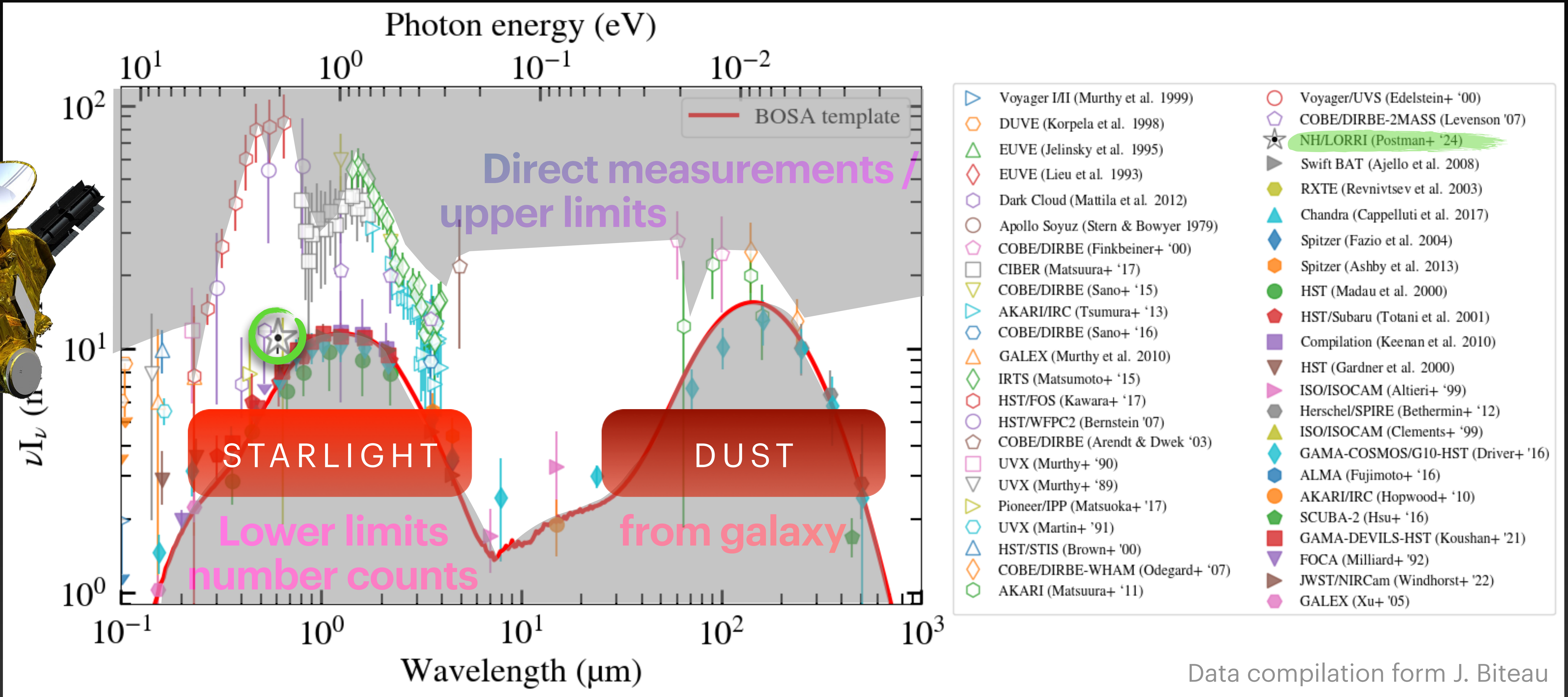


New Horizons Spacecraft / Long Range Reconnaissance Imager (LORRI): EBL measurement at **53 AU!**



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[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013]

Ingredients to the EBL: stars

EBL forward folding model

PhD Student
Sara Porras Bedmar (UHH)

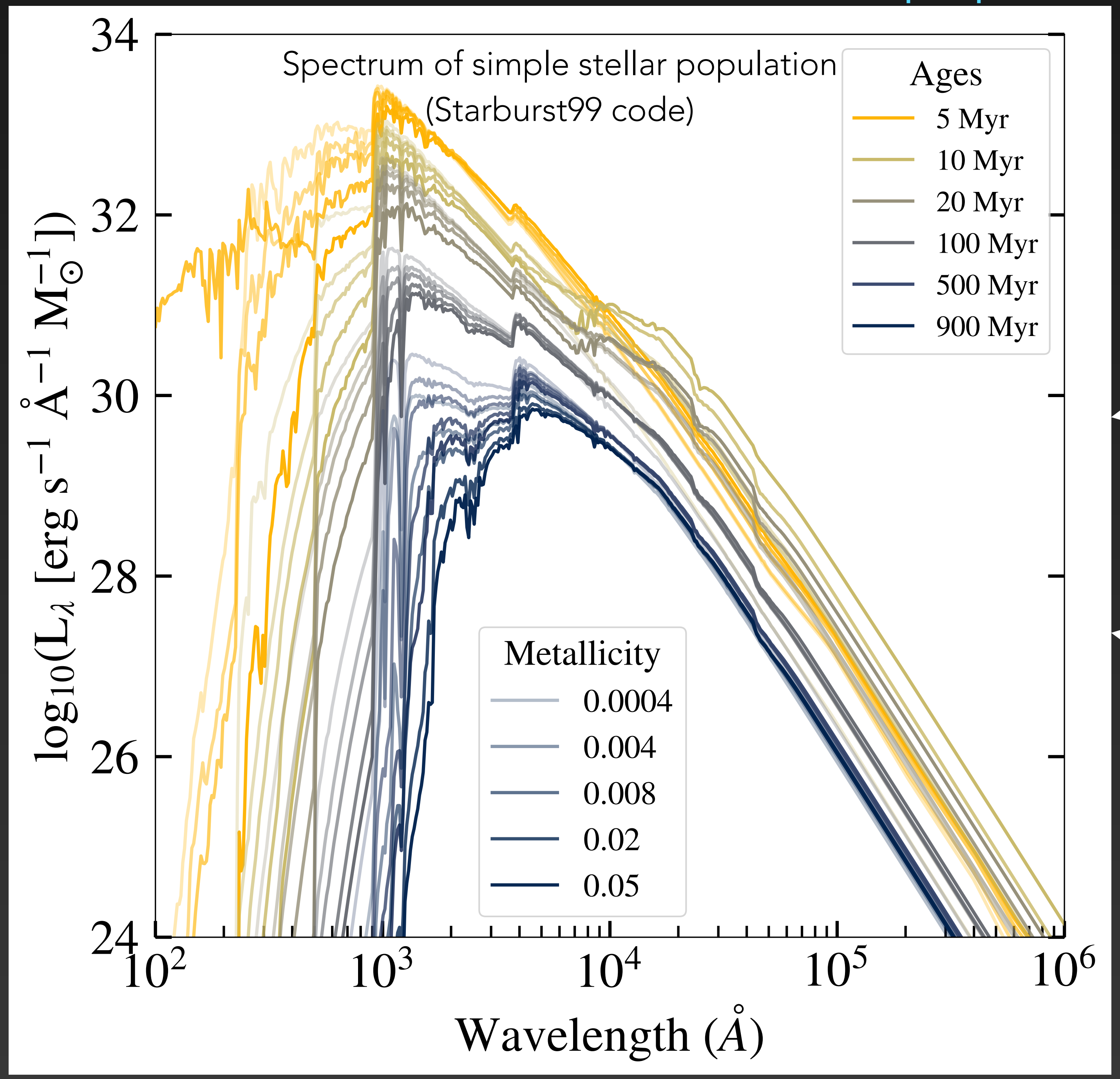
$$\mathcal{E}_\nu^{\rm stars}(z) = f_{\rm esc}(\lambda, z) \int_z^{z_{\max}} L_\nu^{\rm stars}(t_\star(z, z'))\ \psi(z') \left| \frac{dt}{dz'} \right| dz'$$

Photons escaping dust absorption

Luminosity of stellar population of age $t_\star$

$$t_\star(z, z') = \int_z^{z'} \left| \frac{dt}{dz''} \right| dz''$$

Age of stellar population



Initial mass function

Stellar metallicity

[Porras Bedmar, MM, Horns 2024, e.g. Finke et al. 2022]

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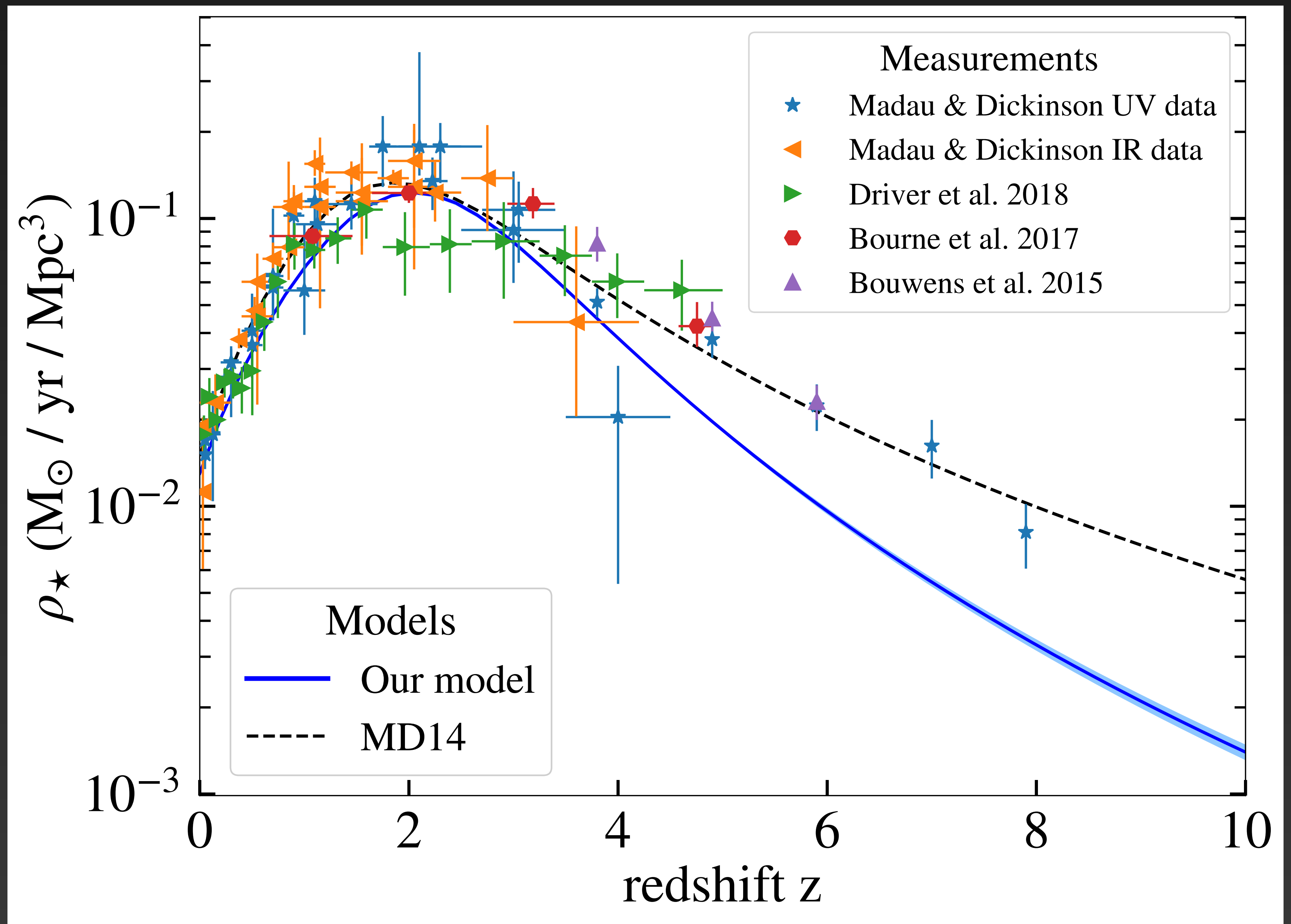
- $f_{\rm esc}(\lambda, z)$: Photons escaping dust absorption
- $L_\nu^{\rm stars}(t_\star(z, z'))$: Luminosity of stellar population of age $t_\star$
- $\psi(z')$: Cosmic star formation rate density



$$\psi(z) = \psi_0 \frac{(1+z)^\alpha}{1 + (\gamma(1+z))^\beta}$$

$$\psi_0 = 0.015\ M_\odot\ \mathrm{year}^{-1}\,\mathrm{Mpc}^{-3}$$

$$\alpha = 2.7$$

$$\beta = 5.6$$

$$\gamma = 1/2.9$$

MD14 parameters

[Porras Bedmar, MM, Horns 2024, e.g. Finke et al. 2022, Madau & Dickinson 2014]

Ingredients to the EBL: dust

EBL forward folding model - work in progress

PhD Student
Sara Porras Bedmar (UHH)

$$\mathcal{E}_\nu^{\mathrm{dust}}(z) = \int_z^{z_{\max}} L_\nu^{\mathrm{dust}}(t_\star(z, z'))\ \psi(z') \left| \frac{dt}{dz'} \right| dz'$$

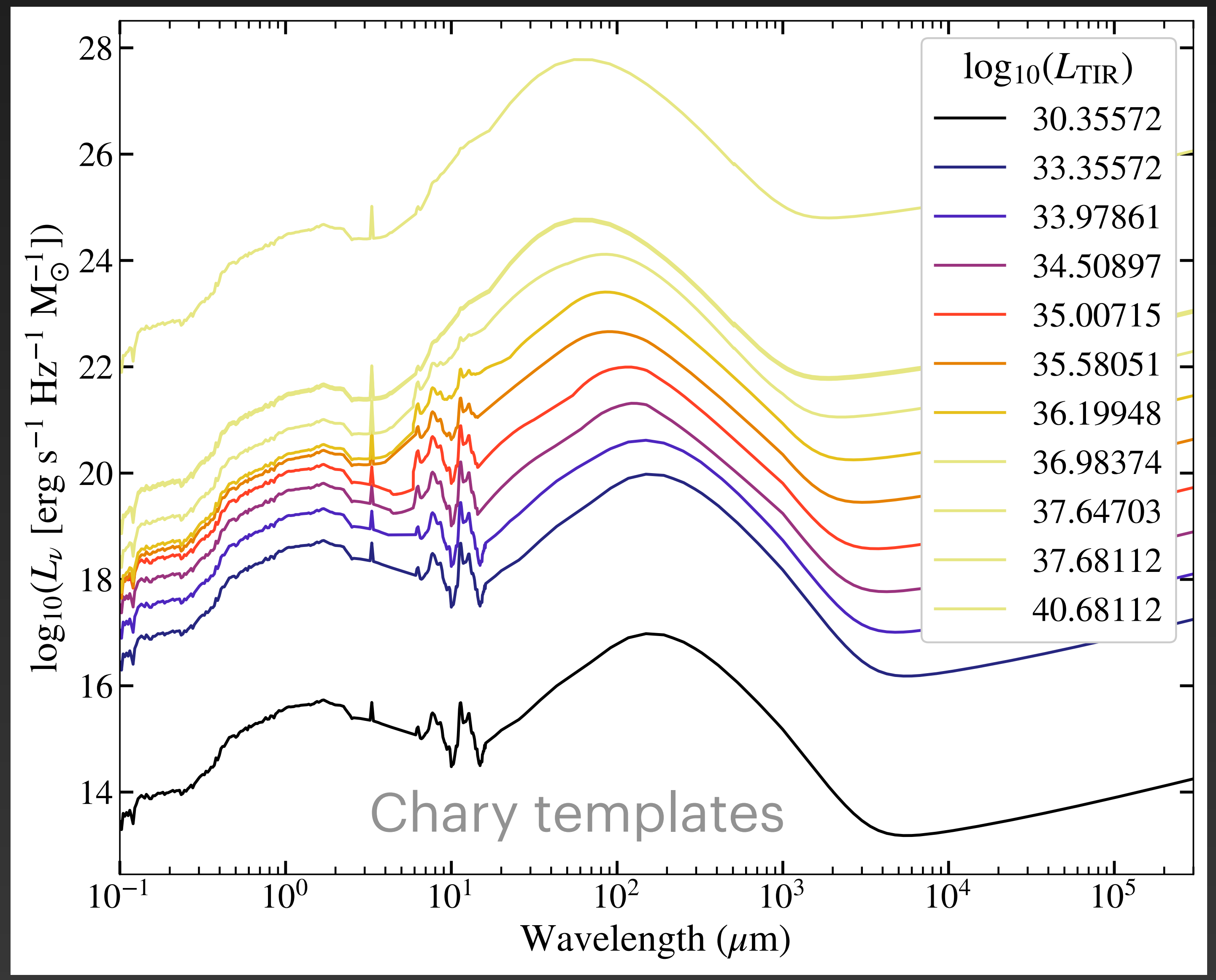
Luminosity of dust for stellar population of age $t_\star$

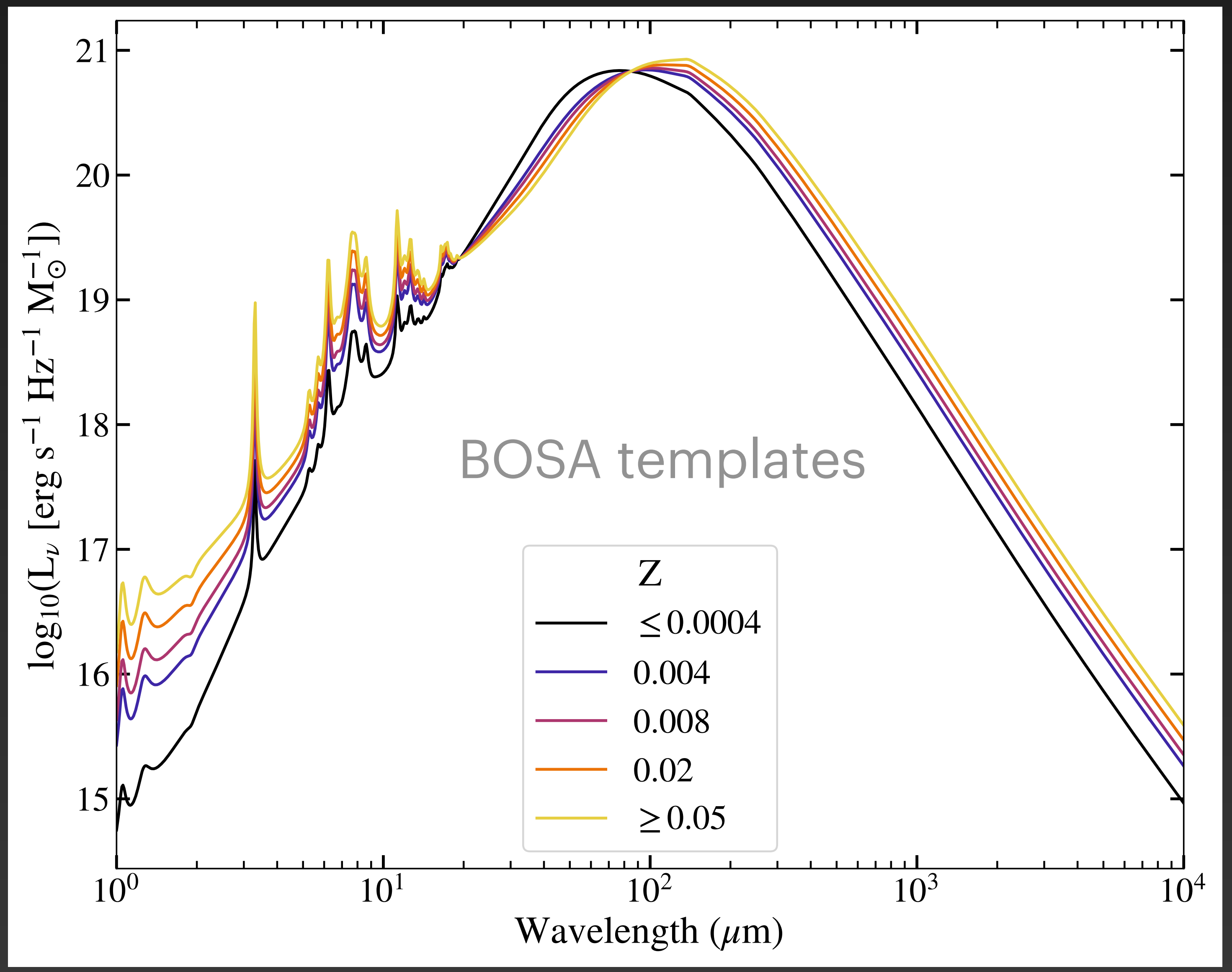
Normalized such that the total emitted luminosity is equal to the absorbed luminosity

$$L_{\mathrm{abs,SSP}}(t_\star) = \int \left(1 - f_{\mathrm{esc}}(\lambda, z)\right) L_\nu^{\mathrm{stars}}(\lambda, t_\star) d\nu$$

Dust reemission:

1. Templates from Chary et al. (2001)
2. BOSA Templates from Boquien & Salim (2021)
3. Three grey body spectra (three dust grain populations, Finke et al. 2022)





Putting it all together in a fit

COB fixed through emissivity data from galaxy number counts

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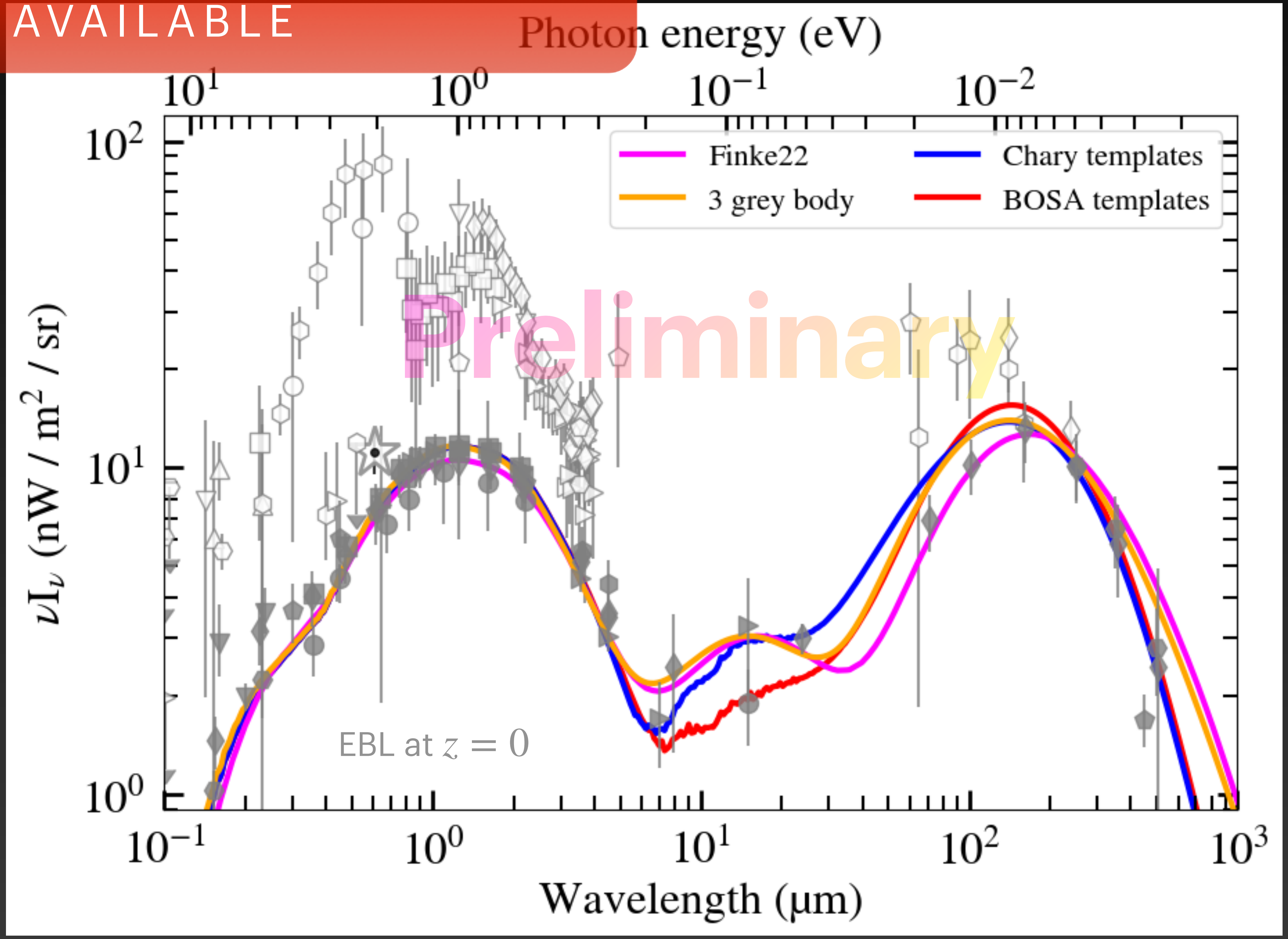
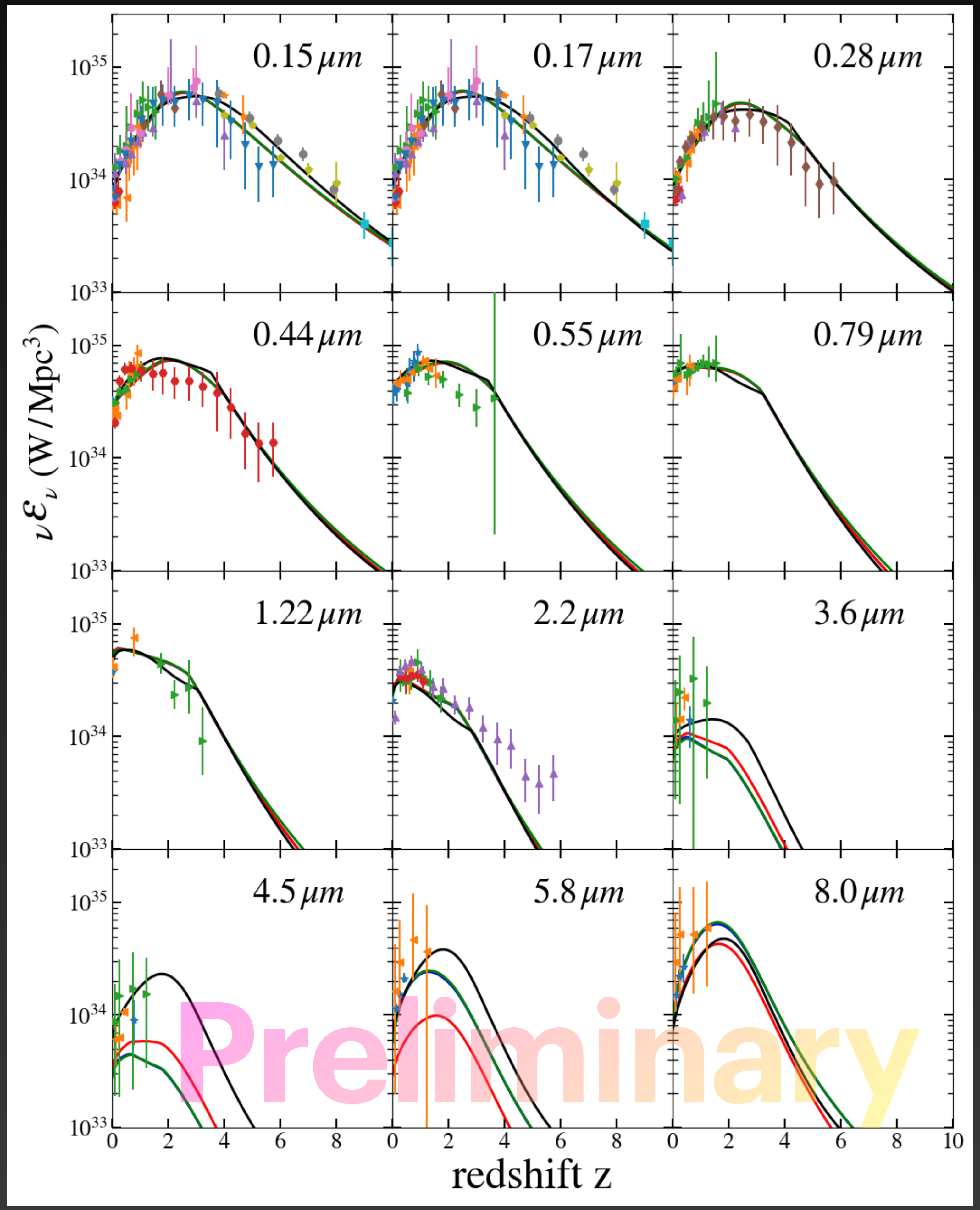
Sara Porras Bedmar (UHH)

EBL CODE WILL BE MADE PUBLICLY AVAILABLE



Fit to emissivity data



[Porras Bedmar, MM, Horns 2024, work in progress]

Additional contributions to the EBL?

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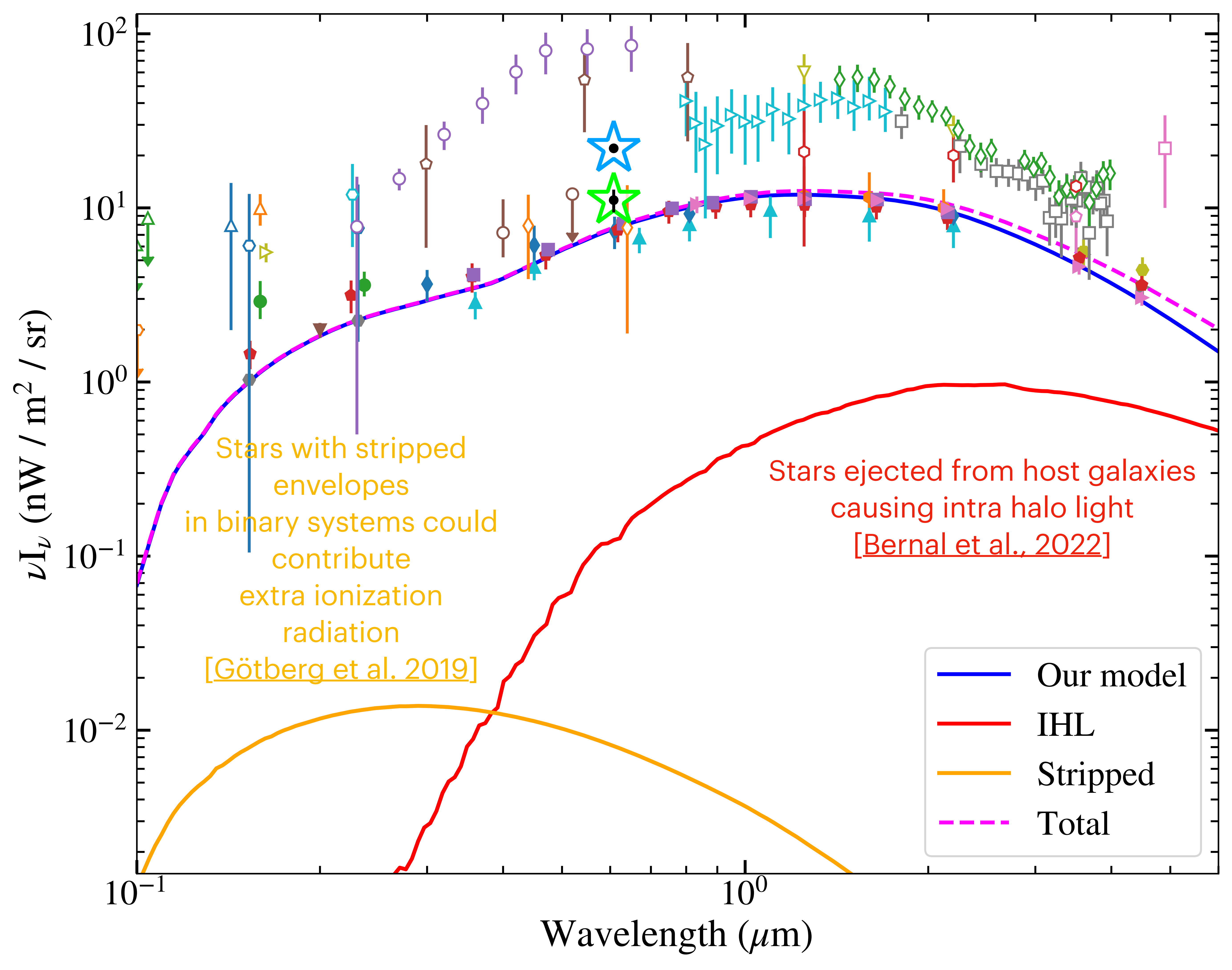
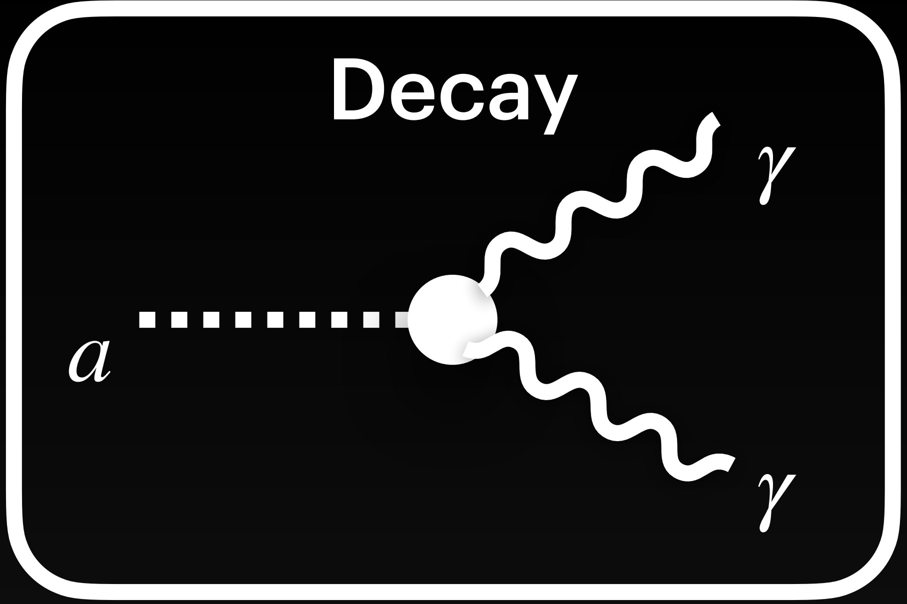


For COB: contributions negligible

[Porras Bedmar, MM, Horns 2024]

Cosmic axion decay



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- Axion dark matter would also decay over the entire history of the universe
- Contributes to isotropic photon backgrounds (see lecture on EBL)

$$\nu I_\nu(\lambda, z) = \frac{\Omega_a \rho_{\mathrm{crit},0}}{64\pi} \frac{m_a^2 g_{a\gamma}^2}{\lambda H(z_*)} \Theta(z_* - z)$$

With $z_* = \frac{m_a}{2} \frac{\lambda}{2\pi}(1+z) - 1$

Decay rate:

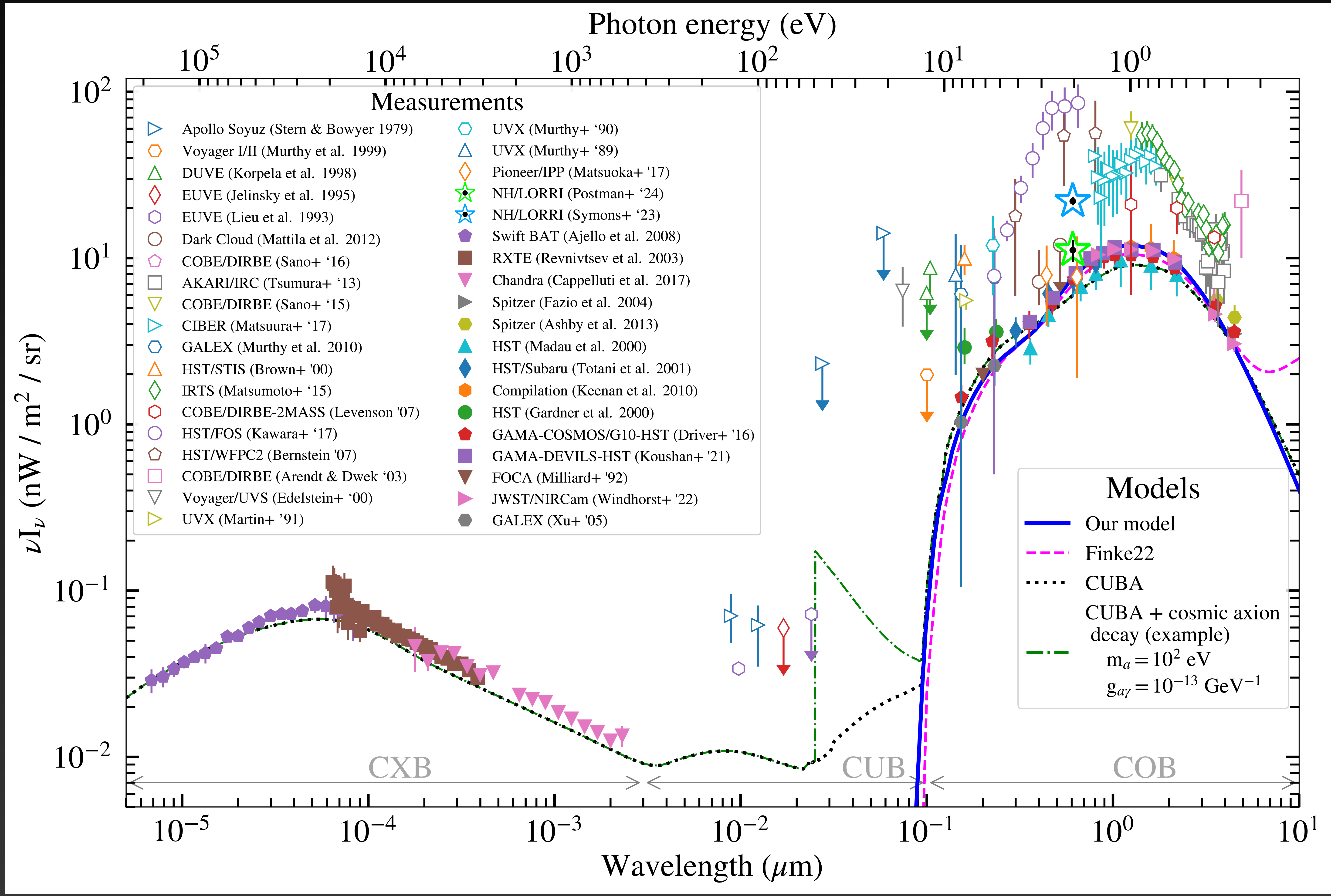
$$\Gamma_{a\gamma} = \tau_{a\gamma}^{-1} = \frac{m_a^3 g_{a\gamma}^2}{64\pi}$$

Decay time:

$$\tau_{a\gamma} \gtrsim 13.8\,\mathrm{Gyr} \left(\frac{5.5\times10^{-7}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2 \left(\frac{1\,\mathrm{eV}}{m_a}\right)^3$$

Decay wavelength:

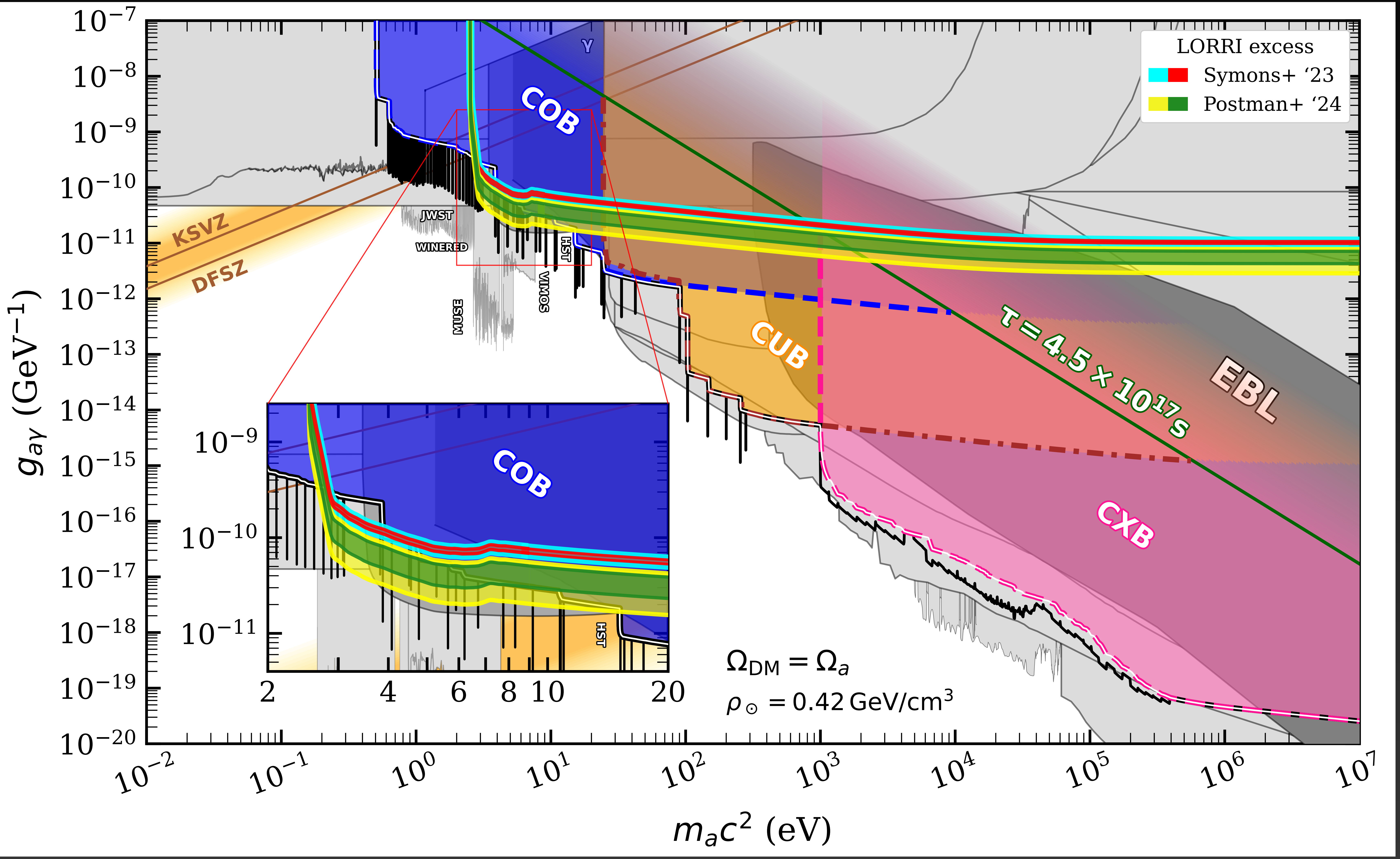
$$\lambda_a = \frac{4\pi}{m_a} = 2.48\,\mu\mathrm{m}\left(\frac{1\,\mathrm{eV}}{m_a}\right)$$



[Porras Bedmar, MM, Horns 2024]

Overduin 2002,
Cadamuro & Redondo 2012,
Bernal et al. 2023

Constraints from ALP decay



[Porras Bedmar, MM, Horns 2024]

Optical Depth

[redacted]

[redacted]

Line of sight integral to source

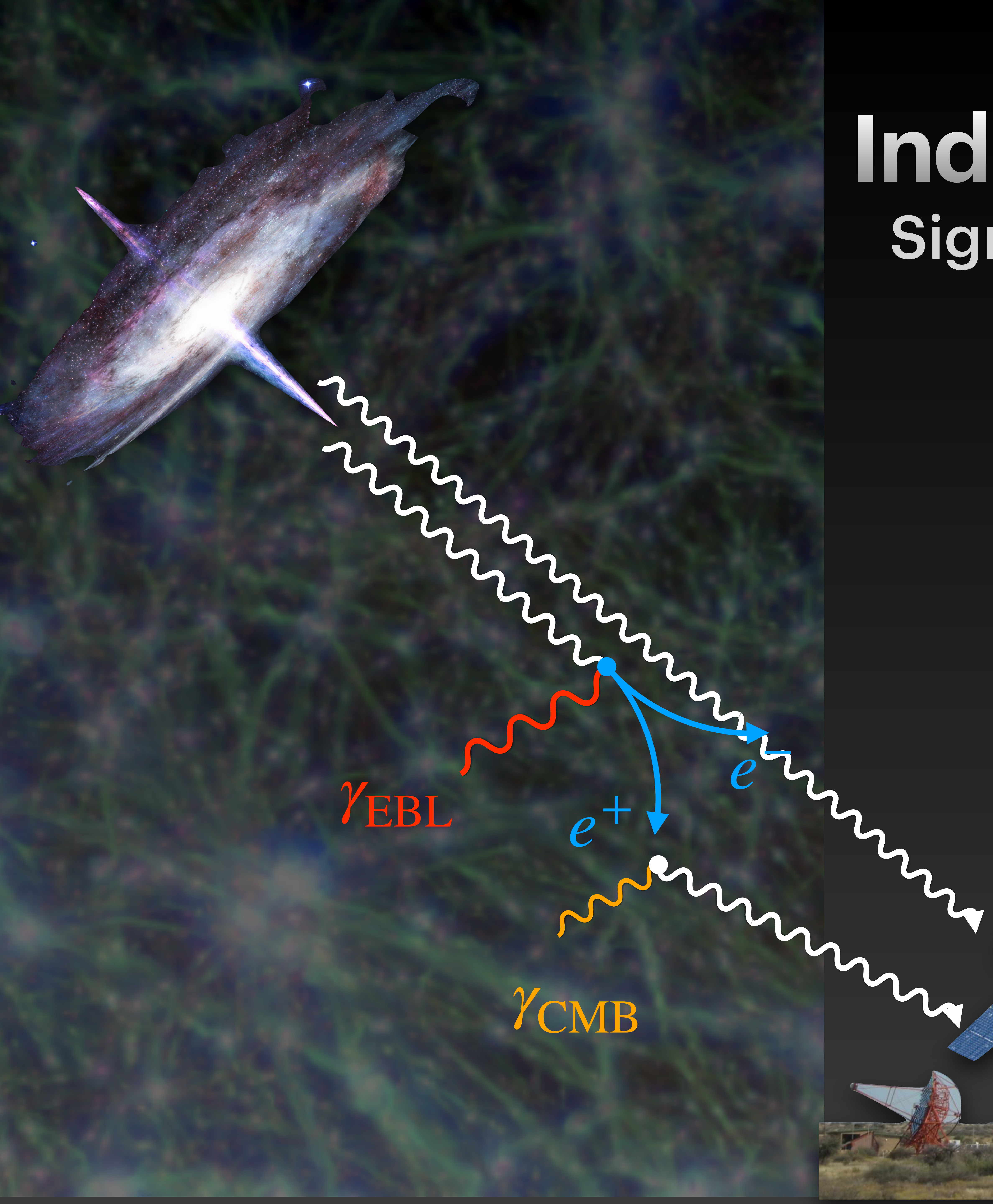
Integral over energy over photon density of background radiation field

Integral over angle $\mu = \cos\theta$ between photon momenta over pair-production cross section

[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013, Biteau & MM 2022]

Indirect detection of the IGMF

Signatures of an IGMF in γ-ray observations



- Excess ɣ rays at lower energies
  [e.g. Neronov & Semikoz 2008]
- Extended ɣ-ray halos [Aharonian et al. 1994]
- Time delayed ɣ-ray emission [Plaga 1995]
- Biggest uncertainty: blazar duty cycle
  [Dermer et al. 2011]

Constraints from Fermi LAT and H.E.S.S.

Aharonian et al. (2023), ApJL 950, 2, id.L16, 16, arXiv:2306.05132

Source Selection

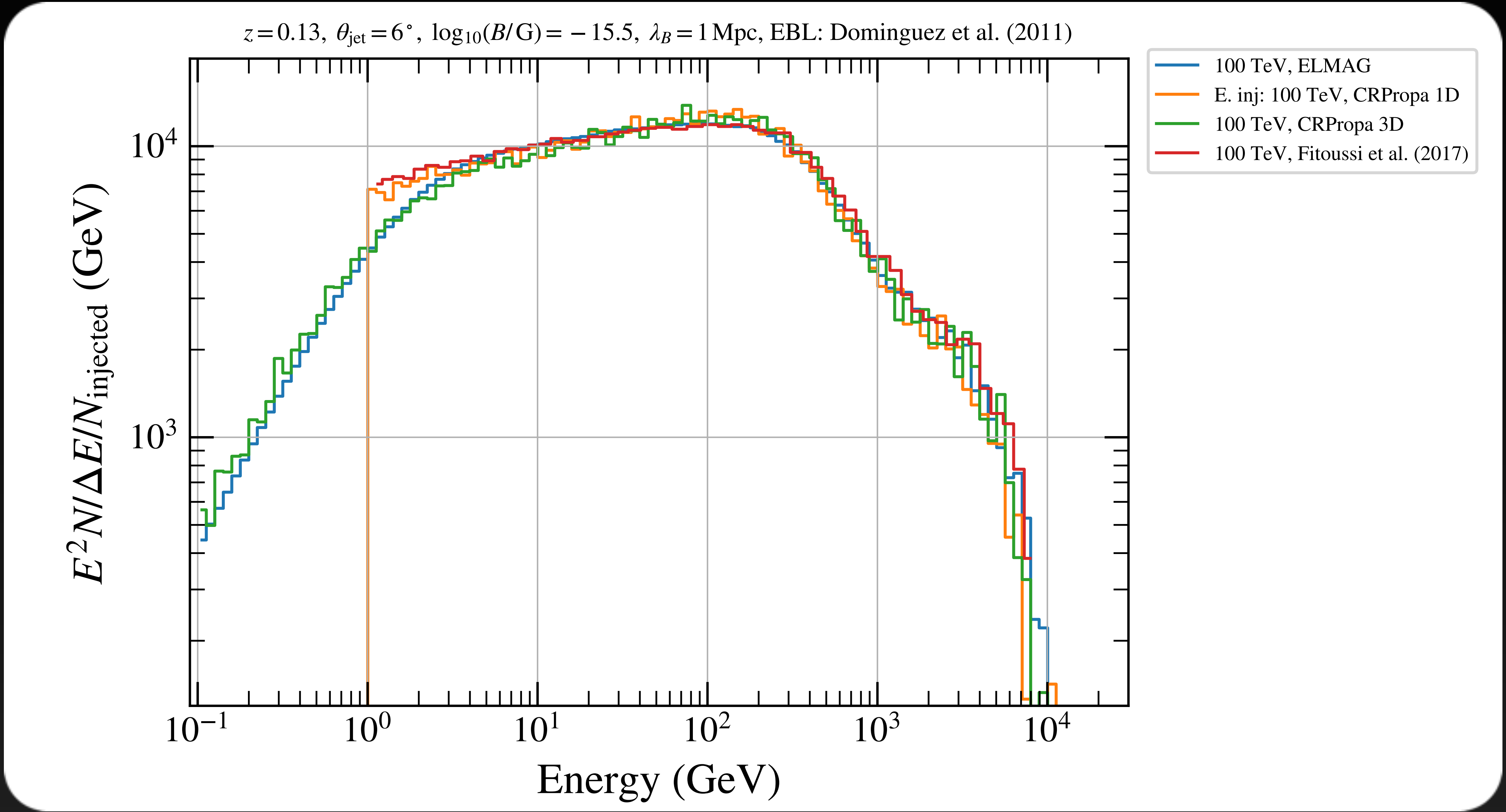
- **Demands**:
  - Emission at energies corresponding to strong absorption
  - Stable gamma-ray emission in time as seen with the LAT
  - $\Rightarrow$ extreme HBL sources
- **Source selection from 4LAC-DR2 catalog**:
  - Spectral type: power law & $\Gamma + \sigma_\Gamma < 2$
  - Redshift known
  - BL Lac source type with synchrotron peak $\nu_{\mathrm{Sync}} > 10^{17}\,\mathrm{Hz}$
  - Chance probability < 99% that source is variable
  - Sources with TeV counterpart observed with H.E.S.S.

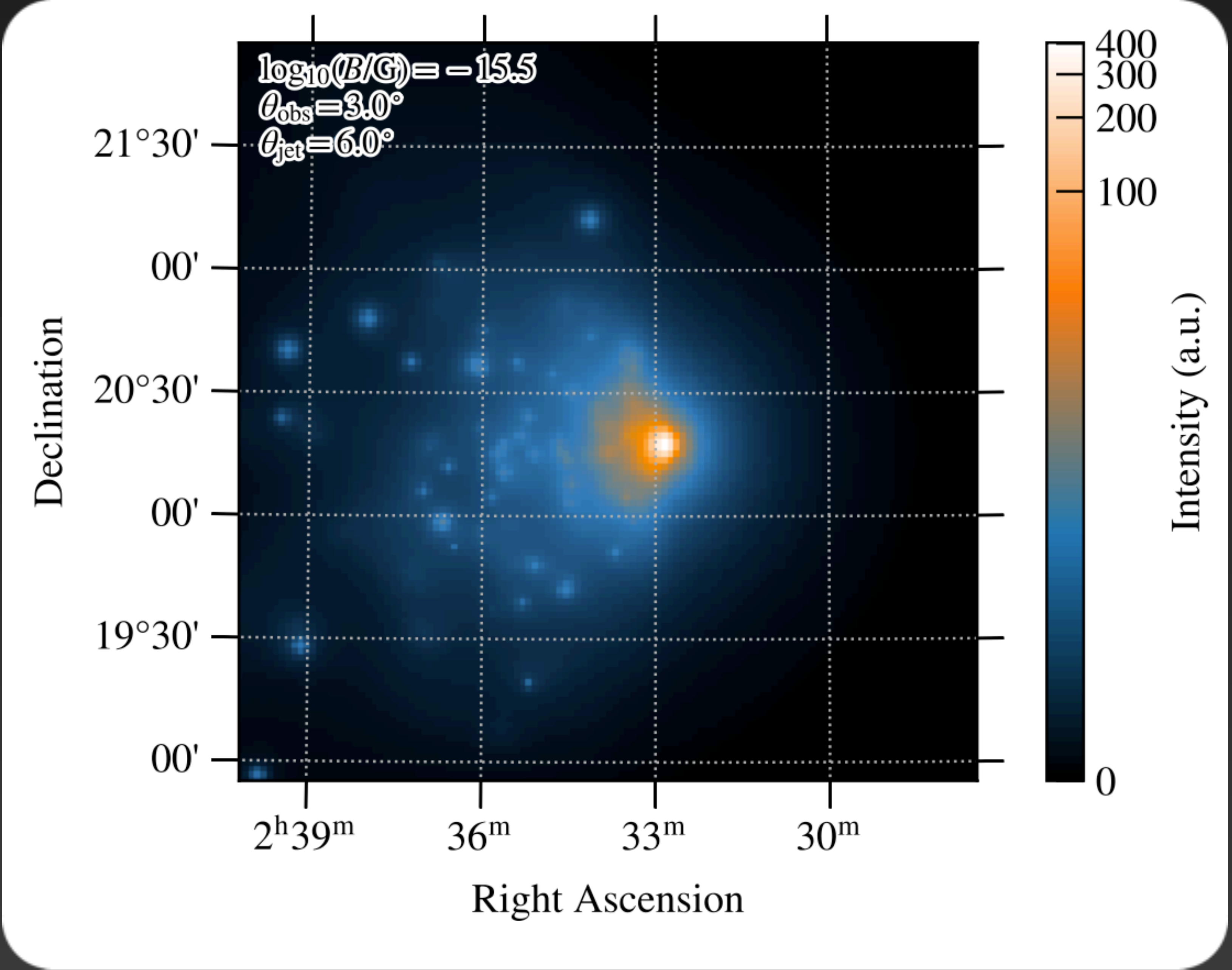
Resulting sources:

Source Name	Redshift
1ES 0229+200	0,139
1ES 0347-121	0,188
PKS 0548-322	0,069
1ES 1101-232	0,186
H 2356-309	0,165

Modeling the halo with CRPropa3

- CRPropa 3 Monte Carlo Code used to generate 4D (spatial + energy + delay time) halo templates
- In comoving coordinates
- Assumed magnetic field: **simple cell like structure**
  - $B = 10^{-16}\,\mathrm{G}, \ldots, 10^{-13}\,\mathrm{G}$
  - $\lambda_B = 1\,\mathrm{Mpc}$
- EBL model of Dominguez et al. (2011)

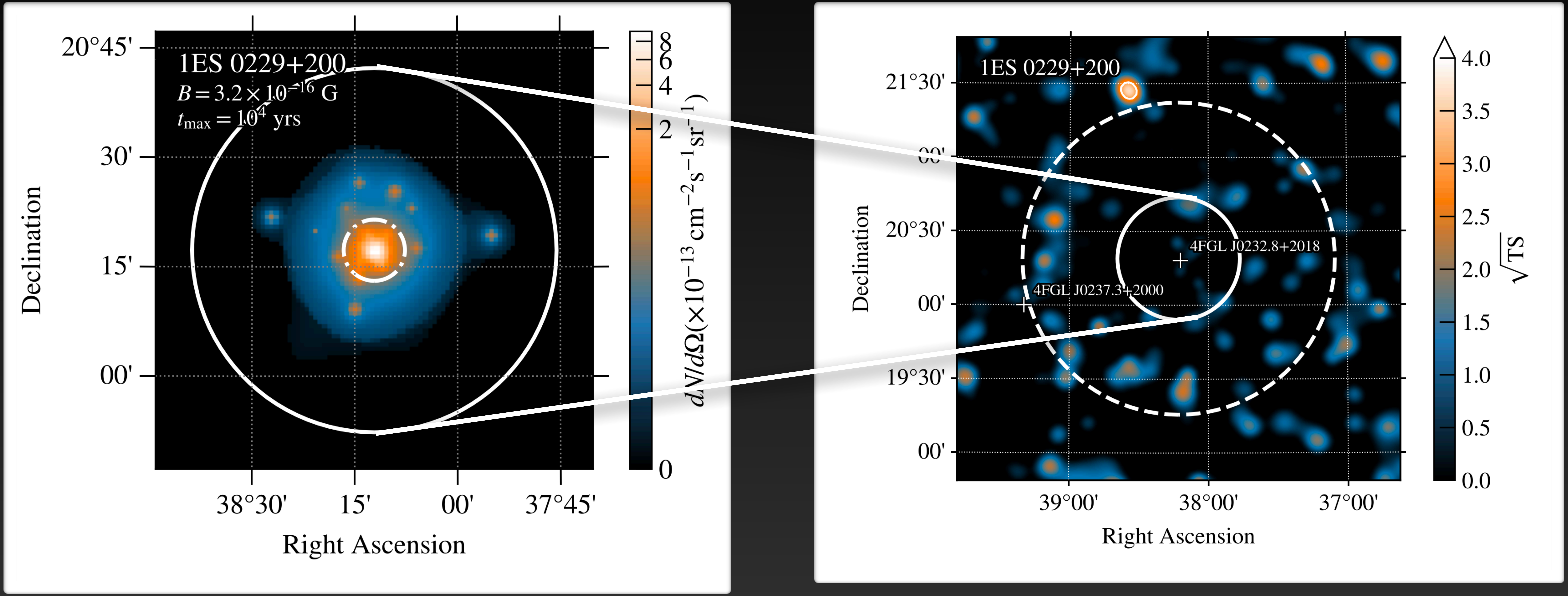




Searching for cascade emission in LAT data

Model expectation

TS map from data



- TS map tests at each pixel if additional emission is present
- No un-modeled excess emission in vicinity of sources observed

H.E.S.S. Data sets

- Data taken with small telescopes up to 2018 considered here
- Analysis performed using gammapy [Deil et al. 2017]
- Source spectra $\phi_{\rm obs}$ well described by power law including EBL absorption, $\phi_{\rm obs} = N(E/E_0)^{-\Gamma}\exp(-\tau)$

Source	Life time (hours)	Detection significance	Power law index Γ
1ES 0229+200	144,1	16.5σ	1.76 ± 0.12
1ES 0347-121	59,2	16.1σ	2.12 ± 0.15
PKS 0548-322	53,9	10.2σ	1.92 ± 0.12
1ES 1101-232	71,9	18.7σ	1.66 ± 0.09
H 2356-309	150,5	23.4σ	2.10 ± 0.09

Combined H.E.S.S. and LAT analysis

- Intrinsic blazar model **(assumed constant over activity time)**:

$$\phi(E) = N\left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

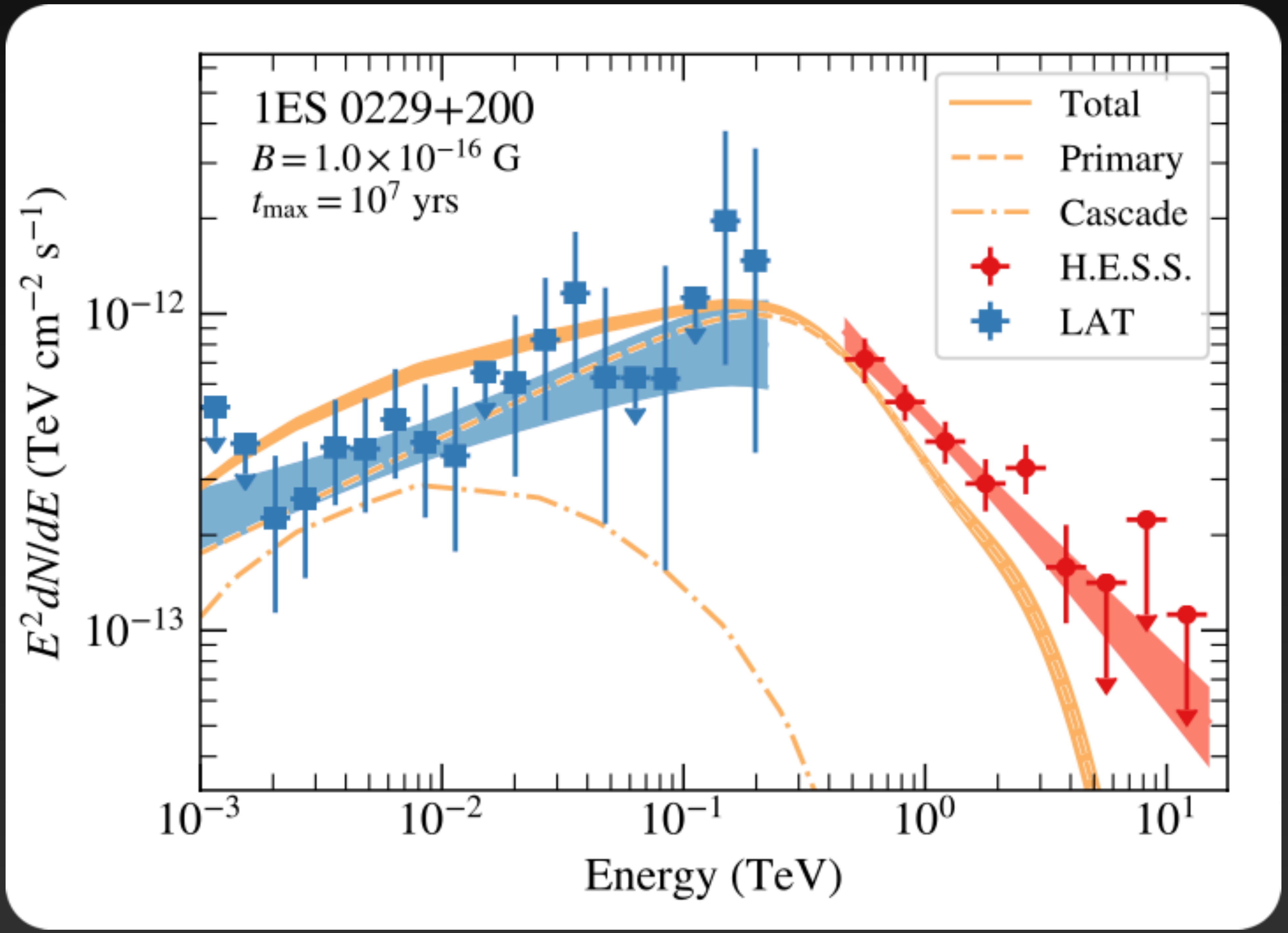
- Total source model: $\phi_{\mathrm{tot}}(E,B) = \phi(E)\exp(-\tau) + \phi_{\mathrm{halo}}(E,B)$

- Halo flux taken from CRPropa3 simulation; depends on spectral parameters, blazar activity time...

- Spectral parameters optimized using combined H.E.S.S. and LAT likelihoods:

$$\ln \mathscr{L} = \ln \mathscr{L}_{\mathrm{LAT}} + \ln \mathscr{L}_{\mathrm{H.E.S.S.}}$$

- Takes both spectral and spatial (for LAT) information into account



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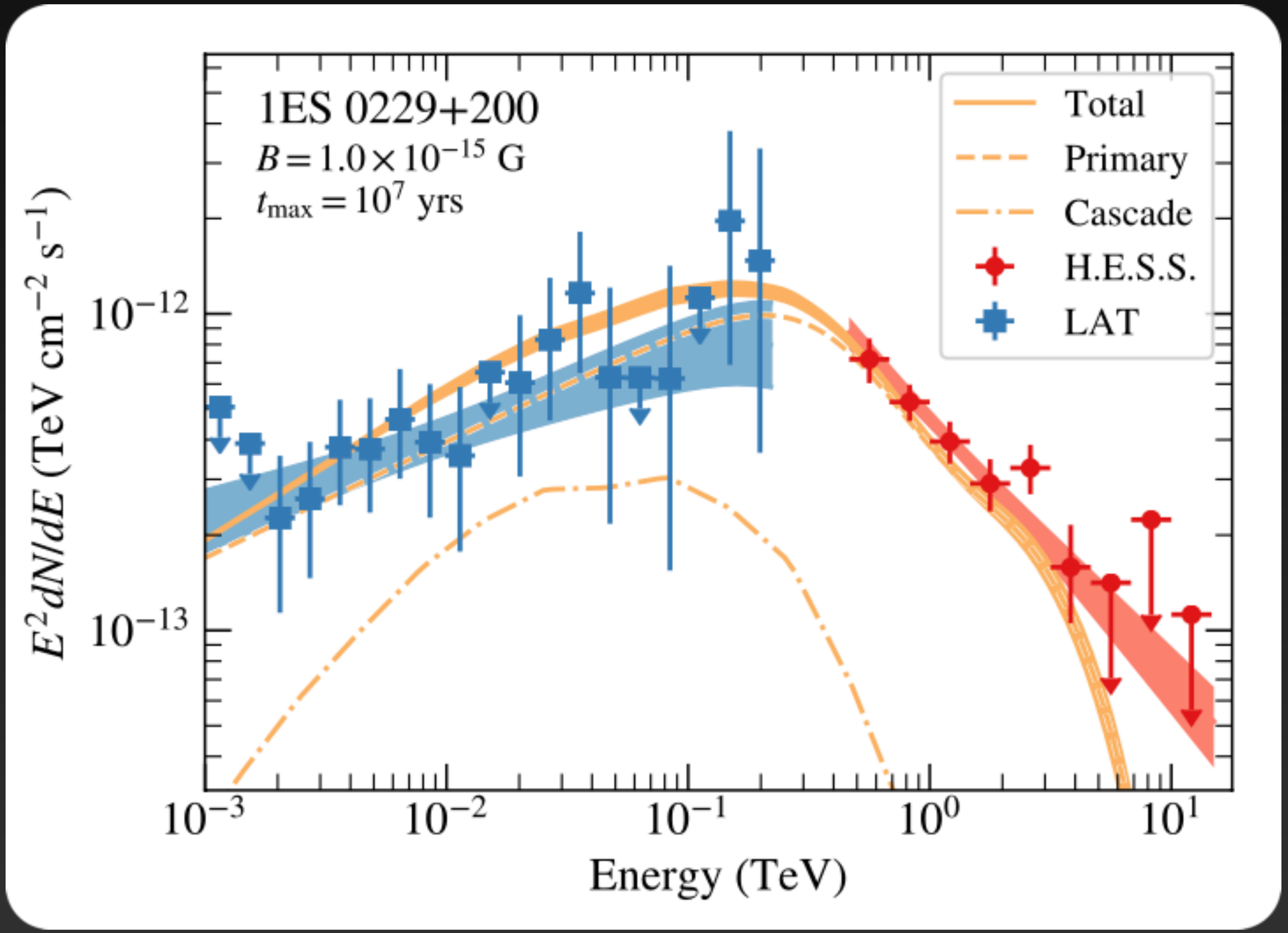

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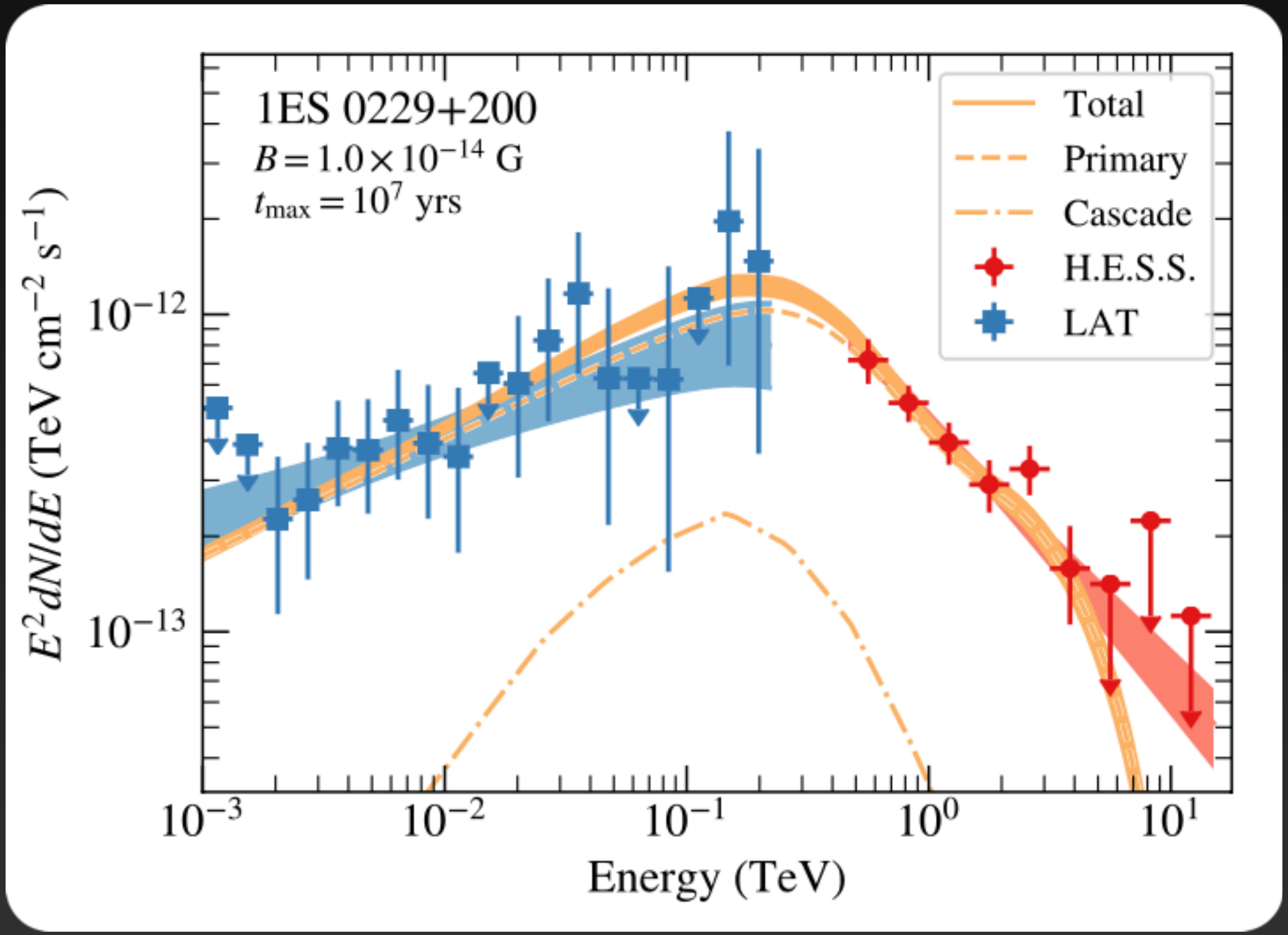

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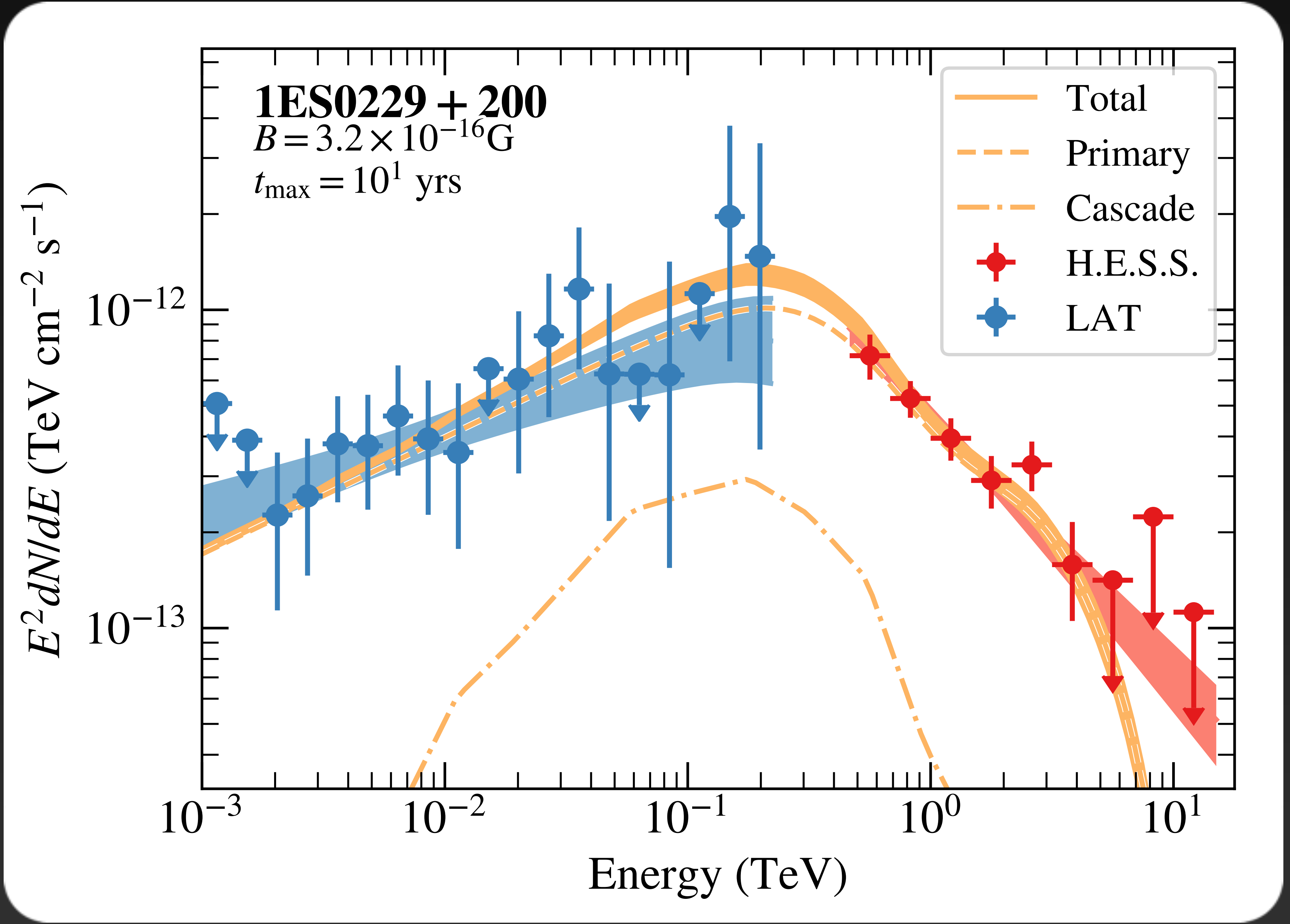

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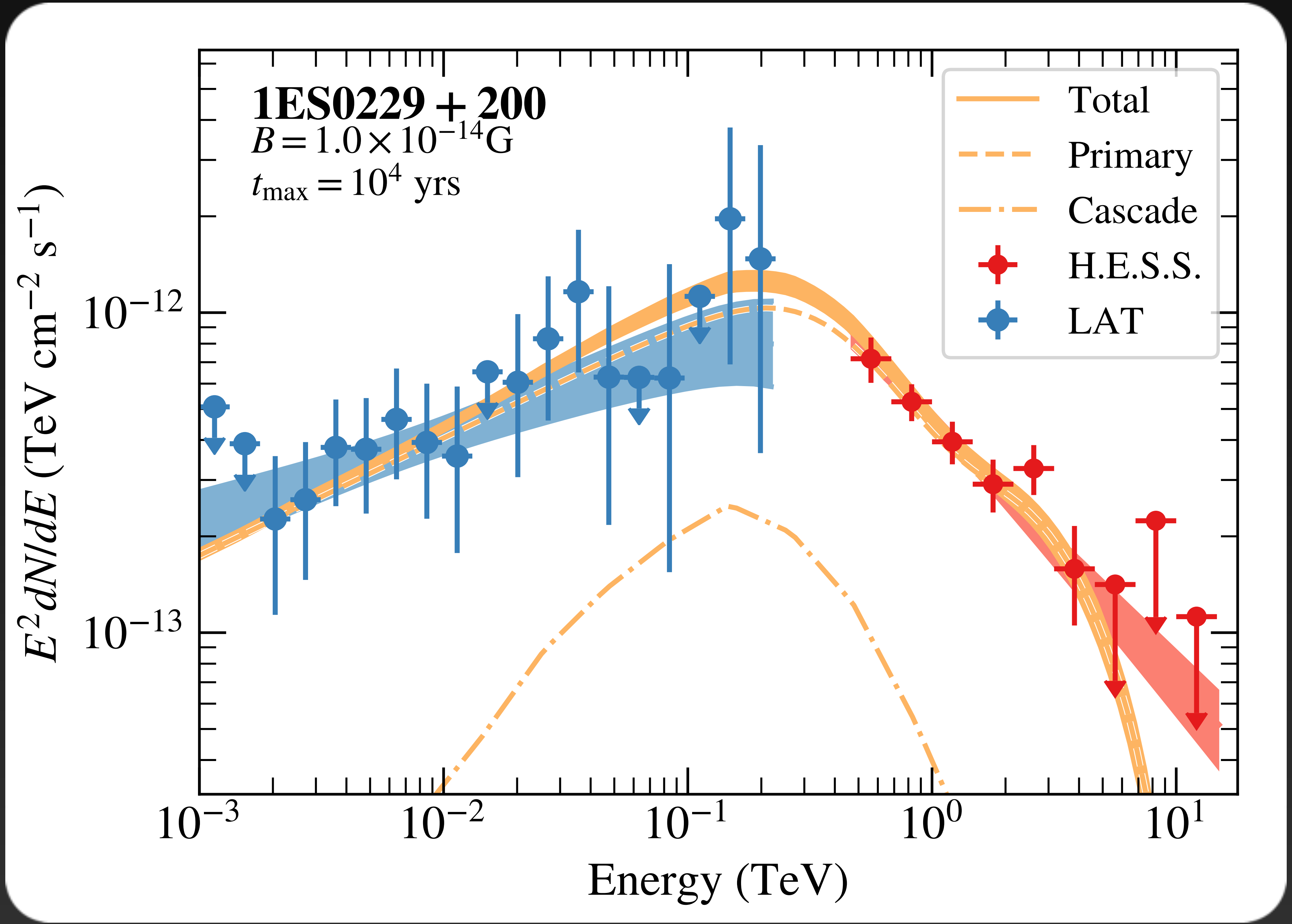
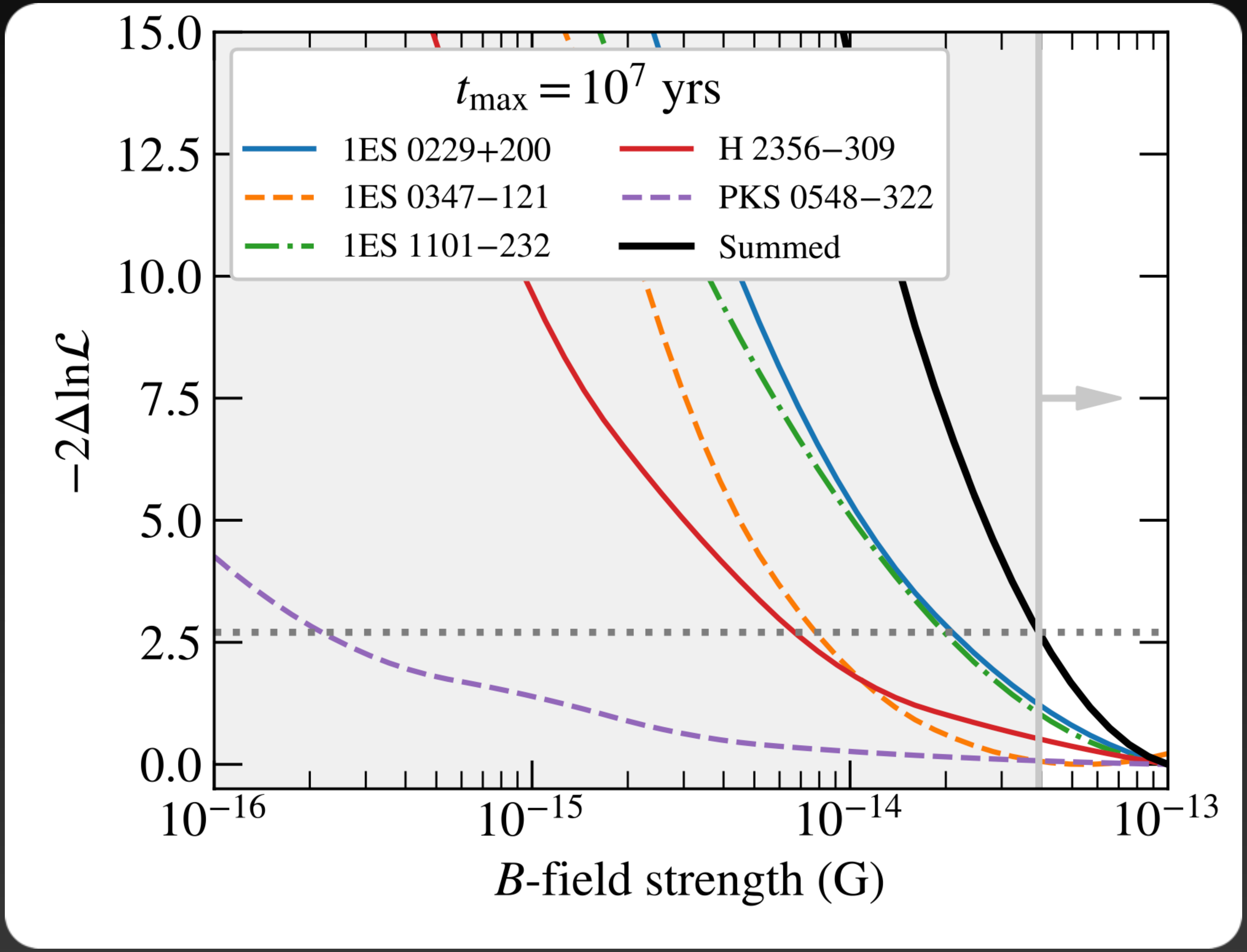


Results: lower limits on IGMF

Data does not prefer presence of halo



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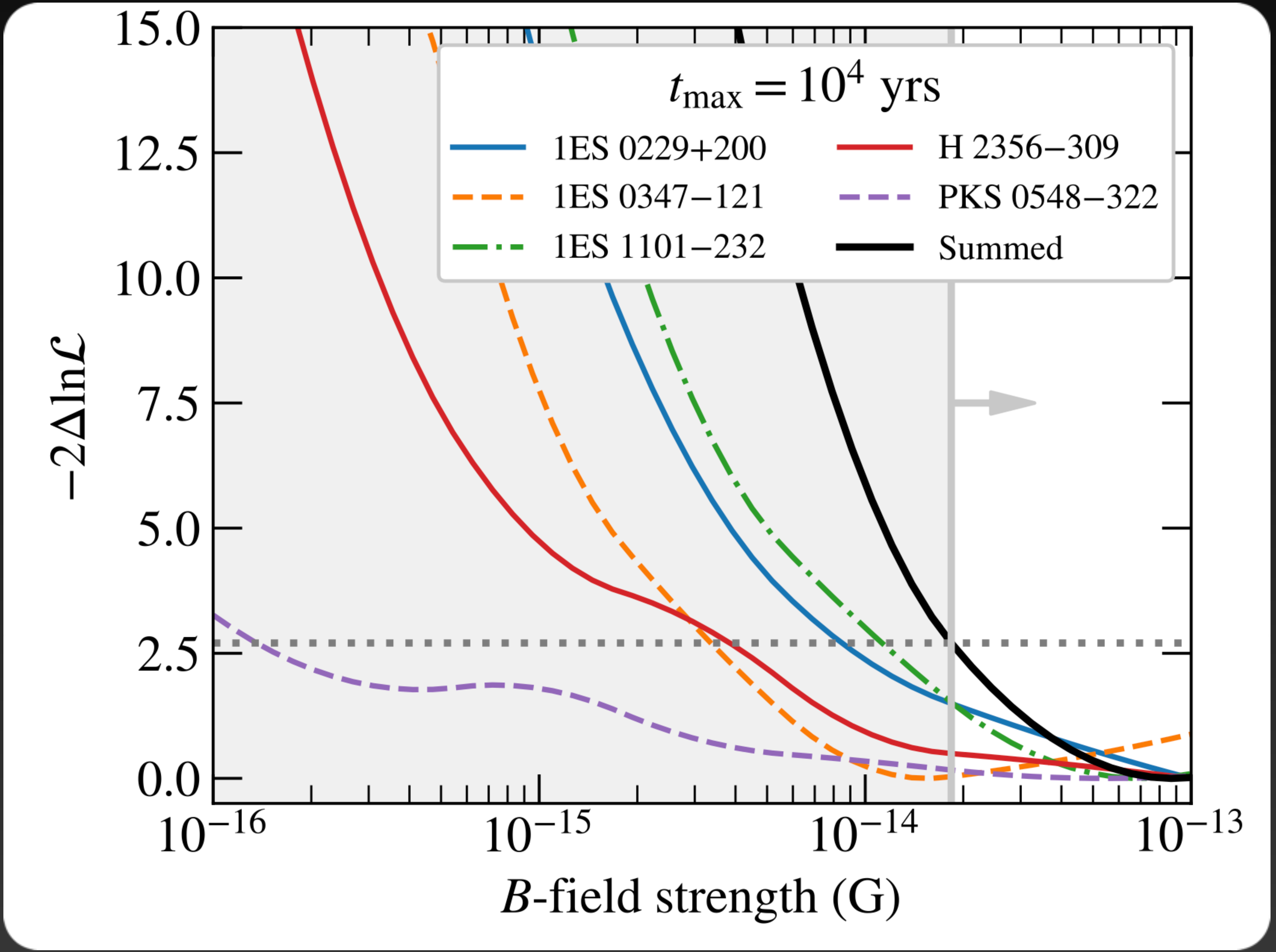
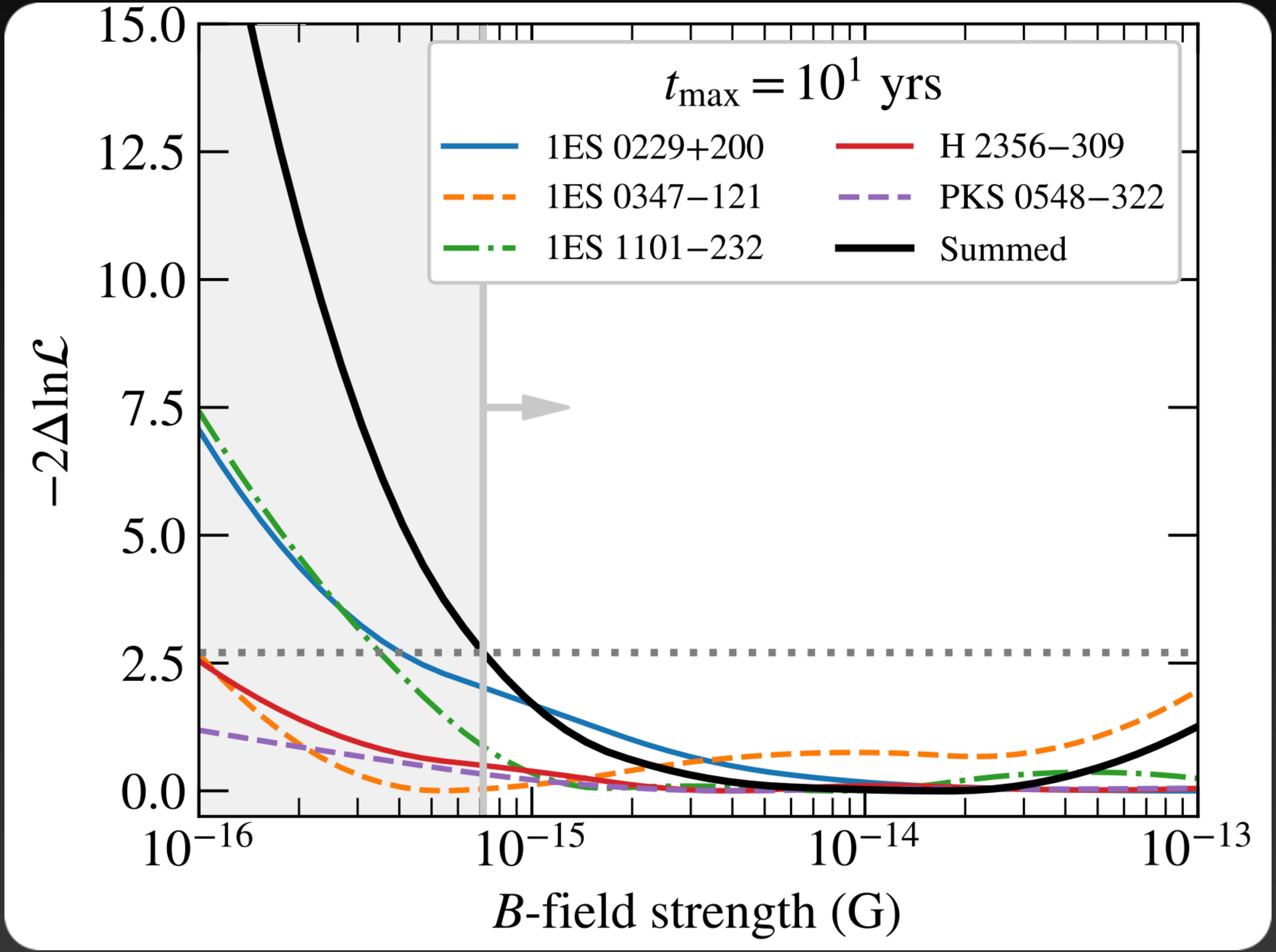


Results: lower limits on IGMF

Data does not prefer presence of halo



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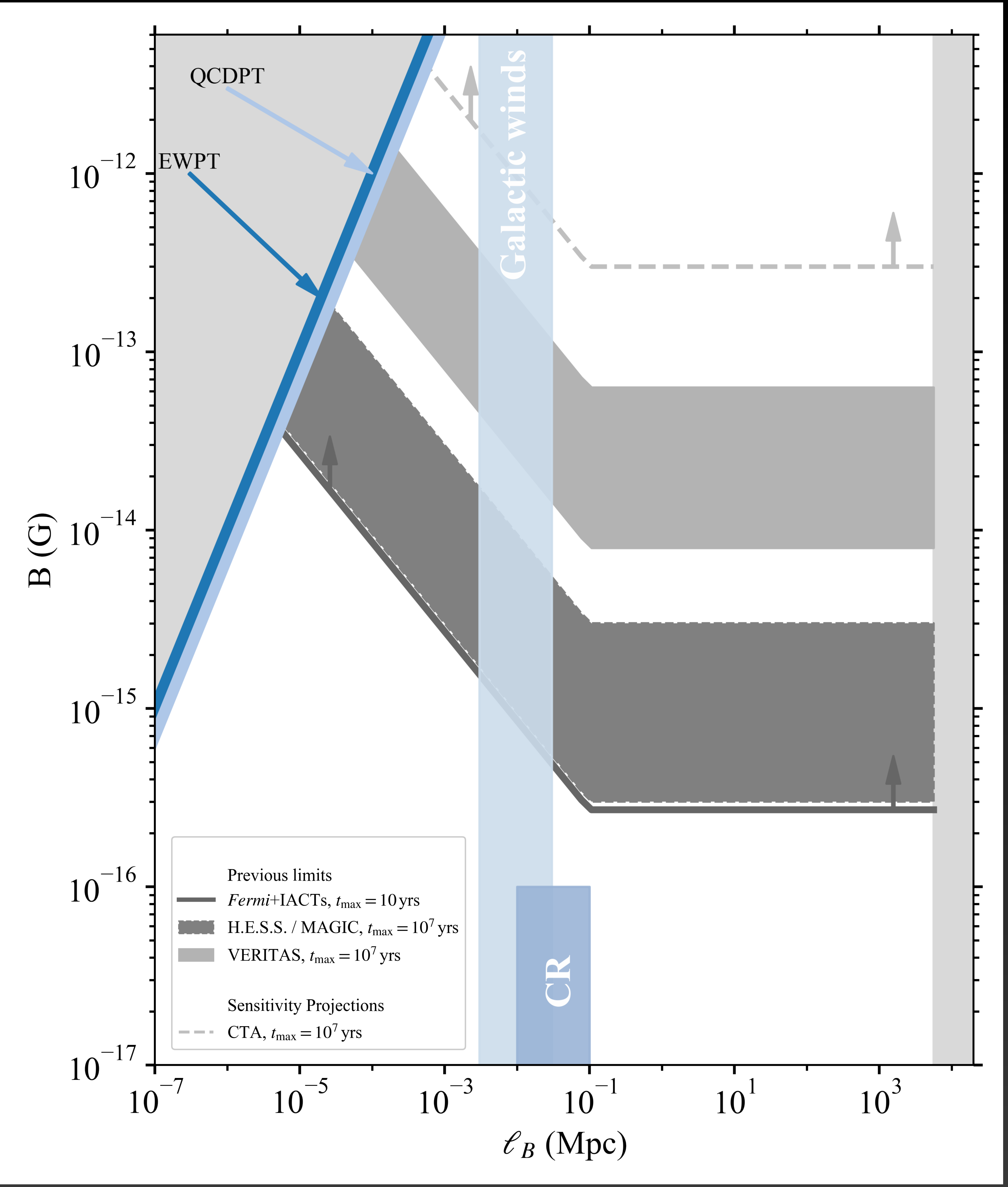
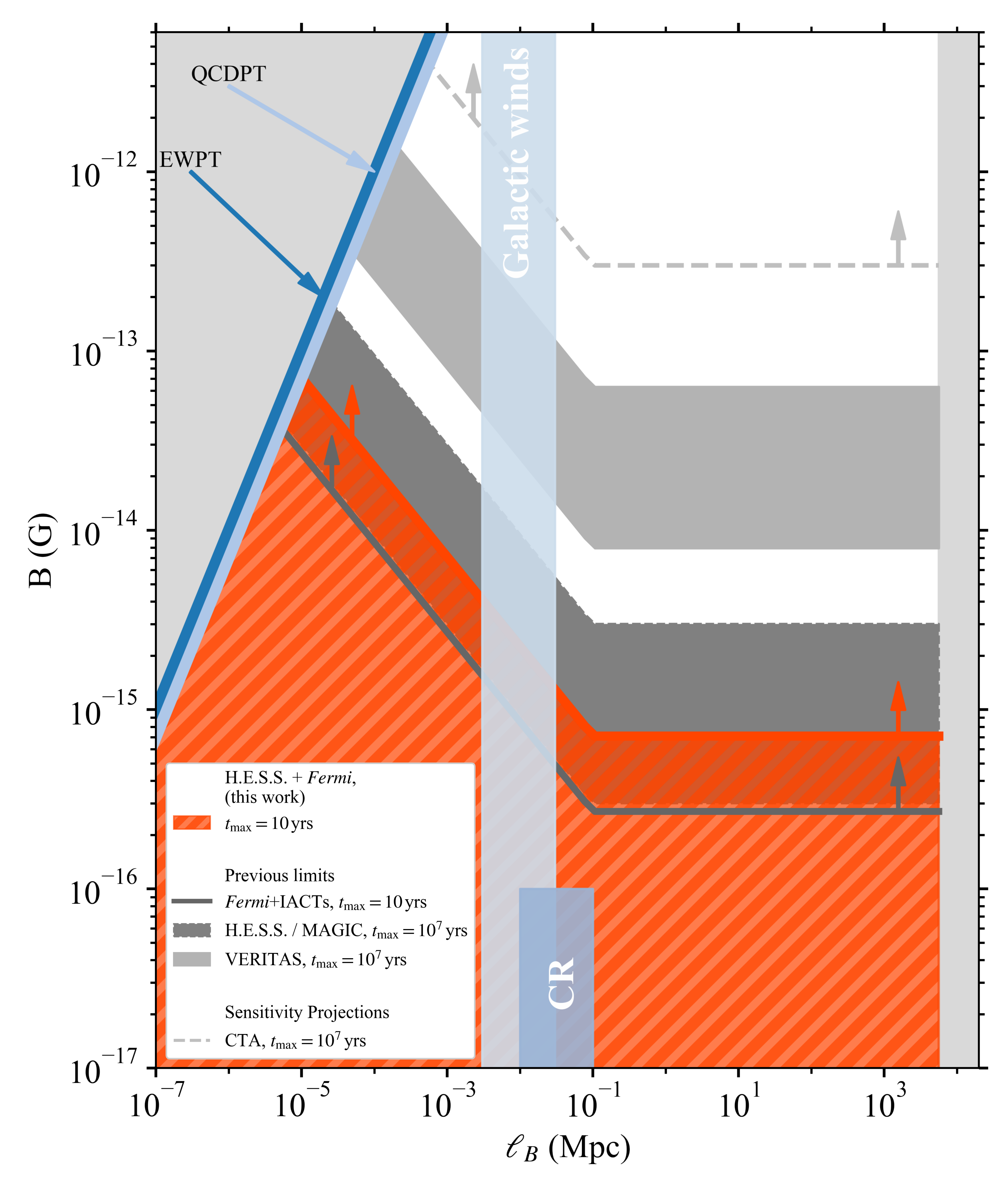


[Adapted from Durrer & Neronov 2013 and Abdalla et al. 2021]

Results: lower limits on IGMF



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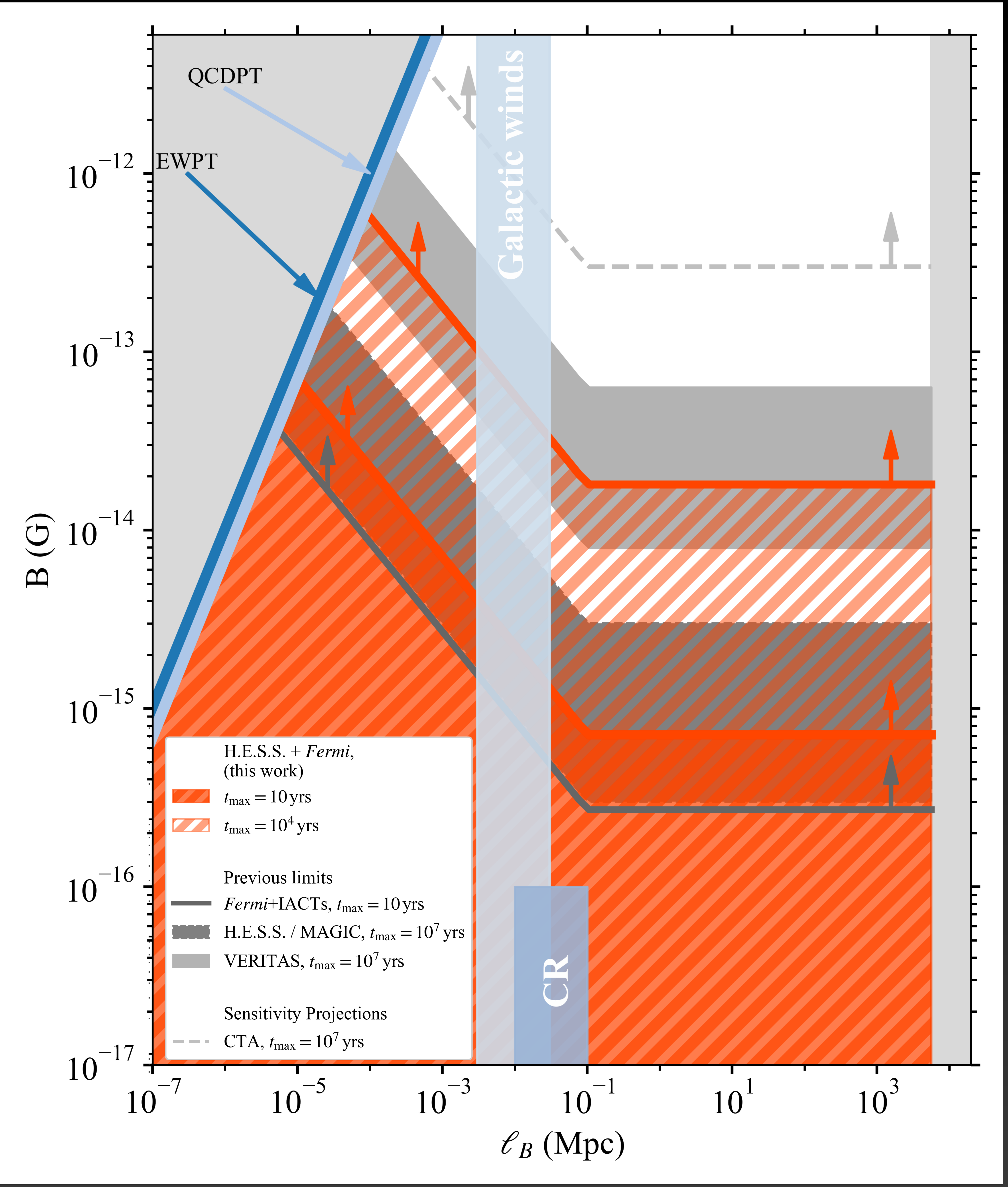
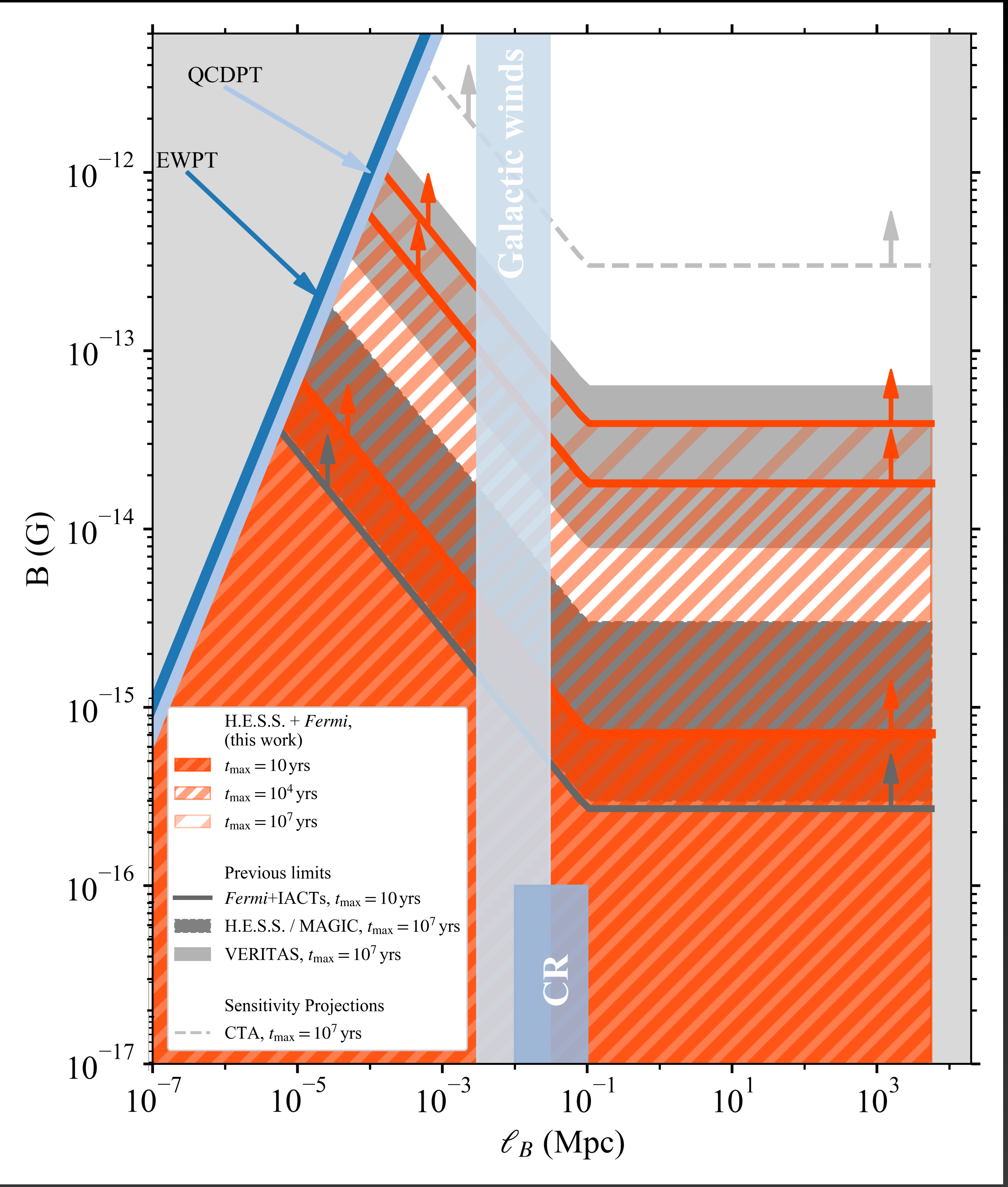
Results: lower limits on IGMF



[Adapted from Durrer & Neronov 2013 and Abdalla et al. 2021]

Results: lower limits on IGMF

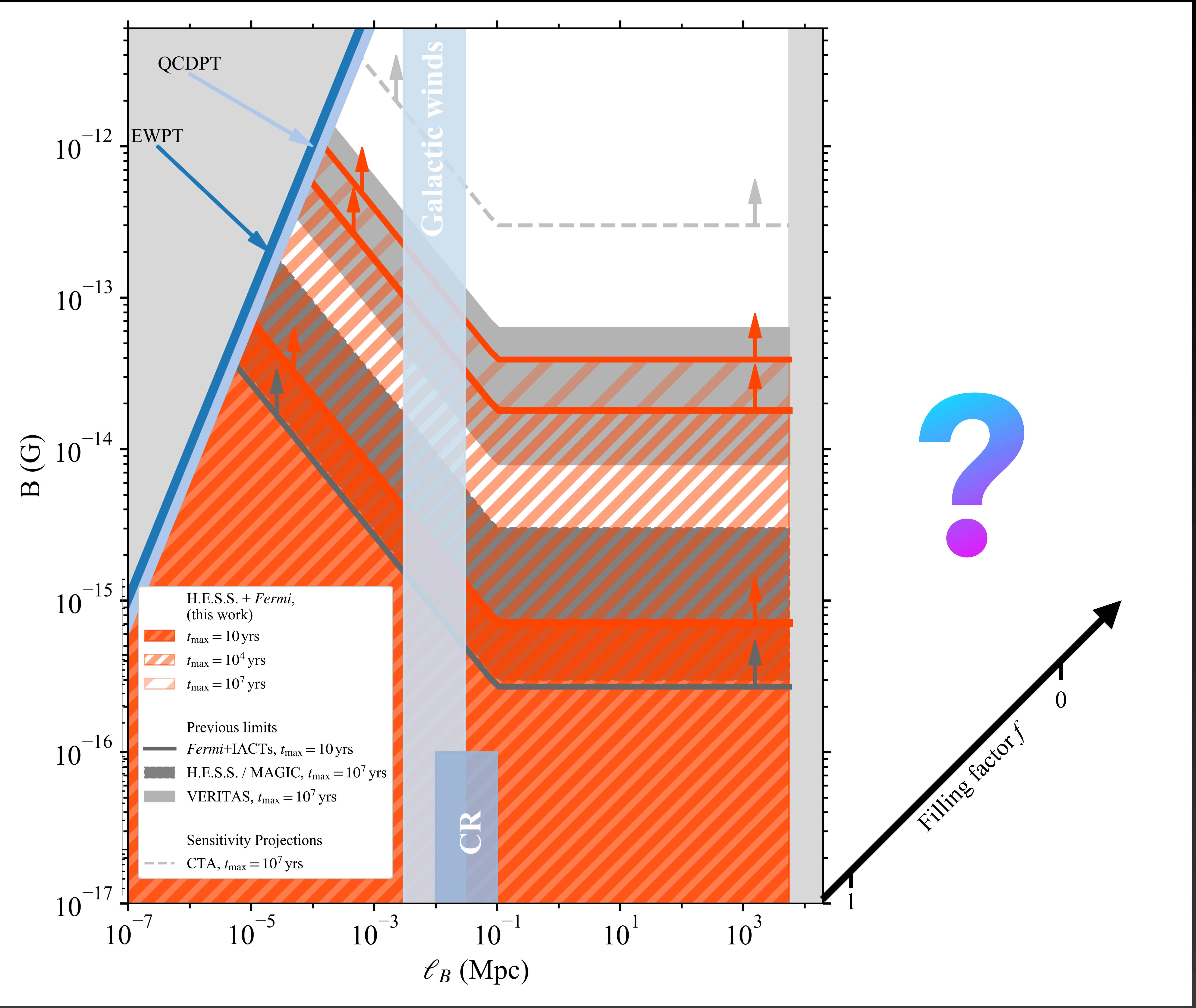
- If pairs lose energy through scattering CMB photons, B fields weaker than $B \lesssim 7 \times 10^{-16}\,\mathrm{G}$ for $t_{\mathrm{max}} = 10\,\mathrm{yr}$ are ruled out
- Previous constraints improved by factor of 2
- Gamma-ray emission is assumed to be constant over activity time
- Can we actually say something about the origin of the B fields?



[Adapted from Durrer & Neronov 2013 and Abdalla et al. 2021]

What about the filling factor?

- Lower filling factor: less deflection
- Previous results: $f > 0.6$ from 1ES0229+200 for $t_{\rm max} \gtrsim 10^2$ years [Dolag et al. 2012]
- In principle:
  - Primordial fields: high f
  - Astrophysical fields: lower f
  - But how low / high and what are the constraints?



[Adapted from Durrer & Neronov 2013 and Abdalla et al. 2021]

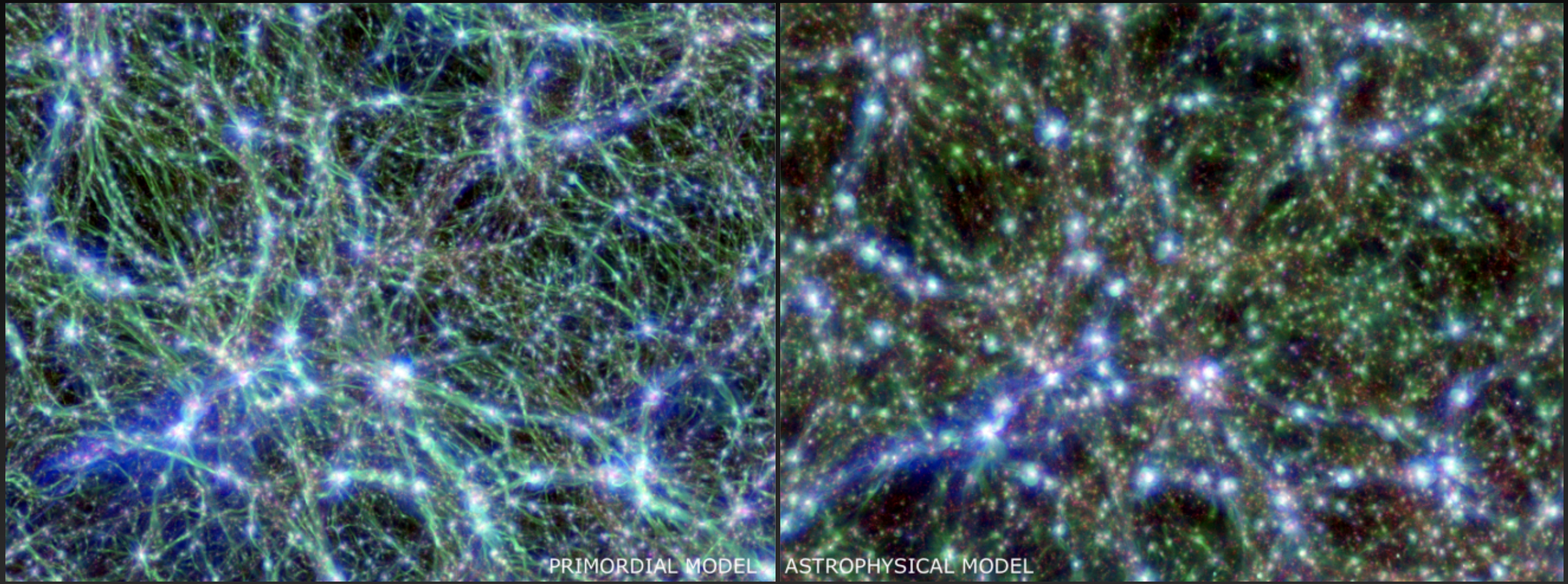
Work led by **Jonas Tjemsland**

Constraints for IGMFs predicted in MHD simulations

Jonas Tjemsland, MM, Franco Vazza (2024), ApJ 963, 2, id.135, arXiv: 2311.04273

Using cosmological MHD simulations

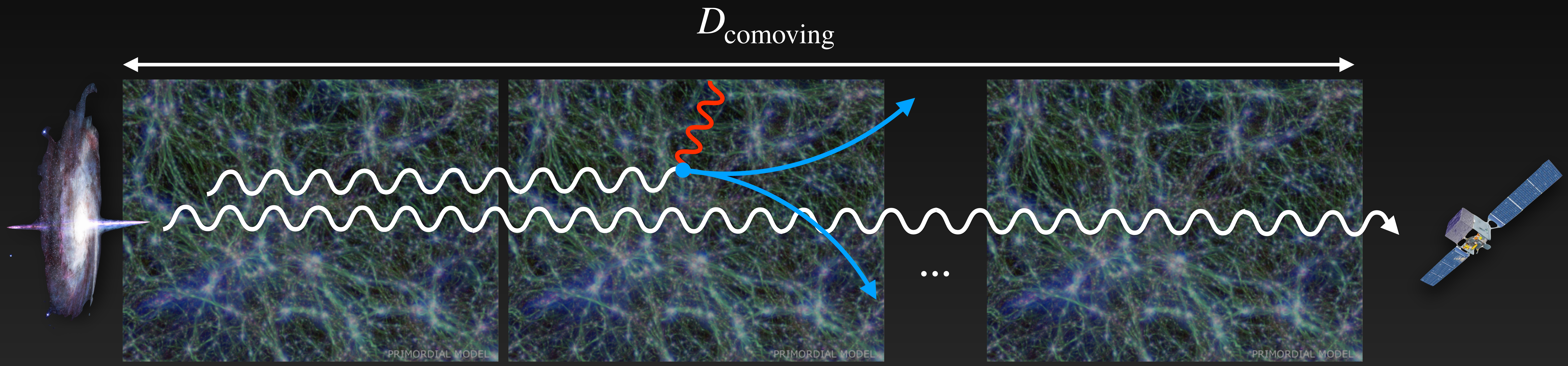
Probe the cascade with more realistic magnetic field configurations



- MHD simulations from Vazza et al. 2017, 1711.02669
- Different generation mechanisms considered (see Franco's talk): astrophysical and primordial

Implementation

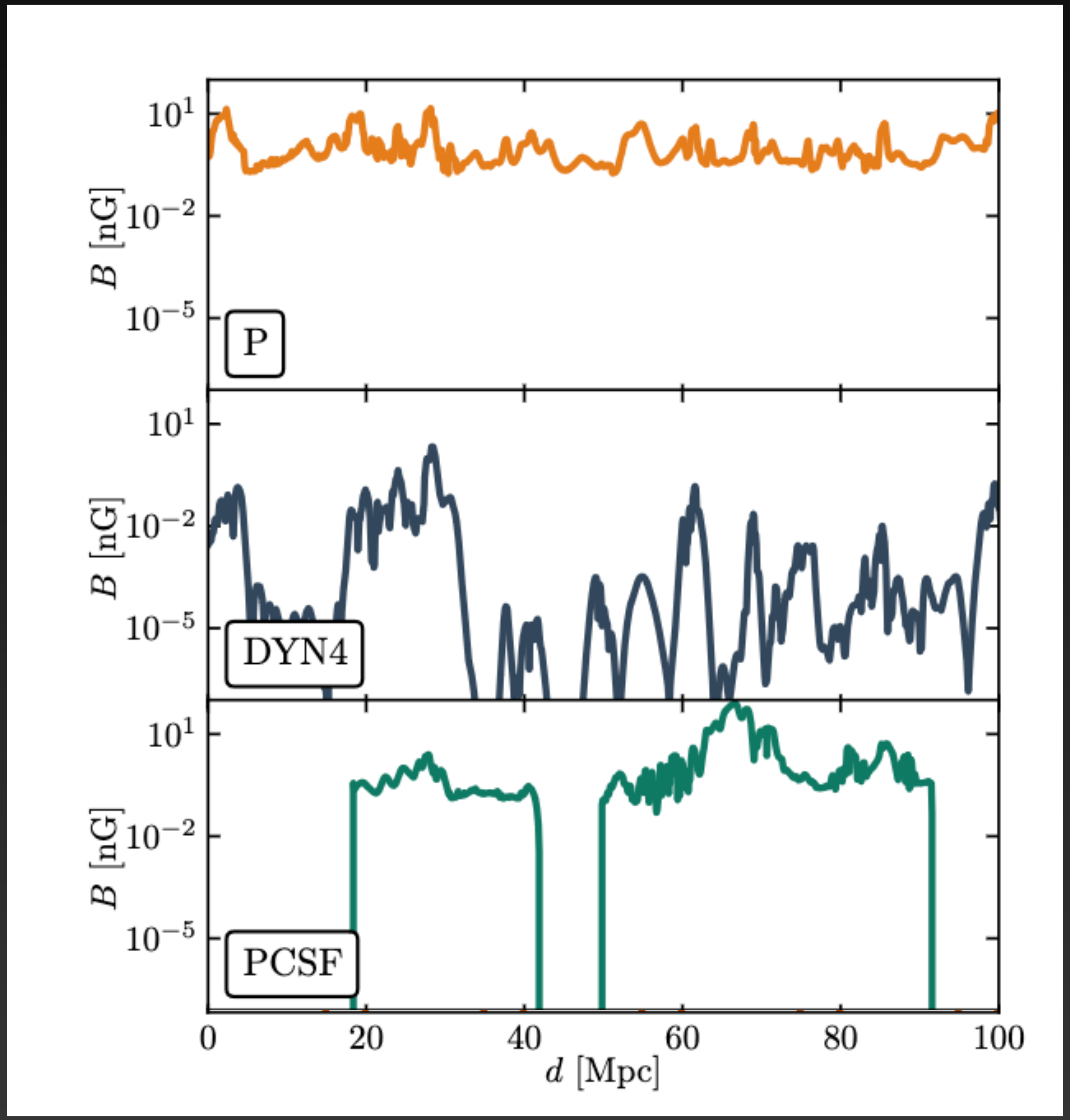
Probe the cascade with more realistic magnetic field configurations

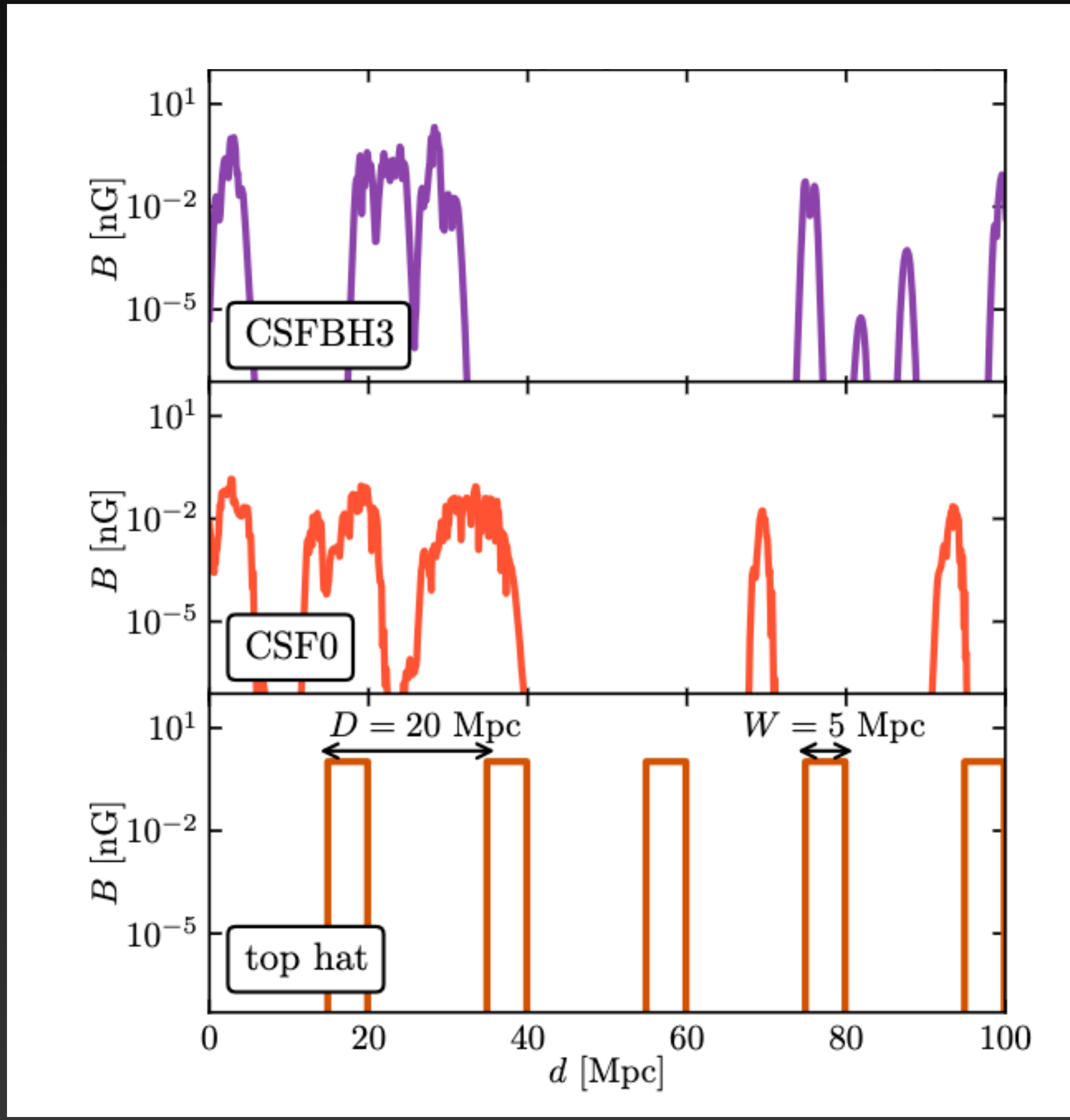


- Simulation volume periodically repeated
- Tested 100 random lines of sight through simulation volume (with random starting points)
- Magnetic fields fed into ELMAG code, gives cascade prediction

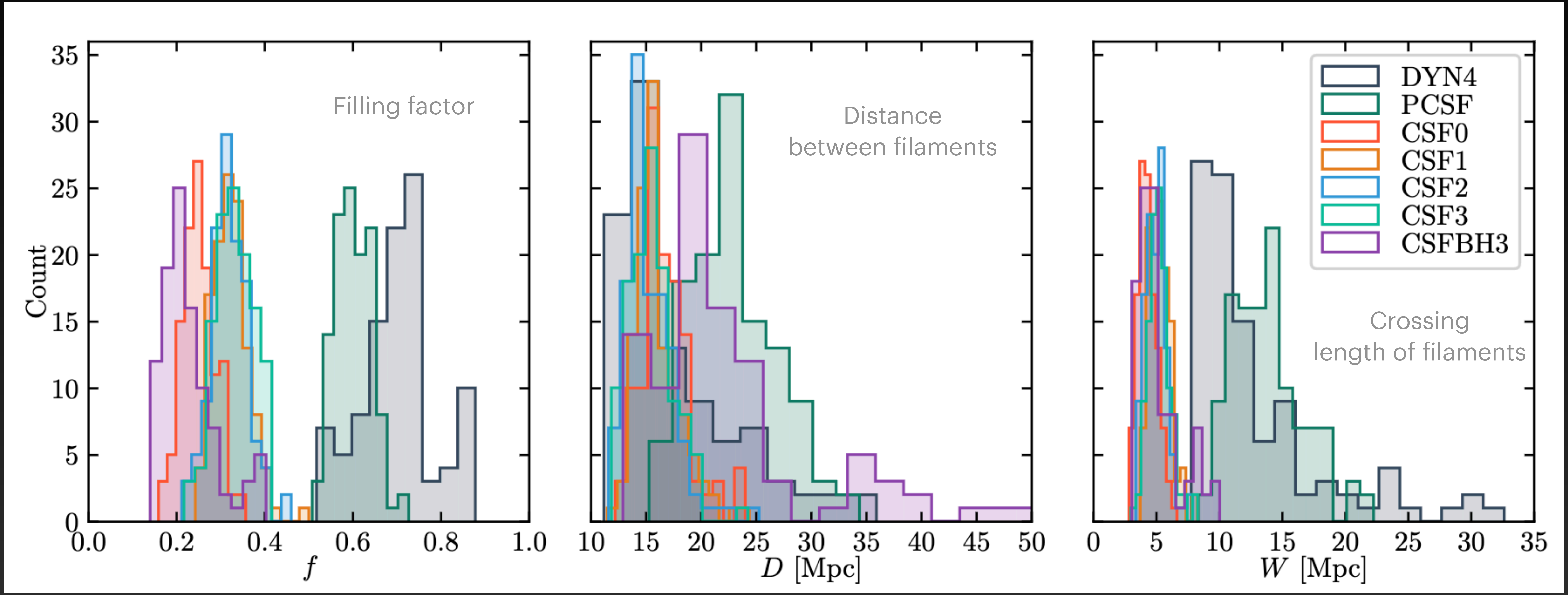
Tested IGMF simulations

Primordial and astrophysical origin



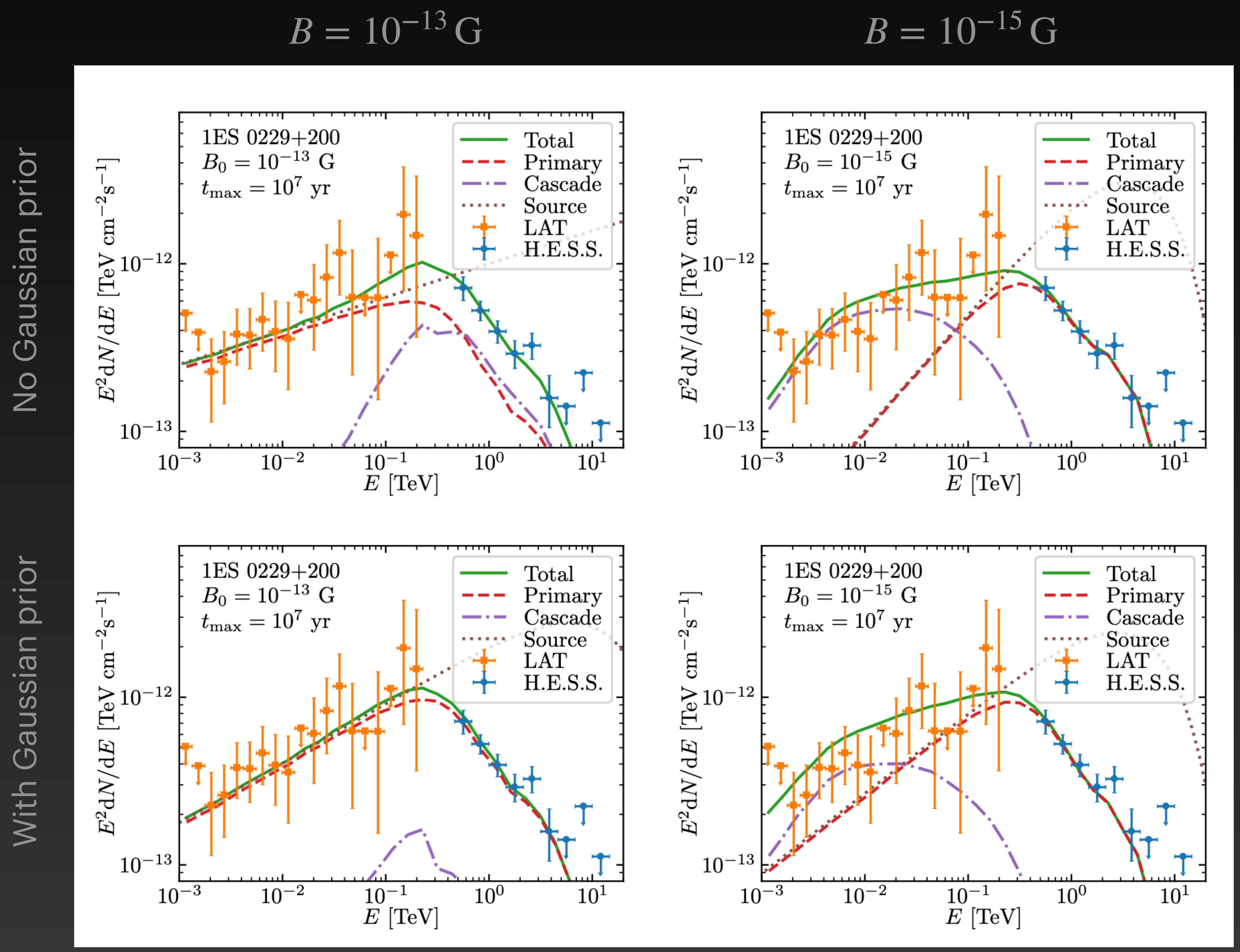


Characteristics of MHD simulations



- Sampled 100 random lines of sight through periodically repeated simulation volume
- Overdensities identified for $B > 10^{-15}\,\mathrm{G}$
- Astrophysical models have low values of W, results in low filling factor

Analysis procedure

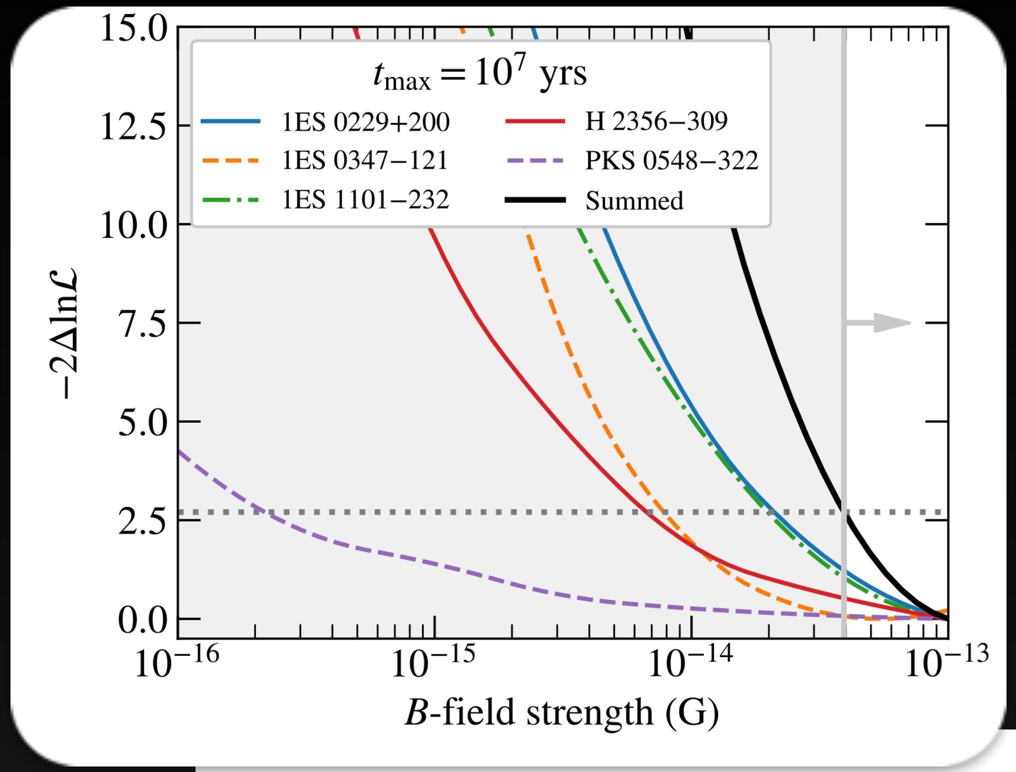


- Simplification: only use spectral information
- Use cascade that arrives within 68% of Fermi PSF
- Intrinsic source parameters optimized
- Can lead to false detection of IGMF (with hard intrinsic spectrum)
- Use Gaussian prior on spectral index
- Yields consistent results with full spectral + spatial analysis
- Full likelihood:

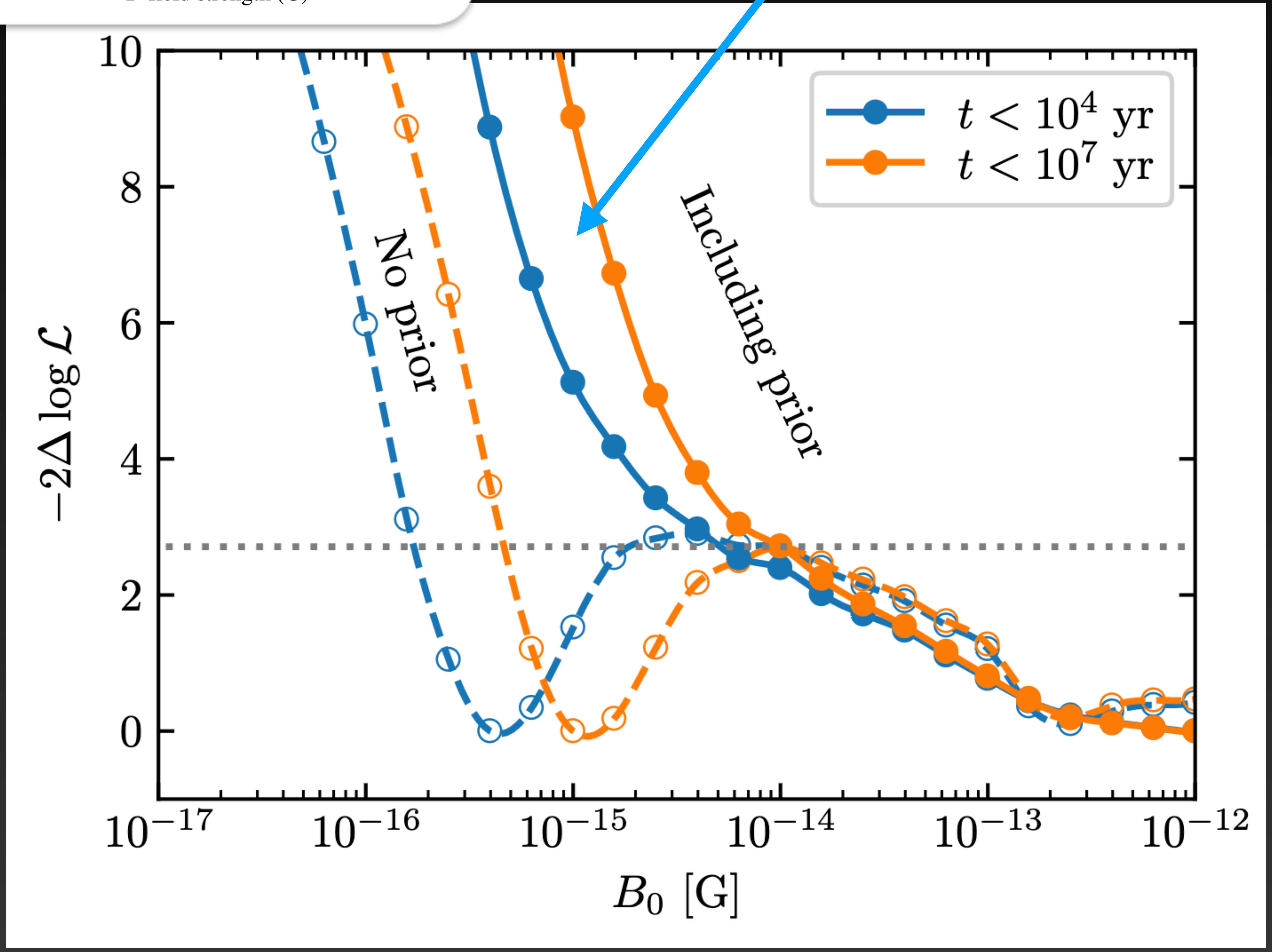
$$-2\ln\mathscr{L} = -2\ln\mathscr{L}_{\text{LAT, spectrum}} + \chi^2_{\text{H.E.S.S.}} + \left(\frac{\Gamma - \Gamma_0}{\sigma_\Gamma}\right)^2$$

For testing analysis: domain like fields with $f = 1$

Analysis procedure



With Gaussian prior on Γ, $\sigma_\Gamma = 0.1$



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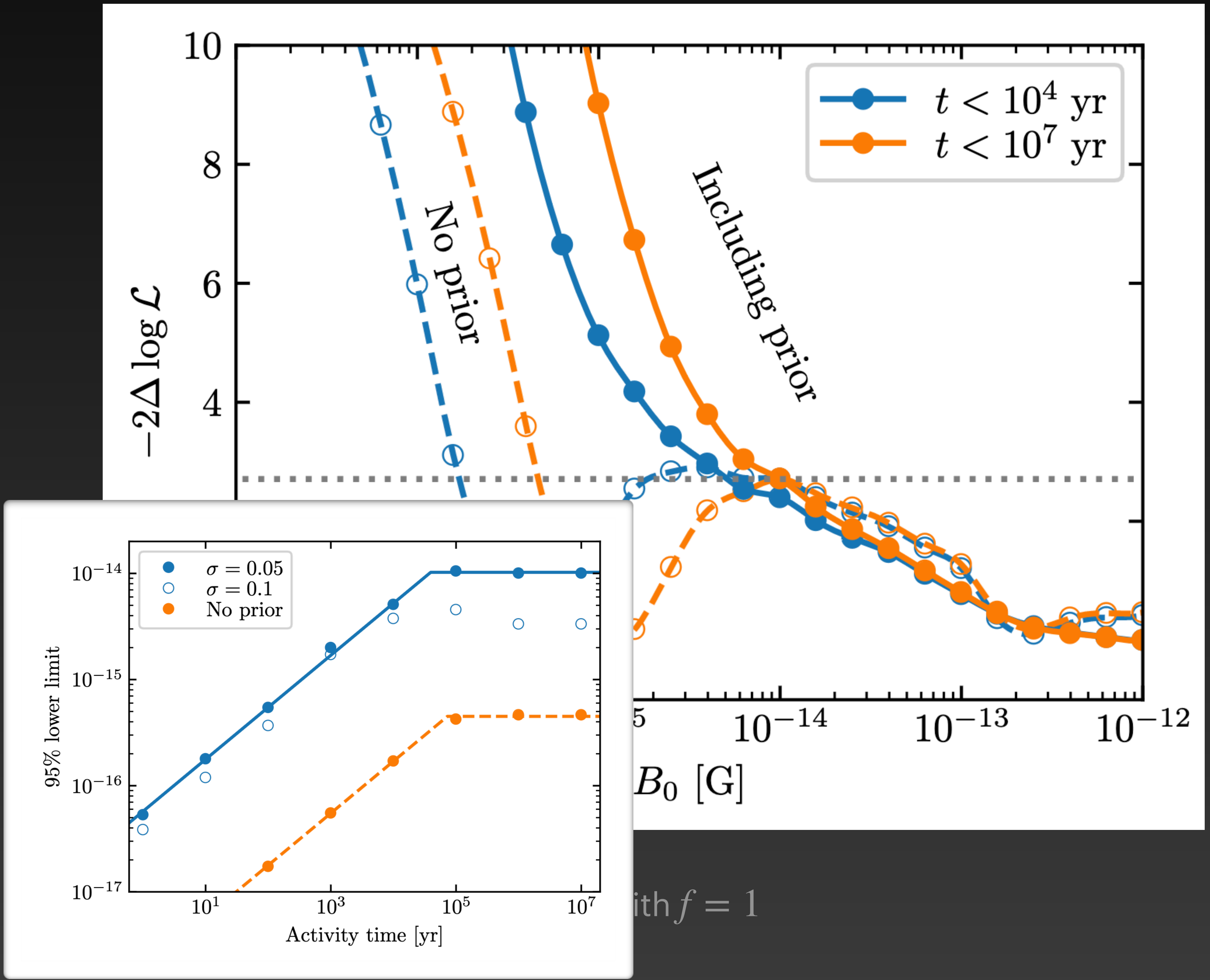

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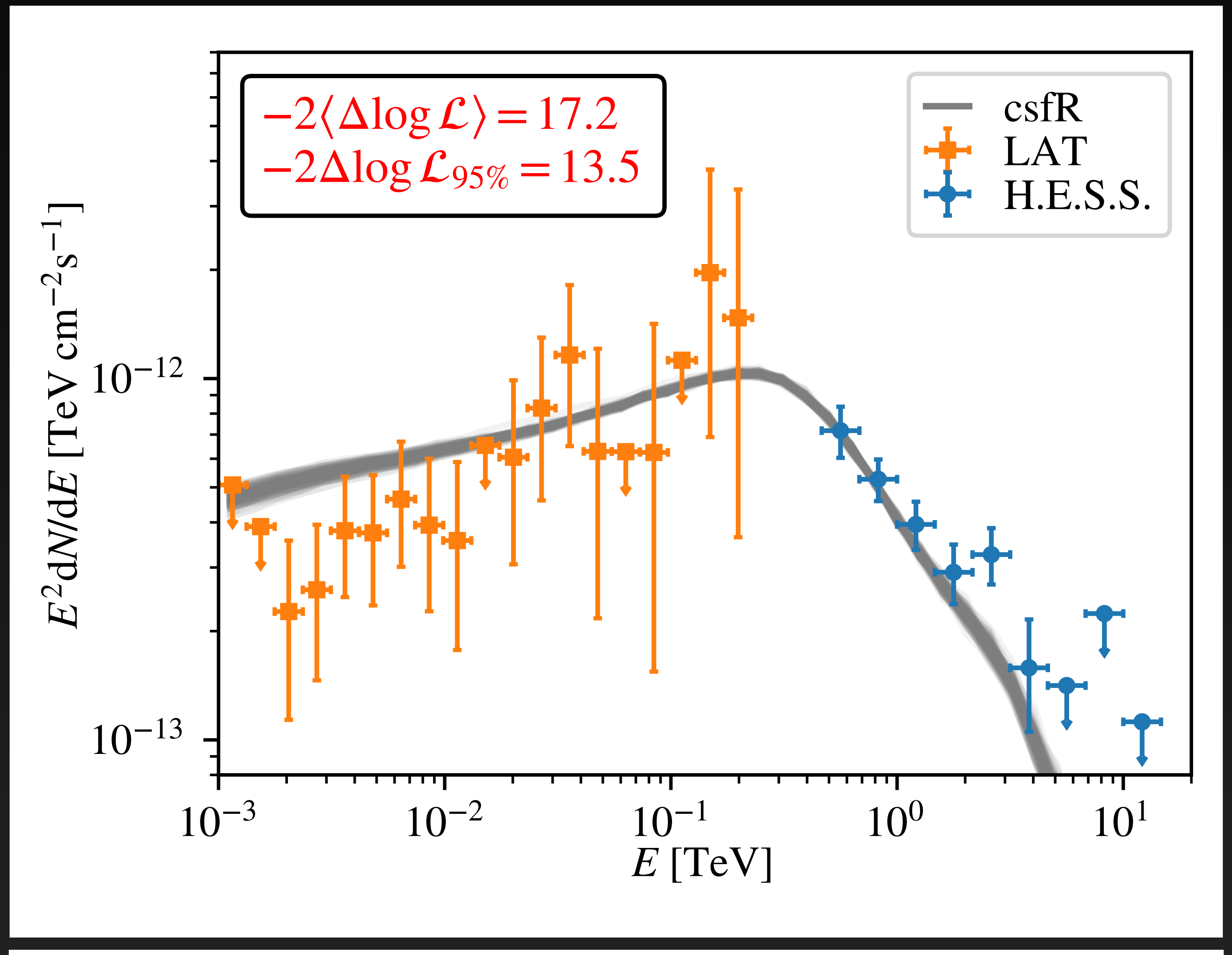
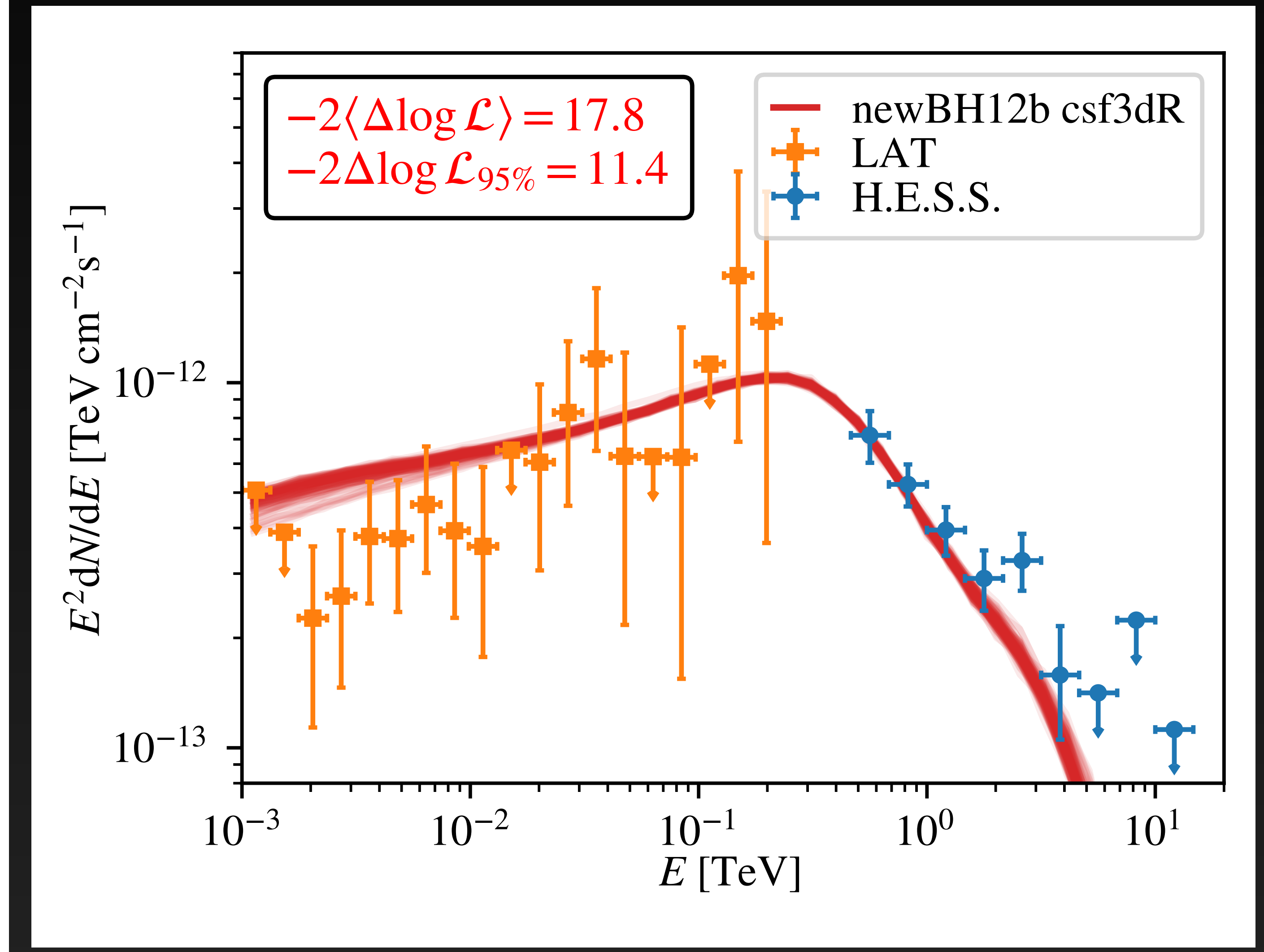
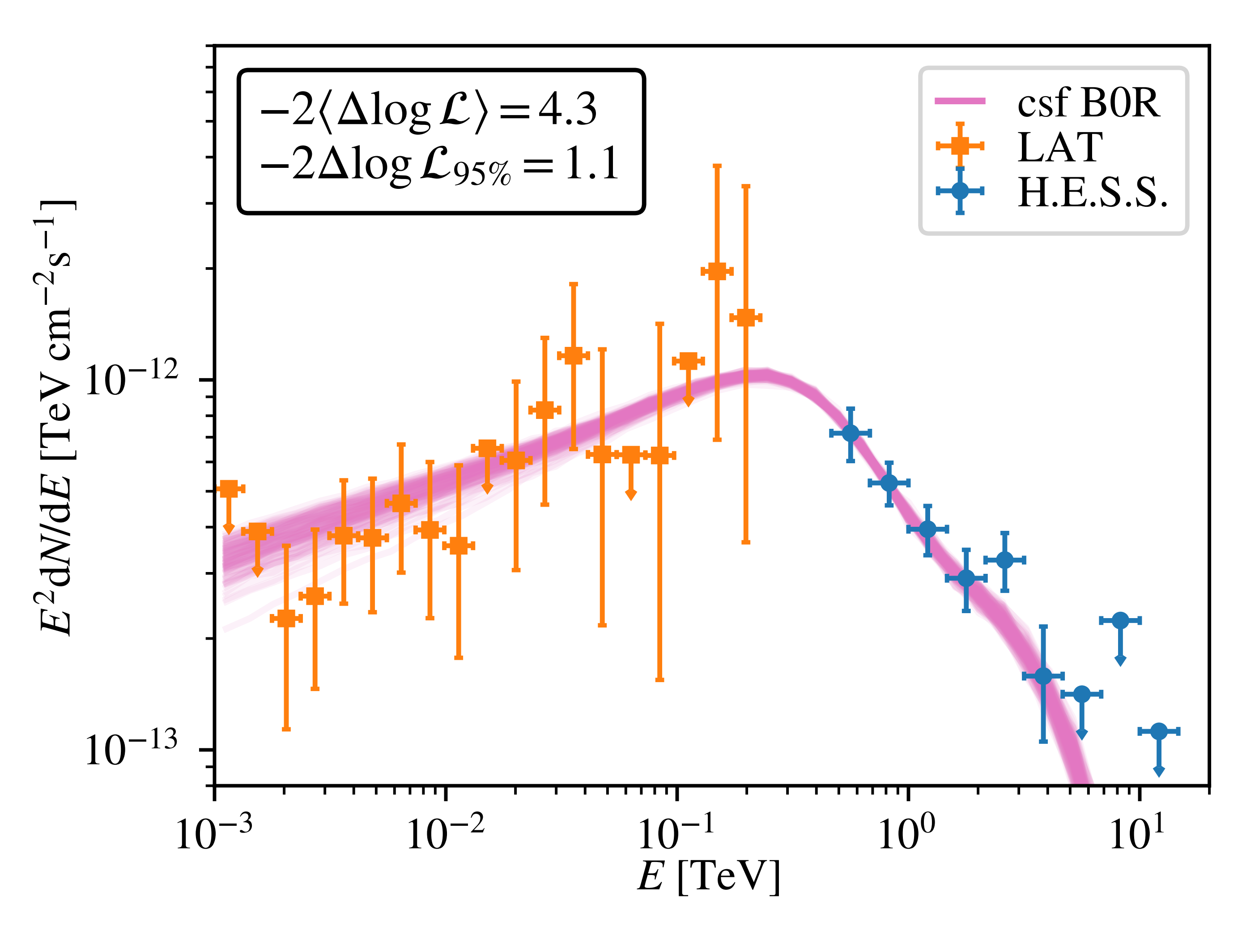
Result spectra for different models

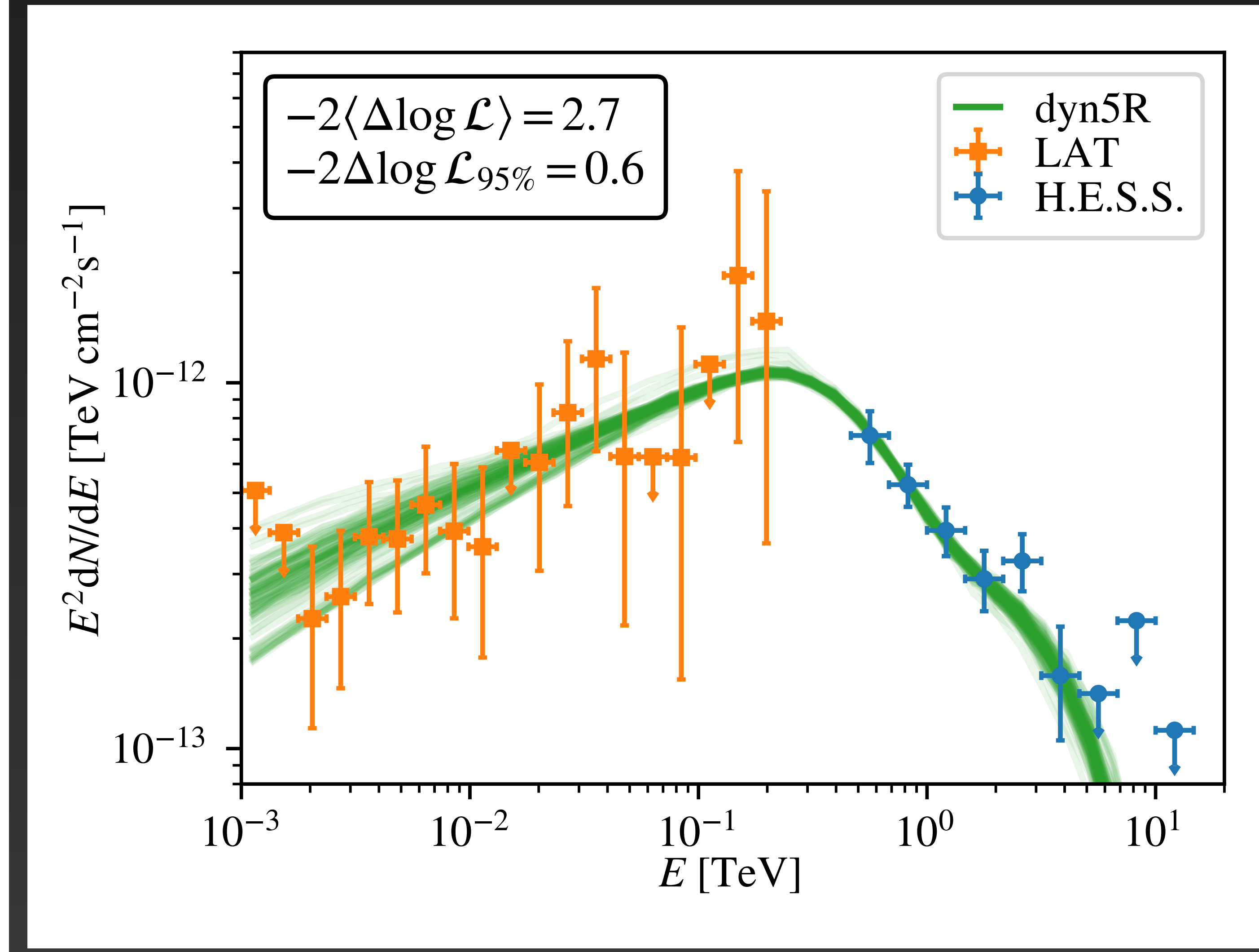
Purely astrophysical fields



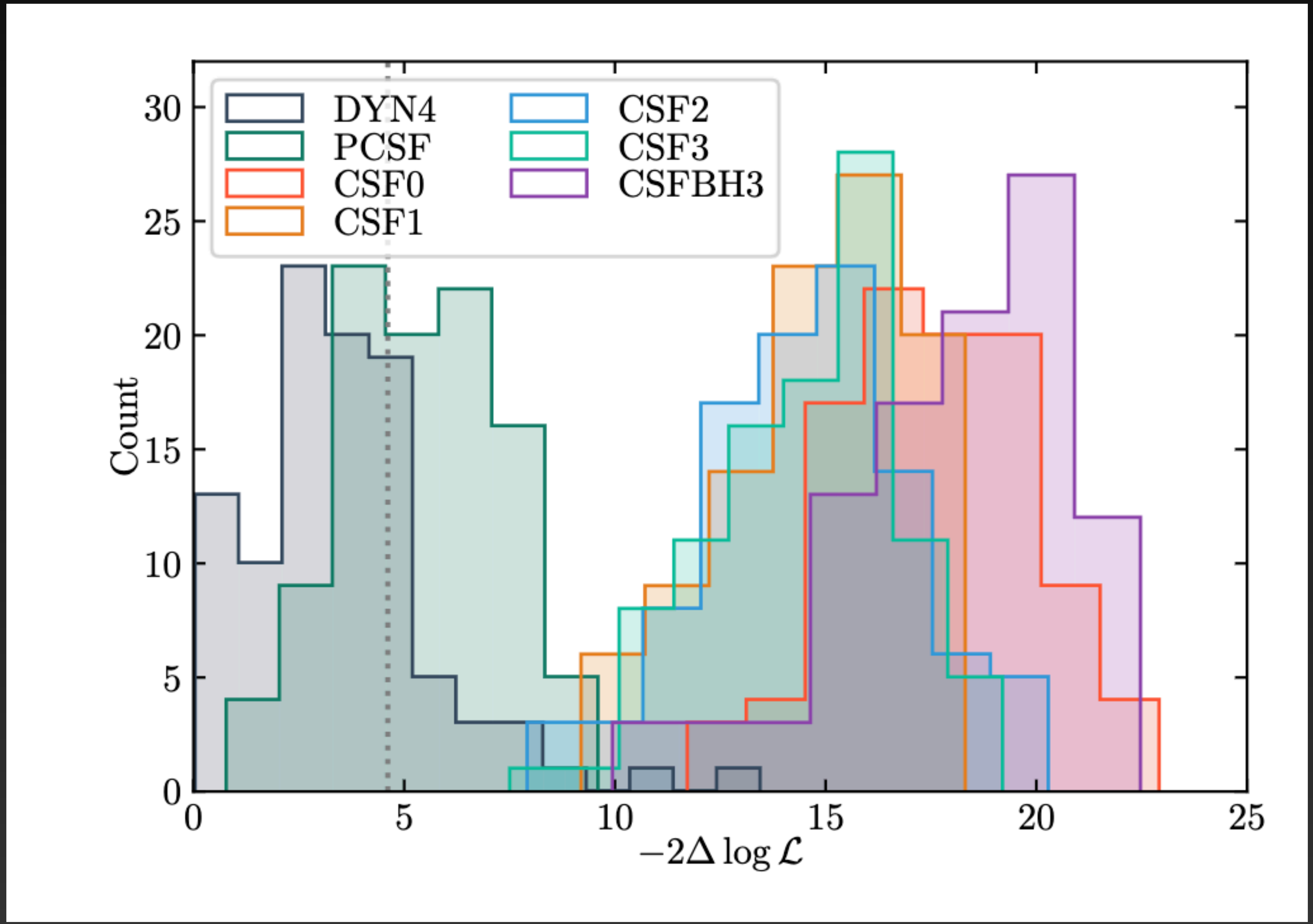


With primordial component





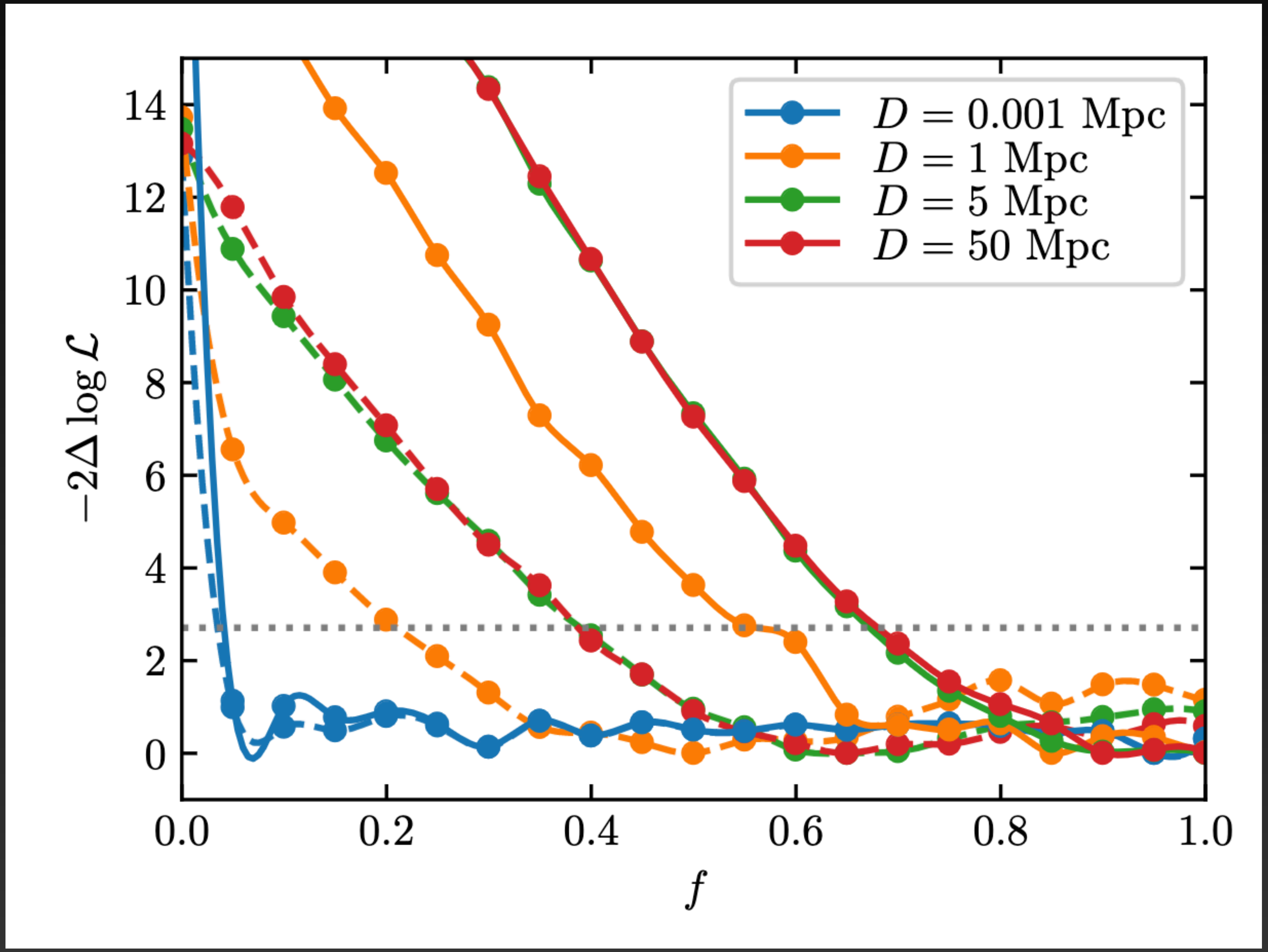
Results for MHD simulated IGMF



- All simulations with astrophysical IGMF can be ruled out
- Valid for all considered lines of sight
- Assumes activity time of 10^7 years

Constraints for filling factor

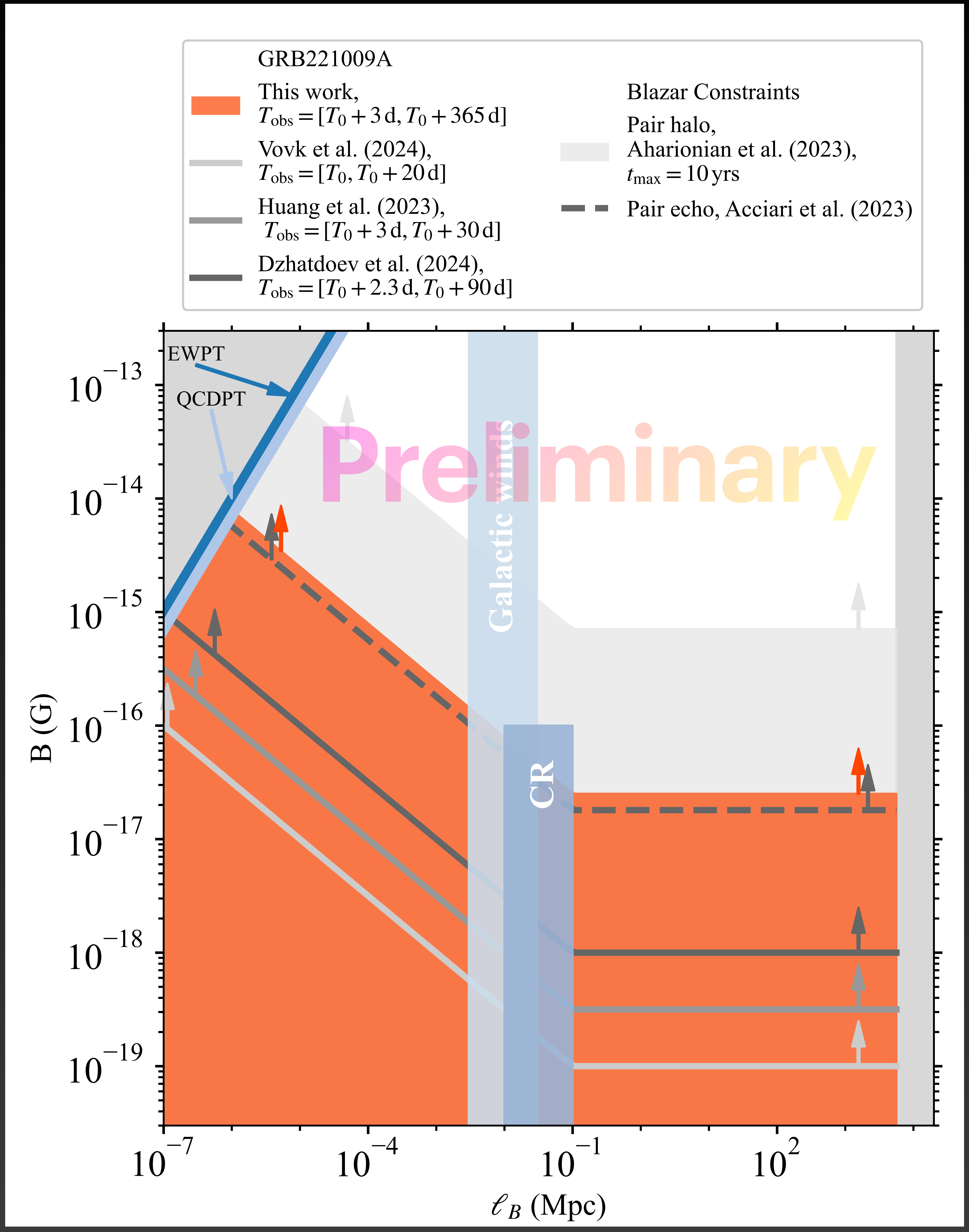
For top-hat distributed *B* field



- Assuming top-hat like magnetic field with $B = 10^{-12}\,\mathrm{G}$
- Results independent for distance between structures for $D \gtrsim 5\,\mathrm{Mpc}$
- With prior on Γ: filling factor must be larger than $f \gtrsim 0.7$

E > 100 MeV
10 hours of observation
20° x 20°
Credit: NASA/DOE/*Fermi* LAT Collaboration

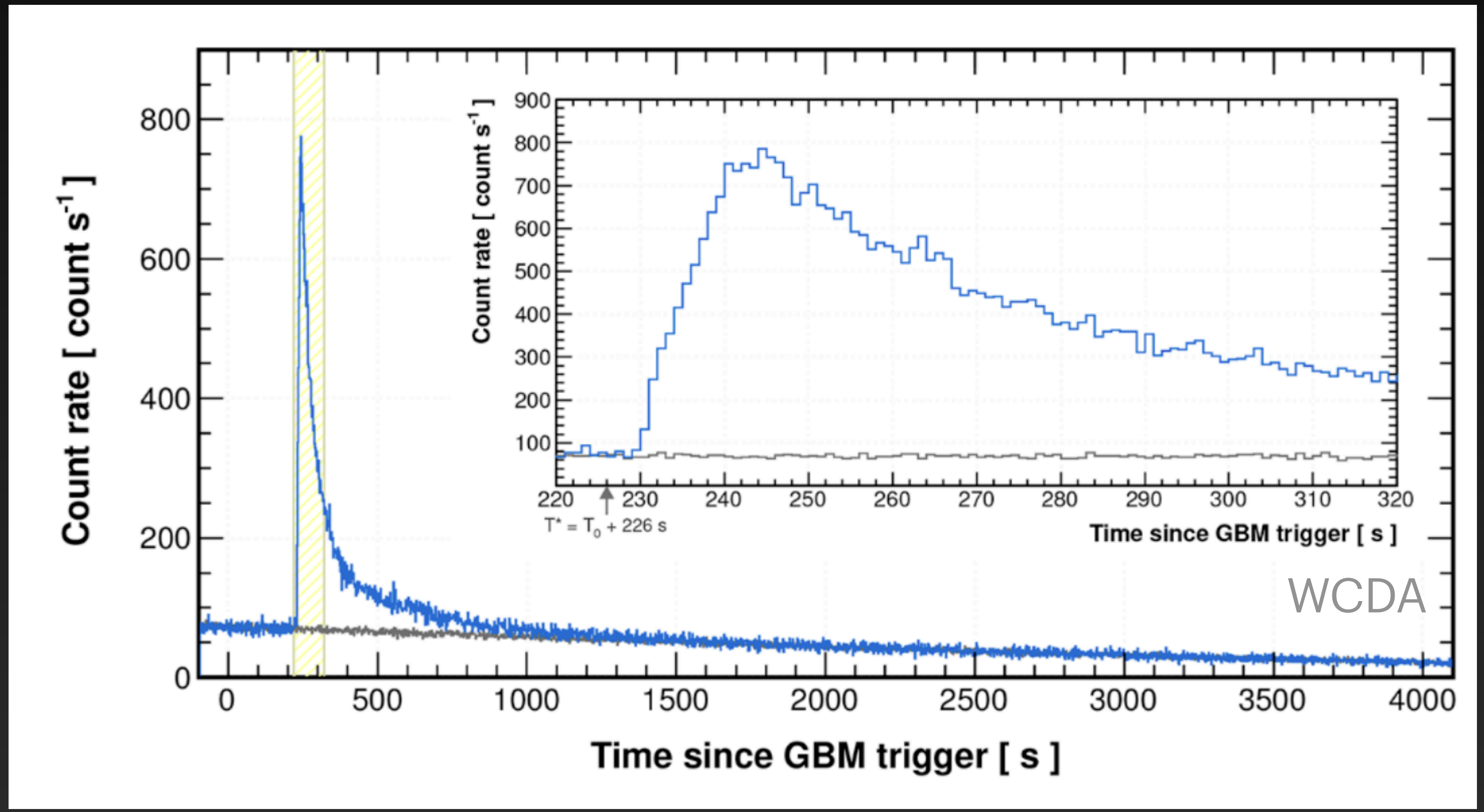
Constraints on the intergalactic magnetic field from Fermi-LAT observations of GRB 221009A

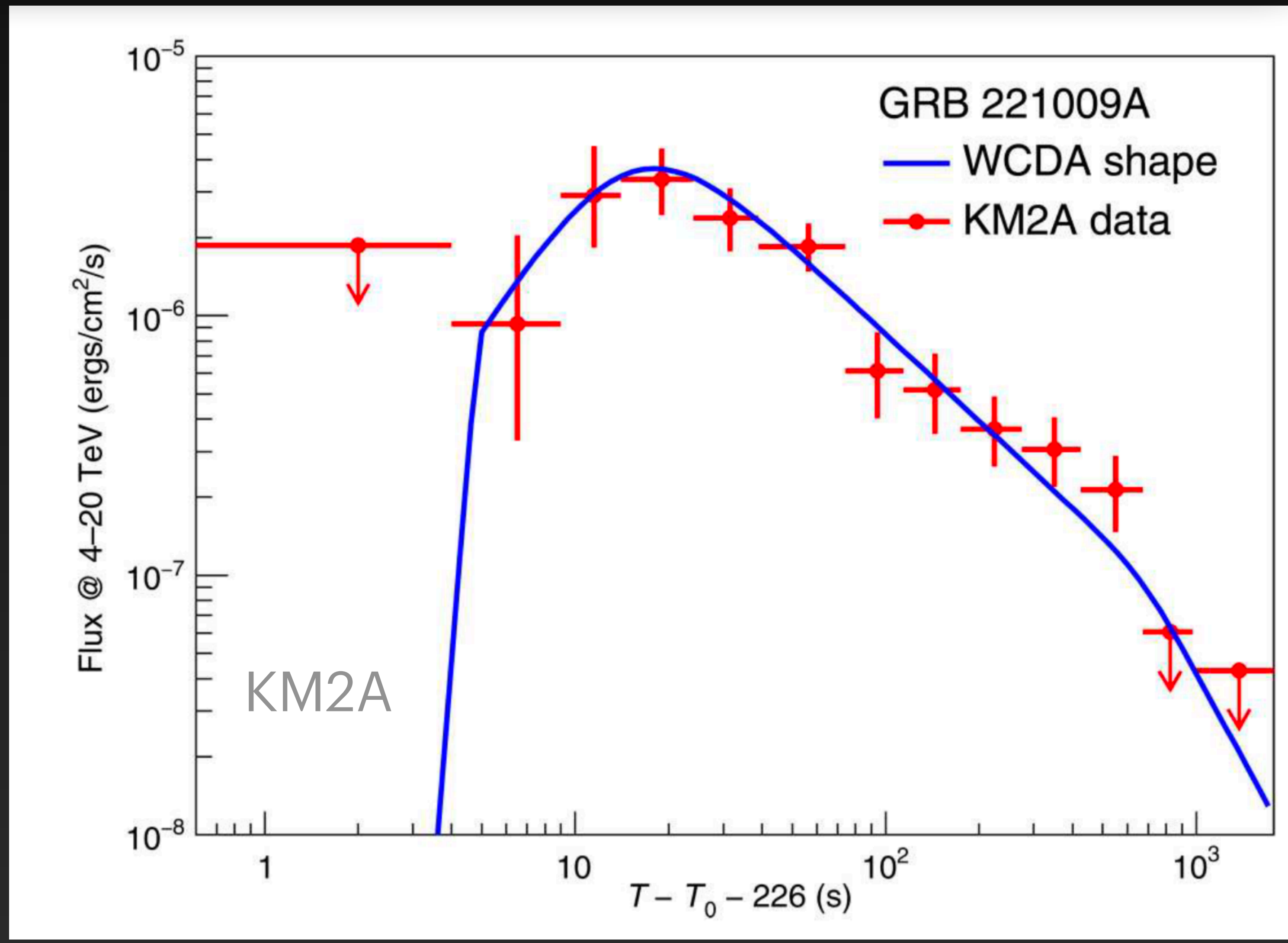


See Paolo's talk on Monday

Gamma-ray Space Telescope

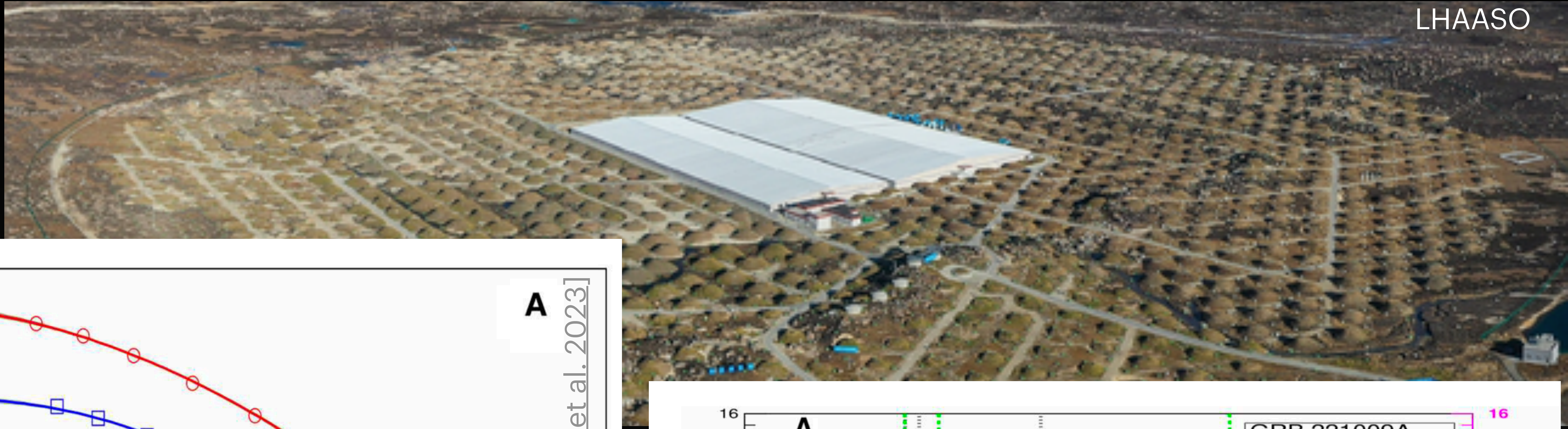
VHE photons seen with LHAASO



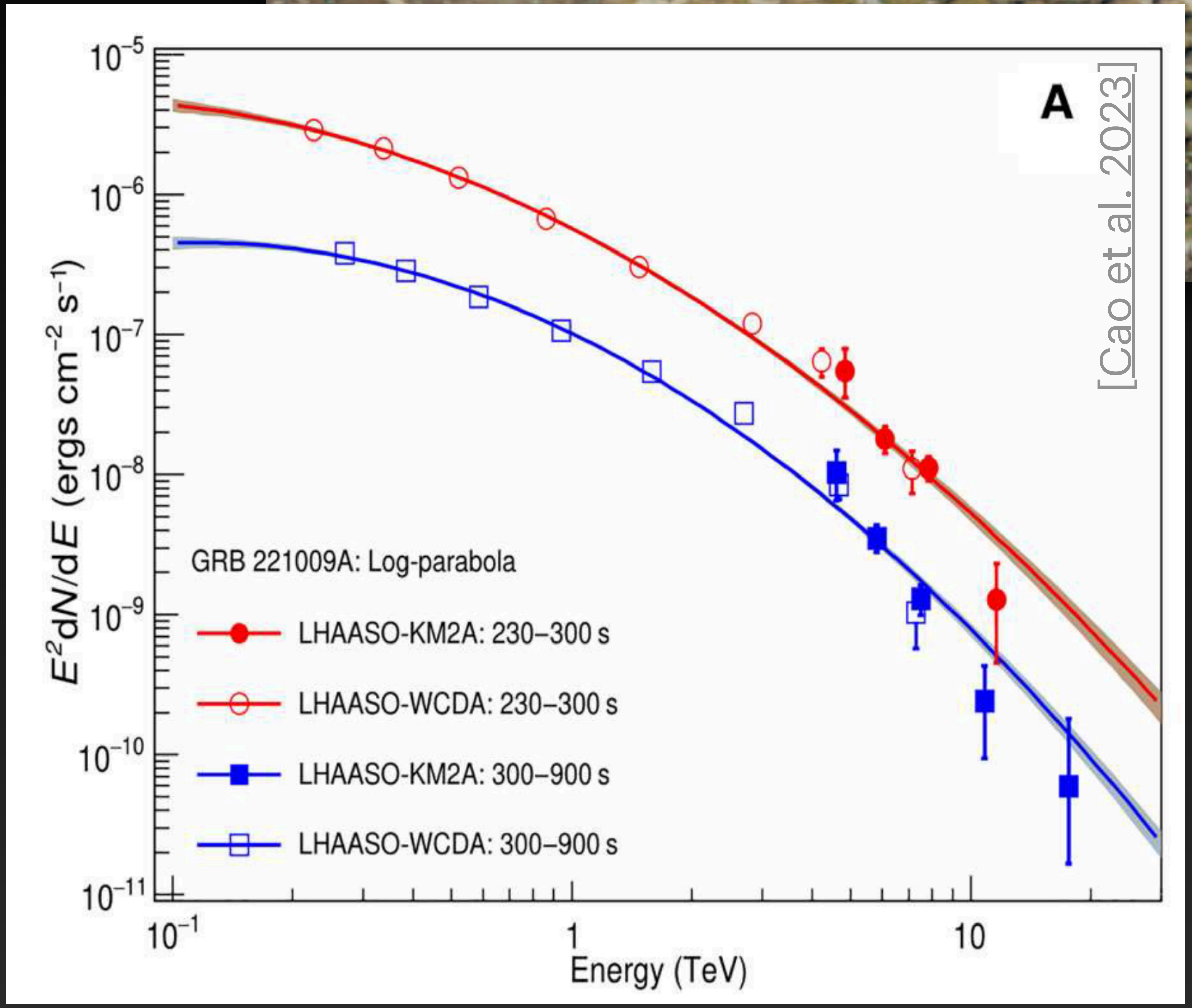


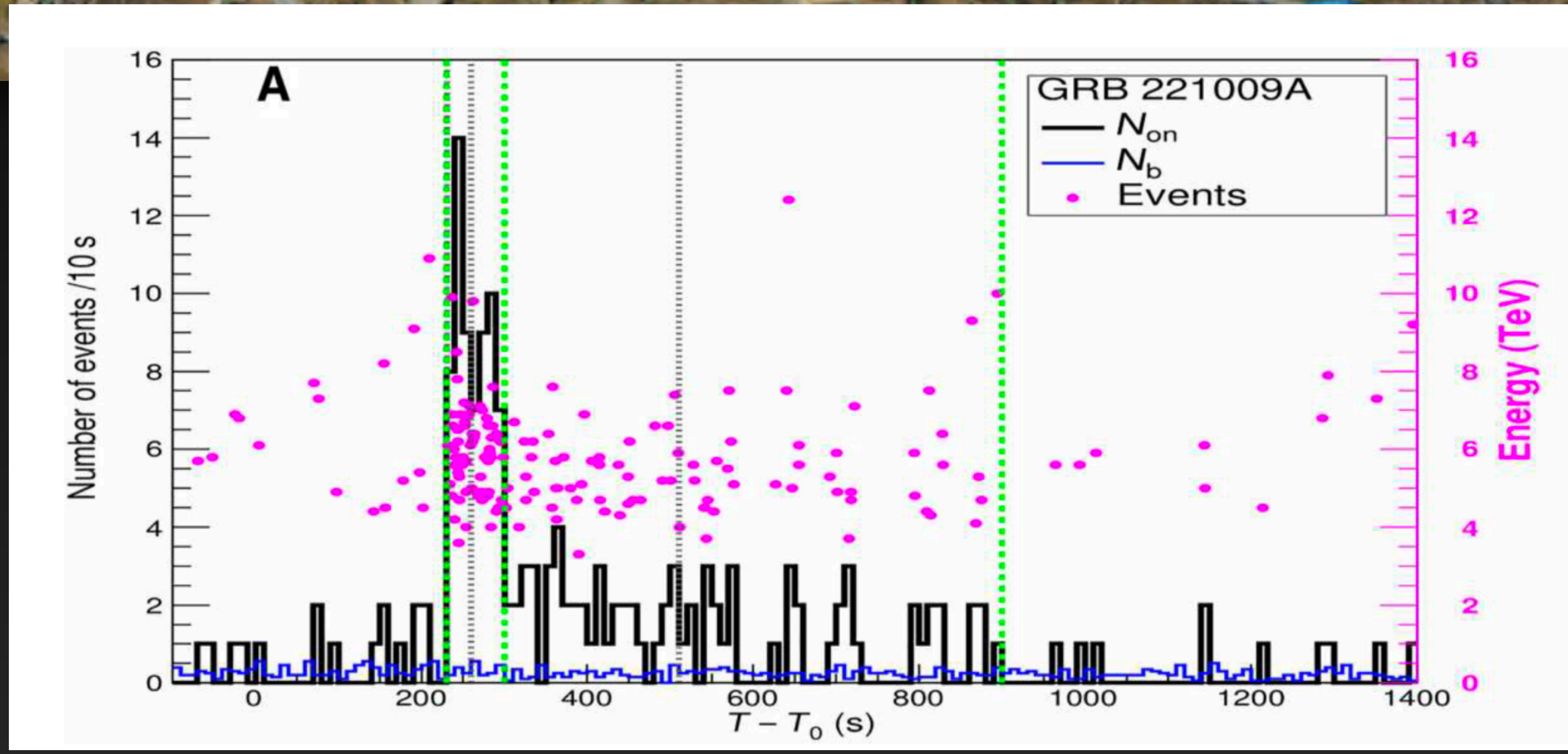
- WCDA: > 64,000 gamma rays between 0.2 TeV and 7 TeV in ~3000s
- KM2A: 140 gamma rays between 3 and 13 TeV in ~900s
- Light curve suggests jet opening angle of 1.6º
- Distance and highest energies: strong absorption on EBL

[LHAASO Collaboration Science 2023, Sci. Adv. 2023]



KM2A sees 13 TeV photon





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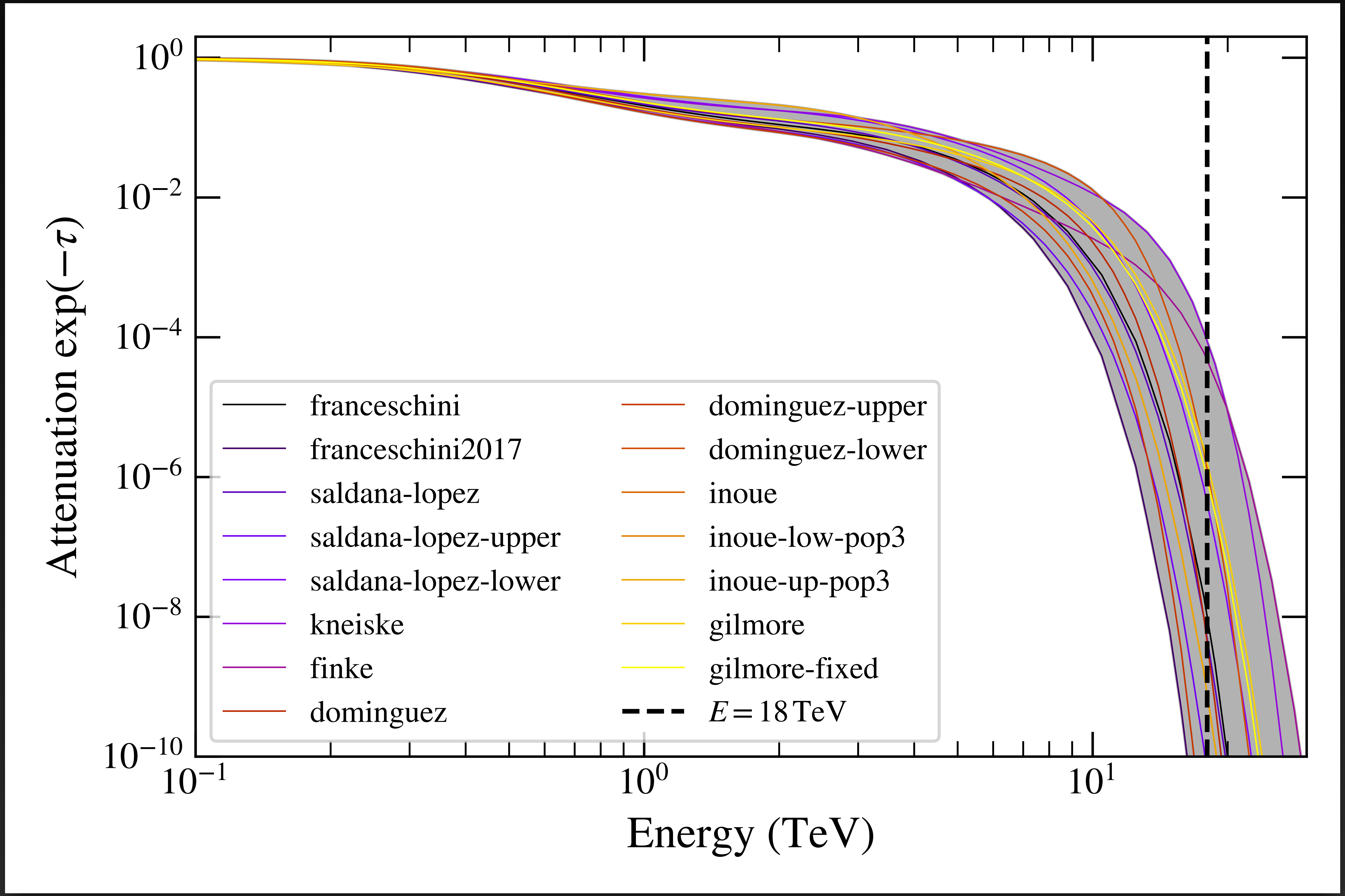
- Light curve suggests jet opening angle of 1.6º
- Distance and highest energies: strong absorption on EBL

[LHAASO Collaboration Science 2023, Sci. Adv. 2023]

13 (18) TeV photon exceptional!?

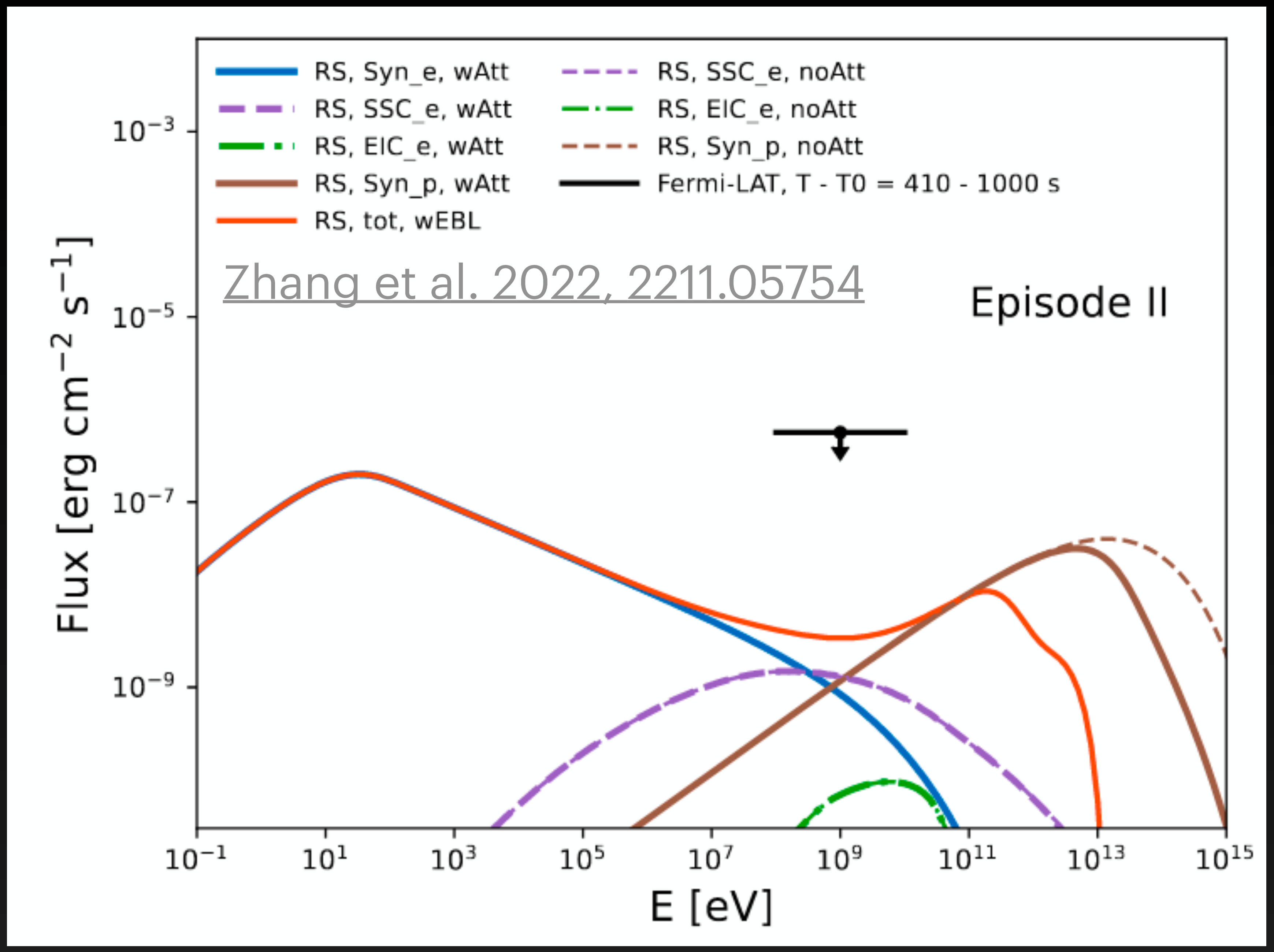
(Considering $z = 0.1505$)

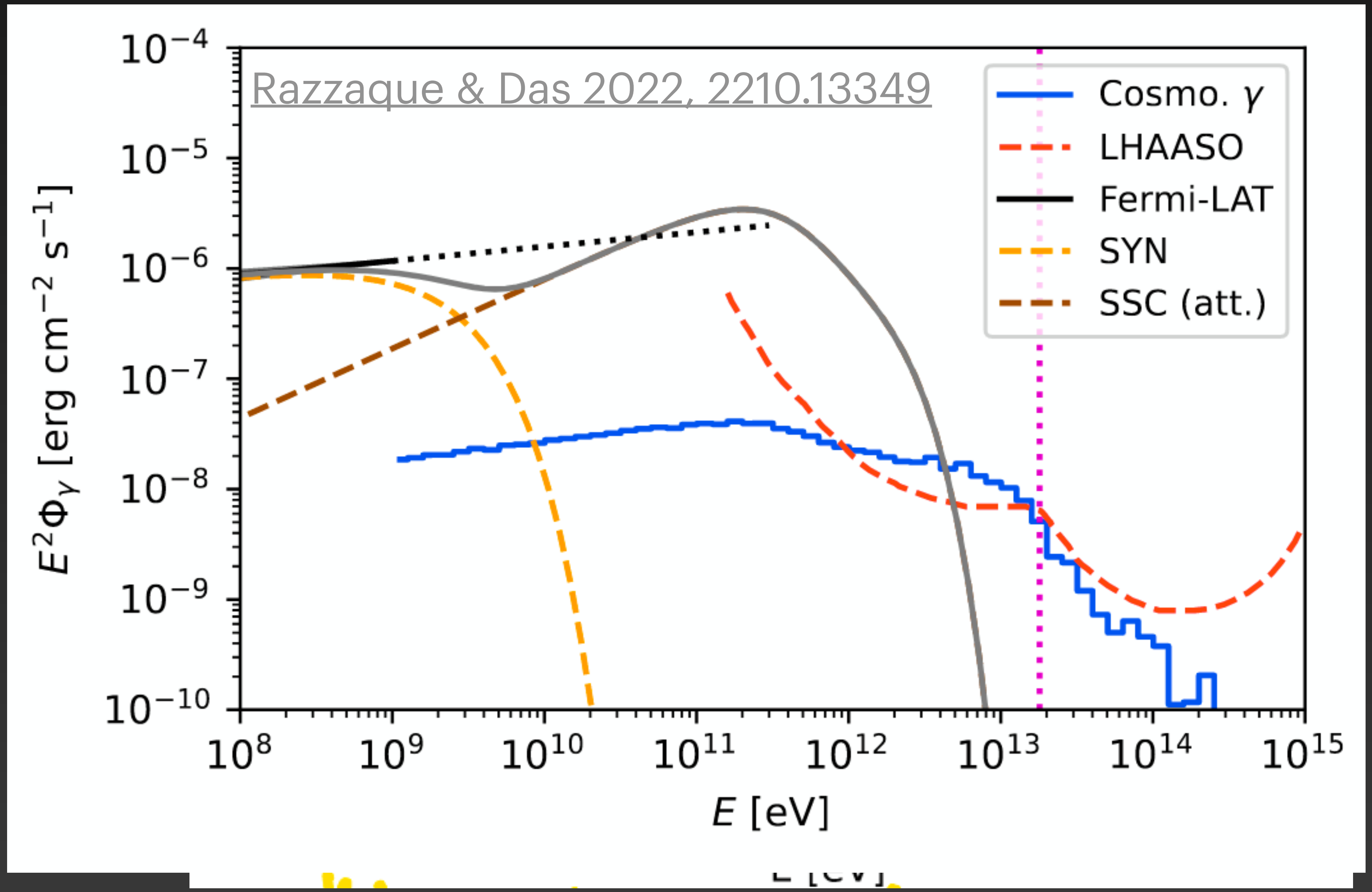


Generated with https://github.com/me-manu/ebltable/

Astrophysical interpretations

- Reverse shock propagating through ejecta leads to proton acceleration and proton synchrotron emission up to 10s of TeV at $T > 400\,\mathrm{s}$
  [Zhang et al. 2022, 2211.05754]
- Requires efficient proton acceleration and high B fields inside source
- And / or: UHECR protons accelerated in fireball scenario interact with EBL and produce *cosmogenic* gamma rays (and neutrinos)
  [Rudolph et al. 2022, 2212.0076, Razzaque & Das 2022, 2210.13349, Alves Batista 2022, 2210.12855]
- Requires efficient proton acceleration and small deflection of UHECR in host galaxy and intergalactic medium

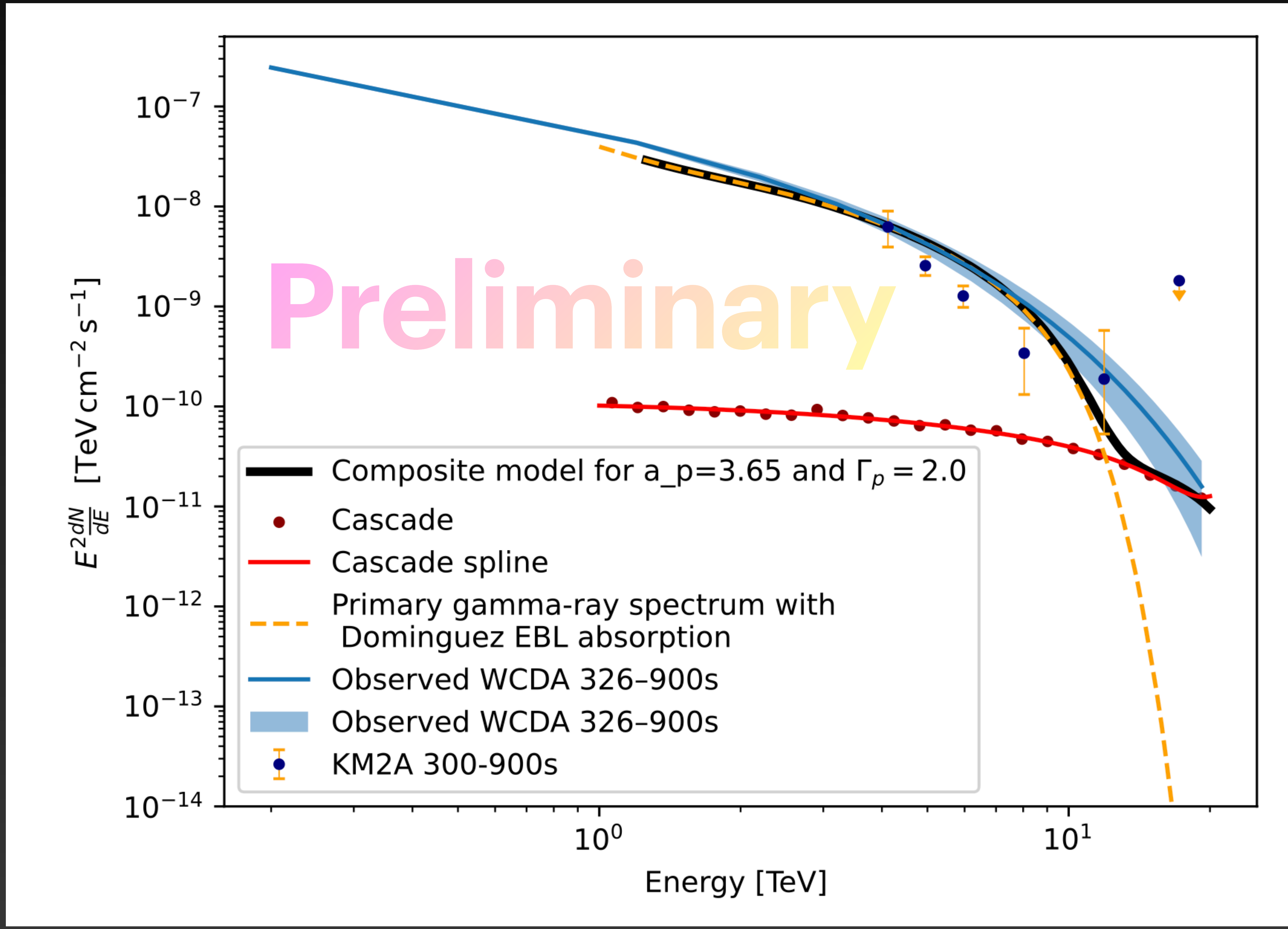




Proton induced cascades?

Johanna Müller
Master student (just finished)
at SDU

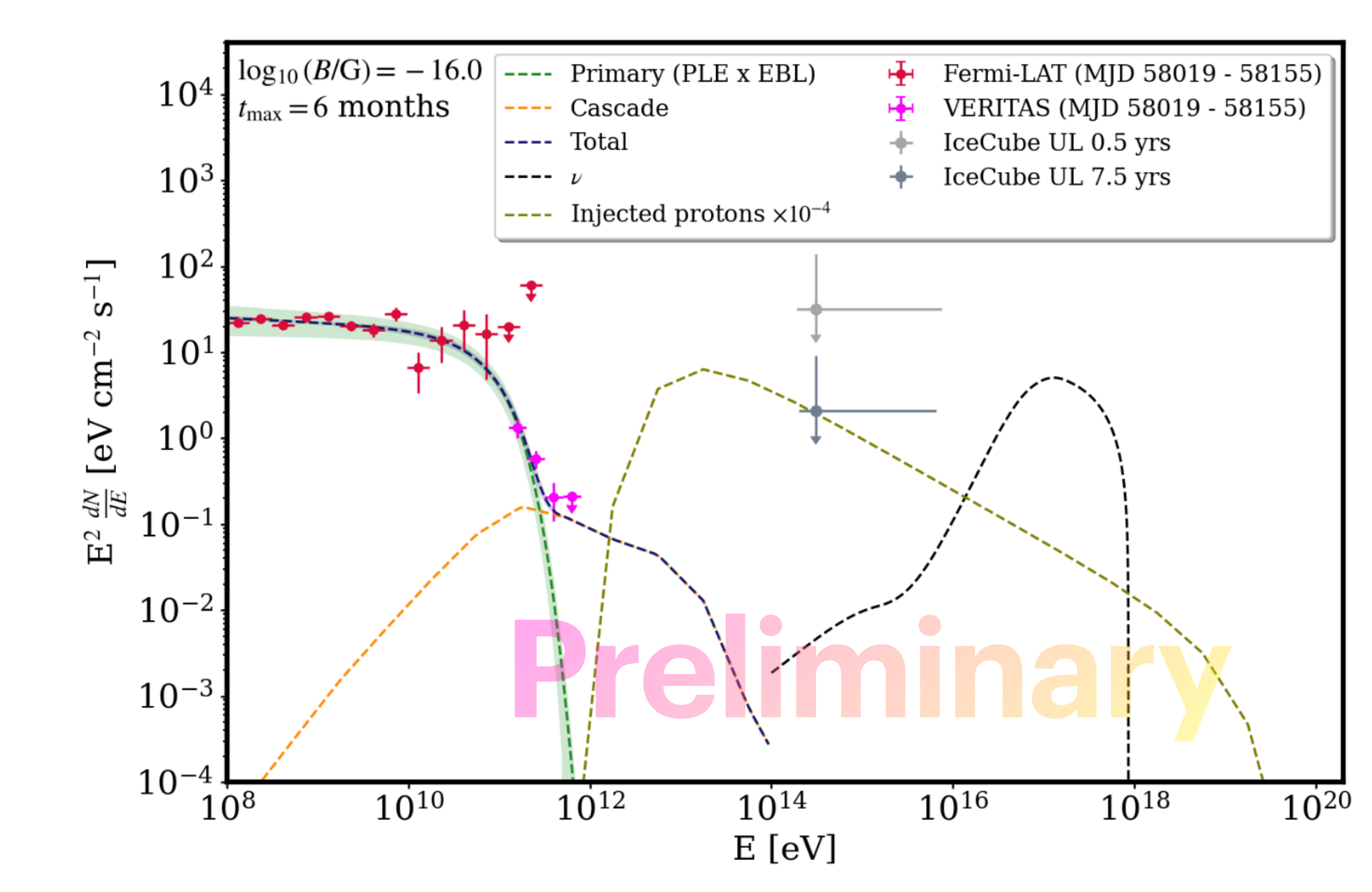
- Injected protons up to 10^{18}eV and traced electromagnetic cascade with CRPropa
- Can improve fit at highest energy bin
- Only for low IGMFs of 10^{-20} G and 10^{-18} G so far
- High resolution leads to extremely expensive simulations
- Do we need dedicated software?

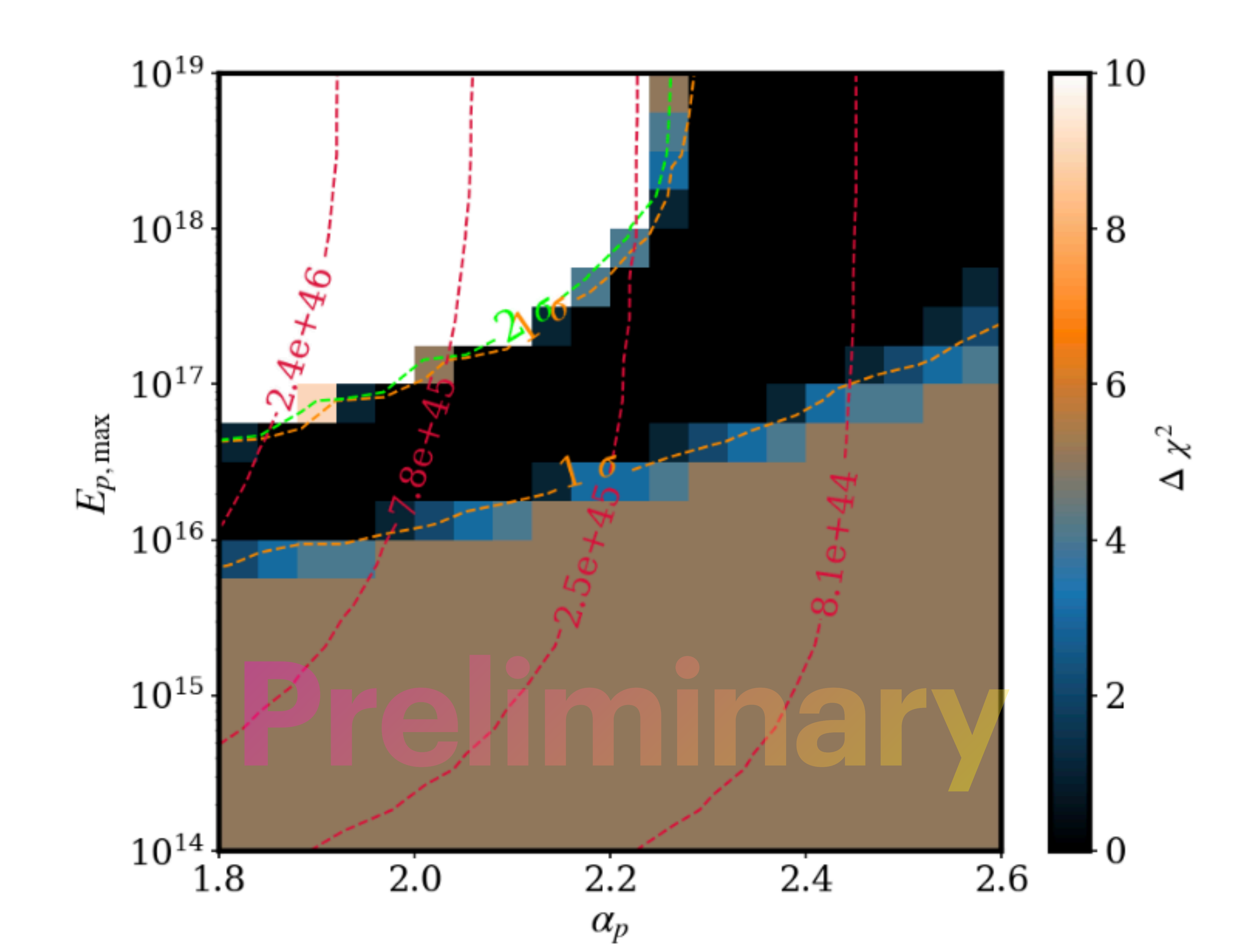


Proton induced cascades?

Atreya Archayya
Post Doc
at SDU

- We are also investigating possible contributions to gamma-ray spectrum of TXS0506+056
- Allows us to derive constraints on the luminosity of protons escaping the source

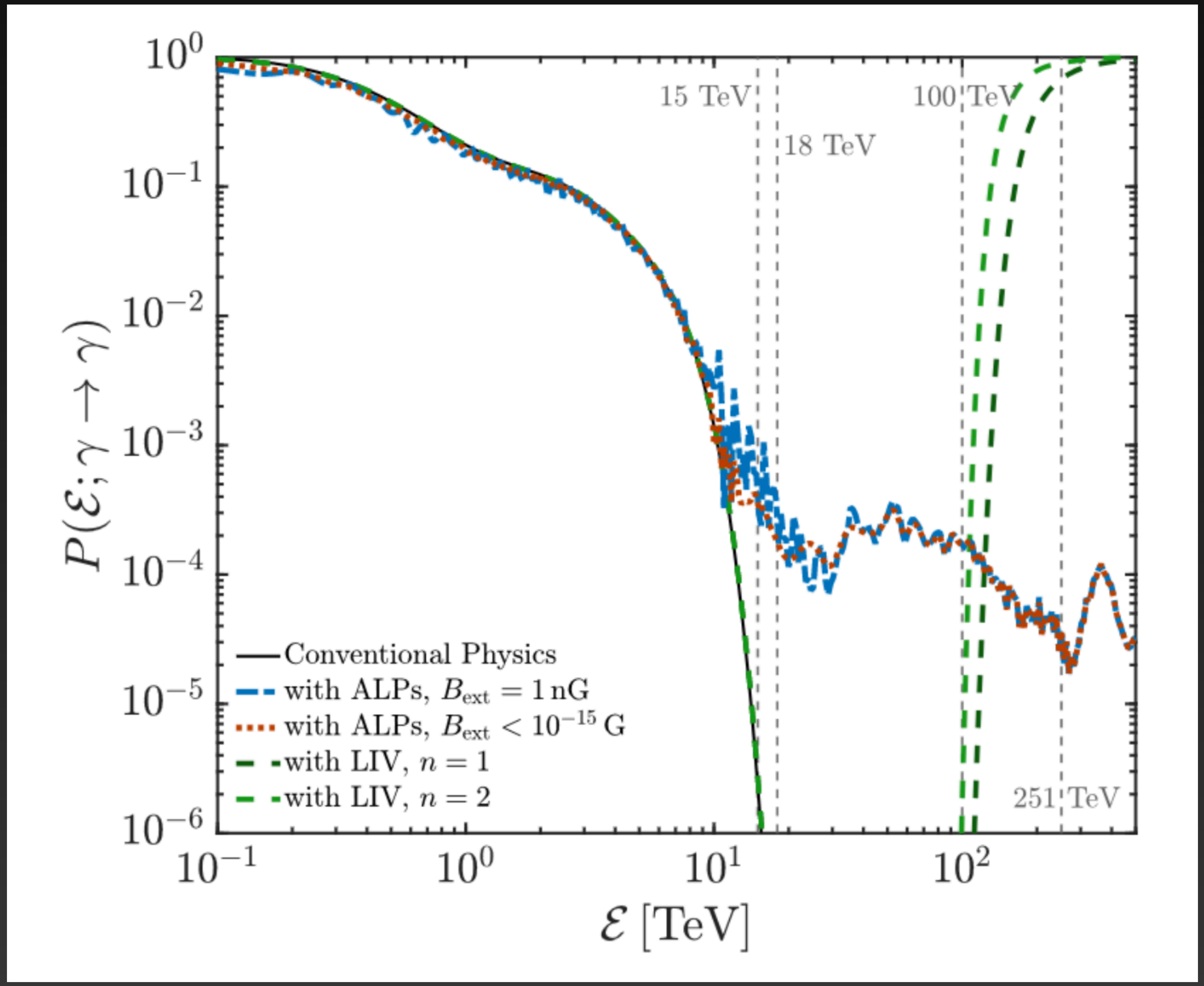




ALP interpretation?

- Astrophysical environments considered:
  - Mixing in GRB
  - Host galaxy (starburst with high B field or spiral)
  - IGMF
  - Milky Way
- EBL model: Saldana Lopez et al. 2021
- Photon flux considerably boosted at 18 TeV

[Galanti et al. 2024]



[Galanti et al. 2024 and 10+ other papers]

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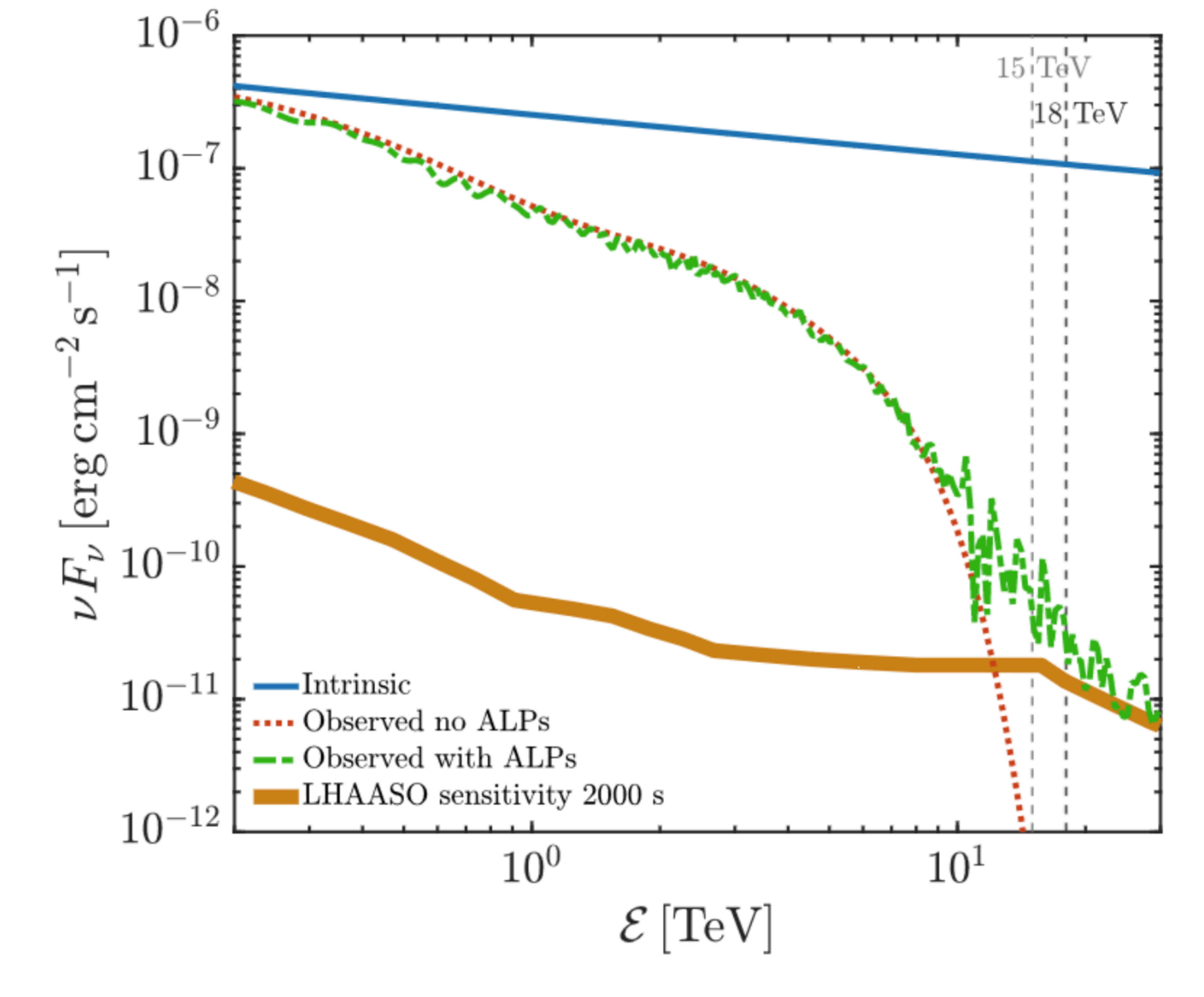
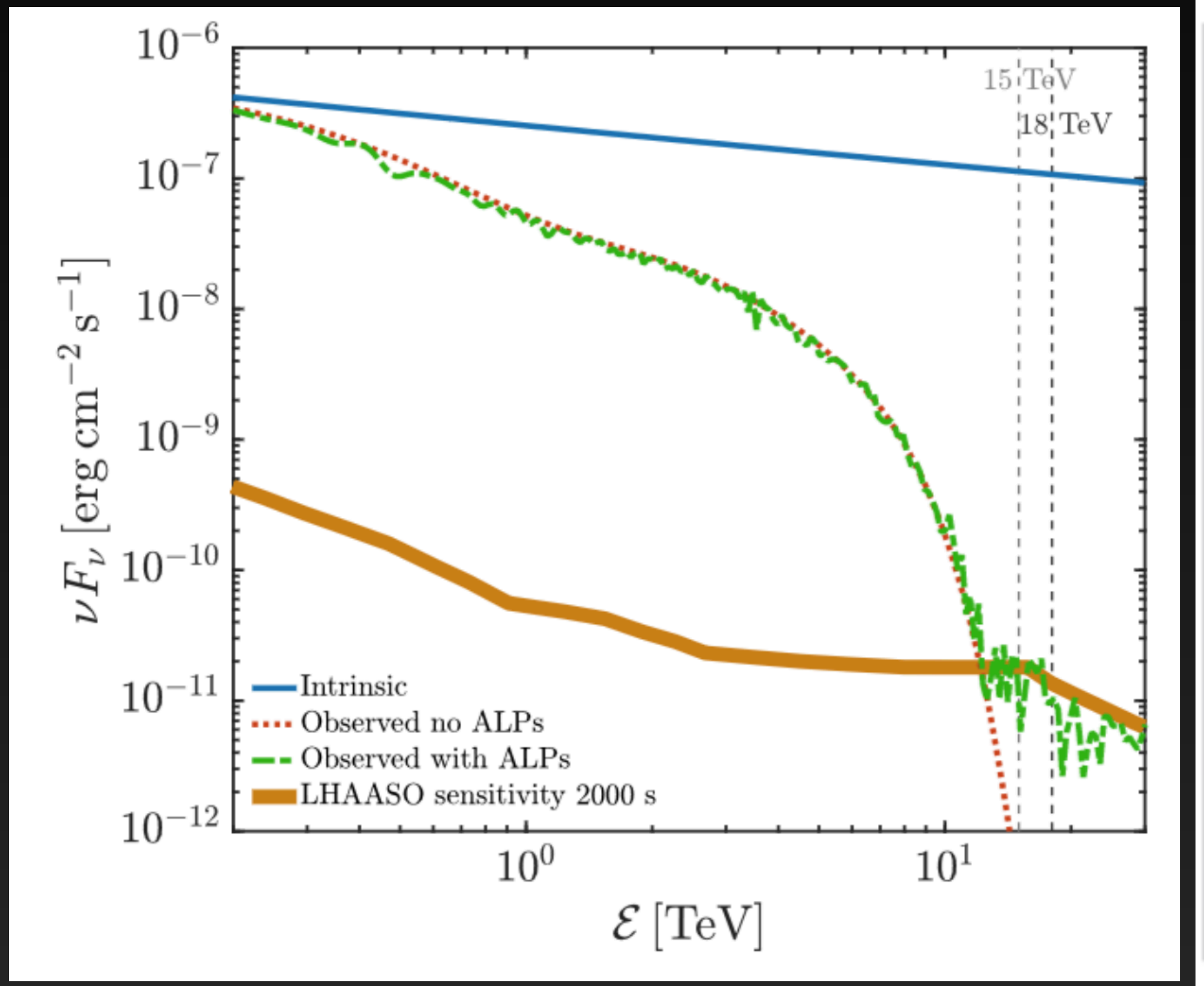
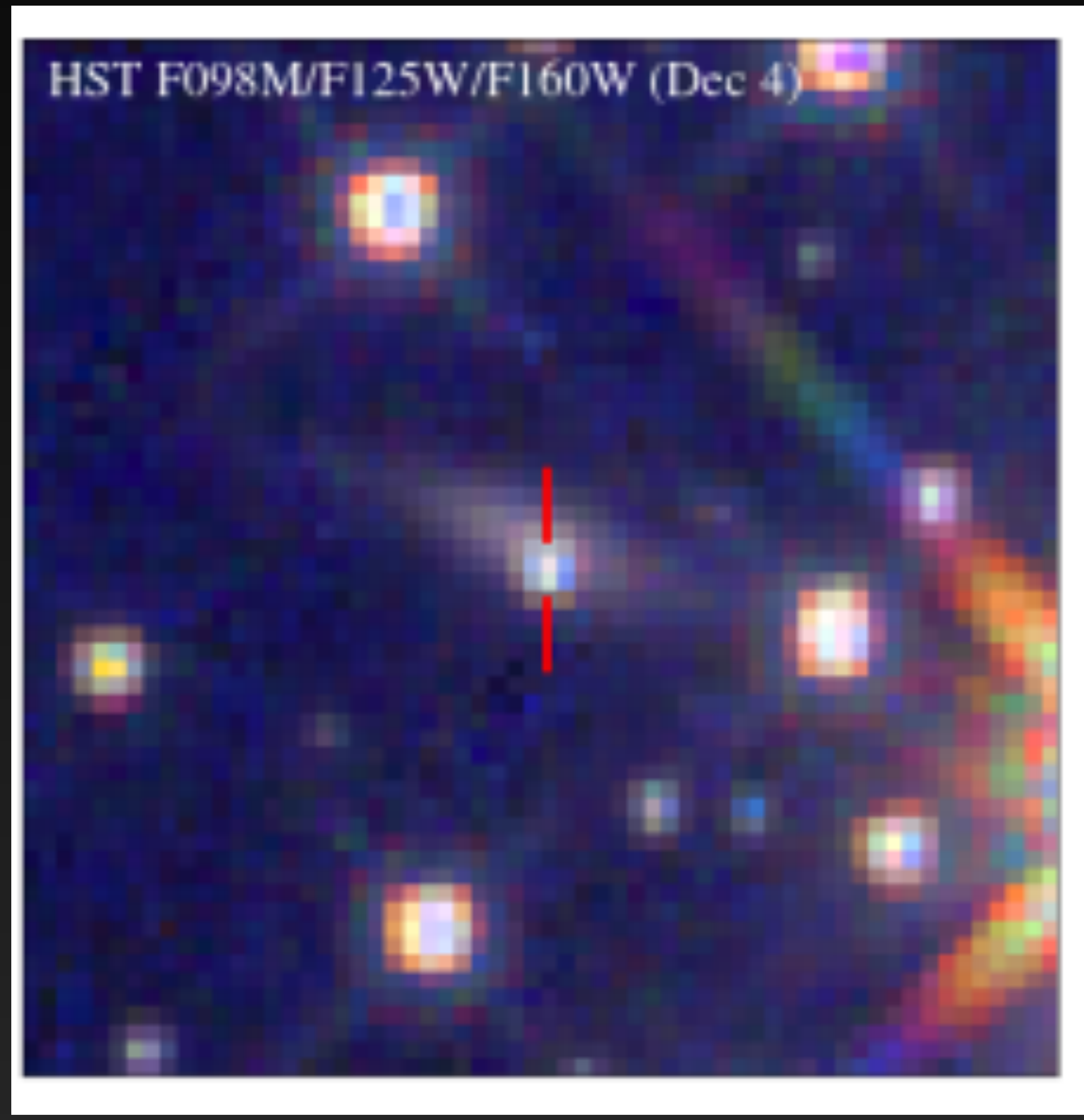


Caveats

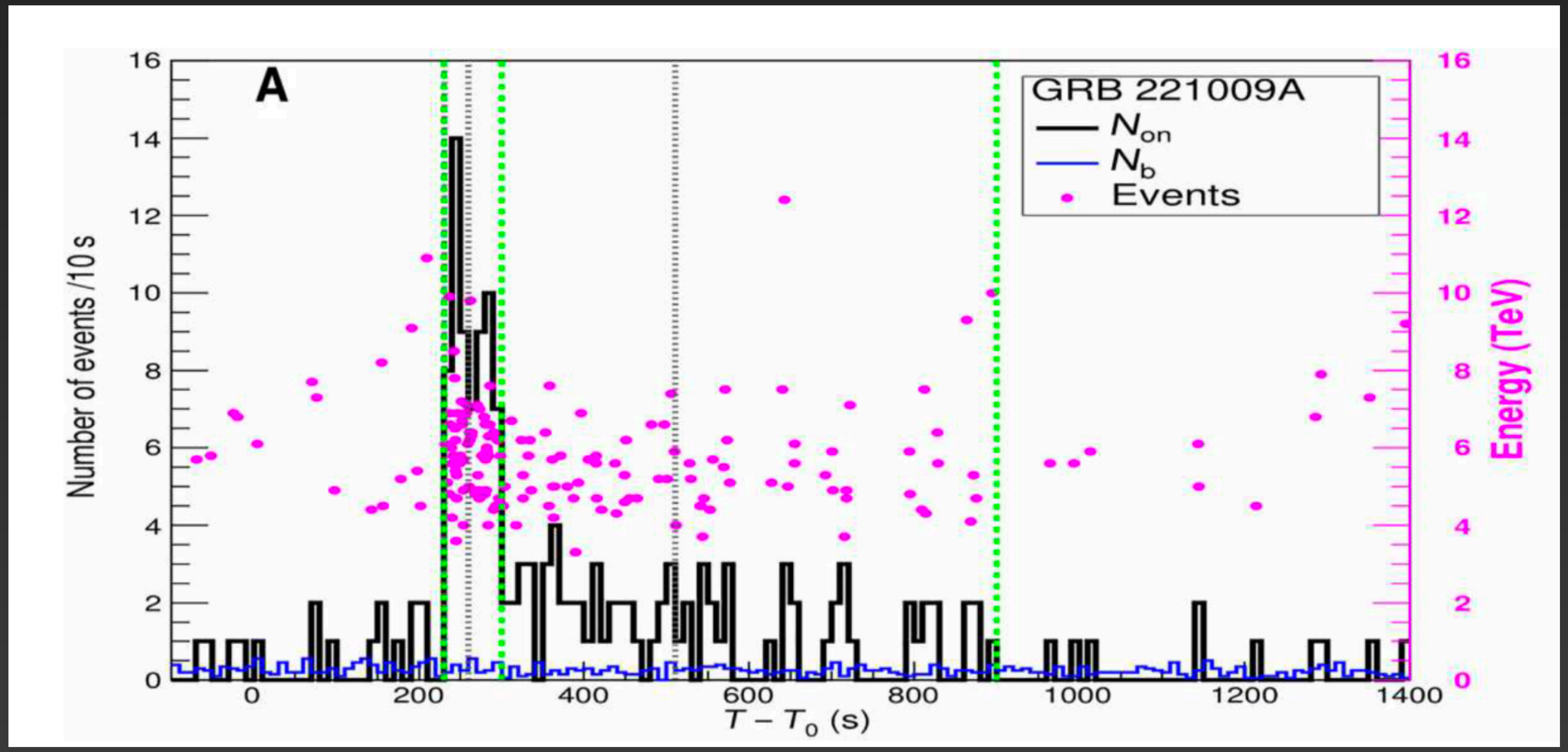
- Host galaxy observed with JWST and HST:
  - Appears to be ordinary spiral galaxy
  - Observed edge-on
  - Strong B field unlikely
- LHAASO observations:
  - Highest energy photon at 13 (not 18 TeV)

Galanti et al. 2024





[Levan et al. 2023]

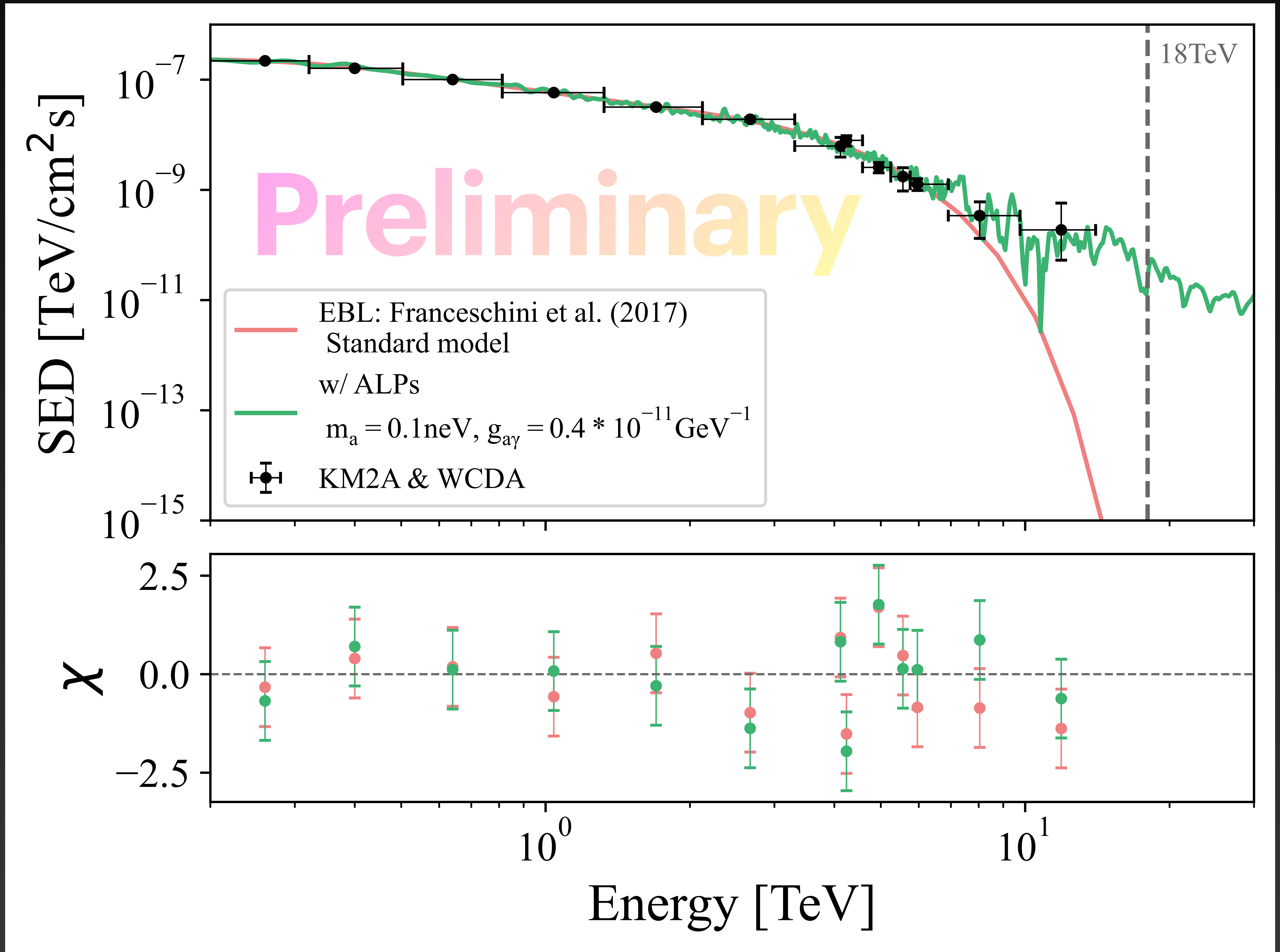


[Cao et al. 2023]

Using the actual KM2A spectral data

Katrine Vølund Kennedy
Master student at SDU

- Fit over WCDA and KM2A with log parabola and EBL attenuation provides good fit
- Max contribution from last data point to χ^2: 1.8
- Mixing inside GRB negligible effect



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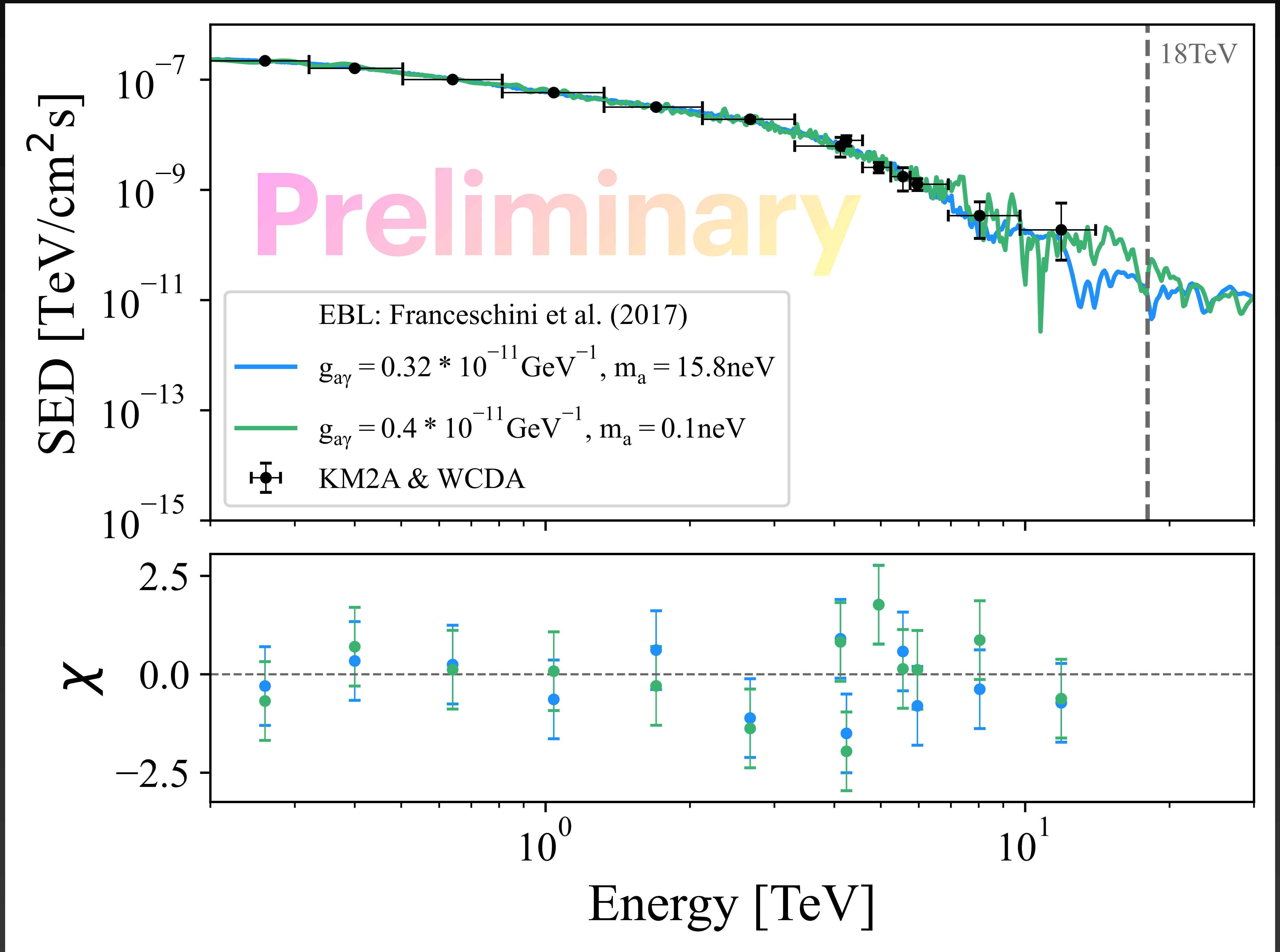
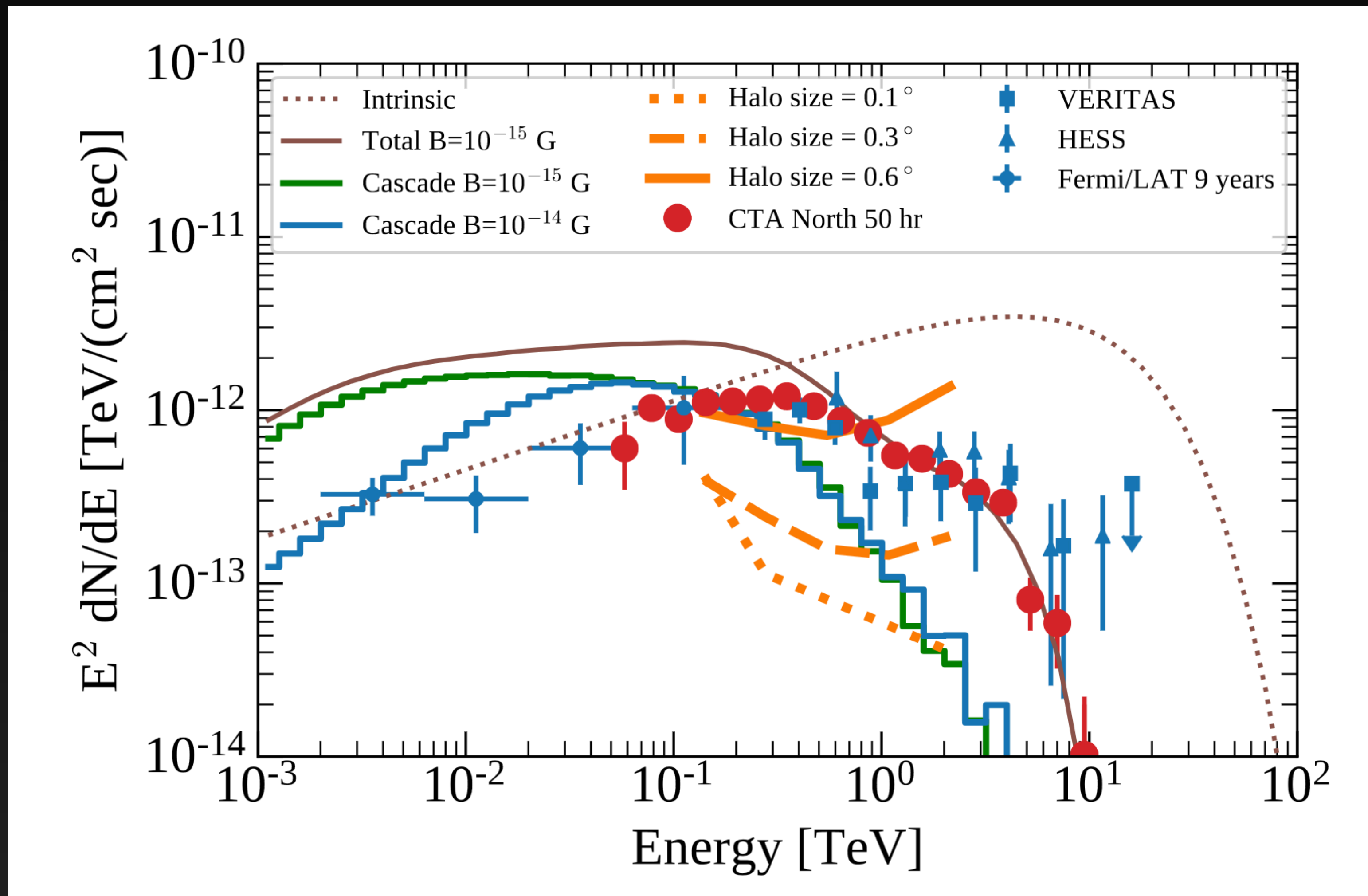
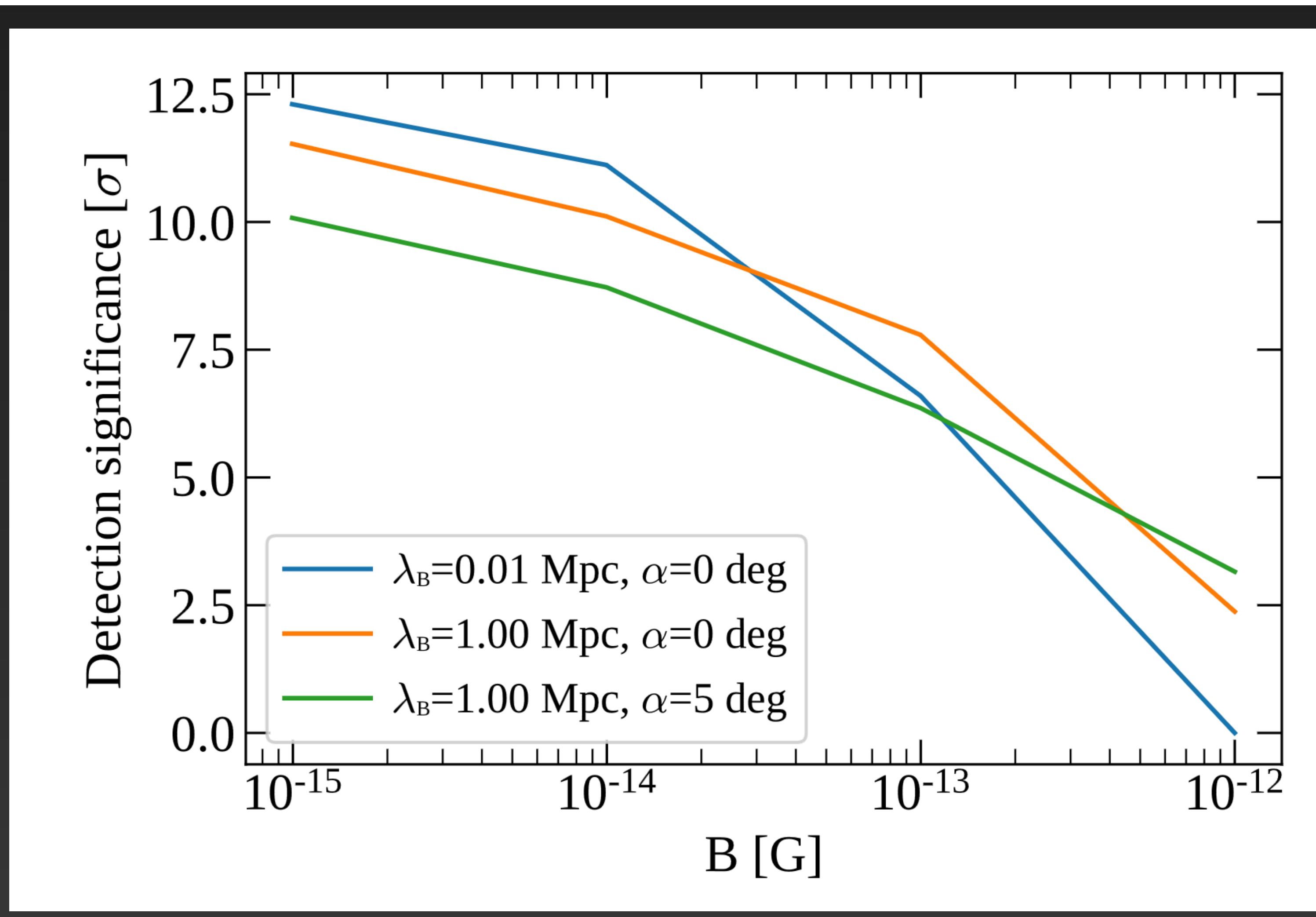
- Max contribution from last data point to χ^2: 1.8
- Mixing inside GRB negligible effect
- Best-fit ALP parameters give improvement
  $\Delta\chi^2 = 11.74 - 10.14 = 1.60$



Conclusions

- Level of EBL still uncertain but well constrained in the optical from galaxy number counts
- So far: no additional contribution to EBL detected / required to explain observations
- Combination of data from IACTs and the LAT yield strong constraints on the IGMF through non-observation of pair cascade from blazars
- If pairs lose energy through scattering CMB photons, domain-like B fields weaker than $B \lesssim 7 \times 10^{-16}\,\mathrm{G}$ for $t_{\max} = 10\,\mathrm{yr}$ are ruled out
- Magnetic fields from purely astrophysical origin can be ruled out from blazar observations
- GRB221009A provides strong additional probe of IGMF with less uncertainties
- Axion interpretation of highest energy photons observed with LHAASO KM2A questionable
- Outlook: CTA observations with improved sensitivity, PSF, energy range will yield new constraints in the next years [Abdalla et al. (including MM) 2021]



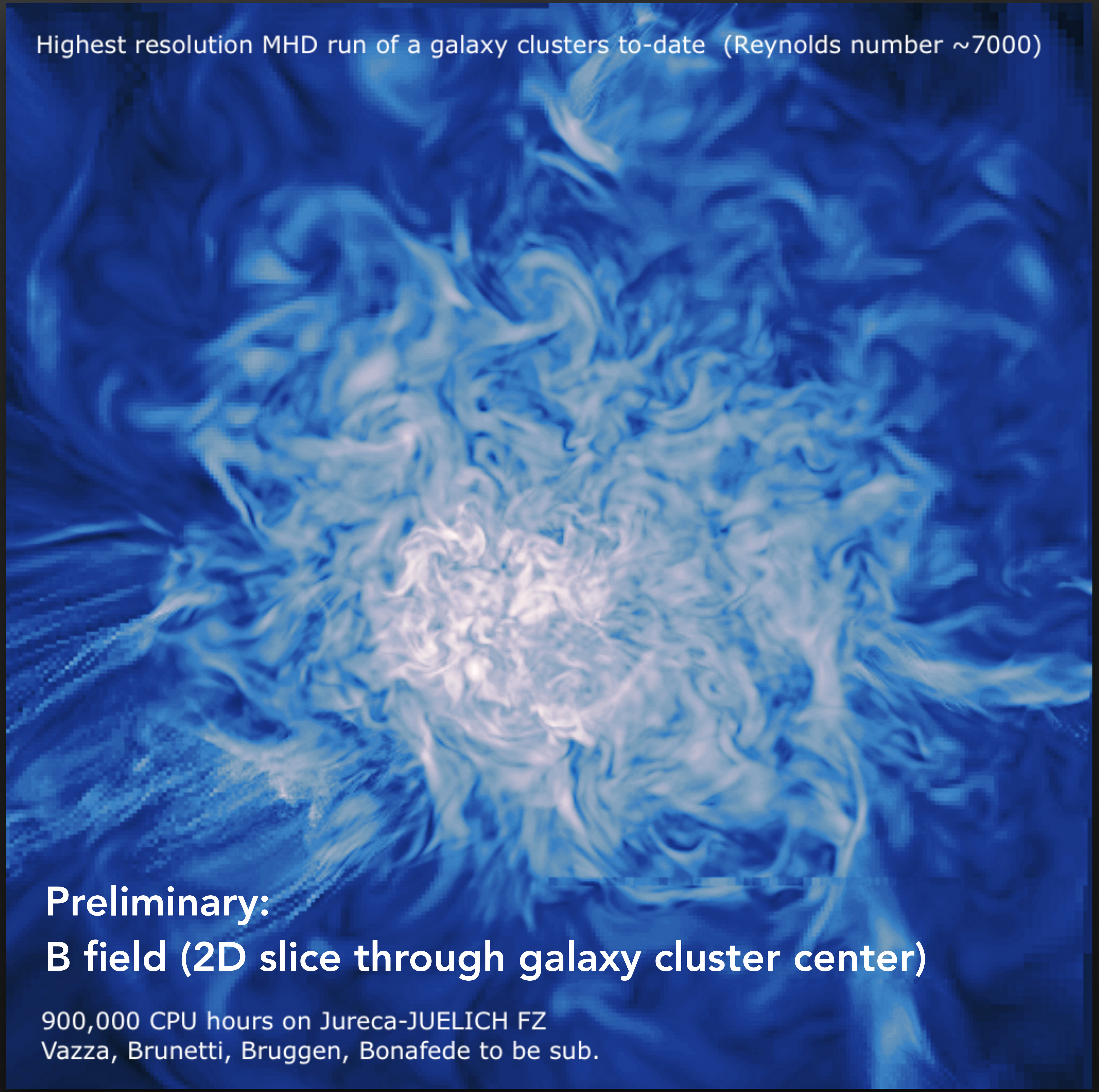


Axion outlook

- Better understanding of intervening magnetic fields (in IGMF, clusters, AGN jets, host galaxy, our own MW) helps to look for axion signatures
- Could we look for them in AGN spectra behind mega radio halos?
- If IGMF is large ~ 0.1 nG, photon-axion oscillation in IGMF could be relevant

OUTLOOK IN 2017: SIMULATIONS OF THE CLUSTER MAGNETIC FIELD

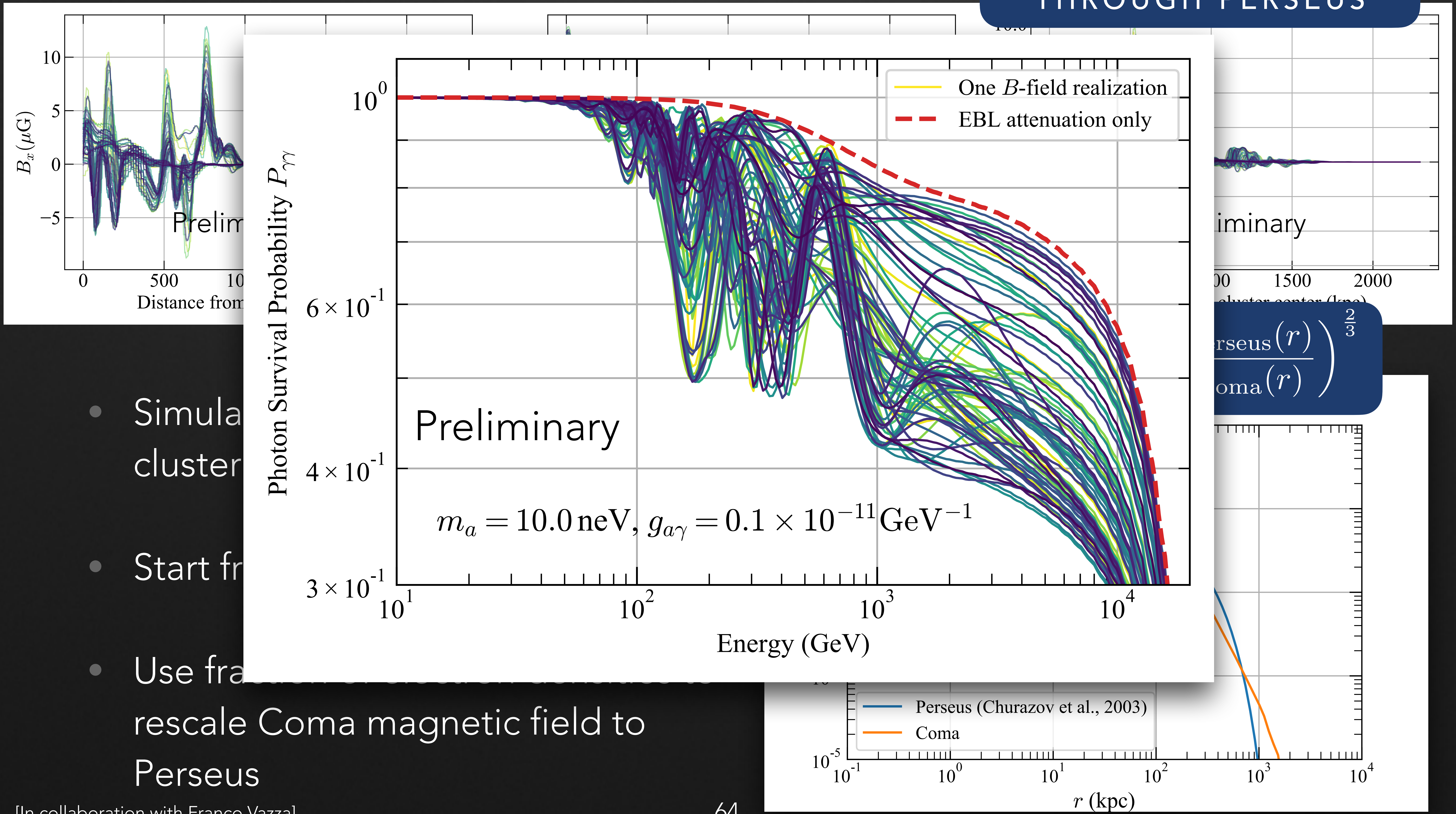
- Enable to properly resolve dynamo amplification of primordial fields
- Match the observed Faraday Rotation of Coma
- At the moment: do not include radiative feedback or cooling
- Simulating Perseus difficult due to the (likely) importance of AGN feedback



[Vazza; Brunetti; Brüggen; Bonafede, submitted]

OUTLOOK IN 2017: USING THE CLUSTER MAGNETIC FIELD FOR PHOTON-ALP OSCILLATIONS

100 LINES OF SIGHTS THROUGH PERSEUS



- Simula
  cluster
- Start fr
- Use fra
  rescale Coma magnetic field to Perseus

[In collaboration with Franco Vazza]