

# Anisotropy in the gamma-ray transparency of the Universe

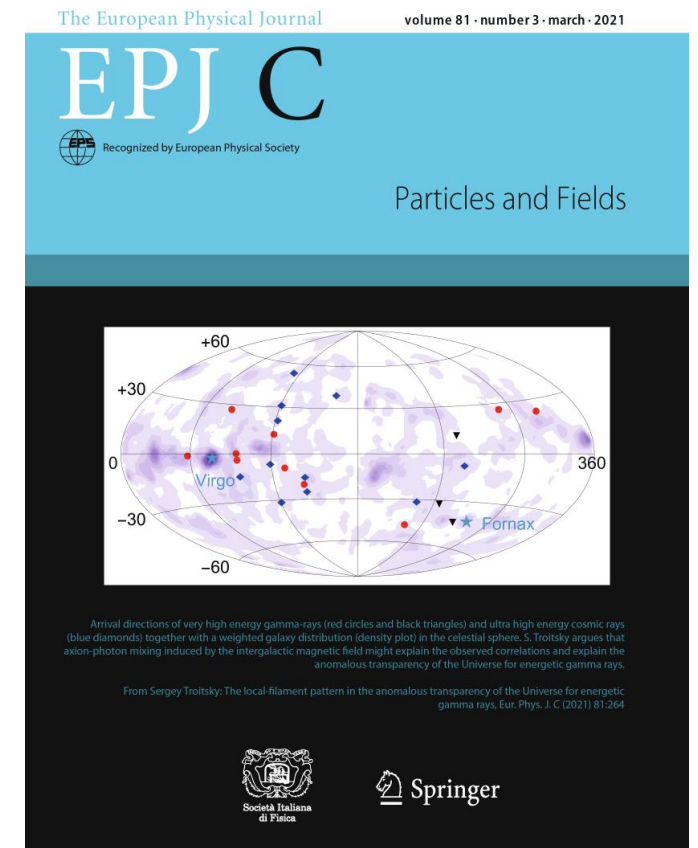
**Sergey Troitsky**  
(INR, Moscow)

*16<sup>th</sup> Patras Workshop, June 15, 2021*



# Plan of the talk

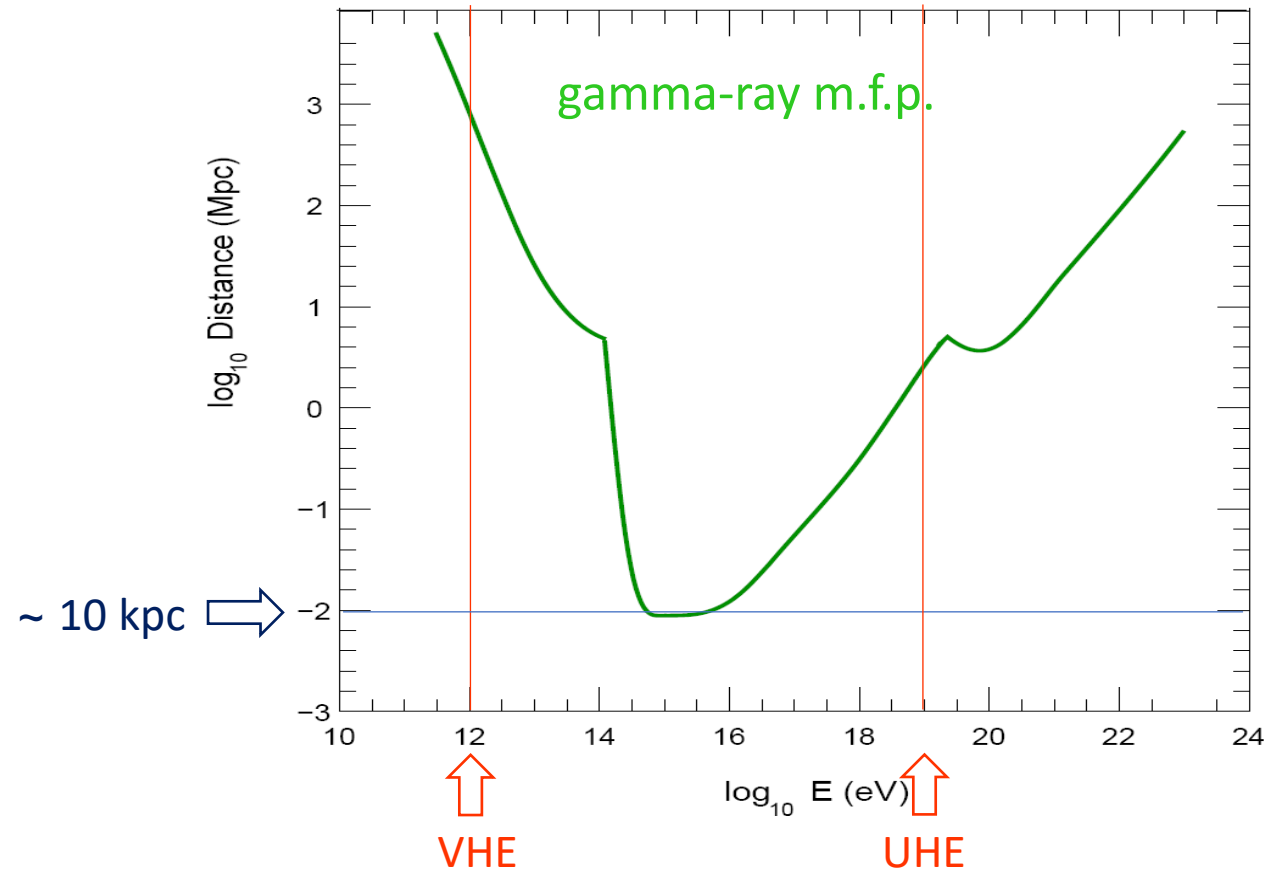
1. Pair production and gamma-ray opacity:
  - “IR/TeV crisis” – history and state of the art
2. Distribution of “anomalous” VHE gamma-ray sources in the sky
  - trace magnetic field in the ALP explanation
3. HiRes UHE cosmic ray / BL Lac story
  - similar troubles for  $E > 10^{18}$  eV back in 2004
4. Distribution of “HiRes BL Lacs” in the sky
  - the same pattern at  $10^{12}$  eV and  $10^{19}$  eV
5. Fitting all together (with ALPs)
6. Further steps



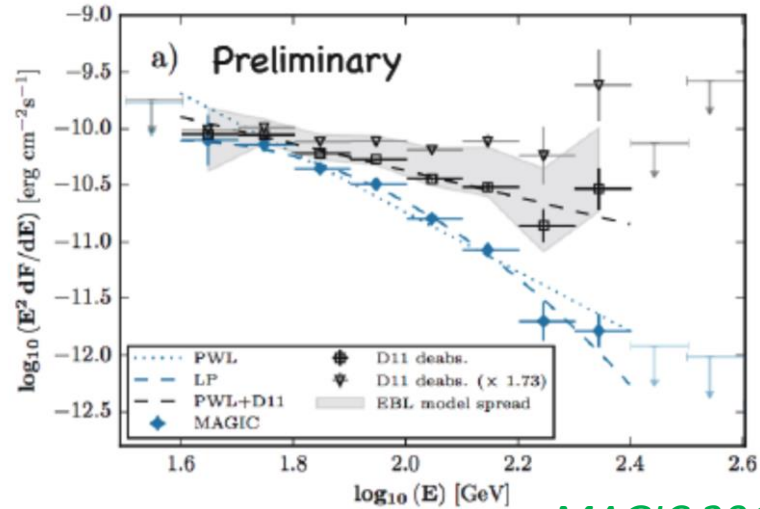
[Eur. Phys. J. C 81 \(2021\) 3, 264 =  
https://arxiv.org/abs/2004.08321](https://arxiv.org/abs/2004.08321)



# Pair production



# Too distant VHE sources: “anomalous transparency of the Universe”?



- “IR/TeV crisis” – individual sources *Protheroe, Meyer 2000 + .....*
- spectra of distant sources look differently compared to physically similar nearby ones *Kneiske, unpublished*
- statistics of “deabsorbed” spectra:  
**features right at the energies for which the correction becomes important!** *Horns, Meyer 2012*  
*Rubtsov, ST 2014*

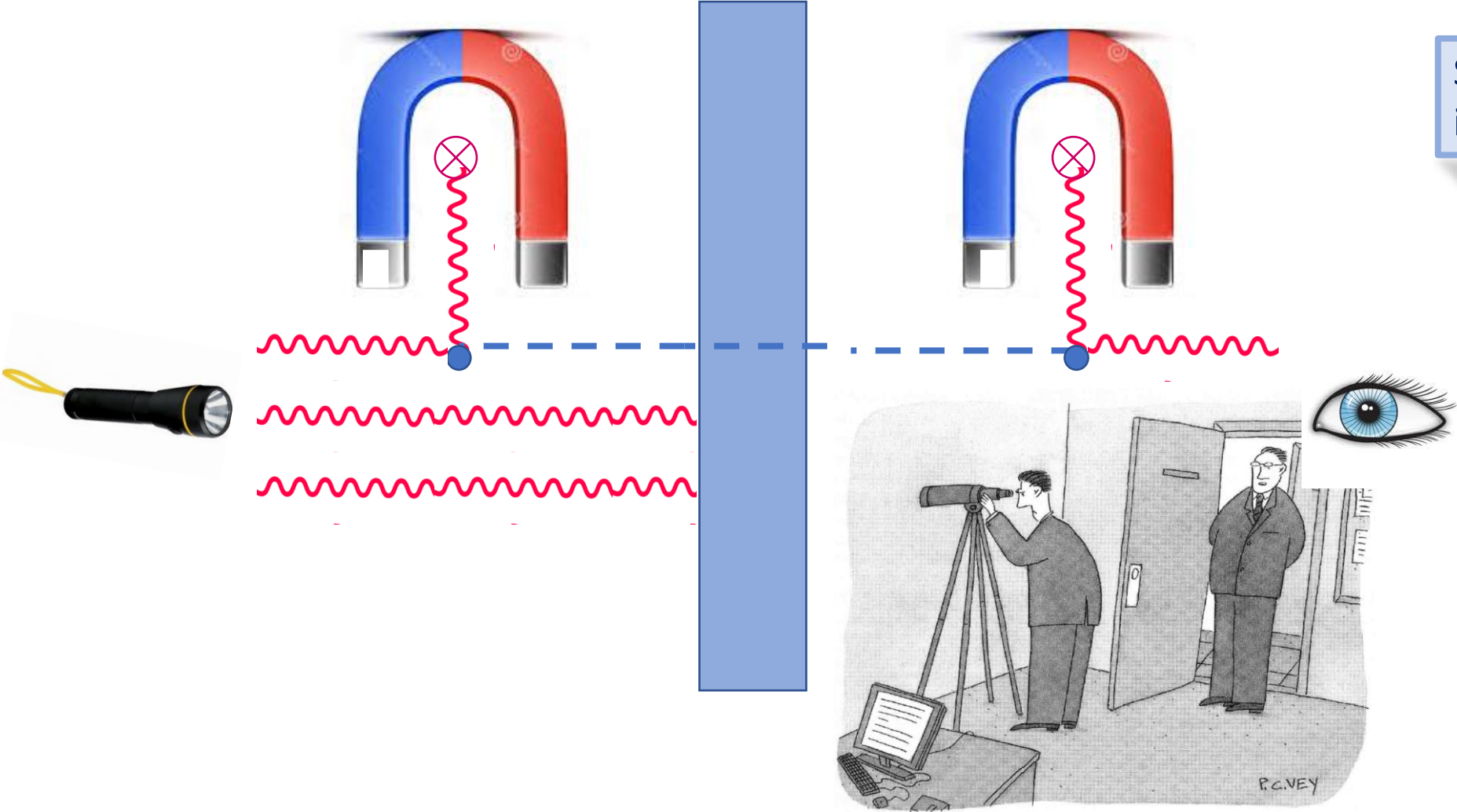
State of the art – increasing statistics, better known distances:

- the anomaly is confirmed for a part of sources – both “old” and “new” ones
- many new, weaker sources do not demonstrate any problem
- modest overall statistical significance of the anomaly

*Korochkin, Rubtsov, ST 2019*



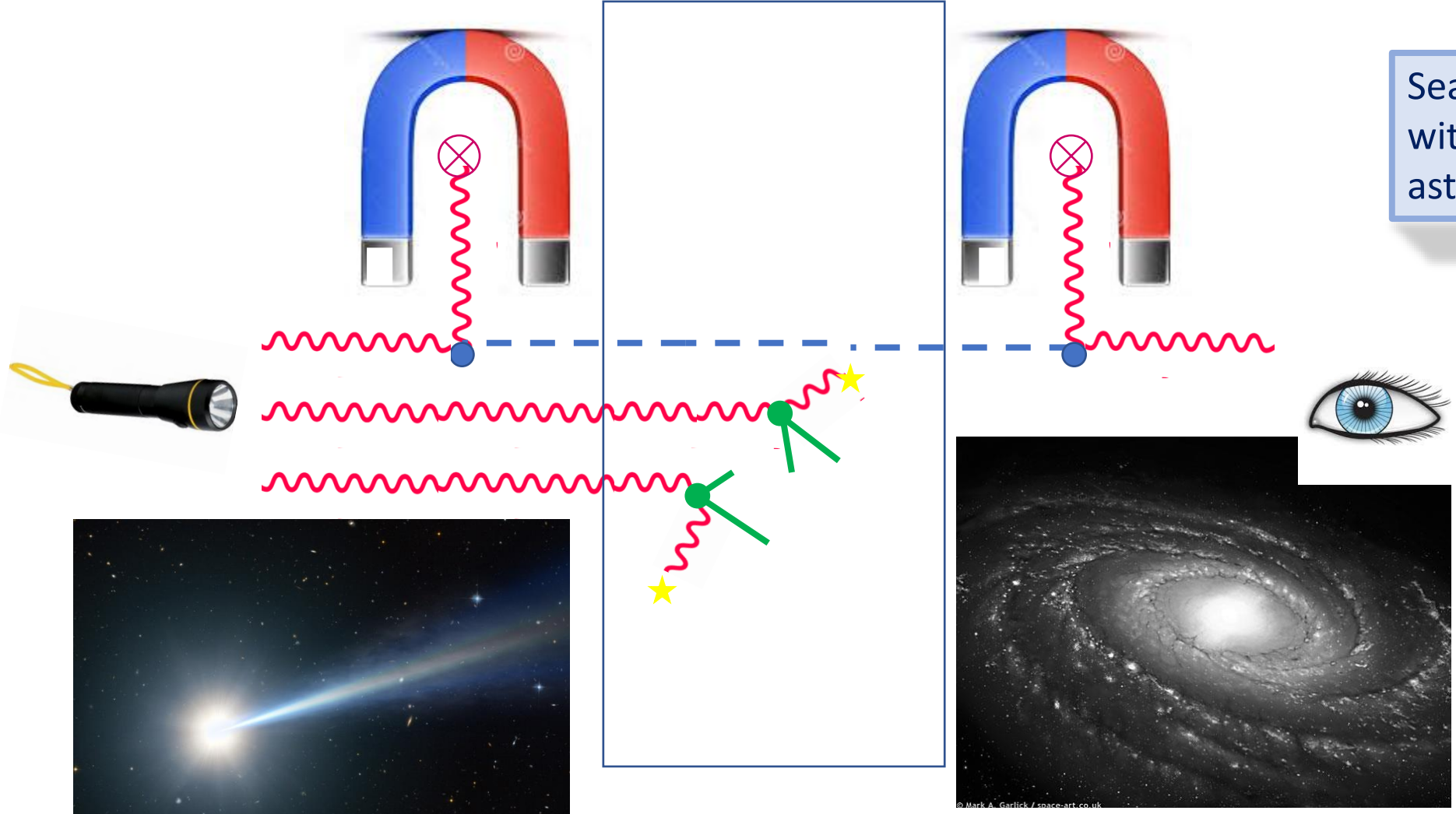
# ALP-photon: shining light through walls



Search for axions  
in a laboratory



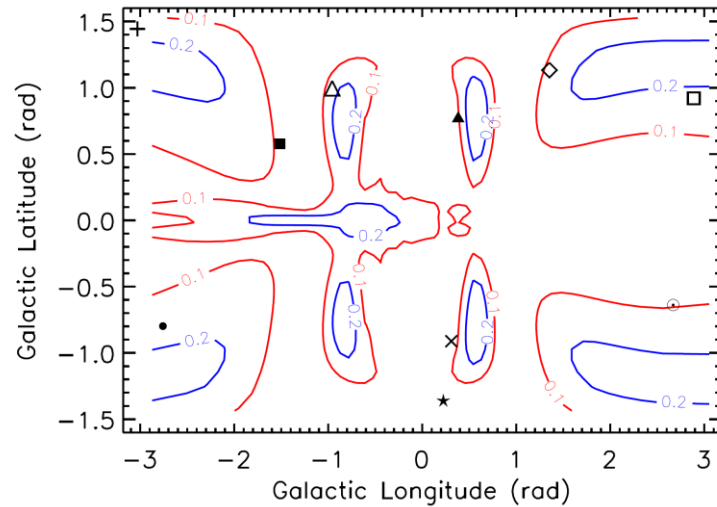
# ALP-photon: shining light through the Universe



Search for axions with gamma-ray astronomy



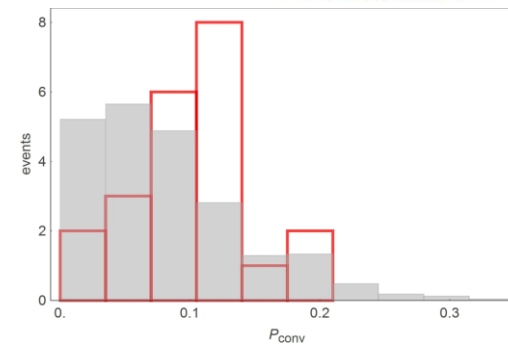
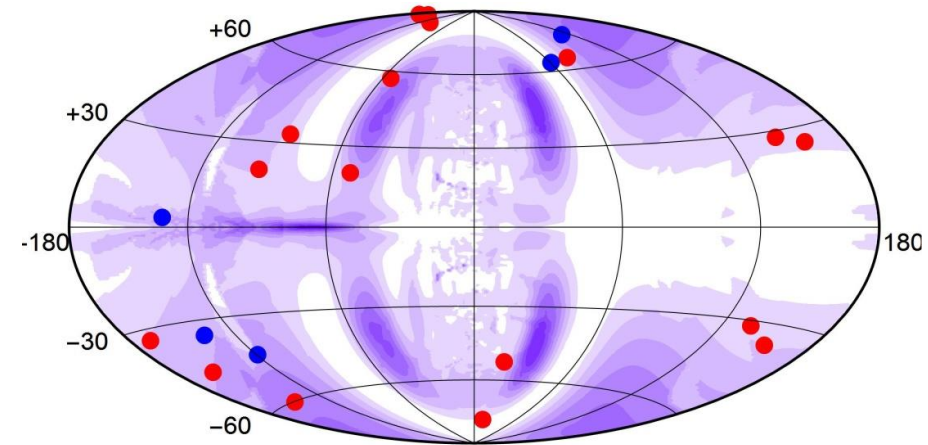
# ALP: photon regeneration in the Milky Way



Conversion probability in the Galaxy

*Simet, Hooper, Serpico 2008*

symbols = VHE blazars (2008),  $z > 0.1$



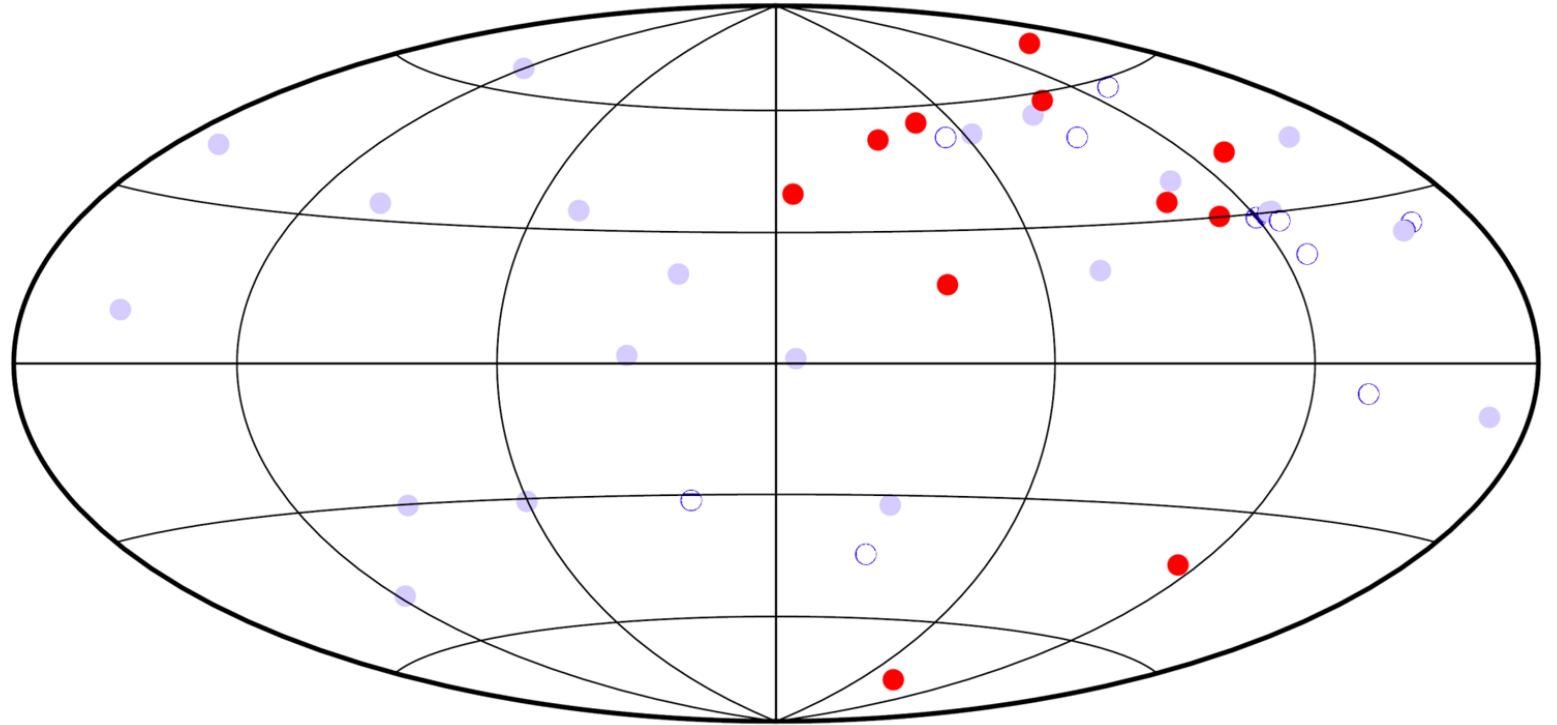
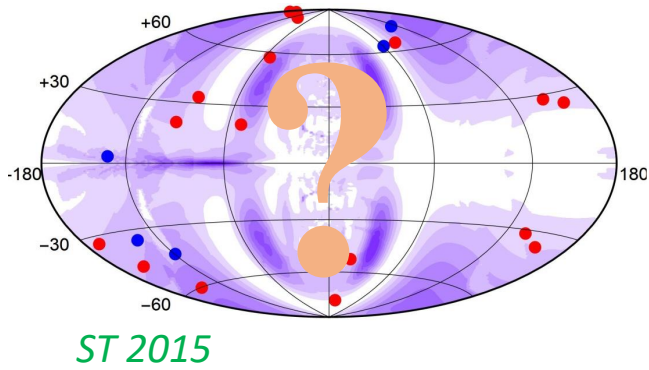
The same as of 2015  
(same field model)

*ST 2015*

For modern models of the Galactic magnetic field, the picture is very different...



# Anisotropy of the “anomalous transparency of the Universe”?

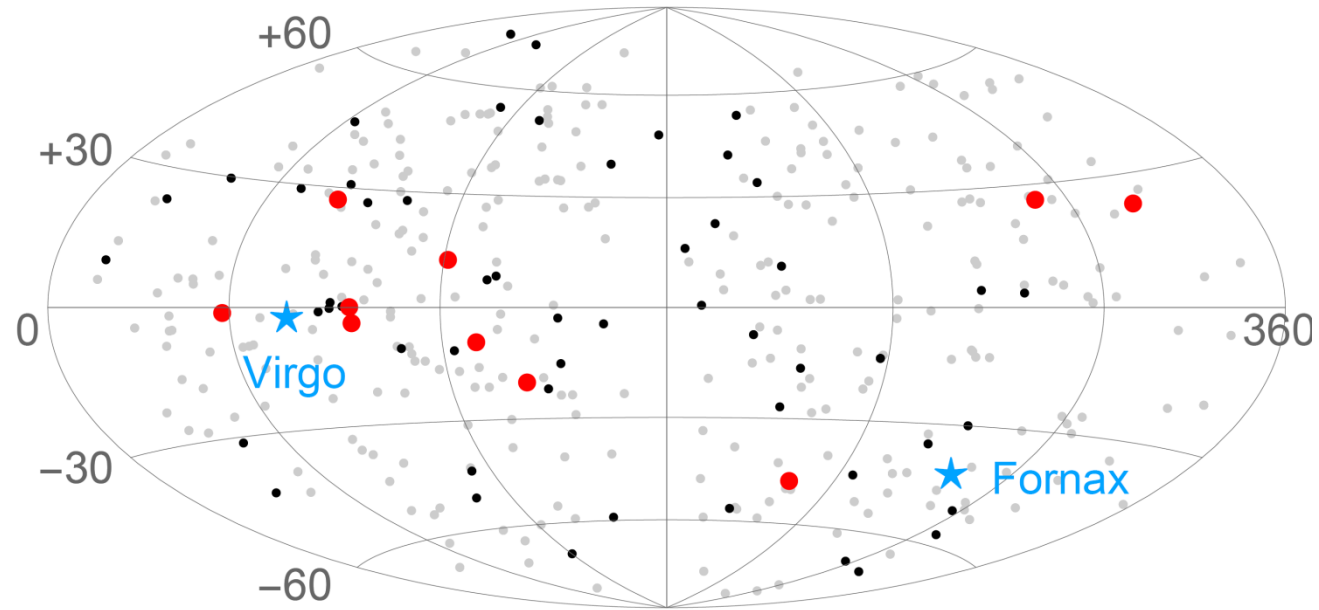


“Anomalous” and “non-anomalous” blazars from *Korochkin et al. 2019* on the skymap





# Anisotropy of the absorption, related to the local filament?



“Anomalous” and “non-anomalous” sources on the skymap

*ST 2020*



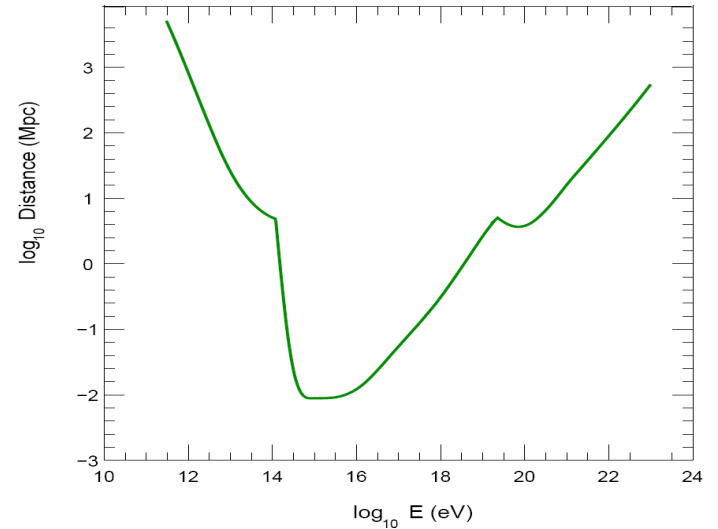
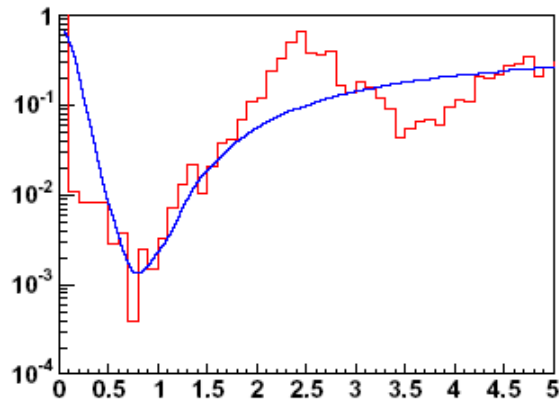
# Cosmic rays and BL Lacs: an old story...

Correlations of arrival directions of  $E > 10^{19}$  eV cosmic rays with cosmologically distant objects, indicating neutral primary particles

- 11 pairs “BLL-cosmic ray” observed
  - 3 pairs expected for isotropy
- $p = 10^{-3}$  post trial

*Gorbunov, Tinyakov,  
Tkachev, ST 2004*

confirmation and extension  
down to  $E \sim 10^{18}$  eV :  
*HiRes Collaboration  
2005*



- cannot be explained by usual cosmic rays (deflections)
- cannot be explained by photons from the sources (pair-production opacity)
- can be explained by the ALP-gamma mixing
- does not work in the Milky Way, **works in the filament**

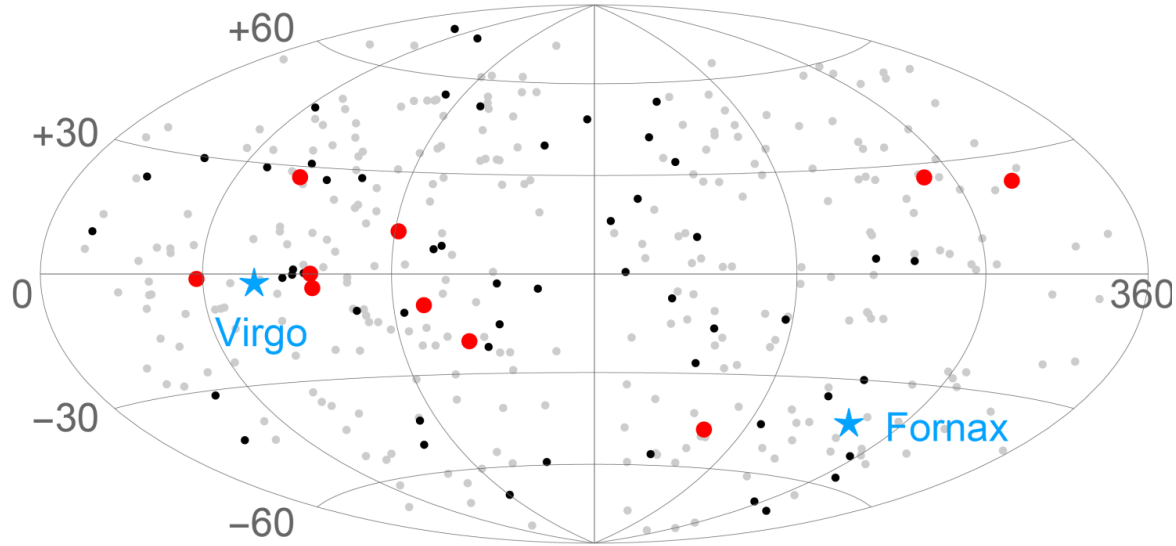
*Fairbairn, Rashba, ST 2009*

Note: HiRes stereo angular resolution remains unsurpassed as of 2021...

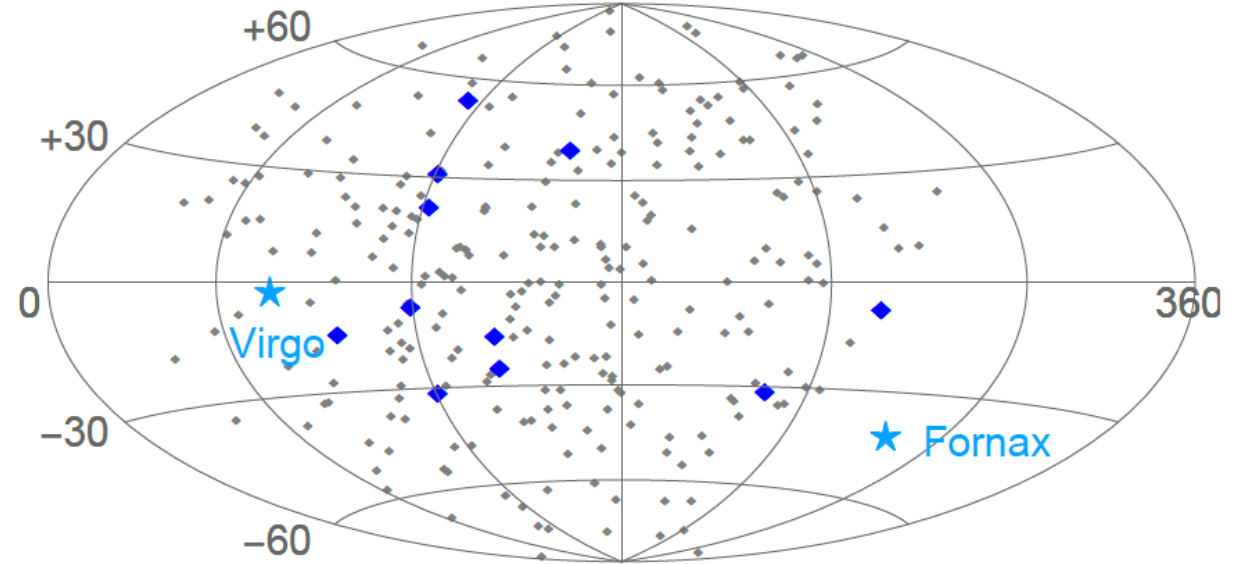


# Anisotropy of the absorption, related to the local filament?

## VHE



## UHE

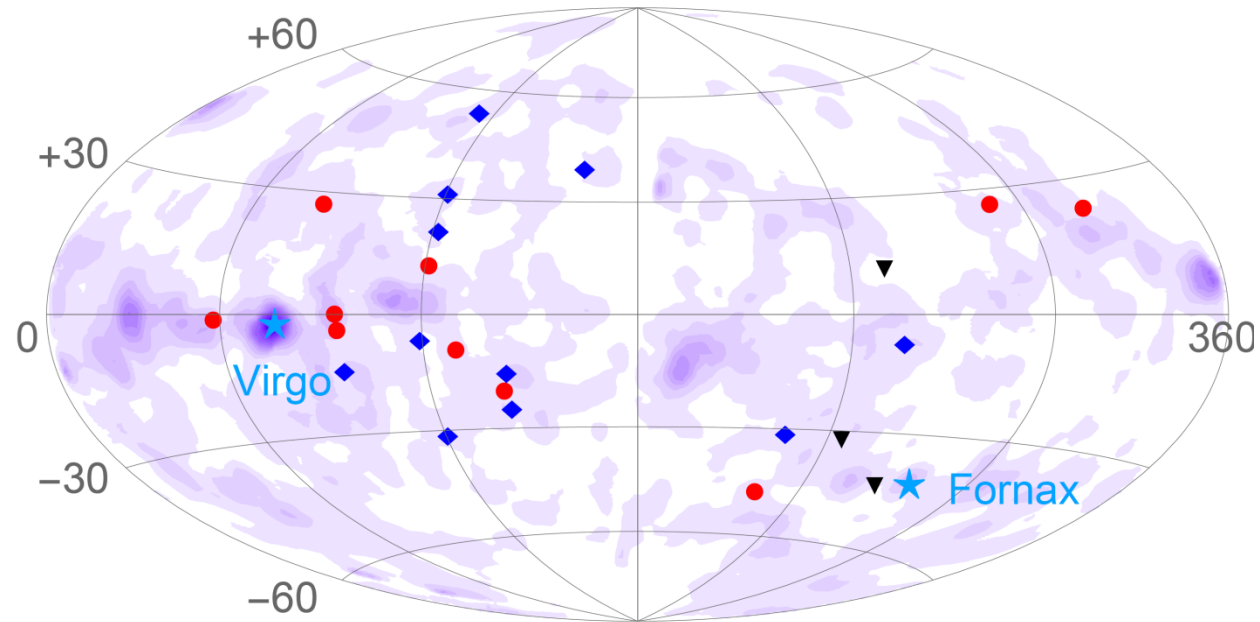


ST 2020

“Anomalous” and “non-anomalous” directions on the skymap



# Anisotropy of the absorption, related to the local filament?



$p=7.5 \times 10^{-5}$   
 $4.0\sigma$   
*post trial*

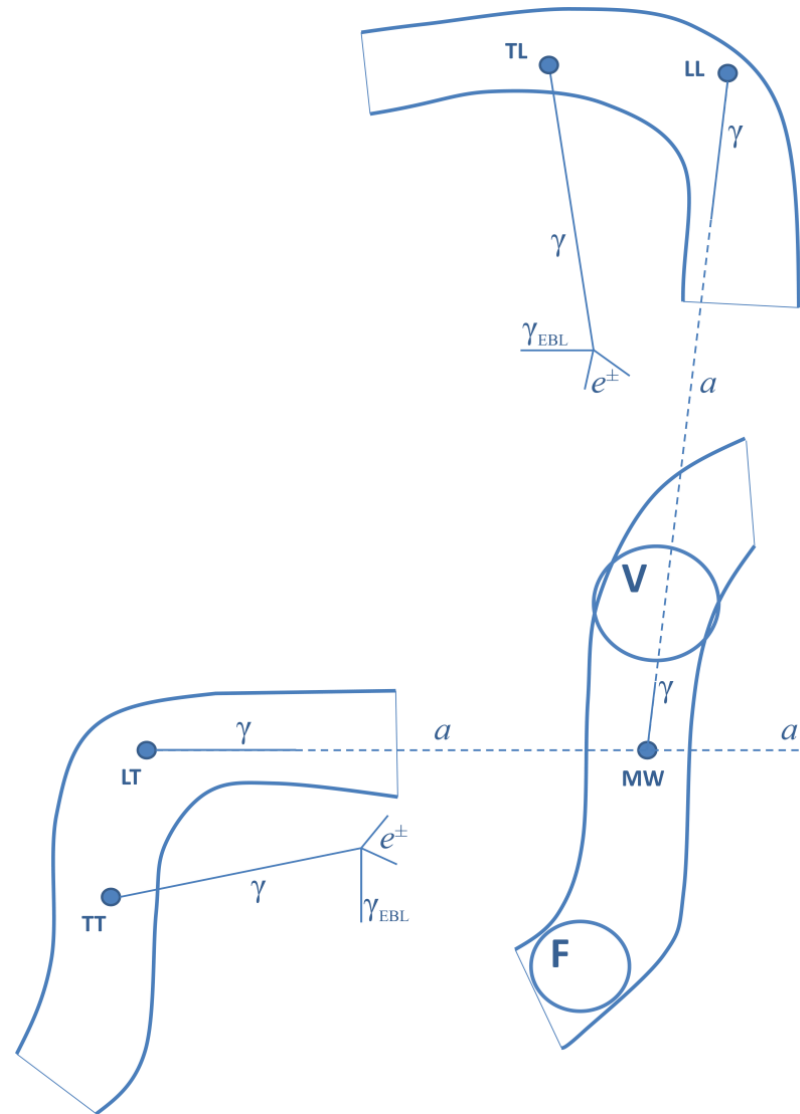
*(trials = smoothing)*

- Red: “anomalous” VHE blazars ( $p=0.028$ )
- ◆ Blue: “HiRes” BL Lacs ( $p=1.1 \times 10^{-3}$ )
- ▼ Black: VHE GRB (*not counted in the statistical analysis*)
- Shadow: smoothed number density of nearby galaxies

*ST 2020*



# ALPs, filaments and the “anomalous transparency”



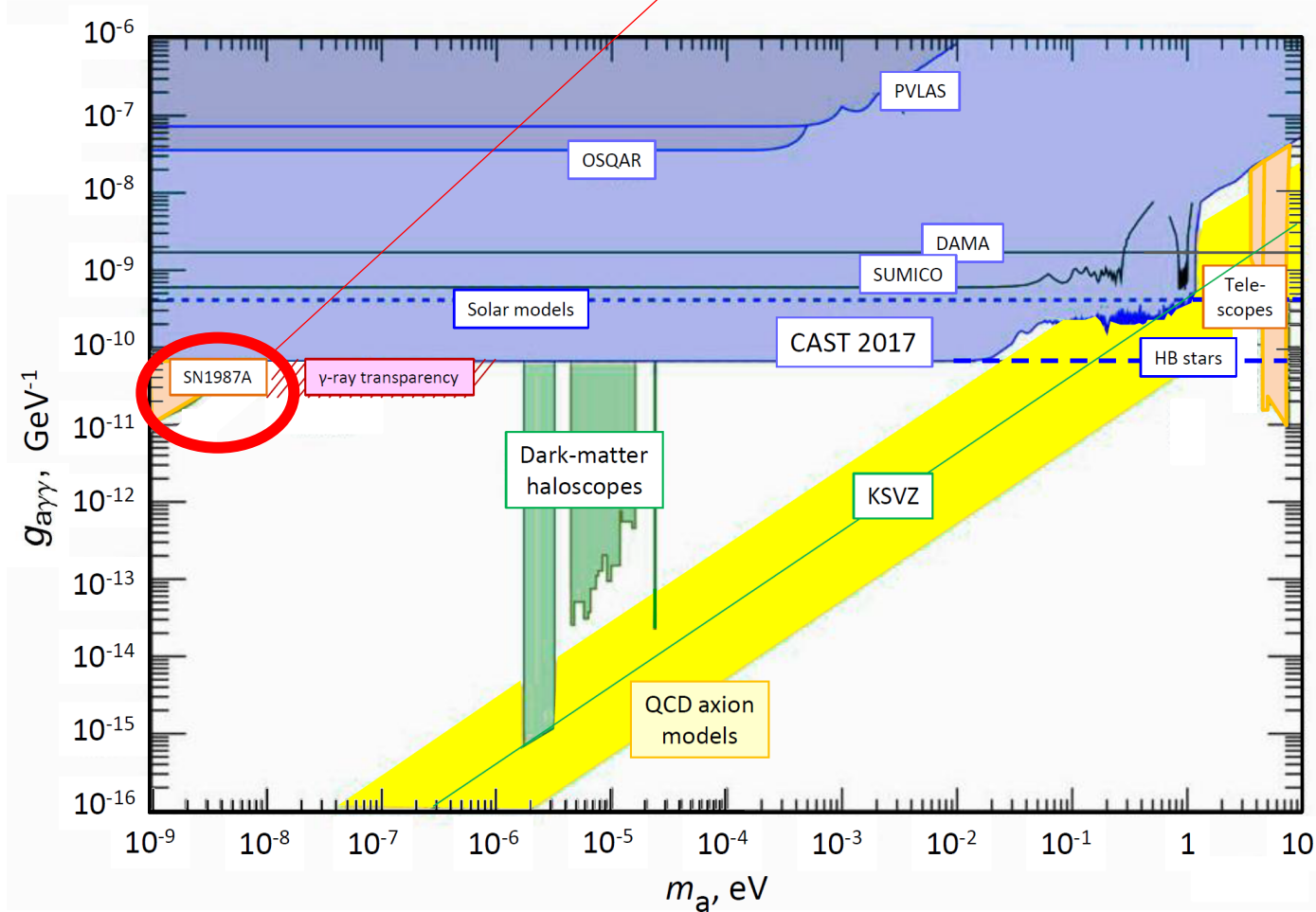
*ST 2020*

<sup>3</sup>The author thanks O. Troitskaya for her help with this sketch.



# ALP parameters

$$m \sim (\text{a few}) 10^{-9} \text{ eV}, \quad g_{a\gamma} \sim (\text{a few}) 10^{-11} \text{ GeV}^{-1}$$



- allowed range of parameters
- stellar evolution hints
- (in simple models) – neither the QCD axion, nor the dark-matter particle



# What next?

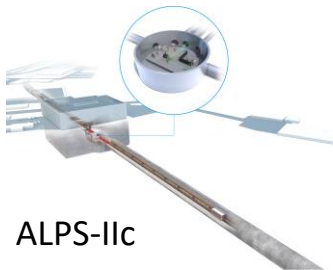
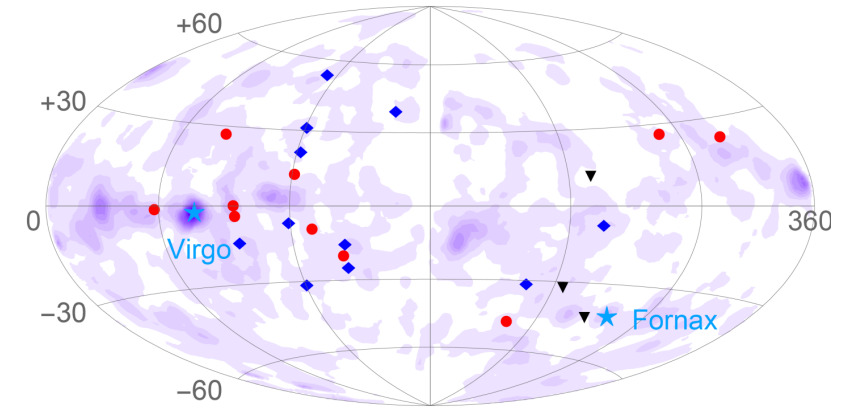
- isotropic flux-limited samples of blazars

*Kudenko, ST, in progress*

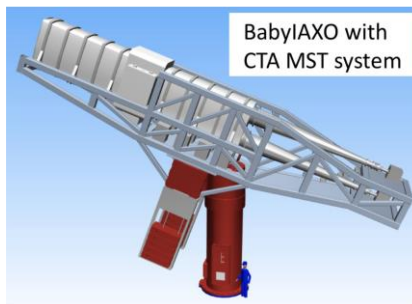
- tests at EeV – correlations, anisotropy, photons

*Telescope Array collaboration, in progress*

- Fermi LAT – full sky, but too low energies
- CTA – future sky surveys at TeV
- experimental searches for ALPs...



ALPS-IIc



BabyIAXO with  
CTA MST system

**THANK YOU!**



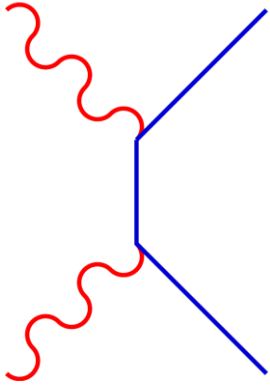
# BACKUP





# Pair production: the Universe is opaque to gamma rays

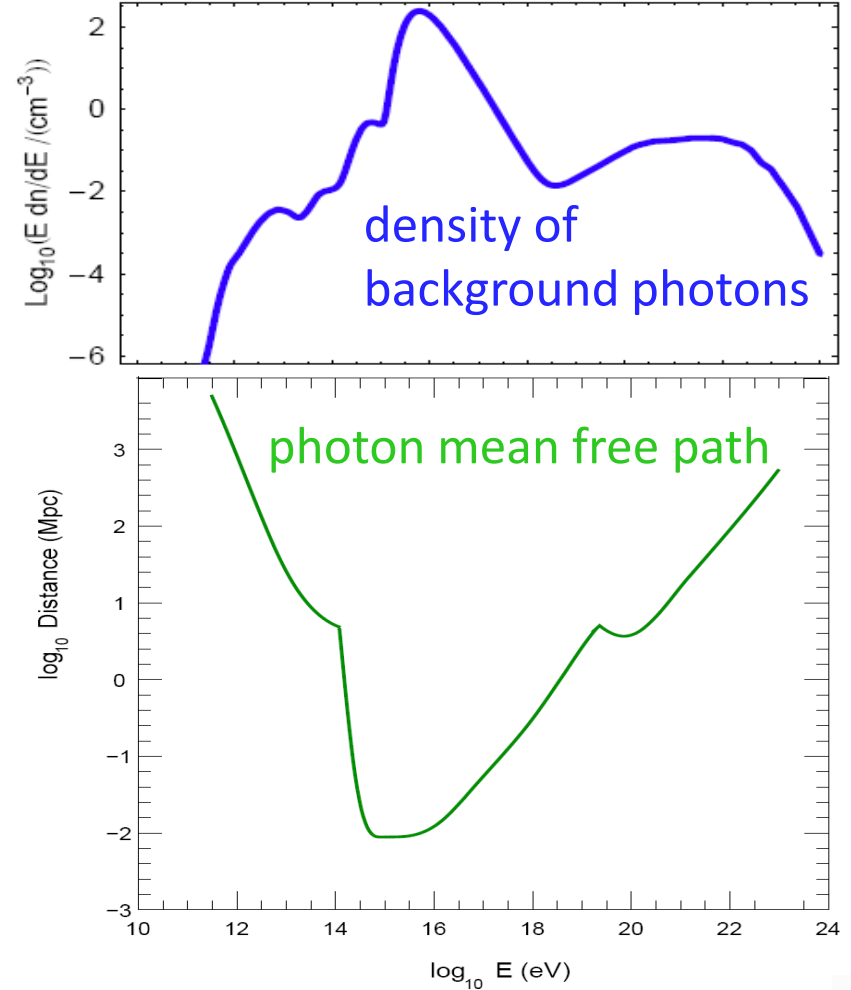
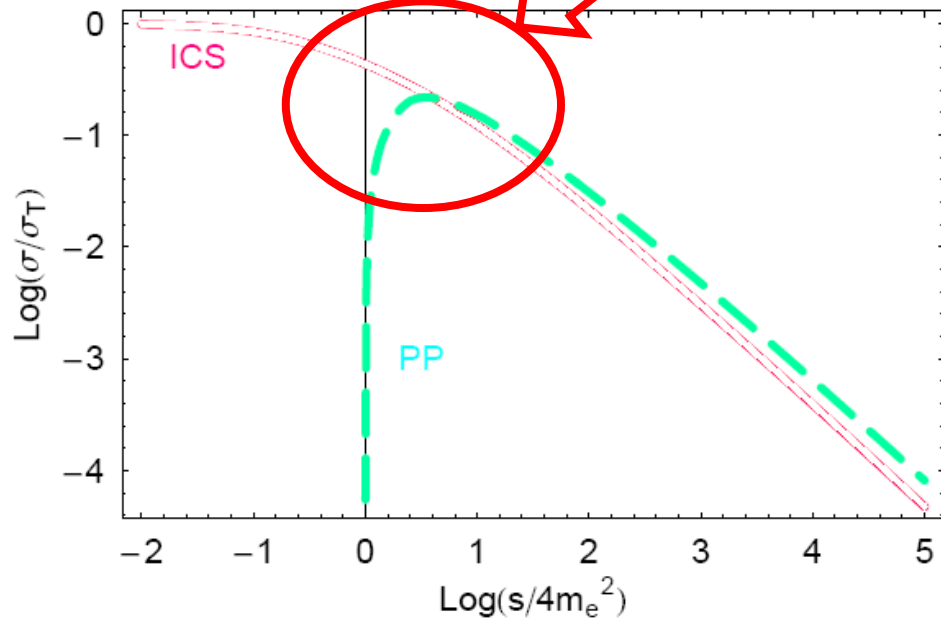
Nikishov 1962



the most intense pair production:

$$s/4m_e^2 \sim 2 \dots 4$$

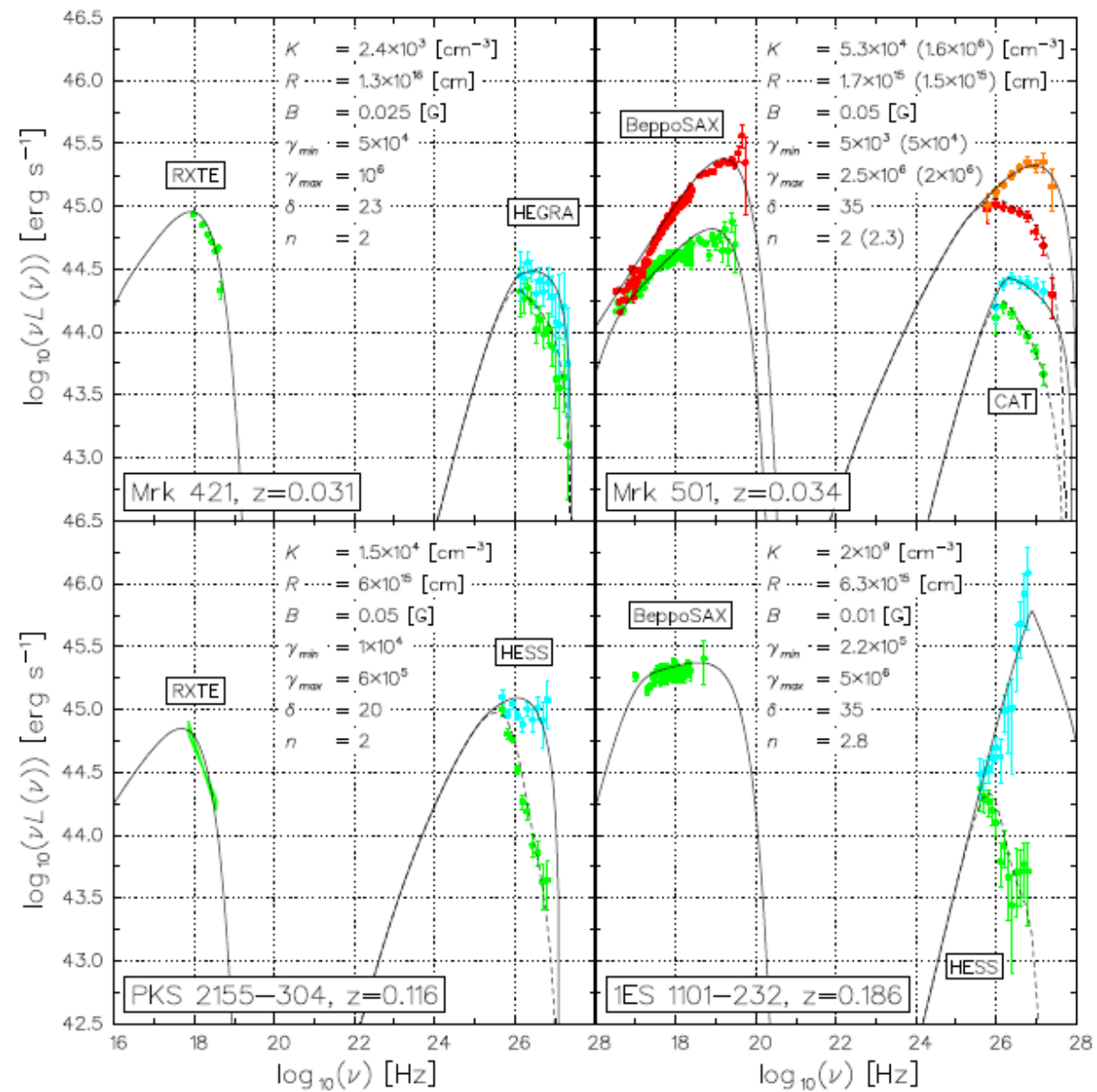
$$E_\gamma \sim 5 \times 10^{11} (\omega/eV)^{-1} \text{ eV}$$



# The IR/TeV crisis?

- an upward break is required to explain observations above 100 GeV
- this break does not depend on the source class (HBL, LBL, FSRQ)
- but it depends on the source distance!

➔ **strange...**

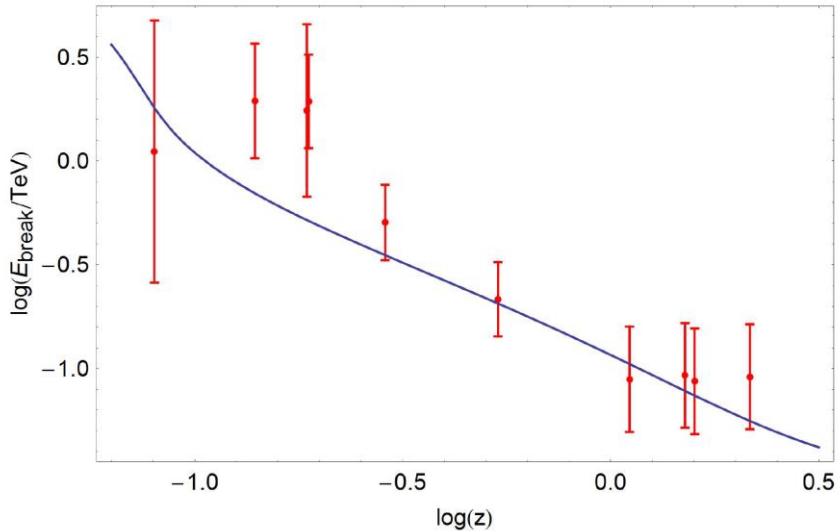


*Kneiske ~2008*

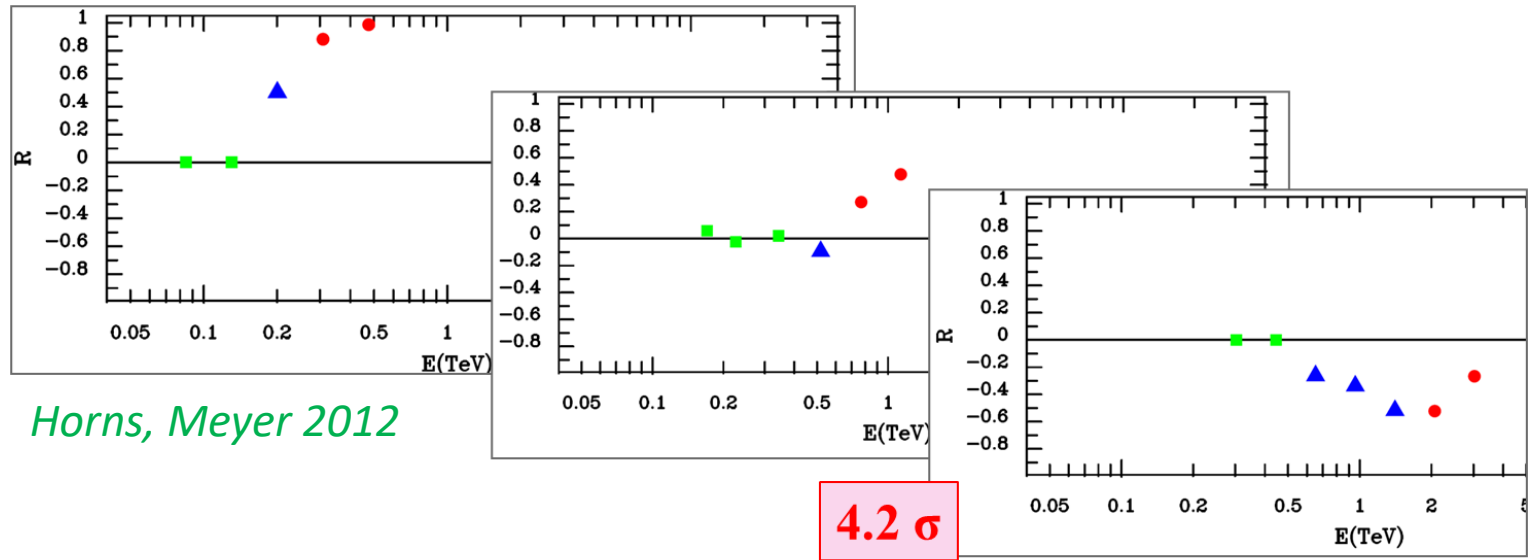


# The IR/TeV crisis?

7 blazars, opacity  $>2$ ,  $z \leq 0.536$



Ebreak depends on the distance  
*Rubtsov, ST 2014*



*Horns, Meyer 2012*

- “IR/TeV crisis” – individual sources

*Protheroe, Meyer 2000*

+ .....

- nearby and distant look different

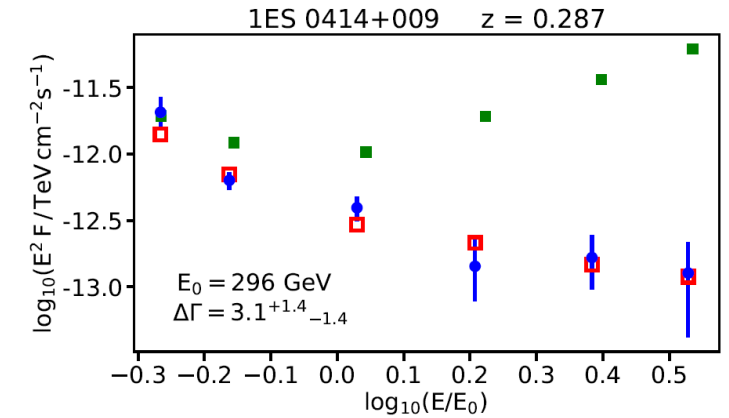
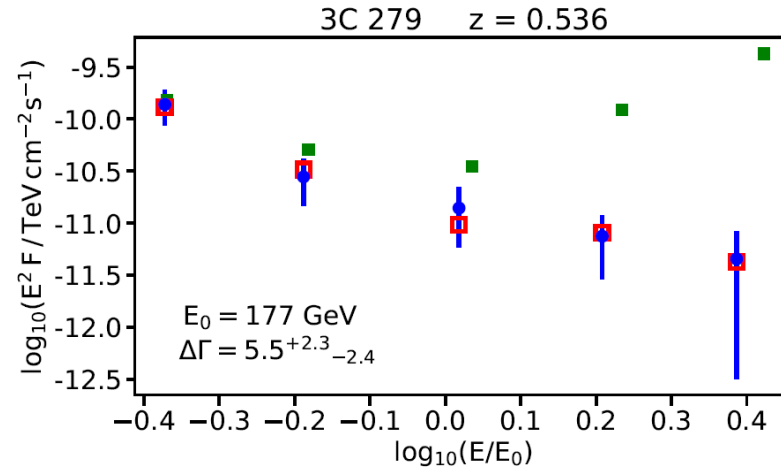
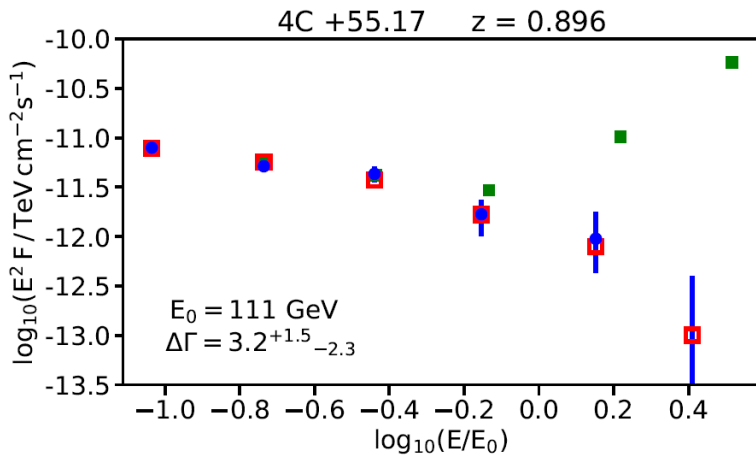
*Kneiske, unpublished*

- statistics of breaks in deabsorbed spectra: **breaks right at the energies for which the absorption becomes important!**

*Horns, Meyer 2012; Rubtsov, ST 2014*



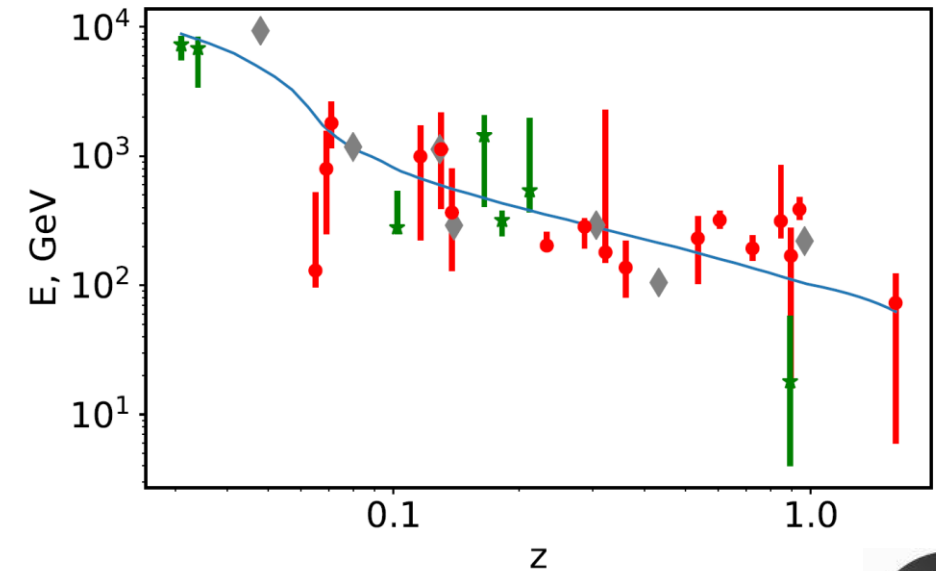
# “Anomalous transparency of the Universe”, state of the art



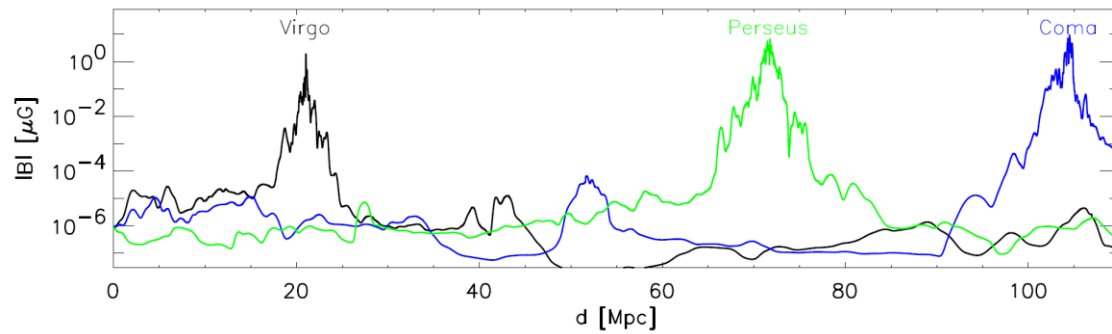
Large statistics, better known distances:

- the problem persists for individual sources – old and some new
- many new, weaker sources do not have any problem
- overall statistical significance modest

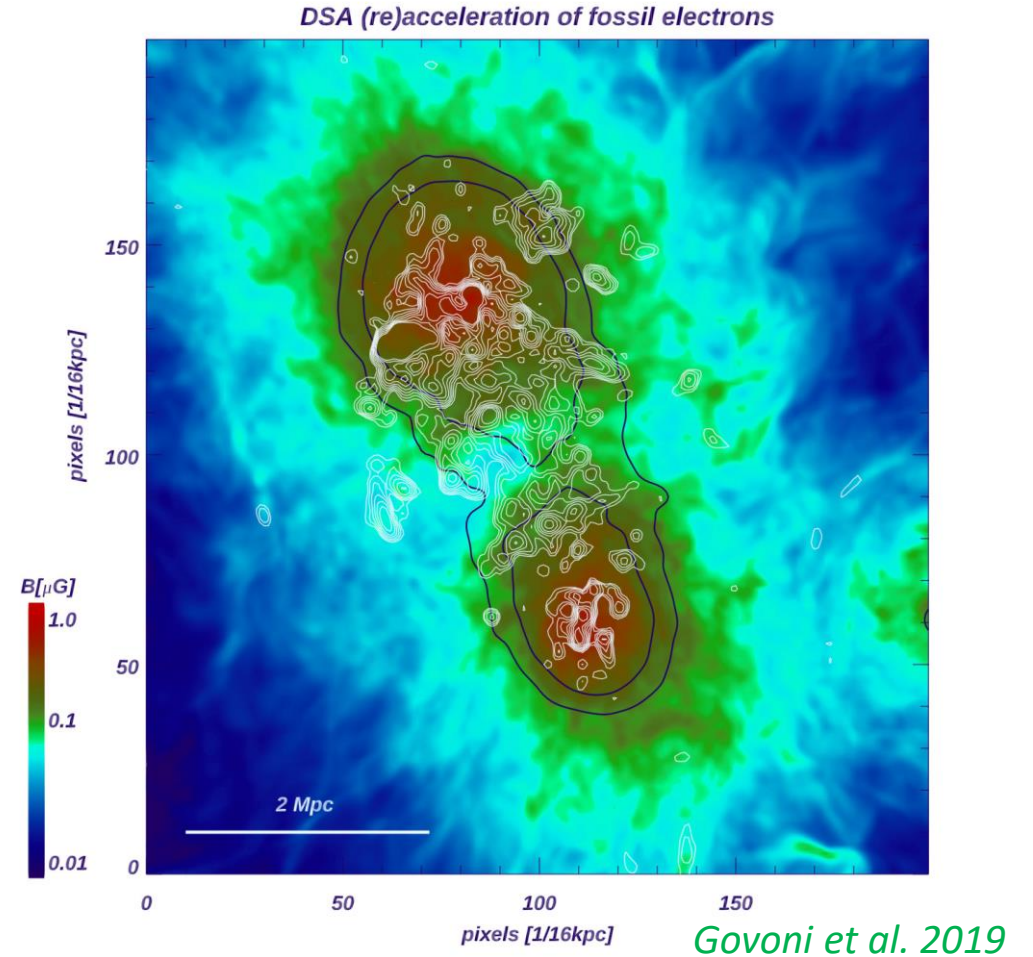
*Korochkin, Rubtsov, ST 2019*



# Magnetic fields in filaments?



*Dolag et al. 2004*



*Govoni et al. 2019*



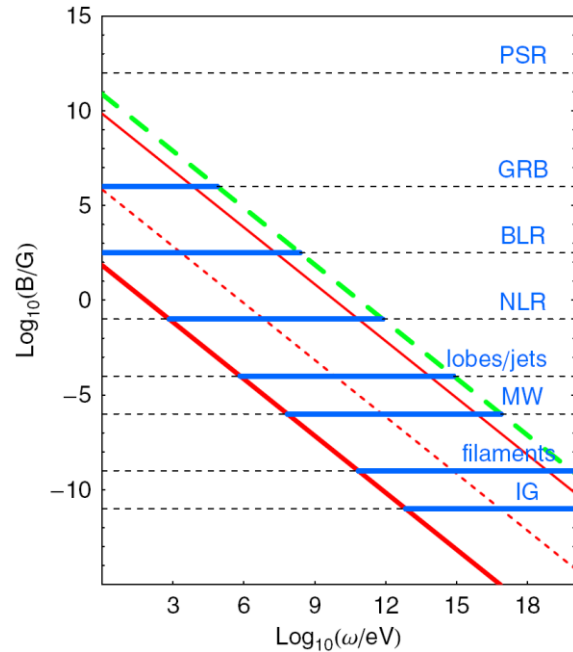
# Photon/ALP conversion

*estimates of required parameters*

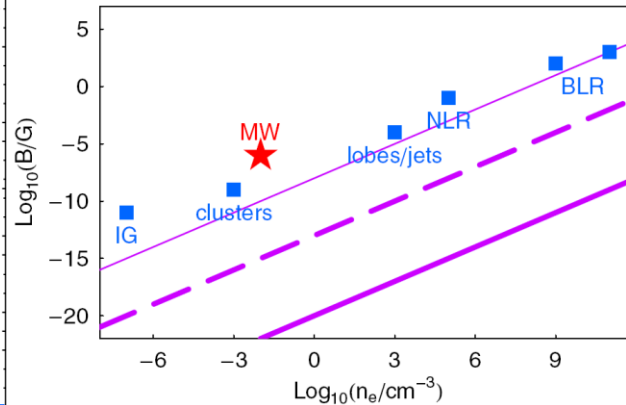
maximal mixing conditions:

$$\Delta_m \ll 2\Delta_M$$

$$\Delta_{Q,\perp} \ll \Delta_M$$



$$\Delta_p \ll 2\Delta_M$$

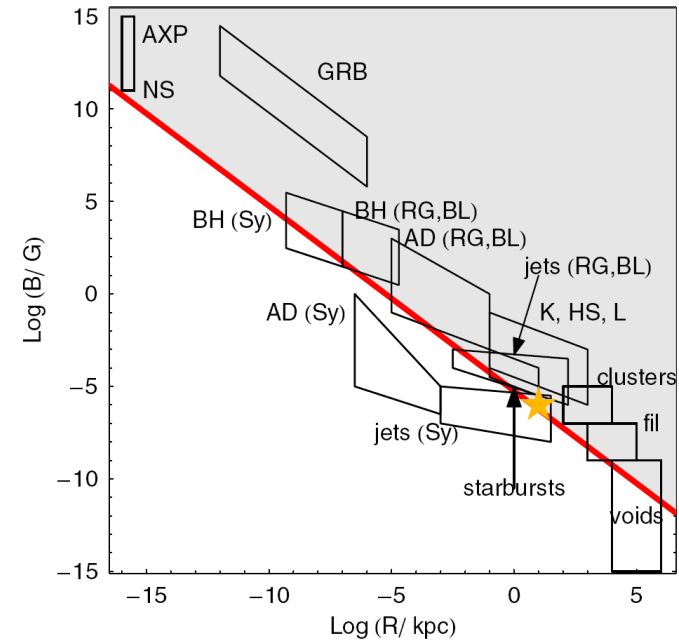


*Fairbairn et al. 2009*

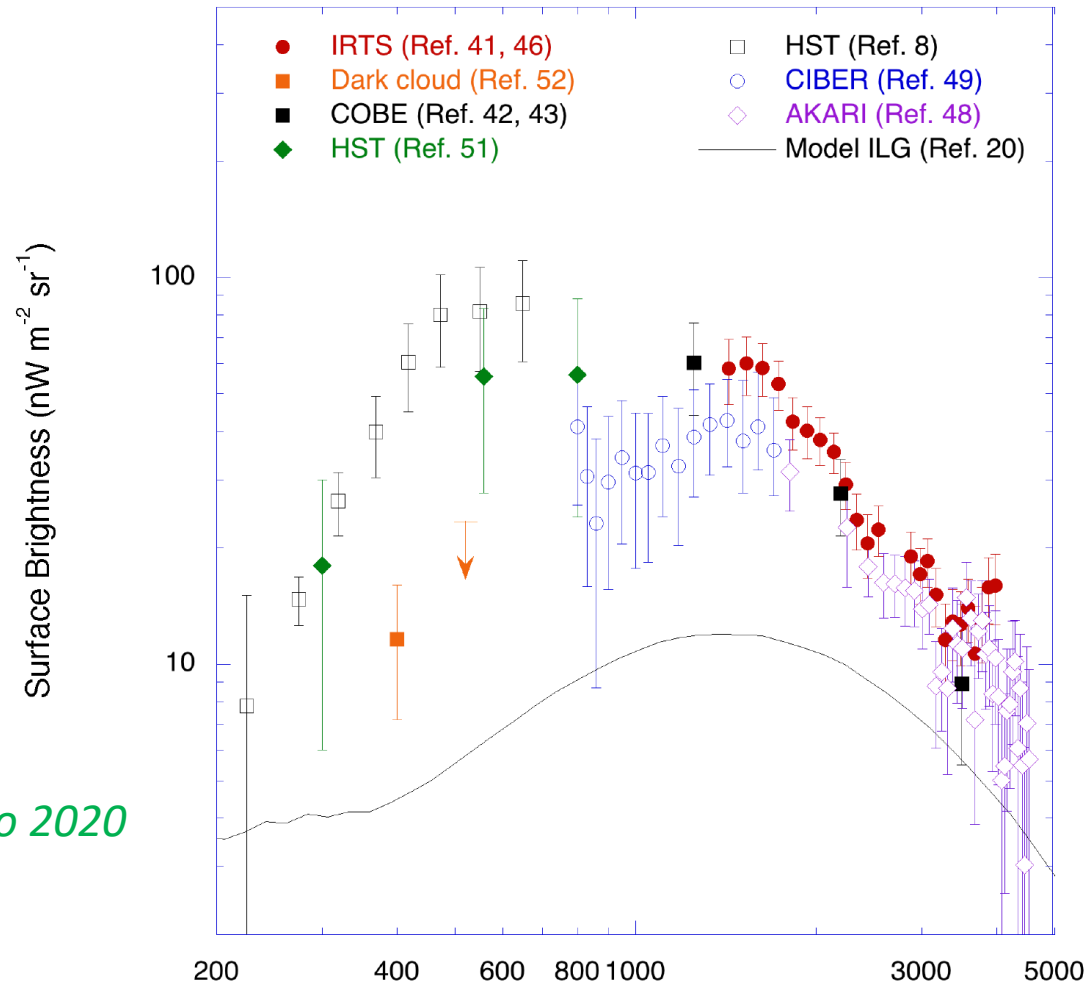
$$L \gtrsim \frac{\pi}{\Delta_{\text{OSC}}}$$



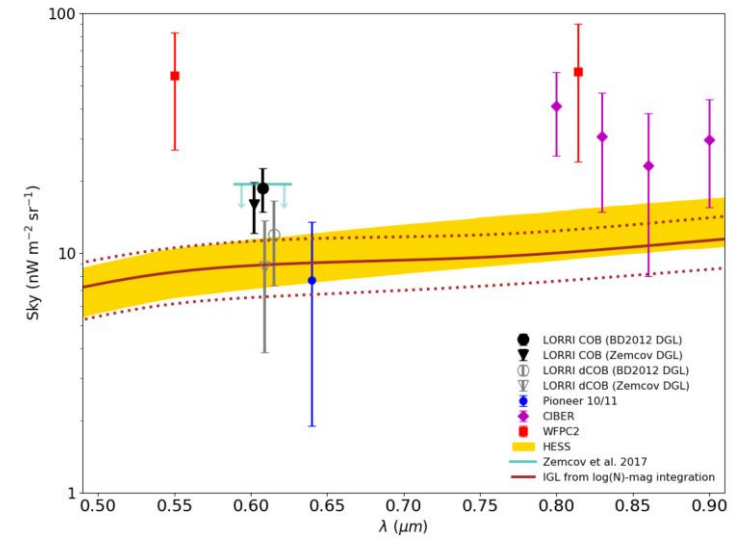
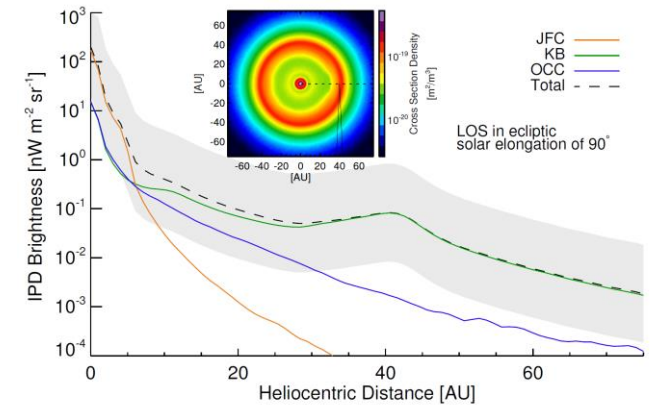
$M=10^{10}$  GeV axion



# Infrared background - 2020



Matsumoto 2020



New Horizons 2020

