



# First constraints on axion-like particles from Galactic sub-PeV gamma rays

based on [arXiv:2204.12487](https://arxiv.org/abs/2204.12487), submitted to Phys. Rev. D  
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— Vienna, 21<sup>st</sup> July 2022 —  
— IDM 2022 —

# Why sub-PeV gamma rays?

Gamma-ray indirect searches for exotic physics means finding a tiny signal in a sea of astrophysically produced gamma rays.

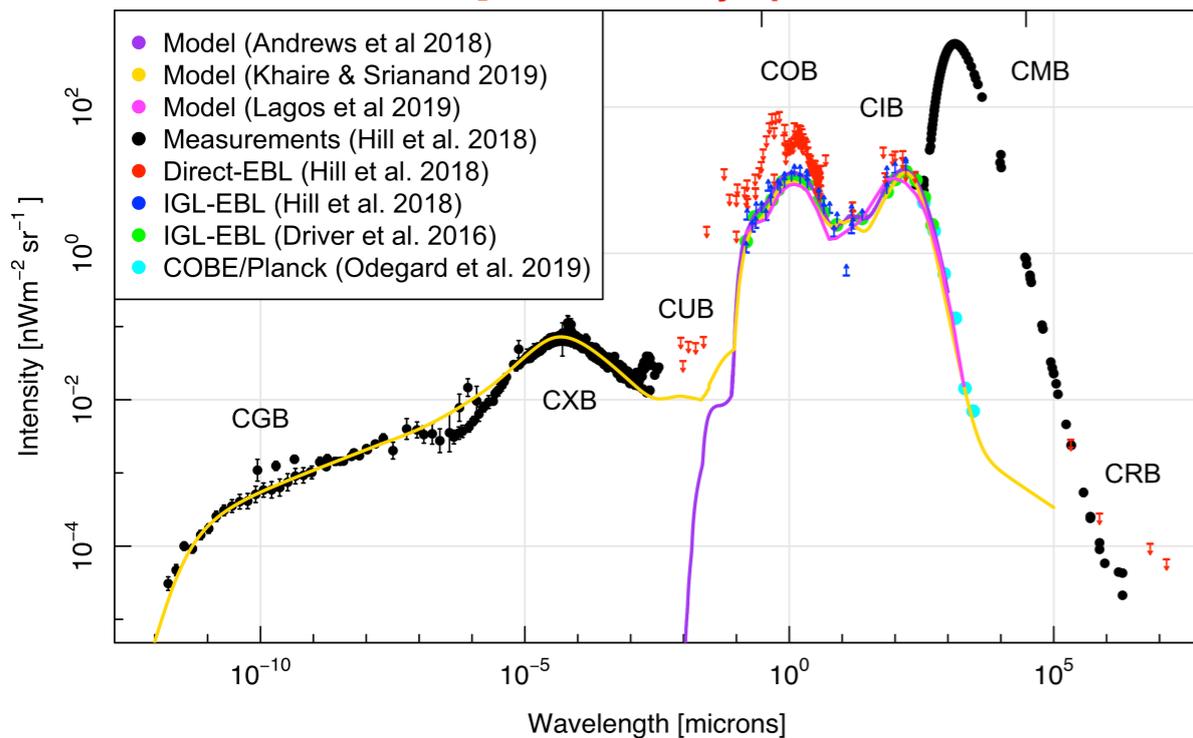


**The sub-PeV range ([10,1000] TeV) is devoid of most of the extragalactic contributions known at lower energies.**

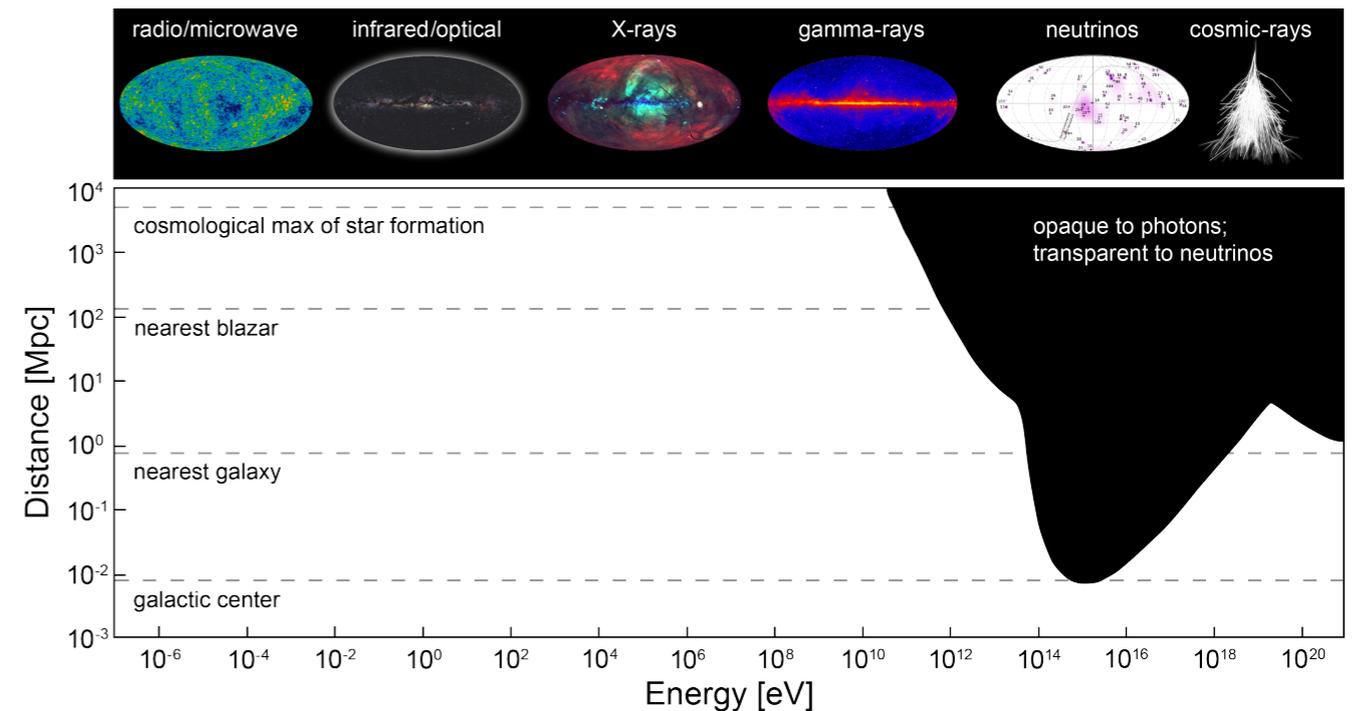
**The reason: absorption on the extragalactic background light (EBL)**

mixture of radiation fields, e.g.: light from stars/galaxies,  
light re-radiated after absorption by dust

[Driver, IAU Symposium 355, 2102.12089]



credit: IceCube collab.

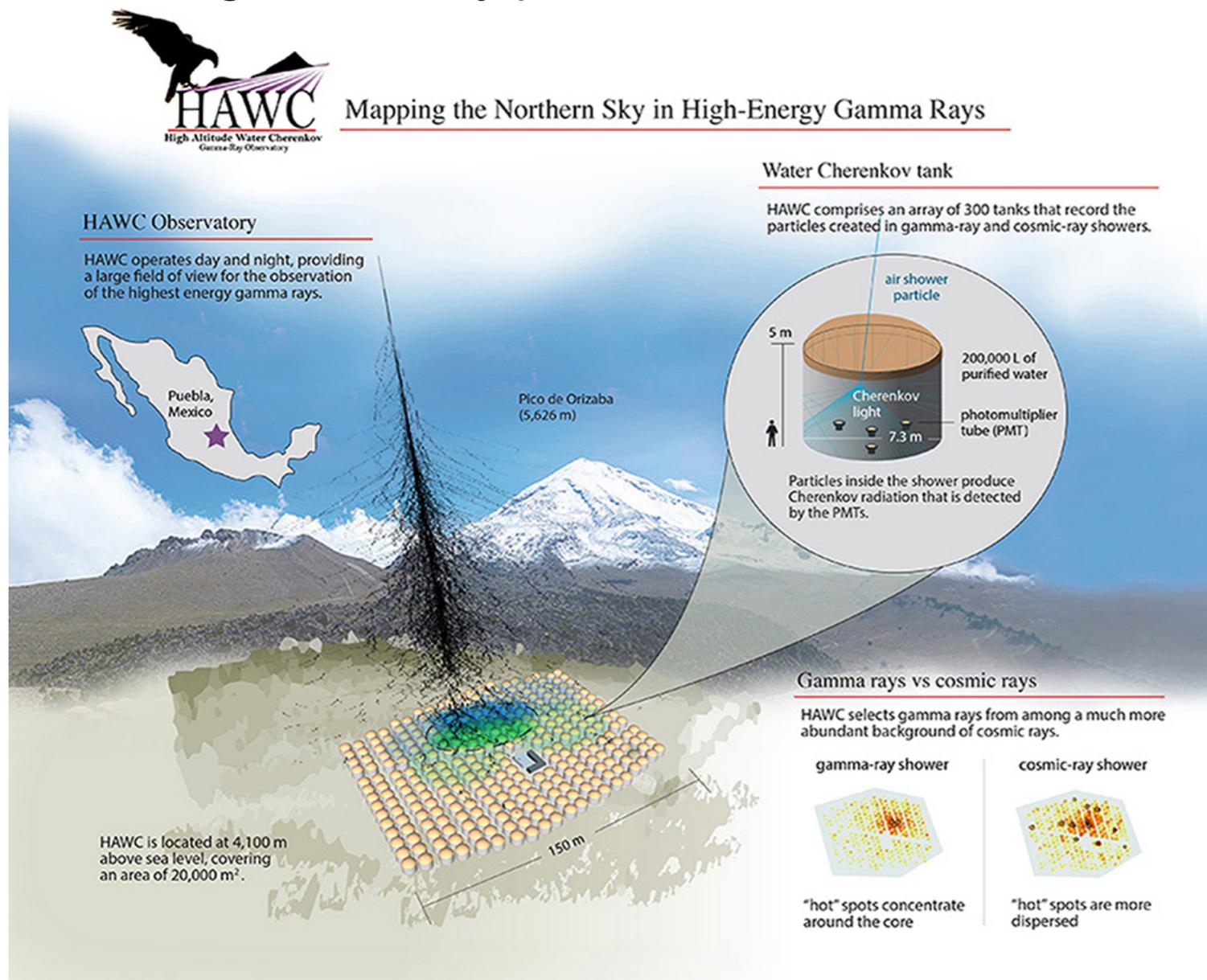


- ◆ At sub-PeV energies, Galactic physics probably only major contributor.
- ◆ Exotic physics, especially feebly interacting particles as ALPs, circumvent EBL absorption. —> **May give rise to extragalactic gamma-ray contribution.**

# Current instruments

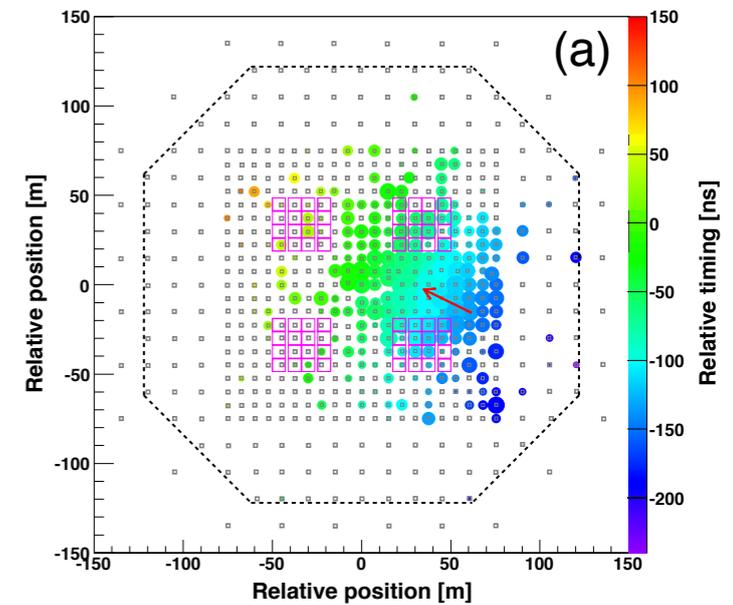
- ◆ The frequency of gamma rays decreases with increasing energy, hence detectors must **cover large areas** to gather sufficient statistics → Limits us to ground-based observations.
- ◆ Indirect detection and reconstruction of primary cosmic rays via secondary particles of the triggered extensive air shower.
- ◆ Current experimental setup: **Array of scintillators and water tanks** to measure the properties of incoming secondary particles

HAWC



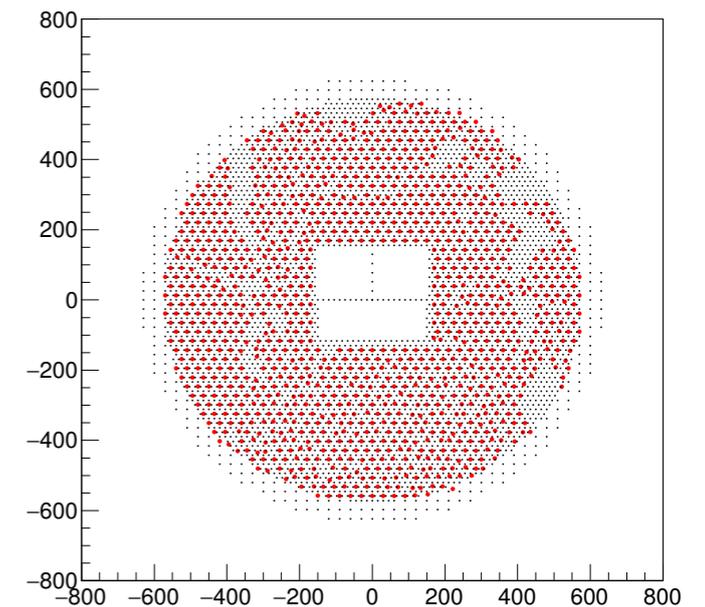
[A. Nayerhoda+, Front. Astron. Space Sci., 2018]

Tibet AS $\gamma$ +MD



[M. Amenomori+, PRL 123 (2019) 5, 051101]

LHAASO



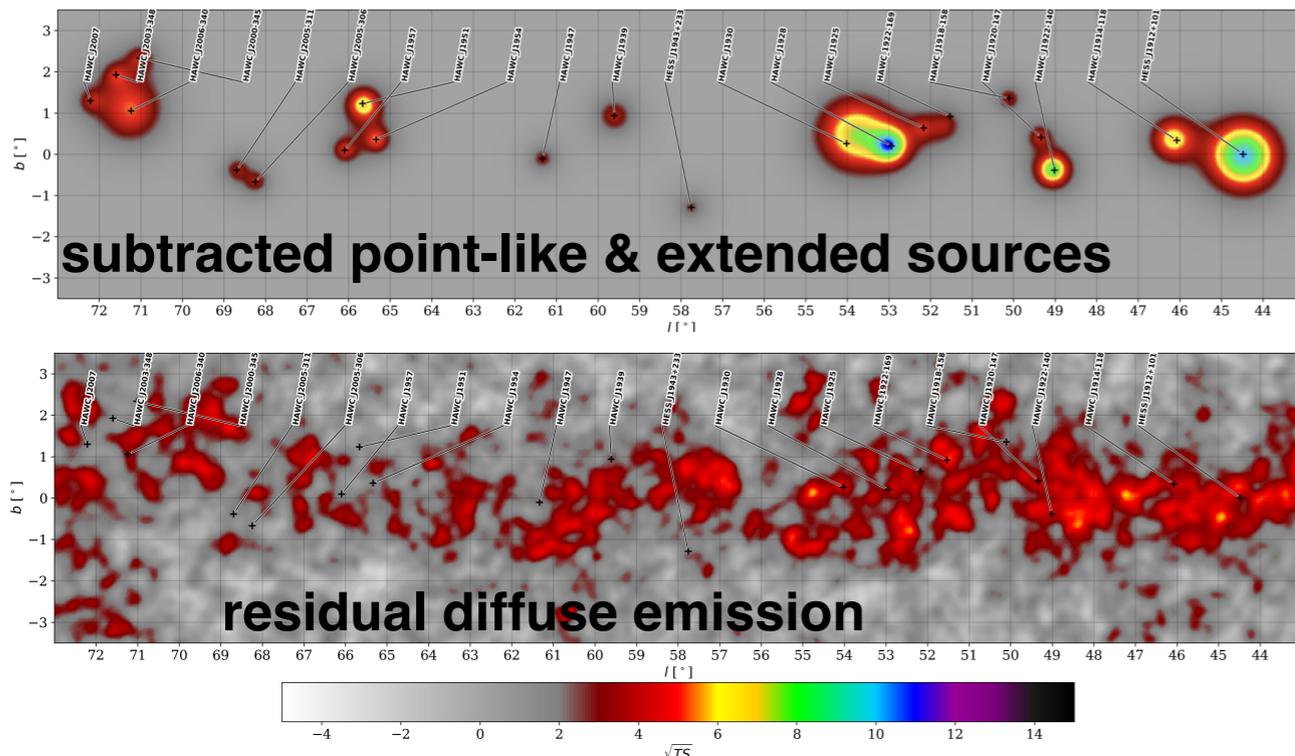
[S. Vernetto, J. Phys.: Conf. Ser. 718 052043]

# Gamma rays from the Galactic disc < 1PeV

- ◆ HAWC, Tibet ASg and LHAASO are located on the northern hemisphere.
  - > Galactic centre only visible at large zenith angles (deteriorates particle reconstruction quality) / measurement of diffuse Galactic emission along the disc possible.
- ◆ Large instantaneous field of view (more than 45°) and long duty-cycle.

## HAWC (10 to 100 TeV)

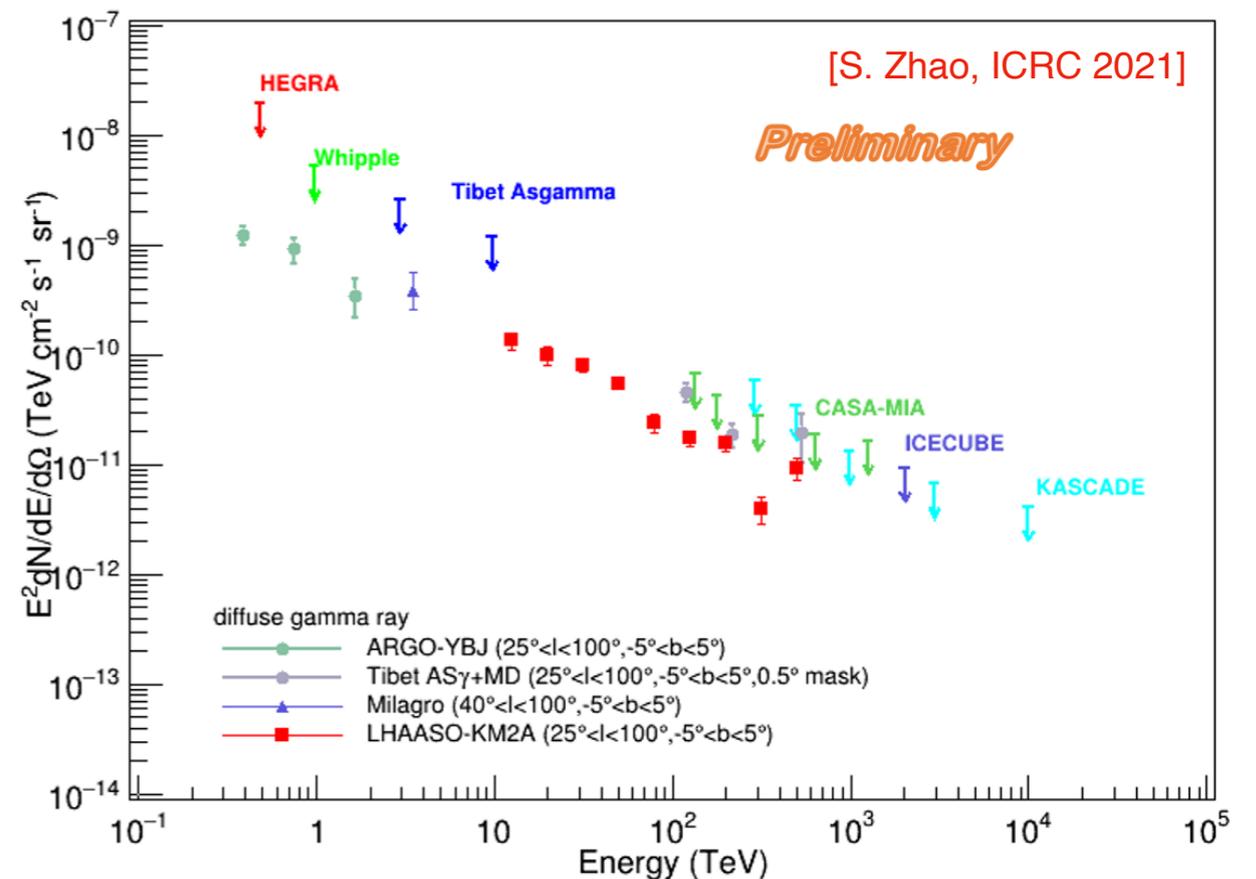
$$43^\circ < \ell < 73^\circ, |b| \leq 4^\circ$$



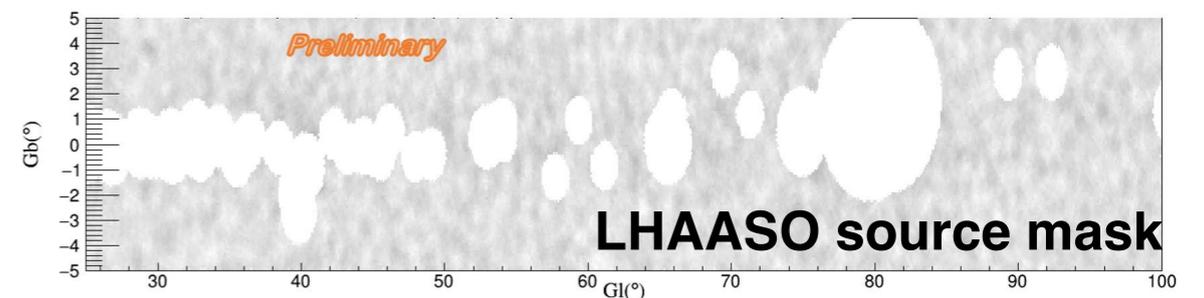
[HAWC collaboration, ICRC 2021]

## LHAASO and Tibet AS $\gamma$ +MD

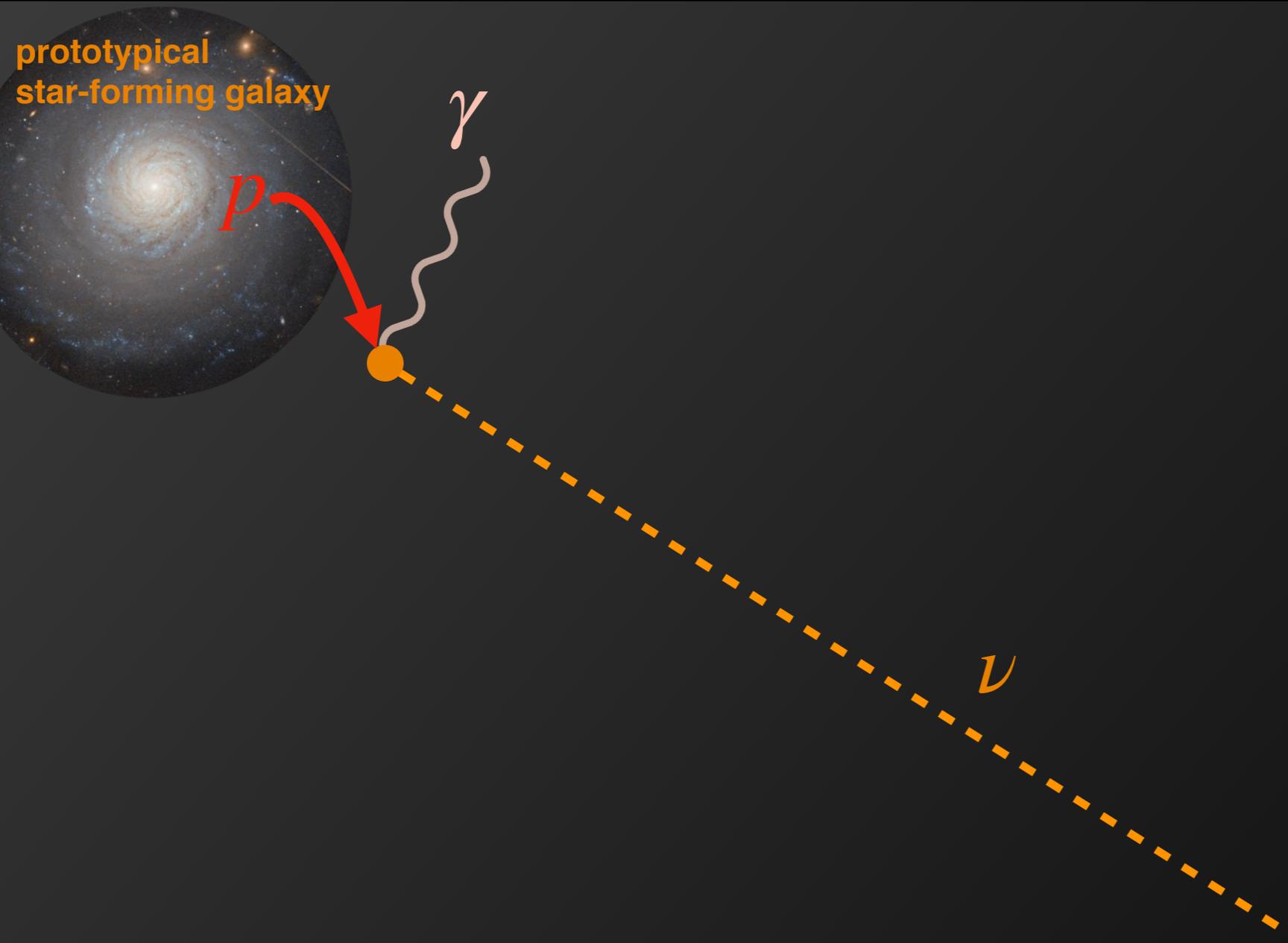
$$25^\circ < \ell < 100^\circ, |b| \leq 5^\circ$$



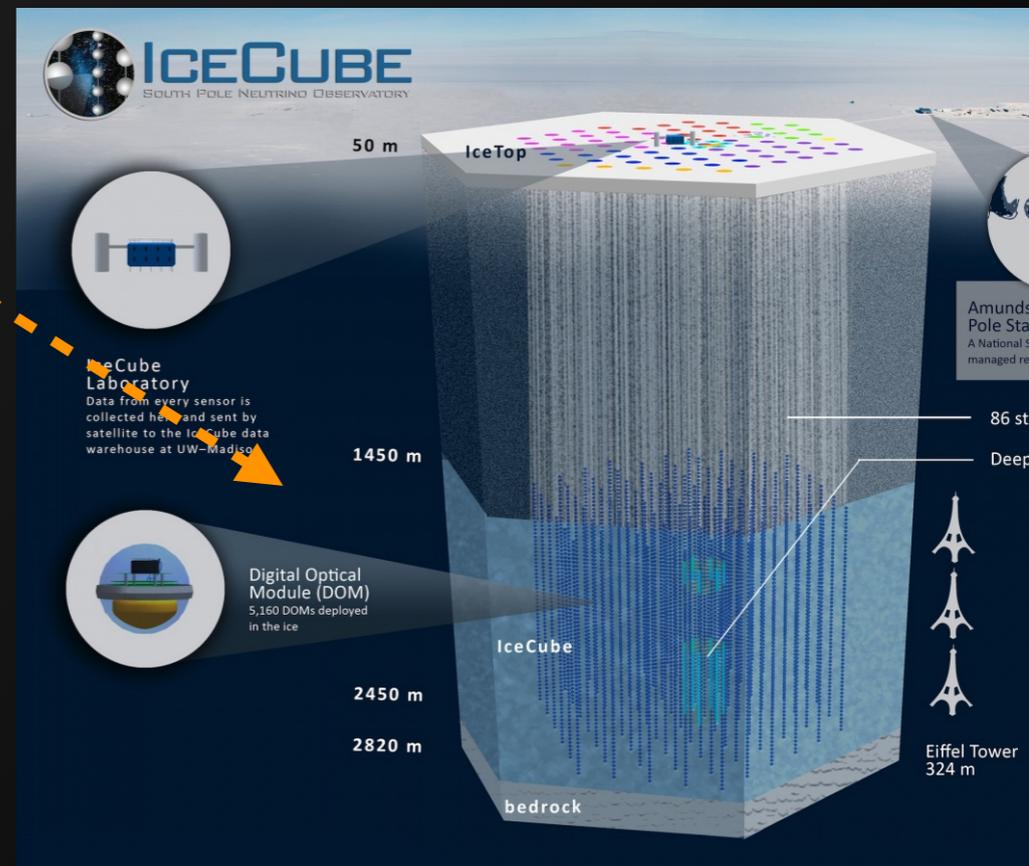
**Reported measurements of diffuse emission depend on the applied experimental procedures! —> We do not consider the LHAASO data set for this reason.**



# Connecting neutrinos and axion-like particles



Credit: IceCube collaboration



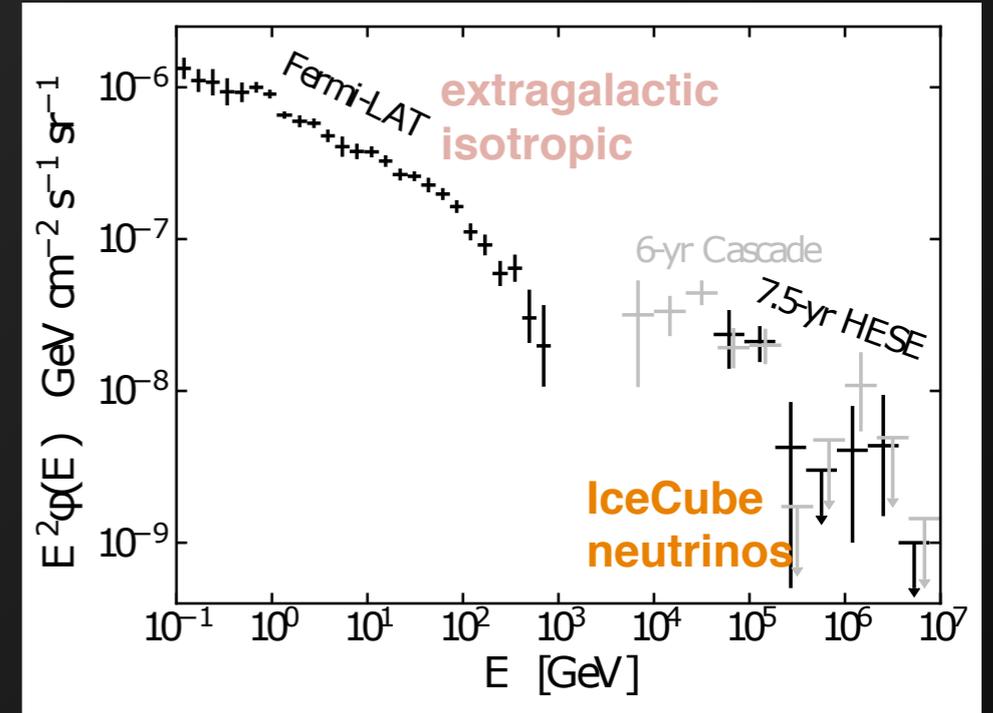
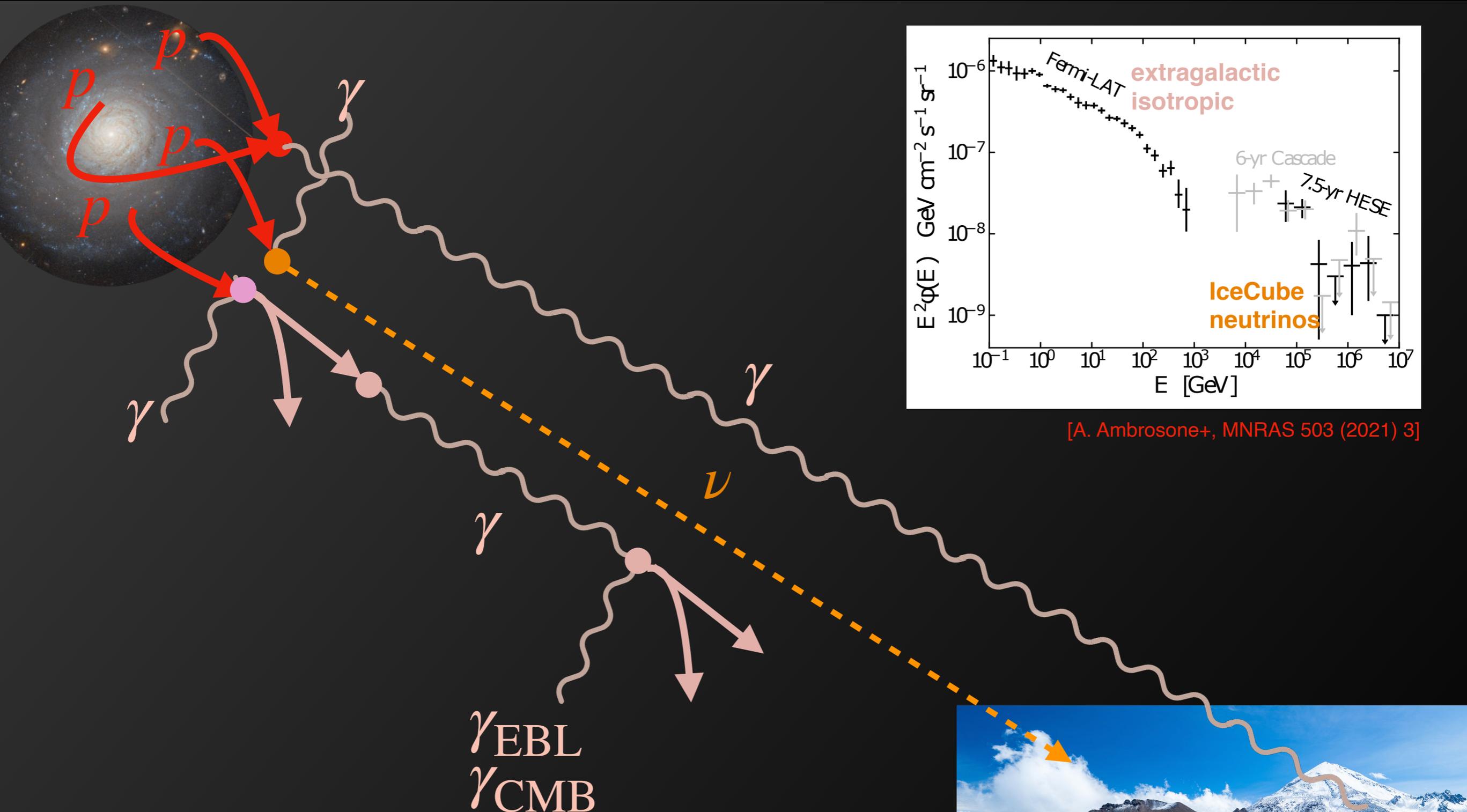
- ◆ Charged very high energy cosmic rays (e.g., protons) are copiously produced in distant galaxies ( $> 1$  PeV).
- ◆ They scatter on intergalactic medium ( $pp$ -interaction) and radiation fields ( $p\gamma$ -interaction).
- ◆ Both interaction types produce neutrinos, which are not affected by the EBL or CMB.

# From astrophysical neutrinos to axion-like particles



- ◆  $p\gamma$ -interactions can also produce gamma rays, which get absorbed by the EBL or CMB.

# From astrophysical neutrinos to axion-like particles



[A. Ambrosone+, MNRAS 503 (2021) 3]

- ◆ Gamma rays from  $pp$ -interactions are less energetic and can saturate the extragalactic emission measured by Fermi-LAT.

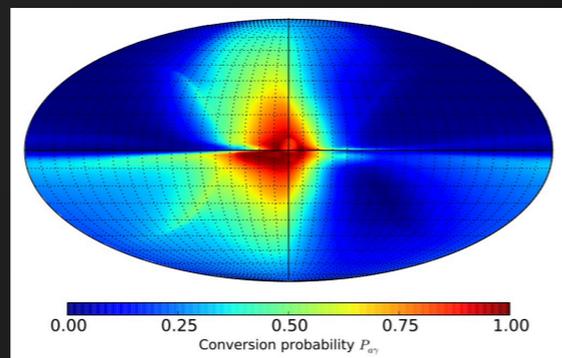
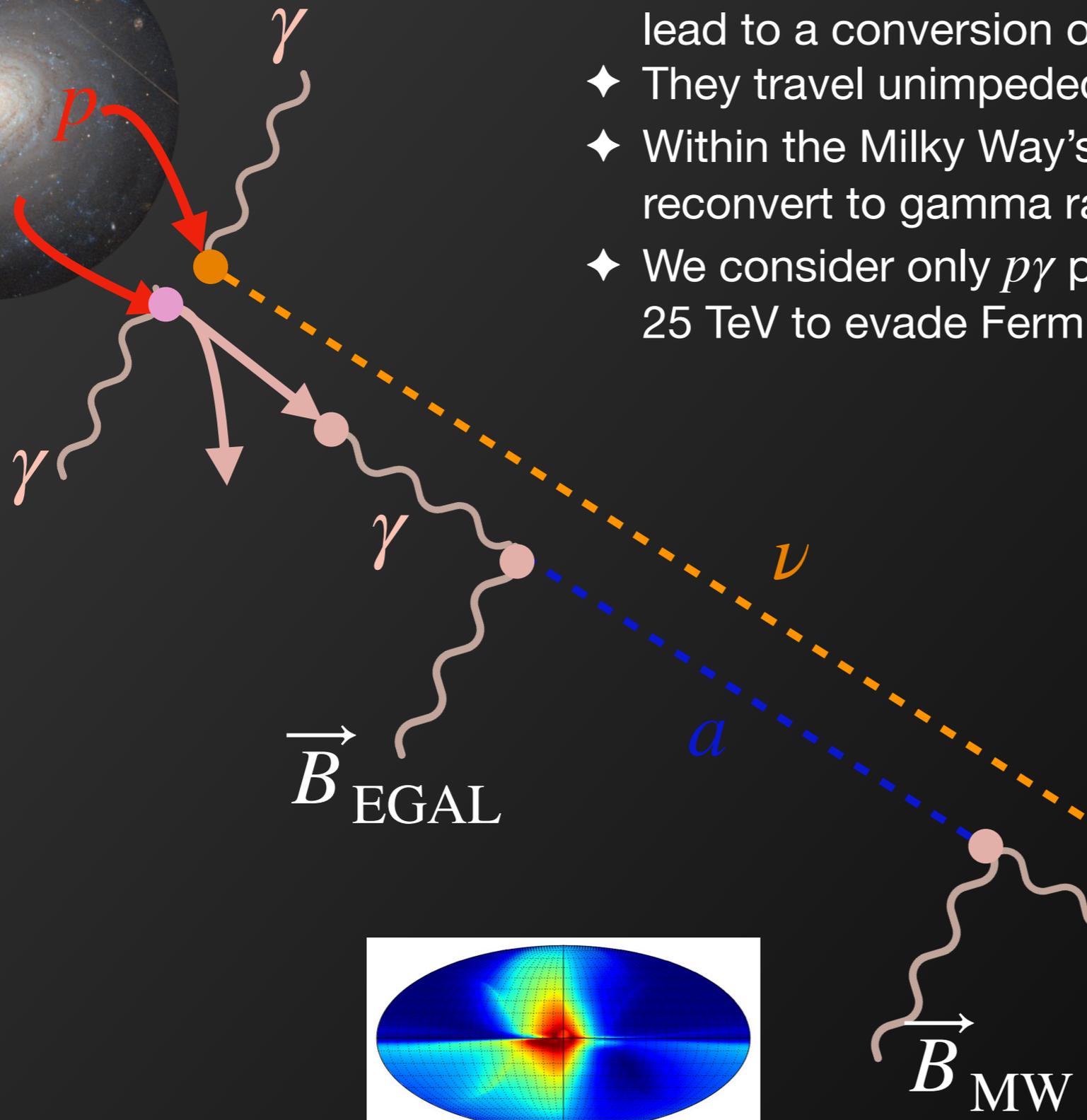


Credit: HAWC collaboration

# From astrophysical neutrinos to axion-like particles



- ◆ With the distant galaxy, magnetic fields  $\vec{B}_{EGAL}$  may lead to a conversion of the gamma ray into an ALP.
- ◆ They travel unimpeded through the universe.
- ◆ Within the Milky Way's magnetic field  $\vec{B}_{MW}$  they reconvert to gamma rays.
- ◆ We consider only  $p\gamma$  plus energy cutoff at 25 TeV to evade Fermi-LAT constraints.



Credit: HAWC collaboration

# Deriving the axion-like particle contribution

- ◆ Gamma rays and neutrinos generated by  $p\gamma$ -interactions are linked via:

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \left( E_\nu = \frac{E_\gamma}{2} \right) = \frac{3}{2} E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}$$

- ◆ Adopt best-fitting power law for IceCube neutrino flux + break at low energies:

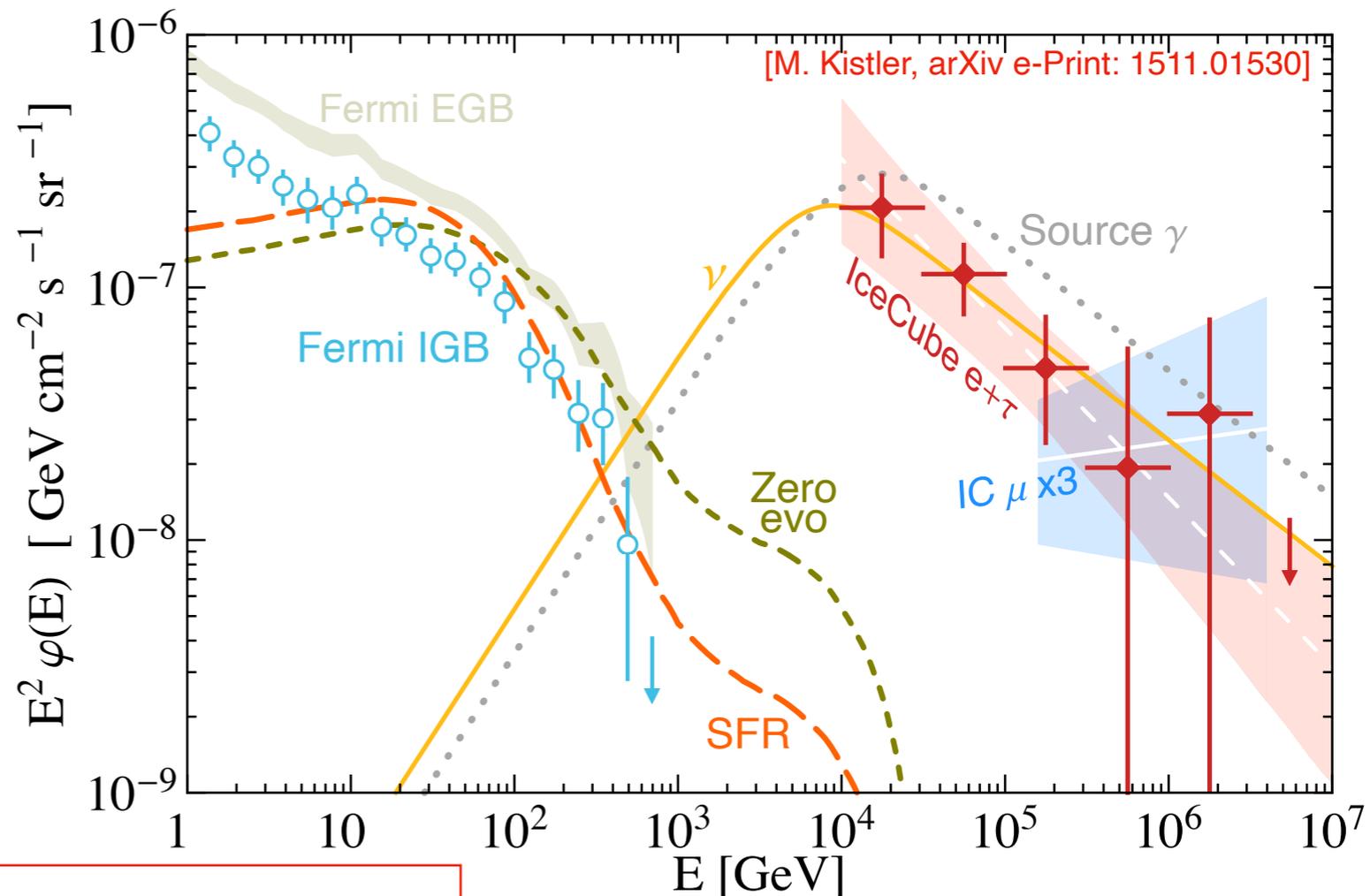
$$\frac{dN_\nu}{dE_\nu} = N_0 \left[ \left( \frac{E_\nu}{E_b} \right)^2 + \left( \frac{E_\nu}{E_b} \right)^{2\alpha} \right]^{-\frac{1}{2}} \quad \alpha = 2.87 \quad [\text{IceCube collab., PRD 104 (2021) 022002}]$$

- ◆ Fix breaking energy at  $E_b = 25$  TeV; consistent with IceCube HESE and Cascade data + *Fermi*-LAT IGB.

- ◆ In situ neutrino spectrum normalisation  $N_0$  via matching with IceCube measurement:

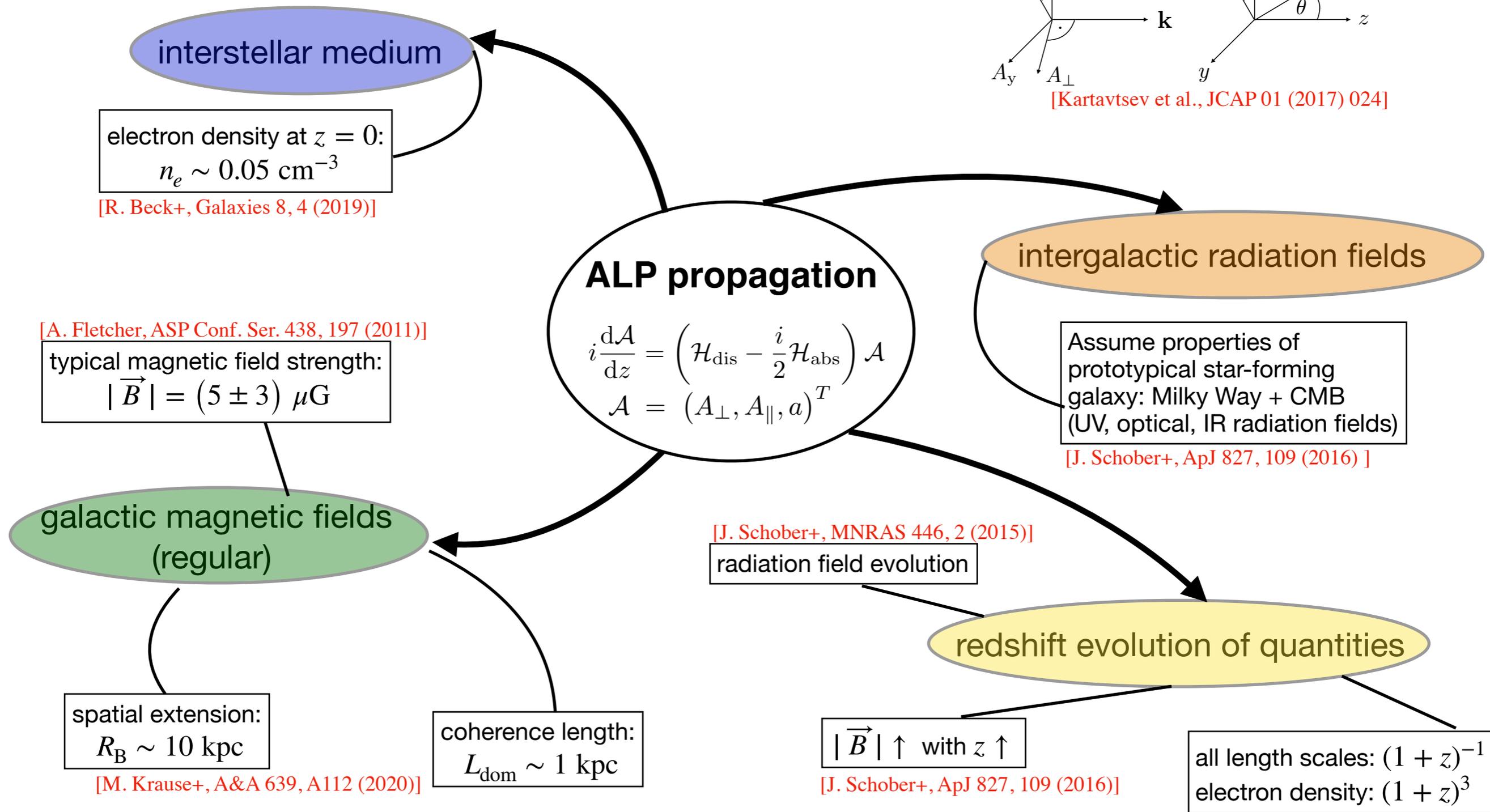
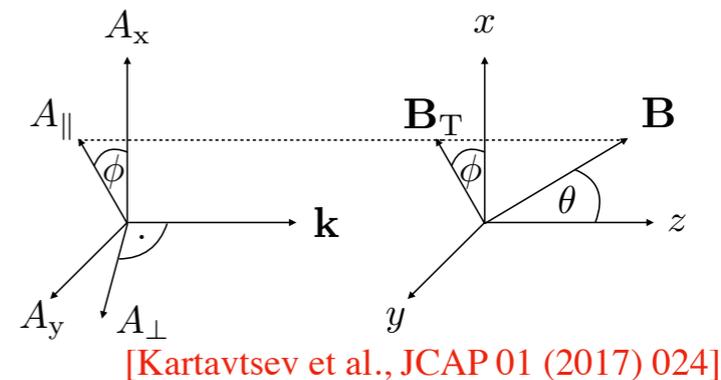
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{c}{4\pi} \int_0^\infty \frac{dN_\nu}{dE'_\nu} (1+z) \dot{\rho}_*(z) \left| \frac{dt}{dz} \right| dz$$

star formation rate density taken from [H. Yüksel, APJ L. 683 (2008)]



# Deriving the axion-like particle contribution

◆ Photon-ALP mixing in star-forming galaxies according to transfer matrix method implemented in gammaALPs. [M. Meyer+, "gammaALPs" (2021)].



# How do we observe such an ALP-flux?

## ALP-photon conversion in the Milky Way's magnetic field.

[credit: FC+ PRD'20, 2110.03679]

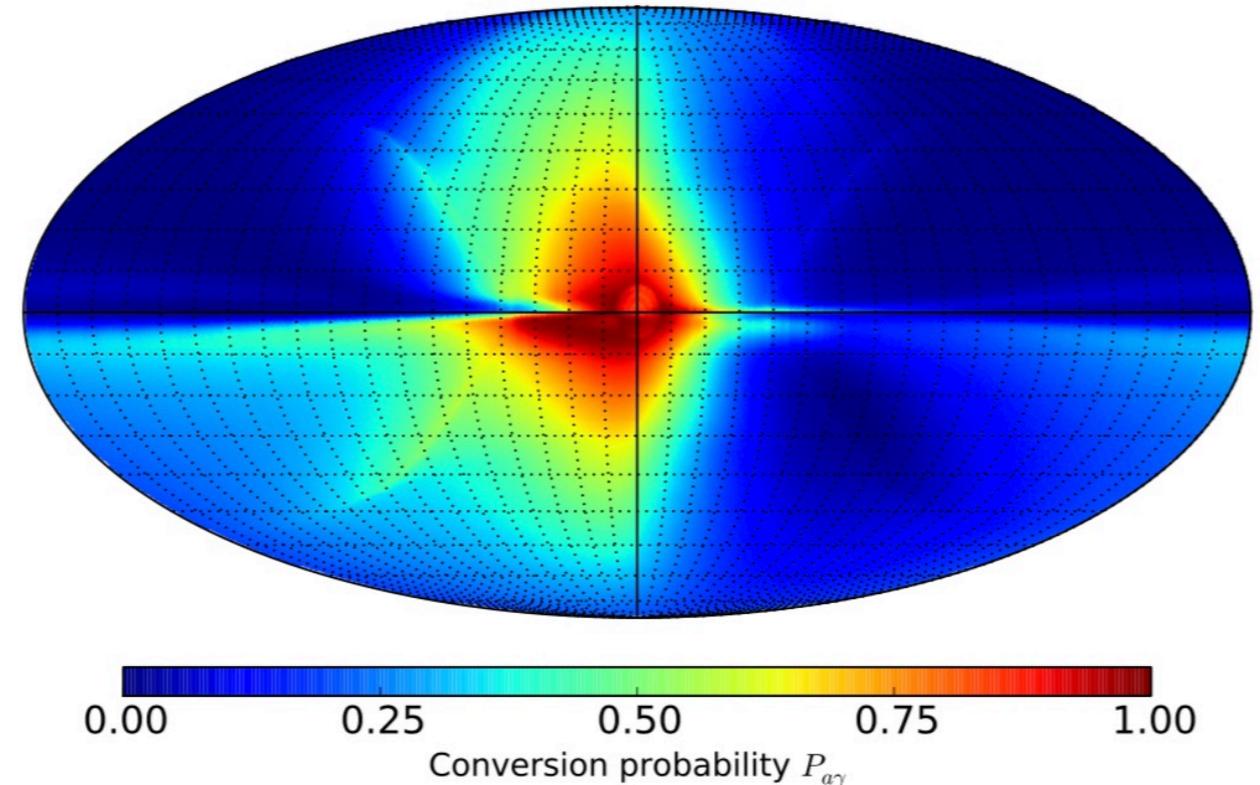
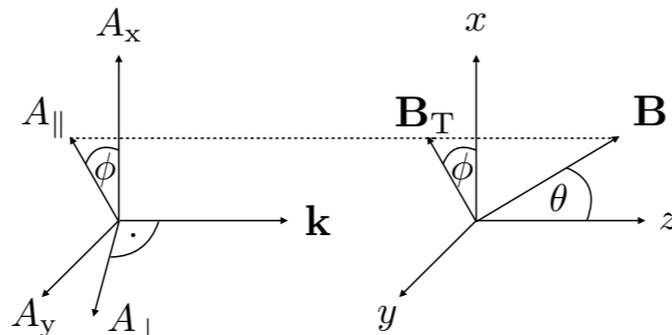
- ◆ In an external magnetic field, ALPs reconvert into photons states perpendicular to the propagation direction.
- ◆ The probability of such a conversion is proportional to the magnetic field component in this transversal plane  $B_T$ .

[Kartavtsev et al., JCAP 01 (2017) 024]

$$P_{a \rightarrow \gamma} = \left( \frac{g_{a\gamma} B_T}{2} \right)^2 d^2$$

$$\sim 0.015 \left( \frac{g_{a\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^2 \left( \frac{B_T}{10^{-6} \text{ G}} \right) \left( \frac{d}{\text{kpc}} \right)^2$$

(assuming a homogeneous magnetic field.)



- $g_{a\gamma\gamma} = 5 \times 10^{-11} \text{ GeV}^{-1}$ , “massless” ALP
- pure initial ALP state
- magnetic field model of Jansson & Farrar 2012
- propagation through entire MW

### Extragalactic ALP-flux:

$$\frac{d\Phi_a}{dE}$$

The energy correspondence is perfect in the case of massless ALPs.



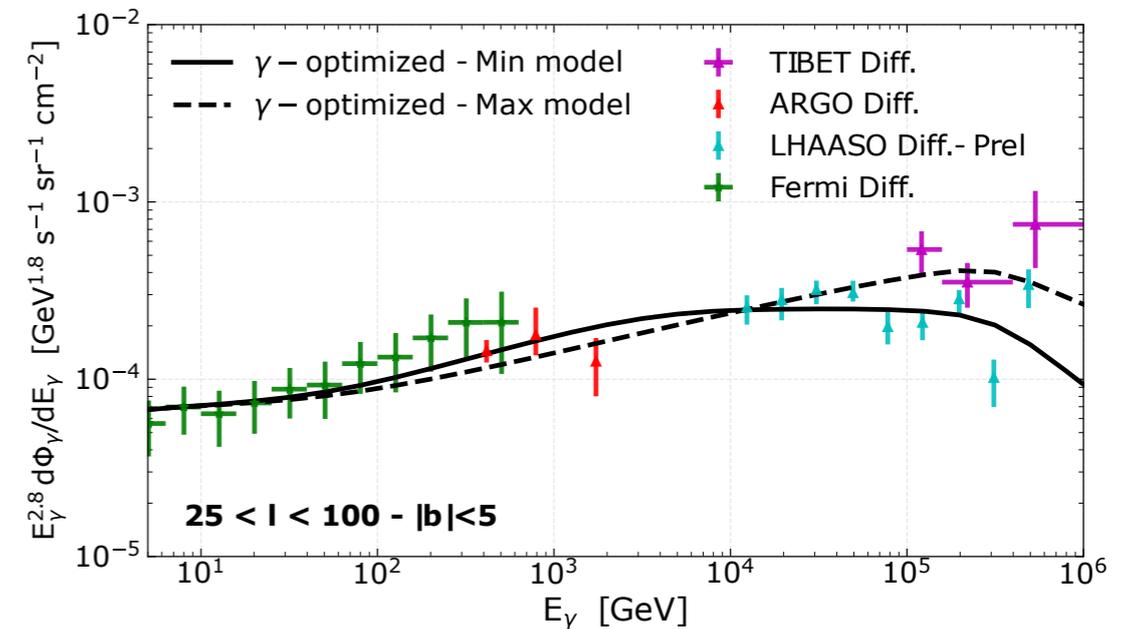
### Associated gamma-ray flux:

$$\frac{d\Phi_\gamma}{dE} = \frac{d\Phi_a}{dE} P_{a \rightarrow \gamma}(E)$$

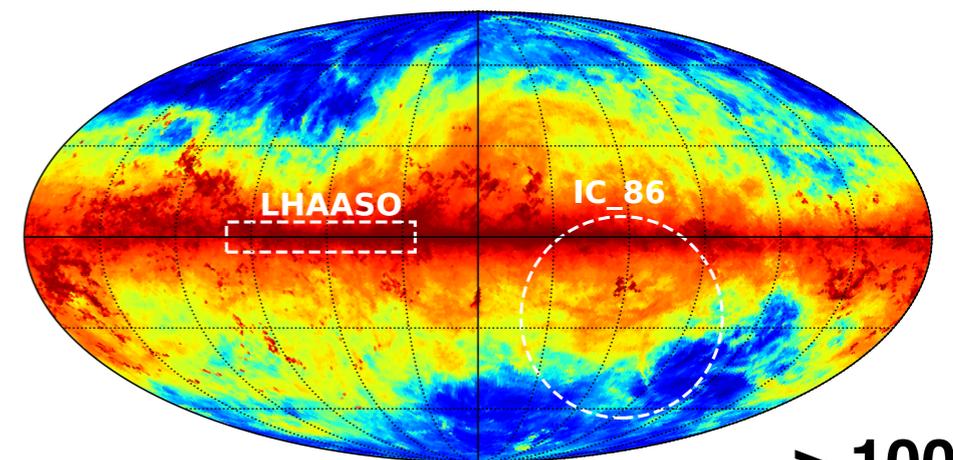
# Galactic astrophysics at the sub-PeV scale

- ◆ Assume that only Galactic astrophysics generates the observed sub-PeV gamma-ray emission along the Galactic disc.
- ◆ Known bright localised sources already subtracted: Remaining two contributions
  - interstellar emission (IE)** and
  - sub-threshold point-like and extended sources.**

- ◆ Large-scale emission from very-high-energy cosmic ray interactions with particles of the interstellar medium, structure roughly follows gas and radiation distribution in Milky Way.
- ◆ Spatially dependent cosmic-ray diffusion coefficient better reflects the data. (In line with independent studies and models.)
- ◆ Adopt two models shown on the right, tuned to LHAASO, Tibet ASg, *Fermi*-LAT +++  
 → uncertainty of constraints w.r.t. IE



[De la Torre Luque et al., arXiv:2203.15759]



3.24993e-21 J [cm<sup>-2</sup>s<sup>-1</sup>GeV<sup>-1</sup>sr<sup>-1</sup>] 2.86481e-16

# Galactic astrophysics at the sub-PeV scale

- ◆ Assume that only Galactic astrophysics generates the observed sub-PeV gamma-ray emission along the Galactic disc.
- ◆ Known bright localised sources already subtracted: Remaining two contributions
  - interstellar emission (IE)** and
  - sub-threshold point-like and extended sources.**

- ◆ We adopt the model of [\[V. Vecchiotti+, arXiv e-prints: 2107.14584\]](#) with modified parameters which yields the number of sources per unit volume and luminosity:

$$\frac{dN}{d^3r dL_{\text{TeV}}} = \boxed{\rho(\mathbf{r})} \times \boxed{\mathcal{L}(L_{\text{TeV}})}$$

pulsar spatial distribution in Milky Way [D. R. Lorimer+, MNRAS 3721,138 777 (2006)]  
 parametric fit matching H.E.S.S. Galactic plane survey results

- ◆ Assumption: TeV sub-threshold sources mostly pulsar wind nebulae with common average spectrum:

$$\varphi(E) = K_0 \left( \frac{E}{1 \text{ TeV}} \right)^{-\beta} \exp \left( -\frac{E}{E_c} \right)$$

$\beta = 2.6 \rightarrow$  average index of known TeV-bright sources (TeVCat)  
 $E_c = 300 \text{ TeV} \rightarrow$  ensures non-detection of photons by Tibet AS $\gamma$  beyond 400 TeV associated to localised sources

- ◆ The sub-threshold flux follows by integrating out the spatial dependence and a change of variables  $L_{\text{TeV}} = 4\pi d^2 \Phi_{\text{TeV}} \langle E \rangle$

$$\Phi^{\text{sTH}}(E) = \varphi(E) \int_0^{\boxed{S_{\text{TH}}}} \Phi_{\text{TeV}} \frac{dN}{d\Phi_{\text{TeV}}} d\Phi_{\text{TeV}} \longrightarrow$$

**What is the detection threshold of HAWC and Tibet AS $\gamma$ ?**

# Galactic astrophysics at the sub-PeV scale

- ◆ Assume that only Galactic astrophysics generates the observed sub-PeV gamma-ray emission along the Galactic disc.
- ◆ Known bright localised sources already subtracted: Remaining two contributions
  - (i) **interstellar emission** (IE) and
  - (ii) **sub-threshold point-like and extended sources.**

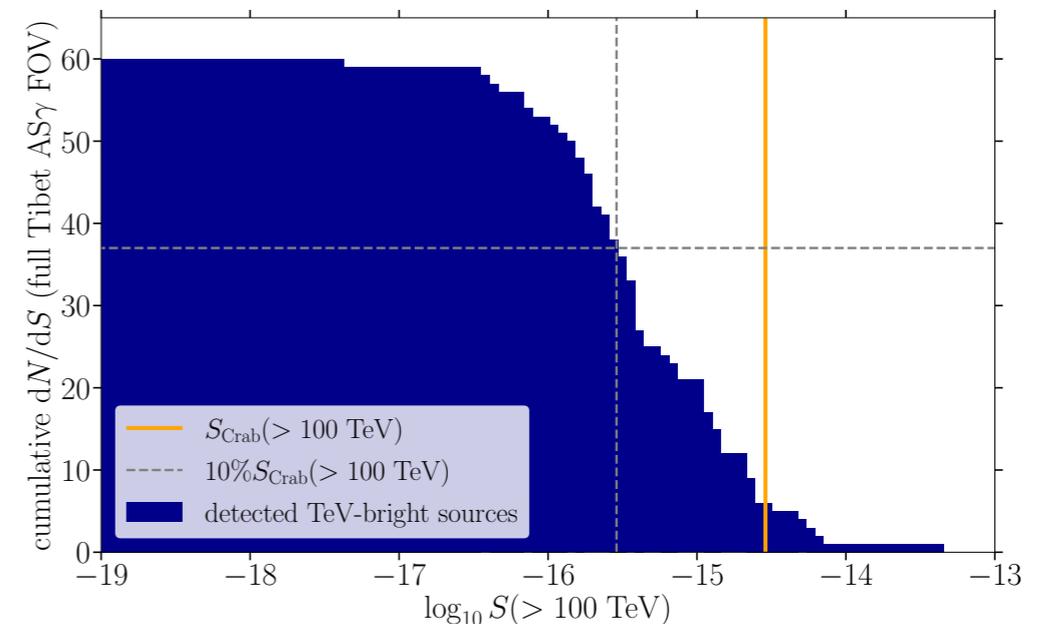
◆ Tibet AS $\gamma$  reports 37 sub-PeV gamma-ray events from stacking the emission seen from the direction of all known TeV-bright sources in its region of interest.

➔ **most optimistic interpretation: 1 photon from each of the 37 brightest sources**

➔ Collect spectral information for all these sources from TeVCat (<http://tevcat2.uchicago.edu/>)

➔ Impose cutoff at 300 TeV (no matter what).

➔ Find 37 brightest sources among them  
→  $S_{\text{TH}} \approx 10\%$  Crab flux ( $> 100$  TeV).



◆ For HAWC: Take flux of faintest detected source that has been subtracted from the data set →  $S_{\text{TH}} = 2\%$  of the Crab flux (10 - 100 TeV).

# Statistical framework

- ◆ We combine the diffuse measurement of Tibet AS $\gamma$  and HAWC in a joint binned likelihood analysis such that:  $\ln \mathcal{L} \propto \chi^2$ .

$$\chi_j^2(\theta) = \sum_k \frac{(\Phi_k^{\text{ALP}}(\theta) + \Phi_k^{\text{IE}}(\theta) + \Phi_k^{\text{sTH}}(\theta) - \Phi_{j,k})^2}{\sigma_{j,k}^2}$$

- ◆ HAWC provides the measurement in form of a power-law fit, hence we bin the functional parameterisation and its uncertainty.

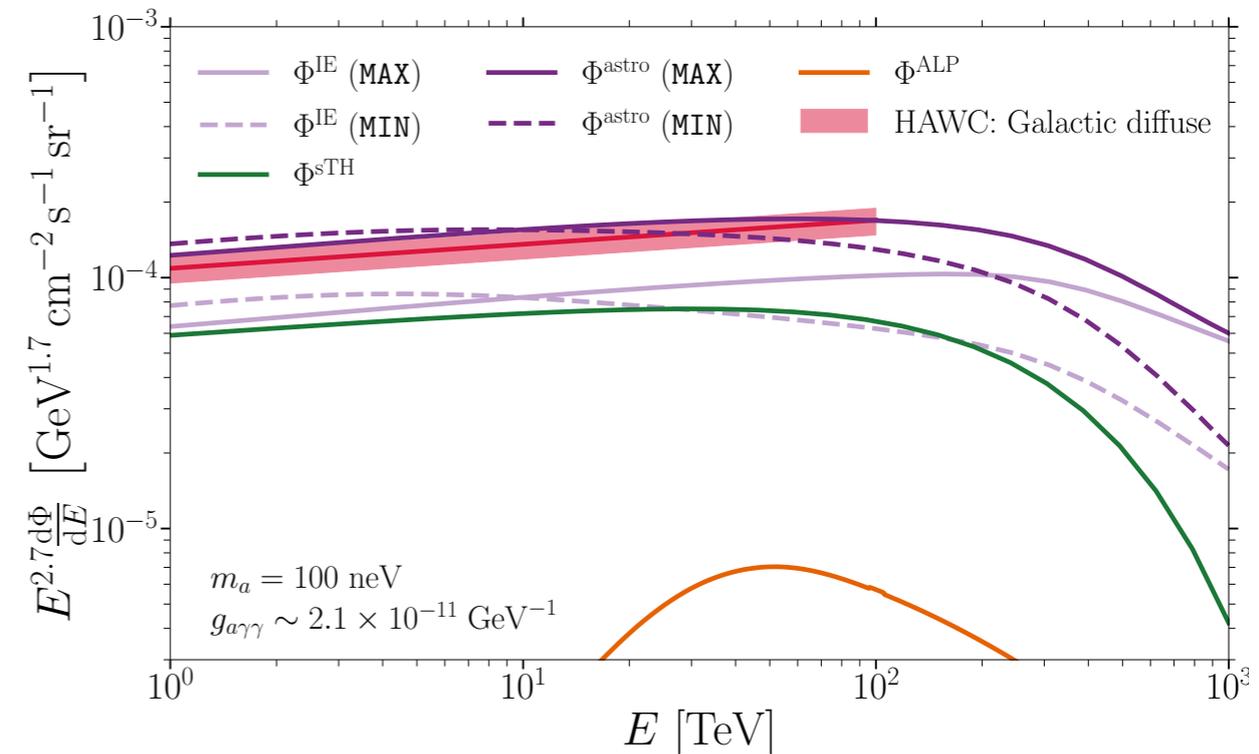
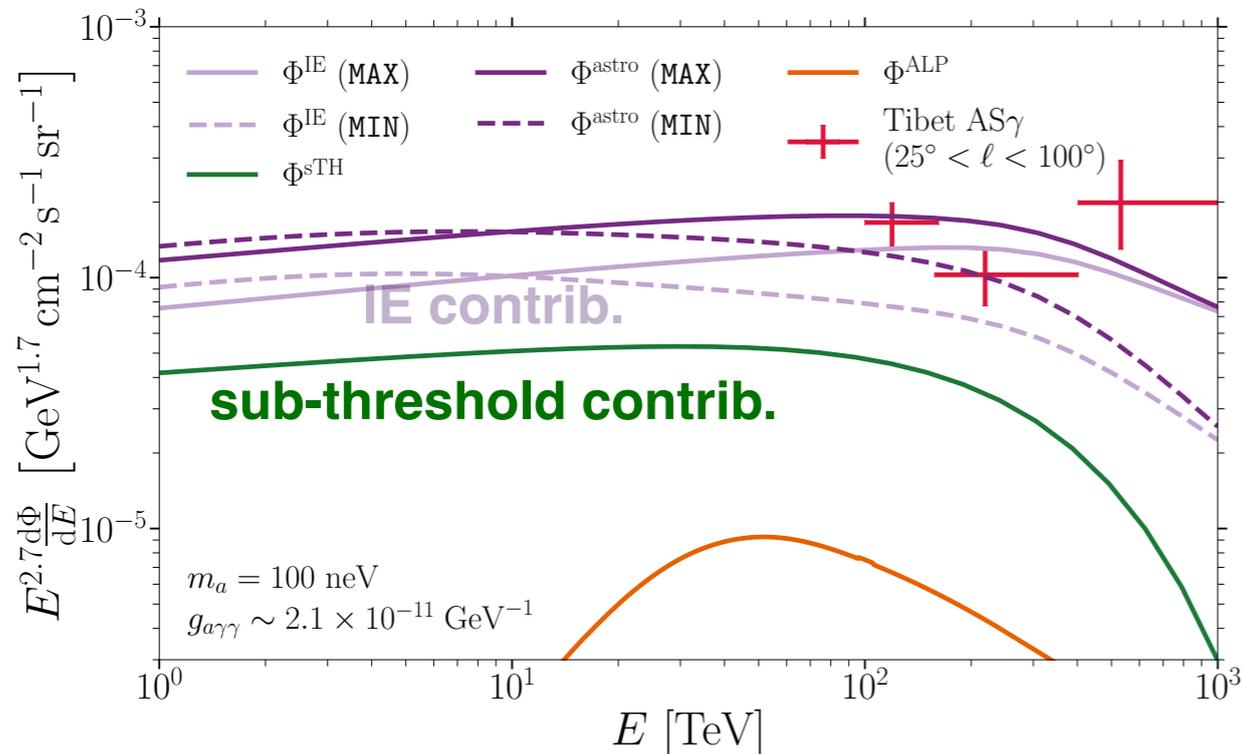
NOTE: The astrophysical components are also affected by the presence of a non-vanishing coupling to ALPs

—> In the Galactic magnetic field, locally generated gamma rays may convert into ALPs thus reducing the naive model expectations.

# Results

- ◆ The astrophysical contribution to the physics probed by both instruments is already sufficient to explain the measurements.

—> Plotted spectra for  $g_{a\gamma\gamma} \equiv 0$ .

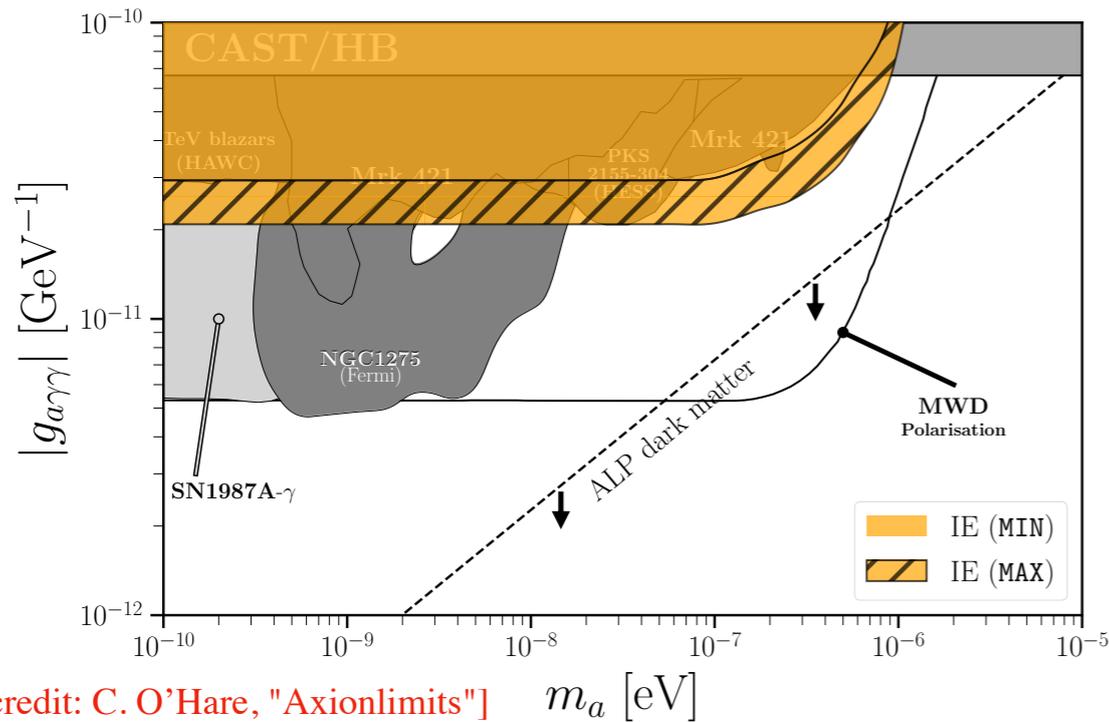


- ◆ Little space for an additional exotic component: For 100 neV axion-like particle this scenario translates to an upper limit on the photon-ALP coupling (at a 95% confidence level) of (using the maximal scenario for IE)

$$g_{a\gamma\gamma} \lesssim 2.1 \times 10^{-11} \text{ GeV}^{-1}$$

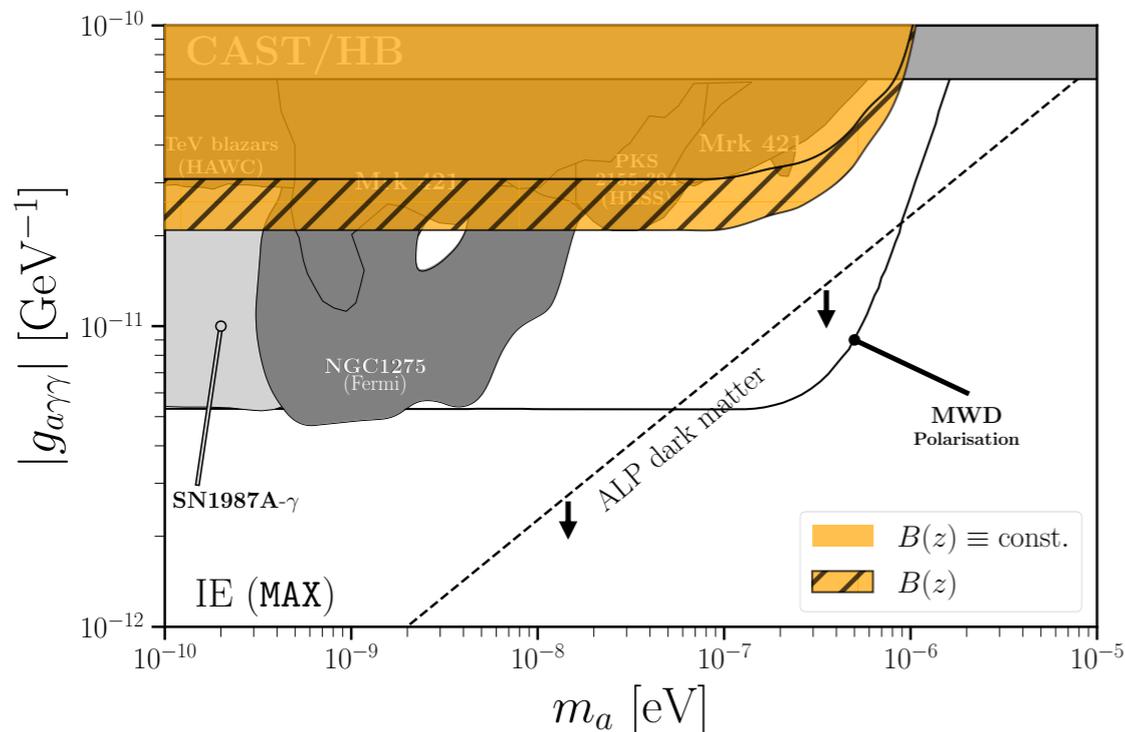
# Discussion

## ◆ Uncertainty due to modelling of interstellar emission:



- > Uncertainty between minimal and maximal IE around a factor of 1.5
- > Even in minimal scenario, competitive constraints.
- > ALPs-only constraints worse by a factor of 3.

## ◆ Uncertainty due to redshift-dependence of magnetic fields in star-forming galaxies:



- > Formation and evolution of galactic magnetic fields is a subject of ongoing theoretical and experimental research [T. G. Arshakian+, A&A 494, 21 (2009)]
- > Increase of field strength with redshift by no means necessary.
- > What happens if it stays constant? Factor of  $\sim 1.5$  deterioration of limits (since we are not very sensitive to the high- $z$  sky).

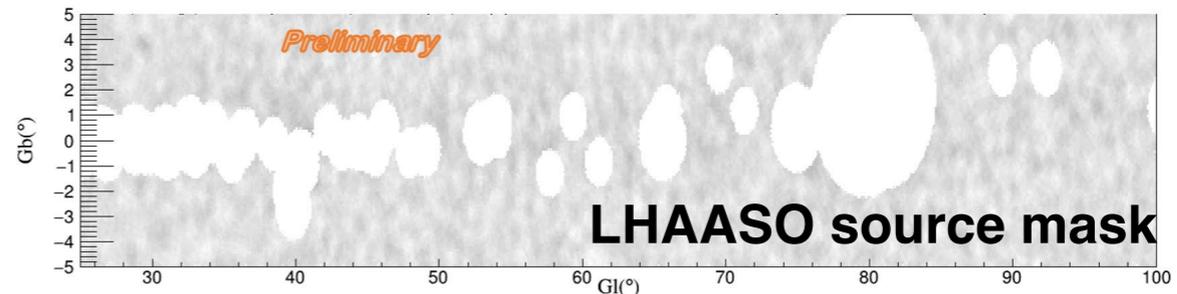
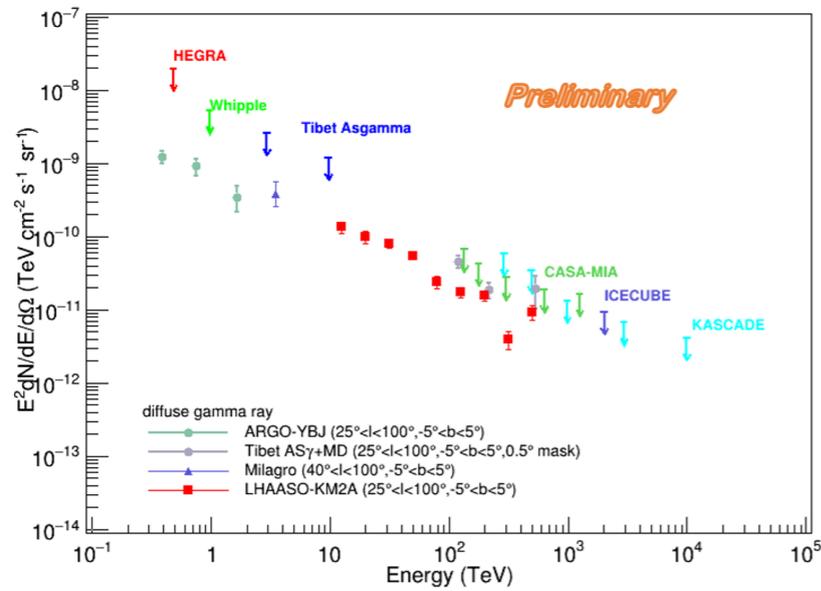
# Summary

- ◆ **Sub-PeV gamma rays** provide a **unique way to search for exotic physics** due to the limited list of potential astrophysical contributors.
- ◆ The **astrophysical neutrino flux measured by IceCube is tied to a concomitant gamma-ray flux** that is mostly attenuated on the extragalactic background light.
- ◆ We impose that **star-forming galaxies are responsible for the observed IceCube neutrino flux via  $p\gamma$ -interactions**, which consequently **leads to an axion-like particle flux** due to *in situ* photon-ALP conversions.
- ◆ Given the observed star-formation rate density evolution in the universe, **we derive the cumulative isotropic ALP flux from neutrino-generating star-forming galaxies** as well as the associated gamma-ray flux due to re-conversion in the magnetic field of the Milky Way.
- ◆ Based on realistic models for interstellar emission and sub-threshold source populations in the Milky Way, we quantify the expected astrophysical contribution to the sub-PeV measurements of the Galactic diffuse emission seen by HAWC and Tibet AS $\gamma$ .
- ◆ **From the HAWC and Tibet AS $\gamma$  data sets we derive competitive upper limits on the photon-ALP coupling constant  $g_{a\gamma\gamma}$  for ALP masses  $m_a \leq 2 \times 10^{-7}$  eV at a 95% confidence level, thus progressively closing the mass gap towards ADMX limits.**

# Backup slides

# What about LHAASO in the end?

- ◆ We did not consider LHAASO in our study because of the inaccessible(?) / insufficient public information about its derivation (source mask, background vs. signal events).
- ◆ However, the LHAASO data cover both the HAWC and Tibet AS $\gamma$  energy range.



- ◆ If we try to digitise the ICRC mask and only account for IE (no data about det. threshold) we find (see also [L. Mastrototaro+, arXiv e-Print:2206.08945] for a similar approach).

**Less constraining but with full exp. approach available quite promising!**

