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

based on arXiv:2204.12487, accepted for publication in Phys. Rev. D
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—on-line, 7th October 2022—

—YOUNGST@RS - Shoot for the Stars, Aim for the Axions—

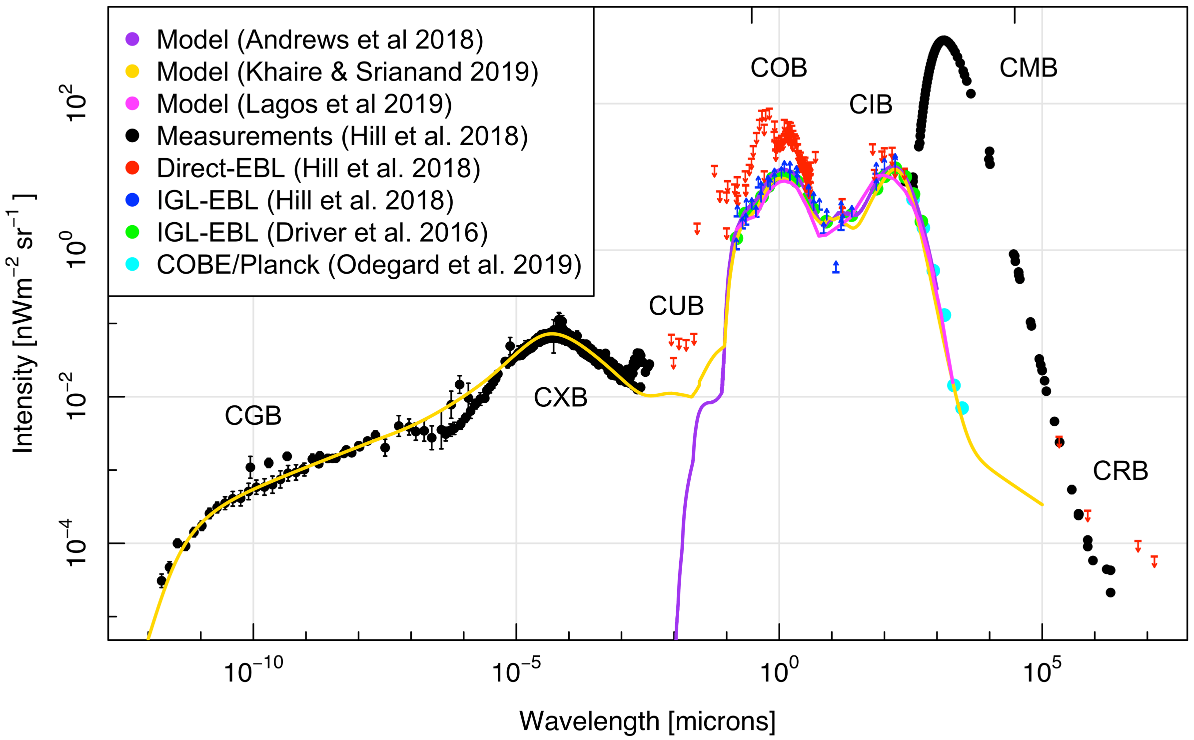
Credit: P. Oesch/University of Geneva; M. Montes/University of New South Wales/ESA/NASA
ESA, Planck

Why sub-PeV gamma rays?

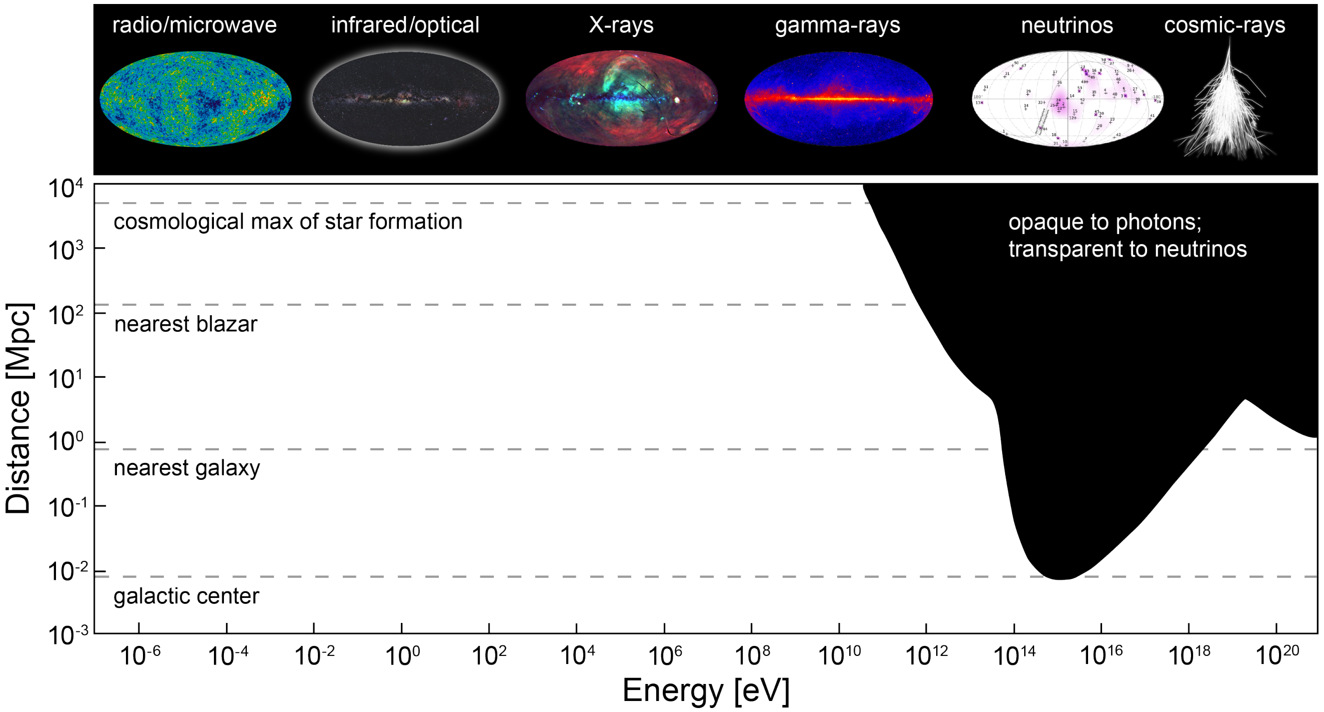
Gamma-ray indirect searches for exotic physics means finding a tiny signal in a sea of astrophysically produced gamma rays.

→ **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.

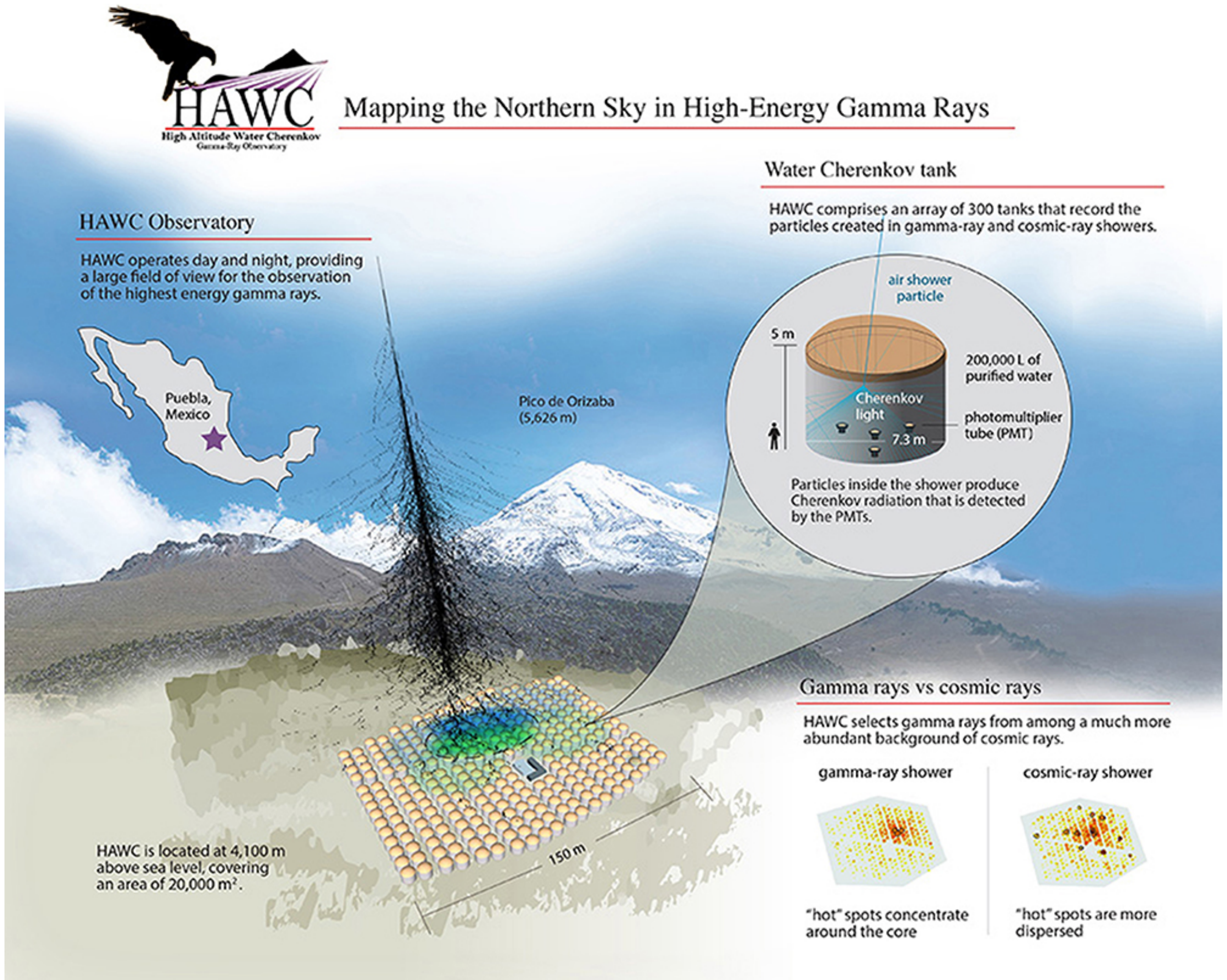


- ✦ At sub-PeV energies, Galactic physics probably only major contributor.
- ✦ Exotic physics, especially feebly interacting particles as ALPs, circumvent EBL absorption. —> **May give rise to extragalactic gamma-ray contribution.**

Current instruments

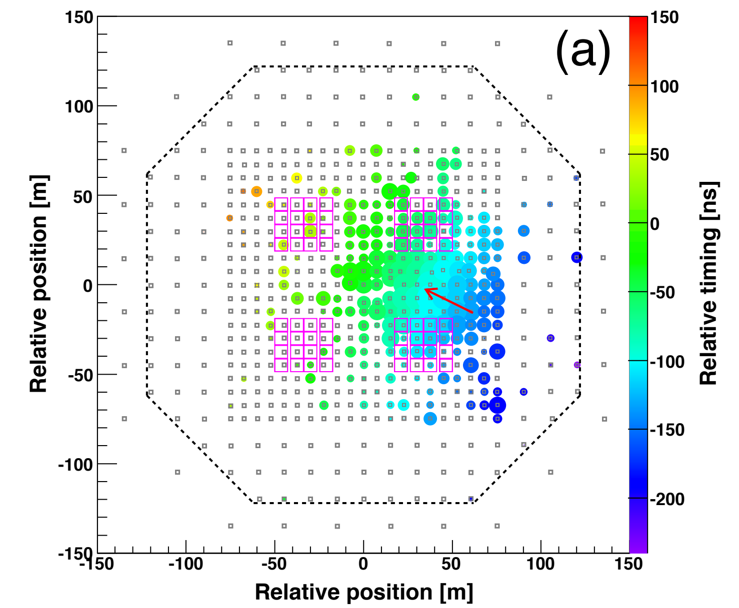
- ✦ The **frequency of gamma rays decreases with increasing energy, hence** detectors must **cover large areas** to gather sufficient statistics —> Limits us to ground-based observations.
- ✦ Indirect detection and reconstruction of primary cosmic rays via secondary particles of the triggered extensive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

HAWC



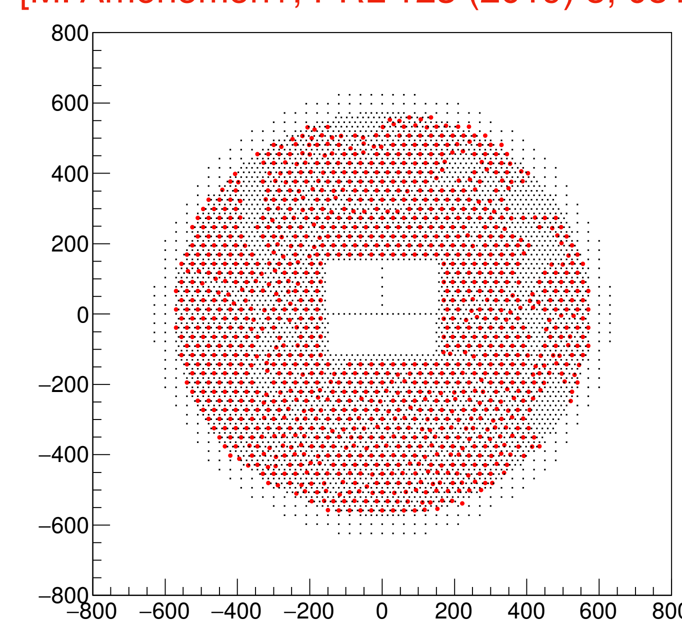
[A. Nayerhoda+, Front. Astron. Space Sci., 2018]

Tibet ASγ+MD



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

LHAASO



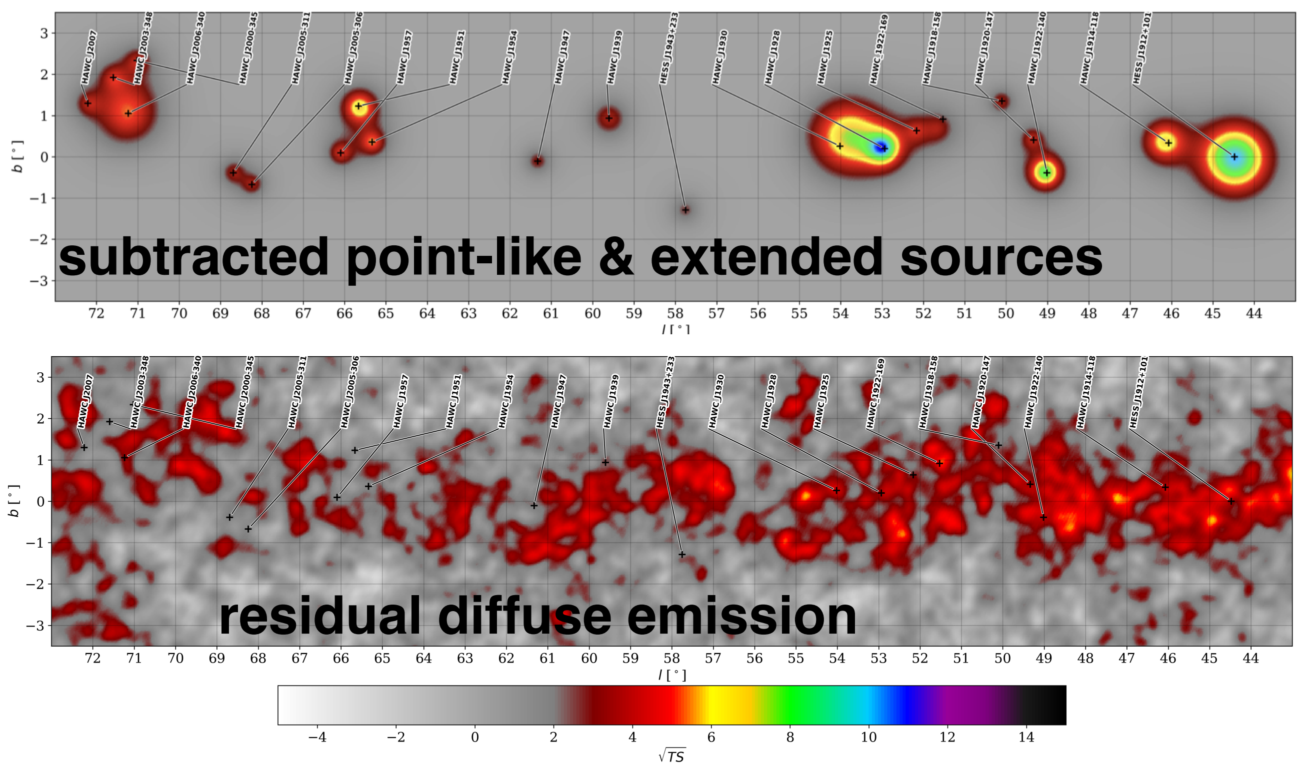
[S. Vernetto, J. Phys.: Conf. Ser. 718 052043]

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)

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

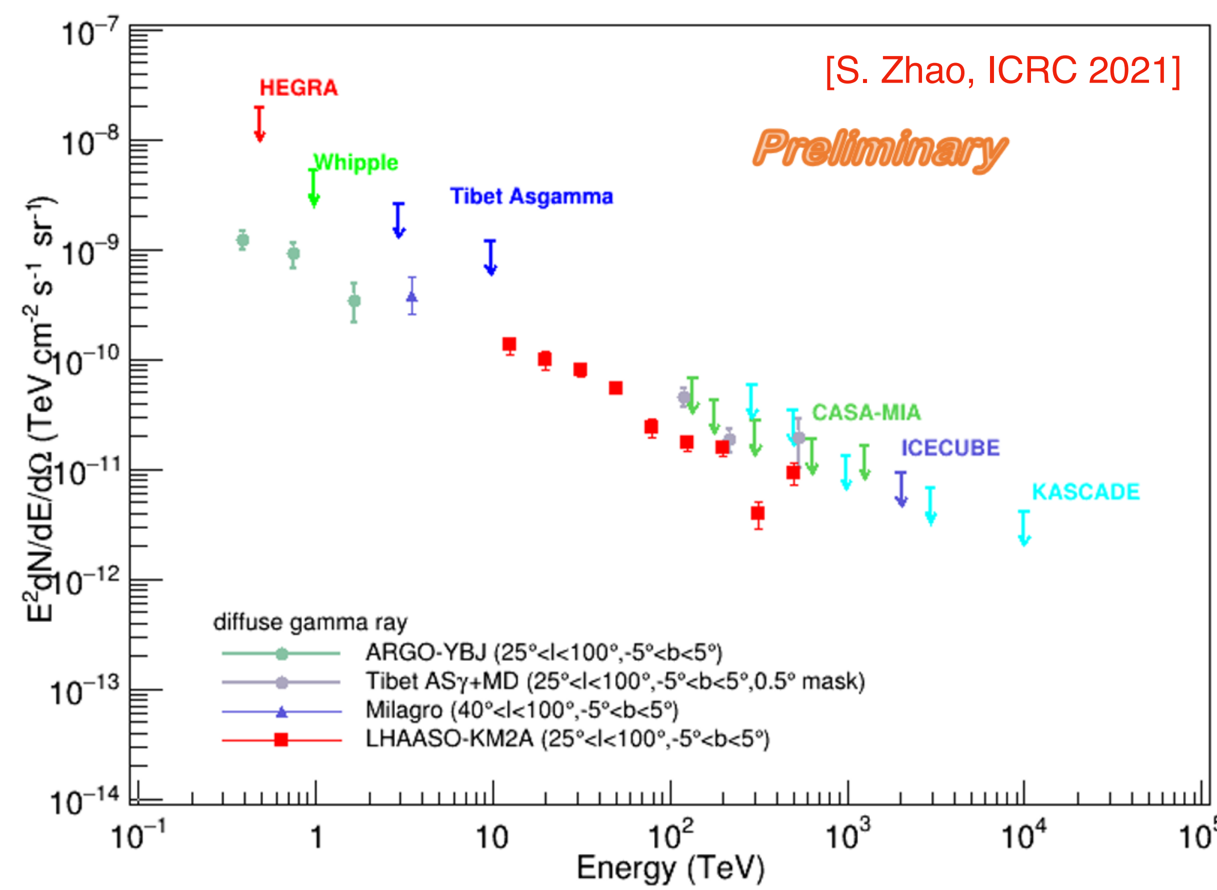


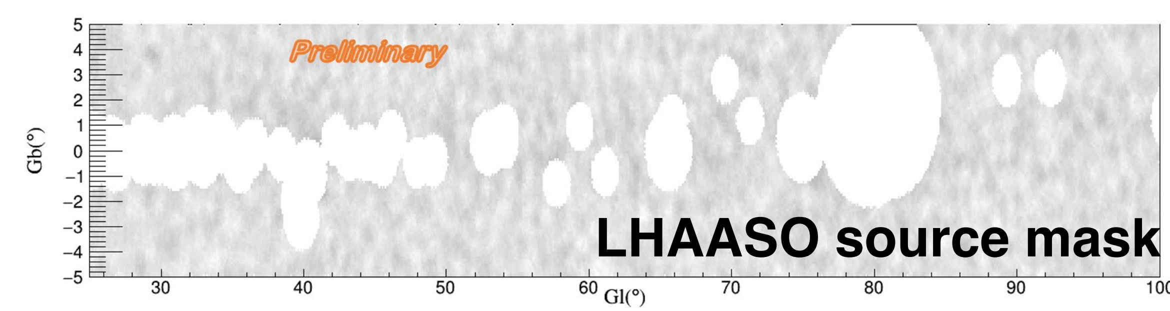
[HAWC collaboration, ICRC 2021]

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

LHAASO and Tibet ASγ+MD

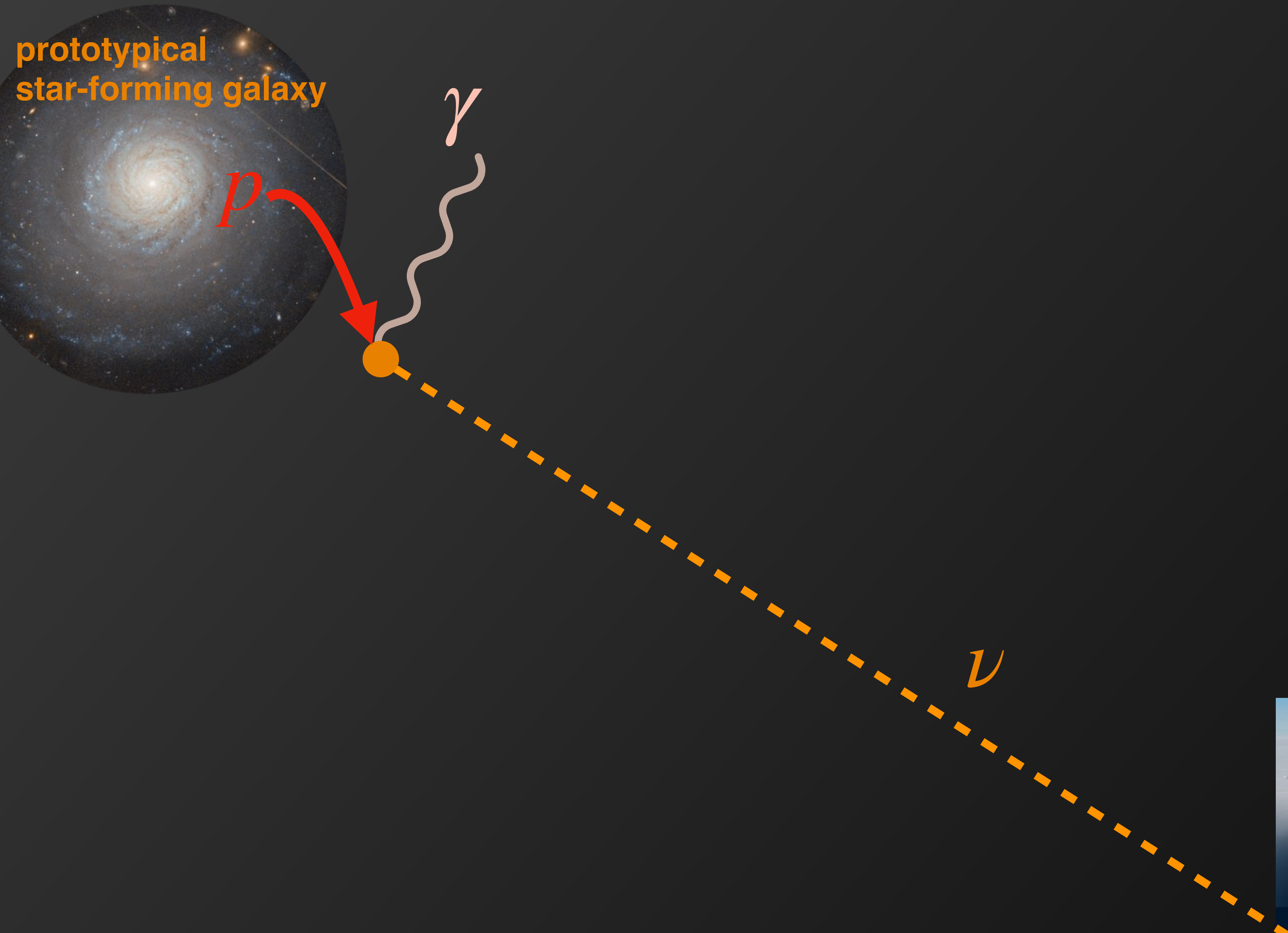
$$25^\circ < \ell < 100^\circ, |b| \leq 5^\circ$$



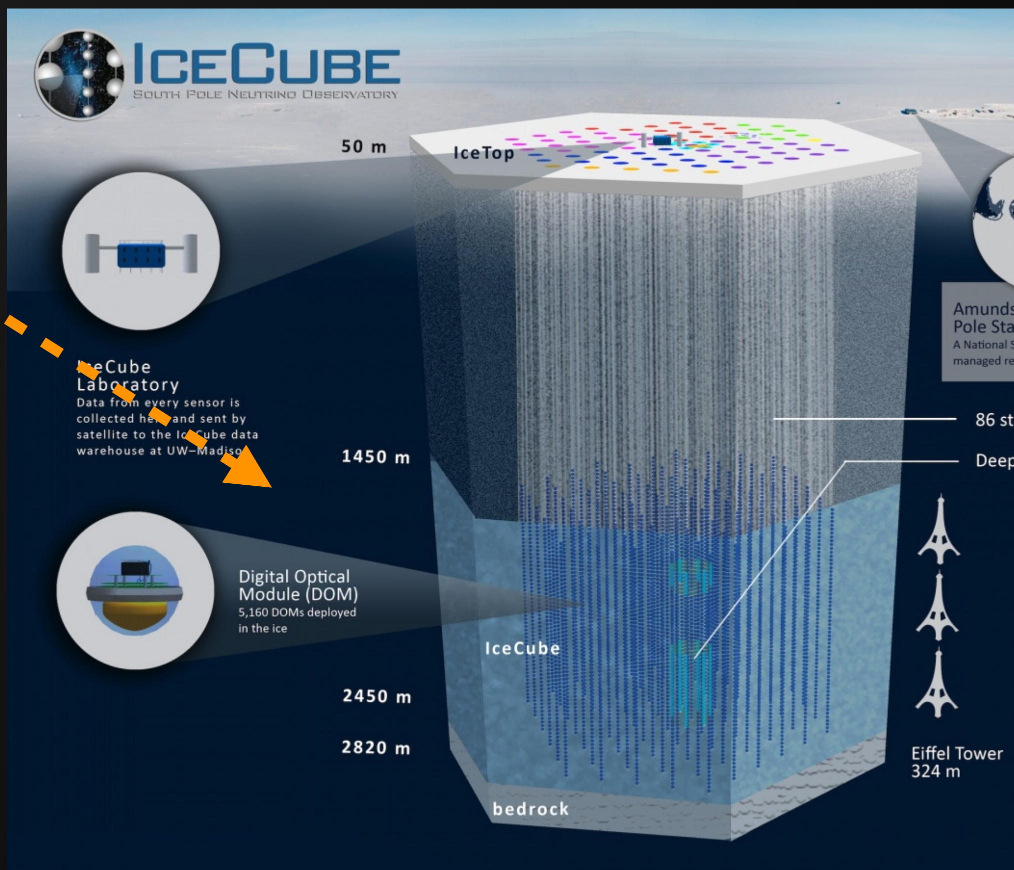


Connecting neutrinos and axion-like particles

Illustration inspired by: M. Meyer



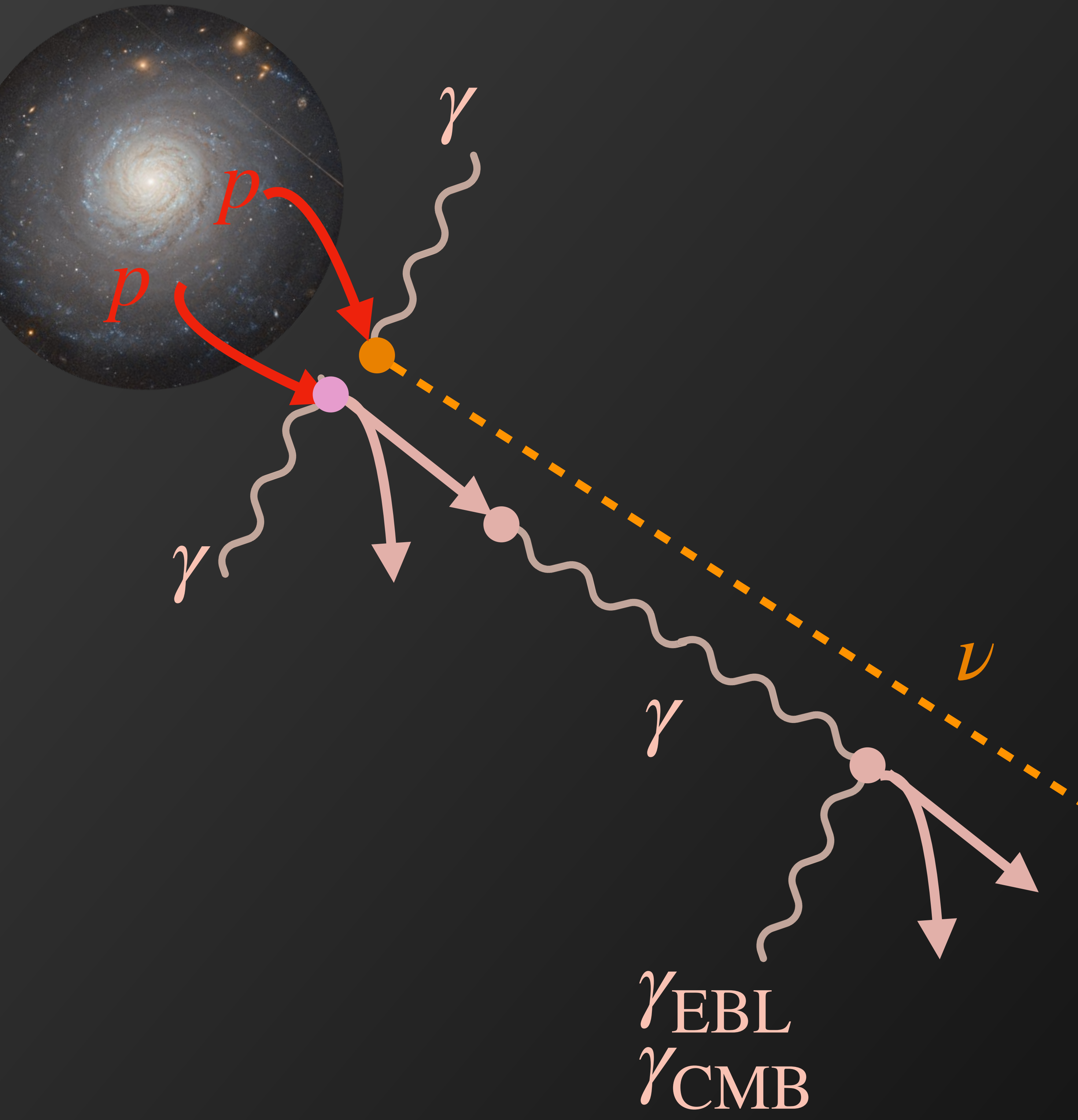
Credit: IceCube collaboration



- ✦ 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

Illustration inspired by: M. Meyer

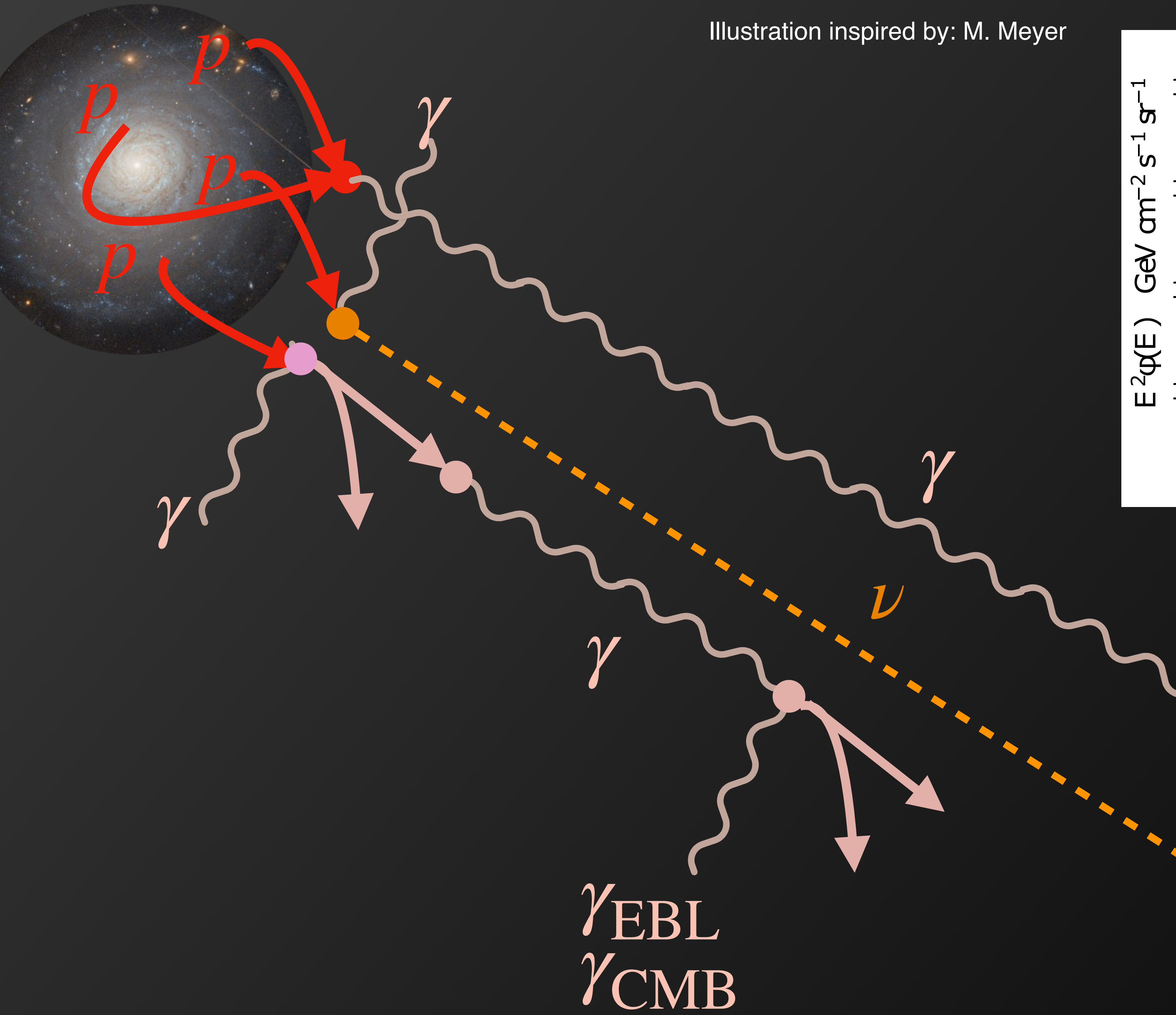


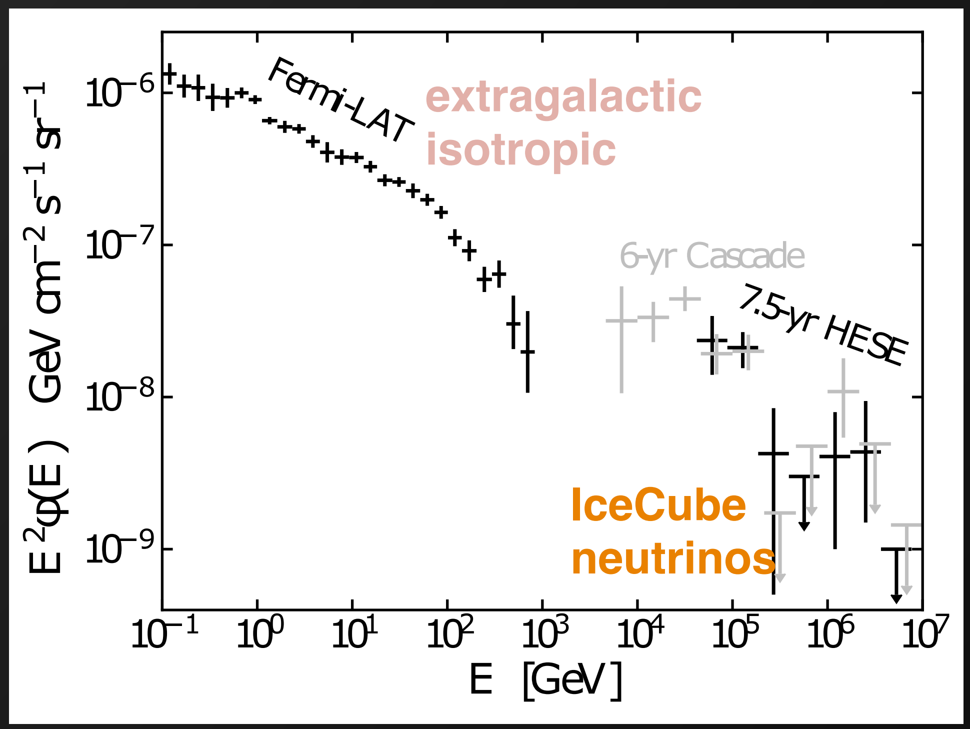

Credit: HAWC collaboration

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

From astrophysical neutrinos to axion-like particles

Illustration inspired by: M. Meyer





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

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

From astrophysical neutrinos to axion-like particles

- ✦ With the distant galaxy, magnetic fields $\overrightarrow{B}_{\mathrm{EGAL}}$ 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 $\overrightarrow{B}_{\mathrm{MW}}$ they reconvert to gamma rays.
- ✦ We consider only $p\gamma$ plus energy cutoff at 25 TeV to evade Fermi-LAT constraints.

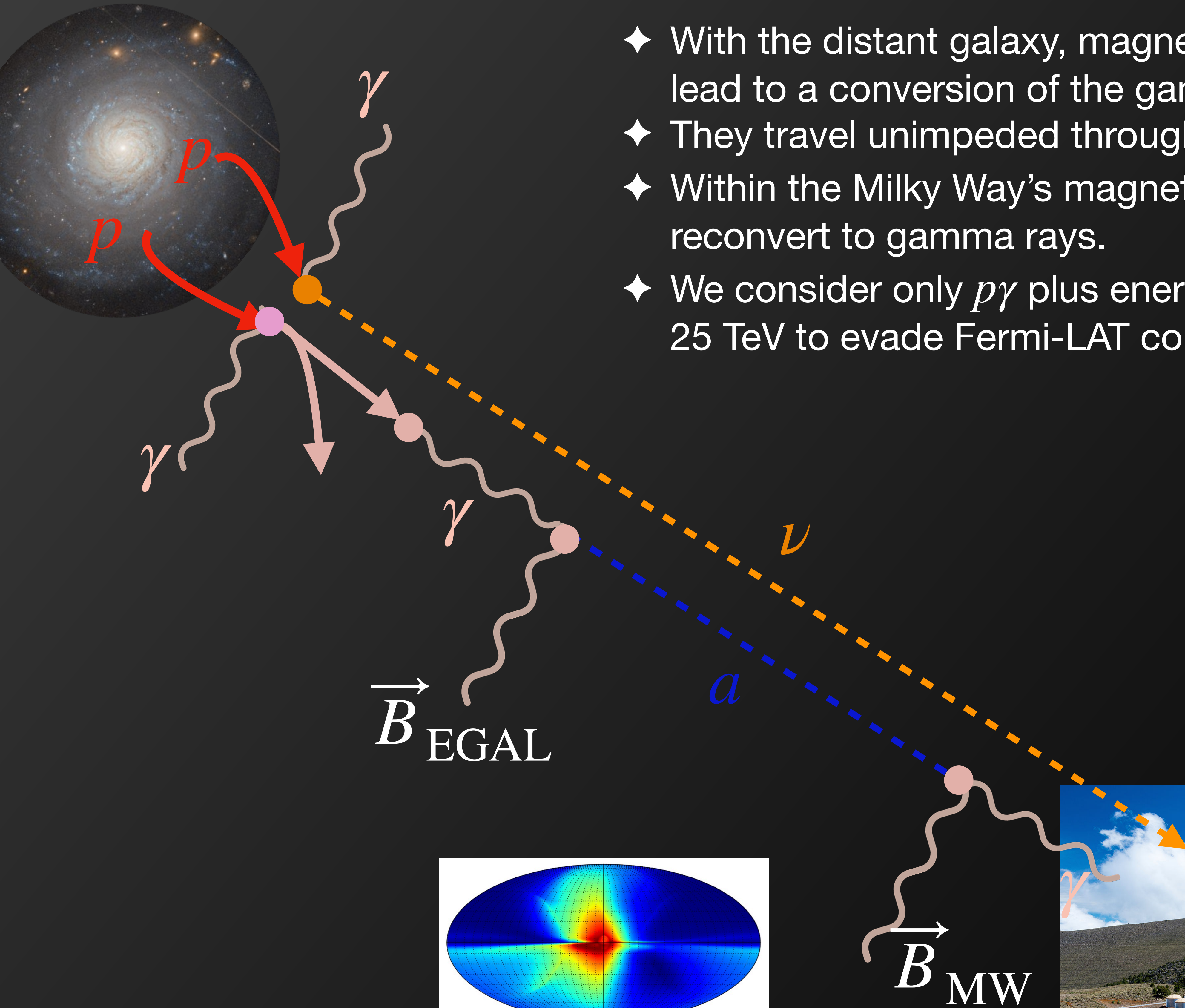


Illustration inspired by: M. Meyer

Credit: HAWC collaboration

Deriving the *in situ* gamma-ray spectrum

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

$$E_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\left(E_\nu = \frac{E_\gamma}{2}\right) = \frac{3}{2} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$

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

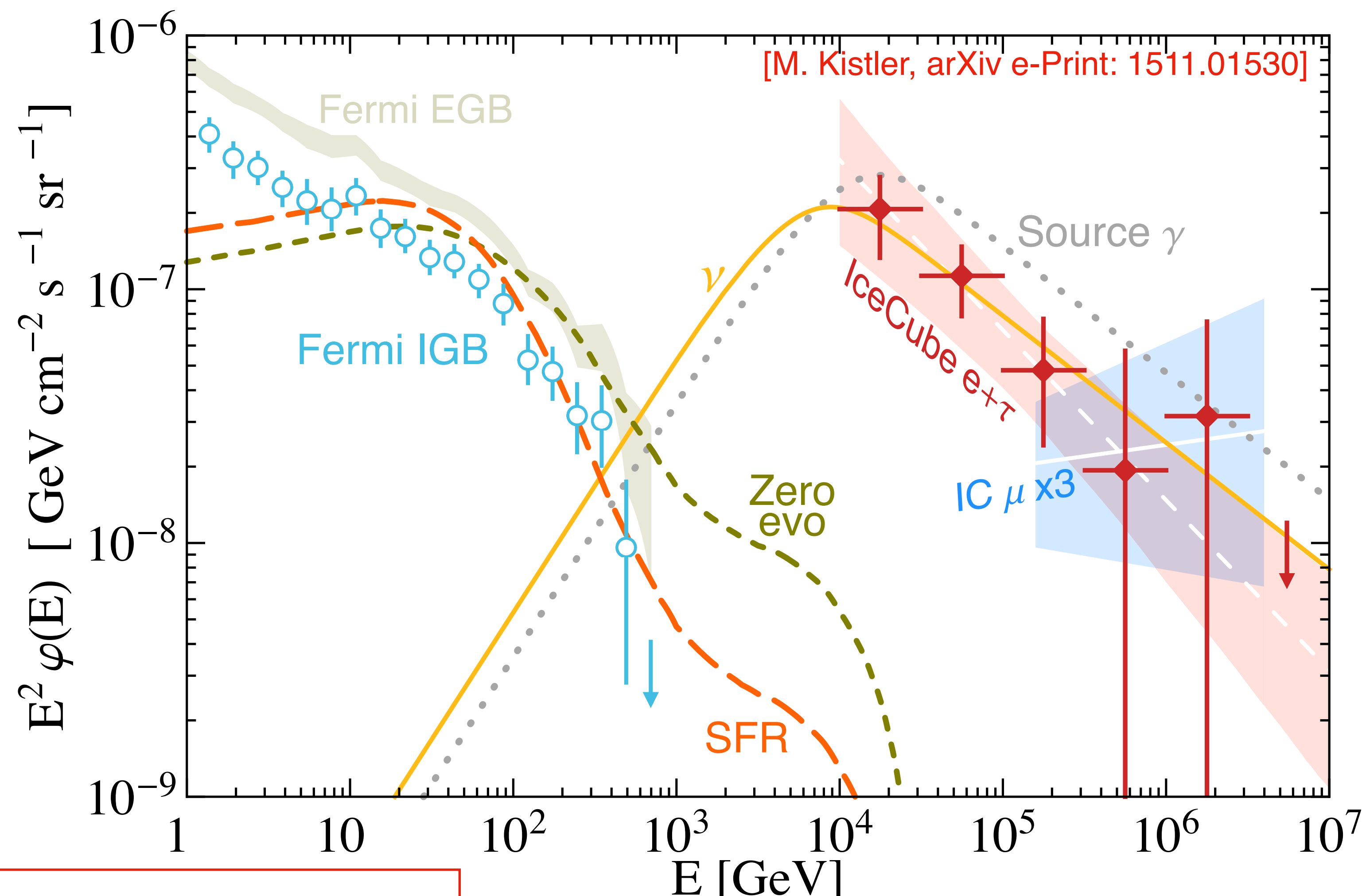
$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = N_0 \left[\left(\frac{E_\nu}{E_b}\right)^2 + \left(\frac{E_\nu}{E_b}\right)^{2\alpha}\right]^{-\frac{1}{2}} \qquad \alpha = 2.87$$

[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:

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{c}{4\pi}\int_0^\infty \frac{\mathrm{d}N_\nu}{\mathrm{d}E'_\nu}(1+z)\,\dot{\rho}_*(z)\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right|\,\mathrm{d}z$$



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

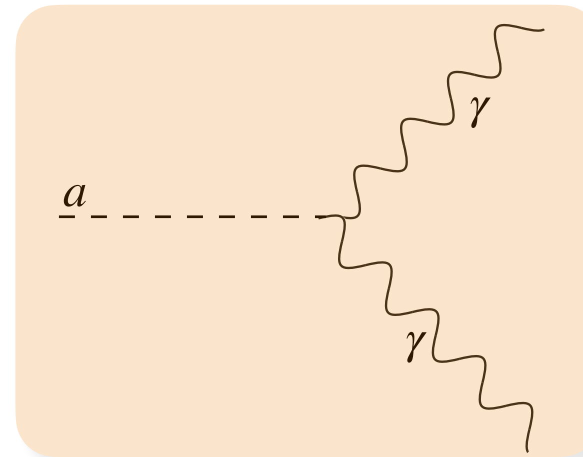
ALP-photon conversion in magnetic fields

✦ Photons and axion-like particles may mix in the presence of magnetic fields when coupled.

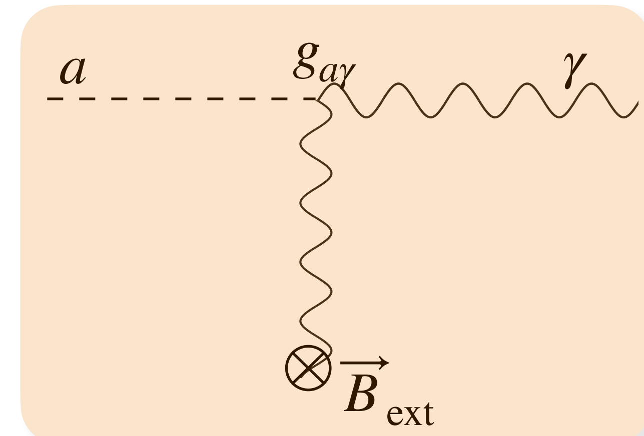
E.g.: Minimal scenario

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

$$g_{a\gamma} = \frac{\alpha}{2\pi} \frac{1}{f_a} \mathcal{N}$$



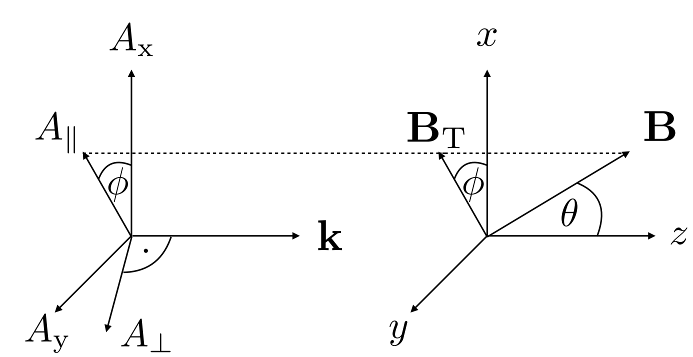
decay



Primakoff effect

✦ For highly relativistic ALPs, the equations of motion can be formulated in a Schrödinger-like propagation equation (ignoring γ-absorption; ω—frequency of photon-ALP state):

$$\left[\omega + \begin{pmatrix} \Delta_\perp & \Delta_R & 0 \\ \Delta_R & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} - i\partial_z \right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$



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

✦ Effect of Faraday rotation is usually neglected ($\Delta_R = 0$) so that we obtain a mixing of the photon state parallel to the transversal component of the magnetic field and ALPs.

ALP-photon conversion in magnetic fields

✦ Matrix elements relevant for mixing require knowledge of environmental properties:

$$\left[\omega + \begin{pmatrix} \Delta_\perp & \Delta_R & 0 \\ \Delta_R & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} - i\partial_z\right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

$$\Delta_\parallel = \Delta_{\rm pl} + \frac{7}{2}\Delta_{\rm B} + \Delta_{\gamma\gamma} \qquad \Delta_{\rm pl} = -\frac{2\pi\alpha n_e}{m_e\omega}$$

$$\Delta_a = -\frac{m_a^2}{2\omega} \qquad \Delta_{\rm B} = \frac{24\alpha^2\rho_B}{135 m_e^4}\sin^2\theta\omega$$

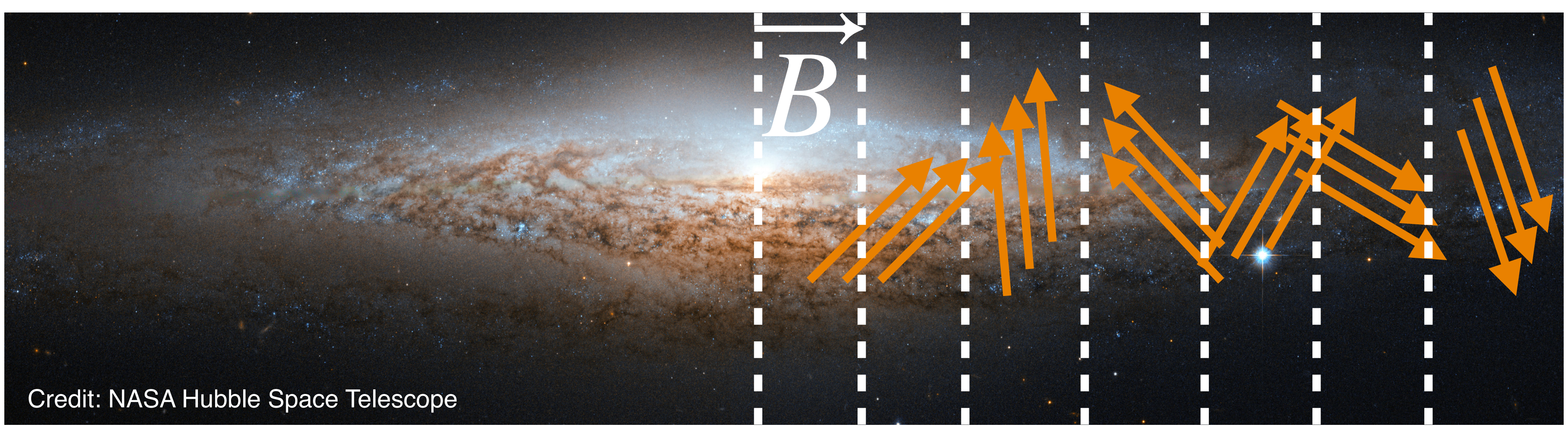
$$\Delta_{a\gamma} = \frac{g_{a\gamma\gamma}}{2}|B_T| \qquad \Delta_{\gamma\gamma} \approx \frac{44\alpha^2\omega}{135 m_e^2}\sum_i \rho_\gamma^i$$

Magnetic field strength and orientation: $B, \sin\theta$

local electron density: n_e

(Stellar) radiation fields: ρ_γ

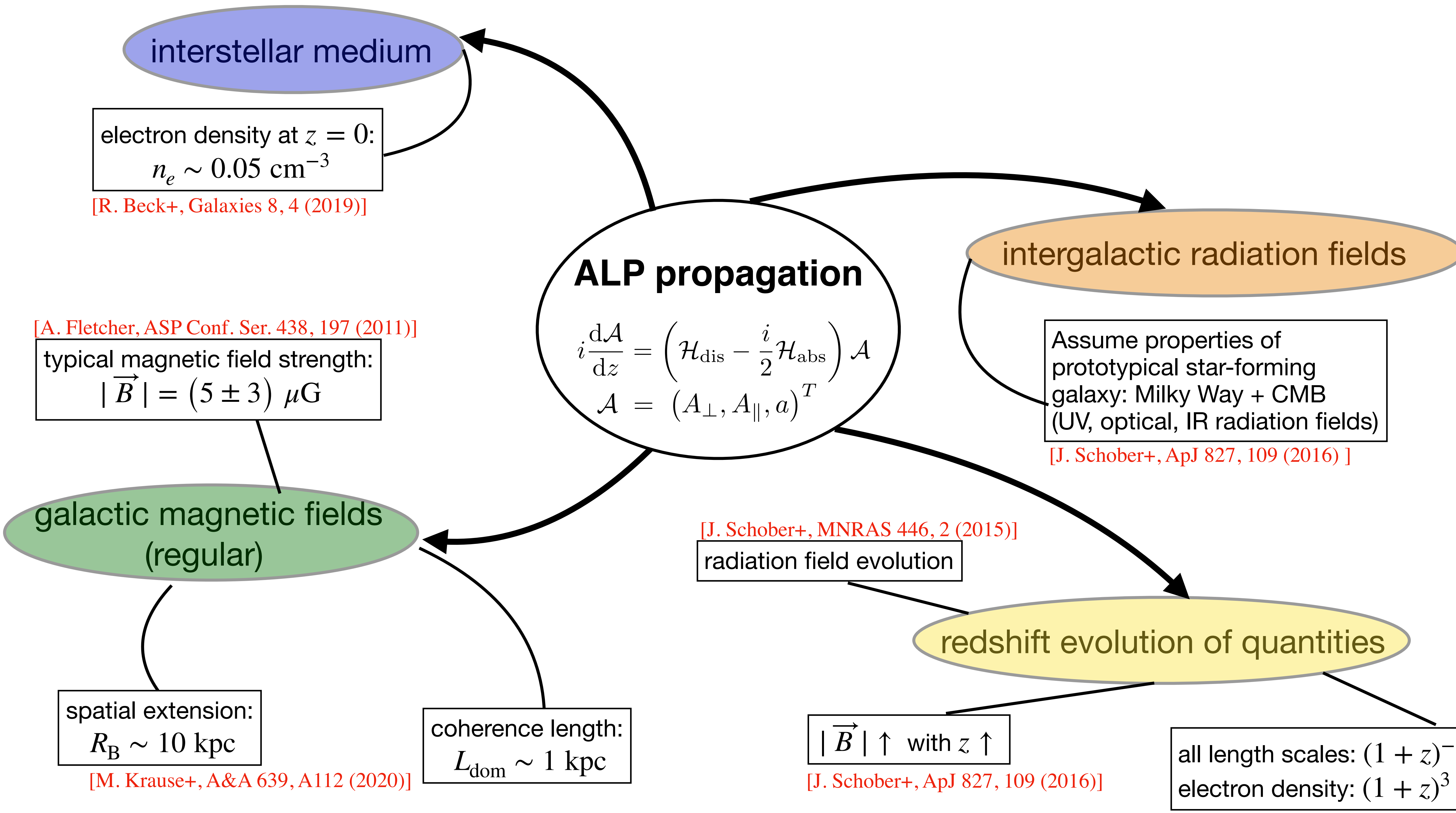
✦ B-field coherent over typical length scale $L_{\rm dom}$, orientation changes from domain to domain —> solve propagation for each domain and iteratively apply outcome on initial state via transfer matrices.



domain approximation

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)]
- ✦ Average over multiple realisations of galaxies at given redshift z. [H. Vogel+, arXiv:1712.01839 (2017)]



How do we observe such an ALP-flux?

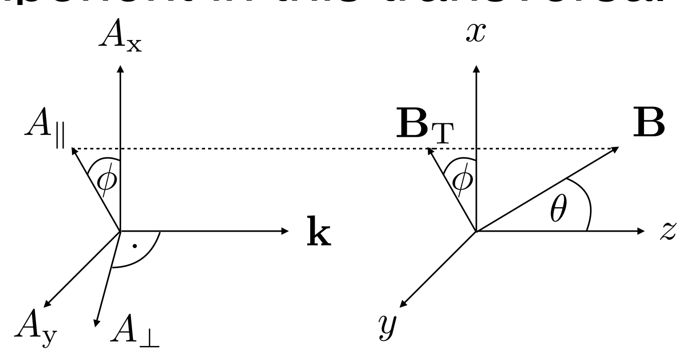
ALP-photon conversion in the Milky Way's magnetic field.

[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.

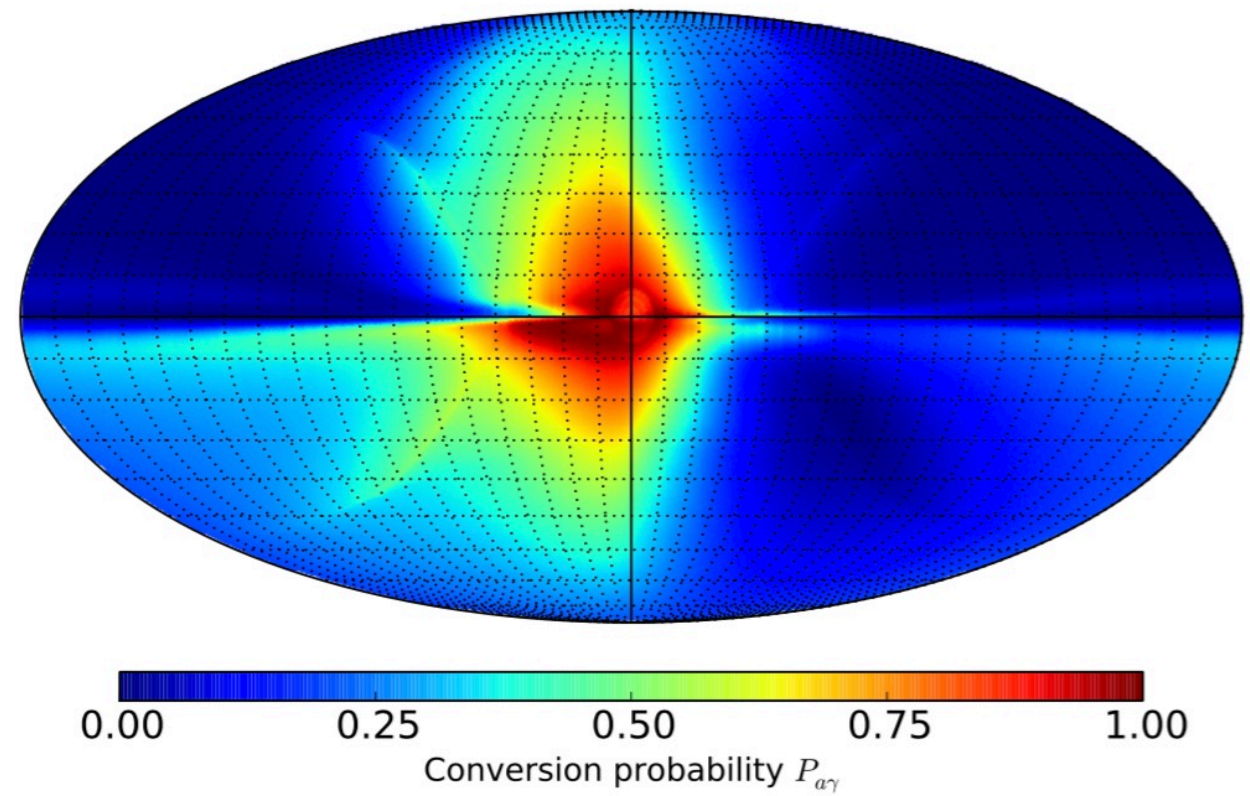
[Kartavtsev et al., JCAP 01 (2017) 024]



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

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

(assuming a homogeneous magnetic field.)



— $g_{a\gamma\gamma} = 5\times10^{-11}\,\mathrm{GeV}^{-1}$, "massless" ALP
— pure initial ALP state
— magnetic field model of Jansson & Farrar 2012
— propagation through entire MW

Extragalactic ALP-flux:

$$\frac{\mathrm{d}\Phi_a}{\mathrm{d}E}$$

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

Associated gamma-ray flux:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E} = \frac{\mathrm{d}\Phi_a}{\mathrm{d}E}P_{a\to\gamma}(E)$$

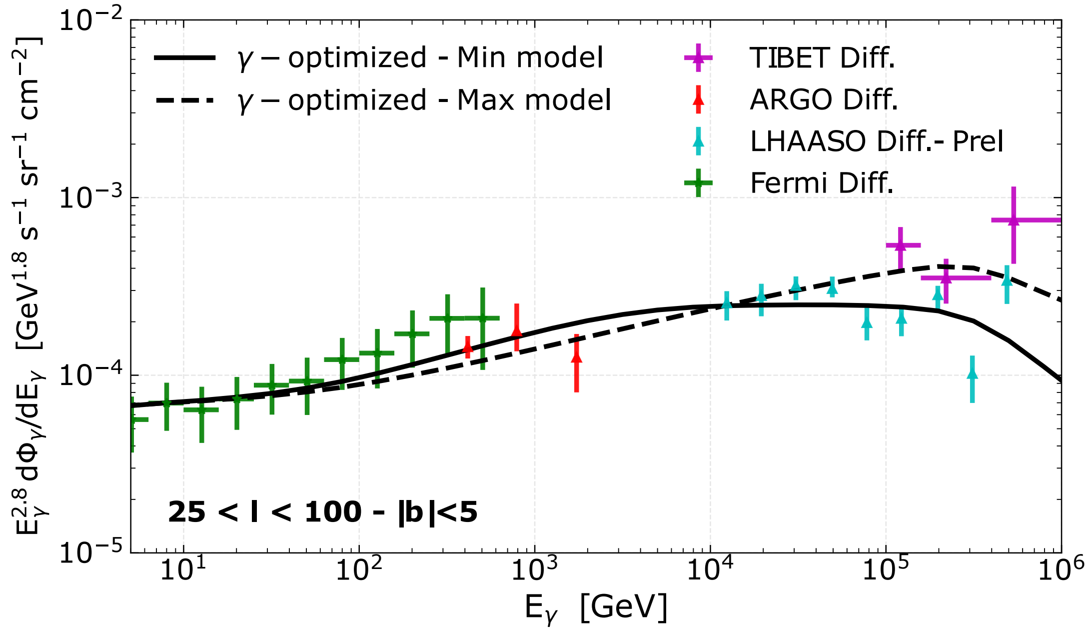
Galactic astrophysics at the sub-PeV scale

- 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
  (i) **interstellar emission** (IE) and
  (ii) **sub-threshold point-like and extended sources.**

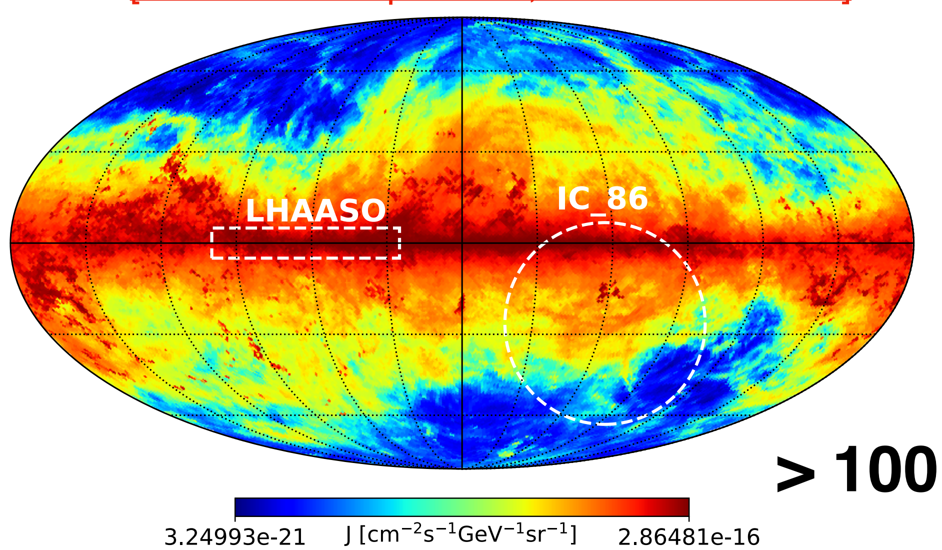
- Large-scale emission from very-high-energy cosmic ray interactions with particles of the interstellar medium, structure roughly follows gas and radiation distribution in Milky Way.

- 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]



> 100 TeV

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.**

  - 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:

$$\frac{\mathrm{d}N}{\mathrm{d}^3r\,\mathrm{d}L_{\mathrm{TeV}}} = \boxed{\rho(\boldsymbol{r})} \times \boxed{\mathcal{L}(L_{\mathrm{TeV}})}$$

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:

$$\varphi(E) = K_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\beta} \exp\left(-\frac{E}{E_{\mathrm{c}}}\right)$$

$\beta = 2.6$ —> average index of known TeV-bright sources (TeVCat)
$E_c = 300$ TeV —> ensures non-detection of photons by Tibet ASγ beyond 400 TeV associated to localised sources

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

$$\Phi^{\mathrm{sTH}}(E) = \varphi(E) \int_0^{\boxed{S_{\mathrm{TH}}}} \Phi_{\mathrm{TeV}} \frac{\mathrm{d}N}{\mathrm{d}\Phi_{\mathrm{TeV}}}\, \mathrm{d}\Phi_{\mathrm{TeV}}$$

⟶ **What is the detection threshold of HAWC and Tibet ASγ?**

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.**

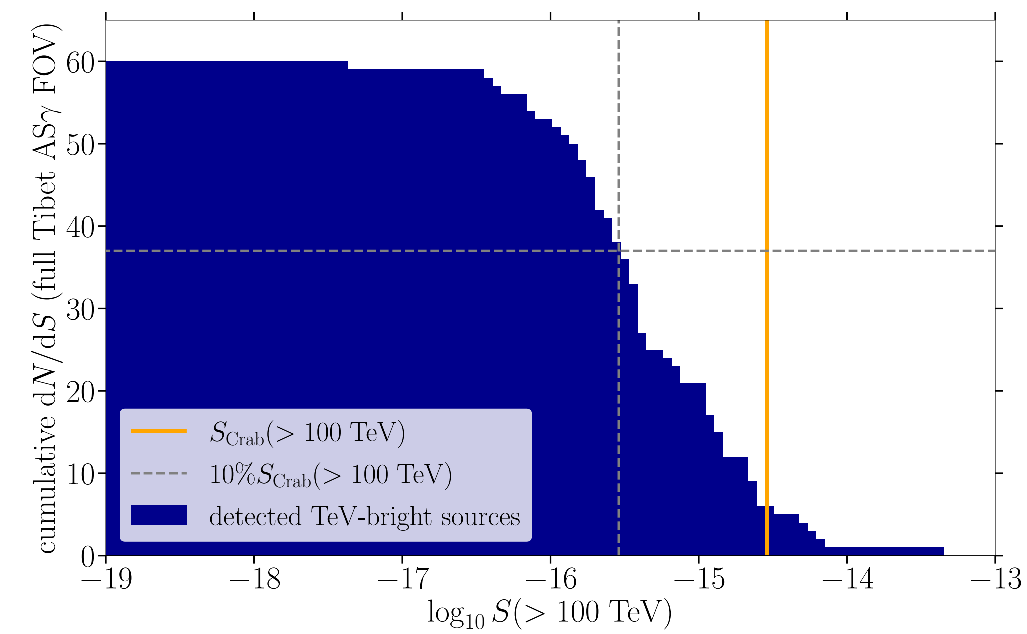
  - Tibet ASγ reports 37 sub-PeV gamma-ray events from stacking the emission seen from the direction of all known TeV-bright sources in its region of interest.

    → **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 –> $S_{\mathrm{TH}} \approx 10\,\%$ Crab flux (> 100 TeV).



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

Statistical framework

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

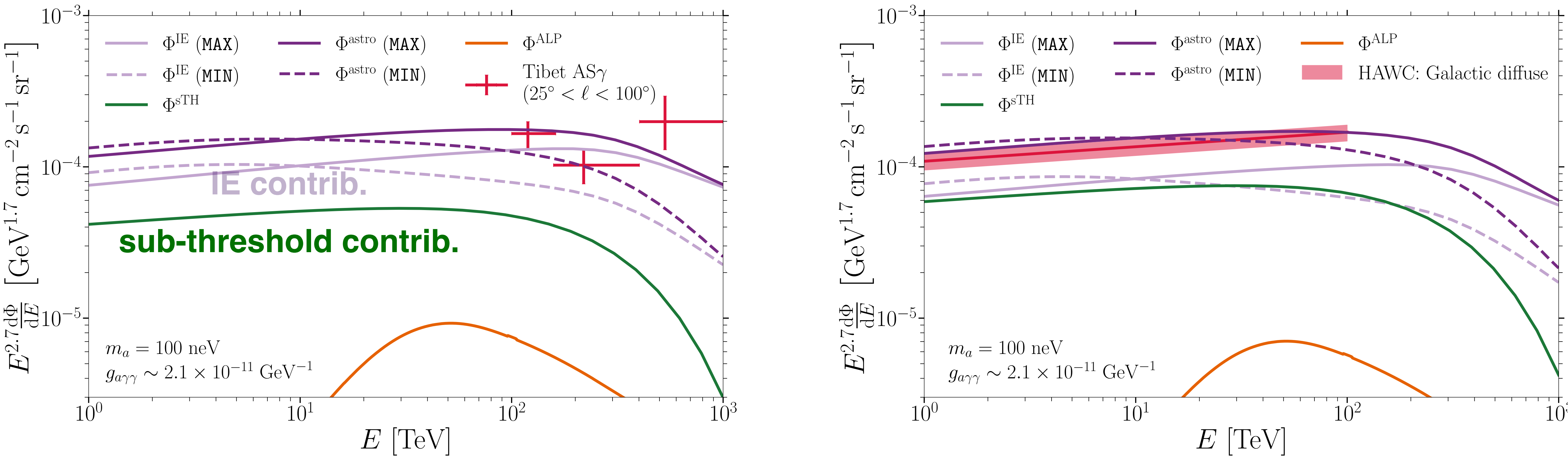
$$\chi_j^2(\theta) = \sum_k \frac{\left(\Phi_k^{\mathrm{ALP}}(\theta) + \Phi_k^{\mathrm{IE}}(\theta) + \Phi_k^{\mathrm{sTH}}(\theta) - \Phi_{j,k}\right)^2}{\sigma_{j,k}^2}$$

- 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 $g_{a\gamma\gamma} \equiv 0$.

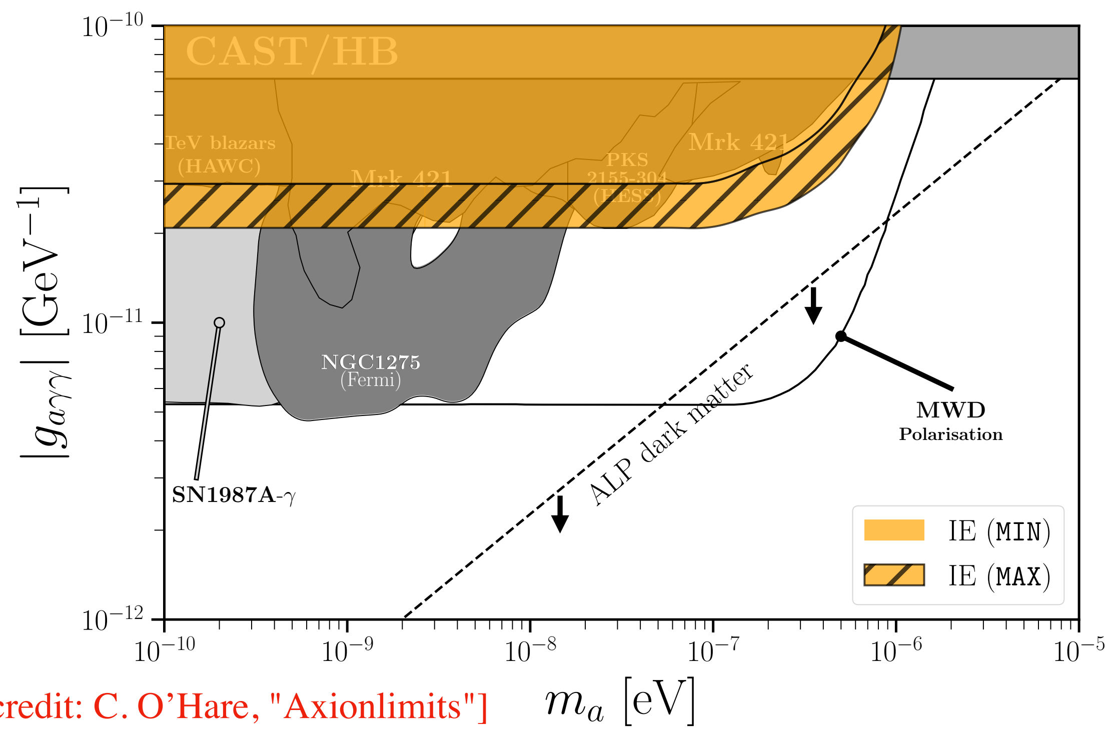


- Little space for an additional exotic component: For 100 neV axion-like particle this scenario translates to an upper limit on the photon-ALP coupling (at a 95% confidence level) of (using the maximal scenario for IE)

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

Discussion

✦ **Uncertainty due to modelling of interstellar emission:**



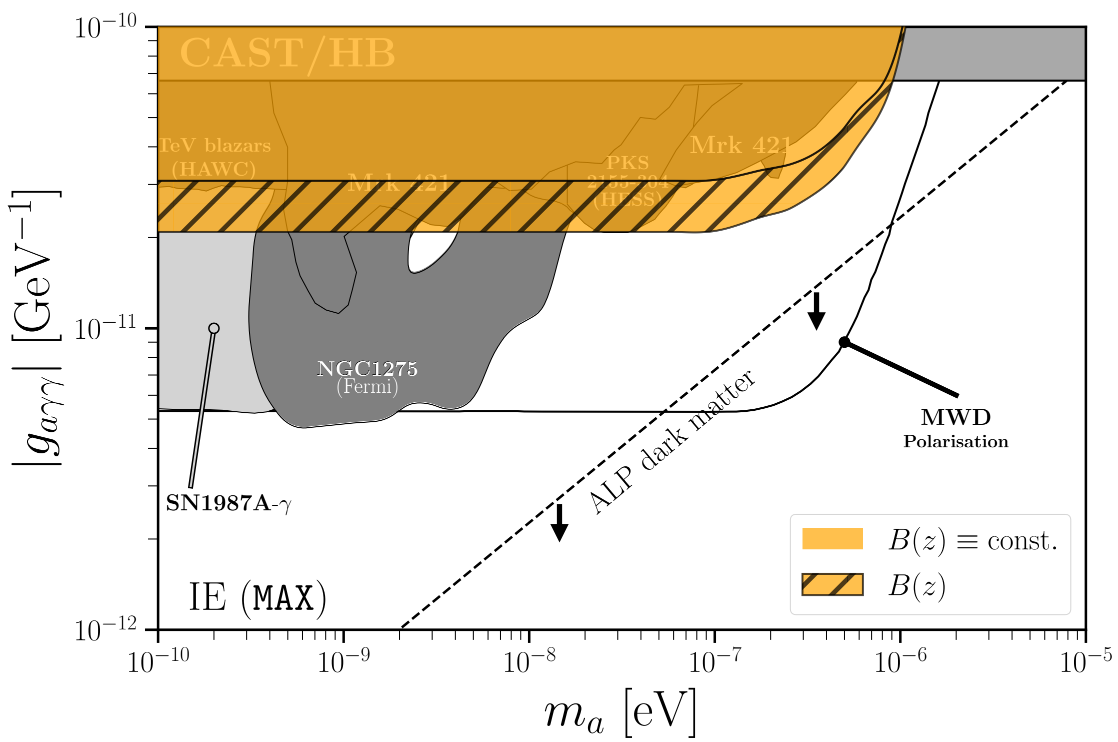
[credit: C. O'Hare, "Axionlimits"]

—> 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 ~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.

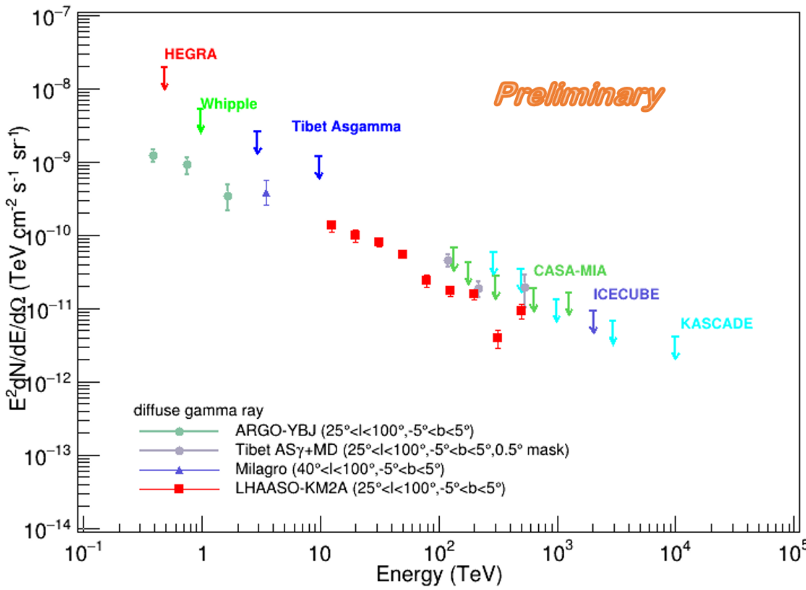
- Given the observed star-formation rate density evolution in the universe, **we derive the cumulative isotropic ALP flux from neutrino-generating star-forming galaxies** as well as the associated gamma-ray flux due to re-conversion in the magnetic field of the Milky Way.

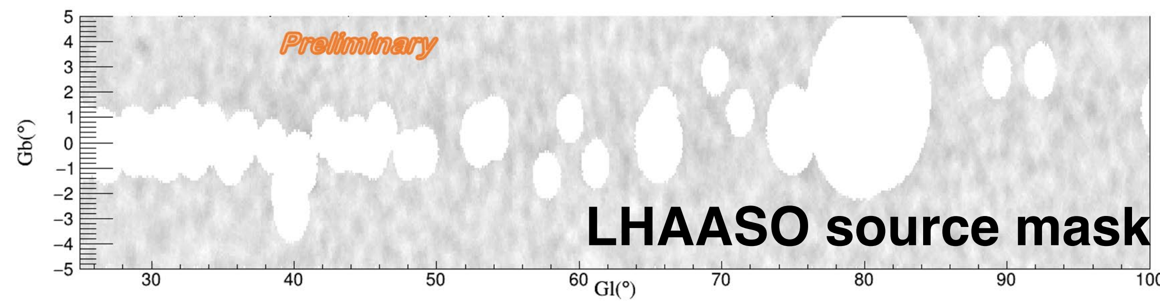
- Based on realistic models for interstellar emission and sub-threshold source populations in the Milky Way, we quantify the expected astrophysical contribution to the sub-PeV measurements of the Galactic diffuse emission seen by HAWC and Tibet ASγ.

- **From the HAWC and Tibet ASγ 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.

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 ASγ 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!