

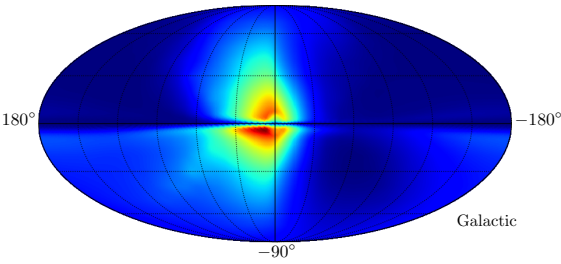


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Diffuse axion-like particle searches

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Thanks to my collaborators: Hendrik Vogel and Manuel Meyer
[arXiv: 1712.01839](https://arxiv.org/abs/1712.01839)



Cluster of Excellence
PRISMA

Precision Physics, Fundamental Interactions
and Structure of Matter



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

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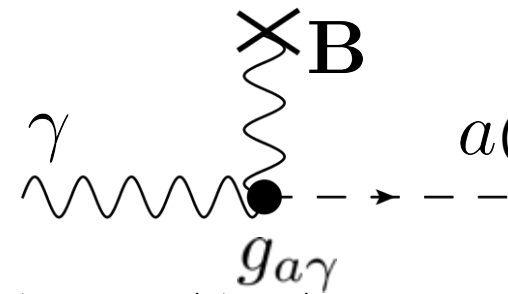
- Motivation
- IceCube observations
- Methodology
- Results

Motivation

Axion-like particles (ALPs)

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

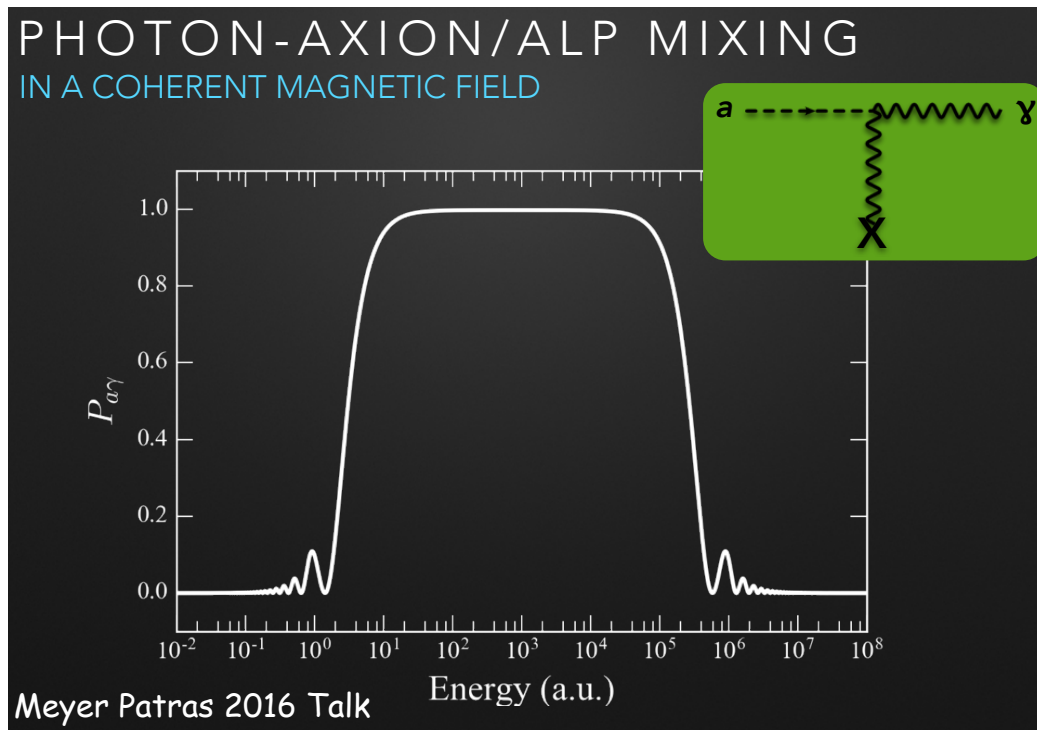
Mediates photon - ALP oscillations



$$P_{a\gamma} \propto (g_{a\gamma} B_T \ell)^2$$

Oscillation probability

Laboratory searches: large B_T , small ℓ



Astrophysical searches:

small B_T , large ℓ

Milky Way: $B \approx 1 - 3 \mu\text{G}$

$\ell \lesssim \text{few kpc}$

Galaxy clusters: $B \approx 1 \mu\text{G}$

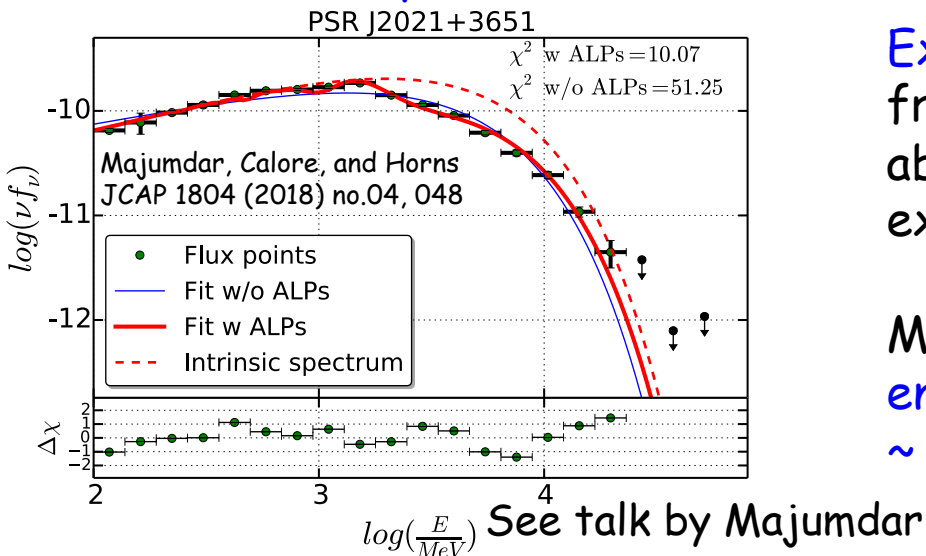
$\ell \approx 10 \text{ kpc}$

Intergalactic magnetic field:

$B < 1 \text{ nG}$ $\ell \approx \text{few Mpc}$

Existing searches with gamma-rays

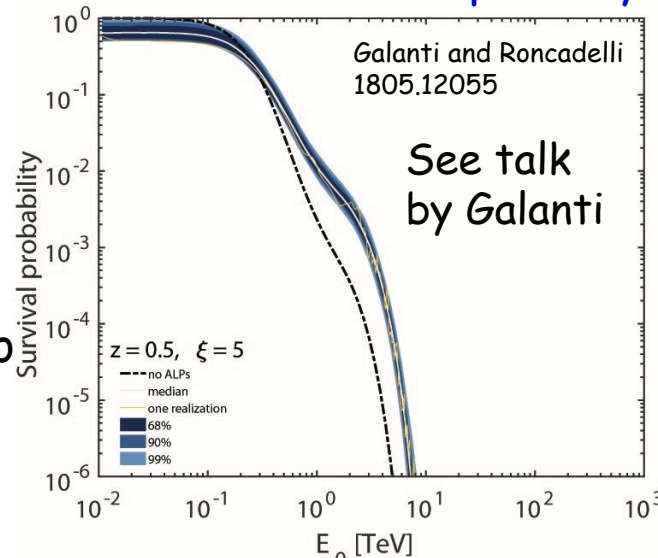
(a) Search for spectral features:



(b) Search for anomalous transparency:

Excess photons from a source above standard expectations

Most sensitive to energies above ~ 500 GeV



See also Meyer and Conrad, H.E.S.S., and many others

Oscillations in the photon spectrum of astrophysical objects

No conclusive evidence of spectral distortion due to ALPs has been found

See also Wouters and Brun, Liang et al., Xia et al., Malyshev et al., Fermi-LAT, H.E.S.S., and many others

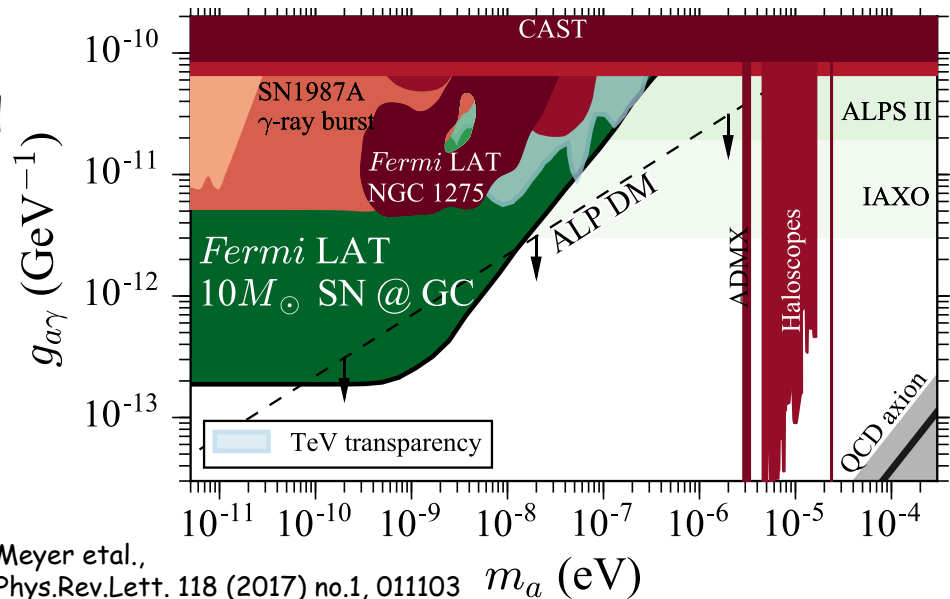
(c) Search from a supernova:

Strong limits from SN 1987A

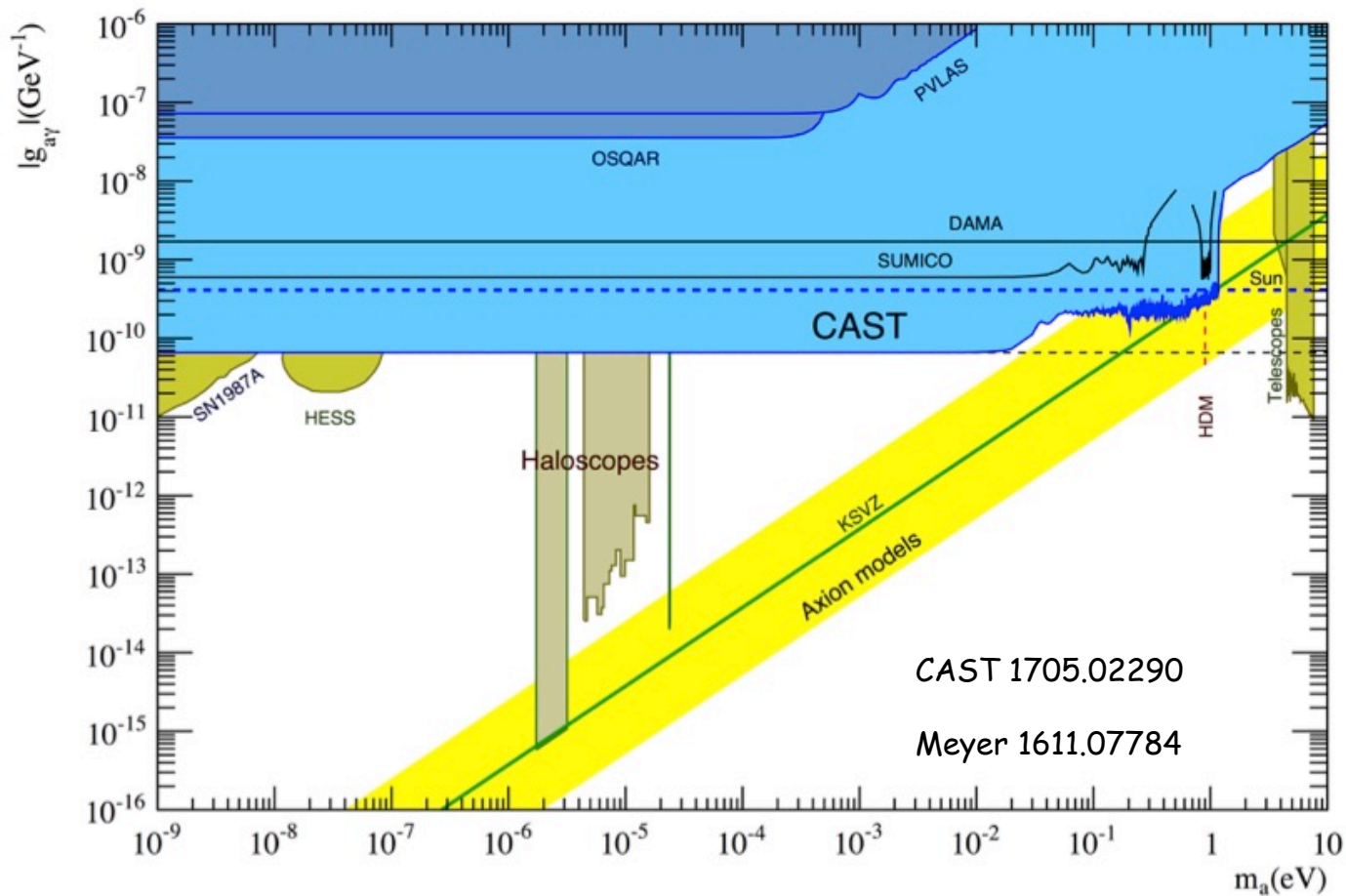
Next Galactic supernova holds great promise

See talk by Mirizzi

See also Payez et al., Brockway et al., Grifols et al., and many others



Parameter space for ALPs



Many different ways to search for ALPs in **astrophysical systems**

Can we make progress in the **unconstrained regions**?

Can we devise a **new search strategy**? Can we search for ALPs in the **energy range where photons are maximally absorbed**?

Motivation from IceCube:
a new source of high-energy photons

IceCube neutrino telescope designed to detect astrophysical neutrinos

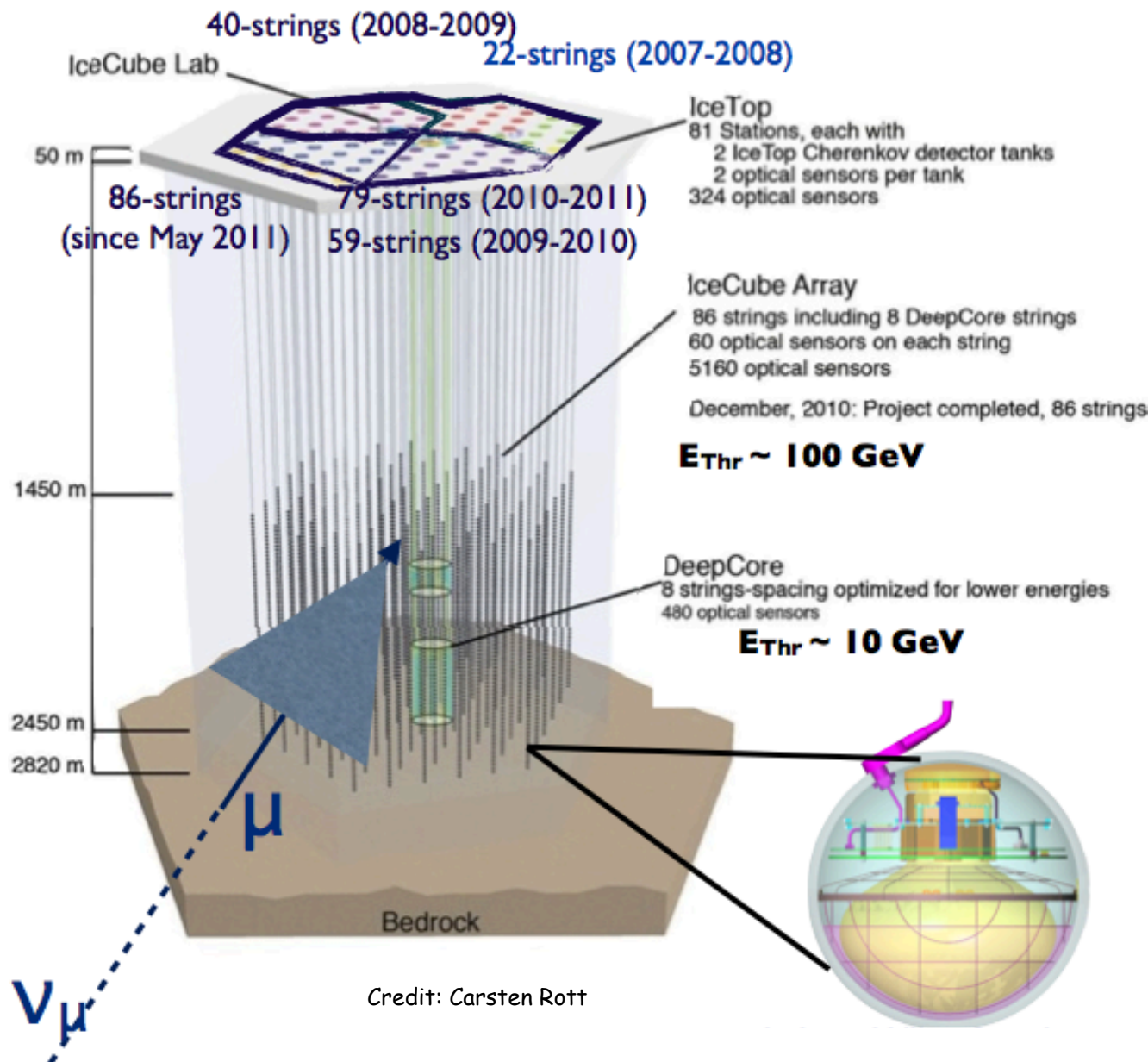
Gigaton effective volume
neutrino detector at
South Pole

5160 Digital Optical
Modules distributed over
86 strings

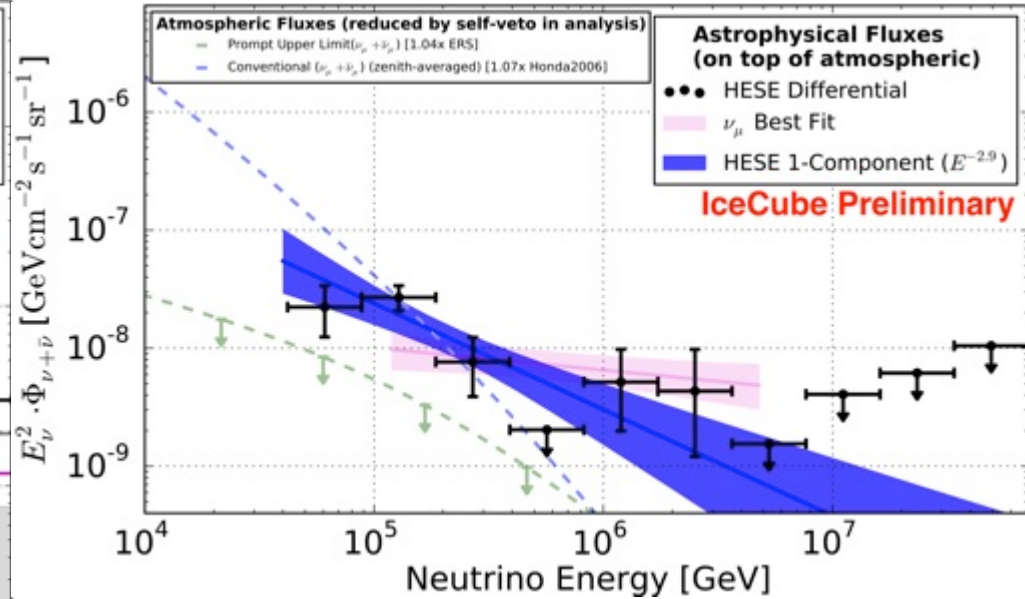
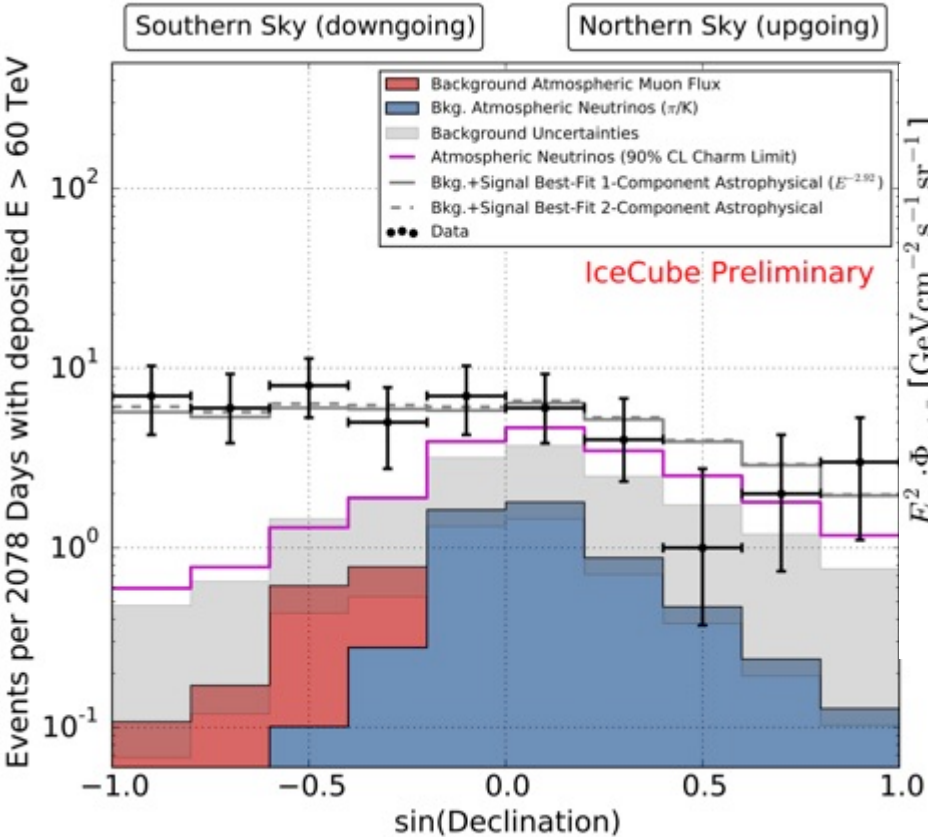
Completed in Dec 2010;
data in full configuration
from May 2011

Data acquired during
construction phase is
analyzed

Neutrino detected
through Cherenkov light
emission from charged
particles produced due to
neutrino CC/NC
interactions



IceCube data



Courtesy: IceCube

Latest update in the
Neutrino 2018 conference

Strong evidence of these
neutrinos being **extra-galactic**

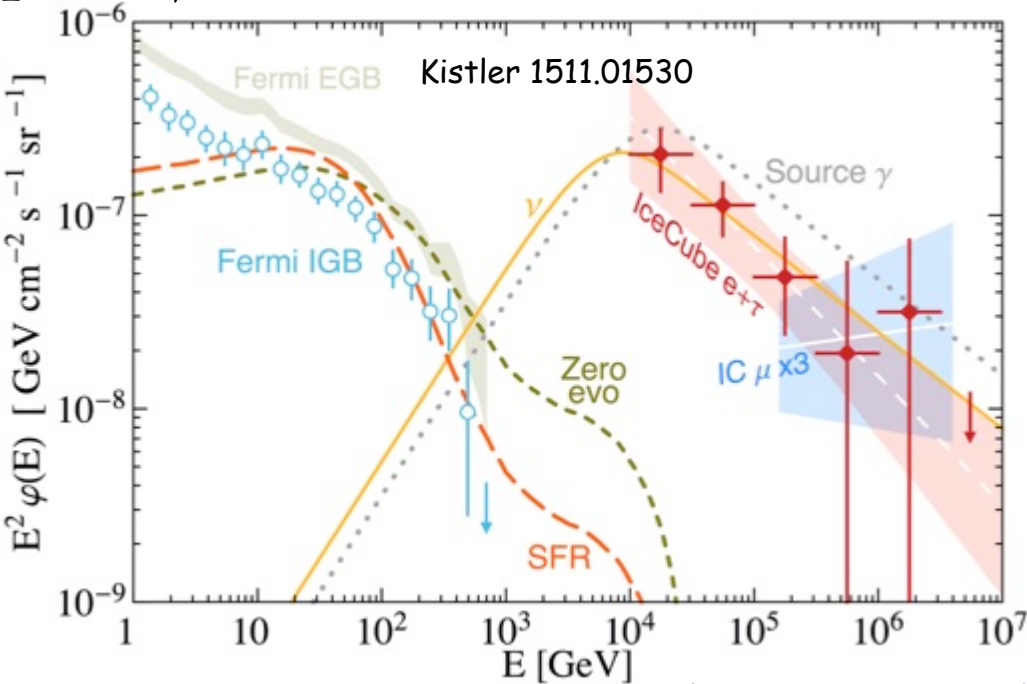
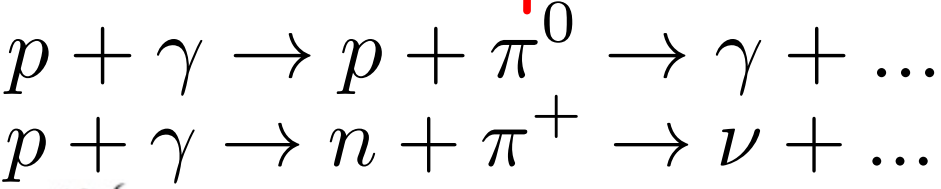
Diffuse and isotropic spectrum of neutrinos

Time-independent

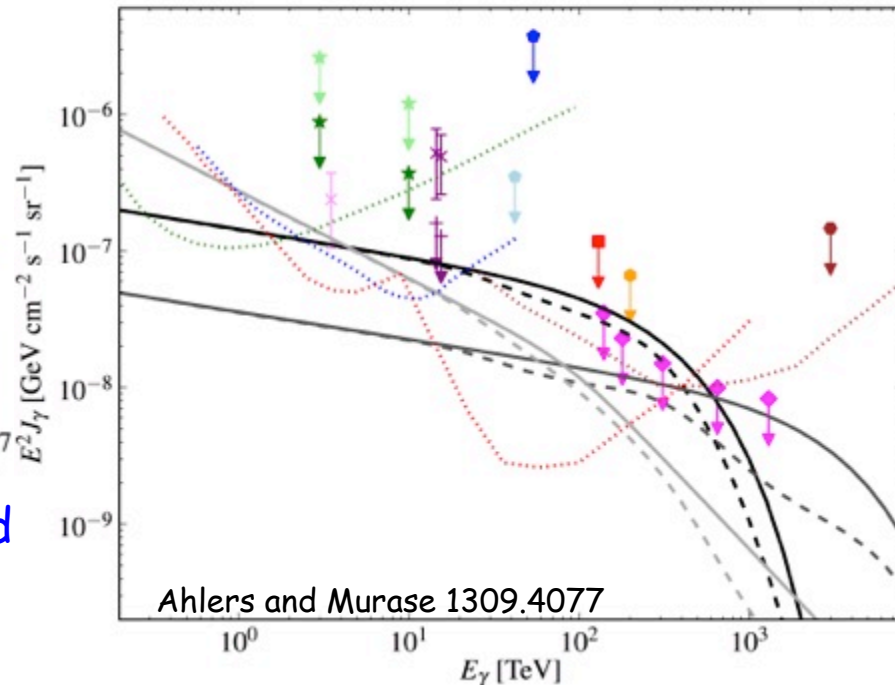
Clear evidence of the **astrophysical** nature of these neutrinos

None of them **point** to a specific source

Photons corresponding to IceCube excess neutrinos produced in astrophysical sources



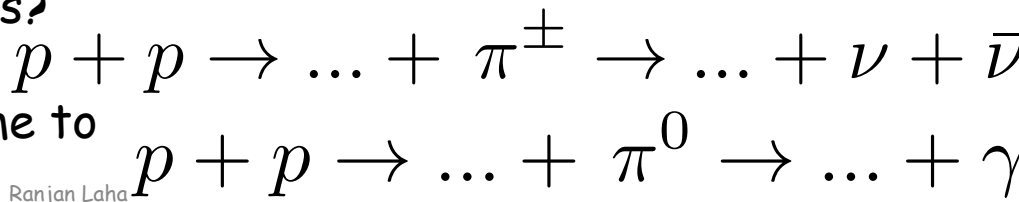
- supernova remnants ($|b| < 2^\circ$)
- hypernova remnants ($|b| < 2^\circ$)
- diffuse cosmic rays ($|b| < 2^\circ$)
- ⋯ HISCORE (5yrs, $|b| < 2^\circ$)
- ⋯ LHAASO (1yr, $|b| < 2^\circ$)
- ⋯ HAWC (3yrs, $|b| < 2^\circ$)
- ⋯ CTA (100h, $|b| < 2^\circ$)
- ⊙ HEGRA ($|b| < 5^\circ, 0^\circ < l < 255^\circ$)
- ⊙ HEGRA ($|b| < 5^\circ, 20^\circ < l < 60^\circ$)
- ⊙ UMC ($|b| < 10^\circ, 30^\circ < l < 220^\circ$)
- ⊙ IC-40 (γ) ($-10^\circ < b < 5^\circ, 280^\circ < l < 330^\circ$)
- ⊙ EAS-TOP ($|b| < 5^\circ, l \in [40^\circ, 111^\circ] \cup [134^\circ, 205^\circ]$)
- ⊙ Tibet ($|b| < 2^\circ, 20^\circ < l < 55^\circ$)
- ⊙ Tibet ($|b| < 2^\circ, 140^\circ < l < 225^\circ$)
- ⊙ CASA-MIA ($|b| < 5^\circ, 50^\circ < l < 200^\circ$)
- ⊙ Milagro ($|b| < 5^\circ, 40^\circ < l < 100^\circ$)
- ⊙ Milagro ($|b| < 2^\circ, l \in [30^\circ, 65^\circ] \cup [65^\circ, 85^\circ]$)
- ⊙ Milagro ($|b| < 2^\circ, l \in [85^\circ, 110^\circ] \cup [136^\circ, 216^\circ]$)



IceCube excess neutrinos imply a **guaranteed high energy gamma-ray background**

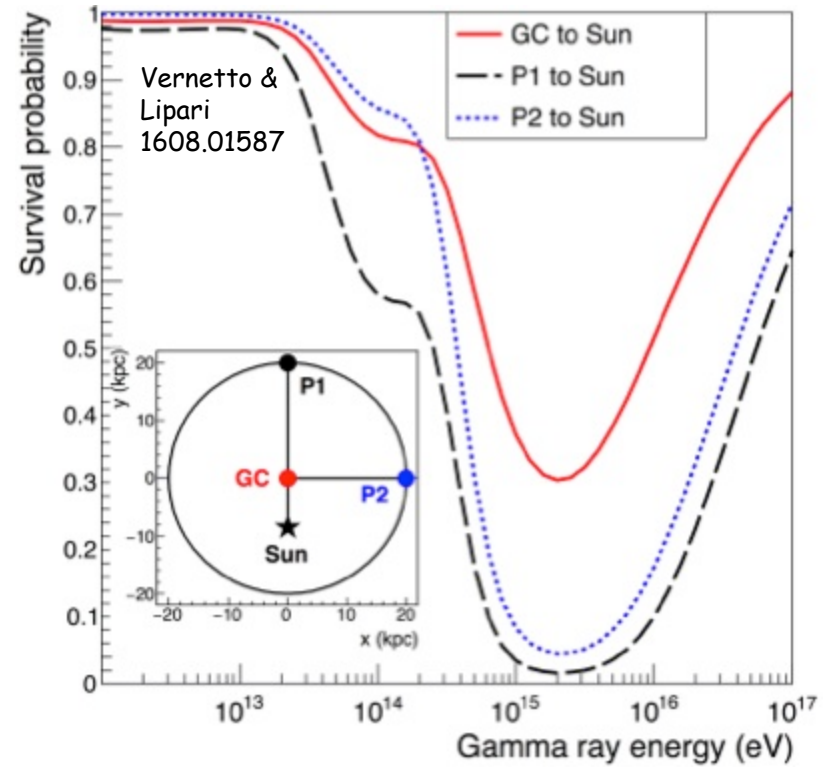
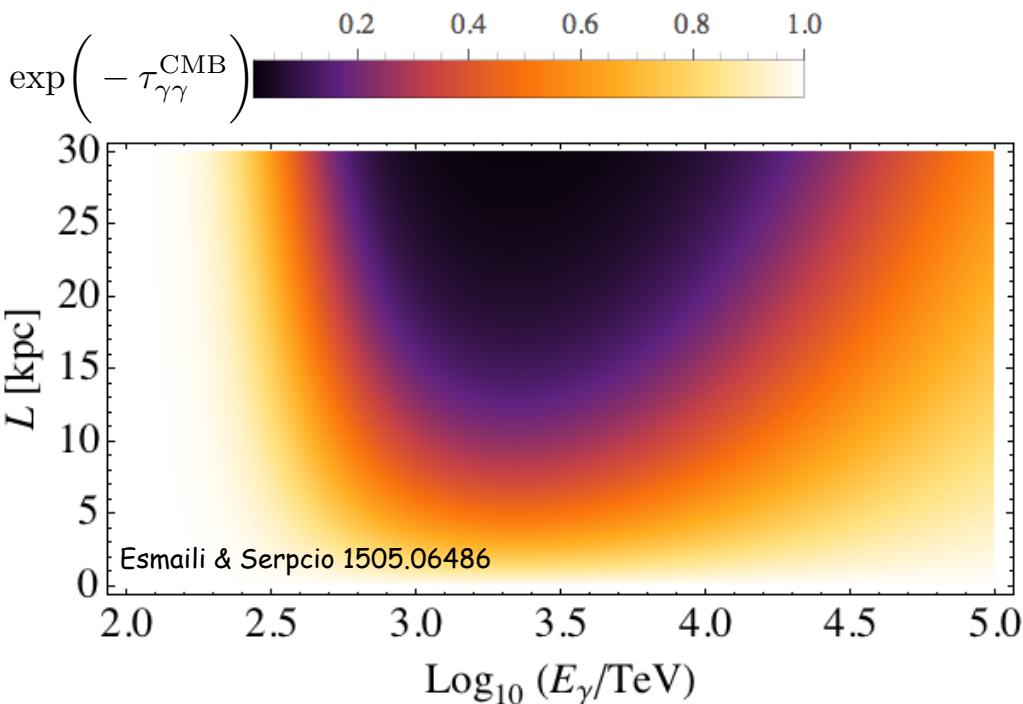
Can one use these photons to do physics?

We use these photons for the first time to **search for new physics**



Very high-energy gamma-rays

- Search for very high energy (VHE) gamma-rays (> 100 TeV) are useful in this context: **CASA-MIA, KASCADE**
- **Attenuation** of VHE gamma-rays important $\gamma_{\text{VHE}} \gamma_{\text{CMB/EBL}} \rightarrow e^+ e^-$
- Inverse Compton of the background photons by the electron - positron pair produce gamma-rays with energy in the **Fermi-LAT** band



ALPs help us observe these very high-energy gamma-rays

High energy astrophysical source



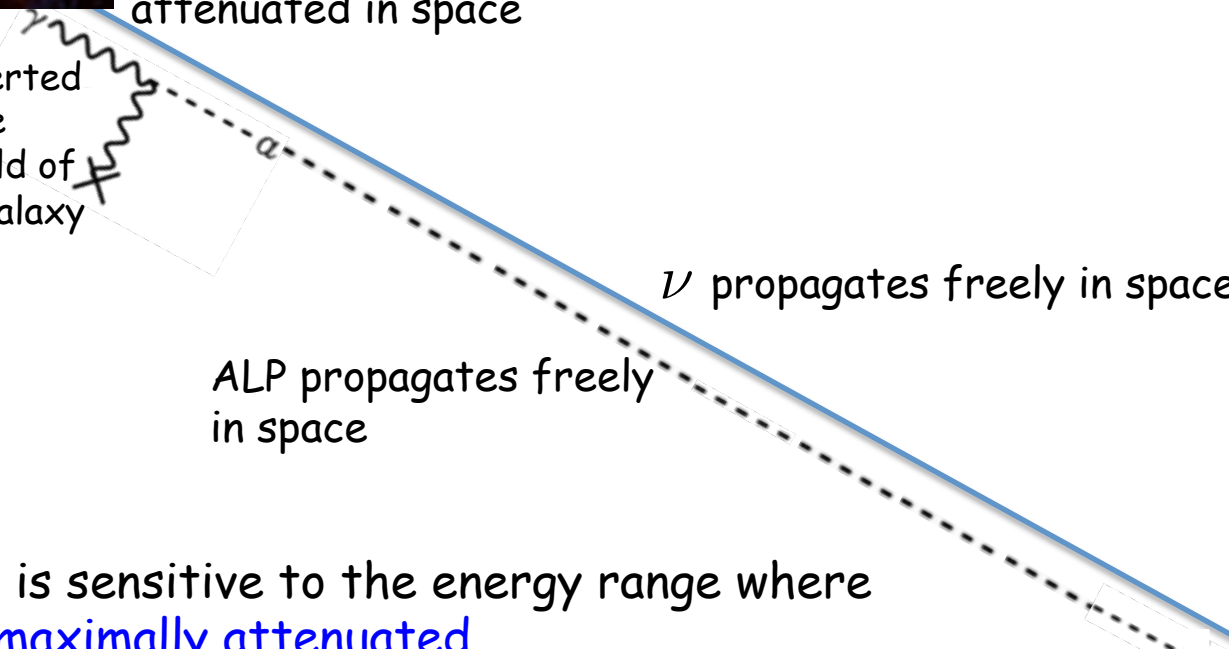
VHE photons get attenuated in space

ON - OFF search technique:

✓ in the presence of ALPs, we will observe these photons

✗ otherwise we will not observe these photons

Photon converted to ALP in the magnetic field of the source galaxy



ν propagates freely in space

ALP propagates freely in space

Milky Way Galaxy



ALP converted back to photon in the magnetic field of the Milky Way

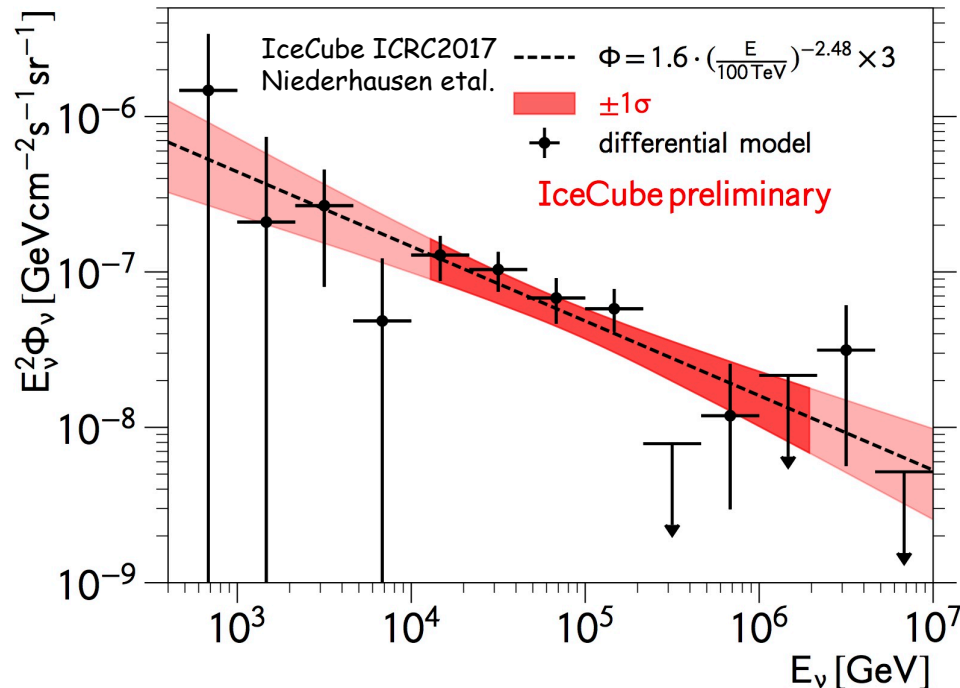
Our proposal is sensitive to the energy range where photons are maximally attenuated

Our technique is sensitive to a new ALP parameter space

Present and near-future gamma-ray instruments like HAWC, CTA, LHAASO can detect these photons and put a new bound on the ALP parameter space

Methodology

Astrophysical neutrino spectrum

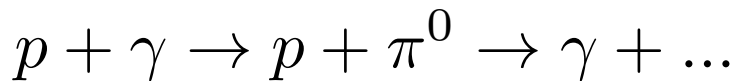
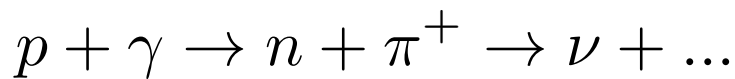


We use two different fits to the astrophysical neutrino spectrum

$$\phi(E_\nu) \propto \left[\left(\frac{E_\nu}{E_b} \right)^2 + \left(\frac{E_\nu}{E_b} \right)^{2\alpha} \right]^{-\frac{1}{2}}$$

↑ Neutrino energy

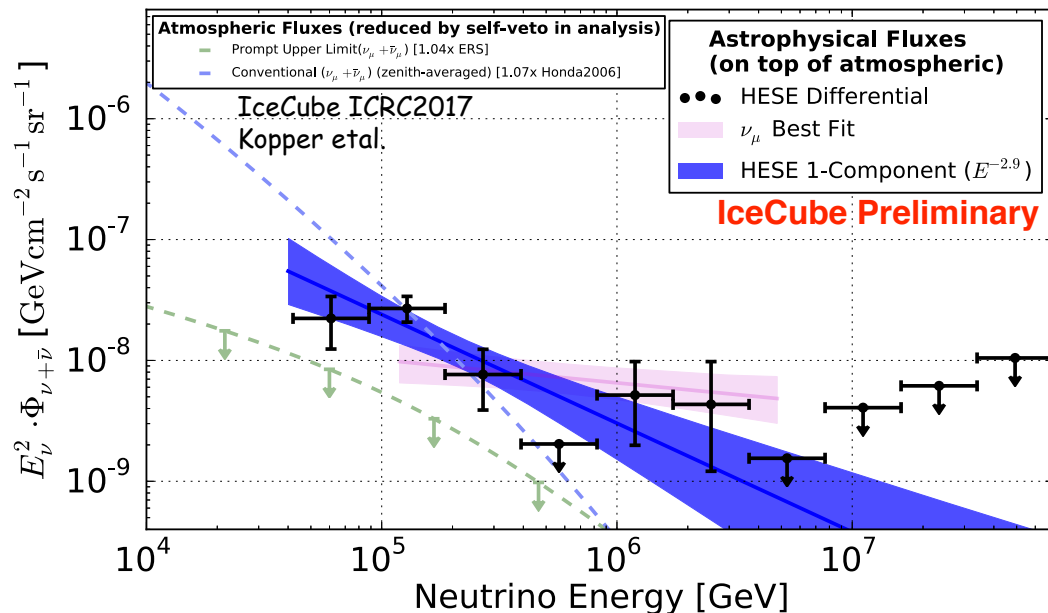
	E_b (TeV)	α
Niederhausen et al.	12	2.48
Kopper et al.	40	2.92



$$E_\gamma \approx 2 E_\nu \quad \text{IceCube ICRC2017, Niederhausen et al.}$$

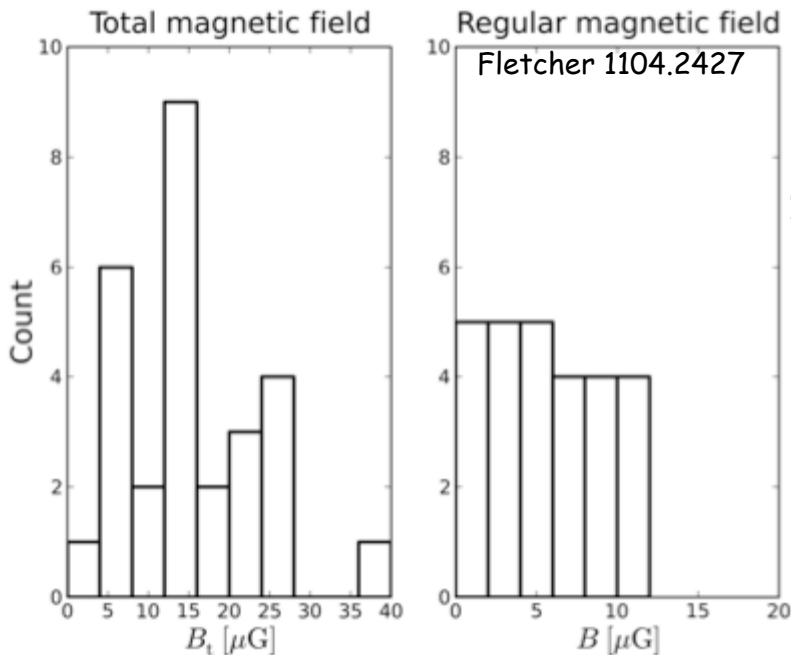
2 photons for 3 neutrinos

Many models which reproduce the spectrum of these neutrinos



Astrophysical parameters

- There are **various models** ($\sim 100+$) in the literature which postulate the astrophysical sources producing the IceCube observations
- **Astrophysical parameters** (like magnetic field, photon density, plasma density) **vary** between them
- We try to follow a **model-independent** and **conservative** approach where we only take the magnetic field of the galaxy in which the neutrino source is embedded

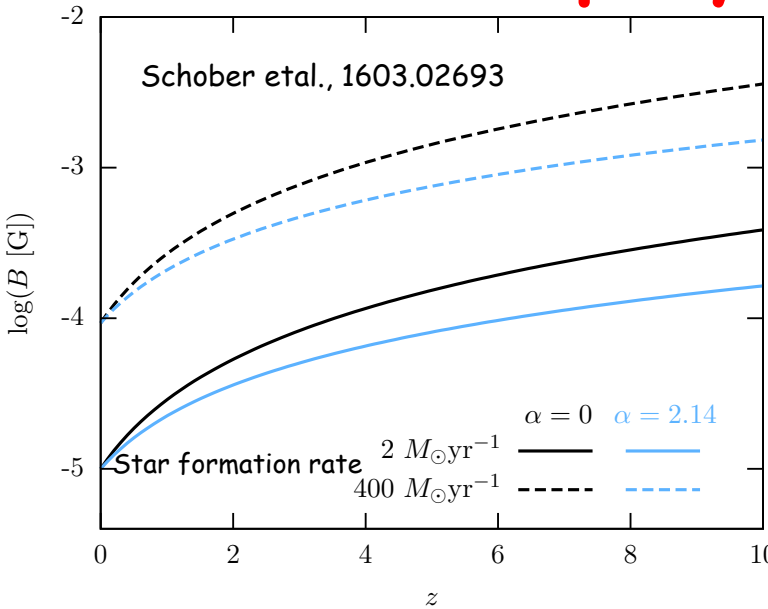


Typical values for the total and regular equipartition magnetic field strengths for 21 galaxies

We use the variations $B_{\perp} = 3, 5, \text{ and } 10 \mu\text{G}$ at zero redshift

Coherence length at zero redshift = 1 kpc

Astrophysical parameters



$$B(z, \dot{\rho}_*) = B_0 n(z)^{1/6} (\dot{\rho}_* H(z))^{1/3}$$

local magnetic field

star formation rate

$$n(z, \dot{\rho}_*) = n_0 (1+z)^{3-\alpha} \left(\frac{\dot{\rho}_*}{\dot{\rho}_{*,0}} \right)^{1/1.4}$$

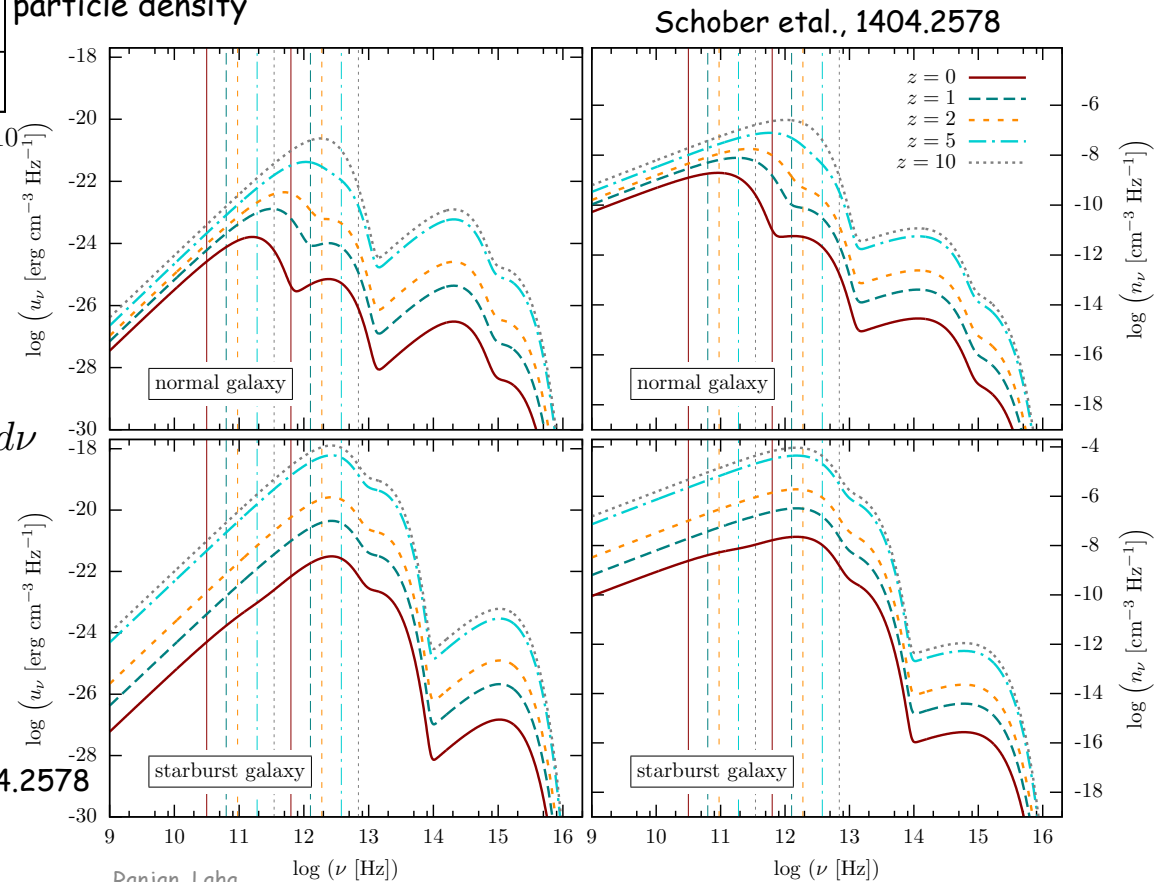
particle density

Model for interstellar photon density in progenitor galaxies

$$u_{\text{ISRF}, \nu} d\nu = \sum_i f_i \frac{8\pi h}{c^3} \frac{\nu^3}{\exp(h\nu/kT_i) - 1} d\nu$$

spectral energy density

Schober et al., 1404.2578



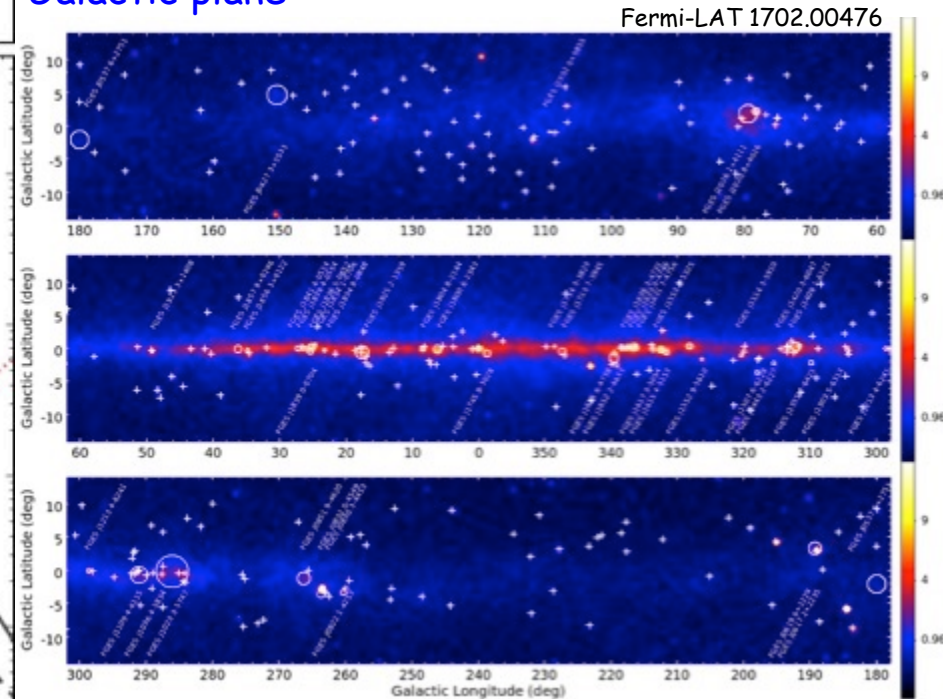
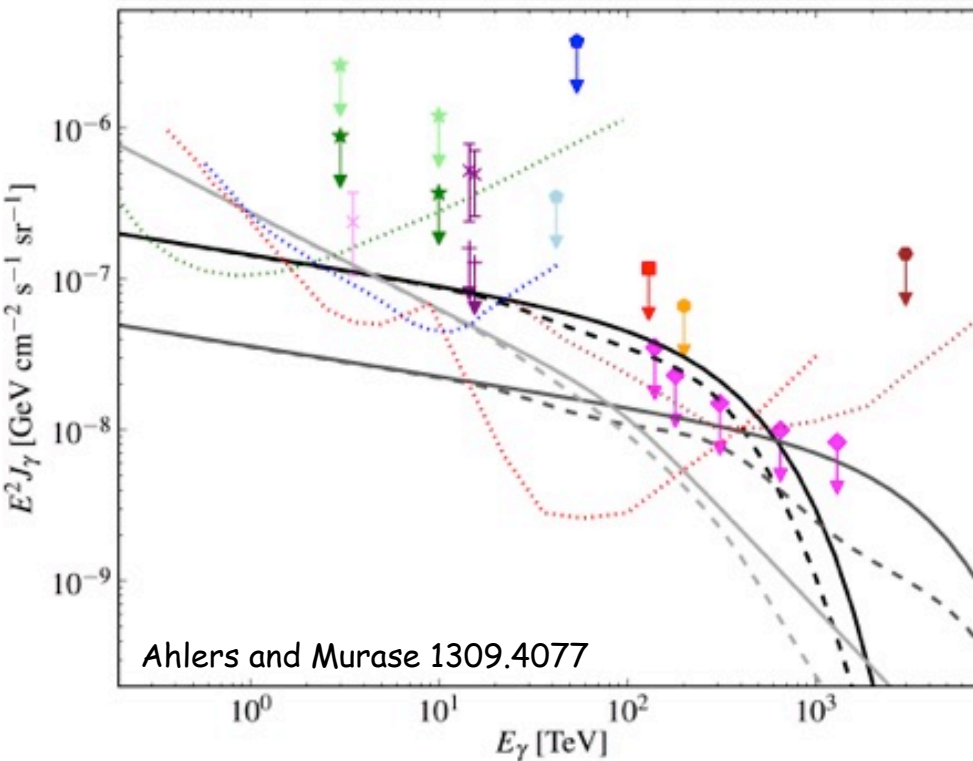
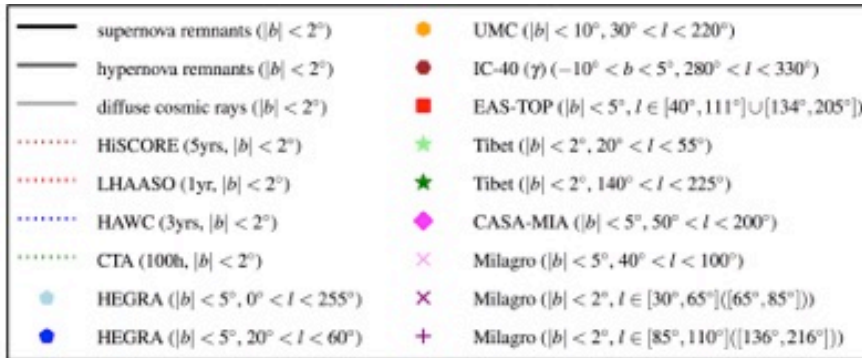
High-energy gamma-ray production in the Milky Way

- The photons that we are concerned with have an **energy $\gtrsim 20$ TeV**
- An important source of photons at these energies is **cosmic-ray interaction with the interstellar medium** $p + p \rightarrow \dots + \pi^0 \rightarrow \dots + \gamma$

Photons at these energies have not been detected

ALPs can induce **spectral distortions** in this gamma-ray spectrum

These photons are strongly correlated with the **Galactic plane**



Gamma-ray detectors (HAWC)

Gamma-rays and cosmic-rays between 100 GeV and 100 TeV


Angular resolution varies from $\sim 0.2^\circ$ to 2°

Above 10 TeV the energy resolution is below 50%

Reject > 99% of cosmic-ray showers at energies above roughly 3 TeV

hawc-observatory.org


DuVernois "HAWC and HAWC-South: TeV all-sky gamma-ray experiments for the Northern and Southern hemispheres"



Mapping the Northern Sky in High-Energy Gamma Rays

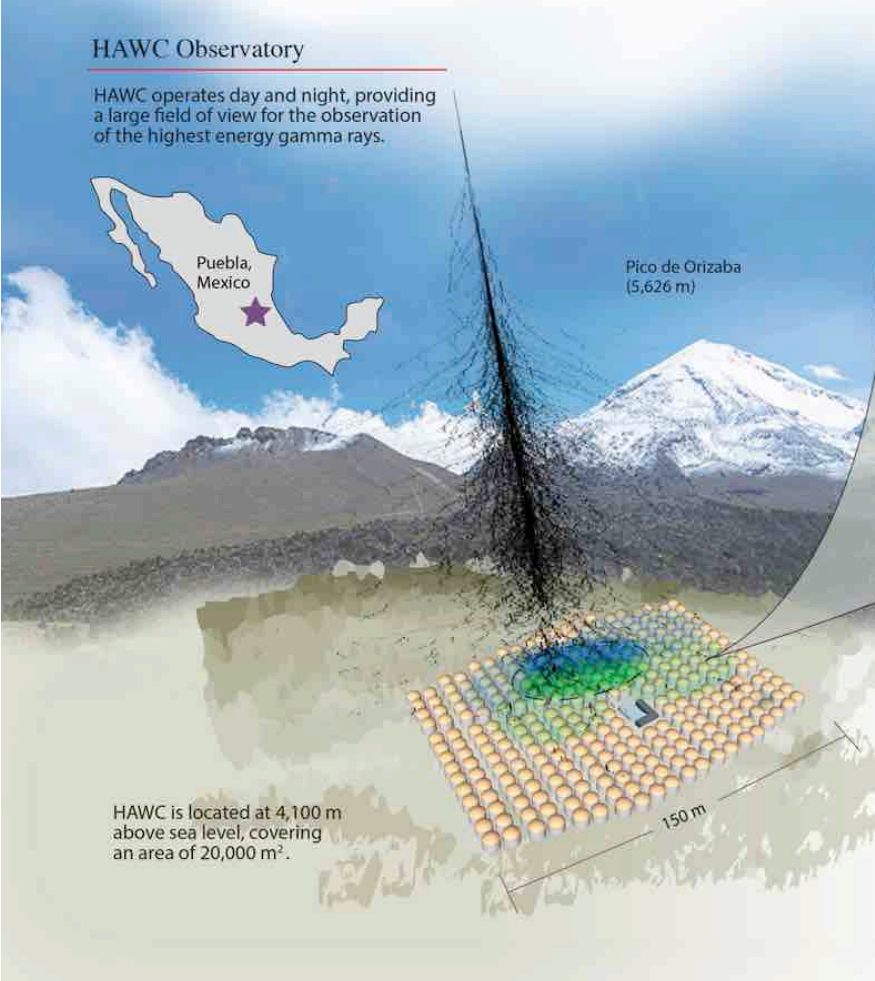
HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



Puebla, Mexico

Pico de Orizaba (5,626 m)

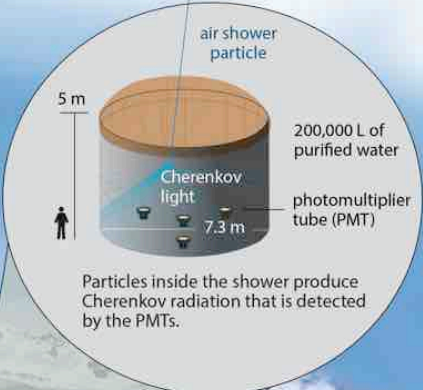


HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

150 m

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



air shower particle

5 m

200,000 L of purified water

Cherenkov light


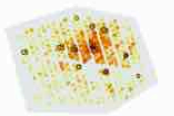
7.3 m

photomultiplier tube (PMT)

Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower	cosmic-ray shower
	
"hot" spots concentrate around the core	"hot" spots are more dispersed

Gamma-ray detectors (LHAASO)

The Large High Altitude Air Shower Observatory (LHAASO) project

All-sky instrument

Detect cosmic Rays and Gamma-Rays in the wide energy range $\sim 10^{11}$ eV - 10^{17} eV

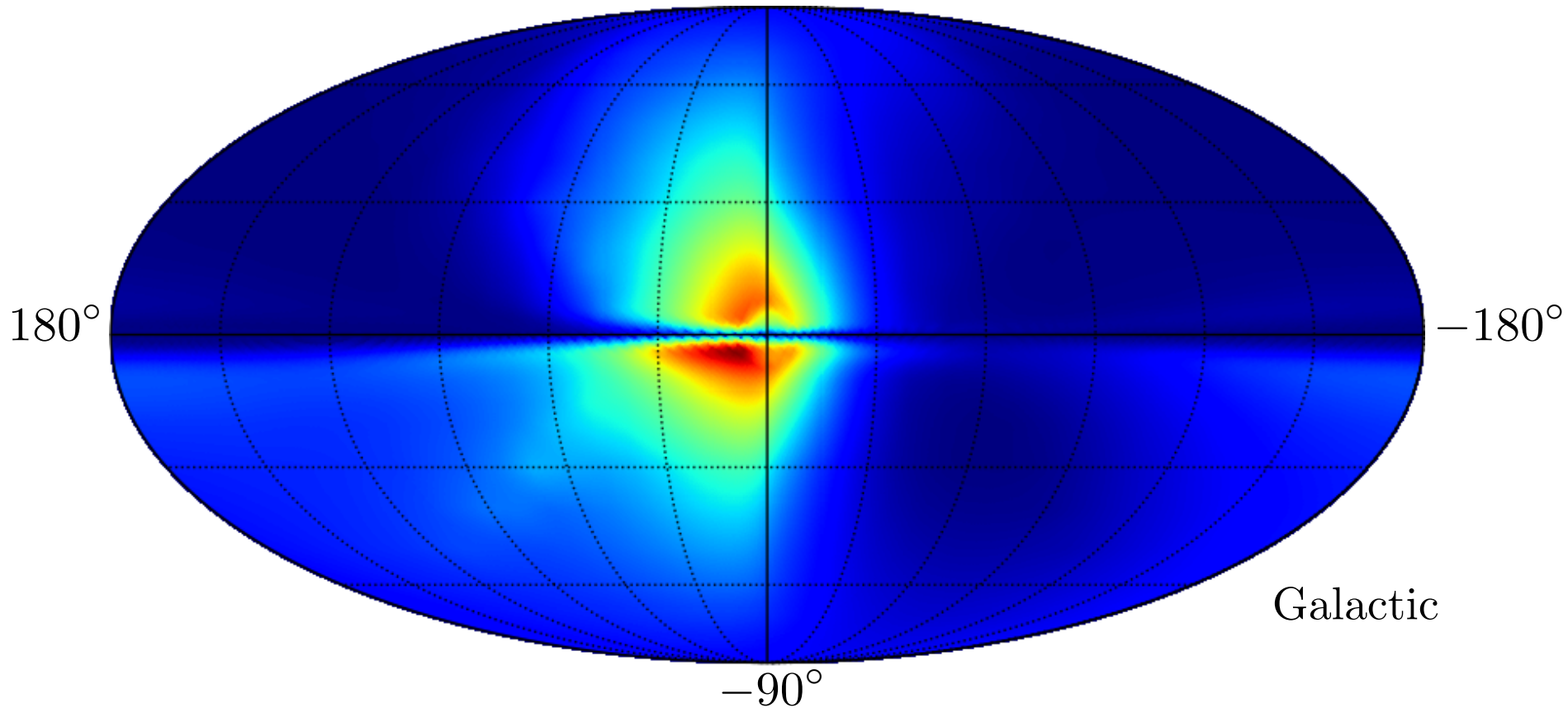
Uses different detection techniques:

- (1) **LHAASO-KM2A**: 1 km² array of 5635 scintillator detectors for electromagnetic particle detection
- (2) **LHAASO-MD**: 1 km² array of underground water Cherenkov tanks for muon detection
- (3) **LHAASO-WCDA**: Surface water Cherenkov detector facility ~ 90000 m²
- (4) **LHAASO-WFCTA**: 24 wide field-of-view air Cherenkov and fluorescence telescopes

Sciascio "The LHAASO project: a new generation cosmic-ray experiment"

Signal morphology

Vogel, Laha, and Meyer
1712.01839

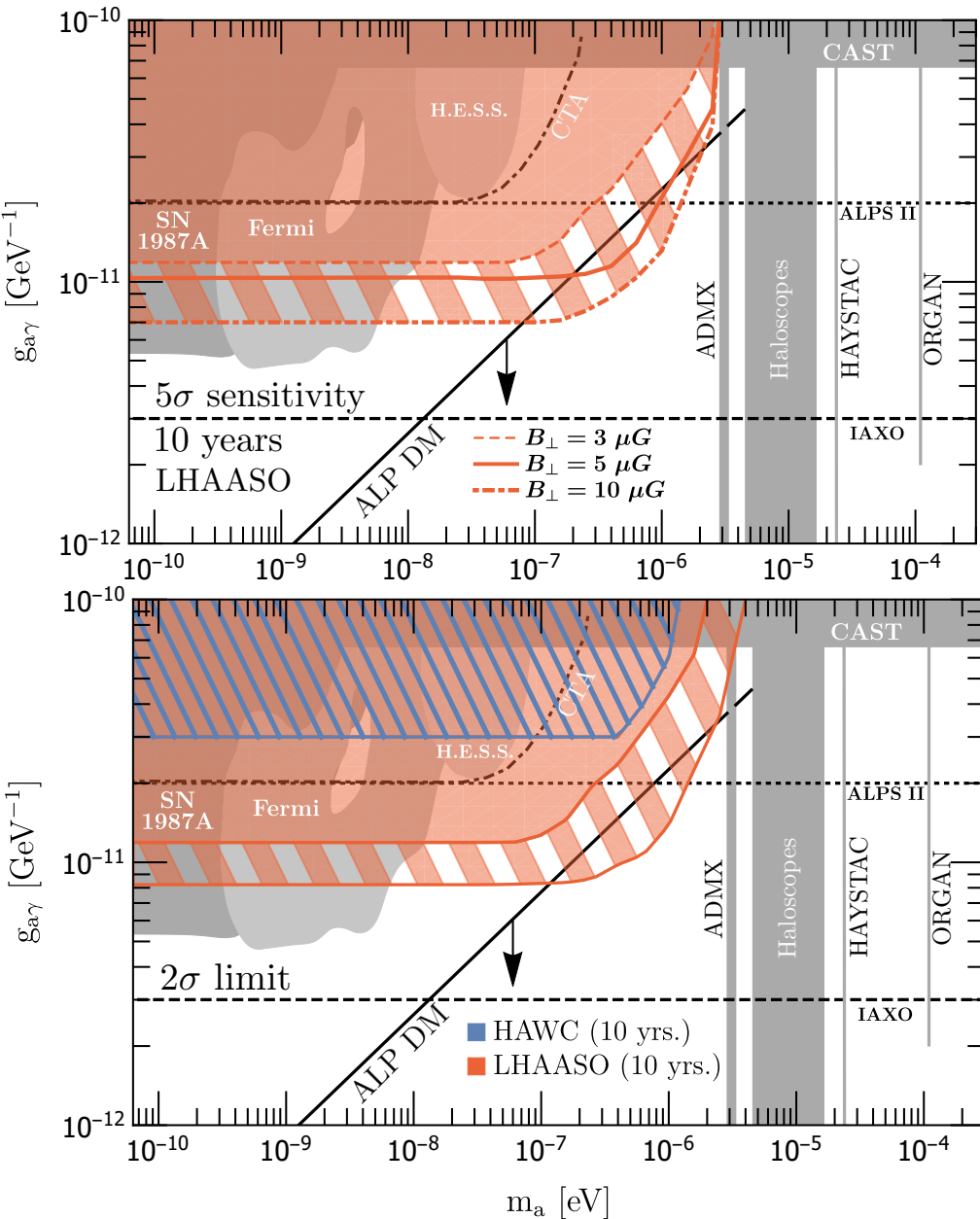


The incident ALP flux is isotropic and homogenous

Due to the Galactic magnetic field, the signal on Earth is highly anisotropic: "ALP bubble" for Jansson & Farrar magnetic field

Useful for signal v/s background discrimination

Results



LHAASO and HAWC will probe **new parameter space**

These are the **farthest source of high-energy photons** that we know

Very difficult to mimic these photons by astrophysical spectrum modifications

Astrophysical uncertainties will decrease in the near future

New physics result with these guaranteed photon sources

Promising probe

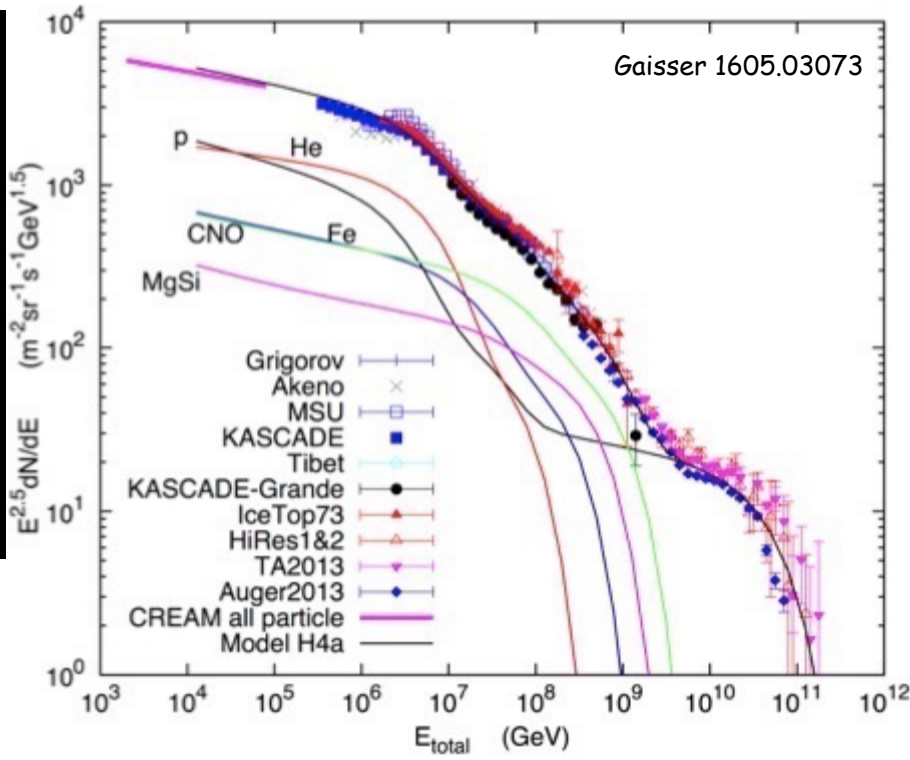
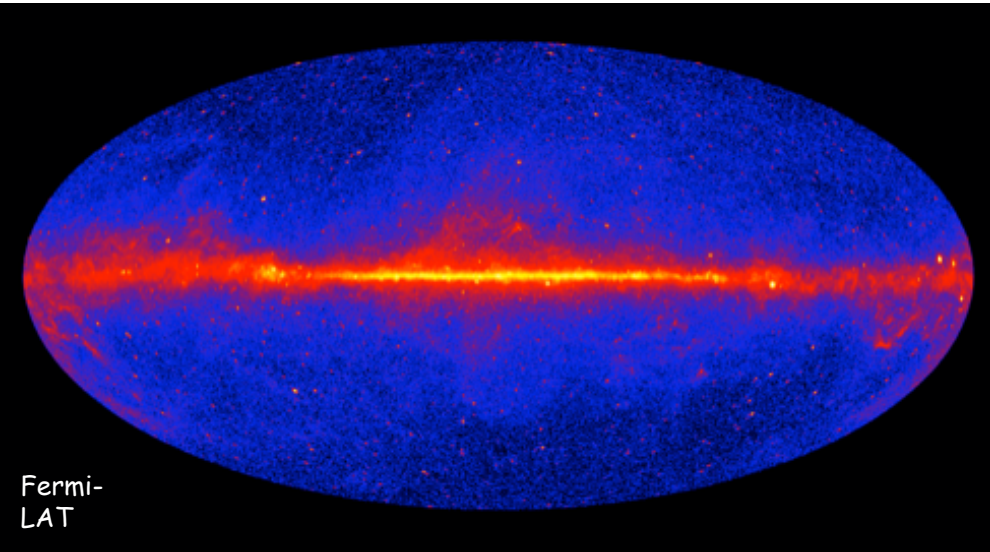
Vogel, Laha, and Meyer
1712.01839

Conclusions

- Searching for **axion-like particles** is one of the major frontiers of physics
- Many of the **well motivated parameter space** can be probed by **astrophysical systems**
- We show that searching for the **very high-energy photon flux** corresponding to the IceCube neutrinos will probe **new ALP parameter space**
- This is a **new search technique** in ALP physics

Questions and comments:
ranjalah@uni-mainz.de

Puzzling questions about the high energy astrophysical universe



Gamma-ray sky: what process produces them?

Leptonic: $e^- + \gamma \rightarrow e^- + \gamma$

Hadronic: $p + p \rightarrow \pi^0 \rightarrow \gamma + \gamma$

$p + p \rightarrow \pi/K + \dots \rightarrow \nu/\bar{\nu}$

Cosmic rays observed over a huge energy range

Neutrinos are inevitably produced in cosmic ray interactions

The key difference are the neutrinos