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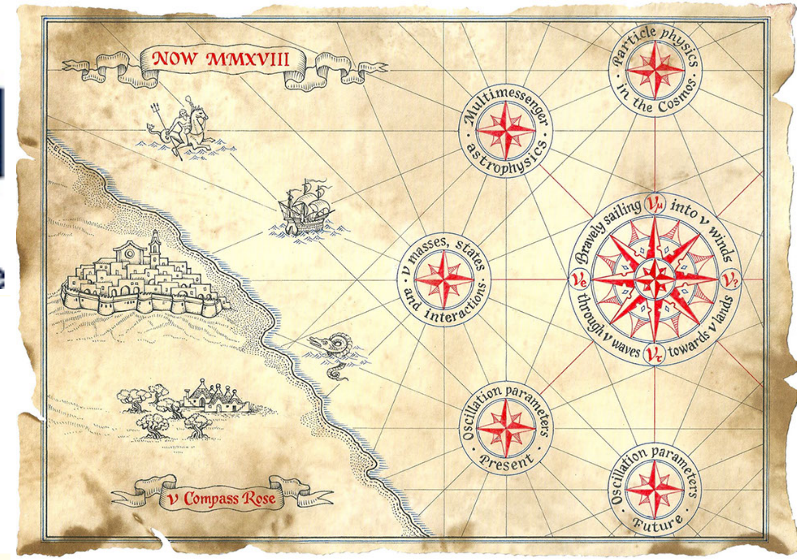
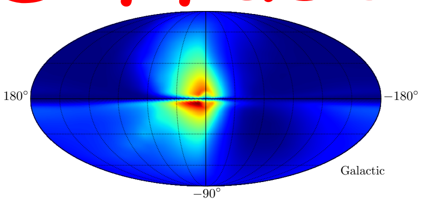


Diffuse axion-like particle searches



Ranjan Laha

PRISMA Cluster of Excellence and Mainz Institute for Theoretical Physics

Johannes Gutenberg-Universität Mainz

Thanks to my collaborators: Hendrik Vogel and Manuel Meyer

arXiv: 1712.01839

JG|U

Cluster of Excellence
PRISMA
Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Contents

- Motivation
- IceCube observations
- Methodology
- Results

Motivation

Possible dark matter masses

~ 10^{-22} eV — What is the dark matter particle mass? — ~ 100 $M_\odot$

Important to search the full mass range --- a comprehensive search is required to understand new physics

We know the dark matter density

See talks by Pradler, Kopp, Redondo

Dark matter "particle" density varies by a large amount in the entire mass range

Search techniques depend on the mass range considered

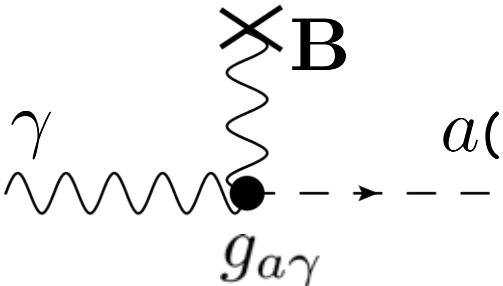
I will consider a light mass particle: axion-like particle, a

I will consider some astrophysical techniques to constrain these particles

Other papers: Bar etal. 1805.00122 for connection to rotation curves; Brdar etal. 1705.09455 for connection to neutrinos

Axion-like particles (ALPs)

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



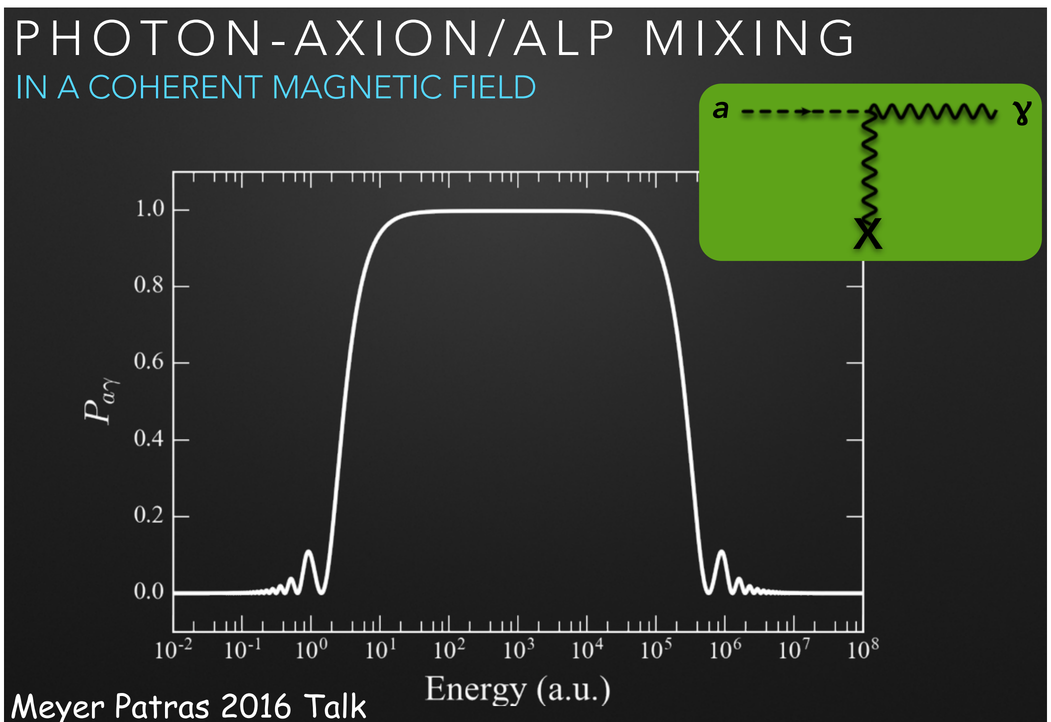
Courtesy: Hendrik Vogel

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: $B \approx 1 - 3\,\mu{\rm G}$

$\ell \lesssim$ few kpc

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

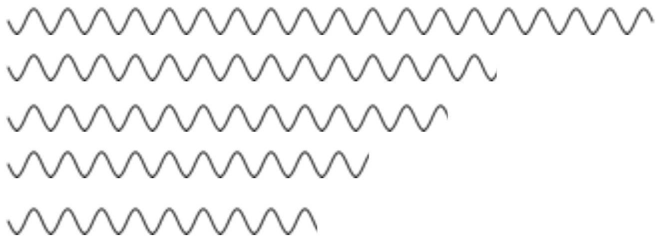
$\ell \approx 10\,{\rm kpc}$

Intergalactic magnetic field:

$B < 1\,{\rm nG} \quad \ell \approx$ few Mpc

Gamma-ray opacity

Gamma-ray astrophysical source
Credit: ESA/Hubble



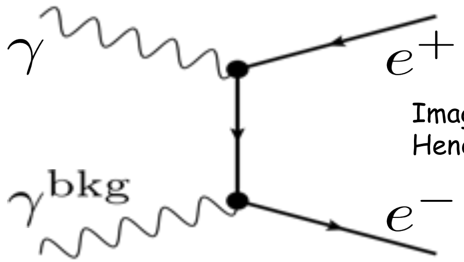
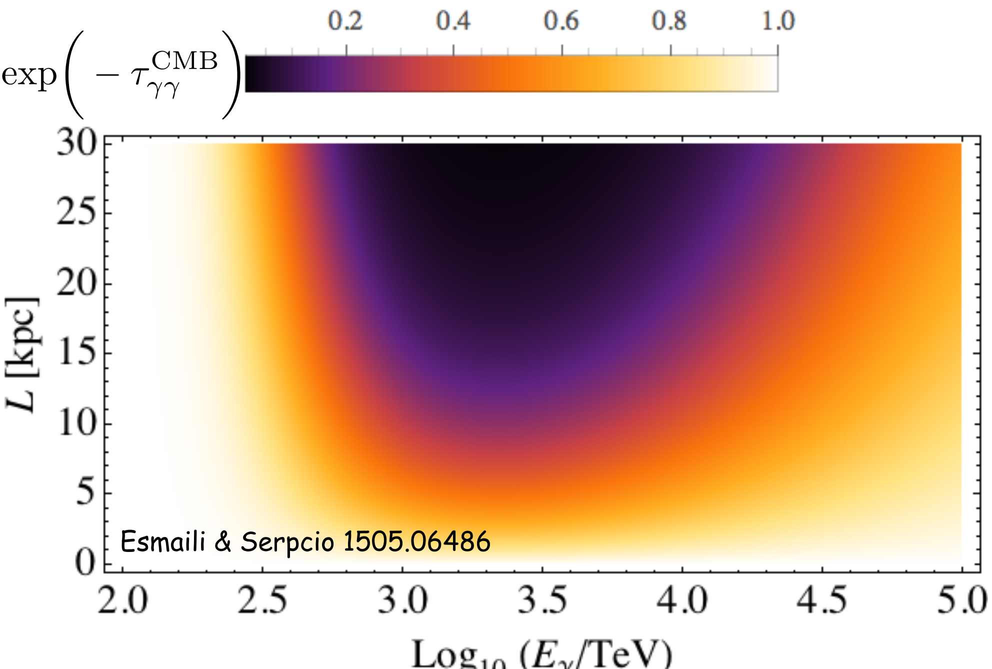
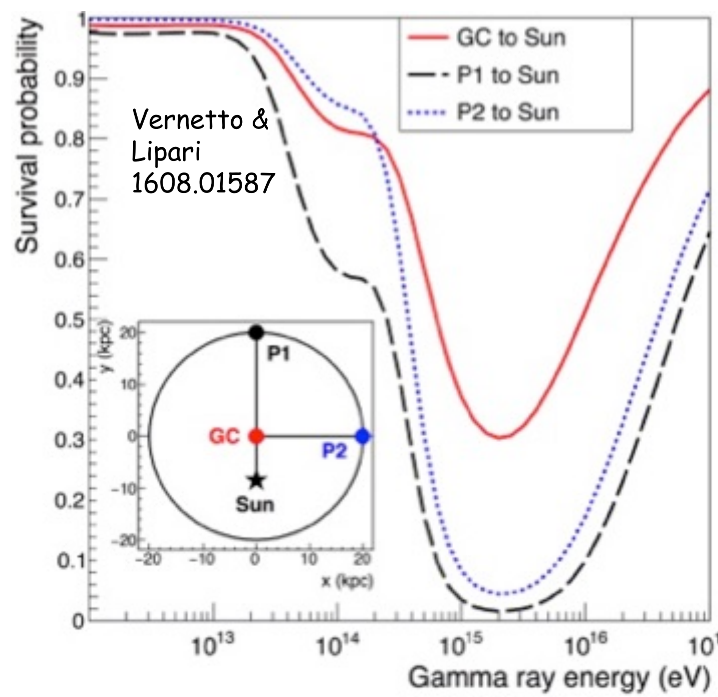


Image credit: Hendrik Vogel

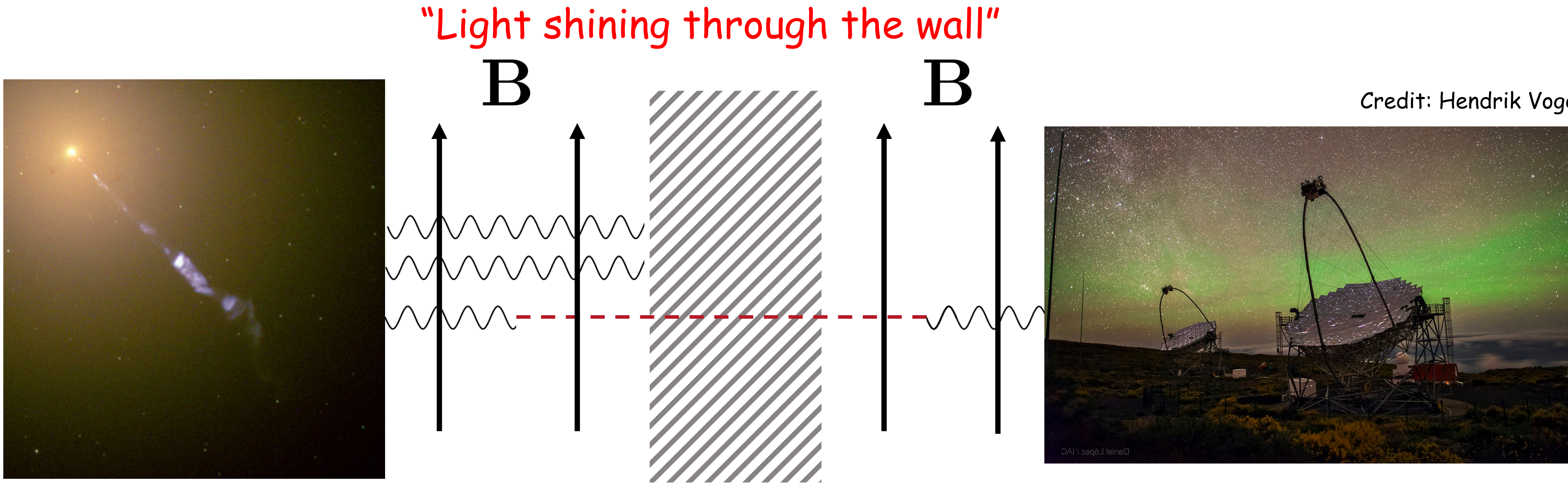
Image credit: Daniel Lopez/IAC

Image credit: Wikipedia





Light shining through the Universe

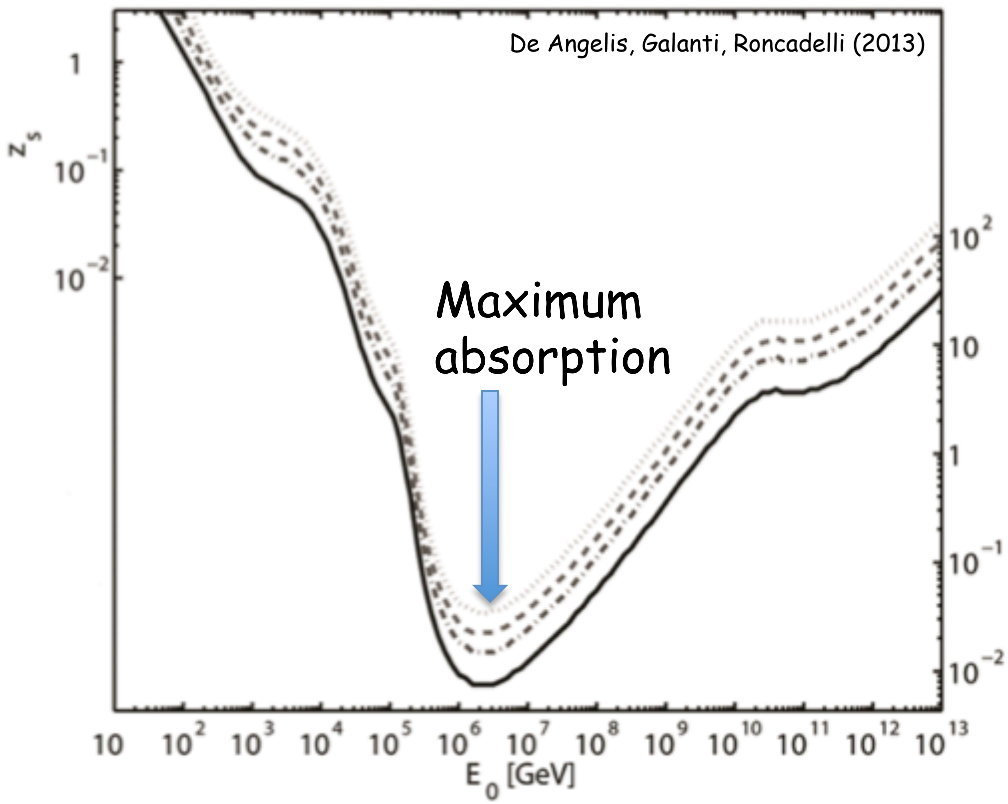


Extra-galactic background light/ CMB/ …

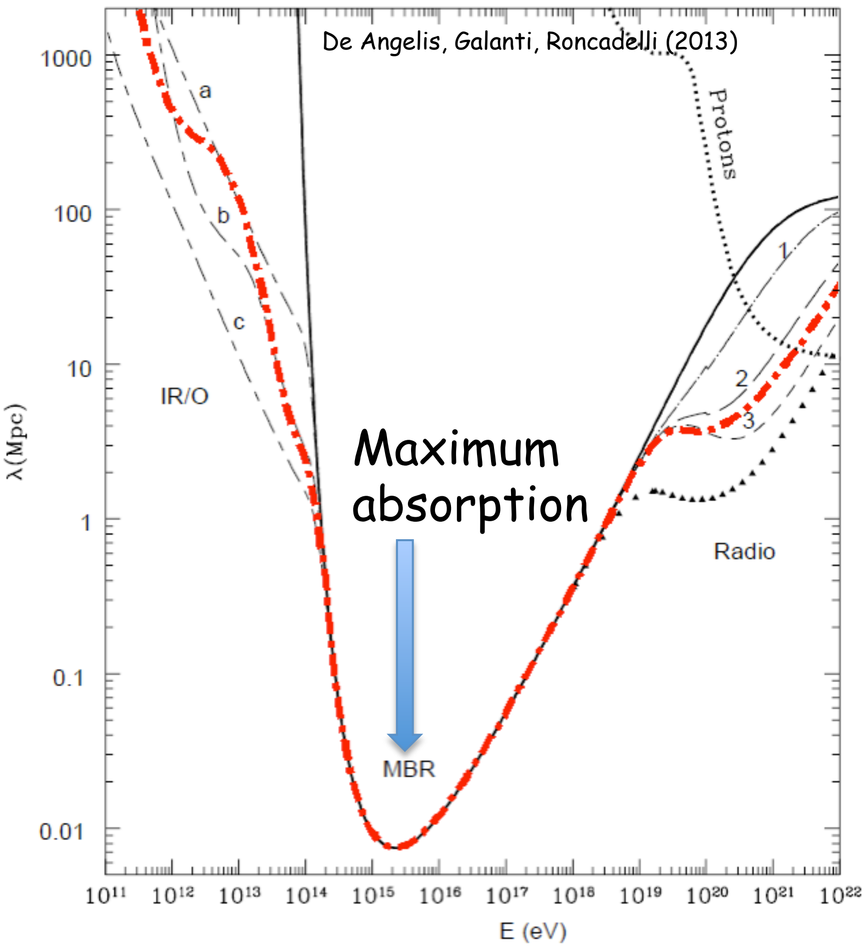
The magnetic fields and photon density that can be used: astrophysical source, source galaxy, host cluster, intergalactic space, Milky Way

Depending on the ALP parameters, the maximum ALP ⟷ photon conversion can happen for any of these choices

Opacity of the Universe



Source redshifts z_s at which the optical depth takes fixed value as a function of the photon energy E_0



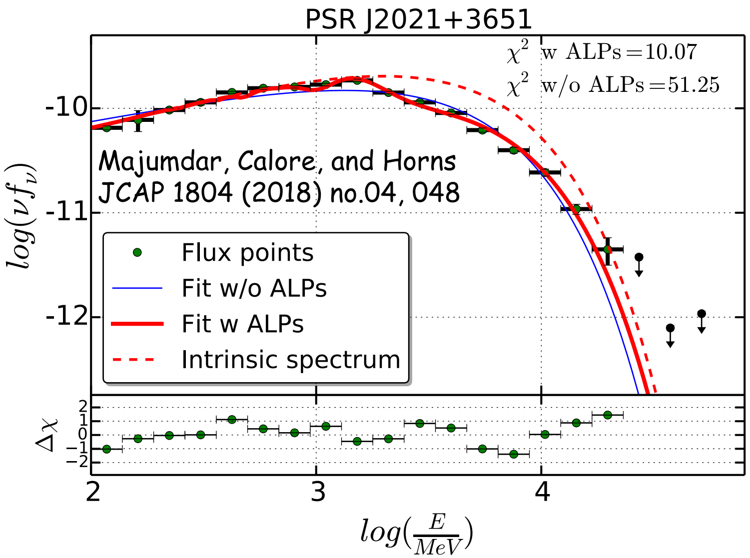
Mean free path of gamma-ray photons

Maximum absorption at PeV => most efficient search will be carried at around that energy

Mean free path at ~ PeV energies ≈ 10 kpc. Extragalactic sources are at distances Mpc or much greater => a signal of ALP at these energies cannot be mimicked by astrophysics

Existing searches with gamma-rays

(a) Search for spectral features:



Oscillations in the photon spectrum of astrophysical objects

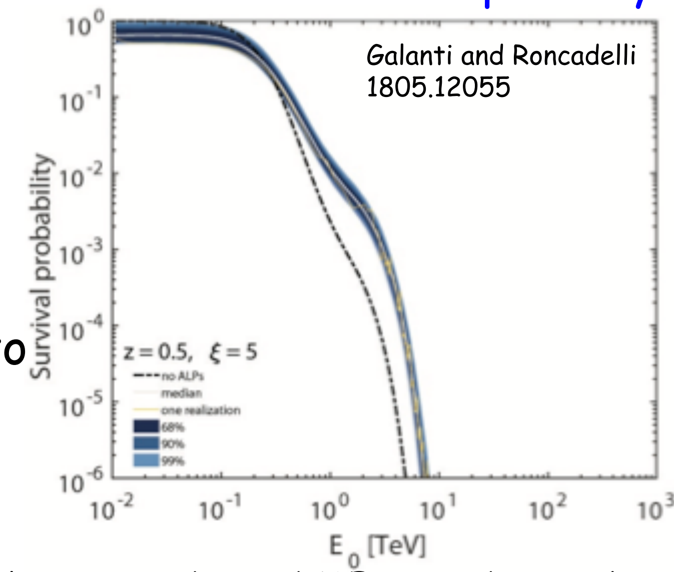
No conclusive evidence of spectral distortion due to ALPs has been found

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

(b) Search for anomalous transparency:

Excess photons from a source above standard expectations

Most sensitive to energies above ~ 500 GeV



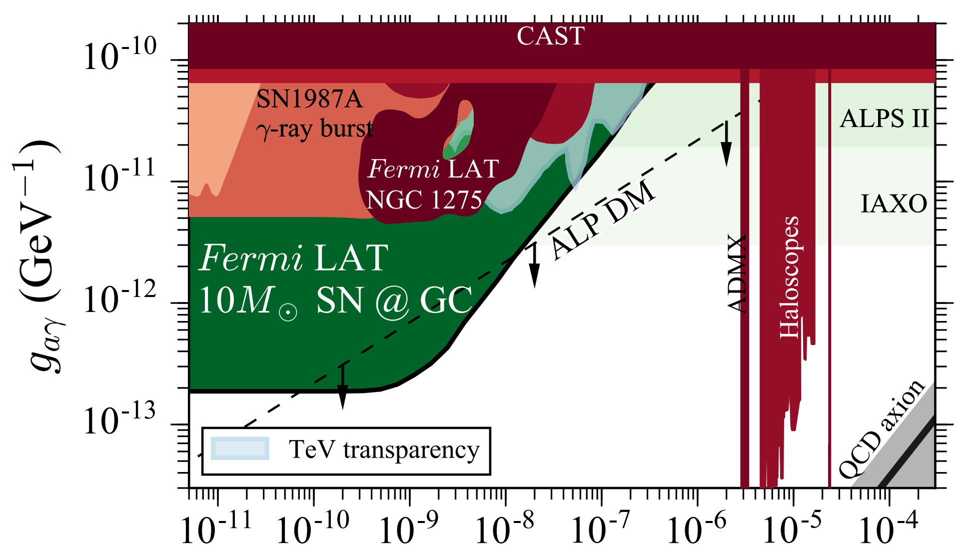
See also Meyer and Conrad, H.E.S.S., and many others

(c) Search from a supernova:

Strong limits from SN 1987A

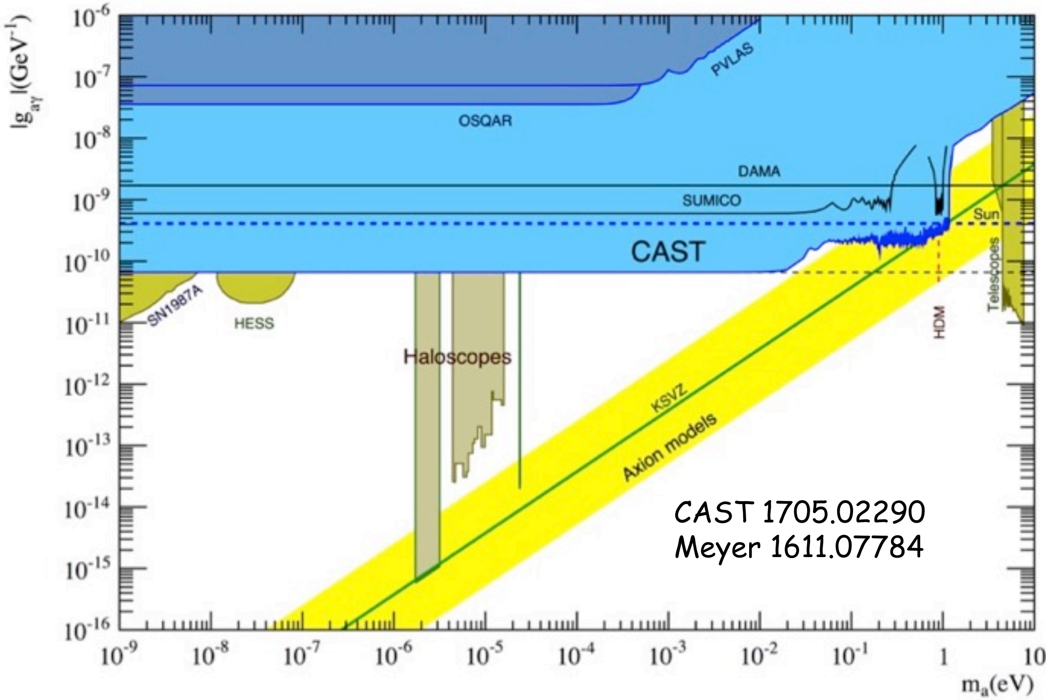
Next Galactic supernova holds great promise

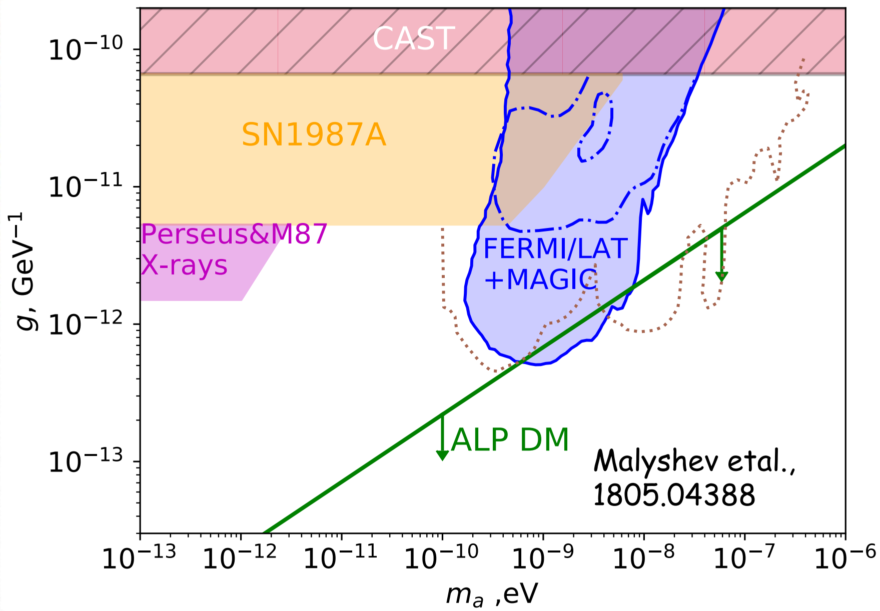
See also Payez etal., Brockway etal., Grifols etal., and many others



Meyer etal., Phys.Rev.Lett. 118 (2017) no.1, 011103

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

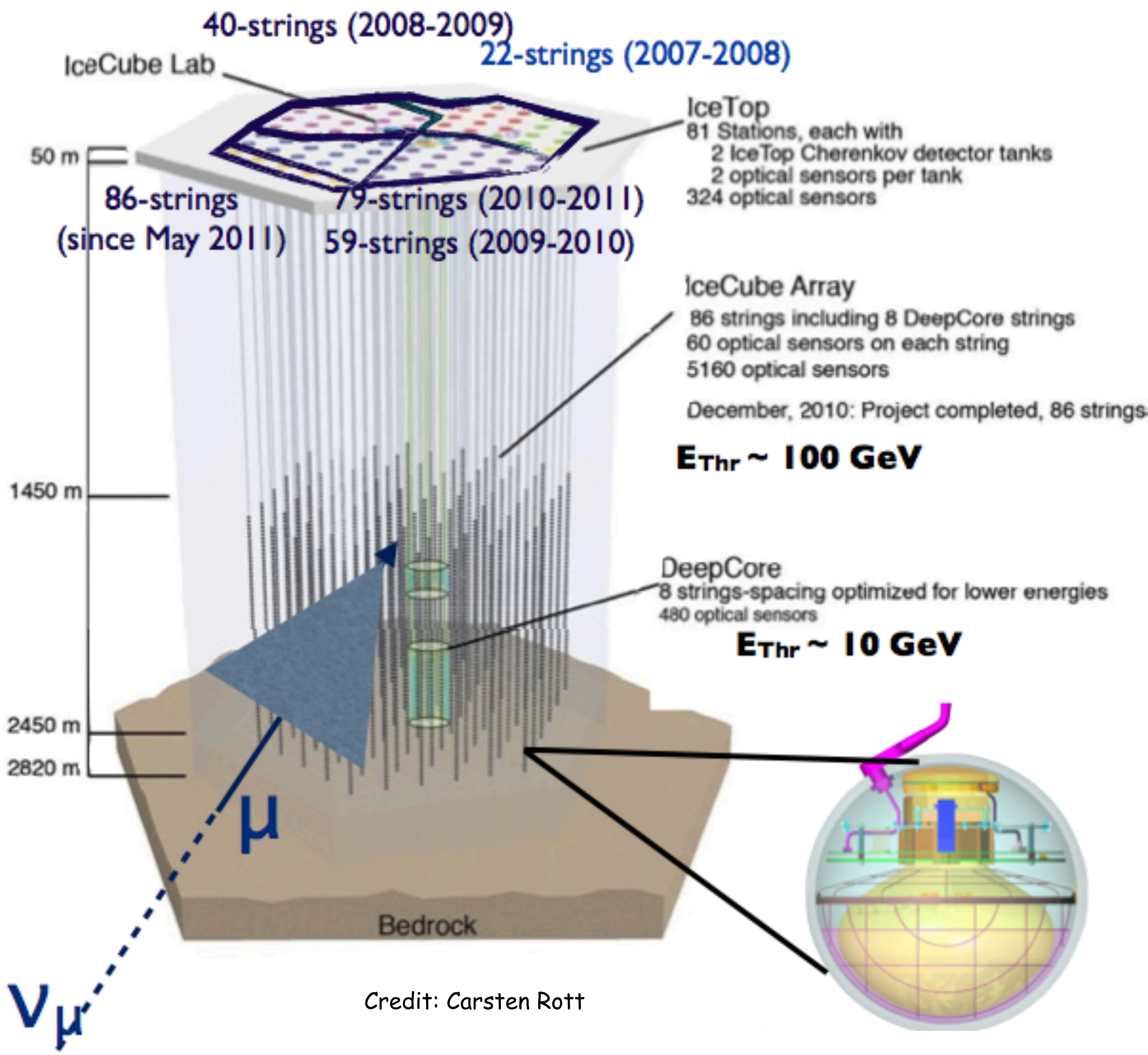
Gigaton effective volume neutrino detector at South Pole

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

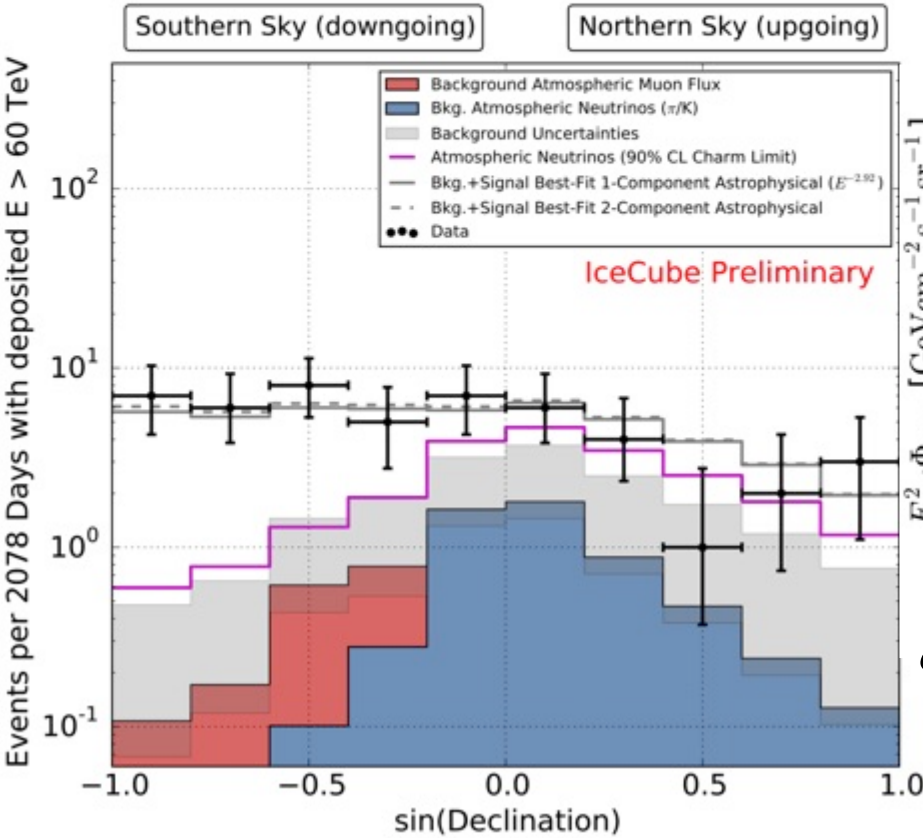
Neutrino detected through Cherenkov light emission from charged particles produced due to neutrino CC/NC interactions

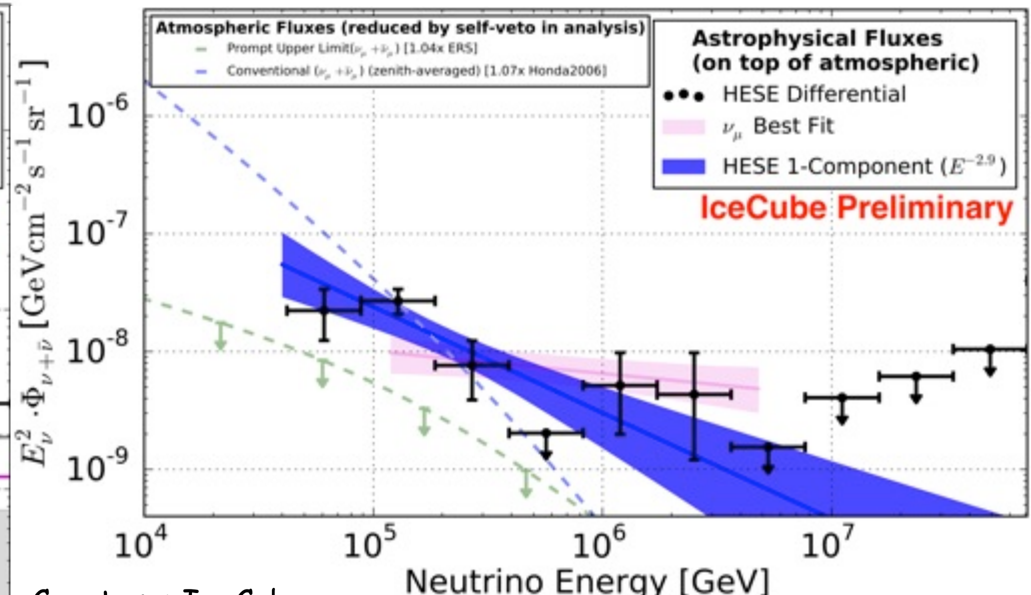


Credit: Carsten Rott

IceCube data

See the talks by Kopper, Horiuchi, and Coniglione





Courtesy: IceCube

Latest update in the Neutrino 2018 conference

Diffuse and isotropic spectrum of neutrinos

Time-independent

Strong evidence of these neutrinos being extra-galactic

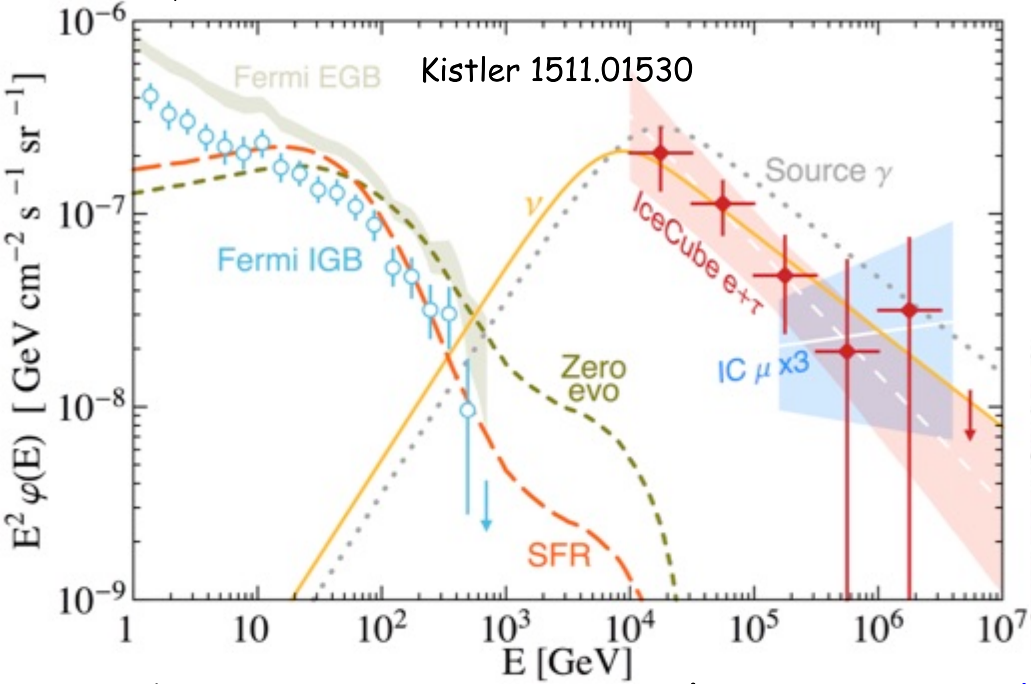
Clear evidence of the astrophysical nature of these neutrinos

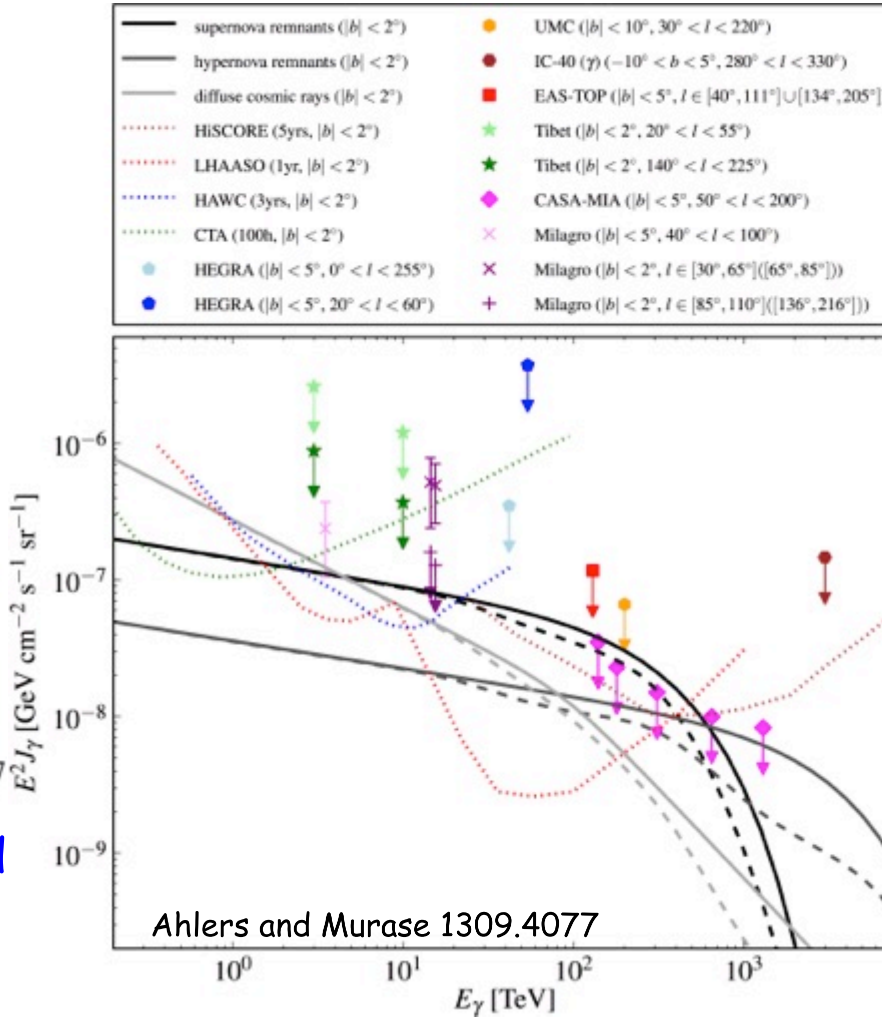
Recently there has been a detection of a high-energy astrophysical neutrino source TXS 0506+056 (IceCube 1807.08794 and 1807.08816) (see Laha 1807.05621 for exotic physics constraints)

Photons corresponding to IceCube excess neutrinos produced in astrophysical sources

$$p + \gamma \rightarrow p + \pi^0 \rightarrow \gamma + \ldots$$

$$p + \gamma \rightarrow n + \pi^+ \rightarrow \nu + \ldots$$





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

Can one use these photons to do physics?

$$p + p \rightarrow \ldots + \pi^{\pm} \rightarrow \ldots + \nu + \bar{\nu}$$

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

$$p + p \rightarrow \ldots + \pi^0 \rightarrow \ldots + \gamma$$

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

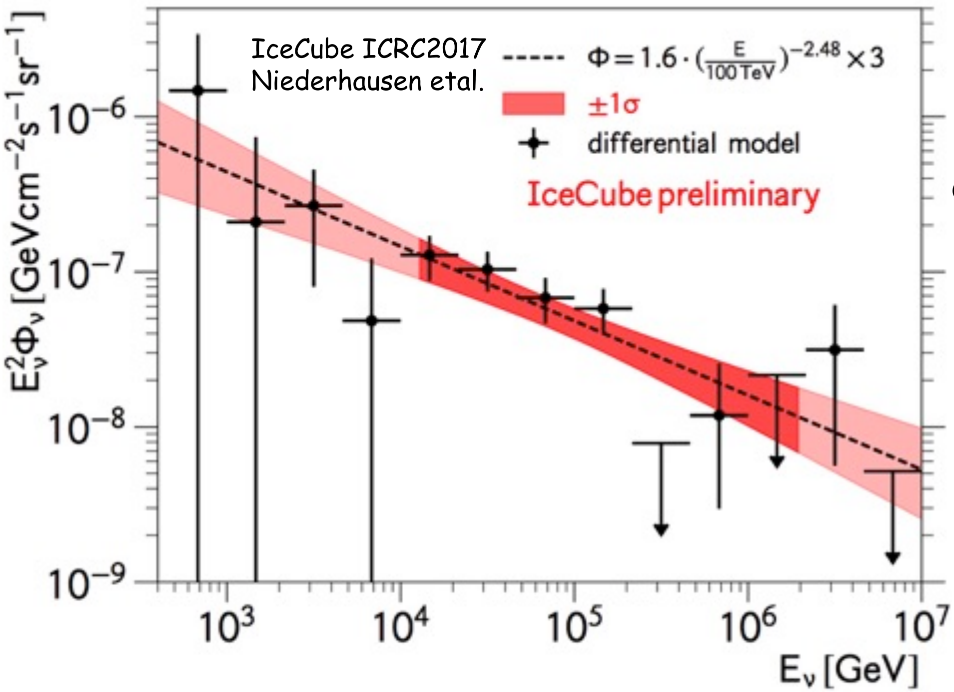
Our proposal is sensitive to the energy range where photons are maximally attenuated

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 etal.	12	2.48
Kopper etal.	40	2.92

$$p + \gamma \to n + \pi^+ \to \nu + \ldots$$

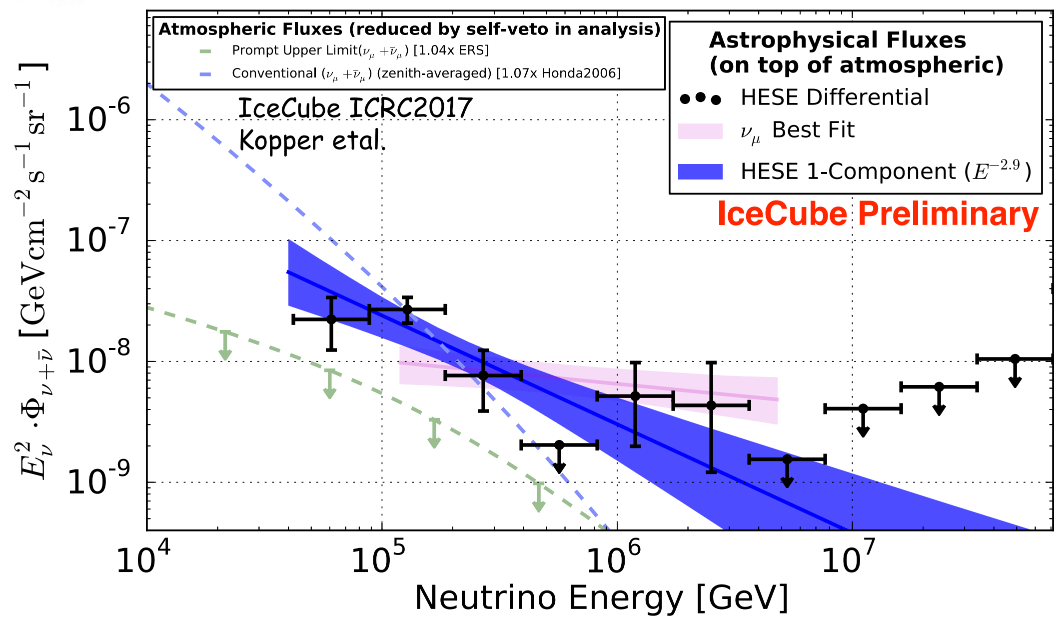
$$p + \gamma \to p + \pi^0 \to \gamma + \ldots$$

$$E_\gamma \approx 2\, E_\nu$$

IceCube ICRC2017
Niederhausen etal.

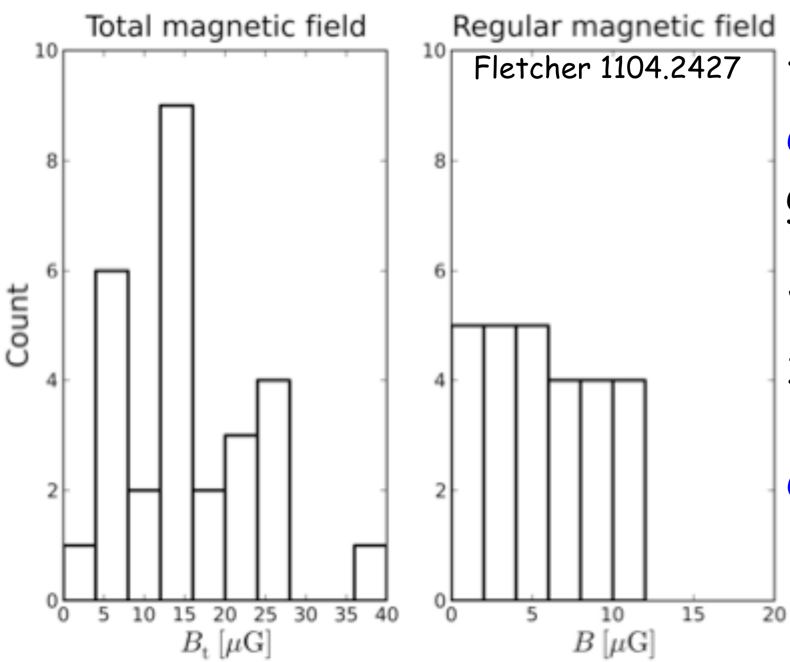
2 photons for 3 neutrinos

Many models which reproduce the spectrum of these neutrinos



Astrophysical parameters

- There are various models (~ 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

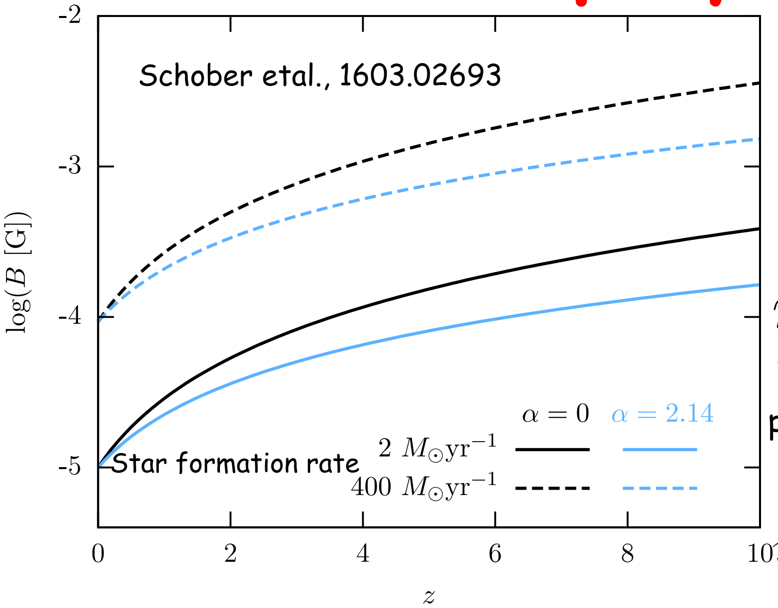


Typical values for the total and regular equipartition magnetic field strengths for 21 galaxies

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



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

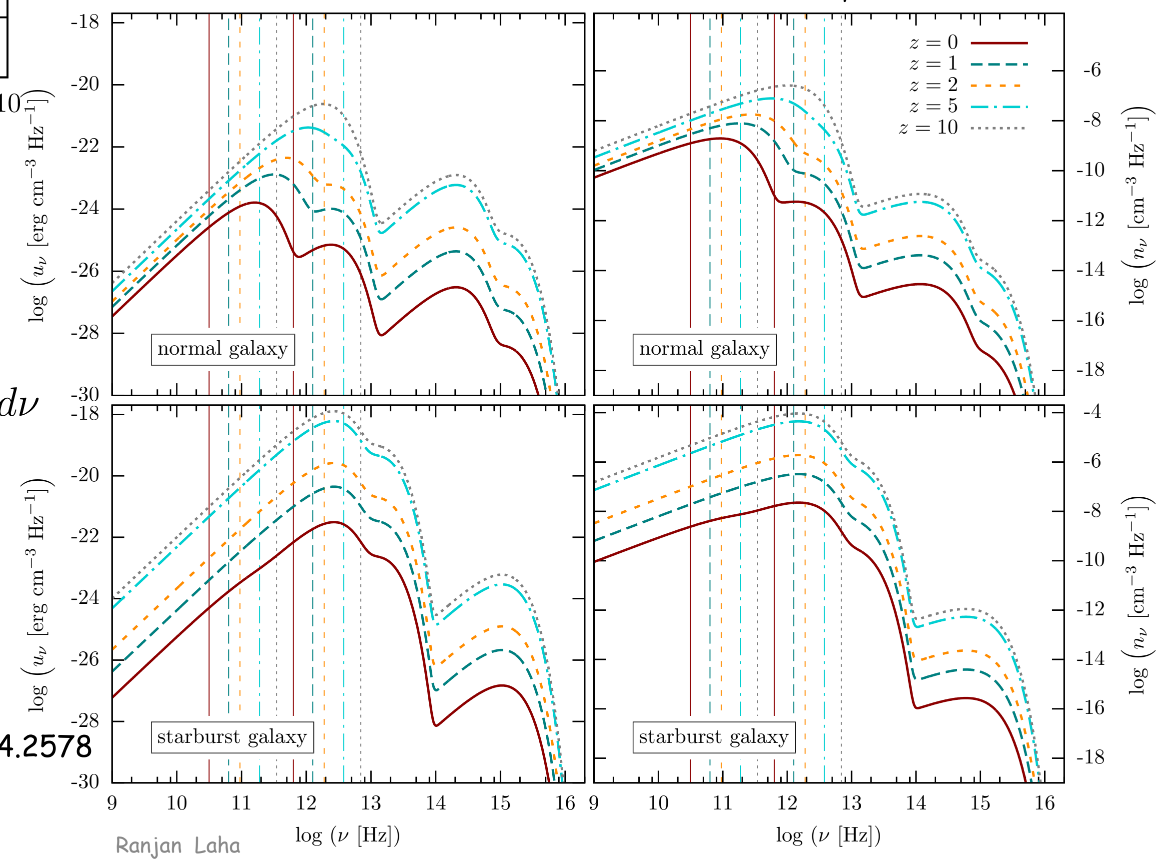
local magnetic field

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

Schober etal., 1404.2578



Model for interstellar photon density in progenitor galaxies

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

spectral energy density

Schober etal., 1404.2578

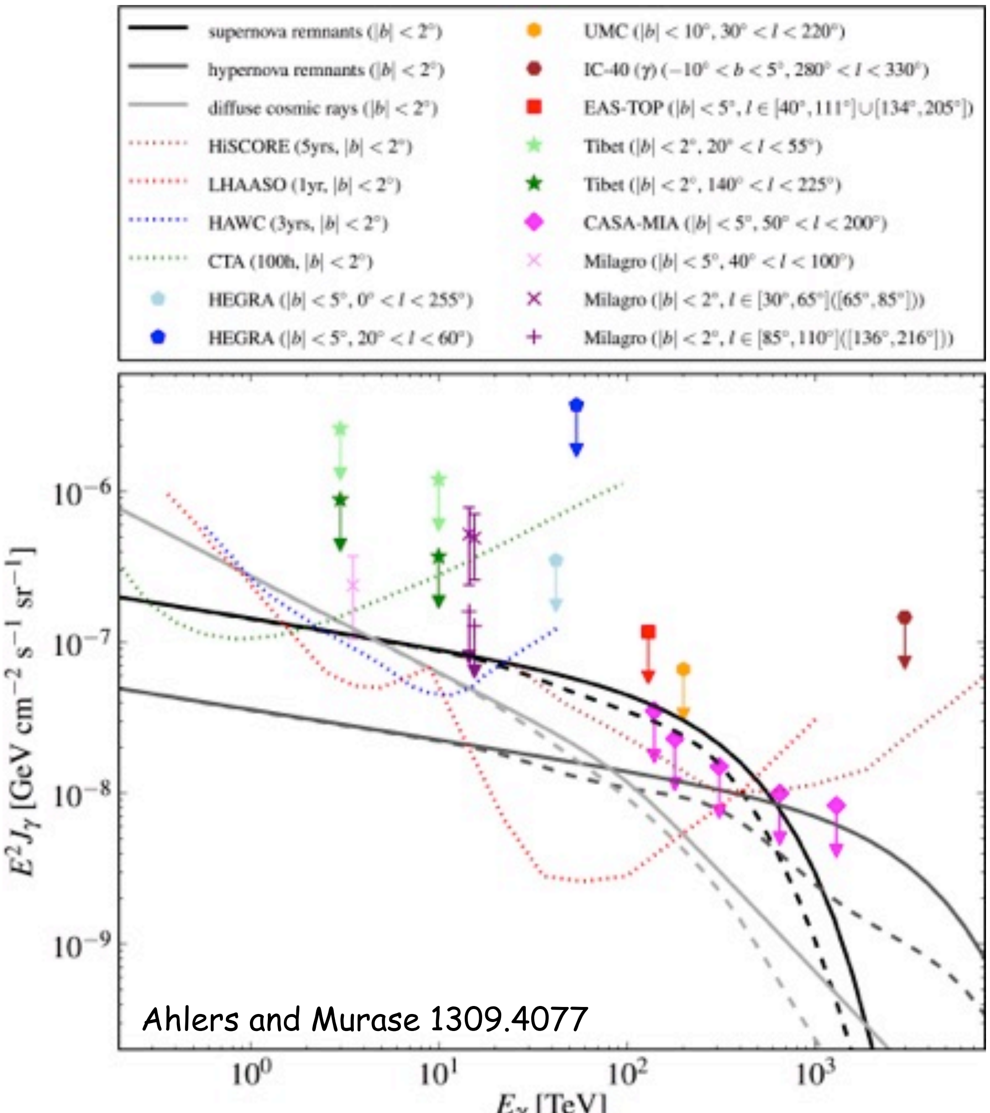
High-energy gamma-ray production in the Milky Way

- 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 $p + p \to \ldots + \pi^0 \to \ldots + \gamma$

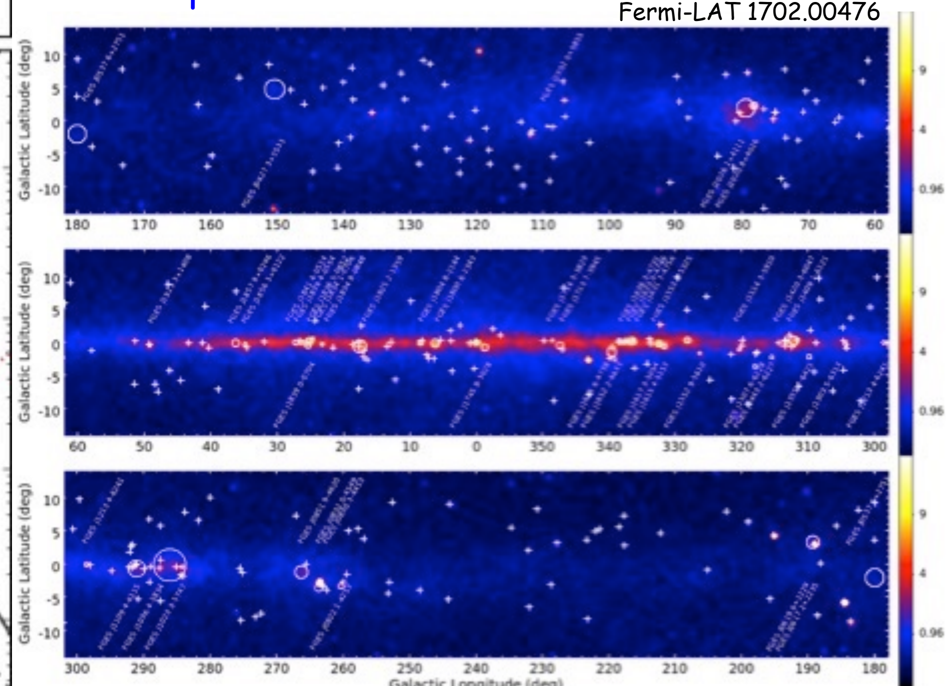
Photons at these energies have not been detected

ALPs can induce spectral distortions in this gamma-ray spectrum

These photons are strongly correlated with the Galactic plane



Fermi-LAT 1702.00476



Galactic plane in 10 GeV – 2 TeV

Gamma-ray detectors (HAWC)

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

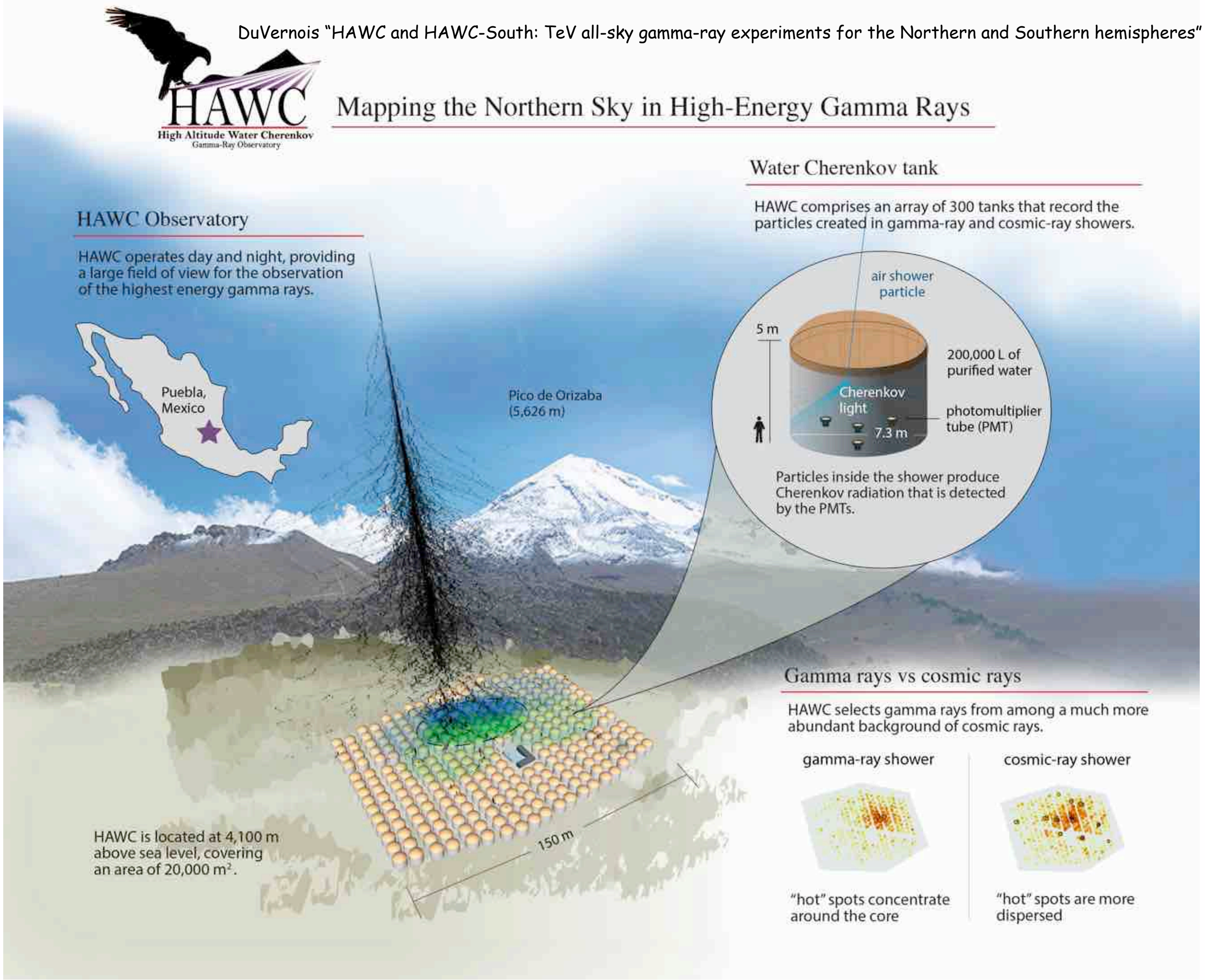
Angular resolution varies from ~ 0.2^0 to 2^0

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"



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 ~10^{11} eV - 10^{17} eV

Uses different detection techniques:

(1) LHAASO-KM2A: 1 km^2 array of 5635 scintillator detectors for electromagnetic particle detection

(2) LHAASO-MD: 1 km^2 array of underground water Cherenkov tanks for muon detection

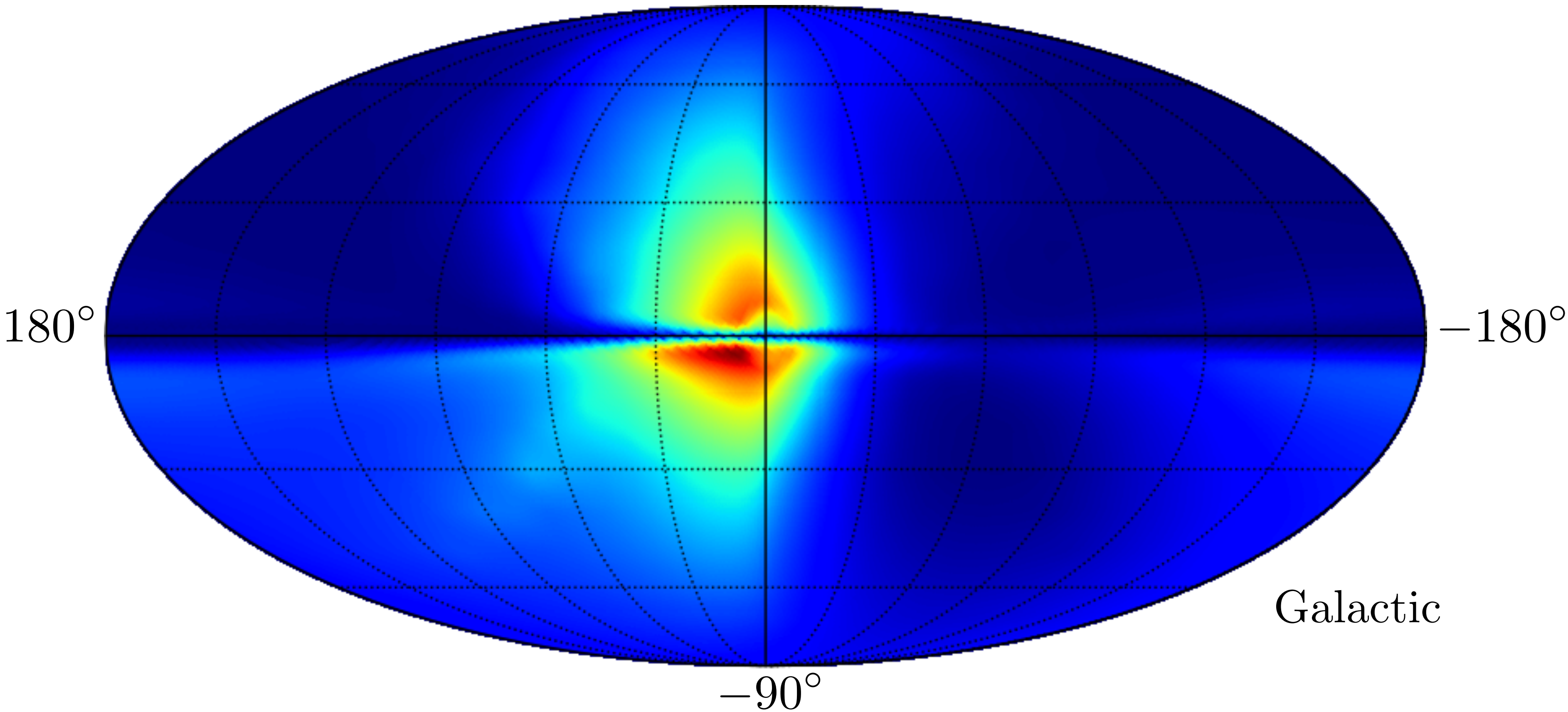
(3) LHAASO-WCDA: Surface water Cherenkov detector facility ~90000 m^2

(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

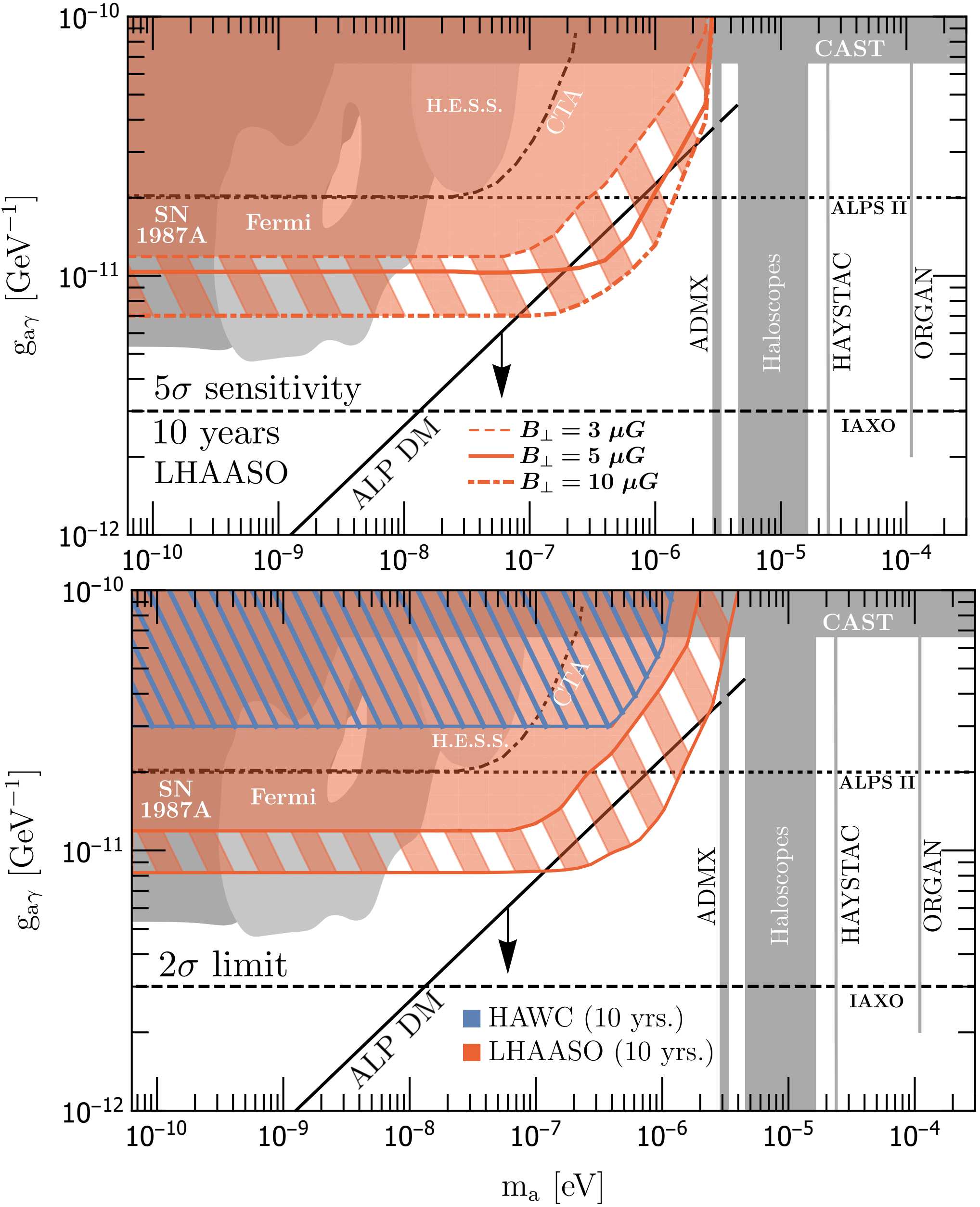


The incident ALP flux is isotropic and homogenous

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 sources 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

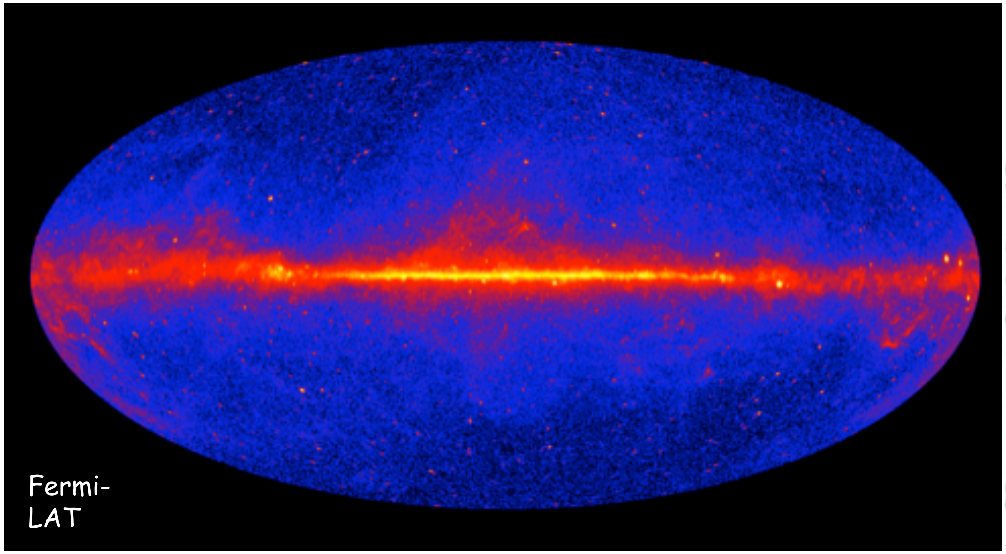
Vogel, Laha, and Meyer
1712.01839

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



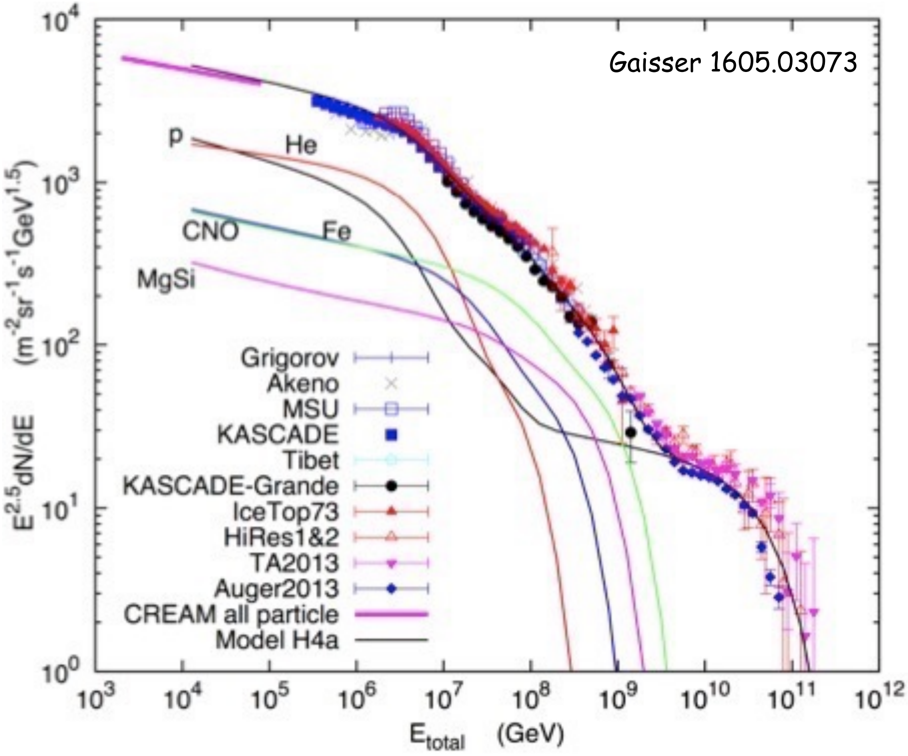
Gamma-ray sky: what process produces them?

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

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

$p + p \to \pi/K + ... \to \nu/\bar{\nu}$

The key difference are the neutrinos



Cosmic rays observed over a huge energy range

Neutrinos are inevitably produced in cosmic ray interactions