Magic trick of the Month: hiding blazars with decaying ALPs

IMPRS colloquium, Munich (Germany)
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MAX-PLANCK-GESELLSCHAFT

elusives
neutrinos, dark matter & dark energy physics

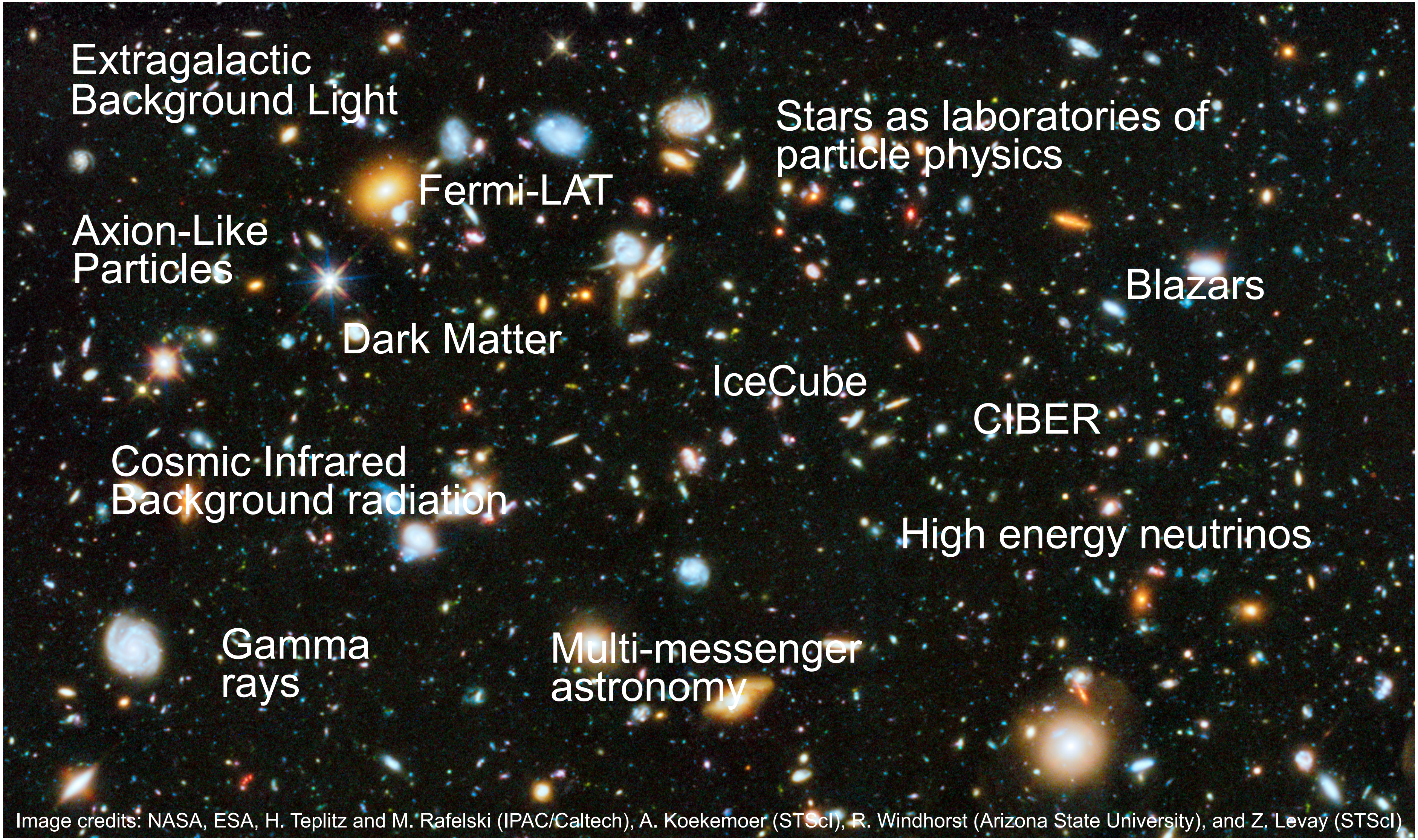
Max-Planck-Institut für Physik

Based on arXiv:1808.05613 w/ O.E. Kalashev and A. Kusenko star-forming

A long time ago in a galaxy far,
far away....

Images credits: Star Wars (movie, 1977)

An astroparticle physics story



Outline of the talk

Introduction to multi-messenger astronomy

- What is multi-messenger astronomy?
- The neutrino-gamma-cosmic rays connection
- Experimental status: IceCube, Fermi, CIBER

One ALP to rule them all

- Axion-Like Particles (aka: a new dark matter paradigm)
- Enhancing the Cosmic Infrared Background radiation…
- …and understanding its redshift evolution
- A mixed top-down/bottom-up (ALP+blazar) explanation for data

Exploring the parameter space of ALPs

time dependent!

- Stars as laboratories of particle physics
- Limits from anisotropy measurements
- Is the model excluded by blazar observations? (spoiler alert: it's not)

Conclusions

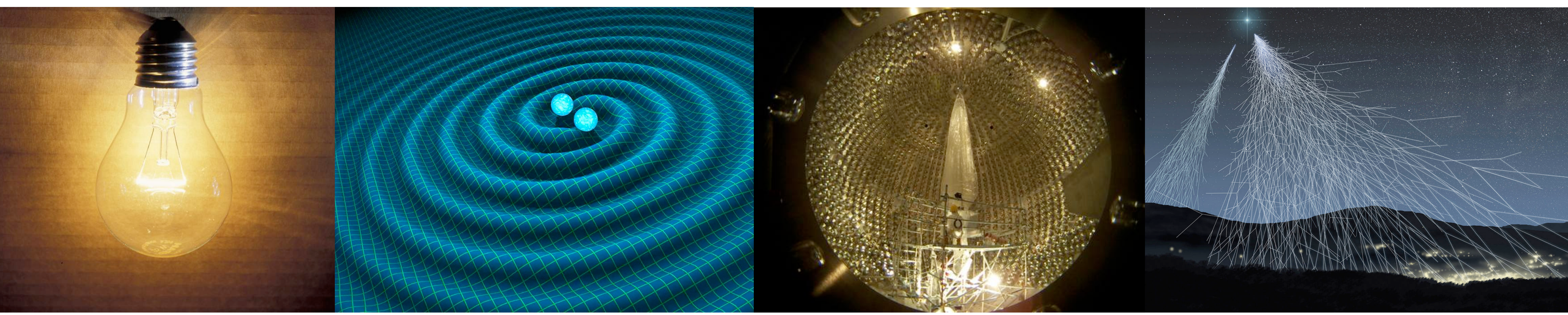
Introduction to multi-messenger astronomy

Dawn of multi-messenger astronomy

From Wikipedia…

Multi-messenger astronomy is astronomy based on the coordinated observation and interpretation of disparate "messenger" signals. The four extrasolar messengers are ***electromagnetic radiation****,* ***gravitational waves****,* ***neutrinos****, and* ***cosmic rays****. They are created by different astrophysical processes, and thus reveal different information about their sources.*

https://en.wikipedia.org/wiki/Multi-messenger_astronomy

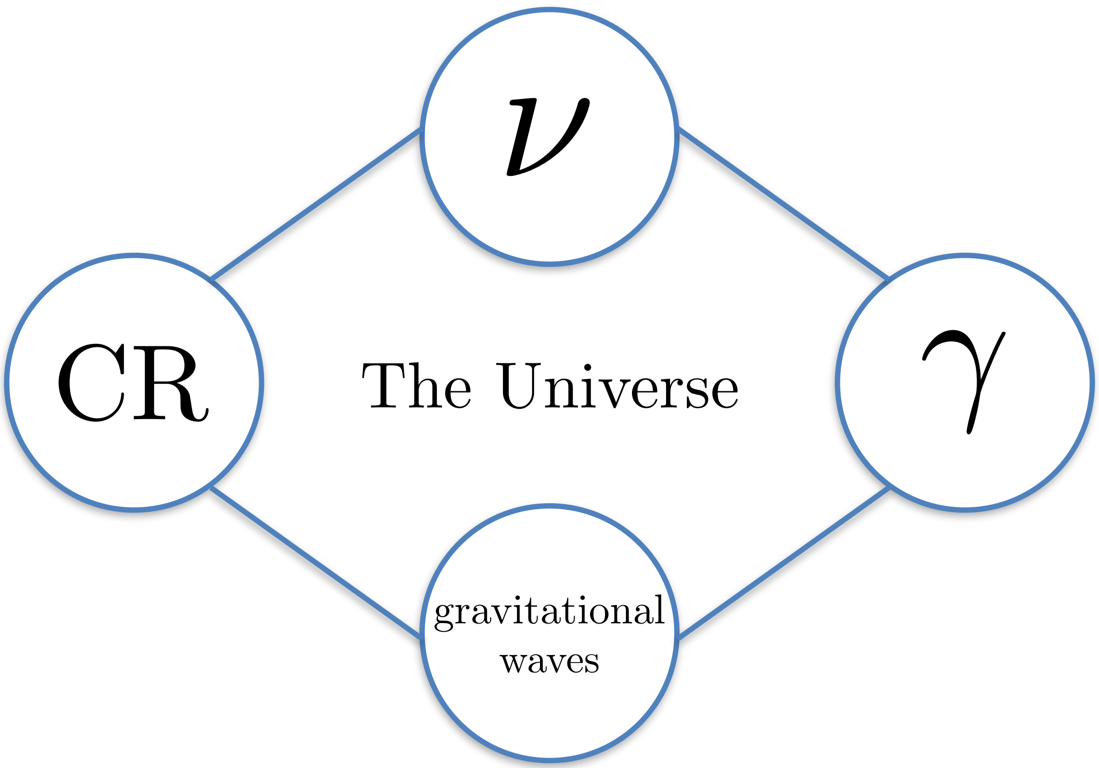


Images credits: Rex, R. Hurt/Caltech-JPL/EPA, Virginia Tech Physics, ASPERA/Novapix/L. Bret

A new way to explore the universe

The universe is no longer explored with electromagnetic radiation alone.

In particular, **Neutrinos** are becoming crucial astrophysical probes!



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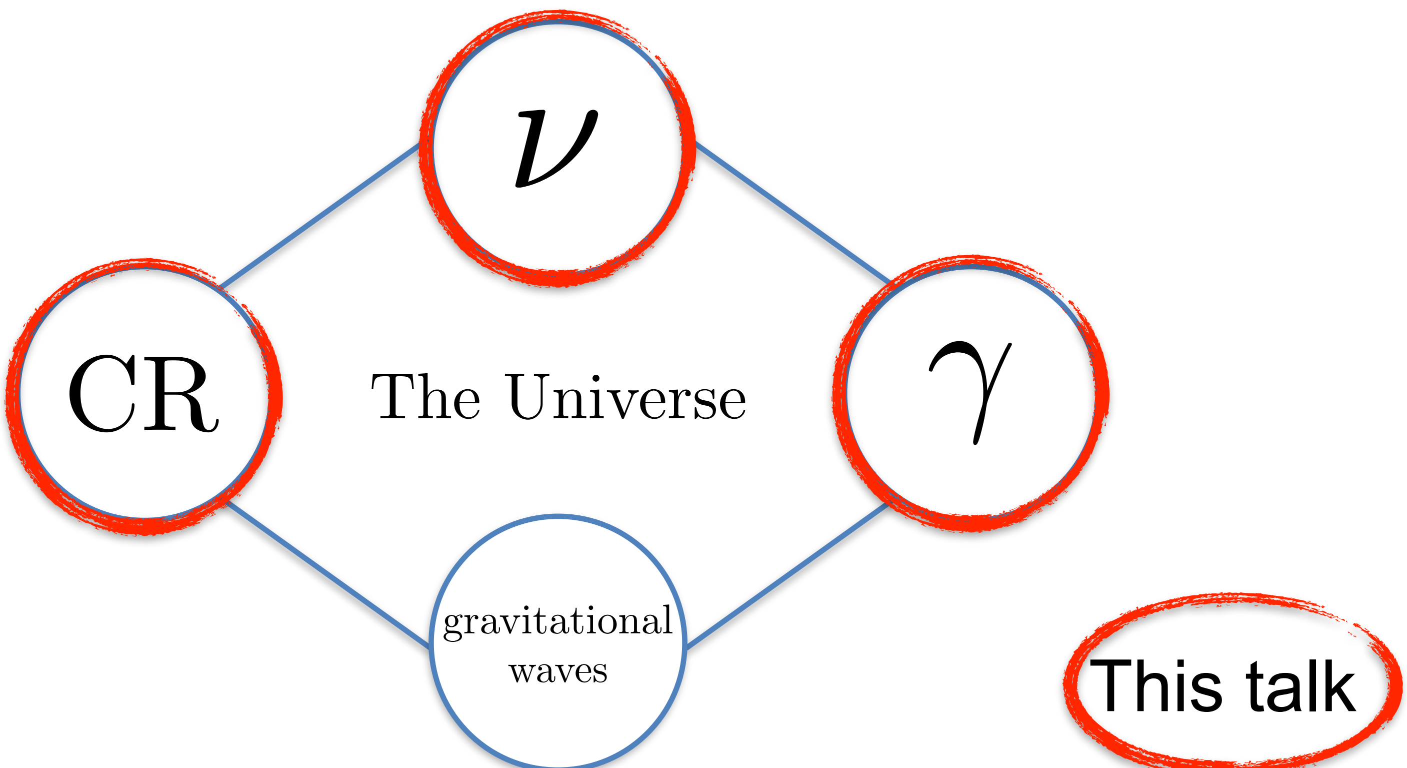
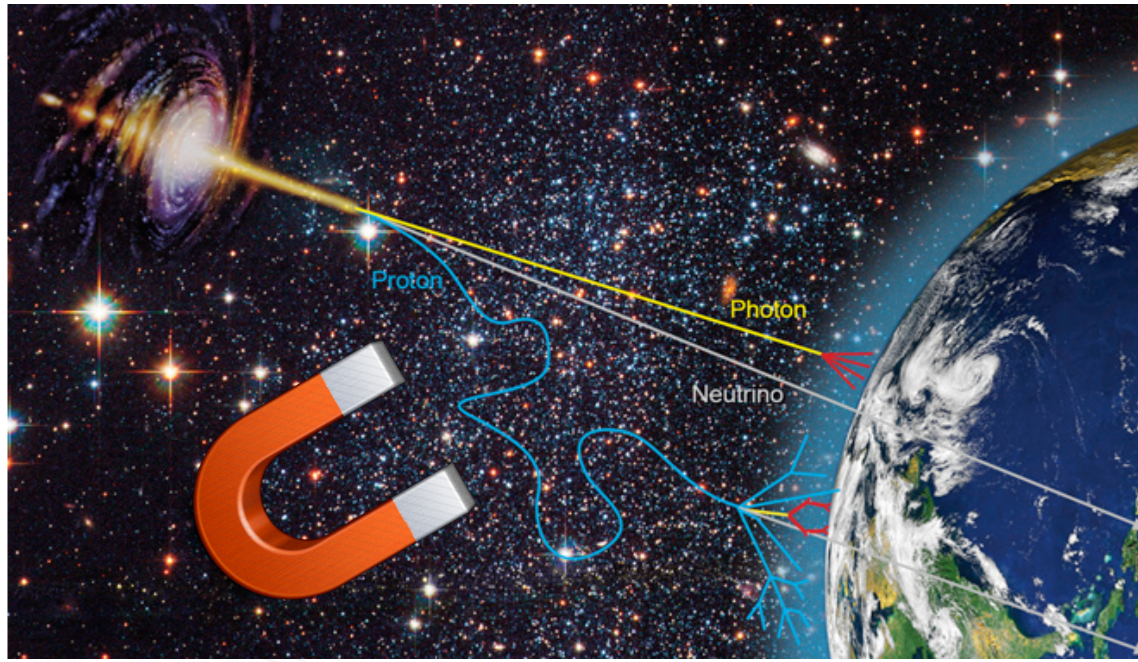
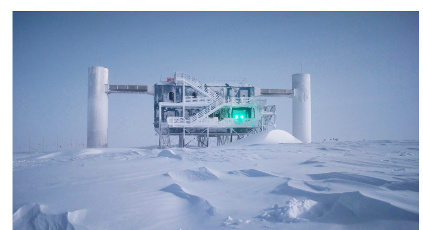


More about the various messengers

A short recap:

- **Photons:**
  easy to detect 👍
  point back at the source(s) 👍
  get absorbed 👎
- **Cosmic rays:**
  easy to detect 👍
  don't point back 👎
- **Neutrinos:**
  point back 👍
  don't get absorbed 👍
  difficult to detect 👎

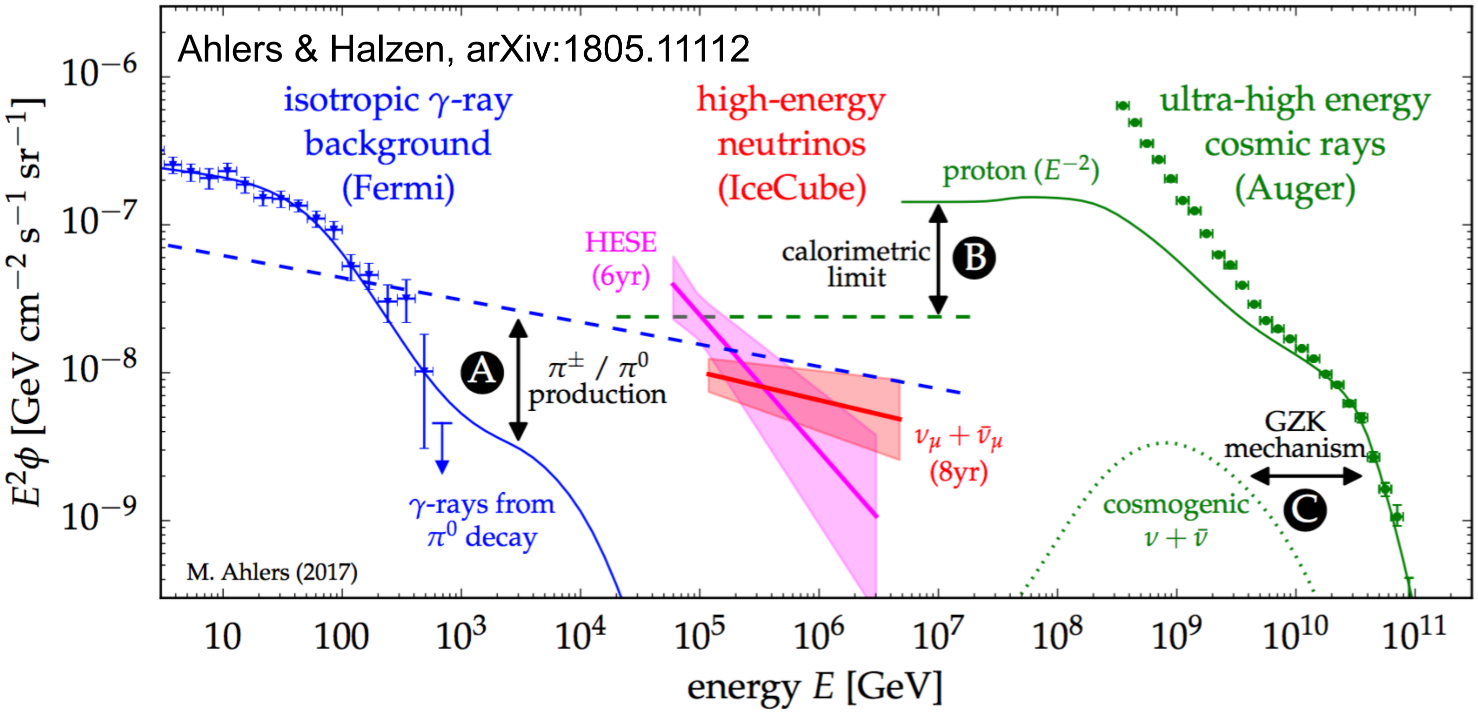




Images credits: https://astro.desy.de, http://www.ung.si, E. Jacobi/NSF, T. Arai/University of Tokyo

The messengers connection

Are neutrino/CR/gamma astronomy independent?



Anchordoqui et al., PLB (2004). Kelner, Aharonian, Bugayov, PRD (2006). Kelner, Aharonian, PRD (2008)

Slide adapted from I. Tamborra talk at Invisibles18

Similar energies…

The messengers connection

Neutrino Production Processes

Hadronuclear, aka as pp interaction (e.g. star-burst galaxies)

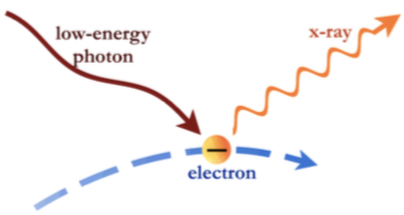
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

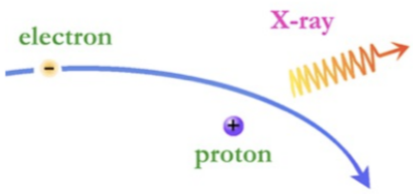
$$E_\nu \approx 0.05 E_p$$

Photohadronic, aka as pγ interaction (e.g. active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

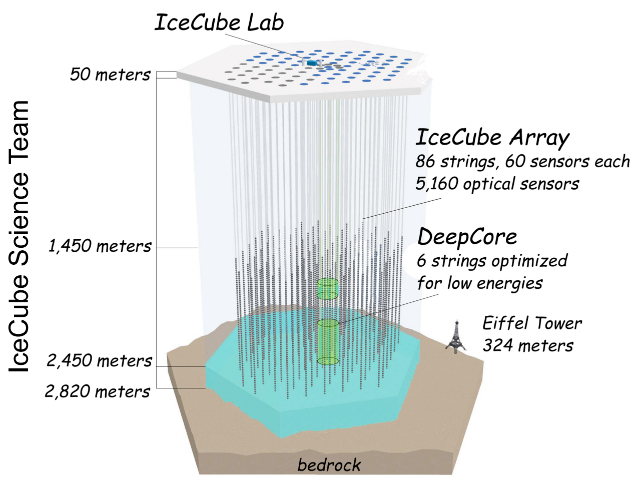
Gamma-rays are not exclusively produced in hadronic processes!

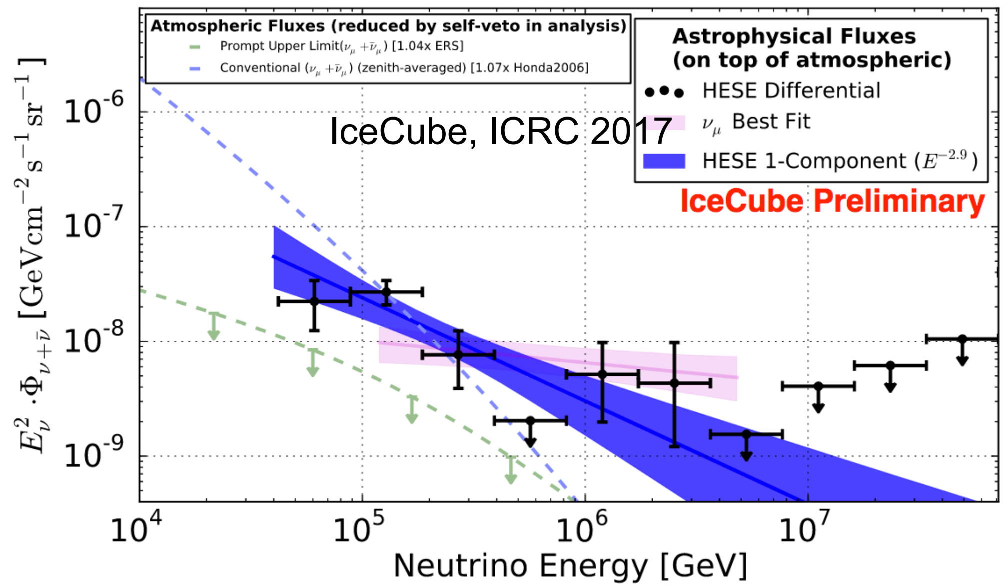




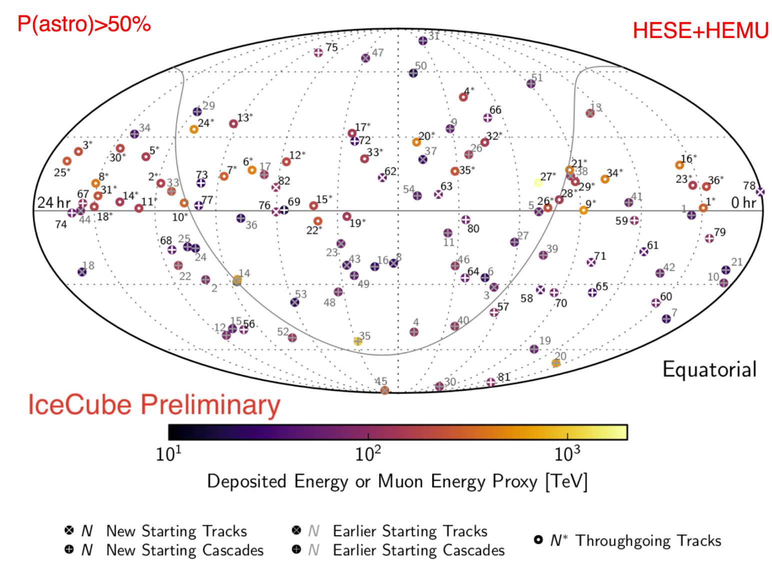
Slide adapted from A. Franckowiak talk at Invisibles18

Experimental status: IceCube





- Neutrino Cherenkov detector at the South Pole
- More than 80 obs. events [background 25.2 ± 7.3 (muons) and $11.6^{+11.4}_{-3.9}$ (atm.neutrinos)]
- Mostly isotropic, no correlation with the galactic plane -> **Extragalactic origin**



Characterizing IceCube data

From model of diffusions and the cosmic rays-neutrino connection, we expected a flux

$$\phi_\nu \propto E^{-\gamma} \ , \ \gamma \simeq 2$$

(also, that's what you expect from Fermi mechanism). Data shows that it's more complicated than this.

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Many different sources could produce high energy neutrinos…

- Top-down mechanism, big-bang relic particles decay or annihilate producing a neutrino flux:
  Kopp et al. (arXiv:1503.02669), Esmaili & Serpico (arXiv:1308.1105), Feldstein et al. (arXiv:1303.7320), Murase et al. (arXiv:1503.04663), **Boucenna et al. (arXiv:1507.01000), Chianese et al (arXiv:1601.02934)**, Chianese et al. (arXiv:1610.04612) [Strongly challenged by Cohen et al. (arXiv:1612.05638), dependence on the channel?]
- Galactic origin (must be subdominant): galactic disk, supernova remnants, galactic center, Fermi bubbles…
  Murase (arXiv:1410.3680), Lunardini et al. (arXiv:1311.7188), Taylor et al. (arXiv:1403.3206)
- Extragalactic origin: star-forming galaxies, Gamma-ray bursts, AGNs, Cluster of galaxies, choked sources…
  Meszaros (arXiv:1511.01396), Waxman (arXiv:1511.00815), Murase (arXiv:1511.01590), Tamborra & Ando (arXiv:1504.00107), Palladino et al. (arXiv:1806.04769)

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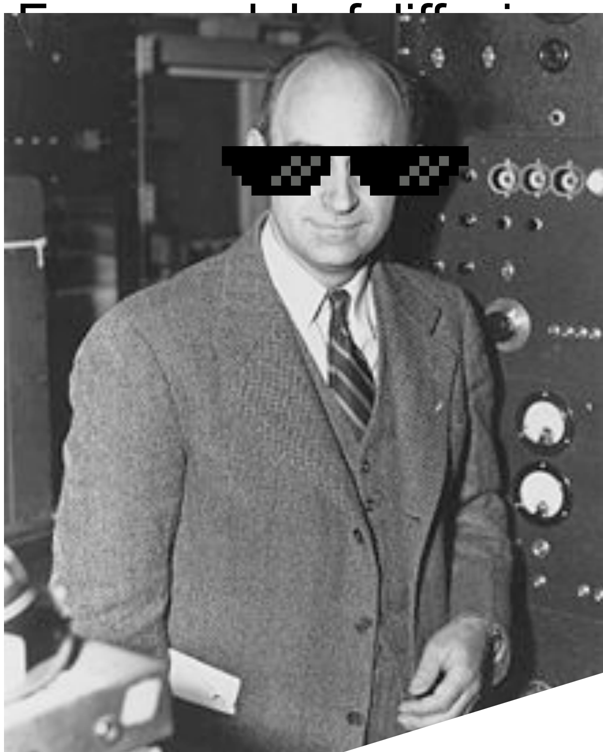

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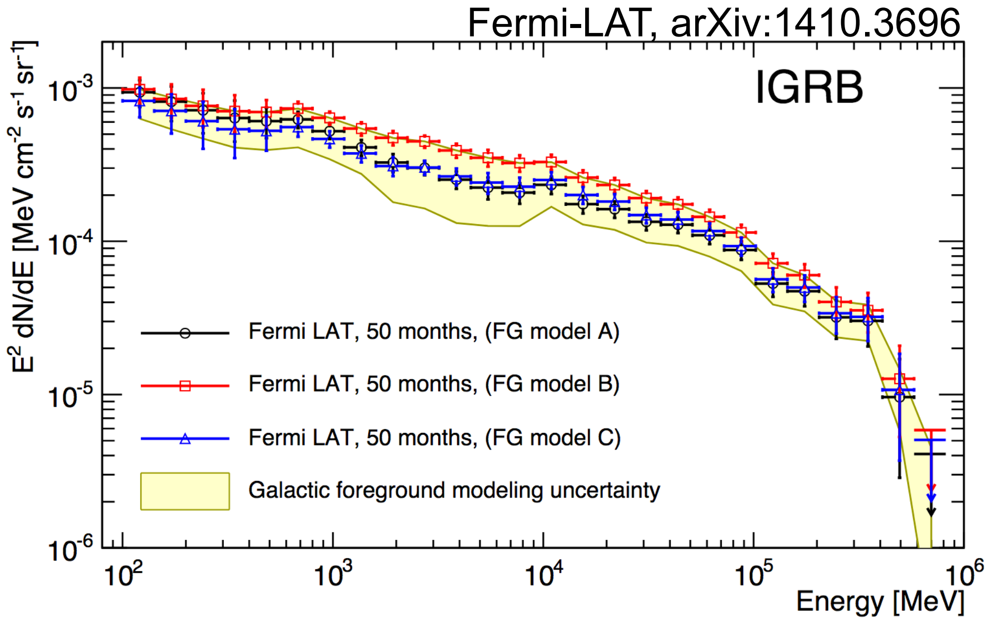
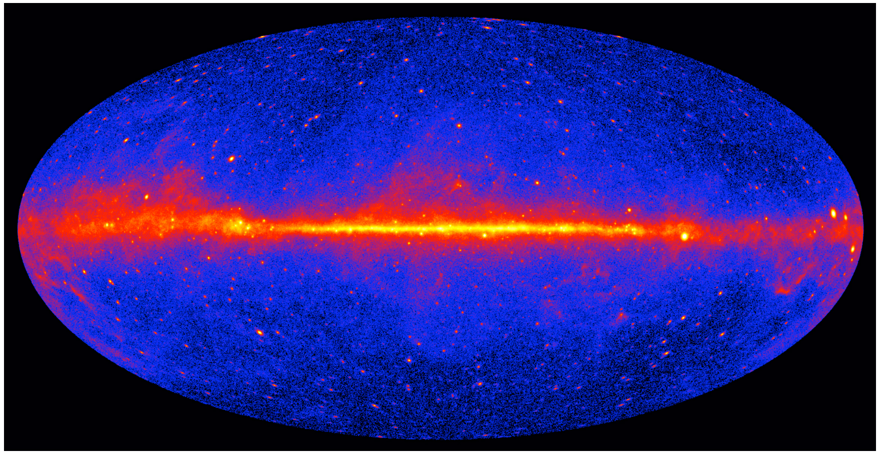
Maybe Fermi-LAT can help!

Experimental status: Fermi

NASA/Aurore Simonnet, Sonoma State University. Photo-illustration: Sandbox Studio



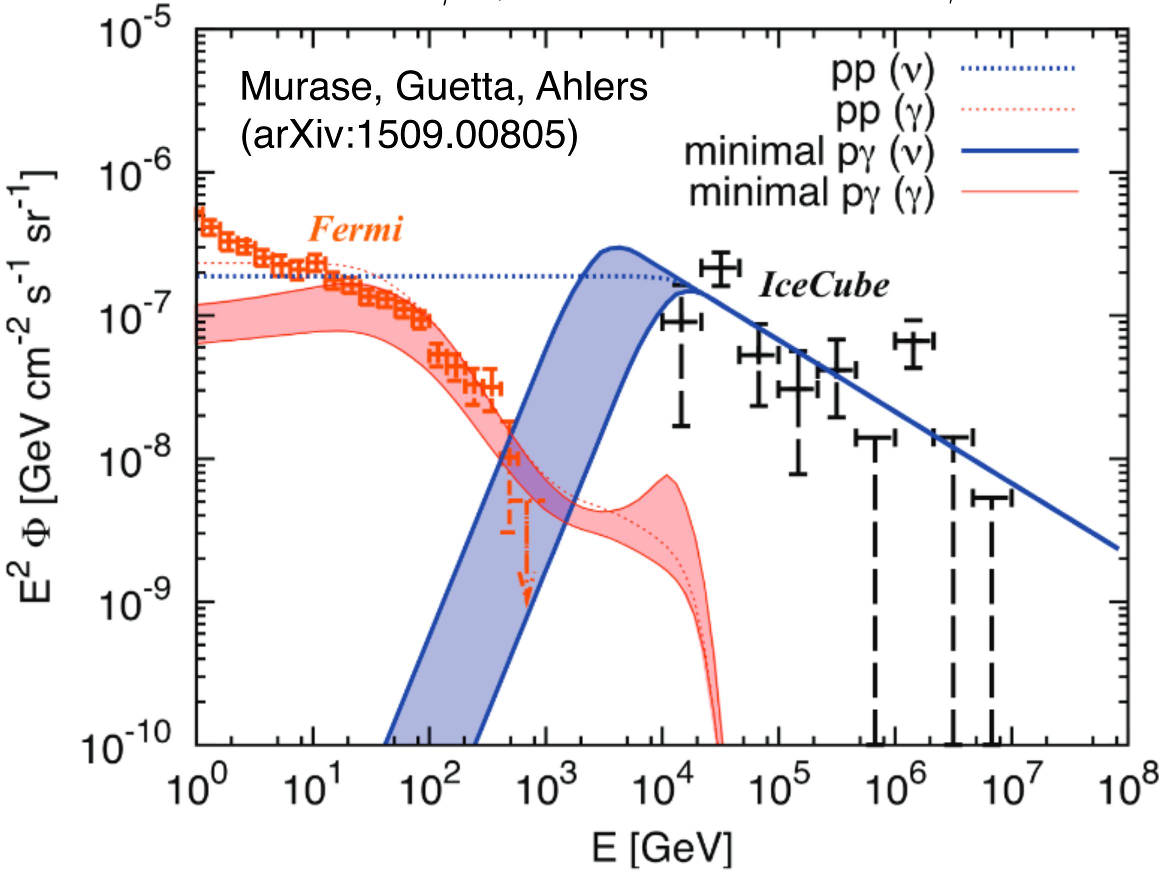
- Space observatory with a Large Area Telescope for all-sky survey
- Isotropic Gamma-ray Background Radiation (the diffuse spectrum of photons at high energies) measured with a data accumulation of 50 months
- The diffuse spectrum can be used to constrain IceCube data modelling…



Tension between Fermi and IceCube

- **Neutrinos** are becoming crucial astrophysical probes…
- …but we don't know where they are coming from
- Assuming a certain production mechanism (e.g. pp or pɣ sources), there is tension between Fermi data and IceCube data: we see less gamma-rays than expected

$$E_\gamma^2 \phi_\gamma = 2(E_\nu^2 \phi_\nu)|_{E_\nu = 0.5 E_\gamma}$$

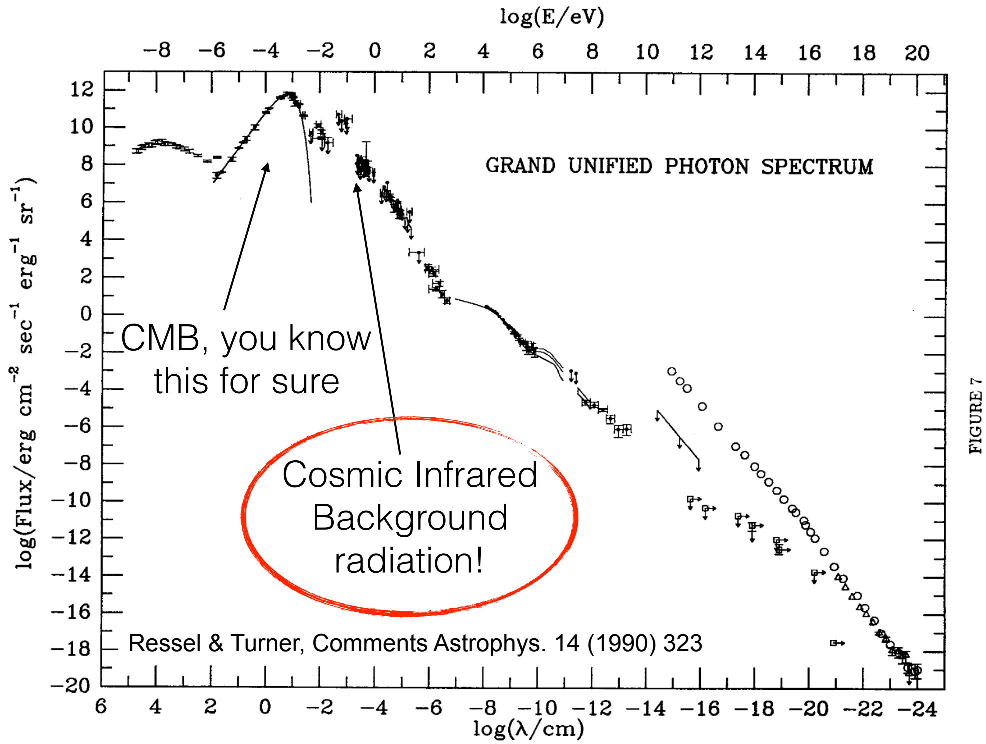


Sources must be hidden, Murase et al. (arXiv:1509.00805)

Going multi-wavelength

- Suppose you have TeV photons. Scattering on the background of eV photons (i.e. infrared!), you have enough energy to produce e+e- pairs. So you lose TeV gamma-rays.

- The CIBER (🚀) collaboration has claimed the detection of an unexpectedly high flux of CIB (EBL at z=0) in the 0.8-1.7 μm range



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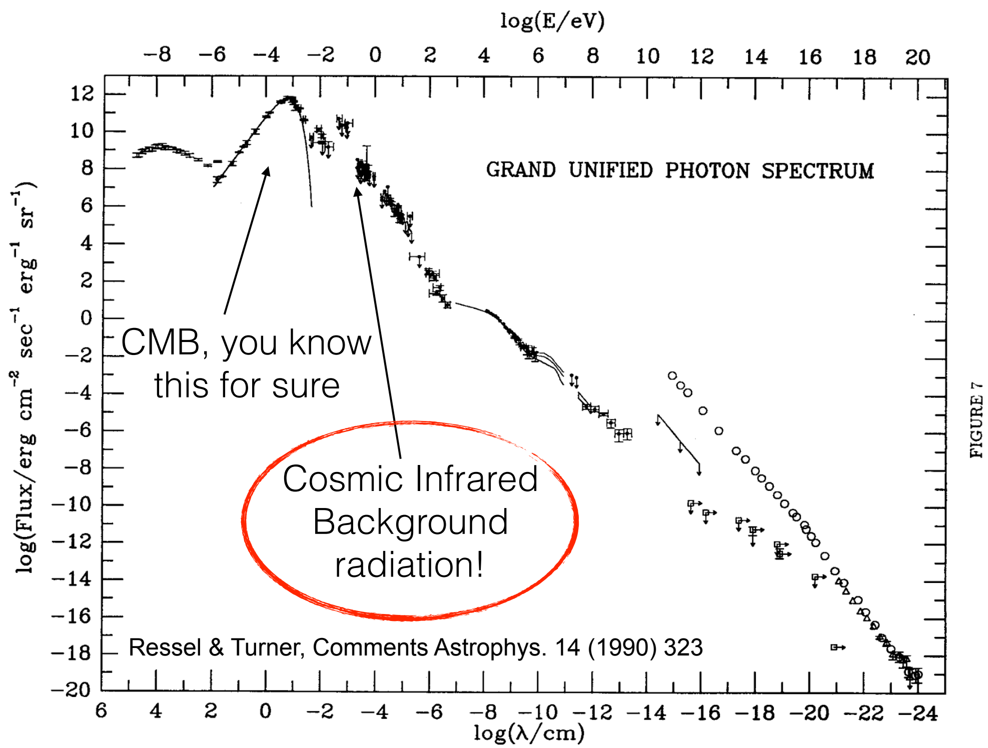
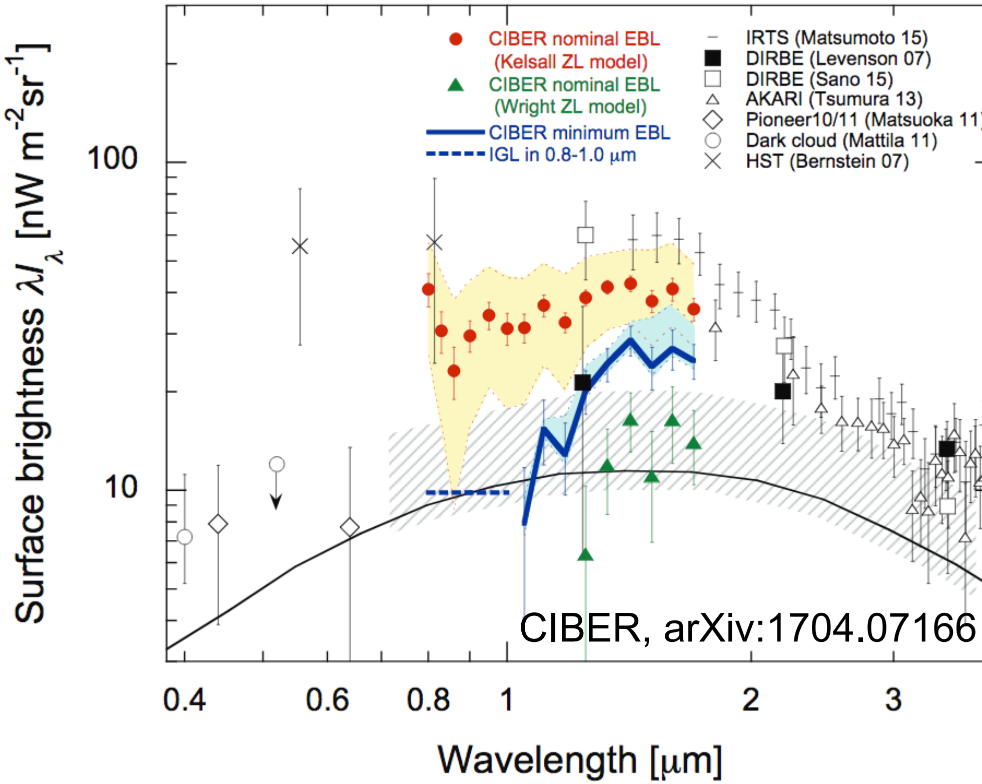


Are dark matter, axion-like particles (ALPs) with eV mass hiding sources by increasing the Extragalactic Background Light in the infrared wavelength range?

Experimental status: CIBER

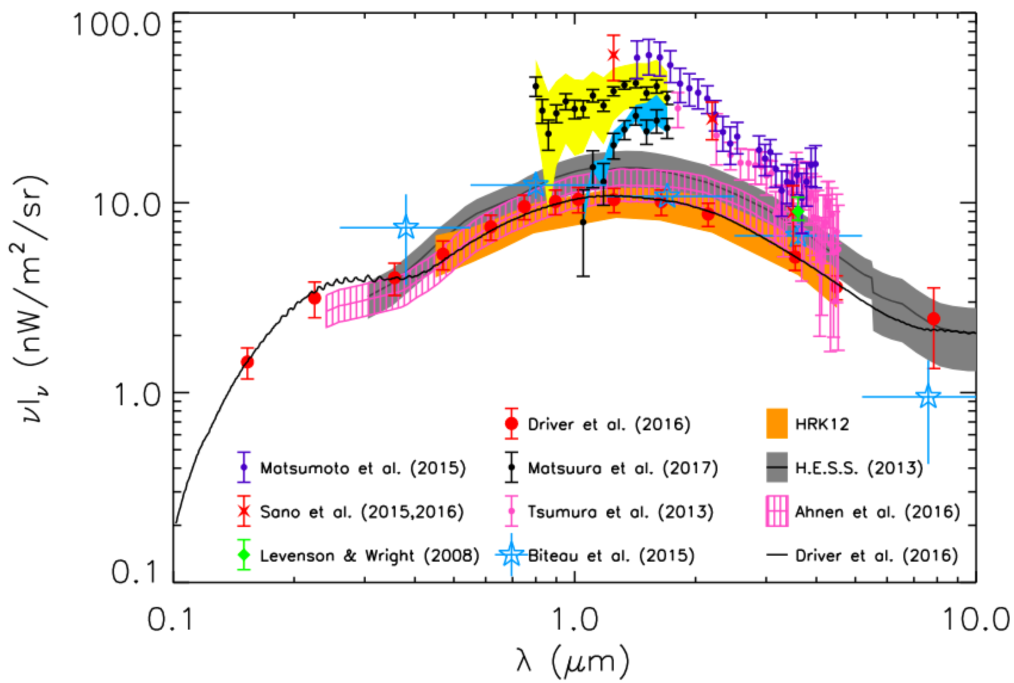

T. Arai/University of Tokyo



- Sounding rocket, equipped with a narrow-band spectrometer and wide-field imagers
- Detection of the Cosmic Infrared Background (CIB) radiation with the narrow-band spectrometer: **CIB excess detected around 1 eV**
- Measurement of anisotropies with the wide field ($\Delta\lambda = 0.5\lambda$) imagers

Why CIBER?

Kashlinsky et al. (arXiv:1802.07774)



- Difficulties: large systematic effects (Zodiacal light background, see arXiv:1704.07166 and ref. therein)
- CIB measured also indirectly (deep sky surveys, i.e. galaxy counting)+source modelling
- On the other hand, galaxy counting would miss **additional contributions** (both unresolved bottom-up accelerators or **fundamental physics contributions**)

Complementary measurements

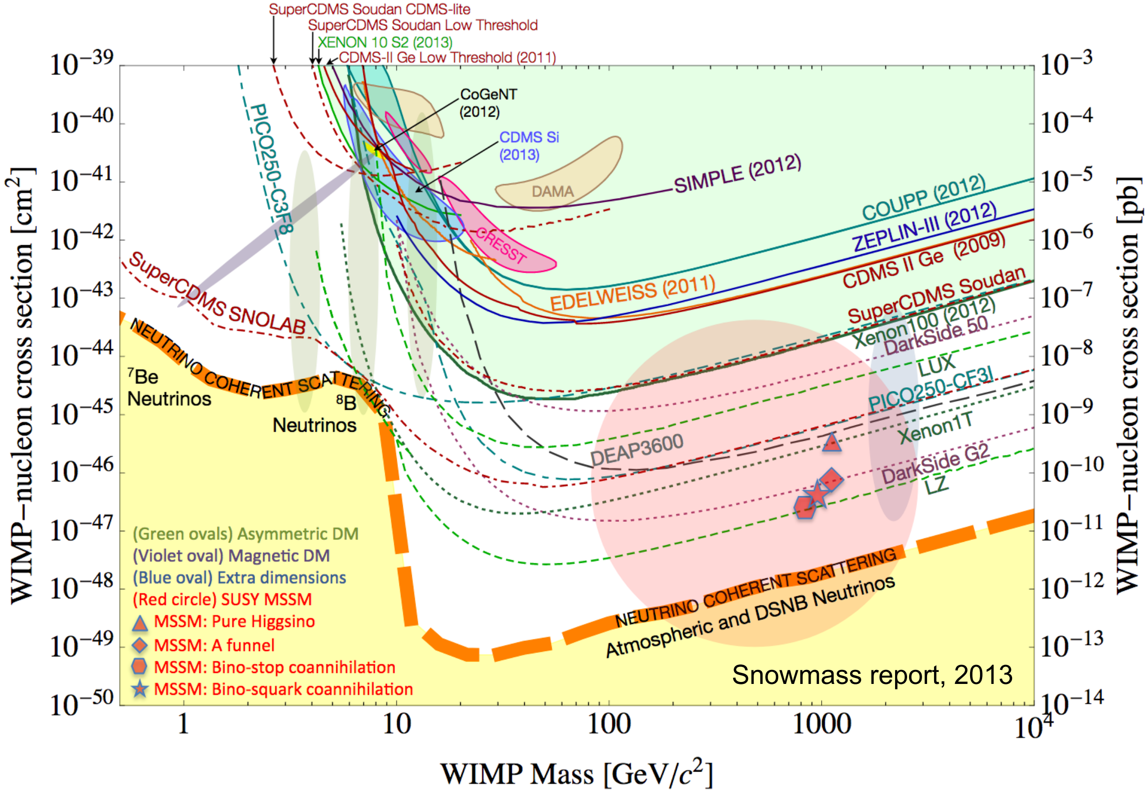
One ALP
to rule them all

A passion for detergents

An aside: new dark matter paradigms

WIMPs searches are a success (*WIMP-Moore's Law*: factor of 10 every 6.5 years!)

During the last few years lot of discussions about several dark matter candidates (from axions to MACHOs…)



Slide adapted from K.Zurek Elusives Webinar, https://projects.ift.uam-csic.es/VirtualInstitute/

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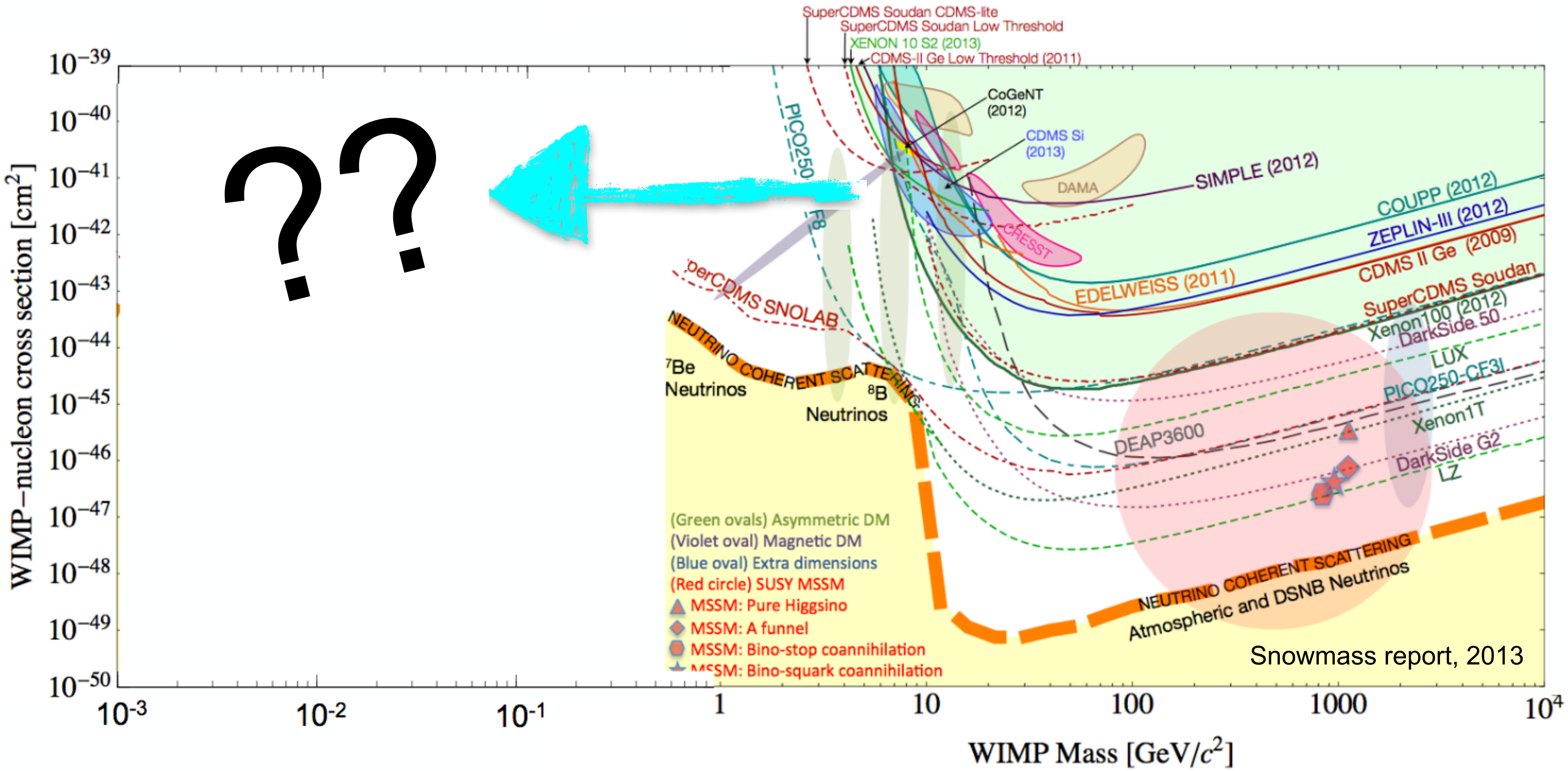

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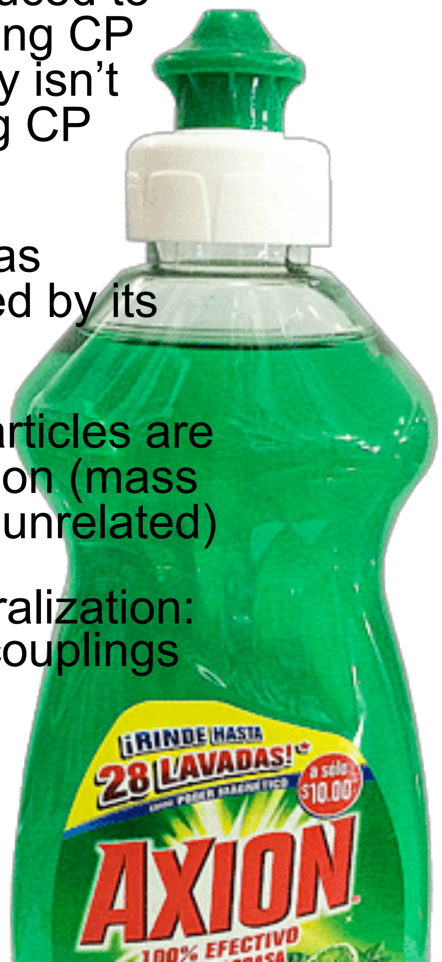
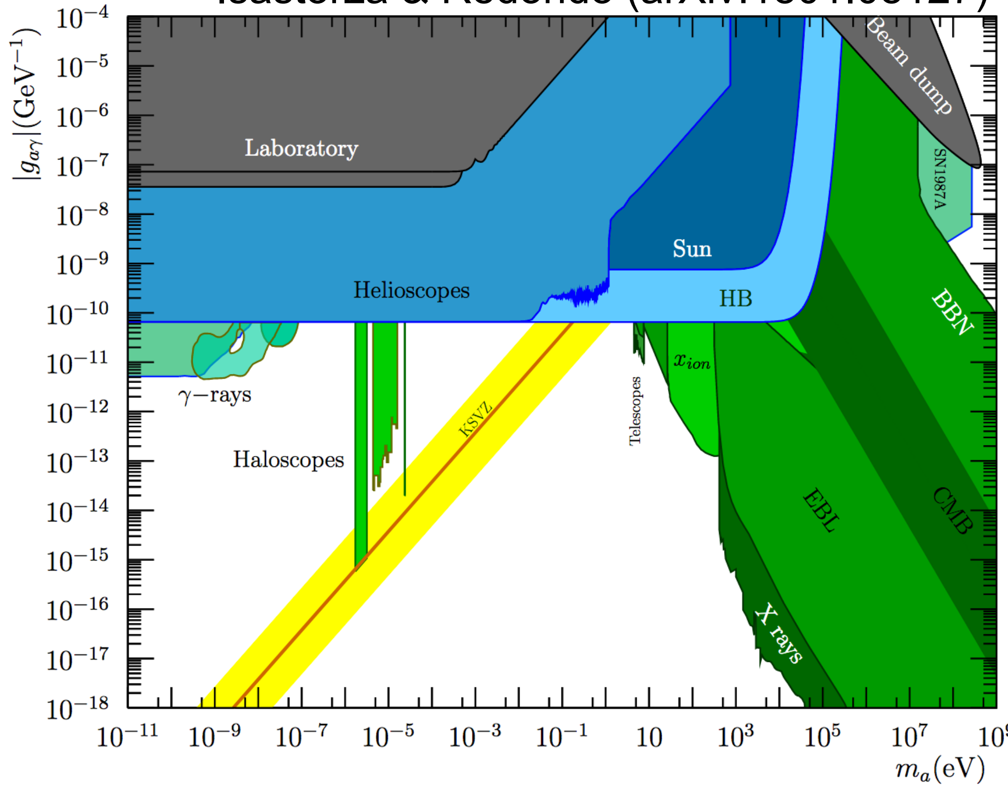
Axion-Like Particles

- Axions introduced to solve the strong CP problem ("why isn't QCD violating CP symmetry?")
- QCD axion has couplings fixed by its mass
- Axion-Like particles are a generalization (mass and coupling unrelated)
- Further generalization: generalized couplings



Isastorza & Redondo (arXiv:1801.08127)



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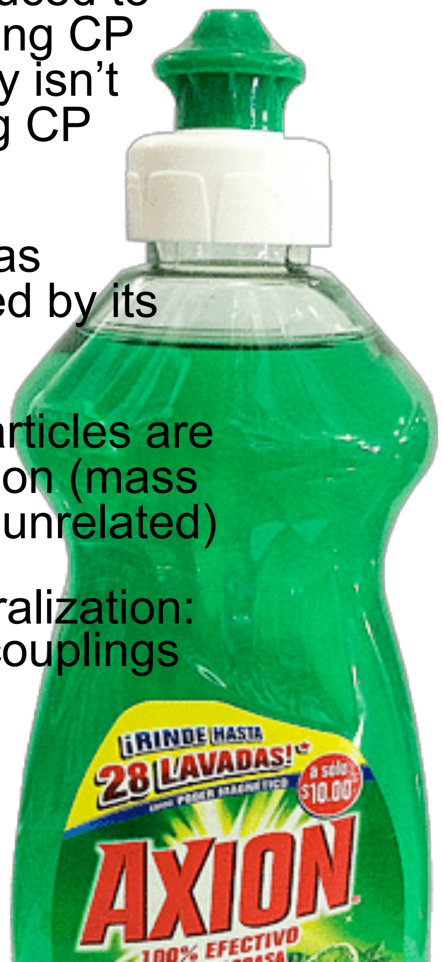

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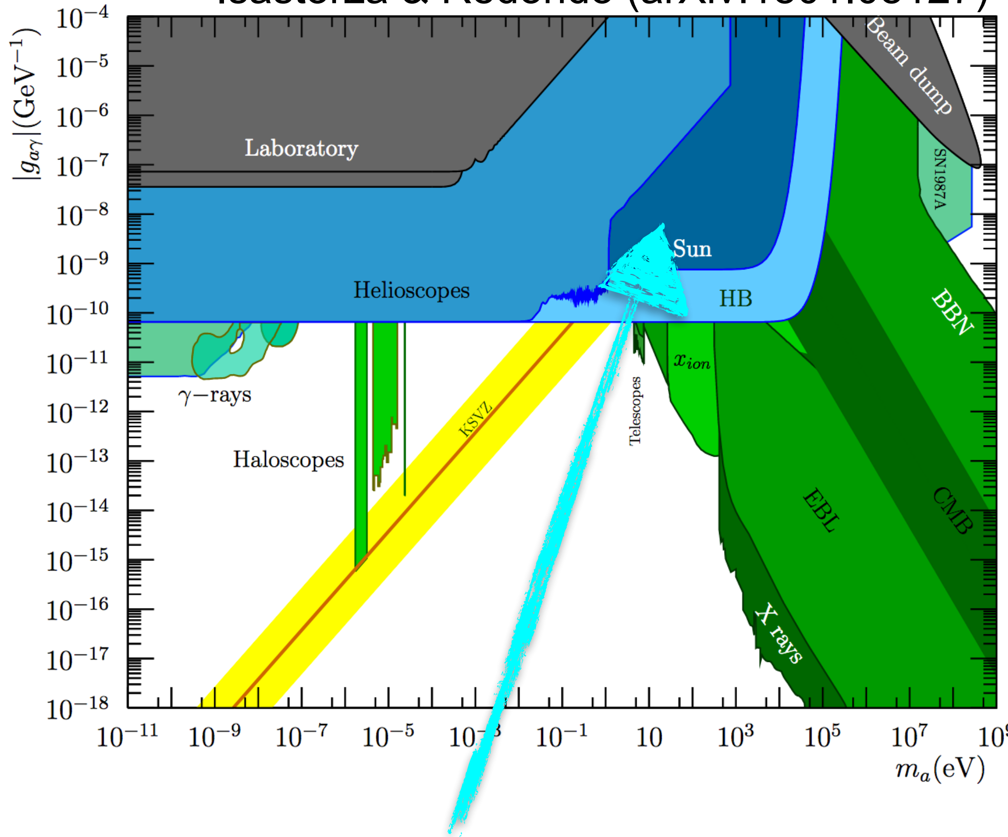


Must avoid star cooling bound!

A top-down explanation for the IR excess

We consider a photophobic ALP decaying to a photon and a hidden photon [(Kohri et al. (arXiv:1706.04921)]

$$a \to \gamma + \chi$$

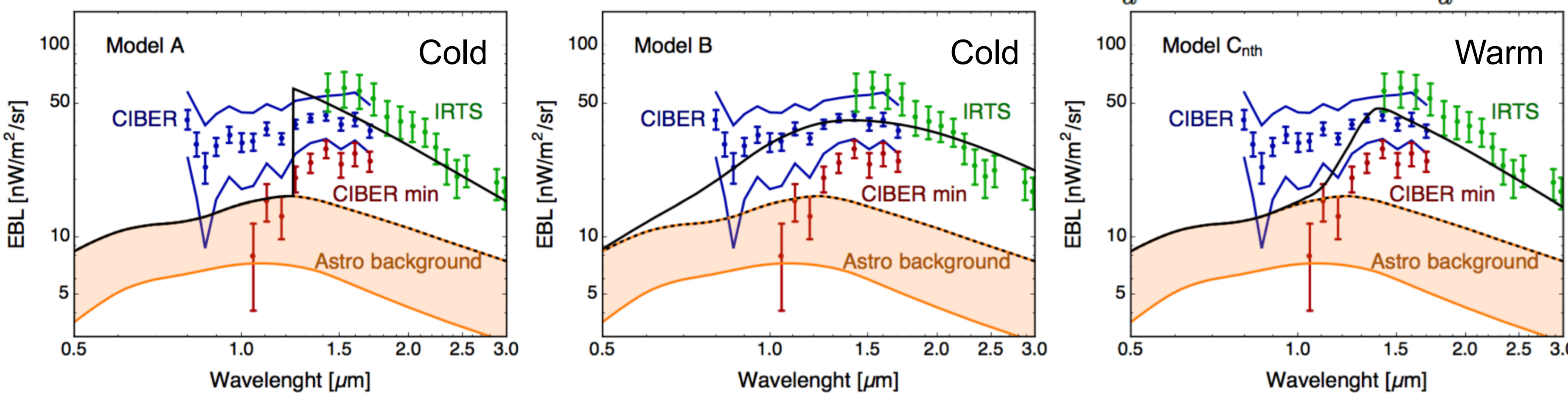
The decay is due to the Chern-Simons interaction Lagrangian

$$\mathcal{L} \supset \frac{g_{a\chi\gamma}}{4} a F^{\mu\nu} \tilde{F}^{\chi}_{\mu\nu}$$

where $\tilde{F}^{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu}$

decay rate

$$\Gamma = \frac{g^2_{a\chi\gamma}}{128\pi} \overline{|\mathcal{M}|^2} \frac{m_a^2 - m_\chi^2}{m_a^3} = \frac{g^2_{a\chi\gamma}}{128\pi} \frac{(m_a^2 - m_\chi^2)^3}{m_a^3}$$

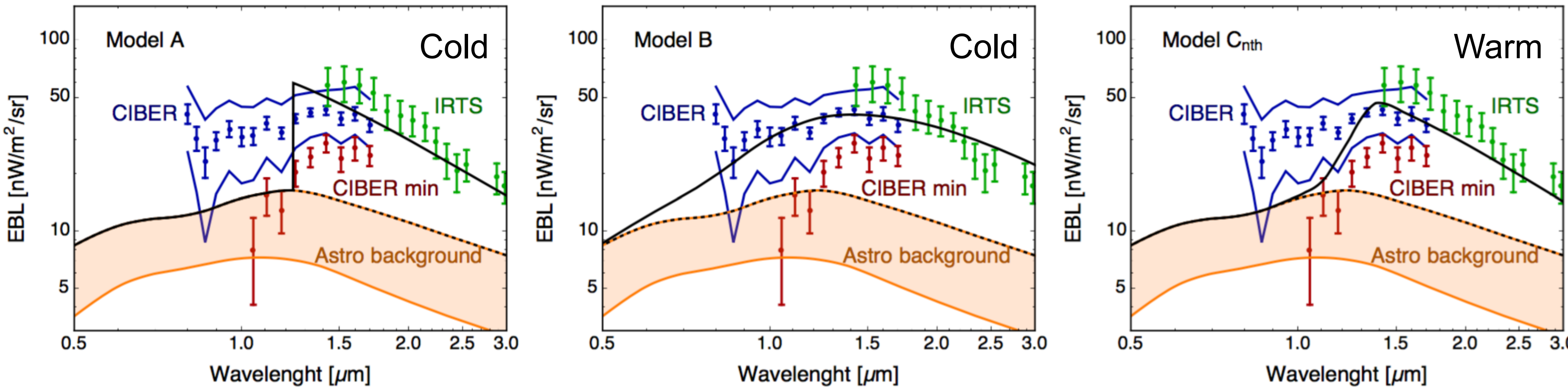


This explains the excess detected in the Cosmic Infrared Background

A top-down explanation for the IR excess

decay rate depends in non relativistic approximation only from $\omega_{\max} = (m_a^2 - m_\chi^2)/m_a$ not on m_a and m_χ

$$\Gamma = \frac{g^2_{a\chi\gamma}}{128\pi}\overline{|\mathcal{M}|^2}\frac{m_a^2 - m_\chi^2}{m_a^3} = \frac{g^2_{a\chi\gamma}}{128\pi}\frac{(m_a^2 - m_\chi^2)^3}{m_a^3}$$



Left, model A: CDM, $\omega_{\max} = 1\,\mathrm{eV}$, $\tau = 2\times 10^{22}\,\mathrm{s}$, $m_a/R = 3\,\mathrm{eV}$.
Center, model B: CDM, $\omega_{\max} = 8\,\mathrm{eV}$, $\tau = 1\times 10^{16}\,\mathrm{s}$, $m_a/R = 80\,\mathrm{keV}$.
Right, model C: WDM, $\omega_{\max} = 1\,\mathrm{eV}$, $\tau = 1/\Gamma = 3\times 10^{21}\,\mathrm{s}$, $m_a/R = 3\,\mathrm{keV}$, $T_{\mathrm{nth}} = 100\,T_\nu = 0.0167\,\mathrm{eV}$.

Redshift evolution of the EBL*

- ALPs explain the excess of CIB (infrared EBL at redshift z=0)
- If we want to explain also Fermi and IceCube we need the redshift evolution of the intensity spectrum

$$I(\omega) = \frac{\omega^2}{4\pi}\frac{dN}{dS\,d\omega\,dt} = \frac{\omega^2}{4\pi}\int_z^\infty \frac{dz'}{H(z')}\frac{(1+z)^2}{(1+z')^3}e^{-\Gamma t(z')}$$
$$\times \int \frac{d^3\mathbf{p}'_a}{(2\pi)^3 2E'_a}\frac{d^3\mathbf{p}'_\chi}{(2\pi)^3 2E'_\chi}\frac{\omega'}{4\pi^2}$$
$$\times (2\pi)^4\delta^{(4)}(p'_\chi + k' - p'_a)\overline{|\mathcal{M}|^2} f_a(\mathbf{p}'_a)$$

$$t(z') = \frac{1}{3H^{(0)}\sqrt{\Omega_\Lambda}}\log\frac{\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3} + \sqrt{\Omega_\Lambda}}{\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3} + \sqrt{\Omega_\Lambda}}$$

$$n_a = \int d^3\mathbf{p}/(2\pi)^3 f_a(\mathbf{p}_a)$$

(emitted at z', detected at z), conveniently expressed as

$$I(\omega) = \omega^2\int_z^\infty dz' W(z',\omega')$$

where $W(z',\omega')$ is a window function

*Extragalactic Background Light: diffuse spectrum, the definition includes different frequency ranges and redshifts

Hiding blazars with decaying ALPs

- Remember the tension between Fermi and IceCube?
- Assume a vanilla pɣ scenario [Murase, Guetta, Ahlers (arXiv:1509.00805)]

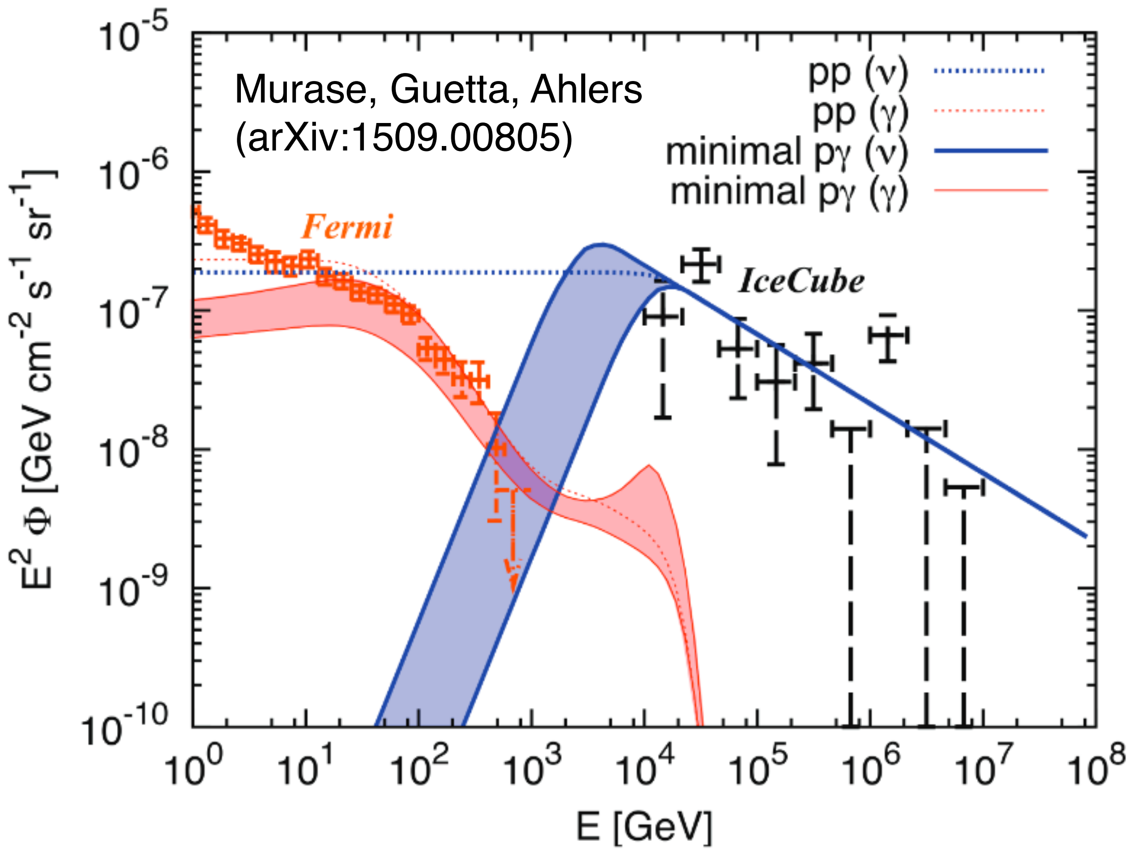
$$E_\nu^2 W(E'_\nu) \propto (E'_\nu)^{2-s}$$

$$s = 2.5 \text{ if } \mathrm{E}_\nu < 25\mathrm{TeV}$$

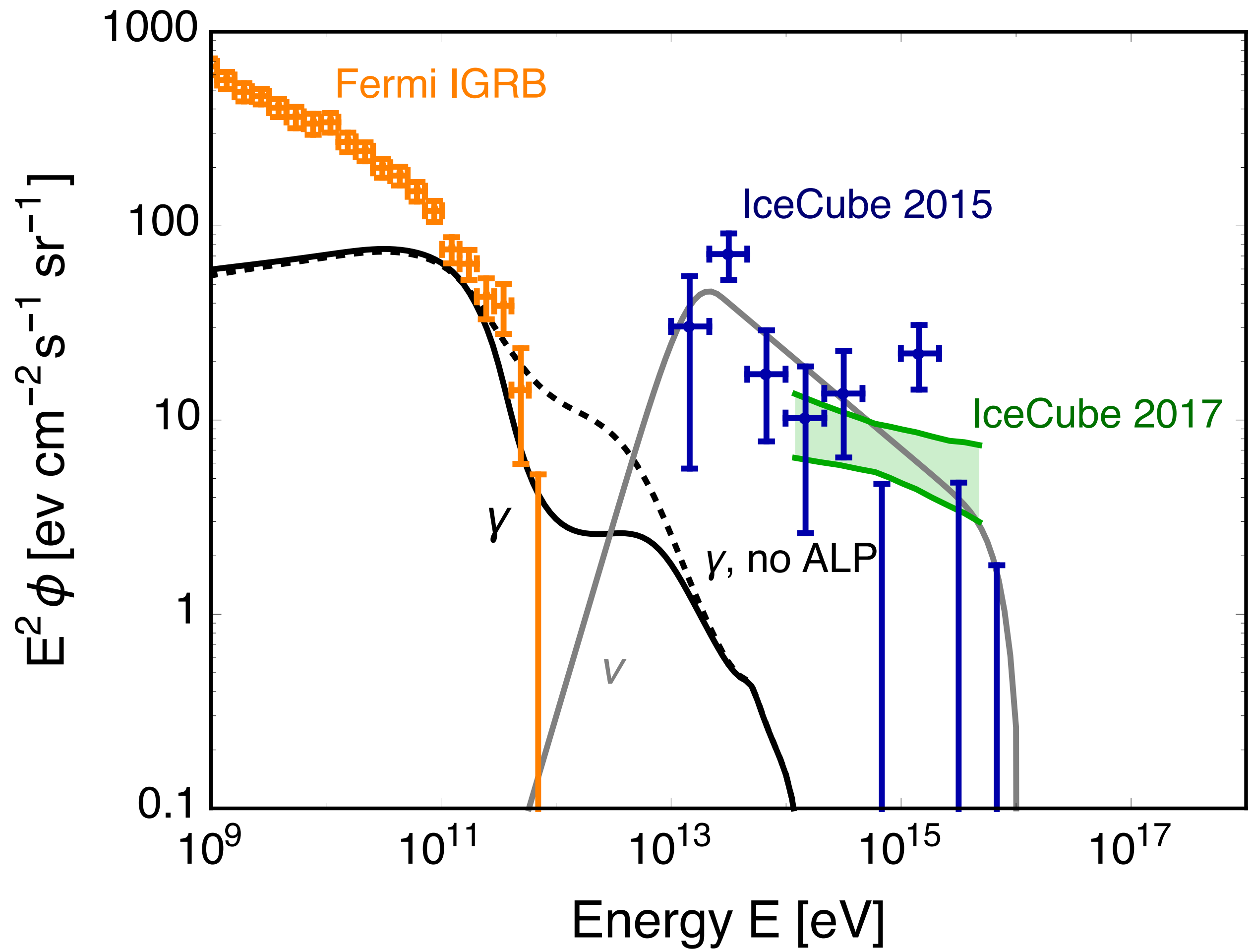
- Use as CIB a model [e.g. Stecker et al. (arXiv:1605.01382)]

  +flux due to the ALP

- Assume a model for luminosity evolution [e.g. Hasinger et al. (arXiv:0506118)]



Hiding blazars with decaying ALPs



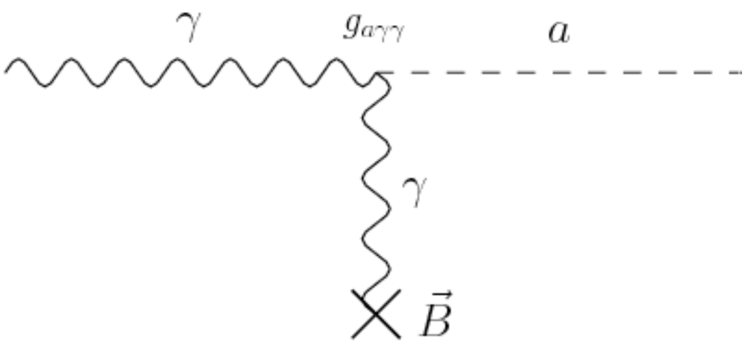
And here is the magic: blazars are now hidden

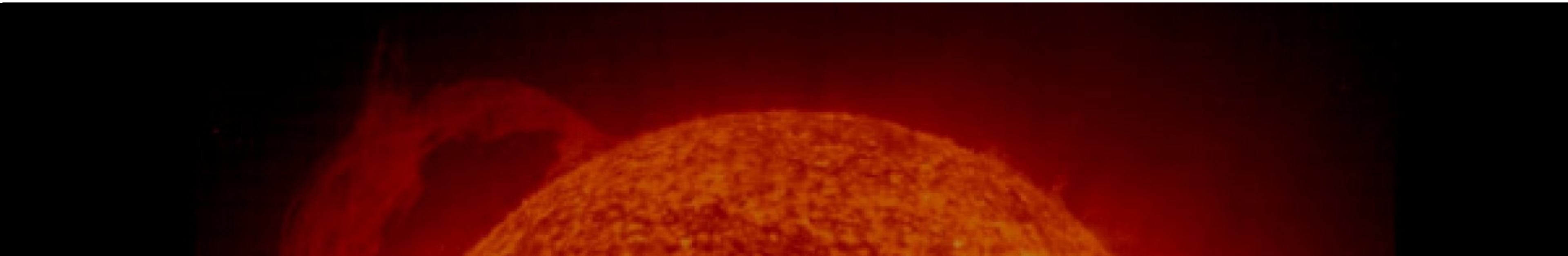
Exploring the parameter space of ALPs

Stars as laboratories of particle physics

Why did we choose a model with a hidden photon?

- Suppose we had chosen a coupling to two photons
- Primakoff process (with a photon propagating in an external field) would have converted photons into axions
- This accelerate the cooling of stars, since axions can escape easily!





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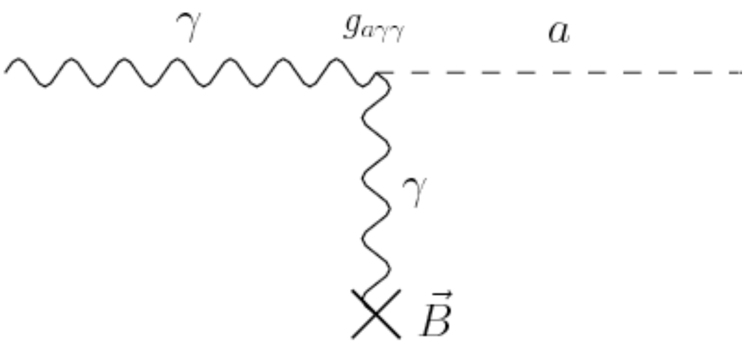
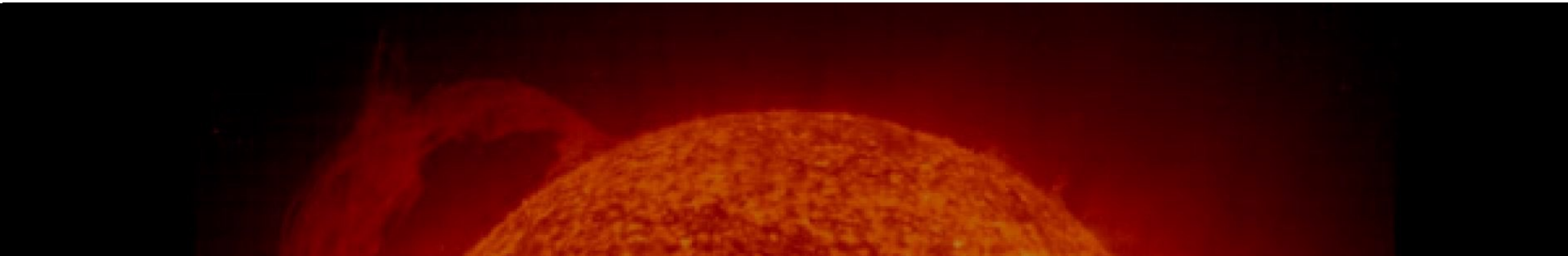


Also, other observables: the star contracts, surface luminosity increases, as well as central temperature

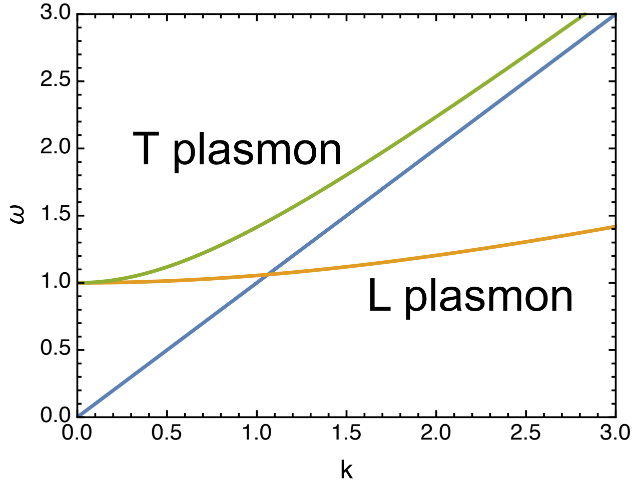


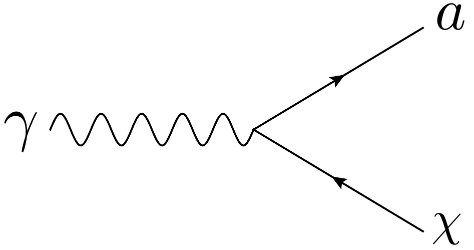
Stars as laboratories of particle physics

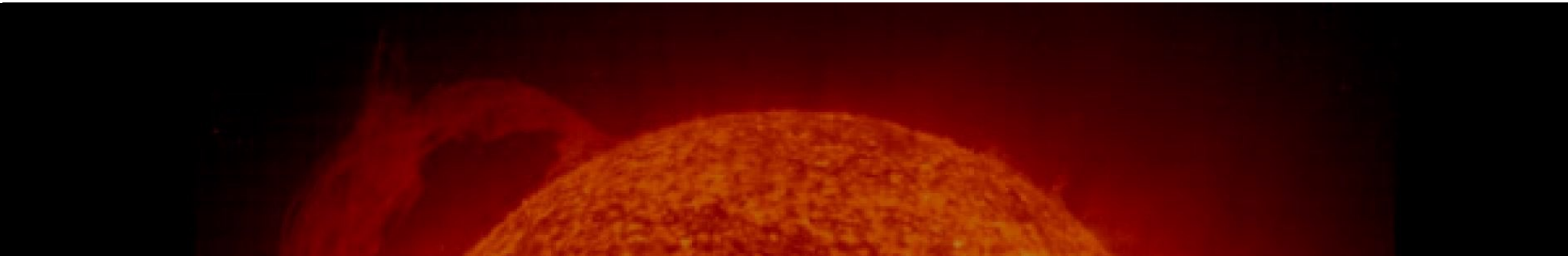
Other constraints: plasmon decay

- We can have however plasmon decay
- It's different from Compton scattering! It's the photon gaining mass from the scattering
- The photon in the medium has nontrivial dispersion relation

$$\omega^2 - \mathbf{k}^2 = \Pi(\mathbf{k})$$







Stars as laboratories of particle physics

Other constraints: plasmon decay

From Kohri et al. (arXiv:1706.04921) $\Gamma(\gamma \to \phi\chi) \simeq \frac{\omega_P^3}{8\pi M^2}\frac{\omega_P}{E}$

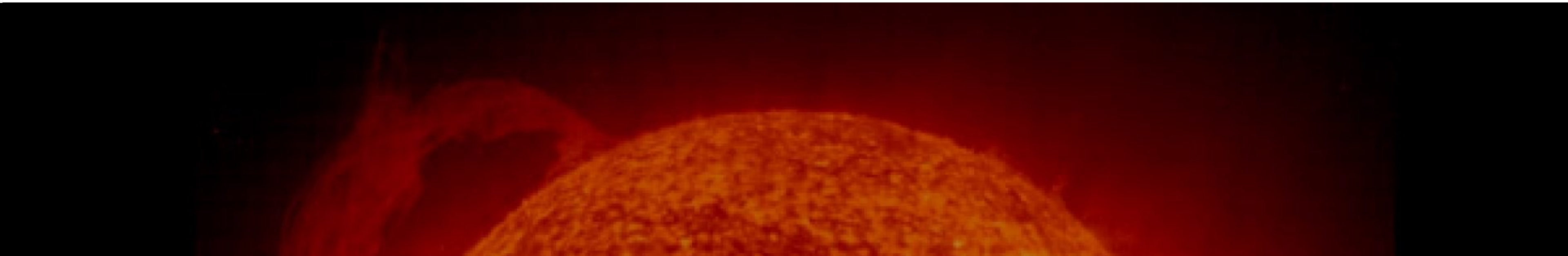
(L plasmon negligible, no resonant production)

$$\epsilon = \frac{1}{\rho_s \pi^2}\int dk k^2 \frac{E}{e^{E/T}-1}\Gamma(\gamma \to \phi\chi)$$

Taking $\omega_p \ll T$

$$\epsilon = \frac{\zeta(3)}{4\pi^3}\frac{\omega_p^4 T^3}{\rho_s M^2} \simeq 3\times 10^{-1}\,\mathrm{erg/g/s}\times\left(\frac{\omega_p}{1\,\mathrm{keV}}\right)^4\left(\frac{T}{10\,\mathrm{keV}}\right)^3\left(\frac{10^4\,\mathrm{g/cm^3}}{\rho_s}\right)\left(\frac{10^9\,\mathrm{GeV}}{M}\right)^2$$

G.G. Raffelt, Chicago, USA:Univ. Pr.(1996) → $\epsilon \lesssim 10\,\mathrm{erg/g/s}$



Parameters

So far, we have been quite generic. Which parameters for our ALP?

$$R = \frac{n_a^{(0)} m_a}{\rho_{\rm DM}}$$ How much DM is ALP?

m_a How massive is the ALP?

m_χ How massive is the hidden photon?

Γ Decay rate

$T_{\rm eff}$ Effective temperature of the ALP (could be warm dark matter!)

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Many parameters…
how can we constrain them?

Anisotropies

Anisotropies are very useful to put constraints on the parameters (not properly treated in previous analyses). The intensity, averaged over the detector bandwidth, is

$$I(\omega, \Delta\omega) = \frac{1}{\Delta\omega} \int_{\Delta\omega} d\omega\, \omega^2 \int_z^\infty dz' W(z', \omega')$$

$$\Delta\omega = \omega \text{ flat passband filter for the detector}$$

The fluctuation towards a direction is then

$$\begin{aligned} \delta I(\omega, \Delta\omega, \hat{\mathbf{n}}) =& I(\omega, \Delta\omega, \hat{\mathbf{n}}) - I(\omega, \Delta\omega) \\ =& \sum_{l,m} a_{l,m}(\omega, \Delta\omega) Y_{l,m}(\hat{\mathbf{n}}) \end{aligned}$$

Anisotropies (continued)

Usually one defines the anisotropy spectrum

$$C_l(\Delta\omega) = \langle |a_{l,m}(\Delta\omega)|^2 \rangle = \frac{1}{2l+1} \sum_{m=-l,+l} |a_{l,m}(\Delta\omega)|^2$$

So that in the Limber approximation (the power spectrum varies slowly as a function of k)

$$C_l(\Delta\omega) = \int_{z_\mathrm{m}}^{z_\mathrm{M}} dz \left\{ \frac{1}{4\pi} \frac{e^{-\Gamma t(z)}}{H(z)(1+z)^3} \omega_\mathrm{max}^2 \Gamma n_a^{(0)} \frac{1}{\Delta\omega} \right\}^2 \times \frac{1}{r(z)^2} P_\delta\left(k = \frac{l}{r(z)}, r(z)\right) H(z)$$

$$\langle \delta_{\mathbf{k}_1}(r(z_1)) \delta_{\mathbf{k}_2}(r(z_2)) \rangle = (2\pi)^3 \delta^{(3)}(k_1 - k_2) P_\delta(k_1, r(z_1), r(z_2))$$

Anisotropies (continued)

CLASS

the Cosmic Linear Anisotropy Solving System

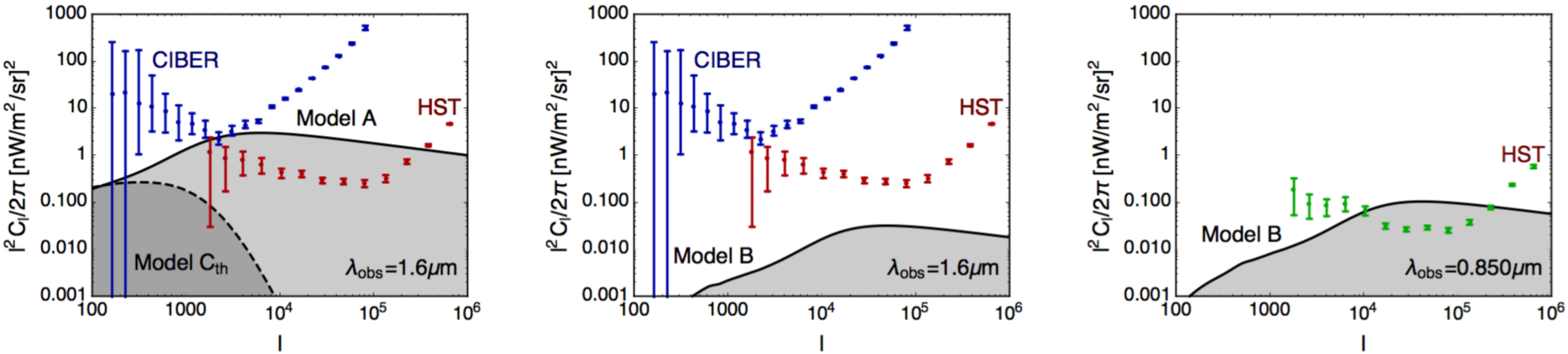
Using CLASS code (http://class-code.net/) for z=0 and

$$P_\delta\left(k=\frac{l}{r(z)},r(z)\right)=P_\delta\left(k=\frac{l}{r(z)},r=0\right)D(z)^2$$

$D(z)\,\propto\,H(z)\int_z^\infty dz'(1+z')H(z')^{-3}$ Linear growth factor

We obtained

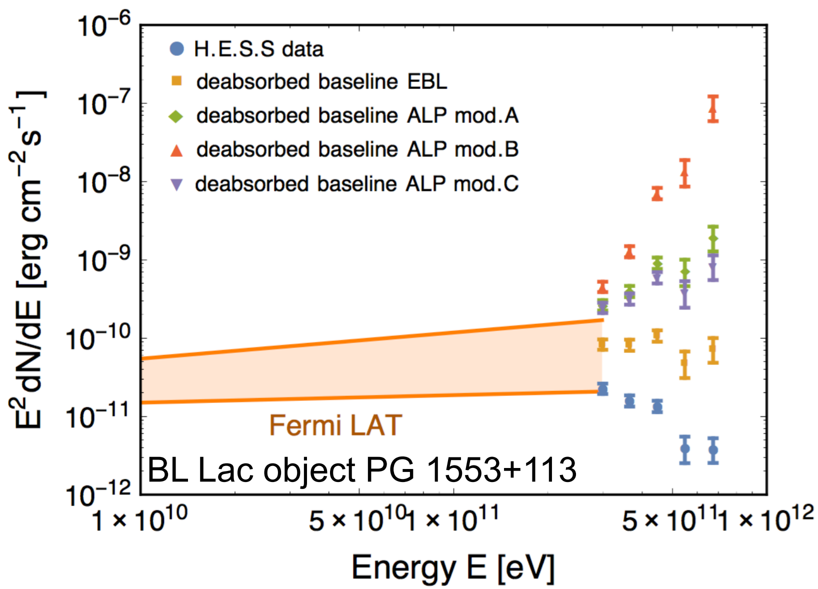
Data from Zemcov et al. (arXiv:1411.1411) and Mitchell-Wynne et al. (arXiv:1509.02935)

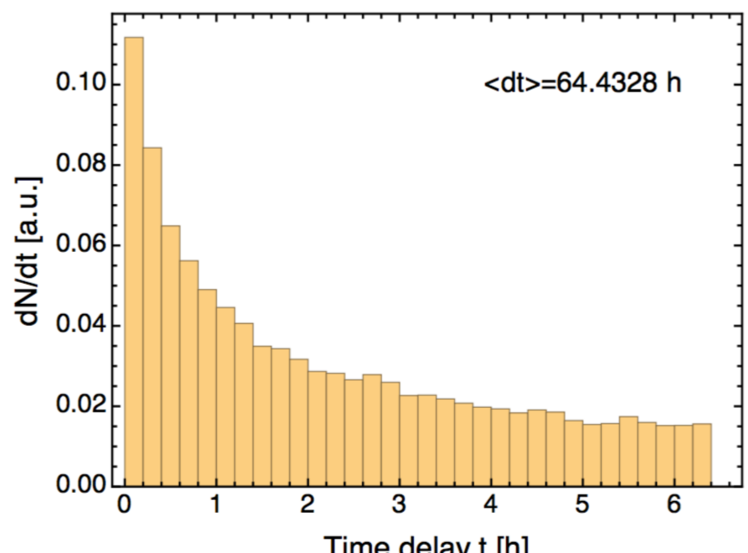


Cold dark matter is not strongly excluded, warm dark matter is totally viable!
(This could be used in the future to falsify the model)

Constraints from blazars

- Enhanced EBL sharpens the problem of blazars hard spectra (no cutoff observed experimentally)
- However, blazars could produce a secondary flux from cosmic ray electromagnetic cascades
- Besides model B, the ratio of maximal flare integral flux to minimal extra-component integral flux is in line with expectations
- Time delay of the secondary spectrum (no variability observed for distant blazars in the energy range where secondary gamma-ray flux is expected to dominate over primary gamma rays)





Conclusions

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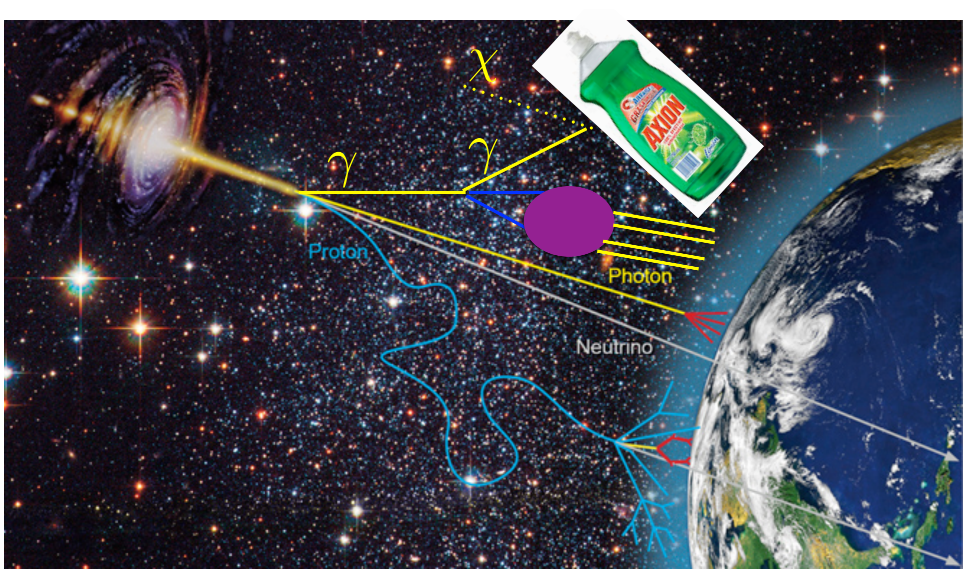
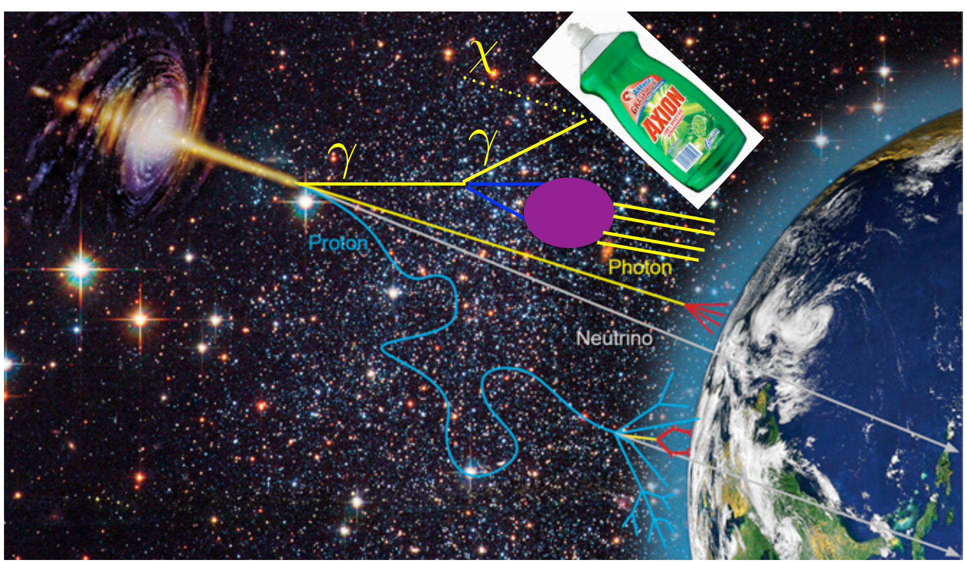
- Neutrinos are becoming crucial astrophysical probes



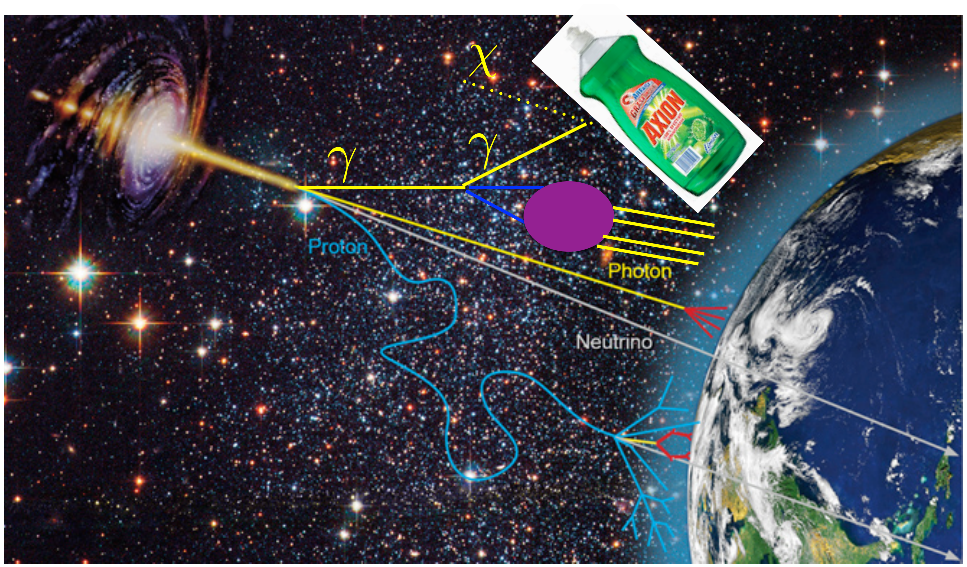
Conclusions

- Neutrinos are becoming crucial astrophysical probes
- There are tensions in *multi-messenger, multi-wavelength astronomy* observations: too much diffuse Cosmic Infrared Background radiation, too many neutrinos compared to gamma-rays



Conclusions

- Neutrinos are becoming crucial astrophysical probes
- There are tensions in *multi-messenger, multi-wavelength astronomy* observations: too much diffuse Cosmic Infrared Background radiation, too many neutrinos compared to gamma-rays
- All observations can be explained by the decay of a (warm?) axion-like particle population to photons and hidden photons



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Thank you

(You find me in 343 for more neutrino astronomy, decaying neutrinos, dark matter and fundamental physics with astrophysical systems)

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