

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters in shades of red, orange, and blue.

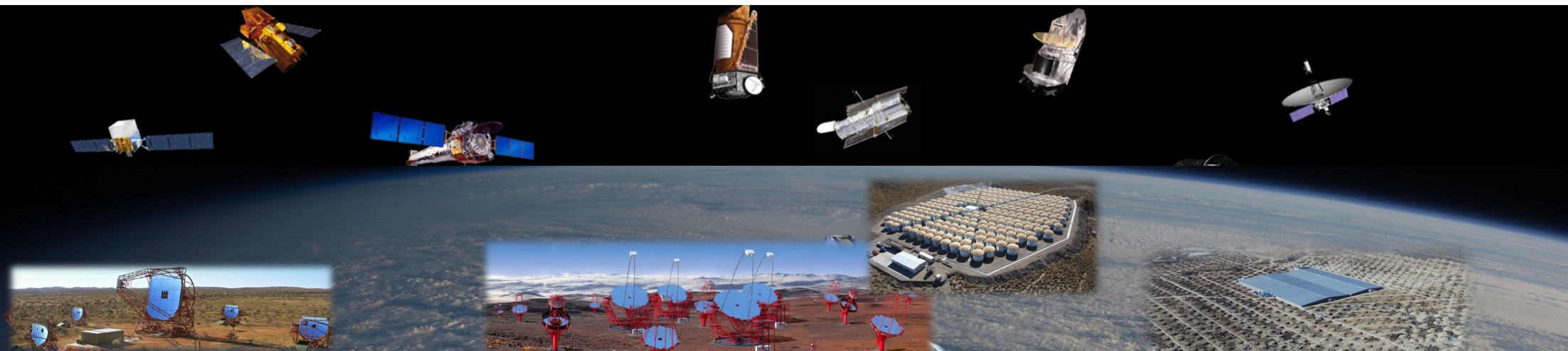
Part 2

Fundamental physics with high-energy messengers

ISAPP School 2026 – Astrophysical sources and detection

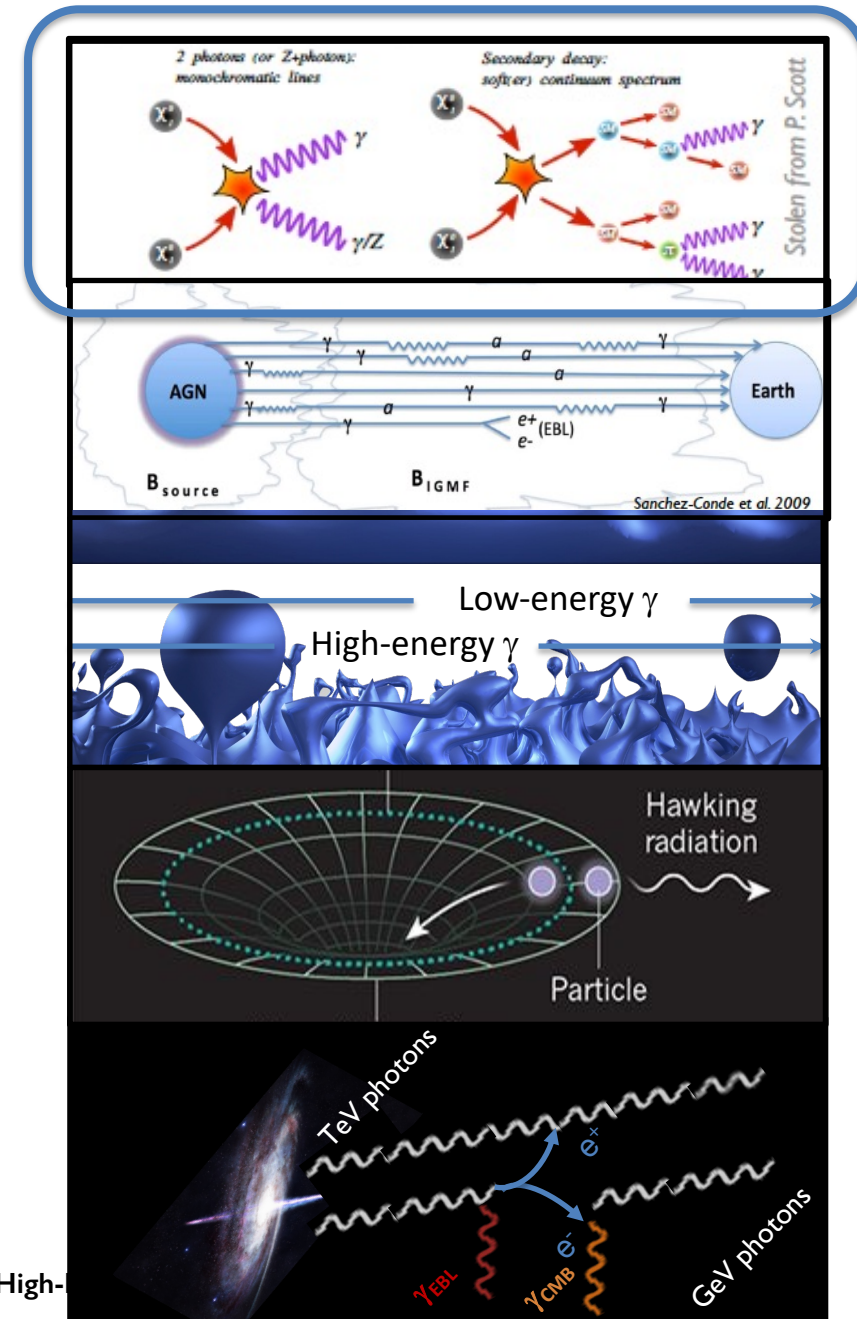
June 8-19, 2026

Emmanuel Moulin, Irfu, CEA, Université Paris-Saclay



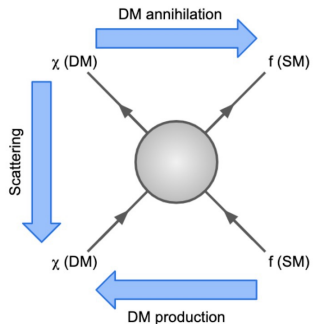
What we discussed so far:

- Dark matter evidences, WIMP paradigm, annihilation/decay
- Dark matter distribution, targets:
 - Galactic Centre, dwarf galaxies, substructures
- Gamma-ray signals /backgrounds
- J-factor estimates/measurements
- Model-independent constraints from GeV-TeV gamma rays
- Neutrino telescope limits



WIMP sensitivity prospects

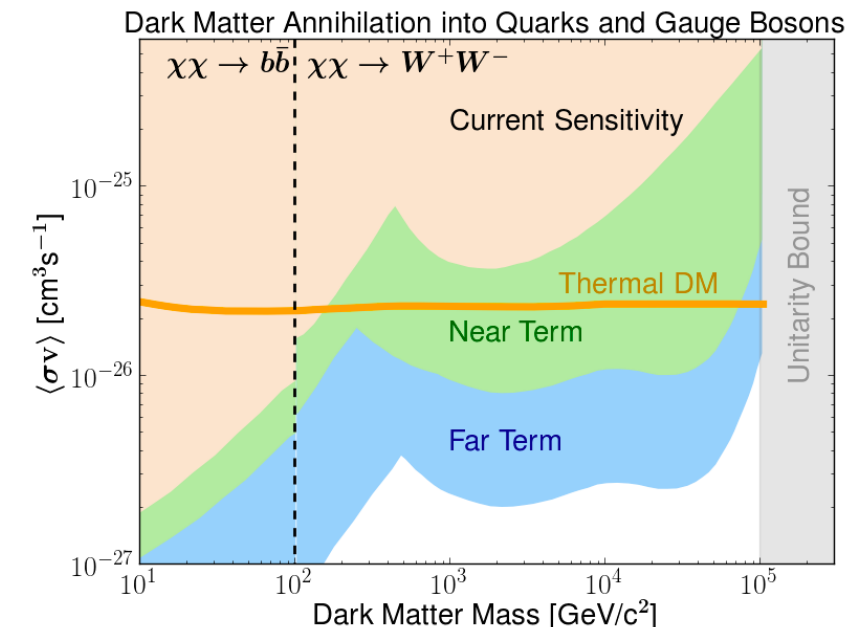
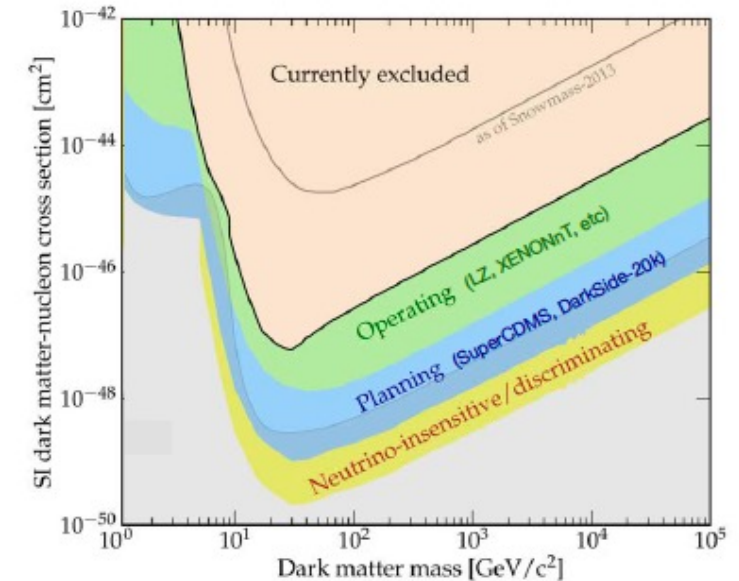
1 GeV – 100 TeV, electroweak couplings with SM bosons



- **No detection (yet) of new weak-scale physics at the LHC**
- **No detection (yet) of WIMPs in direct dark matter searches**

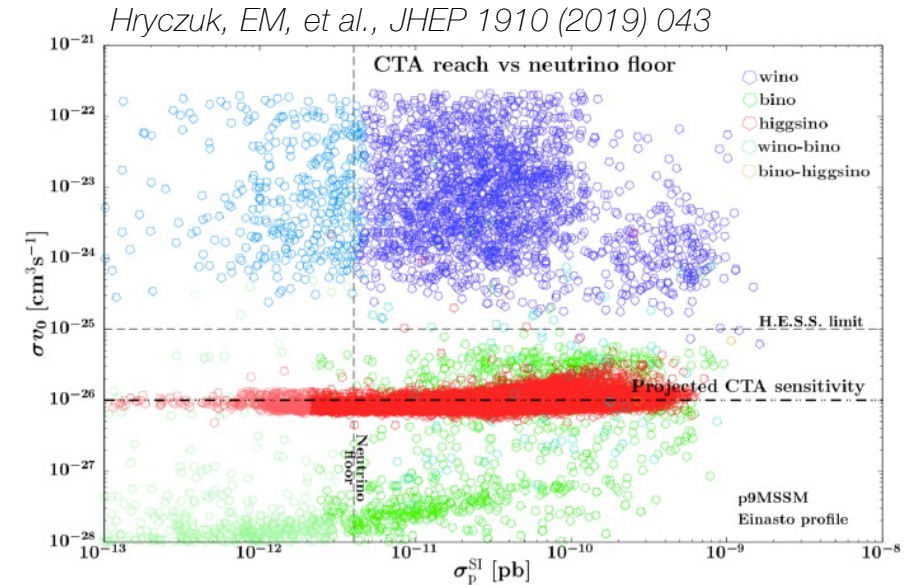
- Strong constraints from direct searches probing cross sections as small as 10^{-47} cm^2 @ 30 GeV
- Strong constraints from VHE gamma rays probing thermal relic TeV DM
- **Some of the simplest WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**

2021 Snowmass Community Study
Chapter 5: Cosmic Frontier



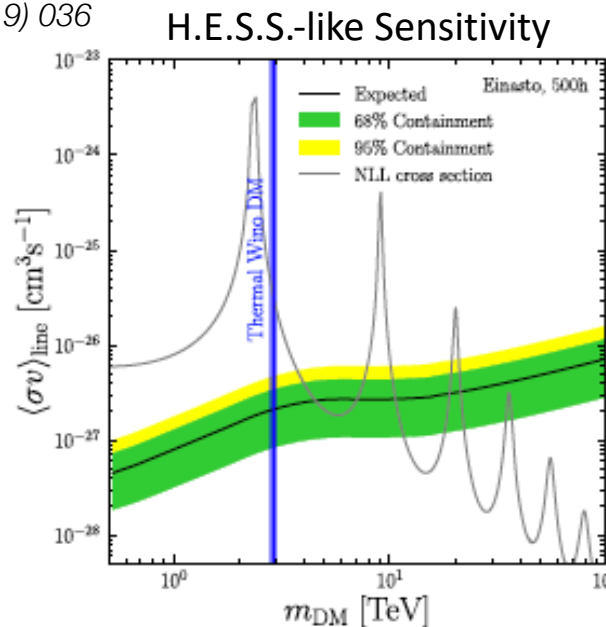
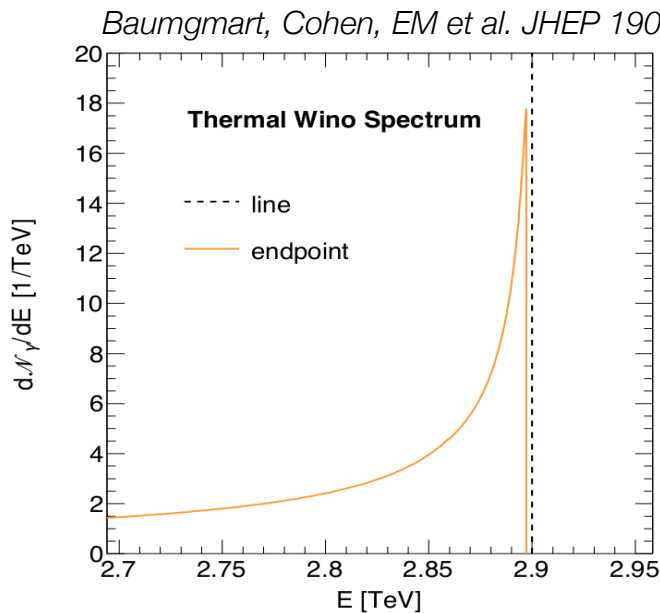
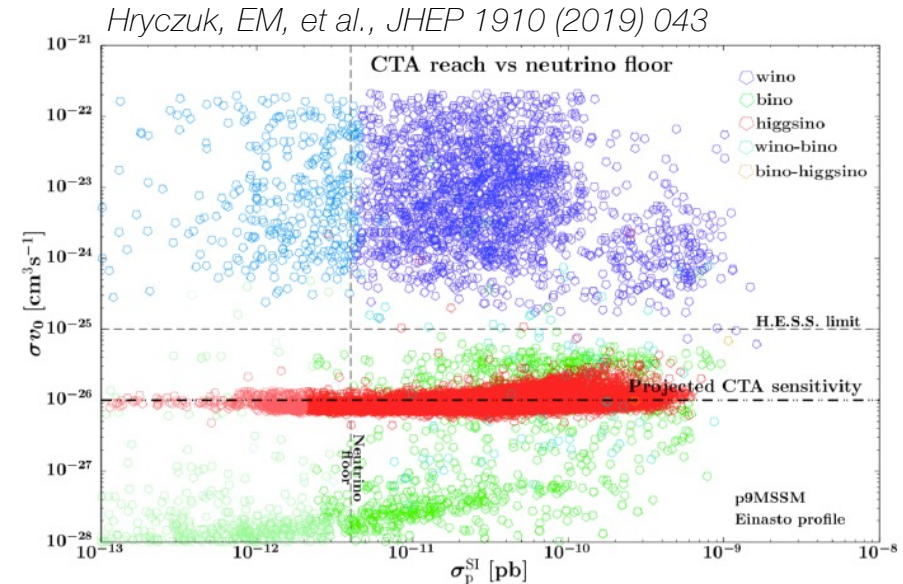
TeV DM models : Wino and Higgsino

- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!



TeV DM models : Wino and Higgsino

- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons
- Wino/Higgsino show a prominent gamma-ray line (-like) feature in the annihilation spectra



Montanari, EM, Rodd, PRD107, 043038 (2023)

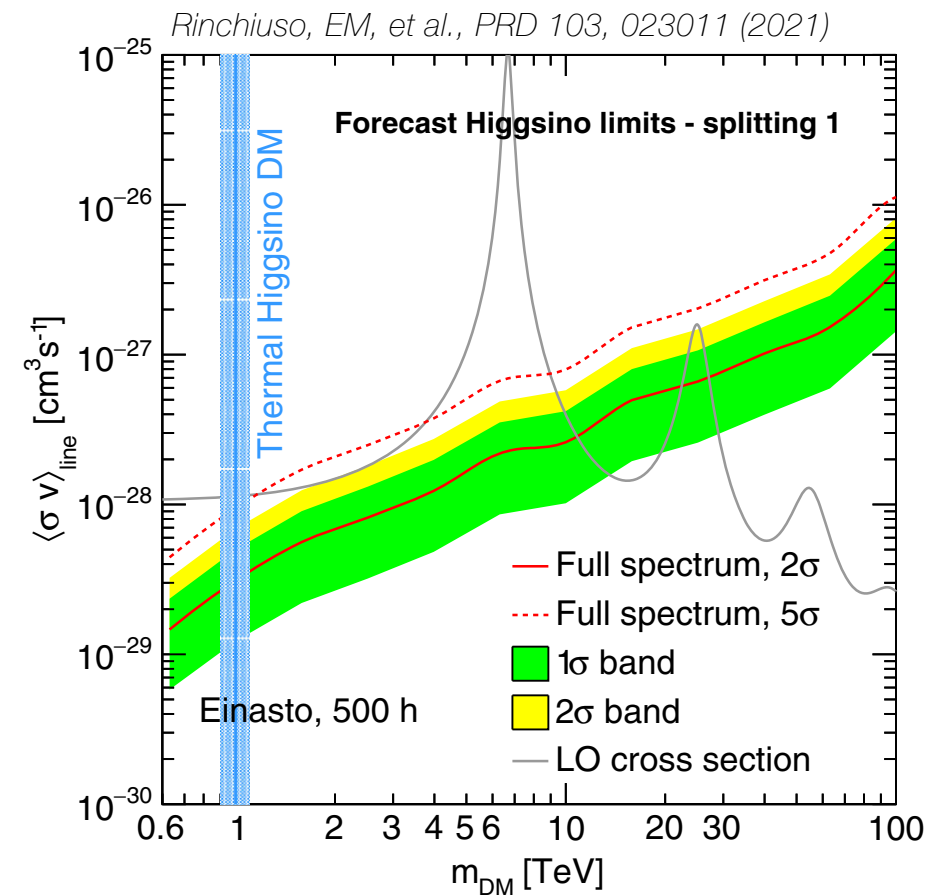
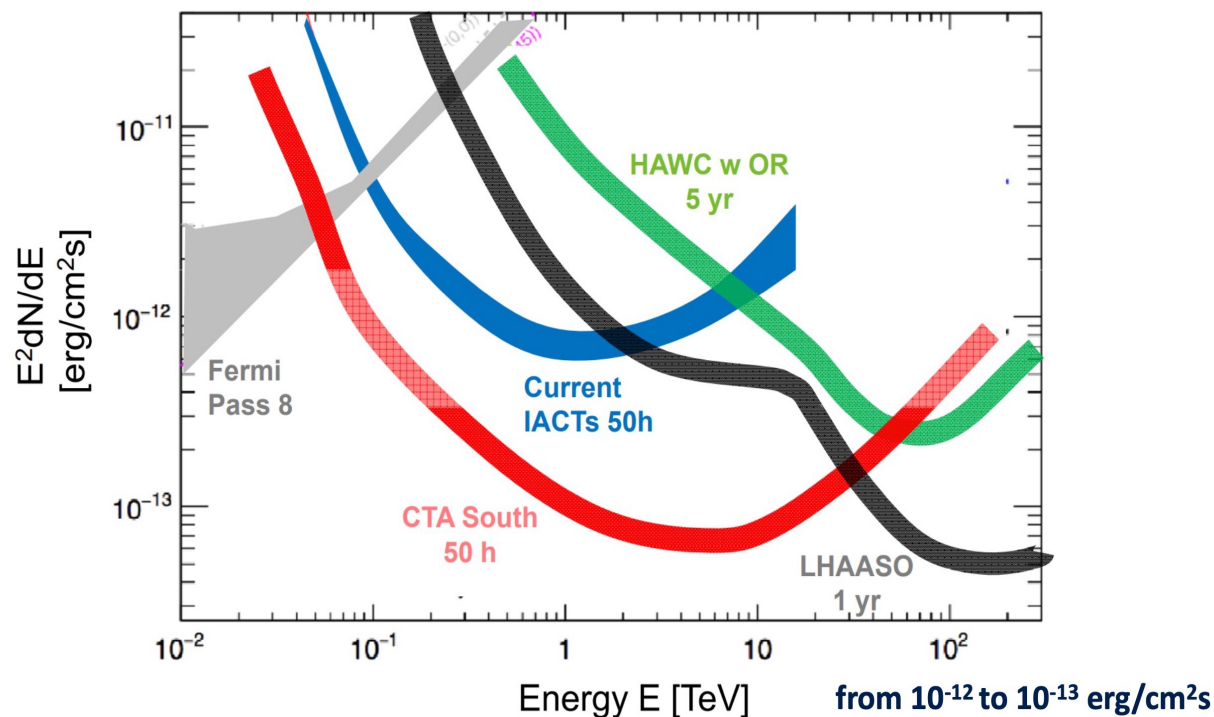
Strong constraints on Thermal Wino dark matter

- DM cores up to several kpc excluded at ~ 2 TeV
e.g, Rinchiuso, Rodd, EM, et al., PRD 98, 123014 (2018)

TeV DM models : Wino and Higgsino

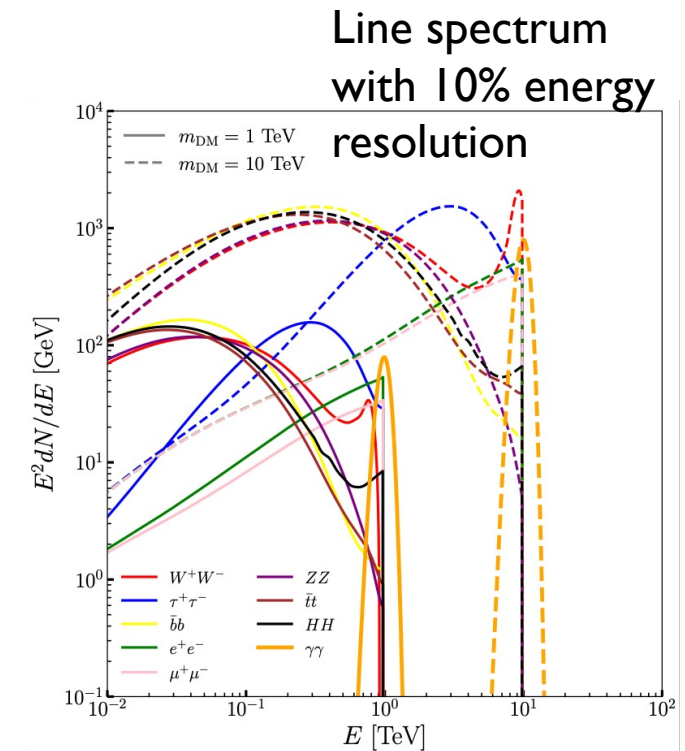
- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons

- Higgsino sensitivity forecast with CTA**



Dark matter line searches

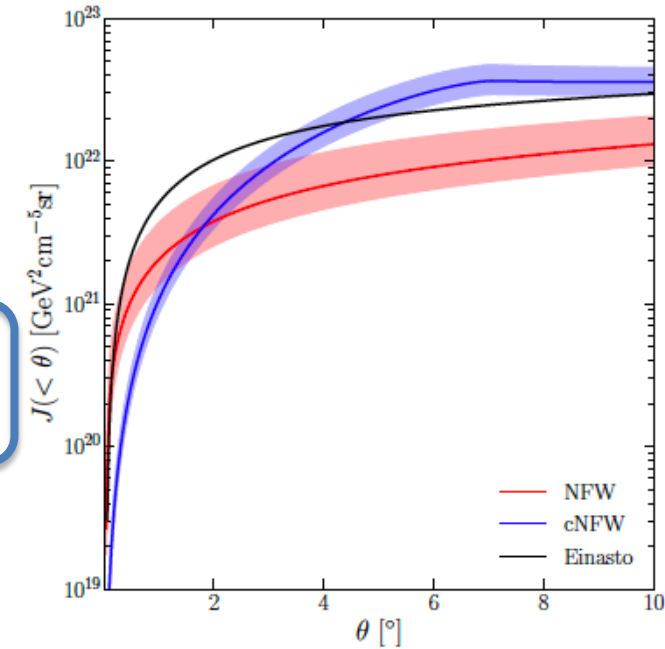
- Gamma-ray line signal from $\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow \gamma Z$ is a very “clean” possible annihilation channel
 - No astrophysical lines expected
- Best prospect for a “smoking gun” indirect signal for DM



Dark matter line searches in the GC

- Considering the DM distribution according to a standard Einasto profile with a local DM density of 0.39 GeV/cm^3 , the gamma-ray flux in the inner 1 degree around the GC can be estimated as :

$$\Phi_{\gamma}(> 0.1 \text{ TeV}) \simeq 4 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{\langle \sigma v \rangle}{2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \left(\frac{\int_{0.1 \text{ TeV}} \frac{dN}{dE} dE}{0.1} \right) \left(\frac{m_{\text{DM}}}{1 \text{ TeV}} \right)^{-2}$$



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- Gamma-ray line signal from $\chi\chi \rightarrow \gamma\gamma$ channel :

$$dN/dE = 2 \delta(E - m_{\text{DM}})$$

- Assuming a residual background (assumed to be isotropic)

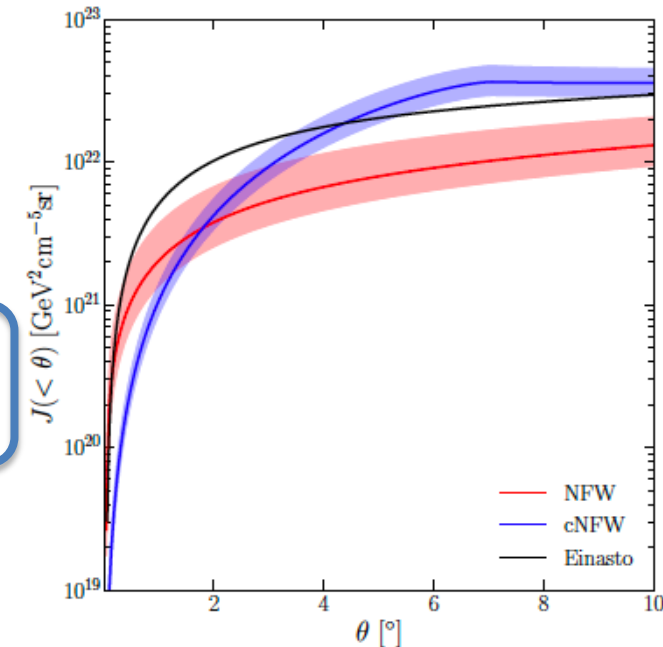
$$d\Phi_{\text{Res.Bkg.}}/dE \simeq 10^{-8} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} (E/1 \text{ TeV})^{-2.3}$$

one can estimate the value of $\langle \sigma v \rangle_{\gamma\gamma}$ for a detection at $n\sigma$ confidence level: the number of gamma rays from DM annihilation exceeds the statistical background

$$N_{\gamma}^{\text{DM}} / \sqrt{N_{\text{Res.Bkg.}}} \geq n$$

- For an observation time of 100 hours with a constant acceptance of 10^5 m^2 above 100 GeV, one can show that:

$$\langle \sigma v \rangle_{\gamma\gamma} \gtrsim 2n \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \times (m_{\text{DM}}/1 \text{ TeV})^2$$

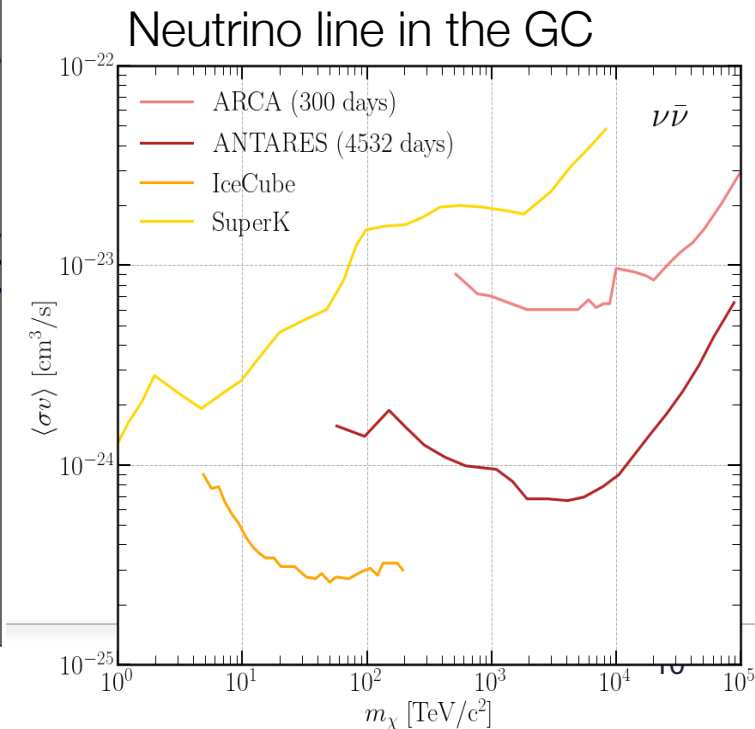
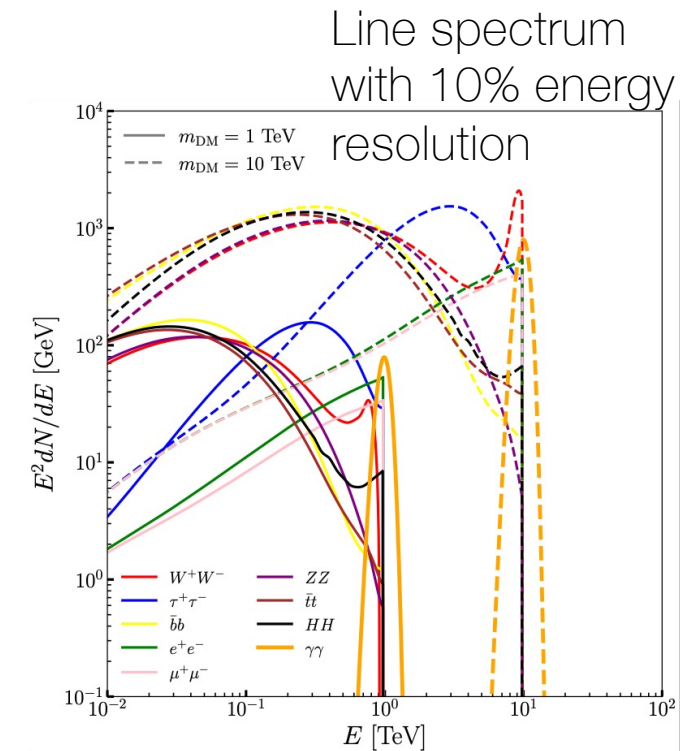
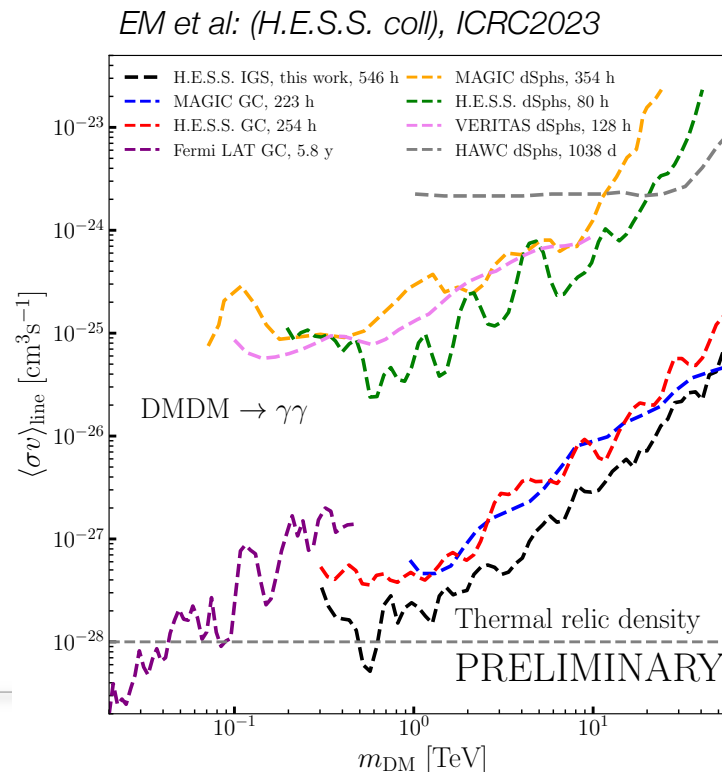


Dark matter line searches

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Stringent constraints :

- from Fermi-LAT at sub-TeV
- IACTs at $> \text{TeV}$

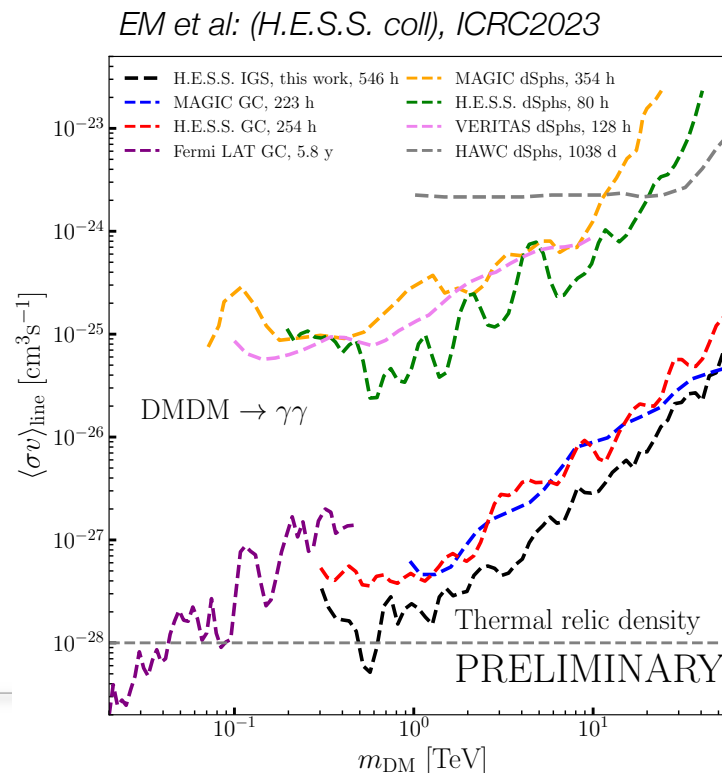
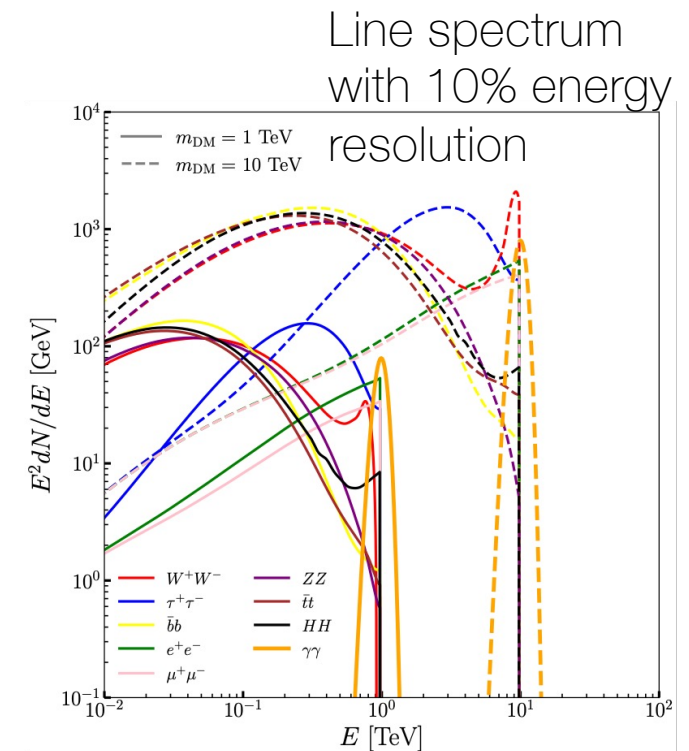


Dark matter line searches

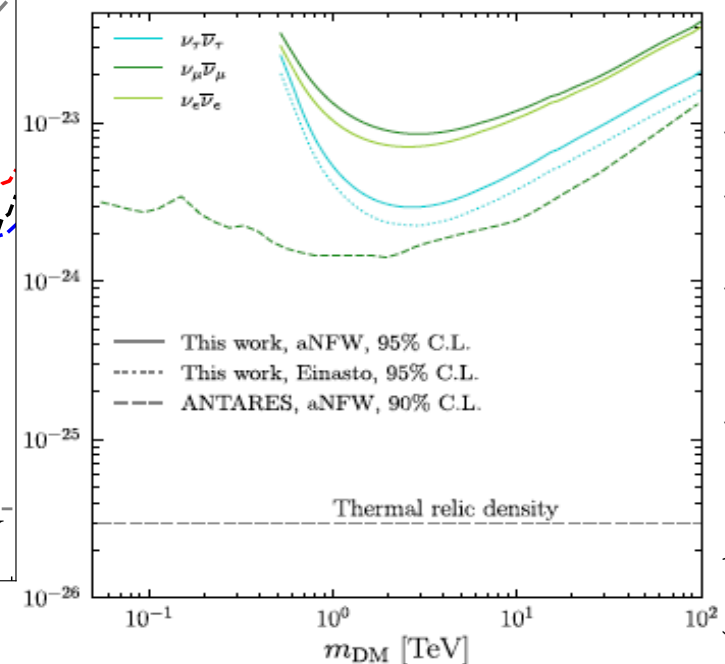
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Neutrino line in the GC



Higgsino dark matter

- Comparing to theoretical line cross section for Higgsinos

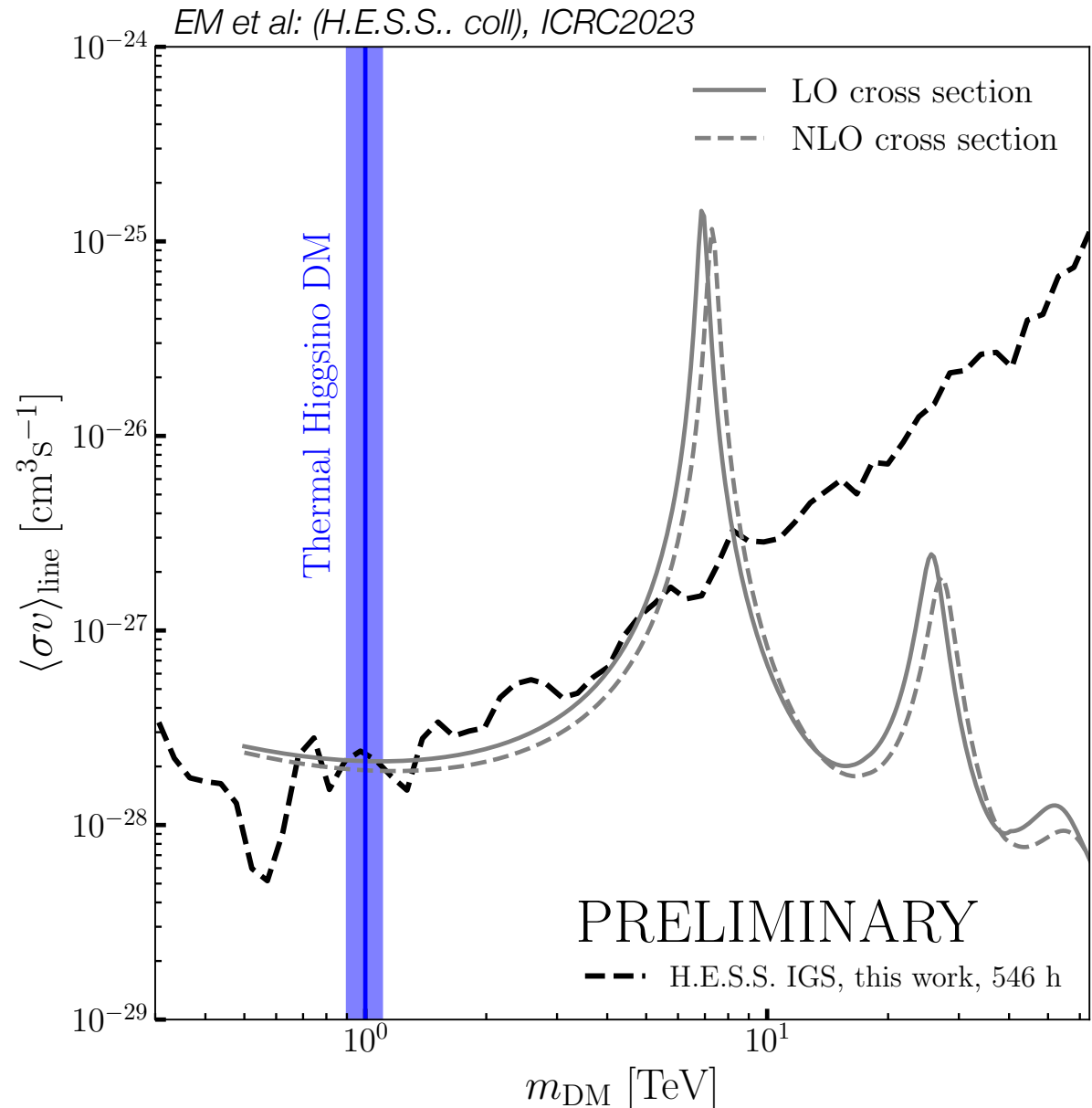
Beneke et al, PLB, 834, 137248 (2022)

- Important contribution to the annihilation spectrum for TeV Higgsino DM comes from the gamma-ray line

Rinchiuso et al. PRD 103 (2021) 023011

- Thermal Higgsino mass: 1.1 ± 0.1 TeV

- The thermal Higgsino model is probed for the first time



DM line status and prospects

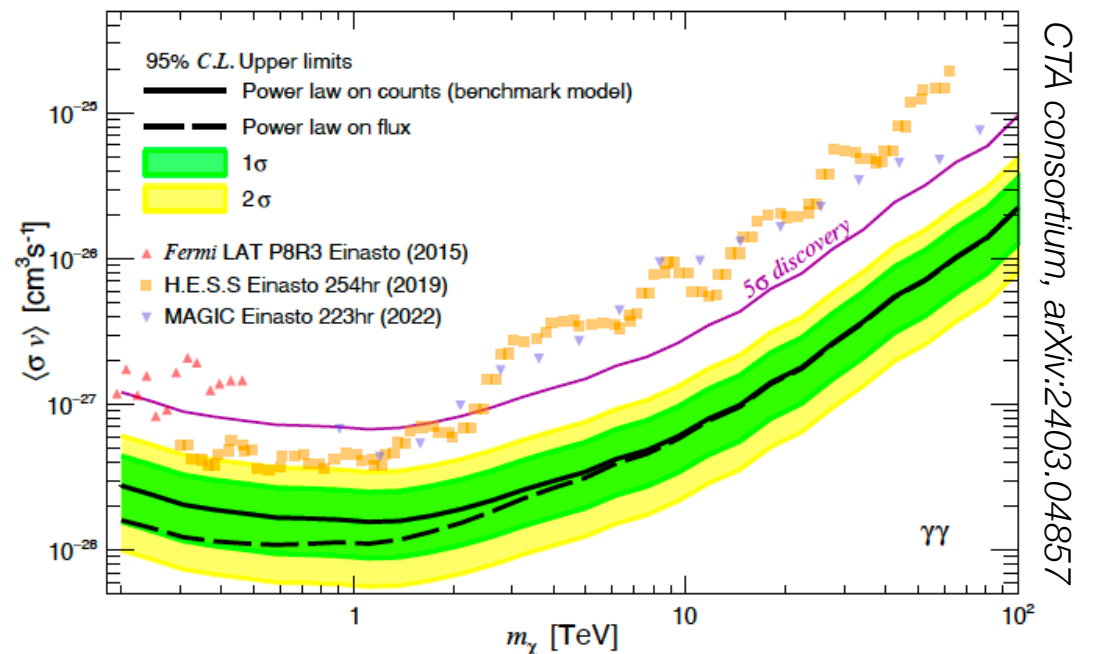
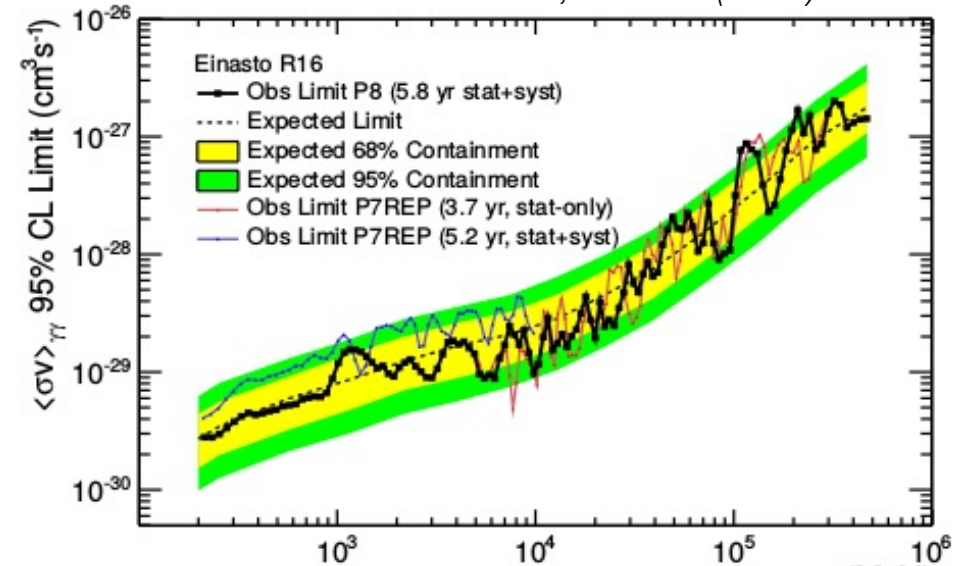
Fermi-LAT gamma lines towards the GC

- DM mass range 200 MeV–500 GeV

Prospects with Galactic Center observations with CTA:

- a total of 500 hours of observation time with a roughly homogeneous exposure over the inner 4°
- A factor of 2-to-10 improvement compared to H.E.S.S./MAGIC

Fermi-LAT Coll. PRD. 91, 122002 (2015)



Heavy Decaying Dark Matter

DM $\rightarrow$ SM SM

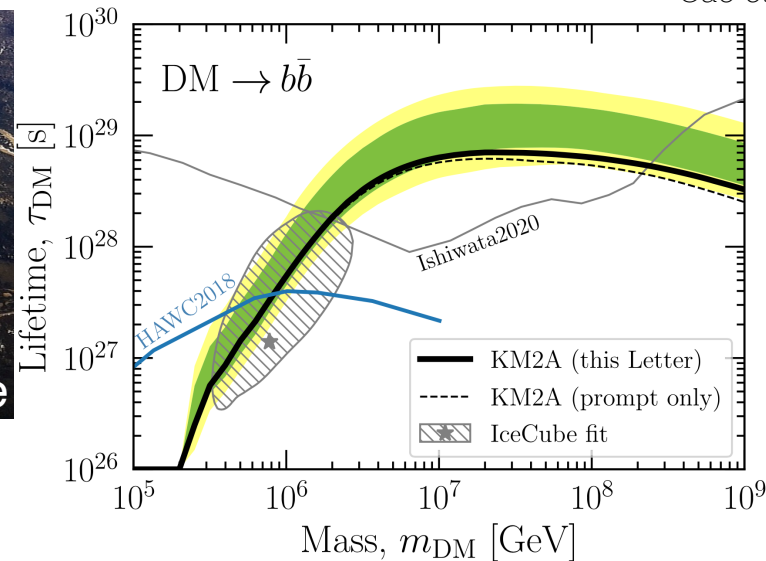
- Decaying DM searches target regions of the sky where large volumes can be probed, i.e., galaxy clusters

- > PeV dark matter with wide FoV instruments

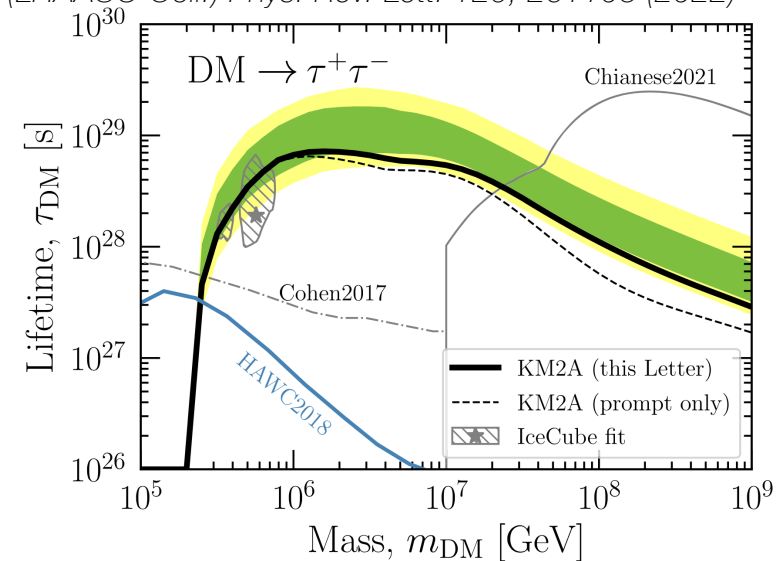
570 days of LHAASO Observations

$\sim 15^\circ < b < 45^\circ; 30^\circ < l < 60^\circ: 0.27 \text{ sr}$

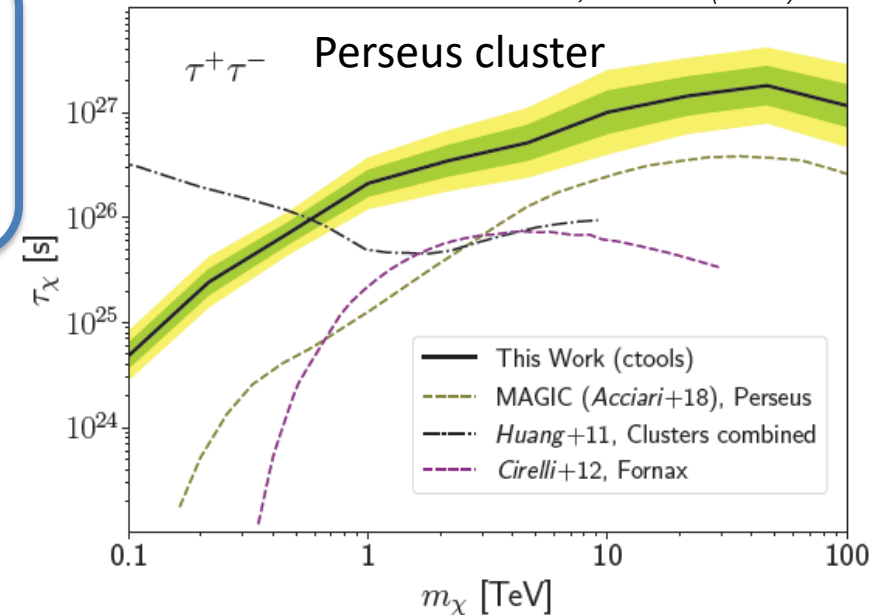
$\rightarrow$ Strongest constraints on PeV DM



Cao et al. (LHAASO Coll.) Phys. Rev. Lett. 129, 261103 (2022)

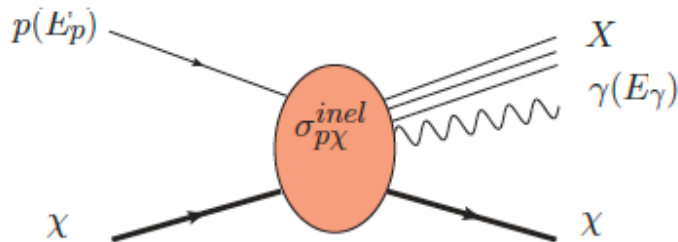


CTA consortium, JCAP10(2024)004



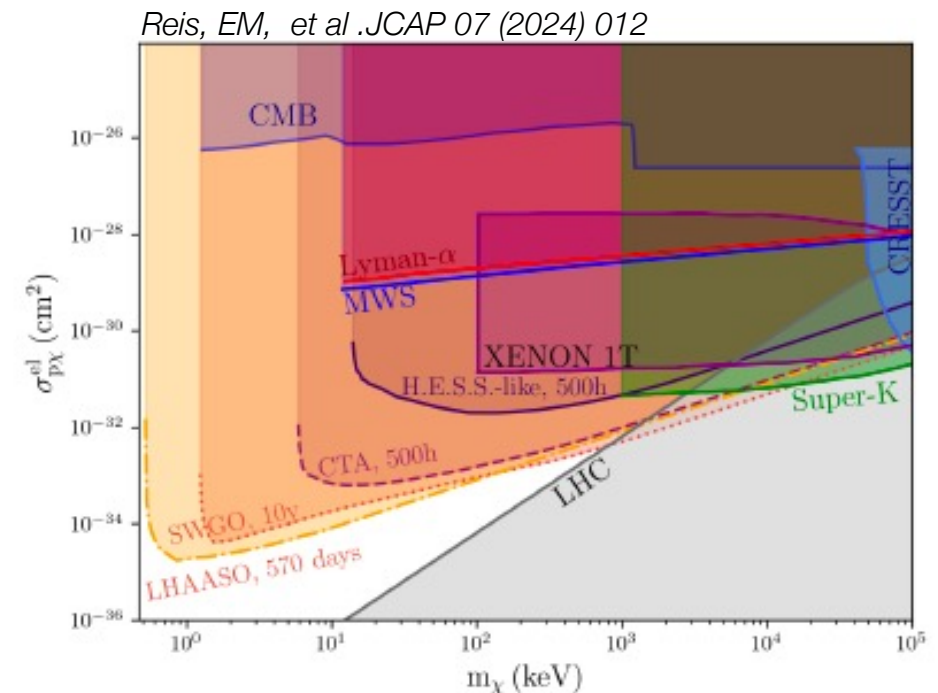
Alternatives to dark matter annihilation/decay

- Cosmic particle interaction with dark matter
 - interactions of dark matter with ordinary matter
 - astrophysical sources of high-energy neutrinos, electrons, protons as a particle beam
- Inelastic scattering:
 - $\chi + p \rightarrow \chi + p + \text{hadronic showers} + \gamma\text{-rays} + \text{neutrinos}$
- GC harbors both high DM density and hadronic accelerator

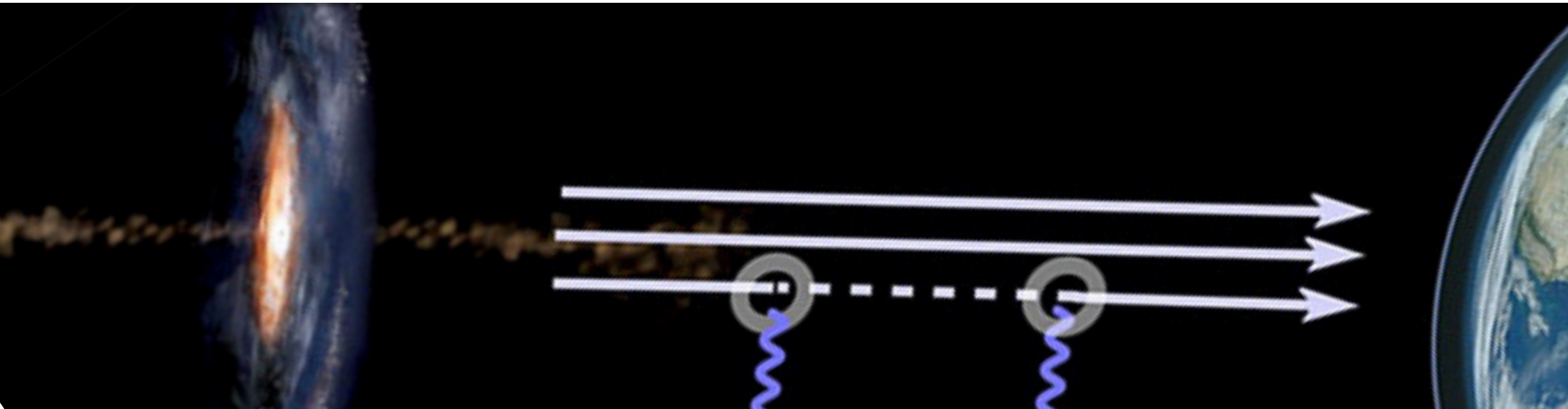


In absence of specific underlying DM models:
the inelastic to the elastic cross section can be related such as $\sigma_{p\chi}^{inel} = 8/3 \sigma_{p\chi}^{el}$

Broilo, et al. Phys. Rev. D 101 (2020) 074034



AXION AND AXION-LIKE PARTICLES



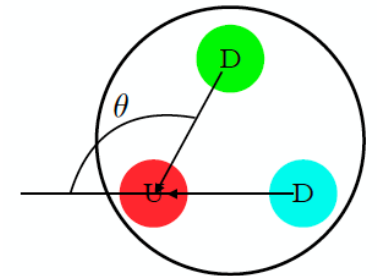
Axions and the strong CP problem

- Strong CP problem : no violation of the CP-symmetry observed in strong interaction
- Axion is by-product of a solution of strong CP problem in QCD:
 - Standard Model involves a parameter θ : one expects $\theta \sim O(1)$. When sent to zero it, no violation is expected.

$$\mathcal{L}^{QCD} \subset \frac{\theta \alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

- Observable: electric dipole moment of the neutron
 - A classical estimate :

$$|d_n| \approx 10^{-13} \sqrt{1 - \cos \theta} \text{ e cm}$$



Classical picture of a neutron

- A small electric dipole moment of neutron could be explained by approximate CP symmetry of strong interaction.

Axions and the strong CP problem

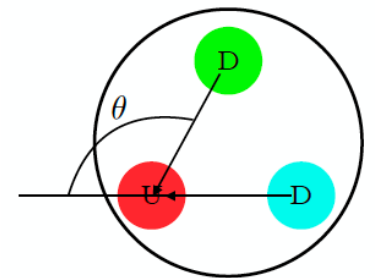
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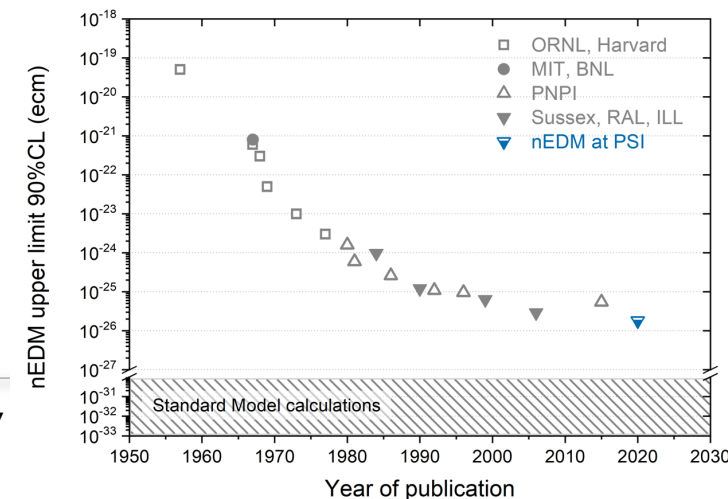
- Observable: electric dipole moment of the neutron
 - A classical estimate :

$$|d_n| \approx 10^{-13} \sqrt{1 - \cos \theta} e \text{ cm}$$

- Current bound is: $|d_n| \leq 10^{-26} e \text{ cm}.$
 - why $\theta \leq 10^{-13}$?
 - strong CP problem



Classical picture of a neutron



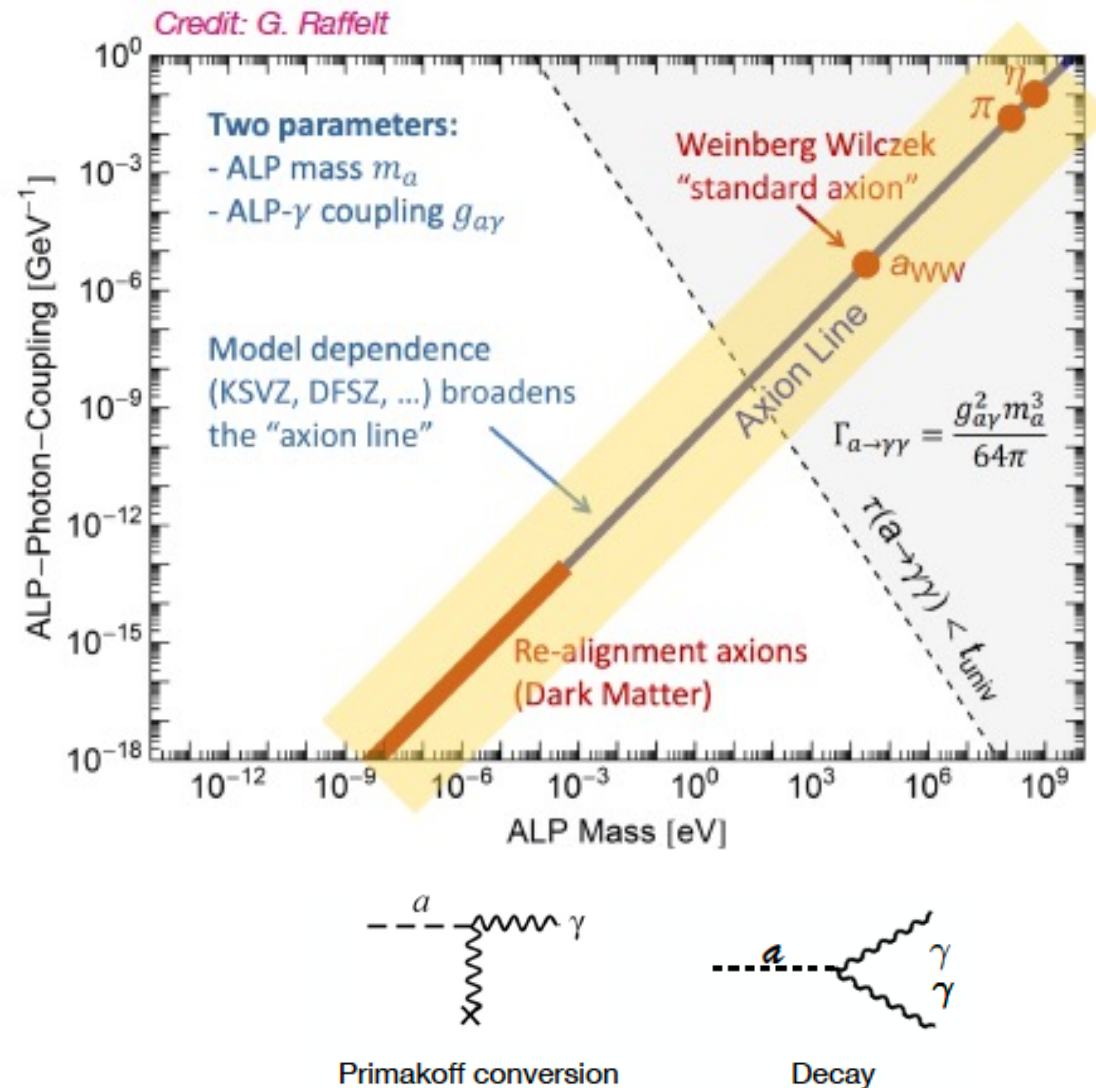
Axions and the strong CP problem

- Strong CP problem : no violation of the CP-symmetry observed in strong interaction
- Axion is by-product of a solution of strong CP problem in QCD:
 - Peccei Quinn Solution: introduce a new field ϕ coupled to GG with a spontaneously broken symmetry at scale f_A
 - CP violating term in QCD Lagrangian is cancelled out by the VEV of ϕ

$$\mathcal{L}^{QCD} \subset \left(\frac{\phi_A}{f_A} - \theta \right) \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

- QCD axion : $m_A = 5.7 \left(\frac{10^9 \text{ GeV}}{f_A} \right) \text{ meV}$

The QCD Axion



Quick ID:

- Light pseudo-scalar particle
- Minimal coupling with gluons to solve the strong CP problem
- Production through PQ symmetry breaking at the energy scale
- Viable cold dark matter candidate over a large mass range
- Induced coupling with photons

Axion-Like Particles

- Predicted in several extensions of the standard model
- Phenomenology closely related to that of axions
- Pseudo scalar boson characterized with a two-photon coupling $g_{a\gamma\gamma}$
 - As opposed to axions, mass and coupling constant are unrelated
 - Depending on their actual mass and coupling, they can play a role in cosmology as dark matter particles or in dark energy
- ALPs can to explain the current amount of DM with :

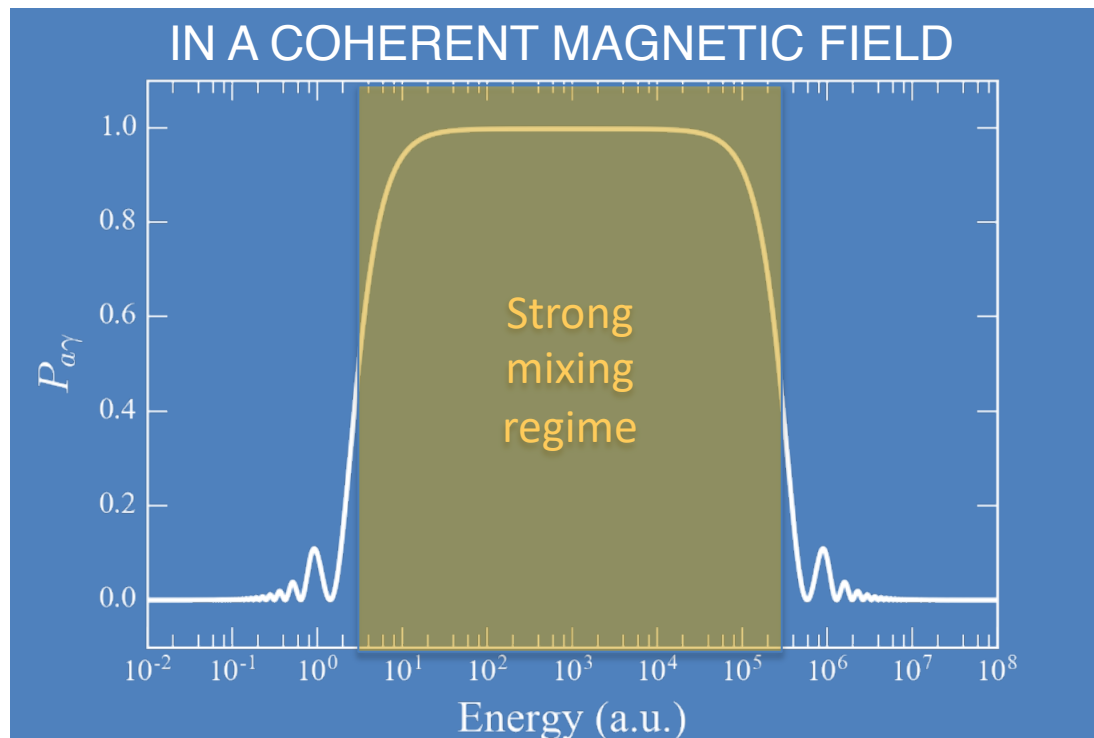
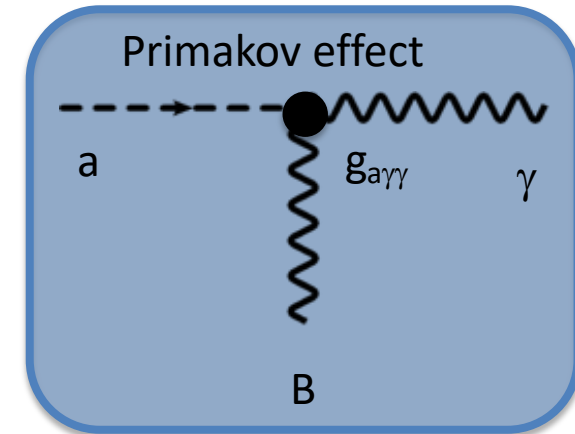
$$g_{a\gamma\gamma} < 10^{-12} \left[\frac{m_a}{1 \text{ neV}} \right]^{1/2} \text{ GeV}^{-1} \quad \begin{array}{l} \text{[e.g. Arias et al. 2012]} \\ \text{from misalignment mechanism} \end{array}$$

→ **Very Weakly Interacting Slim Particles - WISPs**

Photon-ALP mixing

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

- Consequence of the coupling $g_{a\gamma\gamma}$
→ photon-ALP oscillation in cosmic magnetic fields along the line of sight



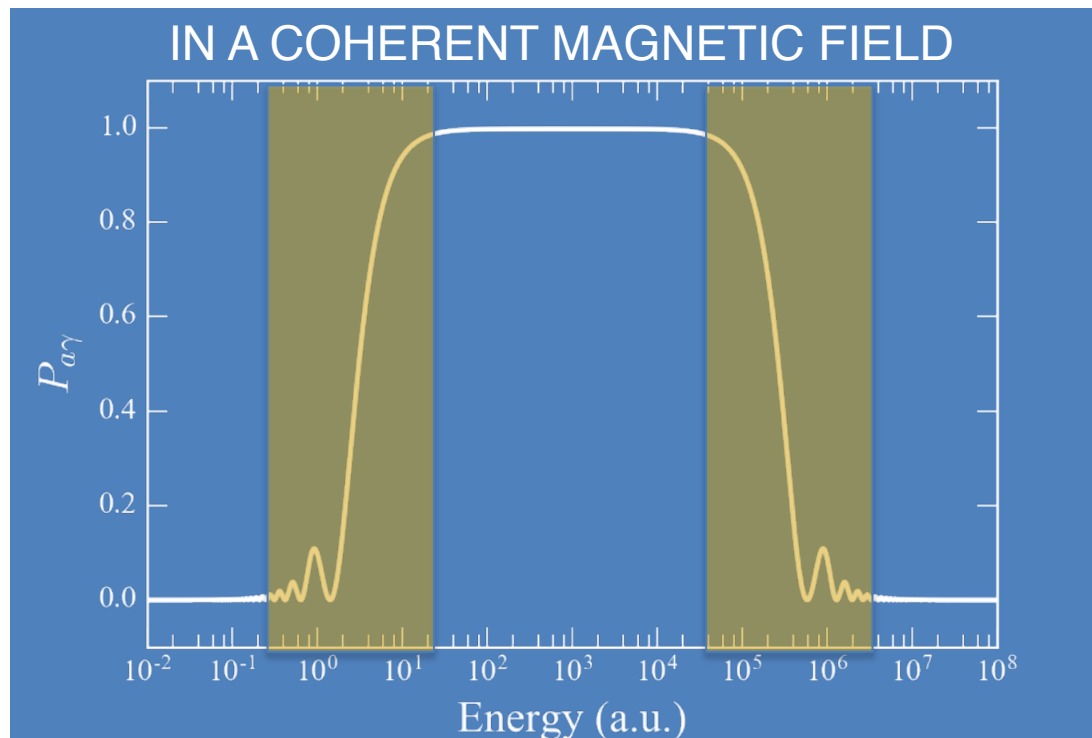
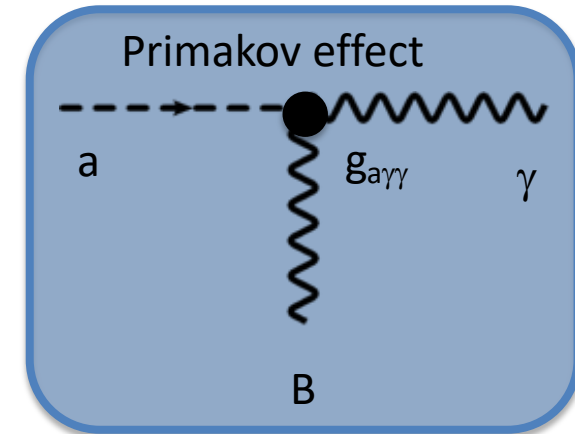
Raffelt & Stodolsky 1988

axions/ALPs do not get absorbed during propagation
→ might lead to a boost in photon flux

Photon-ALP mixing

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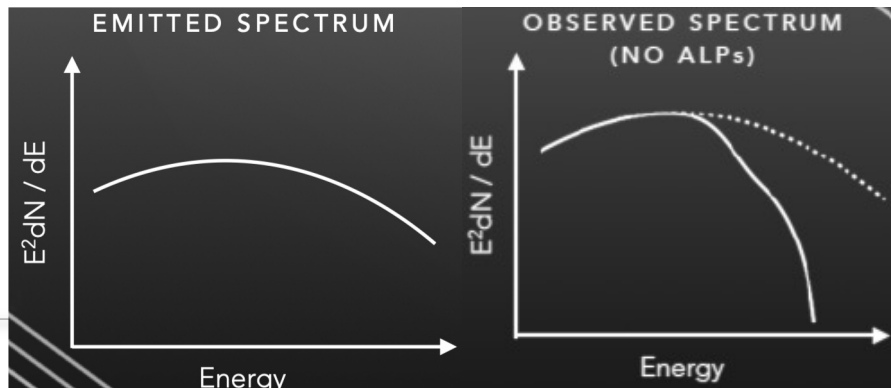
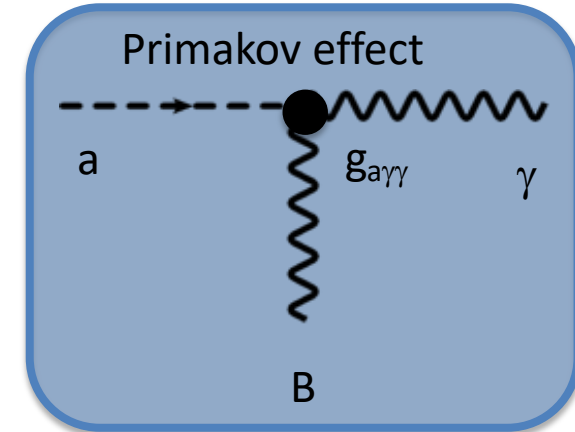


Raffelt & Stodolsky 1988

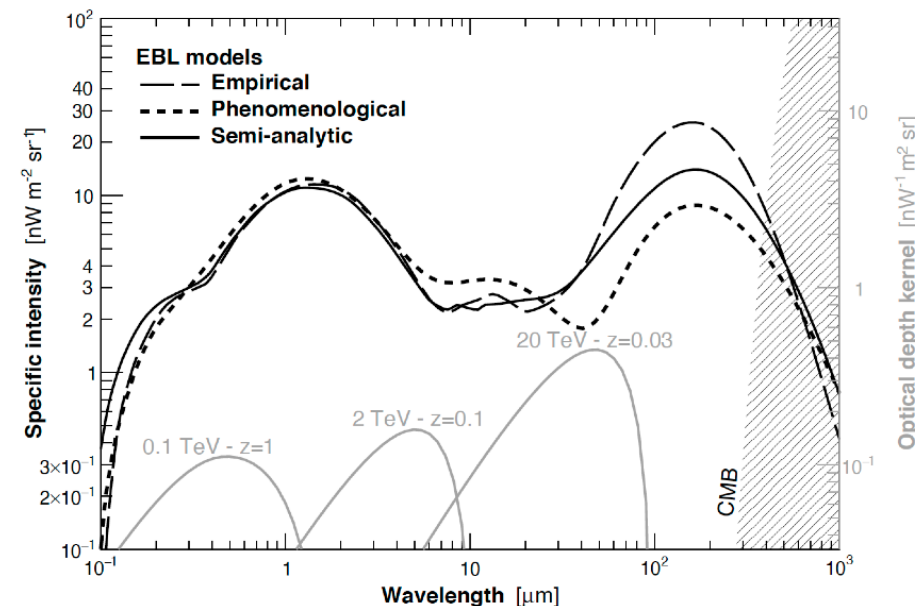
→ irregularities in energy spectrum around E_{crit} and E_{max}

Photon-ALP mixing

- Consequence of the coupling $g_{a\gamma\gamma}$
 - photon-ALP oscillation in cosmic magnetic fields along the line of sight
 - effect increases with distances: AGN with the beam pointing towards us, i.e., blazars, are the most obvious cases
- Caveat : absorption of gamma rays on extragalactic background light (a.k.a EBL) due to pair creation
 - exponential absorption with optical depth
 - gamma-ray flux attenuated

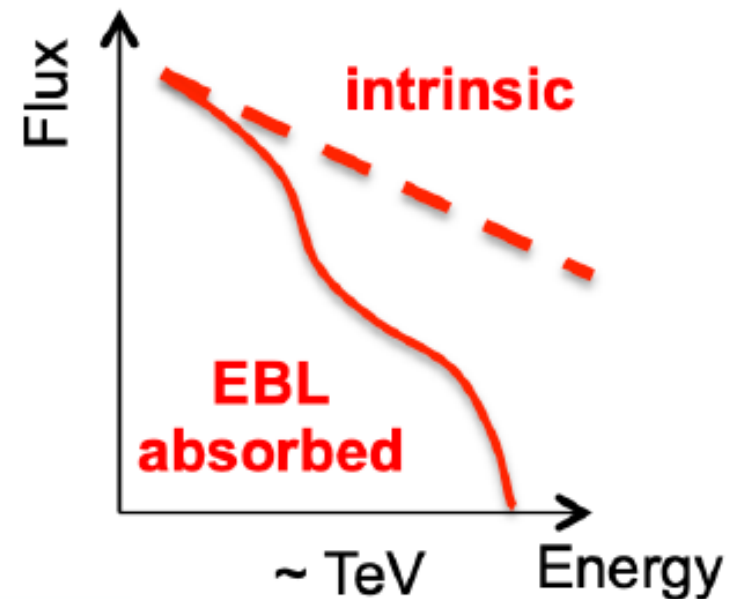
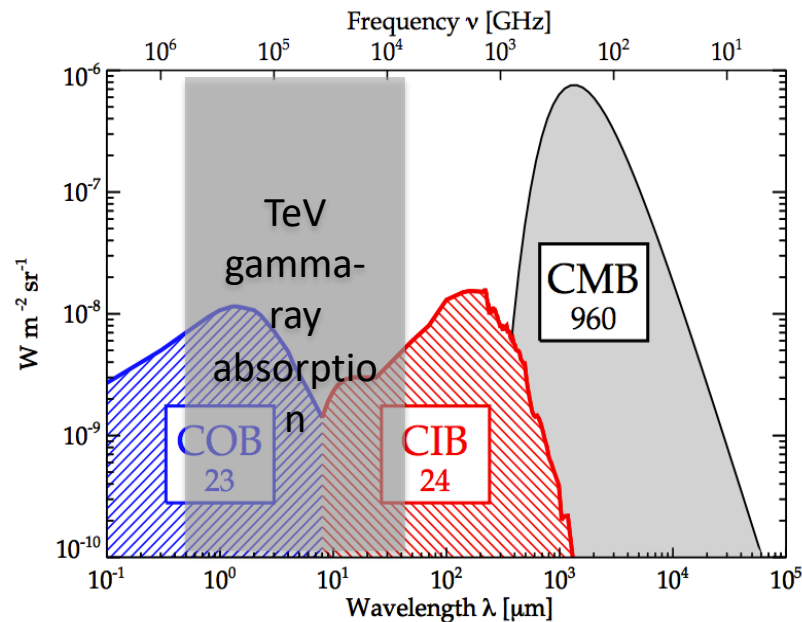


ouloulin – ISAPP20



Photon-ALP mixing

- Caveat : absorption of gamma rays on extra background light (a.k.a EBL) due to pair creation
 - exponential absorption with optical depth
 - gamma-ray flux attenuated



- Observed flux : $\Phi(E_\gamma, z_s) = \Phi(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$
- Energy-differential flux shows a characteristic EBL cutoff at about $E_{\gamma, \text{cutoff}}(z_s) \sim 800 (1 + z_s)^{-2.4} \text{ GeV}$

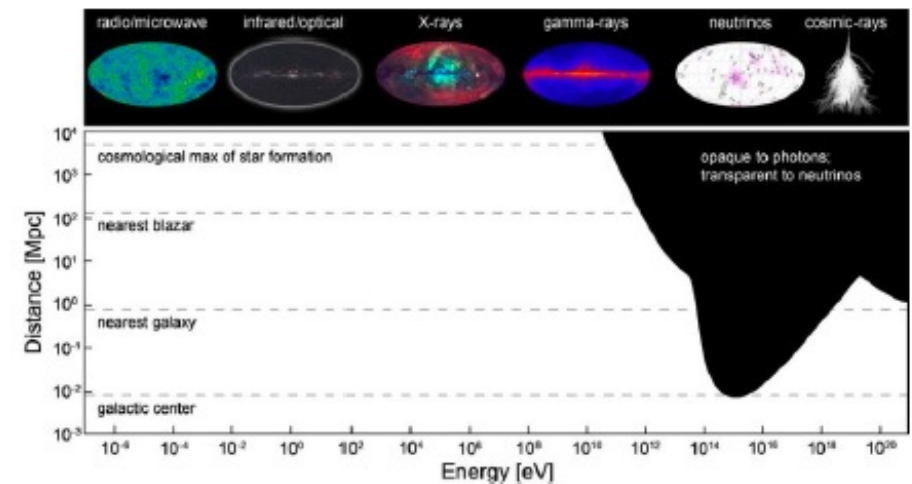
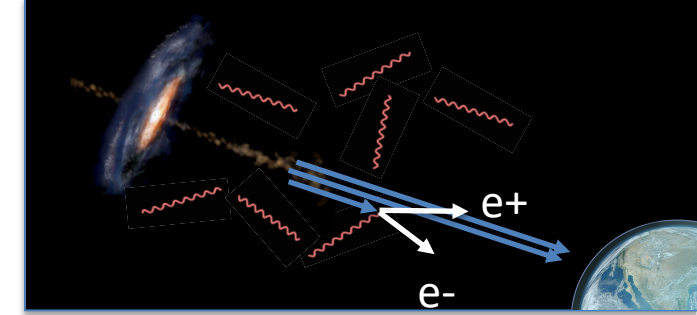
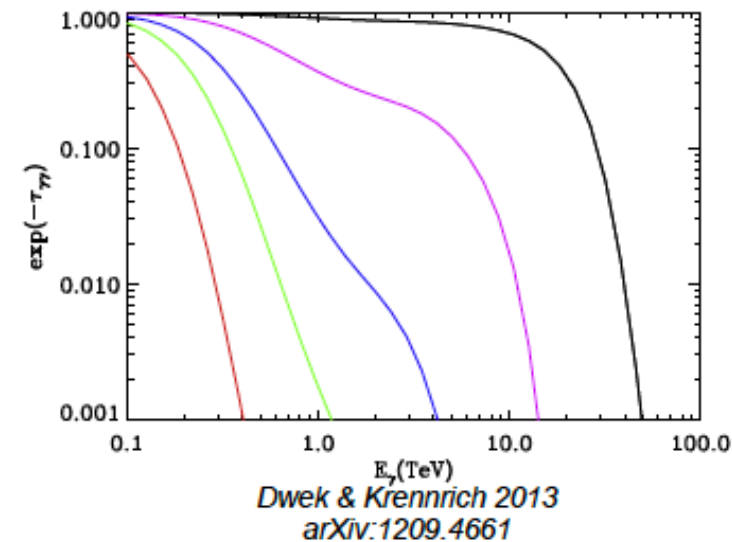
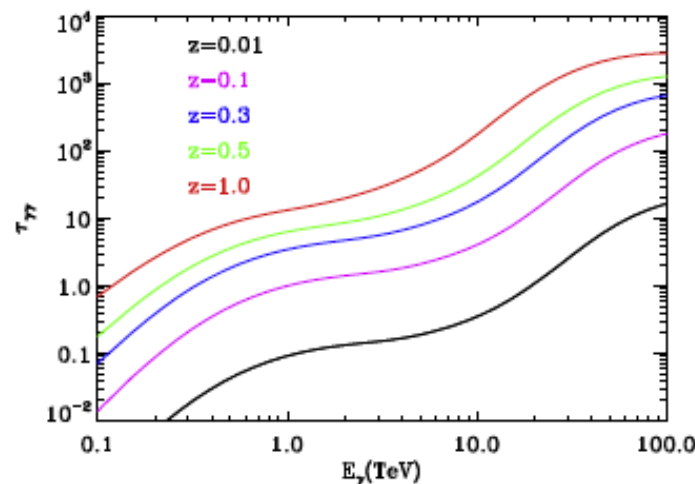
Extra Background Light

- Limits the distances accessible with photons
- Impacts photon spectra (& detectability) of extragalactic γ -ray sources
- Optical depth:

$$\tau(E_0, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^\infty d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^1 d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}[\beta(E_0, z, \epsilon, \mu)]$$

distance element
depends on Λ_{CDM} parameters
number density
of EBL photons
scattering angle
Thomson cross section

- Increase with redshift and energy



Photon-ALP mixing

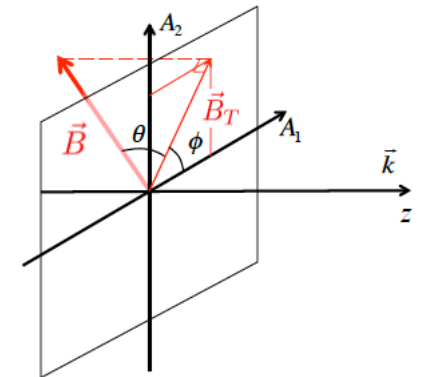
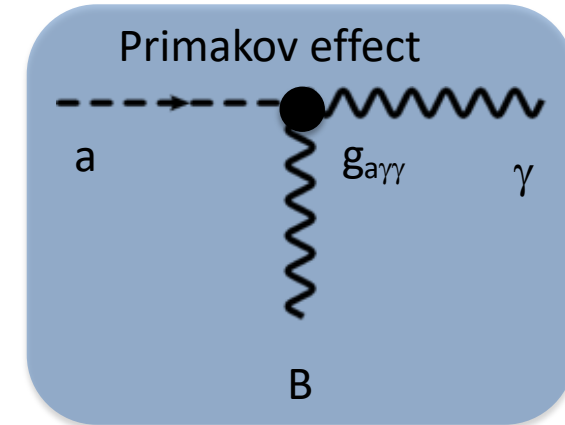
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- Consequence of the coupling $g_{a\gamma\gamma}$
→ photon-ALP oscillation in cosmic magnetic fields along the line of sight
- Propagation in magnetic field given by e.o.m:

$$(E - i\partial_z + \mathcal{M})\Psi = 0 \quad \text{with} \quad \Psi = \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \quad \text{for } E \gg ma$$

where $\mathcal{M}$ is the mixing matrix depending on the external magnetic field, coupling constant, ALP mass, photon energy, plasma density in medium

Raffelt, Phys.Rept. 198 (1990) 1-113



Photon-ALP mixing

- Coherent magnetic field : uniform orientation and strength
 - Conversion in one domain of size s :

$$P_{\gamma \rightarrow a} = \frac{1}{2} \frac{1}{1 + \frac{E_c^2}{E^2}} \sin^2 \left(\frac{gBs \sin \theta}{2} \sqrt{1 + \frac{E_c^2}{E^2}} \right) \quad \text{Hochmuth \& Sigl, 2007, PRD}$$

$\delta = gBs \sin \theta / 2$ strength of the coupling

- Effect is energy dependent

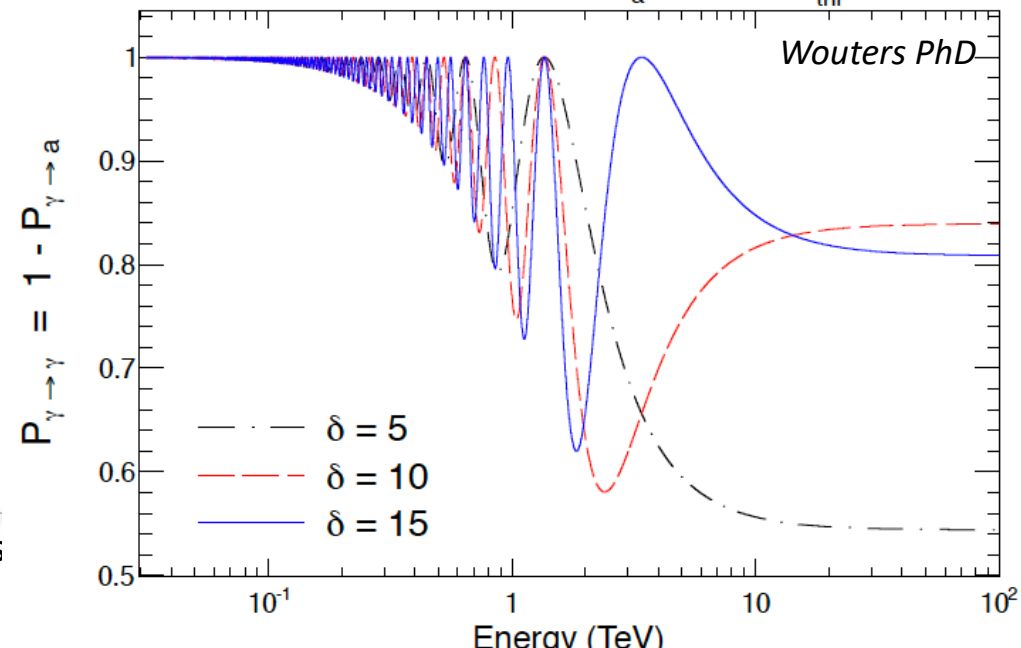
- Critical energy $E_c = \frac{m_a^2}{2gB \sin \theta}$

- $E \ll E_c$: no conversion
- $E \sim E_c$: spatial oscillations, energy dependent
- $E \gg E_c$: spatial oscillations, energy independent

Search for oscillation pattern in energy-differential spectra

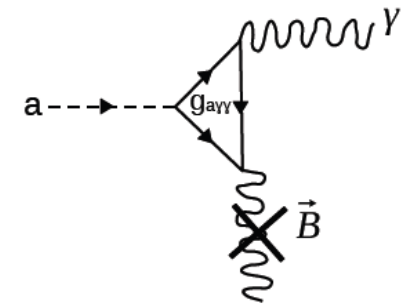
Survival probability of an unpolarized photon as a function of the energy

1 domain, $g = 8 \times 10^{-11} \text{ GeV}^{-1}$, $m_a = 2 \text{ neV}$, $E_{\text{thr}} = 1 \text{ TeV}$

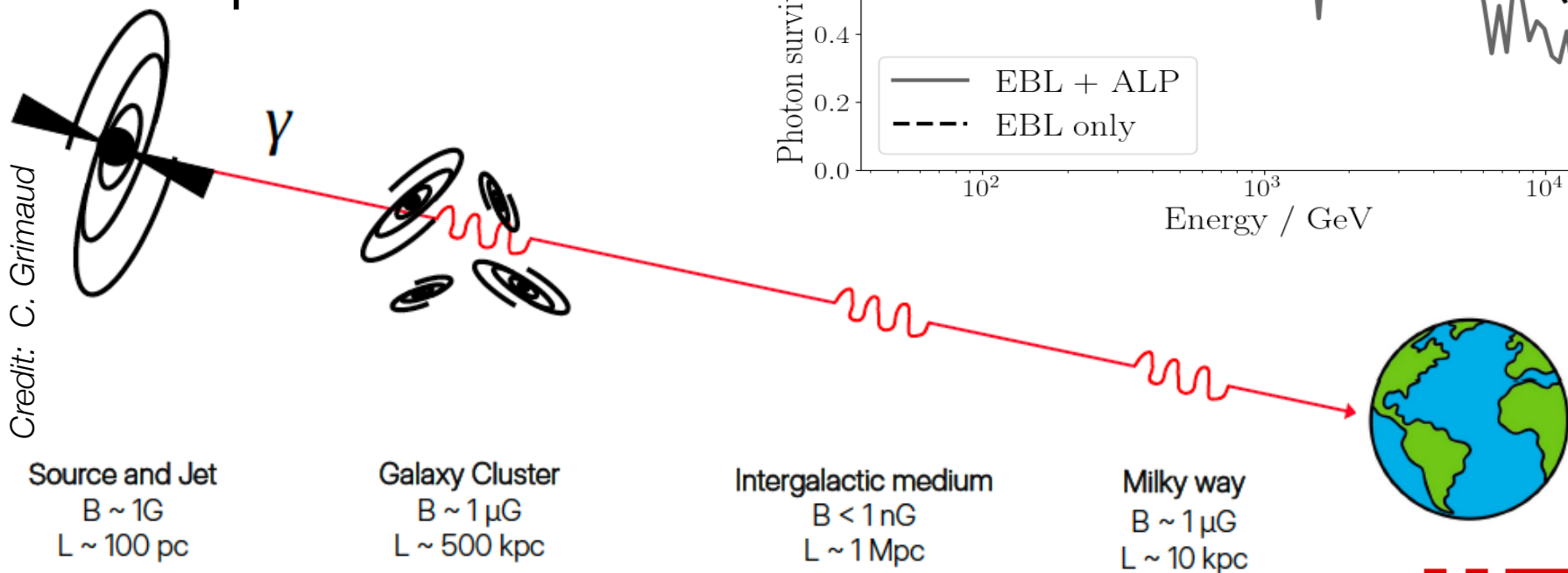
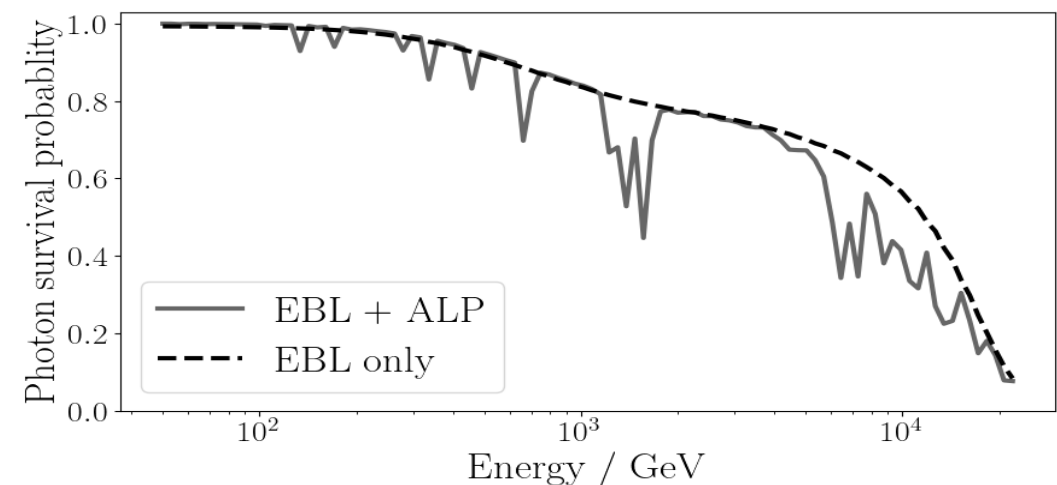


ALP searches with VHE gamma rays

- In the presence of an external magnetic field
→ possibility to have ALP-Photon oscillations
- The conversion probability $P_{\gamma\gamma}$ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region



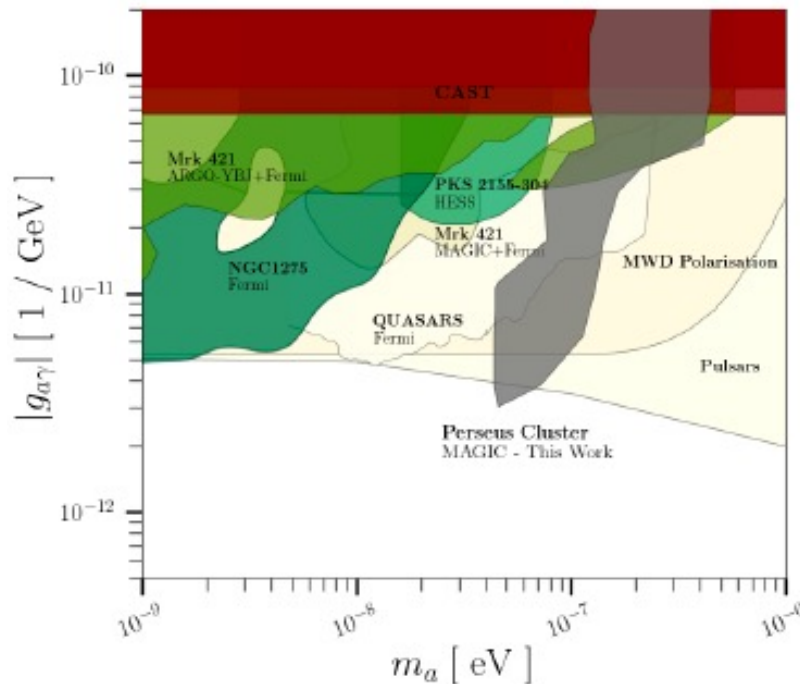
- Wiggles: energy-dependent deviations from smooth GeV-TeV spectrum



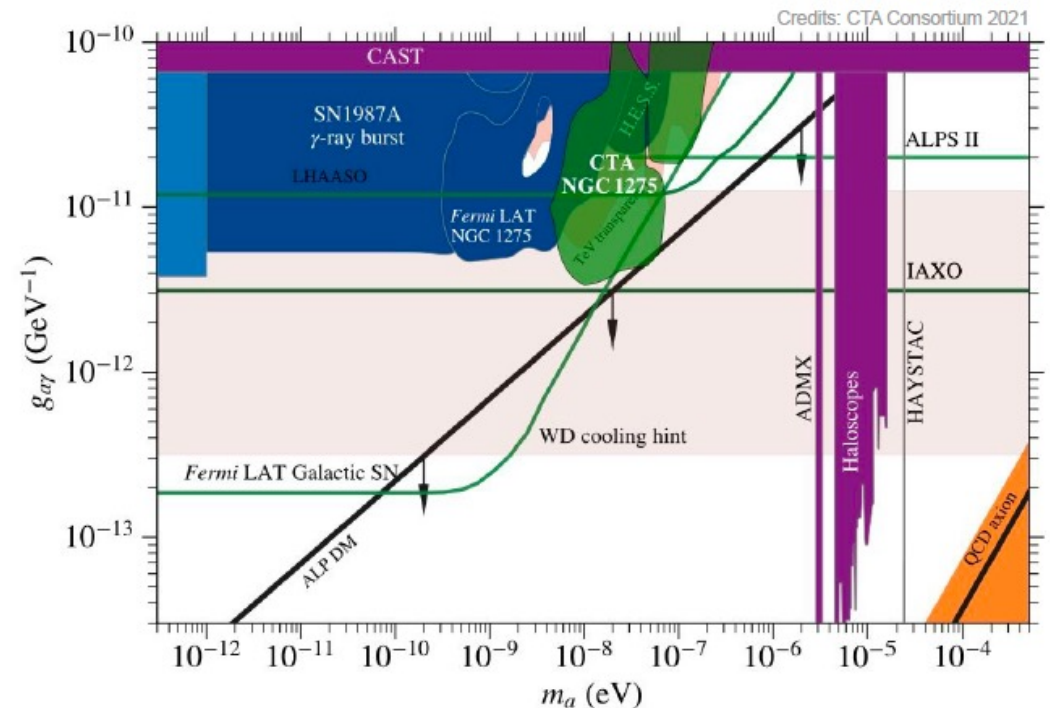
ALP searches with VHE gamma rays

- Astrophysical magnetic fields - Milky-way, Cluster of galaxies, Intergalactic Magnetic Field : not coherent
- The conversion probability $P_{\gamma\gamma}$ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region
→ average over all possible realizations of B

*S. Abe et al., MAGIC Coll.
Phys.Dark Univ. 44 (2024) 101425*



Prospects for CTA: Perseus cluster



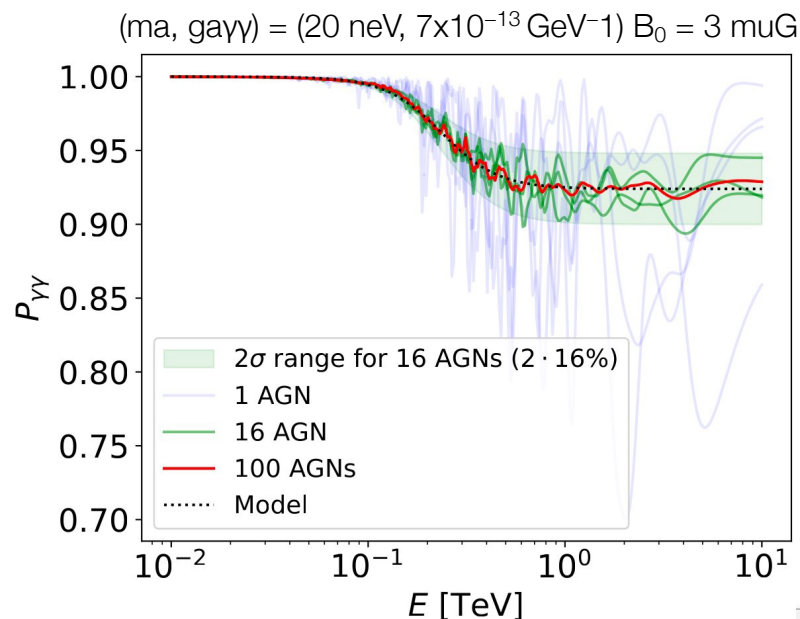
Probing ALP with AGN-GalaxyCluster pairs

Caveat: for GC, no reliable measurement of the small-scale properties of the field (orientation, domain length) → need to marginalize over a large number of small-scale configuration of the magnetic field

Probing ALP with AGN-GalaxyCluster pairs

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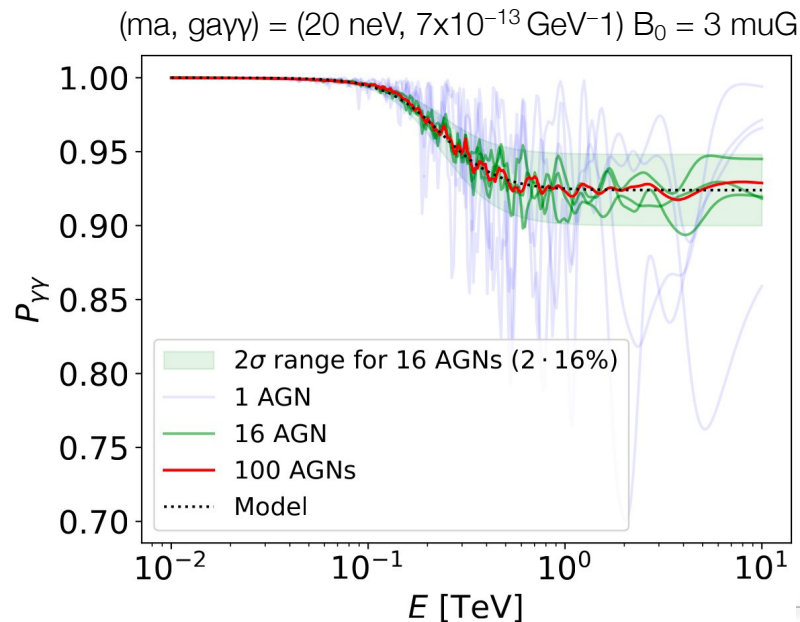
- Stacking analysis of multiple AGN-GC pairs
→ gives a smooth predictable spectral imprint



Probing ALP with AGN-GalaxyCluster pairs

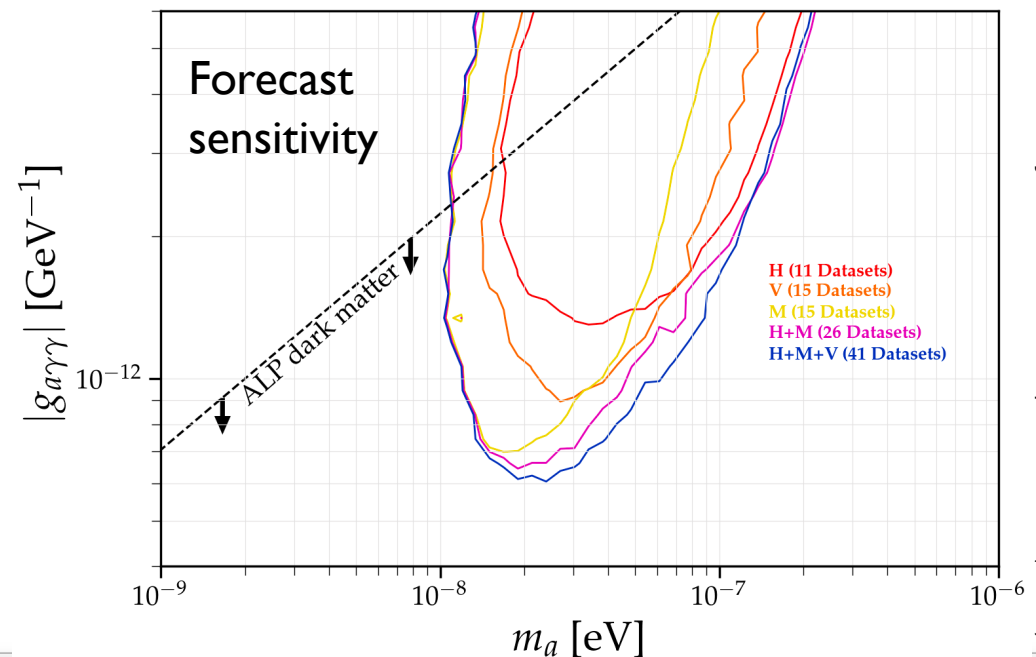
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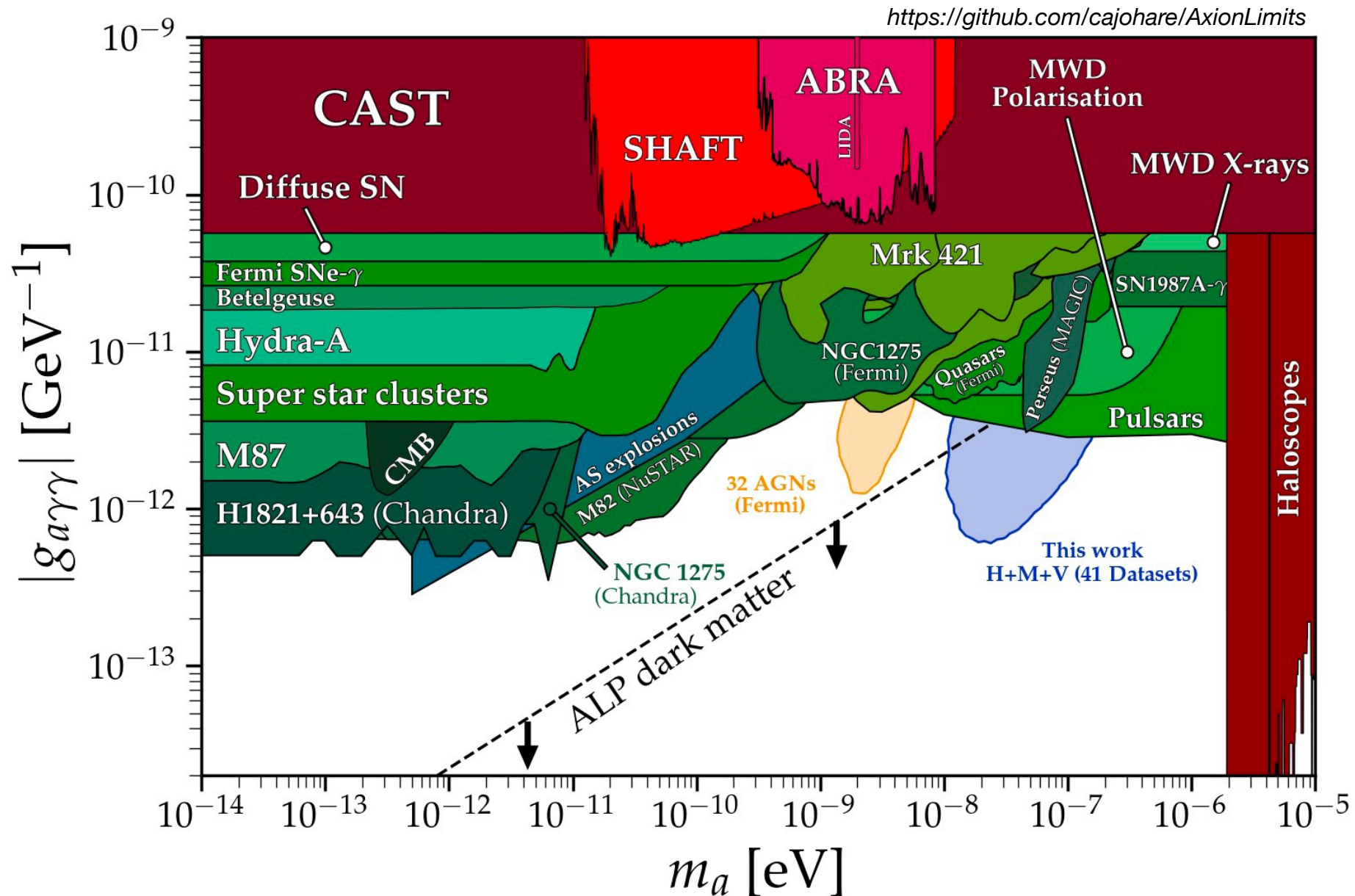
AGN-GC selection

- >10 GeV gamma-ray bright AGNs with SZ catalog (GC)
- 16 AGN-GC pairs selected
- 41 datasets from H.E.S.S., MAGIC and VERITAS



Grimaud, EM, Malyshev et al. accepted JCAP (2026)

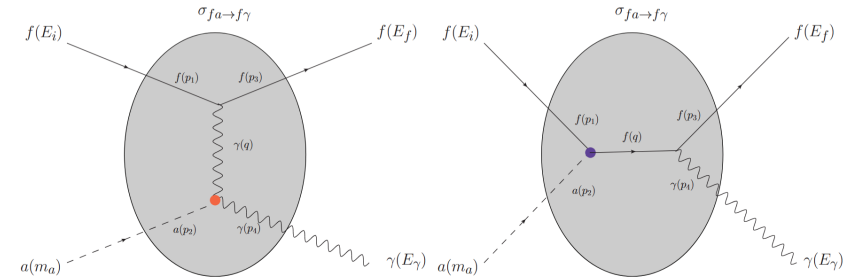
High-energy astrophysics limits



Probing ALPs from cosmic-ray scattering in the Milky Way dark matter halo

- VHE CR protons and electron interaction with ALPs
 - Inverse Primakoff and Inverse Compton scatterings
- For IP process:
 - CR protons :

$$\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} = \frac{1}{m_a} \times D(\Delta\Omega) \times \int_{E_p^{\min}(E_\gamma)} dE_p \frac{d\Phi_p}{dE_p}(E_p) \cdot \frac{d\sigma_{p+a \rightarrow p+\gamma}}{dE_\gamma}(E_p, E_\gamma)$$



Probing ALPs from cosmic-ray scattering in the Milky Way dark matter halo

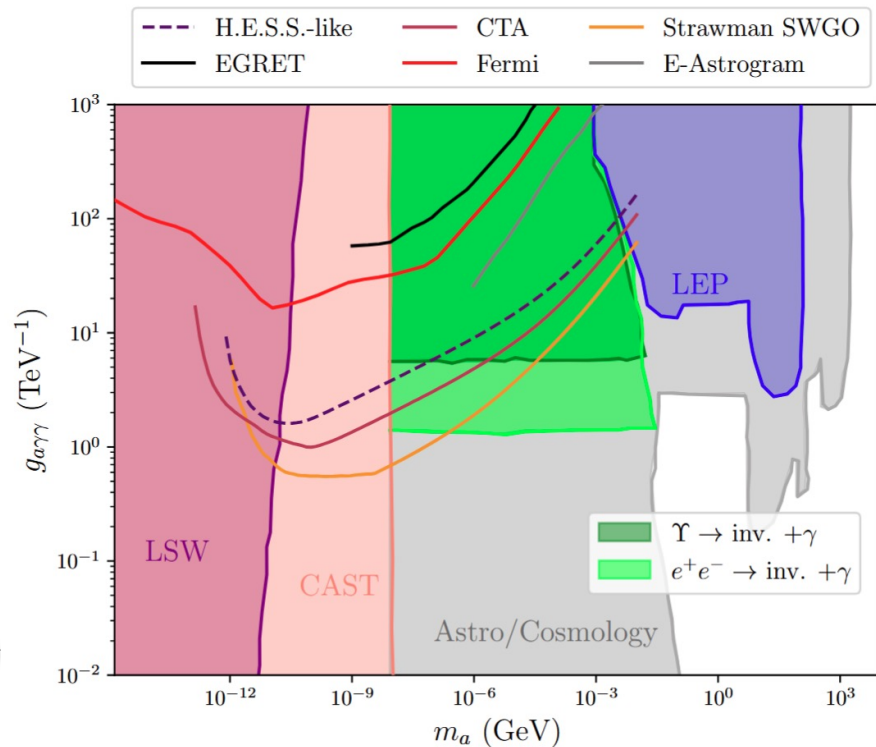
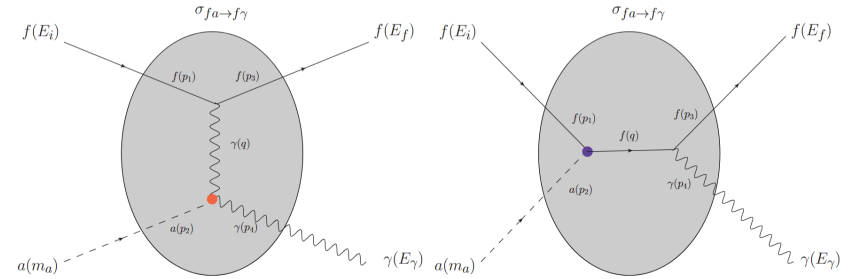
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Goncalves, EM, et al. PRD 111 (2025) 043011

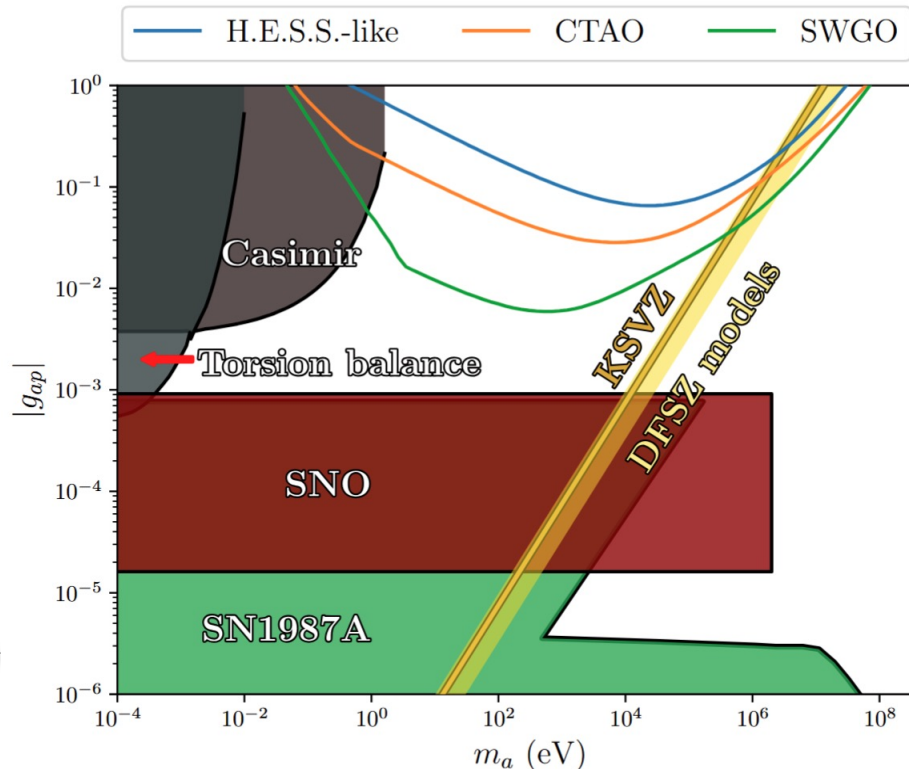
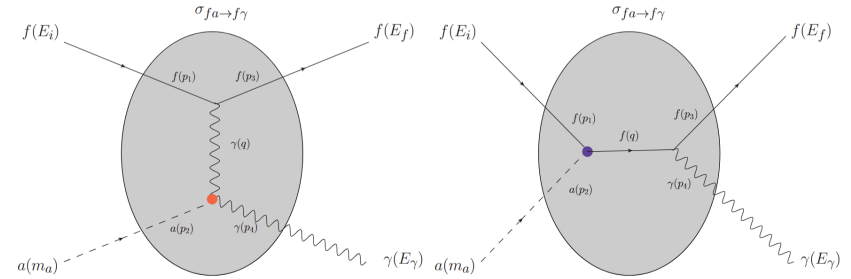
Probing ALPs from cosmic-ray scattering in the Milky Way dark matter halo

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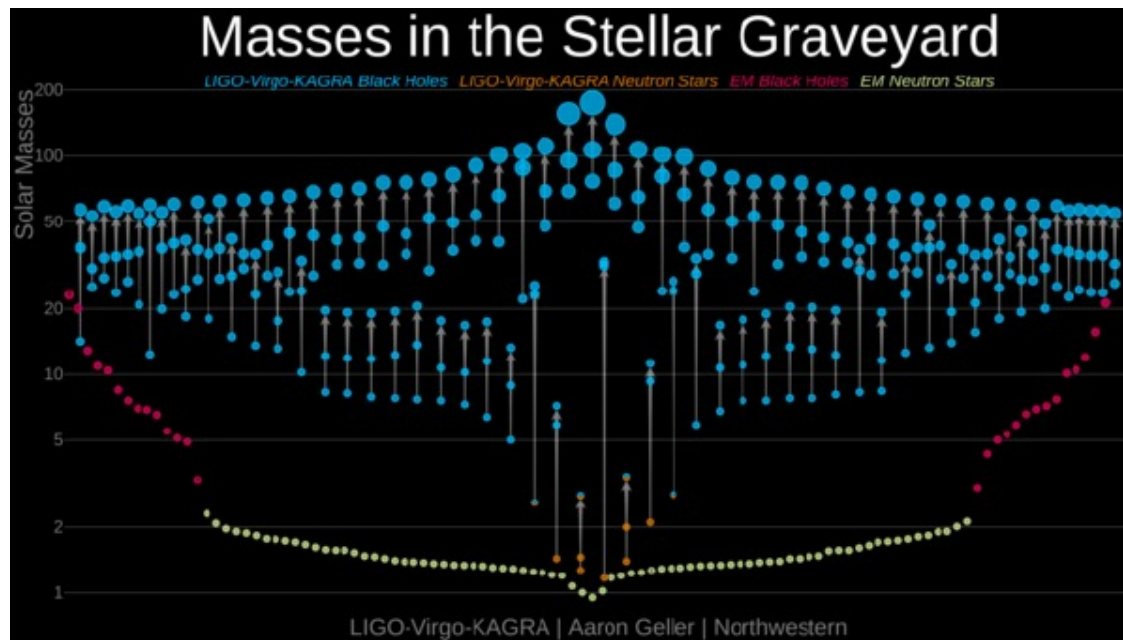
Goncalves, EM, et al. accepted PRD (2026)

- Alternative approach sensitive in a region probed by different measurements
- Complementarity between different detection techniques
- Could probe ~MeV QCD axion models

PRIMORDIAL BLACK HOLES

Observed black holes

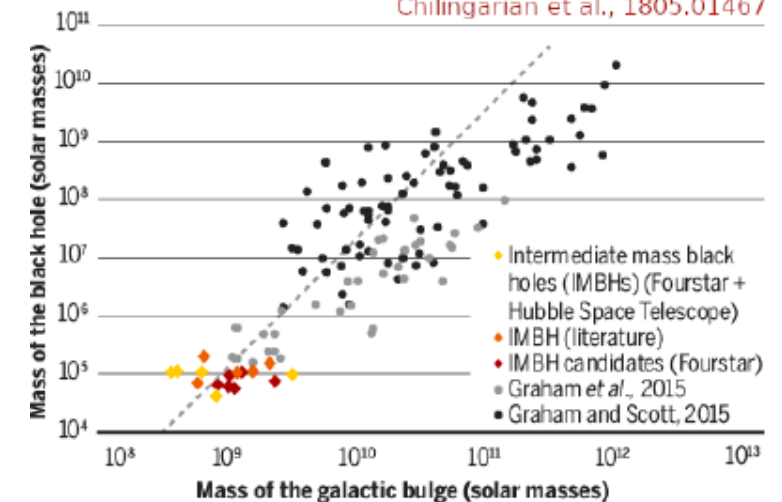
- Stellar black holes : BHs originated in the explosion of massive stars/supernovae, $\sim 3 - 100 M_{\odot}$
- Intermediate mass black holes (IMBH) New class of recently discovered BHs, $\sim 10^2 - 10^6 M_{\odot}$
- Supermassive black holes (SMBH) : BHs at the center of galaxies, $\sim 10^6 - 10^9 M_{\odot}$



Black hole growth chart

Black holes, including the newly discovered middleweights (color), have masses that correlate with the size of their host galaxy.

Chilingarian et al., 1805.01467



Observed black holes

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2015 : 1st ever observation of merging BHs by LIGO/VIRGO

~90 events detected in total today (GWTC-3)

majority of the events are BHs of ~20 Msun mass

→ Unexpectedly high masses! Did LIGO detect Primordial black holes?

- If primordial BHs forms binaries – much more events should be seen by LIGO/VIRGO

<https://arxiv.org/abs/1603.08338> ; <https://arxiv.org/abs/1709.06576> ; <https://arxiv.org/abs/1709.09007>

- “Eliminating the LIGO bounds on primordial black hole dark matter”

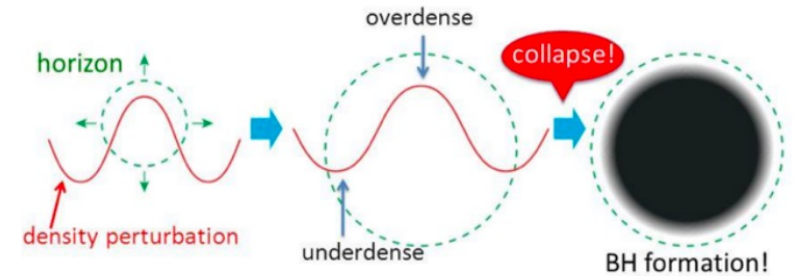
<https://arxiv.org/pdf/2008.10743.pdf>

Did LIGO detected dark matter in form of ~20 Msun BHs? **Probably not**, but too early to draw firm conclusions!

PBH in a nutshell

- Black holes created during the early universe :
 - collapse of large primordial overdensities

Zeldovich & Novikov 67, Carr & Hawking 74, Carr 75...



Kawasaki, et al. PRD D. 87, 063519 (2012)

- The resulting BH inherits the mass corresponding to the Hubble radius at the time of collapse t_c , i.e. Hubble horizon at time t , ct , same order as Schwarzschild radius $\sim GM/c^2$,

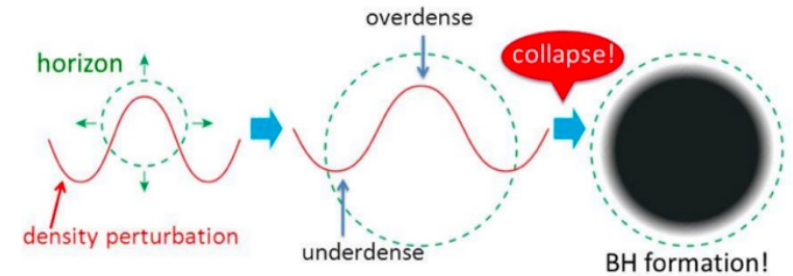
$$M_{PBH} = M_H(t_f) \simeq \frac{c^3}{G} t_f$$



$$M_i(t_f) \sim 10^{15} \text{ g} \left(\frac{t_f}{10^{-23} \text{ s}} \right)$$

PBH in a nutshell

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Kawasaki, et al. PRD D. 87, 063519 (2012)

- For PBH formed in the radiation-dominated area:

$$M_i(t_f) \sim 10^{15} \text{ g} \left(\frac{t_f}{10^{-23} \text{ s}} \right)$$

(Possible formation of BHs with smaller masses due to incomplete collapse or to other formation channels : phase transitions, collapse of cosmic strings, domain walls)

- PBH mass bounds:
 - lower limit : at Planck time (10^{-43} s) ... $M \sim 10^{-5} \text{ g}$, from CMB: $M \sim 0.1 \text{ g}$
 - upper limit : PBH should form before the onset of BBN for them not to spoil the baryon-to-photon ratio

$$M_{\text{BBN}} \sim M(t_f \approx 1 \text{ s}) \sim 10^5 M_{\odot}$$

PBH in a nutshell

$$M_i(t_f) \sim 10^{15} \text{ g} \left(\frac{t_f}{10^{-23} \text{ s}} \right)$$



- Age of the Universe $t_U = 10 \text{ Gyr} \rightarrow M \sim 10^{15} \text{ g}$
 - The PBHs with masses $M \lesssim 10^{15} \text{ g}$ would have been completely evaporated since the Big Bang by now
- Some of which with $M \sim 10^{15} \text{ g}$ would be evaporating today in bursts of short, intense transient emissions of gamma rays
- More massive, stable counterparts to these evaporating PBHs are a candidate for some of the DM density of the universe

Black hole evaporation

- Hawking temperature $T_H = 1/(4\pi/G_N M_{BH}) \simeq 1.06 \times (10^{16} \text{ g}/M_{BH}) \text{ MeV},$

Hawking '74

- Expected particle yield per unit time and energy from a nonrotating black hole with mass M_{BH} and corresponding Hawking temperature T_H

$$\frac{d^2 N_k}{dE_k dt} = \frac{1}{2\pi} \frac{\Gamma_k(E_k, M_{BH}, m)}{e^{E_k/T_{BH}} - (-1)^{2s}}$$

$\Gamma(E_k, M_{BH}, m)$ is the particle-dependent gray-body factor and E_k indicates the energy of the emitted particle k of mass m and spin s

- Note that the emission is **not exactly black-body** but depends upon the spin and charge of the emitted particle, the average energy for neutrinos, electrons and photons being $4.22T_{BH}$, $4.18T_{BH}$ and $5.71T_{BH}$, respectively.
- All of the black holes that we know exist (Stellar-mass, supermassive) have temperatures much smaller than the CMB temperature ($\sim 2.7 \text{ K}$); since no heat can flow from a colder to a hotter “body”, massive black holes do not evaporate

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- From **Stefan-Boltzmann** law and change of mass one can show that an (approximate) BH **lifetime** is

$$\tau(M) \sim \frac{G^2 M^3}{\hbar c^4} \sim 10^{64} \left(\frac{M}{M_\odot} \right)^3 \text{ yr}$$

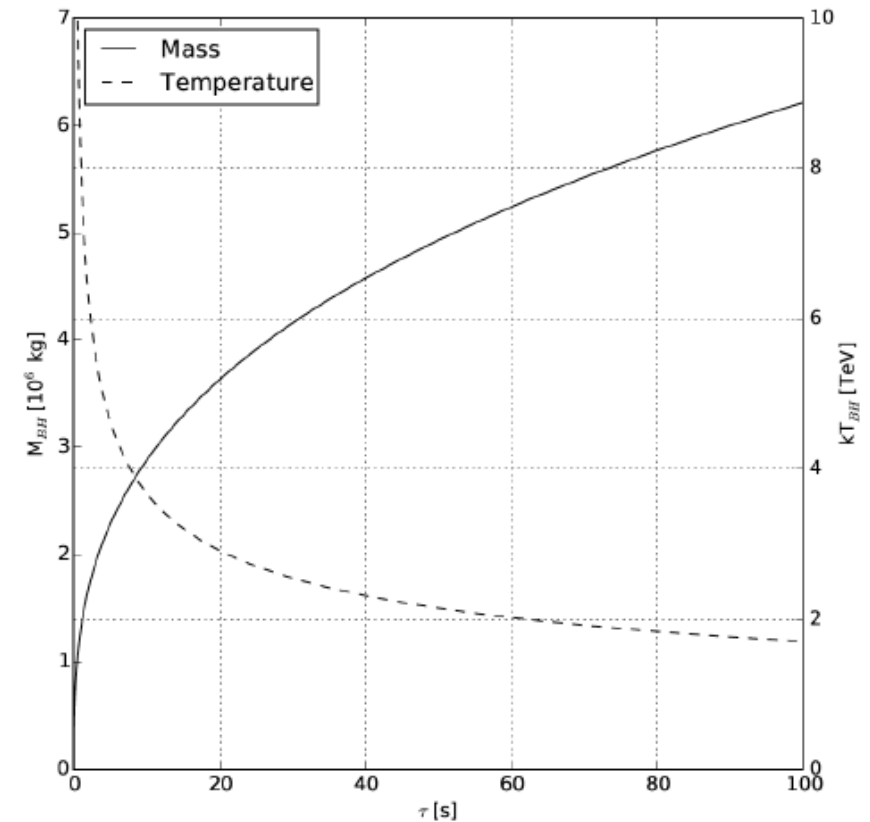
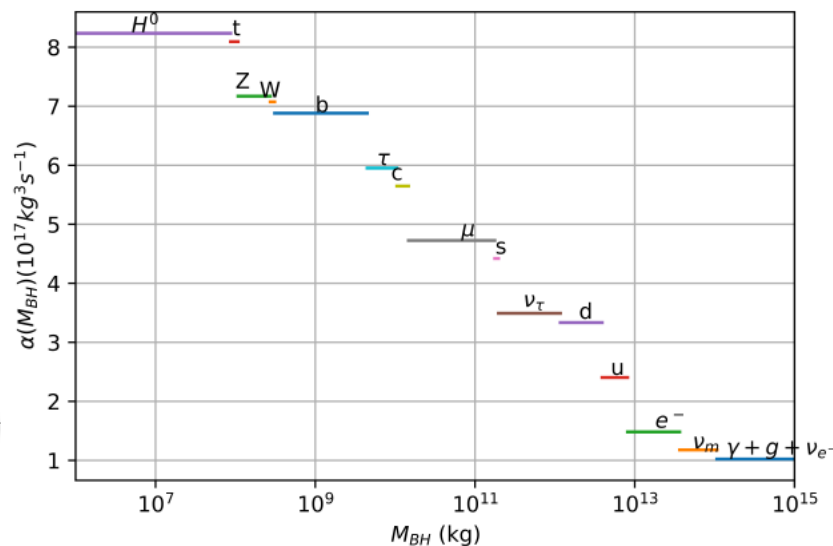
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- Accounting for the SM degrees of freedom gives :



E

Figure 6: Black hole mass and temperature for the final 100 seconds of the BH evaporation lifetime (τ is the remaining time). The decrease of mass and the increase of temperature accelerate as $\tau \rightarrow 0$.

Search for photon bursts from PBH evaporation

- Final-stage emission searches for high-energy photon bursts expected before $\sim 10^{15}$ g mass PBHs « completely » evaporate
→ look for cluster of N_{obs} photons
- Expected rate of cluster of N_{obs} observed photons:

$$R(N_{\text{obs}}) = \int d\Omega \int_0^\infty dr r^2 \dot{\rho}_{\text{PBH}} \mathcal{P}(N_{\text{obs}}|\lambda)$$

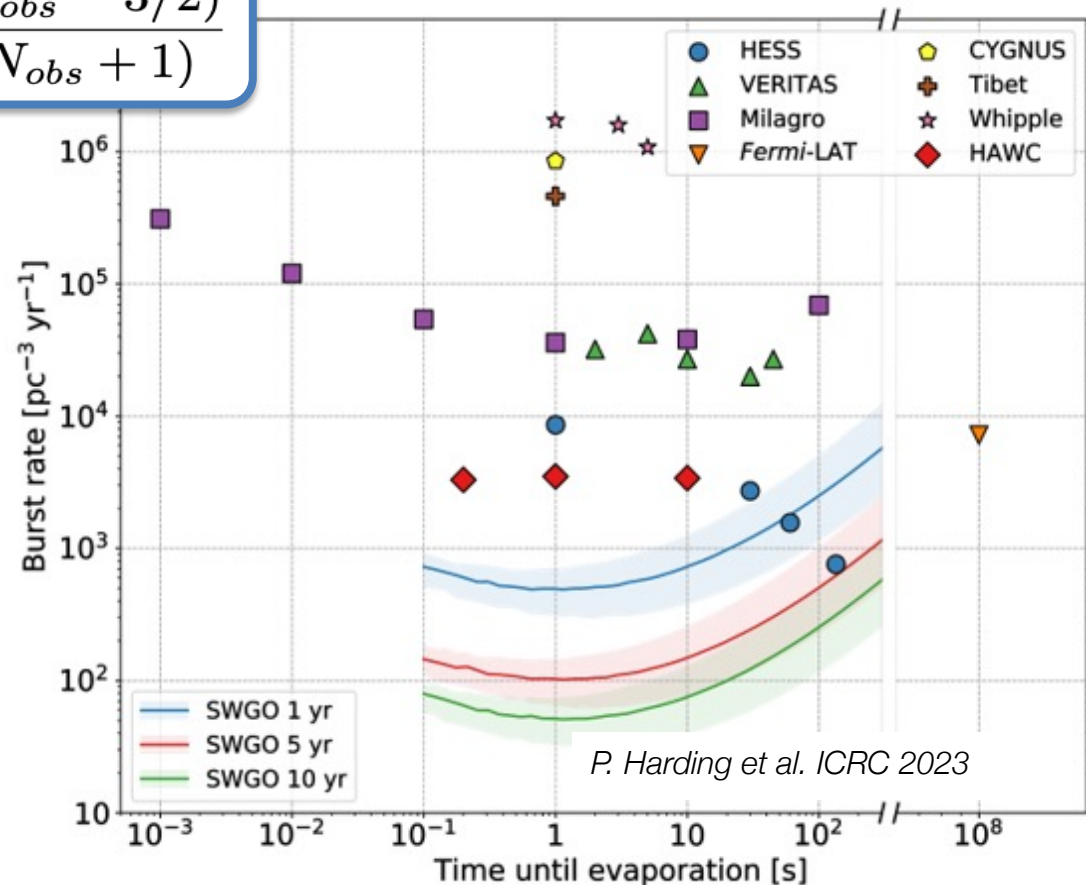
- Ω solid angle of observations
- r distance of the PBH
- λ the expected number of photons
- $\dot{\rho}_{\text{PBH}}$: PBH evaporation rate per unit volume

Search for photon bursts from PBH evaporation

- Final-stage emission searches for high-energy photon bursts expected before $\sim 10^{15}$ g mass PBHs « completely » evaporate
- The number of cluster of N_{obs} observed photons in a time T and solid angle Ω is therefore:

$$N_{\text{cluster}}(N_{\text{obs}}) = \dot{\rho}_{\text{PBH}} T \Omega \frac{(r_0 \sqrt{N_0})^3}{2} \frac{\Gamma(N_{\text{obs}} - 3/2)}{\Gamma(N_{\text{obs}} + 1)}$$

for isotropic evaporation rate
with N_0 is the expected number of
photons seen by the detector for a PBH
evaporation at distance r_0



Isotropic gamma ray background (IGRB) constraints

Diffuse background +

- Active galactic nuclei
- Gamma ray bursts
- DM annihilation/decay?
- Hawking radiation?

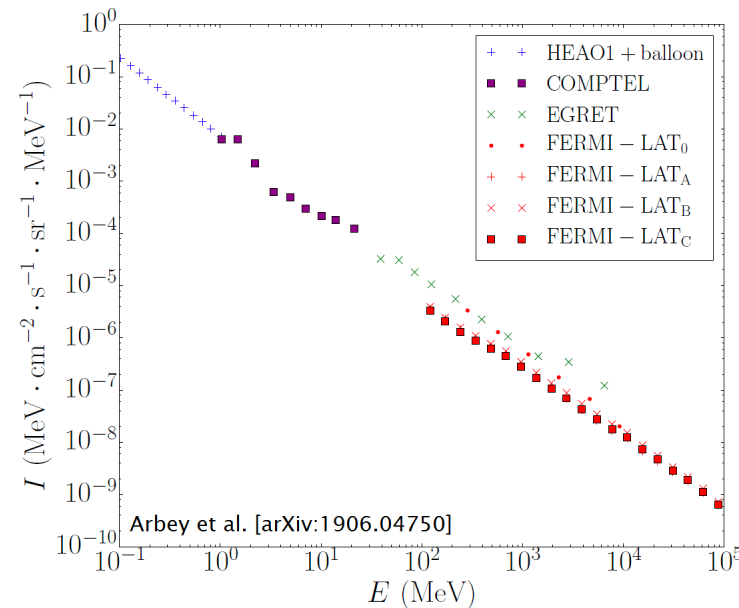
Flux estimation for BHs

$$I \approx \frac{1}{4\pi} E \int_{t_{\min}}^{t_{\max}} (1+z(t)) \frac{d^2 n}{dt dE} ((1+z(t))E) dt$$

$$\approx \frac{1}{4\pi} E \int_{t_{\min}}^{t_{\max}} (1+z(t))$$

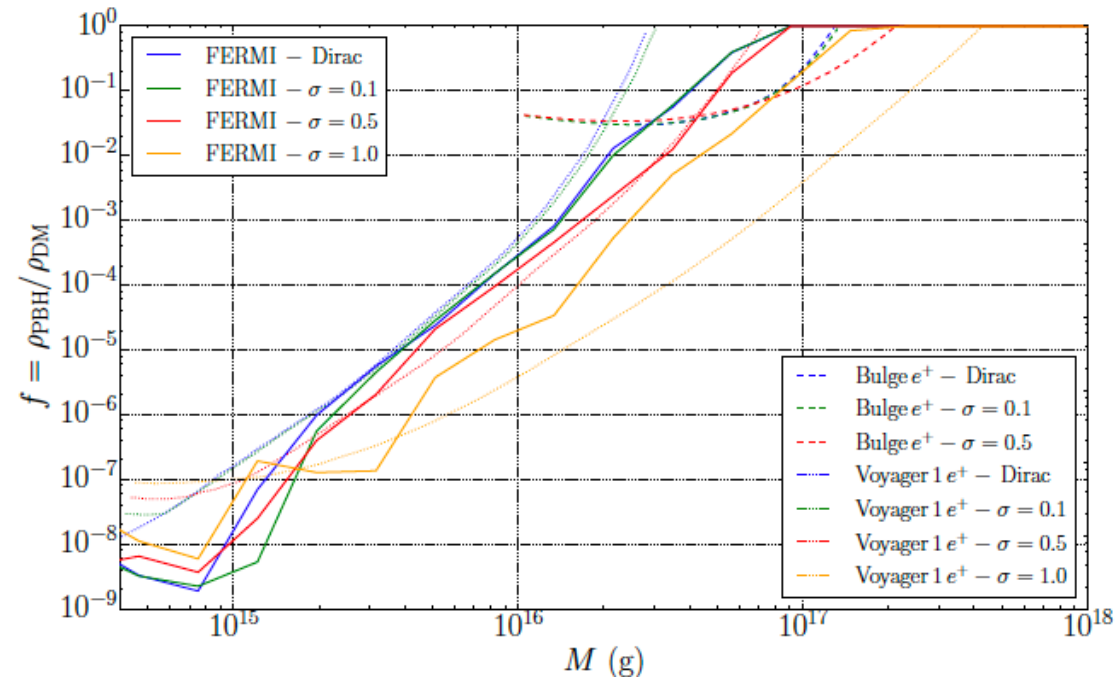
$$\times \int_{M_{\min}}^{M_{\max}} \left[\frac{dn}{dM} \frac{d^2 N}{dt dE} (M, (1+z(t))E) dM \right] dt$$

- Limits for monochromatic mass functions as well as log-normal mass functions with different gaussian width



The IGRB as measured by HEAO1+balloon, COMPTEL, EGRET and FERMI-LAT missions.

Arbey et al. arxiv:1906.04750



PBH searches with keV/MeV photons

- PBHs with masses $10^{16} - 10^{21}$ g are poorly constrained and can make all dark matter :
 - Hawking temperature of such black holes is in keV-MeV range
- Expected particle yield per unit time and energy from a nonrotating black hole with mass M_{BH} :

$$\frac{d^2 N_k}{dE_k dt} = \frac{1}{2\pi} \frac{\Gamma_k(E_k, M_{\text{BH}}, m)}{e^{E_k/T_{\text{BH}}} - (-1)^{2s}} \quad \text{Hawking 1974}$$



INTEGRAL [ESA]



XMM-Newton [ESA]

- Expected energy-differential gamma-ray flux

$$\frac{d^2 \Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\text{LOS}} ds \frac{f_{\text{pbh}} \rho_{\text{DM}}(r(s, d, \theta))}{M_{\text{pbh}}} \frac{d^2 N_\gamma}{dE_\gamma dt}$$

$$D(\Delta\Omega) = \int_{\Delta\Omega} \int_{\text{LOS}} \rho_{\text{DM}}(r(s, d, \theta)) ds d\Omega.$$

Framework similar to standard decaying DM:

- the strength $\sim$ D-factor; the spectrum is hard in keV-MeV bands
- best targets : dSphs, GC, clusters...

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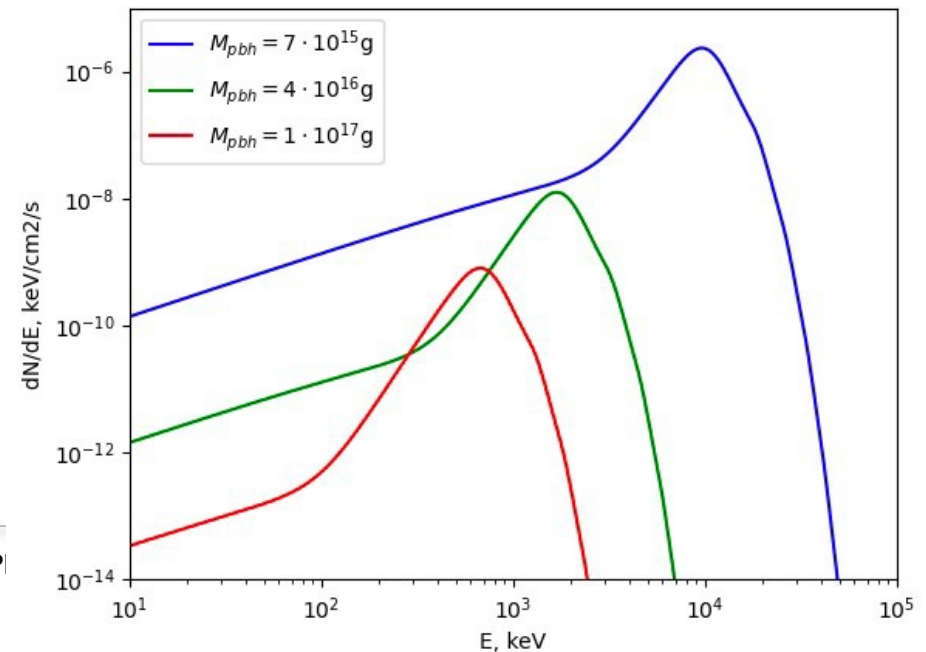
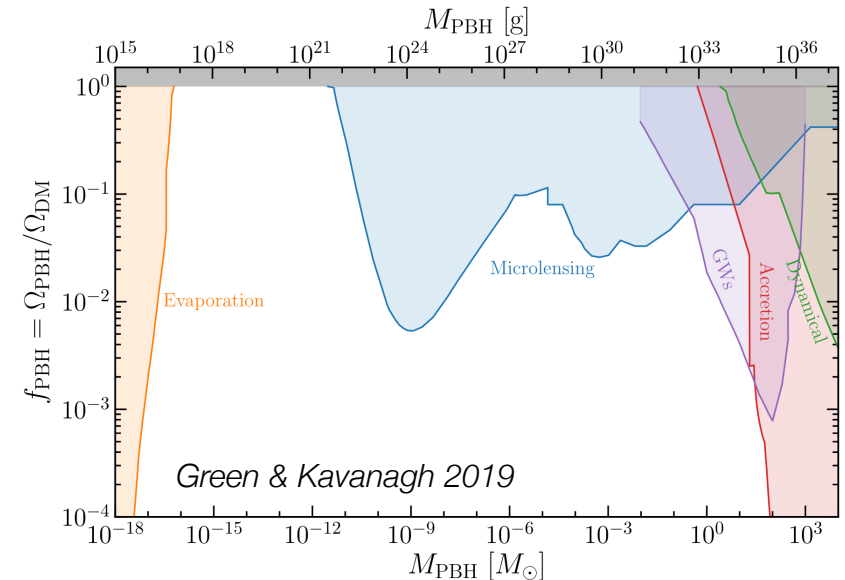


XMM-Newton [ESA]



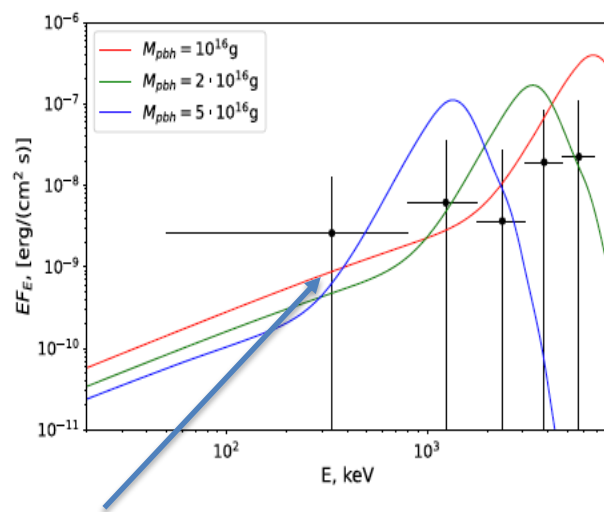
INTEGRAL [ESA]

Emmanuel Moulin – ISAP

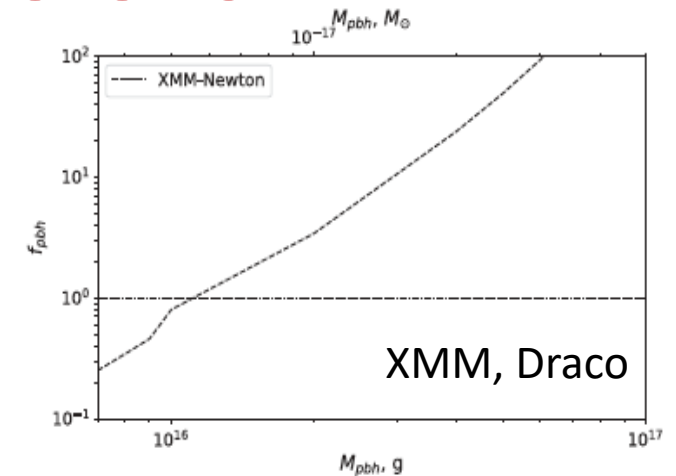
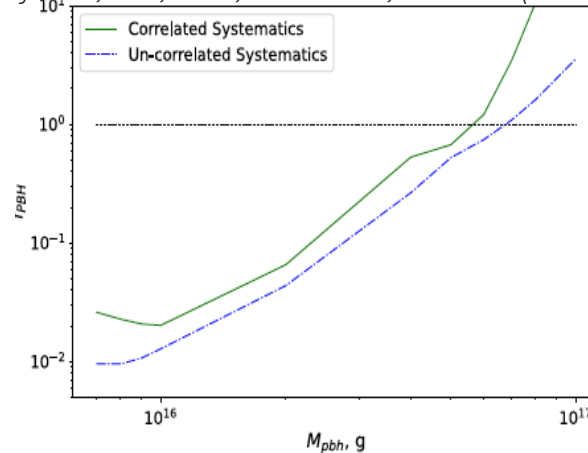


PBH searches with keV/MeV photons

- ~3 Ms XMM observations of Draco
- MeV Galactic diffuse emission
 - INTEGRAL SPI observations of the inner Milky Way between 2002/11 and 2021/10



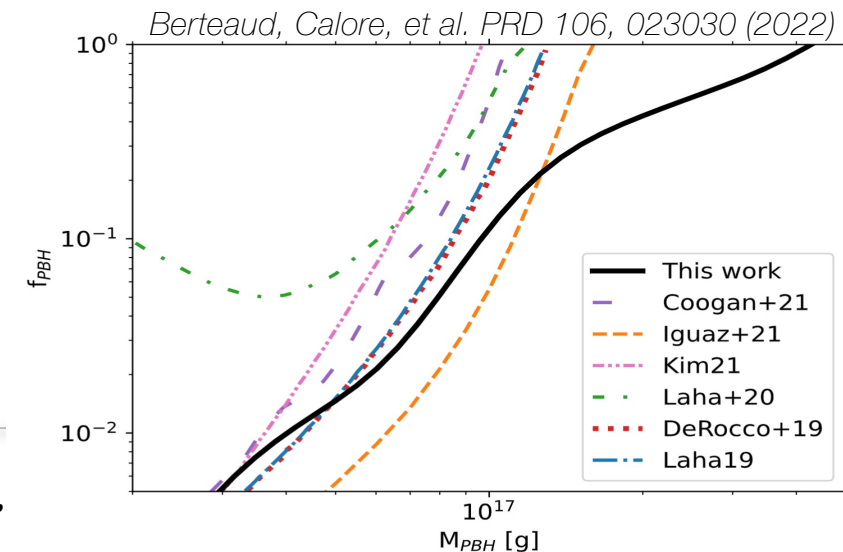
Malyshev, EM, et al, PRD 106, 123020 (2022)



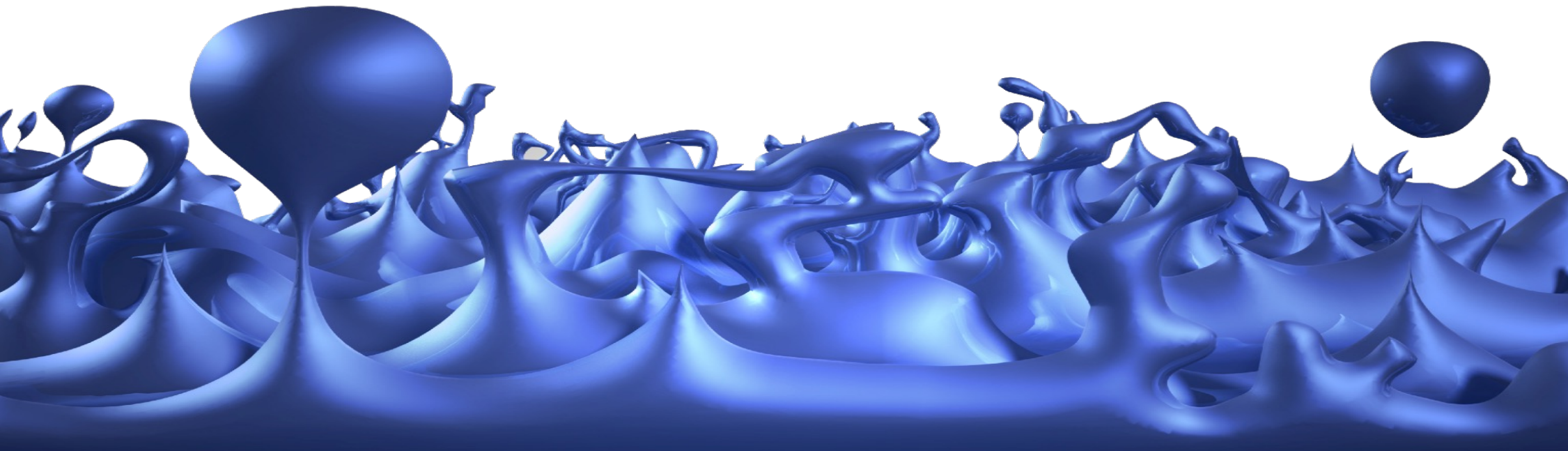
- Background template modelling approach
 - ICS of electrons off the interstellar radiation field
 - unresolved sources
 - nuclear lines, ...

Residual INTEGRAL/SPI background from ON/OFF observation pairing to minimize the effects of the time-dependent background variability

$$\frac{d^2 \Phi_\gamma}{dE_\gamma dt} = \frac{f_{pbh}}{4\pi M_{pbh}} \frac{d^2 N_\gamma}{dE_\gamma dt} \sum_i (D_{ON,i} - \alpha_i D_{OFF,i})$$



LORENTZ INVARIANCE VIOLATION SEARCHES AT VERY HIGH ENERGIES



Modified dispersion relation

$$l_P = \sqrt{\frac{\hbar G}{c^2}} \approx 1.6 \times 10^{-35} \text{ m},$$

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 2.18 \times 10^{-8} \text{ kg},$$

$$E_P = m_P c^2 \approx 1.22 \times 10^{19} \text{ GeV}$$

- Lorentz invariance is central in modern physics theories

- However close to Planck energy $E_{Pl} = \sqrt{\hbar c^5 / G} \approx 1.22 \times 10^{19} \text{ GeV}$ some quantum gravity models (QG) predict that spacetime fluctuations modify photon propagation in vacuum according to their energy $\rightarrow$ Lorentz invariance violation (LIV)

- LIV induced effects can be introduced in a model-independent way in the standard dispersion relation of photons :

$$E^2 = p^2 c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{E}{E_{QG,n}} \right)^n \right]$$

- Subluminal or superluminal LIV $\rightarrow +/-$
- Experiments are only sensitive to $n = 1, 2$

Note that E_{QG} is often compared to E_{Pl} , but could be very different from it

$\rightarrow$ Photon speed depends on their energy

Search for time delays

- Considering only the linear ($n = 1$) or quadratic ($n = 2$) term, it can be shown that the group velocity of photons acquires a dependence on their energies :

$$v_g(E) = \frac{\partial E}{\partial p}$$

- From $E^2 \simeq p^2 c^2 \times \left[1 \pm \left(\frac{E}{E_{QG}} \right)^n \right]$, one gets $E = pc \left[1 \pm \frac{1}{2} \left(\frac{E}{E_{QG}} \right)^n \right]$

with first-order Taylor expansion.

- Therefore : $v_g(E) = \frac{\partial E}{\partial p} = c \left[1 \pm \frac{1}{2} \left(\frac{E}{E_{QG}} \right)^n \right] \pm \frac{pc}{2E_{QG}^n} \frac{\partial E^n}{\partial E} \frac{\partial E}{\partial p}$

With $E \sim pc$ ($E \ll E_{QG}$), $\frac{\partial E}{\partial p} = c \left[1 \pm \frac{1}{2} \left(\frac{E}{E_{QG}} \right)^n \right] \left[1 \mp \frac{n}{2} \left(\frac{E}{E_{QG}} \right)^n \right]^{-1}$

Neglecting the $2n$ -order term, one shows that

$$v_g(E) = \frac{\partial E}{\partial p} = c \left[1 \pm \frac{n+1}{2} \left(\frac{E}{E_{QG}} \right)^n \right]$$

Search for time delays

- As Universe is expanding, the expansion has to be taken into account when calculating the delay (Jacob & Piran, 2008)
- The time delay between two photons of energies E_h and E_l is therefore :

$$\Delta t_n \simeq s_{\pm} \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

with $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

Note that other models it can have different redshift dependence.

- For subluminal effect, the two photons are assumed to be emitted at the same time, the HE photon arrives first

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with $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

CMB+lensing/BAO (2018):
 $H_0 [\text{kms}^{-1} \text{Mpc}^{-1}]$
 $= 67.66 \pm 0.42$
 $\Omega_m = 0.3111 \pm 0.0056$
 $\Omega_\Lambda = 0.6889 \pm 0.0056$

- Note that time delays are expected from source intrinsic effect, plasma effect, photon interaction with dark matter, cascade in the IGMF, ...
- For source intrinsic effect : Population studies (all sources) or Full modeling of source intrinsic effects

Astrophysical sources for time delay searches

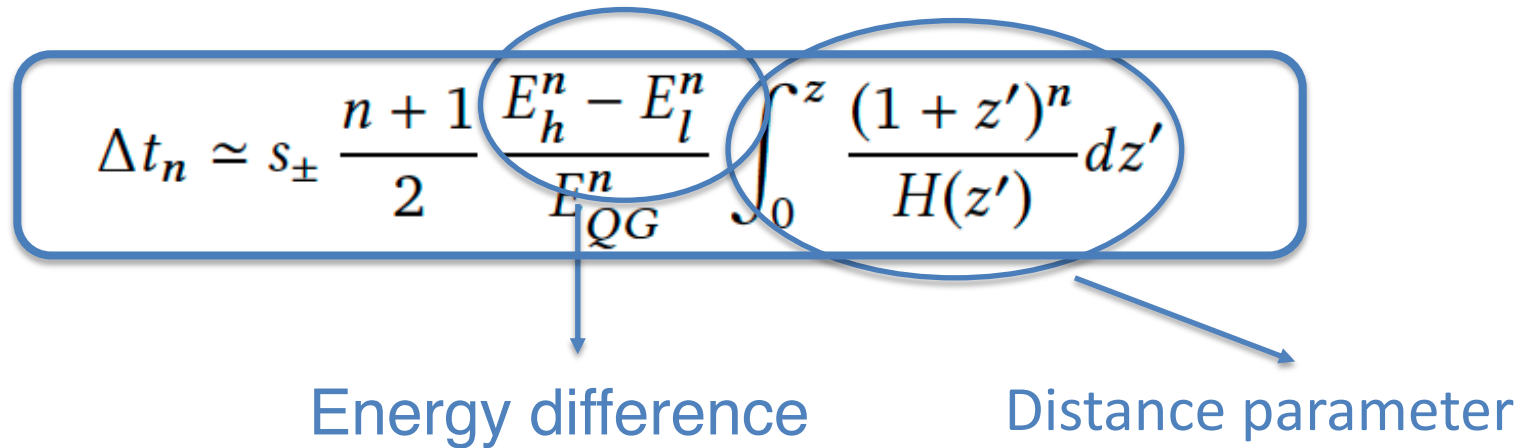
$$\Delta t_n \simeq s_{\pm} \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

Distance parameter

- Need for sources that are
 - Distant
 - Variable or transient
 - Energetic
- Candidates:
 - Gamma-Ray Bursts (GRBs)
 - Flaring Active Galactic Nuclei (AGNs)
 - Pulsars (PSRs)

Astrophysical sources for time delay searches



The diagram shows the equation for time delay $\Delta t_n \simeq s_{\pm} \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$. The entire equation is enclosed in a blue rounded rectangle. Two blue circles highlight specific parts: one circle encloses the energy difference term $\frac{E_h^n - E_l^n}{E_{QG}^n}$, and another circle encloses the integral term $\int_0^z \frac{(1+z')^n}{H(z')} dz'$. A blue arrow points from the first circle down to the text "Energy difference". Another blue arrow points from the second circle down and to the right to the text "Distance parameter".

$$\Delta t_n \simeq s_{\pm} \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

Distance parameter

Caveats:

A measured lag is the combination of lags from different origins : expected and some hypothetical ones:

- source effect : delays due to emission and acceleration mechanisms at the source
- source plasma effect
- cascade in IGMF
- ...

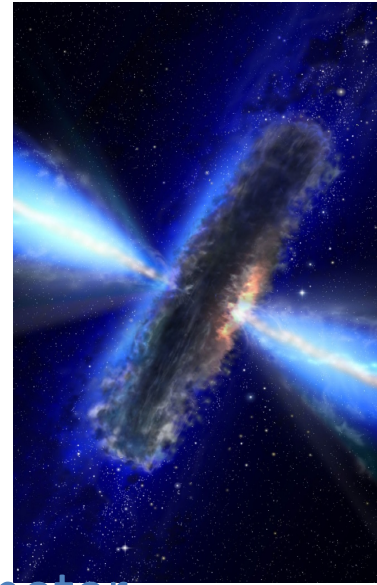
Careful estimates needed

Example : flaring AGN

$$\Delta t_n \simeq s_{\pm} \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

Distance parameter



Blazars

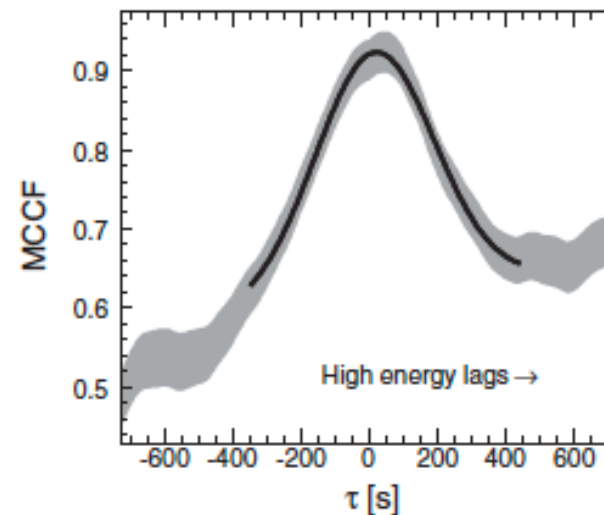
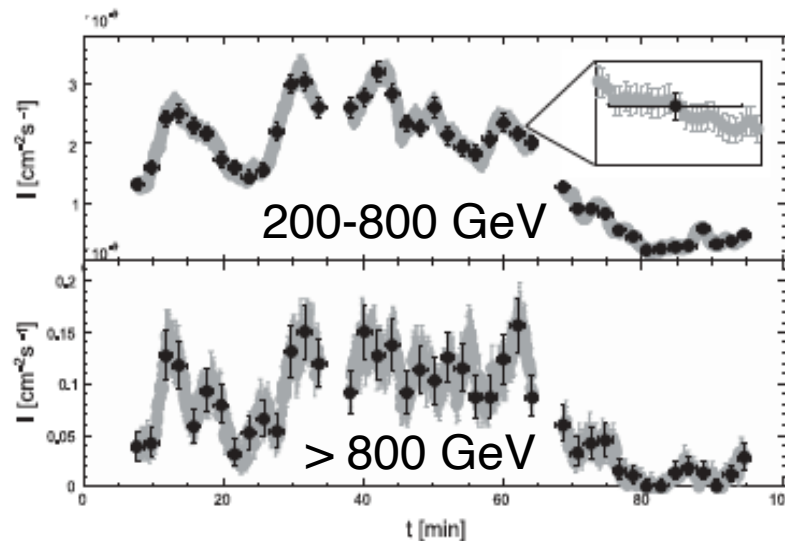
- Jet close to the line-of-sight
- High variability (flares)

- 👍 Good statistics with IACTs
- 👍 High variability (O(min))
- 👍 Distant sources
- 👎 Flares happen randomly
- 👎 Hints of intrinsic temporal effects
- 👎 Details of emission mechanisms poorly understood

Example : PKS 2155-304 flare in 2006



- $z = 0.116$ (~ 490 Mpc)
- 2006 flare :
 - Very high flux $\rightarrow \sim 14$ Crab; High statistics $\rightarrow \sim 10000$ photons
- Time lag between two light curves with the modified cross correlation function



- Best-fit function peaks at 20 s
 - Error on the measured time delay is determined by propagating the flux errors via simulations:
 - cross correlation peak distribution : mean of 25s and a rms of 28s
- $\rightarrow$ Time lag not significant

- The best limit obtained by HESS is currently $E_{QG} = 2.1 \times 10^{18}$ GeV with the Big flare of PKS 2155 ($n = 1$, 95% CL)
- Stronger limits obtained on E_{QG} are of $\sim 10 E_{Pl}$ for individual GRBs

Modified pair cross section

- A Modified Dispersion Relation can also induce a modified photon kinematics, which can lead to modifications of the $\gamma\gamma$ interaction cross-section
 - change in the energy threshold of the $\gamma\gamma \rightarrow e^+e^-$ pair production reaction
- Cosmic opacity for VHE γ rays ($E > 10$ TeV) that result from the interaction with the extragalactic background light can be strongly reduced

- Let's rewrite the modified relation for photons as

- The term $m_\gamma^2 \equiv -E_\gamma^3/E_{\text{LIV}}$ acts as an effective mass term for photons

$$E_\gamma^2 = p_\gamma^2 c^2 - \frac{E_\gamma^3}{E_{\text{LIV}}}$$

- Assuming the same MDR, the minimum energy of the soft target photons that allow the pair-production reaction is

$$\epsilon_{th} = \frac{(m_e c^2)^2}{E_\gamma} \left[1 \pm \frac{1}{4} \left(\frac{E_\gamma}{E_{\text{LIV}}} \right)^{n+2} \right]$$

Fairbairn 2014

Modified pair cross section

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Fairbairn 2014

$$\epsilon_{th} = \frac{(m_e c^2)^2}{E_\gamma} \left[1 \pm \frac{1}{4} \left(\frac{E_\gamma}{E_{LIV}} \right)^{n+2} \right]$$

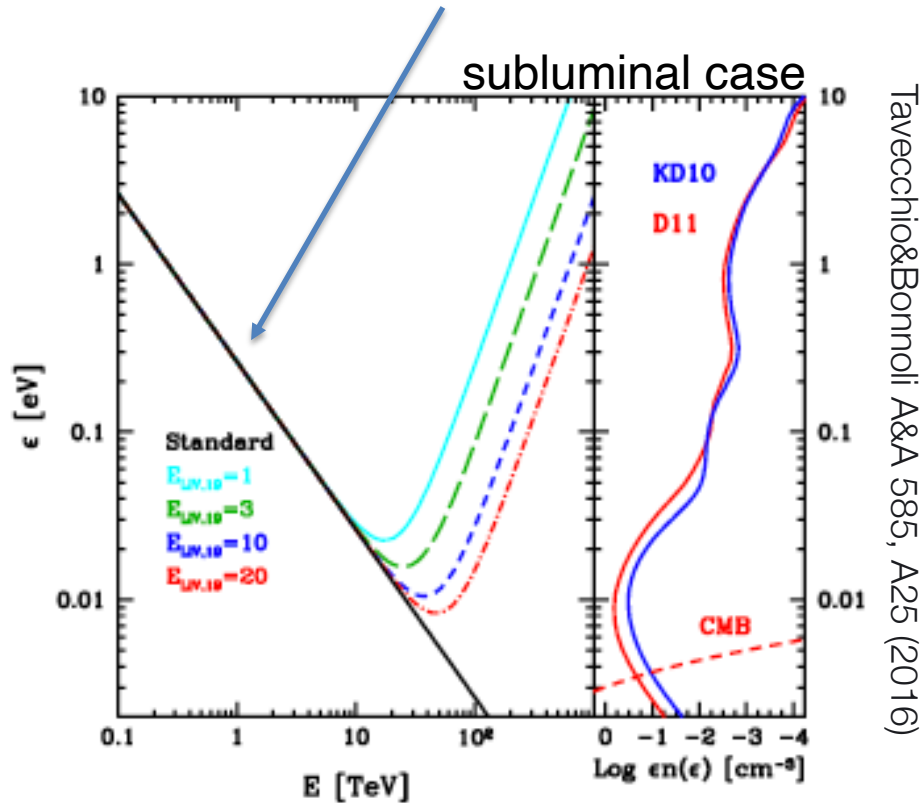
- superluminal case (-): the threshold is lowered and photons undergo a stronger absorption leading to steeper energy spectra
- subluminal case (+): higher threshold leading to a reduction of VHE photon absorption and less attenuated energy spectra
- Accounting for propagation over cosmological distances :

$$\epsilon_{th} \longrightarrow \frac{\epsilon_{th}}{1+z}$$

Modified pair cross section and opacity

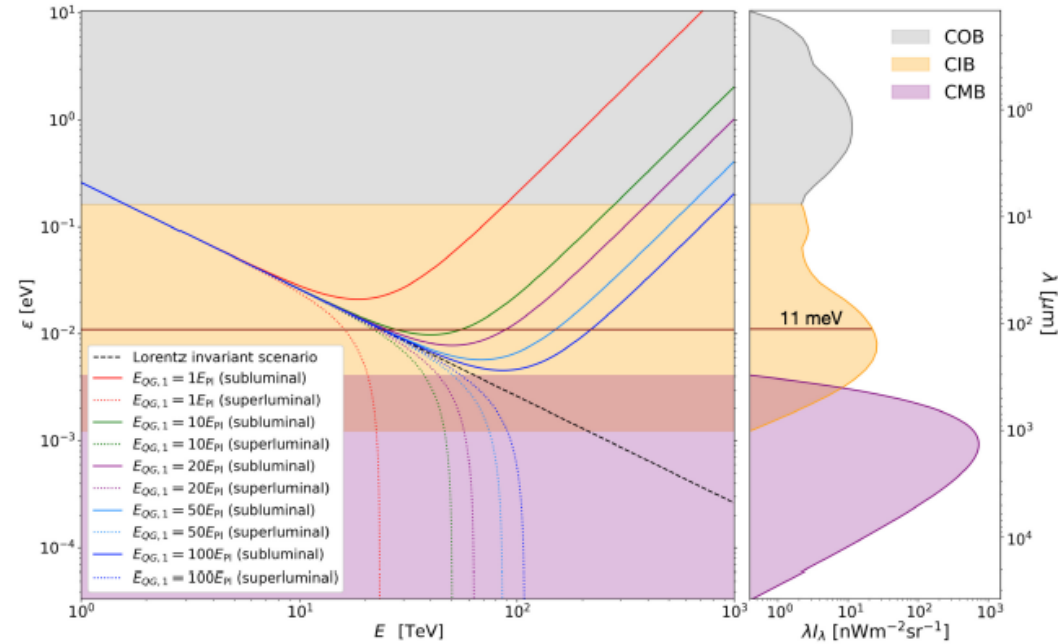
Standard value (i.e. w/o LIV)

$$\epsilon_{\min} = m_e^2 c^4 / E_\gamma \simeq 0.26 / E_{\gamma, \text{TeV}} \text{ eV}.$$



EBL models from
Dominguez 2011
and Kneiske 2010

Tavecchio&Bonoli A&A 585, A25 (2016)

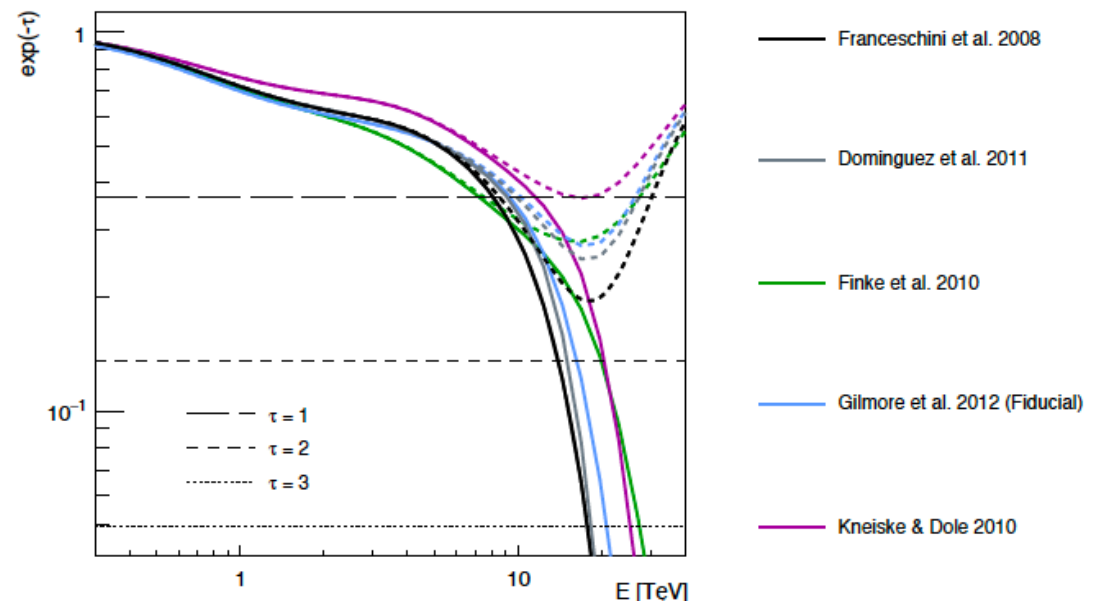
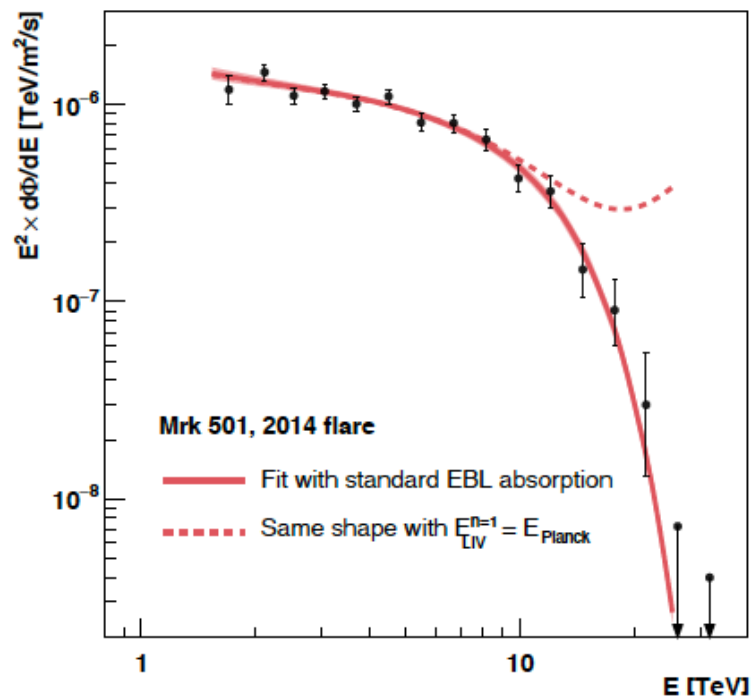


Evolution of the background photon energy threshold versus gamma-ray energy E (here noted E) for LIV effects ($n=1$) at $z=0$.

Right: spectral energy distribution of target photon fields: optical (COB), infrared (CIB) and CMB.

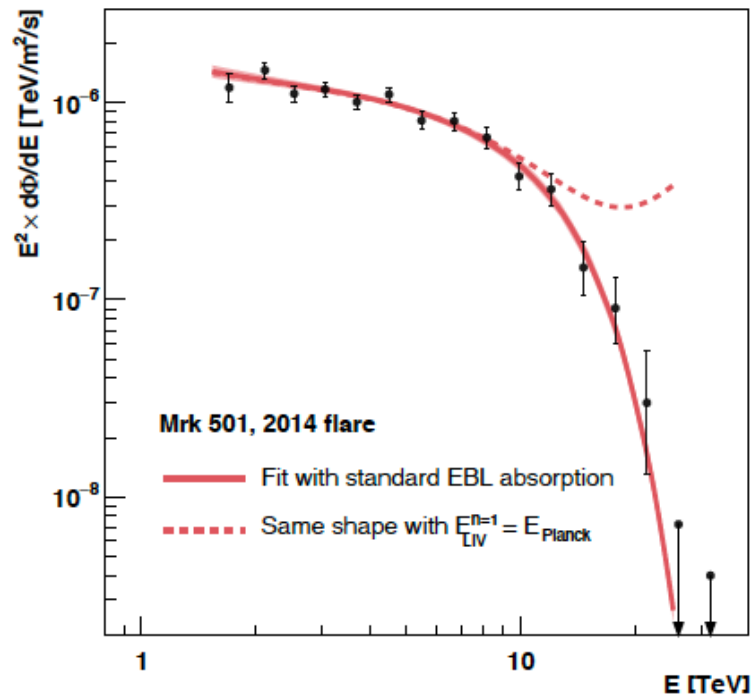
Astrophysical sources for LIV-induced modified pair cross section searches

- An ideal source to test possible modifications of the γ -ray opacity induced by LIV should be a bright emitter above 20–30 TeV
 - Flaring blazars may display hard and bright TeV emission
 - “extreme” BL Lacs
- The example of Mrk 501 flare:



Attenuation factor in presence of LIV at Planck scale

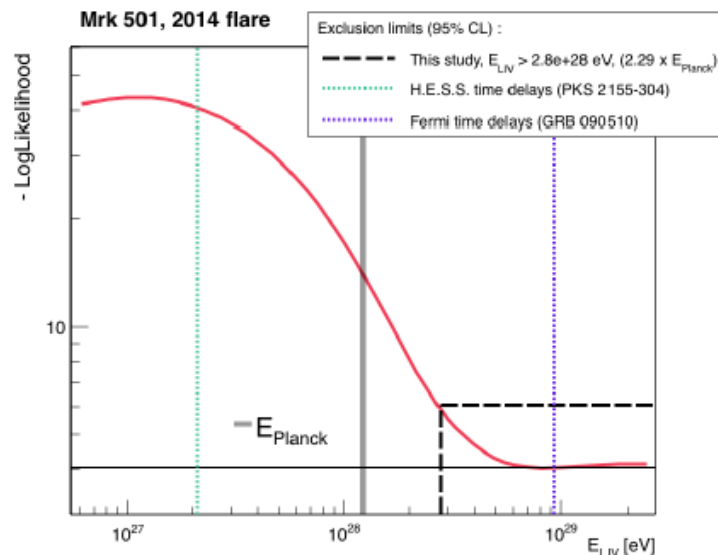
H.E.S.S. observations of 2014 Mkr 501 flare



$$\Phi_{\text{obs}}(E_\gamma) = \Phi_0 \frac{E_\gamma^{-\alpha}}{E_0} \times \exp[-\tau_{\text{Fr08}}(E_\gamma, z = 0.034, E_{\text{LIV}}^n)]$$

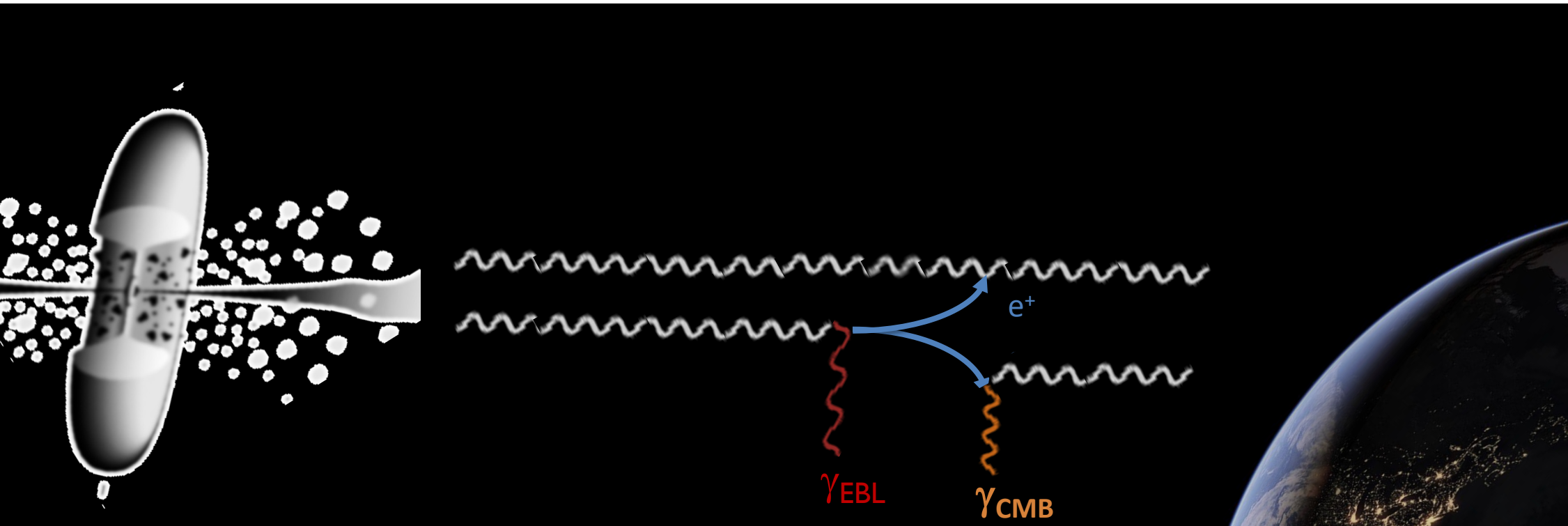
$$\tau(E_\gamma, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_0^2 d\mu \frac{\mu}{2} \int_{\epsilon_{\text{seuil}}}^\infty d\epsilon \frac{dn_{\text{EBL}}}{d\epsilon}(\epsilon, z) \sigma_{\gamma\gamma}[\beta(E_\gamma(1+z), \epsilon, \mu)]$$

LIV effect encoded in ϵ and in the pair production cross. section



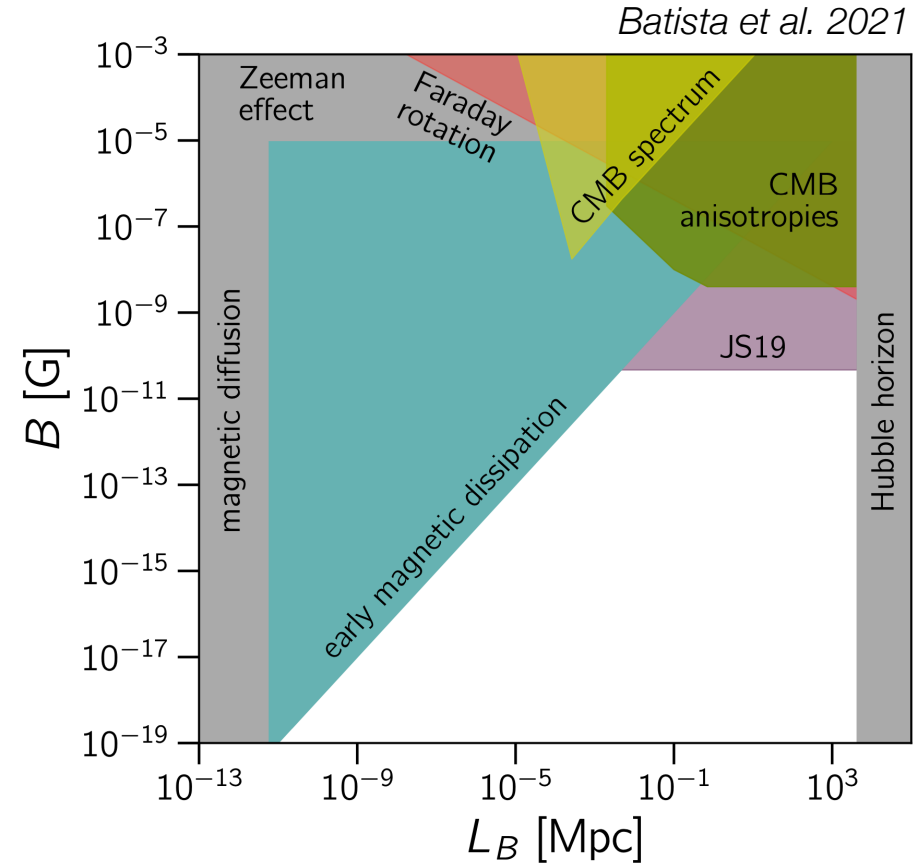
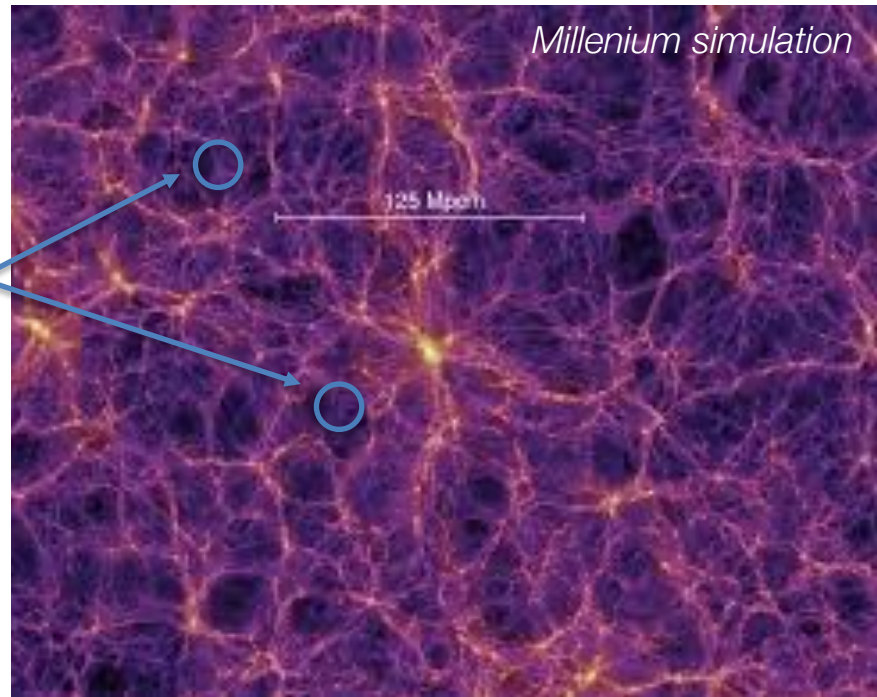
- $E_{\text{LIV}} > 2.3 E_{\text{pl}}$ for $n=1$ (95% C.L.)
- Stronger constraints obtained from time delay searches with GRB 090510

INTERGALACTIC MAGNETIC FIELD AND HIGH-ENERGY GAMMA RAYS



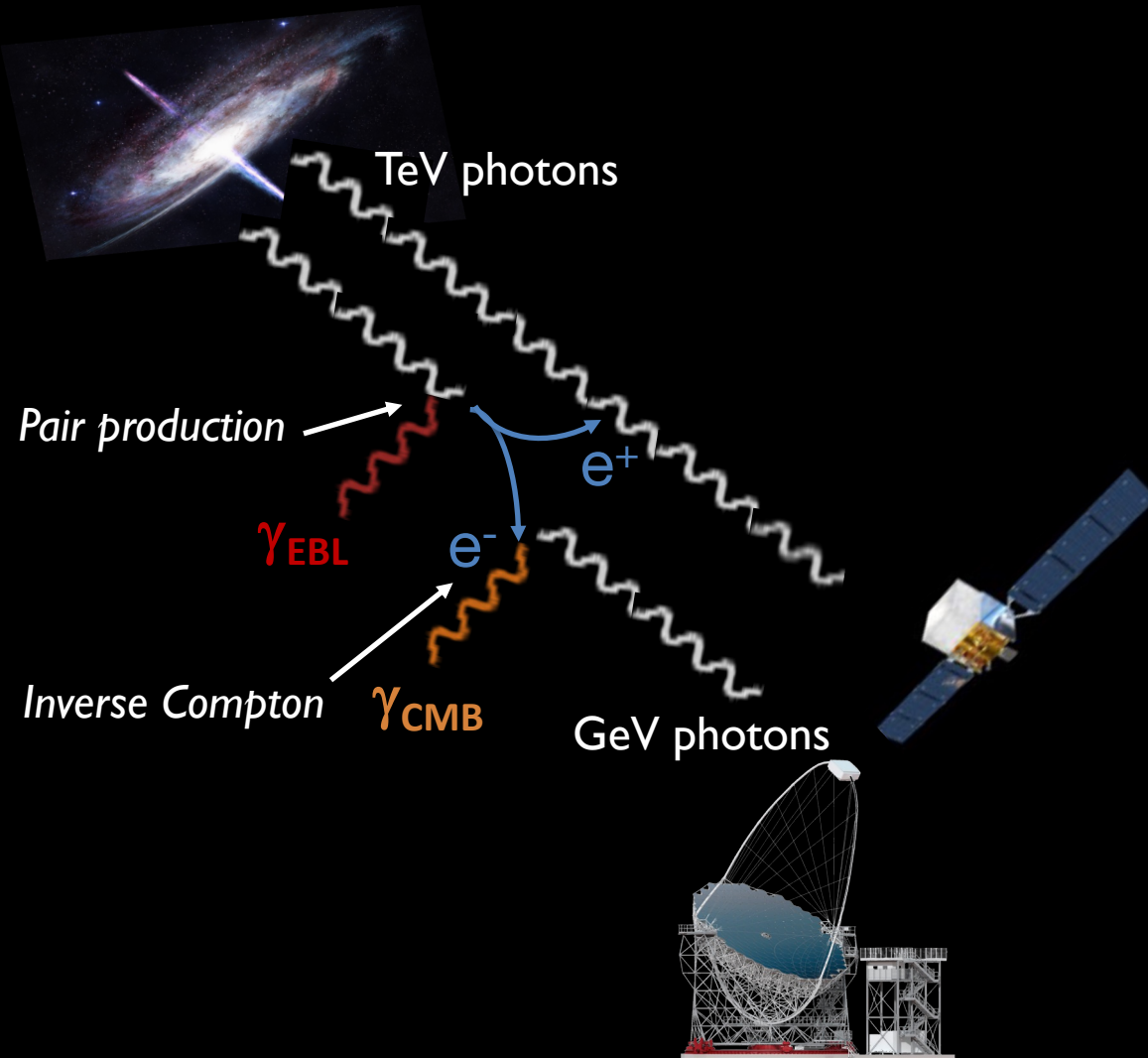
InterGalactic Magnetic Field (IGMF)

IGMF ?
 $B \gtrsim 10^{-16} \mu\text{G}$
 $\lambda_B \sim \text{Mpc}$



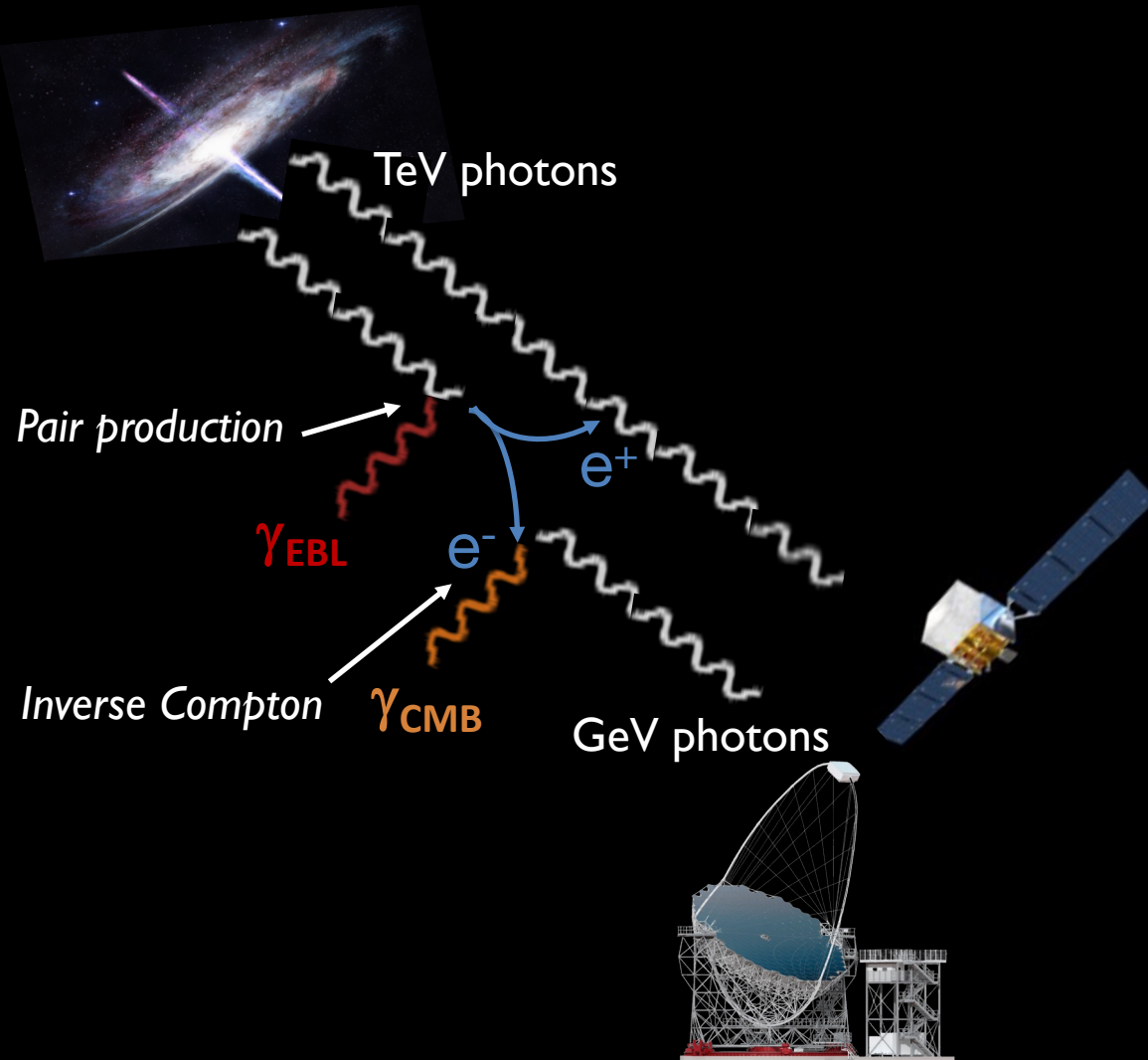
- Magnetic fields exist at every scale : stars, galaxies, clusters, filaments, voids
- But what is the origin : IGMF ?

Signatures of IGMF in gamma rays



- Excess γ rays at lower energies
e.g. Neronov & Semikoz 2008
- Extended γ -ray halos
Aharonian et al. 1994
- Time delayed γ -ray emission
Plaga 1995
- Biggest uncertainty: blazar duty cycle
Dermer et al. 2011

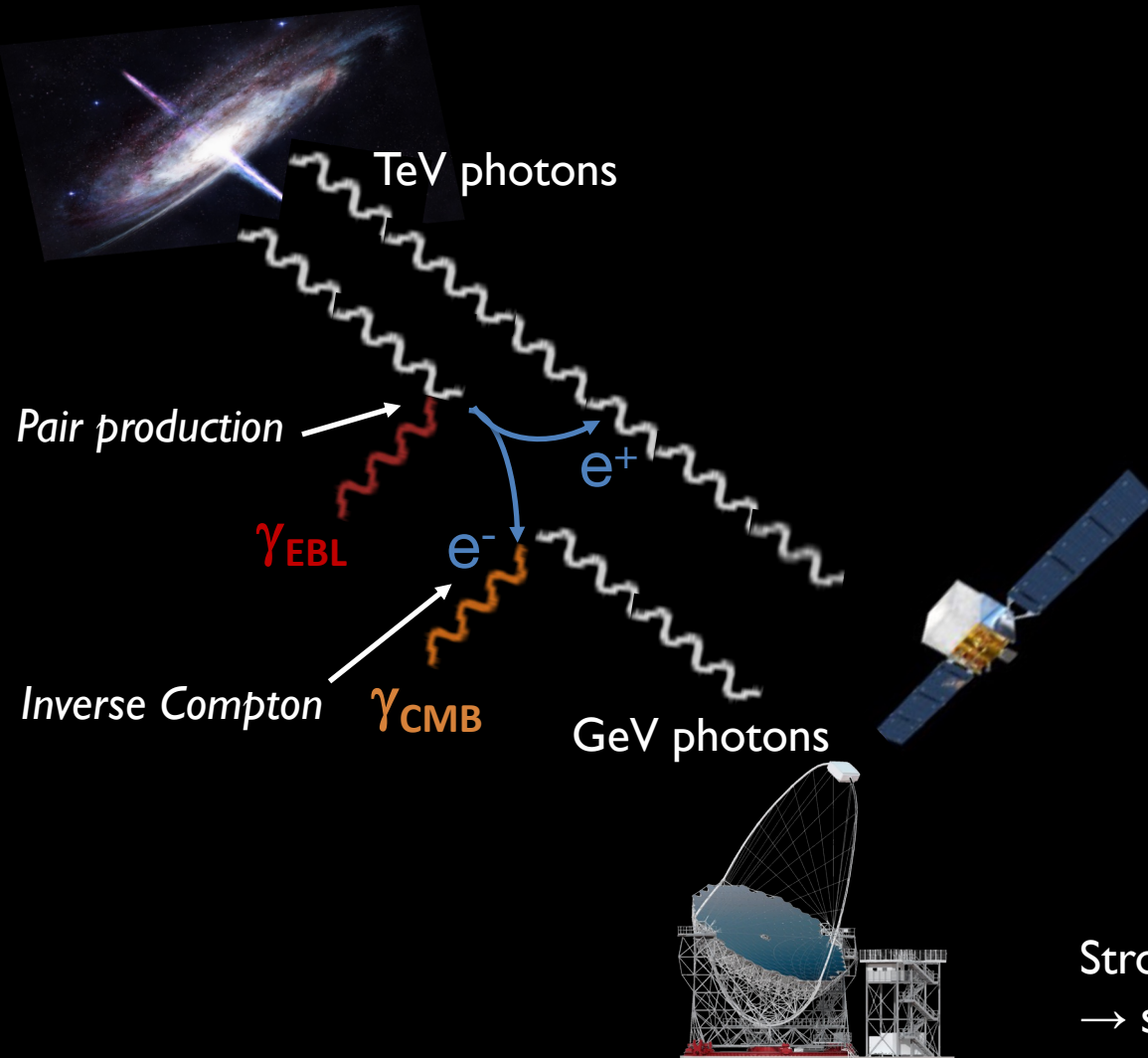
Signatures of IGMF in gamma rays



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Search for cascade emission from blazars in Fermi-LAT data

Signatures of IGMF in gamma rays

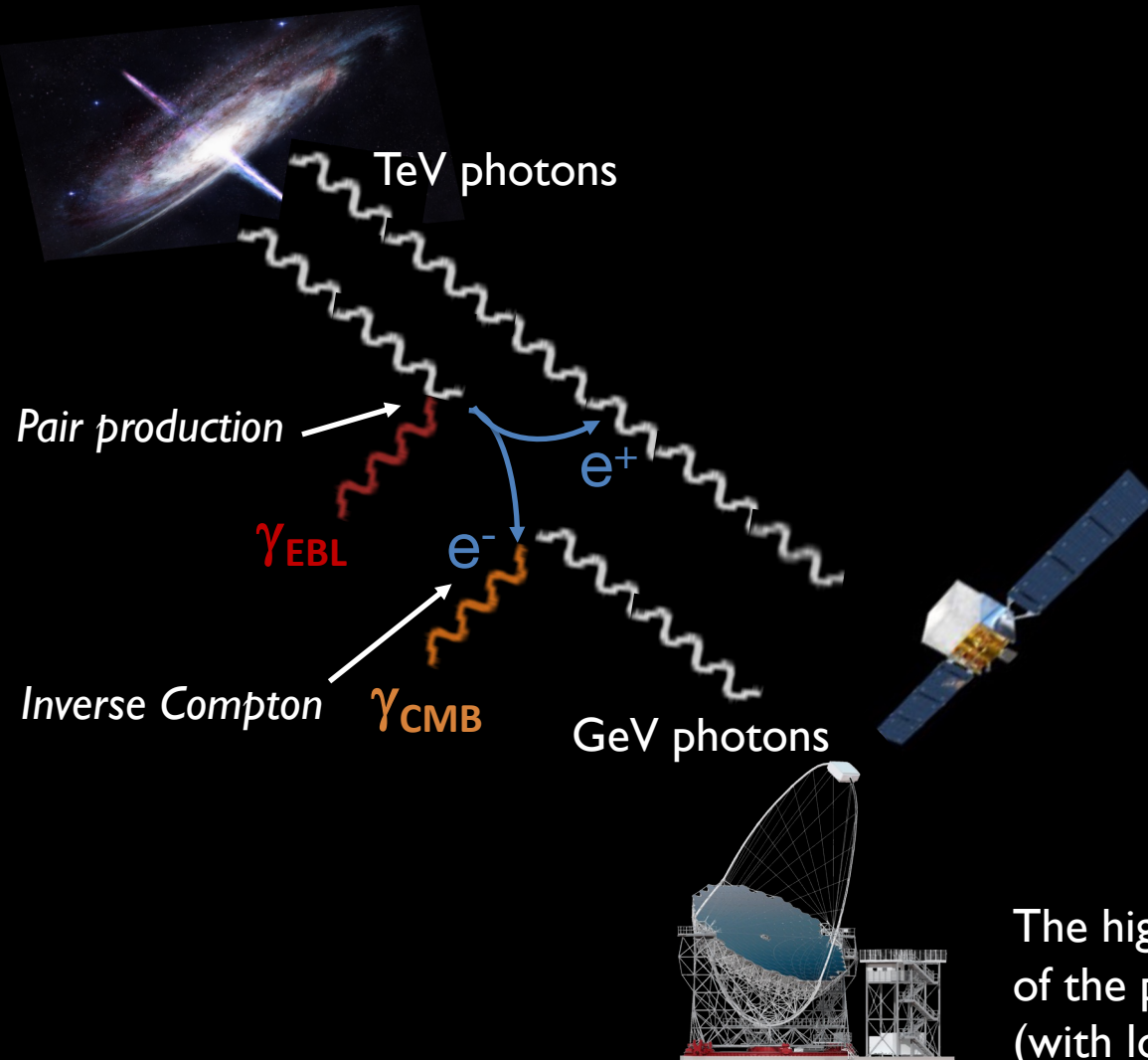


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Search for cascade emission from blazars in Fermi-LAT data

Strong enough IGMF deflects electron-positron pairs
→ suppression of secondary emission

Signatures of IGMF in gamma rays

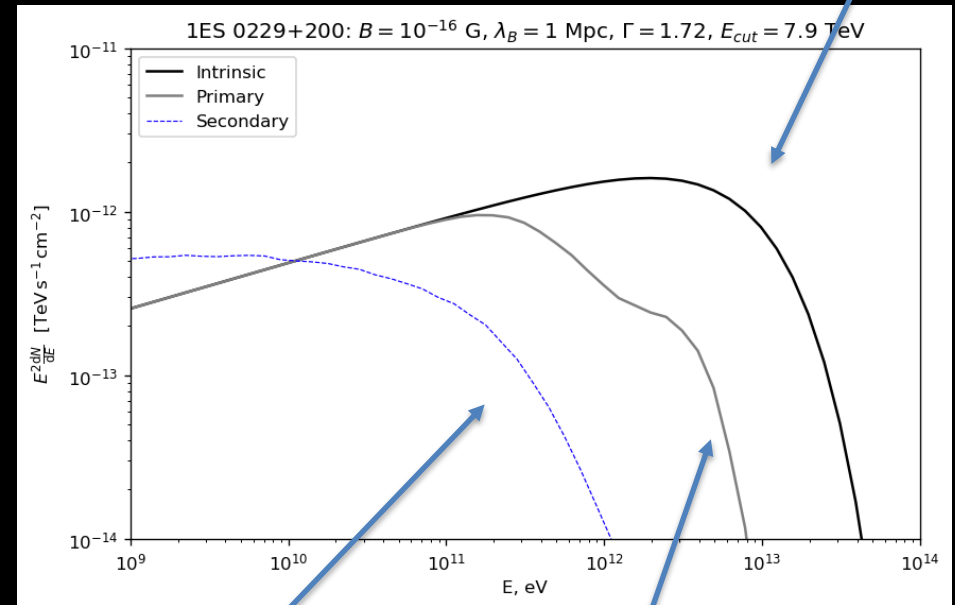
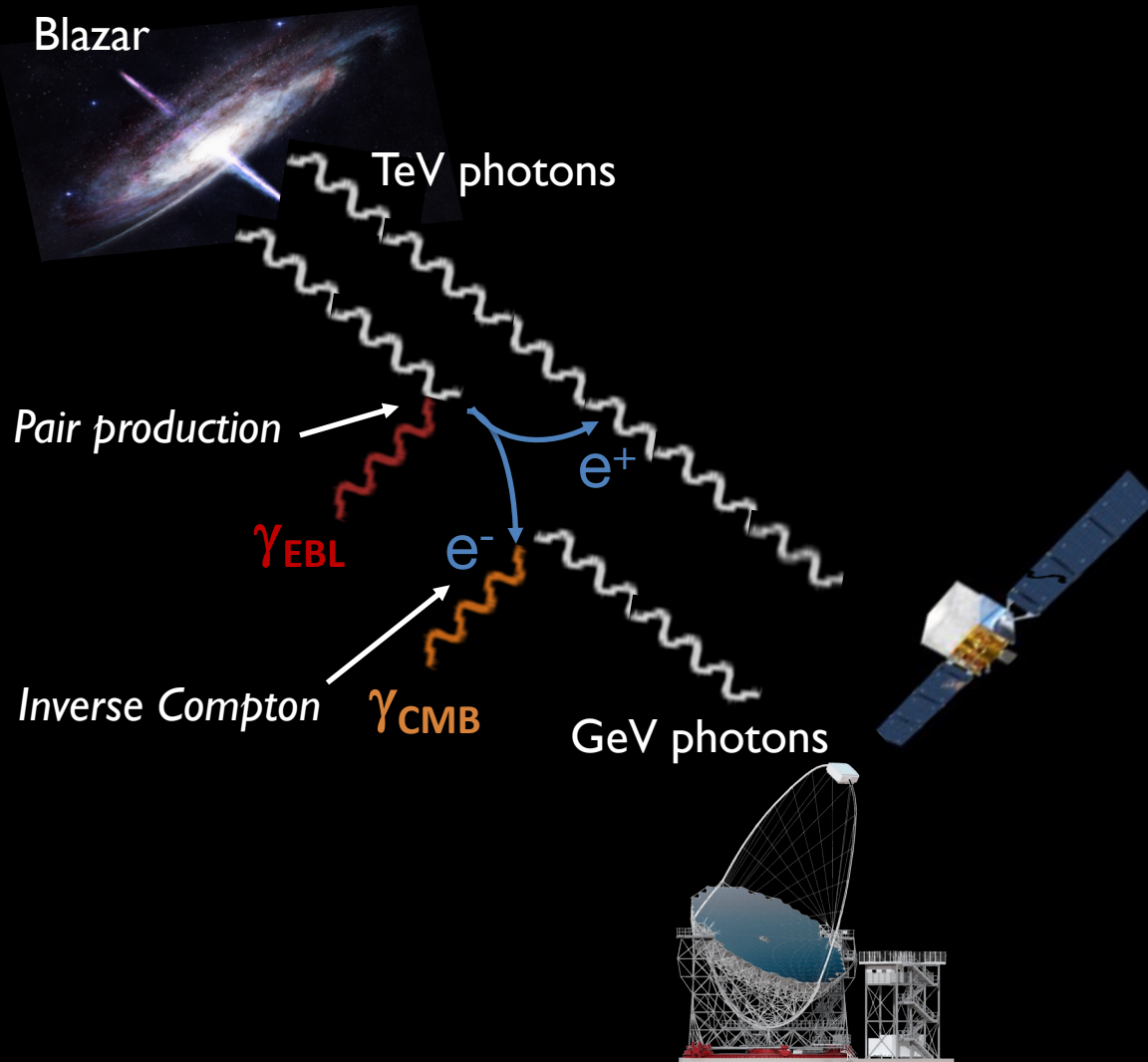


- Excess γ rays at lower energies [e.g. Neronov & Semikoz 2008]
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- Time delayed γ -ray emission [Plaga 1995]
- Biggest uncertainty: blazar duty cycle [Dermer et al. 2011]

Search for cascade emission from blazars in Fermi-LAT data

The higher the value of the IGMF, the stronger the deflection of the pairs and, in turn, the larger the pair halos (with lower surface brightness), the lower the GeV excess of cascade photons, and the longer the time delays.

Signatures of IGMF in gamma rays

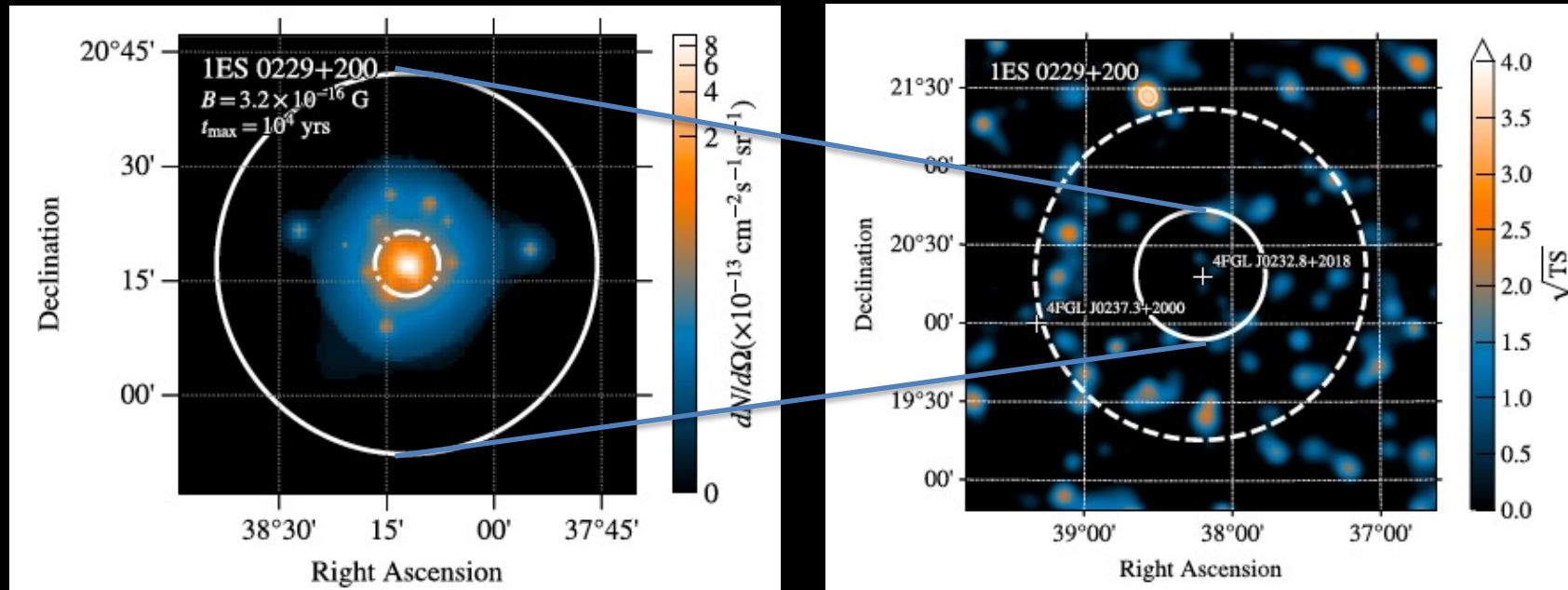


Spectrum at the source

Spectrum of photons from cascade

Spectrum of photons that do not interact

Combined H.E.S.S. and Fermi-LAT analysis



- Intrinsic blazar model (assumed constant over activity time):

$$\phi(E) = N \left(\frac{E}{E_0} \right)^{-\Gamma} \exp \left(-\frac{E}{E_{\text{cut}}} \right)$$

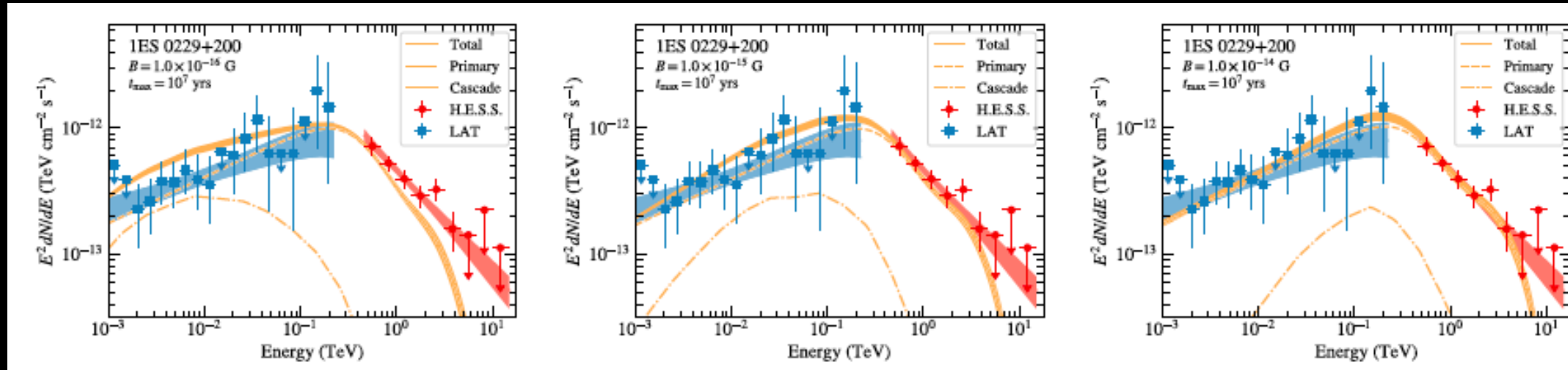
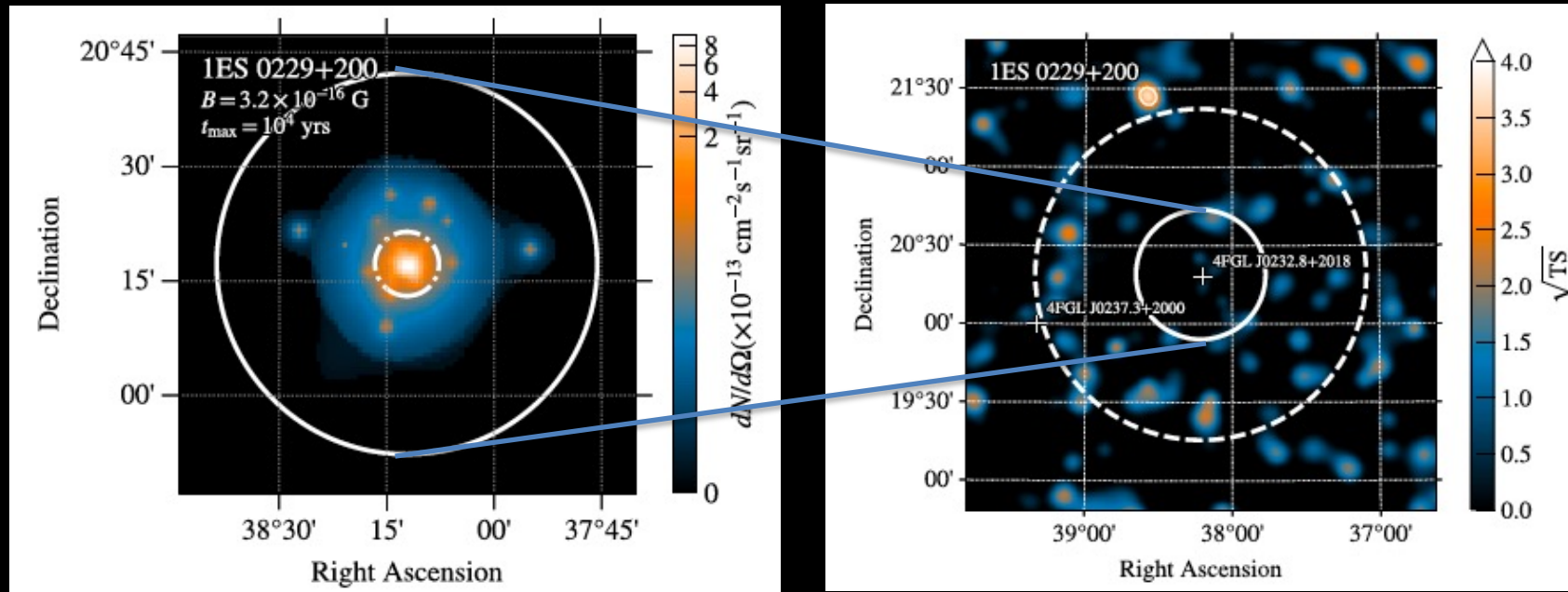
- Total source model: $\phi_{\text{tot}}(E, B) = \phi(E) \exp(-\tau) + \phi_{\text{halo}}(E, B)$

- Halo flux taken from CRPropa3 simulation; depends on spectral parameters, blazar activity time*...

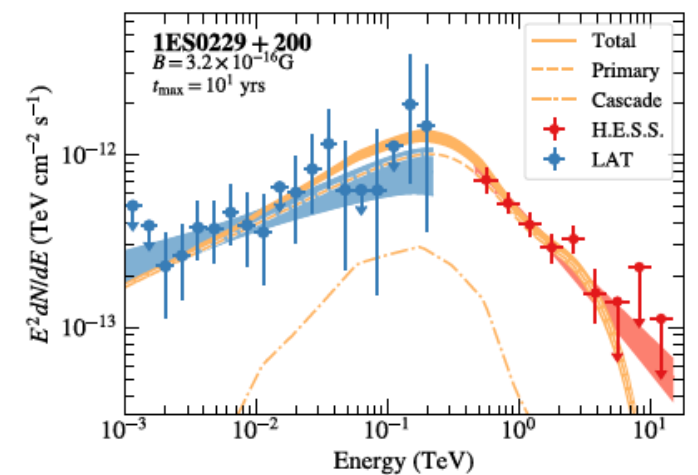
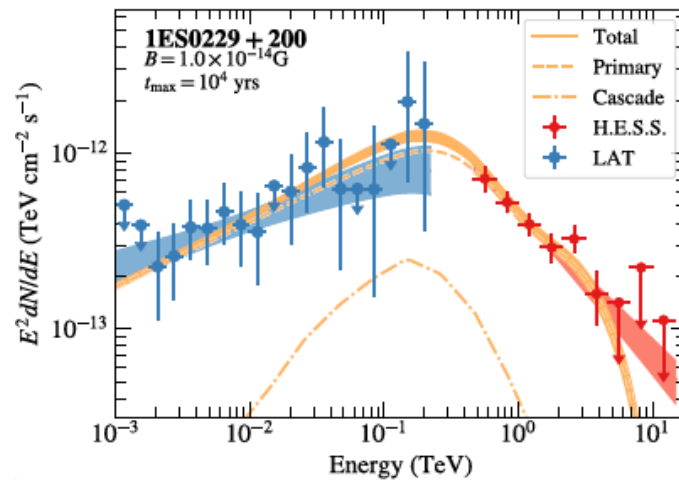
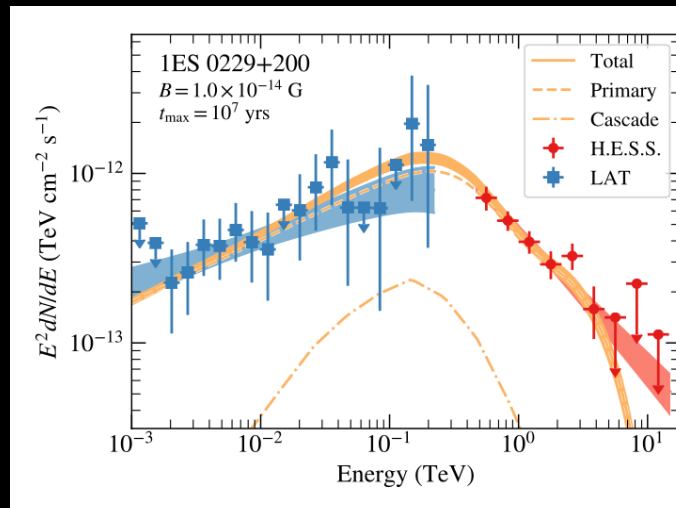
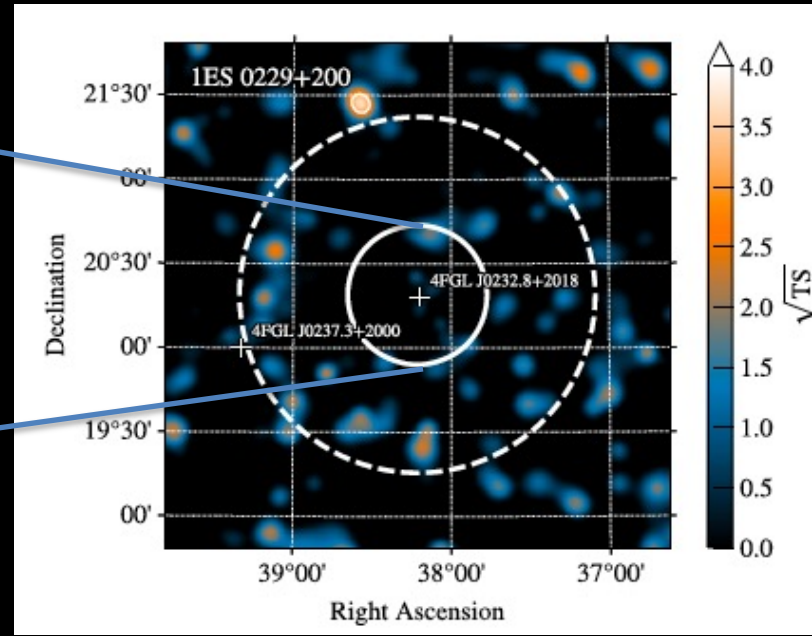
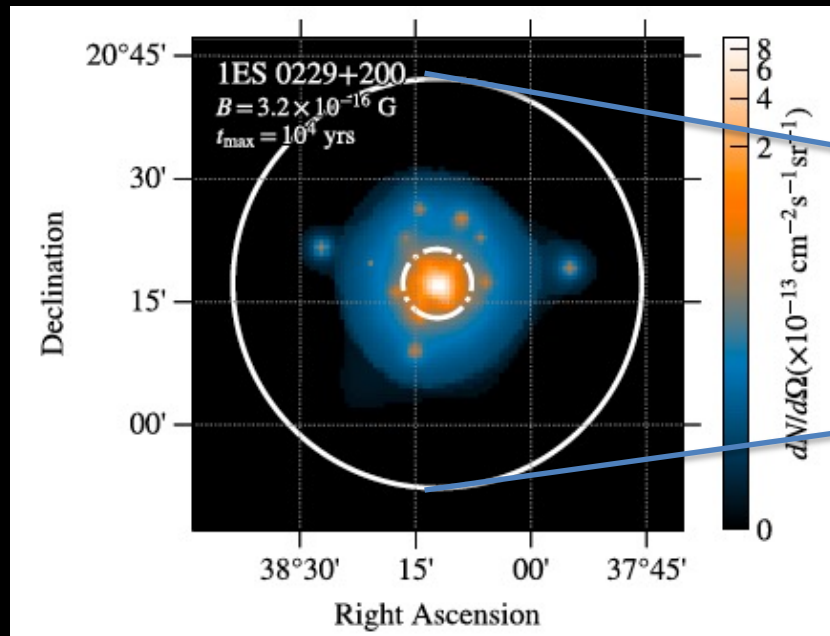
Takes both spectral and spatial (for LAT) information into account

**Activity time (duty cycle) : length of the time during which the blazar has been emitting gamma rays. Assume that a blazar has emitted a flux that is constant in time, which can be described with the average spectrum observed today.*

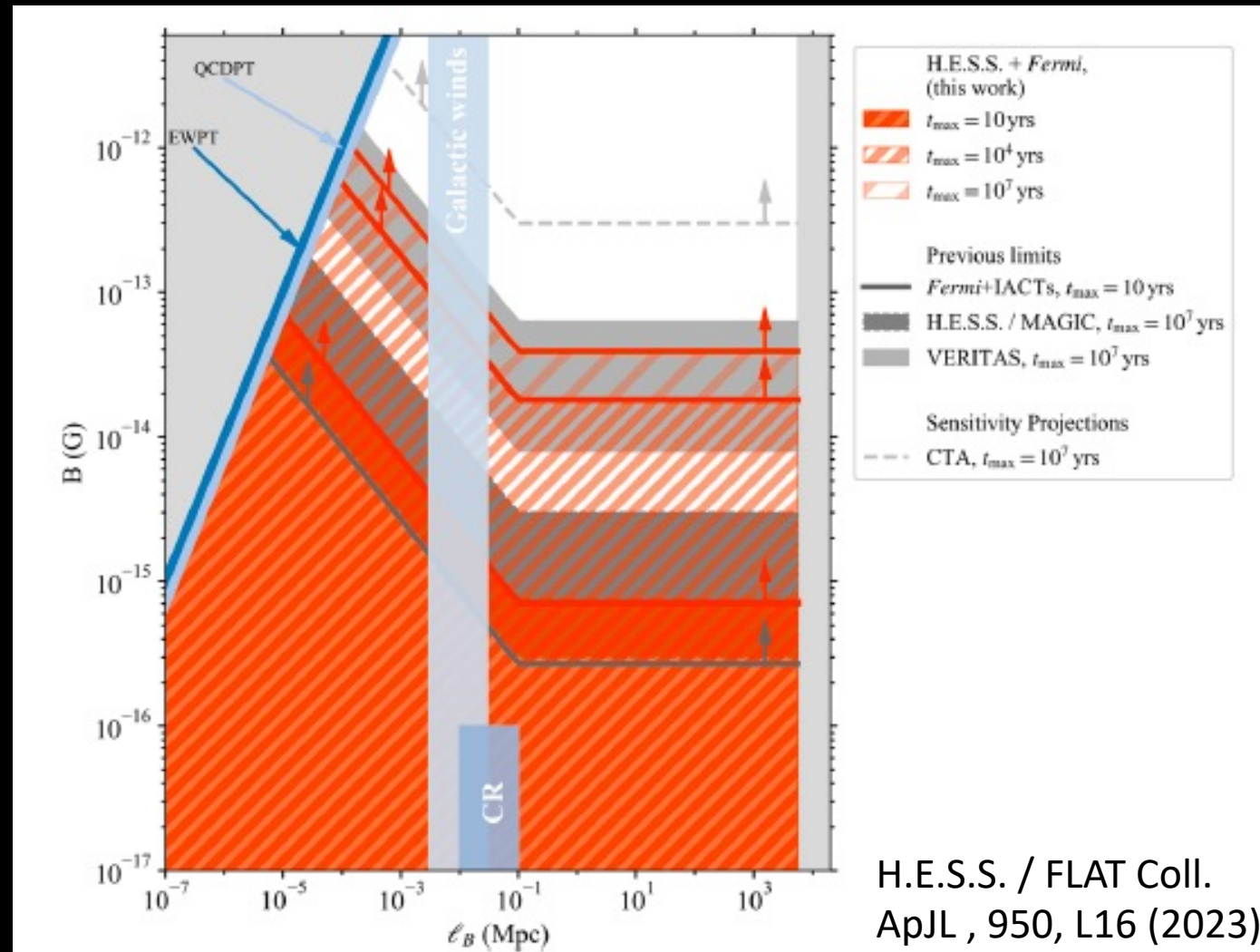
Combined H.E.S.S. and Fermi-LAT analysis



Combined H.E.S.S. and Fermi-LAT analysis



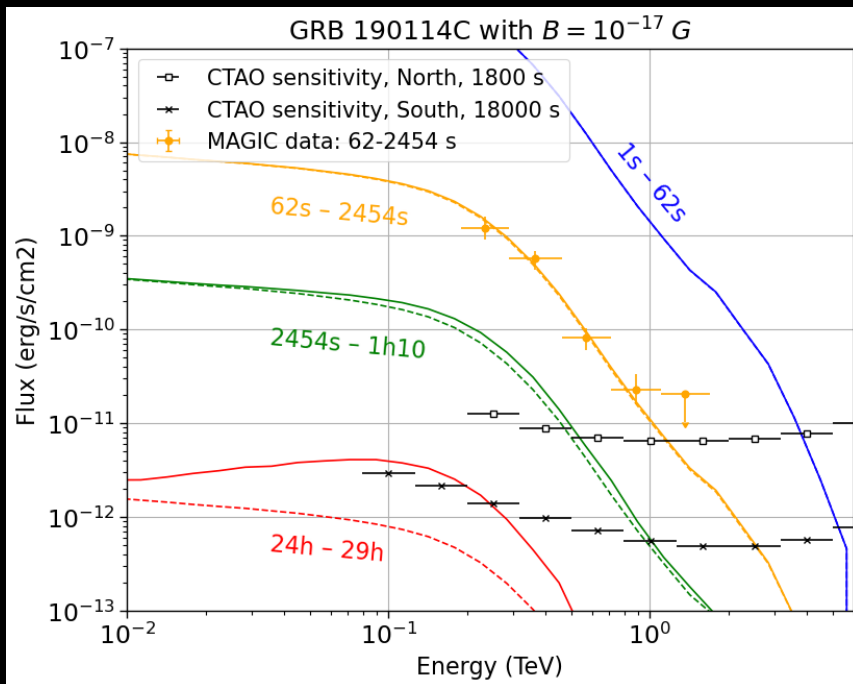
Combined H.E.S.S. and Fermi-LAT analysis



- Gamma-ray emission is assumed to be constant over activity time
- The assumed activity time of the sources poses the largest systematic uncertainty
- Pairs could predominantly lose their energy by heating the intergalactic medium through plasma instabilities, which would suppress the cascade

IGMF sensitivity from GRB afterglows w/ CTAO

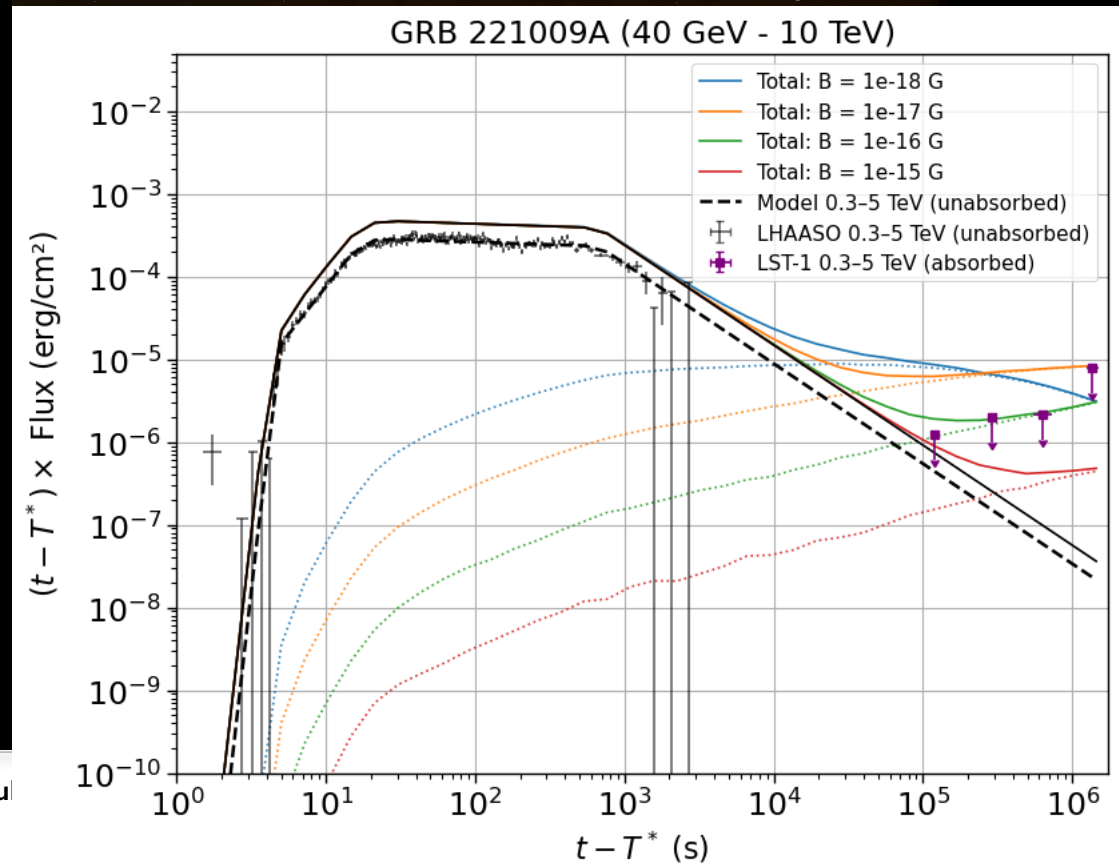
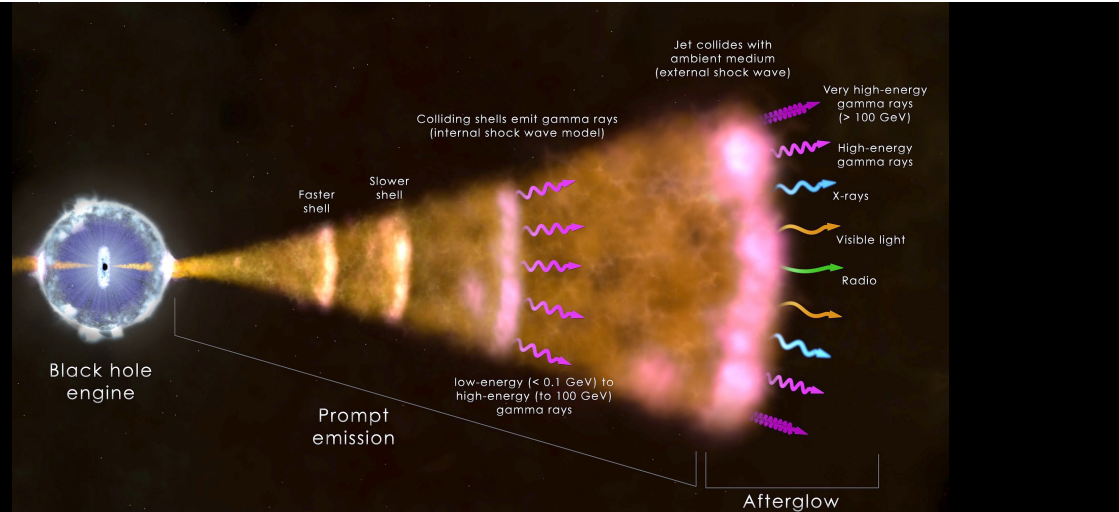
Secondary emission from GRBs



- Detectable for several nights with CTAO
- LST-I: $B > \sim 10^{-16}$ G
- If full array: lower limits up to $\sim 10^{-15}$ G

Keita, Belmont, Stolarzyck et al. <https://arxiv.org/pdf/2604.25647>

Emmanuel Mou



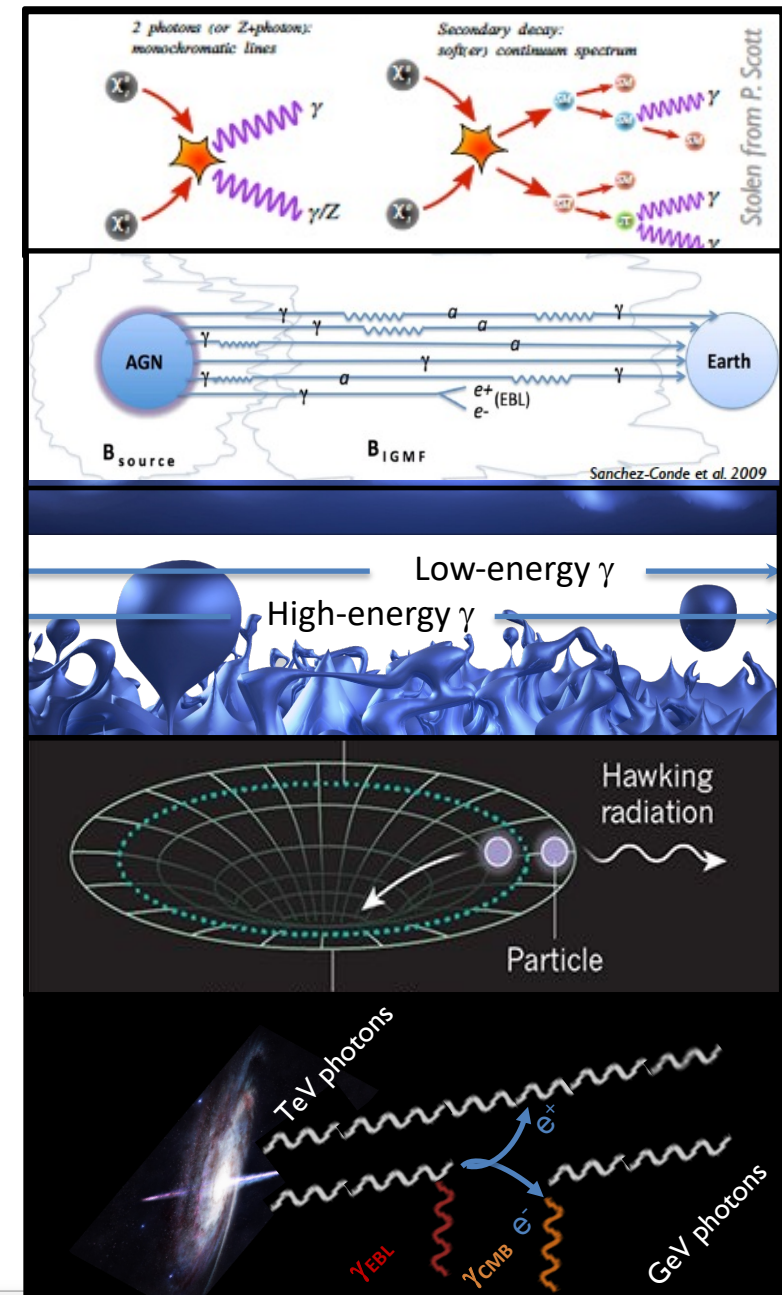
« Fundamental physics » in the context of multi-messenger astronomy

No conclusive identification of DM, but enormous progress in astrophysical sensitivity

- WIMP paradigm dominated the searches for decades
 - Still alive, but not alone! WIMP exploration will continue
 - Limitations in our understanding of the ‘background’ (aka astrophysics)
- Alternative candidates gain more and more attention
 - Rich phenomenology with PeV decaying DM, ALP, PBH, ...

BSM physics can also manifest as apparent violations of laws/symmetries of the SM:

- ALPs/LIV may alterate the apparent transparency of the universe
- LIV may induce a modified dispersion relation of photons
- IGMF : HE/VHE gamma-ray observations relevant to probe models for IGMF generation in the early universe



End

Thank you for your attention!

For further questions do not hesitate to reach me
emmanuel.moulin@cea.fr