New Physics with Cosmic Rays and Neutrinos

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But some of the deepest questions in fundamental physics and cosmology cannot be answered with electromagnetic radiation alone

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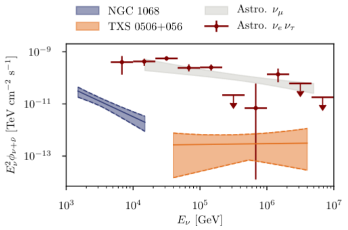
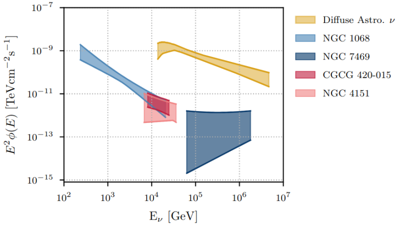
Cosmic rays and neutrinos are crucial (arguably necessary) to answer these questions

The high-energy neutrino sky

Reference	Milestone	Energy scale	Evidence
IceCube, 13'	**Diffuse flux**	30 TeV–1 PeV	$> 5\sigma$ discovery
IceCube, 17', 18'	**TXS 0506+056**	40 TeV–4 PeV	3.5σ flare
IceCube, 22'	**NGC 1068**	2–20 TeV	4.2σ steady source
IceCube, 23'	**Galactic plane**	$\gtrsim$ 1 TeV	4.5σ extended emission
KM3NeT, 25'	**KM3-230213A**	220 PeV	highest-energy event
IceCube, 25'	**X-ray-bright AGN**	0.5 TeV–3 PeV	3.3σ population excess





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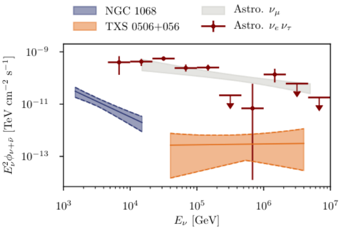
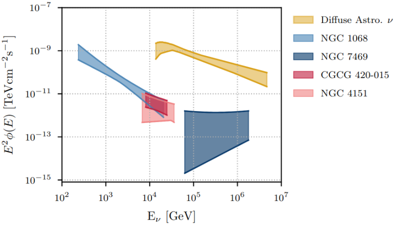
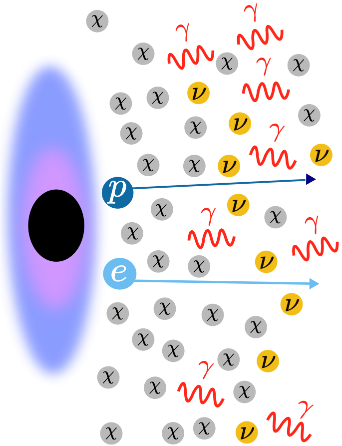




Diffuse emission is established; individual source populations are now emerging


χ
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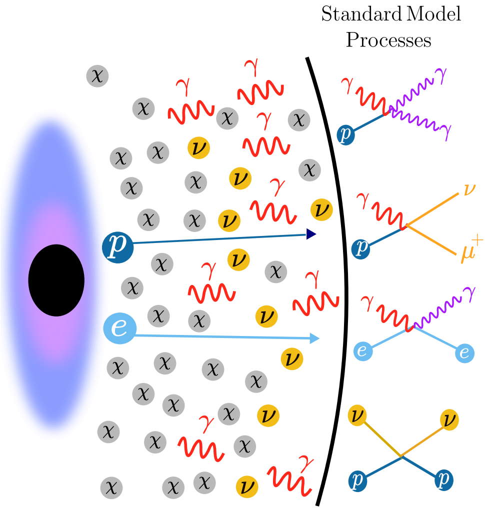
Standard Model Processes
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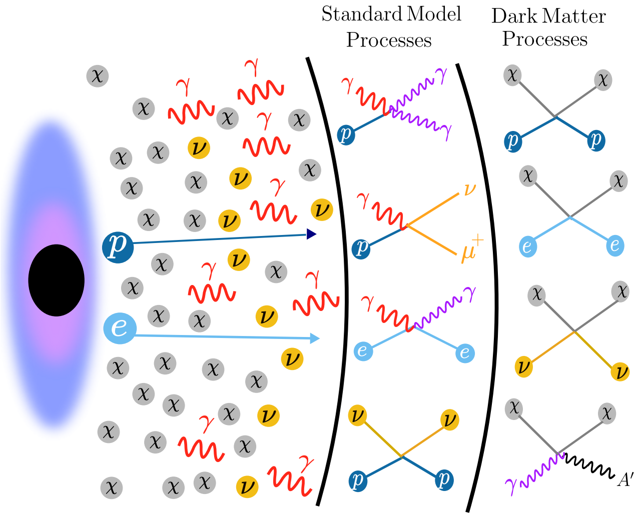
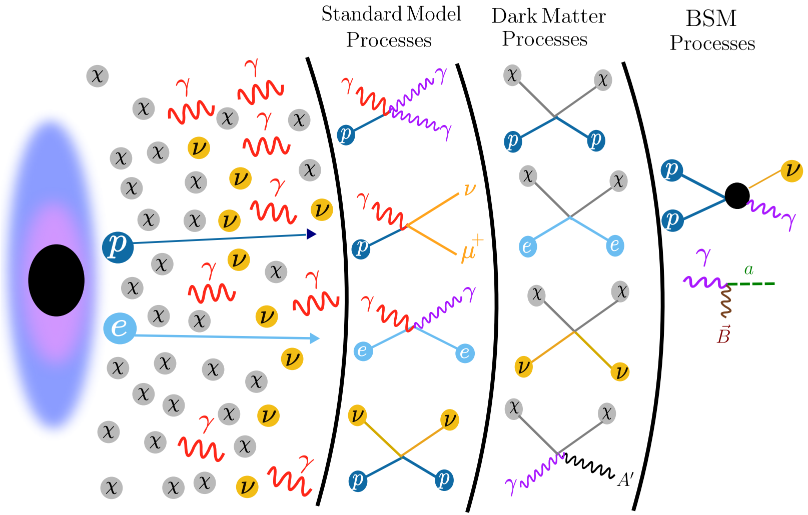

Standard Model Processes
Dark Matter Processes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χ
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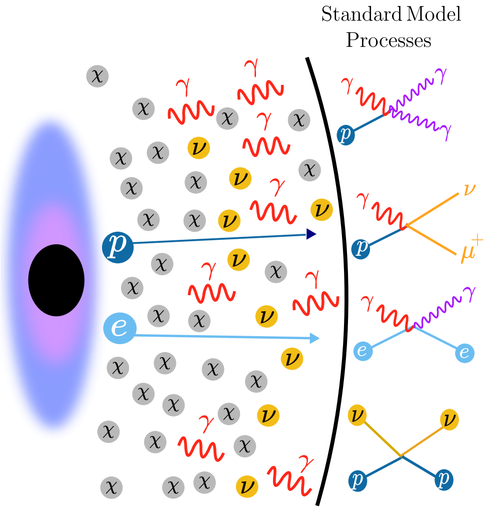
B⃗

Standard Model processes



Cosmic Neutrino Background (CνB)

- Neutrinos decoupled from the early Universe plasma $\sim$ 1s after the Big Bang via electroweak processes

$$\nu_e + \bar{\nu}_e \leftrightarrow e^+ + e^-$$
$$e^- + \bar{\nu}_e \leftrightarrow e^- + \bar{\nu}_e$$

$$\frac{\Gamma}{H} \sim \frac{\alpha^2 M_{\rm pl} T^3}{M_W^4} \sim \left(\frac{T}{1\,\mathrm{MeV}}\right)^3$$

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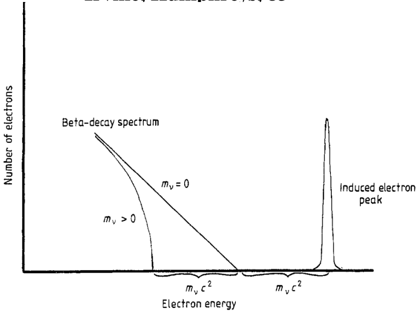
Earliest Universe particle probe observationally accessible

CMB happened ~ 380.000 yr after the Big Bang

Direct detection of the CνB: neutrino capture

Electron neutrino capture on tritium : $\nu + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$

Weinberg, 62'
Irvine, Humphreys, 83'



KATRIN places a limit on the local relic neutrino overdensity of $\sim 10^{11}$

PTOLEMY may improve this bound by orders of magnitude

The feasibility of this proposal is limited by Heisenberg's uncertainty principle

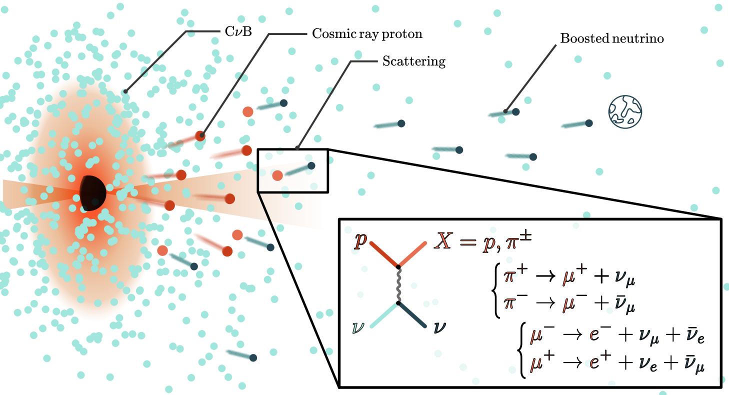
$$\Delta E \simeq \hbar^{1/2}\kappa^{1/4}(m_e Q)^{1/2} m_{\text{nucl}}^{-3/4} \simeq 0.3 - 0.7 \text{ eV}$$

Cheipesh, Cheianov, Boyarsky, 21'

Cosmic-ray boosted cosmic neutrino background

Císcar-Monsalvatje, Herrera, Shoemaker, 24’

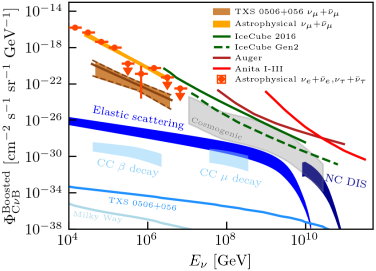
(see also **Hara, Sato, 80’, 81’**)

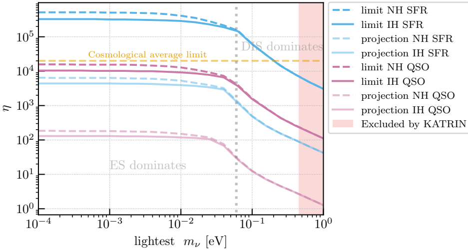


This flux extends to energies comparable to those from ultra-high energy cosmic rays $E_\nu \sim 10^9 - 10^{12}$ GeV

Diffuse boosted cosmic neutrino background

Císcar-Monsalvatje, Herrera, Shoemaker, 24'; **De Marchi, Granelli, Nava, Sala, 24'**; **Herrera, Horiuchi, Qi, 24'**; **Herrera, Horiuchi, Qi, Shoemaker, 26'**; **Zhang, Sandrock, Liao, Yue, 25'**; **Herrera, Loeb, 26'**; **Azeredo, Souza, 26'**; **Zhang, Liao, 26'**





- Neutrino telescopes are $\sim 3-7$ orders of magnitude away from being sensitive to the ΛCDM-expected CνB

- The signal is hidden below a background of cosmogenic neutrinos, except at the highest energies, due to the larger inelasticity of $p\nu$ vs $p\gamma$

- Future neutrino telescopes will likely probe CνB densities below the critical density of the Universe, and directly test neutrinos as a dark matter candidate, **Cline, Herrera, Roux, 26'**

A neutrino–X-ray relation becomes a distance ladder

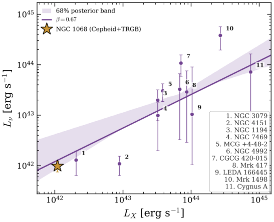
Herrera, Kamp, Argüelles, 26'

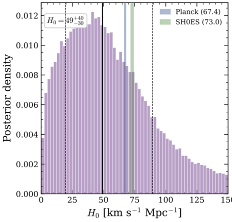
$$L_\nu = \kappa L_X^\beta \quad \Longrightarrow \quad F_\nu \propto F_X^\beta \, d_L^{2(\beta-1)}$$

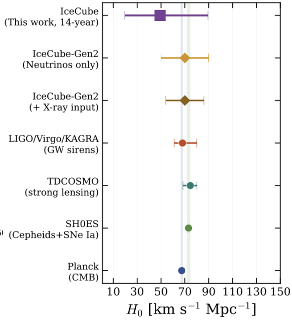
1		**2**		**3**
Standardize		**Anchor**		**Measure**
Neutrino and X-ray luminosities trace the same disk-corona	$\Longrightarrow$	Non-redshift distances to NGC 1068 (Cepheids + TRGB) fix the absolute scale	$\Longrightarrow$	Eleven galaxies in the Hubble flow determine $d_L(z; H_0)$
Stecker, Done et al, 91' **Murase, Kimura et al, 20'** **Kheirandish et al., 21'**		**Markham et al., 26'** **Tikhonov & Galazutdinova, 21'**		**IceCube, 25'**

If $\beta \neq 1$, observed high-energy neutrinos retain distance information

A first measurement of H_0 with neutrinos



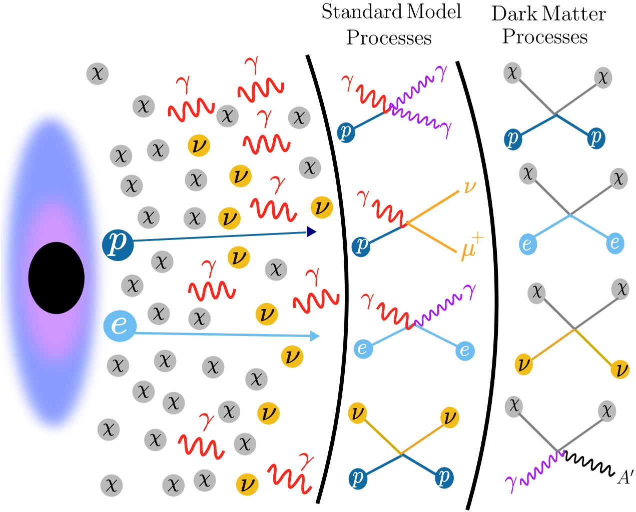




Herrera, Kamp, Argüelles, 26'

- **Complementary systematics:** neutrinos undergo no extinction, absorption, or scattering in transit; systematic uncertainties instead arise from source physics and the L_ν–L_X relation
- **Future reach:** IceCube–Gen2, more distance anchors, and improved X-ray/corona modeling could reach $\sigma(H_0) \simeq 10\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, competitive with gravitational-wave measurements

Dark matter processes



Dark matter distribution around black holes

Adiabatic growth: A substantial increase in M_{BH} takes place after its initial formation, and the mass is accreted slowly.

Peebles, 72'
Quinlan, Hernquist, Sigurdsson, 95'
Gondolo, Silk, 99'

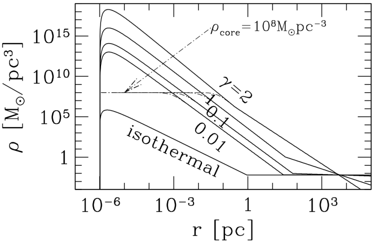
$$t_{\text{dyn}} = GM_{\text{BH}}/\sigma^3$$

$$t_S = M_{\text{BH}}/\dot{M}_{\text{Edd}}$$

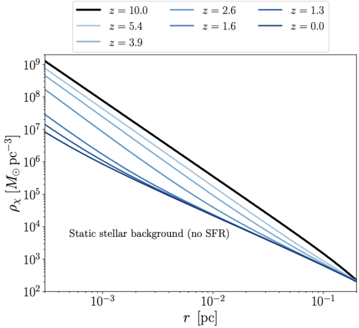
For most SMBH: $t_{\text{dyn}} \ll t_S$

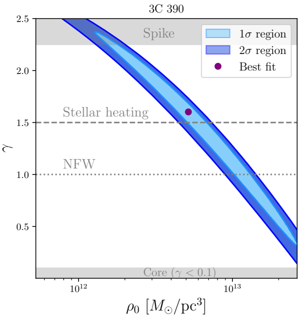
- **Adiabatic conditions** : Phase-space distribution, angular momentum and radial action conservation
- The spike cuspiness is $\gamma_{\text{sp}} = \frac{9-2\gamma}{4-\gamma}$
- If the dark matter self-annihilates, the density is saturated to

  $\rho_{\text{sat}} = m_{\text{DM}}/(\langle\sigma v\rangle t_{\text{BH}})$



Uncertainties in dark matter spikes





Sharma, Herrera, Arav, Horiuchi, 25'

Stellar scattering

Gravitational encounters with stars deplete the spike and drive it toward $\rho_\chi \propto r^{-3/2}$.

Merritt, 04'; Gnedin & Primack, 04'
Herrera, Hussein, Necib et al, 26'

Finite black-hole seed

A nonzero initial seed mass and baryonic halo suppresses adiabatic contraction.

Caiozzo, Bertone, et al, 25'
Herrera, Hussein, Necib, et al, 26'

Relativistic effects

General relativity enhances the innermost density and moves the cutoff from $4R_S$ to $2R_S$.

Sadeghian, Ferrer, Will, 13'

AGN reverberation mapping provides the first population-based hint on the existence of spikes

Within present-day uncertainties on the dark matter density in AGN, what can we meaningfully say about dark matter-Standard Model interactions?

Dark matter-neutrino interactions

Ferrer, Herrera, Ibarra, 22'

Cline et al, 22'

Fujiwara, Herrera, 23'

Cline, Puel, 23'

Zapata, Pérez, Gago, 25'

Bertólez-Martínez, Herrera, Martínez-Miravé, Terol Calvo, 25'

Mondol, Bouri, Saha, Laha, 25'

Dixit, Mohlabeng, Razzaque, 26'

Esteban, Gago, Gonzalez-Garcia, Zapata, 26'

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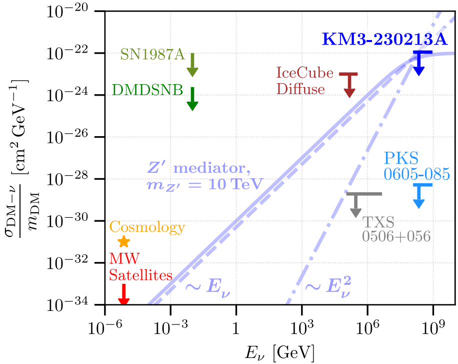


- Neutrino observations from AGN set the **most stringent constraints at the highest energies**
- These constraints overcome lower-energy laboratory and cosmological bounds in models where the cross section rises with energy
- Not all bounds are stronger than unitarity, and model-building challenges remain open

Dark matter–cosmic ray interactions

Gorchtein, Profumo, Ubaldi, 10’

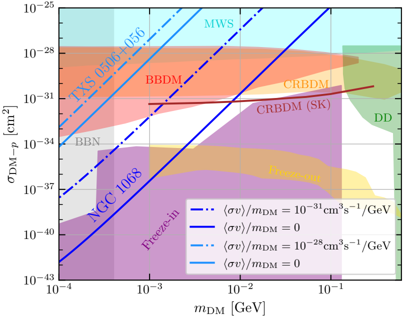
Wang, Granelli, Ullio, 21’

Herrera, Murase, 23’

De Marchi, Granelli, Nava, Sala, 24’, 25’

Gustafson, Herrera, Mukhopadhyay, Murase, Shoemaker, 24’, 25’

...



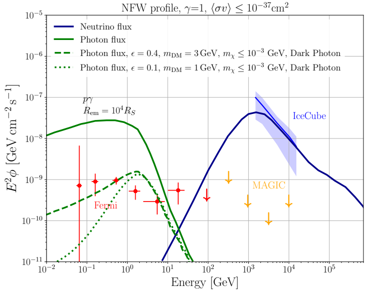
- AGN observations from IceCube allow to place leading constraints on sub-GeV and inelastic dark matter models in some parameter space
- These constraints arise from various different considerations: cosmic-ray cooling, subsequent production of neutrinos and gamma-rays, and the production of cosmic-ray boosted dark matter
- **Some thermal and non-thermal dark matter models can only be probed through cosmic-ray-dark matter interactions in AGN**

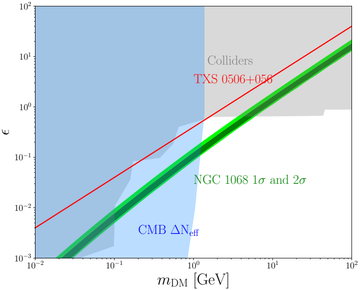
Dark matter-photon interactions

$$\Delta\mu(E_\gamma) \simeq \left(\frac{M_{\rm BH}}{2{\times}10^7 M_\odot}\right)^{3/4}\left(\frac{r_0}{10\,{\rm kpc}}\right)^{1/2}\left(\frac{\rho_0}{0.043 M_\odot/{\rm pc}^3}\right)^{3/8}\left(\frac{R_{\rm em}}{10^3 R_{\rm S}}\right)^{-11/8}\left(\frac{m_{\rm DM}}{1\,{\rm GeV}}\right)^{-1}\left(\frac{\sigma_{{\rm DM}-\gamma}(E_\gamma)}{10^{-29}\,{\rm cm}^2}\right)$$

- O(1) absorption requires cross sections of $\sim 10^{-29} - 10^{-30}{\rm cm}^2$
- These values can be achieved via the inelastic scattering **DM + $\gamma \to$ DM+X, where X is a dark state**.

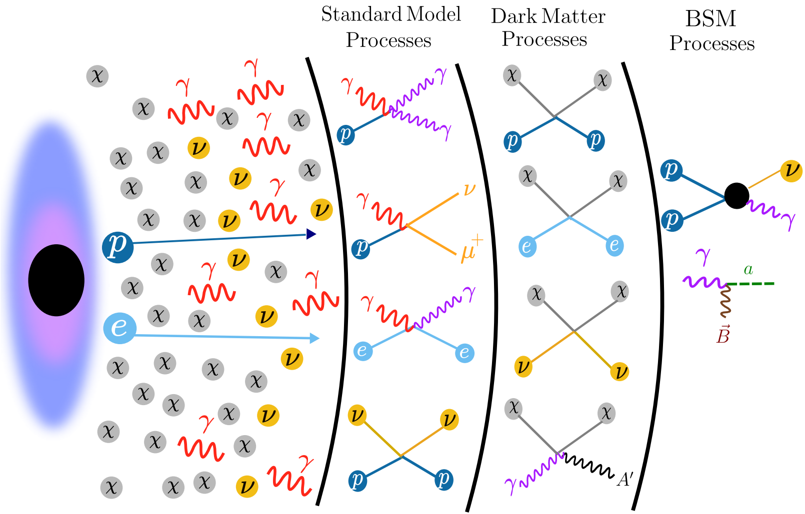
Herrera, 25'





The large neutrino-to-gamma-ray flux ratio observed in NGC 1068 can be explained by dark matter-photon interactions

BSM processes



ALP–photon oscillations

Raffelt & Stodolsky, 88'

Hooper & Serpico, 07'

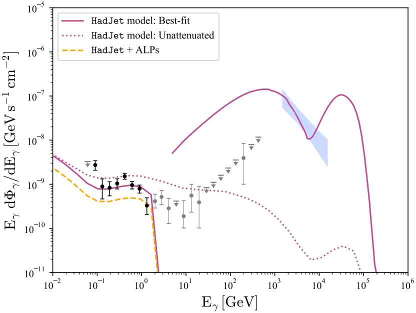
De Angelis, Galanti, Roncadelli, 11'

Wouters & Brun, 12'

H.E.S.S., 13'

Fermi-LAT, 16'

...



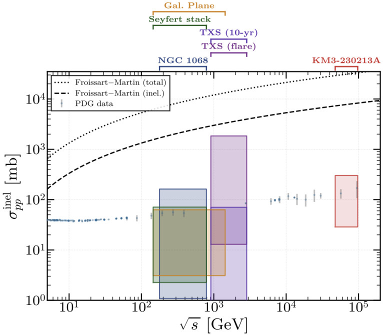
Dekker, Herrera, Kantzas, 25'

- In a transverse magnetic field, $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$ induces $\gamma \leftrightarrow a$ oscillations and an **energy-dependent modification of the γ-ray spectrum**.
- Limits are typically derived for particular assumptions on the intrinsic gamma-ray emission or magnetic field configurations, degenerate in many cases with the ALP-induced effects
- **IceCube neutrinos can be used to anchor the hadronic emission and therefore constrain the intrinsic γ-ray flux**: the limits are weaker than leading electromagnetic-only bounds, but arguably more robust

Astrophysics as collider physics

$$\sqrt{s} \simeq \sqrt{2m_{\text{target}}E_{\text{beam}}}$$

PeV–EeV cosmic particles probe **TeV–PeV center-of-mass energies**, overlapping with and extending far beyond terrestrial colliders.



Argüelles, Dev, Dutta, Herrera, Kamp, Kumar, Meighen-Berger, Rai, Shoemaker, 26'

- The neutrino/cosmic-ray analogy with colliders has traditionally been made through νN interactions in the Earth, probed by IceCube, and p–air collisions in the atmosphere, probed by Auger.

  Alvarez-Muñiz, Halzen, Han, Hooper, 02'; Pierre Auger, 12'; IceCube, 17'; Bustamante & Connolly, 19'; Bai, Xie, Zhou, 25'; Bertólez-Martínez & Hooper, 26'

- **Recently, the analogy has extended to the cosmic-ray and neutrino sources themselves:** this allows us to probe the $p\nu$, pp and $p\gamma$ channels while reducing degeneracies between cross sections and astrophysical parameters.

  Herrera & Horiuchi, 25'; Dev, Dutta, Karthikeyan et al, 25'; Ettengruber & Herrera, 25'

Cosmic messengers turn the Universe into a laboratory

Cosmic messengers turn the Universe into a laboratory

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Cosmic rays and neutrinos open new routes to the CνB and H_0, making high-energy messengers cosmological probes.

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AGN combine intense particle beams, dense matter and dark matter targets, critical to reveal the microphysical nature of dark matter

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The Universe provides extreme energies, vast distances, and extraordinarily dense environments

Multi-messenger observations turn them into quantitative probes of cosmology and fundamental physics