The Cosmic Neutrino Background, Dark Matter, and Neutrino Telescopes

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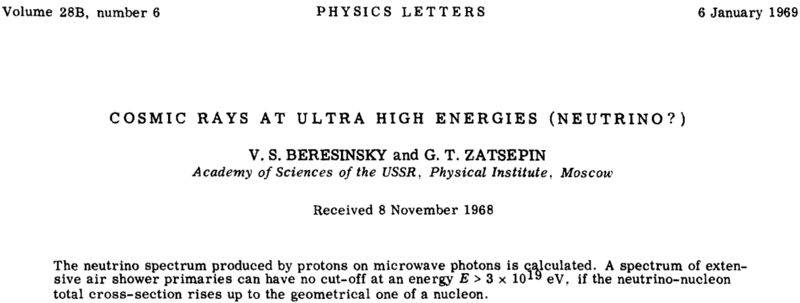

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COSMIC RAYS AT ULTRA HIGH ENERGIES (NEUTRINO?)

V. S. BERESINSKY and G. T. ZATSEPIN
Academy of Sciences of the USSR, Physical Institute, Moscow

Received 8 November 1968

The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Berezinsky, Zatsepin, 69'

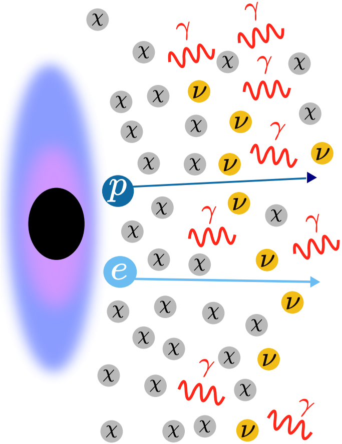
Cosmic rays propagating over the cosmic microwave background induce a predictable cosmic neutrino flux

- $p + \gamma \to n + \pi^+$
  $\pi^+ \to e^+ + \nu_\mu + \nu_e$

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

Both processes occur with similar probability:

Comparable neutrino and gamma-ray fluxes!


p
e
χ
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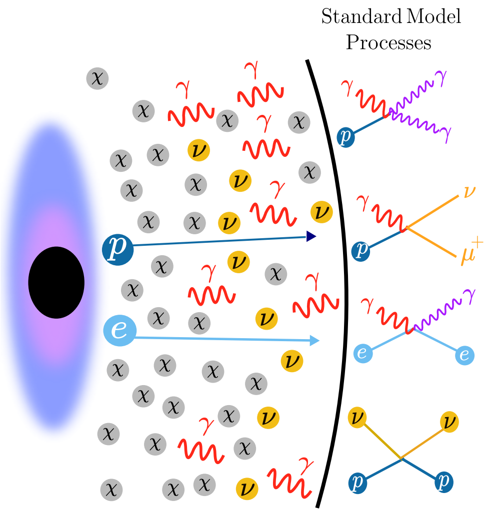
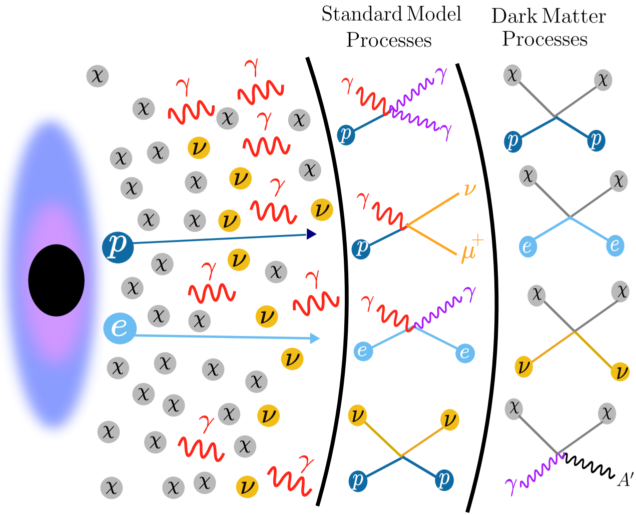
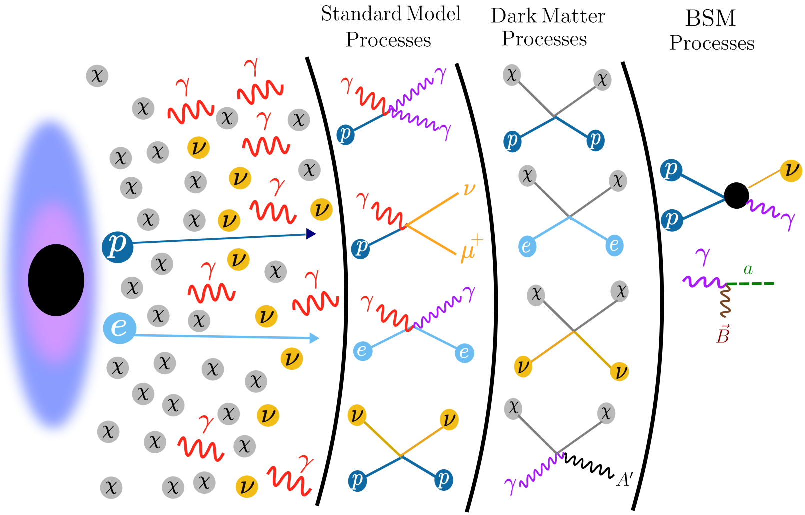
γ


Standard Model Processes

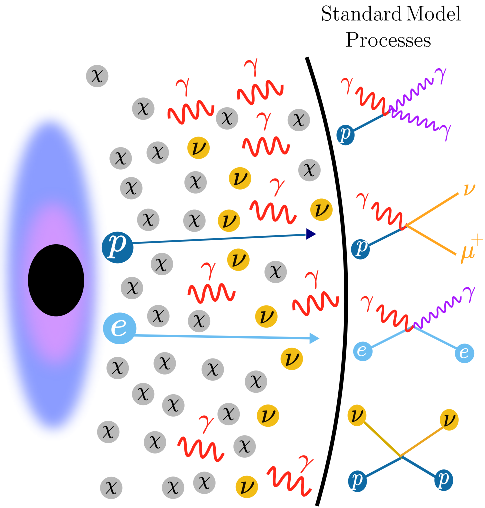

Standard Model Processes
Dark Matter Processes
χ
γ
ν
p
e
μ^+
A'


Standard Model Processes

Dark Matter Processes

BSM Processes

Standard Model processes



Cosmic Neutrino Background (CνB)

- Neutrinos decoupled from the early Universe plasma ~ 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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By far the earliest Universe particle probe observationally accessible (besides, perhaps, dark matter...)

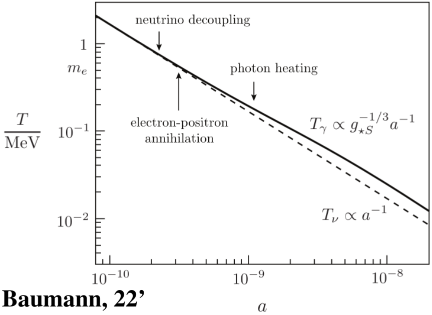
CMB happened ~ 380.000 yr after the Big Bang

Indirect evidence from the CMB and BBN

- After neutrino decoupling, electron-positron annihilation heats the photons

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

- Entropy of each particle in equilibrium $s \propto gT^3$; total entropy is conserved



Baumann, 22'

$$\frac{s_\gamma + s_{e^-} + s_{e^+}}{s_\gamma} = 11/4$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 0.17 \text{ meV}$$

$$n_\nu = \frac{3\zeta(3)}{4\pi^2} g_\nu T_\nu^3 \simeq 336 \text{ cm}^{-3}$$

$\rho_\nu = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\rho_\gamma \to N_{\text{eff}}^{\text{SM}} \simeq 3.045$, compatible with BBN and CMB

Why is it important to detect the CνB directly?

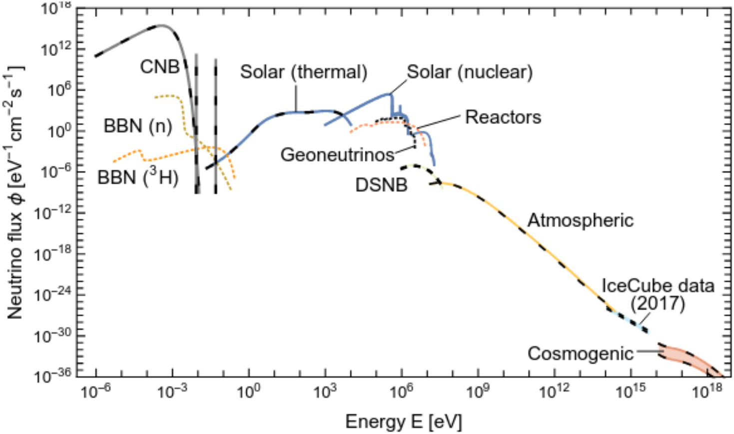
Ultimately, indirect evidence from BBN and CMB is already strong

Why is it important to detect the CνB directly?

Ultimately, indirect evidence from BBN and CMB is already strong

Three reasons:

- BBN and CMB only measure its gravitational effects via inferred energy density at two specific redshifts → no particle properties are actually observed
- No measurement of individual neutrinos, their thermal nature, momentum distribution and spin
- A direct detection may allow to test neutrino masses and clustering, new physics in the neutrino sector, and gives access to the Universe at $t \sim 1\,\mathrm{s}$



Vitagliano, Tamborra, Raffelt, 19'

Most abundant neutrino flux on Earth by orders of magnitude, but with tiny cross sections and energy depositions at experiments

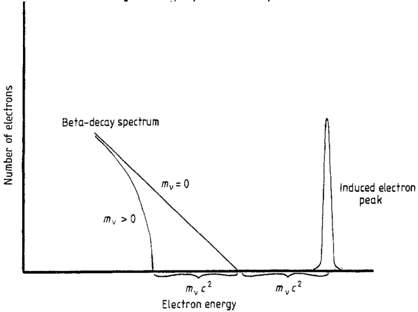
$$\sigma_{\nu p} \sim E_\nu^2/M_Z^4 \sim 10^{-60}\ \text{cm}^2$$

$$q \sim \text{meV}$$

Direct detection of the CνB: neutrino capture

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

Weinberg, 62'
Humphreys, Irvine, 83'



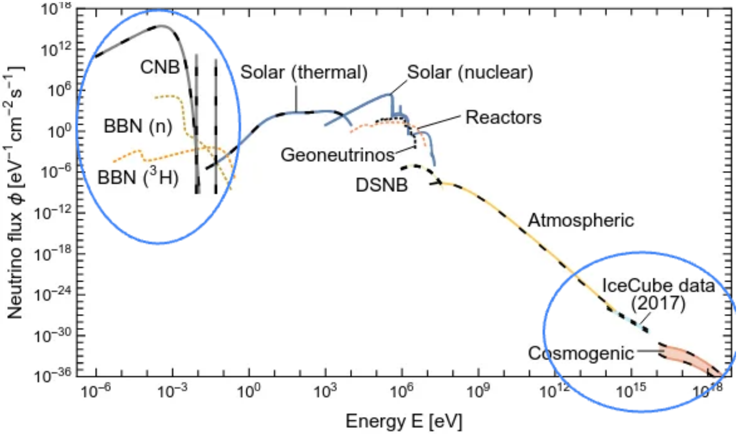
KATRIN places a limit on the local relic neutrino overdensity of $\sim 10^{11}$

PTOLEMY may improve this bound by orders of magnitude

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

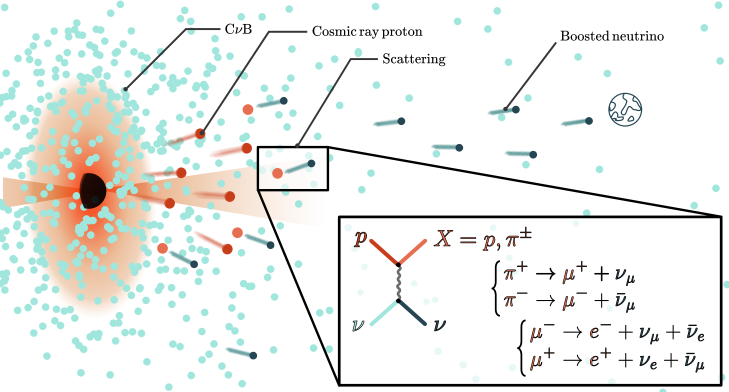
$$\Delta E \simeq \hbar^{1/2} \kappa^{1/4} (m_e Q)^{1/2} m_{\mathrm{nucl}}^{-3/4} \simeq 0.3 - 0.7 \text{ eV}$$

Cheipesh, Cheianov, Boyarsky, 21'


Neutrino flux ϕ [eV^{-1}cm^{-2}s^{-1}]
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Energy E [eV]
CNB
BBN (n)
BBN (^{3}H)
Solar (thermal)
Solar (nuclear)
Reactors
Geoneutrinos
DSNB
Atmospheric
IceCube data (2017)
Cosmogenic

Cosmic-ray boosted cosmic neutrino background

Ciscar, Herrera, Shoemaker, 24’



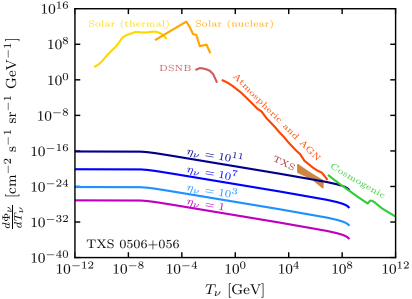
$$\begin{cases} \pi^{+} \to \mu^{+} + \nu_{\mu} \\ \pi^{-} \to \mu^{-} + \bar{\nu}_{\mu} \end{cases}$$

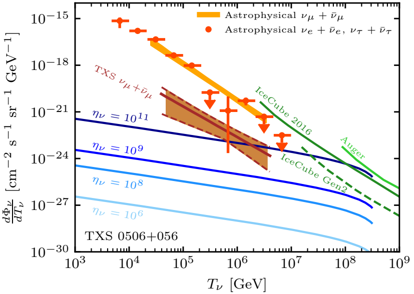
$$\begin{cases} \mu^{-} \to e^{-} + \nu_{\mu} + \bar{\nu}_{e} \\ \mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu} \end{cases}$$

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

Boosted cosmic neutrino background from single galaxies

Ciscar, Herrera, Shoemaker, 24'





- The boosted flux is suppressed due to small center of mass energy of the scattering

$$\frac{d\Phi_\nu}{dT_p} = \sigma_{p\nu} n_\nu \frac{d\Phi_p}{dT_p} D_{\rm eff} \ , \ \sigma_{p\nu} \sim \begin{cases} \frac{G_F^2 s}{\pi} & \text{for } 2m_\nu E_p > m_p^2 \\ \frac{G_F^2 E_p^2 m_\nu^2}{\pi m_p^2} & \text{for } 2m_\nu E_p < m_p^2 \end{cases}$$

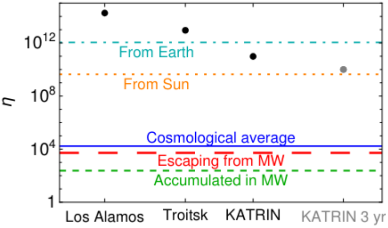
- Upper limits can be placed on the maximal neutrino overdensity in the Milky Way and TXS 0506+056 with high-energy neutrino experiments

Neutrino overdensities

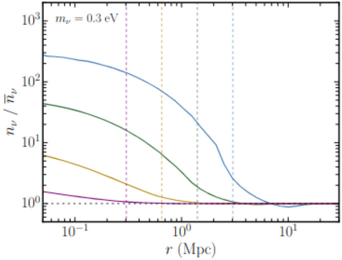
Neutrinos must obey Pauli exclusion principle, which limits the maximum neutrino overdensity η achievable at different physical scales

$$n_\nu \leq \frac{V_p}{(2\pi)^3},\ V_p = \frac{4\pi}{3} p^3_{\nu,\max}$$

- Supermassive black hole scales: $\eta \lesssim 10^5 \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^3 \left(\frac{v_{\mathrm{esc}}}{100\ \mathrm{km/s}}\right)^3$
- Galactic scales: $\eta \leq 240 \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^3 \left(\frac{v_{\mathrm{esc}}}{550\ \mathrm{km/s}}\right)^3$
- Cosmological scales: $\langle E_\nu \rangle n_\nu \ll \rho_c \rightarrow \eta \lesssim 2 \times 10^4$

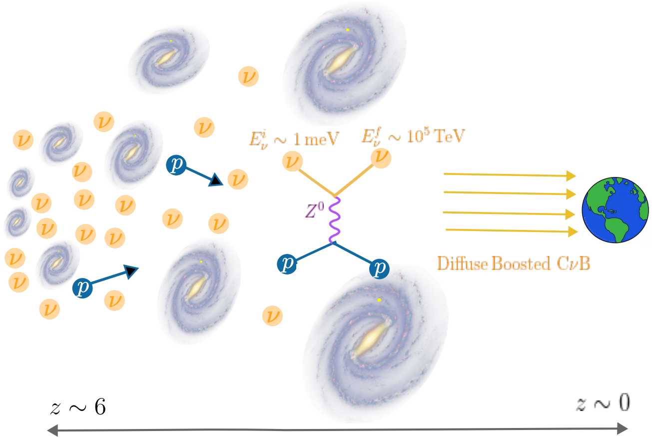


Bondarenko et al 23'



Worku, Sabti, Kamionkowski, 24'

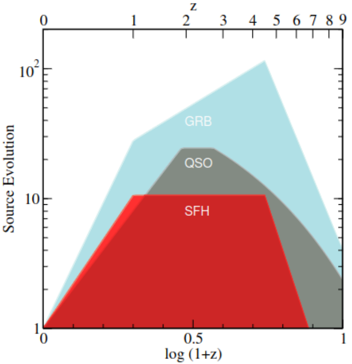
Herrera, Horiuchi, Qi, 24’

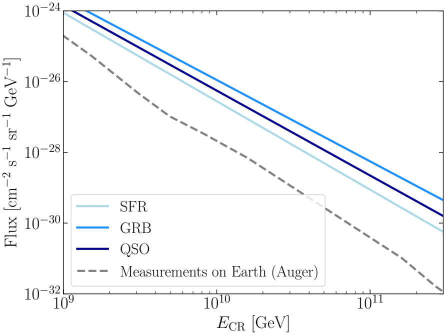


- The previous calculation restricted to the Milky Way and TXS 0506+056

- However, there must be a diffuse contribution arising from all redshifts! Analogous examples → Diffuse supernova ν, cosmogenic ν...

Cosmological cosmic ray flux

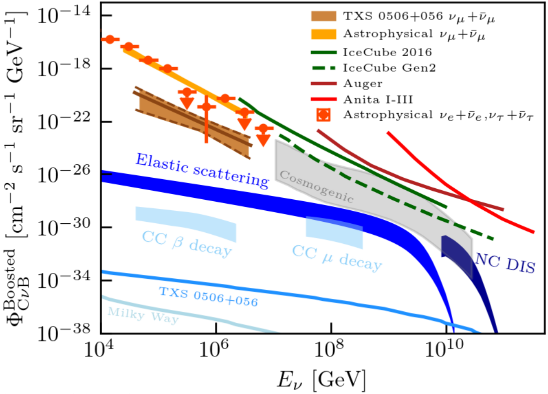




- Normalization of the cosmic ray flux evolves with redshift
  → models differ by up to a factor of ∼ 10

- Spectral dependence with energy is also uncertain → $\alpha \simeq 2.3 - 2.5$

Diffuse boosted cosmic neutrino background



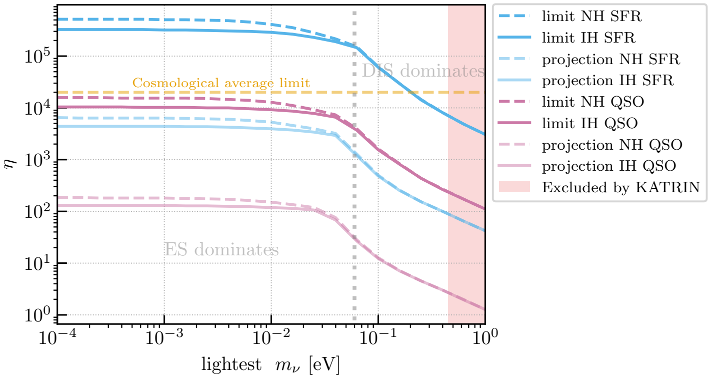
Herrera, Horiuchi, Qi, 24’
Zhang, Sandrock, Liao, Yue, 25’
Herrera, Horiuchi, Qi, Shoemaker, 26’

- **IceCube is only ~ 4 orders of magnitude away from the CνB**
- Enhancement due to larger density of CνB and cosmic rays at high redshifts than today, and favorable inelasticity of DIS

Limits on the CνB

For light neutrinos, ANITA/Auger set the most stringent bounds

For heavy neutrinos, IceCube sets the most stringent limit

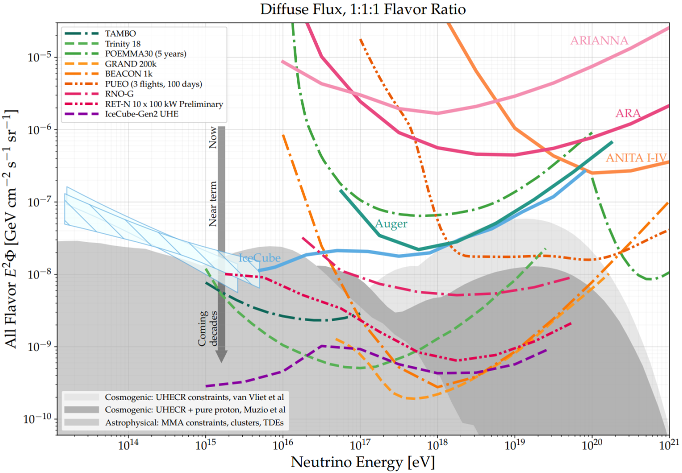


Herrera, Horiuchi, Qi, Shoemaker, 26'

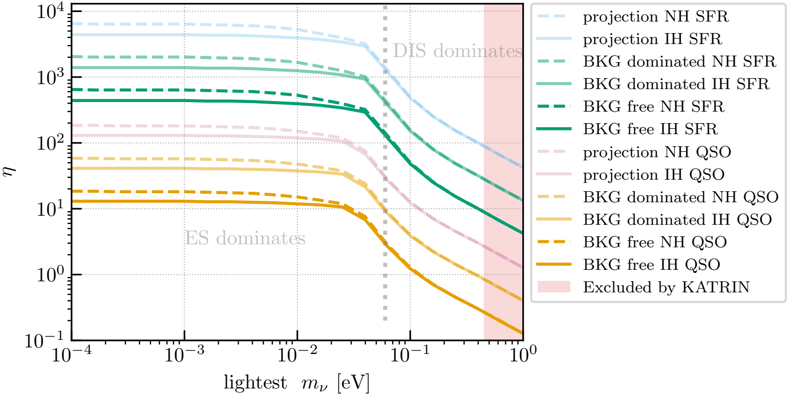
O(1-10) overdensities can be achieved with IceCube-Gen2

One may combine several future high-energy neutrino telescopes

$\mathcal{O}(10)$ proposed experiments with comparable sensitivities



Ackermann et al, 24'



May lead to test the ΛCDM predicted CνB density for $m_\nu \gtrsim 0.1$ eV

Is this enough to claim a detection?

No, expecting some boosted CνB events in the detector is a necessary but not sufficient condition

Backgrounds?

Backgrounds: Cosmogenic (GZK) neutrinos

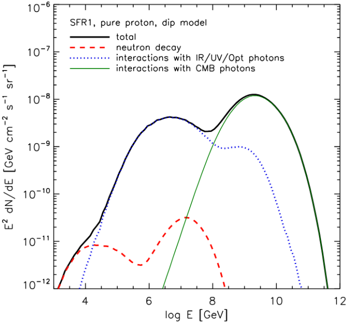
$$p + \gamma_{\text{EBL/CMB}} \to \Delta^+ \to n + \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu$$

Backgrounds: Cosmogenic (GZK) neutrinos

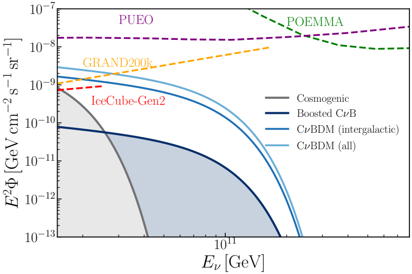
$$p + \gamma_{\text{EBL/CMB}} \longrightarrow \Delta^+ \longrightarrow n + \pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

In principle, larger flux than the boosted CνB due to photopion cross section overcoming weak interactions, and $n_{\text{C}\nu\text{B}} \sim n_{\text{CMB}}$

$E_{\text{GZK}\nu} \sim 0.05 E_{\text{CR}}$, while $E_{\text{BC}\nu\text{B}} \sim 0.5 E_{\text{CR}}$. Important since $\Phi_{\text{CR}} \propto E^{-2.3}$



Kotera, Allard, Olinto, 10'



Cline, Herrera, Roux, 26'

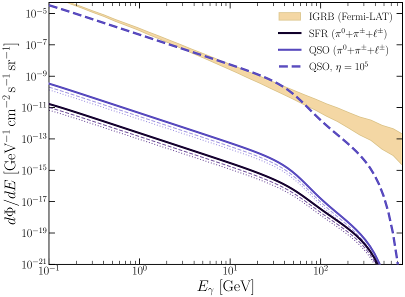
Cosmogenic spectra has two bumps and a lower energy cut-off

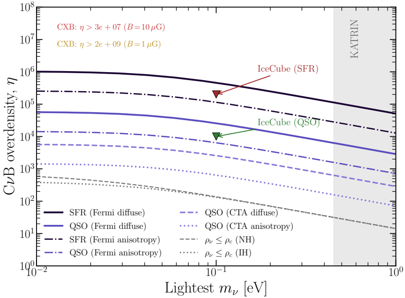
Complementary signals in the electromagnetic spectrum

Cosmic-ray scatterings on the cosmic neutrino background also yield an accompanying gamma-ray and X-ray flux

Herrera, Loeb, 26'

$$\nu_\ell + p \longrightarrow \ell^- + X$$
$$X \longrightarrow \gamma, l^\pm$$
$$l^- + \gamma \longrightarrow l^- + \gamma$$





Fermi-LAT places a limit weaker than IceCube by a factor of ∼ 10

CTA data, source substraction and anisotropies will improve these limits

Could the CνB be enhanced on cosmological scales?

Yes, if additional cold active neutrinos are produced non-thermally

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Wait, could they be the dark matter?

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Wait, could they be the dark matter?

Active neutrinos were ruled out as dark matter in the early 90's. In ΛCDM

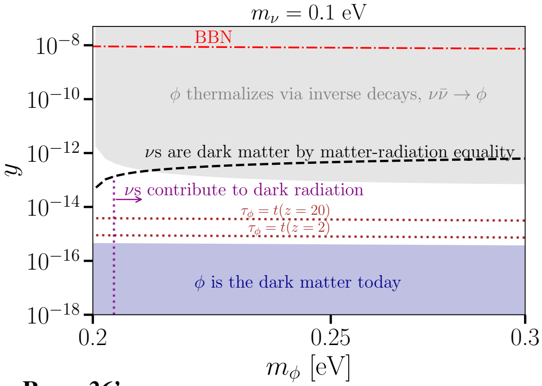
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94\,\mathrm{eV}} \lesssim 0.013 \lesssim \Omega_{\mathrm{DM}} h^2 \simeq 0.12$$

And they suppress structure formation on small scales...

$$\lambda_{\mathrm{FS}} \sim \frac{1}{H_0}\left(\frac{T_\nu}{m_\nu}\right) \sim 10\,\mathrm{Mpc}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)$$

Neutrinos as dark matter

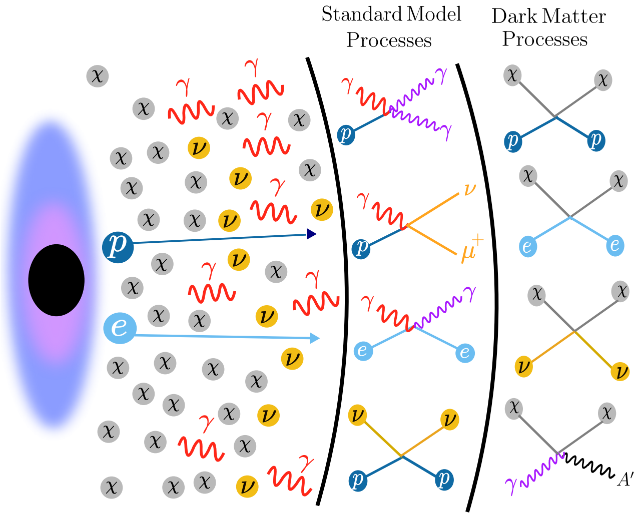
Let an enhanced active cold neutrino population be produced from the decays of a misaligned scalar field $\phi \to \nu\bar{\nu}$



Cline, Herrera, Roux, *26'*

The CνB density is enhanced by a factor of $\sim 100 - 200$

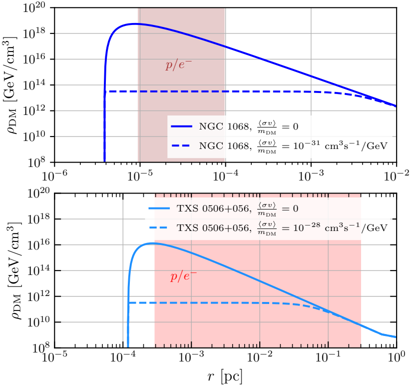
Dark matter processes



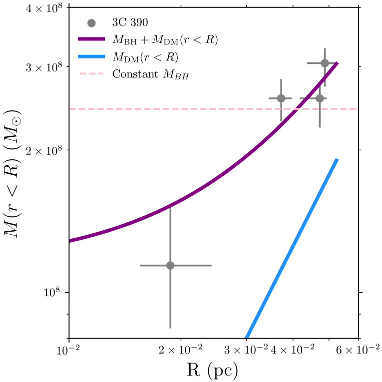
The dark matter content of neutrino sources

Around black holes, the dark matter density is expected to be high
Gondolo, Silk, 01'

Dynamical processes can only partially relax the dark matter spike
Merrit, 03'
Herrera, Necib, et al, *In progress*



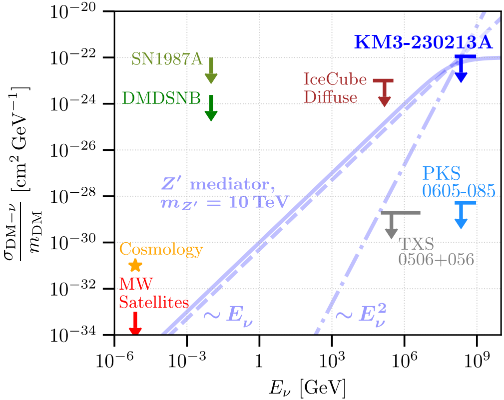
Murase, Herrera, 23'



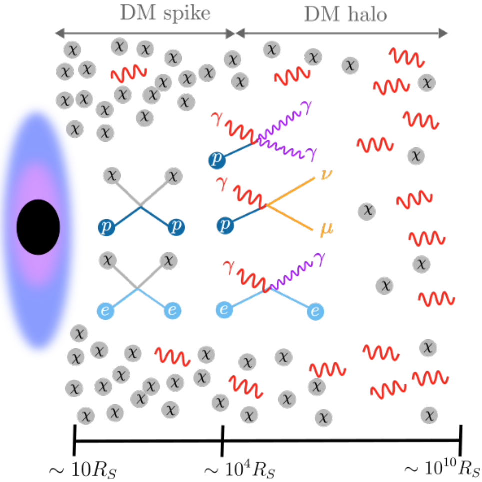
Sharma, Herrera, Arav, Horiuchi, 25'

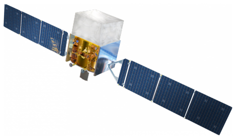
Dark matter-neutrino interactions in AGN

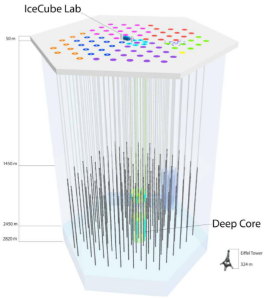
Ferrer, Herrera, Ibarra, 22'
Cline et al, 22'



- Neutrino observations from AGN set the **most stringent constraints at the highest energies**
- These constraints overcome lower-energy laboratory and cosmological bounds in some models







- High-energy protons and electrons can cool efficiently via interactions with ambient photons and gas in the AGN
- **May they also cool via scatterings with the ambient dark matter particles ?**

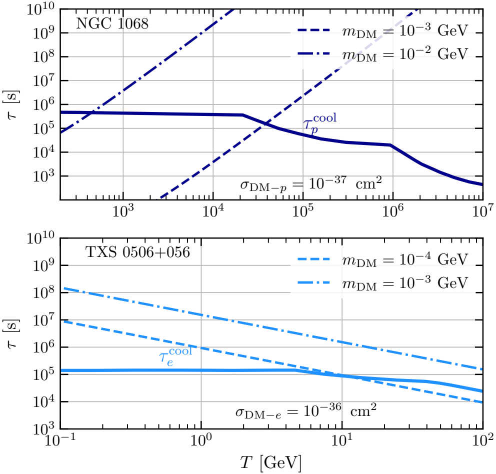
Cosmic ray cooling induced by dark matter

The dark matter cooling timescales need to be comparable to the Standard Model timescales ($p\gamma$, pp, synchroton, inverse compton...)

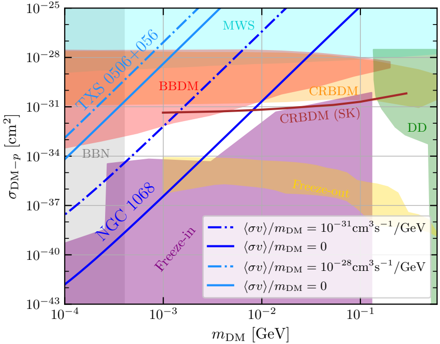
Herrera, Murase, 23'

$$\tau^{\rm el}_{{\rm DM}-i} = \left[-\frac{1}{E} \left(\frac{dE}{dt} \right) \right]^{-1}$$

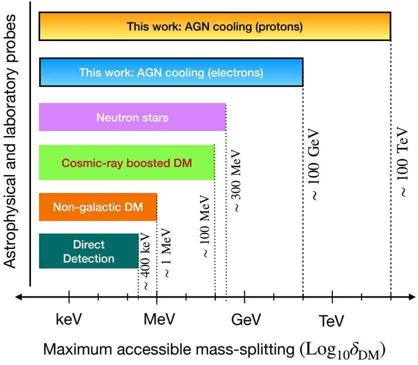
$$\left(\frac{dE}{dt} \right) = \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_0^{T_{\rm DM}^{\rm max}} dT_{\rm DM}\, T_{\rm DM} \frac{d\sigma_{\rm DM-i}}{dT_{\rm DM}}$$



Cosmic ray cooling induced by dark matter

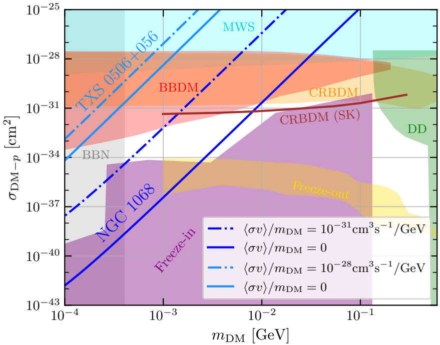


Herrera, Murase, 23’

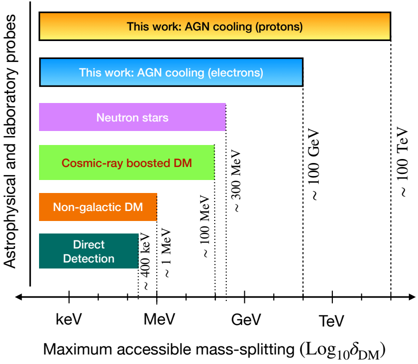


Gustafson, Herrera, Mukhopadhyay, Murase, Shoemaker, 24’

Cosmic ray cooling induced by dark matter



Herrera, Murase, 23'



Gustafson, Herrera, Mukhopadhyay, Murase, Shoemaker, 24'

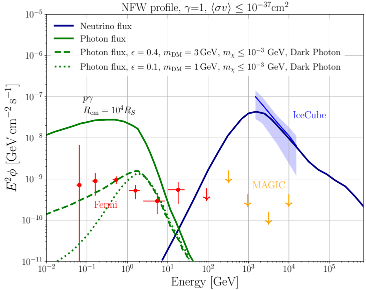
- Strongest constraint on dark matter coupling to **protons** for $m_{\mathrm{DM}} \lesssim 10^{-2}$ GeV
- **Probes thermal and non-thermal dark matter models**
- Probes untested large mass splittings for **inelastic dark matter**

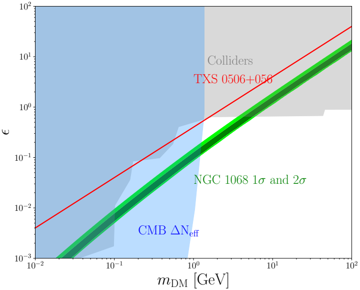
Dark matter-photon interactions in NGC 1068?

$$\Delta\mu(E_\gamma) \simeq \left(\frac{M_{\rm BH}}{2\times10^7 M_\odot}\right)^{3/4}\left(\frac{r_0}{10\,{\rm kpc}}\right)^{1/2}\left(\frac{\rho_0}{0.043 M_\odot/{\rm pc}^3}\right)^{3/8}\left(\frac{R_{\rm em}}{10^3 R_S}\right)^{-11/8}\left(\frac{m_{\rm DM}}{1\,{\rm GeV}}\right)^{-1}\left(\frac{\sigma_{{\rm DM}-\gamma}(E_\gamma)}{10^{-29}\,{\rm cm}^2}\right)$$

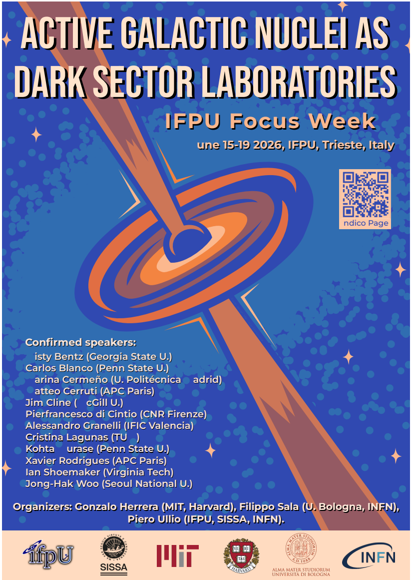
- O(1) absorption requires cross sections of $\sim 10^{-29} - 10^{-30}{\rm cm}^2$
- Achievable via inelastic processes $\mathrm{DM} + \gamma \rightarrow \mathrm{DM}+X$.

Herrera, 25'





Part of the favored region of parameter space is allowed by colliders, cosmology and direct detection



ACTIVE GALACTIC NUCLEI AS DARK SECTOR LABORATORIES

IFPU Focus Week

une 15-19 2026, IFPU, Trieste, Italy

ndico Page

Confirmed speakers:

isty Bentz (Georgia State U.)
Carlos Blanco (Penn State U.)
arina Cermeño (U. Politécnica adrid)
atteo Cerruti (APC Paris)
Jim Cline (cGill U.)
Pierfrancesco di Cintio (CNR Firenze)
Alessandro Granelli (IFIC Valencia)
Cristina Lagunas (TU)
Kohta urase (Penn State U.)
Xavier Rodrigues (APC Paris)
Ian Shoemaker (Virginia Tech)
Jong-Hak Woo (Seoul National U.)

Organizers: Gonzalo Herrera (MIT, Harvard), Filippo Sala (U. Bologna, INFN), Piero Ullio (IFPU, SISSA, INFN).

COSMIC NEUTRINO PRACTICUM

29 June - 03 July

Harvard Physics Department
17 Oxford St Jefferson Laboratory
Cambridge, MA 02138

Lectures:

- Neutrino Telescope Basics, Data Analysis, and Current Measurements
- Neutrino Interactions, Simulation and Event Generation
- Neutrino Telescope Reconstruction Techniques and Machine Learning Methods
- Neutrino Detectors
- BSM Physics with High-Energy Neutrinos
- Neutrino Source Modelling
- BSM Physics with Neutrino Sources
- Neutrino Source Searches
- Diffuse Astrophysical Neutrinos
- Neutrino Oscillation Measurements with Neutrino Telescopes

Organizers: Carlos Argüelles, Gonzalo Herrera, Molly Neylan, Nicholas Kamp, Will Thompson

Conclusions

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A multi-messenger, cosmological, and population-based approach is central to make important discoveries in our field

Thanks for your attention

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