GRB 221009A high-energy γ-rays and new physics explanations

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based on: **2211.00634** w/ Alexei Y. Smirnov

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MAX-PLANCK-GESELLSCHAFT

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Outline

- GRBs and GRB 221009A observational facts
- Propagation and attenuation of high energy gamma rays
- Potential new physics explanations, incl.
- Decaying heavy sterile neutrino scenario

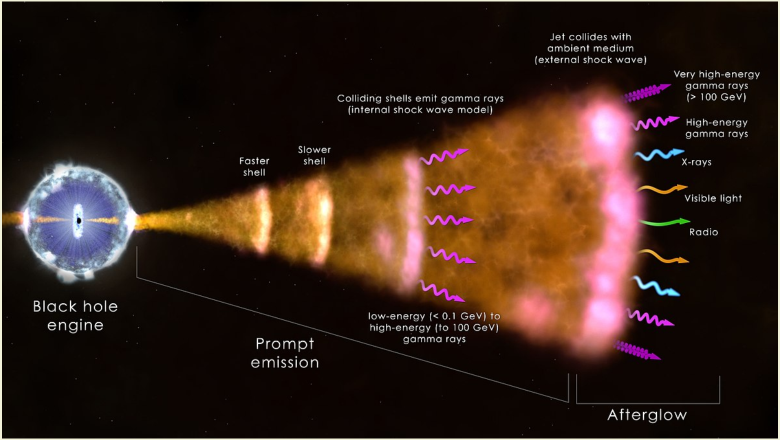
Gamma Ray Bursts (GRBs)

- Transient extreme x-ray events, $t_{90} \sim 10\,\mathrm{ms} \to \mathcal{O}(1000)\,\mathrm{s}$.
- Mechanism not 100% clear, very likely SN / NS-NS mergers.
- “Short GRB” $t_{90} \lesssim 2\,\mathrm{s}$, “long GRB” $t_{90} \gg 2\,\mathrm{s}$.
- Typical energy release $10^{52} \to 10^{54}\,\mathrm{erg}$ $(10^{54}\,\mathrm{erg} \approx M_{\odot})$.
- First detection 1967 (Vela), first afterglow detection 1997 (BATSE@CGRO).
- Angular width of jet $2^{\circ} \to 20^{\circ}$.
- Kilonova GRB 170817A / GW 170817, NS-NS merger, true multi-messenger signal $(z = 0.009)$.
- GRB rate in MW: $1/(10^{4} \to 10^{6})\,\mathrm{yr}^{-1}$, hard to estimate.
- Galactic GRBs potentially life-threatening (mass extinction).

GRB particle production

Mechanism is poorly understood, but models exist.
[Waxmann ’95], [Vietri ’95], see e.g. [Bustamante, Baerwald, Murase, Winter ’15]

- High mass star implosion / NS-NS mergers produces jet.
- Inverse Compton scattering $e^{\mp}_{\mathrm{HE}} + \gamma \longrightarrow e^{\mp} + \gamma_{\mathrm{HE}}$,
- “Fireball”, shock wave acceleration, UHECR, $p + \gamma \rightarrow \pi' s + \ldots$



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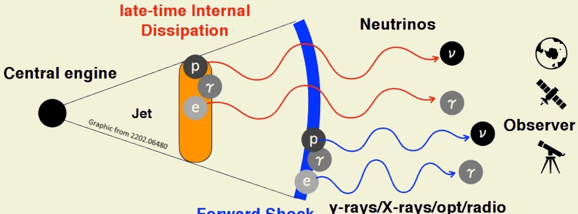
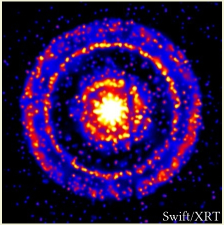
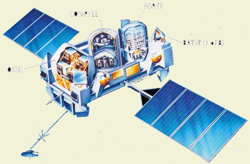


Graphic from 2202.06480

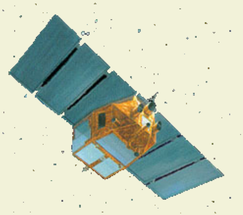


GRB detection, examples

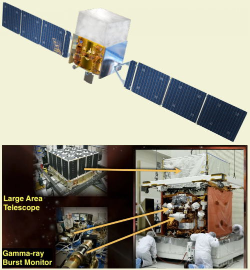
CGRO ('91-'00)



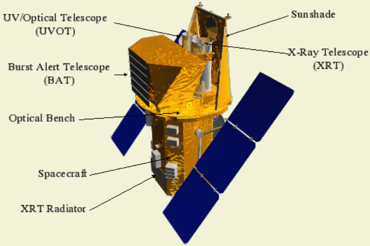
BeppoSAX ('96-'02)



Fermi γ-ray telescope



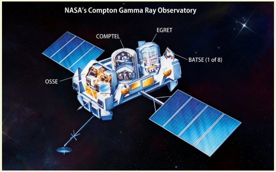
Swift x-ray telescope

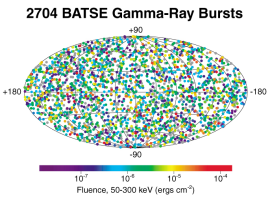


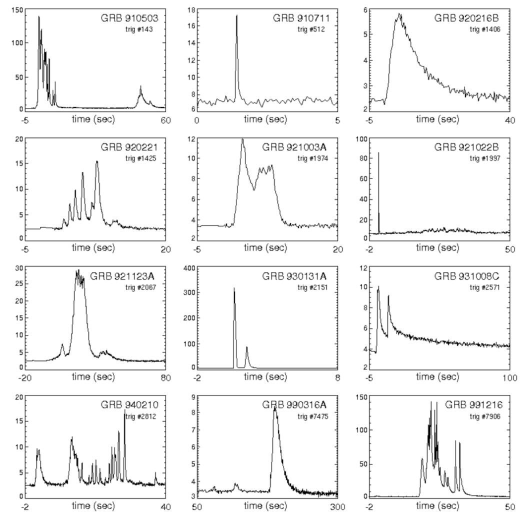
and many others, e.g. Insight-HXMT, INTEGRAL, NuSTAR, ...

GRB diversity

BATSE@CGRO

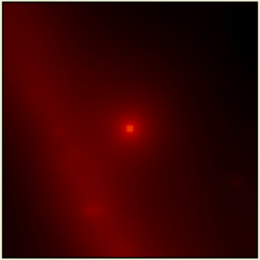




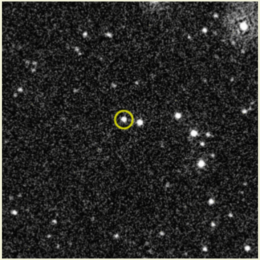


GRB 221009A observation

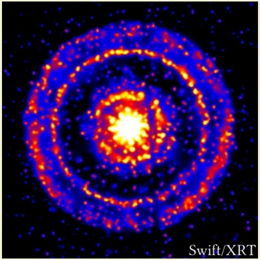
- Fermi-GBM trigger: October 9th 2022, 13:16:59.99 UT $(\equiv T_0)$
  [GCN 32636, 32637, 32642, 32658]
- Also: Swift (BAT,XRT,UVOT), Fermi-LAT, INTEGRAL (SPI-ACS), IPN, *etc.* [GCN 32632, 32635, . . .]
- VLT/X-Shooter and GTC: $z = 0.151$, $d \approx 740\,\mathrm{Mpc}$ [GCN 32648, 32686]
- Tons of follow up observation in optical, radio, low-E x-rays, *etc.*
- LHAASO, $\mathcal{O}(5000)$ γ-ray events with $0.5\,\mathrm{TeV} \leq E_\gamma \leq \mathbf{18\,TeV}$
  [GCN 32677]



NASA/DOE/Fermi LAT Collaboration
$E_\gamma > 100\,\mathrm{MeV}$, $\Delta t > 10\,\mathrm{hrs}$, $\sphericalangle \sim 20^\circ$



NASA/Swift/B. Cenko
optical, $\Delta t > 10\,\mathrm{hrs}$, $\sphericalangle \sim 7^\circ$



see NASA *Gamma-ray Coordinates Network* (GCN) circulars: https://gcn.gsfc.nasa.gov.
as well as *The Astronomers Telegram*: https://www.astronomerstelegram.org.

GRB 221009A evolution

- GRB 221009A was the **brightest** GRB *ever* observed, $E_{\rm iso} \approx 1.5 \times 10^{55}\,\mathrm{erg}(!)$ [GCN 32762], [Lan et al. 2303.10804]
- Peak flux@$(0.01 - 1)\,\mathrm{MeV}$: $> 2.4 \times 10^{3}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$ (Fermi **saturated** $> 100\,\mathrm{s}$!).
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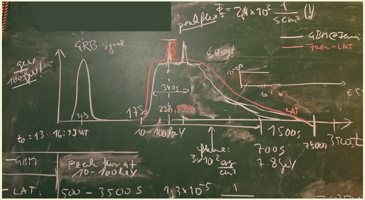

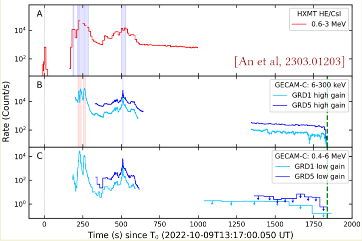

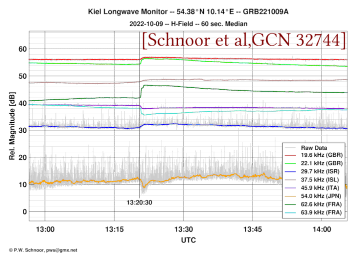

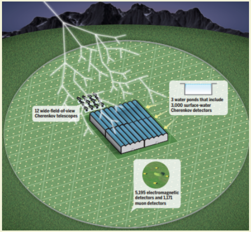

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  CARPET-2: $E_\gamma \sim 251\,{\rm TeV}$ $(T_0 + 4530\,{\rm s}, 3.8\sigma)$ [ATel 15675]
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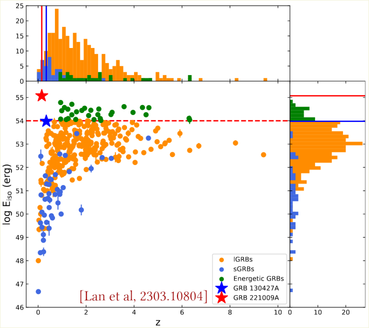
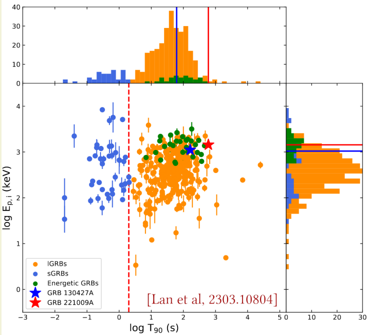
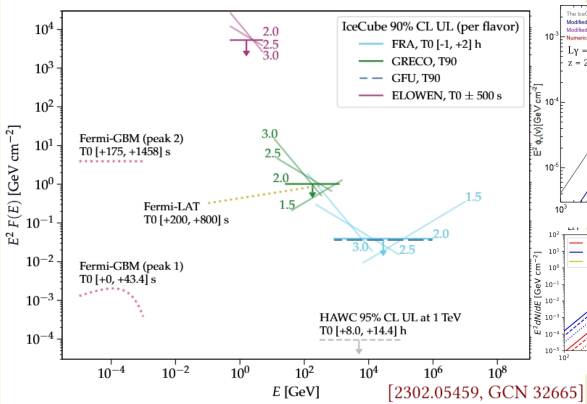
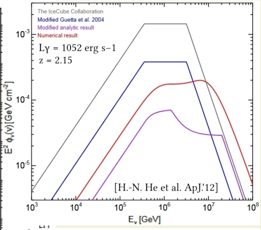


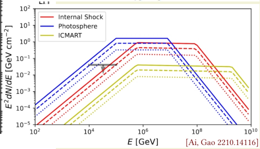


GRB 221009A multi-messenger signals?

- GR waves: LIGO-Virgo-KAGRA not online, GEO600 no sensitivity. [GCN 32877]
- Neutrinos: IceCube no detection, but limits [2302.05459],[GCN 32665]
  [Ai, Gao 2210.14116], [Murase et al 2210.15625]





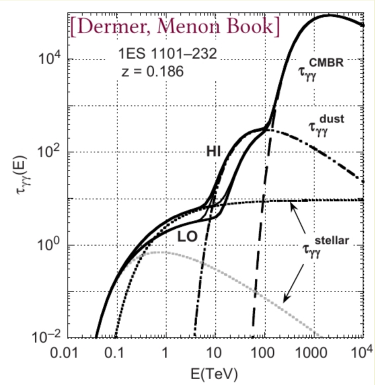


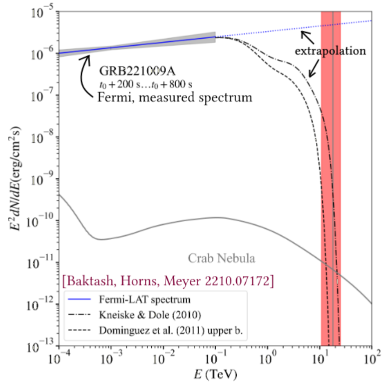
High-E γ propagation

$$\gamma_{\rm HE} + \gamma_{\rm br.} \to e^+ + e^-$$

[Nikishov '62], [Gould, Schréder '66], [Fazio, Stecker '70]

$\Rightarrow$ Flux attenuation: $\Phi_\gamma(E) = \Phi^0_\gamma(E)\, e^{-\tau(E)}$



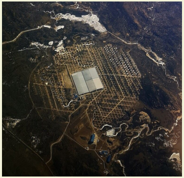


Problem: large uncertainty in τ for $E \lesssim 100\,\text{TeV}$.

@$10\,\text{TeV}$: $e^{-5} \sim 10^{-3}$ @$18\,\text{TeV}$: $e^{-15} \sim 10^{-7}$ @$250\,\text{TeV}$: e^{-6000}

GRB 221009A High energy γ-rays

Above $E_\gamma \gtrsim 20\,\mathrm{TeV}$ this is literally light shining **at** a wall.



- LHAASO observed $\mathcal{O}(5000)$ γ-ray events with $0.5\,\mathrm{TeV} \leq E_\gamma \leq \mathbf{18\,TeV}$ during $[T0, T0 + 2000\,\mathrm{s}]$. Relative error at $E_\gamma \sim 18\,\mathrm{TeV}$: $\delta E/E \approx 40\%$. [GCN 32677]

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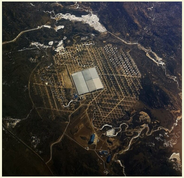

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- Strongly depends on IGM model and the primary flux. Estimates for $\langle N_{\gamma, E_\gamma \approx 18\,\mathrm{TeV}} \rangle$ range from $\mathcal{O}(1)\ldots 10^{-8}$.

see e.g. [Baktash, Horns, Meyer 2210.07172], [Zhao, Zhou, Wang 2210.10778: $\boldsymbol{\mathcal{O}(1)}$ **requires** $\boldsymbol{\sim 3.5\sigma}$ **event**]

- Detection $E_\gamma > 20\,\mathrm{TeV}$ (like $250\,\mathrm{TeV}$@CARPET-2) *certainly* requires a galactic source, or new physics.

candidates could be 3HWC J1928+178, LHAASO J1929+1745 [ATel 15675]

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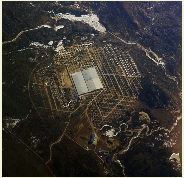

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“Classic” new physics explanations:

- axion/ALP-photon mixing

in context of GRB 221009A: [Baktash, Horns, Meyer], [Galanti, Roncadelli, Tavecchio], [Lin, Yanagida], [Troitsky], [Nakagawa, Takahashi, Yamada, Yin], [Zhang, Ma], [González et al.], …

- Lorentz invariance violation (LIV)

in context of GRB 221009A: [Baktash, Horns, Meyer], [Li, Ma], [Finke, Razzaque]

GRB 221009A, "classic" new physics explanations

- ALP-photon mixing to explain HE γ's

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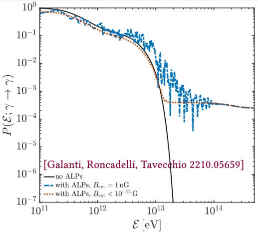
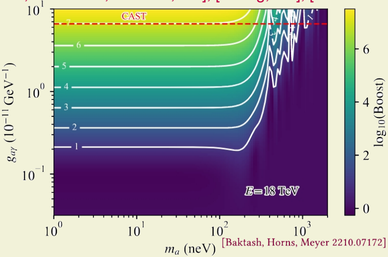




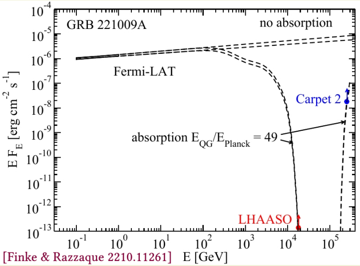
- Lorentz invariance violation (LIV). Modified DPR: $E^2 - p^2 = \pm E^2 \left(E/E_{\rm LIV}^{(n)}\right)^n$

$$10\, M_{\rm Pl} \lesssim E_{\rm LIV}^{(1)} \lesssim 50\, M_{\rm Pl}$$

$$10^{-7}\, M_{\rm Pl} \lesssim E_{\rm LIV}^{(2)} \lesssim 10^{-6}\, M_{\rm Pl}$$

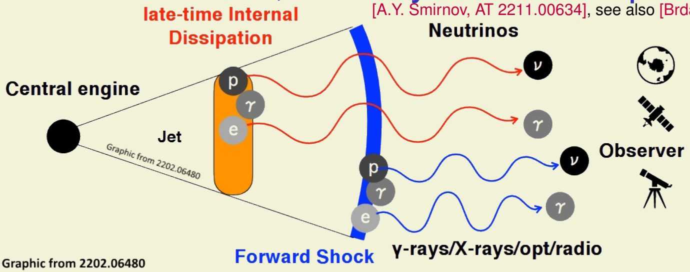
Limits, see e.g. [Martinez, Lang, de Souza '20]

In context of GRB 221009A: [Baktash, Horns, Meyer], [Li, Ma], [Finke, Razzaque]



GRB 221009A, a heavy neutrino explanation

[A.Y. Smirnov, AT 2211.00634], see also [Brdar, Li 2211.02028]



Graphic from 2202.06480

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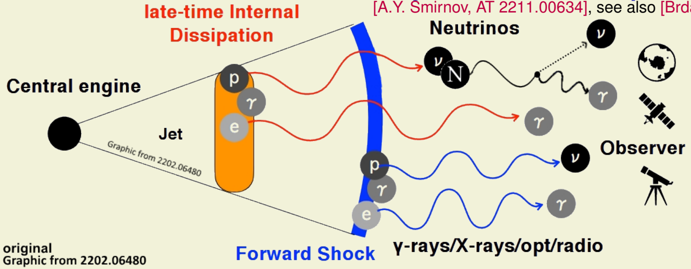

$$r_{\nu\gamma} \equiv \frac{\Phi_\nu}{\Phi_\gamma^0}$$

$$r_{N\nu} \equiv \frac{\Phi_N}{\Phi_\nu}$$

Benchmark:

$$r_{N\nu} \approx |U_{N\mu}|^2$$

$$\text{GRB} \longrightarrow \mu, \pi, K \longrightarrow X + |U_{N\ell}|^2 N \longrightarrow \nu + \gamma$$

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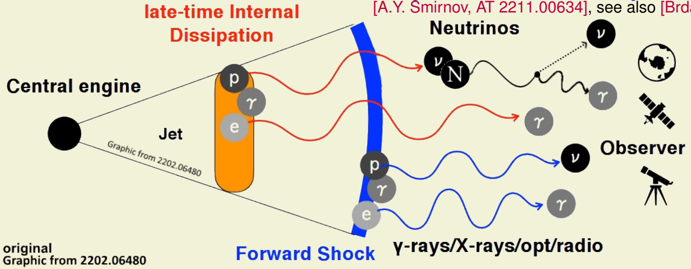

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Probability for individual N decay in $[x, x + \mathrm{d}x]$ and photon attenuation:

$$B_\gamma \, \mathrm{e}^{-x/\lambda_N} \, \frac{\mathrm{d}x}{\lambda_N} \, \mathrm{e}^{-(d-x)/\lambda_\gamma} \; .$$

$B_\gamma \equiv \mathrm{BR}(N \to \nu\gamma)$; $\lambda_N \equiv \frac{E_N}{\Gamma_N \, m_N}$ (N decay length); $\tau \equiv d/\lambda_\gamma$.

$\Rightarrow$ N-induced γ flux:

$$\Phi_\gamma^{(N)} = \Phi_N B_\gamma \frac{1}{\lambda_N/\lambda_\gamma - 1} \left[\mathrm{e}^{-d/\lambda_N} - \mathrm{e}^{-d/\lambda_\gamma}\right] .$$

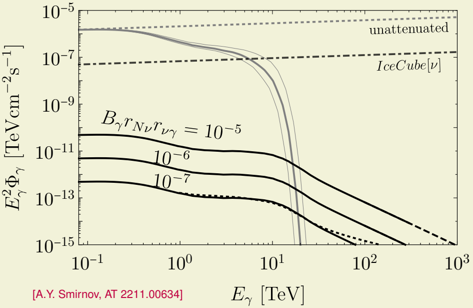
Maximized if $d/\lambda_N \approx 1$ $\curvearrowright$ $\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} \approx B_\gamma \times r_{N\nu} \times r_{\nu\gamma} \times \frac{0.37}{\tau}$. (c.f. $\Phi_\gamma^0(E)\,\mathrm{e}^{-\tau}$)

GRB 221009A, heavy neutrino explanation

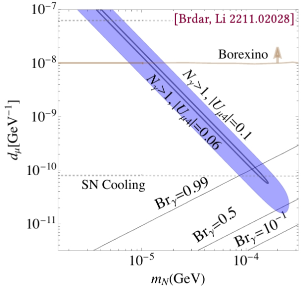
Constraints and shape of N-induced γ spectrum:

- Kinematics: $$m_N \lesssim 4.5\,\mathrm{MeV}\left(\frac{\Delta t}{2000\,\mathrm{s}}\right)^{\frac{1}{2}}\left(\frac{E_N}{18\,\mathrm{TeV}}\right).$$
- Decay length ($\lambda_N \simeq d$): $$\Gamma_N\, m_N \simeq 2\times 10^{-31}\,\mathrm{MeV}^2\left(\frac{E_N}{18\,\mathrm{TeV}}\right).$$

(Implies N-ν transition magnetic moment $\mu_N \simeq \sqrt{8\pi B_\gamma \Gamma_N/m_N^3}$)



[A.Y. Smirnov, AT 2211.00634]



Benchmark: $\mathcal{O}(0.1 \div 1)$ events in $E_\gamma \sim (10 \div 40)$TeV at LHAASO,
for $m_N \sim (0.1 \div 1)\,\mathrm{MeV}$, $|U_{N\mu}|^2 \sim 10^{-3}$, $B_\gamma \sim (0.1 \div 1)$, $(r_{\nu\gamma})_{\mathrm{IceCube}} \lesssim 3\times 10^{-2}$.

Heavy neutrino explanation, further constraints

- No γ's from SN 1987A. [Dar, Dado '87], [Kolb, Tuern '89], [Oberauer, Hagner, Raffelt, Rieger '93]

$$\curvearrowright \; B_\gamma \times \left[\frac{\Phi_N^{(SN)}}{\Phi_\nu^{(SN)}}\right] \lesssim 1.7 \times 10^{-4} \left(\frac{m_N}{\mathrm{MeV}}\right)^2 \qquad (10\mathrm{keV} \lesssim m_N \lesssim \mathrm{MeV}).$$

- Supernova energy loss? For large mixing, $|U_{N_\nu}|^2 \gtrsim 10^{-3}$, no additional cooling.

see e.g. [Zhou '15], [Syvolap, Ruchayskiy, Boyarski '19], [Suliga, Tamborra, Wu '20], [Bar, Blum, D'Amico '20]

$\rightarrow$ **see talk by Camalich**

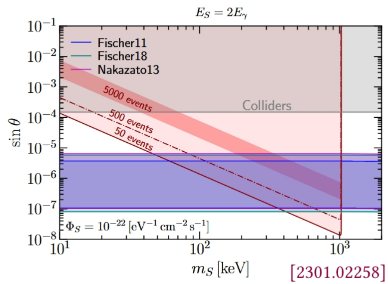
- BBN constraints on sterile N? e.g. [Boyarsky, Ruchayskiy, Shaposhnikov '09]
  Early decoupling of N via $U_{N\nu}$, $d_{N\nu}$, constraints are model dependent.
  (can be avoided in non-standard cosmology)
- Distortion of CMB spectrum? $\tau_N \sim 10^2 (m_N/1\,\mathrm{MeV})\,\mathrm{years} \ll t_{\mathrm{rec.}}$
  [Ressell, Turner '90]
- only for light N's: MINOS ν_μ disappearance $|U_{N\mu}|^2 \lesssim 10^{-2}$ [Adamson et al. '19]
- PMNS unitarity upper limit on $N - \nu$ mixing see e.g. [Parke, Ross-Lonergan '16]
  [Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, Lpoez-Pavon '16]
- Large B_γ? Itself requires a BSM model. Examples: LR-symmetric theories, Zee-type models, . . .
  [Zee '80], [Babu, Jana, Lindner '20]

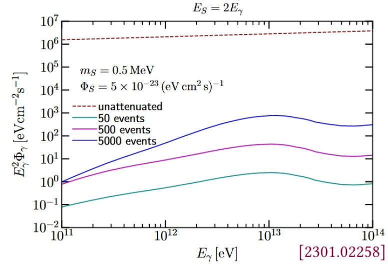
Light scalar explanation

[Balaji, Ramirez-Quezada, Silk, Zhang 2301.02258]

Similar characteristics as the sterile neutrino explanation.

- CP-even scalar S, $m_S \approx 0.5\,\mathrm{MeV}$
- mixing with SM Higgs boson $\sin\theta$
- dominant production mode at souce:
  nucleon-nucleon bremsstrahlung via pion exchange.
- loop level decay $S \to \gamma\gamma$ en route to earth.





Yet another model: $\nu_i \to \nu_j + a$ with $a + B_{\text{galactic}} \to \gamma$.

[Huang, Wang, Yu, Zhou 2212.03477]

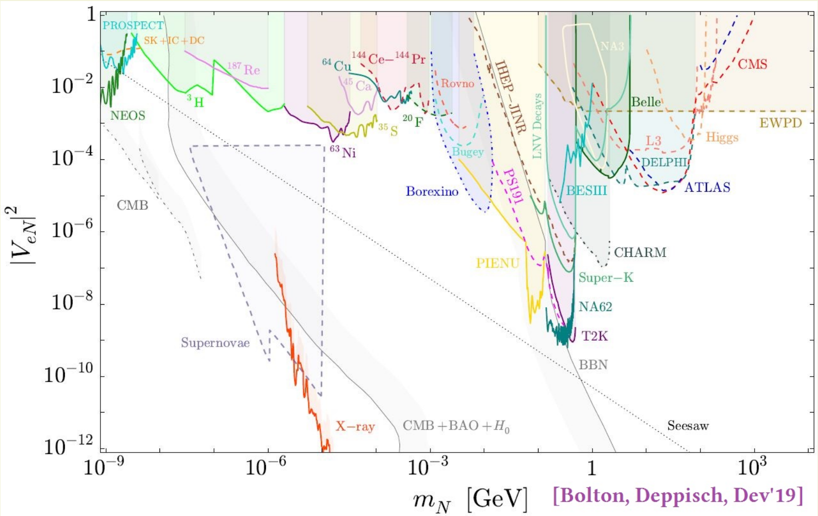
Summary

- GRB 221009A, G.O.A.T, $z = 0.15$, $E_{\rm iso} \sim 10^{55}\,{\rm erg}$
- Not very unlikely, but we got lucky.
- Puzzling observation of HE γ-rays $E_\gamma > 10\,{\rm TeV}$ at LHAASO
- IceCube (+KM3Net) observed no neutrinos $\rightarrow$ upper limits.
- SM explanation of $E_\gamma \sim 18\,{\rm TeV}$ *may* be possible ($\sim 3.5\sigma$ event), $E_\gamma > 20\,{\rm TeV}$ definitely not.
- New physics explanations:
  - ALPs $m_a \lesssim 10^{-6}\,{\rm eV}$, $g_{a\gamma\gamma} \gtrsim 10^{-12}\,{\rm GeV}^{-1}$
  - Lorentz violation $E^{(1)}_{\rm LIV} \lesssim 50\,M_{\rm Pl}$, $E^{(2)}_{\rm LIV} \lesssim 10^{-6}\,M_{\rm Pl}$
  - heavy sterile neutrinos $0.01\,{\rm MeV} \lesssim m_N \lesssim {\rm MeV}$, $|U_{N\nu}|^2 \sim 10^{-3}$, $B_\gamma = (0.1 \div 1)$
  - light higgs-mixed scalar $m_S \lesssim 1\,{\rm MeV}$, $10^{-8} \lesssim \sin\theta_{hS} \lesssim 10^{-4}$
- Interesting times ahead: waiting for LHAASO to release measured spectrum and timing information.

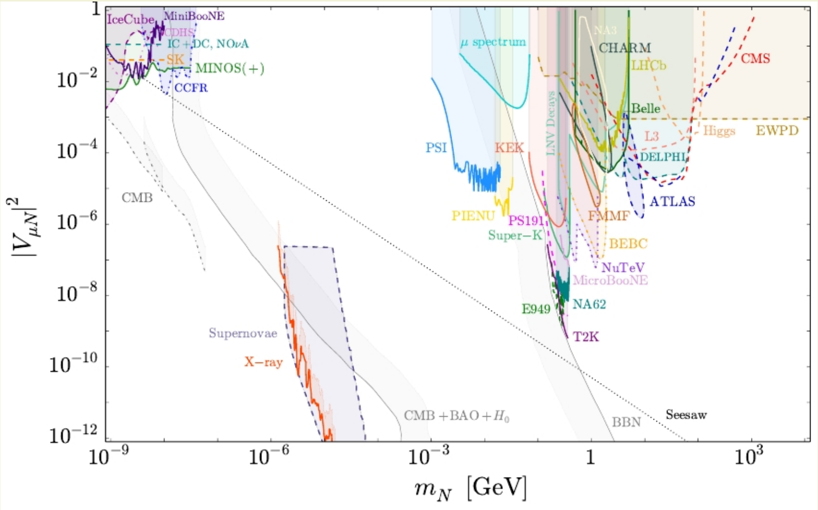
Thank You!

Backup slides

Constraints on mixing angle



Constraints on mixing angle



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Constraints originating from kinematics:

$$m_N \lesssim 4.5\,\mathrm{MeV}\ \left(\frac{\Delta t}{2000\,\mathrm{s}}\right)^{\frac{1}{2}} \left(\frac{E_N}{18\,\mathrm{TeV}}\right)\,.$$

Requiring decay length $\lambda_N \approx d$:

$$\Gamma_N\, m_N \gtrsim 2 \times 10^{-31}\,\mathrm{MeV}^2 \left(\frac{E_N}{18\,\mathrm{TeV}}\right)\,.$$

Using standard assumptions / decay width for $N \to \nu\gamma$:

$$m_N \gtrsim \frac{0.125\,\mathrm{MeV}}{\left|U_{N\mu}\right|^{\frac{1}{3}}} \left(\frac{E_N}{18\,\mathrm{TeV}}\right)^{\frac{1}{6}} \left(\frac{\lambda_N}{d}\right)^{\frac{1}{6}}\ .$$

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Probability for individual N decay in $[x, x+\mathrm{d}x]$ incl. photon attenuation:

$$B_\gamma \, \mathrm{e}^{-x/\lambda_N} \, \frac{\mathrm{d}x}{\lambda_N} \, \mathrm{e}^{-(d-x)/\lambda_\gamma} \; .$$

B_γ: branching ratio of radiative decay. $\lambda_N = E_N/(\Gamma_N \, m_N)$, decay length.
N-induced γ flux

$$\Phi_\gamma^{(N)} = \Phi_N B_\gamma \frac{1}{\lambda_N/\lambda_\gamma - 1} \left[\mathrm{e}^{-d/\lambda_N} - \mathrm{e}^{-d/\lambda_\gamma} \right].$$

Normalizing to Φ_γ^0, the direct unattenuated γ flux, we find

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} = B_\gamma \, \frac{\Phi_N}{\Phi_\gamma^0} \, \frac{1}{\tau\lambda_N/d - 1} \left[\mathrm{e}^{-d/\lambda_N} - \mathrm{e}^{-\tau} \right] \; .$$

Varying d/λ_N we find that the maximal flux is obtained for $d/\lambda_N \approx 1$. Expanding in $\tau \gg 1$ as expected for high energy γ rays we obtain

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} \;\approx\; B_\gamma \; r_{N\nu} \; r_{\nu\gamma} \; \frac{0.37}{\tau} \; .$$

The γ flux produced directly in GRB is attenuated as

$$\frac{\Phi_\gamma^d}{\Phi_\gamma^0} = \mathrm{e}^{-d/\lambda_\gamma} = \mathrm{e}^{-\tau} \; .$$

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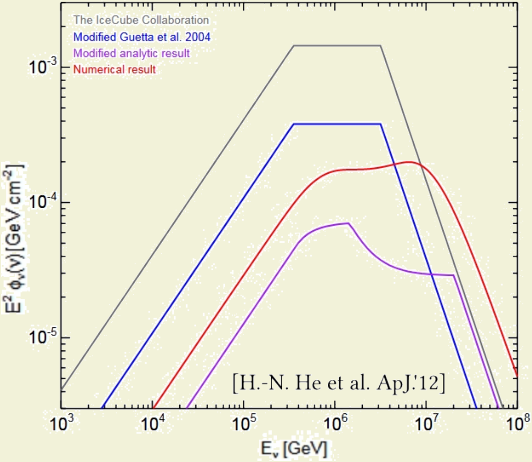
Estimates for neutrino fluences



For masses between $10\,\mathrm{keV}$ and a few MeV there are strong bounds on heavy *active* neutrino radiative decays from SN1987A

$$\Gamma_\nu\, B_\gamma \lesssim 5\times 10^{-14}\left(\frac{m_\nu}{\mathrm{MeV}}\right)\mathrm{s}^{-1}\ . \tag{1}$$

The flux of heavy neutrinos produced by SN1987A can be parametrized by the ratio

$$r_{N\nu}^{(SN)} \equiv \frac{\Phi_N^{(SN)}}{\Phi_\nu^{(SN)}}\ . \tag{2}$$

Naively scaling the limit (1) by this ratio we obtain the constraint

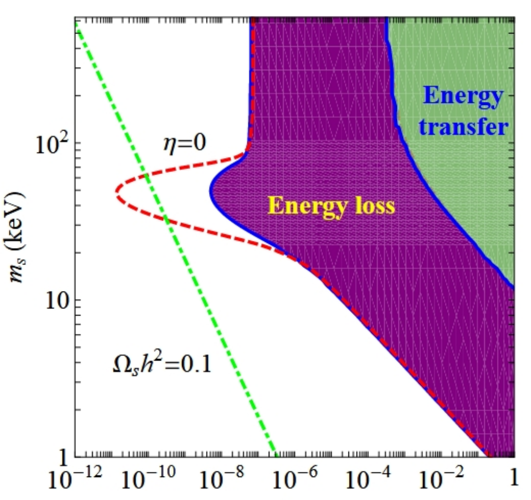
$$\frac{\Gamma_N}{m_N} \lesssim \frac{3\times 10^{-35}}{B_\gamma\, r_{N\nu}^{(SN)}}\ . \tag{3}$$

Combining this with condition (22) requires

$$B_\gamma\, r_{N\nu}^{(SN)} \lesssim 1.7\times 10^{-4}\left(\frac{m_N}{\mathrm{MeV}}\right)^2\ . \tag{4}$$

This shows that a saturation of the inequality $B_\gamma \leq 1$ is not excluded by the model independent constraints if $r_{N\nu}^{(SN)} \ll r_{N\nu} \approx |U_{N\mu}|^2$, which can be the case due to different production mechanisms and flavor composition.

SN constraints on heavy heutrinos



[Zhou 1504.02729]