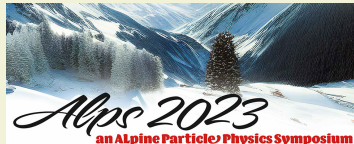


# GRB 221009A high-energy $\gamma$ -rays and new physics explanations

**Andreas Trautner**

contact: trautner AT mpi-hd.mpg.de

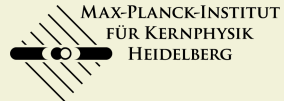
based on: **2211.00634** w/ Alexei Y. Smirnov



30.03.23



MAX-PLANCK-GESellschaft



# 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)

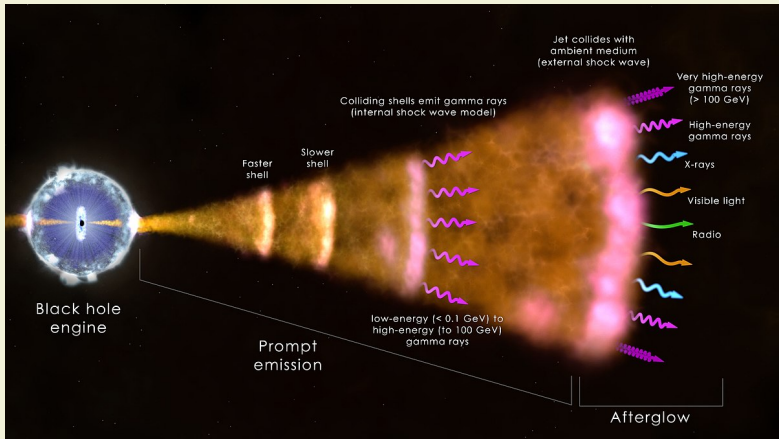
- Transient extreme x-ray events,  $t_{90} \sim 10 \text{ ms} \rightarrow \mathcal{O}(1000) \text{ s}$ .
- Mechanism not 100% clear, very likely SN/NS-NS mergers.
- “Short GRB”  $t_{90} \lesssim 2 \text{ s}$ , “long GRB”  $t_{90} \gg 2 \text{ s}$ .
- Typical energy release  $10^{52} \rightarrow 10^{54} \text{ erg}$  ( $10^{54} \text{ erg} \approx M_{\odot}$ ).
- First detection 1967 (Vela),  
first afterglow detection 1997 (BATSE@CGRO).
- Angular width of jet  $2^{\circ} \rightarrow 20^{\circ}$ .
- Kilonova GRB 170817A / GW 170817, NS-NS merger, true multi-messenger signal ( $z = 0.009$ ).
- GRB rate in MW:  $1/(10^4 \rightarrow 10^6) \text{ yr}^{-1}$ , 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  $e_{\text{HE}}^{\mp} + \gamma \longrightarrow e^{\mp} + \gamma_{\text{HE}}$ ,
- “Fireball”, shock wave acceleration, UHECR,  $p + \gamma \rightarrow \pi' s + \dots$



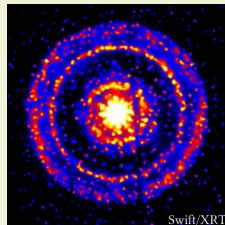
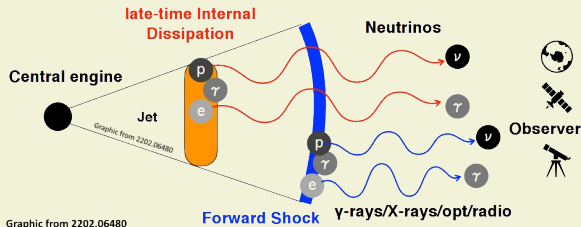


# GRB particle production

Mechanism is poorly understood, but models exist.

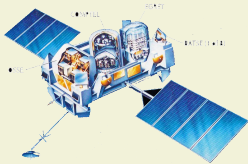
[Waxmann '95], [Vietri '95], see e.g. [Bustamante, Baerwald, Murase, Winter '15]

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

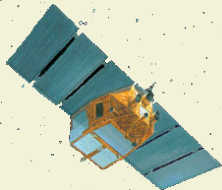


# GRB detection, examples

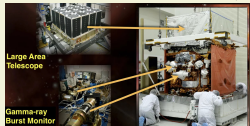
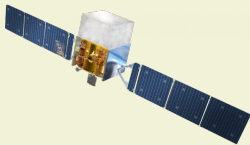
CGRO ('91-'00)



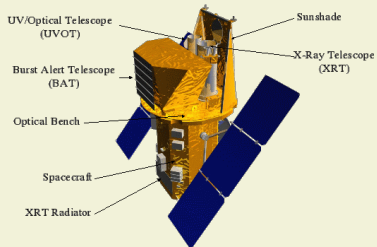
BeppoSAX ('96-'02)



Fermi  $\gamma$ -ray telescope



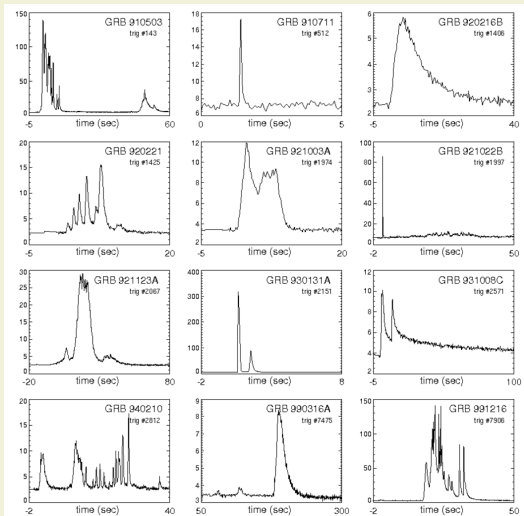
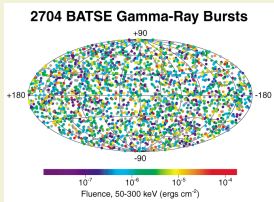
Swift x-ray telescope



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

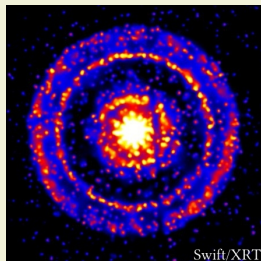
# GRB diversity

## 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:  $z = 0.151$  ,  $d \approx 740$  Mpc [GCN 32648, 32686]
- Tons of follow up observation in optical, radio, low-E x-rays, *etc.*
- LHAASO,  $\mathcal{O}(5000)$   $\gamma$ -ray events with  $0.5 \text{ TeV} \leq E_\gamma \leq 18 \text{ TeV}$   
[GCN 32677]



NASA/DOE/Fermi LAT Collaboration

$E_\gamma > 100 \text{ MeV}$ ,  $\Delta t > 10 \text{ hrs}$ ,  $\angle \sim 20^\circ$

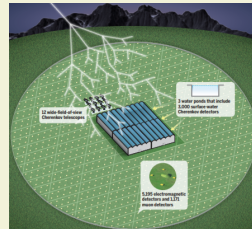
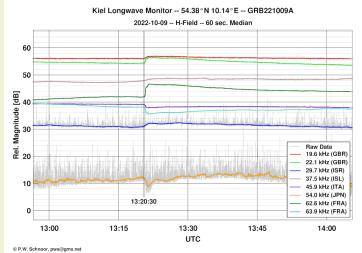
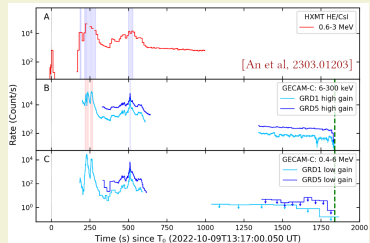
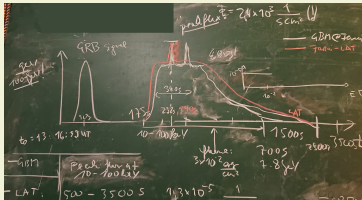
NASA/Swift/B. Cenko

optical,  $\Delta t > 10 \text{ hrs}$ ,  $\angle \sim 7^\circ$

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,  $E_{\text{iso}} \approx 1.5 \times 10^{55}$  erg(!) [GCN 32762], [Lan et al. 2303.10804]
- Peak flux@(0.01 – 1) MeV:  $> 2.4 \times 10^3 \text{ s}^{-1} \text{ cm}^{-2}$  (Fermi **saturated**  $> 100 \text{ s}$ !).
- Fermi: record Energy prompt  $\gamma$ :  $E_{\gamma} \sim 99 \text{ GeV}$  ( $T_0 + 240 \text{ s}$ ) [GCN 32658]
- Significant Earth ionospheric distortions. [GCN 32744,32745]
- LHAASO: First ever detection of  $E_{\gamma} > 10 \text{ TeV}$  from a GRB. [GCN 32677]



# GRB 221009A evolution

- GRB 221009A was the **brightest** GRB ever observed,  $E_{\text{iso}} \approx 1.5 \times 10^{55}$  erg(!)  
[GCN 32762], [Lan et al. 2303.10804]
- Peak flux@(0.01 – 1) MeV:  $> 2.4 \times 10^3 \text{ s}^{-1} \text{ cm}^{-2}$  (Fermi **saturated**  $> 100$  s!).
- Fermi: record Energy prompt  $\gamma$ :  $E_\gamma \sim 99$  GeV ( $T_0 + 240$  s) [GCN 32658]
- Significant Earth ionospheric distortions. [GCN 32744,32745]
- LHAASO: First ever detection of  $E_\gamma > 10$  TeV from a GRB. [GCN 32677]
- Curiosities: tertiary or quaternary HE emission?
  - CARPET-2:  $E_\gamma \sim 251$  TeV ( $T_0 + 4530$  s,  $3.8\sigma$ ) [ATel 15675]
  - DAMPE:  $E_\gamma \sim 35$  GeV ( $T_0 + 4896$  s,  $3.6\sigma$ ) [GCN 32973]
  - Fermi-LAT:  $E_\gamma \sim 397.7$  GeV ( $T_0 + 33554$  s,  $> 3\sigma$ ) [GCN 32748]

# GRB 221009A evolution

- GRB 221009A was the **brightest** GRB ever observed,  $E_{\text{iso}} \approx 1.5 \times 10^{55}$  erg(!)  
[GCN 32762], [Lan et al. 2303.10804]
- Peak flux@(0.01 – 1) MeV:  $> 2.4 \times 10^3 \text{ s}^{-1} \text{ cm}^{-2}$  (Fermi **saturated**  $> 100$  s!).
- Fermi: record Energy prompt  $\gamma$ :  $E_\gamma \sim 99$  GeV ( $T_0 + 240$  s) [GCN 32658]
- Significant Earth ionospheric distortions. [GCN 32744,32745]
- LHAASO: First ever detection of  $E_\gamma > 10$  TeV from a GRB. [GCN 32677]
- Curiosities: tertiary or quaternary HE emission?
  - CARPET-2:  $E_\gamma \sim 251$  TeV ( $T_0 + 4530$  s,  $3.8\sigma$ ) [ATel 15675]
  - DAMPE:  $E_\gamma \sim 35$  GeV ( $T_0 + 4896$  s,  $3.6\sigma$ ) [GCN 32973]
  - Fermi-LAT:  $E_\gamma \sim 397.7$  GeV ( $T_0 + 33554$  s,  $> 3\sigma$ ) [GCN 32748]

Was GRB 221009A special? [GCN 32793]

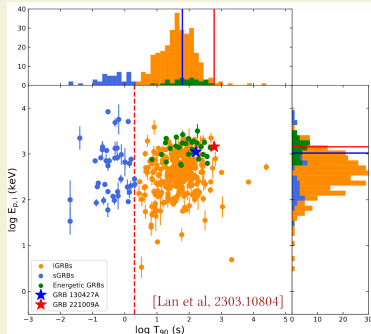
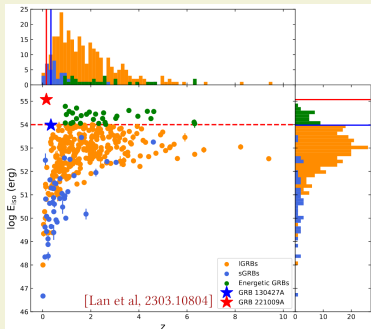
"We conclude that there is a 10% probability to observe an event like GRB 221009A about 50 years after the discovery of the first GRB."

# GRB 221009A evolution

- GRB 221009A was the **brightest** GRB ever observed,  $E_{\text{iso}} \approx 1.5 \times 10^{55}$  erg(!) [GCN 32762], [Lan et al. 2303.10804]
- Peak flux@(0.01 – 1) MeV:  $> 2.4 \times 10^3 \text{ s}^{-1} \text{ cm}^{-2}$  (Fermi **saturated**  $> 100 \text{ s}$ !).
- Fermi: record Energy prompt  $\gamma$ :  $E_\gamma \sim 99 \text{ GeV}$  ( $T_0 + 240 \text{ s}$ ) [GCN 32658]
- Significant Earth ionospheric distortions. [GCN 32744,32745]
- LHAASO: First ever detection of  $E_\gamma > 10 \text{ TeV}$  from a GRB. [GCN 32677]
- Curiosities: tertiary or quaternary HE emission?  
 CARPET-2:  $E_\gamma \sim 251 \text{ TeV}$  ( $T_0 + 4530 \text{ s}$ ,  $3.8\sigma$ ) [ATel 15675]  
 DAMPE:  $E_\gamma \sim 35 \text{ GeV}$  ( $T_0 + 4896 \text{ s}$ ,  $3.6\sigma$ ) [GCN 32973]  
 Fermi-LAT:  $E_\gamma \sim 397.7 \text{ GeV}$  ( $T_0 + 33554 \text{ s}$ ,  $> 3\sigma$ ) [GCN 32748]

## Was GRB 221009A special? [GCN 32793]

"We conclude that there is a 10% probability to observe an event like GRB 221009A about 50 years after the discovery of the first GRB."





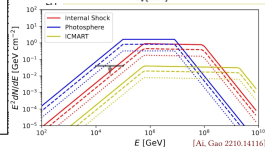
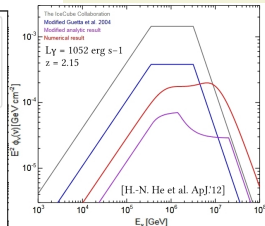
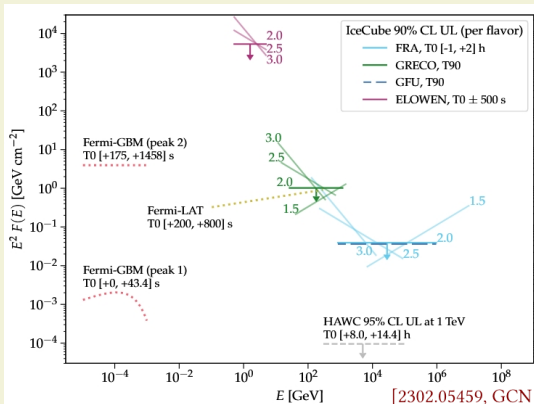
# GRB 221009A multi-messenger signals?

- GR waves: LIGO-Virgo-KAGRA not online, GEO600 no sensitivity.
- Neutrinos: IceCube no detection, but limits

[GCN 32877]

[2302.05459],[GCN 32665]

[Ai, Gao 2210.14116], [Murase et al 2210.15625]



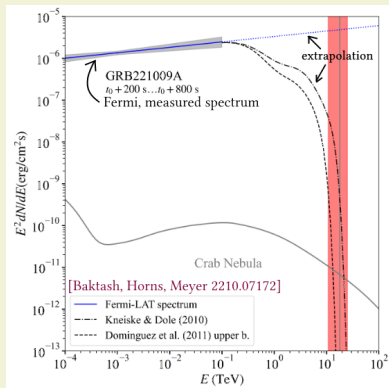
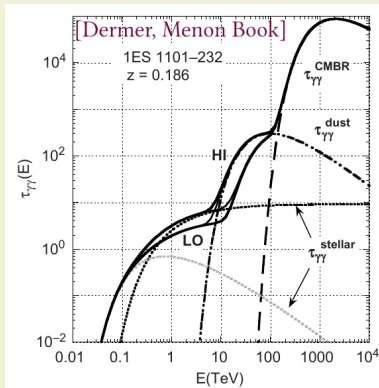
# High-E $\gamma$ propagation

$$\gamma_{\text{HE}} + \gamma_{\text{br.}} \rightarrow e^+ + e^-$$

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

⇒ Flux attenuation:

$$\Phi_{\gamma}(E) = \Phi_{\gamma}^0(E) e^{-\tau(E)}$$



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

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

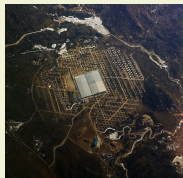
# GRB 221009A High energy $\gamma$ -rays

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

- LHAASO observed  $\mathcal{O}(5000)$   $\gamma$ -ray events with  $0.5 \text{ TeV} \leq E_\gamma \leq 18 \text{ TeV}$  during  $[T_0, T_0 + 2000 \text{ s}]$ .  
Relative error at  $E_\gamma \sim 18 \text{ TeV}$ :  $\delta E/E \approx 40\%$ .

[GCN 32677]

Can this be consistent with SM physics?



# GRB 221009A High energy $\gamma$ -rays

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

- LHAASO observed  $\mathcal{O}(5000)$   $\gamma$ -ray events with  $0.5 \text{ TeV} \leq E_\gamma \leq 18 \text{ TeV}$  during  $[T_0, T_0 + 2000 \text{ s}]$ .  
Relative error at  $E_\gamma \sim 18 \text{ TeV}$ :  $\delta E/E \approx 40\%$ .

[GCN 32677]



Can this be consistent with SM physics?

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

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

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

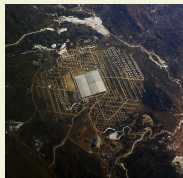
candidates could be 3HWC J1928+178, LHAASO J1929+1745 [ATel 15675]

# GRB 221009A High energy $\gamma$ -rays

Above  $E_\gamma \gtrsim 20$  TeV this is literally light shining at a wall.

- LHAASO observed  $\mathcal{O}(5000)$   $\gamma$ -ray events with  $0.5 \text{ TeV} \leq E_\gamma \leq 18 \text{ TeV}$  during  $[T_0, T_0 + 2000 \text{ s}]$ .  
Relative error at  $E_\gamma \sim 18 \text{ TeV}$ :  $\delta E/E \approx 40\%$ .

[GCN 32677]




Can this be consistent with SM physics?

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

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

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

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

“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.], ...

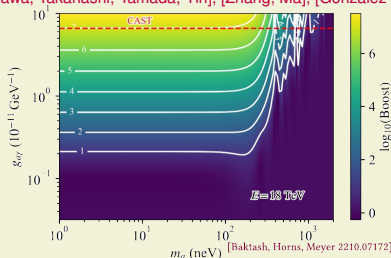
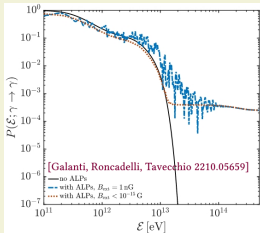
- Lorentz invariance violation (LIV)

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

# GRB 221009A, “classic” new physics explanations

- ALP-photon mixing to explain HE  $\gamma$ 's

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



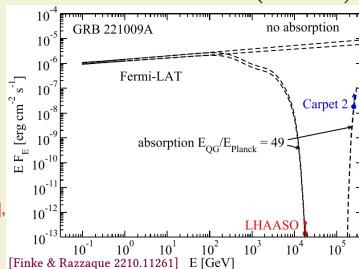
- Lorentz invariance violation (LIV). Modified DPR:  $E^2 - p^2 = \pm E^2 \left( E/E_{\text{LIV}}^{(n)} \right)^n$

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

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

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

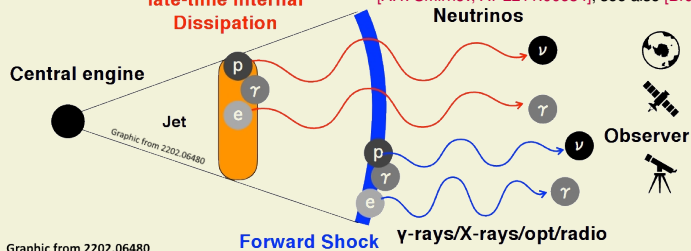
In context of GRB 221009A: [Baktash, Horns, Meyer], [Li, Ma], [Finke, Razzaque]



# GRB 221009A, a heavy neutrino explanation

late-time Internal  
Dissipation

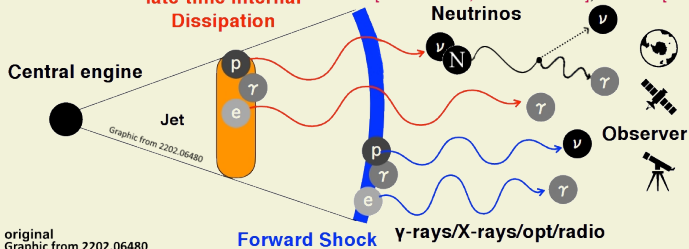
[A.Y. Smirnov, AT 2211.00634], see also [Brdar, Li 2211.02028]



# GRB 221009A, a heavy neutrino explanation

late-time Internal  
Dissipation

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



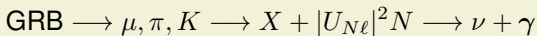
original  
Graphic from 2202.06480

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

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

Benchmark:

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

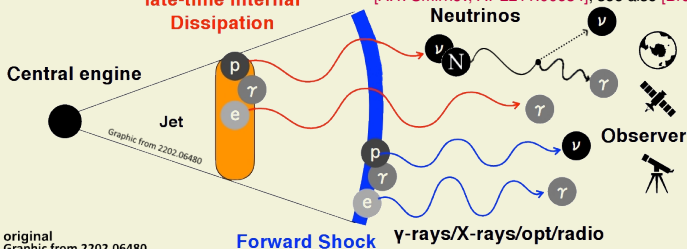




# GRB 221009A, a heavy neutrino explanation

late-time Internal  
Dissipation

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



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

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

Benchmark:

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

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

Probability for individual  $N$  decay in  $[x, x + dx]$  and photon attenuation:

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

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

$\Rightarrow N$ -induced  $\gamma$  flux:

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

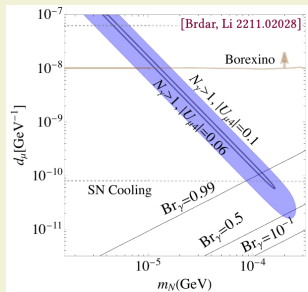
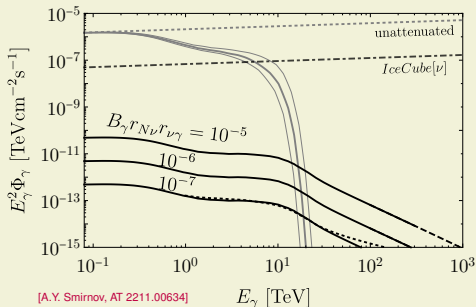
$$\text{Maximized if } d/\lambda_N \approx 1 \quad \rightsquigarrow \quad \frac{\Phi_{\gamma}^{(N)}}{\Phi_{\gamma}^0} \approx B_{\gamma} \times r_{N\nu} \times r_{\nu\gamma} \times \frac{0.37}{\tau} . \quad (\text{c.f. } \Phi_{\gamma}^0(E) e^{-\tau})$$

# GRB 221009A, heavy neutrino explanation

Constraints and shape of  $N$ -induced  $\gamma$  spectrum:

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

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



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

# Heavy neutrino explanation, further constraints

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

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

- 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]

→ see talk by Camalich

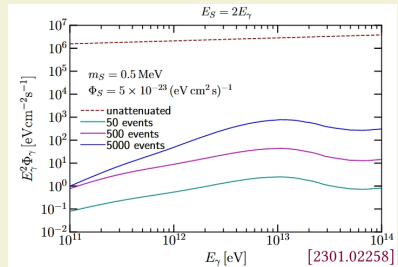
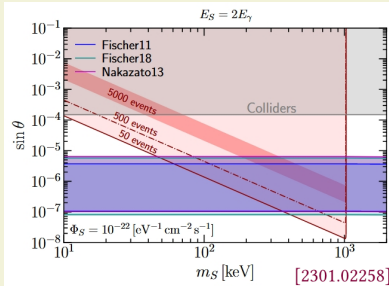
- BBN constraints on sterile  $N$ ? e.g. [Boyarskiy, Ruchayskiy, Shaposhnikov '09]  
Early decoupling of  $N$  via  $U_{N\nu}, d_{N\nu}$ , constraints are model dependent.  
(can be avoided in non-standard cosmology)
- Distortion of CMB spectrum?  $\tau_N \sim 10^2 (m_N/1 \text{ MeV}) \text{ years} \ll t_{\text{rec}}$ . [Ressell, Turner '90]
- only for light  $N$ 's: MINOS  $\nu_\mu$  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  $B_\gamma$ ? 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  $S$ ,  $m_S \approx 0.5 \text{ MeV}$
- mixing with SM Higgs boson  $\sin \theta$
- dominant production mode at source: nucleon-nucleon bremsstrahlung via pion exchange.
- loop level decay  $S \rightarrow \gamma\gamma$  en route to earth.



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

[Huang, Wang, Yu, Zhou 2212.03477]

# Summary

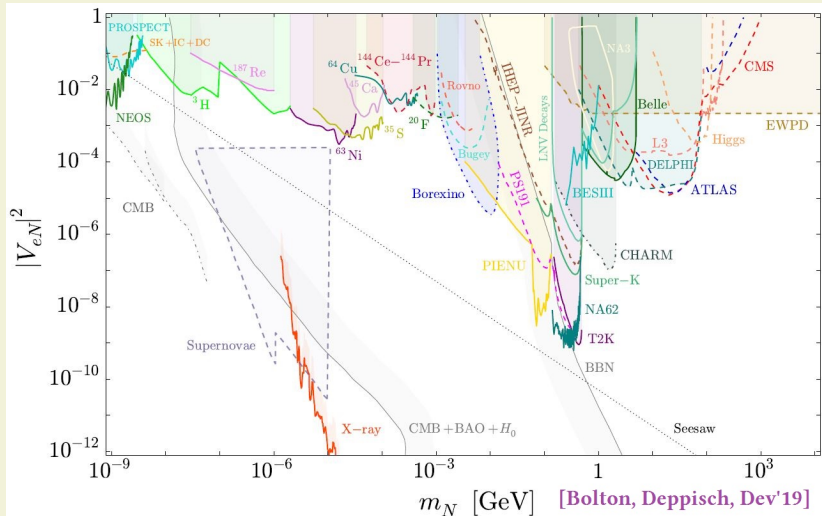
- GRB 221009A, G.O.A.T,  $z = 0.15$ ,  $E_{\text{iso}} \sim 10^{55}$  erg
- Not very unlikely, but we got lucky.
- Puzzling observation of HE  $\gamma$ -rays  $E_\gamma > 10$  TeV at LHAASO
- IceCube (+KM3Net) observed no neutrinos  $\rightarrow$  upper limits.
- SM explanation of  $E_\gamma \sim 18$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

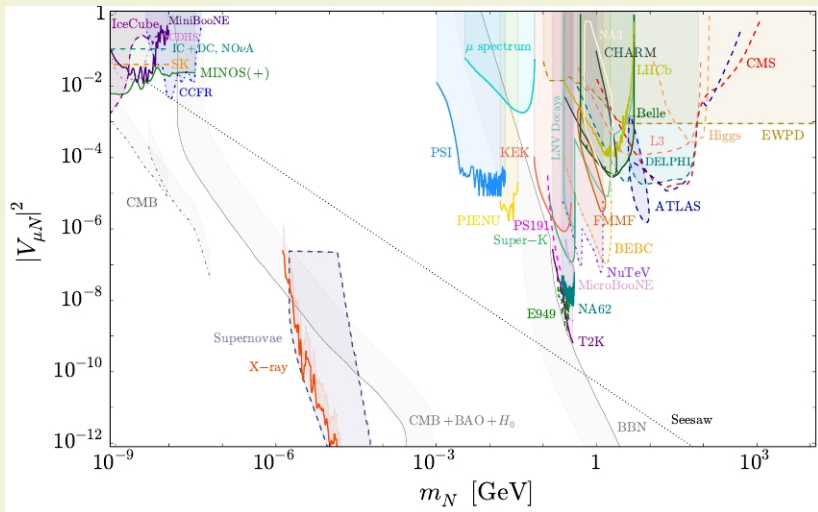
# Backup slides

# Constraints on mixing angle





# Constraints on mixing angle



# GRB 221009A

Constraints originating from kinematics:

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

Requiring decay length  $\lambda_N \approx d$ :

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

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

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

# GRB 221009A

Probability for individual  $N$  decay in  $[x, x + dx]$  incl. photon attenuation:

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

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

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

Normalizing to  $\Phi_\gamma^0$ , the direct unattenuated  $\gamma$  flux, we find

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

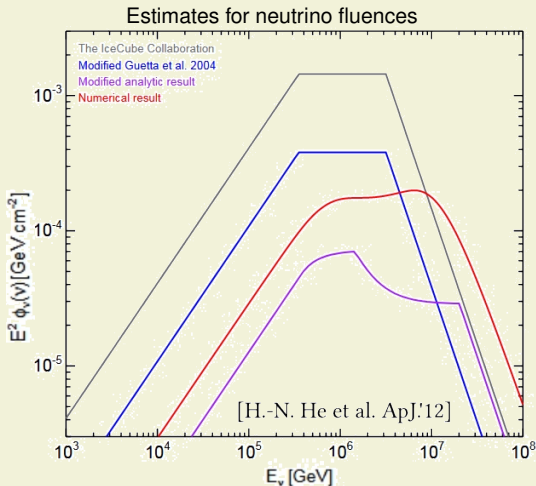
Varying  $d/\lambda_N$  we find that the maximal flux is obtained for  $d/\lambda_N \approx 1$ . Expanding in  $\tau \gg 1$  as expected for high energy  $\gamma$  rays we obtain

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

The  $\gamma$  flux produced directly in GRB is attenuated as

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

# GRB 221009A



For masses between 10 keV and a few MeV there are strong bounds on heavy *active* neutrino radiative decays from SN1987A

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

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

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

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

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

Combining this with condition (22) requires

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

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 neutrinos

