High-energy neutrino signatures from magnetar remnants of binary neutron star mergers

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Pennsylvania State University

GGI Neutrino Frontiers Workshop
Firenze, Italy
July 8 - 19, 2024

PennState

NSF

Prologue

New physics, understanding the fundamentals,….

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Man-made Accelerators

LHC

Tevatron

Image credits: Wikipedia

Science Comm., DESY, Zeuthen

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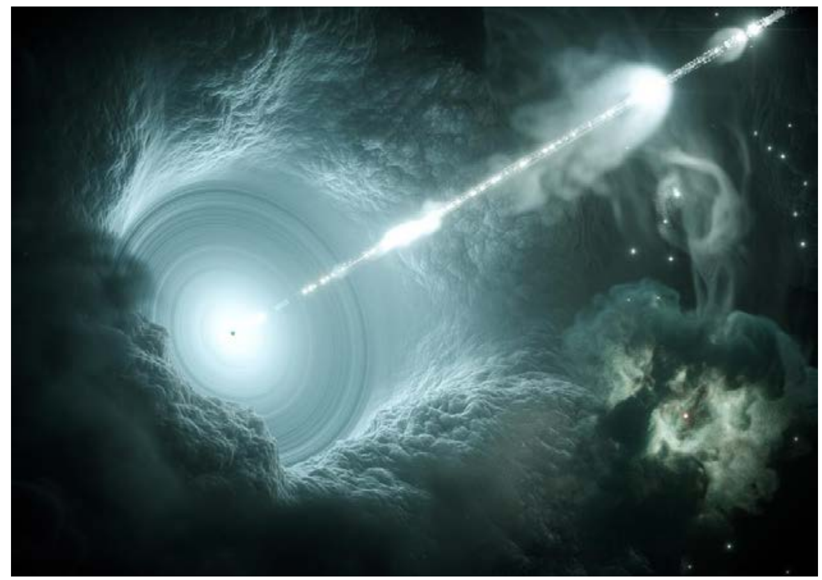
Cosmic Accelerators



High-energy astrophysical phenomena

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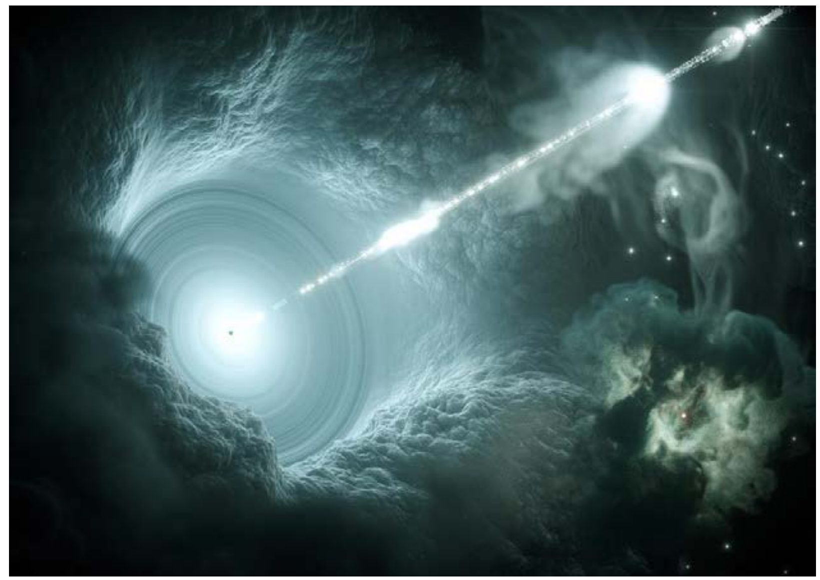

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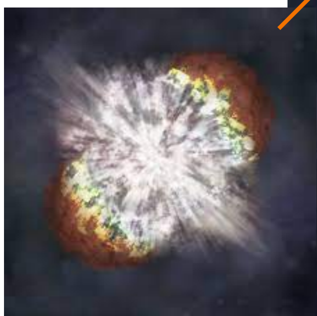
The multi-messenger paradigm

Compact object mergers, TDEs, CCSNe,….



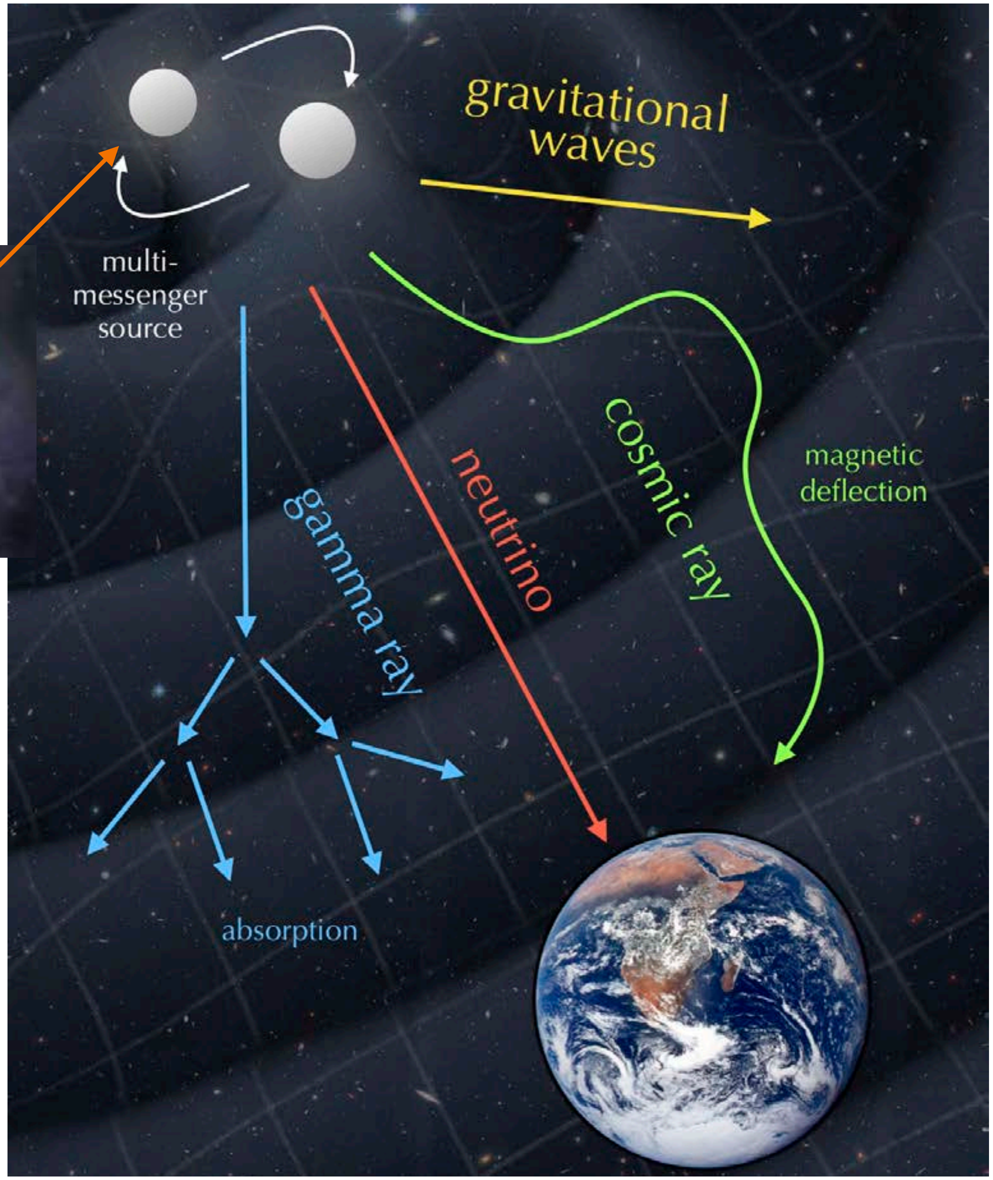


Image credits: NBI
IceCube Collab.+ Science 2022
IceCube Collab.+ Science, 380, 2023

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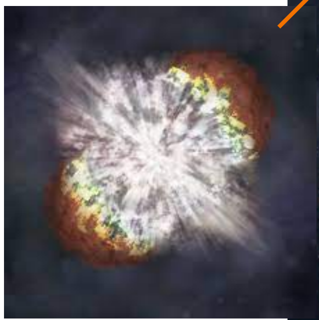

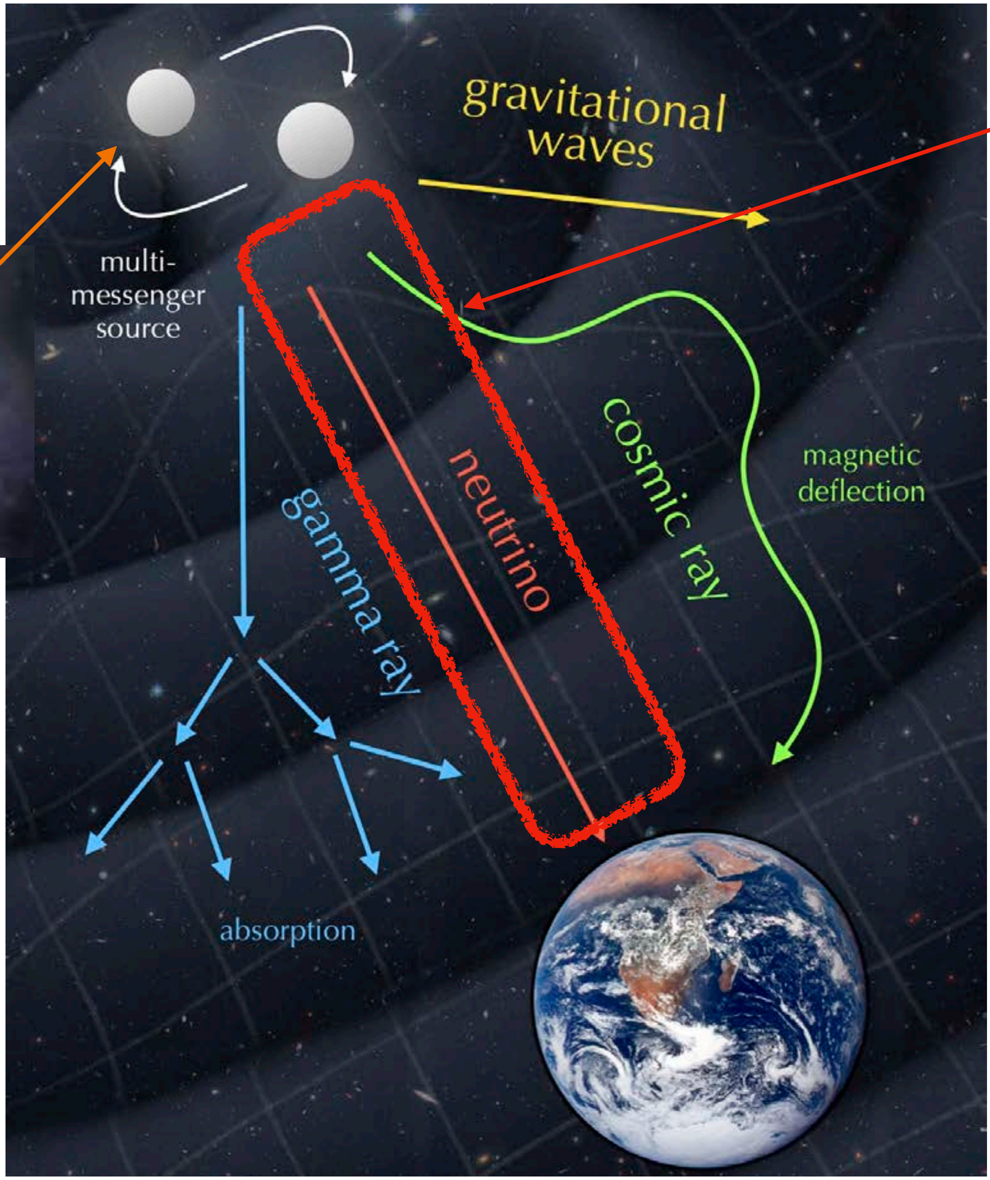

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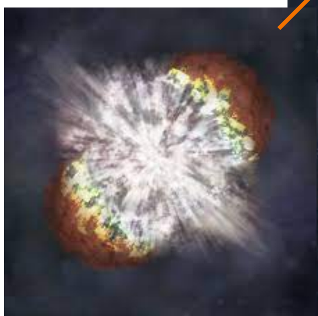

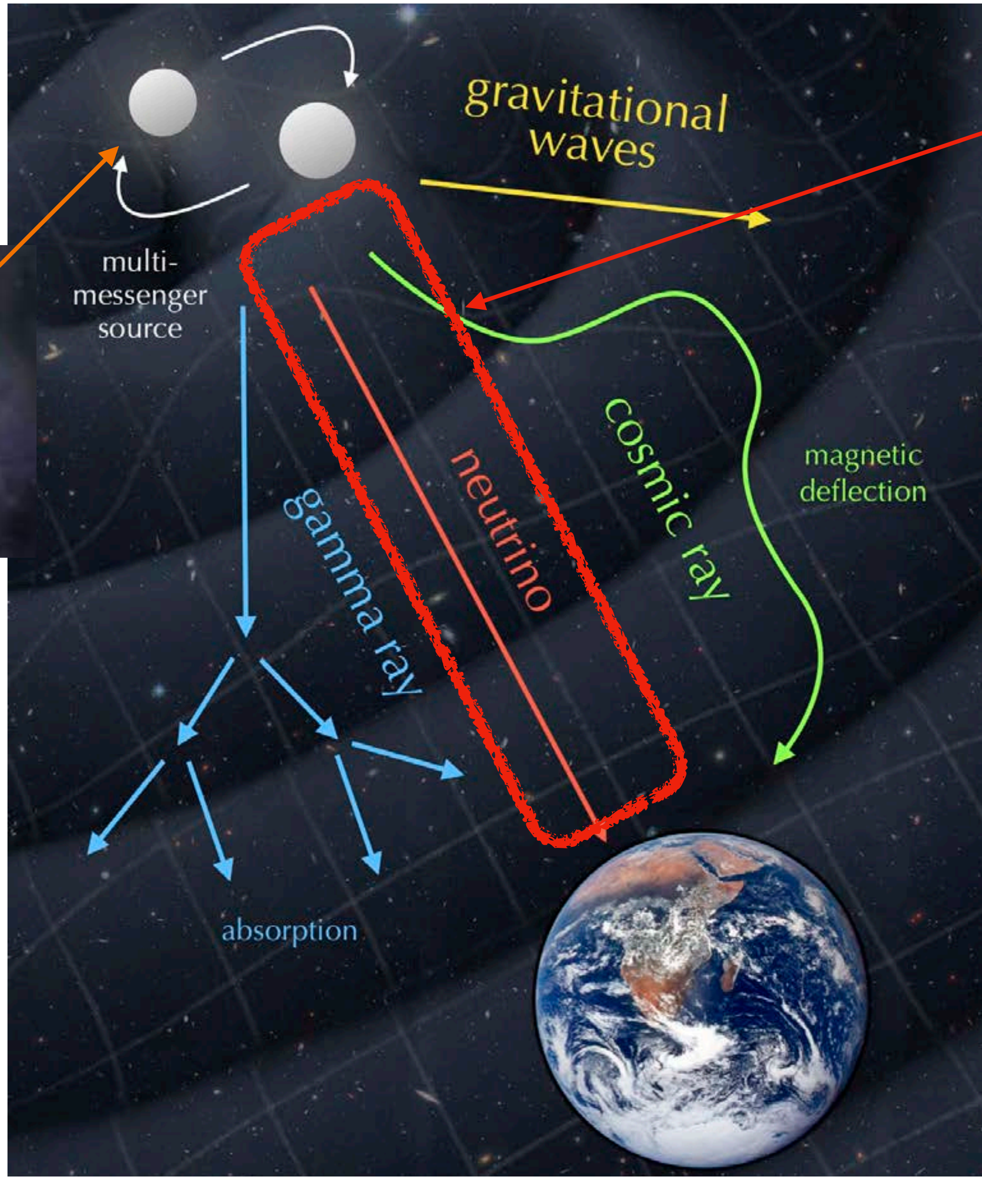

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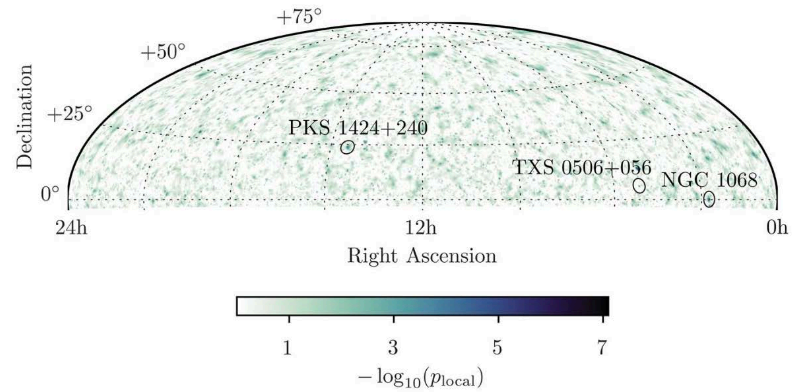
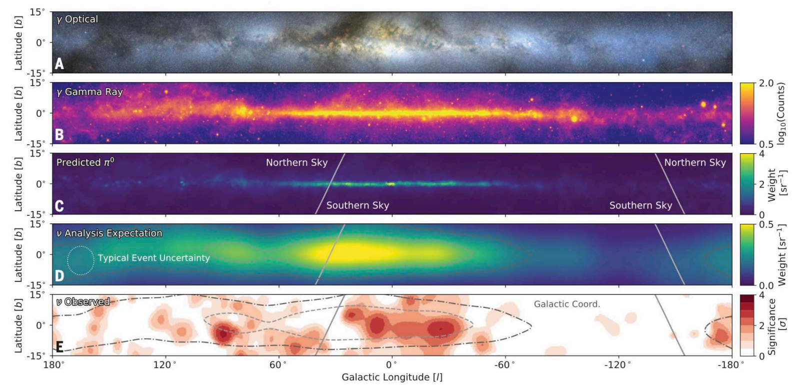


Point Sources

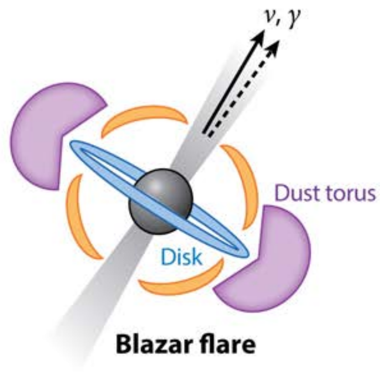


The Galactic plane

Image credits: NBI
IceCube Collab.+ Science 2022
IceCube Collab.+ Science, 380, 2023

The high-energy multi-messenger transients

High-energy astrophysical phenomena



Murase K, Bartos I. 2019.
Annu. Rev. Nucl. Part. Sci. 69:477–506

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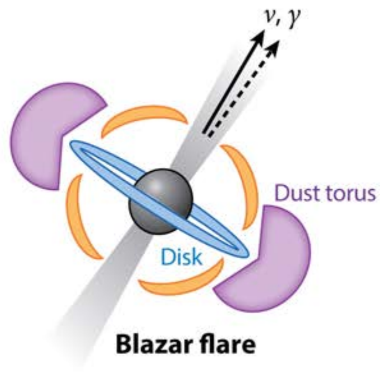

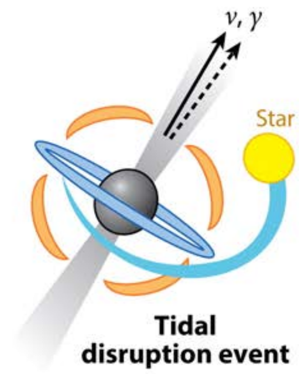

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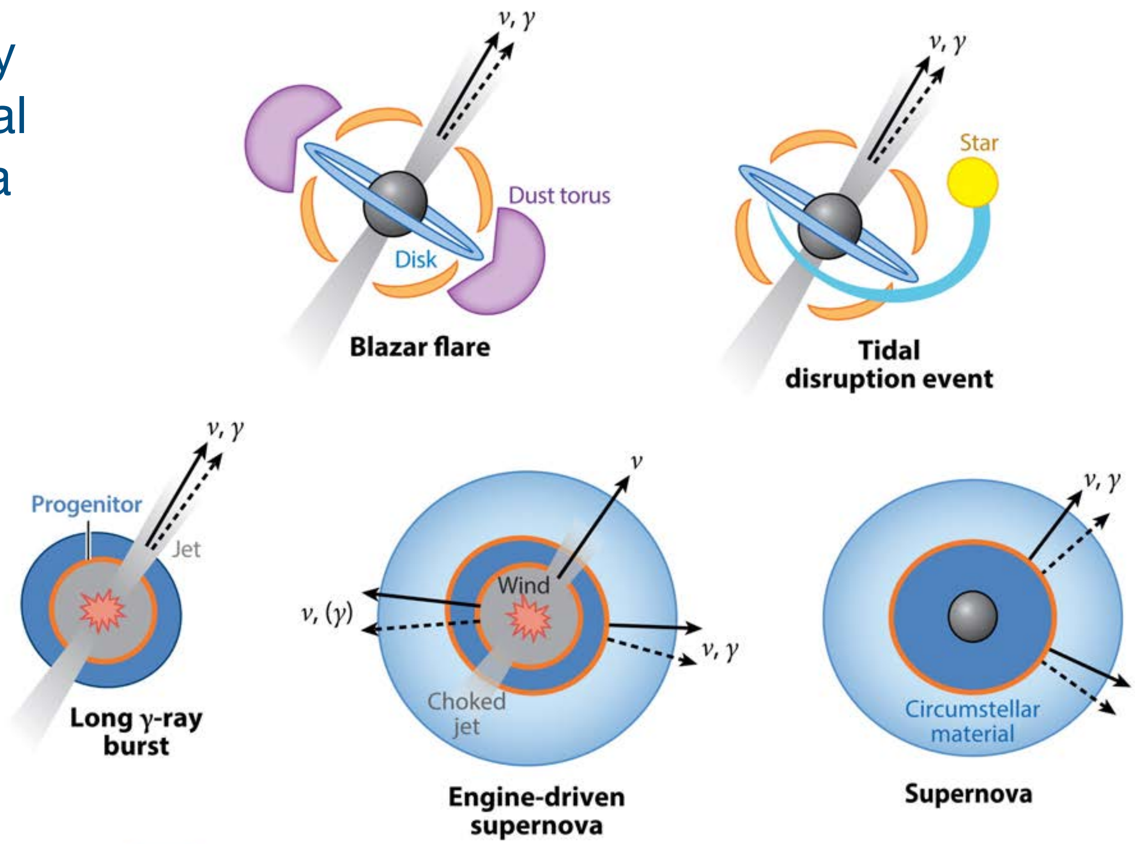

See talk by T. Pitik

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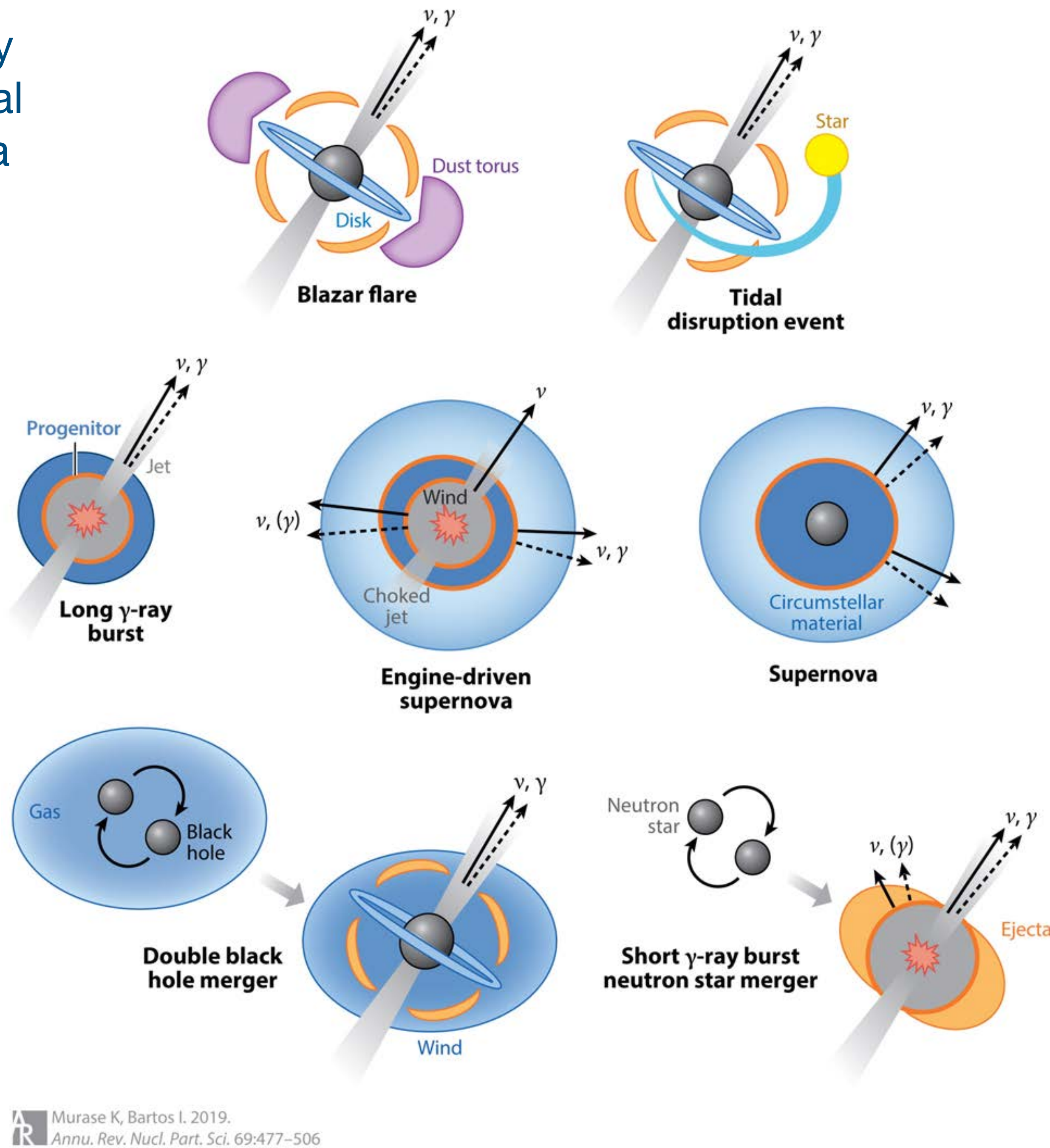

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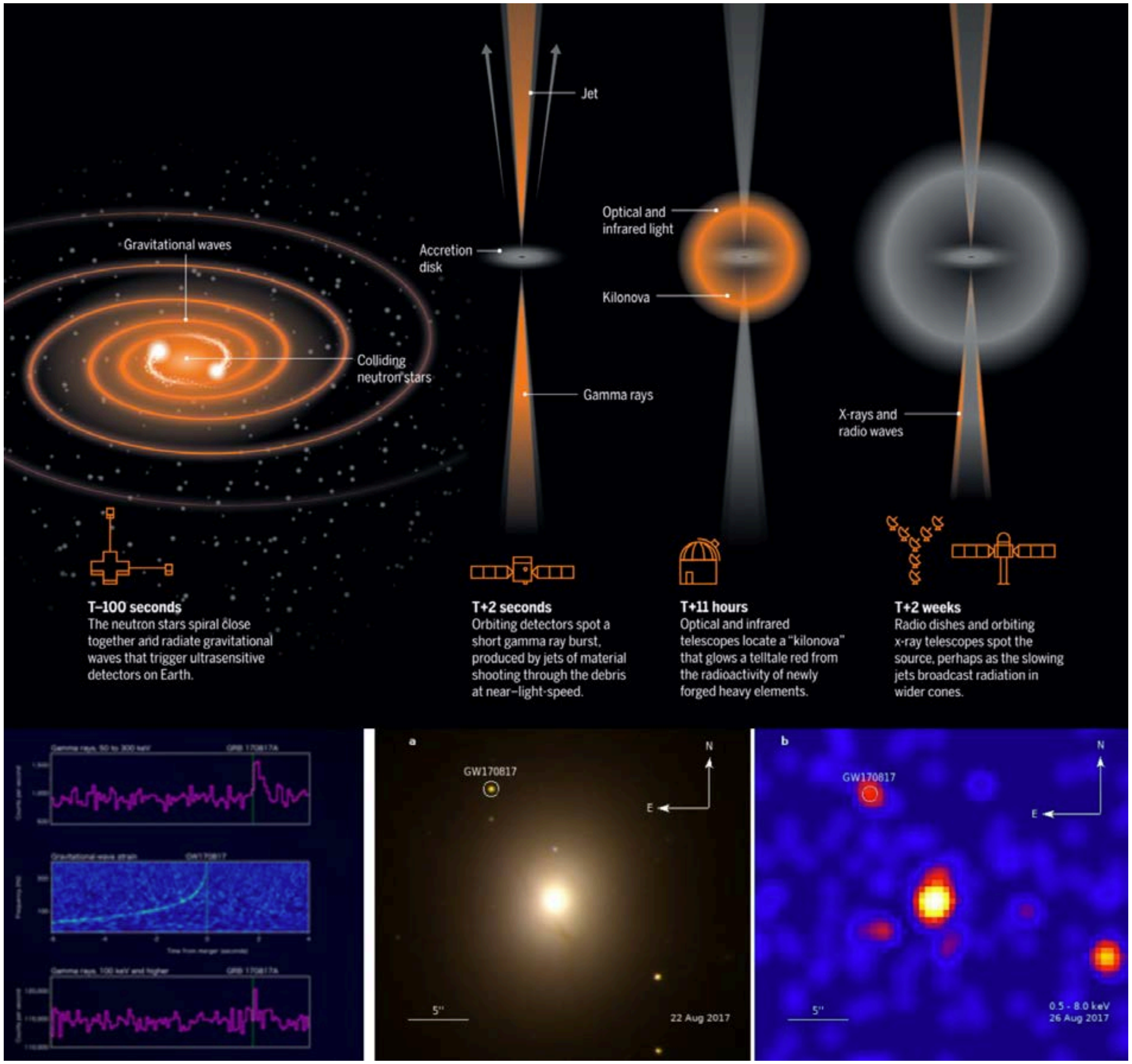
GW170817

~ 40 Mpc (NGC 4993)



Gamma rays
(Fermi+Integral)

GW
(Adv. LIGO+Virgo)

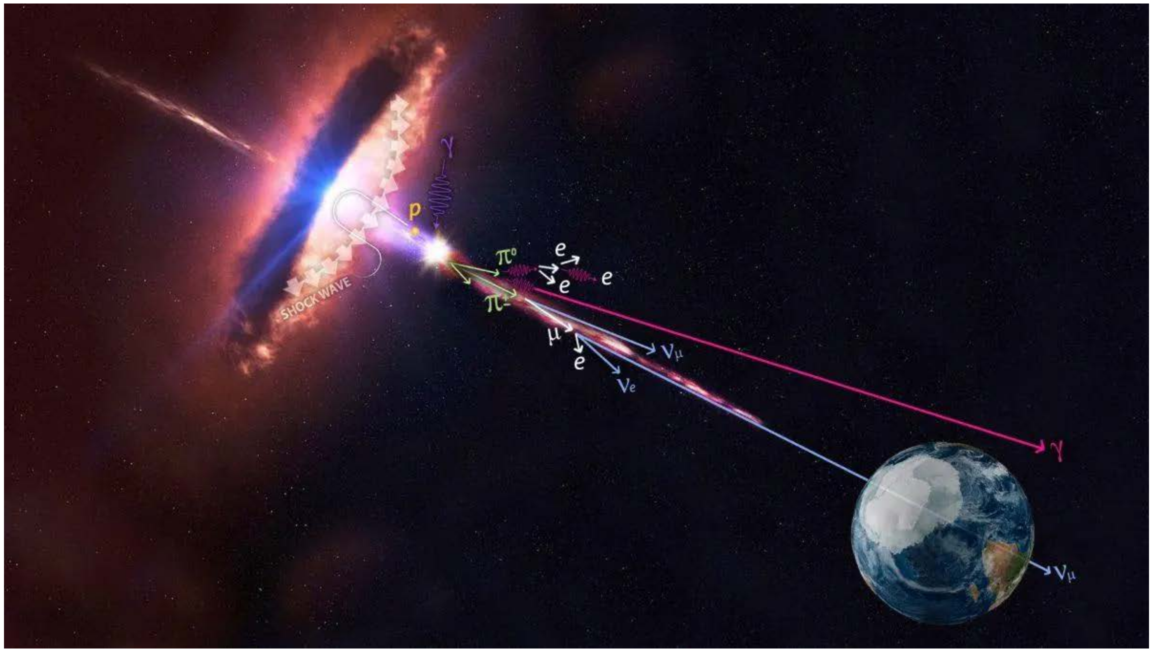
Optical
(HST)

X-rays
(Chandra)

No neutrinos :(

Image credits: https://ahead.iaps.inaf.it
Abbott et al. 2017, ApJ 848, L13
Troja, Piro, van Earthen et al., 2017, Nature, 551, 71

High-energy (HE) neutrinos



$$p + p \rightarrow N\pi + X \qquad\qquad p + \gamma \rightarrow N\pi + X$$

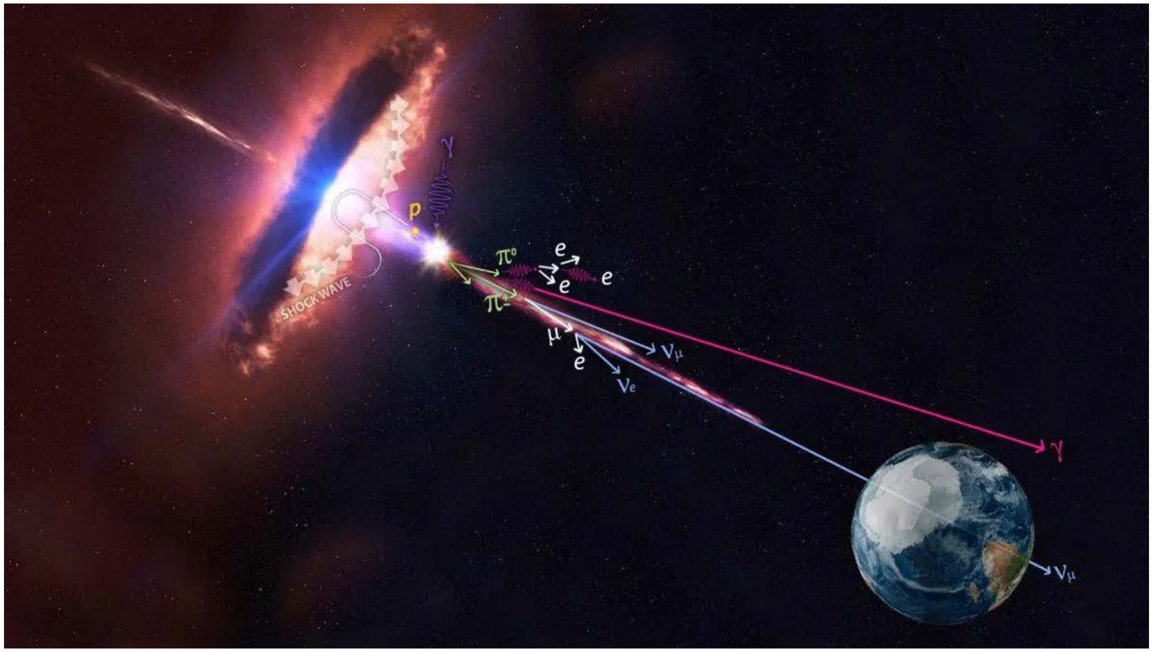
$$\downarrow$$

$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e} (\text{or } \bar{\nu}_{e}) + e^{\pm}$$

$$\downarrow$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

High-energy (HE) neutrinos



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b) Rate of acceleration > Rate of energy loss

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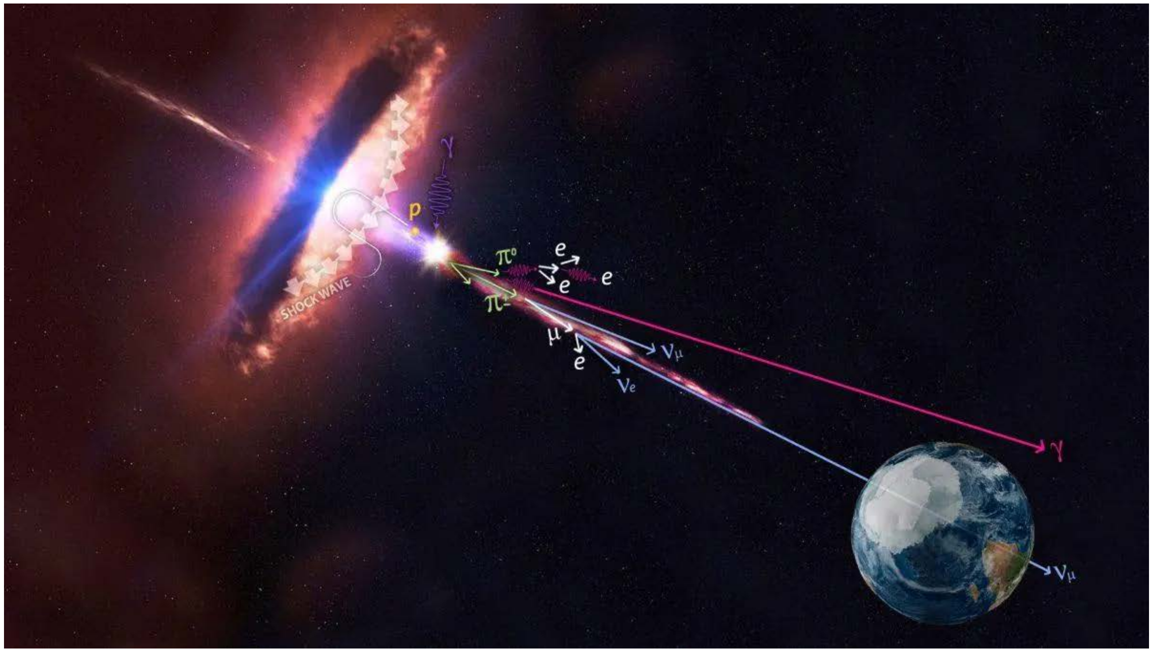

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$$\pi^0 \rightarrow \gamma + \gamma$$

Proton energy loss due to p-p interactions

$$t_{pp}^{-1} = n_N \kappa_{pp} \sigma_{pp} c$$

Nucleon density

p-p cross-section

Proton inelasticity

Proton energy

p-γ cross-section

$$t_{p\gamma}^{-1}(\epsilon_p) = \frac{c}{2\gamma_p^2} \int_{\bar{\epsilon}_{\rm th}}^{\infty} d\bar{\epsilon} \kappa_{p\gamma}(\bar{\epsilon}) \sigma_{p\gamma}(\bar{\epsilon}) \bar{\epsilon} \int_{\bar{\epsilon}/2\gamma_p}^{\infty} d\epsilon \epsilon^{-2} n_\epsilon$$

Photon energy in proton rest frame

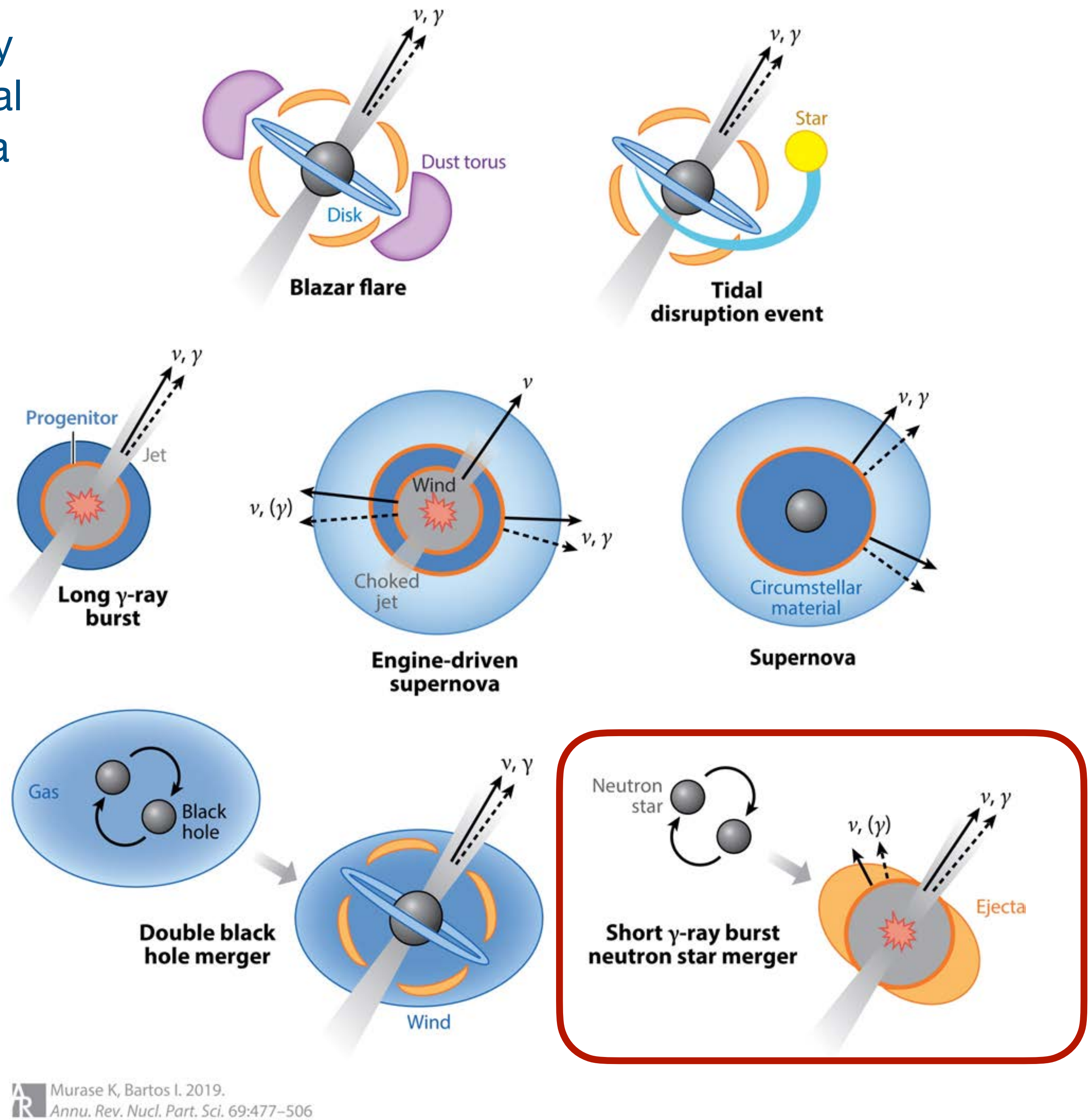
Proton energy loss due to p-γ interactions

Conditions for HE-ν production:

a) Acceleration of ions (p and nuclei) to sufficiently high energies - Shocks, magnetic reconnection, stochastic acceleration aided by turbulence
b) Rate of acceleration > Rate of energy loss
c) Significant density on target media - matter and radiation
d) (a) and (b) -> production of charged mesons - pions that decay into neutrinos, charged leptons, and gamma-rays

The high-energy multi-messenger transients

High-energy astrophysical phenomena



BNS mergers: particle accelerators and multi-messenger zoo

BNS

S. Gezari, Annu. Rev. Astron. Astrophys. 2021. 59:21–58
Kimura+, PRD (2018), Fang & Metzger (2017)
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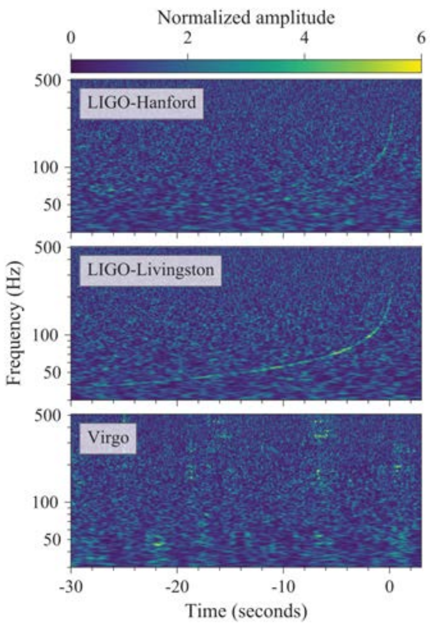

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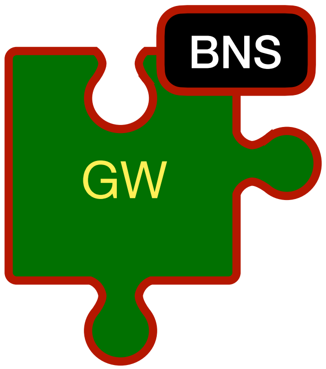

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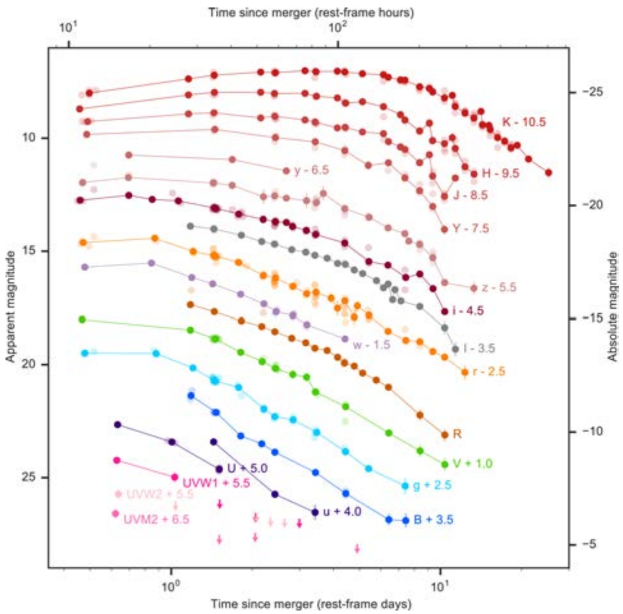
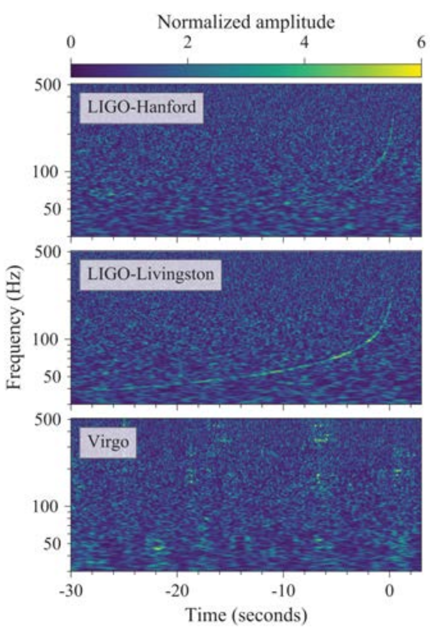
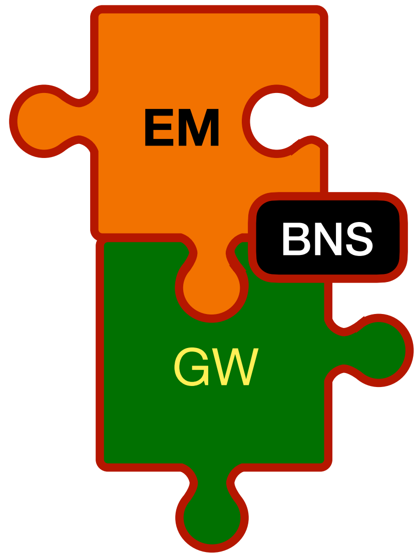




Observed

Kilonova emission
Afterglow emission
Short GRB



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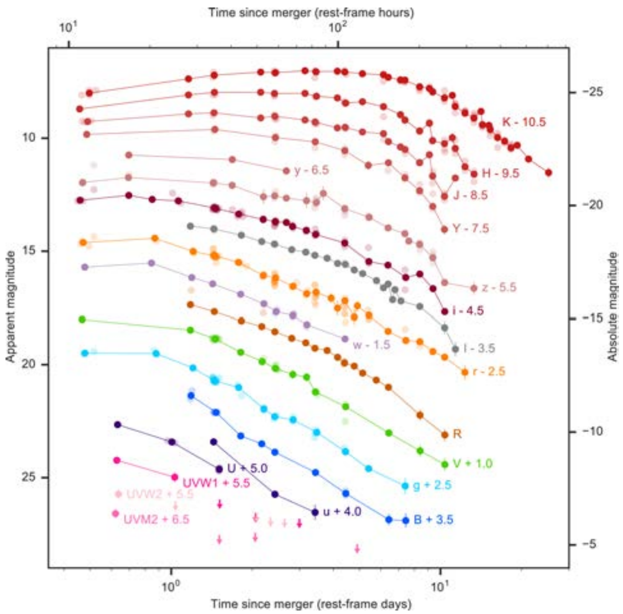

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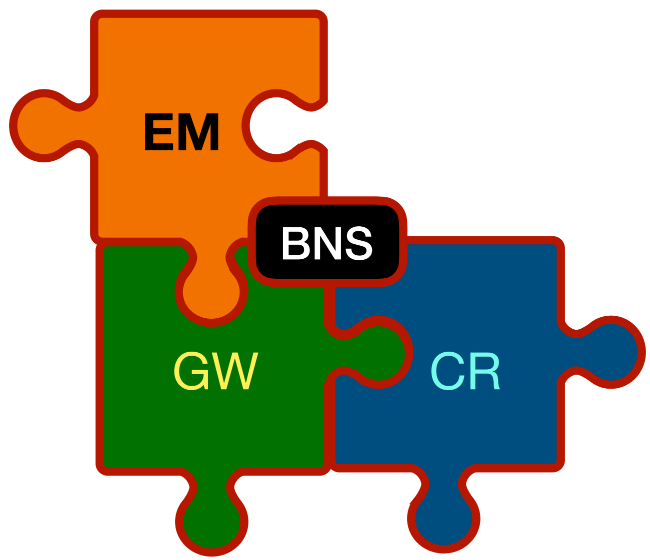

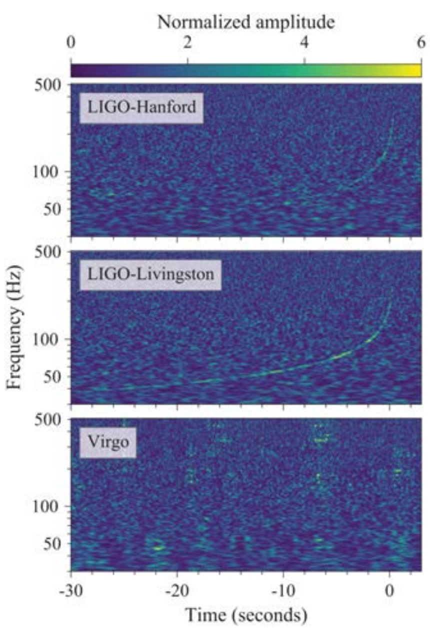

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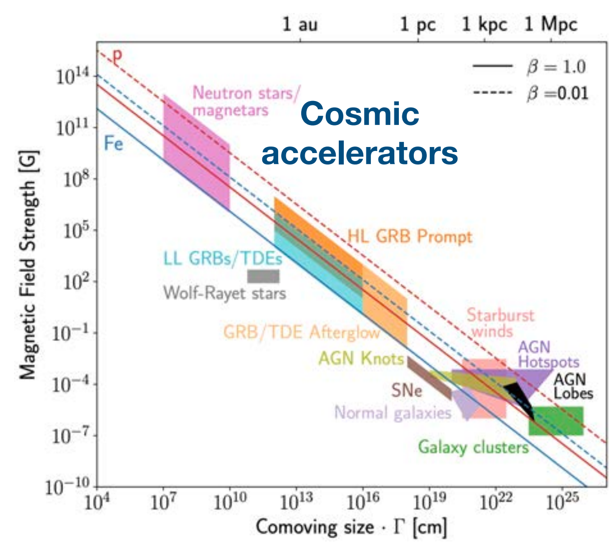

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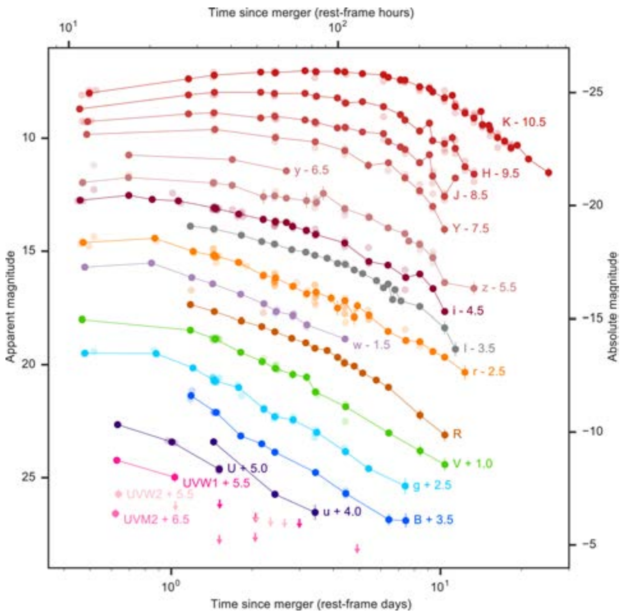

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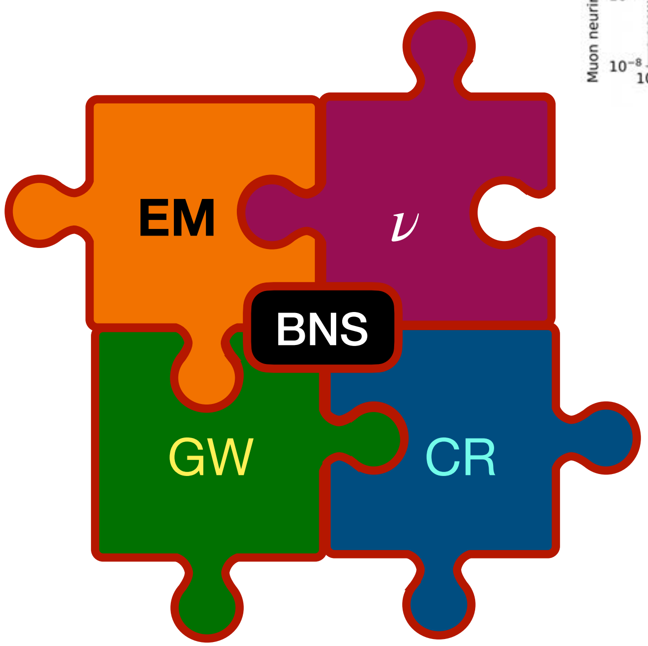

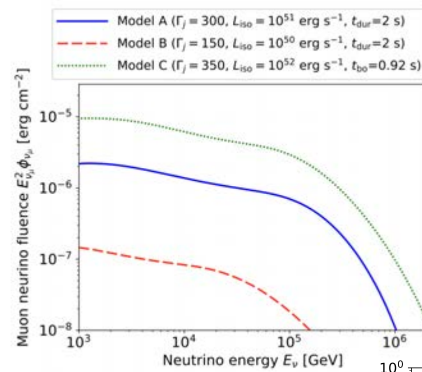

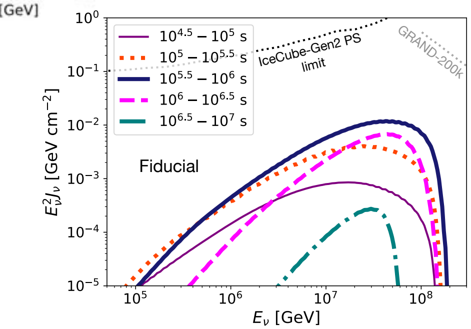

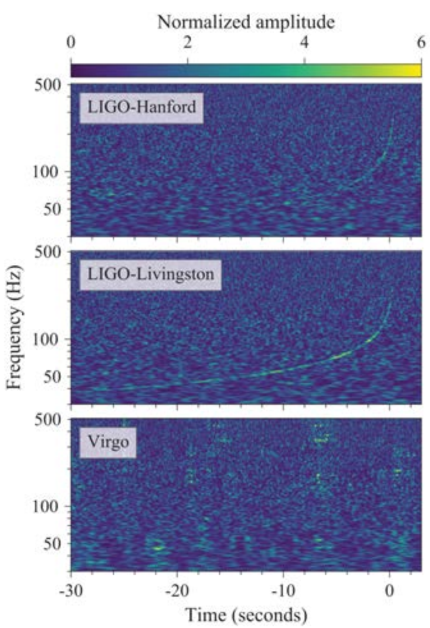

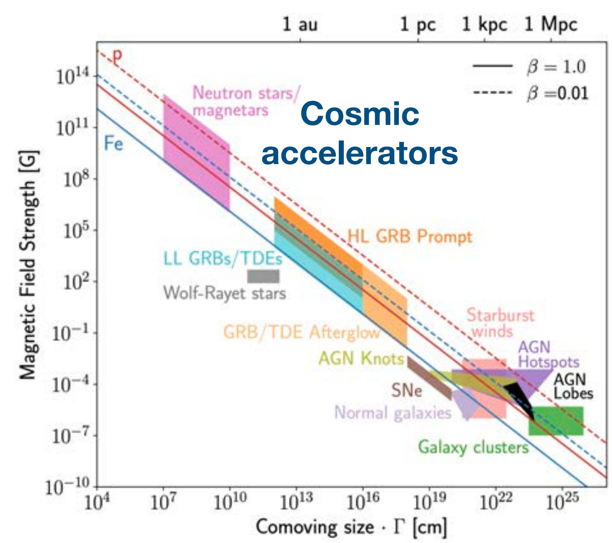

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Batista et al., Front. Astron. Space Sci. 6 (2019), 23
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Outline

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MM, S.S. Kimura
Submitted to ApJ *(arXiv: 2407.04767)*

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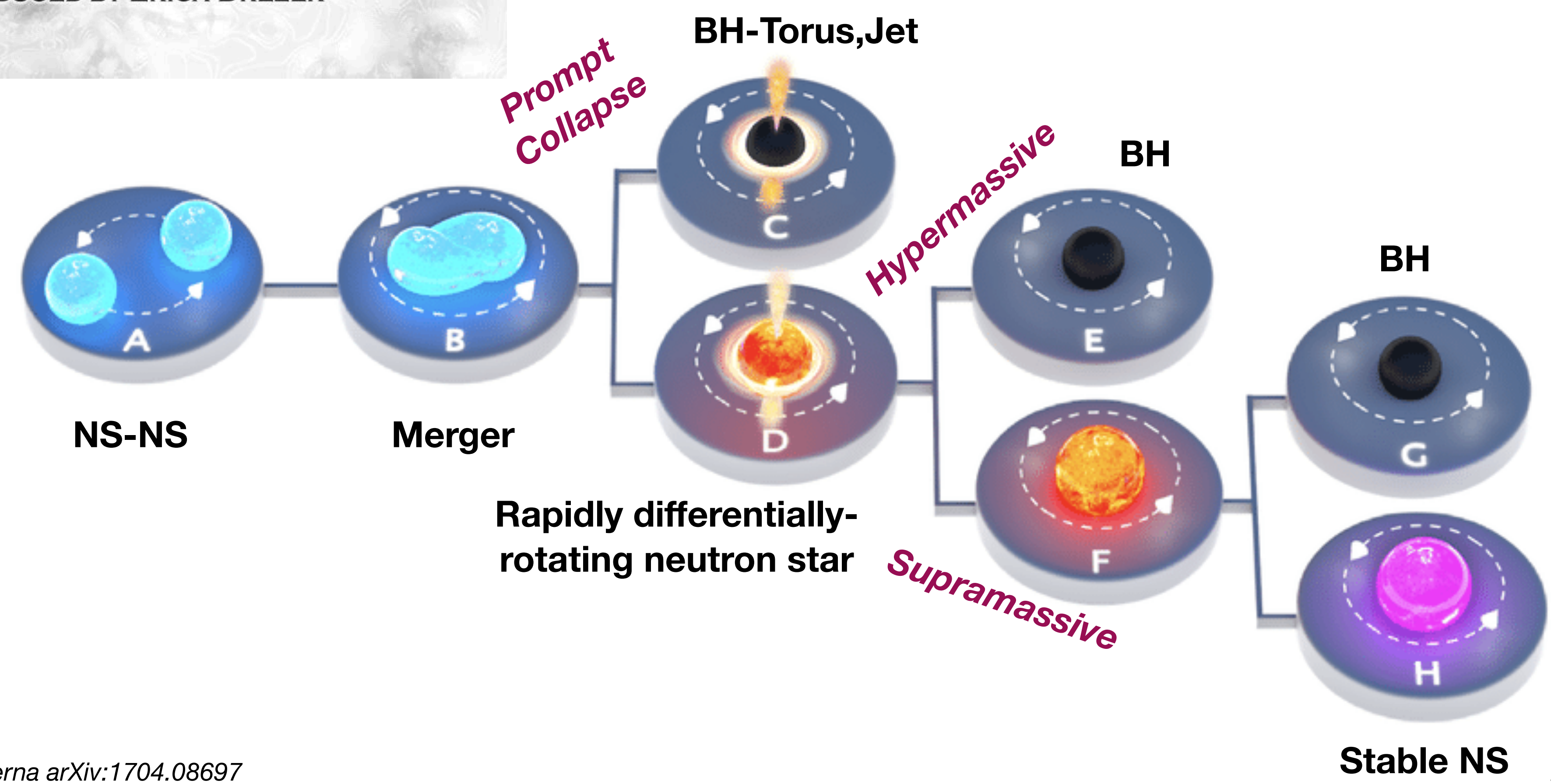
Fate of NS-NS mergers

Fate decided by EOS, Mass, Spin, ….



Piro, Giacomazzo, Perna arXiv:1704.08697

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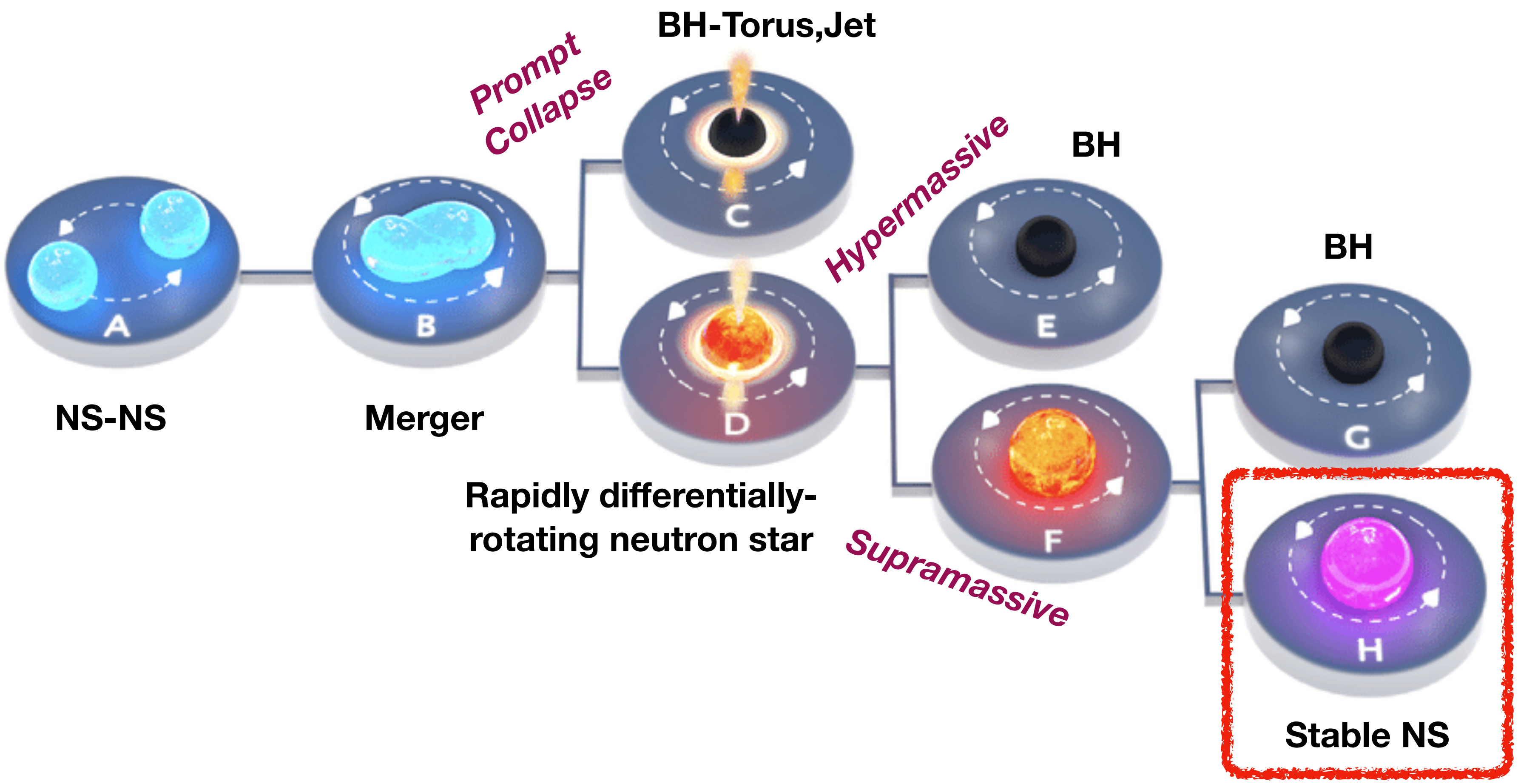
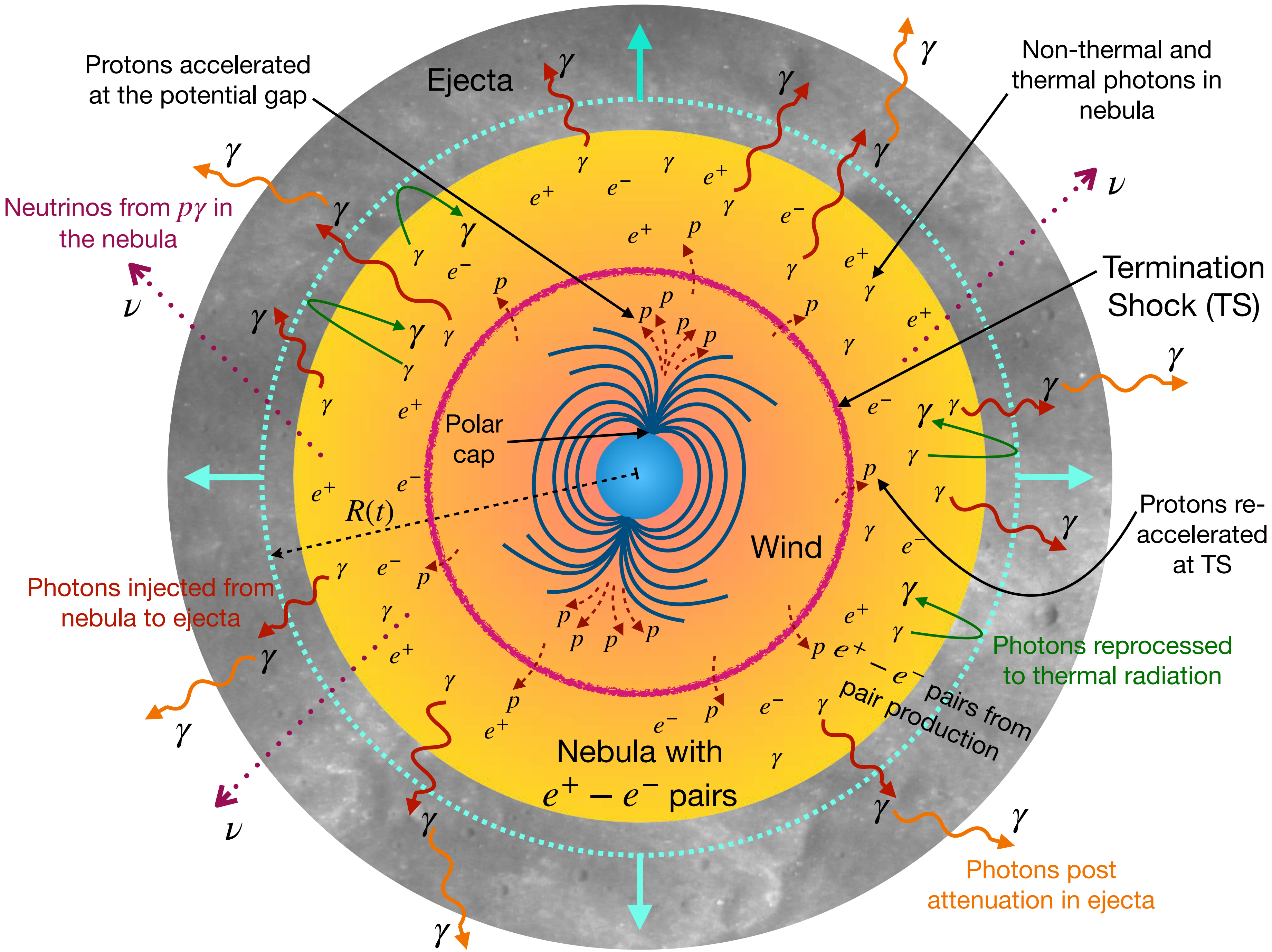


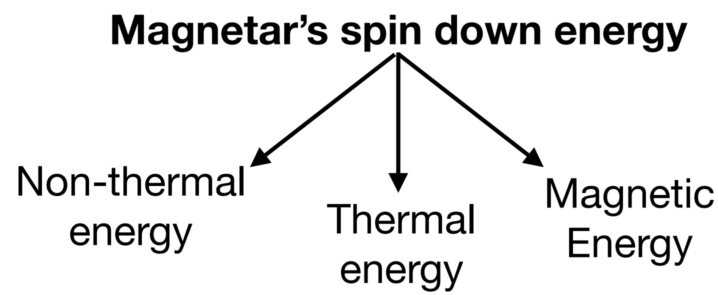
Piro, Giacomazzo, Perna arXiv:1704.08697

Model



Protons accelerated at the potential gap
Ejecta
Non-thermal and thermal photons in nebula
Neutrinos from $p\gamma$ in the nebula
Termination Shock (TS)
Polar cap
$R(t)$
Wind
Protons re-accelerated at TS
Photons injected from nebula to ejecta
Photons reprocessed to thermal radiation
$e^+ - e^-$ pairs from pair production
Nebula with $e^+ - e^-$ pairs
Photons post attenuation in ejecta

Model: Evolution of thermal, non-thermal, and magnetic energies



Metzger, B. D., & Piro, A. L. 2014, MNRAS, 439, 3916
Fang, K. & Metzger, B.D. 2017, ApJ 849, 153

Model: Evolution of thermal, non-thermal, and magnetic energies

Magnetar's spin down energy

Non-thermal energy

Thermal energy

Magnetic Energy

Spin-down luminosity

Photon diffusion from nebula to ejecta

Non-thermal energy

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - \frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}}$$

PdV work by the nebula

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Model: Evolution of thermal, non-thermal, and magnetic energies

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Non-thermal energy

Thermal energy

Magnetic Energy

See talks by Y. Z. Qian and J. Lattimer

Non-thermal energy

$$\frac{dE_{\mathrm{nth}}}{dt} = L_{\mathrm{sd}} - \frac{E_{\mathrm{nth}}}{R}\frac{dR}{dt} - \frac{E_{\mathrm{nth}}}{t_{\mathrm{diff}}^{\mathrm{neb}}}$$

Fraction of non-thermal photons that escape

Heating rate due to decay of r-process elements in the ejecta

Thermal energy

$$\frac{dE_{\mathrm{th}}}{dt} = \left(1 - \mathscr{A}\right)\frac{E_{\mathrm{nth}}}{t_{\mathrm{diff}}^{\mathrm{neb}}} - \frac{E_{\mathrm{th}}}{R}\frac{dR}{dt} - \frac{E_{\mathrm{th}}}{t_{\mathrm{diff}}^{\mathrm{ej}}} + Q_{\mathrm{rp}}^{\mathrm{heat}}$$

Photon diffusion through ejecta

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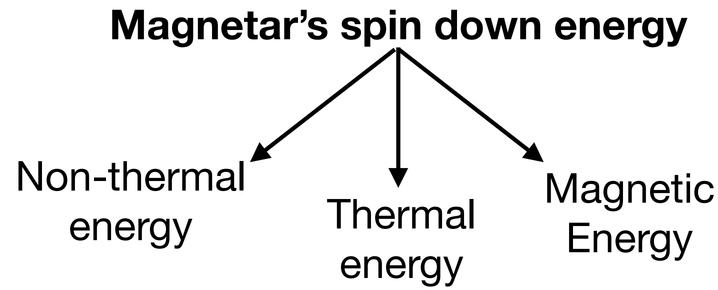

Non-thermal energy

$$\frac{dE_\mathrm{nth}}{dt} = L_\mathrm{sd} - \frac{E_\mathrm{nth}}{R}\frac{dR}{dt} - \frac{E_\mathrm{nth}}{t_\mathrm{diff}^\mathrm{neb}}$$

Thermal energy

$$\frac{dE_\mathrm{th}}{dt} = \left(1 - \mathscr{A}\right)\frac{E_\mathrm{nth}}{t_\mathrm{diff}^\mathrm{neb}} - \frac{E_\mathrm{th}}{R}\frac{dR}{dt} - \frac{E_\mathrm{th}}{t_\mathrm{diff}^\mathrm{ej}} + Q_\mathrm{rp}^\mathrm{heat}$$

Magnetic field strength amplification parameter

$\epsilon_\mathrm{B} \sim 10^{-4}$

Magnetic energy

$$\frac{dE_B}{dt} = \varepsilon_B L_\mathrm{sd} - \frac{E_B}{R}\frac{dR}{dt}$$

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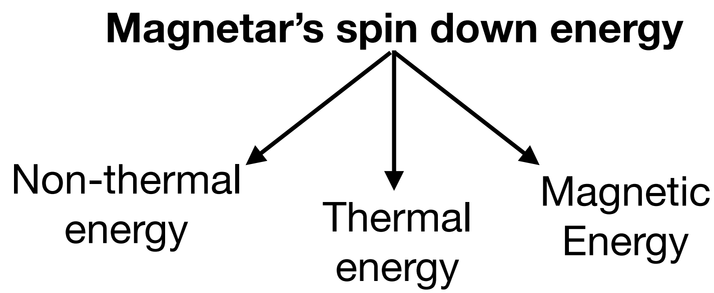

Non-thermal energy

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - \frac{E_{\rm nth}}{t^{\rm neb}_{\rm diff}}$$

Thermal energy

$$\frac{dE_{\rm th}}{dt} = \left(1 - \mathscr{A}\right)\frac{E_{\rm nth}}{t^{\rm neb}_{\rm diff}} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t^{\rm ej}_{\rm diff}} + Q^{\rm heat}_{\rm rp}$$

Magnetic energy

$$\frac{dE_B}{dt} = \varepsilon_B L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

Work done on the ejecta

$$\frac{d}{dt}E_{\rm kin} = \frac{d}{dt}\left[M_{\rm ej}c^2(\Gamma_{\rm ej} - 1)\right] = \frac{v}{R}\left(E_{\rm nth} + E_{\rm th} + E_B\right)$$

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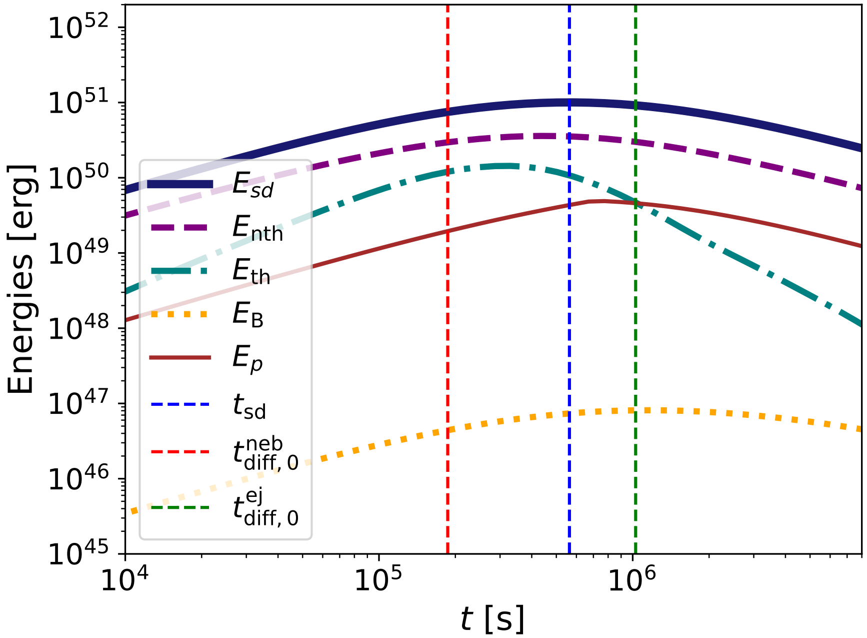
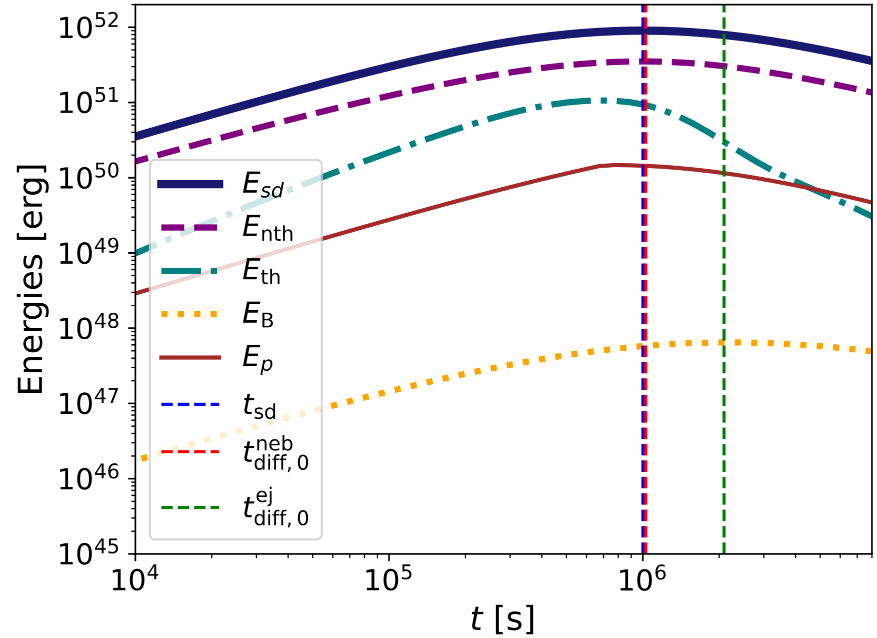
Fang, K. & Metzger, B.D. 2017, ApJ 849, 153

Model: Evolution of thermal, non-thermal, and magnetic energies



Fiducial:

$B_d = 10^{14}$ G, $P_i = 0.003$ s, $M_{ej} = 0.03\ M_\odot$, $\beta_{ej} = 0.03$



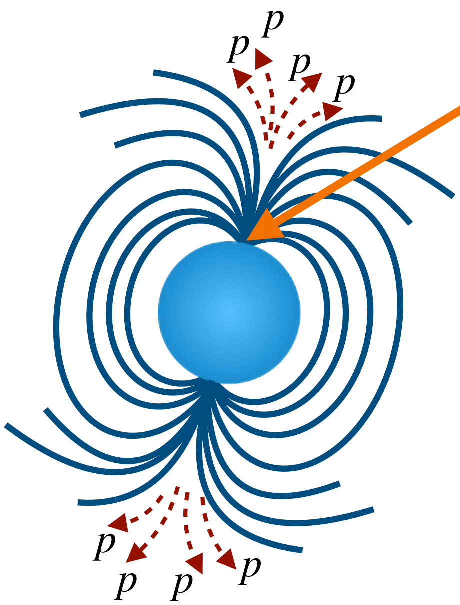
Optimistic:

$B_d = 2.5 \times 10^{13}$ G, $P_i = 0.001$ s, $M_{ej} = 0.1\ M_\odot$, $\beta_{ej} = 0.1$

$$L_{sd} = \alpha \frac{\mu^2 \Omega^4}{c^3} = 7.13 \times 10^{45}\ \mathrm{erg\ s^{-1}} \left(\frac{B_d}{10^{14}\ \mathrm{G}}\right)^2 \left(\frac{P_i}{0.003\ \mathrm{s}}\right)^{-4} \left(1 + \frac{t}{t_{sd}}\right)^{-2}$$

$$t_{sd} = 5.63 \times 10^5\ \mathrm{s} \left(\frac{B_d}{10^{14}\ \mathrm{G}}\right)^{-2} \left(\frac{P_i}{0.003\ \mathrm{s}}\right)^2$$

Cosmic ray (CR) proton acceleration: injection spectra



CR protons extracted from the magnetar surface: Goldreich-Julian (GJ) number density of charges

$$n_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi Zec}$$

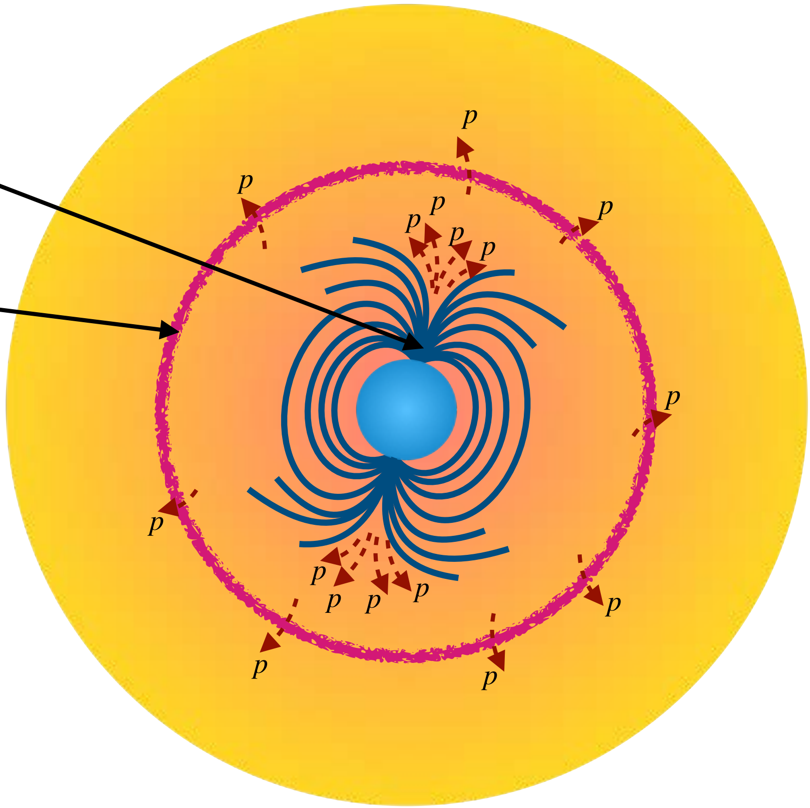
$$\dot{N}_p = n_{\rm GJ} 2 A_{\rm pc} c = \frac{4\pi^2}{Ze}\frac{R_*^3}{c}\frac{B_0}{P^2}$$

Acceleration sites:

Polar cap

+

Termination shock (TS)

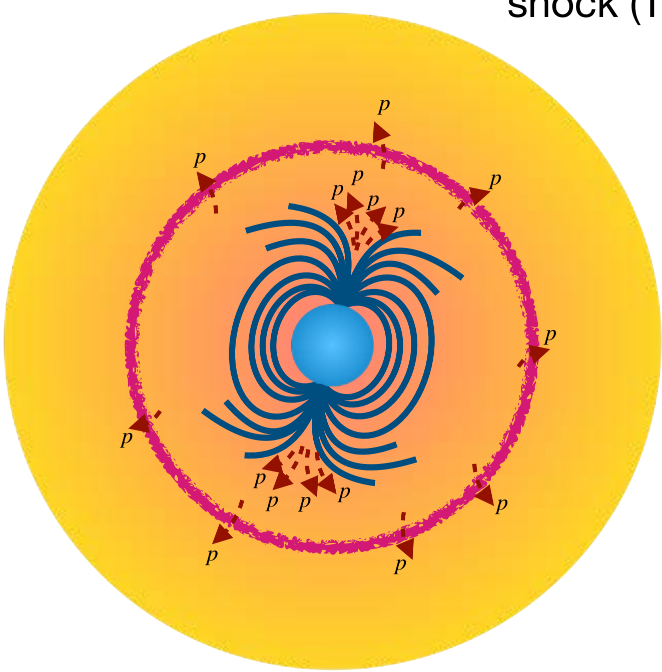


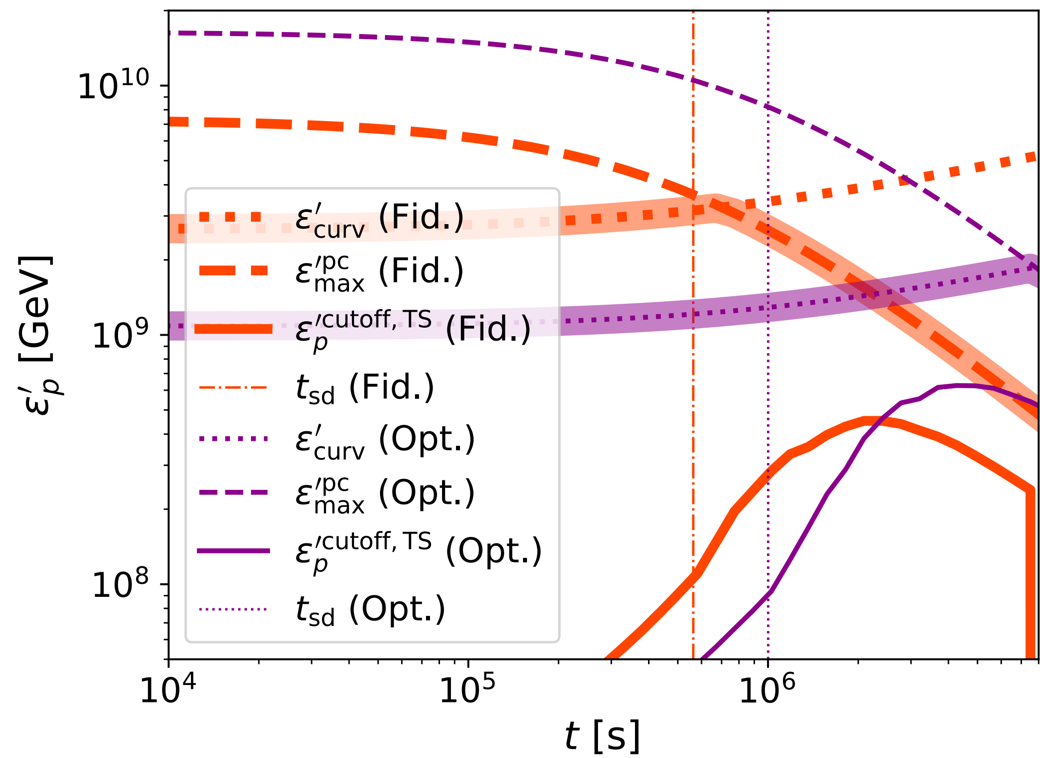
Cosmic ray (CR) proton acceleration: injection spectra

$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\mathrm{cutoff,pc}}\right)$$

$$\varepsilon_p^{\prime\mathrm{cutoff}} = \max\left[\varepsilon_p^{\prime\mathrm{cutoff,pc}}, \varepsilon_p^{\prime\mathrm{cutoff,TS}}\right]$$

Acceleration sites: Polar cap + Termination shock (TS)





Cosmic ray (CR) proton acceleration: injection spectra

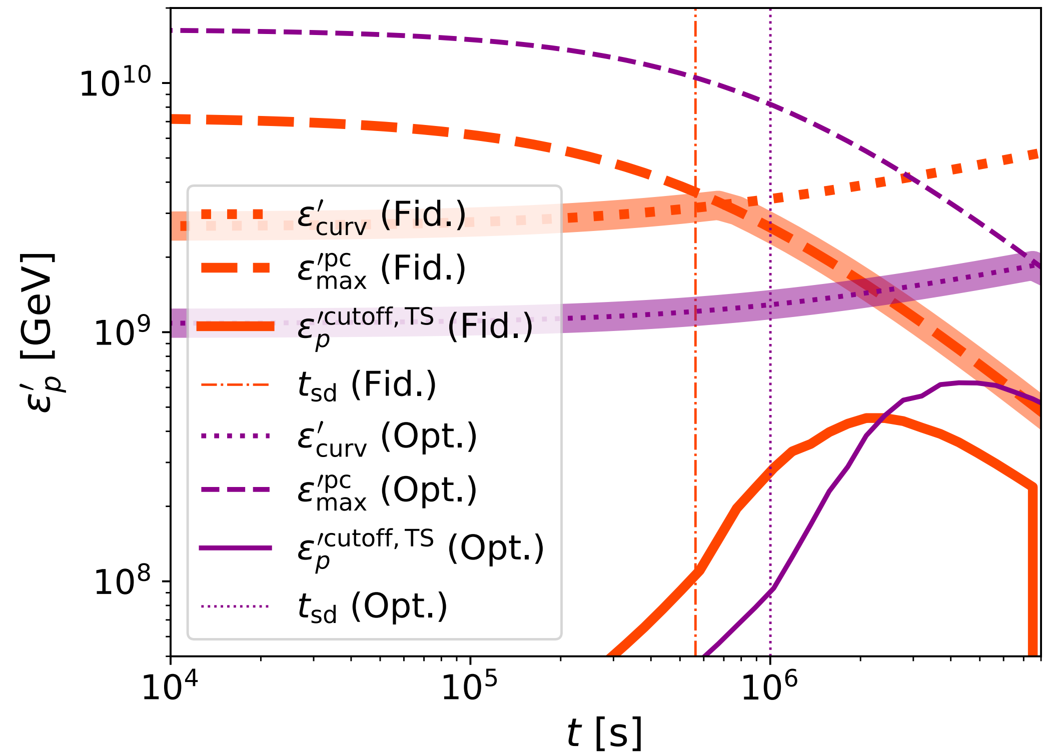
$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\mathrm{cutoff,pc}}\right)$$

$$\varepsilon_p^{\prime\mathrm{cutoff}} = \max\left[\varepsilon_p^{\prime\mathrm{cutoff,pc}}, \varepsilon_p^{\prime\mathrm{cutoff,TS}}\right]$$

$$\varepsilon_p^{\prime\mathrm{cutoff,pc}} = \min\left[\varepsilon_{\mathrm{max}}^{\prime\mathrm{pc}}, \varepsilon'_{\mathrm{curv}}\right]$$

$$\varepsilon_{\mathrm{max}}^{\prime\mathrm{pc}} = 4\eta_{\mathrm{gap}}(Ze)B_d\left(\frac{\pi R_*}{cP}\right)^2 R_*$$

$$\varepsilon'_{\mathrm{curv}} = \gamma_p m_p c^2 = \left[\frac{3m_p^4 c^8 B_d R_{\mathrm{curv}}^2}{2e}\right]^{1/4}$$



Cosmic ray (CR) proton acceleration: injection spectra

$$\frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} = \dot{N}_p^{\rm norm} Q_p^{\rm inj}(\varepsilon'_p) = \dot{N}_p^{\rm norm}\,\delta\left(\varepsilon'_p - \varepsilon_p^{\prime\rm cutoff,pc}\right)$$

$$\varepsilon_p^{\prime\rm cutoff} = \max\left[\varepsilon_p^{\prime\rm cutoff,pc}, \varepsilon_p^{\prime\rm cutoff,TS}\right]$$

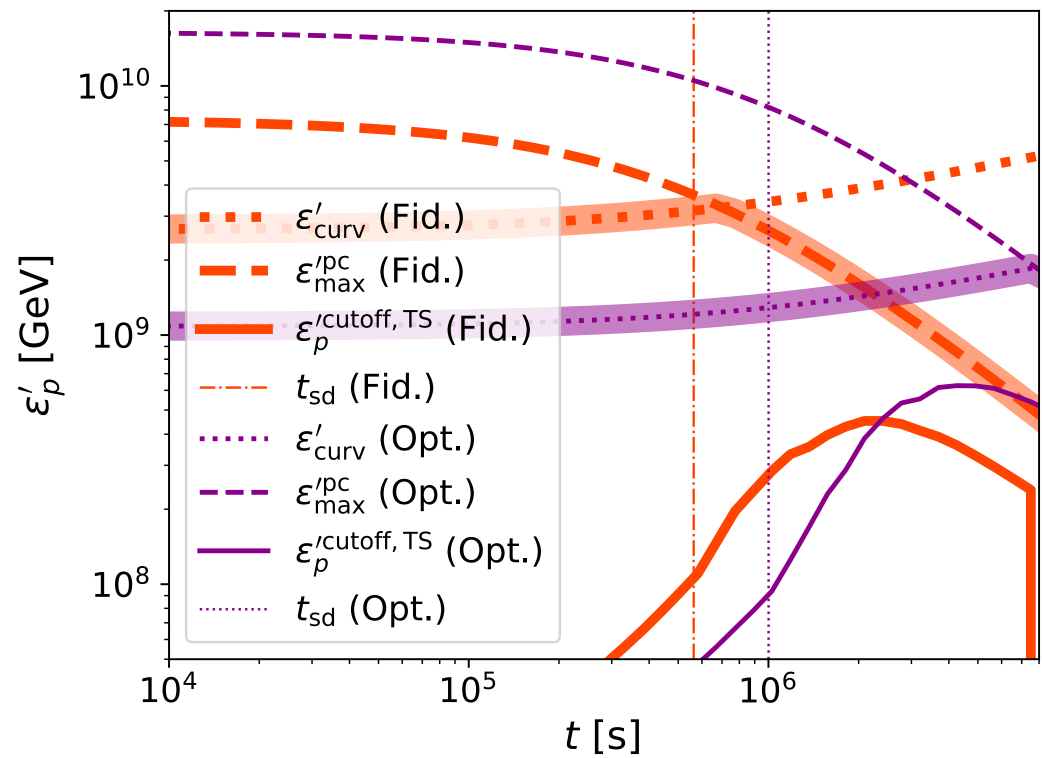
$$t_{\rm acc}^{\prime -1} = t_{\rm loss}^{\prime -1}$$

$$t'_{\rm acc} = \eta_{\rm acc}\varepsilon'_p/\left(ZecB'_{\rm neb}\right)$$

$$t_{\rm loss}^{\prime -1} = t_{\rm esc}^{\prime -1} + t_{\rm cool}^{\prime -1}$$

$$t'_{\rm esc} = \max\left[R(t)^2/D_c(\varepsilon'_p), R(t)/c\right]$$

$$t_{\rm cool}^{\prime -1} = t_{pp}^{\prime -1} + t_{p\gamma}^{\prime -1} + t_{\rm sync}^{\prime -1} + t_{\rm BH}^{\prime -1} + t_{\rm dyn}^{\prime -1}$$



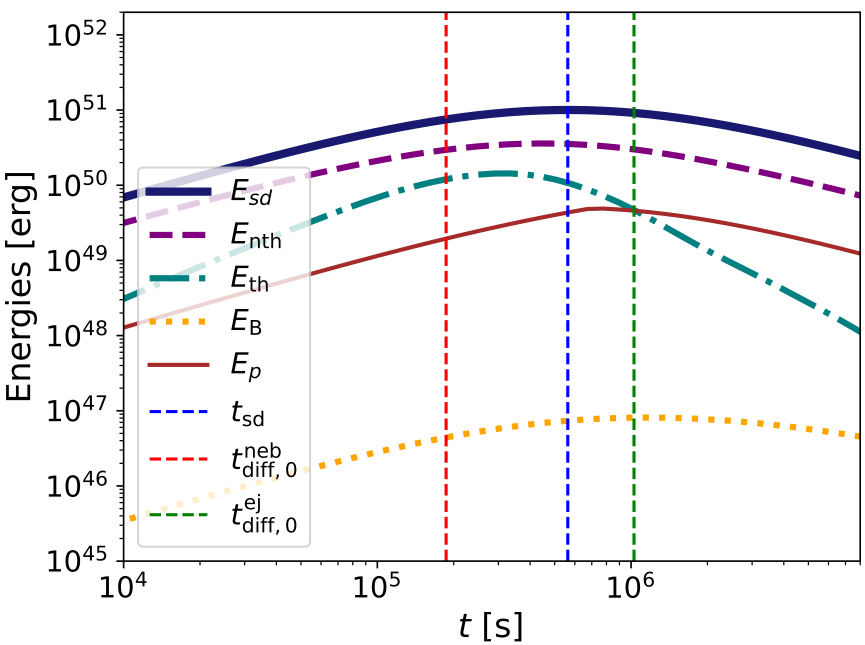
Cosmic ray (CR) proton acceleration

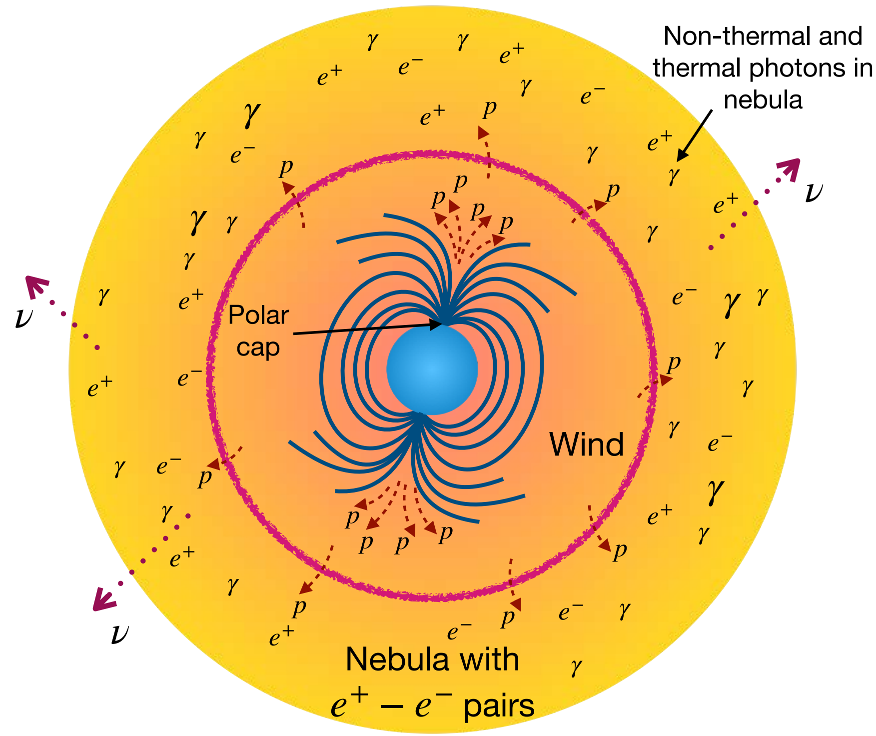
Compute steady state CE spectrum
by solving the transport equation

$$\frac{d}{d\varepsilon'_p}\left(-\frac{\varepsilon'_p}{t'_{\rm cool}}\frac{dN_p}{d\varepsilon'_p}\right) = \frac{d\dot{N}_{p,{\rm inj}}}{d\varepsilon'_p} - \frac{1}{t'_{\rm esc}}\frac{dN_p}{d\varepsilon'_p}$$

$$\frac{dN_p}{d\varepsilon'_p} = \frac{t'_{\rm cool}}{\varepsilon'_p}\int_{\varepsilon'_p}^{\infty} d\tilde{\varepsilon}_p \dot{N}_{p,{\rm inj}}(\tilde{\varepsilon}_p)\, \exp\left(-\mathscr{G}(\varepsilon'_p, \tilde{\varepsilon}_p)\right)$$

$$\mathscr{G}(\varepsilon_1, \varepsilon_2) = \int_{\varepsilon_1}^{\varepsilon_2} \frac{t'_{\rm cool}}{t'_{\rm esc}}\frac{d\tilde{\varepsilon}_p}{\tilde{\varepsilon}_p}$$





$$E_p = \dot{N}_{p,{\rm inj}}\varepsilon_p^{\prime{\rm cutoff,pc}} t$$

Cosmic ray (CR) proton acceleration

Compute steady state CE spectrum
by solving the transport equation

↓

This along with the photon field spectrum
gives the neutrino fluences

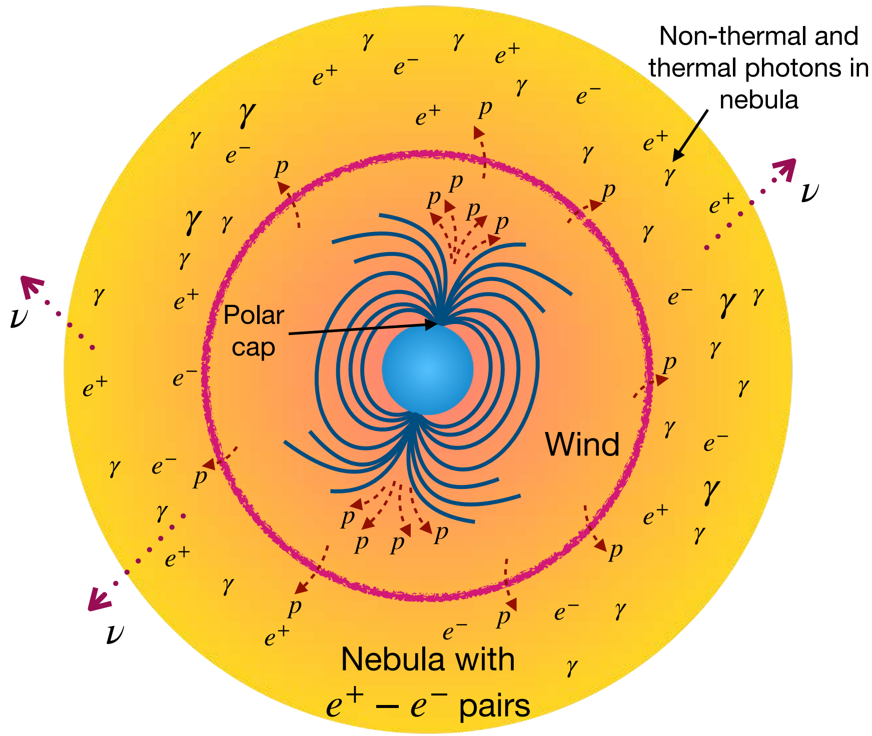
$e^+ - e^-$ spectra

$$\frac{dN}{d\gamma_e} \sim \begin{cases} \gamma_e^{-1.5}, \ \gamma_e \leq \gamma_{e,\mathrm{br}} \\ \gamma_e^{-2.5}, \ \gamma_e > \gamma_{e,\mathrm{br}}, \end{cases}$$

Electron break Lorentz factor

For galactic PWNe:
$\gamma_{e,\mathrm{br}} \sim 10^5 - 10^6$

Pair injection at upstream of TS ->
decreased wind velocity and hence
lower $\gamma_{e,\mathrm{br}}$. We choose $\gamma_{e,\mathrm{br}} = 10^3$



Cosmic ray (CR) proton acceleration

Compute steady state CE spectrum by solving the transport equation

This along with the photon field spectrum gives the neutrino fluences

$e^+ - e^-$ spectra

$$\frac{dN}{d\gamma_e} \sim \begin{cases} \gamma_e^{-1.5}, \ \gamma_e \leq \gamma_{e,\mathrm{br}} \\ \gamma_e^{-2.5}, \ \gamma_e > \gamma_{e,\mathrm{br}}\,, \end{cases}$$

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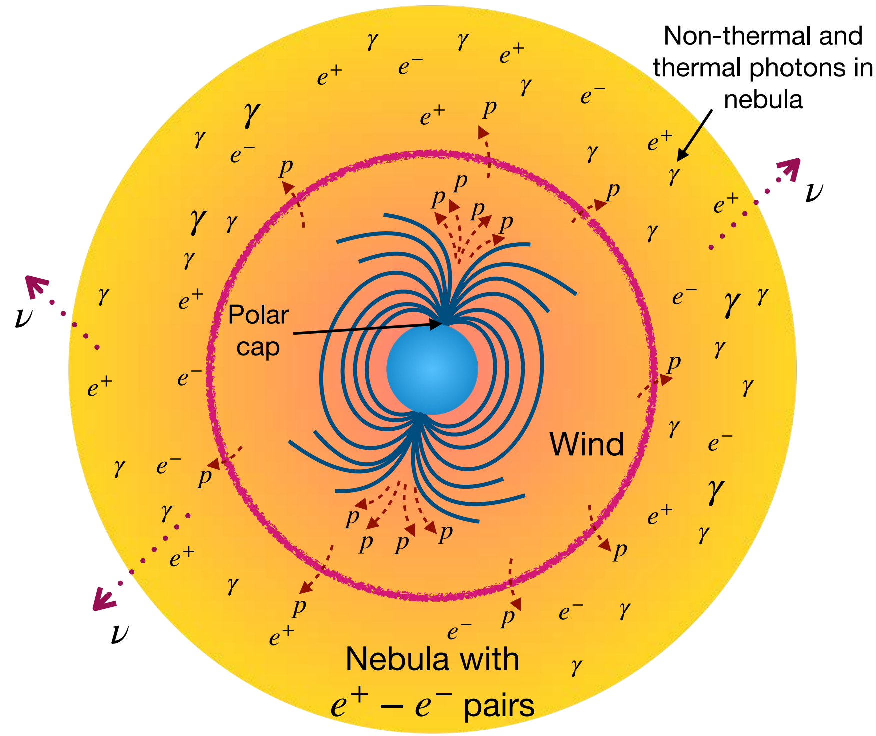
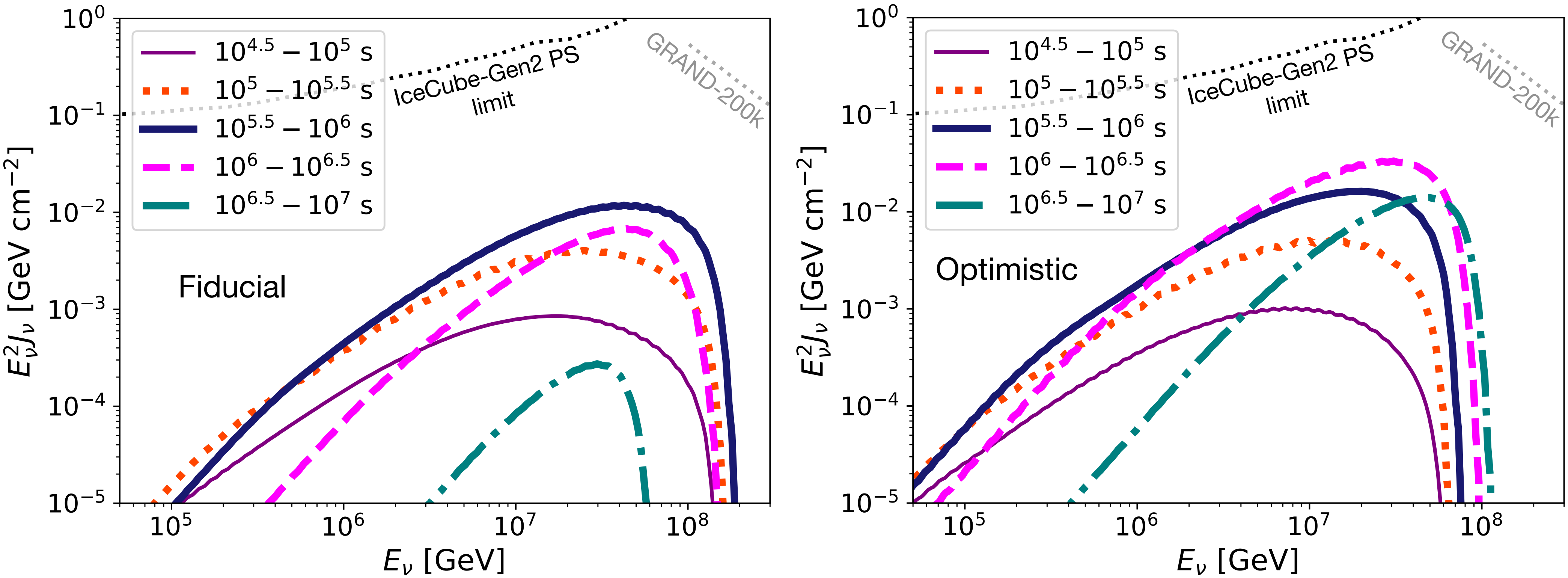
Transport Equation

Synchrotron, inverse Compton, Breit-Wheeler processes

EM cascades



The money plot: Neutrino fluences (takeaway)



$d_L = 40$ Mpc

Peak fluence: $\sim 1 \times 10^{-2}$ GeV cm^{-2}

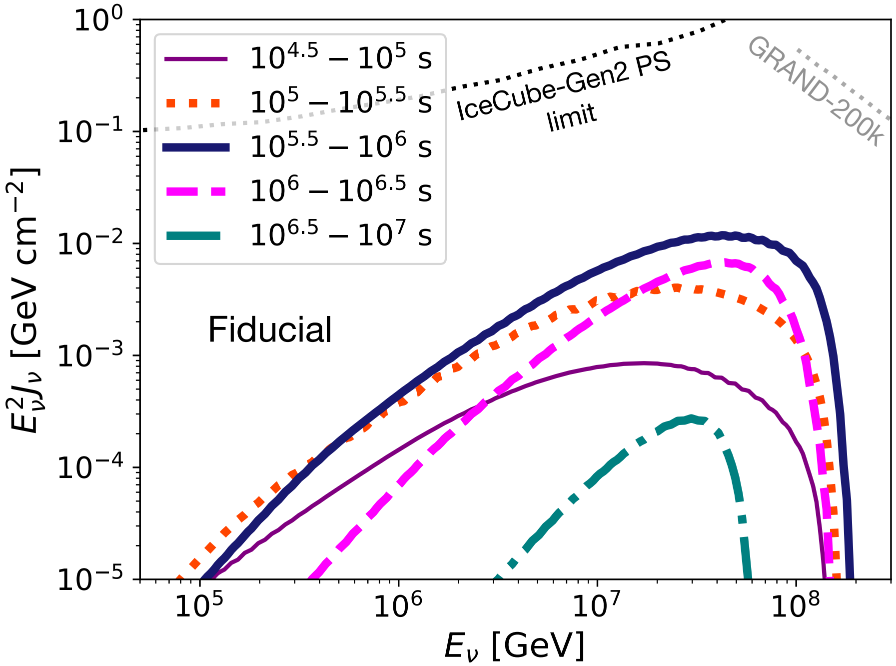
Peak fluence: $\sim 4 \times 10^{-2}$ GeV cm^{-2}

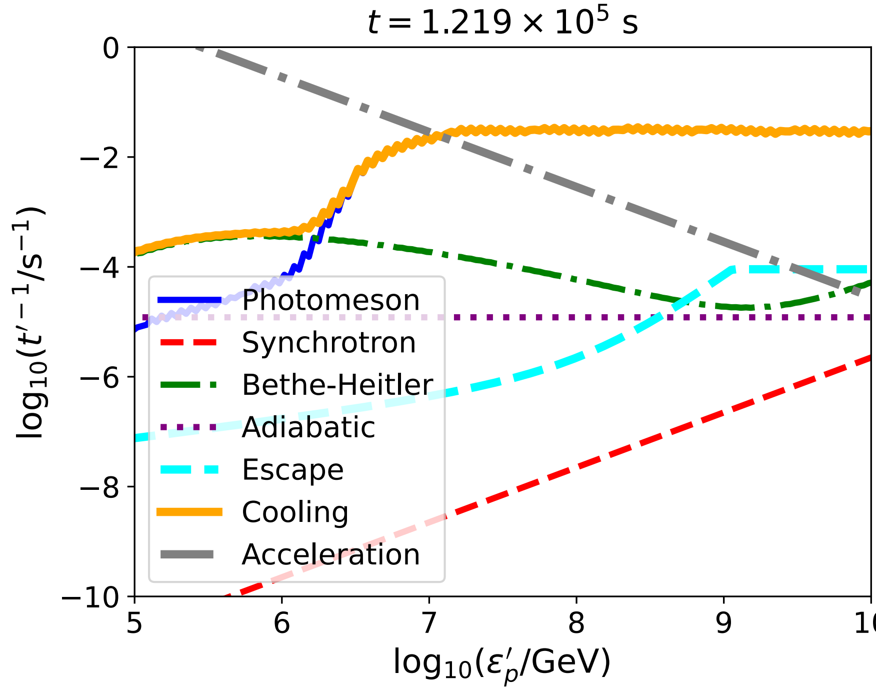
Neutrino energy: $\sim 10^7$ GeV $- 10^8$ GeV

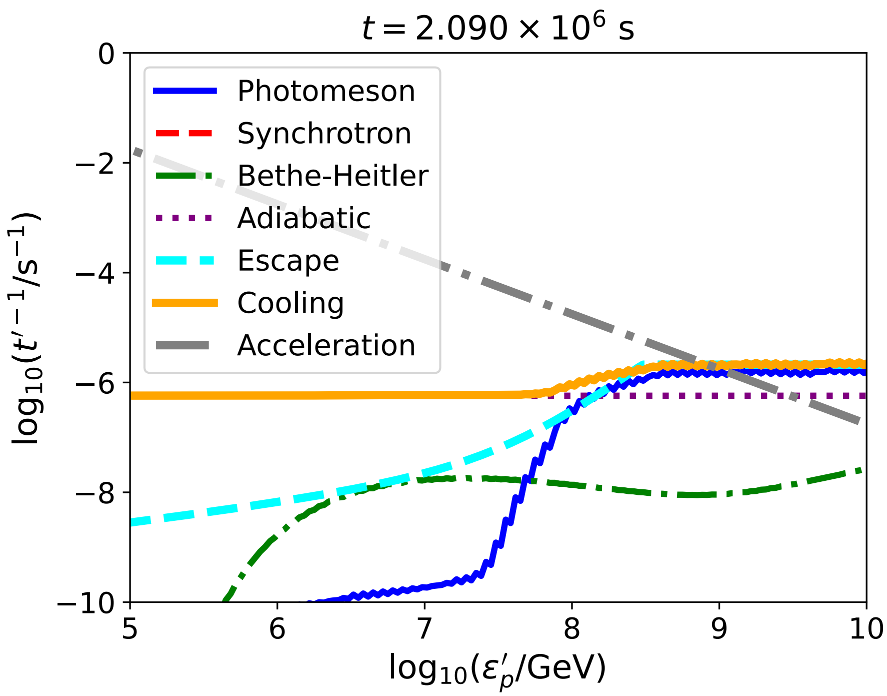
Peak fluence $\sim 10^{5.5}$ s $- 10^6$ s post-merger

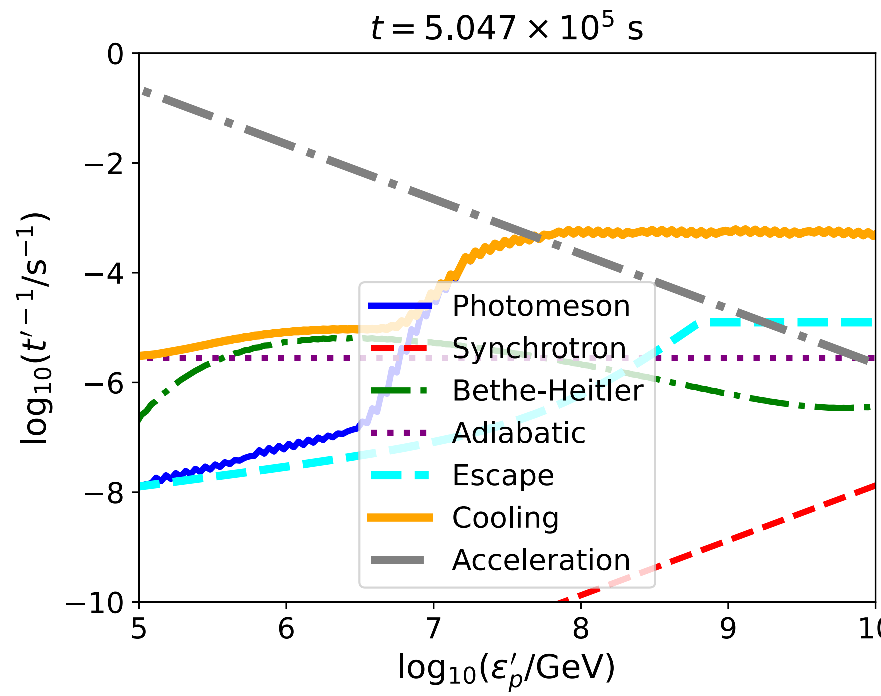
Peak fluence $\sim 10^6$ s $- 10^{6.5}$ s post-merger

Neutrino fluences: timescales

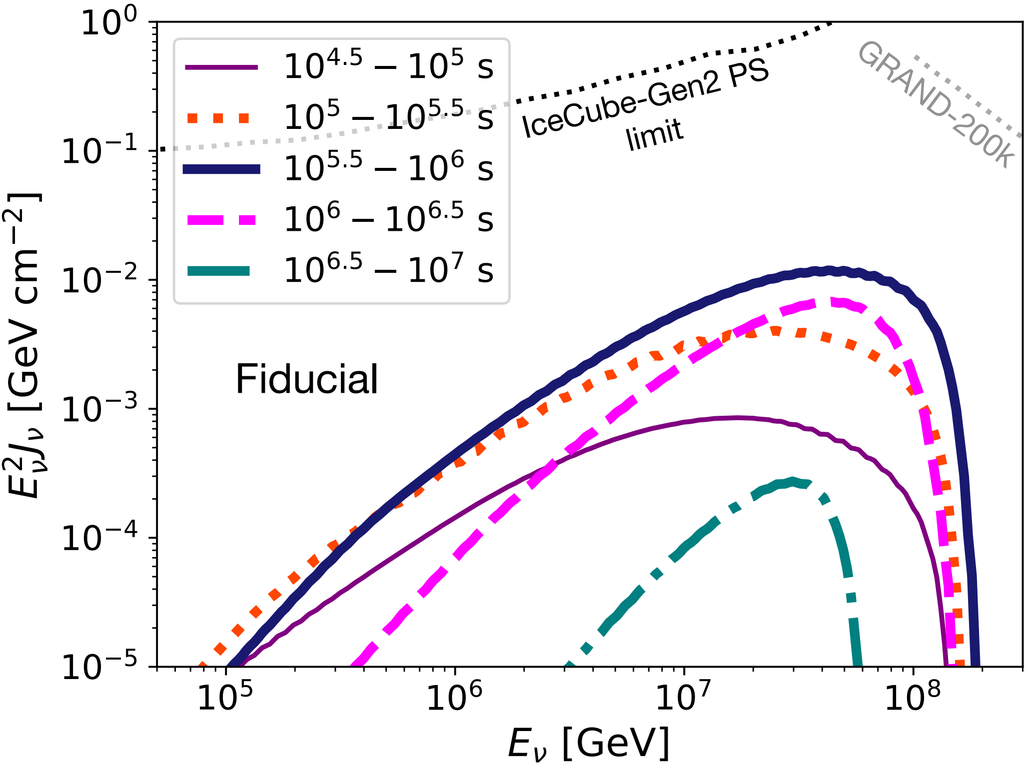


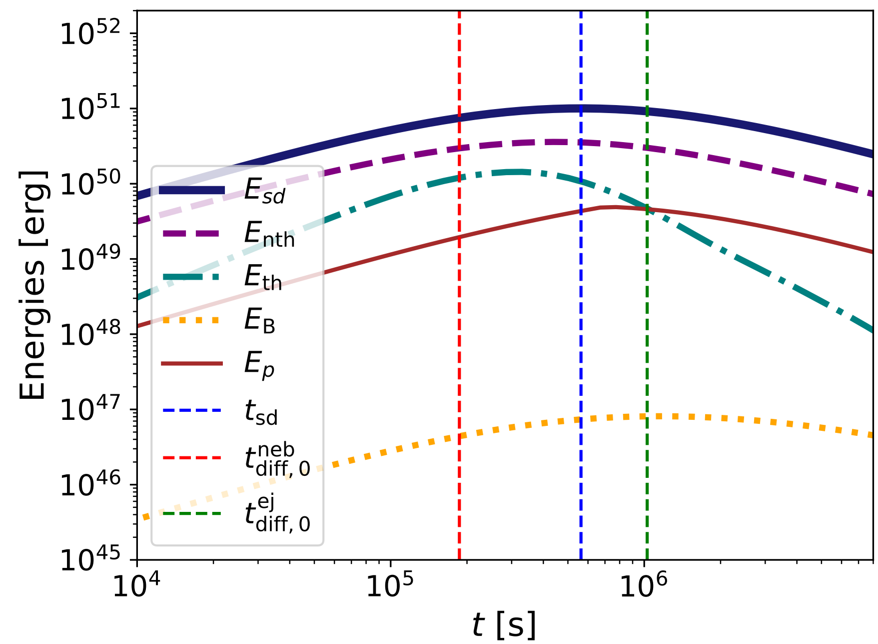


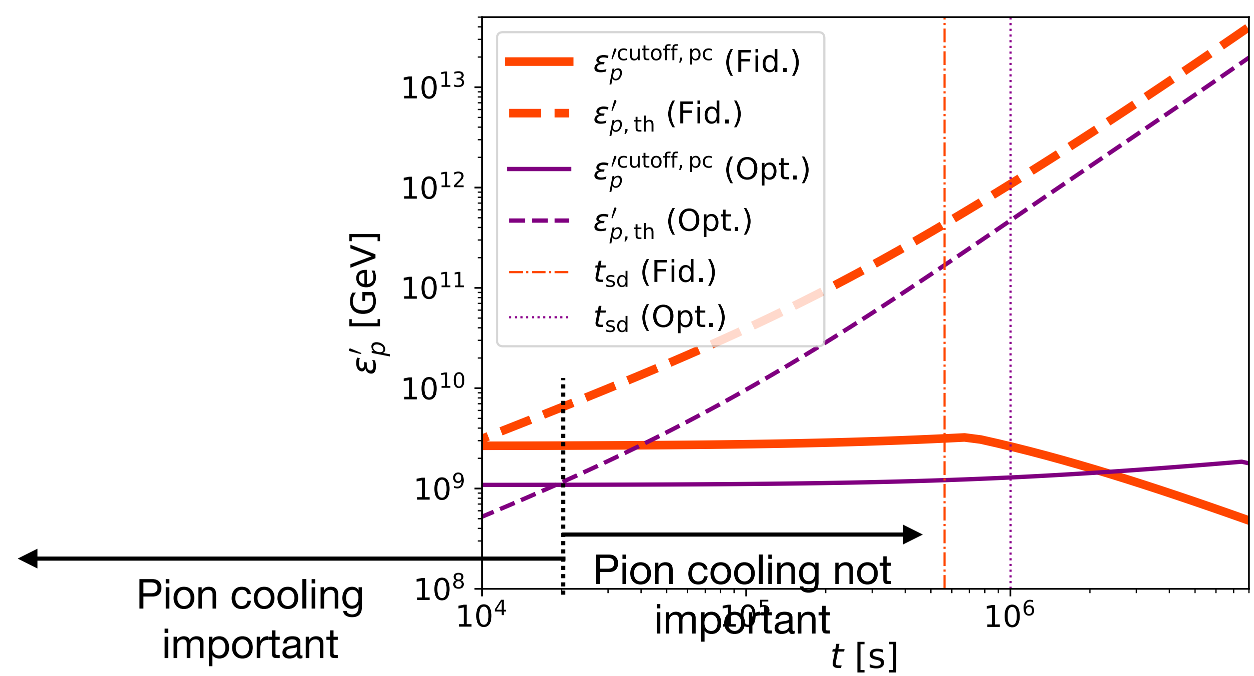




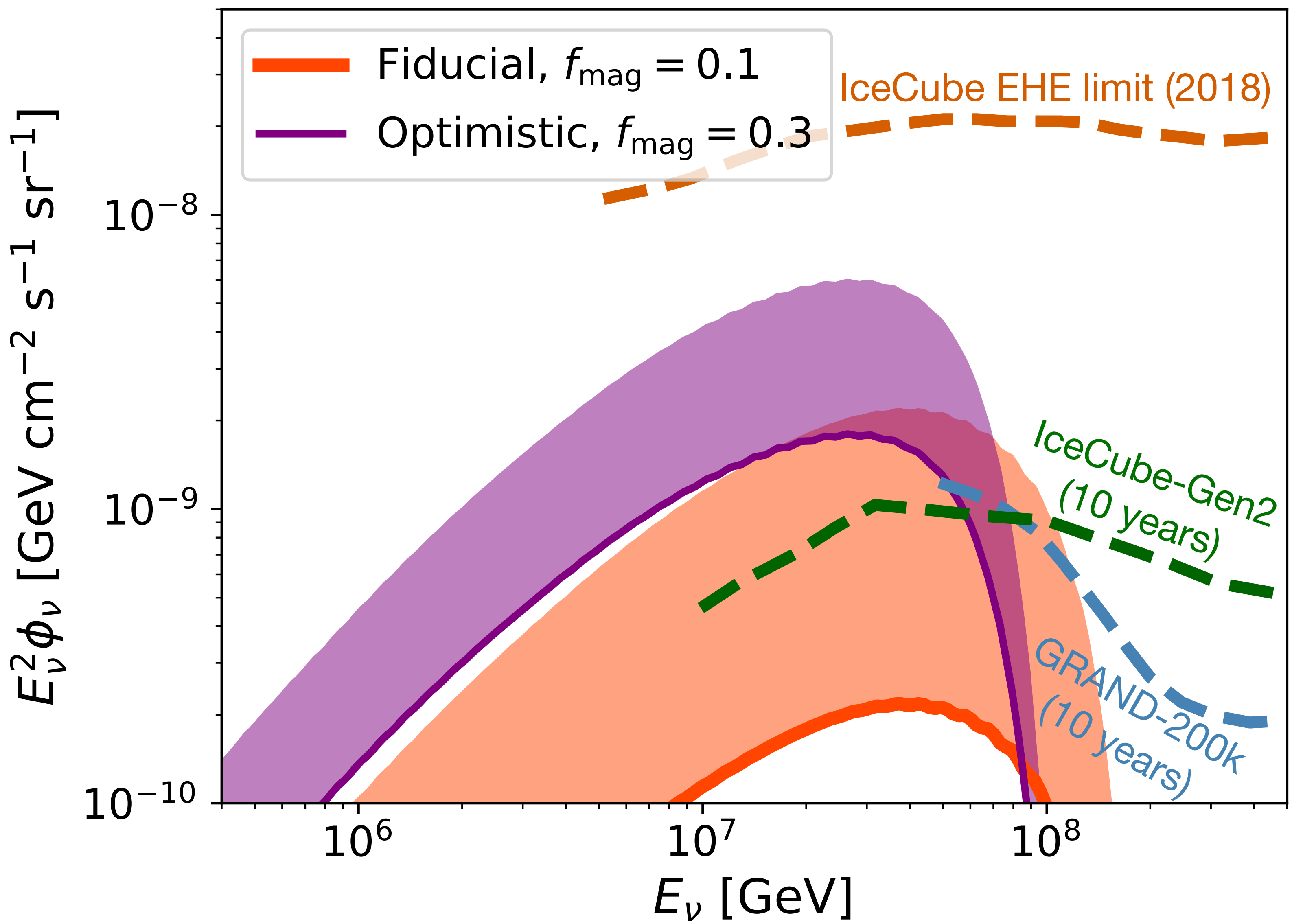
Neutrino fluences: importance of pion cooling







Diffuse neutrino flux



Outline

Part 1: High-energy neutrino emissions from magnetars

Based on: High-energy neutrino signatures from pulsar remnants of binary neutron-star mergers: coincident detection prospects with gravitational waves
MM, S.S. Kimura, B.D. Metzger
Submitted to ApJ (*arXiv: 2407.04767)*

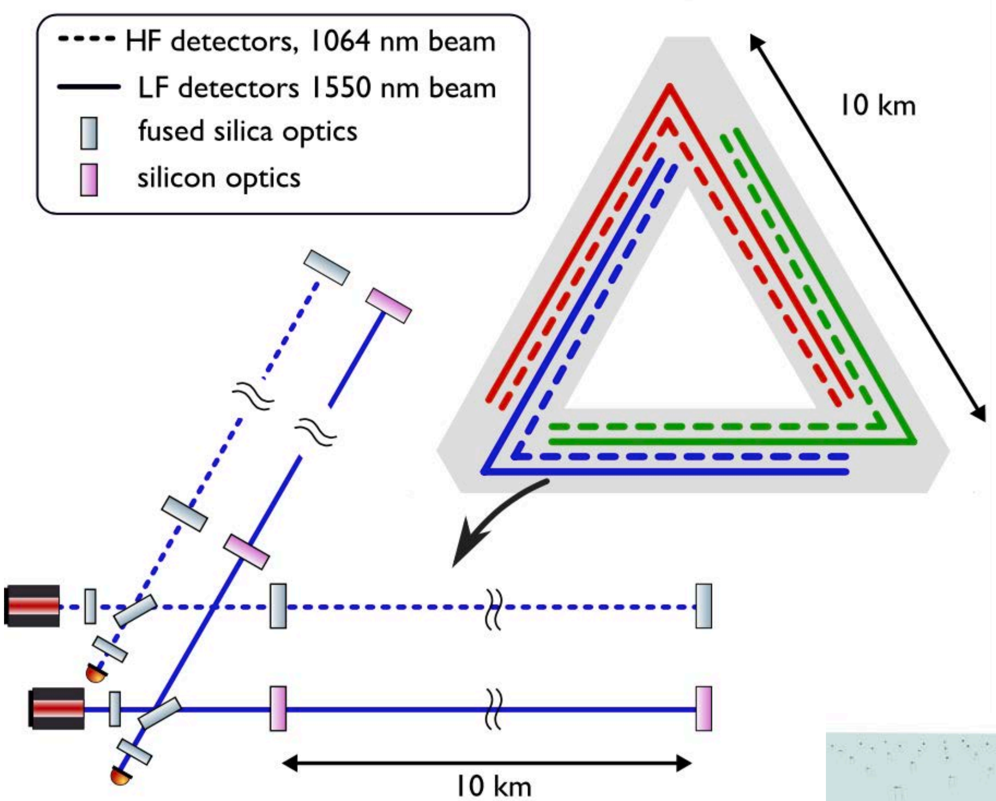
Electromagnetic signatures from pulsar remnants of binary neutron-star mergers
MM, S.S. Kimura
(in preparation)

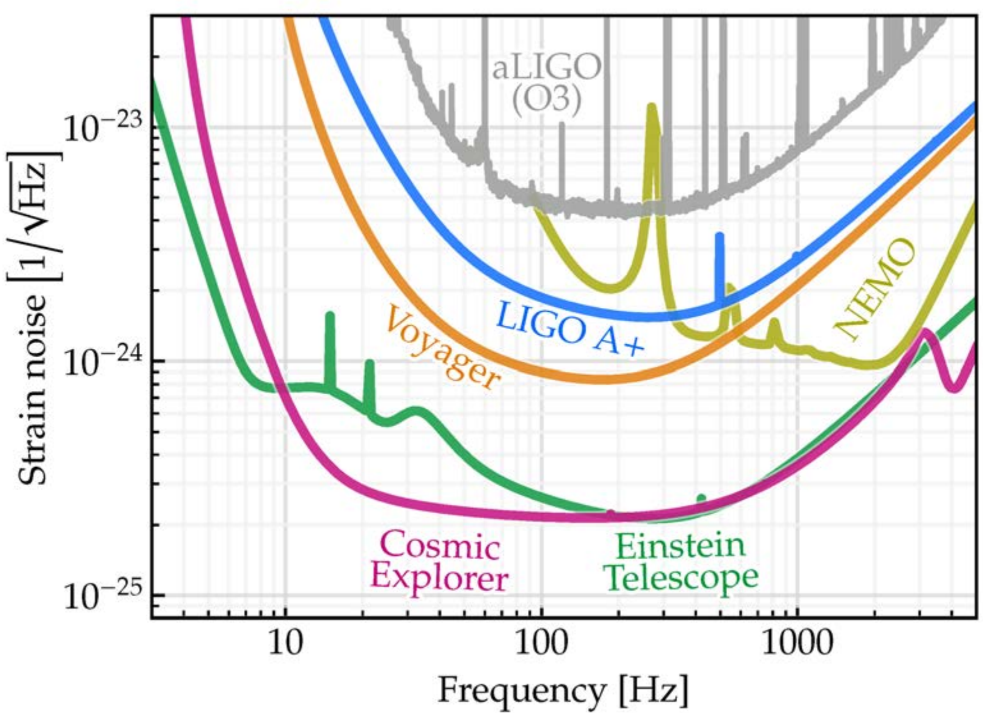
Part 2: Hunting for high-energy and ultrahigh energy neutrinos from BNS mergers at next-generation GW and neutrino detectors

Based on: Gravitational wave triggered high energy neutrino searches from BNS mergers: prospects for next generation detectors
MM, S. S. Kimura, K. Murase
Phys. Rev. D 109, 4, 043053 (2024) ***(arXiv: 2310.16875)***

Ultrahigh energy neutrino searches using next-generation gravitational wave detectors at radio neutrino detectors: GRAND, IceCube-Gen2 Radio, and RNO-G
MM, K. Kotera, S. Wissel, K. Murase, S.S. Kimura
Submitted to Phys. Rev. D ***(arXiv: 2406.19440)***

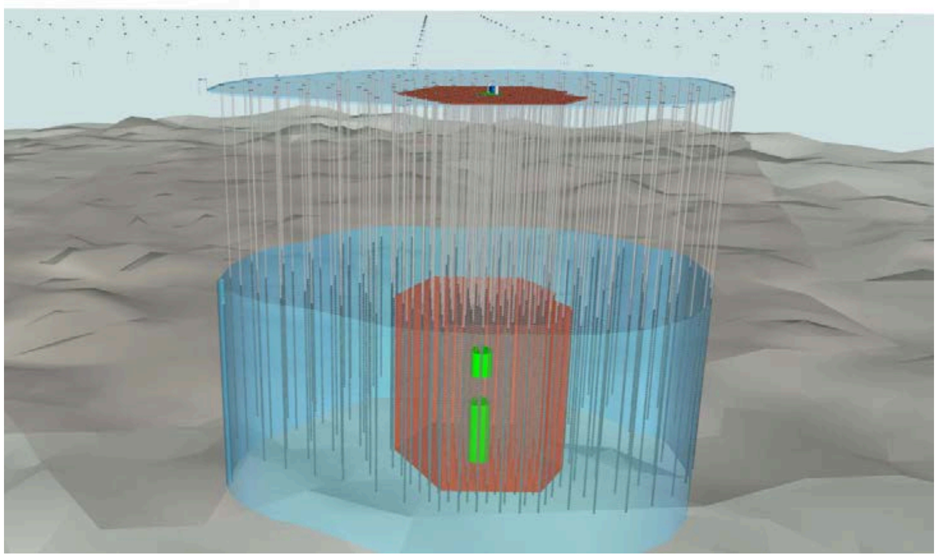
Next-generation GW and neutrino detectors





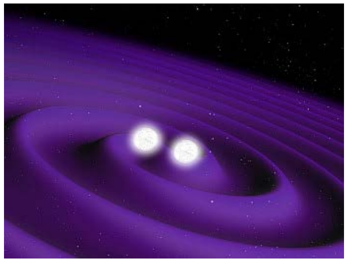
Einstein Telescope (ET)

IceCube-Gen2



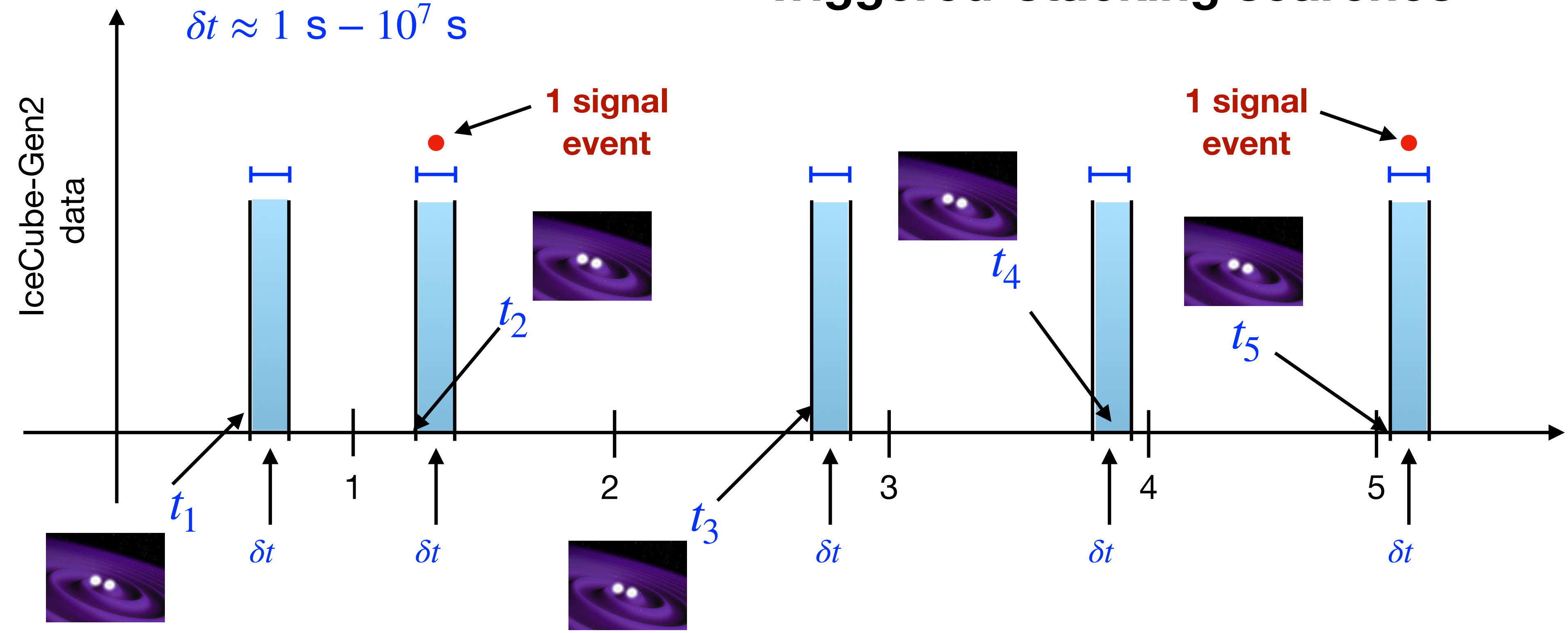
Evans et al., (2021)

Detection strategy: triggered stacking search

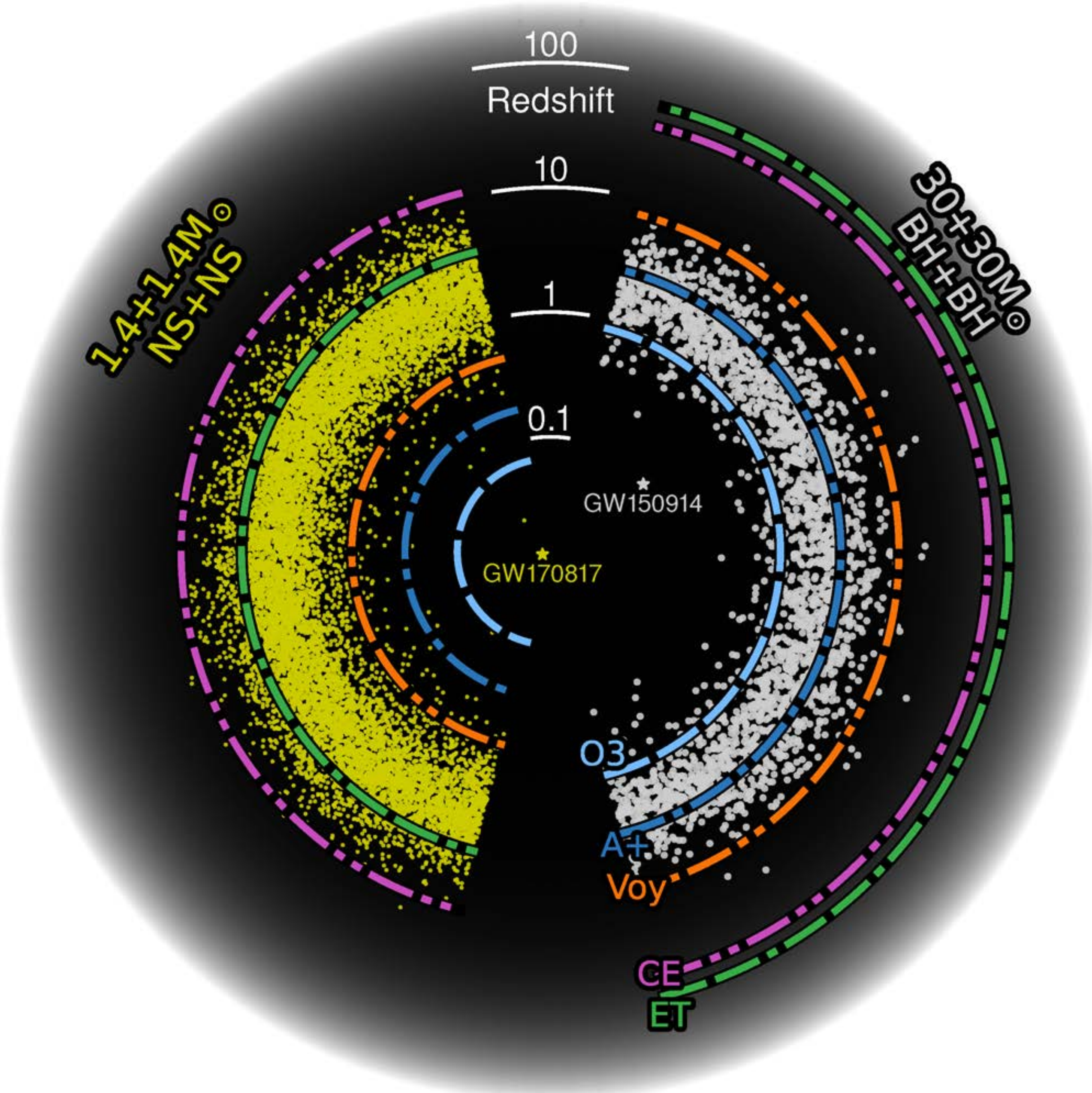


Trigger from next-gen GW detectors → **Neutrinos in IceCube-Gen 2**

Triggered-stacking searches



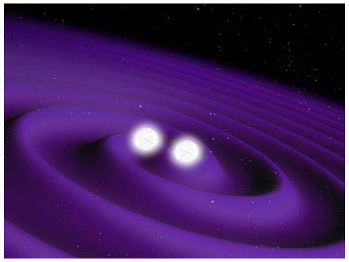
Next-generation GW detectors



Sensitive to NS-NS mergers from very high redshifts

Evans et al., (2021)

Impacts on triggered stacking searches

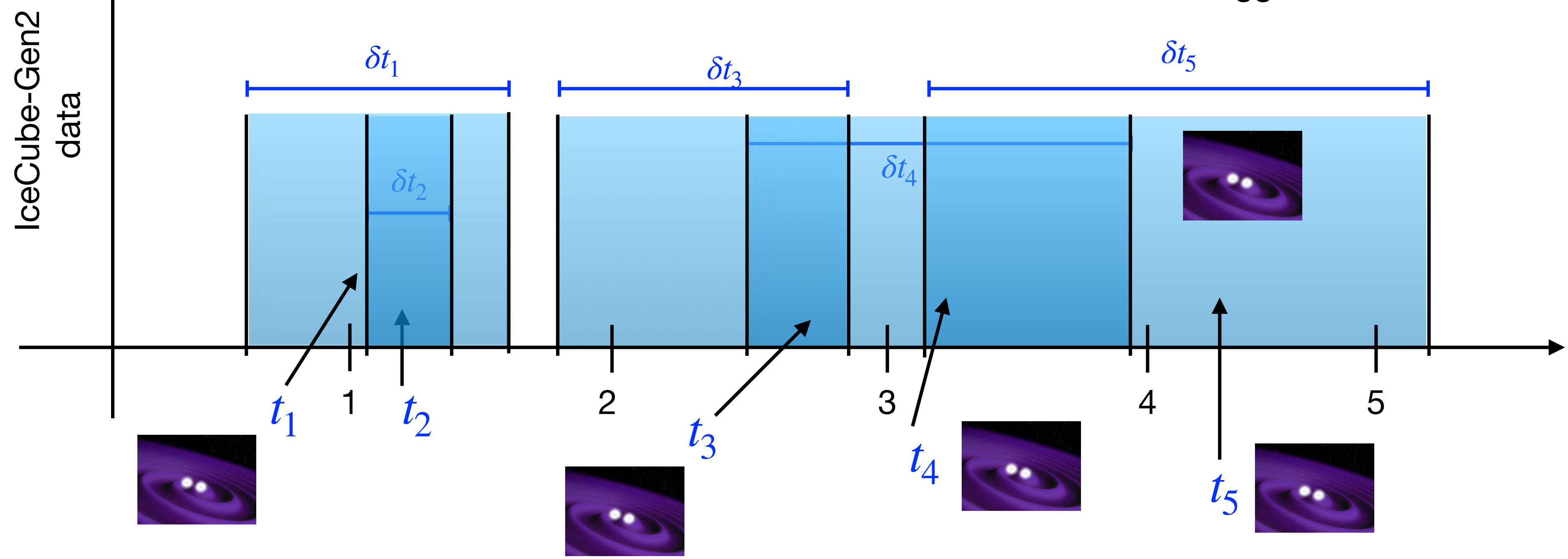


→ **Trigger from next-gen GW detectors** → **Neutrinos in IceCube-Gen 2**

$\delta t \approx 1\ \text{s} - 10^7\ \text{s}$

Largely uncertain time-windows

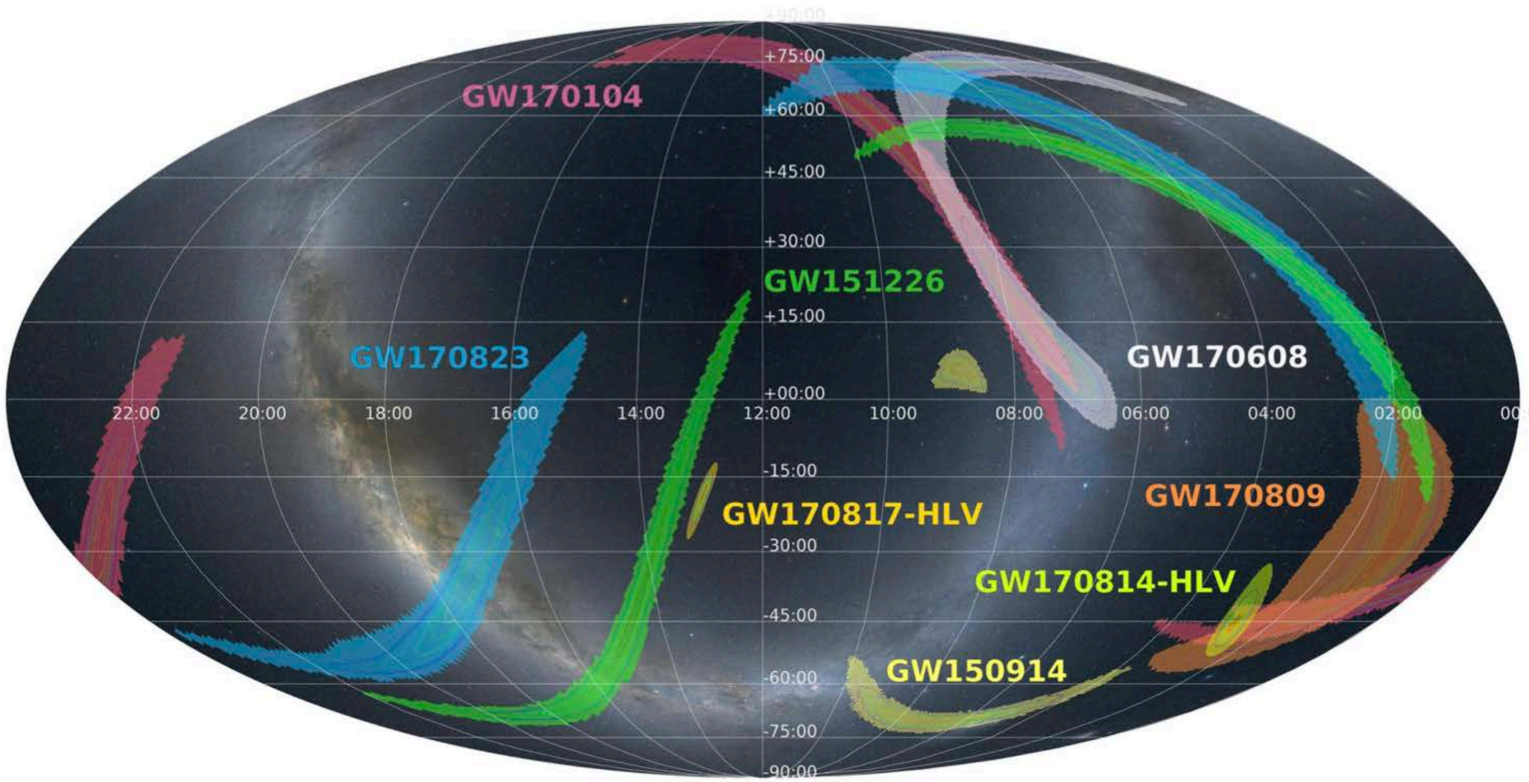
Sensitivity to high-redshifts -> lots of triggers



Spoils triggered stacking searches → **How do we find meaningful triggers?**

Motivations: How to obtain meaningful triggers?

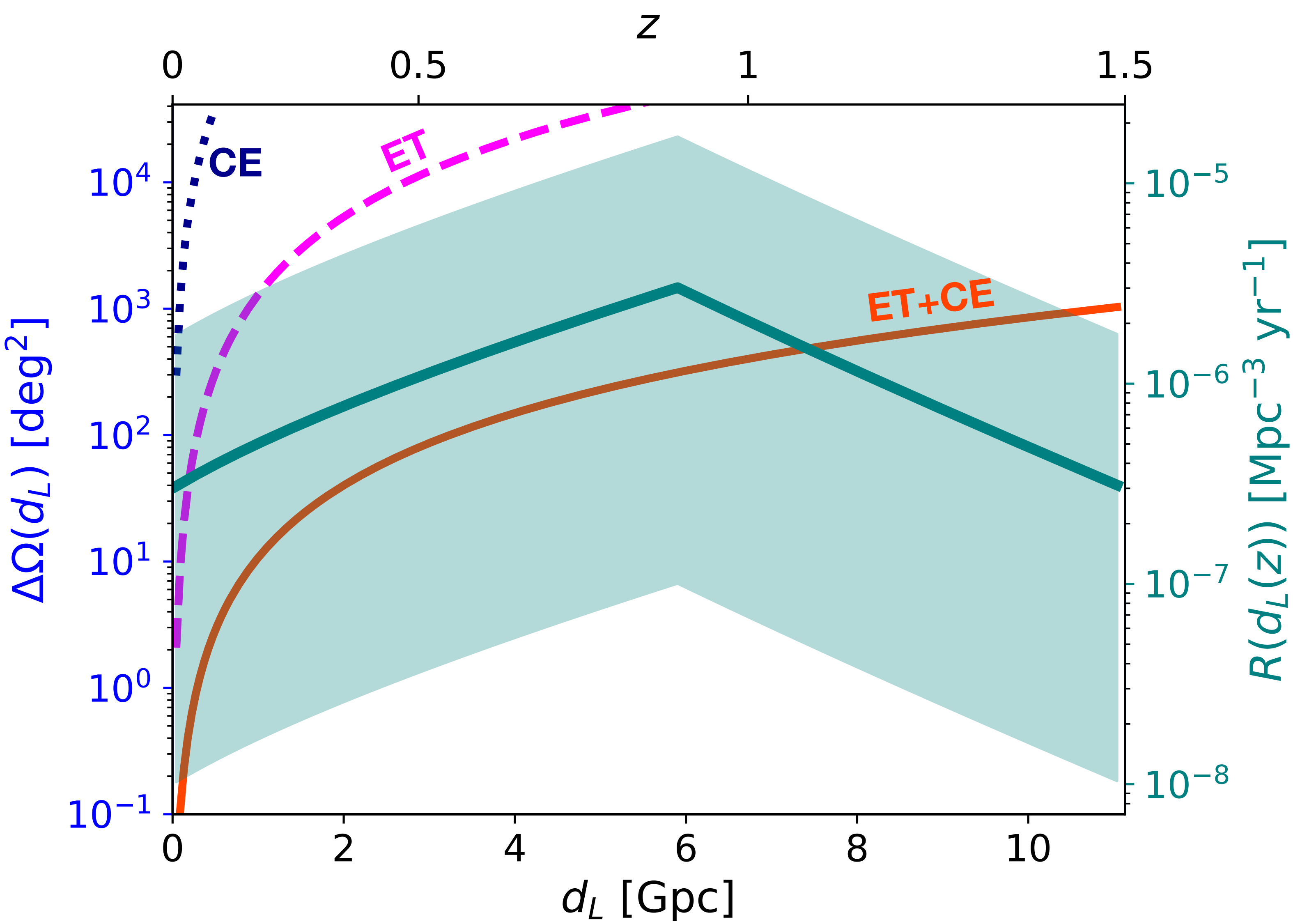
Use the sky localization capabilities of the GW detectors….



Fraction of total sky area covered → Set threshold: $f_{\rm th}$ → Obtain distance limits for GW detectors to collect meaningful triggers

Abbott et al., Liv. Rev. Rel. (2020)

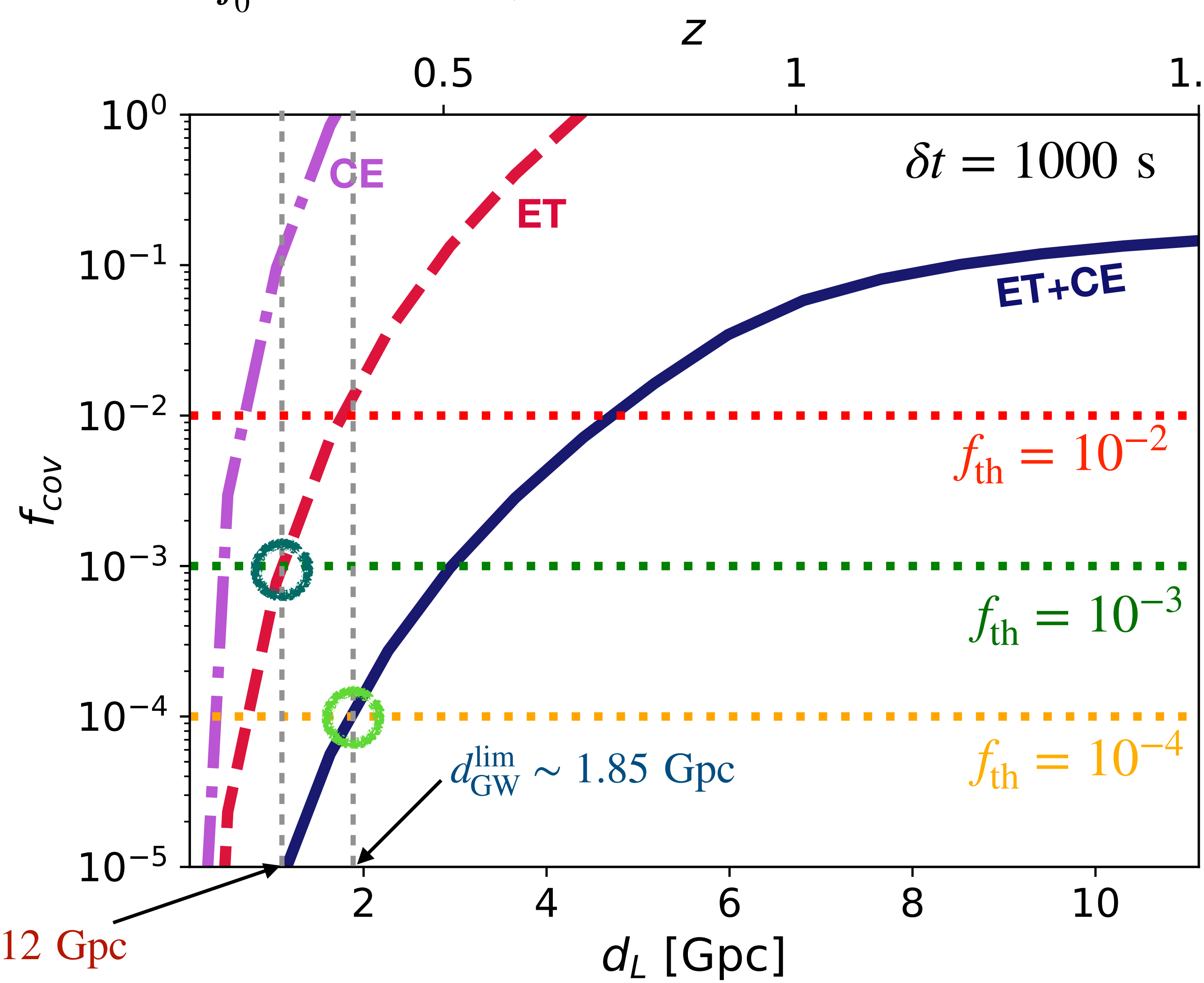
Sky localization and BNS merger rate



Chan et al., PRD (2018)
Wanderman & Piran, MNRAS (2015)

Distance limits for GW detectors

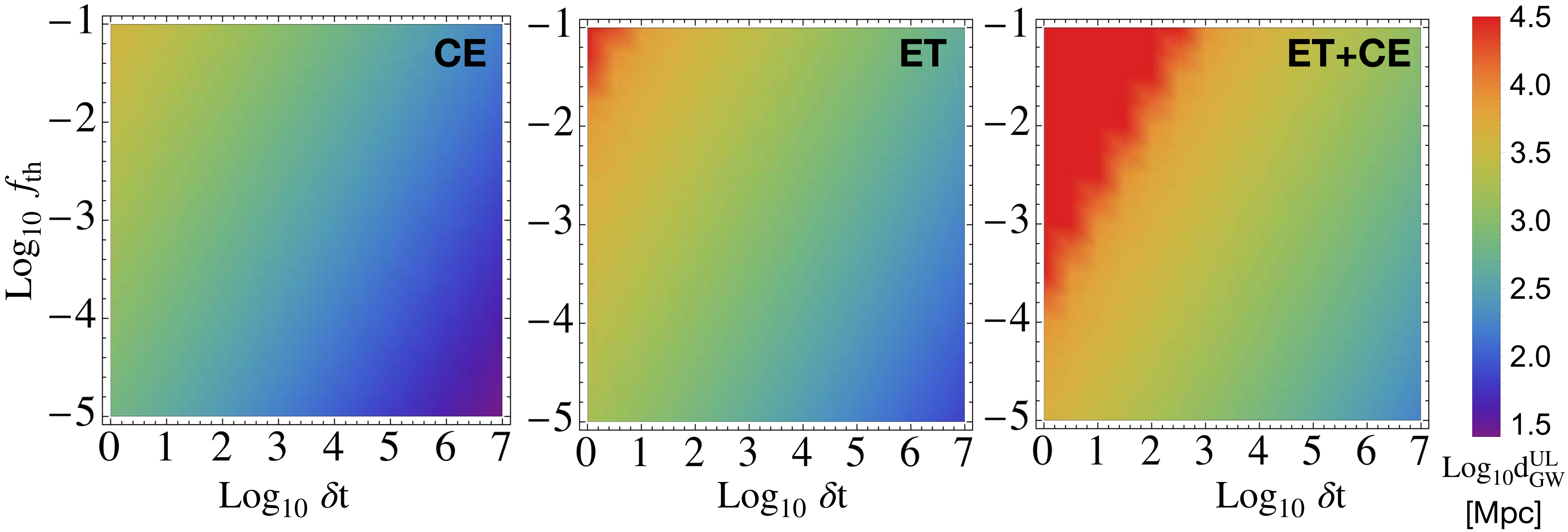
$$\int_0^{d_{GW}^{lim}} d\left(d_{com}\right)\frac{\Delta\Omega\left(d_L\right)}{4\pi}R\left(z\right)4\pi d_{com}^2\delta t = f_{cov}(d_{GW}^{lim})$$



$\delta t = 1000$ s

$d_{GW}^{lim} \sim 1.12$ Gpc

Distance limits for GW detectors - $\delta t - f_{\rm th}$ plane



High energy neutrinos from BNS mergers

Probability to detect more than one neutrino associated with GW signal in T_{op}

$$q\left(d_{\rm GW}^{\rm UL}, T_{\rm op}\right) = 1 - \exp\left(- T_{\rm op} I\left(d_{\rm GW}^{\rm UL}\right)\right)$$

$$I\left(d_{\rm GW}^{\rm UL}\right) = 4\pi \int_0^{d_{\rm GW}^{\rm UL}} d(d_{\rm com}) \frac{T_{\rm op}}{\left(1+z\right)} R\left(z\right) d_{\rm com}^2 P_{n\geq 1}\left(d_L\right)$$

Probability to detect more than one neutrino

$$d_{\rm GW}^{\rm UL} = \min\left(d_{\rm GW}^{\rm lim}, d_{\rm GW}^{\rm hor}\right)$$

Depends on δt

Depends on f_ν

Assume a Poissonian probability

$$\phi_\nu(\mathscr{E}_\nu^{\rm HE,iso}, E_\nu, d_L) = \frac{(1+z)}{4\pi d_L^2} \frac{\mathscr{E}_\nu^{\rm HE,iso}}{\ln\left(\varepsilon_\nu^{\rm max}/\varepsilon_\nu^{\rm min}\right)} E_\nu^{-2}$$

The event rate is calculated is convoluting the IceCube 10 years point source effective area with the muon neutrino flux

$$\mathscr{E}_\nu^{\rm HE,iso} = \frac{\mathscr{E}_\nu^{\rm HE,true}}{f_{\rm bm}} = \left(\frac{f_\nu}{f_{\rm bm}}\right) \mathscr{E}_{\rm GW}$$

The flux is calculated assuming a $dN_\nu/dE_\nu \propto E_\nu^{-2}$spectrum.

$$\mathscr{E}_\nu^{\rm HE,true} = f_\nu \mathscr{E}_{\rm GW} \qquad \mathscr{E}_{\rm GW} \sim \alpha \mathscr{E}^{\rm tot} \qquad \alpha \sim 1\,\%$$

Results - varying f_ν and δt

f_ν

10^{-5}

5×10^{-5}

Fiducial Parameters:

$f_\nu = 2.5 \times 10^{-5}$

$\delta t = 1000 \text{ s}$

$E^{\text{tot}} \sim 5 \times 10^{54} \text{erg}$

Motivated by physical models

1 s

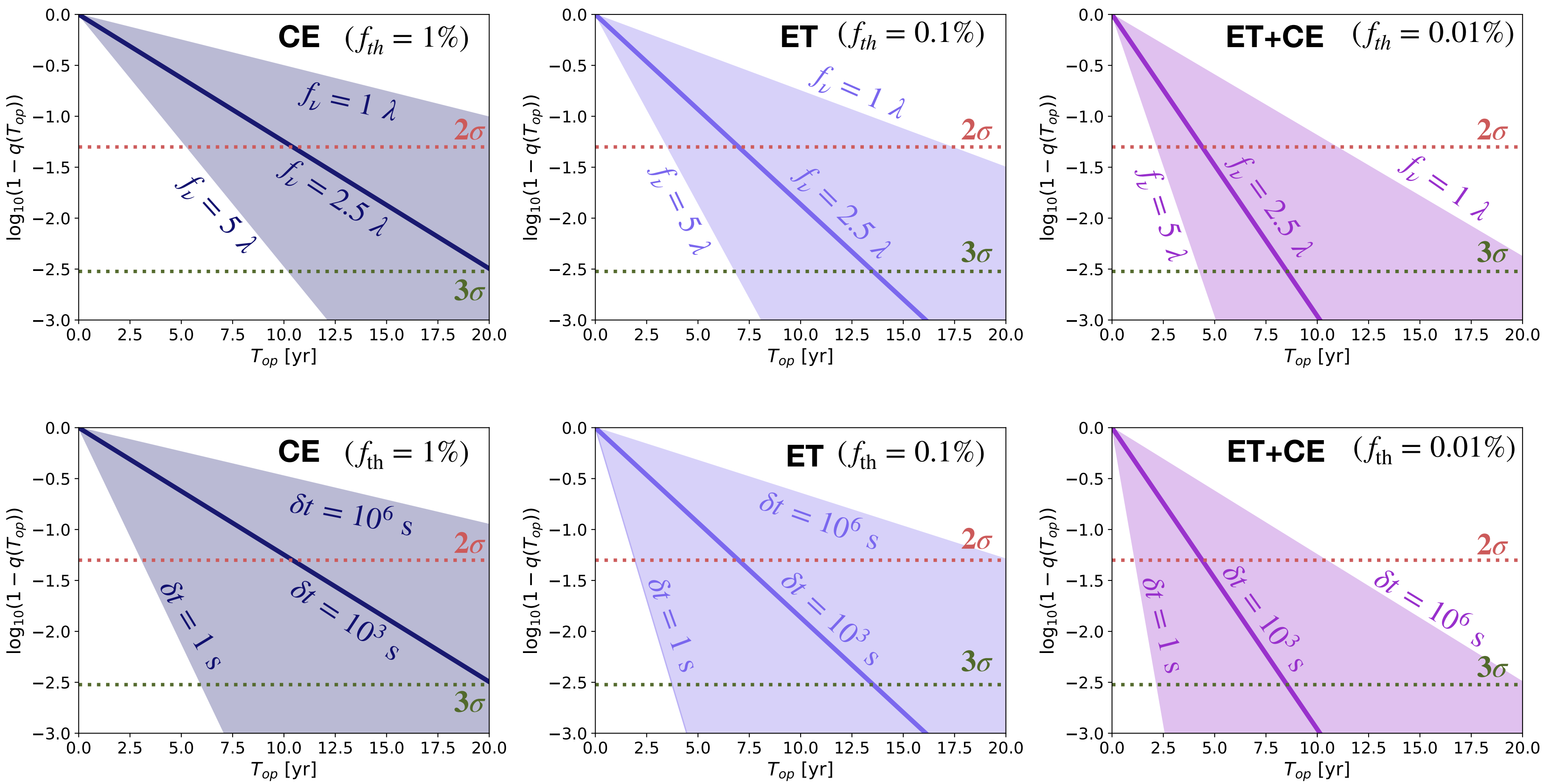
10^6 s

δt

Results - varying f_ν and δt

f_ν

$\delta t = 1000$ s

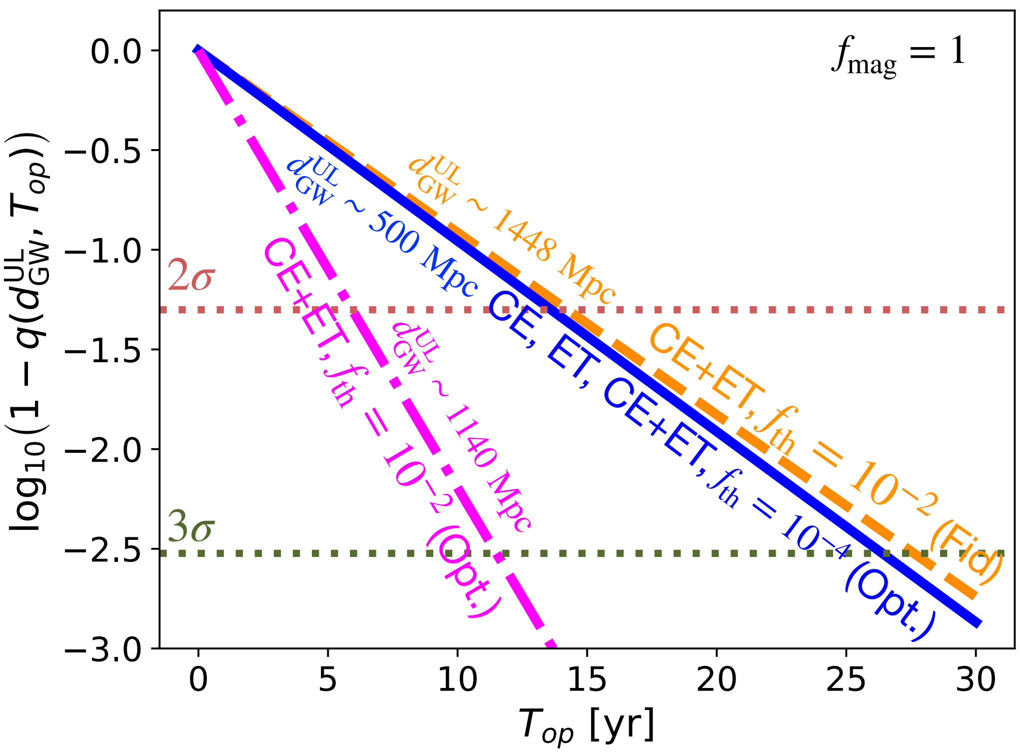


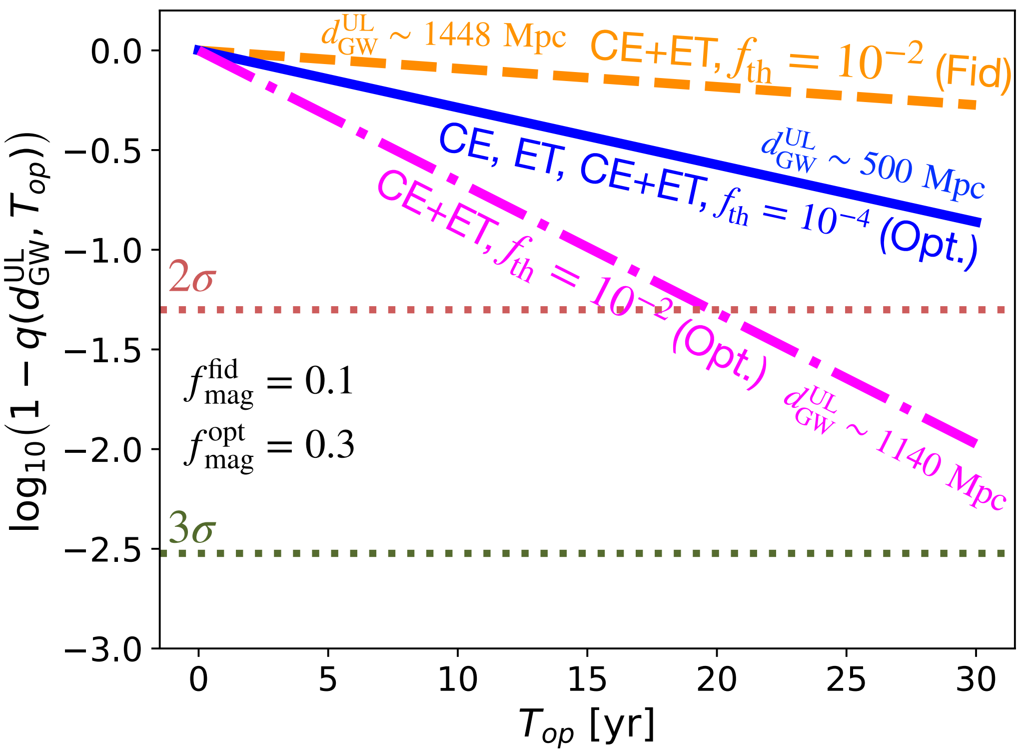
$f_\nu = 2.5\ \lambda$

δt

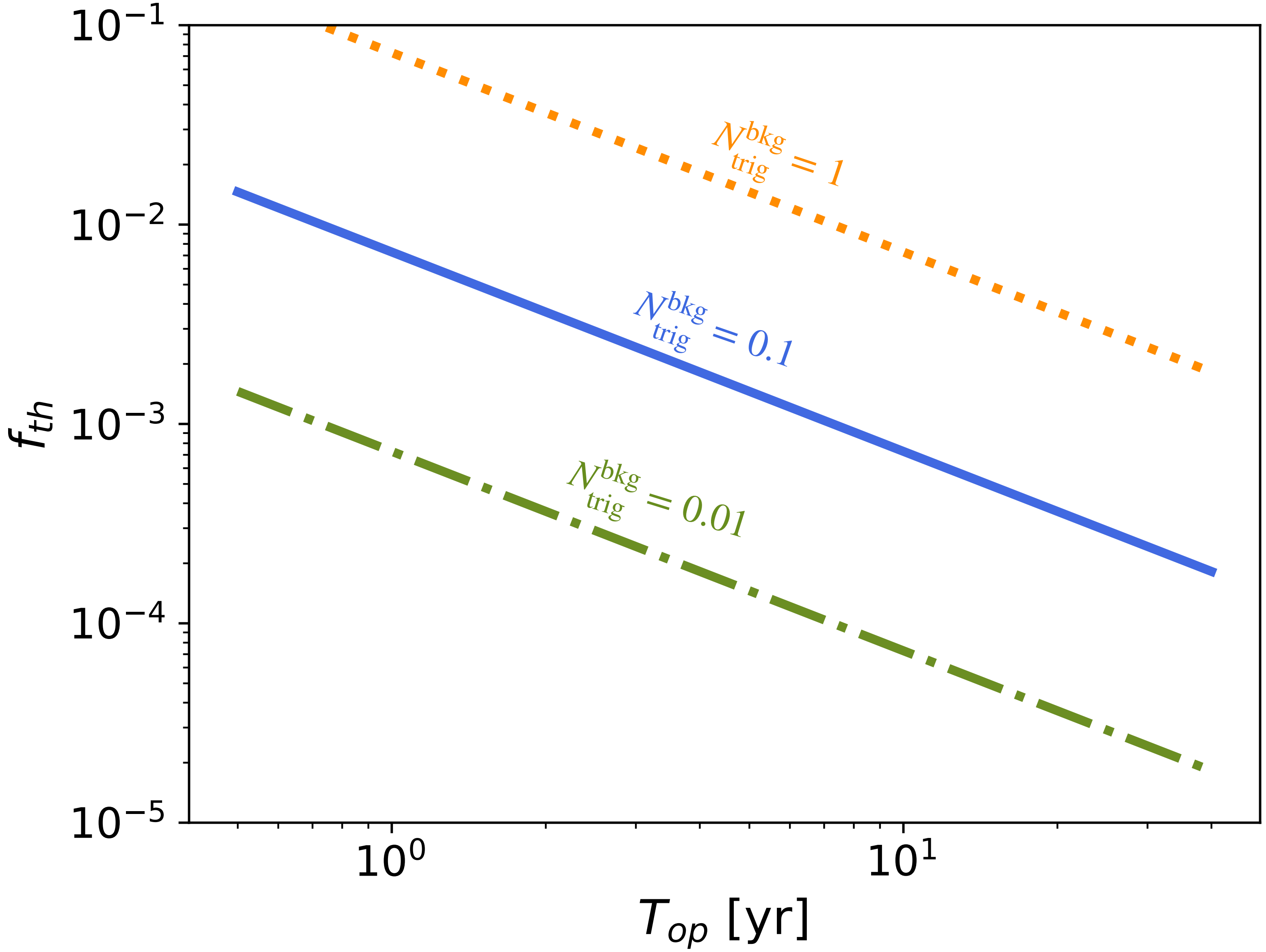
$\lambda = 10^{-5}$

Results: Magnetar remnants from BNS mergers

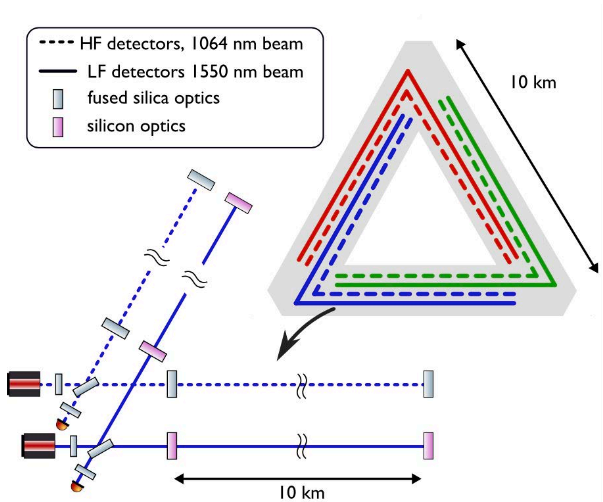




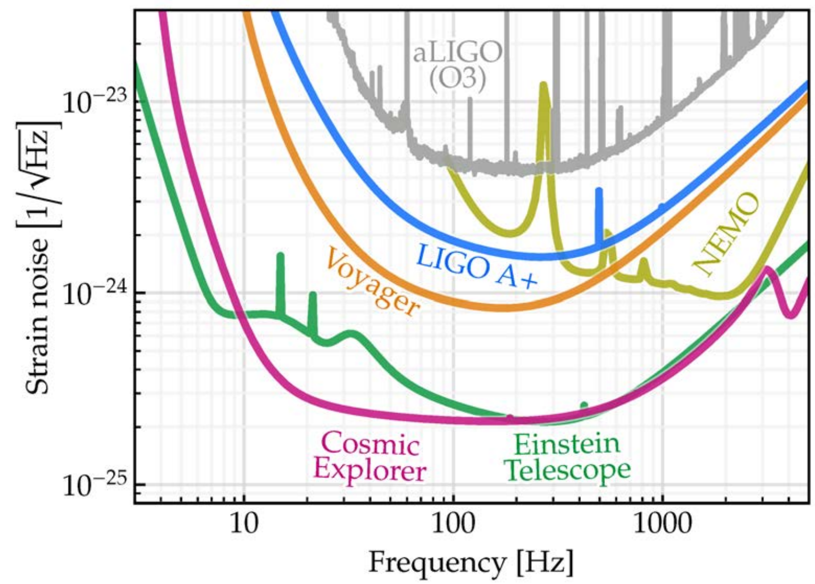
Backgrounds



Next-generation GW and UHE neutrino detectors



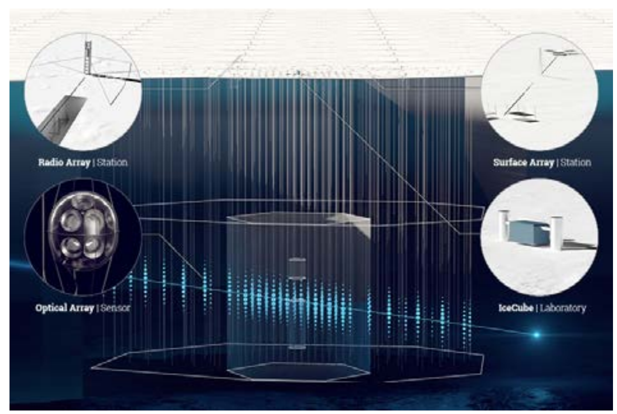
Einstein Telescope (ET)

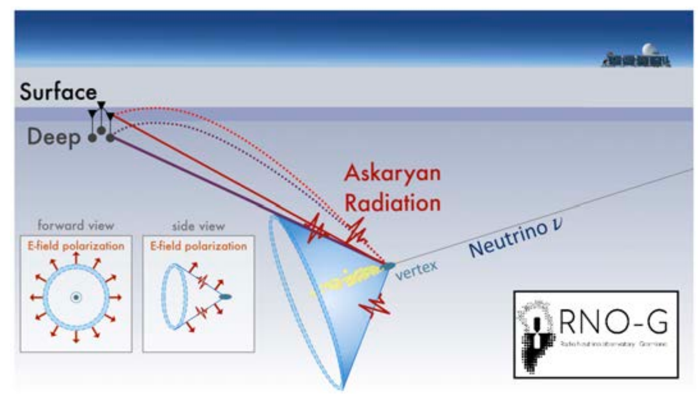


Cosmic Explorer (CE)

GRAND

Giant Radio Array for Neutrino Detection



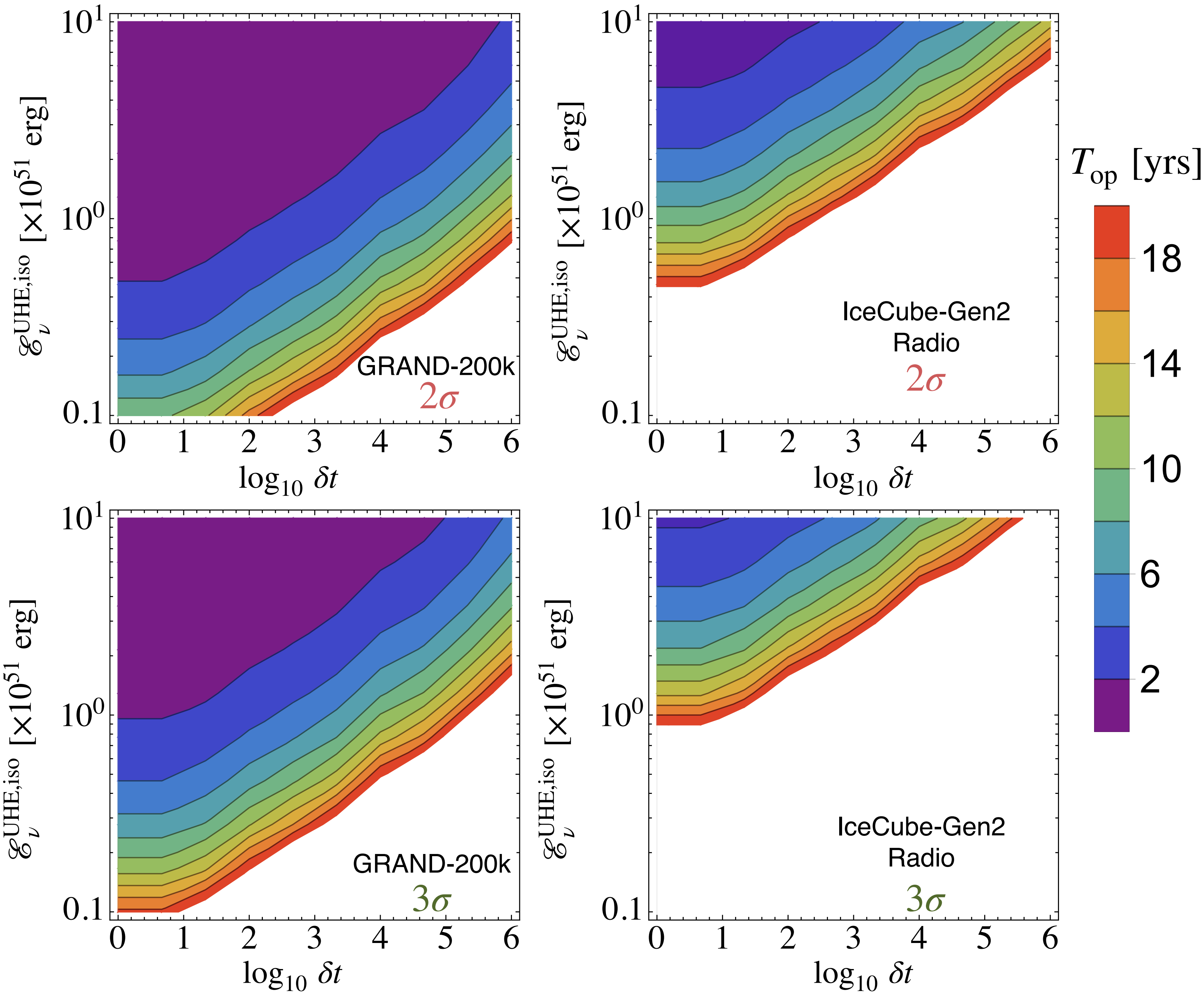


GRAND

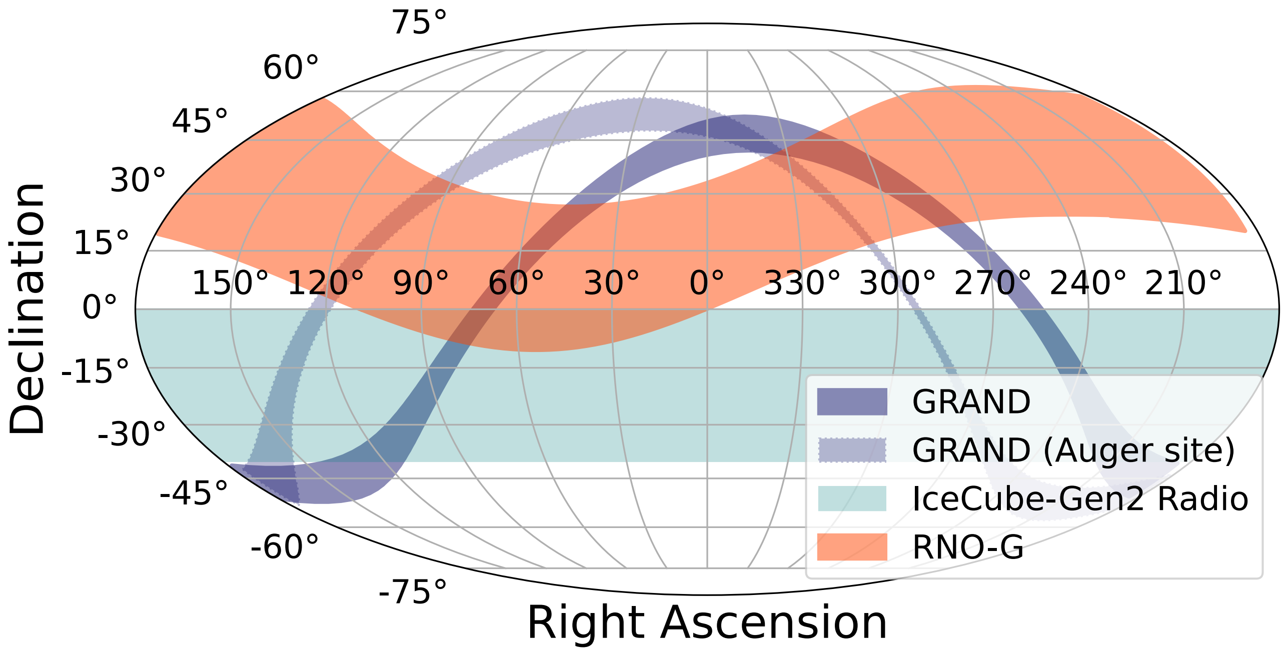
IceCube-Gen2 Radio

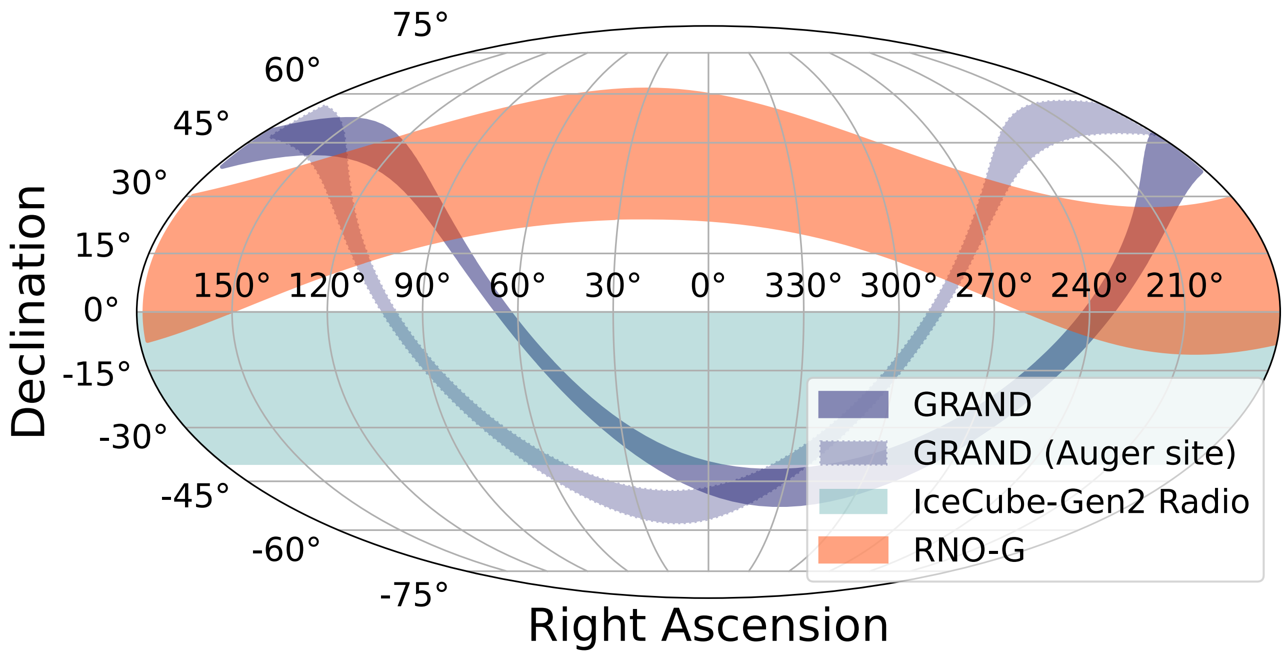
RNO-G

Prospects for GRAND and IceCube-Gen2 Radio

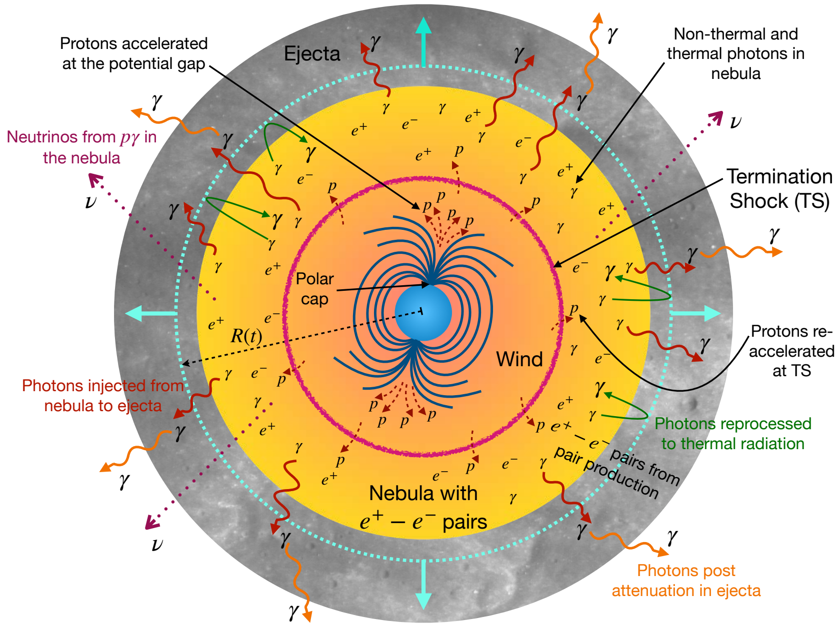


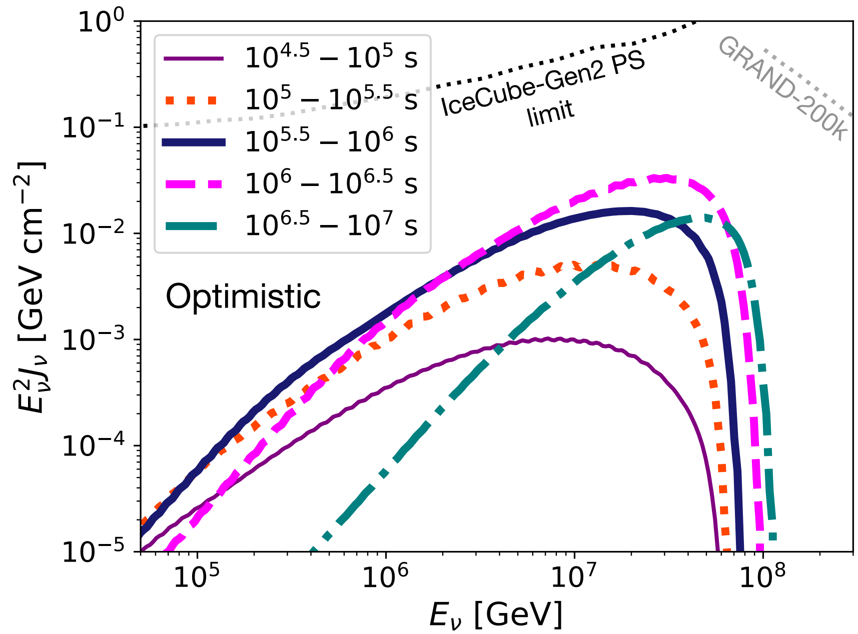
Joint UHE neutrino network: FOV

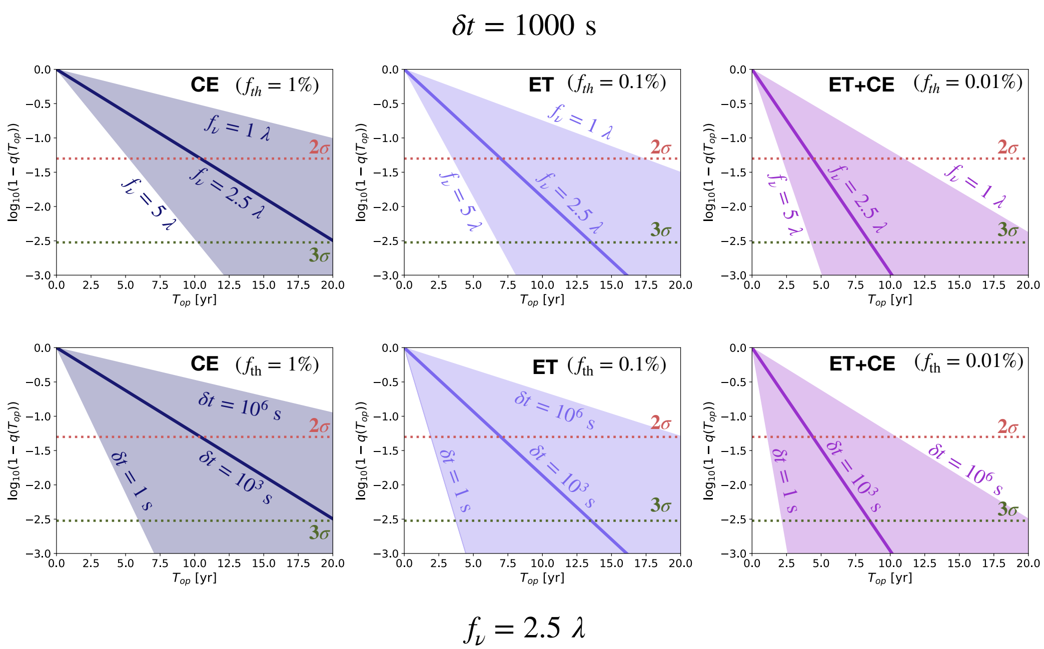


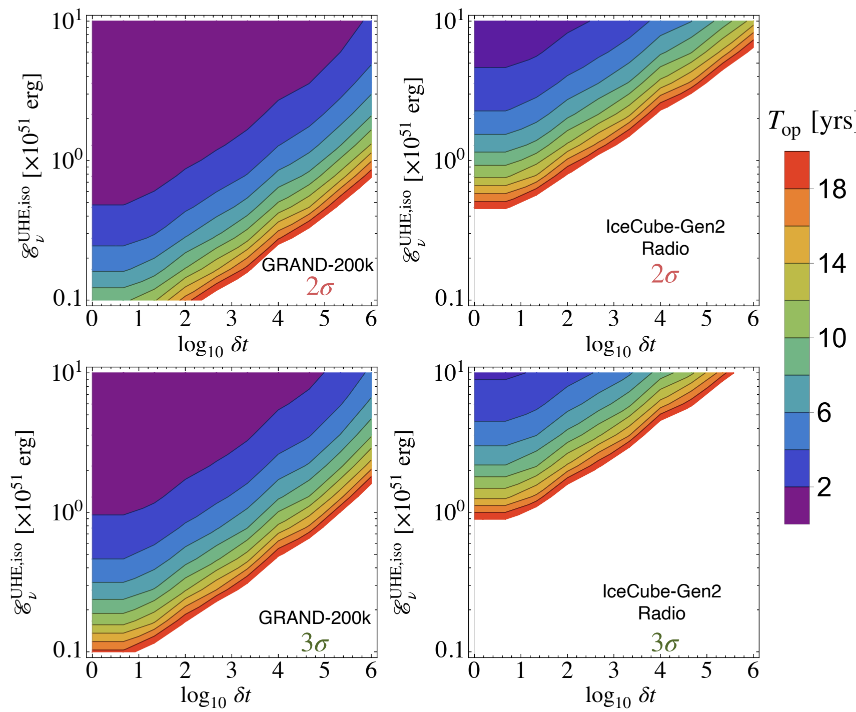


Takeaways


Ejecta
Protons accelerated at the potential gap
Non-thermal and thermal photons in nebula
Neutrinos from pγ in the nebula
Termination Shock (TS)
Polar cap
Wind
R(t)
Protons re-accelerated at TS
Photons injected from nebula to ejecta
Photons reprocessed to thermal radiation
$e^+ - e^-$ pairs from pair production
Nebula with $e^+ - e^-$ pairs
Photons post attenuation in ejecta


$10^{4.5} - 10^5$ s
$10^5 - 10^{5.5}$ s
$10^{5.5} - 10^6$ s
$10^6 - 10^{6.5}$ s
$10^{6.5} - 10^7$ s
IceCube-Gen2 PS limit
GRAND-200k
Optimistic
$E_\nu^2 J_\nu$ [GeV cm^{-2}]
E_ν [GeV]

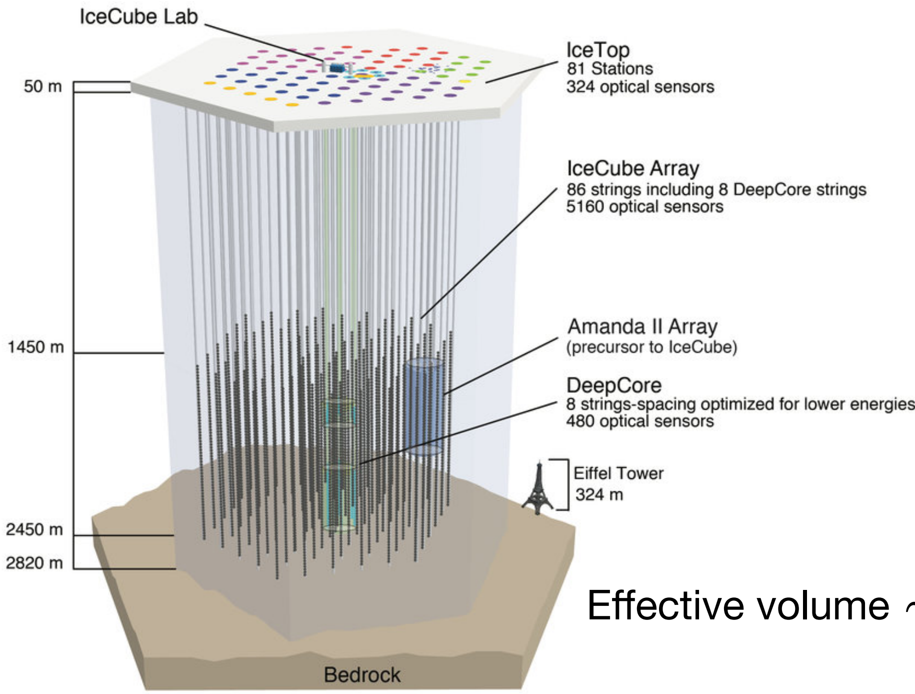

$\delta t = 1000$ s
CE ($f_{th} = 1\%$)
ET ($f_{th} = 0.1\%$)
ET+CE ($f_{th} = 0.01\%$)
$f_\nu = 1\ \lambda$
$f_\nu = 2.5\ \lambda$
$f_\nu = 5\ \lambda$
$\delta t = 10^6$ s
$\delta t = 10^3$ s
$\delta t = 1$ s
2σ
3σ
$\log_{10}(1 - q(T_{op}))$
T_{op} [yr]
$f_\nu = 2.5\ \lambda$

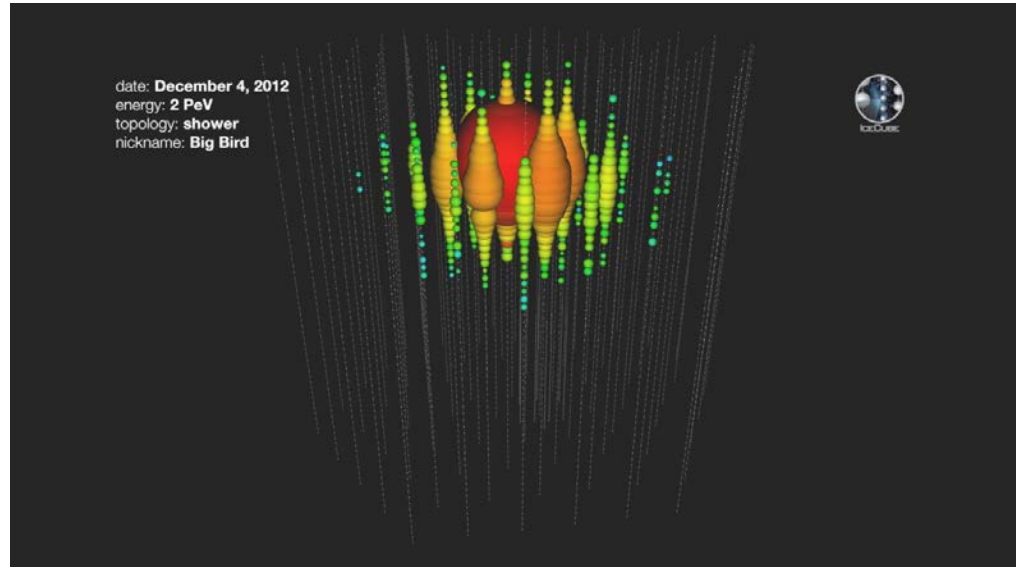

$\mathscr{E}_\nu^{\rm UHE,iso}$ [$\times 10^{51}$ erg]
$\log_{10}\ \delta t$
GRAND-200k
IceCube-Gen2 Radio
2σ
3σ
$T_{\rm op}$ [yrs]


Thank You!

Backup

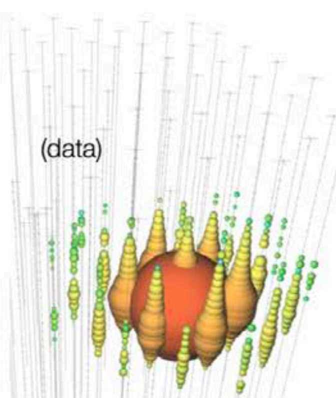
High-energy neutrino detectors





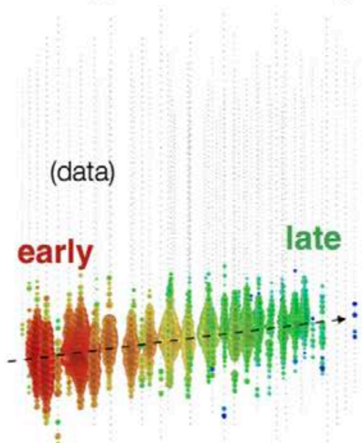
Effective volume $\sim 1\ \mathrm{km}^3$

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_μ

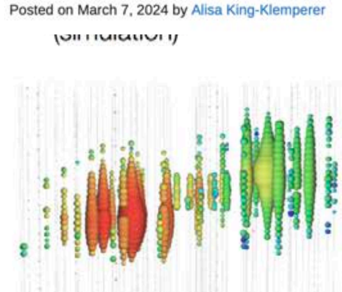


Up-going track

Charged-current ν_τ

IceCube observes seven astrophysical tau neutrino candidates

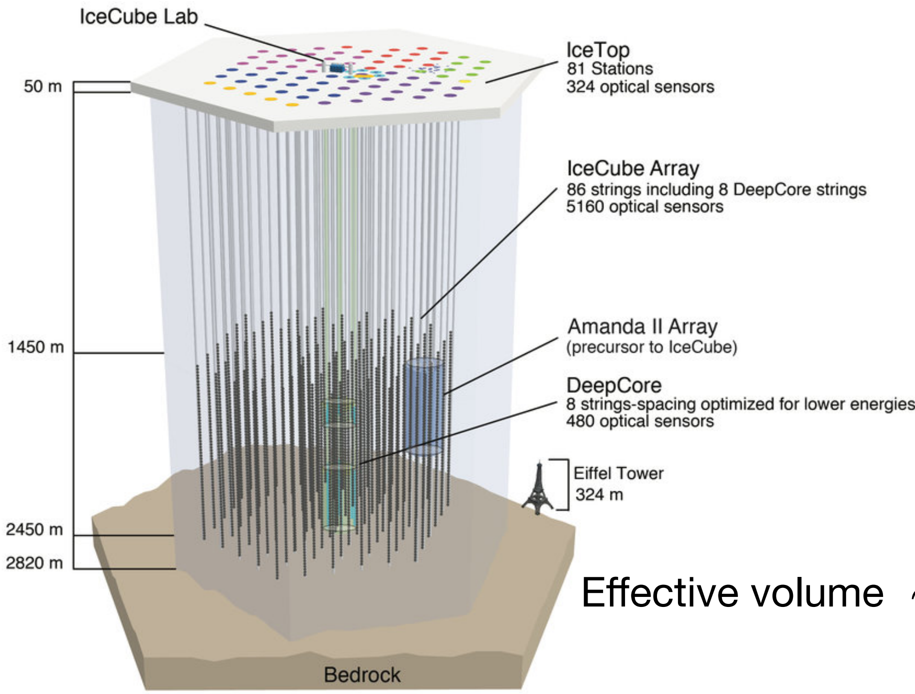
Posted on March 7, 2024 by Alisa King-Klemperer



Double cascade

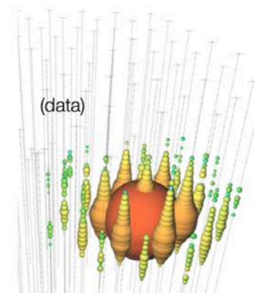
Image credits: icecube.wisc.edu

High-energy neutrino detectors



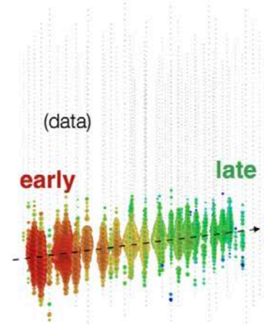
Effective volume $\sim 1\ \mathrm{km}^3$

Neutral-current / ν_e



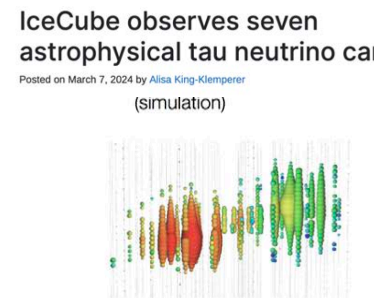
Isolated energy deposition (cascade) with no track

Charged-current ν_μ



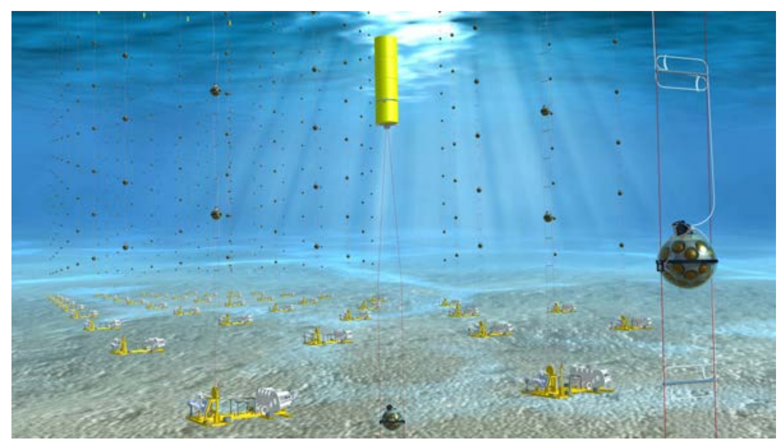
Up-going track

Charged-current ν_τ



Double cascade

KM3NeT



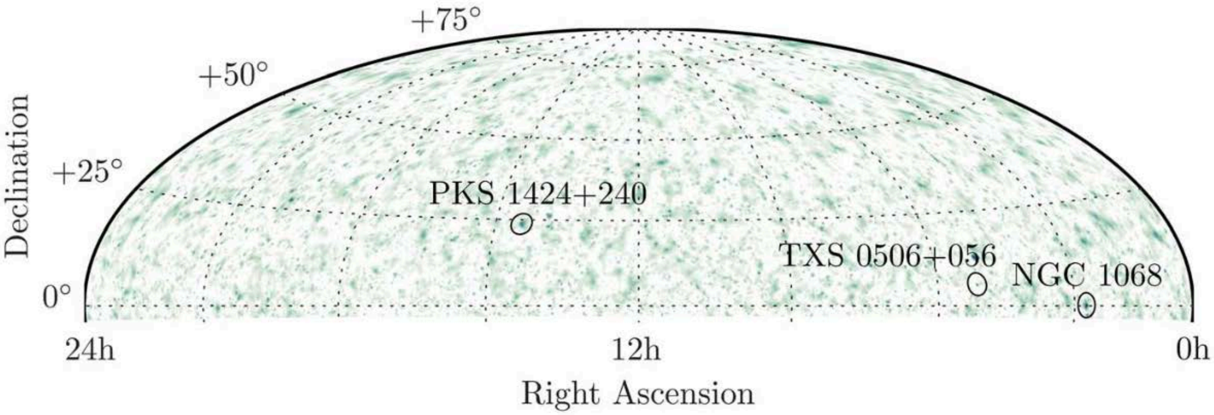
Baikal GVD

ANTARES

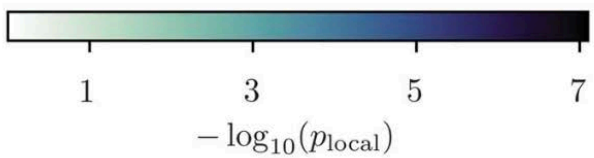
Future detectors: IceCube-Gen2, RNO-G, GRAND, P-ONE….

Image credits: icecube.wisc.edu
KM3NeT: Edward Berber, Nikhef

NGC 1068 (also TXS 0506+056)

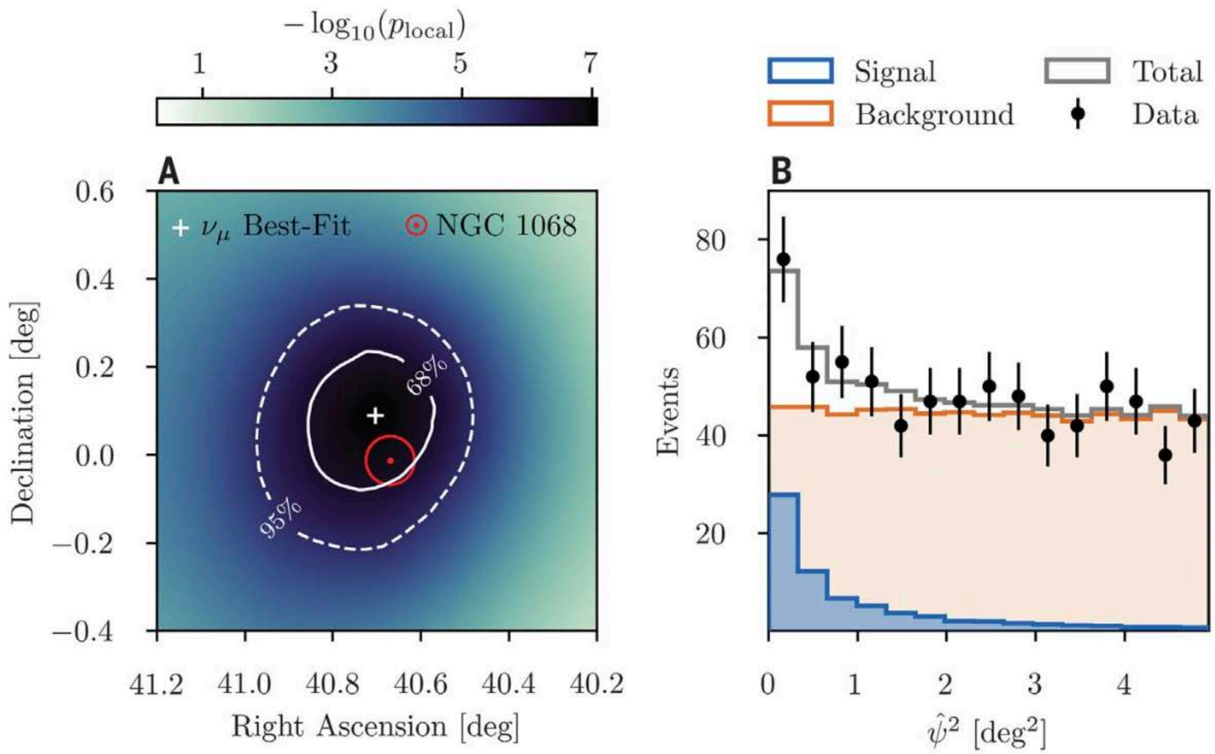


10 years of PS data (2011-2020)



$\sim 4.2\sigma$ w.r.t 110 known gamma ray sources

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\rm local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



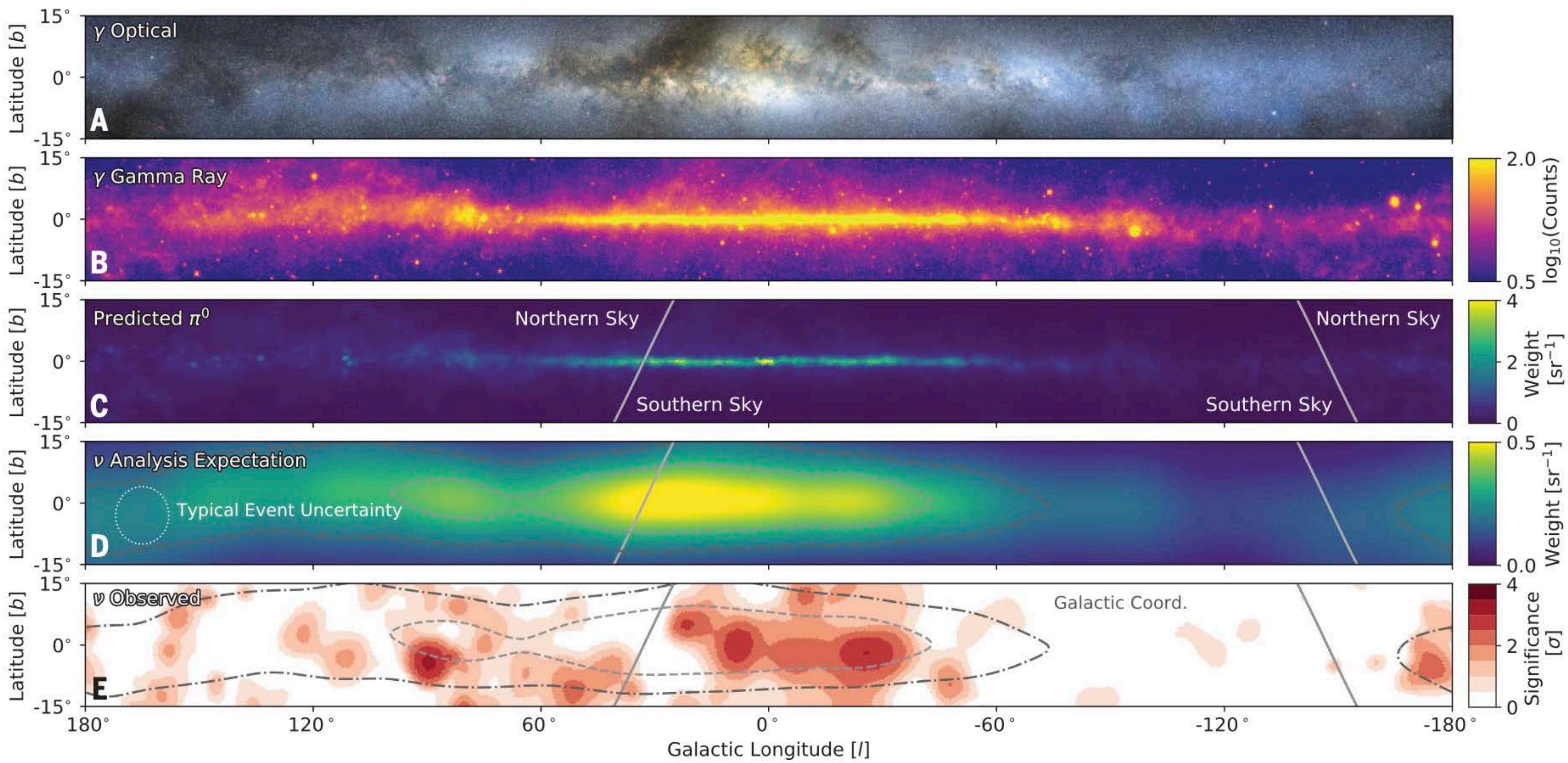
$\sim 79^{+22}_{-20}$ excess events

IceCube Collab.+ Science 2022

The Galactic plane

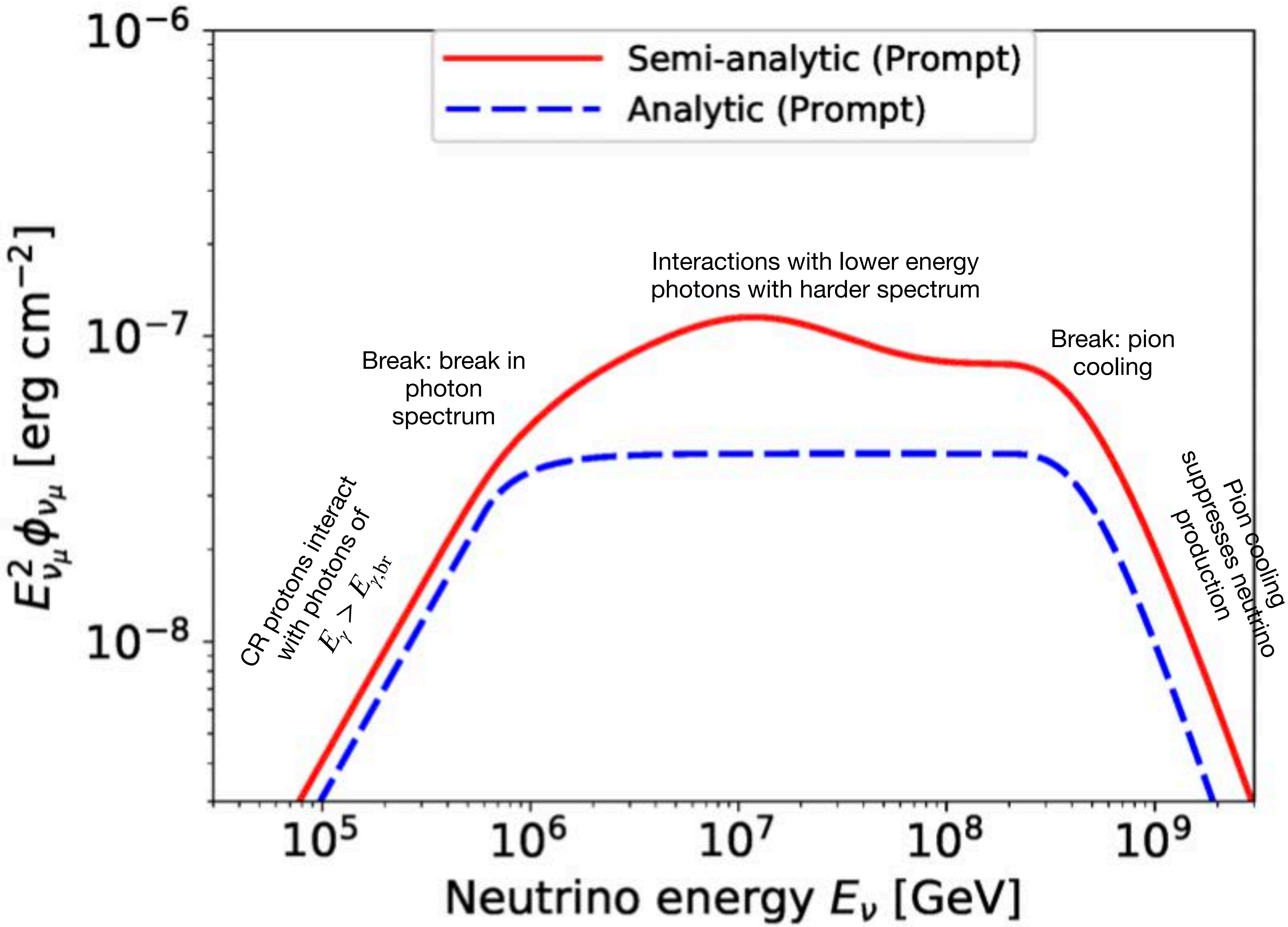
10 years of PS data
(2011-2020)

$\sim 4.5\sigma$ diffuse emission models
w.r.t background only hypothesis



IceCube Collab.+ Science, 380, 2023

Effective $p\gamma$ optical depth



Kimura 2022, arXiv: 2202:06480
Kimura, Murase, Mészáros, and Kiuchi. ApJ, 848:L4, 2017

Details about r-process heating rate

$$Q_{\rm rp}^{\rm heat} = f_{\rm therm} f_{\rm diff} \dot{E}_{\rm rp} M_{\rm ej}$$

Fraction of photons that have thermalized (non-trivial)

Fraction of thermalized photons that diffuse from ejecta to the nebula

$$f_{\rm therm} = \begin{cases} 0.7, & t \le t_{{\rm tr},\gamma} \\ 0.2, & t > t_{{\rm tr},\gamma} \end{cases}$$

$$f_{\rm diff} = \frac{t_{\rm dyn}}{t_{\rm diff}^{\rm ej}}$$

$$t_{\rm diff}^{\rm neb} \approx \frac{R}{c}(1 + \tau_{\rm diff}^{\rm neb})$$

$$t_{\rm dyn} = \frac{R}{\Gamma_{\rm ej} v}$$

$$\tau_{\rm diff}^{\rm neb} = \frac{n'_{\pm}\sigma_T R}{\Gamma_{\rm ej}} = \left(\frac{4YL_{\rm sd}\sigma_T}{\pi m_e c^3 R \Gamma_{\rm ej}^2}\right)^{1/2}$$

Time at which ejecta becomes transparent to gamma-rays

$$t_{{\rm tr},\gamma} \approx \left(\kappa_\gamma M_{\rm ej}/(4\pi v^2)\right)^{1/2} \approx 0.4 \text{ day} \left(\frac{\kappa_\gamma}{0.05 \text{ cm}^2\text{g}^{-1}}\right)^{1/2} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{\beta_{\rm ej}}{0.3}\right)^{-1}$$

Rate of energy generated from r-process nuclei decay

$$\dot{E}_{\rm rp} = \dot{E}_{0,\rm rp} \left(\frac{t}{t_{0,\rm rp}}\right)^{-1.3}$$

$$\dot{E}_{0,\rm rp} = 1.6 \times 10^{11} \text{ erg s}^{-1}\text{g}^{-1}$$

$$t_{0,\rm rp} = 10^4 \text{s}$$

Hotokezaka et al. (2016)

GW-triggered UHE neutrino searches at GRAND-200k

$R_{\mathrm{app},0} = 3\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}, f_{\mathrm{bm}} = 1\ \%$