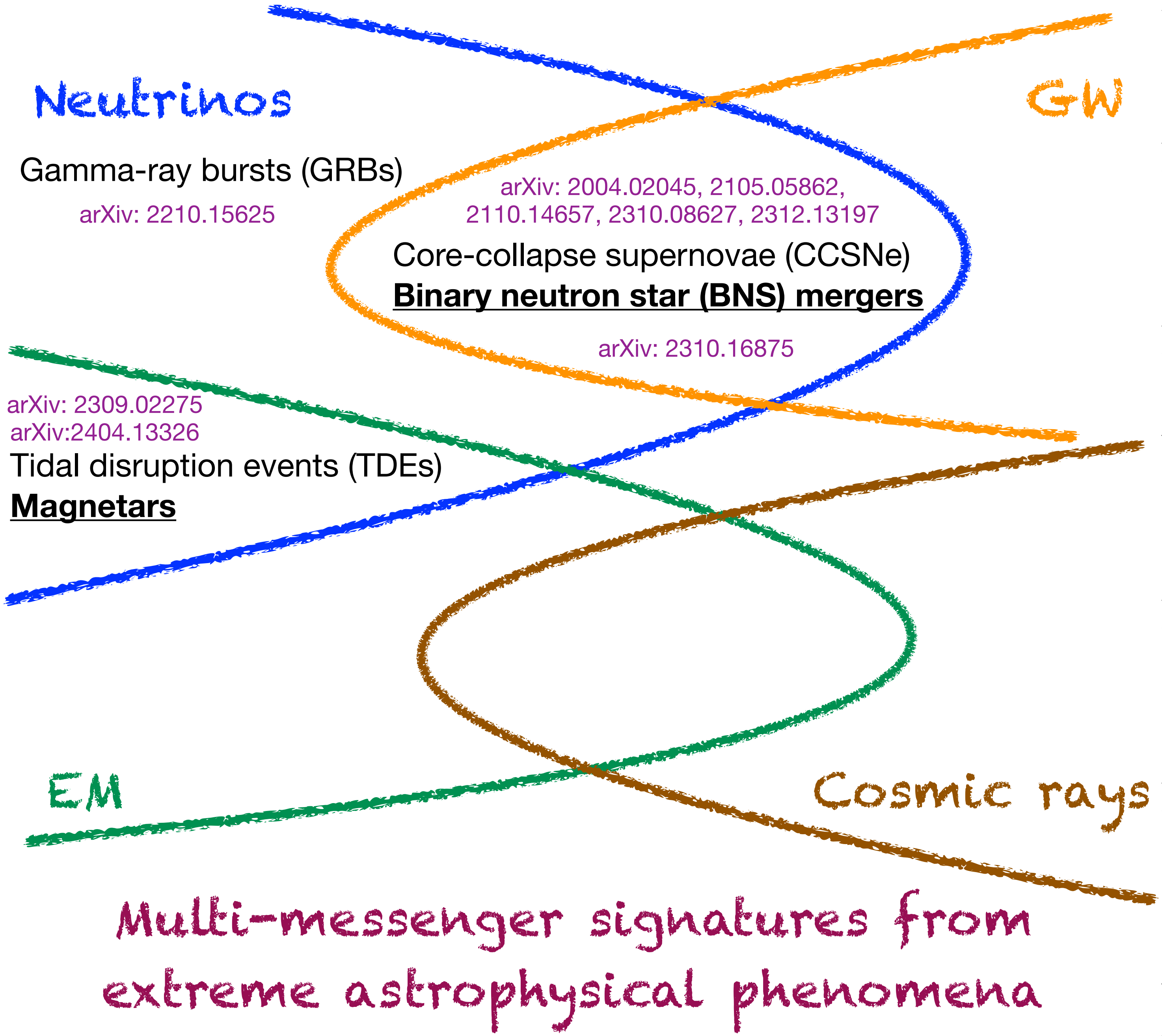
Multi-messenger signatures from high-energy astrophysical phenomena: binary neutron star mergers

Mainak Mukhopadhyay
Pennsylvania State University

TH Cosmo Coffee
CERN, Geneva
June 26, 2024

Research overview



IceCube likelihood analysis pipeline: Correlations with Type Ia/ Type II supernovae
Upcoming JWST searches

Astrophysical signatures of dark matter (DM):
DM cooling in AGNs, CR boosted DM
DM induced neutron star implosions

Quantum fields in time- and space-dependent backgrounds: particle production and back reaction
Applications to early universe cosmology: formation and annihilation of vortices, domain walls, cosmic strings
arXiv:1907.03762, 2004.07249, 2009.11480, 2110.08277, 2303.03415, 2406.13301

Connections to NANOGrav results?

Prologue

New physics, understanding the fundamentals,….

Prologue

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Man-made Accelerators

LHC

Tevatron

Image credits: Wikipedia
Science Comm., DESY, Zeuthen

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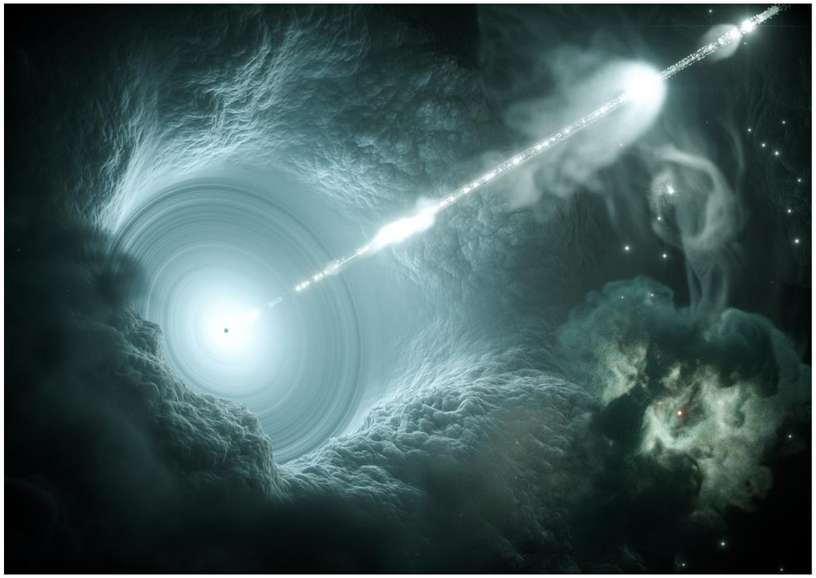
Cosmic Accelerators



High-energy astrophysical phenomena

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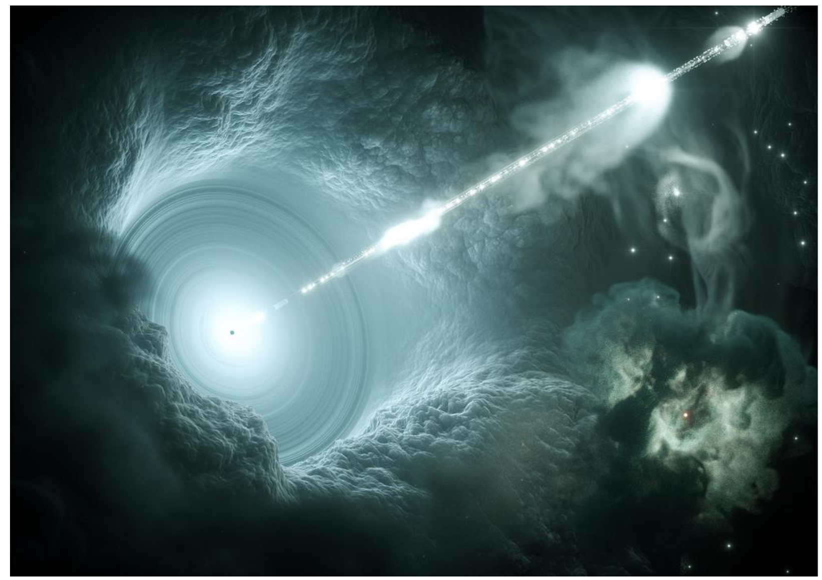

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The multi-messenger paradigm

Compact object mergers, TDEs, CCSNe,….

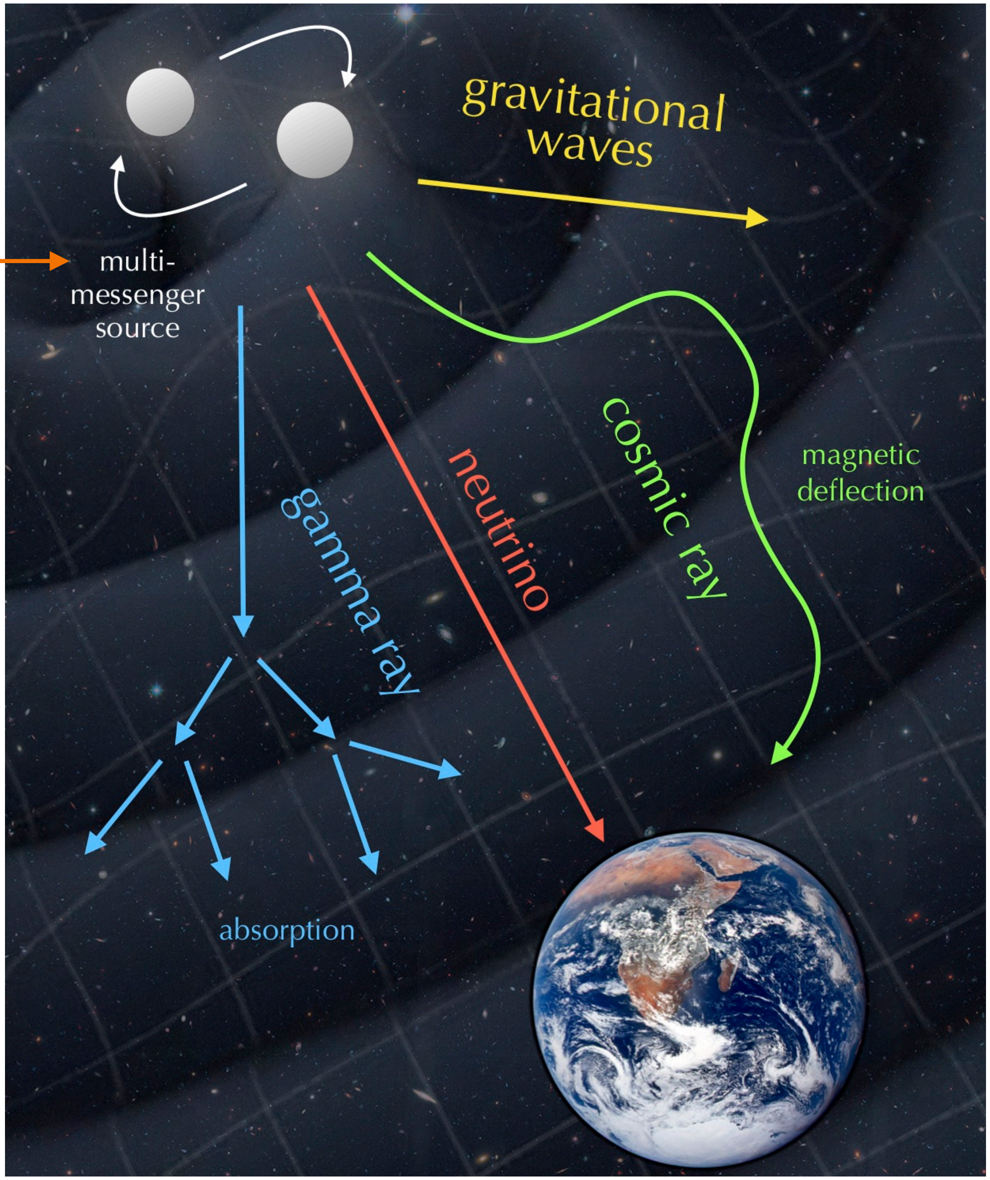
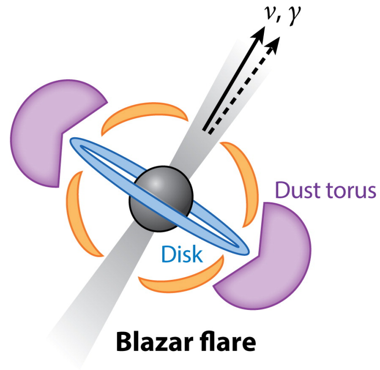


Image credits: https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

The high-energy multi-messenger transients

High-energy astrophysical phenomena



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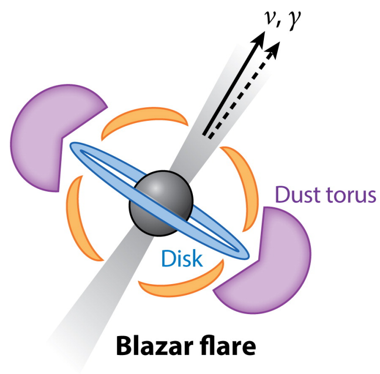

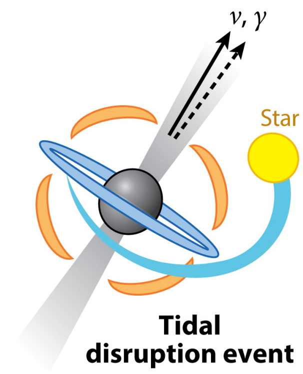

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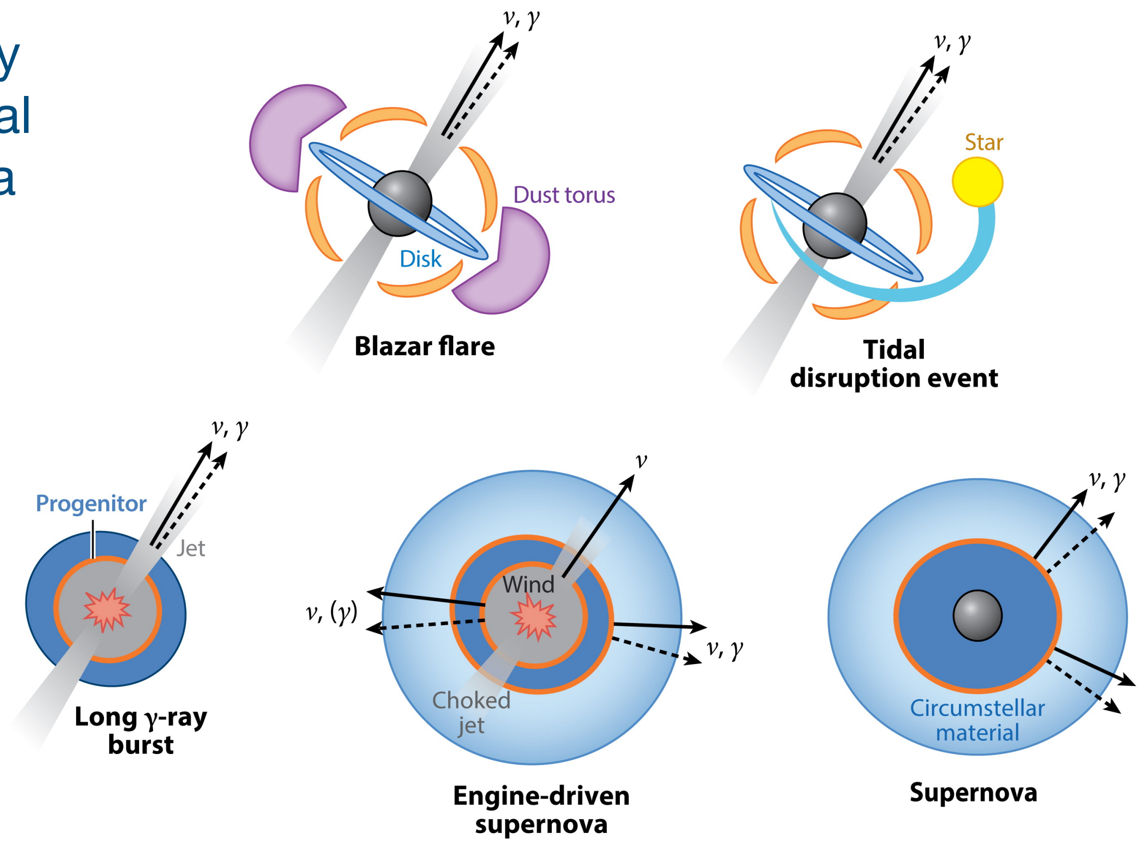

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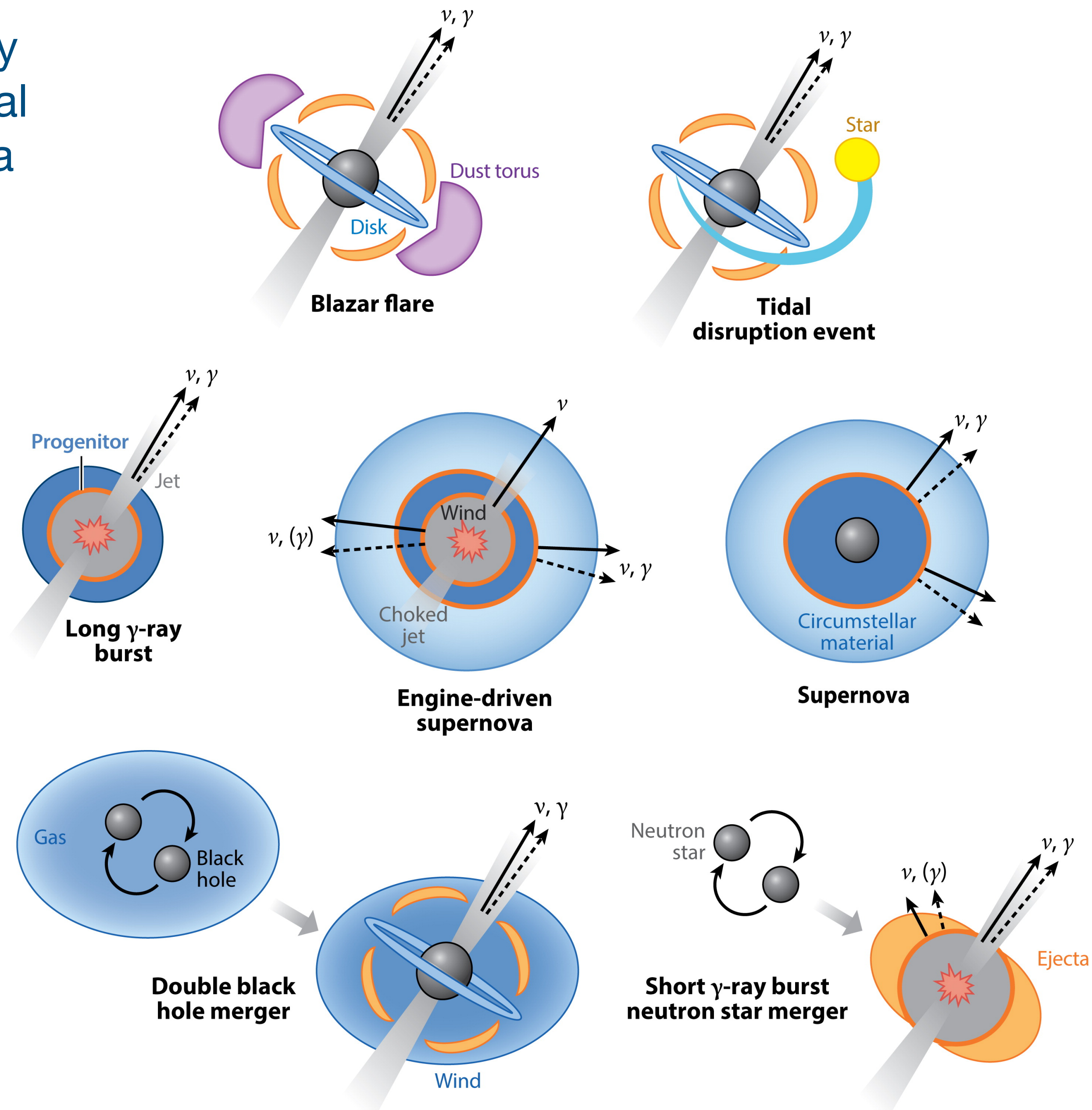

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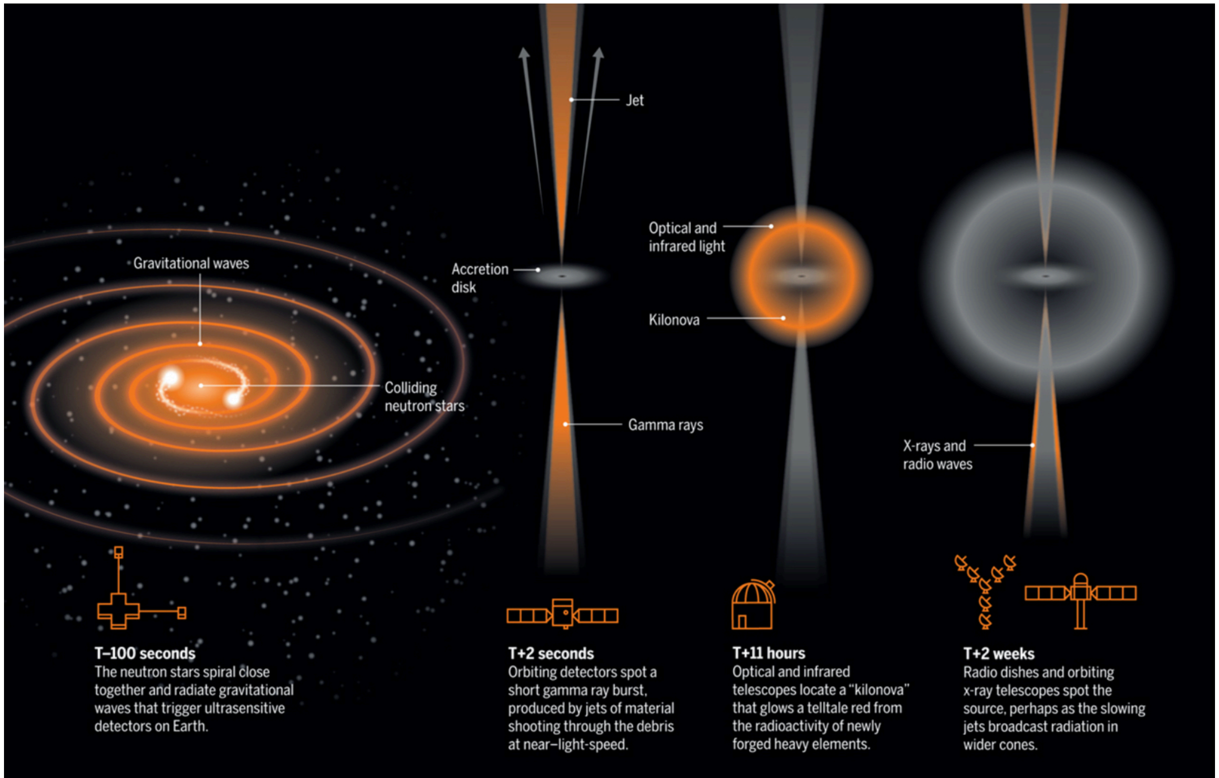
GW170817

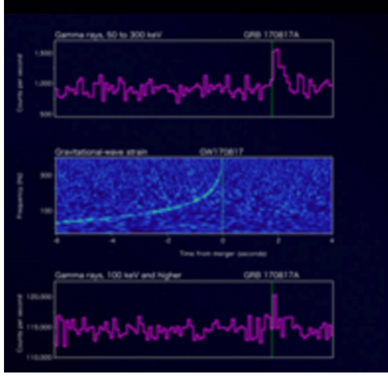
~ 40 Mpc (NGC 4993)

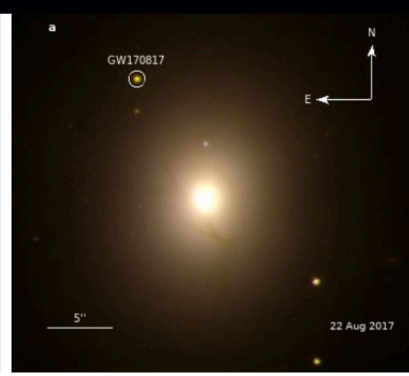


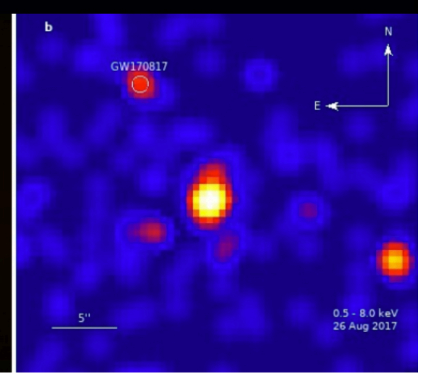
No neutrinos :(

Gamma rays (Fermi+Integral)

GW (Adv. LIGO+Virgo)







X-rays (Chandra)

Optical (HST)

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

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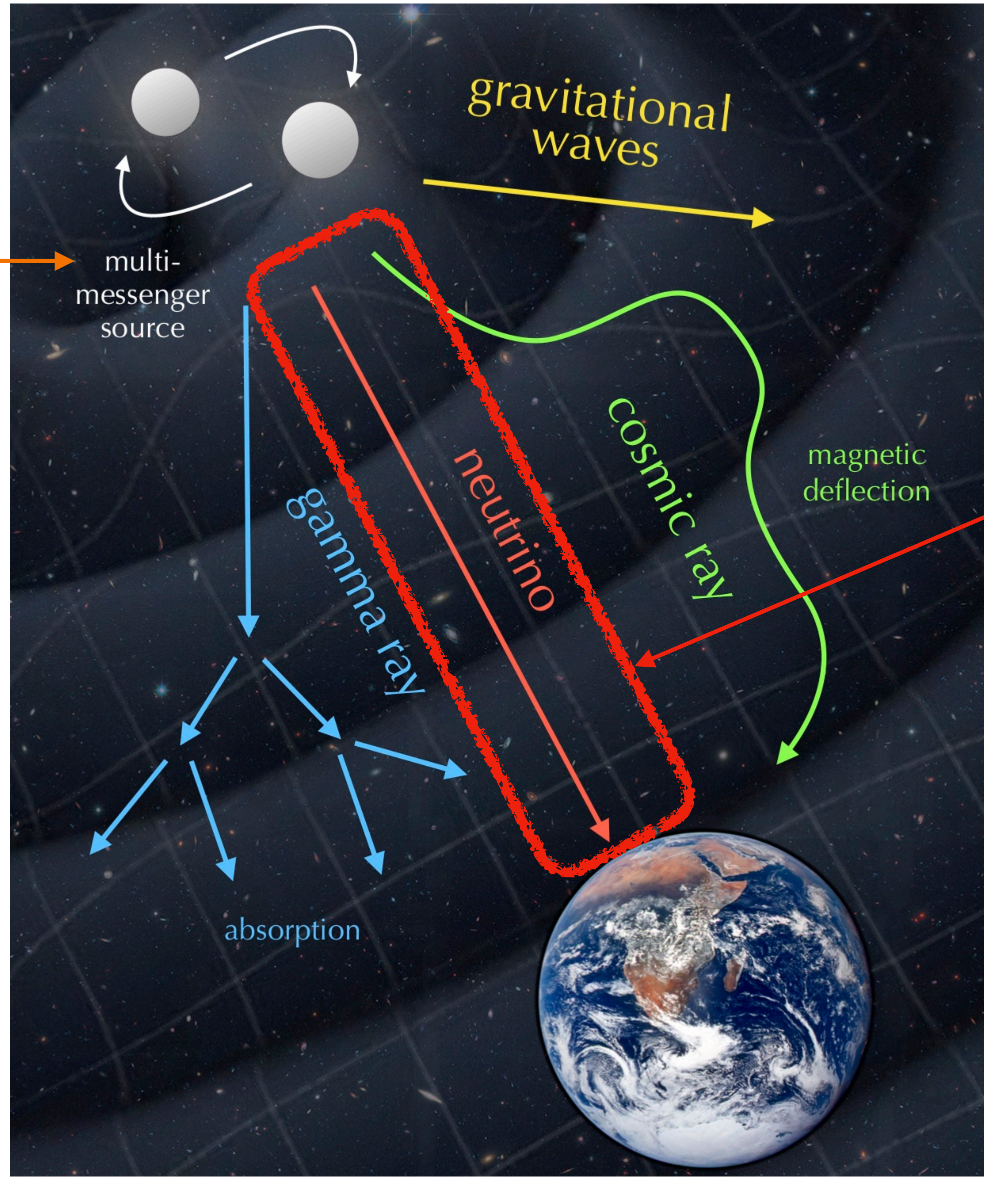

High-energy neutrinos

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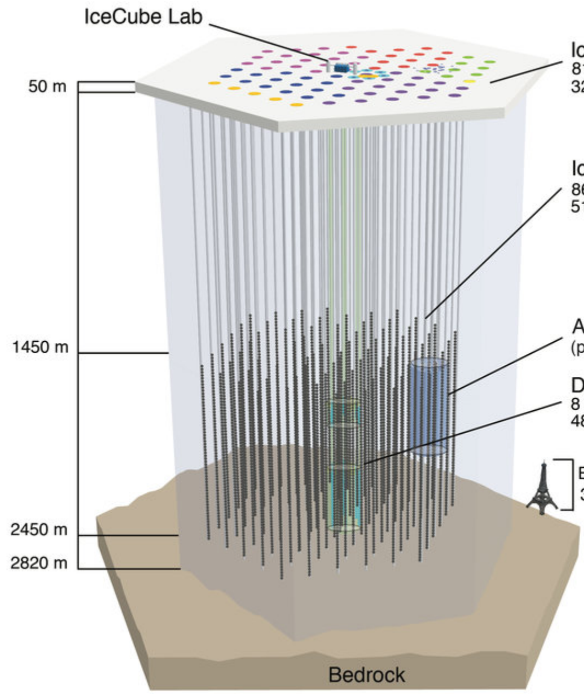
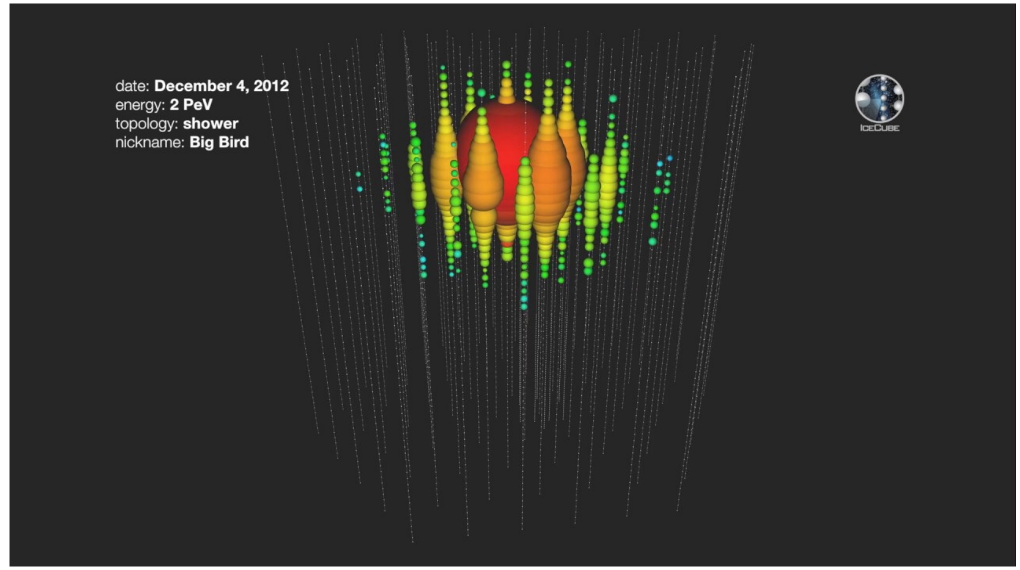
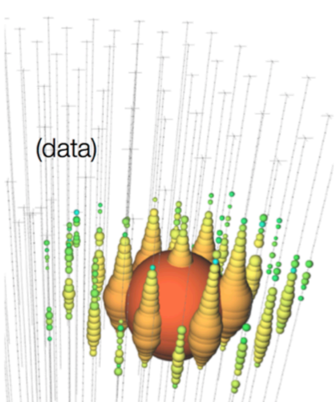
High-energy neutrino detectors





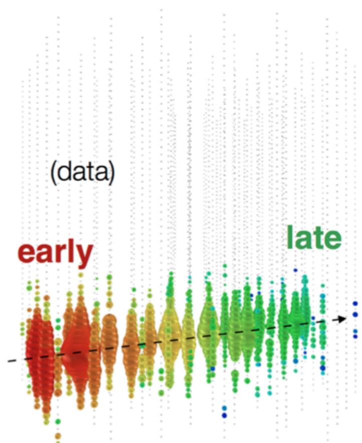
Effective volume $\sim 1\ \text{km}^3$

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_μ

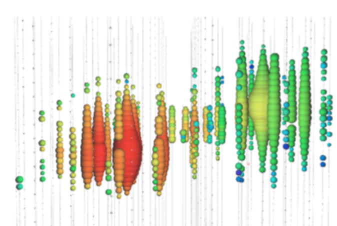


Up-going track

Charged-current ν_τ

IceCube observes seven astrophysical tau neutrino candidates

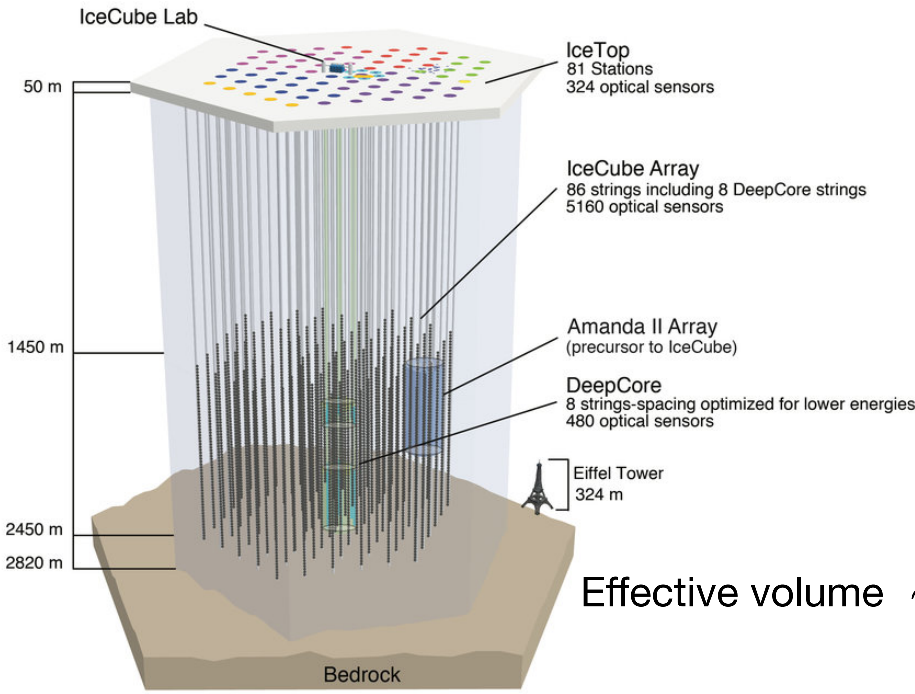
Posted on March 7, 2024 by Alisa King-Klemperer



Double cascade

Image credits: icecube.wisc.edu

High-energy neutrino detectors



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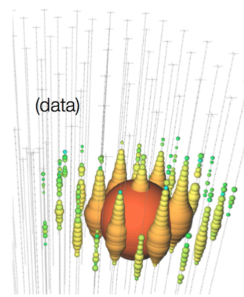

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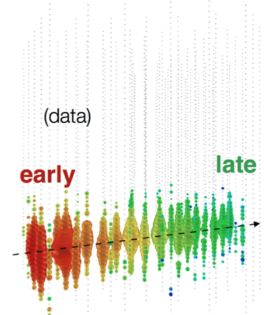

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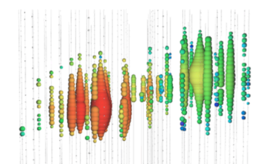
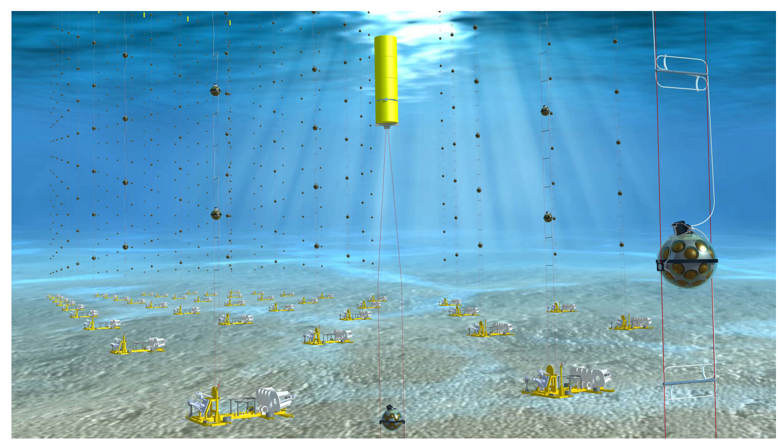
(simulation)



Double cascade

KM3NeT



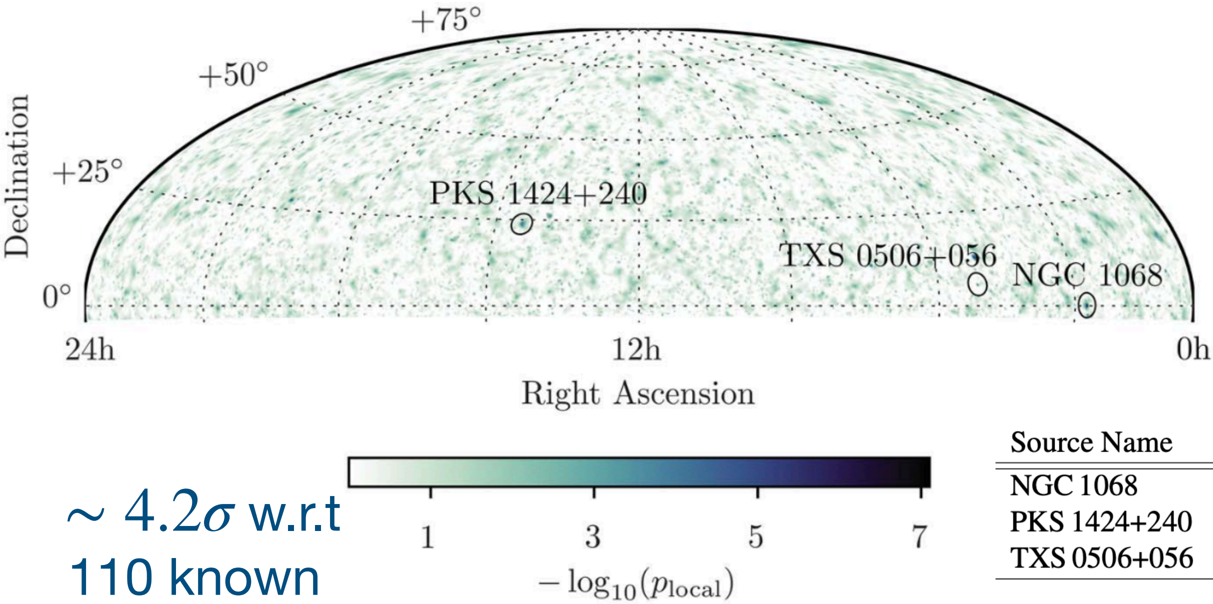
Baikal GVD

ANTARES

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

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

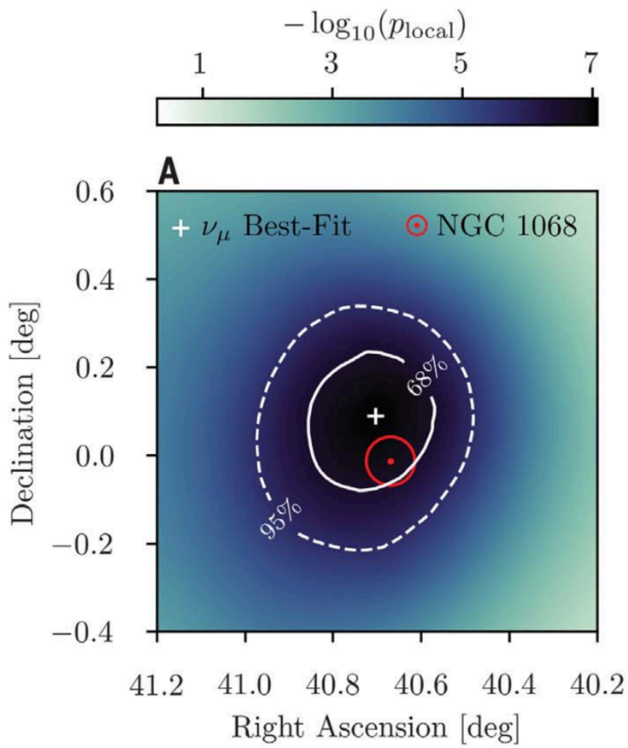
NGC 1068 (also TXS 0506+056)

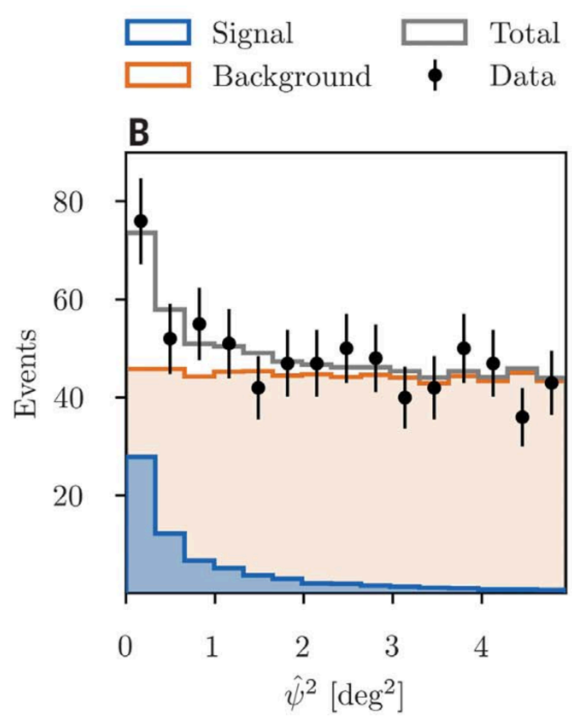


10 years of PS data (2011-2020)

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

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
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





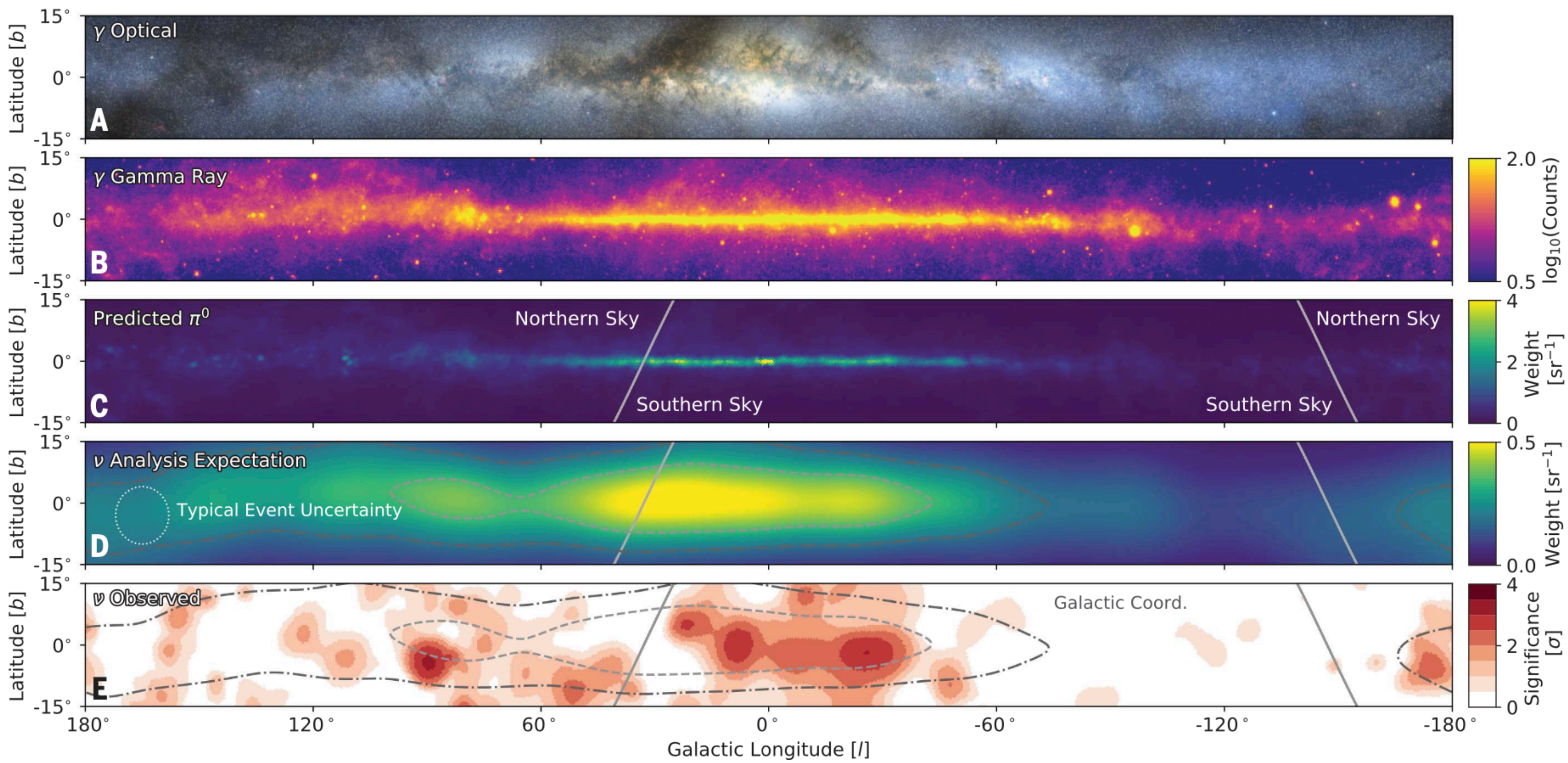
$\sim 79^{+22}_{-20}$ excess events

IceCube Collab.+ Science 2022

The Galactic plane

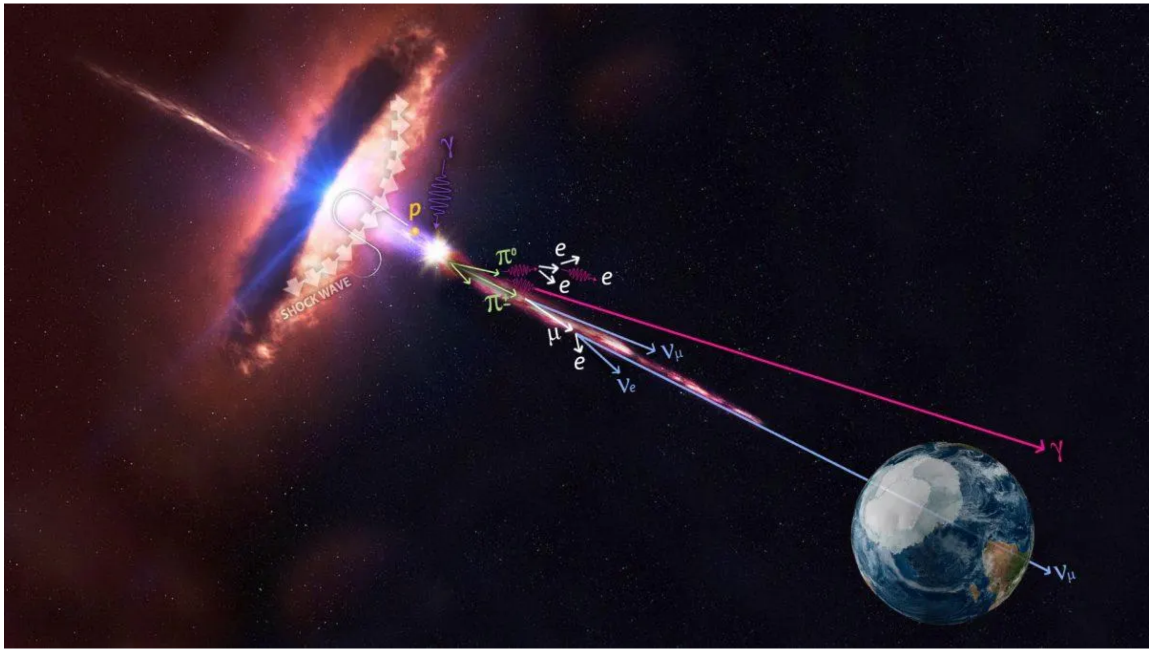
10 years of PS data (2011-2020)

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



IceCube Collab.+ Science, 380, 2023

High-energy (HE) neutrinos



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

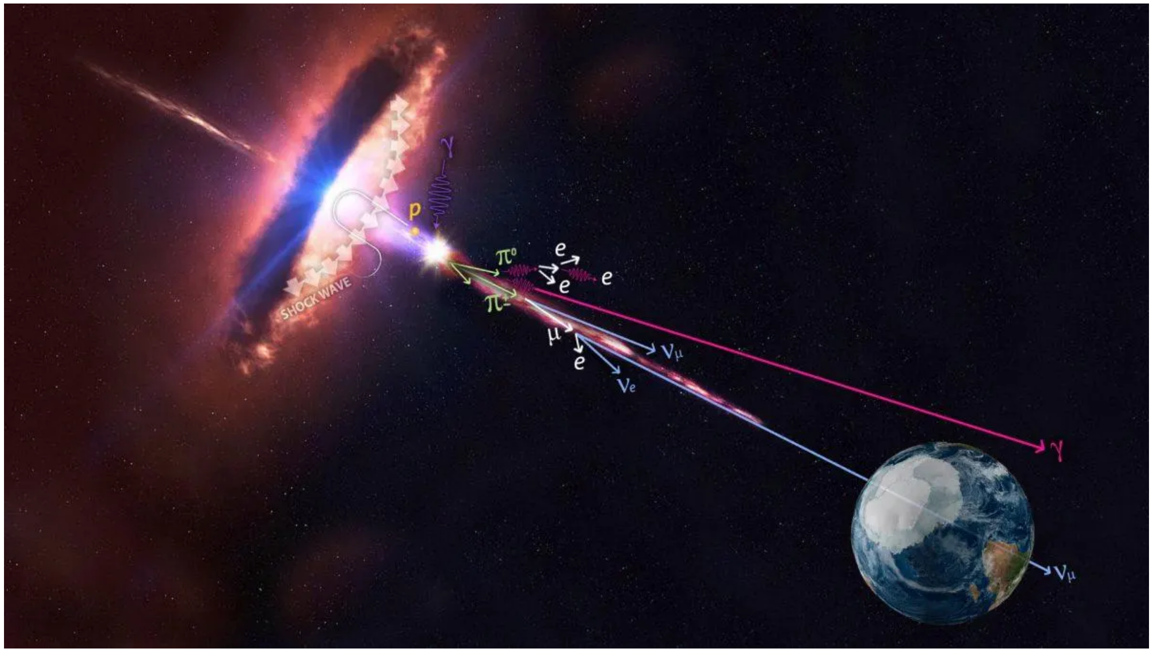
$$\downarrow$$

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

$$\downarrow$$

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

High-energy (HE) neutrinos



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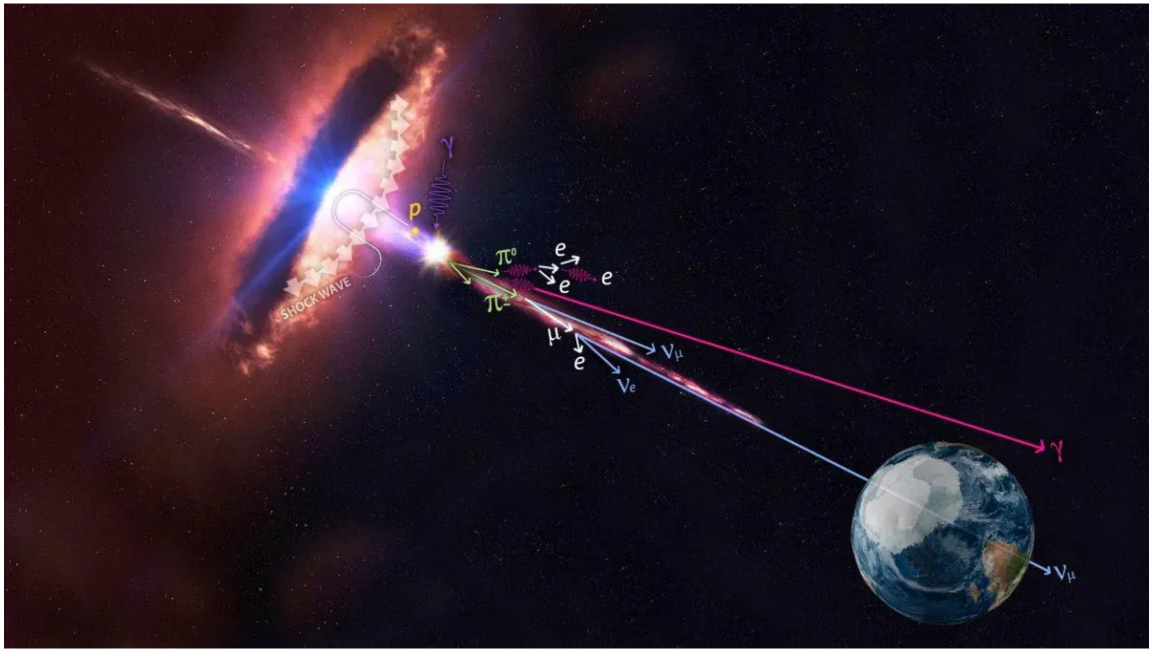
$$\pi^0 \to \gamma + \gamma$$

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

High-energy (HE) neutrinos



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

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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

Proton inelasticity

p-p cross-section

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

Proton energy

p-γ cross-section

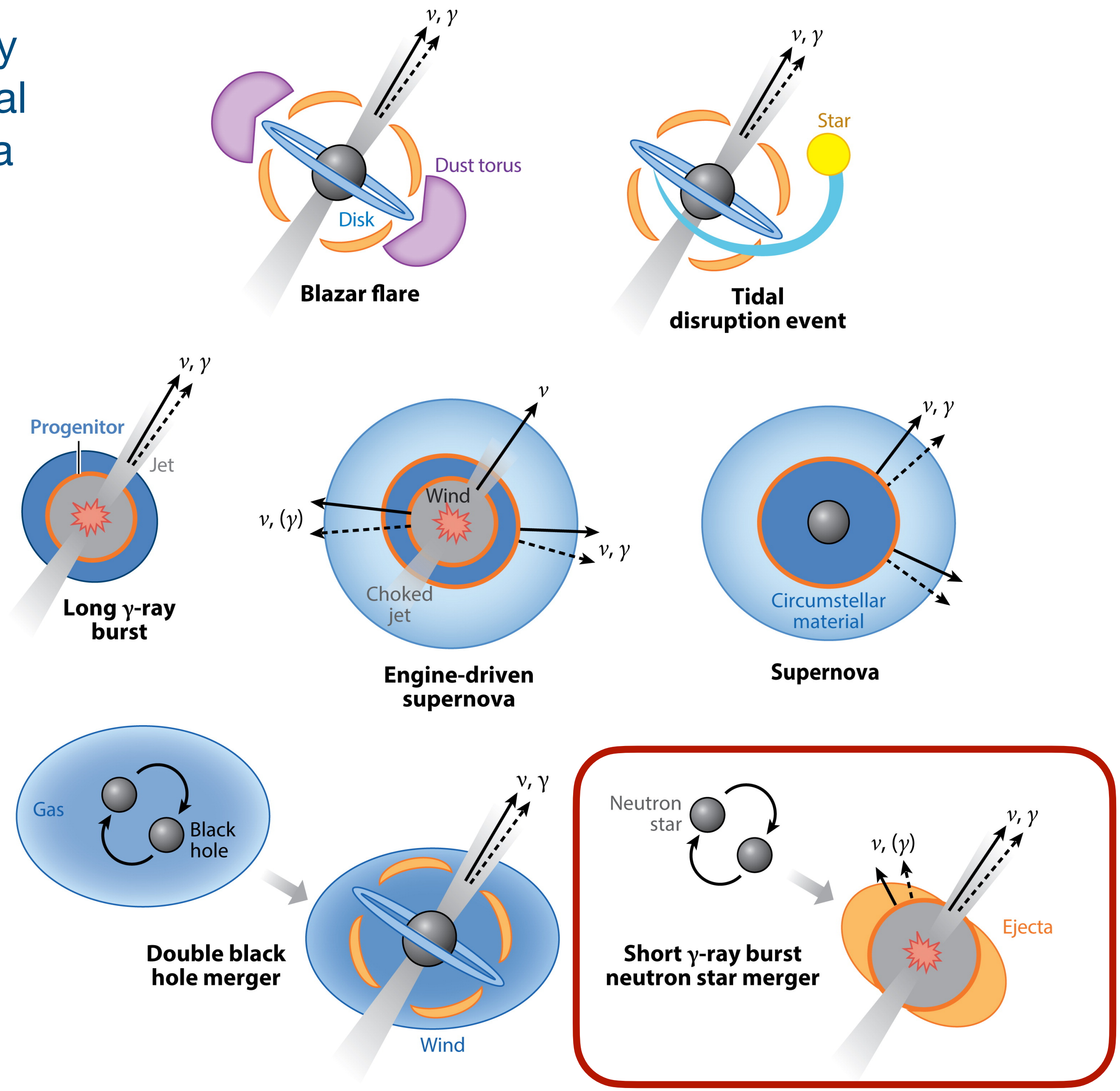
$$t_{p\gamma}^{-1}(\epsilon_p) = \frac{c}{2\gamma_p^2} \int_{\bar{\epsilon}_{\text{th}}}^{\infty} d\bar{\epsilon} \kappa_{p\gamma}(\bar{\epsilon}) \sigma_{p\gamma}(\bar{\epsilon}) \bar{\epsilon} \int_{\bar{\epsilon}/2\gamma_p}^{\infty} d\epsilon \epsilon^{-2} n_\epsilon$$

Photon energy in proton rest frame

Proton energy loss due to p-γ interactions

The high-energy multi-messenger transients

High-energy astrophysical phenomena



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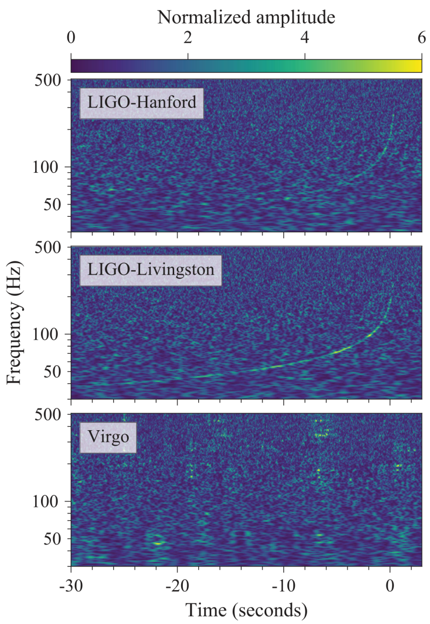
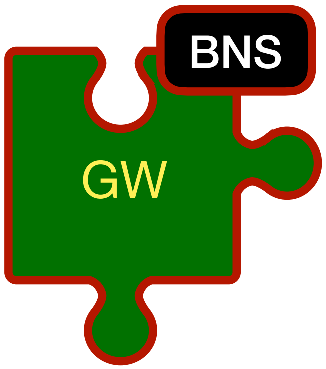
BNS mergers: particle accelerators and multi-messenger zoo



Observed



S. Gezari, Annu. Rev. Astron. Astrophys. 2021. 59:21–58
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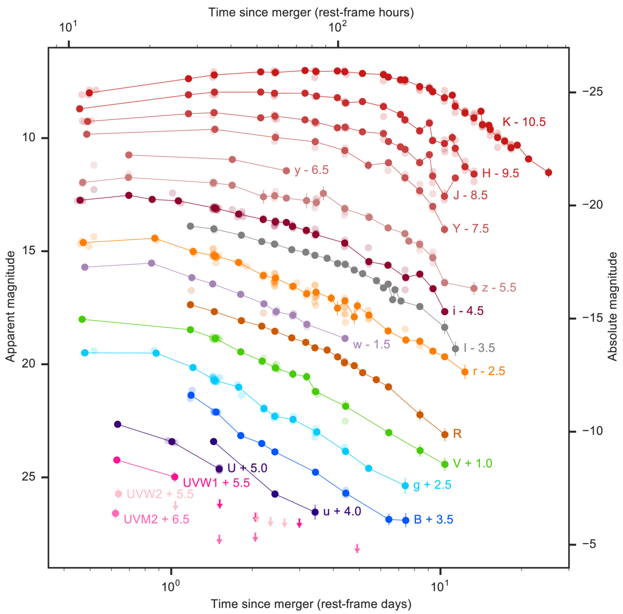
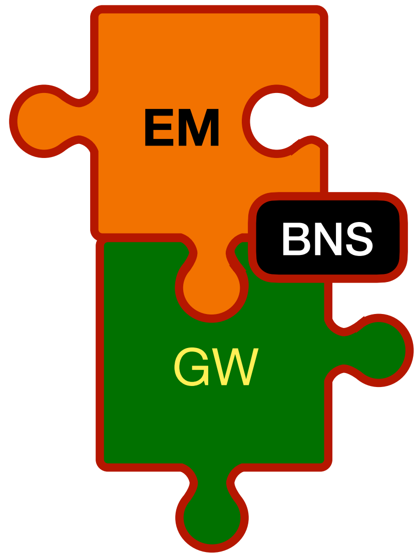
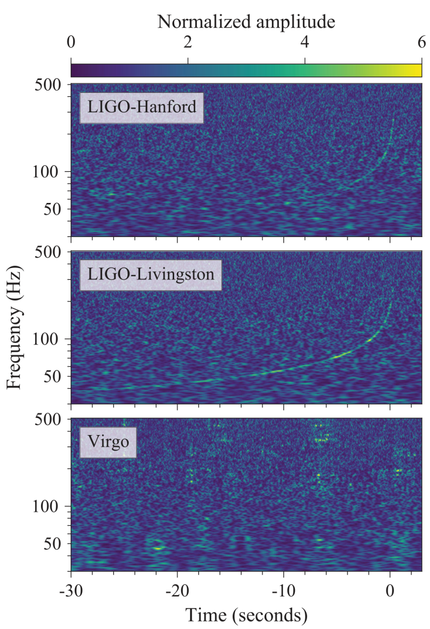


Kilonova emission
Afterglow emission
Short GRB





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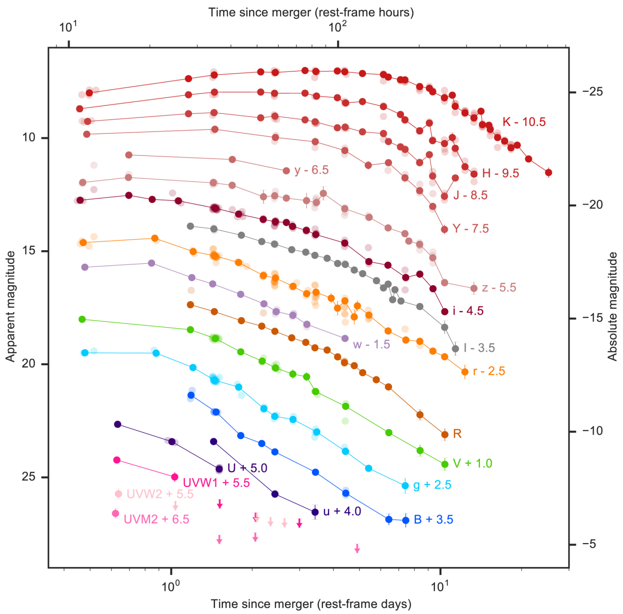

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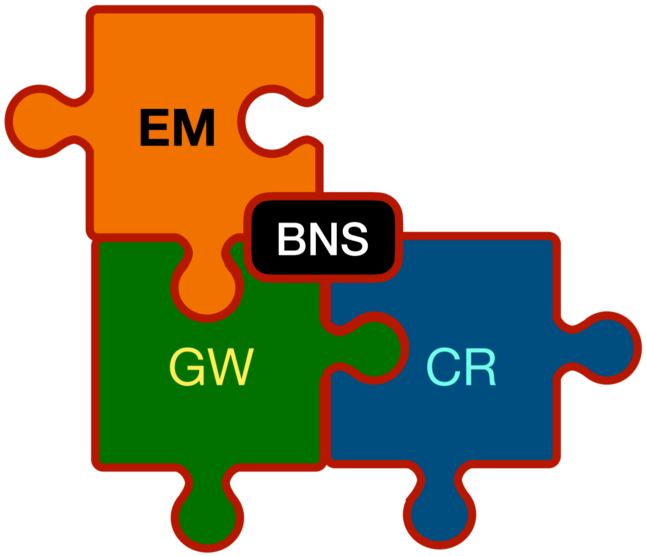

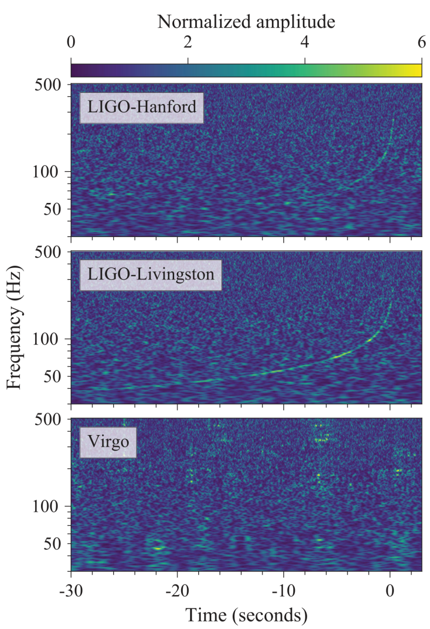

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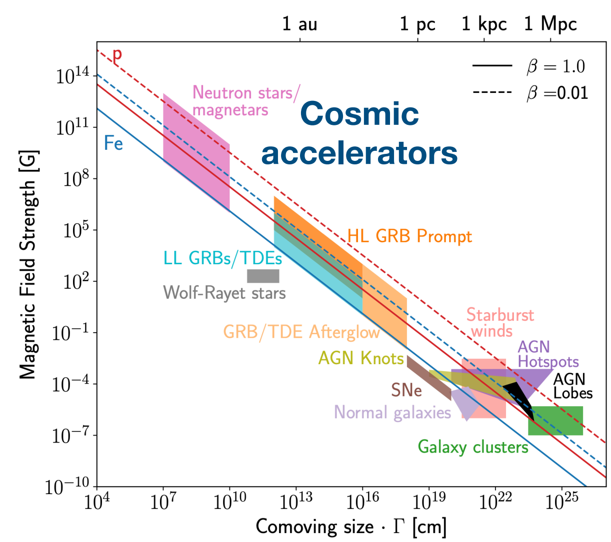

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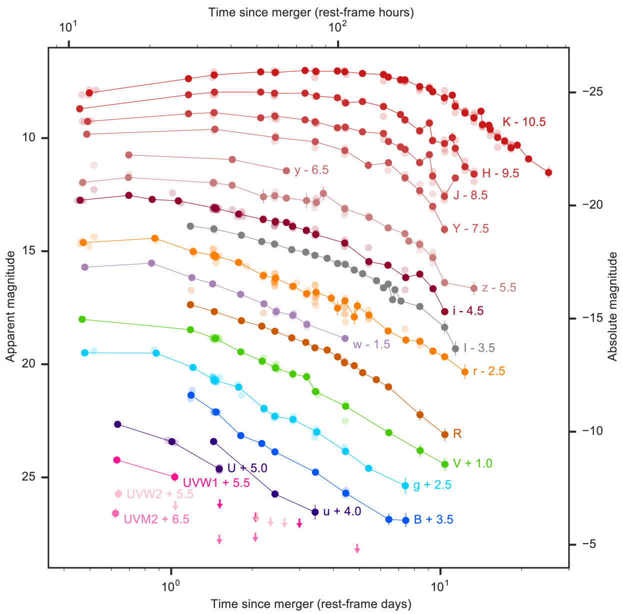

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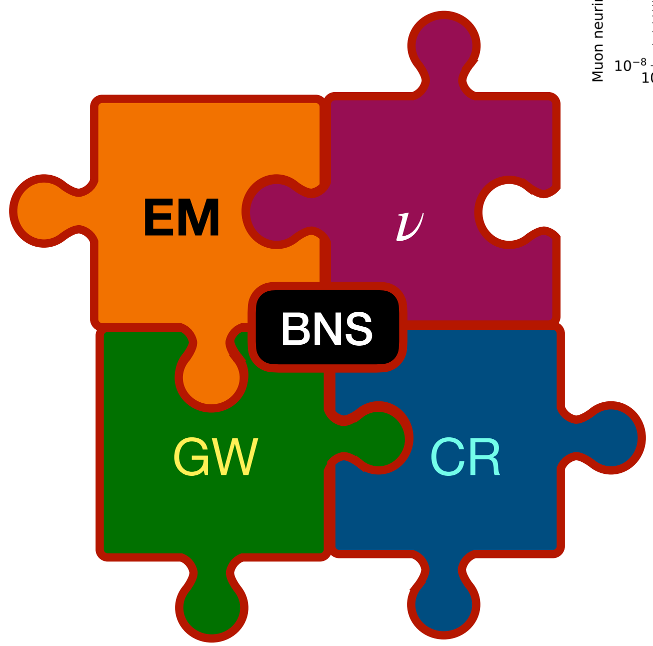

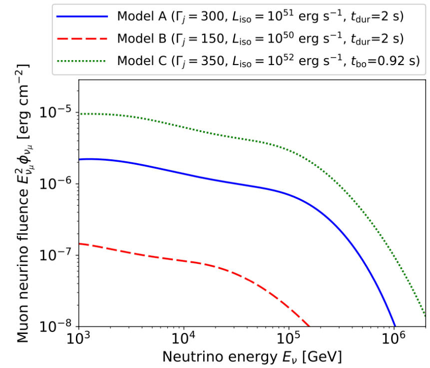

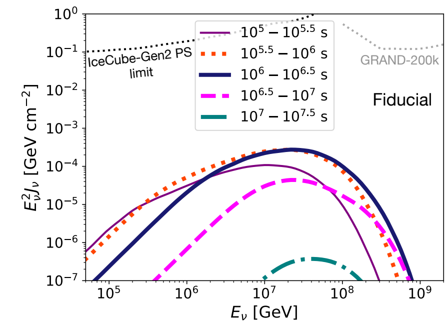

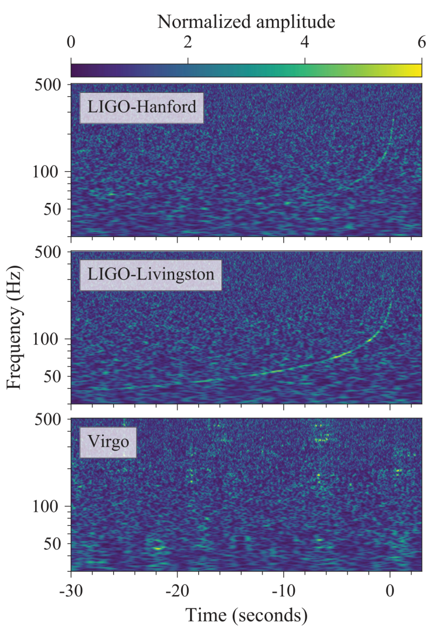

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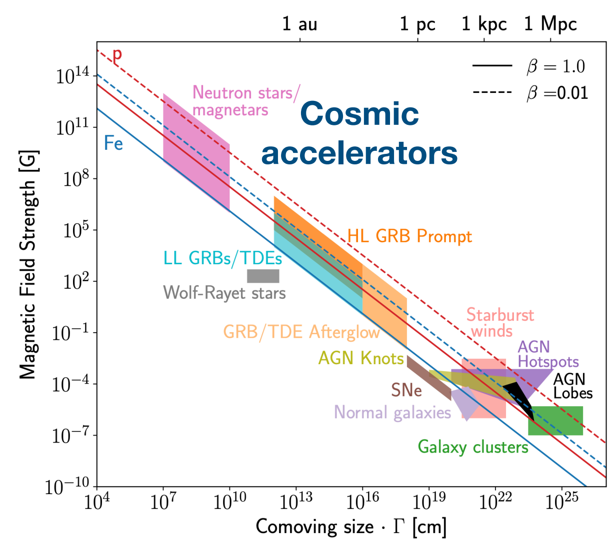

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Outline

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MM, S.S. Kimura
(in preparation)

Electromagnetic signatures from pulsar remnants of binary neutron-star mergers
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Part 2: Hunting for high-energy and ultrahigh energy neutrinos from BNS mergers at next-generation GW and neutrino detectors

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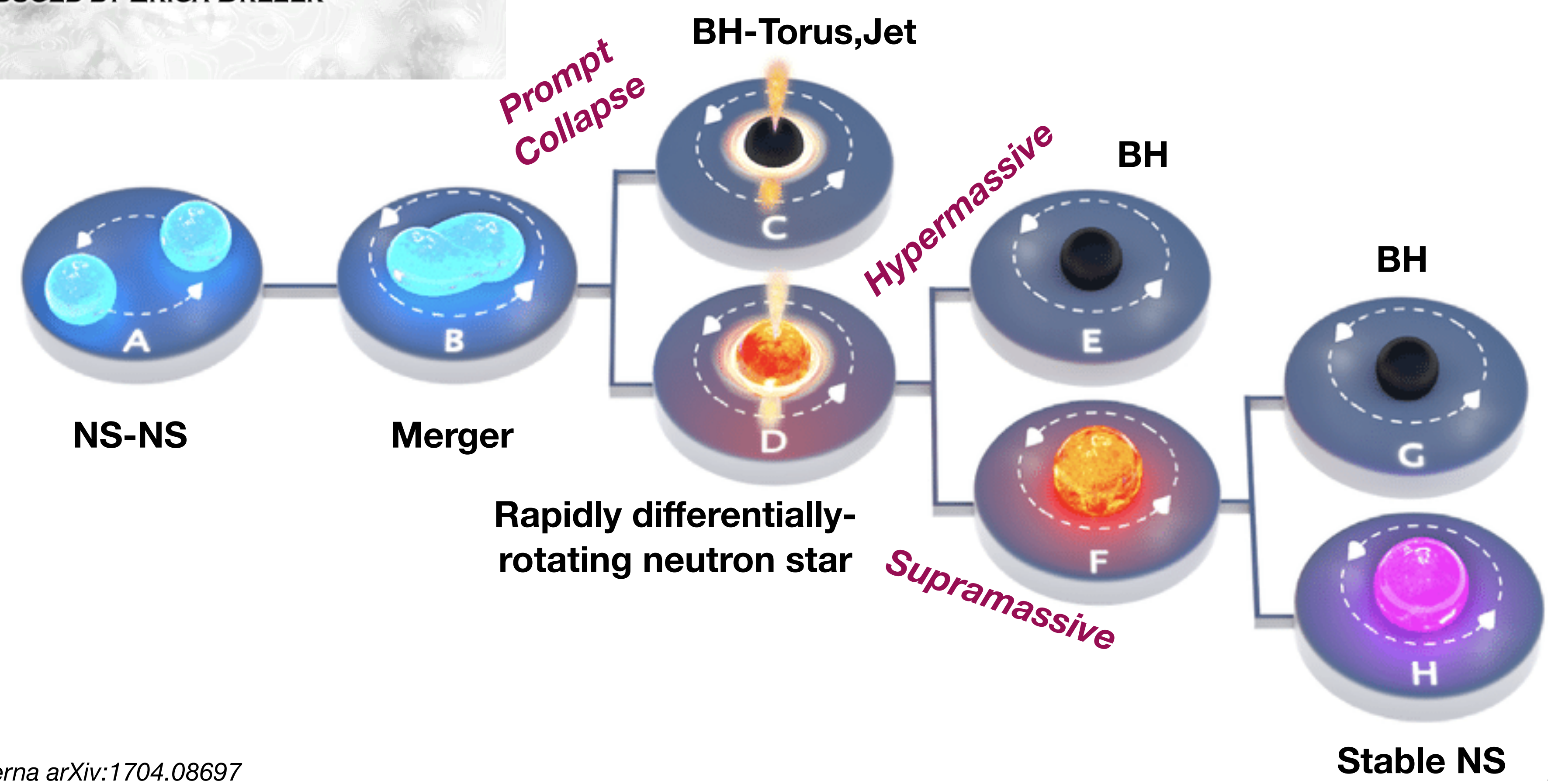
Fate of NS-NS mergers

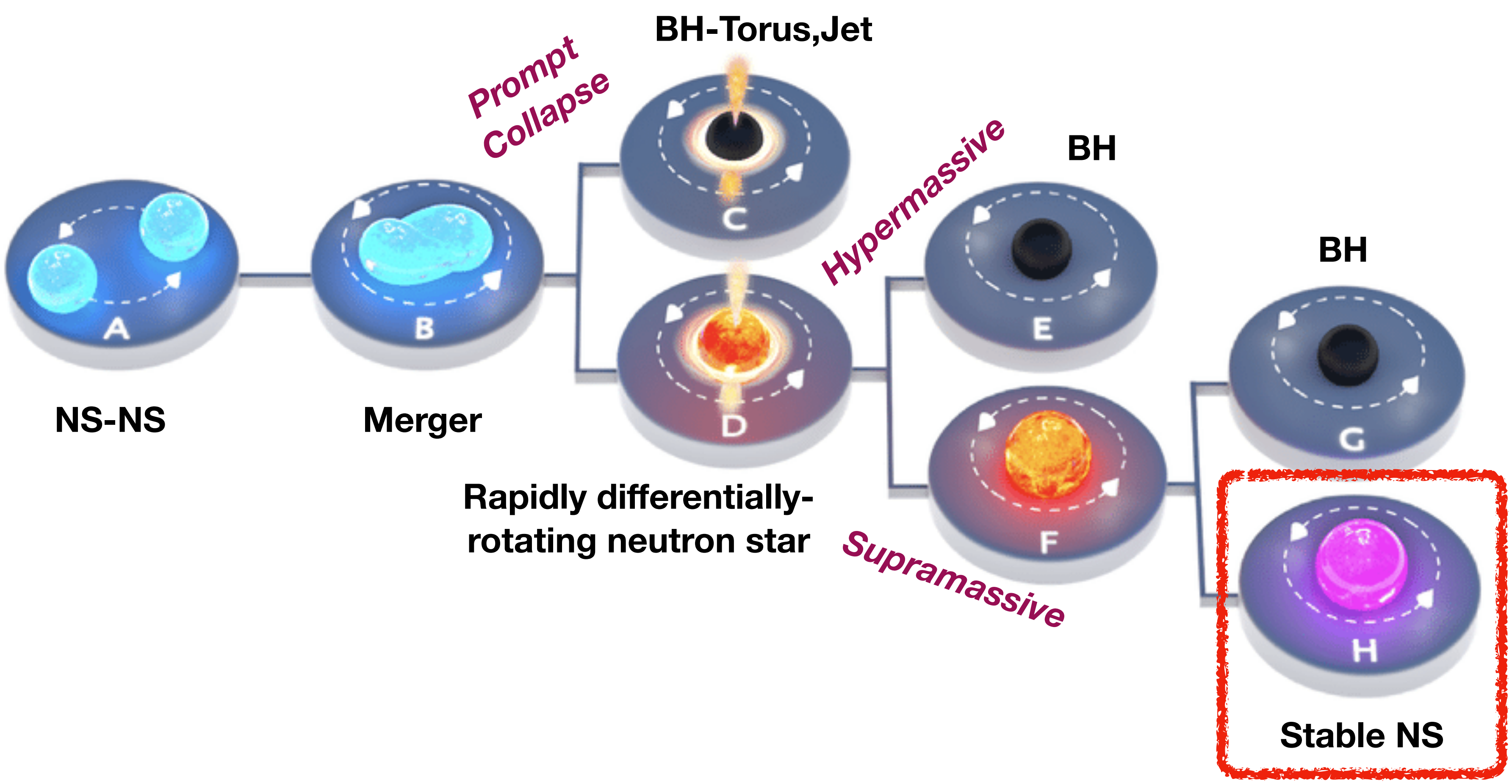
Fate decided by EOS, Mass, Spin, ….



Piro, Giacomazzo, Perna arXiv:1704.08697

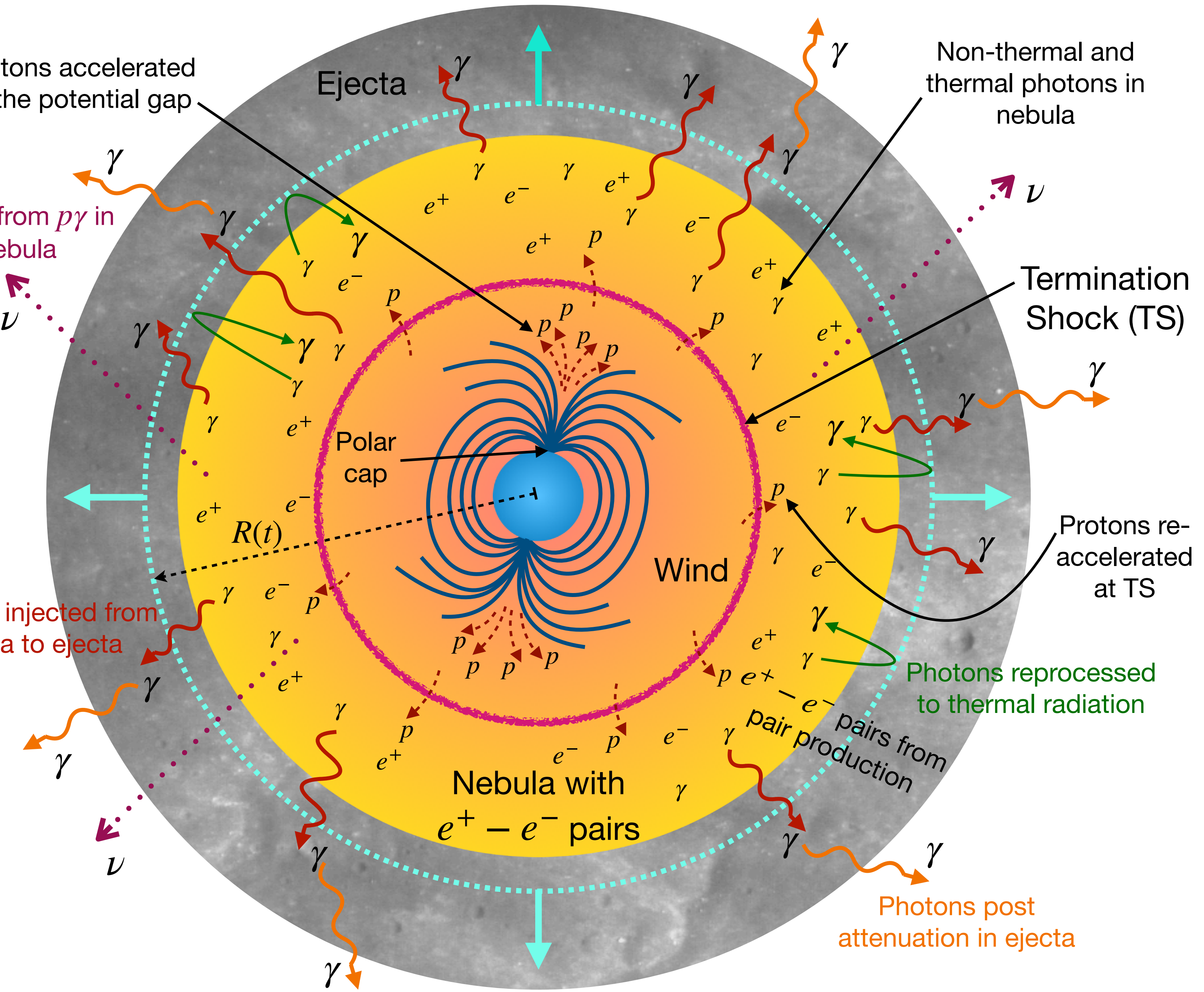
Fate of NS-NS mergers

Fate decided by EOS, Mass, Spin, ….

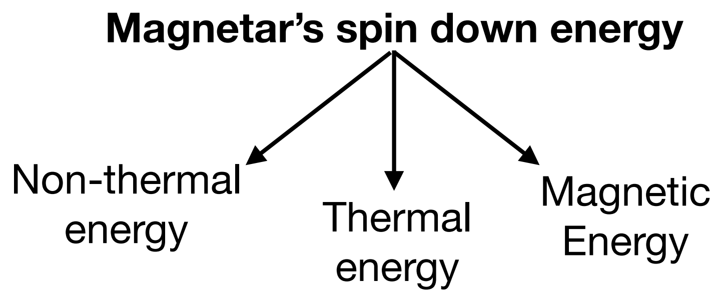


Piro, Giacomazzo, Perna arXiv:1704.08697

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
$e^+ - e^-$ pairs from
pair production
Photons reprocessed
to thermal radiation
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

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

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Spin-down luminosity

PdV work by the nebula

Photon diffusion from nebula to ejecta

Thermal energy

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

Fraction of non-thermal photons that escape

Photon diffusion through ejecta

Metzger, B. D., & Piro, A. L. 2014, MNRAS, 439, 3916
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PdV work by the nebula

Fraction of non-thermal photons that escape

Magnetic field strength amplification parameter

$$\epsilon_{\rm B} \sim 10^{-2}$$

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

Thermal energy

Magnetic energy

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

Photon diffusion through ejecta

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

Non-thermal energy

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

- $L_{\rm sd}$: Spin-down luminosity
- $\frac{E_{\rm nth}}{R}\frac{dR}{dt}$: PdV work by the nebula
- $\frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}}$: Photon diffusion from nebula to ejecta

Thermal energy

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

- $\mathscr{A}$: Fraction of non-thermal photons that escape
- $\frac{E_{\rm th}}{t_{\rm diff}^{\rm ej}}$: Photon diffusion through ejecta

Magnetic energy

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

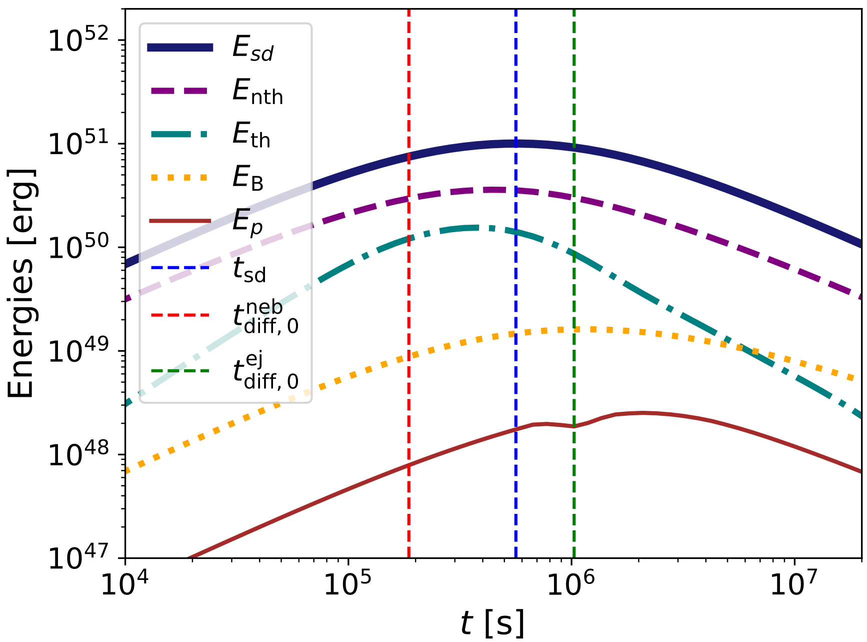
- $\epsilon_{\rm B} \sim 10^{-2}$: Magnetic field strength amplification parameter

Work done on the ejecta

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

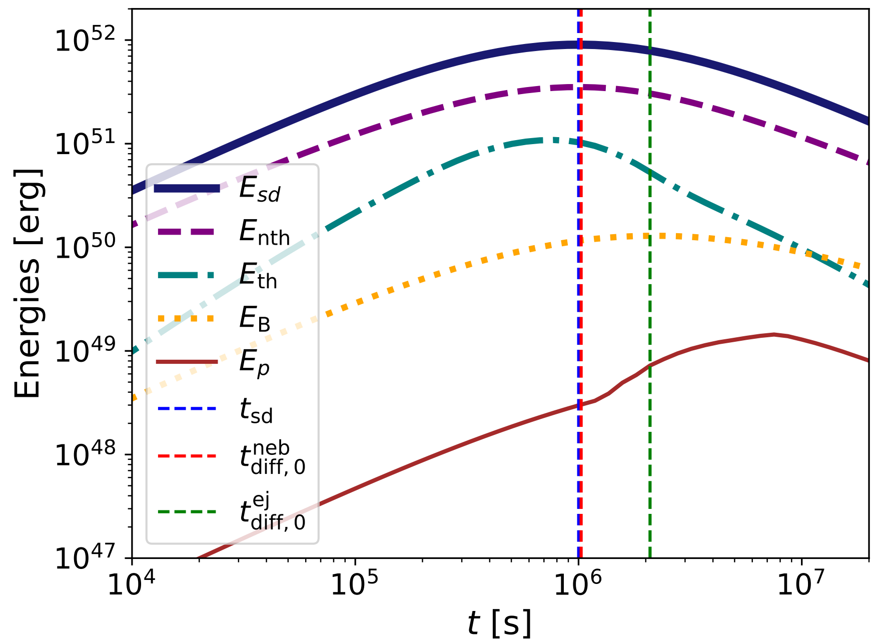
Metzger, B. D., & Piro, A. L. 2014, MNRAS, 439, 3916
Fang, K. & Metzger, B.D. 2017, ApJ 849, 153

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



Fiducial:

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



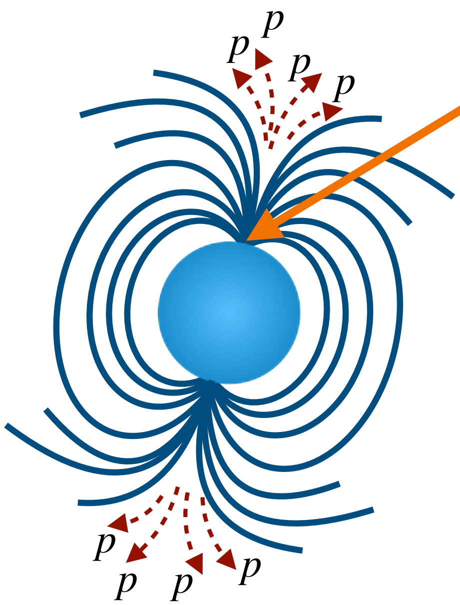
Optimistic:

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

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

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

Cosmic ray (CR) proton acceleration: injection spectra



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

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

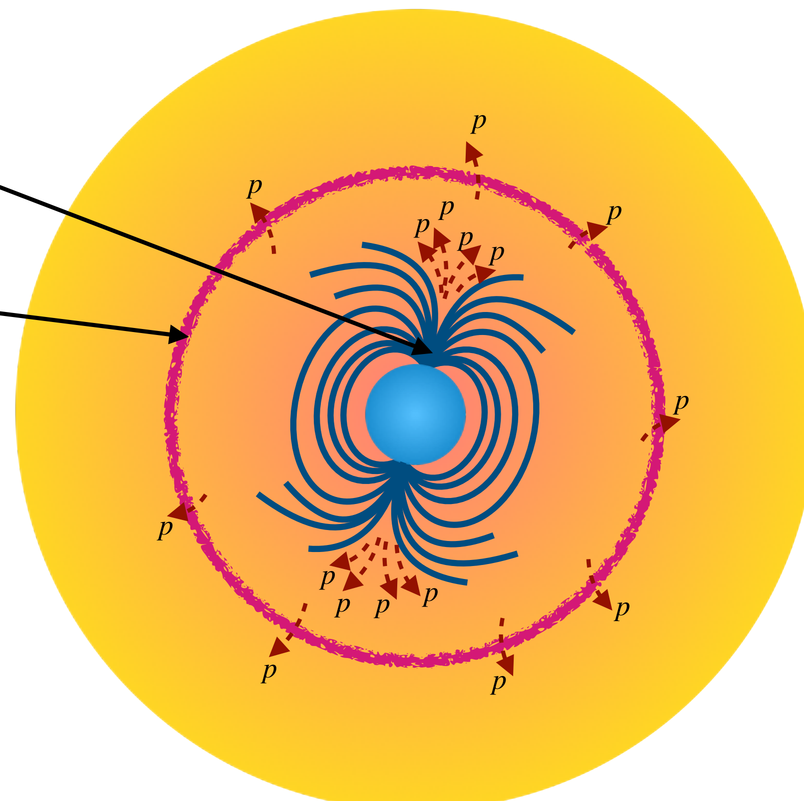
$$\dot{N}_p = n_{\mathrm{GJ}} 2 A_{\mathrm{pc}} c = \frac{4\pi^2}{Ze} \frac{R_*^3}{c} \frac{B_0}{P^2}$$

Acceleration sites:

Polar cap

+

Termination shock (TS)

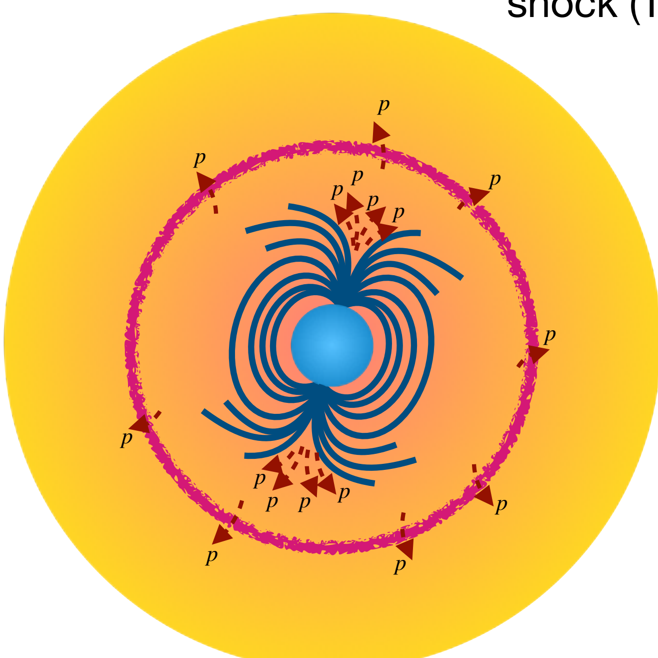


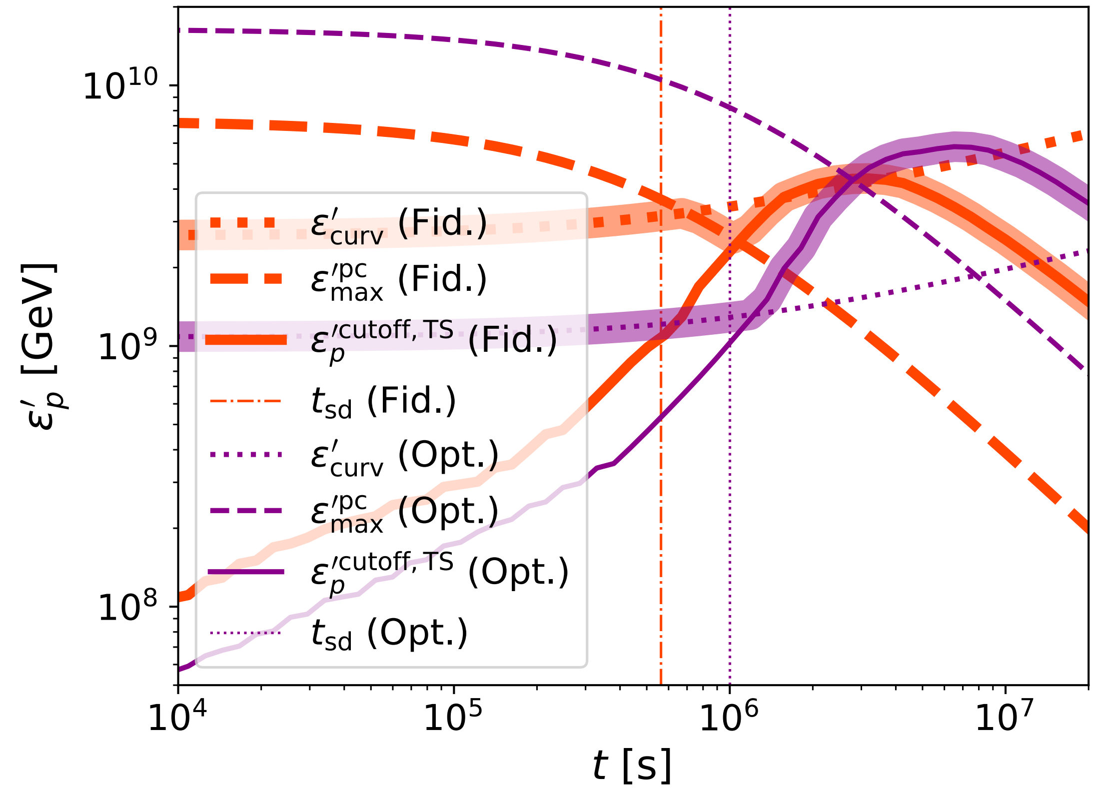
Cosmic ray (CR) proton acceleration: injection spectra

$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \exp\left(-\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right) \begin{cases} \left(\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right)^{-1}, \ \varepsilon'_p < \varepsilon_p^{\prime\mathrm{cutoff,pc}} \ \mathrm{or} \ \varepsilon_p^{\prime\mathrm{cutoff,TS}} < \varepsilon_p^{\prime\mathrm{cutoff,pc}} \\ \left(\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right)^{-2}, \ \varepsilon'_p > \varepsilon_p^{\prime\mathrm{cutoff,pc}} \ \mathrm{and} \ \varepsilon_p^{\prime\mathrm{cutoff,TS}} > \varepsilon_p^{\prime\mathrm{cutoff,pc}}, \end{cases}$$

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

Acceleration sites: Polar cap + Termination shock (TS)





Cosmic ray (CR) proton acceleration: injection spectra

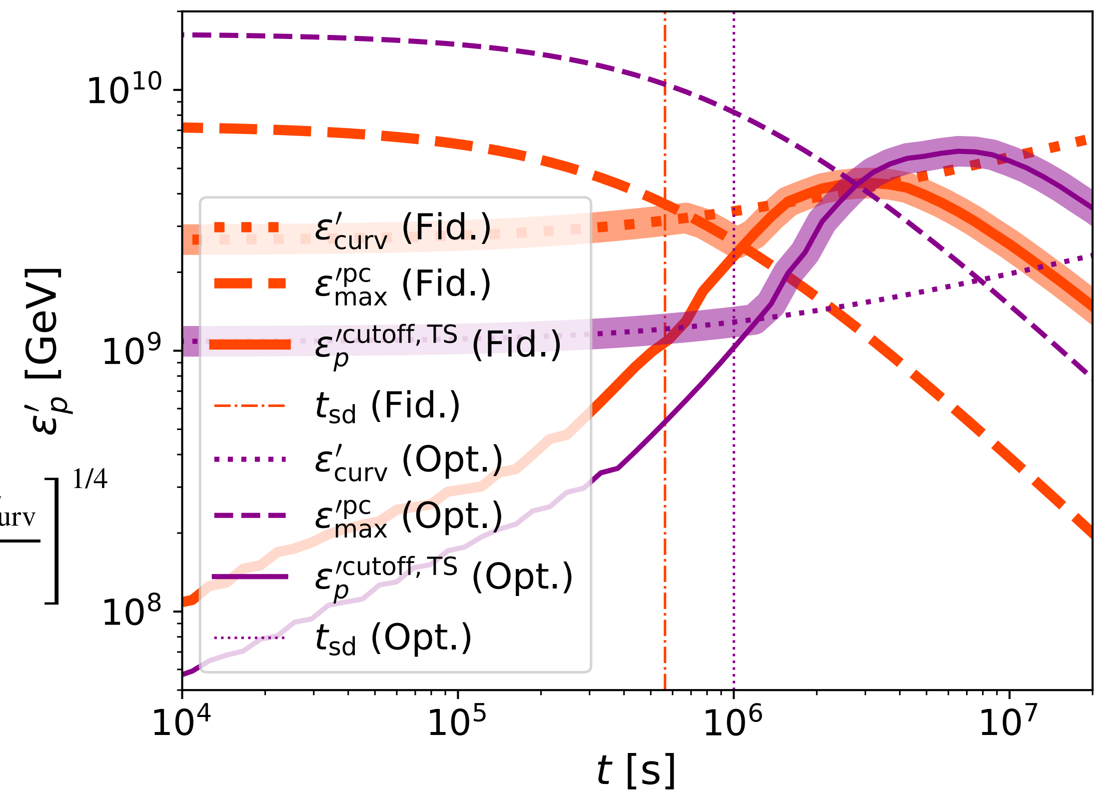
$$\frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} = \dot{N}_p^{\rm norm} Q_p^{\rm inj}(\varepsilon'_p) = \dot{N}_p^{\rm norm} \exp\left(-\frac{\varepsilon'_p}{\varepsilon_p'^{\rm cutoff}}\right) \begin{cases} \left(\frac{\varepsilon'_p}{\varepsilon_p'^{\rm cutoff}}\right)^{-1}, \; \varepsilon'_p < \varepsilon_p'^{\rm cutoff,pc} \text{ or } \varepsilon_p'^{\rm cutoff,TS} < \varepsilon_p'^{\rm cutoff,pc} \\ \left(\frac{\varepsilon'_p}{\varepsilon_p'^{\rm cutoff}}\right)^{-2}, \; \varepsilon'_p > \varepsilon_p'^{\rm cutoff,pc} \text{ and } \varepsilon_p'^{\rm cutoff,TS} > \varepsilon_p'^{\rm cutoff,pc}, \end{cases}$$

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

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

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

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



Cosmic ray (CR) proton acceleration: injection spectra

$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \exp\left(-\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right) \begin{cases} \left(\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right)^{-1}, \ \varepsilon'_p < \varepsilon_p^{\prime\mathrm{cutoff,pc}} \ \text{or} \ \varepsilon_p^{\prime\mathrm{cutoff,TS}} < \varepsilon_p^{\prime\mathrm{cutoff,pc}} \\ \left(\frac{\varepsilon'_p}{\varepsilon_p^{\prime\mathrm{cutoff}}}\right)^{-2}, \ \varepsilon'_p > \varepsilon_p^{\prime\mathrm{cutoff,pc}} \ \text{and} \ \varepsilon_p^{\prime\mathrm{cutoff,TS}} > \varepsilon_p^{\prime\mathrm{cutoff,pc}}, \end{cases}$$

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

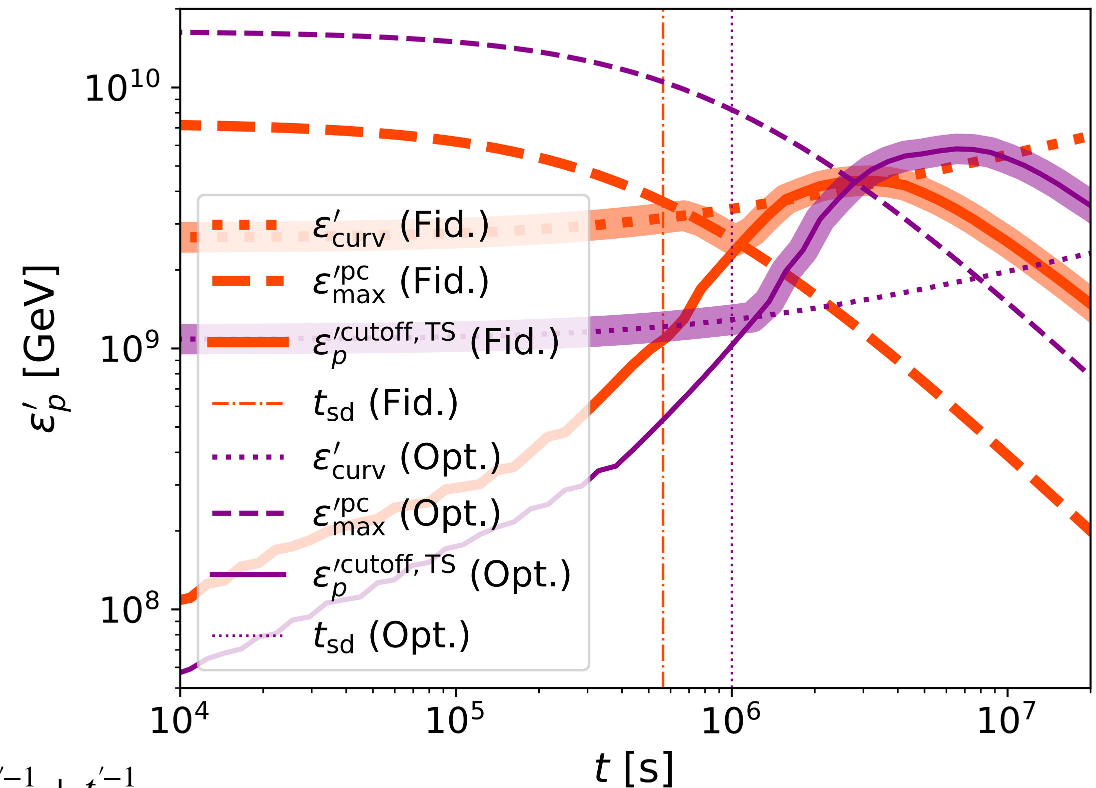
$$t_{\mathrm{acc}}^{\prime -1} = t_{\mathrm{loss}}^{\prime -1}$$

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

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

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

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

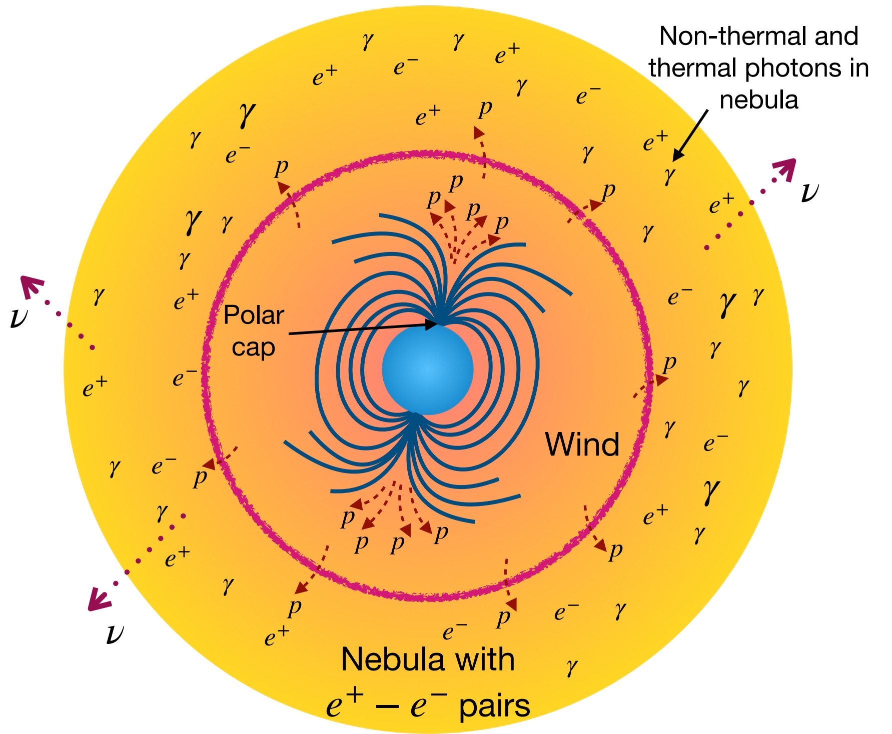


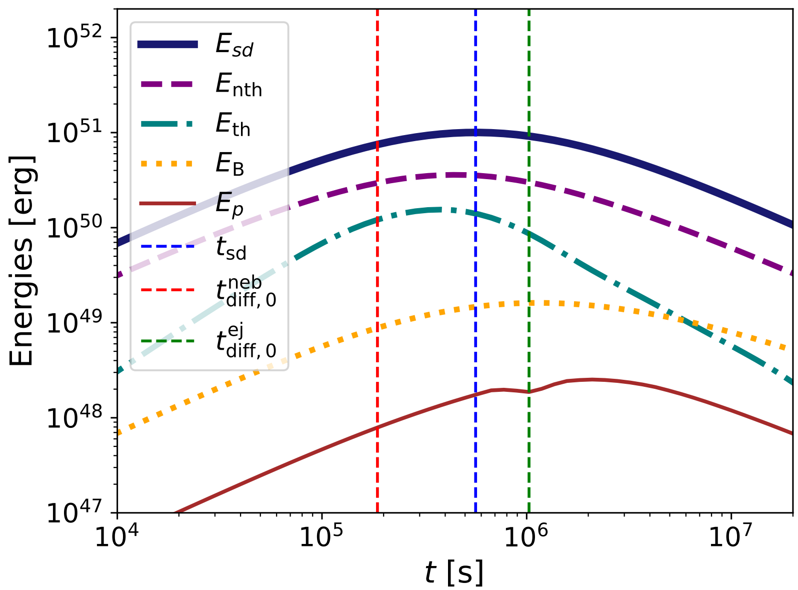
Cosmic ray (CR) proton acceleration

Compute steady state CE spectrum by solving the transport equation

↓

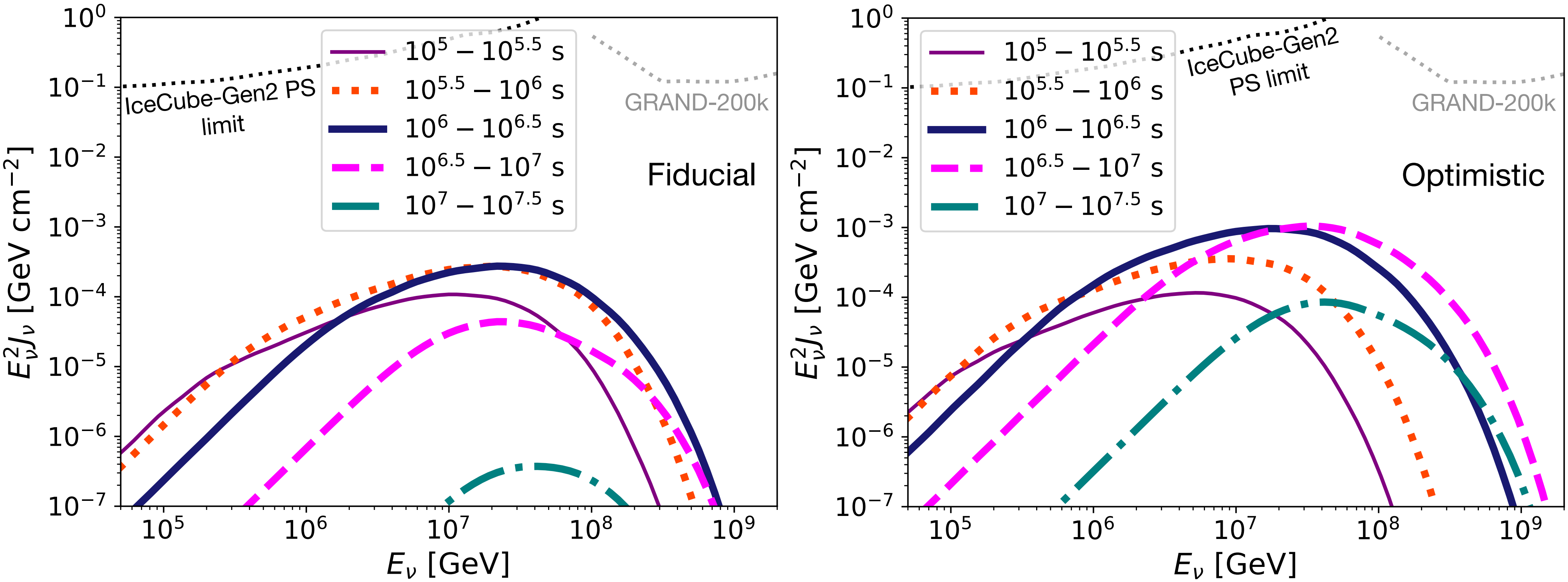
This along with the photon field spectrum gives the neutrino fluences





$$E_p = \int d\varepsilon'_p \, \varepsilon'_p \frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} t$$

The money plot: Neutrino fluences (takeaway)



$d_L = 40$ Mpc

Peak fluence: $\sim 3 \times 10^{-4}$ GeV cm^{-2}

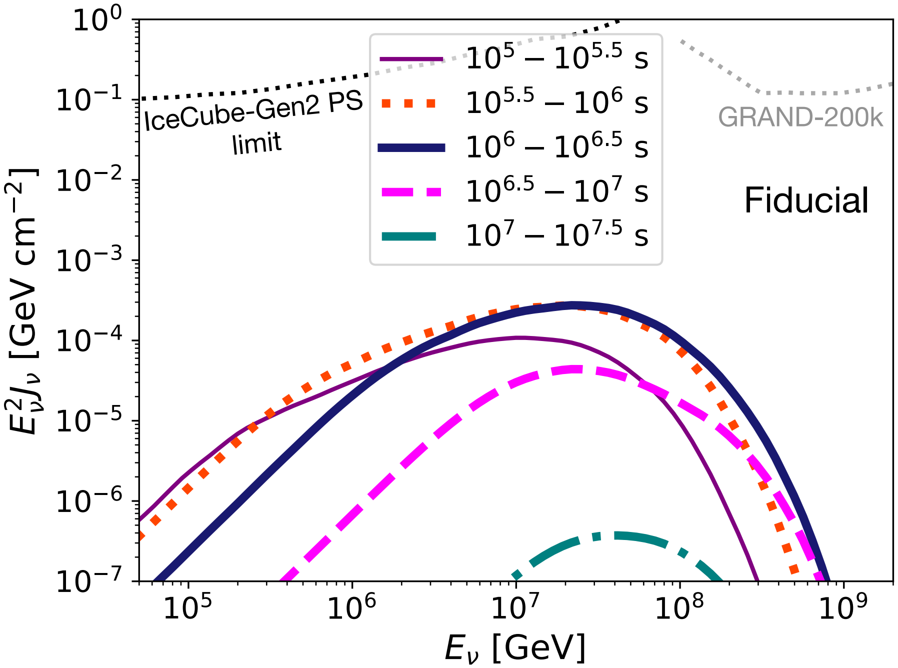
Peak fluence: $\sim 2 \times 10^{-3}$ GeV cm^{-2}

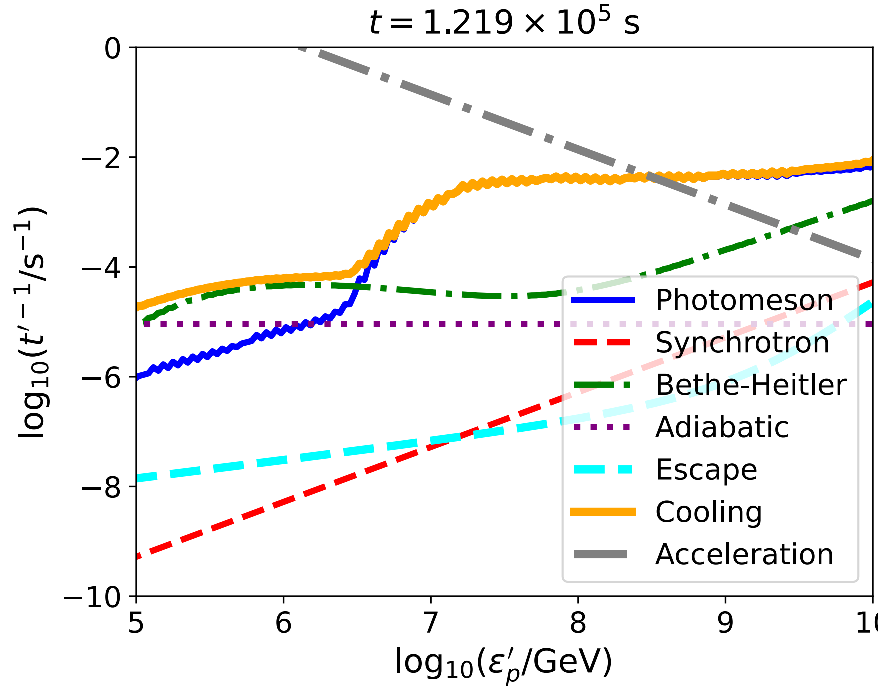
Neutrino energy: $\sim 10^7$ GeV $- 10^8$ GeV

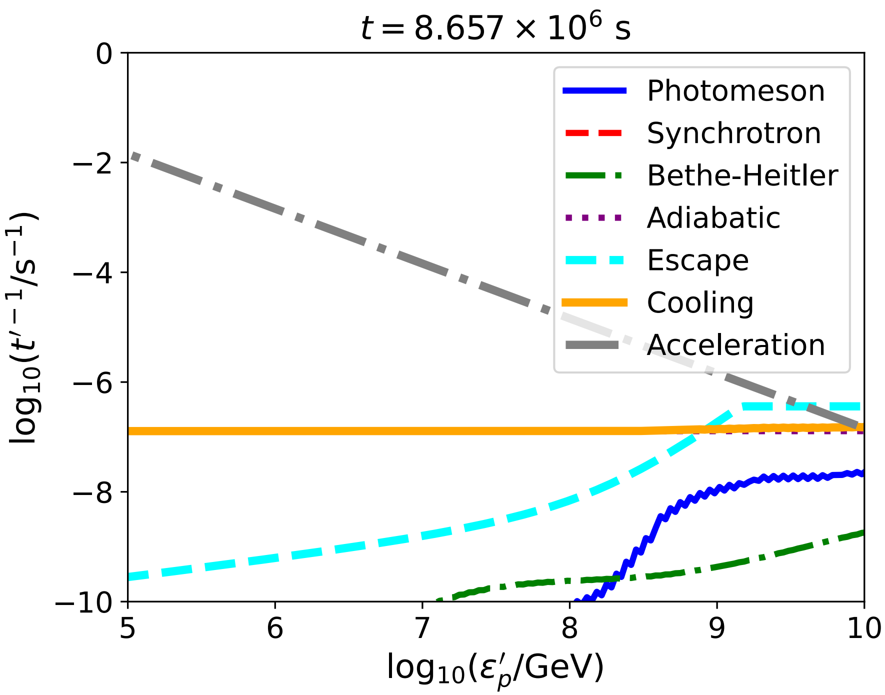
Peak fluence $\sim 10^6$ s post-merger

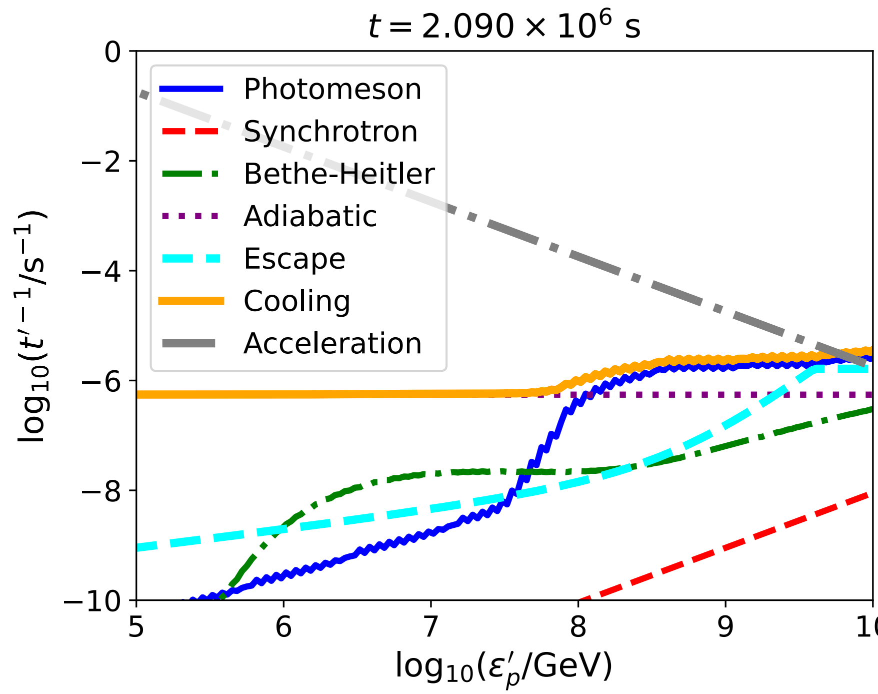
Peak fluence $\sim 10^{6.5}$ s post-merger

Neutrino fluences: timescales

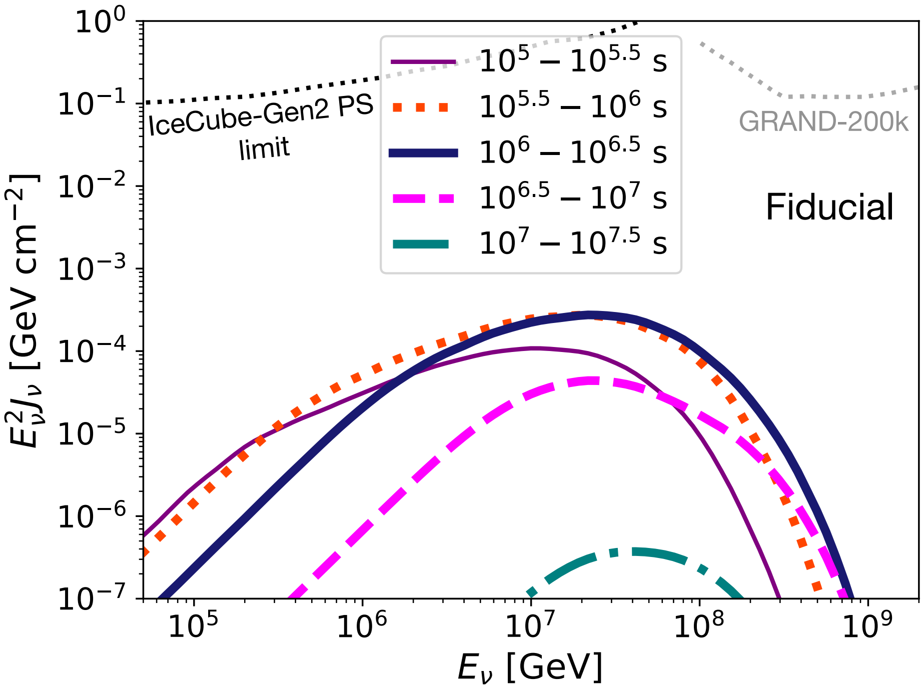


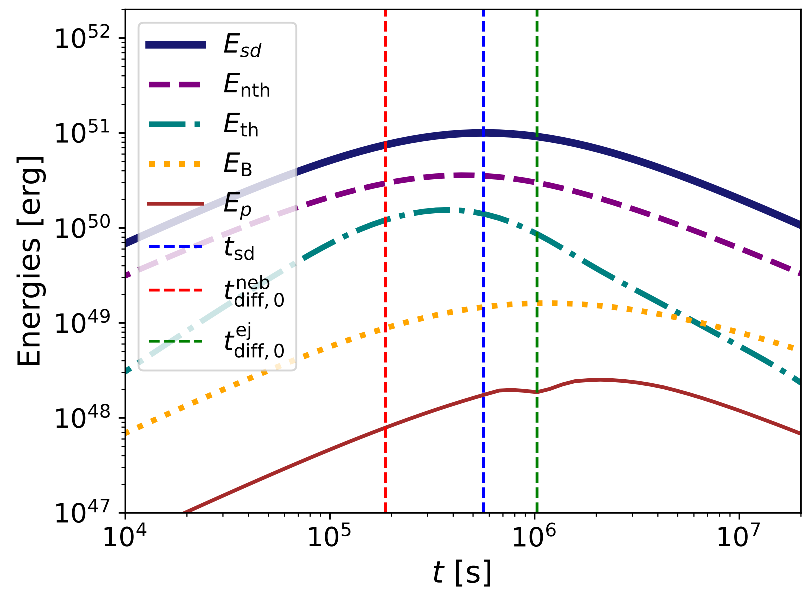


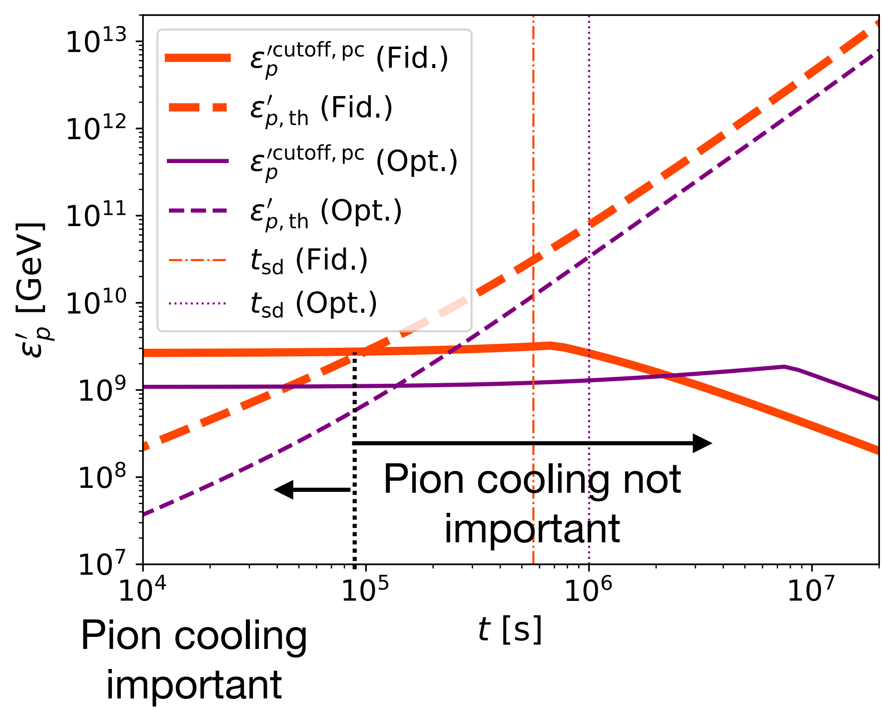




Neutrino fluences: importance of pion cooling







Outline

Part 1: High-energy neutrino emissions from magnetars

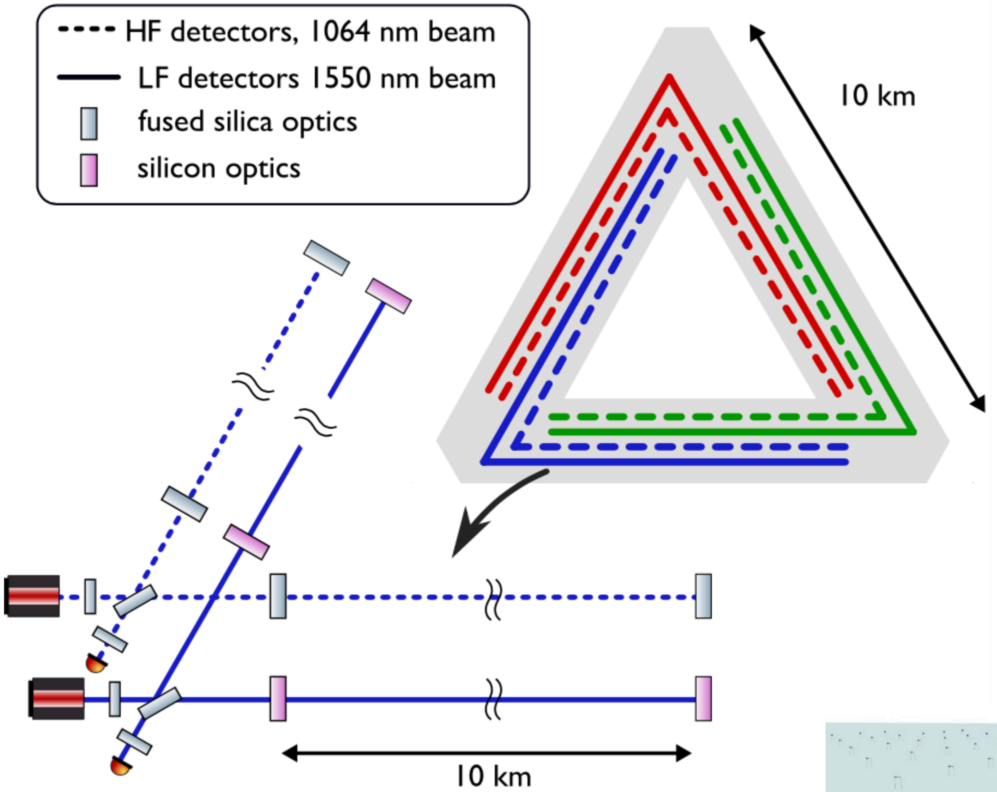
Based on: High-energy neutrino signatures from pulsar remnants of binary neutron-star mergers: coincident detection prospects with gravitational waves
MM, S.S. Kimura
(in preparation)

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

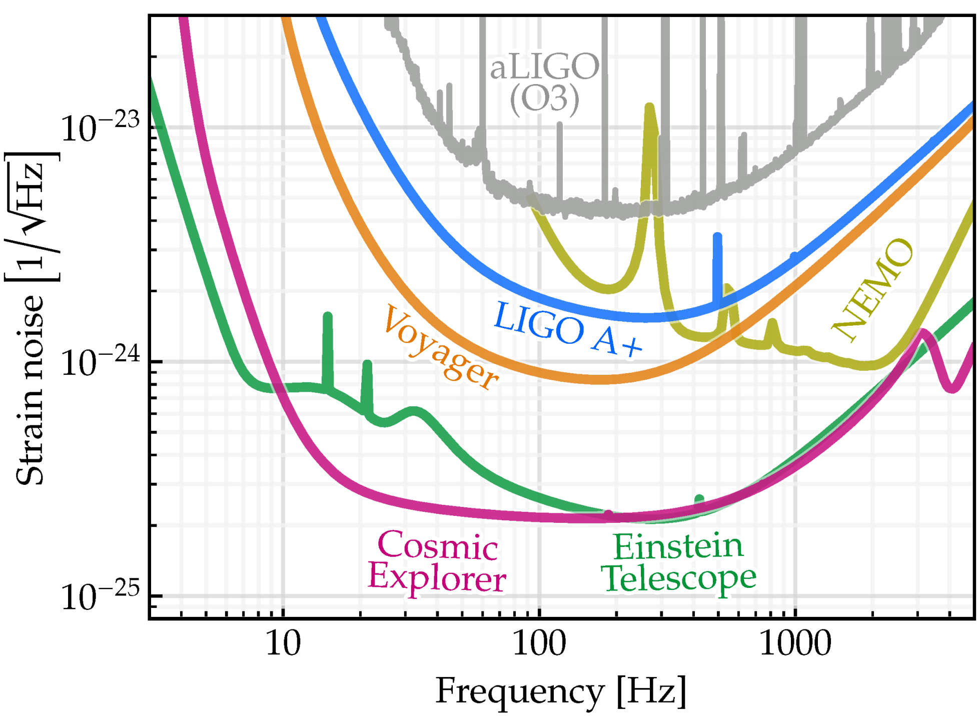
Based on: Gravitational wave triggered high energy neutrino searches from BNS mergers: prospects for next generation detectors
MM, S. S. Kimura, K. Murase
Phys. Rev. D 109, 4, 043053 (2024) ***(arXiv: 2310.16875)***

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
(in preparation)

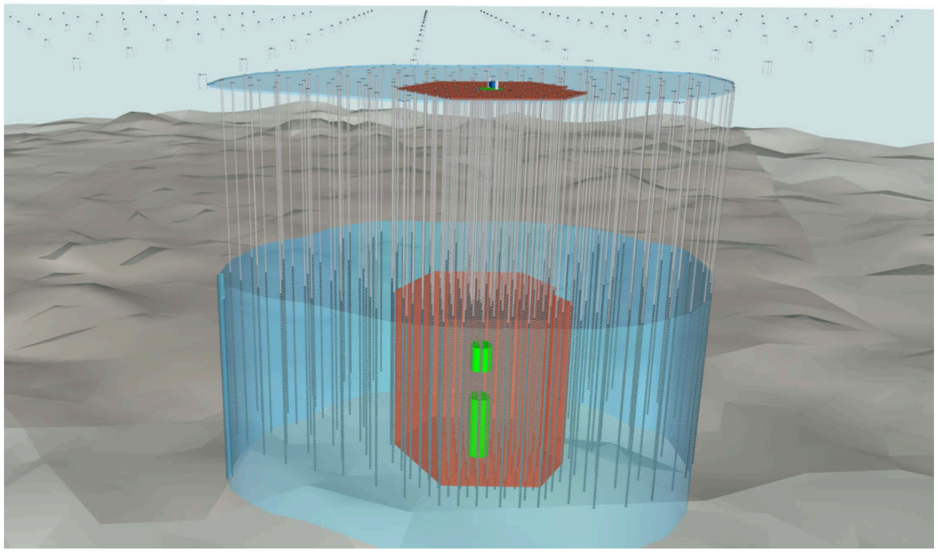
Next-generation GW and neutrino detectors



Einstein Telescope (ET)

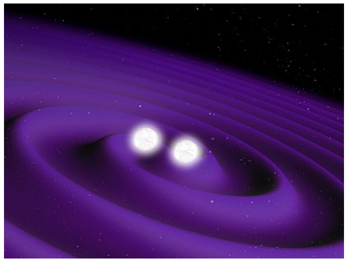


IceCube-Gen2



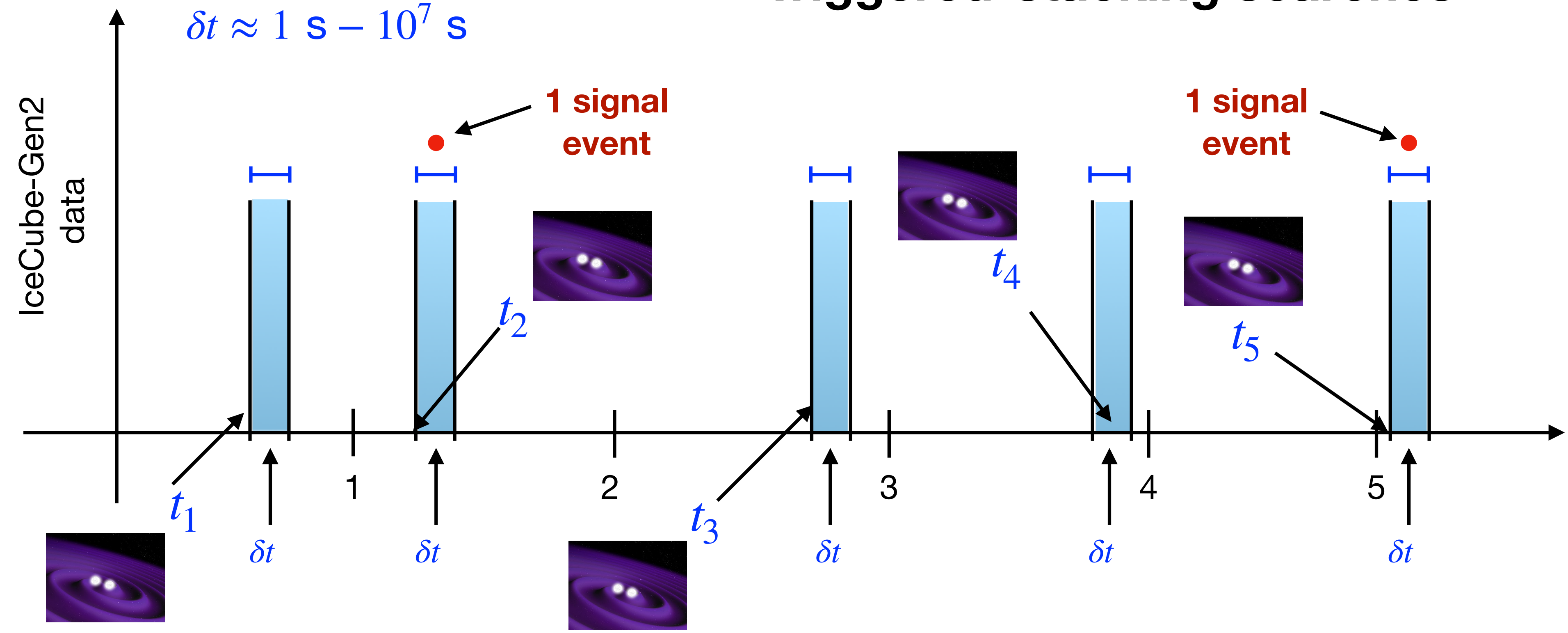
Evans et al., (2021)

Detection strategy: triggered stacking search

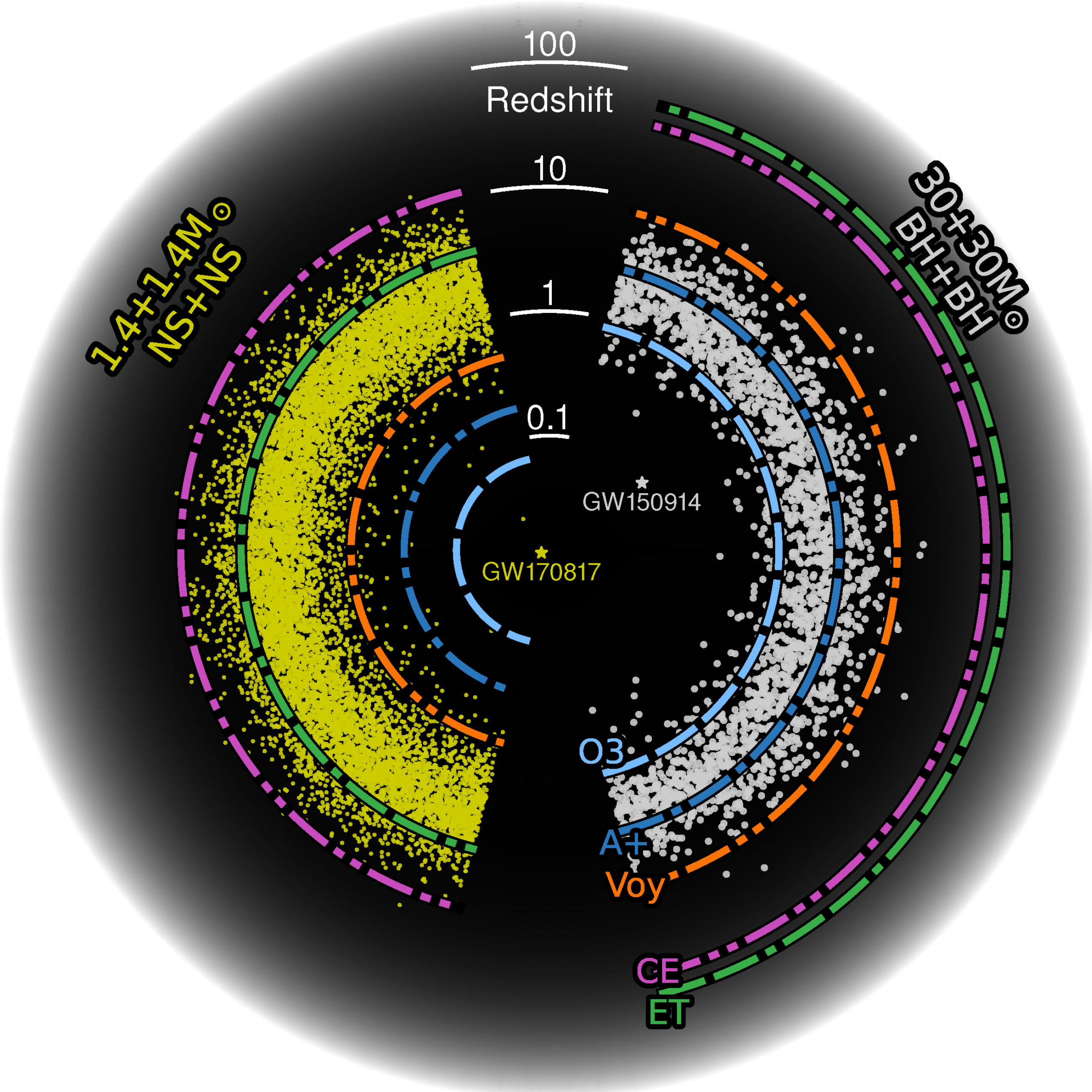


→ **Trigger from next-gen GW detectors** → **Neutrinos in IceCube-Gen 2**

Triggered-stacking searches



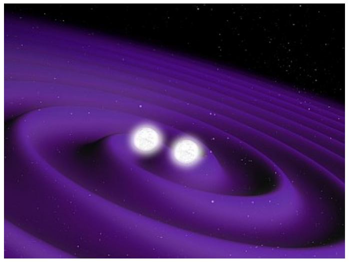
Next-generation GW detectors



Sensitive to NS-NS mergers from very high redshifts

Evans et al., (2021)

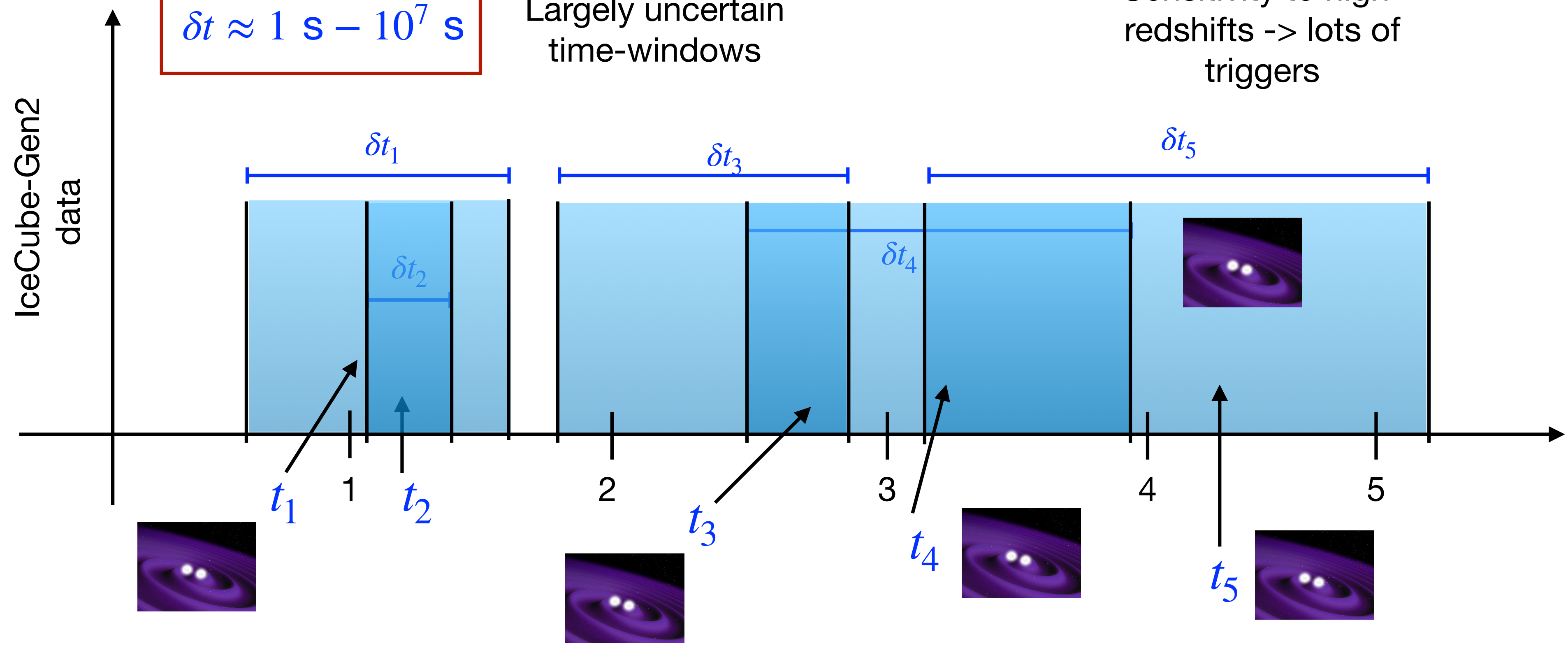
Impacts on triggered stacking searches



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

Largely uncertain time-windows

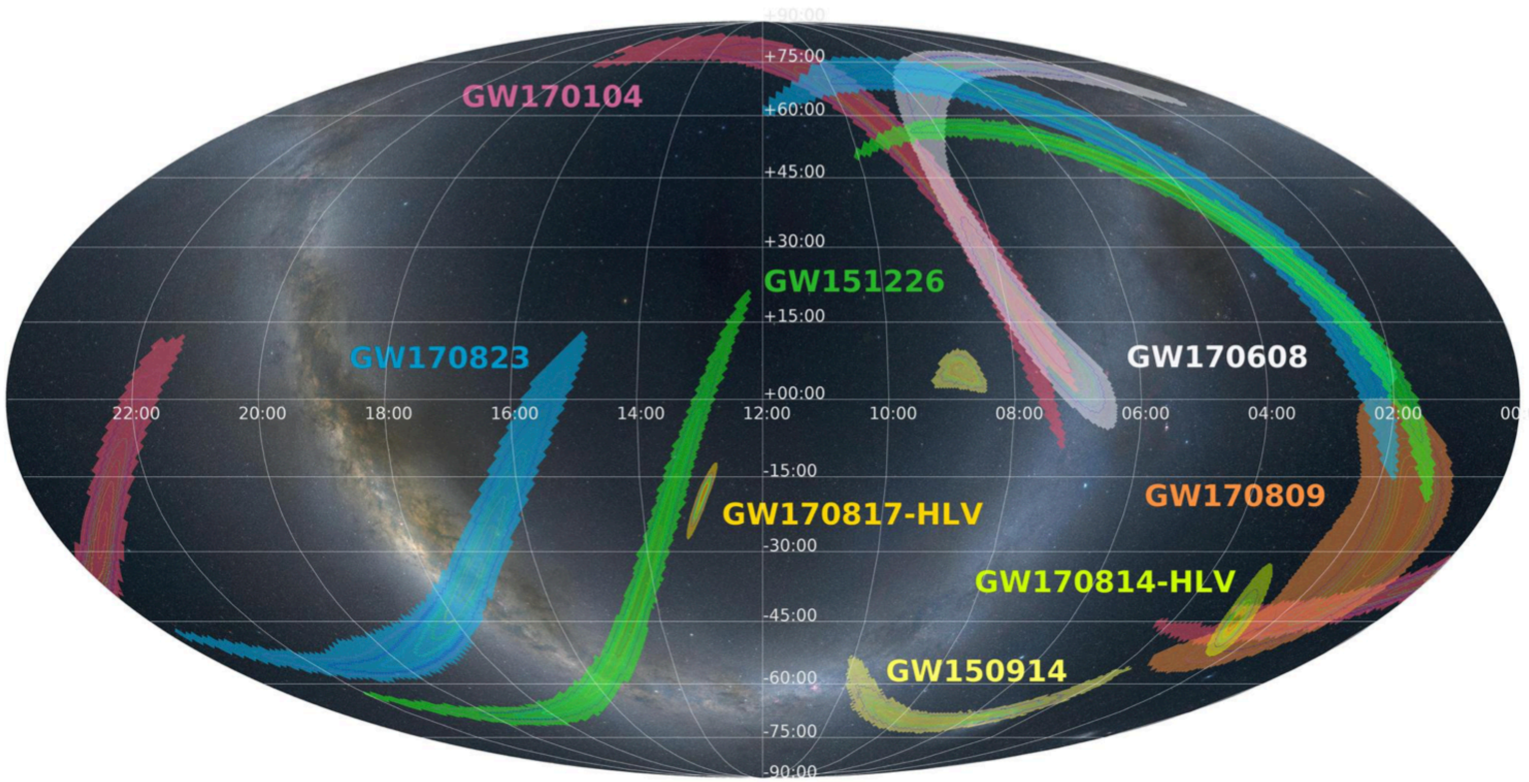
Sensitivity to high-redshifts -> lots of triggers



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

Motivations: How to obtain meaningful triggers?

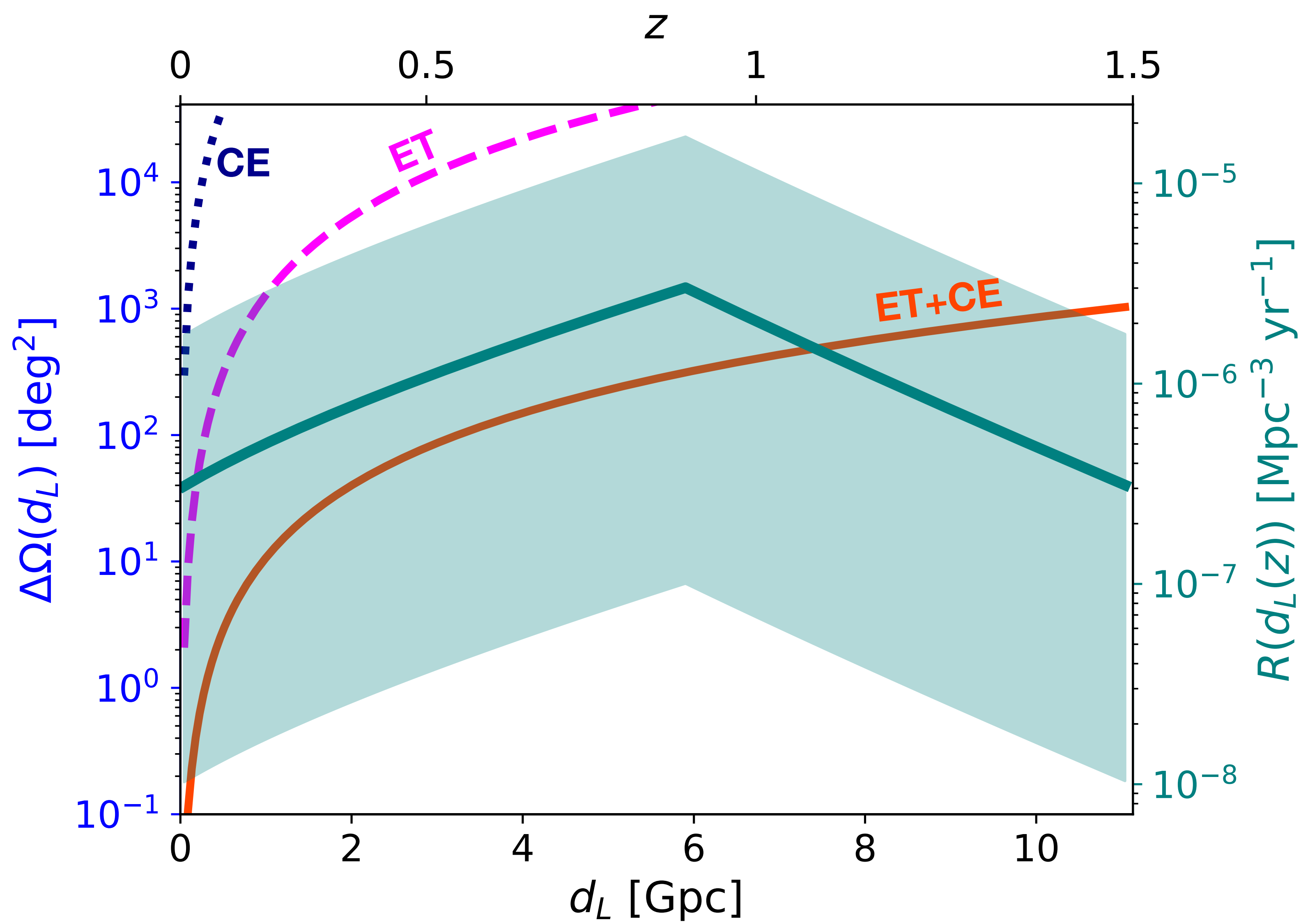
Use the sky localization capabilities of the GW detectors….



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)

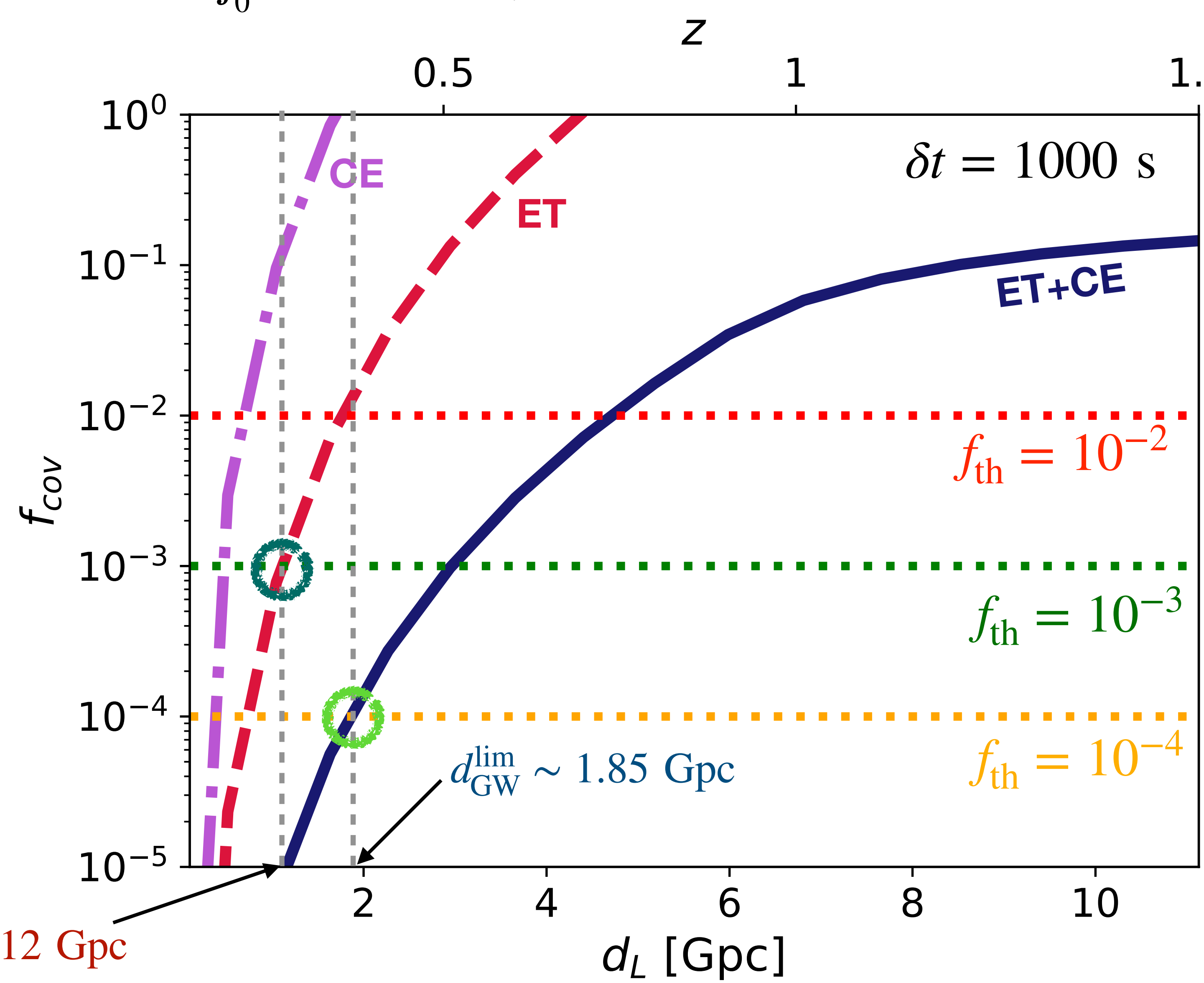
Sky localization and BNS merger rate



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

Distance limits for GW detectors

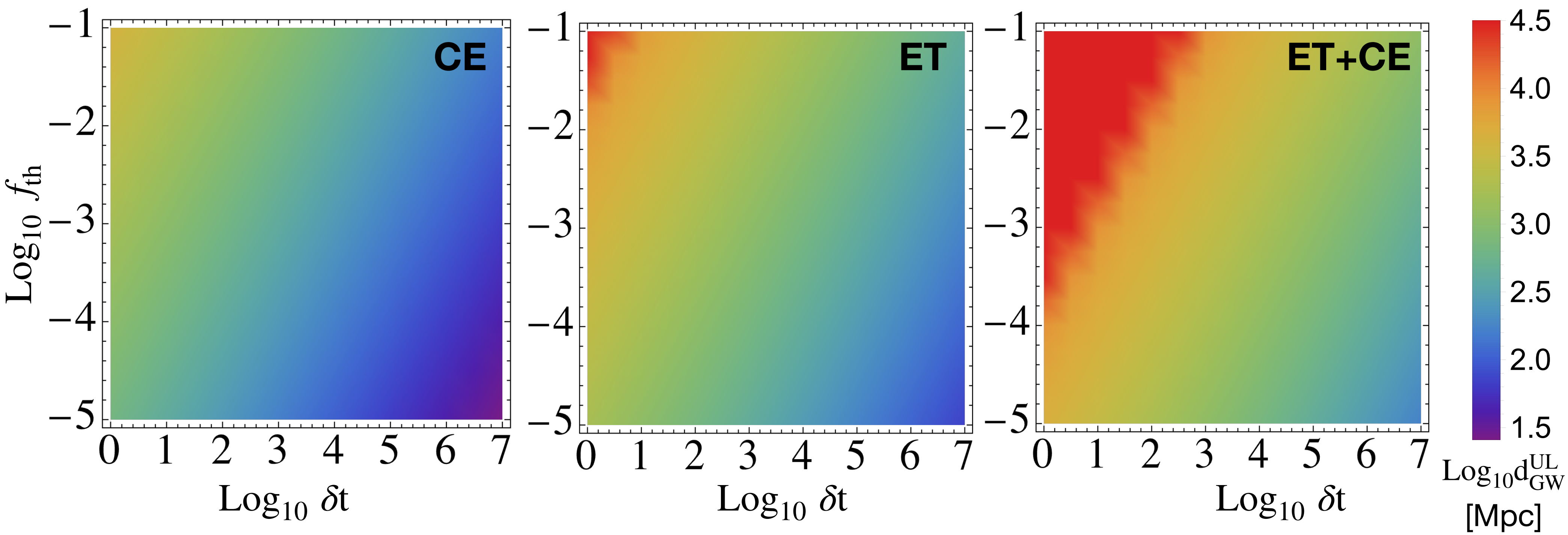
$$\int_0^{d_{\rm GW}^{\rm lim}} d(d_{\rm com}) \frac{\Delta\Omega(d_L)}{4\pi} R(z) 4\pi d_{\rm com}^2 \delta t = f_{\rm cov}(d_{\rm GW}^{\rm lim})$$



$\delta t = 1000$ s

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

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

Assume a Poissonian probability

Depends on f_ν

Depends on δt

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

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

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

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:

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

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

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

Motivated by physical models

1 s

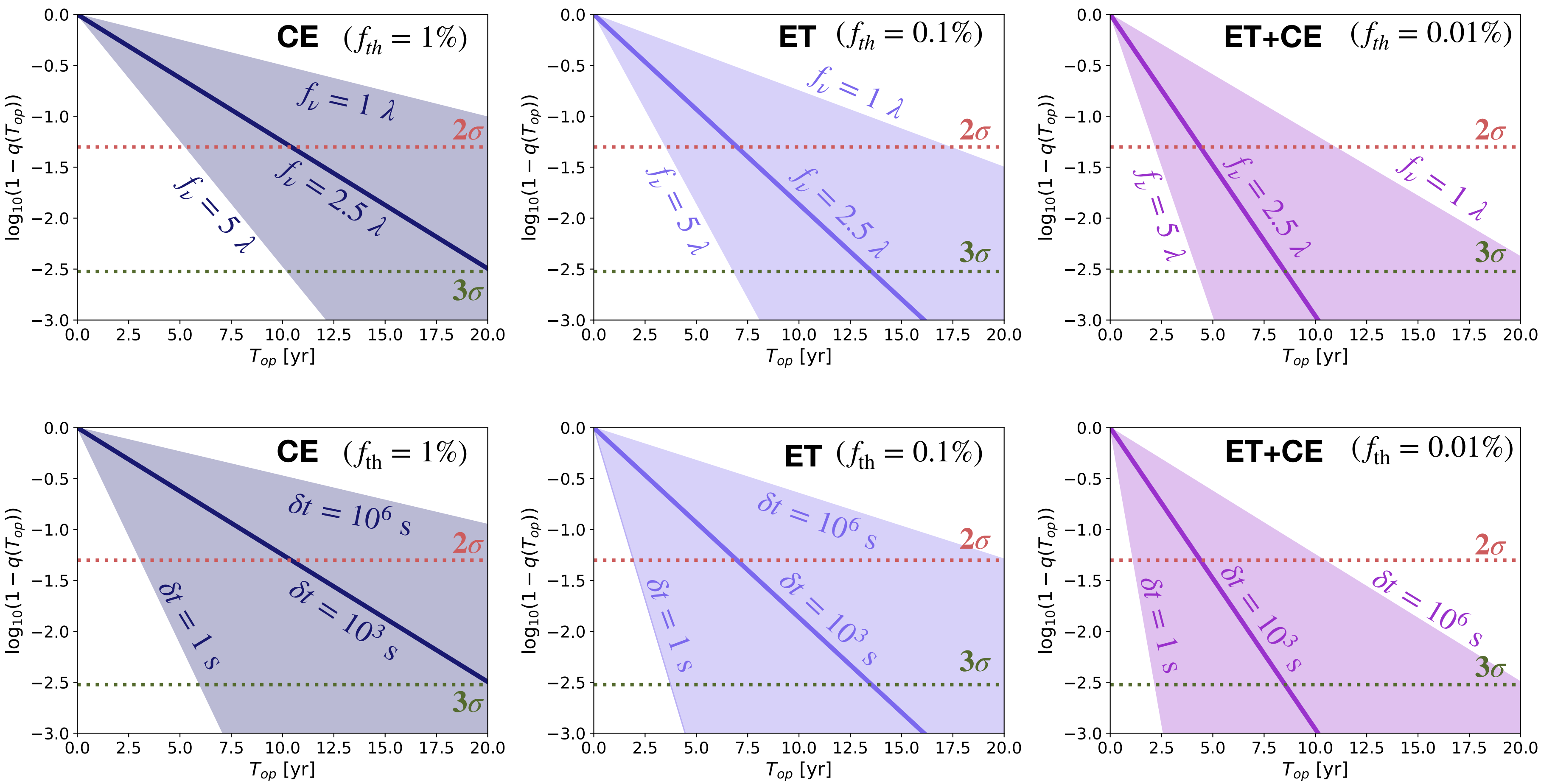
10^6 s

δt

Results - varying f_ν and δt

f_ν

$\delta t = 1000$ s

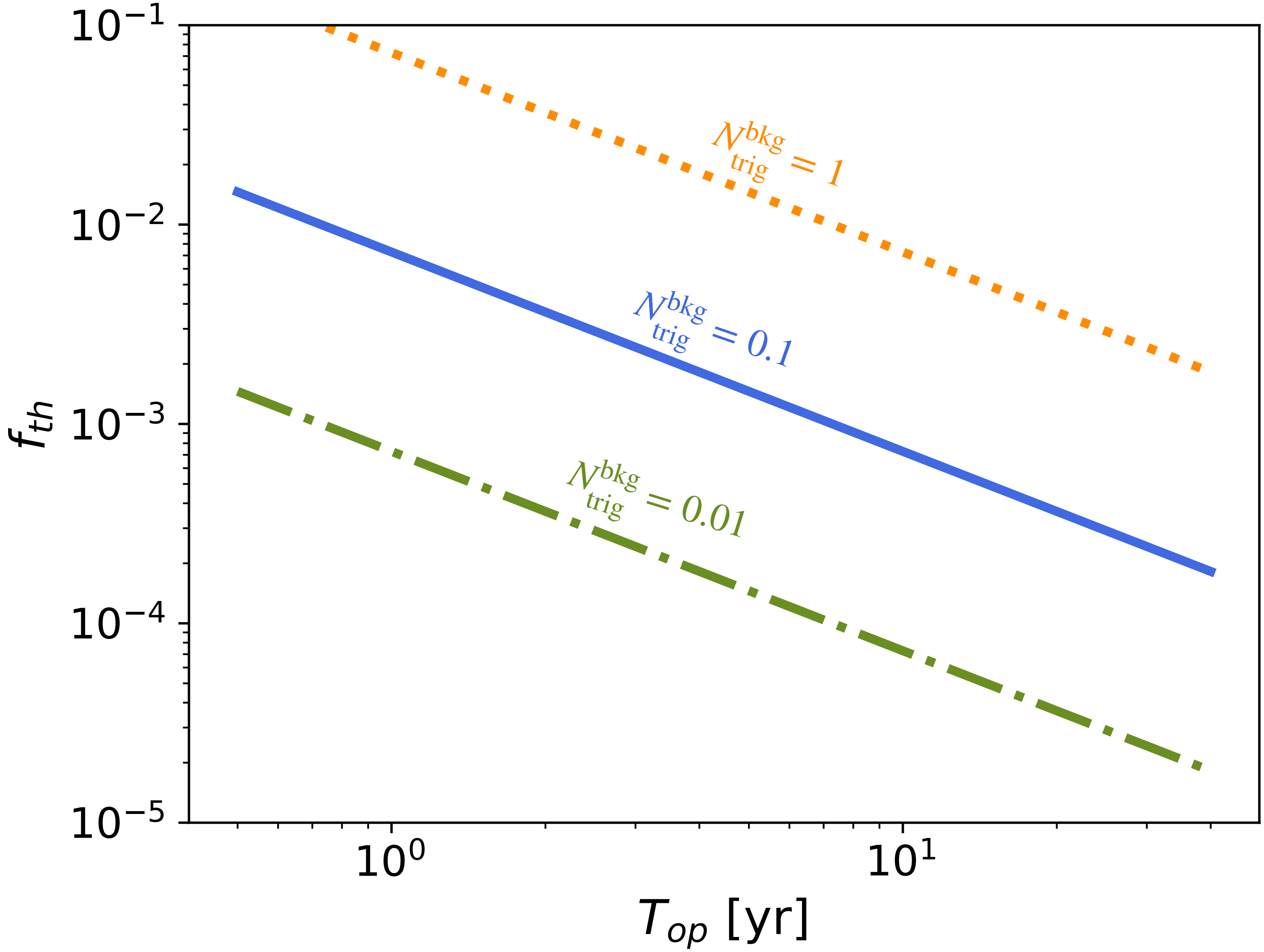


$f_\nu = 2.5\ \lambda$

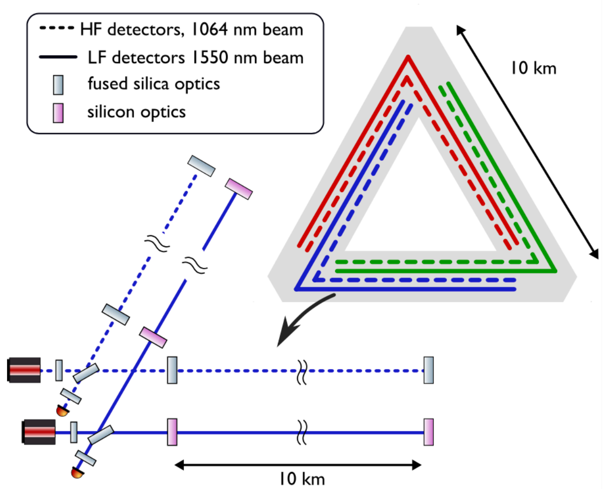
δt

$\lambda = 10^{-5}$

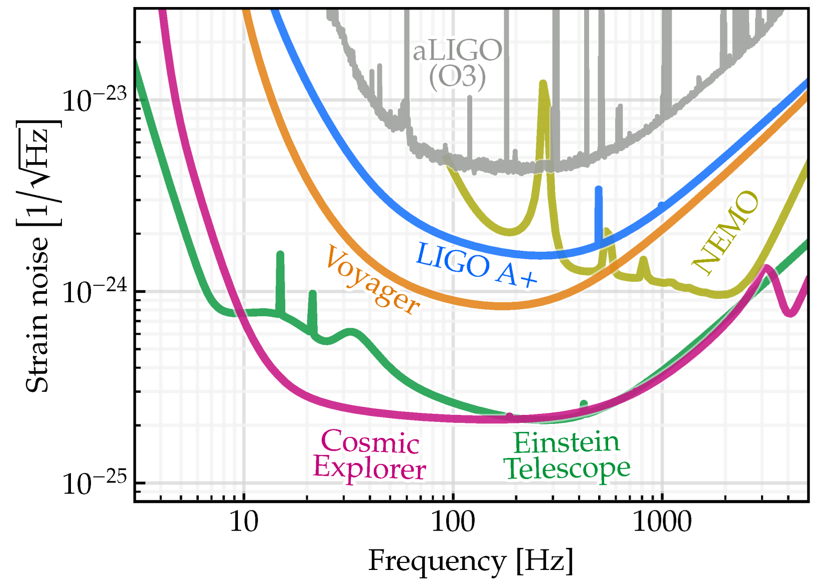
Backgrounds



Next-generation GW and UHE neutrino detectors



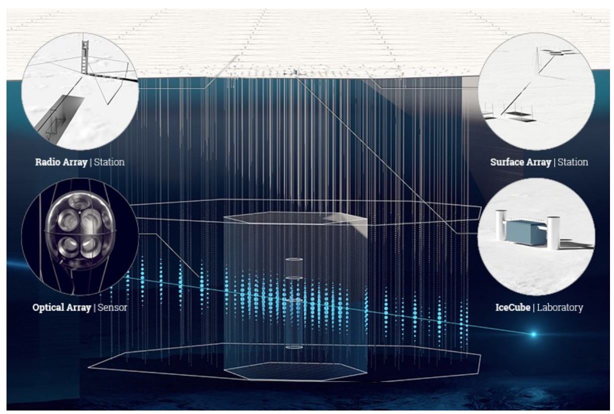
Einstein Telescope (ET)

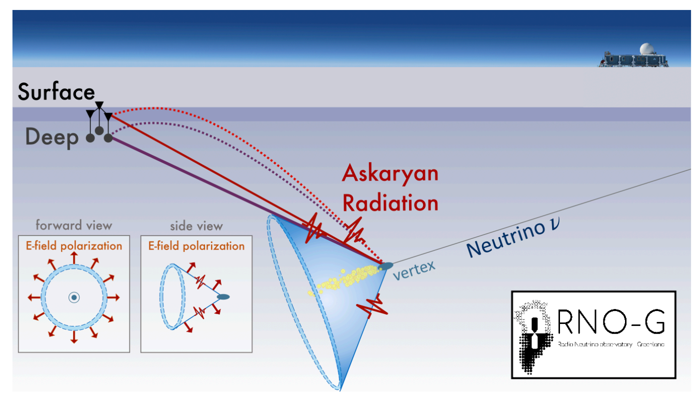


Cosmic Explorer (CE)

GRAND

Giant Radio Array for Neutrino Detection



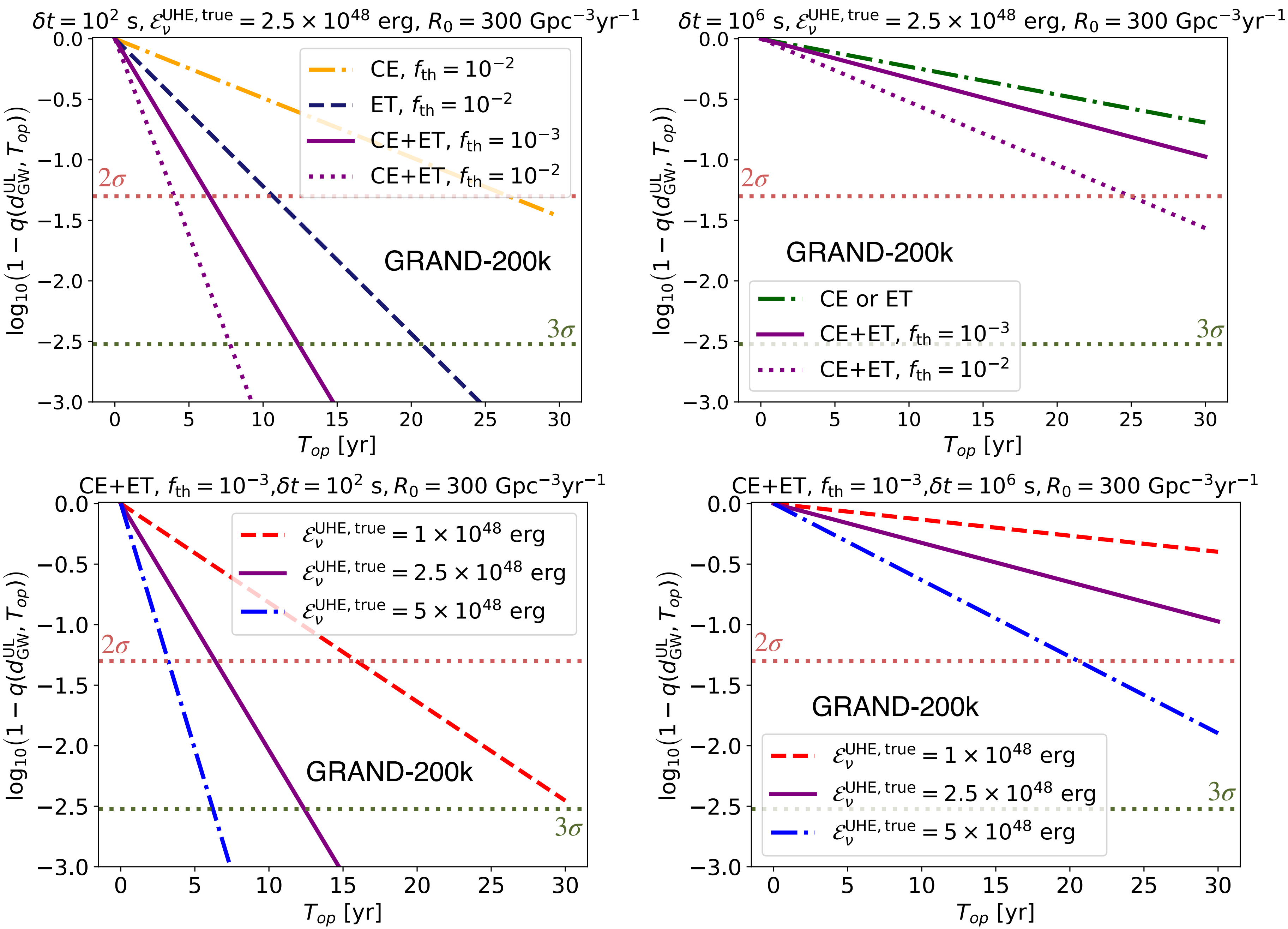


GRAND

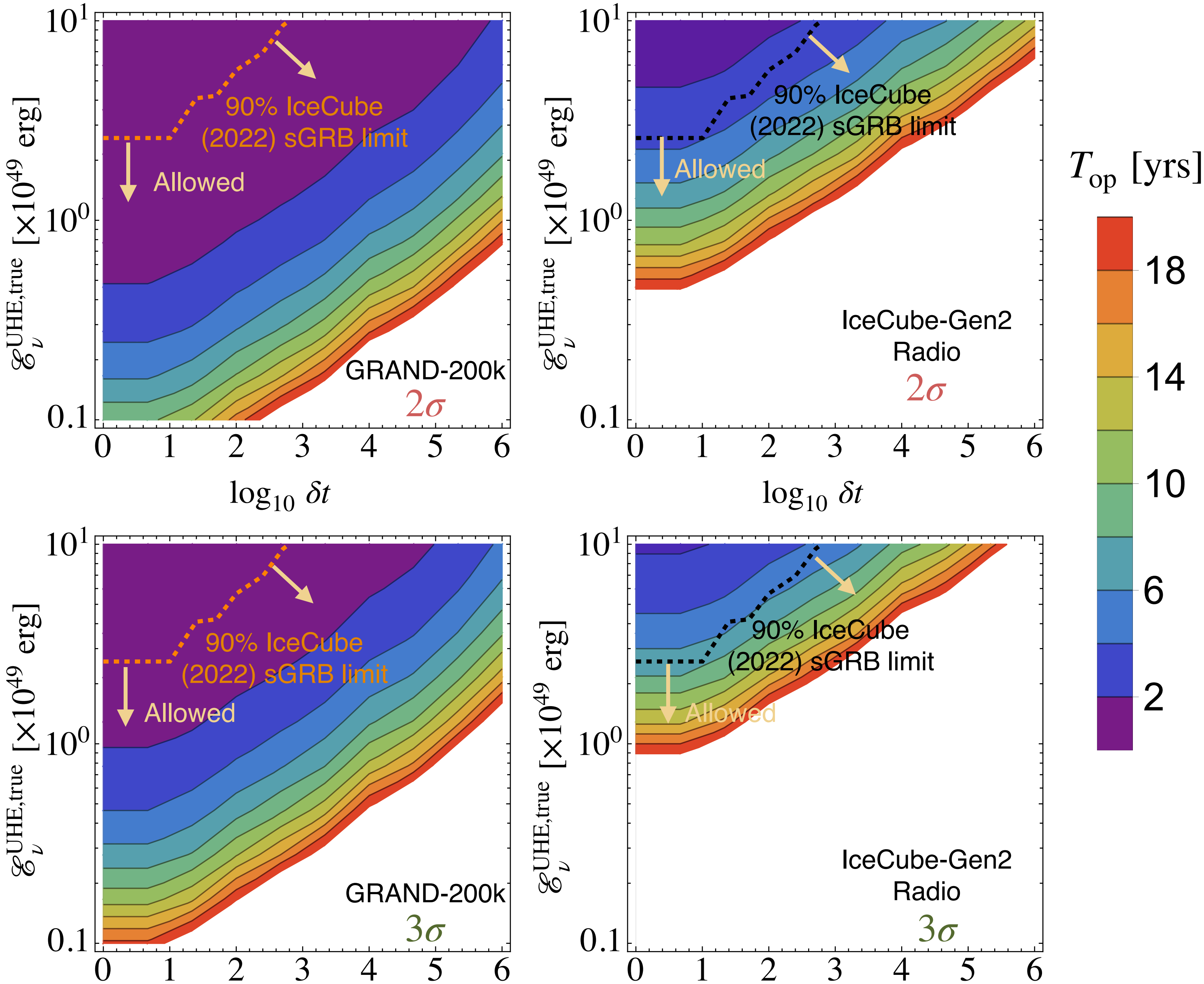
IceCube-Gen2 Radio

RNO-G

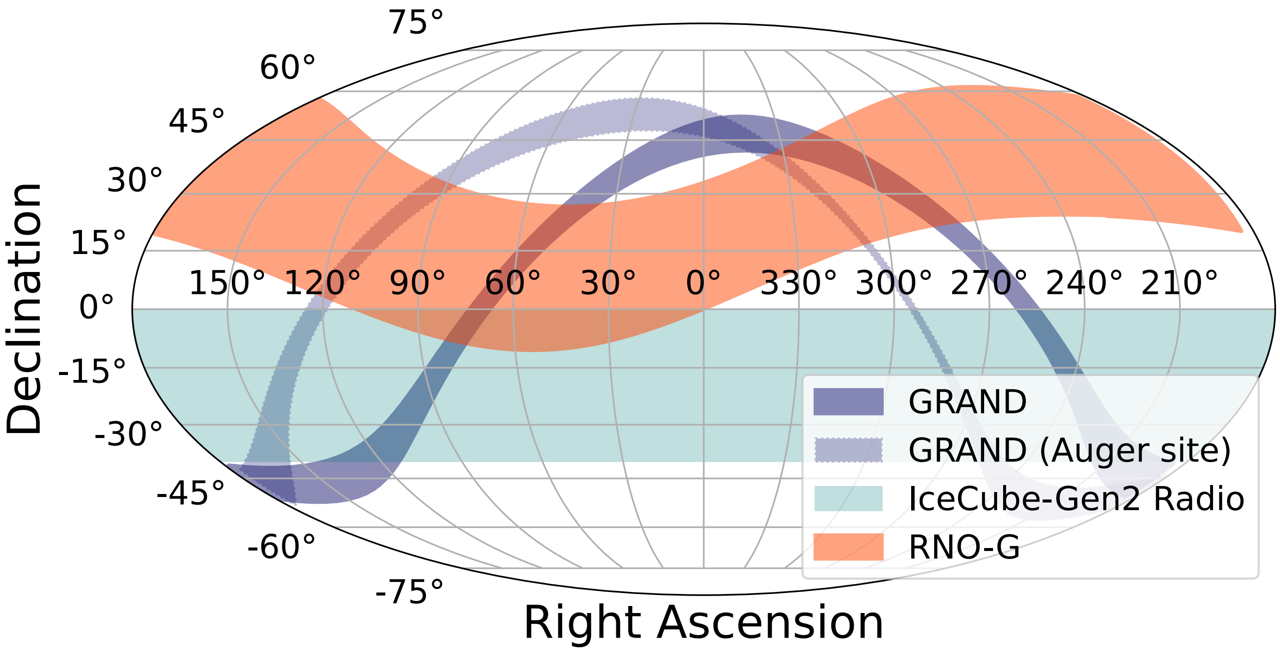
GW-triggered UHE neutrino searches at GRAND-200k

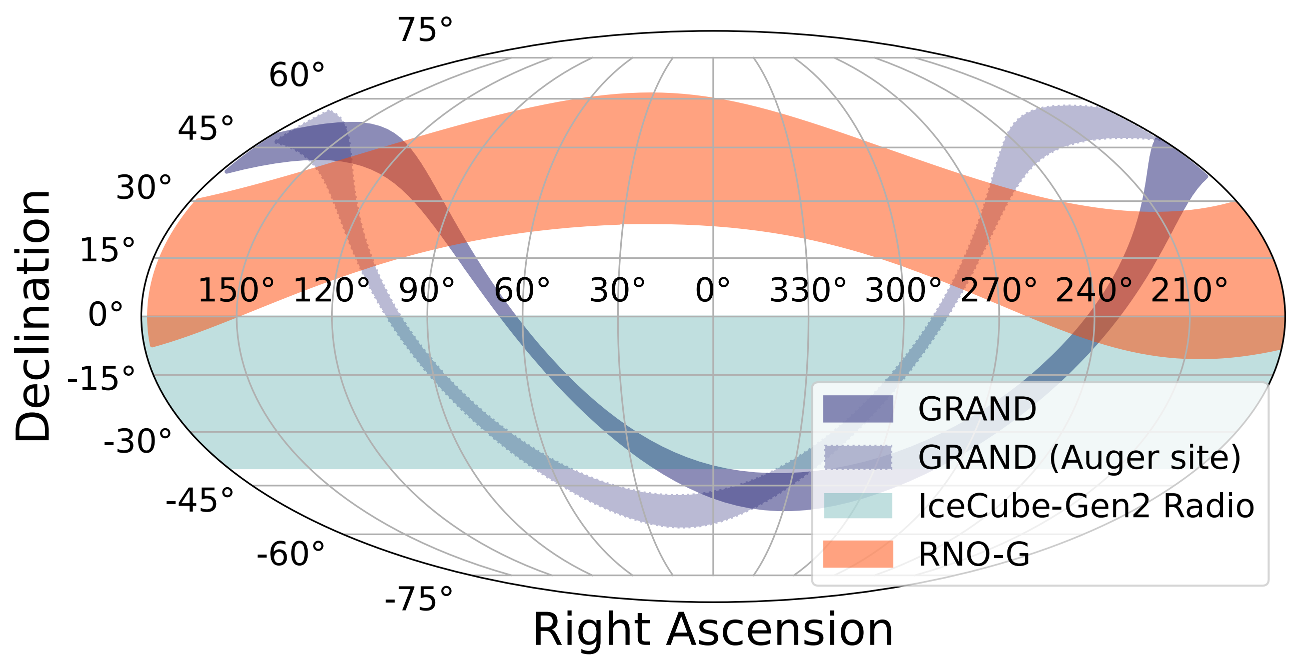


Prospects for GRAND and IceCube-Gen2 Radio

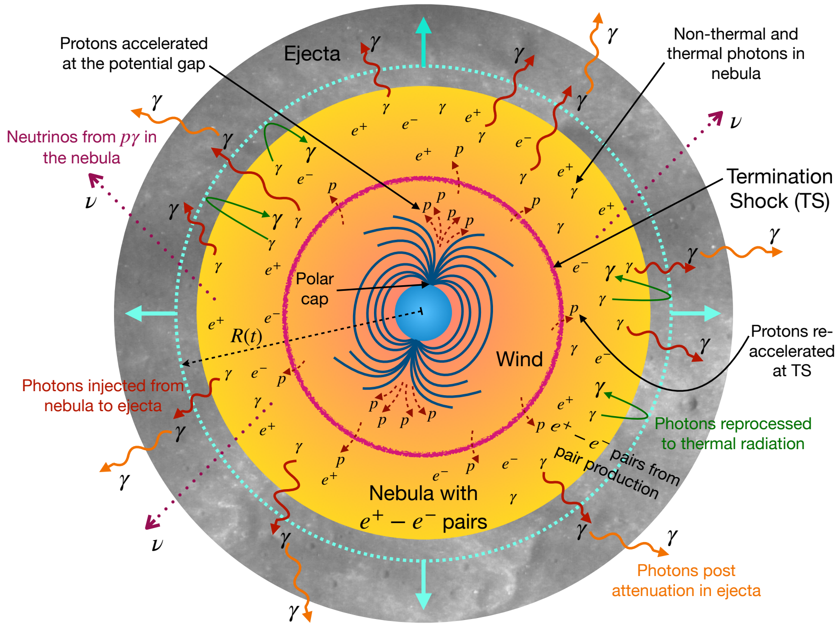


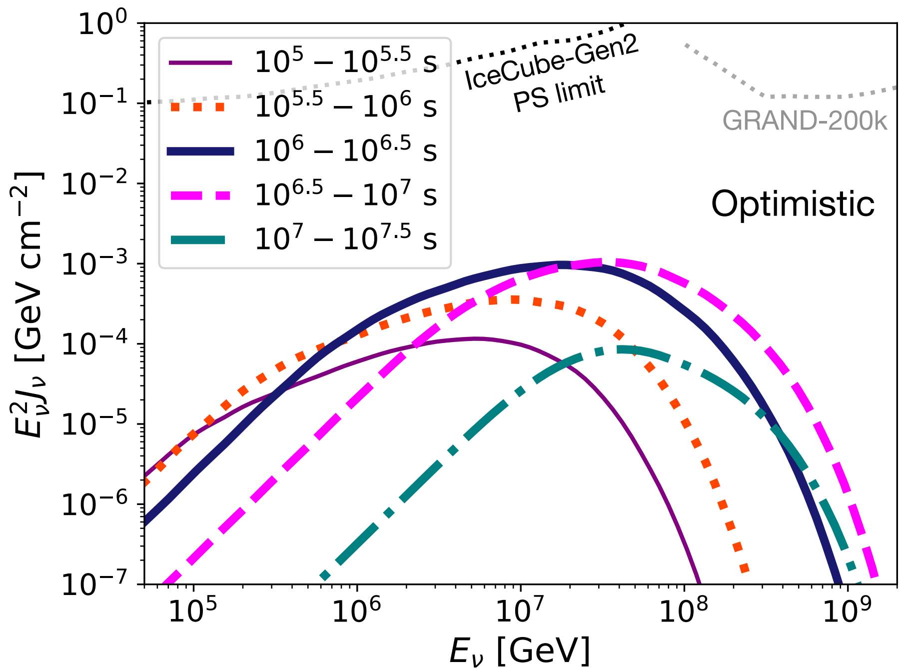
Joint UHE neutrino network: FOV



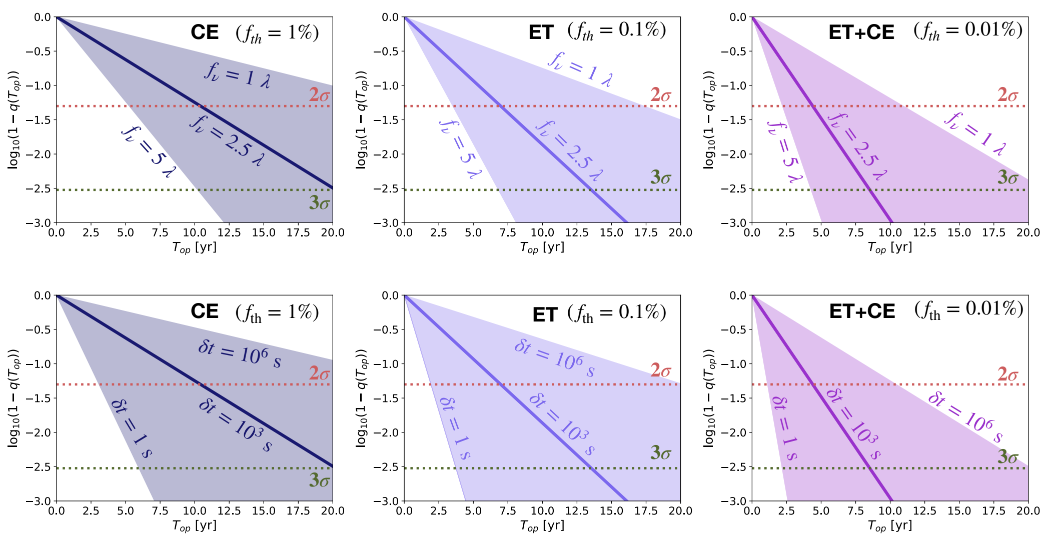


Takeaways

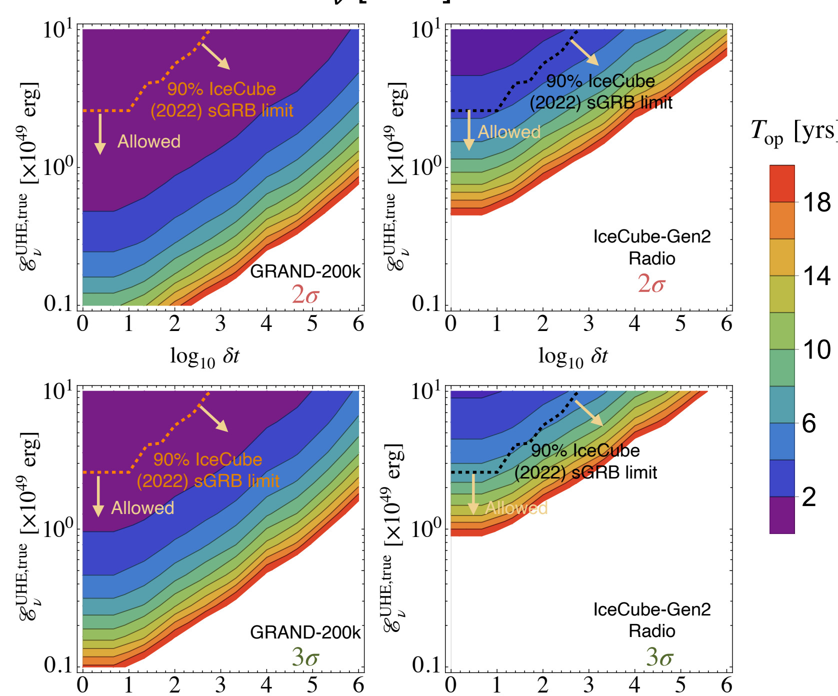




$\delta t = 1000$ s



$f_\nu = 2.5\ \lambda$




Wandering the immeasurable
Pérégrinations à l'infini
CERN 2014
Don de la Fondation Meyrinoise du Casino
Standard Model
Менделеев
Maxwell

Thank You!

Backup