Gamma-ray bursts from compact binary mergers

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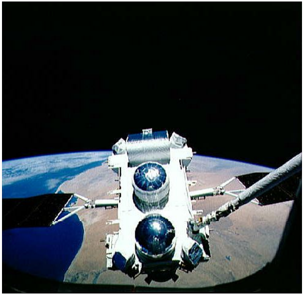
Some gamma-ray burst detectors

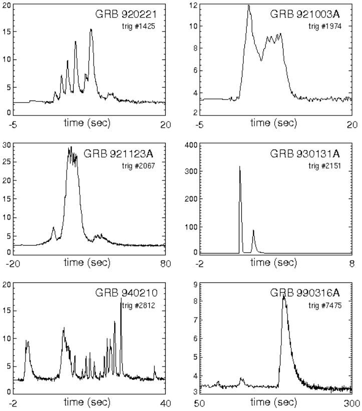
CGRO/BATSE
[20–600] keV
1991-2000



Swift/BAT
[15–150] keV
2004 – present

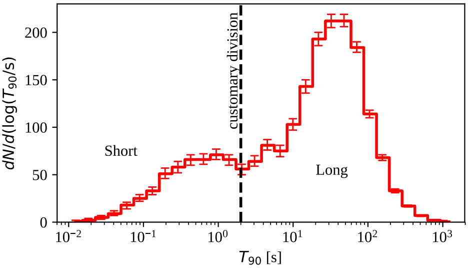
Fermi/GBM
[10–1000] keV
2007 – present

Diverse lightcurves



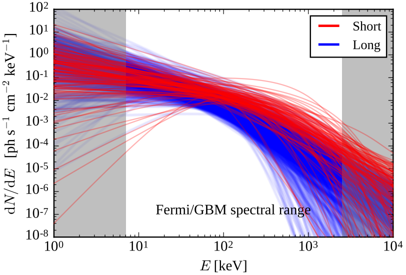
(figure: D. Perley using CGRO/BATSE data)

Bimodal duration distribution

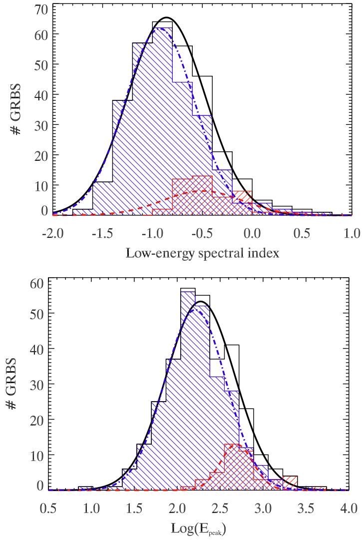


(BATSE data)

Gamma-ray bursts: spectra

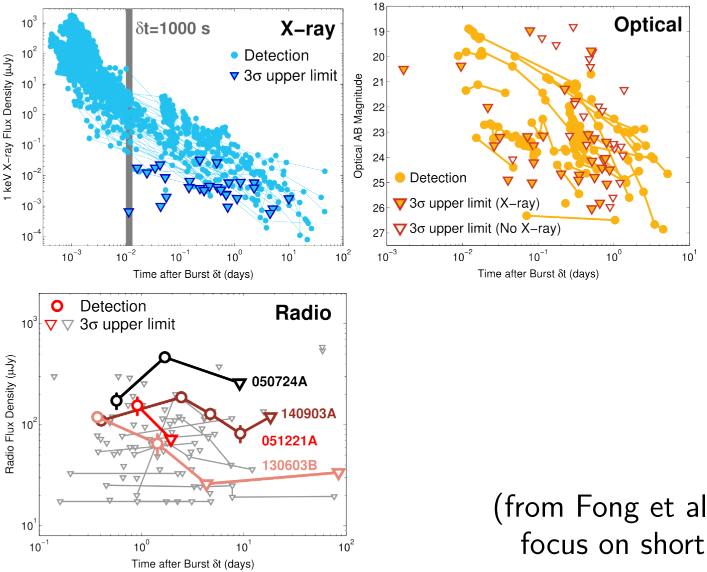


[Spectral fits to Fermi/GBM data]



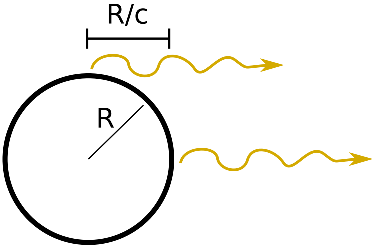
(figures: Nava et al. 2012)

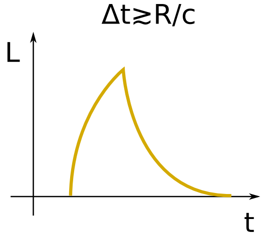
Multi-wavelength ‘afterglow’

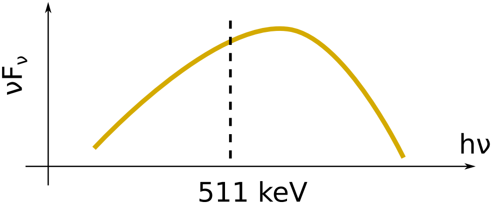


(from Fong et al. 2015, focus on short GRBs)

Compactness problem → relativistic outflow



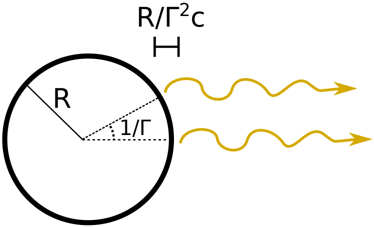


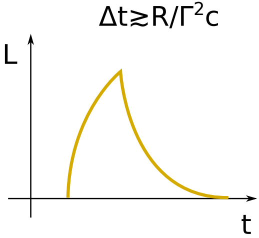


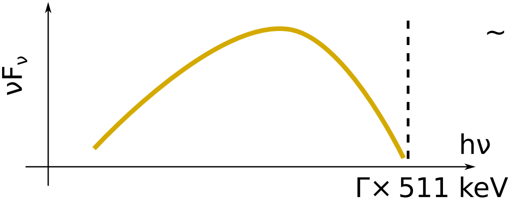
$R \lesssim c\Delta t$
$\sim\ 3\times10^{9}\mathrm{cm}\ (\Delta t/0.1\mathrm{s})$

$$\tau \gg 1$$

Compactness problem → relativistic outflow







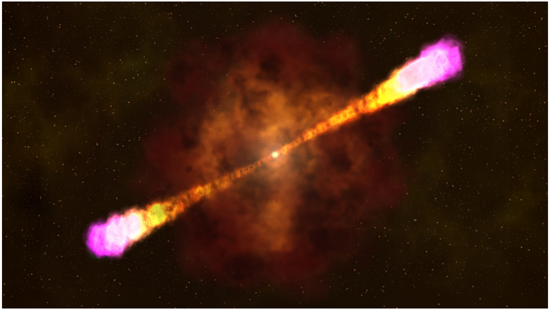
$$R \lesssim c\Gamma^2\Delta t$$
$$\sim 3\times10^{13}\mathrm{cm}\ (\Delta t/0.1\mathrm{s})(\Gamma/100)^2$$

$$\tau<1$$

Energetics → collimation → relativistic jet

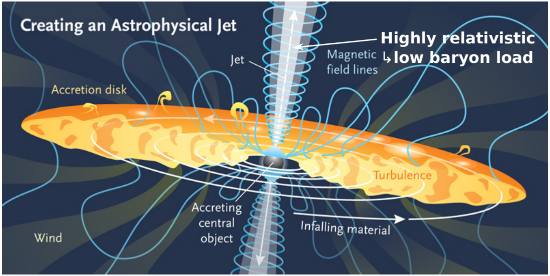
Isotropic-equivalent gamma-ray energy $E_{\gamma,\mathrm{iso}}$ up to $\mathrm{few} \times 10^{54}\,\mathrm{erg} \sim 1\mathrm{M}_{\odot}c^2$, released in $T \sim 1-100\,\mathrm{s}$.

Collimation within half-opening angle θ_j:
$E_\gamma = E_{\gamma,\mathrm{iso}}(1-\cos\theta_\mathrm{j}) \sim E_{\gamma,\mathrm{iso}}\theta_\mathrm{j}^2/2 \sim 5\times10^{51}\mathrm{erg}(E_{\gamma,\mathrm{iso}}/10^{54}\,\mathrm{erg})(\theta_\mathrm{j}/5^\circ)^2$



[Credit: NASA Goddard]

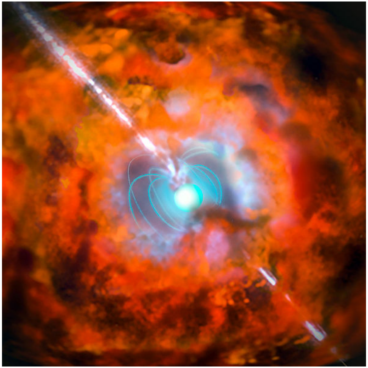
Black hole + accretion disk
→ Blandford-Znajek mechanism
and/or $\nu\bar{\nu}$ annihilation (Eichler+89, Popham+99, ...)



[Credit: McKinney 2012]

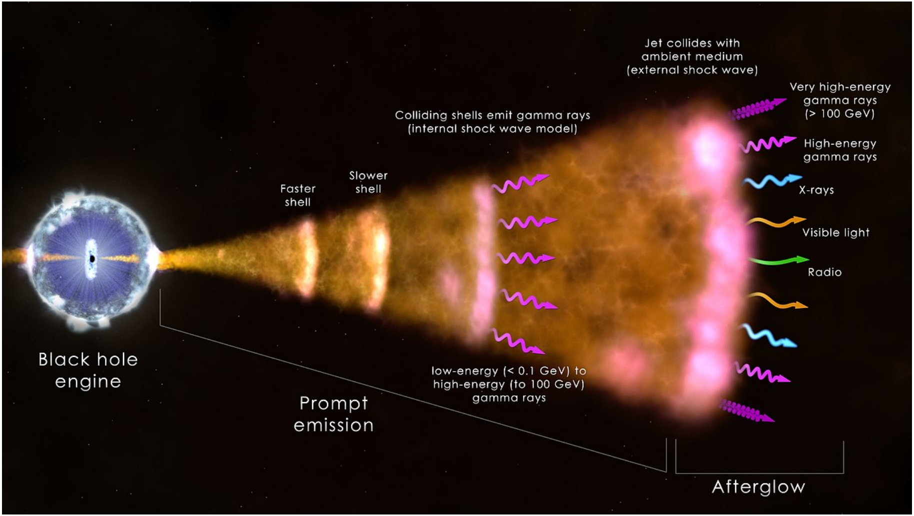
(see talks by J. Jacquemin; V. Rohoza; N. Kaaz; A. Janiuk; O. Gottlieb; A. Lalakos; B. Lowell; & poster by B. James)

Spinning magnetar
(Usov 92; Thompson 94; Thompson 04; Metzger+11)



[Credit: ESO]

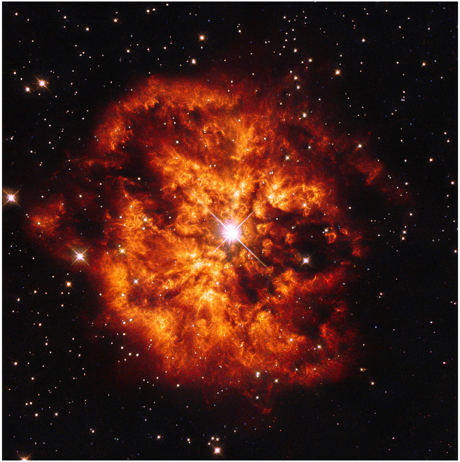
The ‘standard’ GRB scenario



[NASA/Goddard Space Flight Center/ICRAR]

Gamma-ray burst progenitors

Collapsar



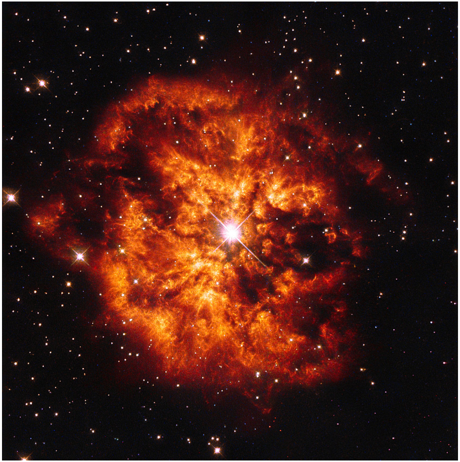
Core-collapse of highly rotating massive star [Woosley 1993]

Compact binary merger with at least one neutron star

[Eichler et al. 1989, Mochkovitch et al. 1991]

Gamma-ray burst progenitors

Collapsar



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– GRB-SN associations –

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Gamma-ray burst progenitors

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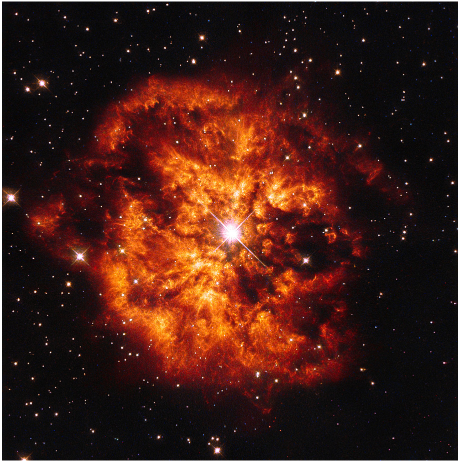

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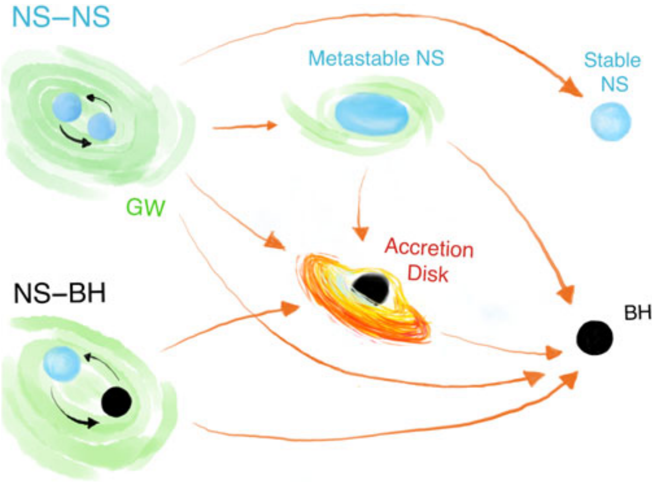
– GRB-SN associations –

Compact binary merger with at least one neutron star

[Eichler et al. 1989, Mochkovitch et al. 1991]

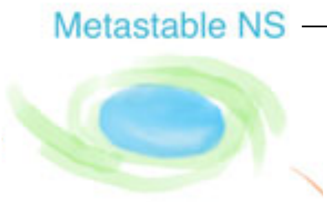
– GW170817 / GRB170817A –

Compact binary merger outcomes



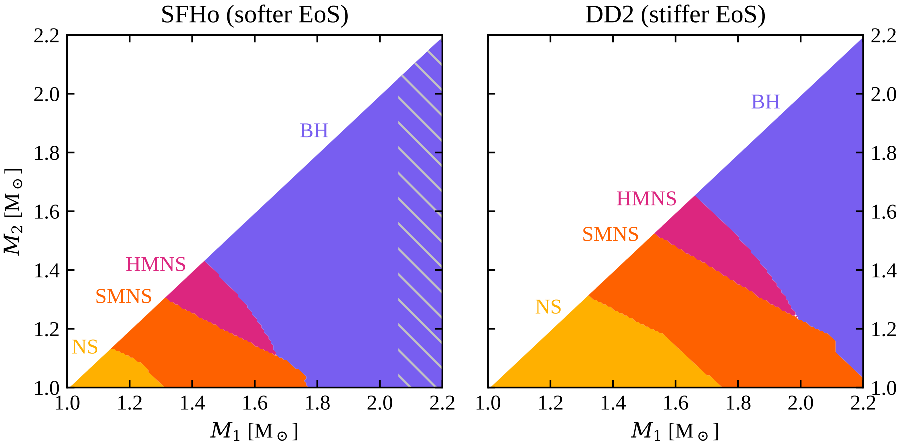
[Figure: Ascenzi+21]

Meta-stable neutron star remnants

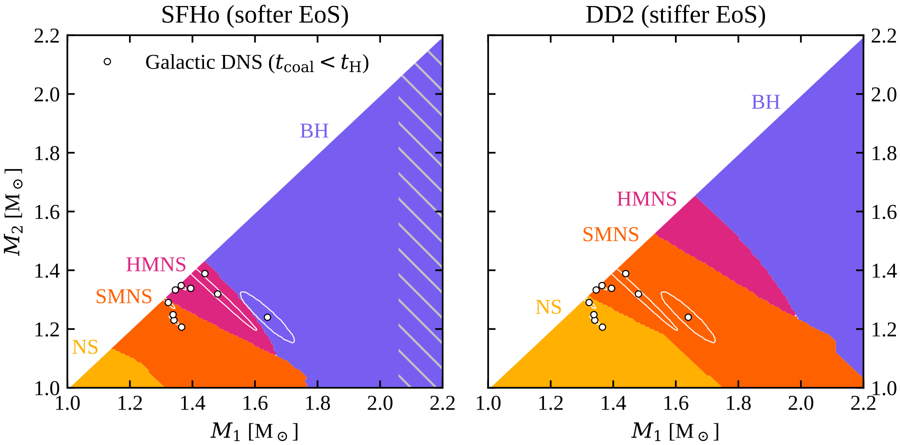


	hyper-massive (HMNS)	*vs*	supra-massive (SMNS)
supported by:	differential rotation		uniform rotation
collapse after:	viscous timescale $t_{BH} \lesssim 0.1$ s		spin-down timescale

NS-NS merger outcomes on M_1, M_2 plane

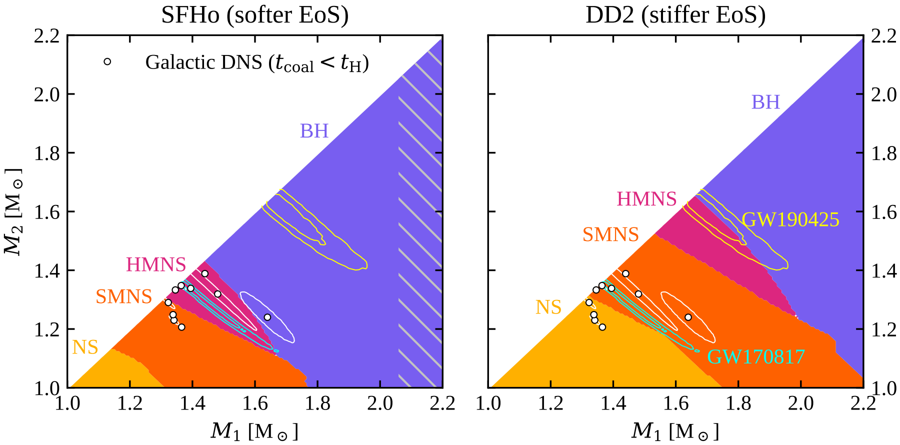


NS-NS merger outcomes on M_1, M_2 plane



[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19]

NS-NS merger outcomes on M_1, M_2 plane



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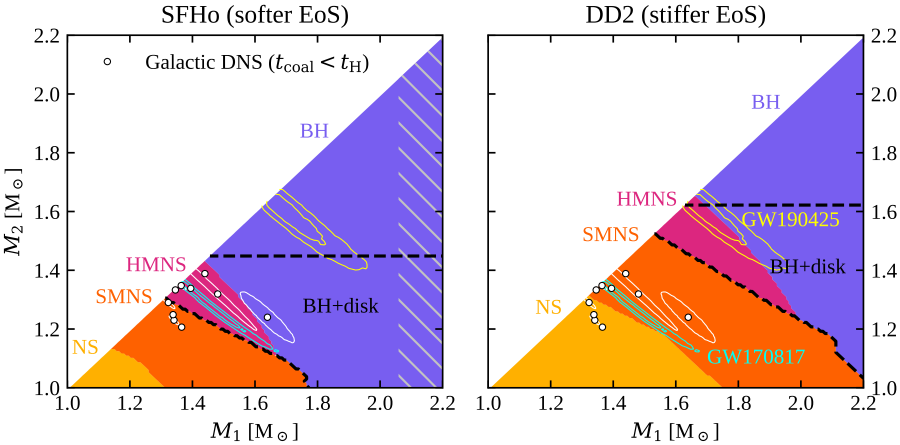
NS-NS merger outcomes on M_1, M_2 plane



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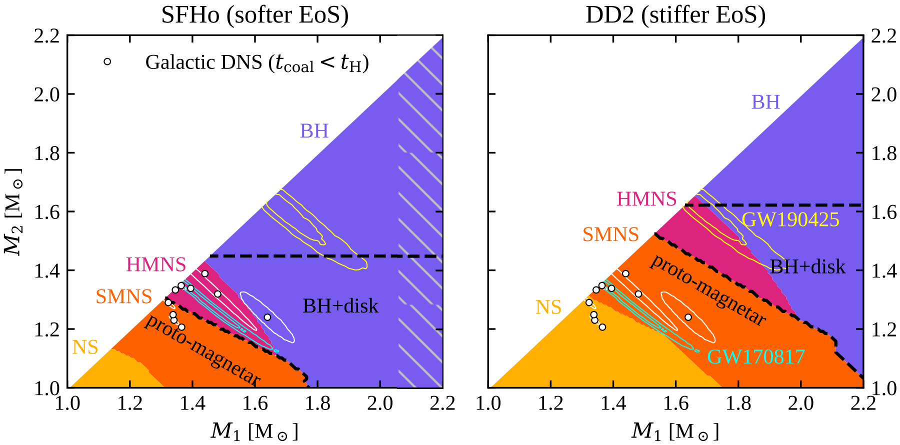

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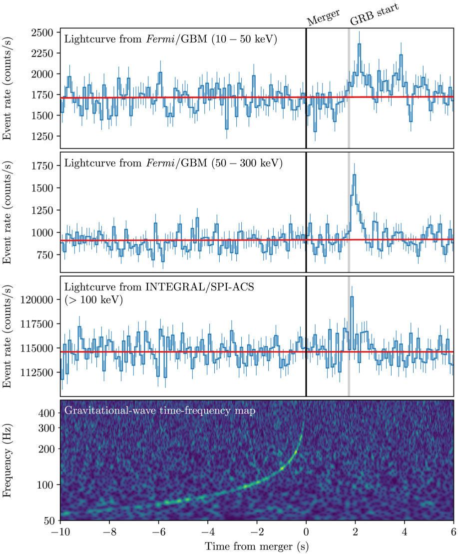
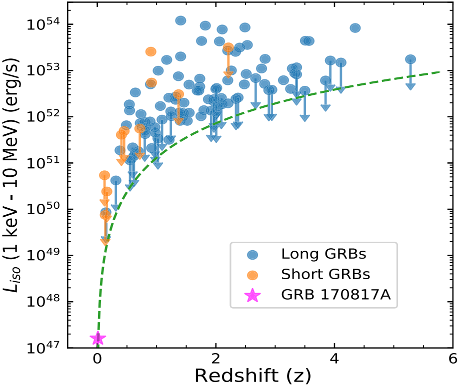


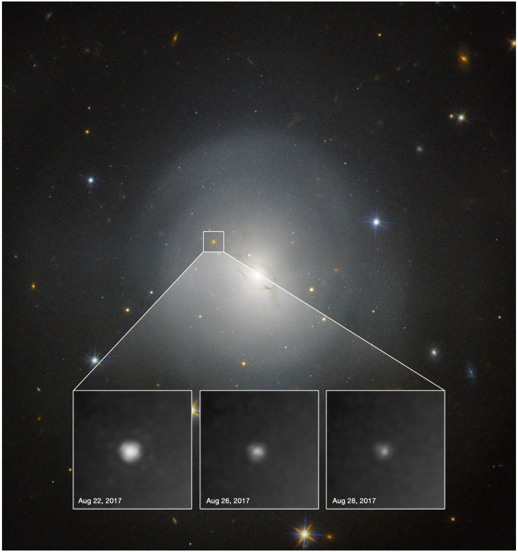
[Abbott+17]

First ever GW+EM multimessenger event

Close temporal + spatial association of (underluminous) short GRB



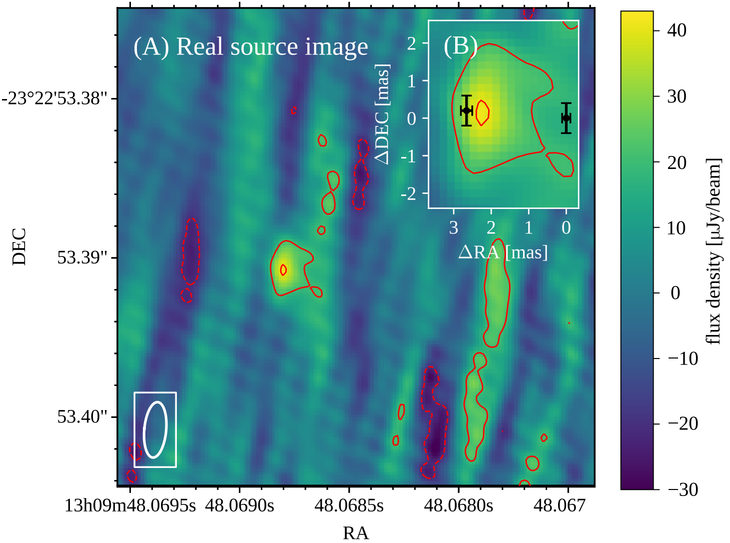
Kilonova & host galaxy



[HST image - NASA/ESA/A.J.Levan/N.R.Tanvir/A.Fruchter/O. Fox]

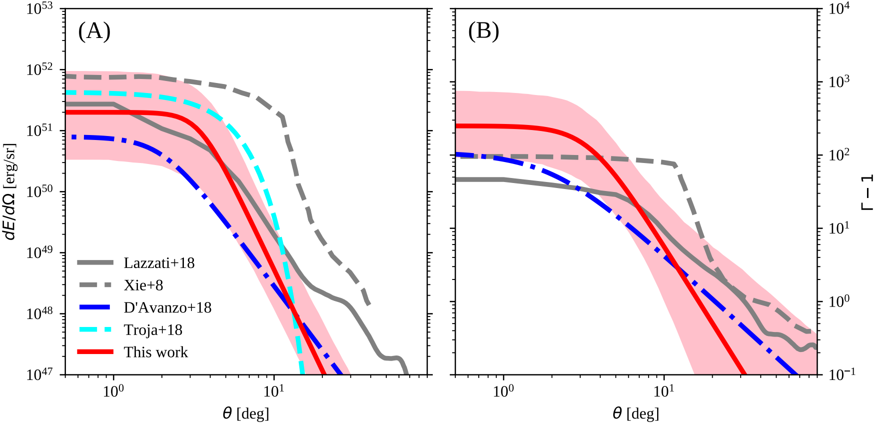
First-ever kilonova identified $\lesssim 12$ h post-merger (Coulter+17) $\rightarrow$ host galaxy & redshift

Solid off-axis jet evidence from VLBI imaging



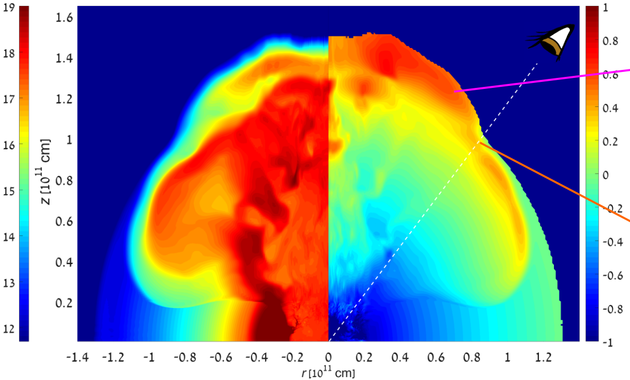
[Mooley+18, Ghirlanda+19]

Afterglow lightcurve + VLBI: jet structure & viewing angle



[Ghirlanda+19, see also Mooley+18 - more in J. Granot's talk!]

Dichotomy on origin of GRB170817A γ-rays



Internal dissipation

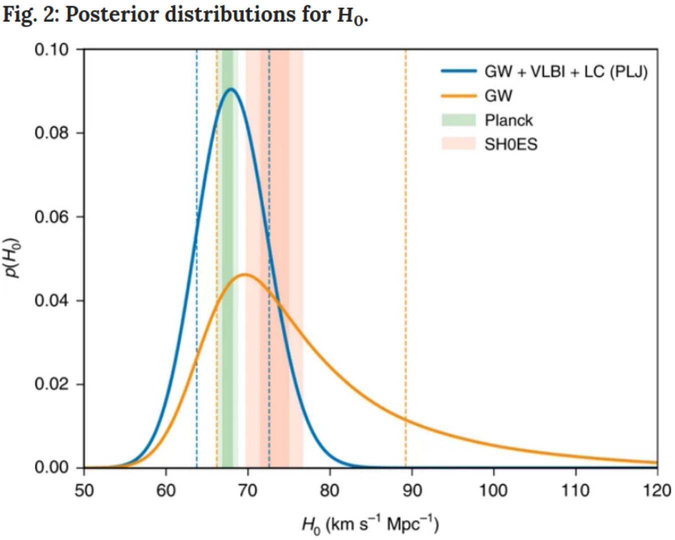
i.e. same mechanism as "classical GRB" emission, but at larger angles

Cocoon shock breakout

Radiation-mediated shock transition to optically thin

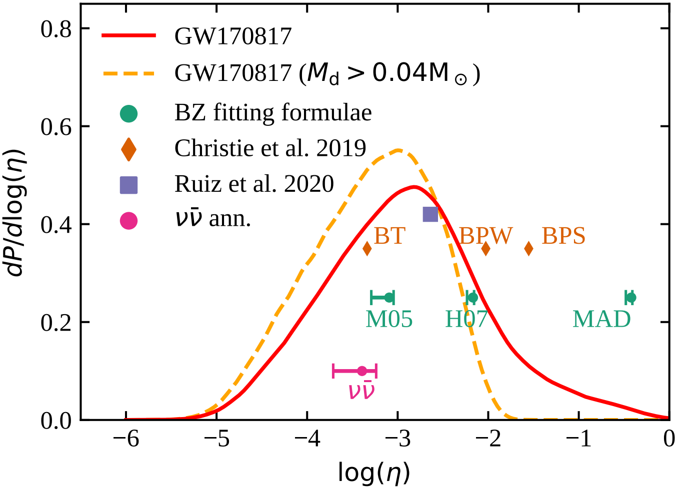
[e.g. Gottlieb+18; **Salafia**+18; Matsumoto+19; Ioka+19]

GW170817 → constraint on Hubble constant



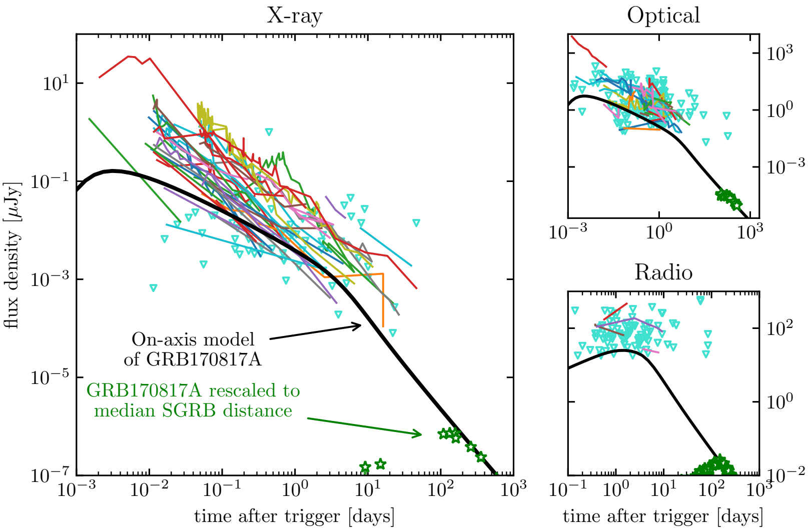
[Hotokezaka et al. 2019]

GW170817 → accretion-to-jet efficiency



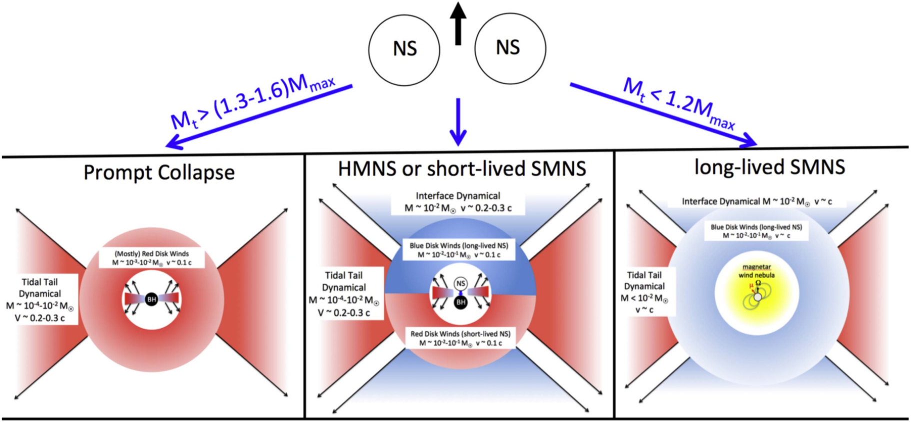
[**Salafia** & Giacomazzo 2021]

GW170817 → on-axis view: universal jet properties?



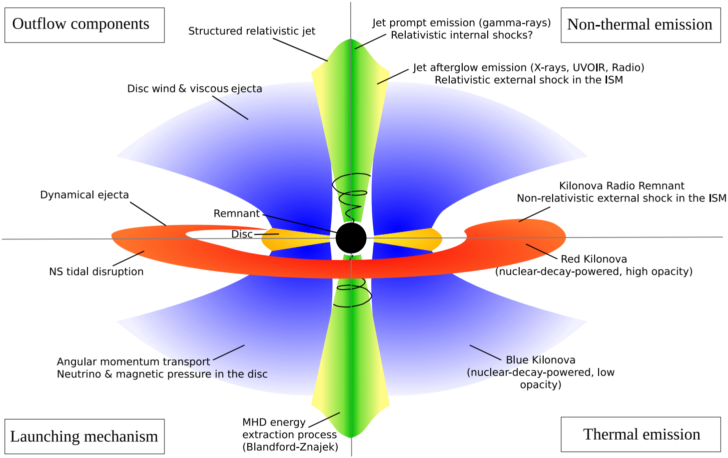
[**Salafia**+19, see also **Salafia**+20; data: Fong+15]

GW170817 → merger remnant and equation of state



[Margalit & Meztger ’17; see also Rezzolla+18; Shibata+19; **Salafia**+22; and others]

What about BH-NS mergers?



[Barbieri,**Salafia**+19; see also simulations by e.g. Ruiz+18,20; but tidal disruption difficult, see e.g. Foucart+12,18; e.g. Broekgaarden+21 for population BH spin predictions; LVK papers on GW200105 & GW200115]

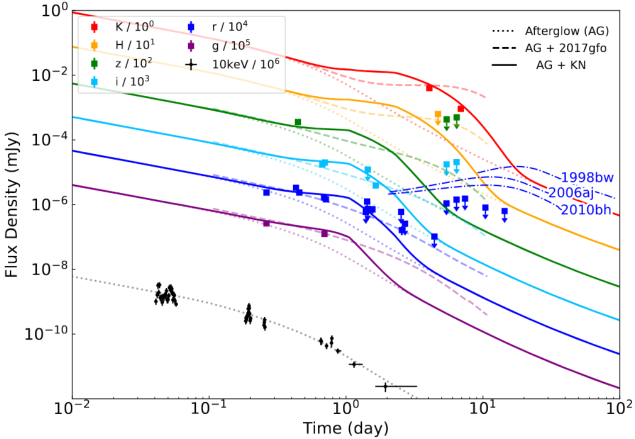
Final remarks & future prospects

- GRB + GW from compact binary mergers: viewport on jet + binary stellar evolution + fundamental physics (nuclear & cosmology)
- LVK GW detector O4 run upcoming → current predictions (e.g. Colombo,**Salafia**+22, arXiv:2204.07592) ~ 1 new GW+GRB event plausible
- BH-NS progenitor fraction soon to be unveiled!
- 3G GW detector era (2030's): GW counterpart to most GRBs from compact binary merger
- 3G GW detector era (2030's): post-merger GW detectable → direct info on central engine

Thank you!

Backup slides

Long/short duration vs massive star/merger progenitor?



[GRB211211A afterglow, Xiao+22, see also Rastinejad+22, Yang+22, Gao+22]

Jet duration in NS-NS/BH-NS mergers (1)

Accretion time scale

$$t_{\rm visc} \sim \frac{2\pi j_{\rm disk}^3 h^2}{G^2 M_{\rm rem}^2 \alpha} \sim 1\,{\rm s}\left(\frac{j_{\rm disk}}{10^{17}\,{\rm cm^2\,s^{-1}}}\right)^3 \left(\frac{M_{\rm rem}}{2.5\,{\rm M_\odot}}\right)^{-2} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{h}{0.5}\right)^2$$

Disk/torus specific angular momentum

$$j_{\rm disk} = J_{\rm disk}/M_{\rm disk}$$

Angular momentum conservation

$$J_{\rm disk} = J_{\rm orb,0} - J_{\rm GW} - J_{\rm rem} - J_{\rm ej} - J_\nu$$

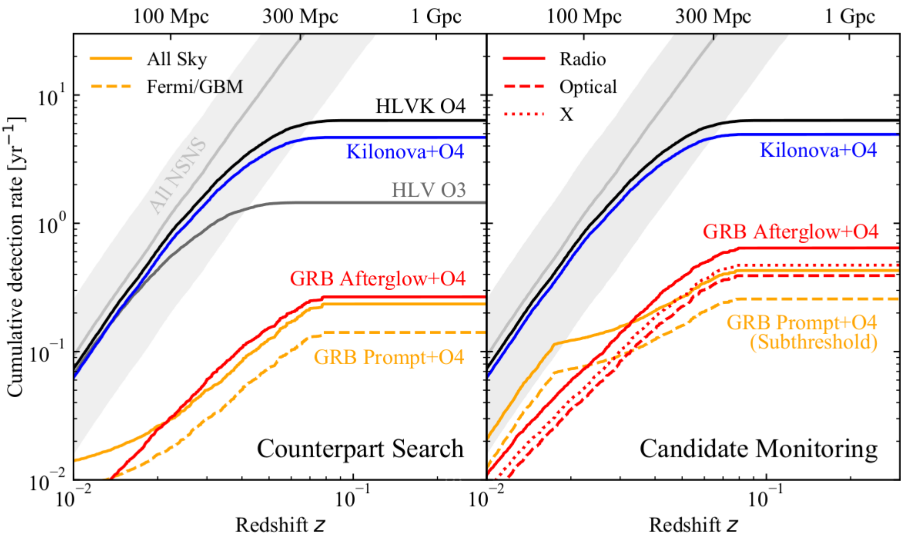
(likely $J_{\rm ej} + J_\nu \ll J_{\rm disk}$)

Jet duration in NS-NS/BH-NS mergers (2)

Angular time scale

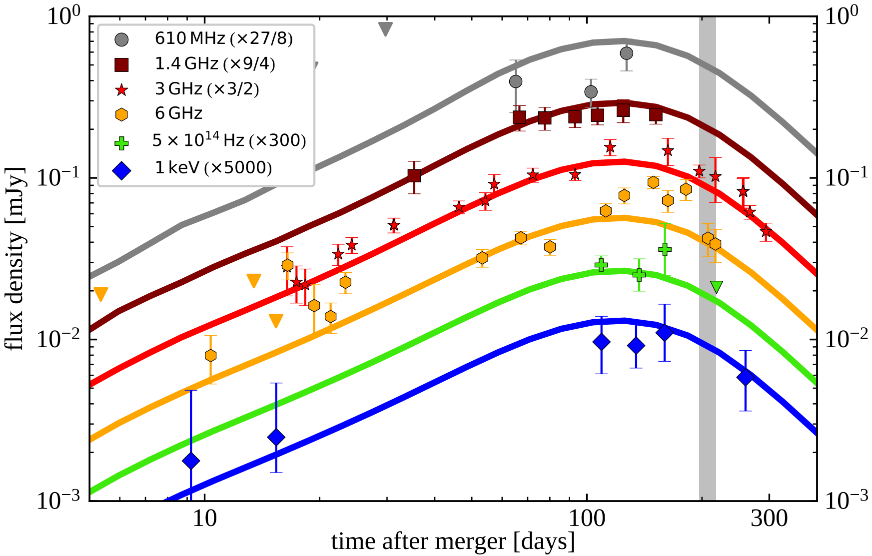
$$T_{\mathrm{GRB}} \gtrsim t_{\mathrm{ang}} \sim \frac{R_{\mathrm{diss}}}{2\Gamma^2 c}\left[1+\Gamma^2\left(\theta_{\mathrm{view}}-\theta_{\mathrm{diss}}\right)^2\right]^2$$

Expected GW+EM detection rates in O4

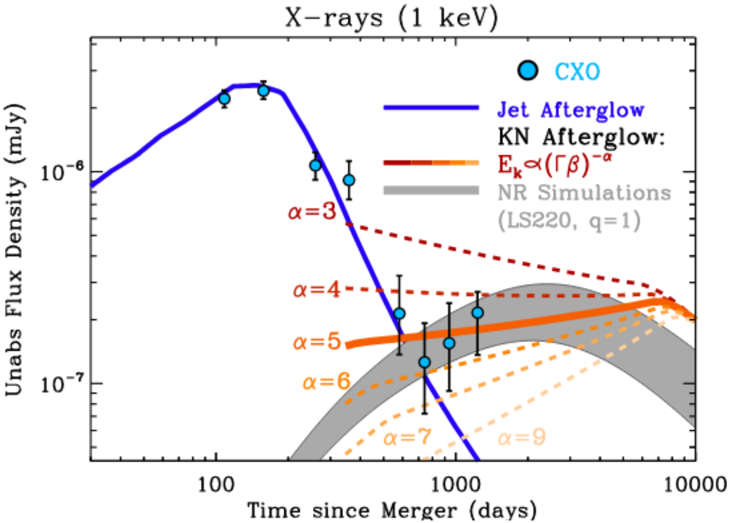


[Colombo,**Salafia**+22]

Multi-wavelength lightcurve of the GRB 170817A afterglow



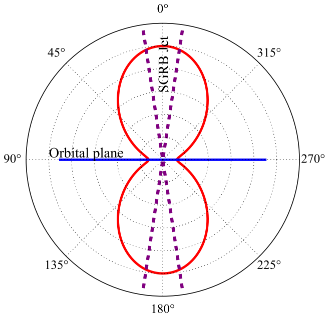
Late-time X-ray excess in GW170817



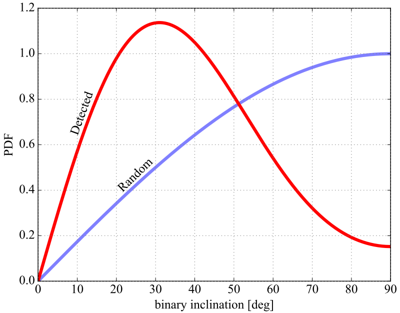
[Hajela+21]

Viewing angle probability

GW radiation pattern

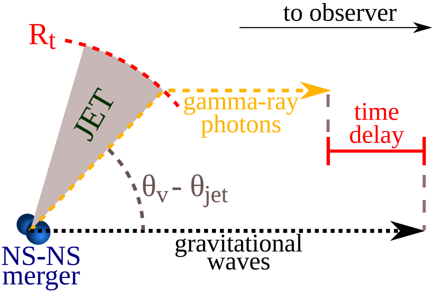


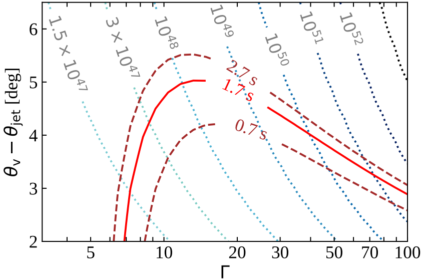
Inclination probability



[Schutz 2011]

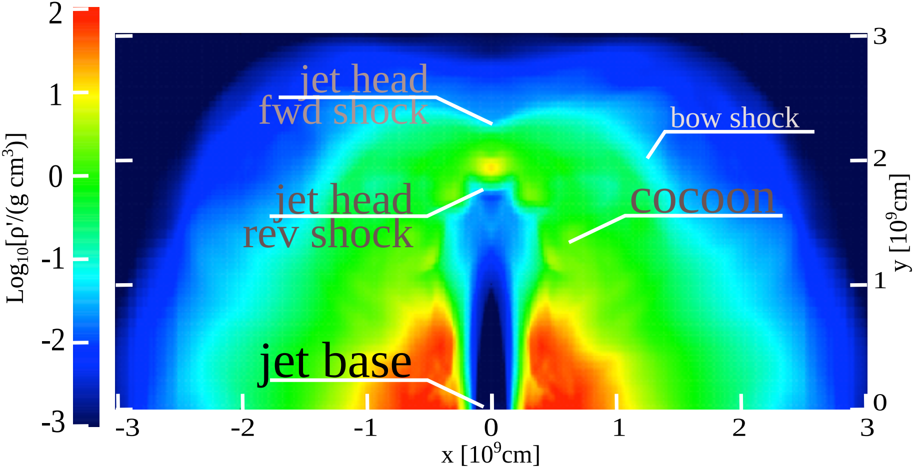
GW – GRB delay





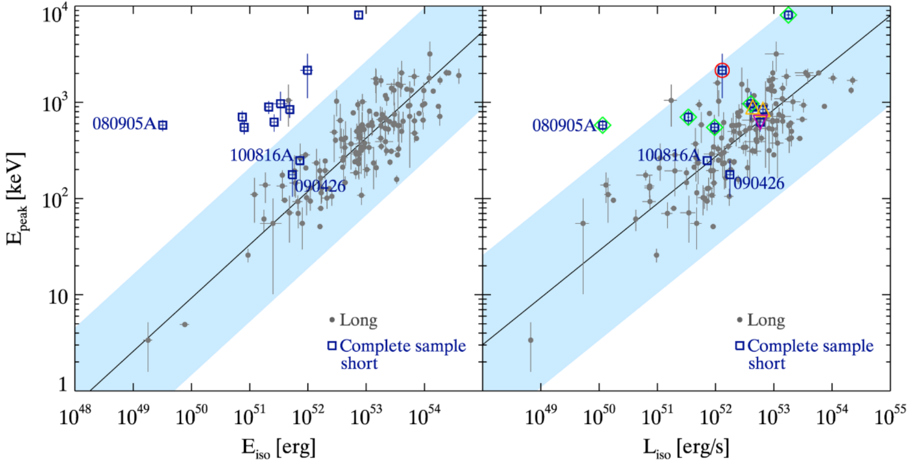
[Salafia et al. 2018]

What the heck is the "cocoon"?

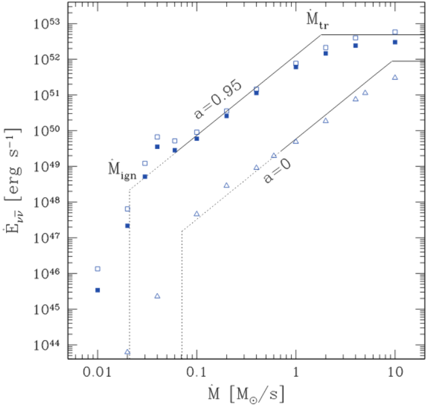


[Lazzati et al. 2016]

Spectral–energy correlations



(figure: D'Avanzo et al. 2014)



$$L_{\mathrm{jet},\nu\bar{\nu}} \propto r_{\mathrm{ISCO}}^{-24/5}\dot{M}^{9/4}M_{\mathrm{BH}}^{-3/2}$$

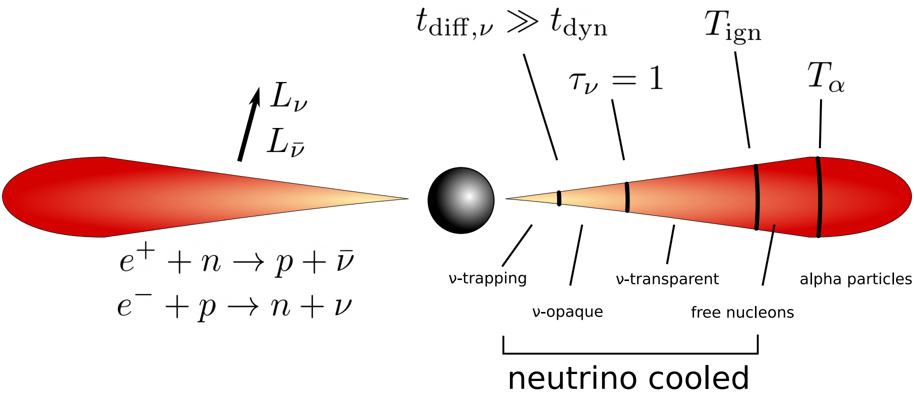
$$(\dot{M}_{\mathrm{ign}} < \dot{M} < \dot{M}_{\mathrm{sat}})$$

$$\dot{M}_{\mathrm{ign}} \sim \mathrm{few} \times 10^{-2}\,\mathrm{M_\odot/s}$$

$$\dot{M}_{\mathrm{sat}} \sim \mathrm{few} \times \,\mathrm{M_\odot/s}$$

[Zalamea & Beloborodov 2011 by GR ray tracing of ν & $\bar{\nu}$'s emitted according to neutrino-cooled accretion flow of Chen & Beloborodov 2007]

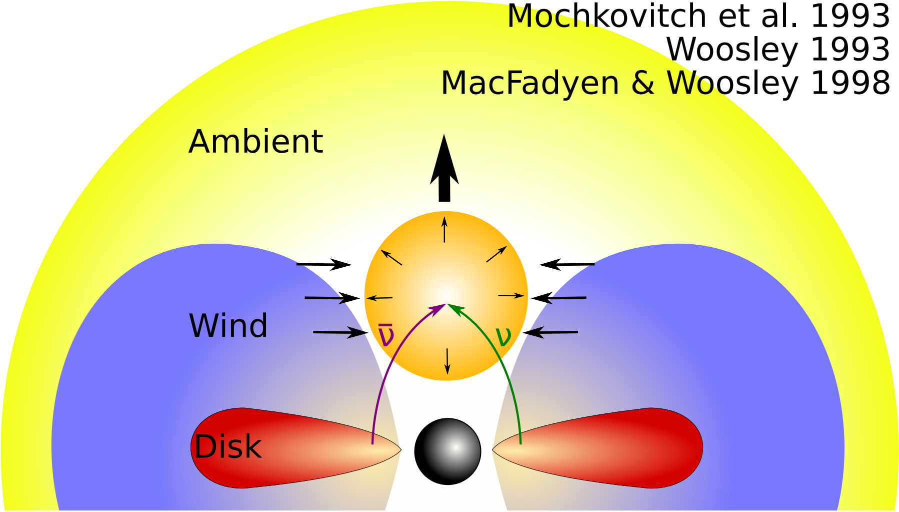
Neutrino-antineutrino annihilation process



[Eichler et al. 1989, Mochkovitch et al. 1993, Chen & Beloborodov 2007]

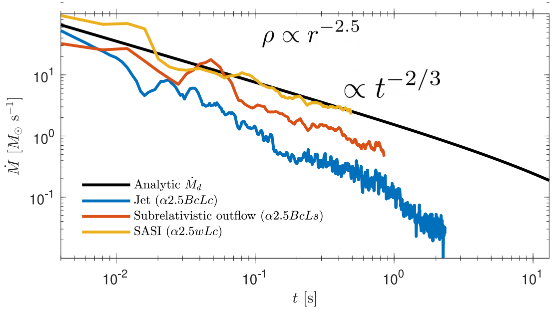
Neutrino-antineutrino annihilation process

Eichler et al. 1989
Mochkovitch et al. 1993
Woosley 1993
MacFadyen & Woosley 1998



$\nu\bar{\nu}$ expected efficiency: long GRB

Accretion rate time evolution



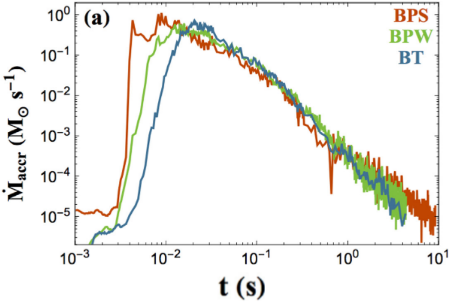
[Gottlieb et al. 2021]

$$\eta_{\nu\bar{\nu}} = 10^{-4} - 10^{-1}$$

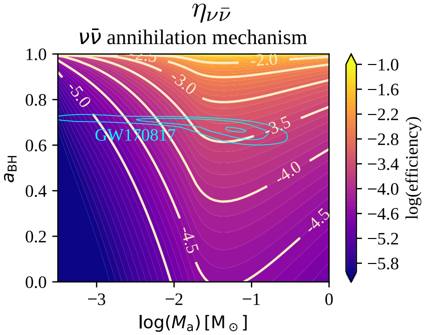
[MacFadyen & Woosley 1998]

$\nu\bar{\nu}$ expected efficiency: short GRBs

Accretion rate time evolution:
$\dot{M} \propto t^{-2}$

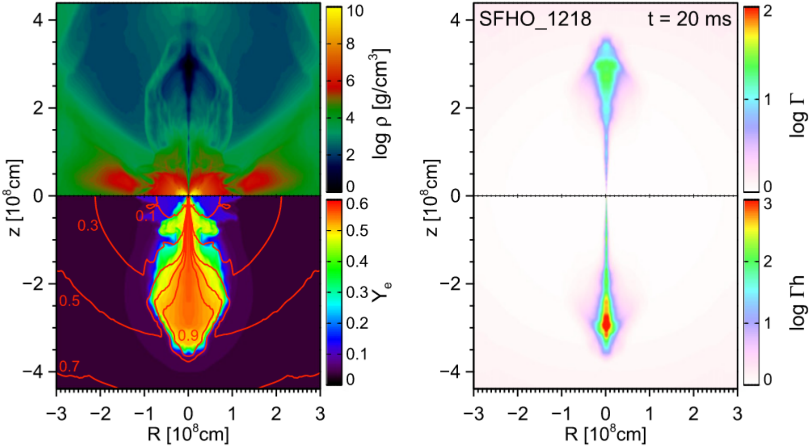


[Christie et al. 2019]



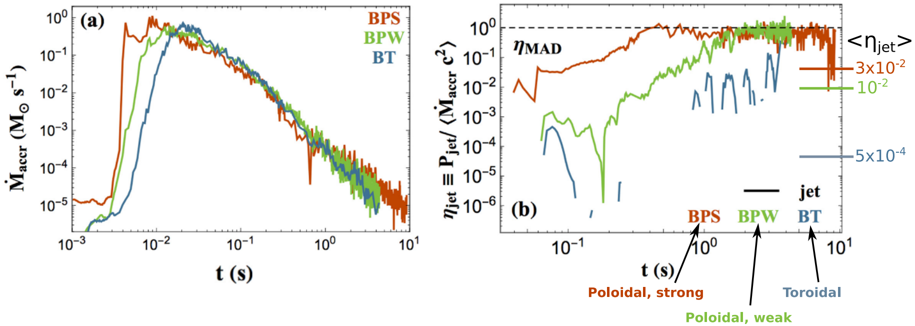
[Salafia & Giacomazzo 2020]

RMHD global simulations of $\nu\bar{\nu}$ mechanism in short GRBs



[Just et al. 2016]

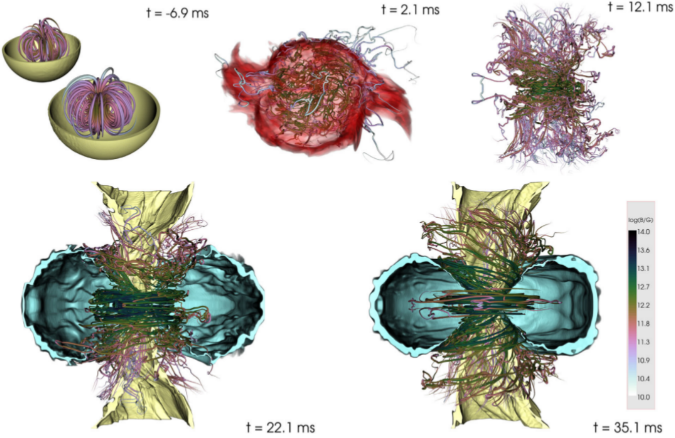
$\eta_{\rm BZ}$ in short gamma-ray bursts: B configuration



[Christie et al. 2019]

Expected B configuration in binary neutron star mergers

Dynamics + flux freezing → predominantly toroidal



[Kawamura et al. 2016]