Multi-wavelength follow up of LIGO/Virgo gravitational wave sources

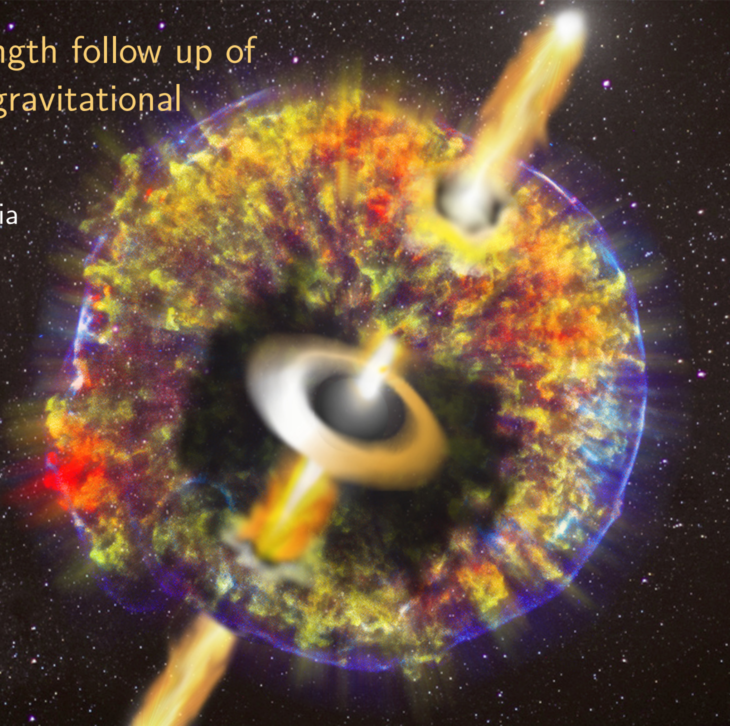
Om Sharan Salafia

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

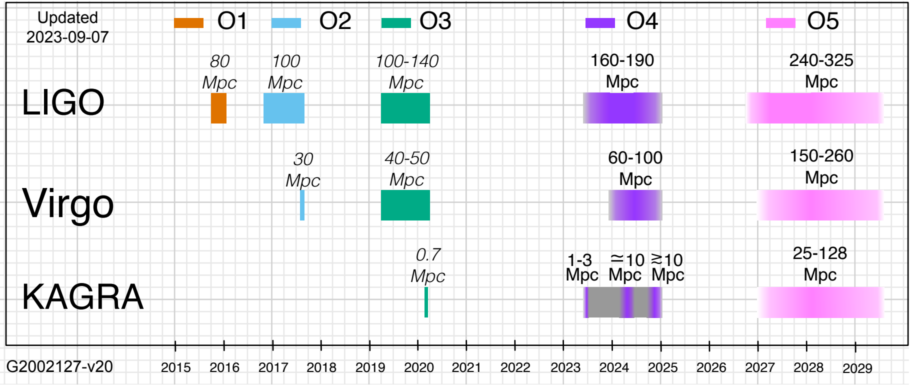
INAF ISTITUTO NAZIONALE DI ASTROFISICA

INFN

OSSERVATORIO ASTRONOMICO DI BRERA



Where are we: LVK observing run timeline



(dcc.ligo.org/G2002127-v20)

O4 run – current status (as of 2023-10-02)

GW source candidates so far:

- 49 significant GW candidates ($\sim 2.6\,\mathrm{wk}^{-1}$)
- 48 most likely binary black hole (BBH) mergers
- 1 most likely a neutron star - black hole (NS-BH) merger
- 0 binary neutron star (BNS) mergers so far

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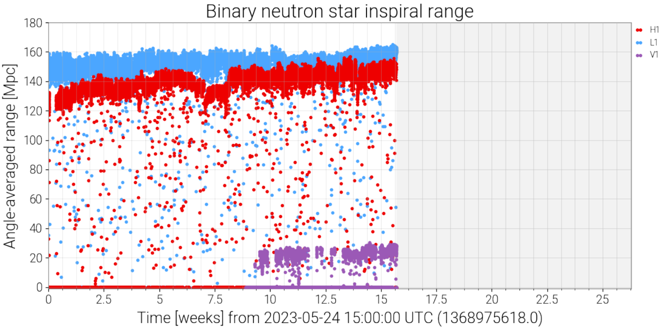
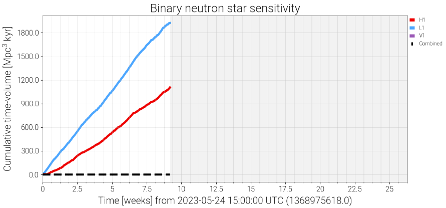
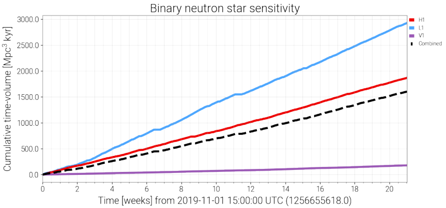
Network status (from `gwosc.org`):



Is there a missing BNS problem?

`gwosc.org/detector_status`





Time-volume covered by BNS search in O4 so far (most sensitive detector): $1.8 \times 10^{-3}\,\mathrm{Gpc^3\,yr}$

O1+O2+O3: $8.1 \times 10^{-3}\,\mathrm{Gpc^3\,yr}$

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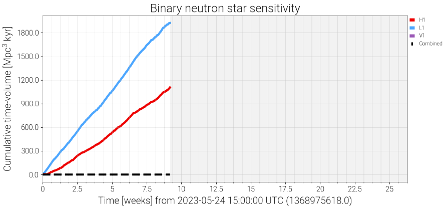

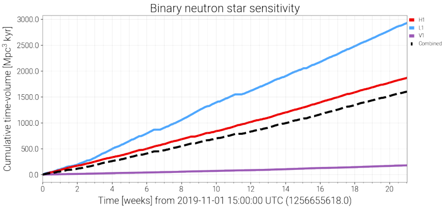

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- Number of BNS detected in O1+O2+O3: 2 (GW170817 and GW190425)

Is there a missing BNS problem?

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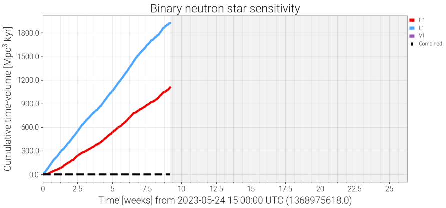

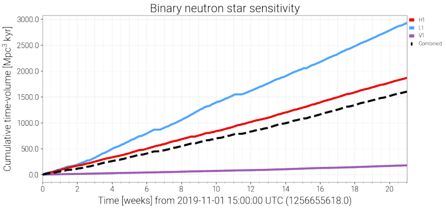

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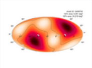
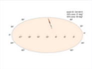
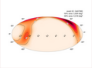
O1+O2+O3: $8.1 \times 10^{-3}\,\mathrm{Gpc}^3\,\mathrm{yr}$

- Number of BNS detected in O1+O2+O3: 2 (GW170817 and GW190425)
- Expected number of detections in O4 so far: $2 \times 1.8/8.1 = 0.44$

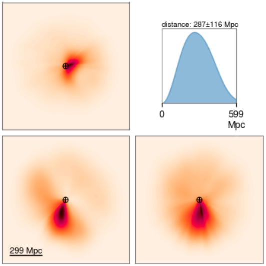
  $\rightarrow$ we must likely wait a few more months for the next BNS

Public Alerts

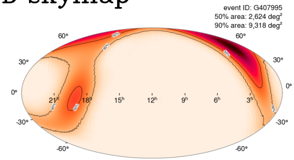
GraceDB LIGO/Virgo/KAGRA Public Alerts

Event ID	Possible Source (Probability) ↓	Significant	UTC	GCN	Location	FAR	Comments	Ω Scan
S230529ay	NSBH (62%), BNS (31%), Terrestrial (7%)	Yes	May 29, 2023 18:15:00 UTC	GCN Circular Query Notices | VOE		1 per 160.44 years		Ω H1 Ω L1 Ω V1
S230627c	NSBH (49%), BBH (48%), Terrestrial (3%)	Yes	June 27, 2023 01:53:37 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years		Ω H1 Ω L1 Ω V1
S230524x	BNS (75%), Terrestrial (25%)	Yes	May 24, 2023 20:22:41 UTC	GCN Circular Query Notices | VOE		2.2799 per year	RETRACTED	Ω H1 Ω L1 Ω V1

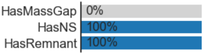
classification



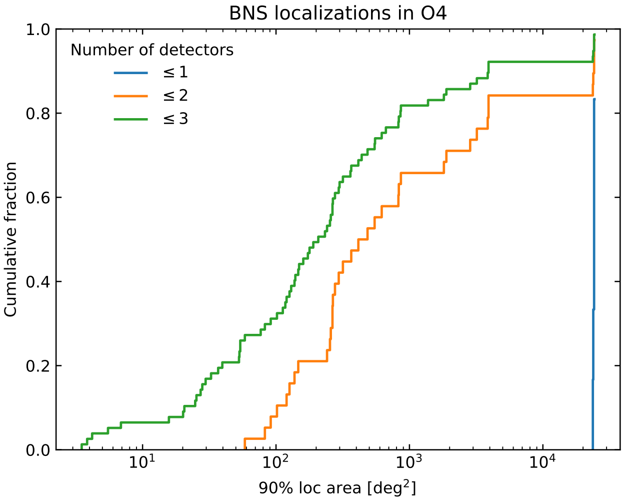
3D skymap



\`EM bright' information



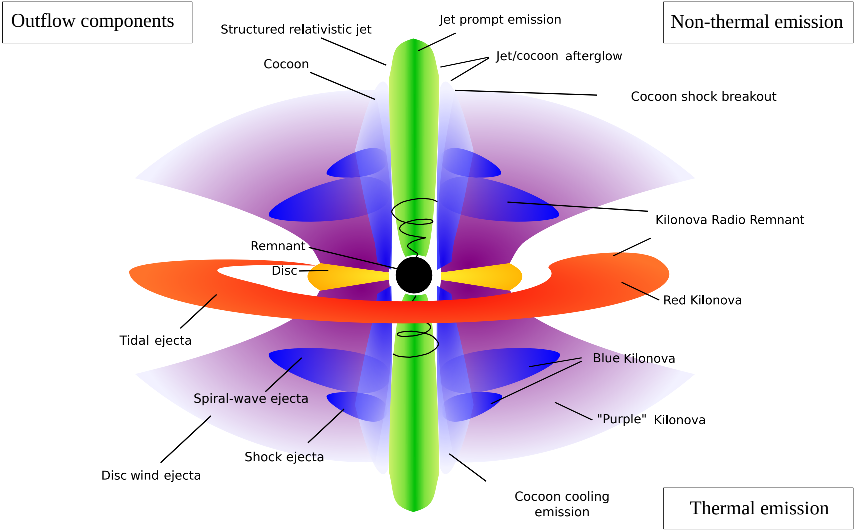
Localization capabilities



→ median expected 90% localization area: $100\,\mathrm{deg}^2$ (3 det) – $500\,\mathrm{deg}^2$ (2 det)
(based on the simulations in Frostig et al. 2022)

But what are we looking for?

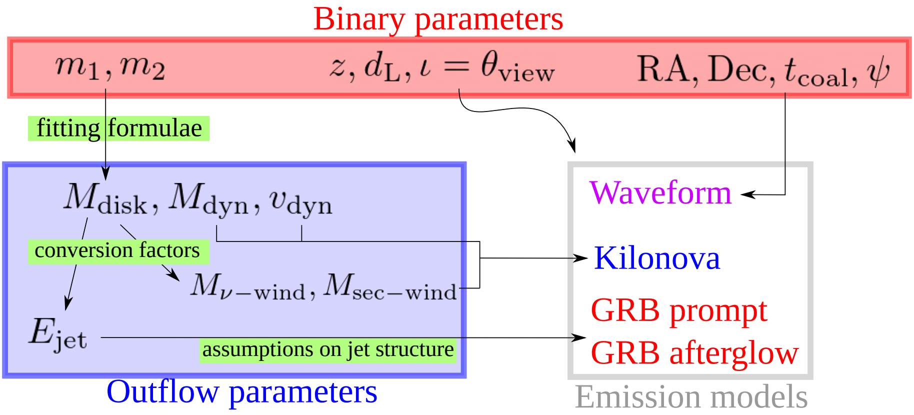
EM counterparts of BNS & BH-NS mergers



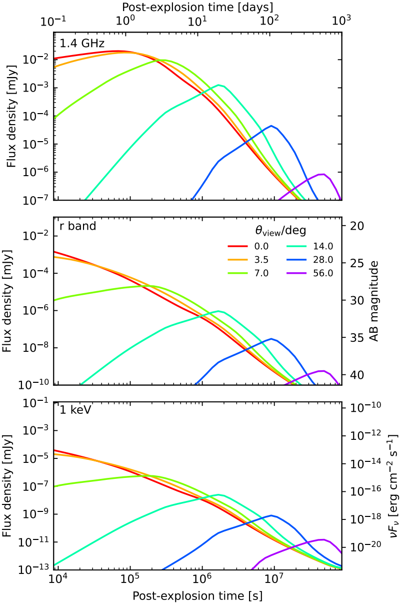
(Adapted from Barbieri, **Salafia**+2019)

Ok, but how does all of this look like in O4?

BNS multi-messenger population model



[Barbieri, **Salafia**+19, Colombo, **Salafia**+22]

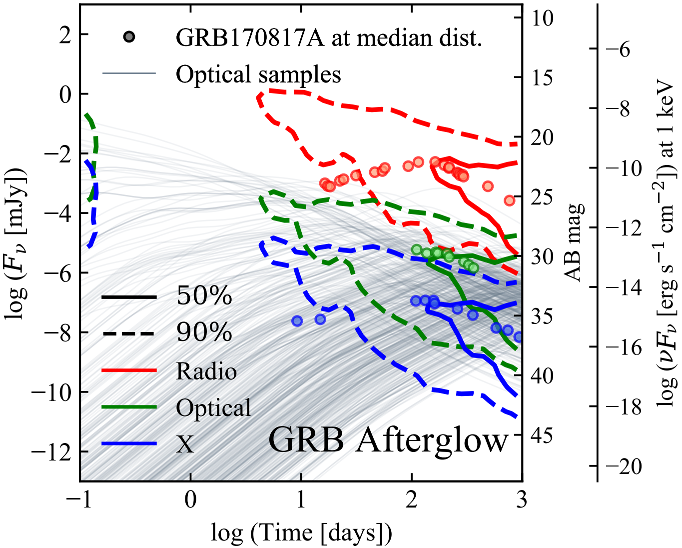


"Standard afterglow" model

- synchrotron emission only
- GRB170817A-like jet structure
- low ISM density $n = 5 \times 10^{-3}\,\mathrm{cm}^{-3}$
- $\epsilon_\mathrm{e} = 0.1$, $\epsilon_\mathrm{B} = 10^{-4}$, $p = 2.15$

← example light curves

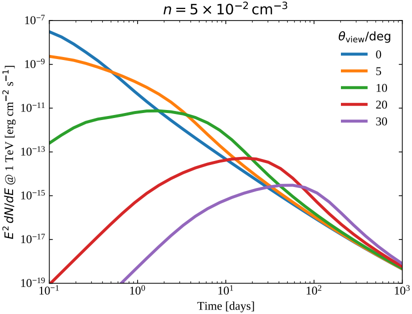
Afterglows from BNS detected by LIGO-Virgo in O4



[Colombo, Salafia et al. 2022]

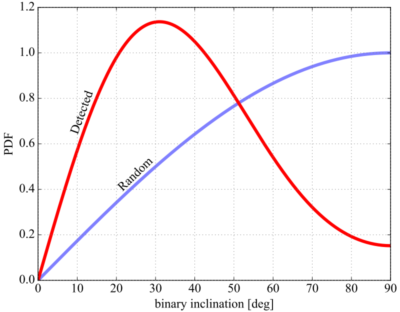
SGRB afterglows at TeV energies

SSC light curves @ 40 Mpc



[Stamerra, Salafia, et al. 2021 – ICRC2021-944]

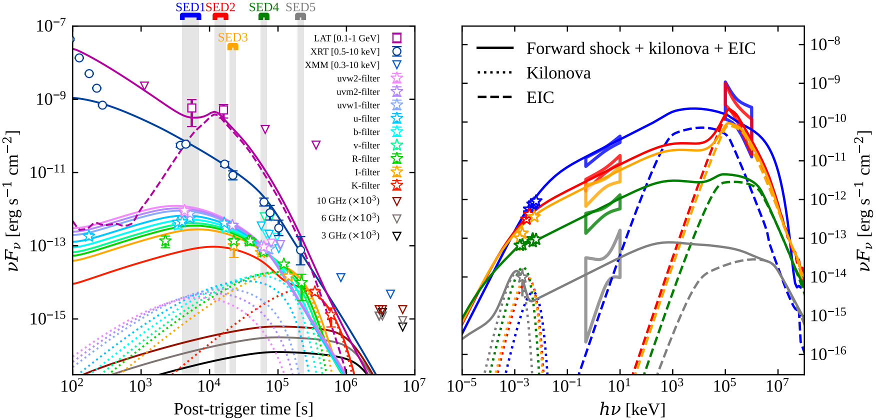
Inclination angle



[Schutz 2011]

Other potential VHE emission mechanisms?

GRB211211A: a long GRB from a compact binary merger



[Mei, ..., Salafia, et al. 2022]

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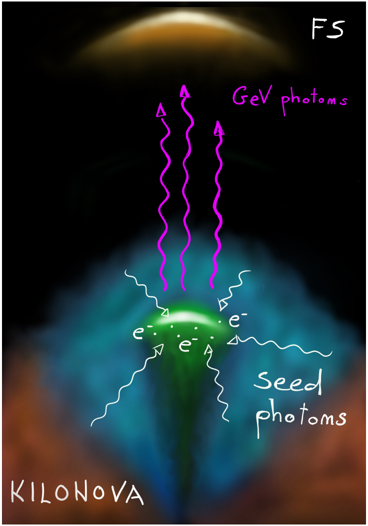
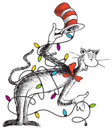


[Mei, ..., Salafia, et al. 2022]

Summary

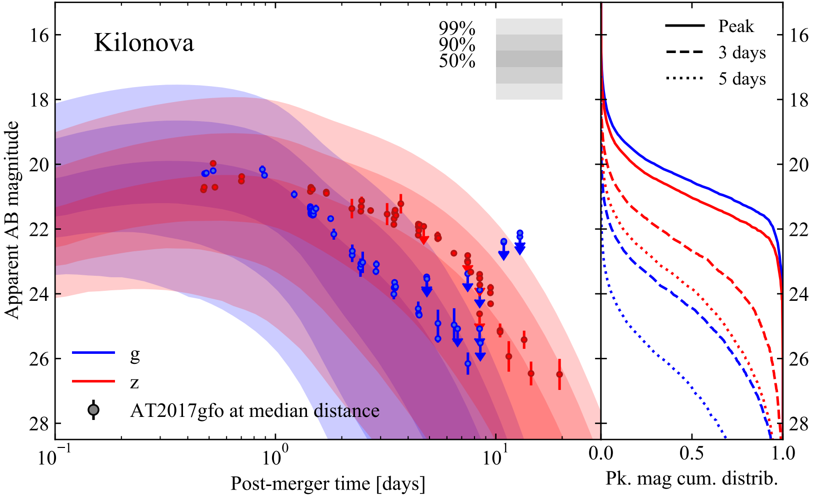
- O4 run started ~ 4 months ago
- Significant GW candidates so far: 48 BBH, 1 NSBH, 0 BNS
- First BNS likely in the next few months (hopefully Virgo will have joined then!)
- Prospects for VHE detection of SGRB external shock in association to GW-detected BNS merger in O4: not promising, but I would love to be proved wrong!
- Potential unforeseen additional VHE counterparts: data needed to contrain them!



Thank you!

Backup slides

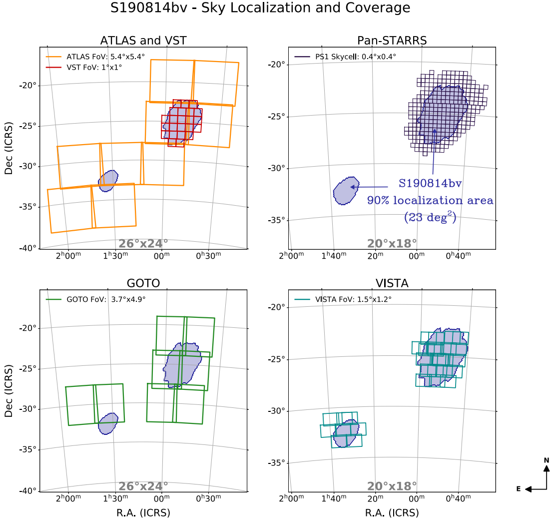
Kilonovae from BNS detected by LIGO-Virgo in O4



[Colombo, Salafia et al. 2022]

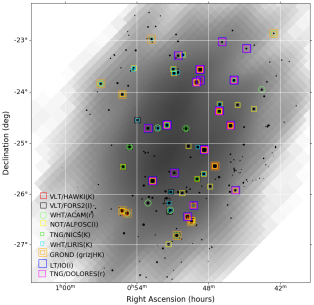
The EM counterpart search challenge

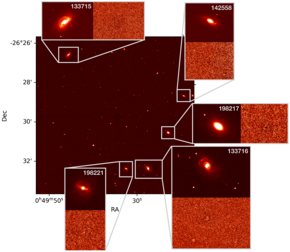
Wide-field telescope search



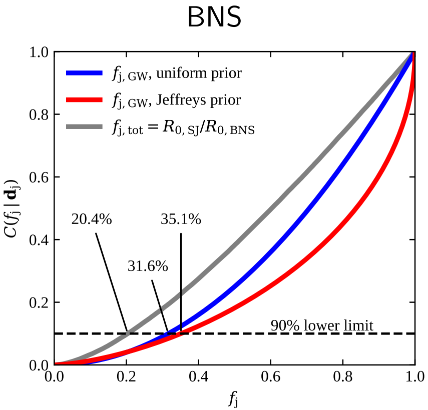
[Ackley et al. 2020 – ENGRAVE collaboration]

Galaxy-targeted search





How common is the jet?

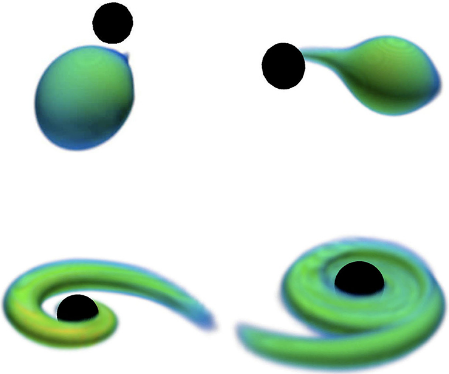


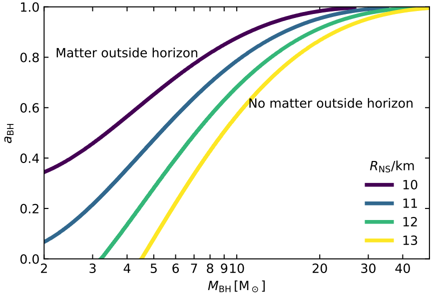
GW170817 indicates that large fraction of BNS mergers lead to a jet

[**Salafia** et al. 2022; see also Ghirlanda et al. 2019; Beniamini et al. 2019]

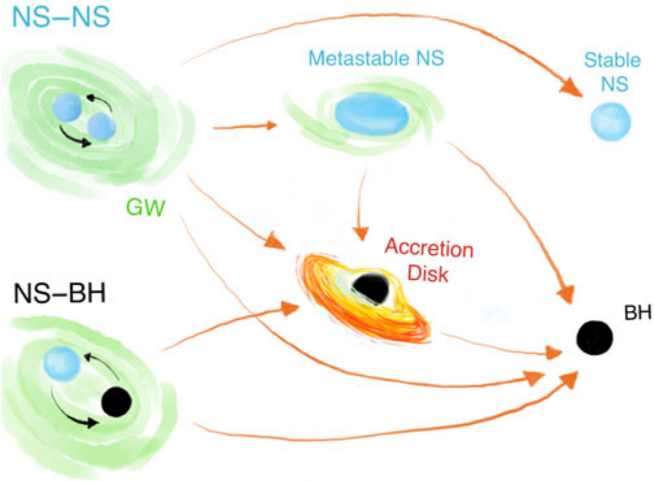
What about BH-NS mergers?

NS tidal disruption in a BH-NS merger



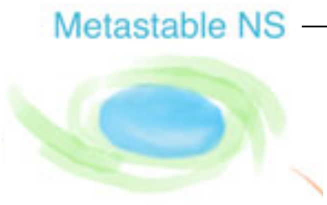


Variety of merger remnants



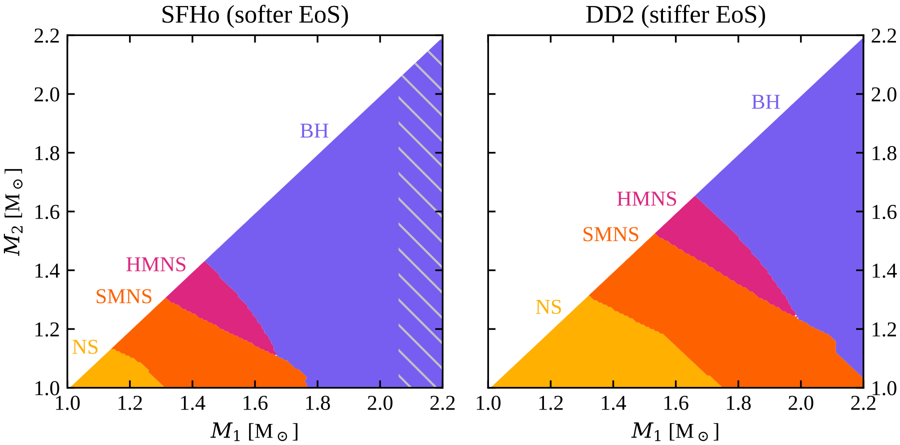
[Figure: Ascenzi+21]

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



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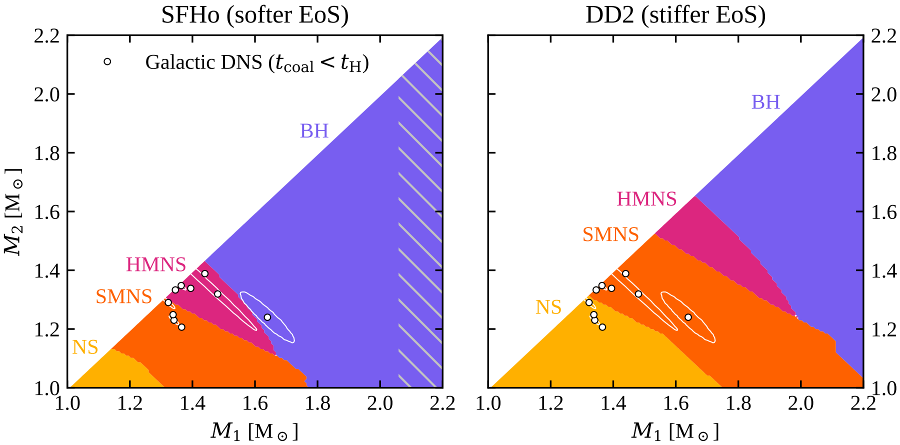

[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19]

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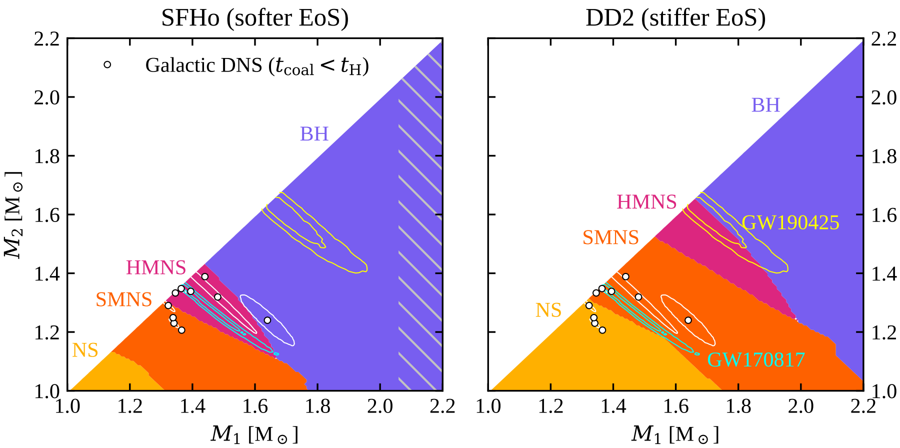

[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19; GW data: Abbott+19,20]

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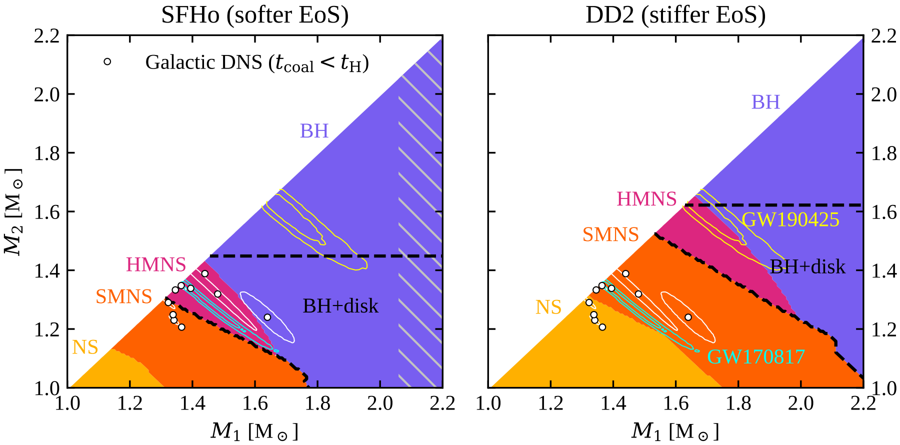

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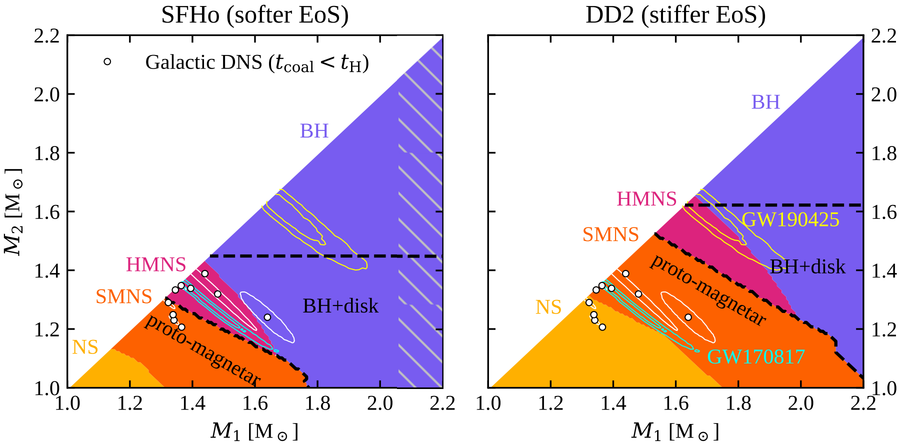

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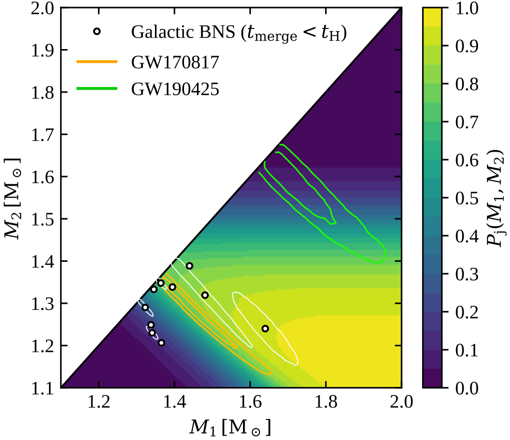
Marginalizing over EoS uncertainty



(Assuming BH remnant + disk needed for jet launching)

[**Salafia** et al. 2022]

BNS merger population multi-messenger model

Need to specify:

- **mass distribution**, $P(m_1, m_2) \propto \mathrm{d}^2N/\mathrm{d}m_1\mathrm{d}m_2$
- **equation of state (EoS) of neutron star matter**, $p = p(\varepsilon)$
- **cosmic merger rate density**, $\dot{\rho}_{\mathrm{BNS}}(z) = \mathrm{d}^2N/\mathrm{d}t\mathrm{d}V(z)$

[Colombo, Salafia, et al. 2022]

BNS merger population multi-messenger model

Need to specify:

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[Colombo, Salafia, et al. 2022]

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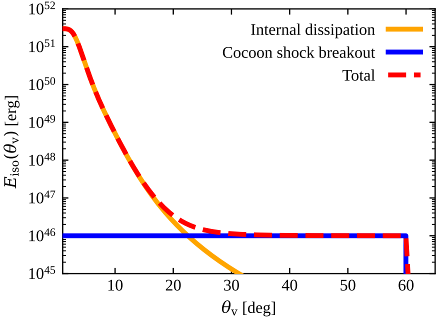
- **equation of state (EoS) of neutron star matter**, $p = p(\varepsilon)$: SFHo (Hempel+12), compatible with multi-messenger constraints
- **cosmic merger rate density**, $\dot{\rho}_{\mathrm{BNS}}(z) = \mathrm{d}^2N/\mathrm{d}t\mathrm{d}V(z)$: assume simple t^{-1} delay time distribution convolved to cosmic SFH

[Colombo, Salafia, et al. 2022]

GRB prompt emission model



Jet

- "Blandford-Znajek" (require BH+disk remnant)
- $E_{\rm jet}/M_{\rm disk}c^2 \sim 10^{-3}$ (Salafia & Giacomazzo 2020)

"Internal dissipation"

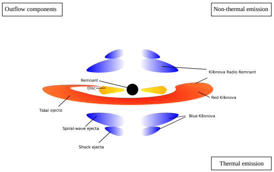
- require $\Gamma > 10$
- 15% energy into γ-rays
- fixed comov. spectrum, $3\,\mathrm{keV}$ peak

"Cocoon shock breakout"

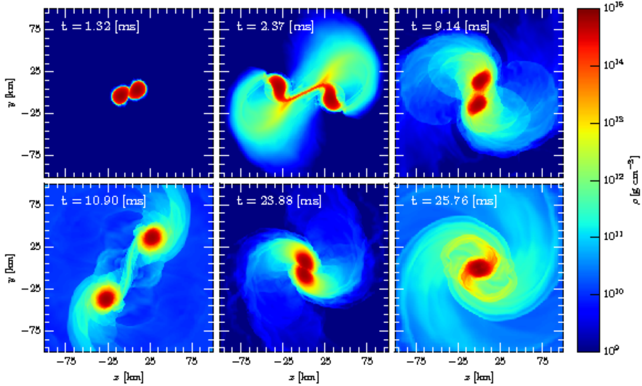
- GRB170817A-like luminosity and spectrum
- visible only if $\theta_{\rm view} < 60^\circ$

[Colombo+22, see also Salafia+15, Ghirlanda+19, Salafia+20, Salafia+23]

Kilonova ejecta – dynamical



Dynamical ejecta



[GRHD simulation from Radice et al. 2016]

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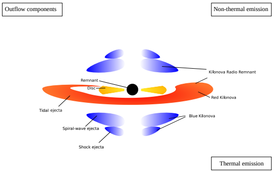

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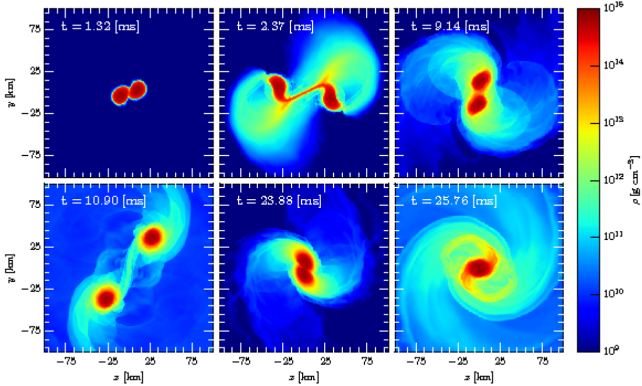

[GRHD simulation from Radice et al. 2016]

- Tidal: $M_{\rm ej} \lesssim 10^{-2}\,\mathrm{M}_\odot$, $Y_{\rm e} < 0.2$, $v_{\rm ej} \gtrsim 0.2\,\mathrm{c}$

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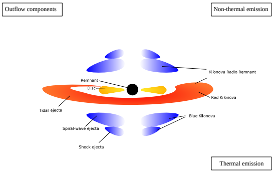
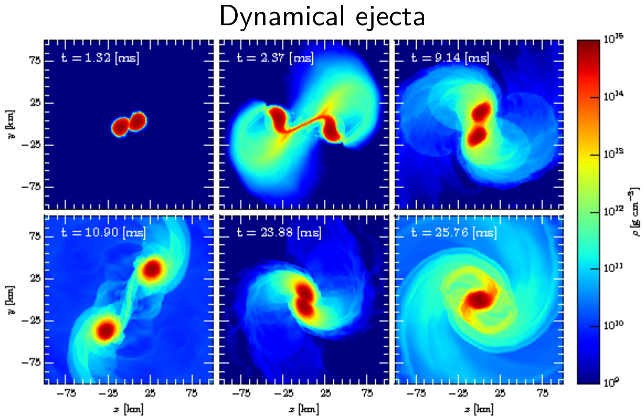
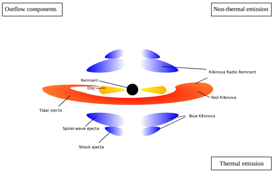


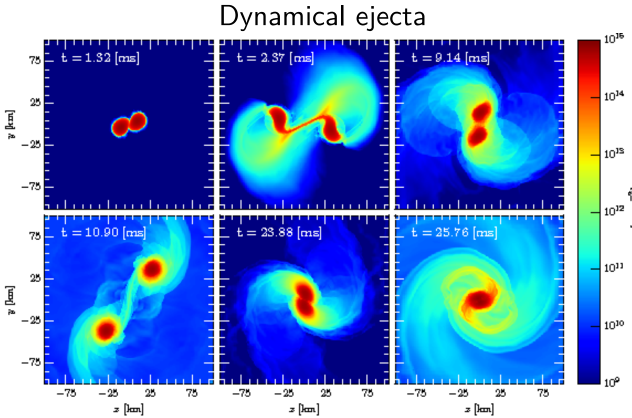


[GRHD simulation from Radice et al. 2016]

- Tidal: $M_{\rm ej} \lesssim 10^{-2}\,{\rm M_\odot}$, $Y_{\rm e} < 0.2$, $v_{\rm ej} \gtrsim 0.2\,{\rm c}$
- Shock-driven: $M_{\rm ej} \lesssim 10^{-3}\,{\rm M_\odot}$, $Y_{\rm e} > 0.2$, $v_{\rm ej} \gtrsim 0.2\,{\rm c}$

Kilonova ejecta – dynamical

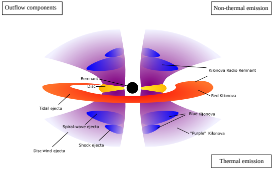


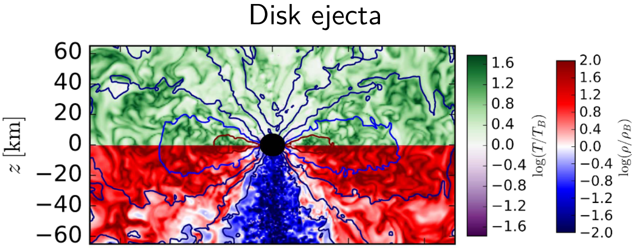


[GRHD simulation from Radice et al. 2016]

- Tidal: $M_{\rm ej} \lesssim 10^{-2}\,\mathrm{M}_\odot$, $Y_{\rm e} < 0.2$, $v_{\rm ej} \gtrsim 0.2\,\mathrm{c}$
- Shock-driven: $M_{\rm ej} \lesssim 10^{-3}\,\mathrm{M}_\odot$, $Y_{\rm e} > 0.2$, $v_{\rm ej} \gtrsim 0.2\,\mathrm{c}$
- Long-lived remnant oscillations: $M_{\rm ej} \sim 10^{-2}\,\mathrm{M}_\odot$, $Y_{\rm e} > 0.2$, $v_{\rm ej} \gtrsim 0.2\,\mathrm{c}$

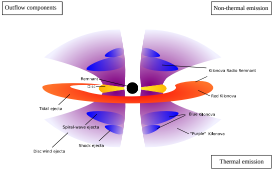
Kilonova ejecta – disk

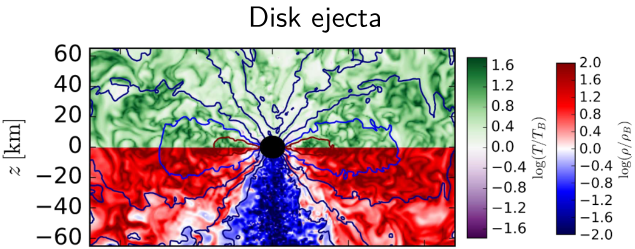




[GRνMHD simulation from Siegel et al. 2018]

Kilonova ejecta – disk

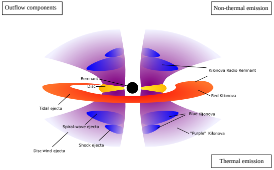


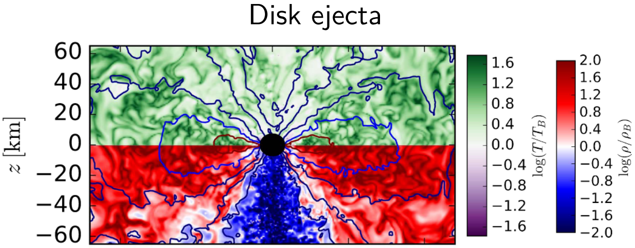


[GRνMHD simulation from Siegel et al. 2018]

- ν-driven: $M_{\rm ej} \lesssim 10^{-4}\,{\rm M_\odot}$, $Y_{\rm e} > 0.2$, $v_{\rm ej} \gtrsim 0.2\,{\rm c}$

Kilonova ejecta – disk





[GRνMHD simulation from Siegel et al. 2018]

- ν-driven: $M_{\rm ej} \lesssim 10^{-4}\,{\rm M_\odot}$, $Y_{\rm e} > 0.2$, $v_{\rm ej} \gtrsim 0.2\,{\rm c}$
- Viscous: $M_{\rm ej} \gtrsim 10^{-2}\,{\rm M_\odot}$, $Y_{\rm e} \sim 0.1 - 0.3$, $v_{\rm ej} \lesssim 0.1\,{\rm c}$

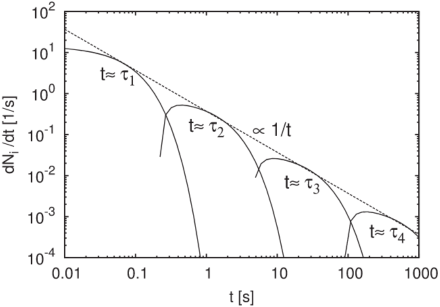
Kilonova emission

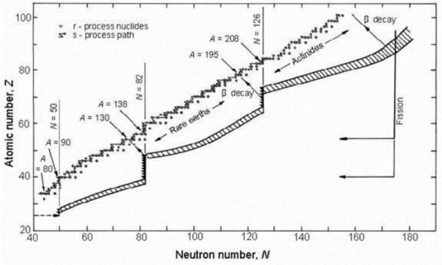
- Decompressing NS material → r-process nucleosynthesis (Lattimer & Schramm 1977). Decay of products heats up ejecta: Kilonova emission (Li & Paczynski 1998).

Heating rate:

$$\dot{\epsilon} \sim \dot{\epsilon}_0 (t/t_0)^{-\alpha}$$

where $\dot{\epsilon}_0 \sim 10^{16}\,\mathrm{erg\,s^{-1}\,g^{-1}}$, $t_0 = 1\,\mathrm{s}$ (e.g. Korobkin et al. 2012) and $\alpha \sim 1.3$ (from Fermi's theory of β decay, see Metzger+2010, Hotokezaka+2017)





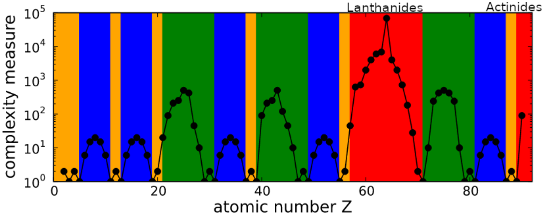
Clayton, *Principles of Stellar Evolution and Nucleosynthesis*, (1983)

Kilonova emission

- Ejecta composition depends on electron fraction: Lanthanides produced if $Y_{\rm e} < 0.2$

Kilonova emission

- Ejecta composition depends on electron fraction: Lanthanides produced if $Y_\mathrm{e} < 0.2$
- Composition has little effect on heating rate, but big difference in opacity and hence photon diffusion time scale: $\kappa \gtrsim 10\,\mathrm{cm^2\,g^{-1}}$ if Lanthanides present; $\kappa \lesssim \mathrm{few\,cm^2\,g^{-1}}$ otherwise



[Kasen et al. 2013 – open f shell elements in red]

Kilonova emission properties

Simple expanding shell toy model

Optical depth:

$$\tau \sim \frac{\kappa M_{\rm ej}\Delta R}{4\pi R^2 \Delta R} = \frac{\kappa M_{\rm ej}}{4\pi (v_{\rm ej} t)^2}$$

Diffusion time:

$$t_{\rm diff} \sim \frac{R}{(c/\tau)} = \frac{\kappa M_{\rm ej}}{4\pi c v_{\rm ej} t}$$

Peak time:

$$t_{\rm diff} = t \sim t_{\rm peak} \rightarrow t_{\rm peak} \sim \sqrt{\frac{\kappa M}{4\pi c v_{\rm ej}}} = 1.5\,{\rm d}\left(\frac{M_{\rm ej}}{10^{-2}{\rm M}_{\odot}}\right)^{1/2}\left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2}\left(\frac{\kappa}{1{\rm cm}^2/{\rm g}}\right)^{1/2}$$

$\rightarrow$ extremely fast transient

Kilonova emission properties

Peak luminosity:

$$L_{\rm peak} \sim \dot{\epsilon}(t_{\rm peak})M_{\rm ej} \sim 4\times 10^{40}\,{\rm erg/s}\left(\frac{M_{\rm ej}}{10^{-2}{\rm M_\odot}}\right)^{1-\alpha/2}\left(\frac{v_{\rm ej}}{0.1c}\right)^{\alpha/2}\left(\frac{\kappa}{1{\rm cm^2/g}}\right)^{-\alpha/2}$$

→ Less luminous than a supernova

Peak effective temperature:

$$L_{\rm peak} \sim 4\pi(v_{\rm ej}t_{\rm peak})^2\sigma_{\rm SB}T_{\rm eff}^4$$

$$\rightarrow T_{\rm eff} \sim 5500\,{\rm K}\left(\frac{M_{\rm ej}}{10^{-2}{\rm M_\odot}}\right)^{-\alpha/8}\left(\frac{v_{\rm ej}}{0.1c}\right)^{(\alpha-2)/8}\left(\frac{\kappa}{1{\rm cm^2/g}}\right)^{-(\alpha+2)/8}$$

→ Optical – Near Infrared

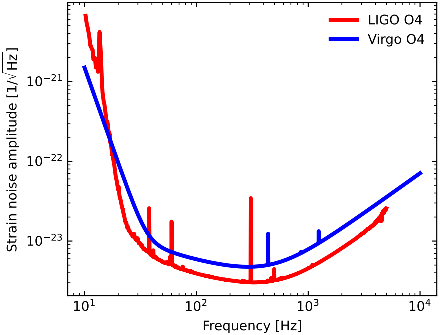
Waveform & SNR

1) generate $h(t)$ with

PyCBC

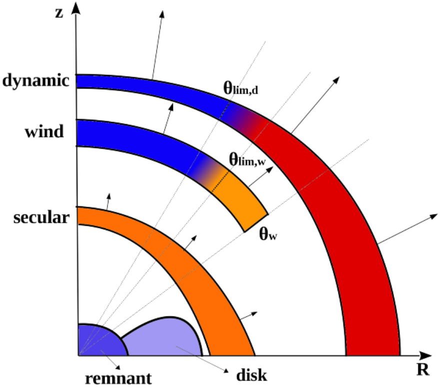
using the Taylor F2 approximant
[e.g. Damour+01]

2) compute GW SNR adopting the



projected sensitivity curves of LIGO and Virgo in O4

Kilonova model



- three components, anisotropic, numerical-relativity-informed
- Arnett-like model, grey opacity in angular bins

[Perego+17, Barbieri+19, Breschi+21]