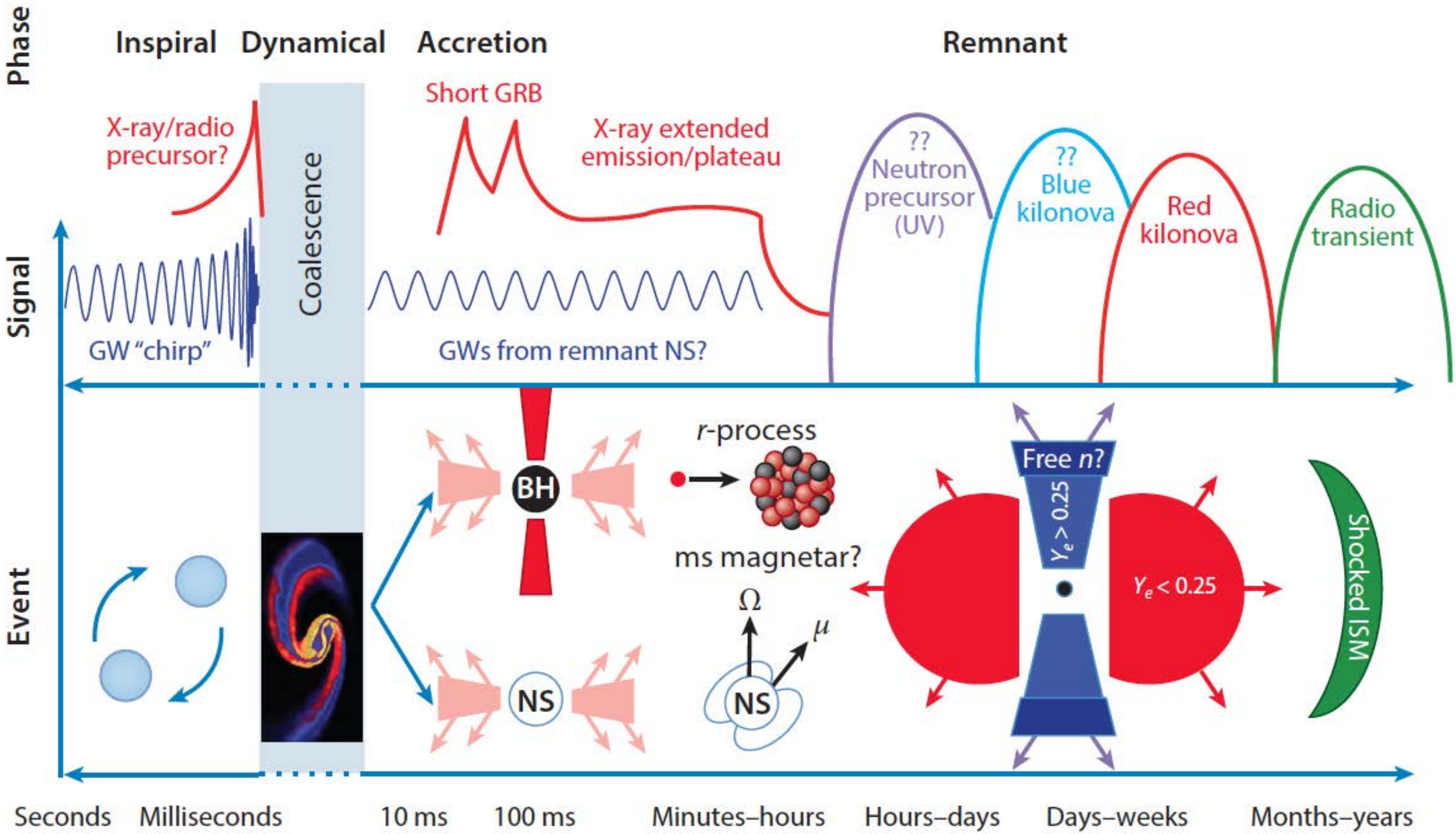
Neutron Star Mergers: Overview



RF & Metzger (2016)

Merger Remnant: Mass Limits

BHNS: remnant is always a BH, semianalytic formulae connect initial binary mass with remnant BH mass, calibrated with Numerical Relativity simulations.

e.g., Pannarale (2014)

NSNS: depending on initial binary mass, remnant can be:

1) Promptly-formed BH (~ 1ms)

2) Hypermassive NS (HMNS): differential rotation, finite lifetime

3) Supermassive NS (SMNS): uniform rotation (low-mass cases)

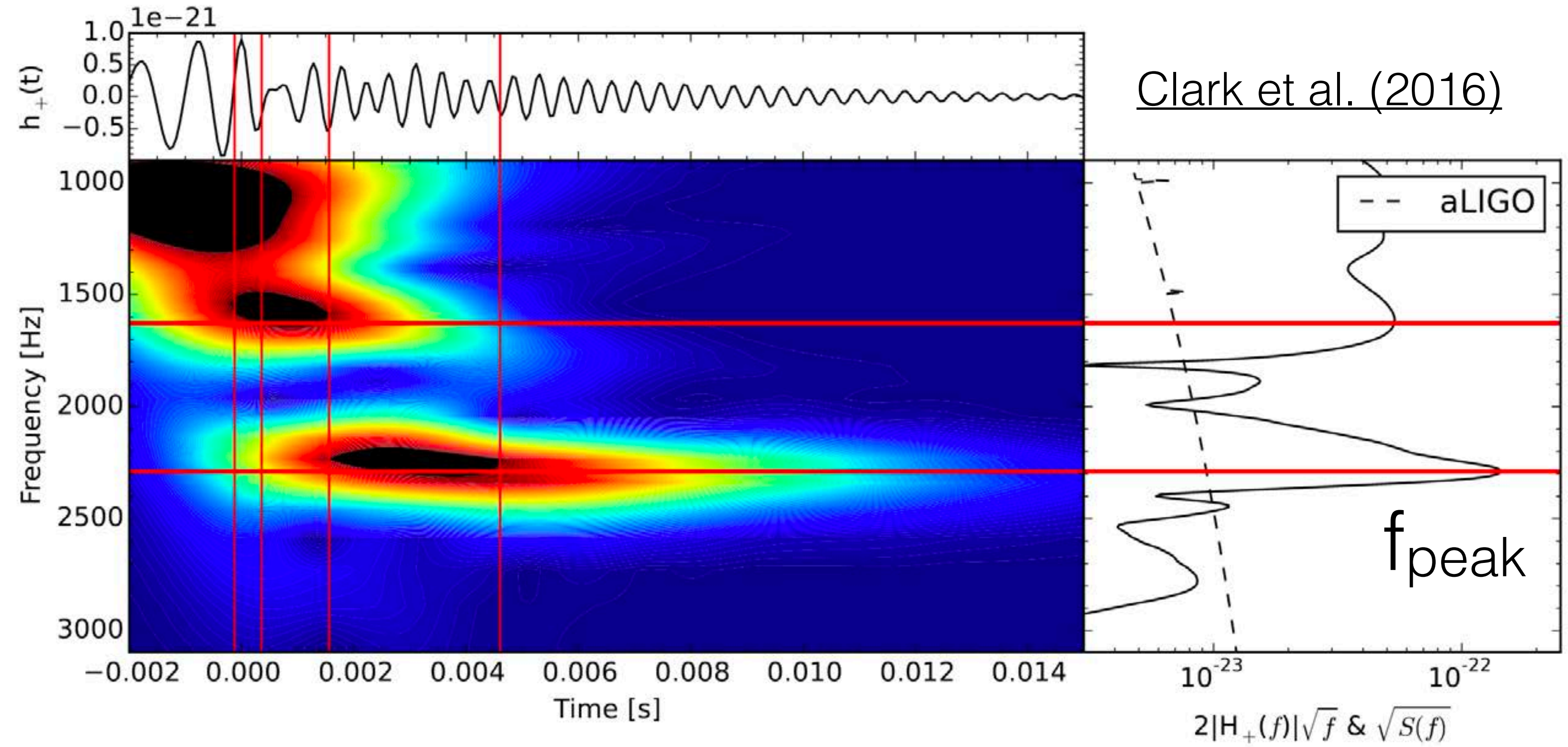
Mass limit for prompt BH formation, and lifetime of HMNS influenced by the EOS, as well as treatment of magnetic fields (which regulates differential rotation support) and neutrino transport (thermal support).

e.g., Anderson et al. (2008), Giacomazzo et al. (2011), Kaplan et al. (2014)

Merger Remnant: Gravitational Waves

The remnant of a NSNS merger executes oscillations at ~few kHz frequencies. Detectable out to ~20Mpc currently.

e.g. Shibata & Taniguchi (2006), Abbott et al. (2017)

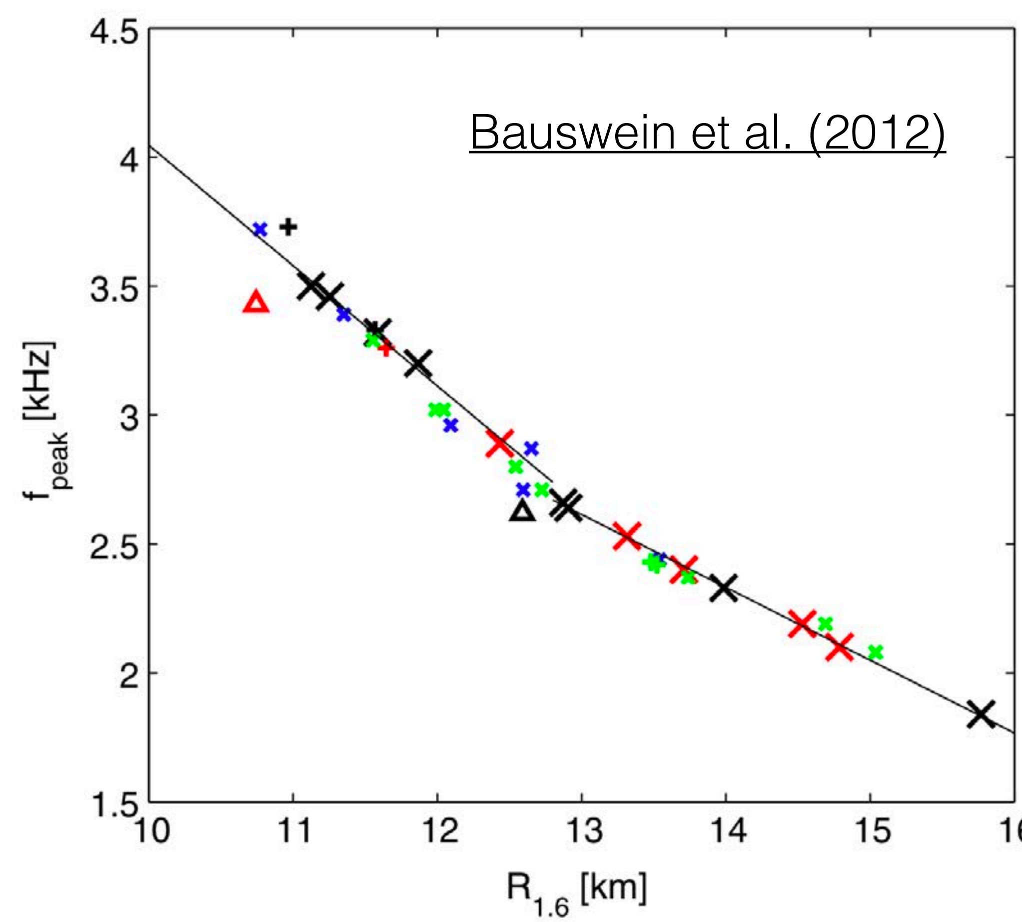


The peak frequency is the ~ inverse dynamical time

$$f_{\rm peak} \sim t_{\rm dyn}^{-1} \propto \left(\frac{M}{R^3}\right)^{1/2}$$

Encodes information about the EOS.

e.g. Palenzuela et al. (2015), Breschi et al. (2022)



Accretion Disk

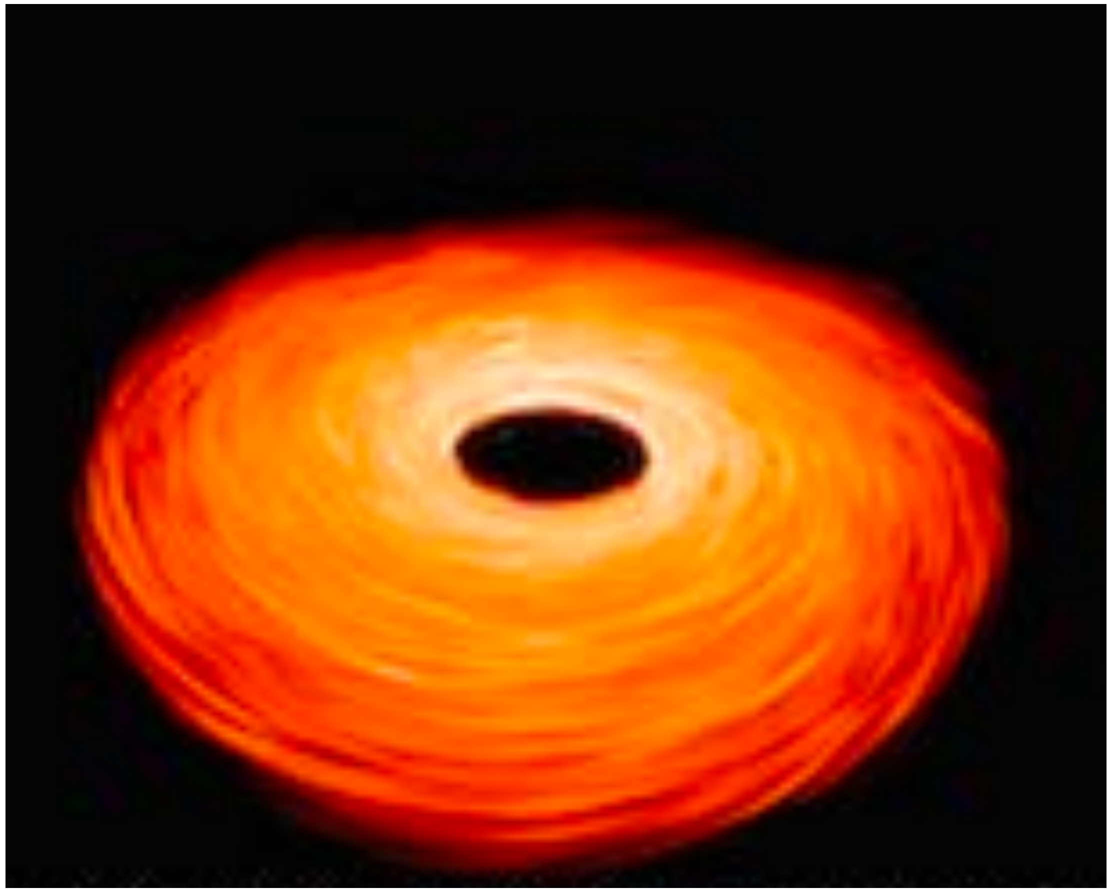
Structure formed by gas orbiting a central object. Gravity balanced mostly by centrifugal acceleration (angular momentum). Matter is (initially) bound gravitationally.

Thermal pressure provides partial support, determines vertical extent of disk ("puffiness").

Settling of mass onto central object ("accretion") requires gas to lose angular momentum and thermal energy.

- angular momentum transport mechanism
- neutrino cooling (for NS mergers)

Mass can be unbound from the accretion disk by a variety of mechanisms: disk outflow



Mario Flock / KITP

Q1: outflow mass, properties

Q2: r-process contribution

Q3: observational EM signature (contribution to kilonova, jet, etc.)

Accretion Disk: Mass ejection mechanisms

Lorentz force

t ~ms

depends on existence and strength of poloidal field at disk formation

e.g. Blandford & Payne (1982)
Blandford & Znajek (1977)

Neutrino absorption

t ~10ms

important for HMNS, sub-dominant for BH

e.g. Ruffert & Janka (1996)

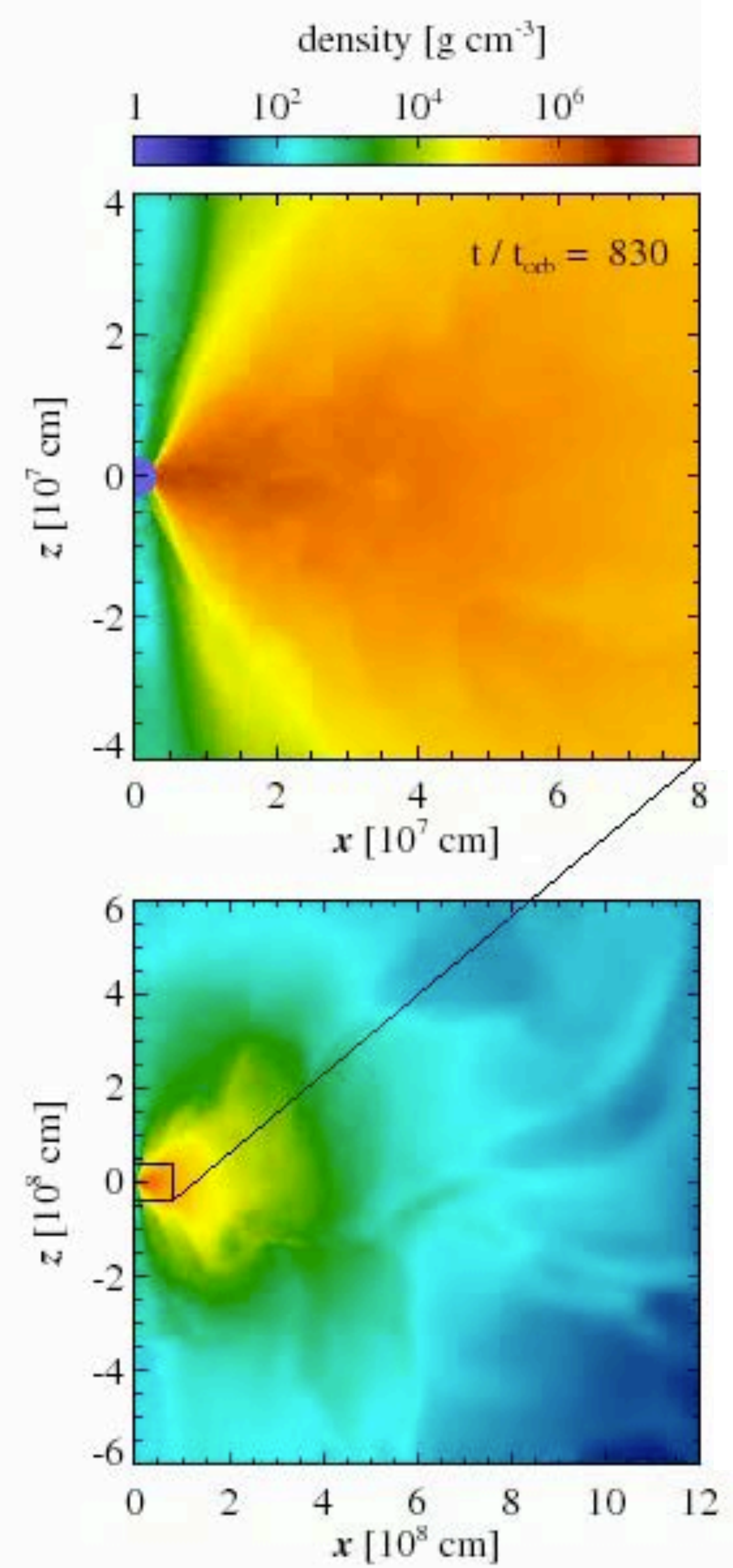
"Thermal" Ejection

t ~100ms

neutrino cooling drops on viscous time

- MRI turbulence (viscous) heating
- nuclear recombination (n,p into alpha)

Metzger, Piro, & Quataert (2009)



Outflow in Viscous Hydrodynamics

- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10-20% of initial disk mass ejected, ~1E-3 to 1E-2 solar masses
- Material is neutron-rich (Ye ~ 0.2-0.4)
- Wind speed (~0.05c) is slower than dynamical ejecta (~0.1-0.3c)

RF+ (2013, 2015, 2020)

Just et al. (2015, 2022)

Fujibayashi et al. (2020a-b)

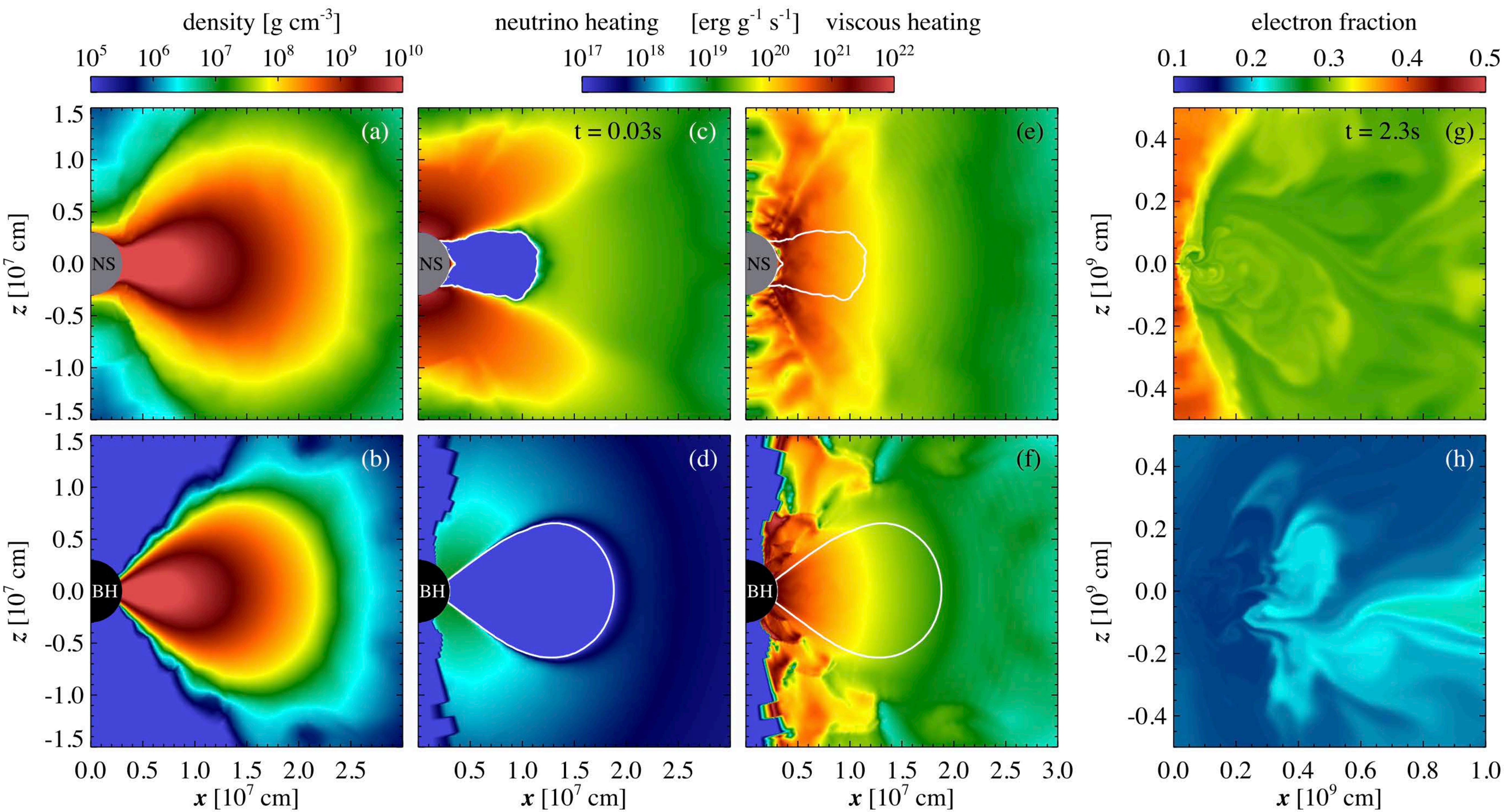
Haddadi et al. (2023)

Setiawan et al. (2006)

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)

Metzger (2009)

Hypermassive NS versus BH



Metzger & RF (2014)

See also: Dessart+ (2009) Martin+ (2015) Moesta+ (2020)

Perego+ (2014) Fujibayashi+ (2017,2018) Ciolfi+ (2020)

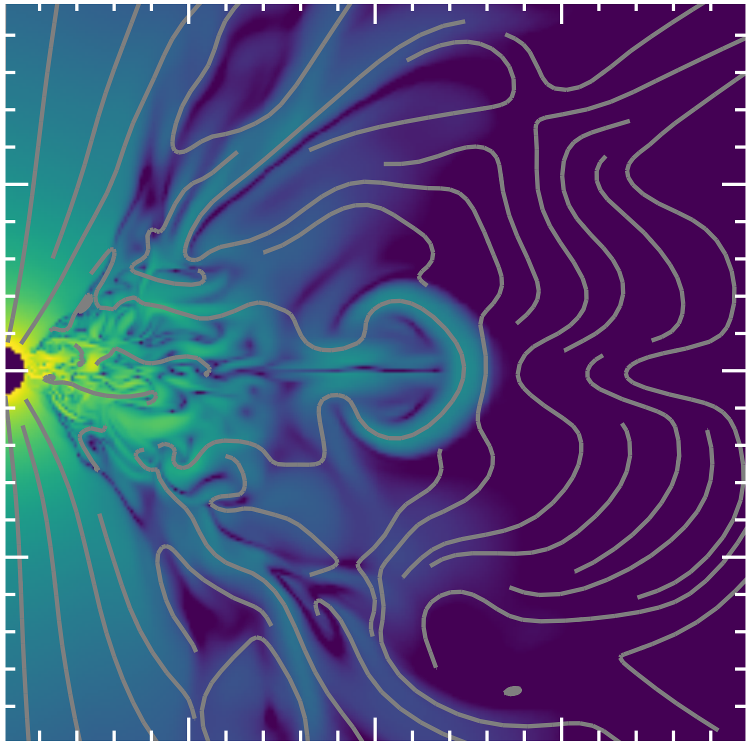
Disk Evolution in GRMHD

Must be done in 3D and with sufficient spatial resolution to capture the MRI. Computationally expensive, but metric can be taken as fixed, so cheaper than numerical relativity.

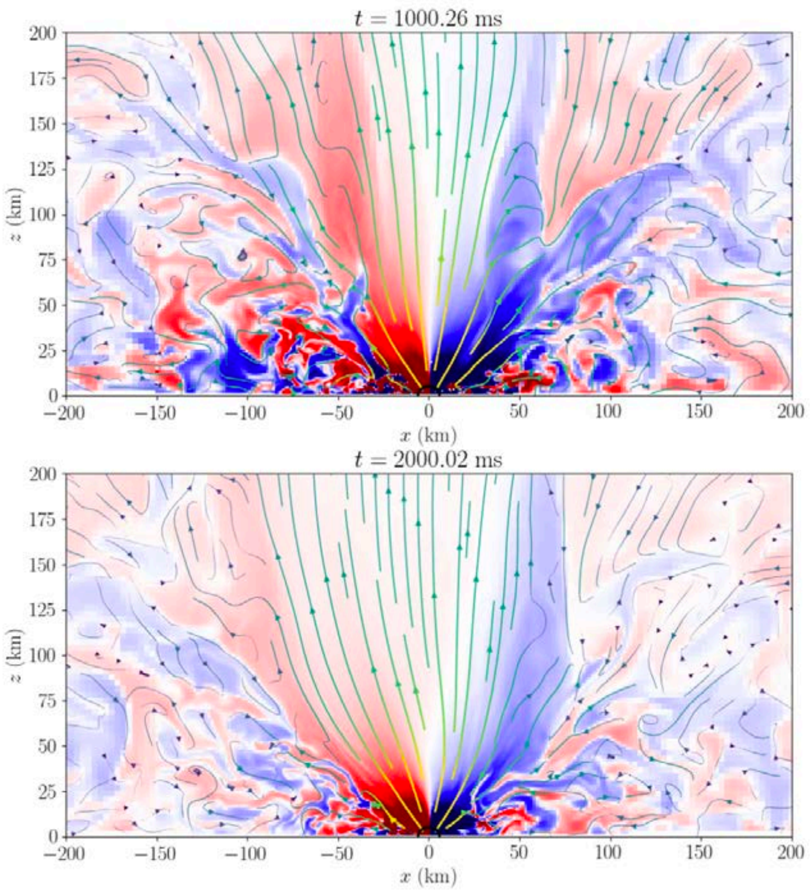
Several groups have carried out GRMHD simulations of accretion disks starting from equilibrium initial conditions, or mapped from a hydrodynamic merger simulation but with an equilibrium initial magnetic field.

Siegel & Metzger (2017), RF et al. (2019), Miller et al. (2019), Just et al. (2022)

More recently: ab-initio simulations of magnetized BHNS and NSNS mergers.



RF et al. (2019)



Hayashi et al. (2022)

GRMHD: poloidal, toroidal & hydro

	Model Name	(%)	$M_{\rm ejec}$ ($10^{-2}\,M_\odot$)	$\langle v_r \rangle$	$\langle Y_{\rm e} \rangle$
GRMHD	BPS	40	1.3	0.18	0.16
	BPW	30	0.99	0.08	0.19
	BT	27	0.89	0.05	0.18
Hydro	$\alpha = 0.1$	22	0.67	0.05	0.17
	$\alpha = 0.03$	21	0.63	0.03	0.20
	$\alpha = 0.01$	16	0.48	0.03	0.26

Main caveat: Ye set only by neutrino cooling

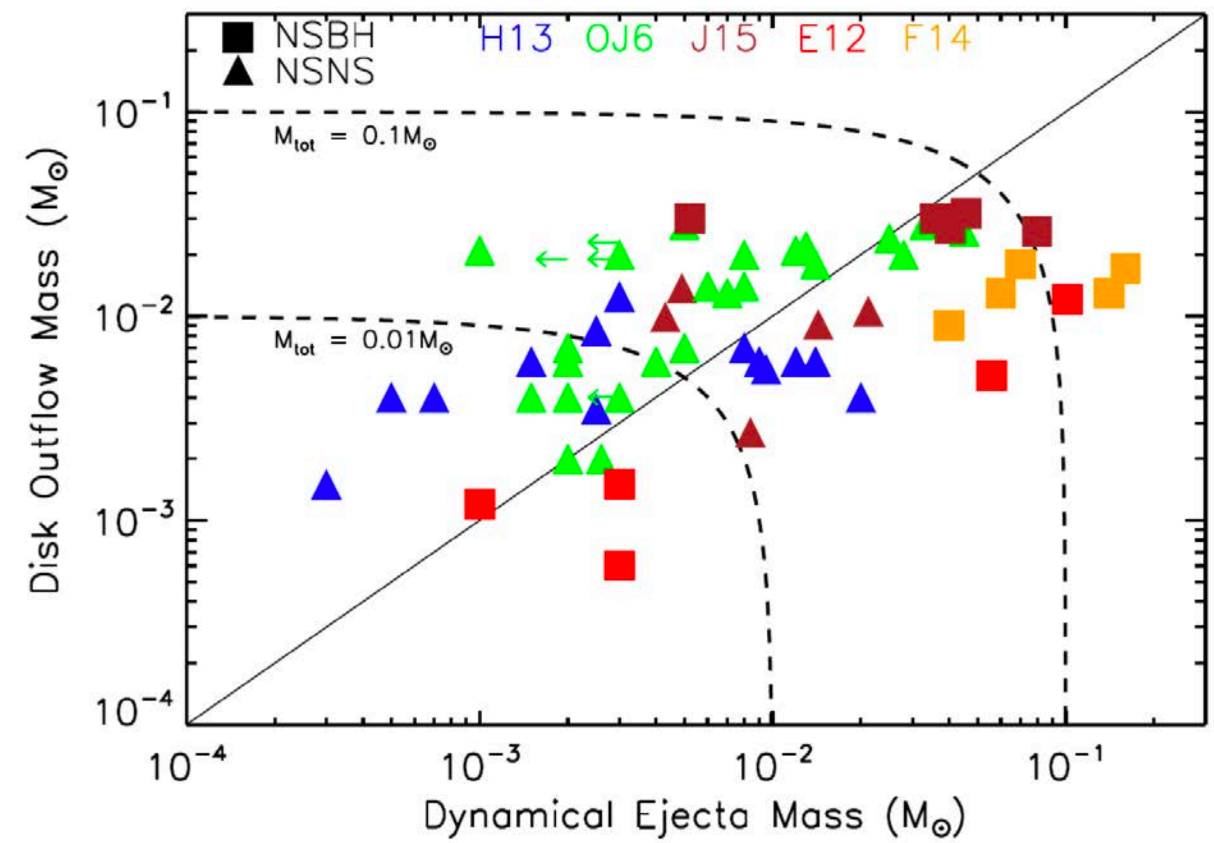
RF et al. (2019)

Christie, Lalakos, Tchekhovsoy, RF+ (2019)

Comparison with Dynamical Ejecta

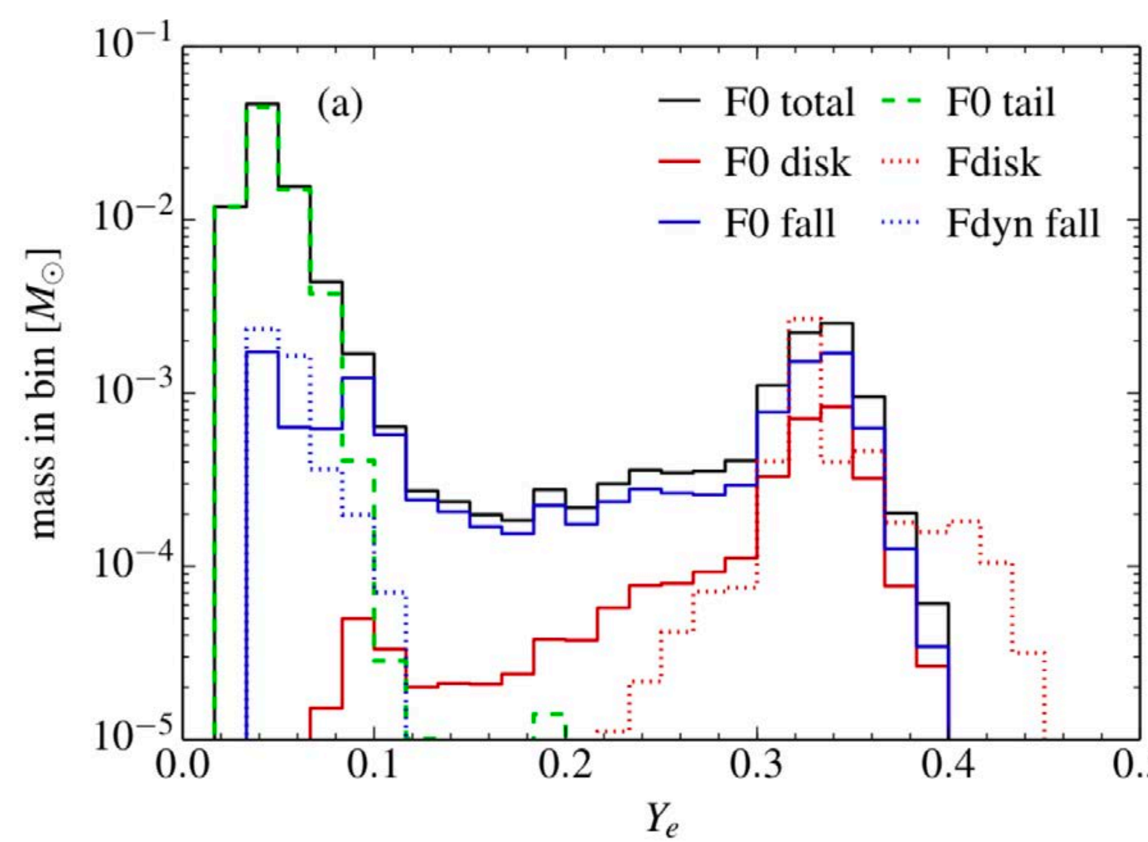
The amount of mass ejected in the disk outflow vs dynamical ejecta depends on the binary properties. For GW170817, the ejecta was most likely dominated by the disk.

e.g., Shibata et al. (2017), Radice et al. (2020)



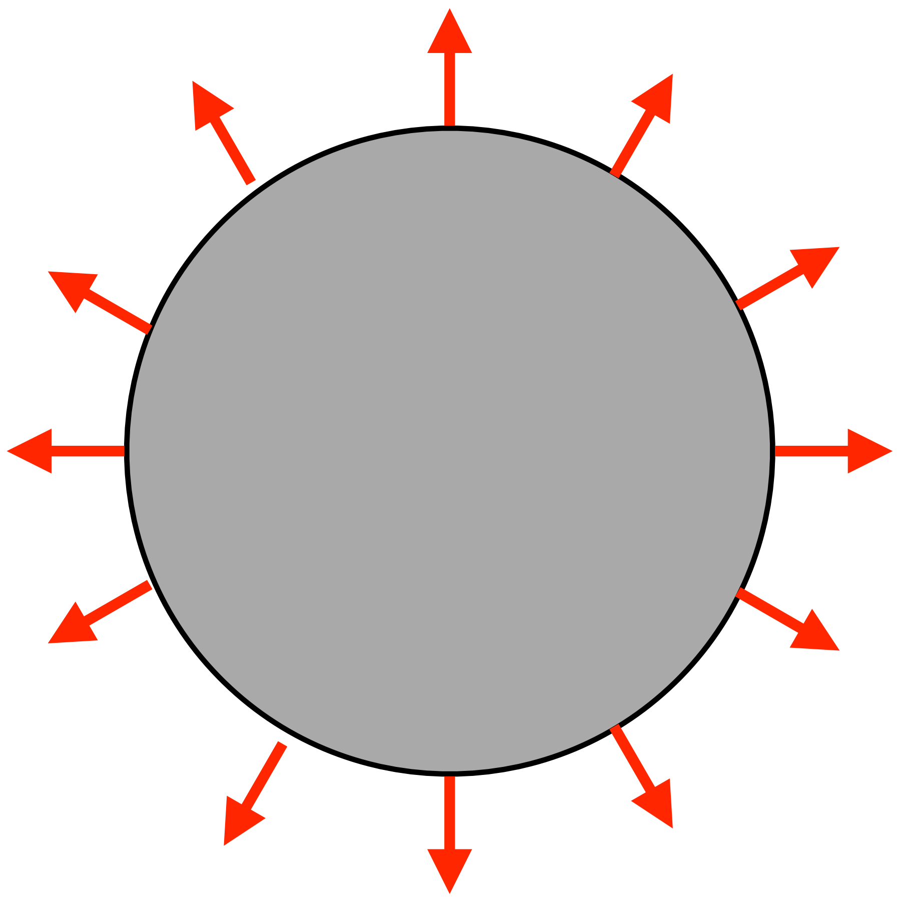
Wu et al. (2016)

The disk outflow ejecta is in general less neutron rich and slower than the dynamical ejecta, although distinction is not sharp.



RF et al. (2017)

Mass Ejection & EM Transients



Matter unbound from a gravitational field by one or more processes that deposit energy or impart momentum.

Ejecta initially opaque to photons, internal energy is trapped.

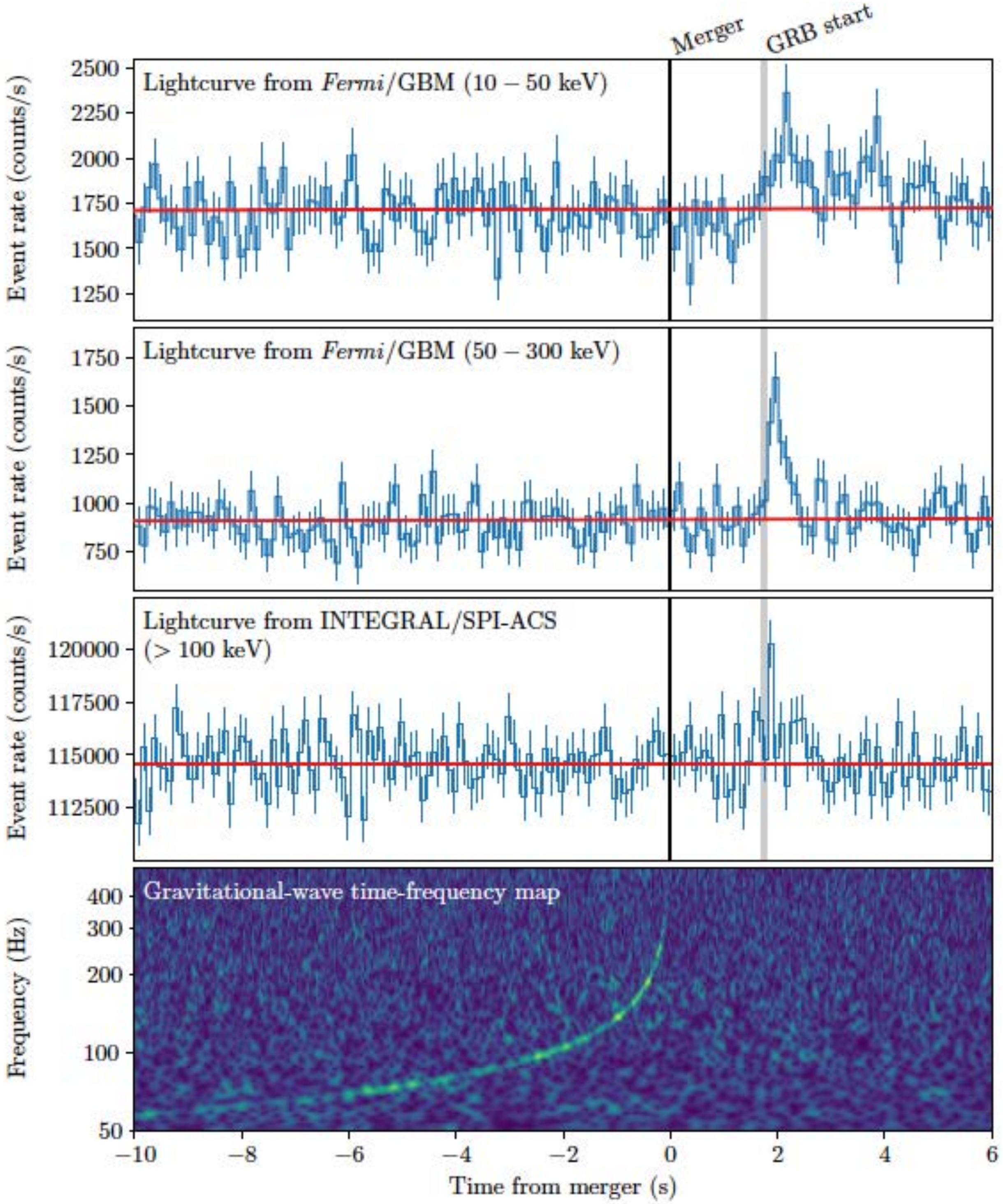
Upon expansion, density drops and photons can escape: peak luminosity.

Further emission requires a persistent energy source (e.g., radioactive heating).

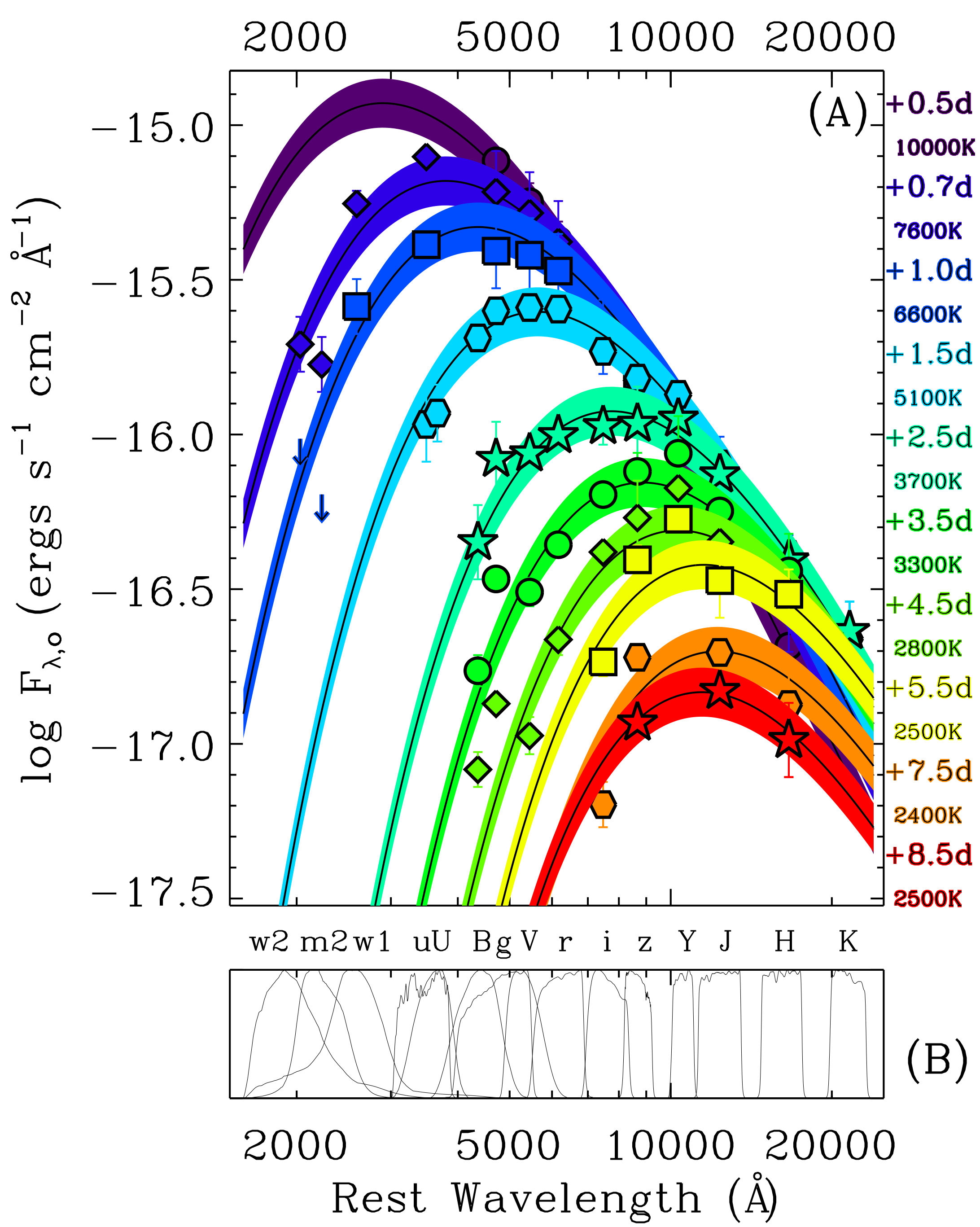
$$t_{\rm peak} \simeq \left(\frac{\kappa M_{\rm ej}}{v_{\rm exp} c}\right)^{1/2}$$

Arnett (1980), Kasen & Woosley (2009)

GW 170817



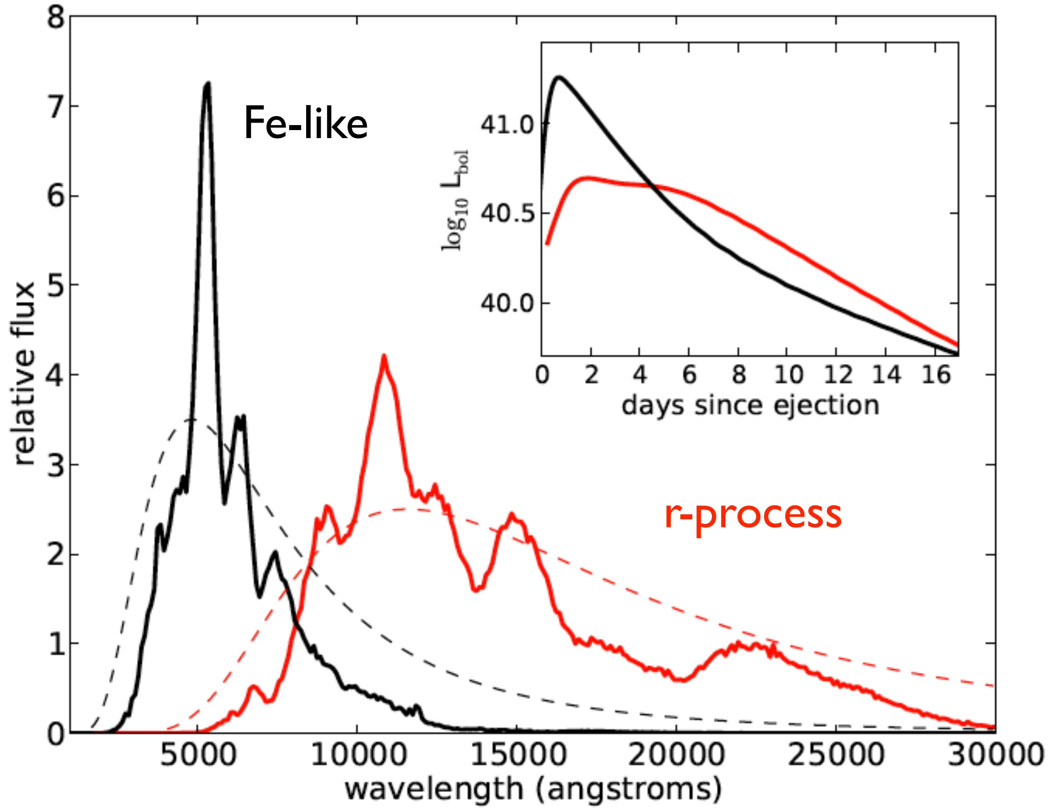
Abbott et al. (2017) [LVC]: GW170817



Drout et al. (2017)

r-process opacities: kilonova color

Theoretical kilonova spectra & light curves:



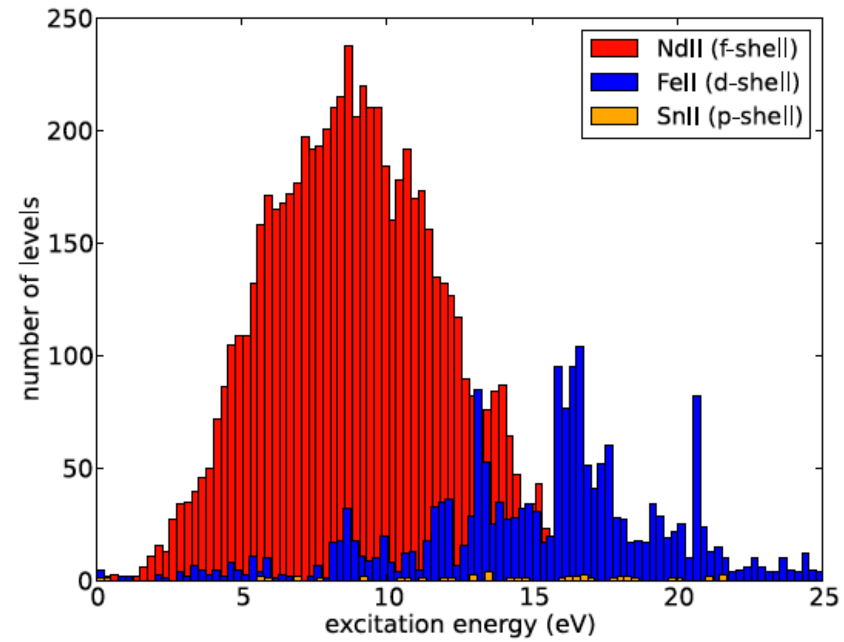
r-process-dominated material generates IR transient

(large number of lines in optical)

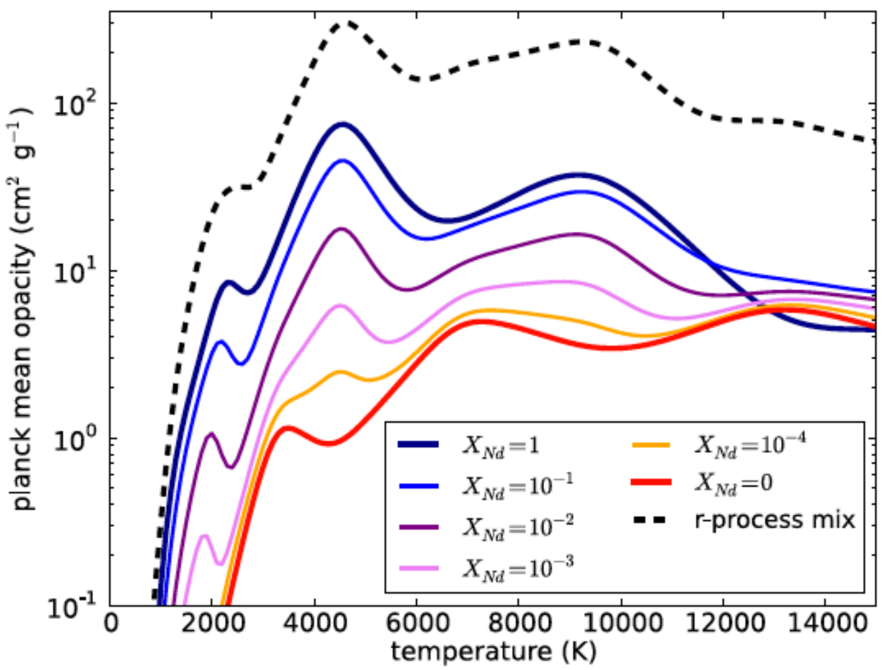
Kasen et al. (2013)

also Tanaka & Hotokezaka (2013), Fontes+ (2015), Tanaka et al. (2020)

Lanthanides have more atomic transitions



Much higher opacity than iron-group elements



Non-LTE modeling: e.g., Pognan et al. (2023)

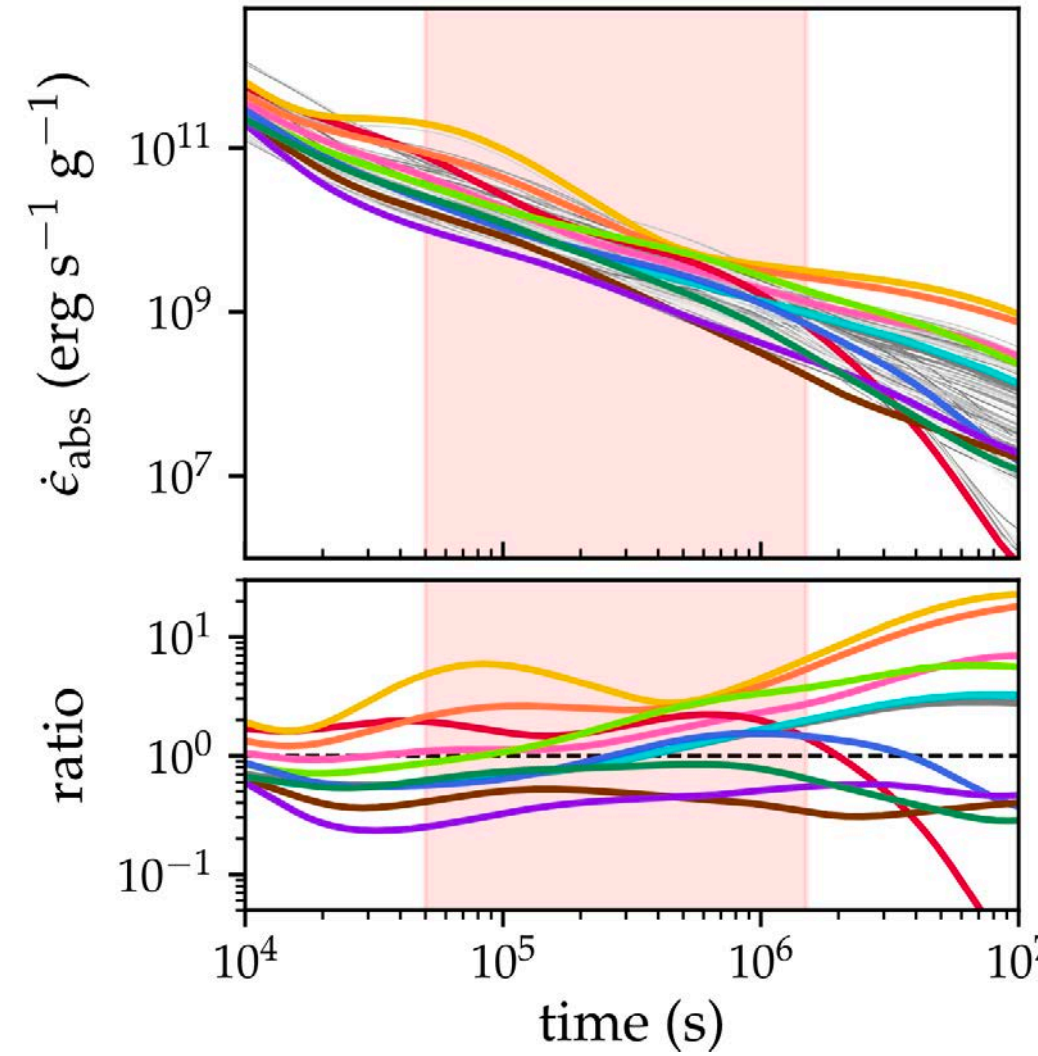
R-process Heating:
Nuclear Uncertainties

Nuclear uncertainties have a direct impact on kilonova predictions in two ways:

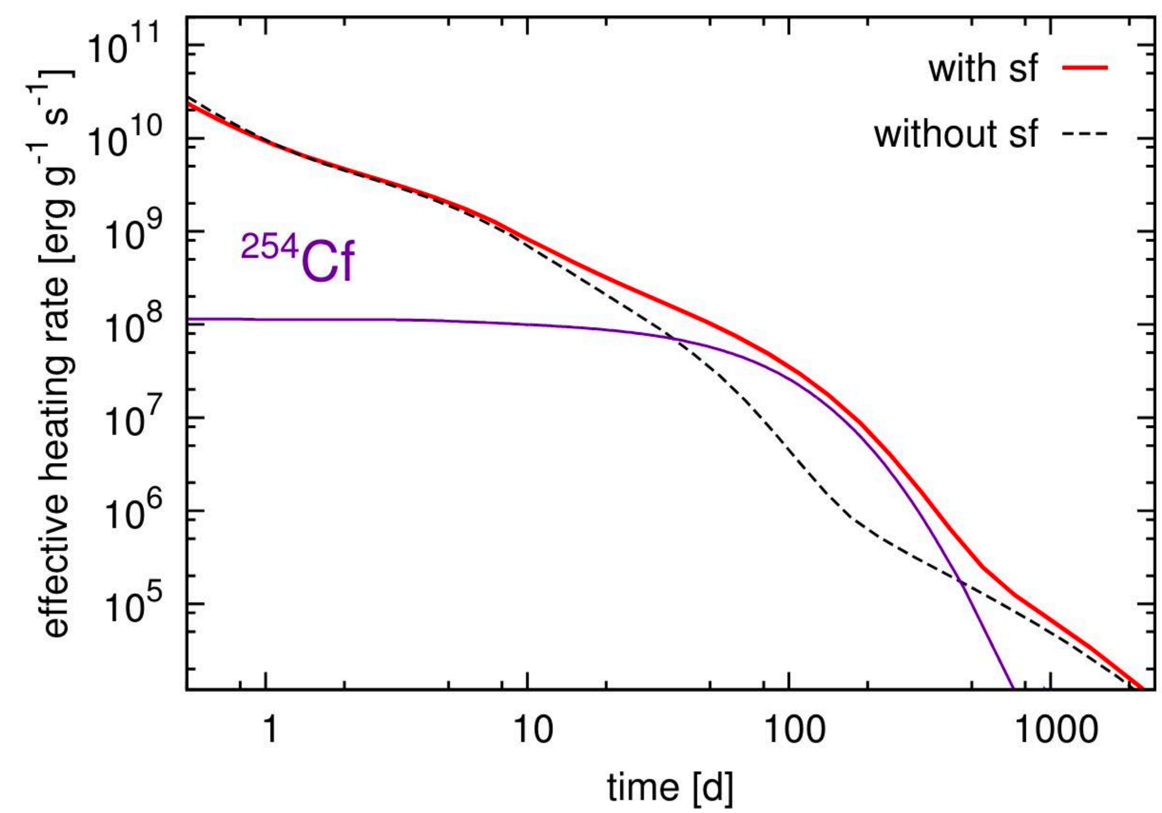
1) Uncertainties in the abundances, which affect opacities and heating rates

2) For fixed abundances, uncertainties in nuclear properties (beta decay, fission, etc) that affect the heating rate.

At late time, individual nuclei can have an outsize importance in setting the heating rate, modifying the time-dependence of kilonova light curves.



Barnes et al. (2021)

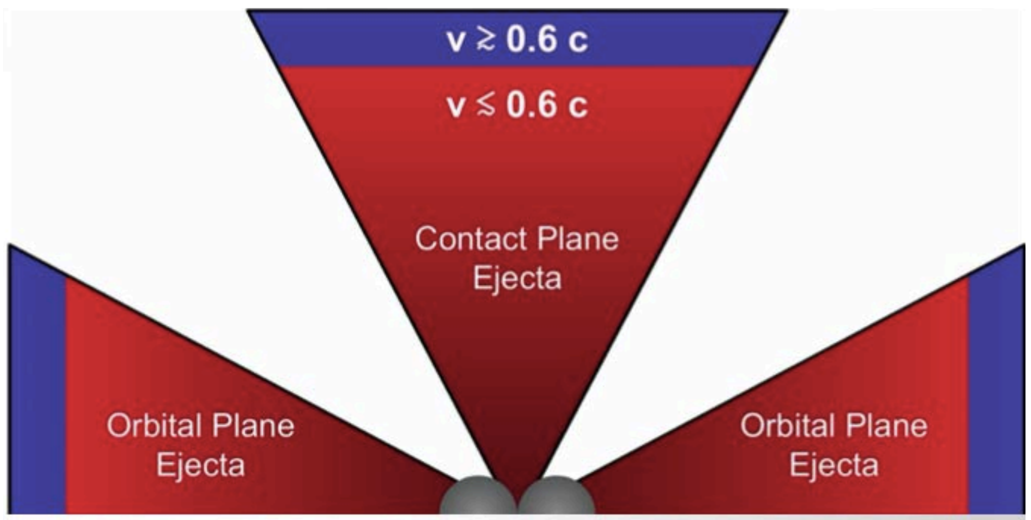


Zhu et al. (2018)

Neutron-powered Kilonova Precursors

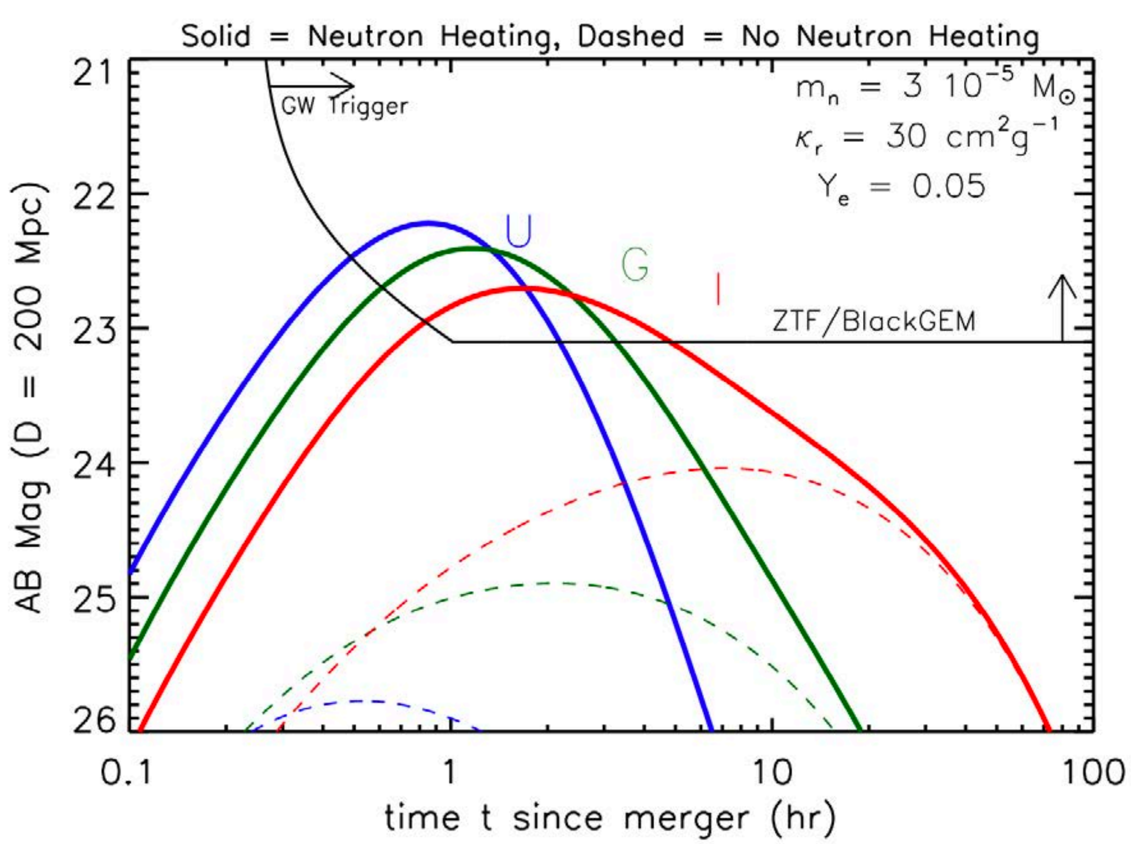
Fastest portion of the ejecta is such that neutron-capture freezes out: free neutrons left over which decay and produce heating.

Metzger et al. (2015)



Dean et al. (2021)

Leading portion of the ejecta, low optical depth: thermal transient peaking on ~hr timescales, powered by neutron decay heating.



Metzger et al. (2015)

Amount of fast ejecta is low (10^{-6} to 10^{-4} M_{sun}), numerical simulations have not converged. First few hours important to constraint KN models.

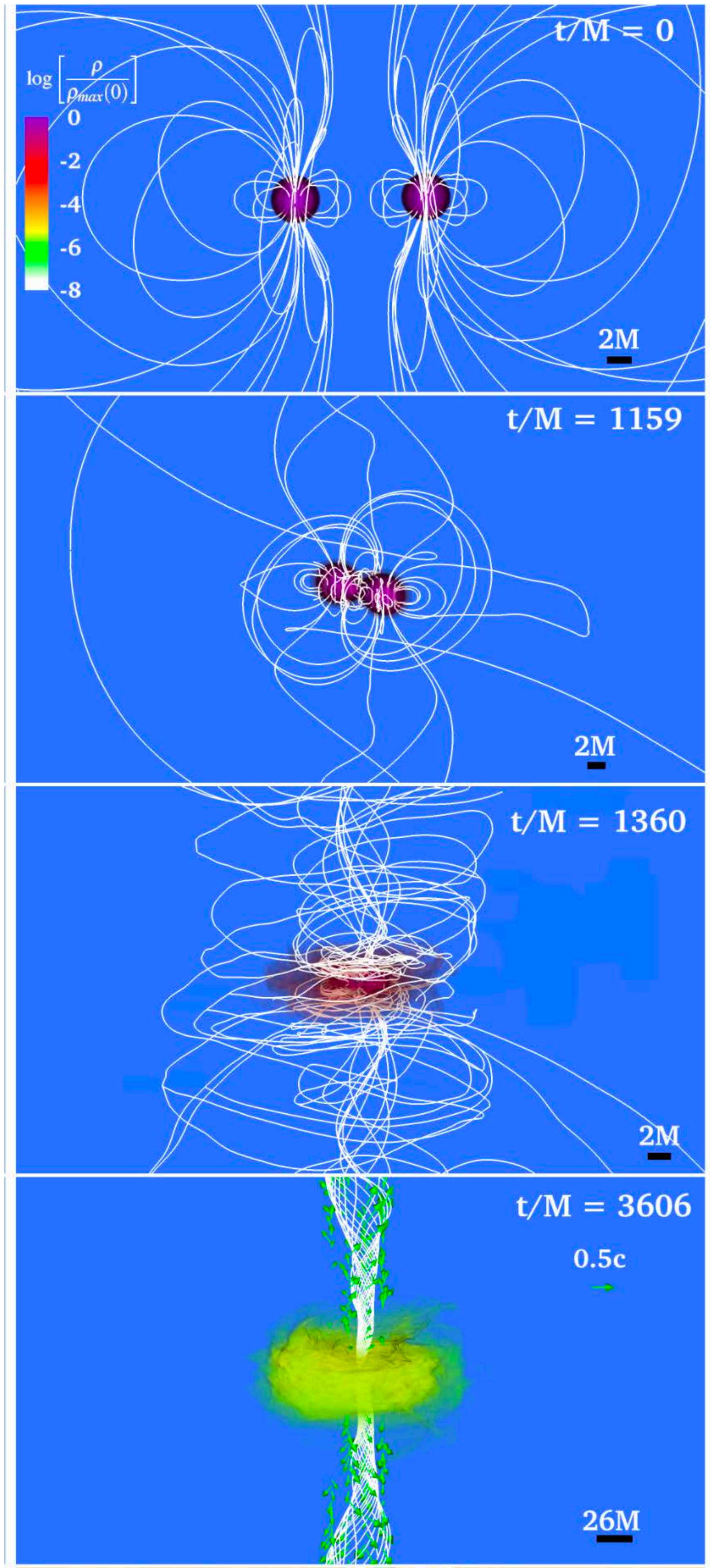
Bauswein et al. (2013), Radice et al. (2018), Dean et al. (2021)

Arcavi (2018)

GRB Emission: Jets

NSs have magnetic fields, merger tangles magnetic fields and can launch magnetically-powered jets. Jet onset can now be obtained self-consistently in GRMHD simulations that form BHs.

Current challenges include obtaining proper field amplification given resolution limitations, and understanding whether successful relativistic jets can be produced with longer-lived HMNS.



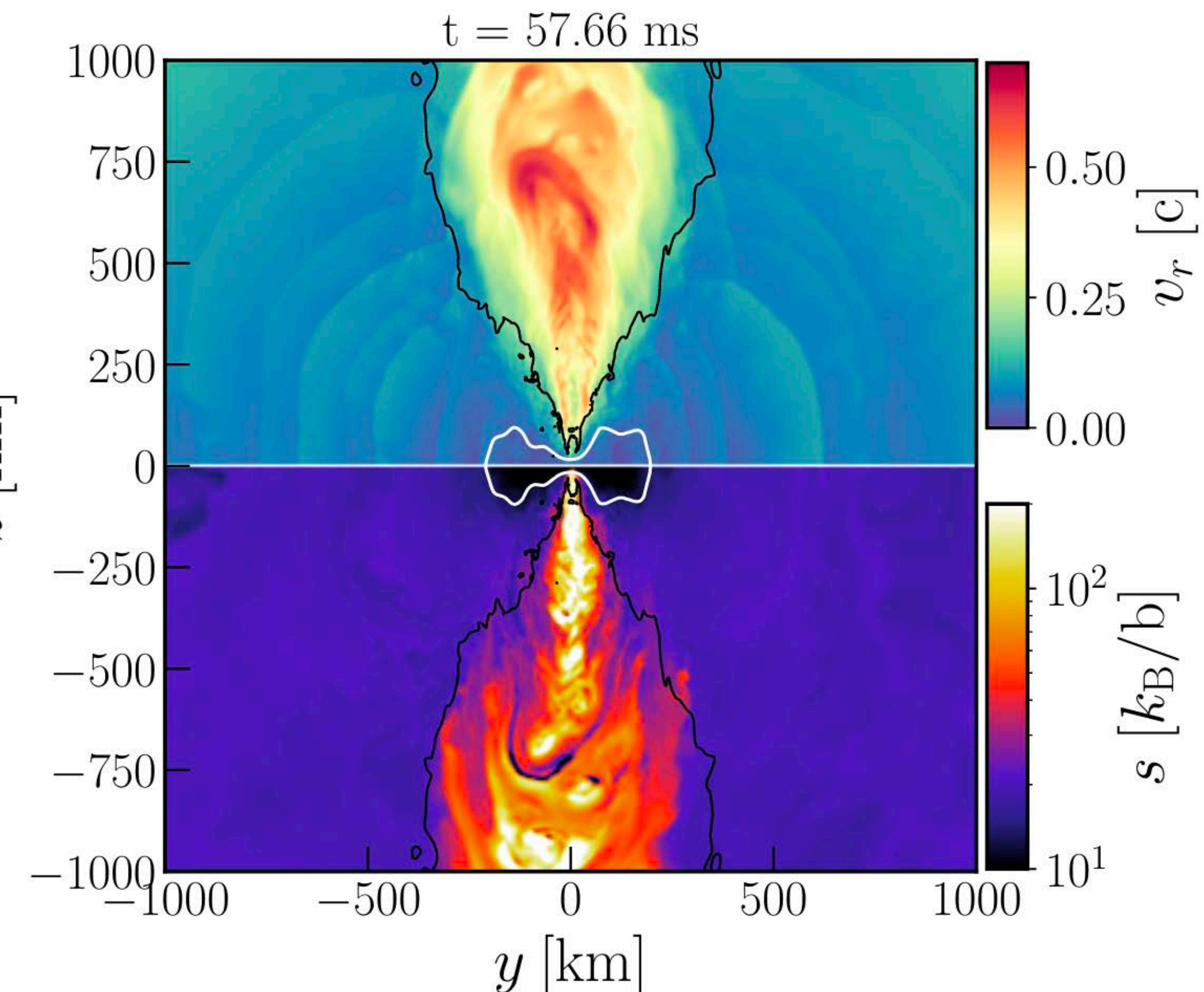
Sun et al. (2022)

GRB Emission: Jets

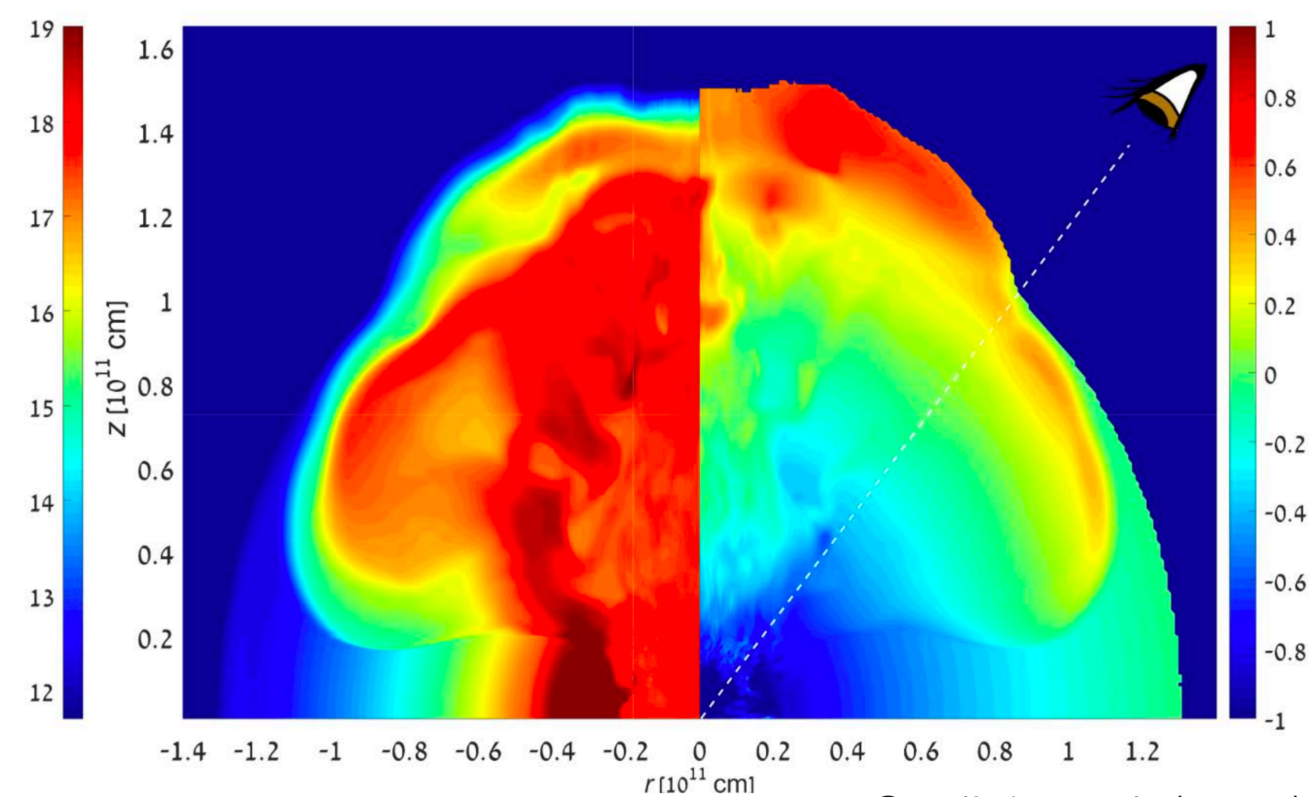
Recent GRMHD simulations of NSNS mergers with full physics have produced successful jets that can break out of the slower ejecta.

Whether the jet can break out depends on the jet power, ejecta mass, and opening angle. Nature of jet in GW170817 was subject of debate. Superluminal apparent motion of radio afterglow centroid favours successful jet.

Duffell et al. (2018) Mooley et al. (2018)



Combi & Siegel (2023)



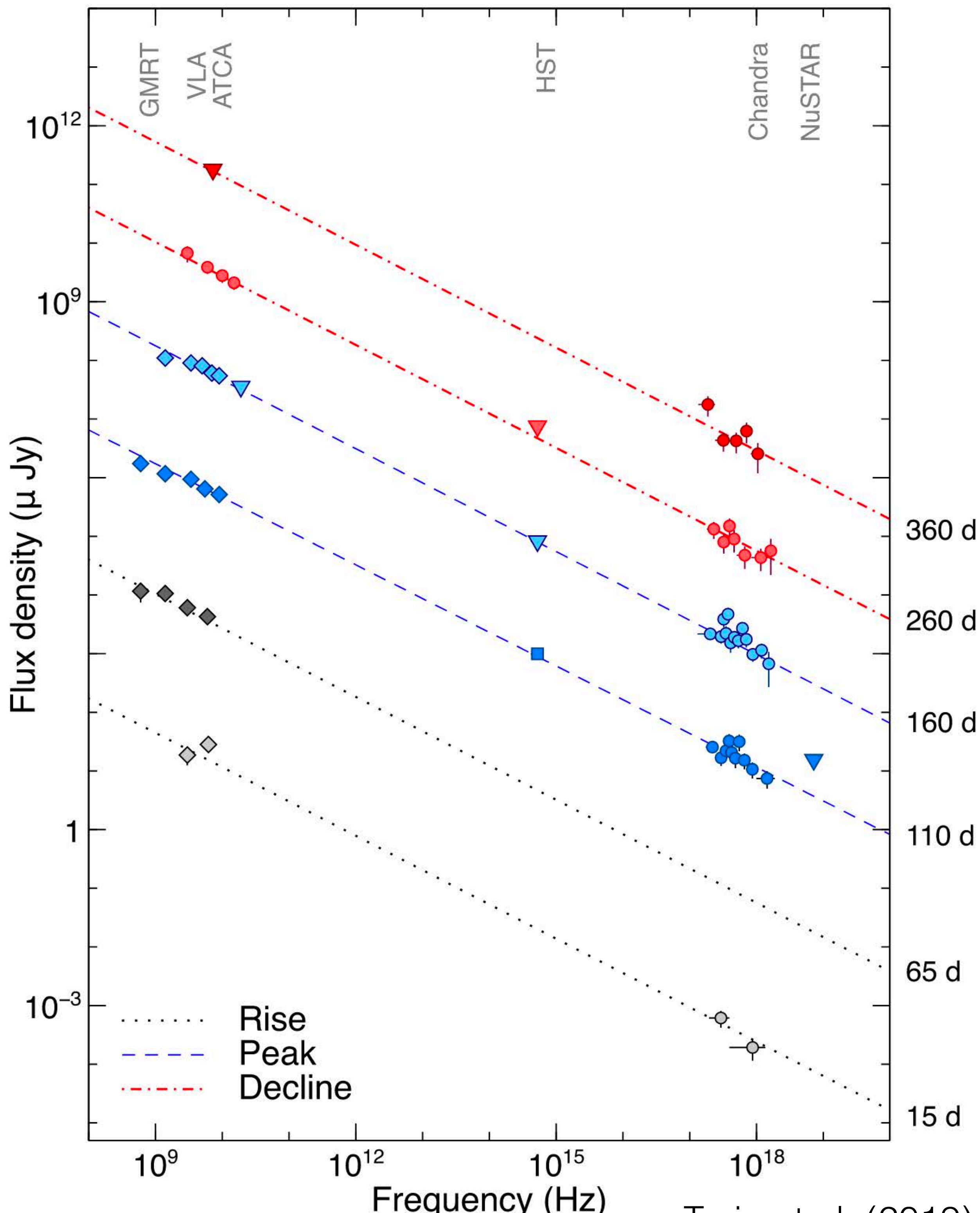
Gottlieb et al. (2018)

GRB Emission: Afterglow in GW170817

GW170817 produced a non-thermal afterglow, generated when the jet collides with the ISM, generating synchrotron emission.

Single power-law spectrum from X-rays to radio was observed for up to 3 yr, when the source started dropping below detection limits, and possible deviations were suspected.

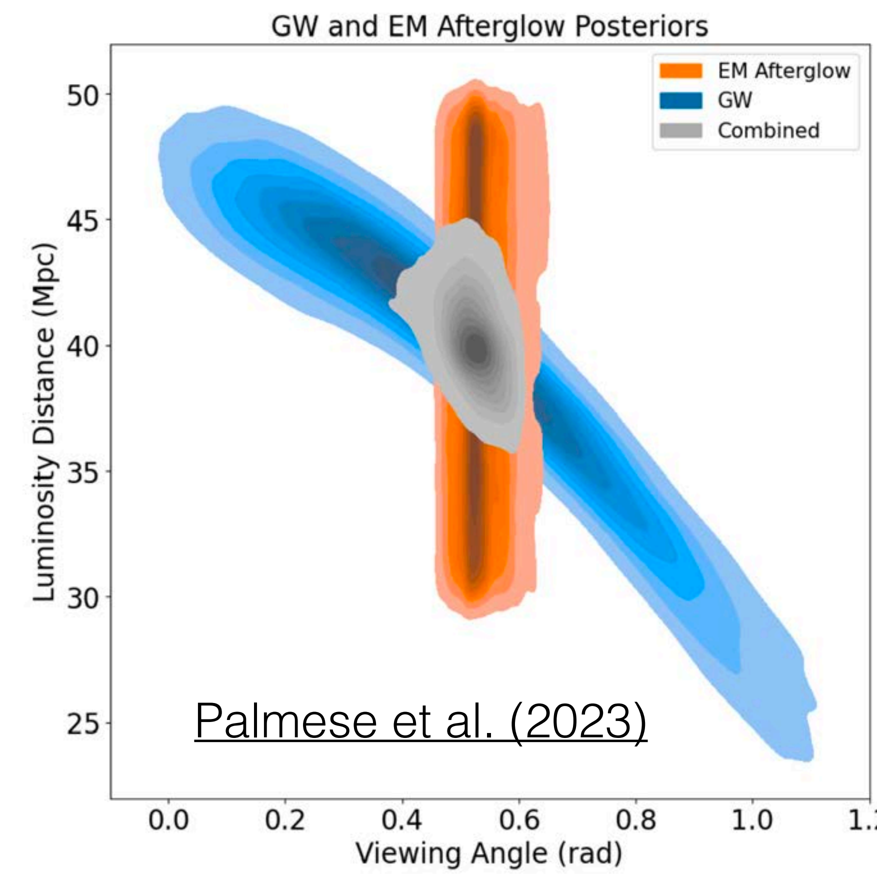
Hajela et al. (2022)



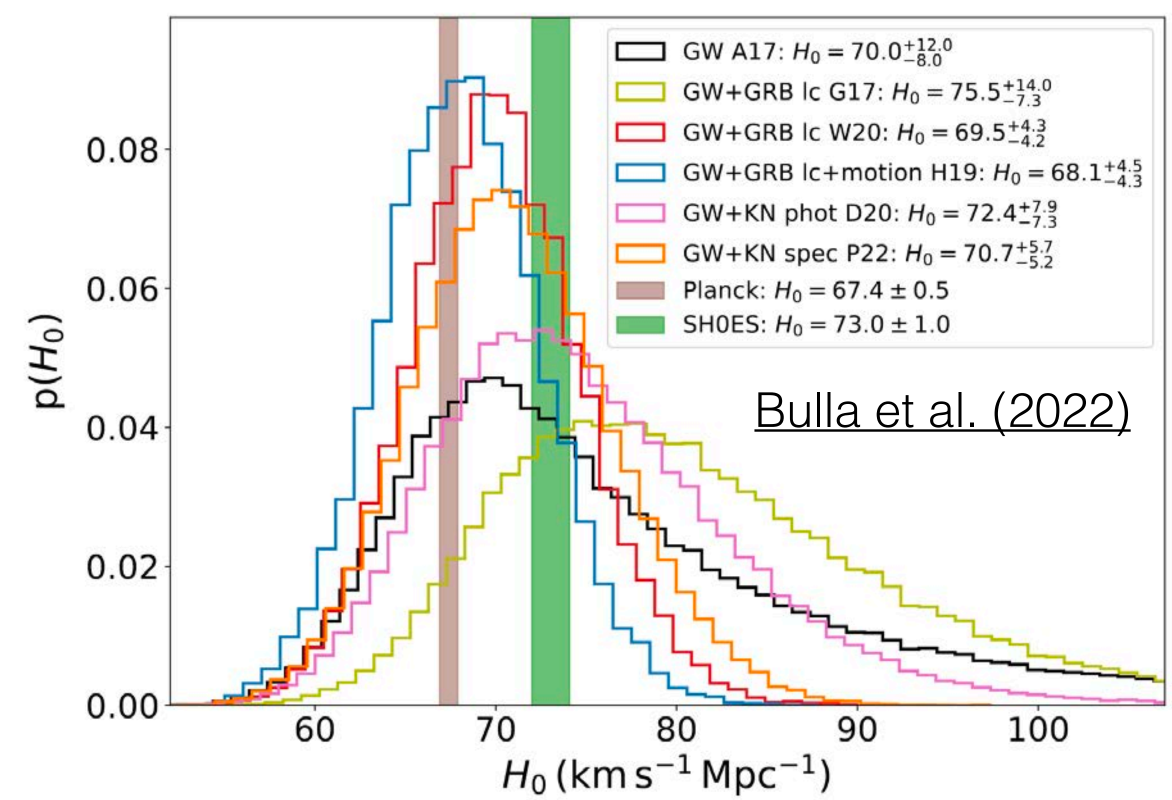
Troja et al. (2019)

GRB Emission: application to Cosmology

There is a degeneracy in gravitational wave luminosity and inclination angle of a source. This degeneracy can be broken by using information from the EM counterpart.



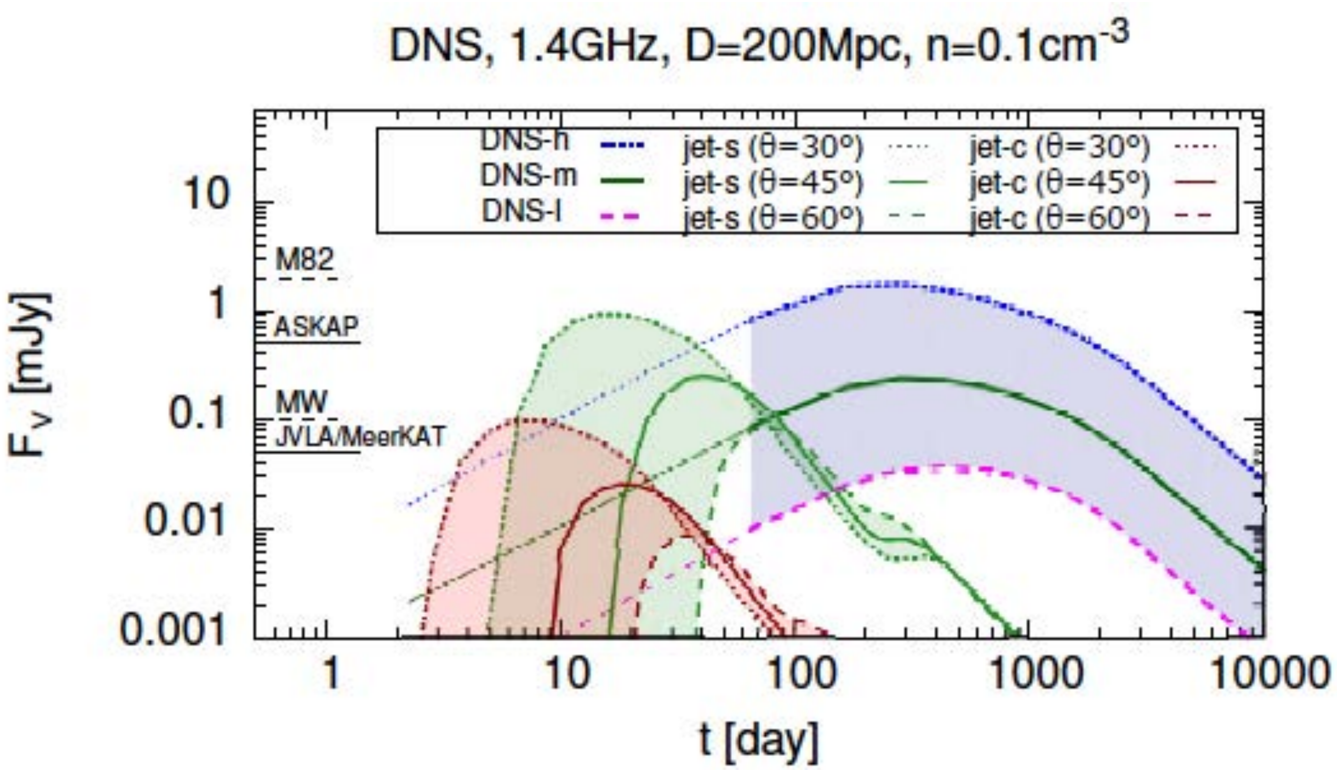
Constraints on the Hubble constant (redshift from host galaxy, luminosity from GWs and inclination angle) have been placed using GW170817. Best constraints use inclination angle information such as that from super-luminal apparent motion of radio afterglow centroid.

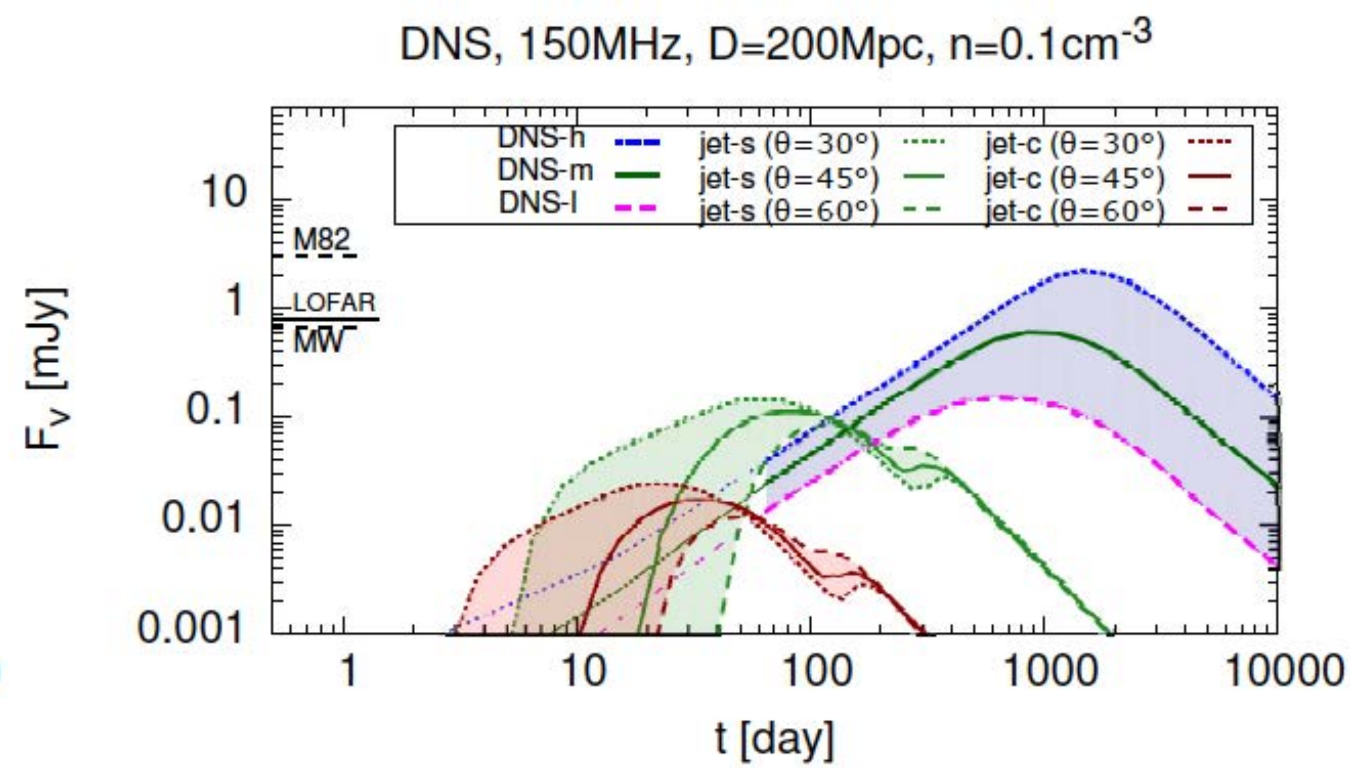


Late-time Radio Transient

Sub-relativistic ejecta interacts with ISM and accelerates particles: synchrotron emission. Distinct from GRB afterglow.

Nakar & Piran (2011)





Hotokezaka et al. (2016)

Radio transient on ~yr to ~decades timescale (predicted).

Dependent on kinetic energy of ejecta and circum-burst densities.

Radio upper limit at 4.5yr: Balasubramanian et al. (2022)