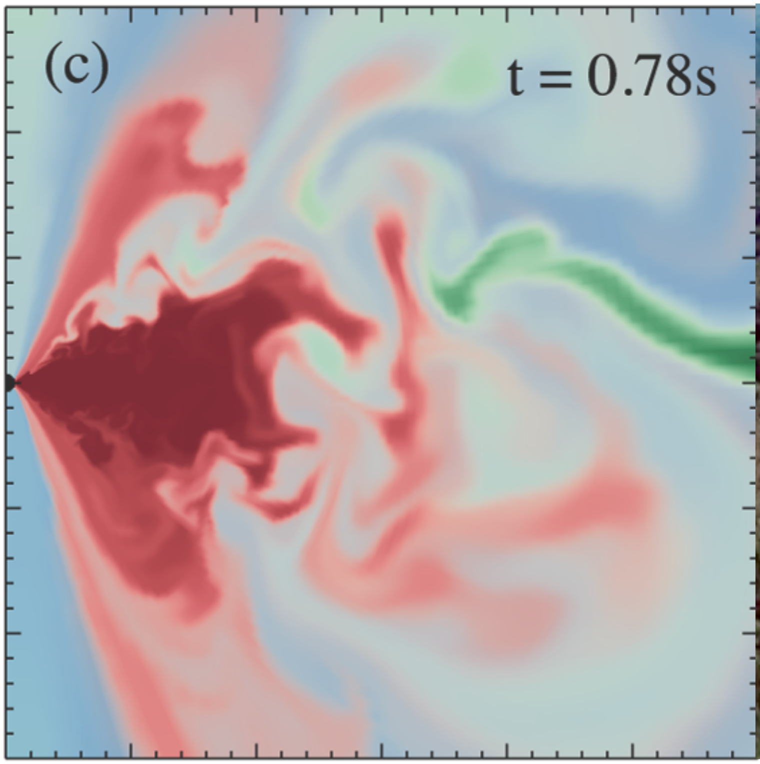
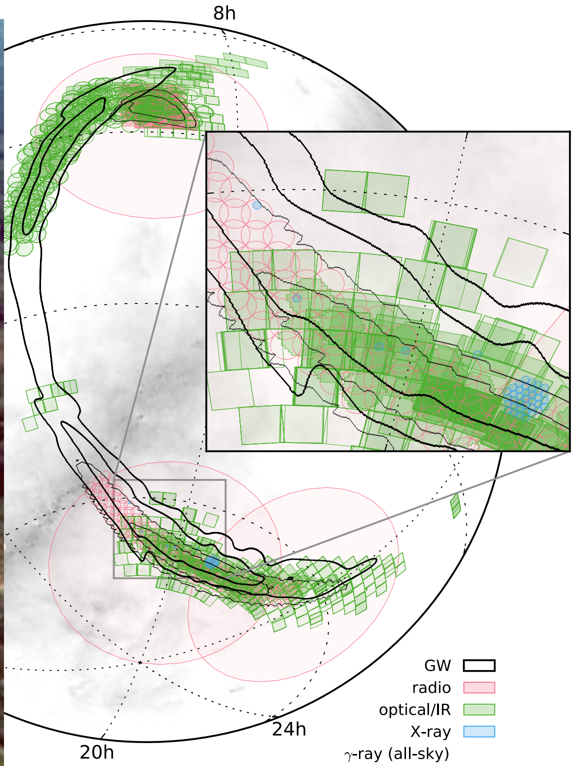




Long-term mass ejection from NS merger remnant accretion disks

Rodrigo Fernández (University of Alberta)

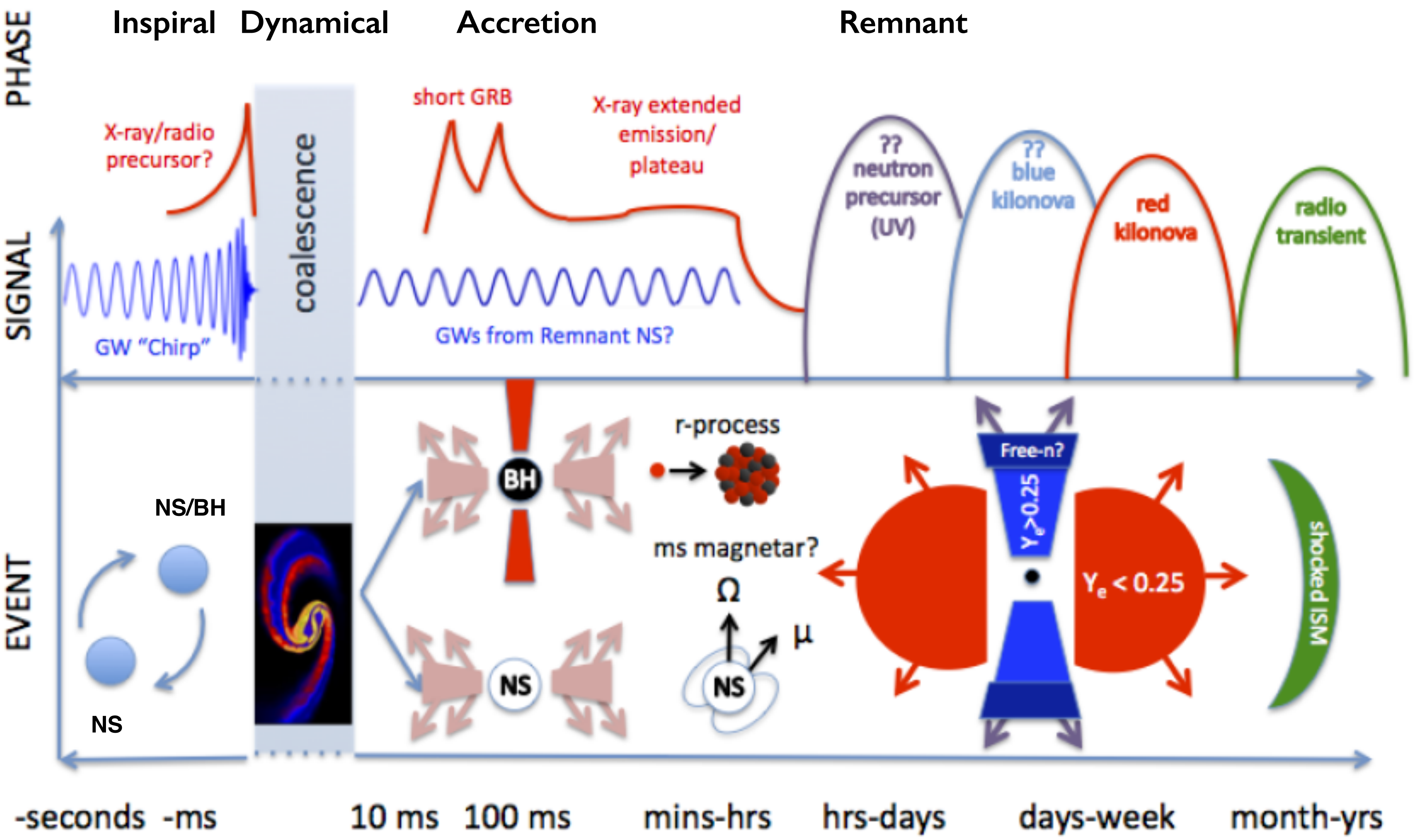
B. Metzger (Columbia), D. Kasen, E. Quataert, F. Foucart, A. Tchekhovskoy (Berkeley)

M-R. Wu, G. Martínez (Darmstadt), J. Lippuner, L. Roberts (Caltech)

Overview

1. Accretion disks & mass ejection
2. Nucleosynthesis
3. Kilonova contribution

Neutron Star Mergers



RF & Metzger (2016)

NS mergers: EM emission

1) SGRB if on-axis $(\theta_j \lesssim 10^\circ)$

Paczynski (1986), Eichler+ (1989)

2) Orphan afterglow $(10^\circ \lesssim \theta_j \lesssim 20^\circ)$

e.g. van Eerten+ (2010), Nakar & Piran (2011)

3) Magnetospheric precursor

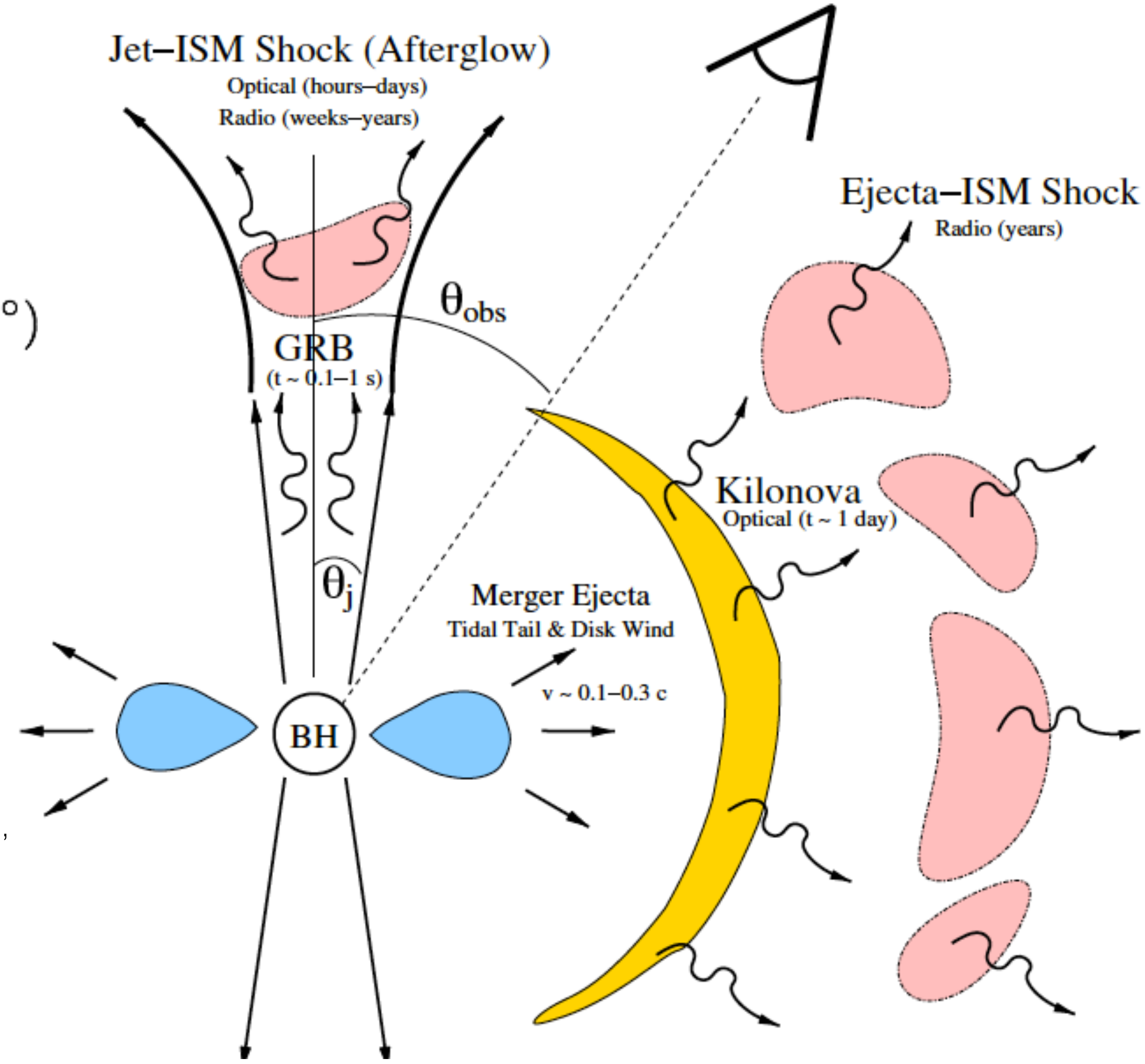
e.g., Hansen & Lyutikov (2001), Palenzuela+ (2013)
Metzger & Zivancev (2016)

4) **Kilonova**

Li & Paczynski (1998), Metzger+(2010), Roberts+(2011),
Bauswein+(2013), Grossman+(2013),
Barnes & Kasen (2013), Tanaka & Hotokezaka (2013)

5) Late-time radio transient

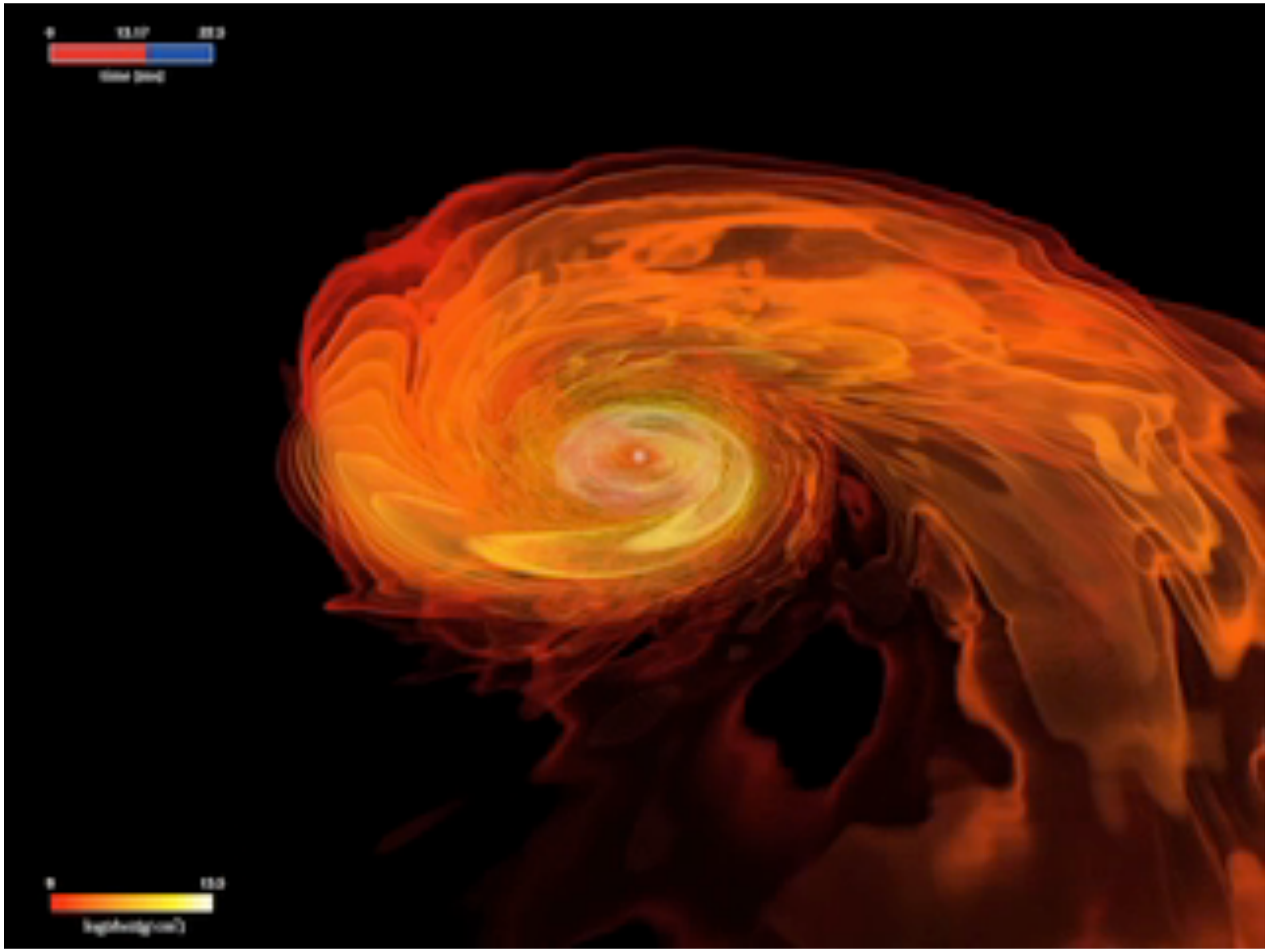
Nakar & Piran (2011), Hotokezaka+(2016)



Metzger & Berger (2012)

NS mergers dynamics

Unequal mass NS-NS merger:



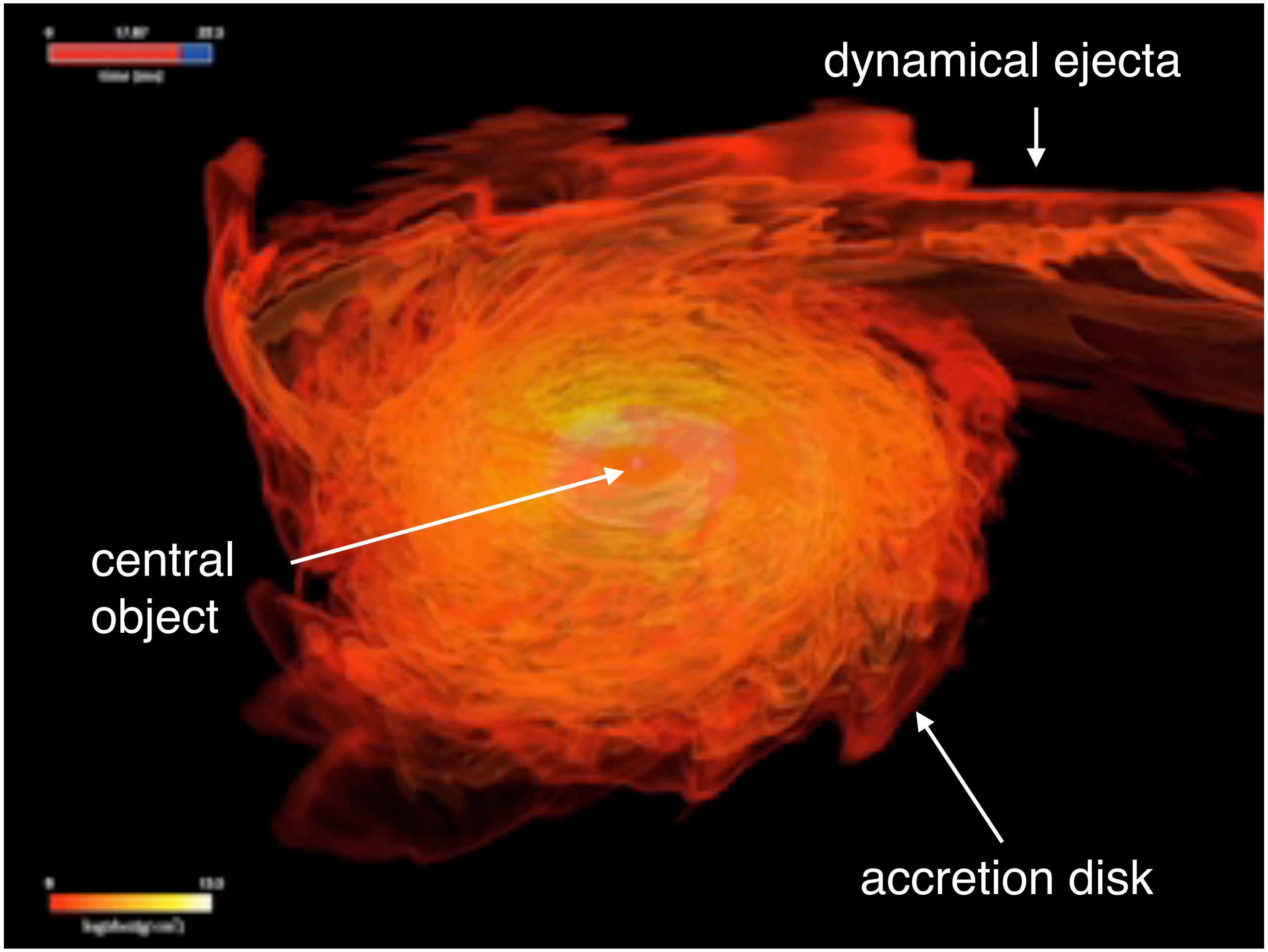
Rezzolla+ (2010)

Phases:

- inspiral
- merger
- remnant + ejecta

NS mergers: Basic Elements

Unequal mass NS-NS merger:



Rezzolla+ (2010)

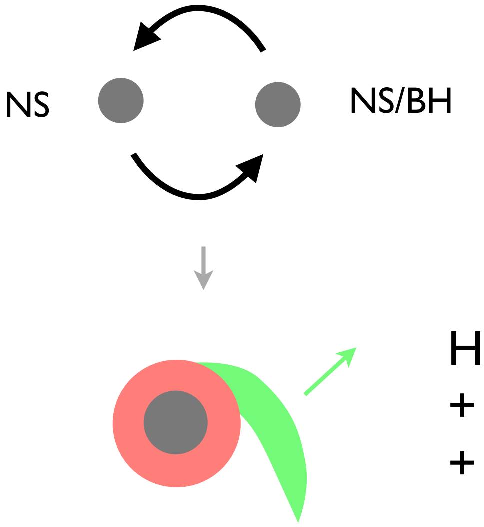
Phases:

- inspiral
- merger
- remnant + ejecta
- relativistic jet (?)

Large body of work:

MPA, Kyoto, Caltech-Cornell-CITA
Princeton, Frankfurt, Stockholm, etc.

NS mergers: Non-Relativistic Ejecta


NS

NS/BH

HMNS or BH
+ Disk
+ Dynamical Ejecta

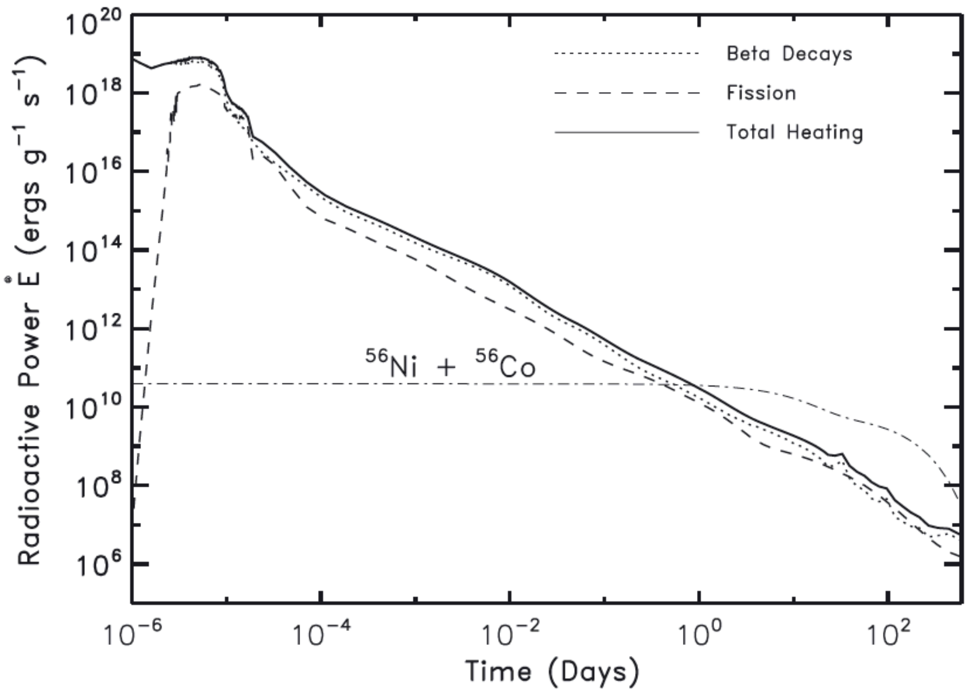
Merger outcome:

1. Central HMNS or BH
2. Material ejected dynamically
3. Remnant disk

Neutron-rich ejecta undergoes radioactive decay over a long timescale:

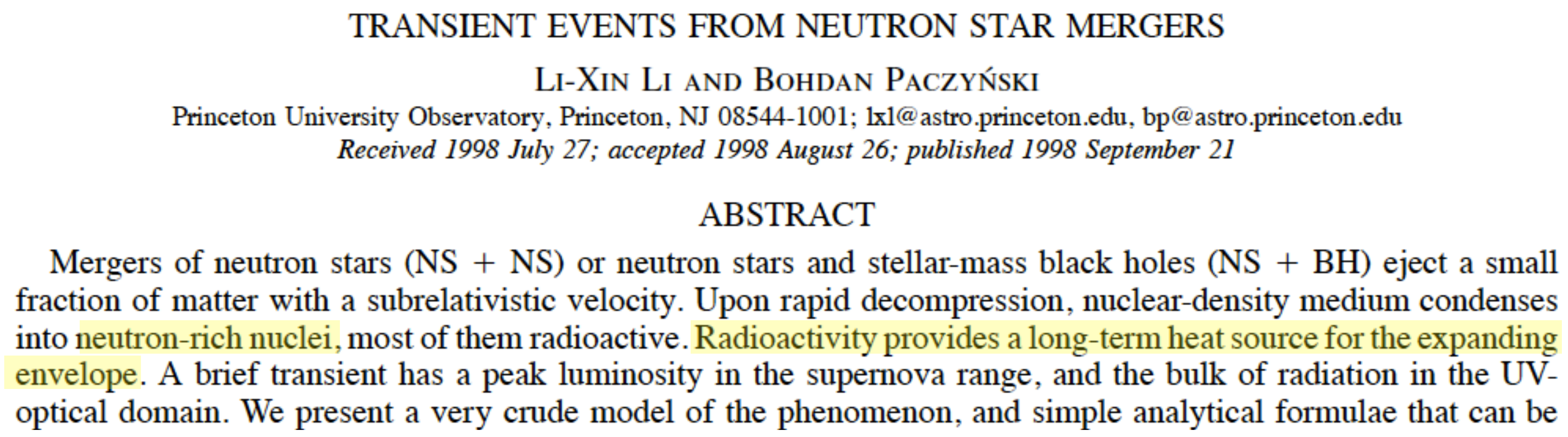
Li & Paczynski (1998), Metzger+(2010), Roberts+(2011)

(see talk by Jenni Barnes)



Metzger+(2010)

Kilonova (aka Macronova)



TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

Li-Xin Li and Bohdan Paczyński
Princeton University Observatory, Princeton, NJ 08544-1001; lxl@astro.princeton.edu, bp@astro.princeton.edu

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ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be

Supernova-like transient, but:

1) smaller ejecta mass → 1) shorter duration

2) higher velocity → 2) dimmer

$$L_{\rm pk} \approx M\dot{\epsilon}_{\rm nuc}(t_{\rm pk}) \approx 5\times 10^{40}\,{\rm erg\,s^{-1}}\,\epsilon_{\rm th}\left(\frac{M}{10^{-2}M_\odot}\right)^{0.35}\left(\frac{v}{0.1\,{\rm c}}\right)^{0.65}\left(\frac{\kappa}{{\rm cm^2\,g^{-1}}}\right)^{-0.65}$$

(Arnett's rule)

$$t_{\rm pk} = \left(\frac{3\kappa M}{4\pi c v}\right)^{1/2} \approx 2.7\,{\rm day}\left(\frac{M}{10^{-2}M_\odot}\right)^{1/2}\left(\frac{v}{0.1\,{\rm c}}\right)^{-1/2}\left(\frac{\kappa}{{\rm cm^2\,g^{-1}}}\right)^{1/2}$$

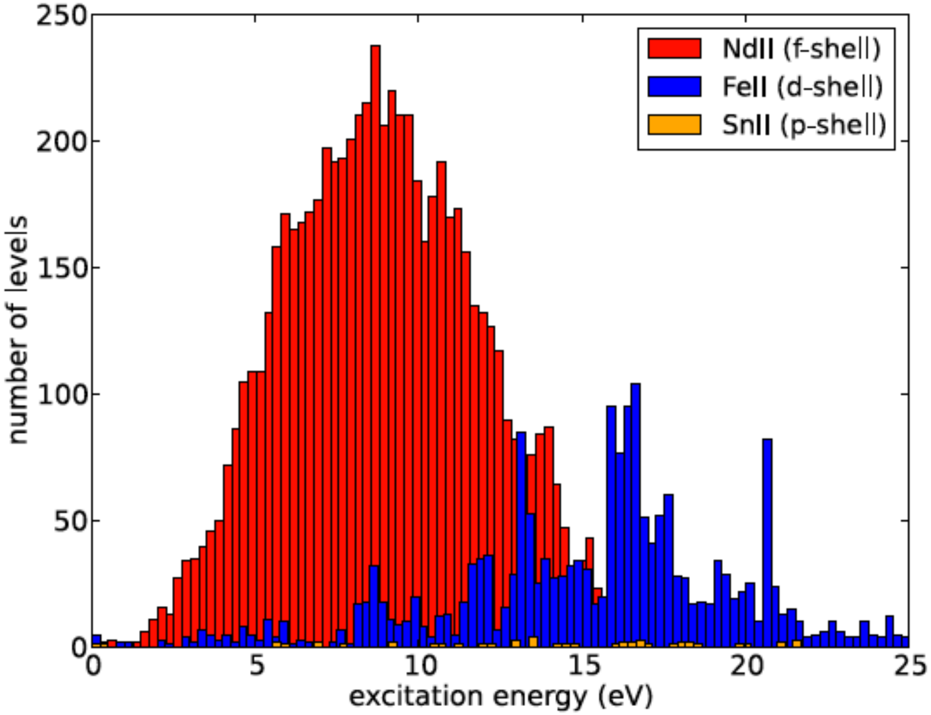
$\kappa \sim 1~{\rm cm}^2~{\rm g}^{-1}$ (iron-like)

$\kappa \sim 10 - 100~{\rm cm}^2~{\rm g}^{-1}$

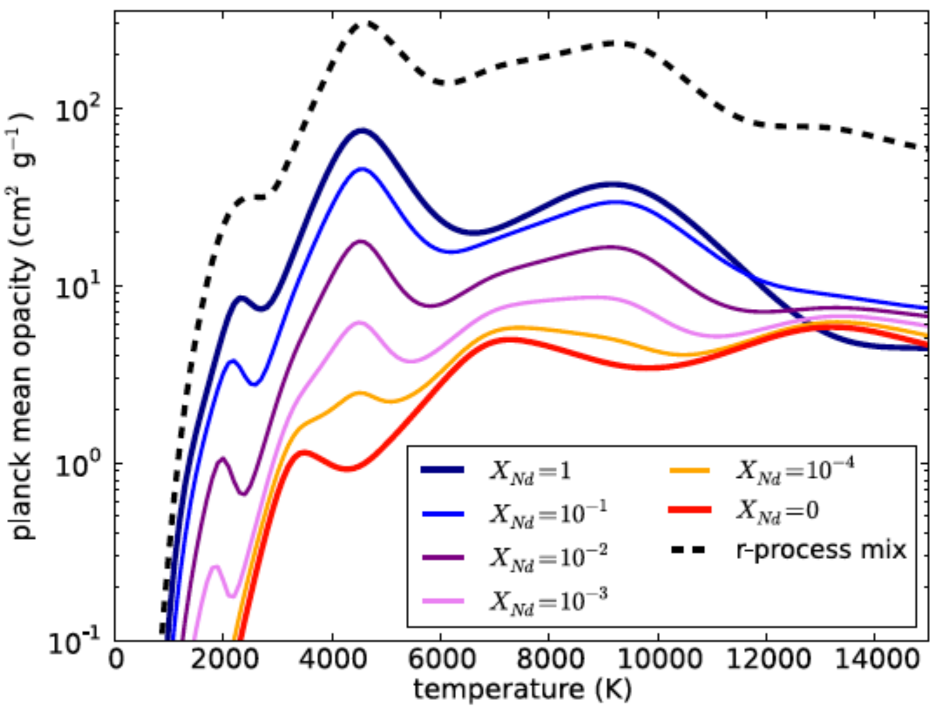
(r-process A > 130)

Optical opacity of Lanthanides (A>130)

Lanthanides have many more atomic levels



Much higher opacity than iron



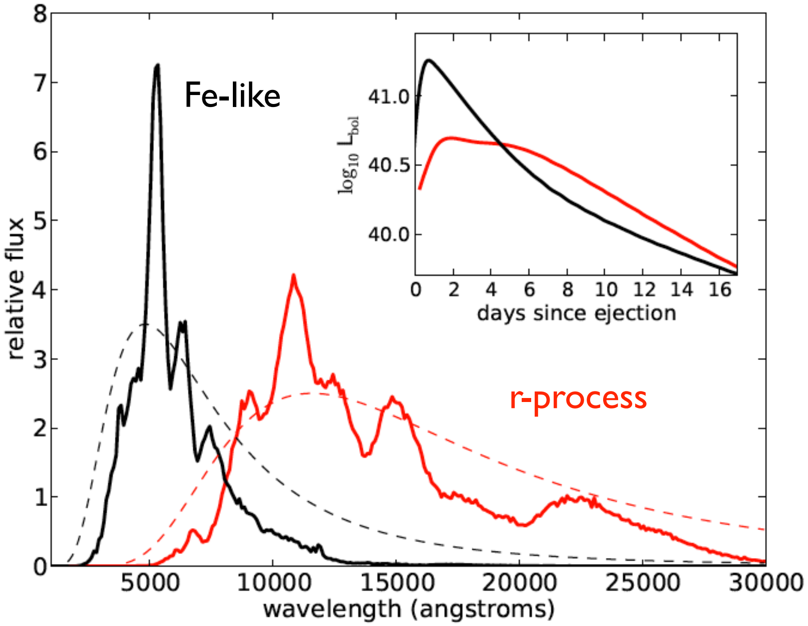
Kasen+ (2013)

(The opacity sets the diffusion time: duration and luminosity)

See also Fontes+ (2015)

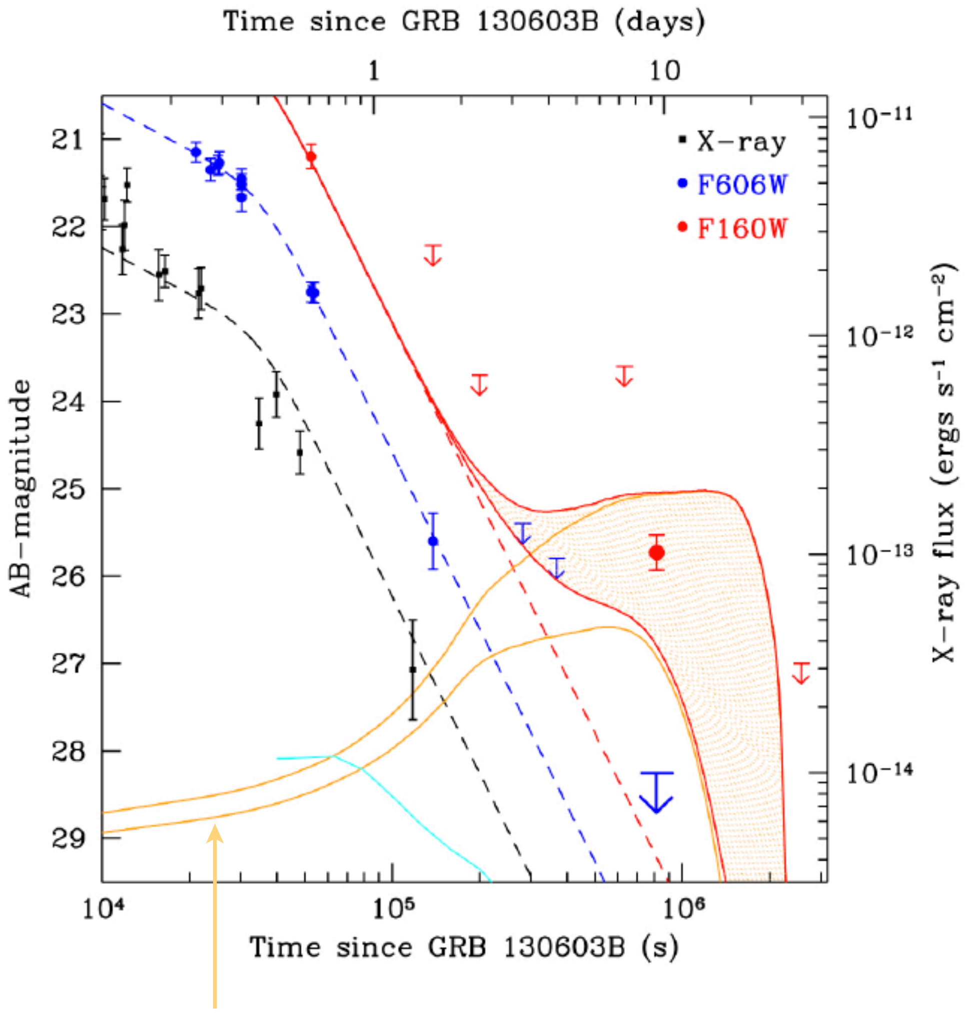
Dynamical Ejecta: r-process kilonova

Theoretical kilonova spectra & light curves:



r-process-dominated material generates IR transient

(large number of lines in optical)



Kilonova models
from Barnes & Kasen (2013)
(dynamical ejecta)

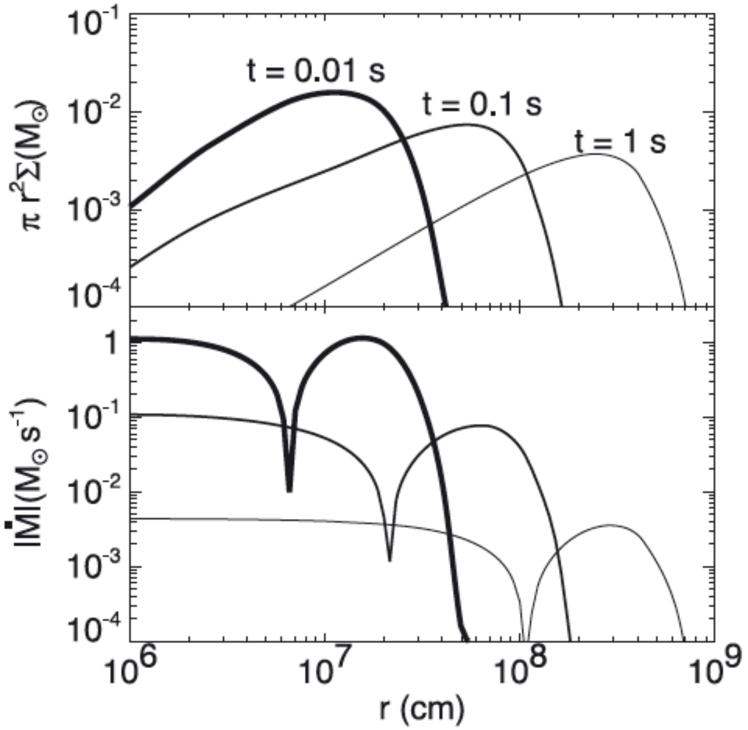
Tanvir+ (2013)

Berger+ (2013)

see also Tanaka & Hotokezaka (2013)

Disk contribution

Evolution of surface density and accretion rate



Metzger+ (2008)

$$t_{\rm orb} \simeq 3 R_{50}^{3/2} M_3^{-1/2}\ {\rm ms}$$

$$t_{\rm visc} \simeq 1\alpha_{0.03}^{-1} R_{50}^{3/2} M_3^{-1/2}\ (H/3R)\ \ {\rm s}$$

$$t_{\rm therm} \simeq \frac{c_s^2}{v_K^2} t_{\rm visc} \lesssim t_{\rm visc}$$

- Disk evolves on timescales long compared to the dynamical (orbital) time, due to viscous processes
- Weak interactions freeze-out as the disk spreads viscously: final Ye
- Gravitationally-unbound outflows driven by:
  - Neutrino heating (on thermal time)

    Ruffert & Janka (1999), Dessart+ (2009)
  - Viscous heating and nuclear recombination (on viscous time)

Metzger+ (2008)

$$\frac{E_\alpha}{GM_{\rm BH}/R} \simeq 1 R_{600} M_3^{-1}$$

Equations

mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

ρ : density

$\mathbf{v}$: velocity

momentum conservation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p = -\nabla\Phi + \frac{1}{\rho}\nabla \cdot \mathbb{T}$$

gas pressure

gravity

angular mom. transport

p : pressure

energy conservation:

$$\frac{De_{\rm int}}{Dt} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = \frac{1}{\rho^2 \nu}\mathbb{T} : \mathbb{T} + Q_{\nu,\rm abs} - Q_{\nu,\rm em}$$

viscous heating

neutrino heating

neutrino cooling

$e_{\rm int}$: int. energy

lepton # conservation:

$$\frac{DY_e}{Dt} = \Gamma_{\nu,\rm abs} + \Gamma_{\nu,\rm em}$$

neutrino absorption

neutrino emission

EOS:

$$p = p(\rho, e_{\rm int}, Y_e)$$

$$Y_e = \frac{n_e}{n} = \frac{n_e}{\rho/m_n}$$

Y_e : electron fraction

Equations

mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

hydrodynamics: FLASH

momentum conservation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p = -\nabla \Phi + \frac{1}{\rho}\nabla \cdot \mathbb{T}$$

gas pressure

gravity

angular mom. transport

pseudo-Newtonian gravity

energy conservation:

$$\frac{De_{\mathrm{int}}}{Dt} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = \frac{1}{\rho^2 \nu}\mathbb{T} : \mathbb{T} + Q_{\nu,\mathrm{abs}} - Q_{\nu,\mathrm{em}}$$

viscous heating

neutrino heating

neutrino cooling

α-viscosity

lepton # conservation:

$$\frac{DY_e}{Dt} = \Gamma_{\nu,\mathrm{abs}} + \Gamma_{\nu,\mathrm{em}}$$

neutrino absorption

neutrino emission

neutrino leakage

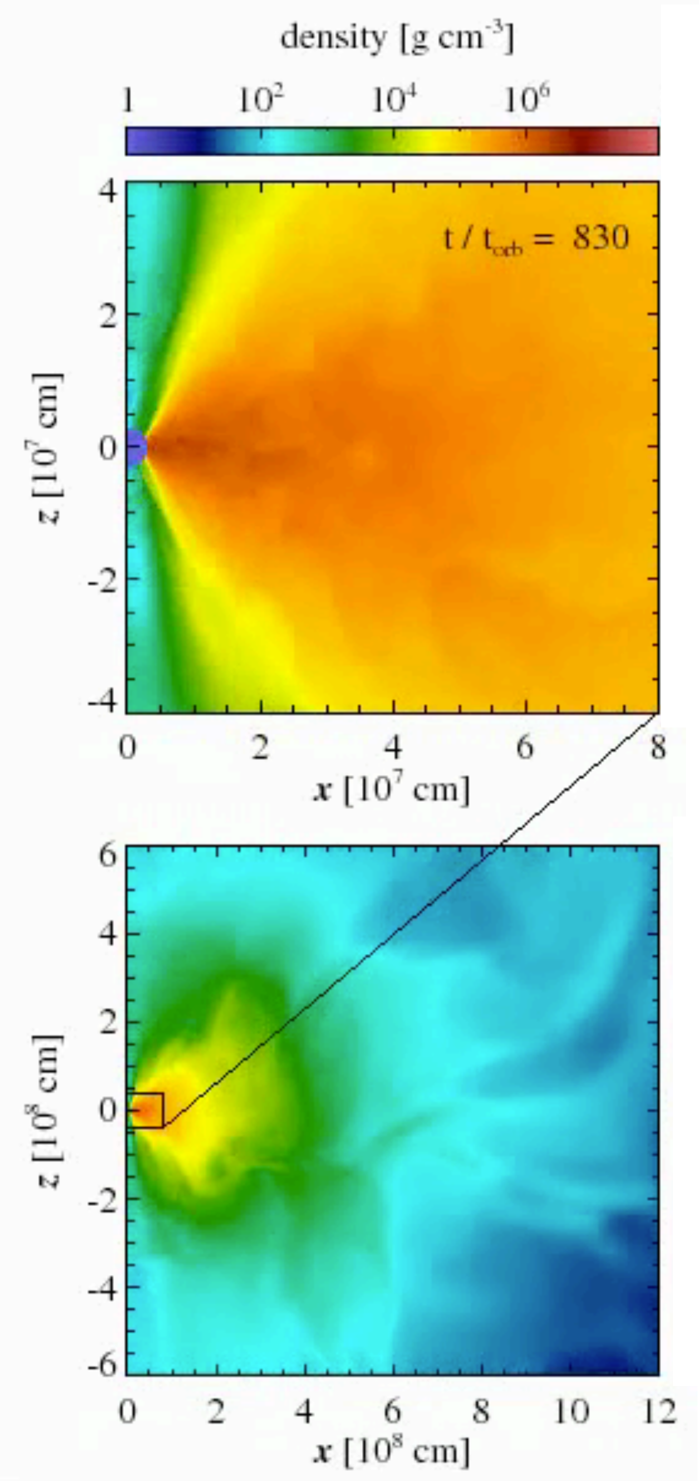
lightbulb self-irradiation

EOS:

$$p = p(\rho, e_{\mathrm{int}}, Y_e) \qquad Y_e = \frac{n_e}{n} = \frac{n_e}{\rho/m_n}$$

Helmholtz EOS

Wind from remnant accretion disk



- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10% 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)

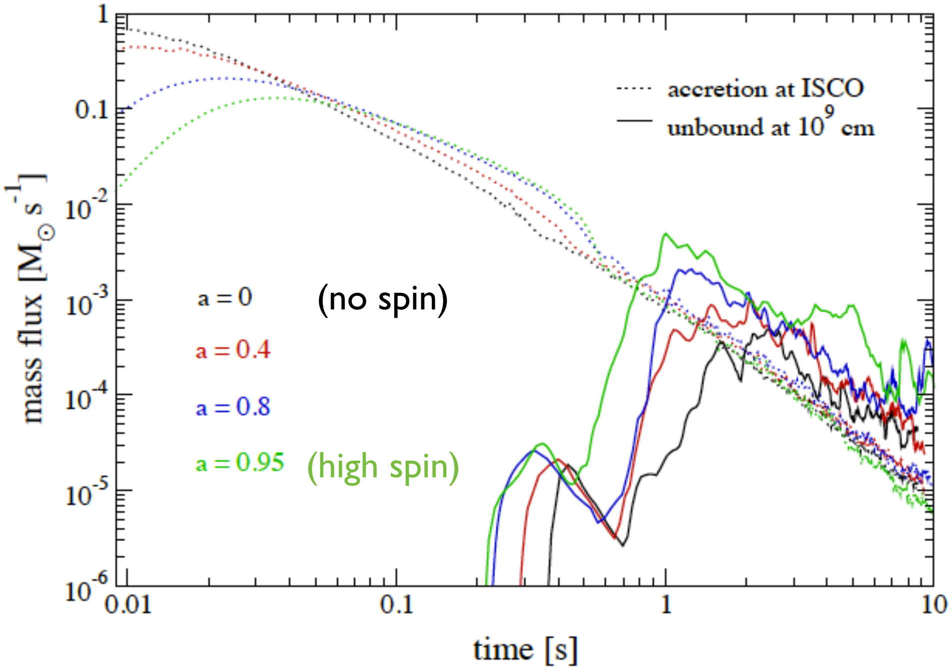
RF & Metzger (2013), MNRAS

Just et al. (2015), MNRAS

RF et al. (2015), MNRAS

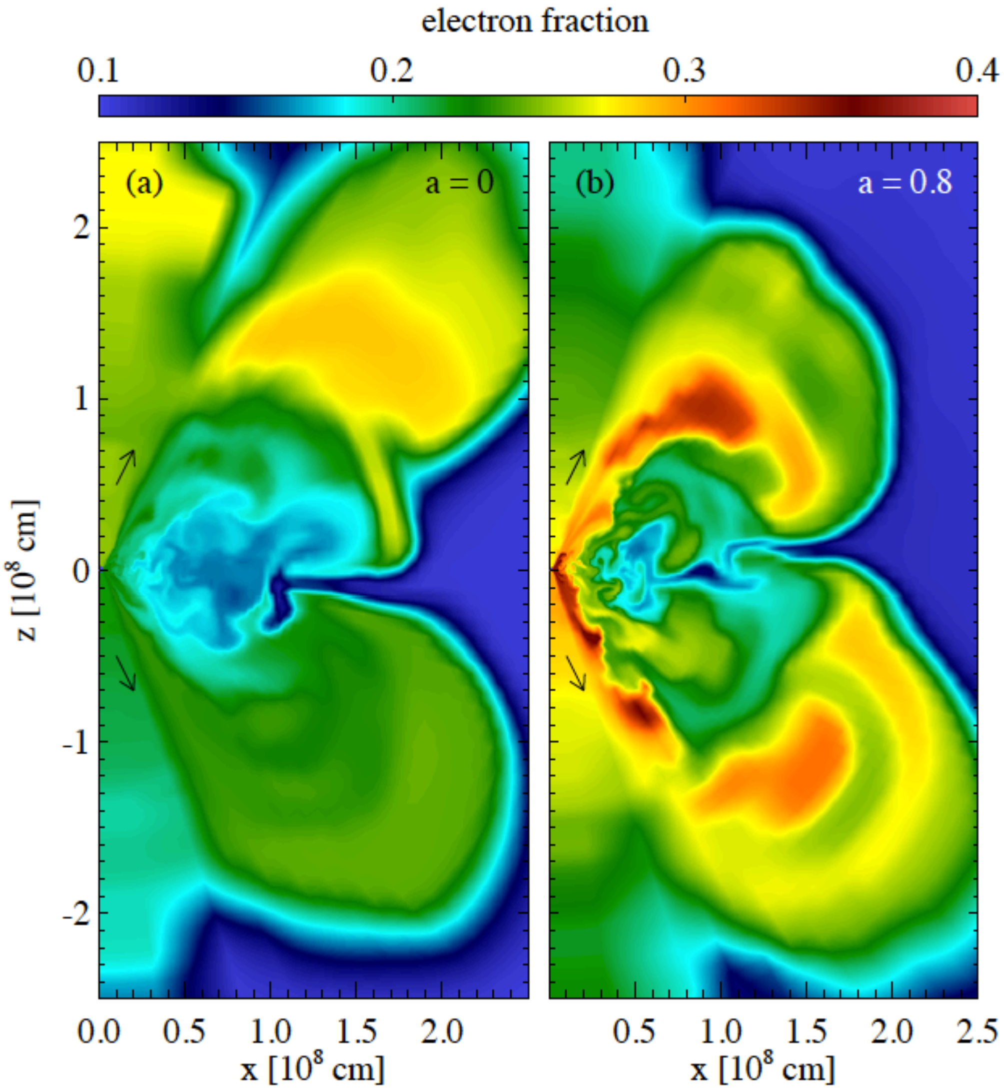
Effect of BH spin on disk wind

Mass ejection as a function of time (solid lines):



(no spin)

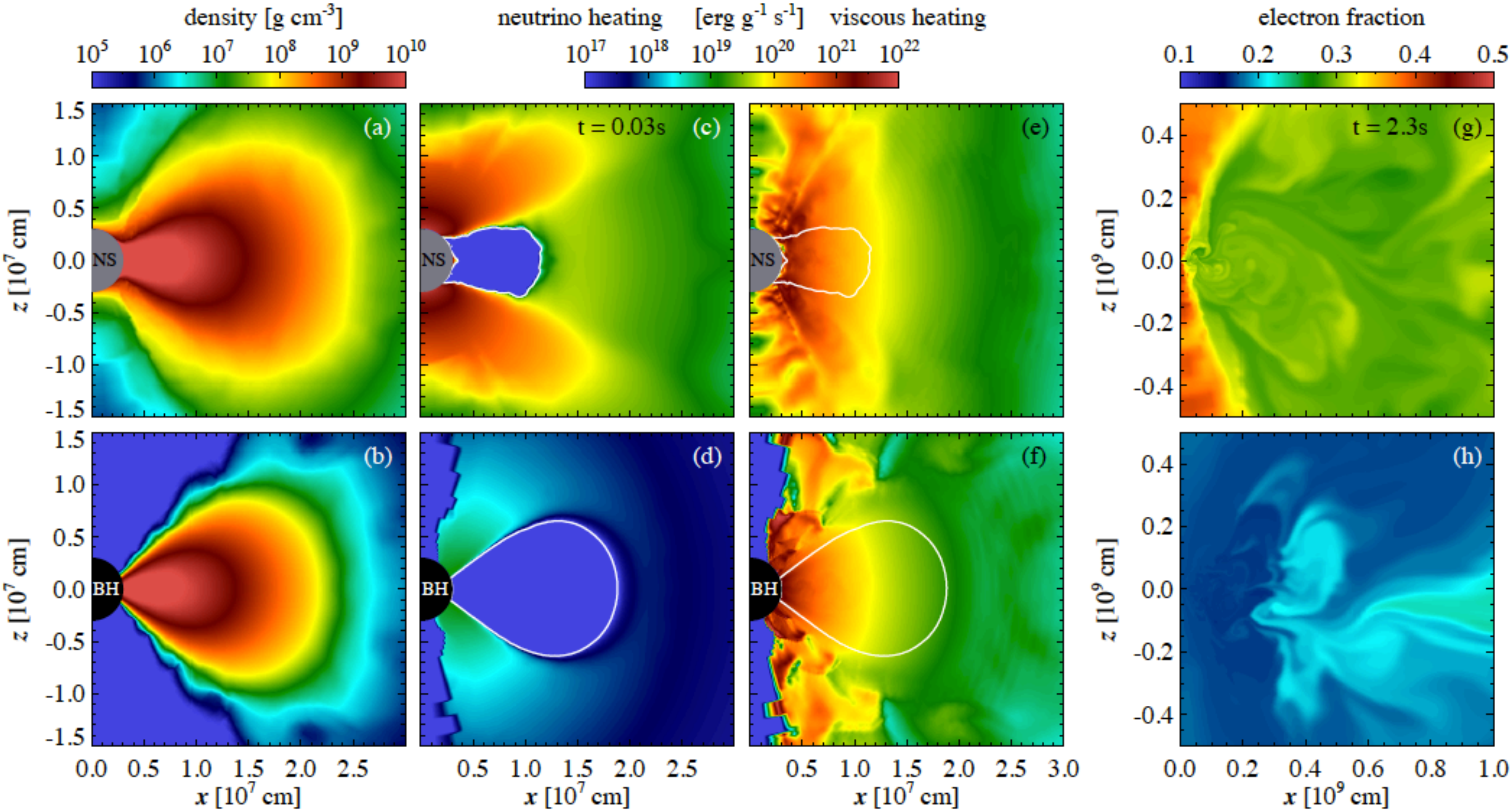
(high spin)



RF, Kasen, Metzger, Quataert (2015), MNRAS

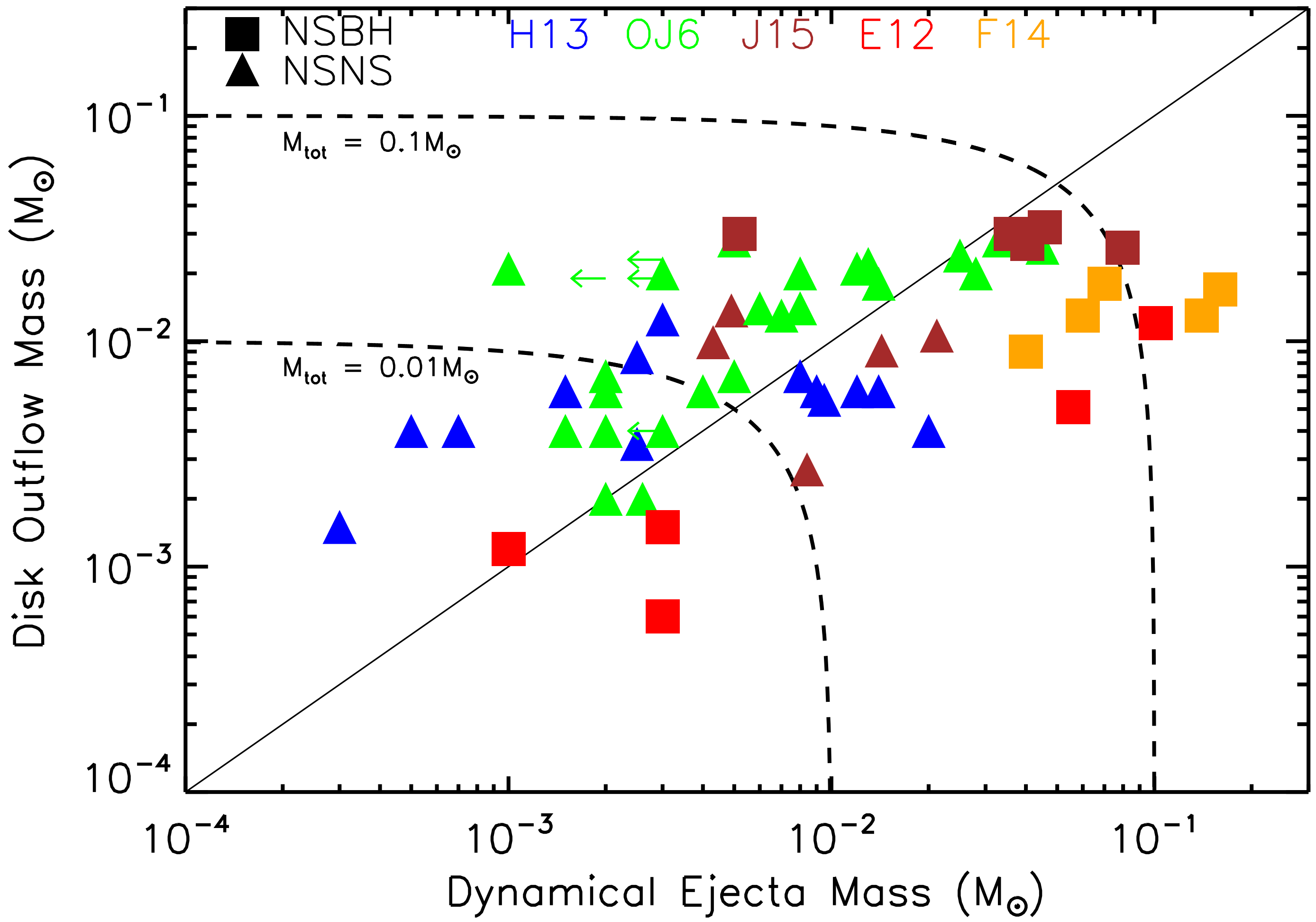
(see also Just et al. 2015)

Hypermassive NS versus BH



Metzger & RF (2014), MNRAS

Disk wind vs. Dynamical Ejecta



Oechslin & Janka (2006)

Hotokezaka+ (2013)

East+ (2012)

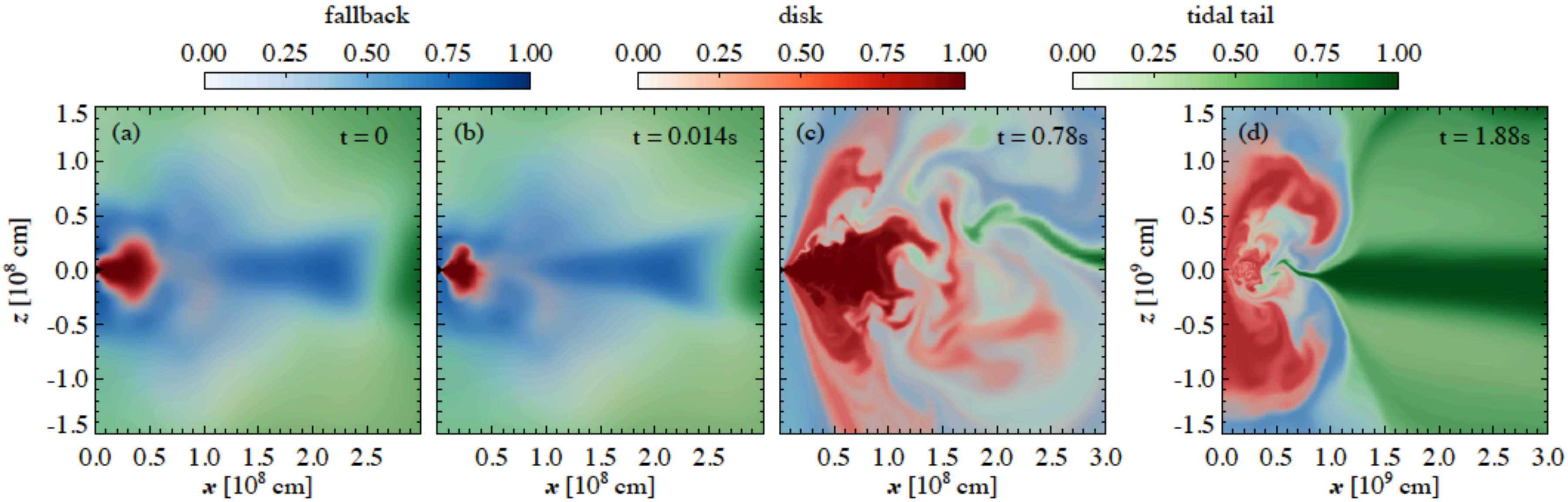
Foucart+ (2014)

Just+ (2015)

RF & Metzger (2016)

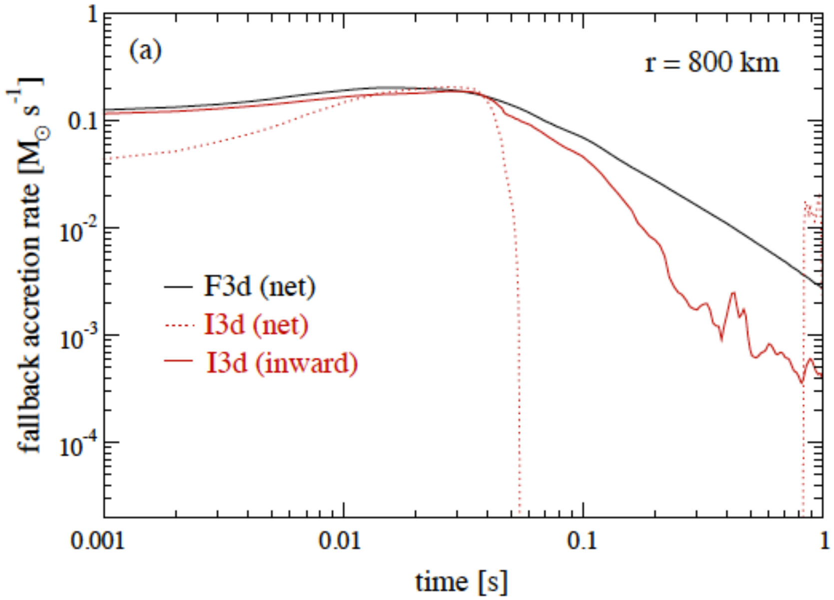
Interplay of disk wind and dynamical ejecta

Mapping from Newtonian BH-NS merger simulation (Rosswog) onto 2D disk code



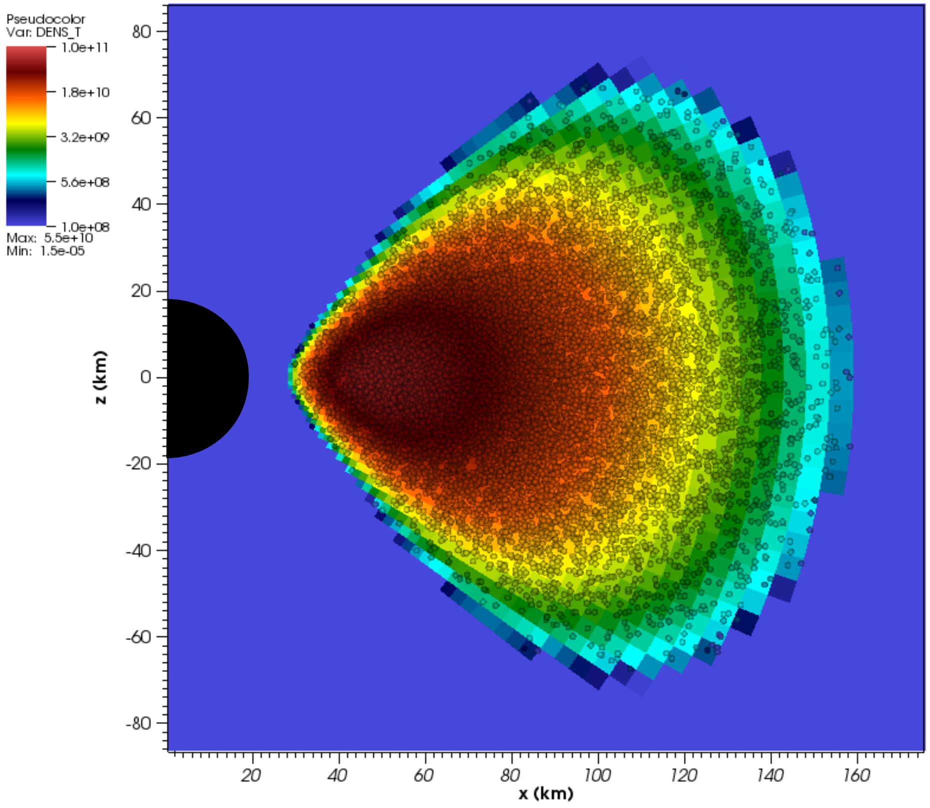
Disk wind can suppress fallback accretion: implications for the late-time emission from GRBs (BH-NS)

RF, Quataert, Schwab, Kasen & Rosswog (2015)

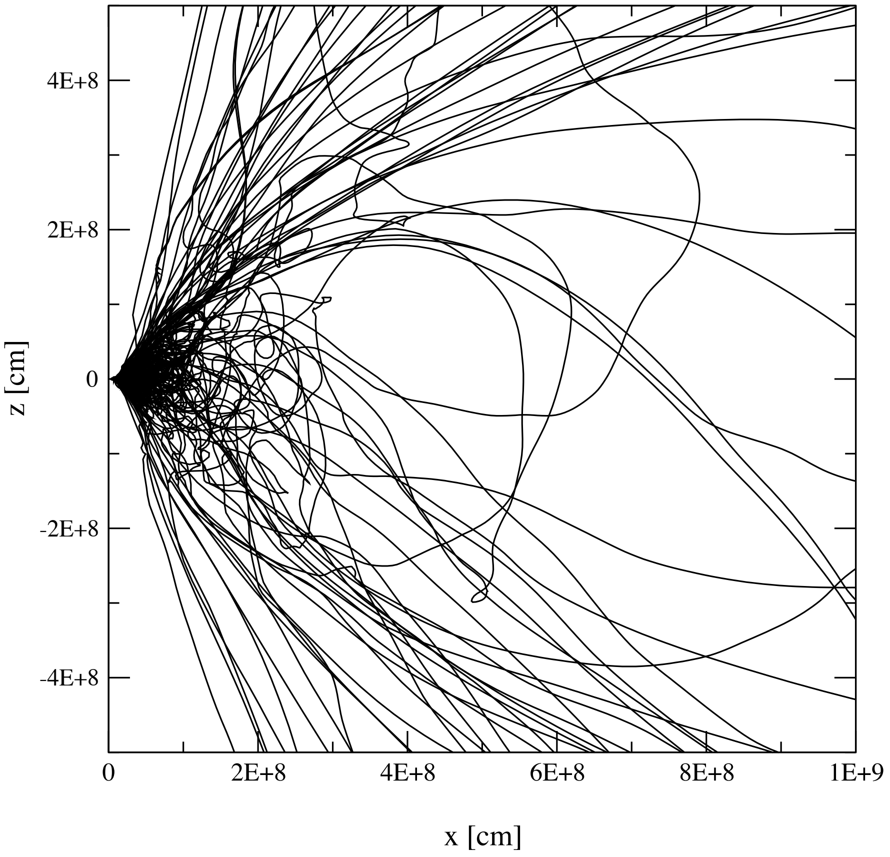


Nucleosynthesis with Tracer Particles

Passive tracers follow density distribution



Disk is convective

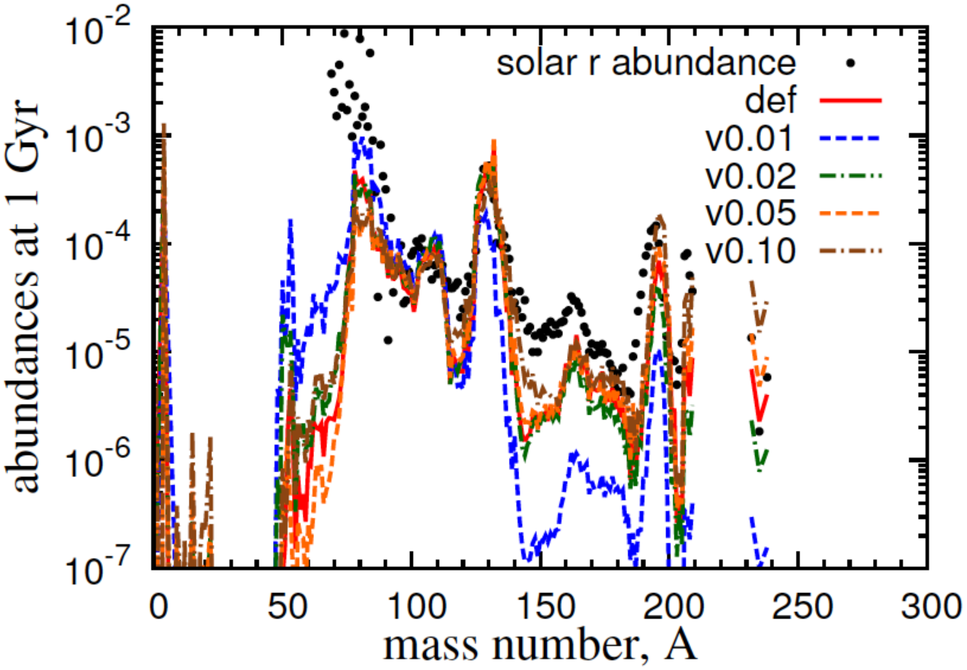


M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

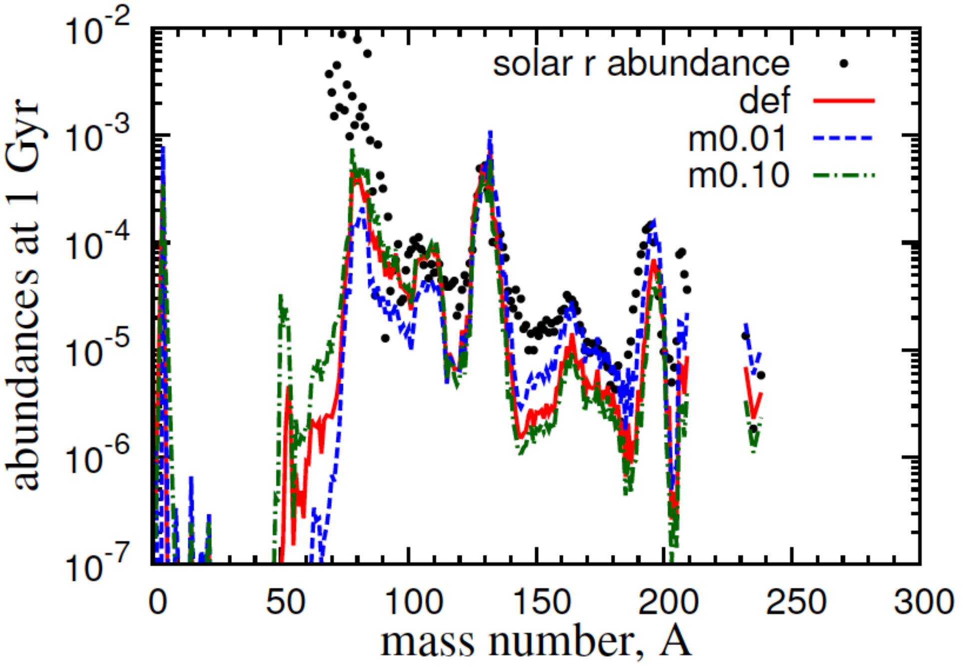
- Nuclear network: ~7000 isotopes, include neutrino effects
- Non-spinning BH, parameter dependencies

Nucleosynthesis with Tracer Particles

Varying disk viscosity:



Varying disk mass:

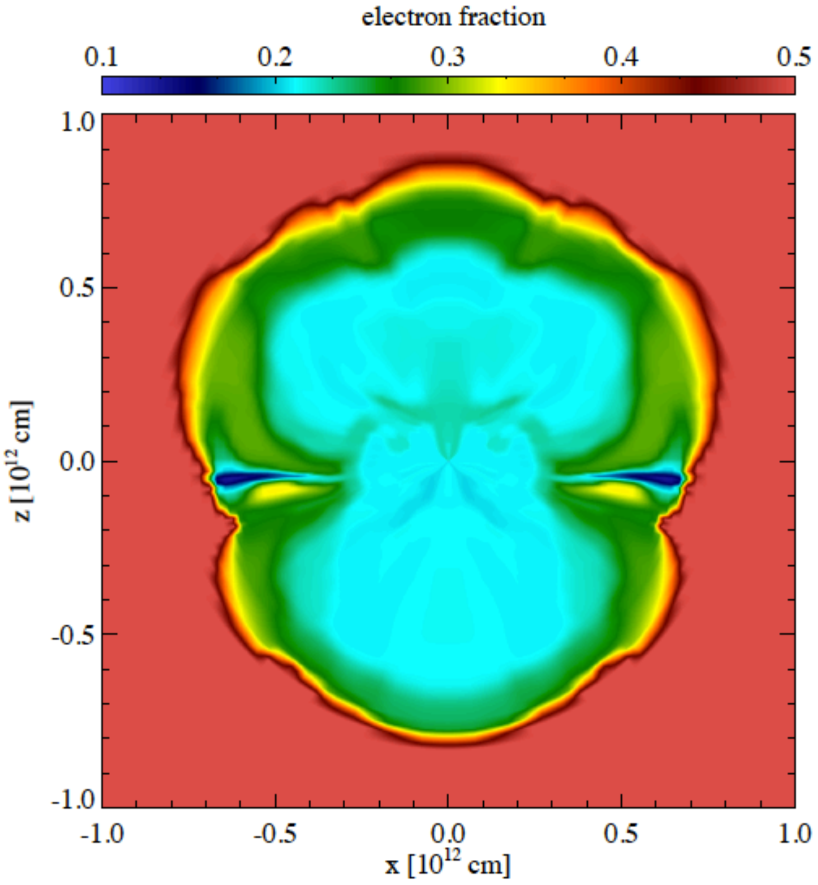


M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

- Most sensitive to viscosity: expansion time vs weak interaction time
- Also sensitive to disk mass and degeneracy: neutrinos & equilibrium Ye
- Not very sensitive to initial Ye
- See also Just et al. 2015

Observational implications: radiative transfer

Evolve disk wind until homologous expansion:



RF, Kasen, Metzger, Quataert (2015), MNRAS

Optica/IR radiative transfer with SEDONA:

Kasen+ (2006)

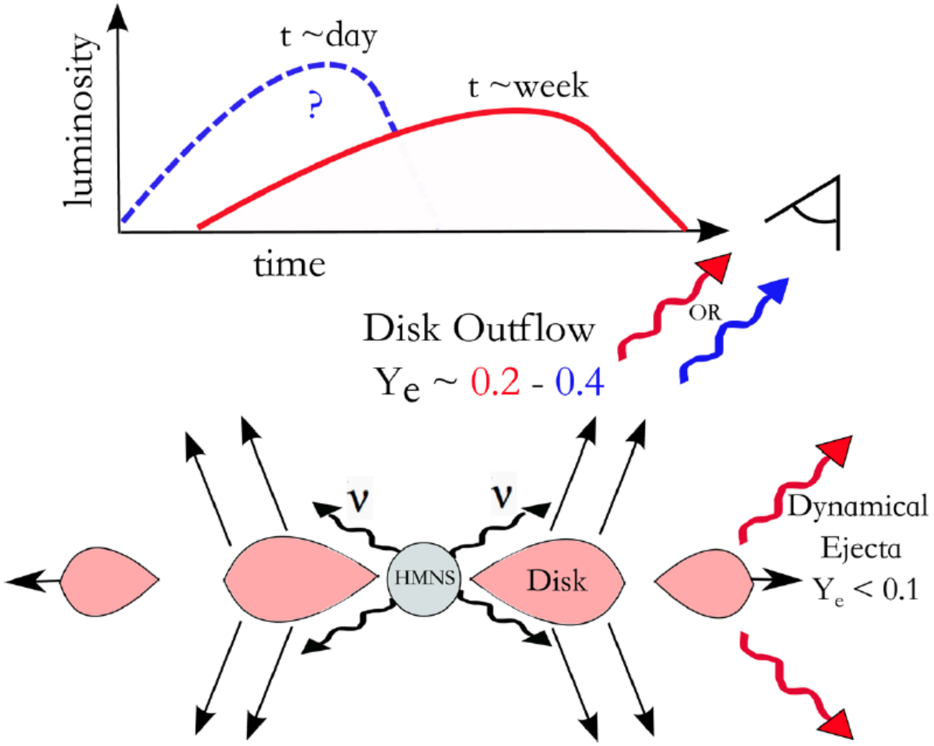
- Monte Carlo method for expanding media
- Wavelength dependent transfer

Need opacity prescription:

- Use critical Ye ~ 0.25 to switch from Lanthanide-like to Iron-like opacities

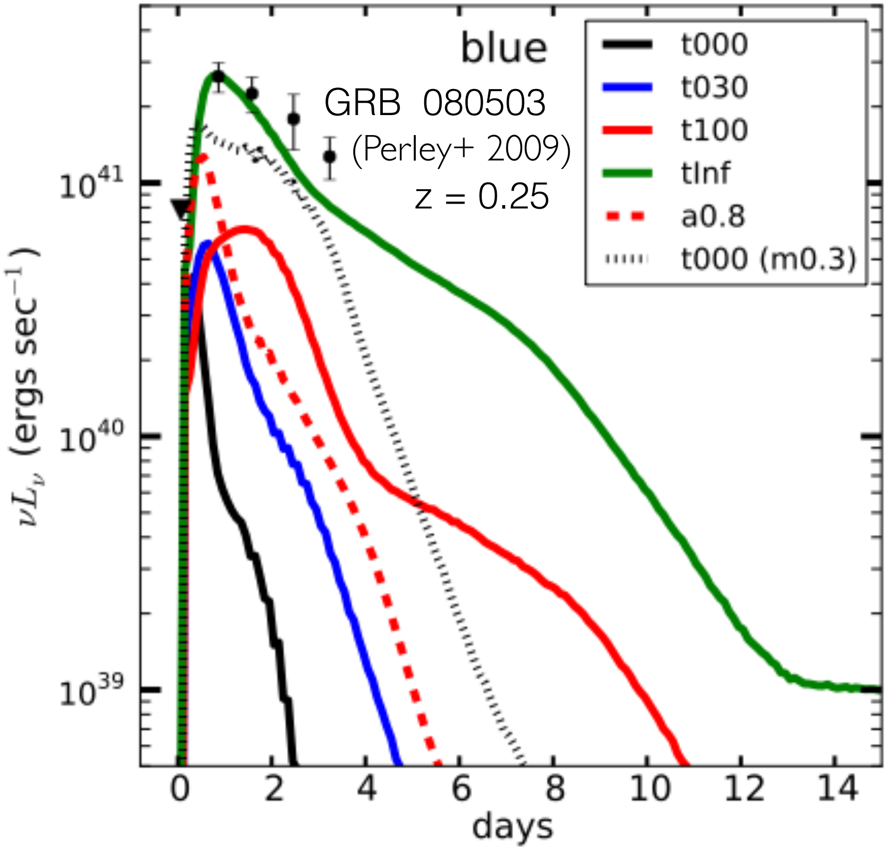
HMNS lifetime and kilonova

Longer lifetime → more neutrino irradiation → less neutrons → smaller opacity → bluer emission



Metzger & RF (2014), MNRAS

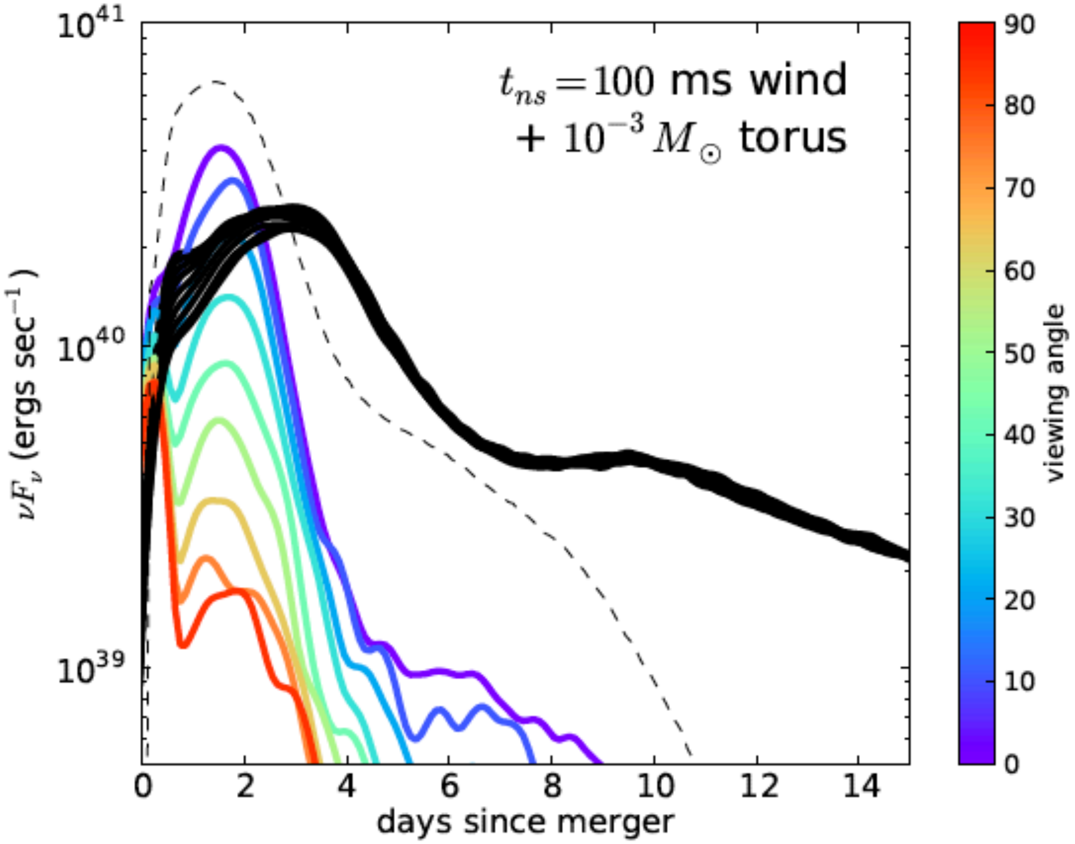
Light curve in 3500-5000 A filter



Kasen, RF, & Metzger (2015), MNRAS

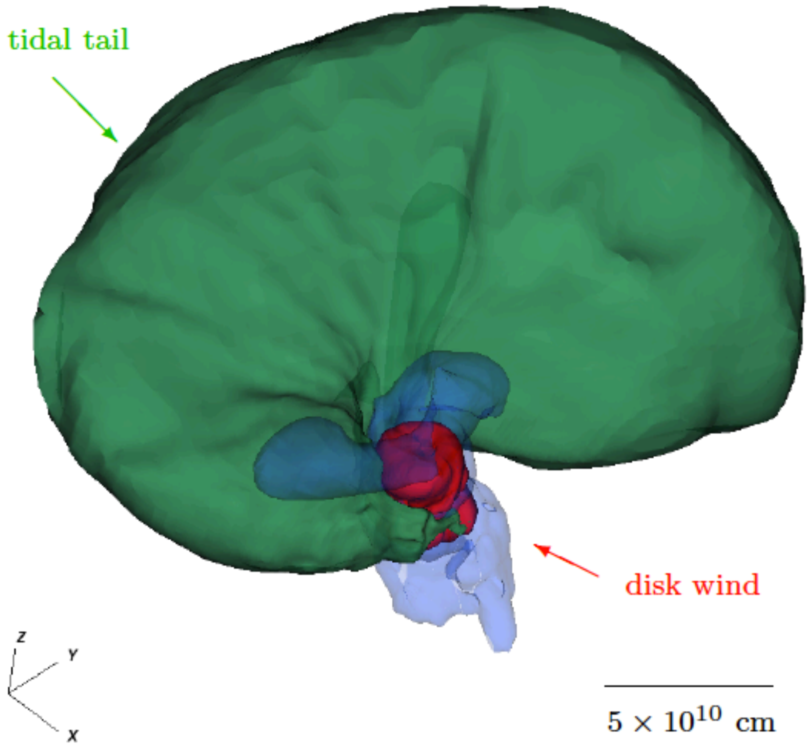
Kilonova: viewing angle dependence

3500 - 5000 A light curve as fn. of viewing angle



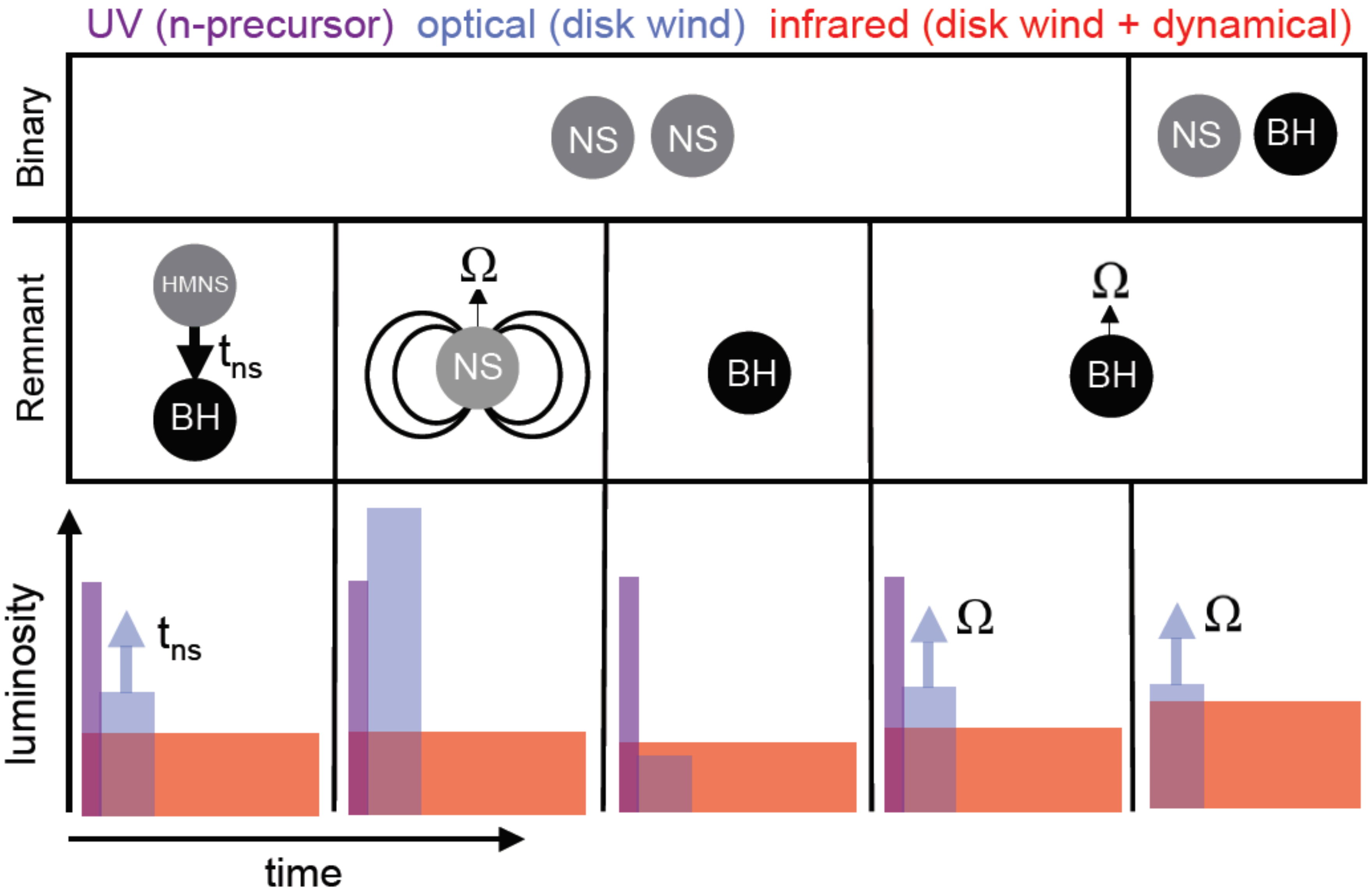
Kasen, RF, & Metzger (2015)

BH-NS merger remnant:



RF, Quataert, Schwab, Kasen & Rosswog (2015)

Diversity of Outcomes & Transients



Kasen, RF, & Metzger (2015)

Future Kilonova Issues (Theory)

1. Optical opacities of r-process elements: spectroscopy

2. MHD & neutrino transport in merger/remnant simulations

3. Improved r-process calculations: abundances & opacities

4. Interplay with jet & SGRB

Summary

1. Accretion disk evolves on timescales much longer than orbital and eject significant amount of mass (compared to dynamical ejecta)

2. Kilonova can be detectable in optical and infrared, and can serve as a diagnostic of the physical conditions in the system

3. Nucleosynthesis contribution of disk mostly for A < 130, with varying amounts of heavier elements.

Thanks to:
UNIVERSITY of CALIFORNIA OFFICE OF THE PRESIDENT
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NERSC
U.S. DEPARTMENT OF ENERGY Office of Science