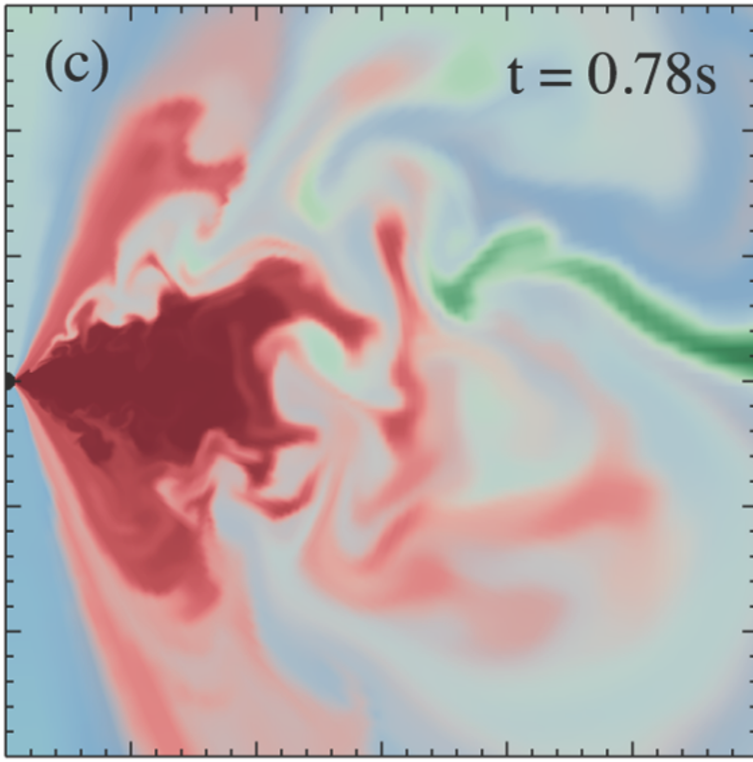
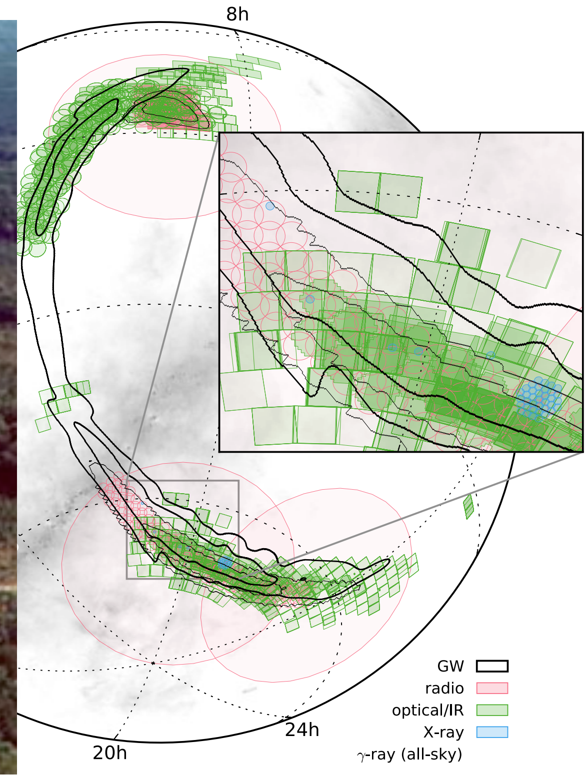




Progress and open questions in Kilonova modeling

Rodrigo Fernández (University of Alberta)

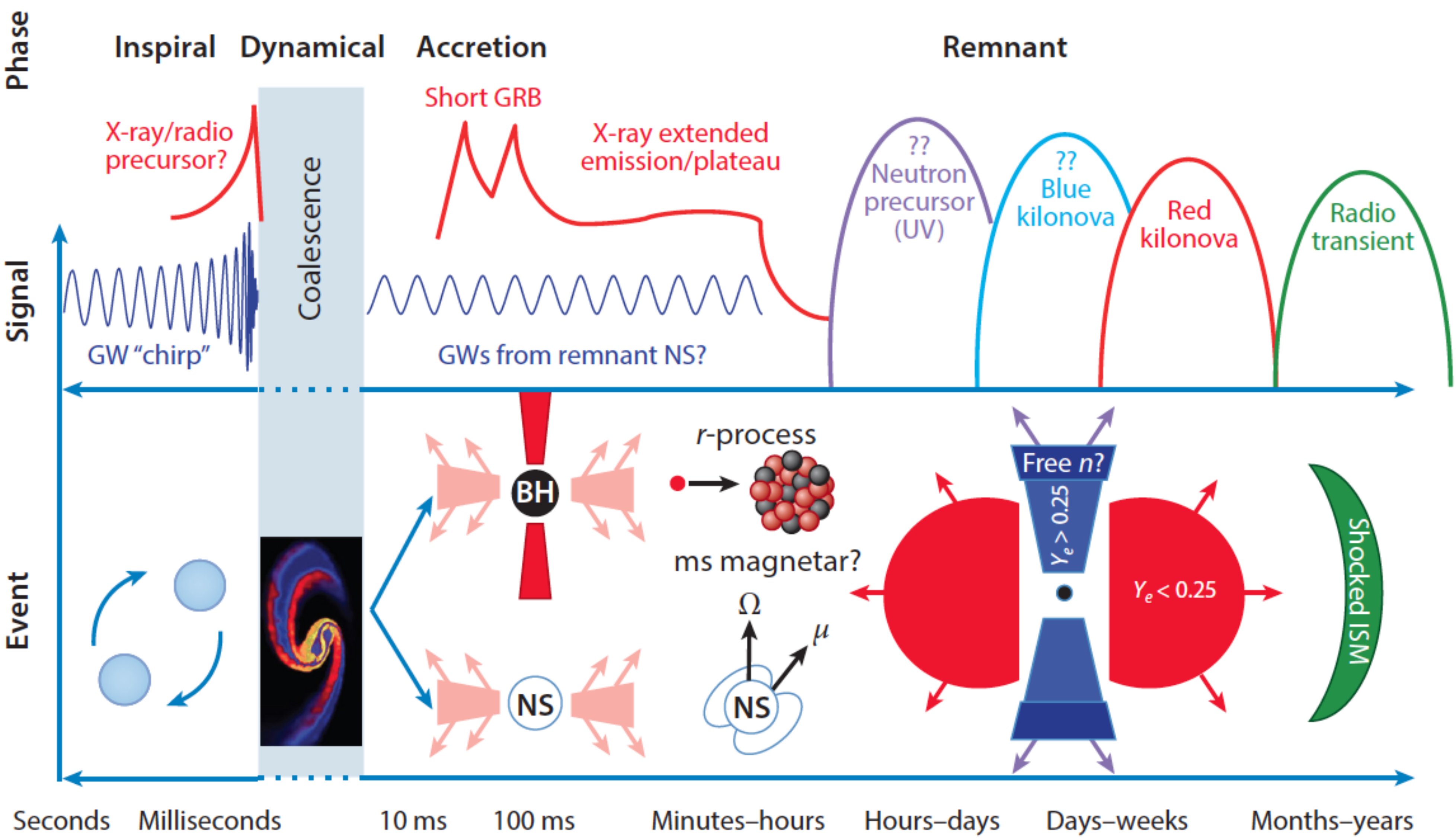
Overview

1. Neutron star merger ejecta and r-process

2. Kilonova properties

3. Current and Future directions

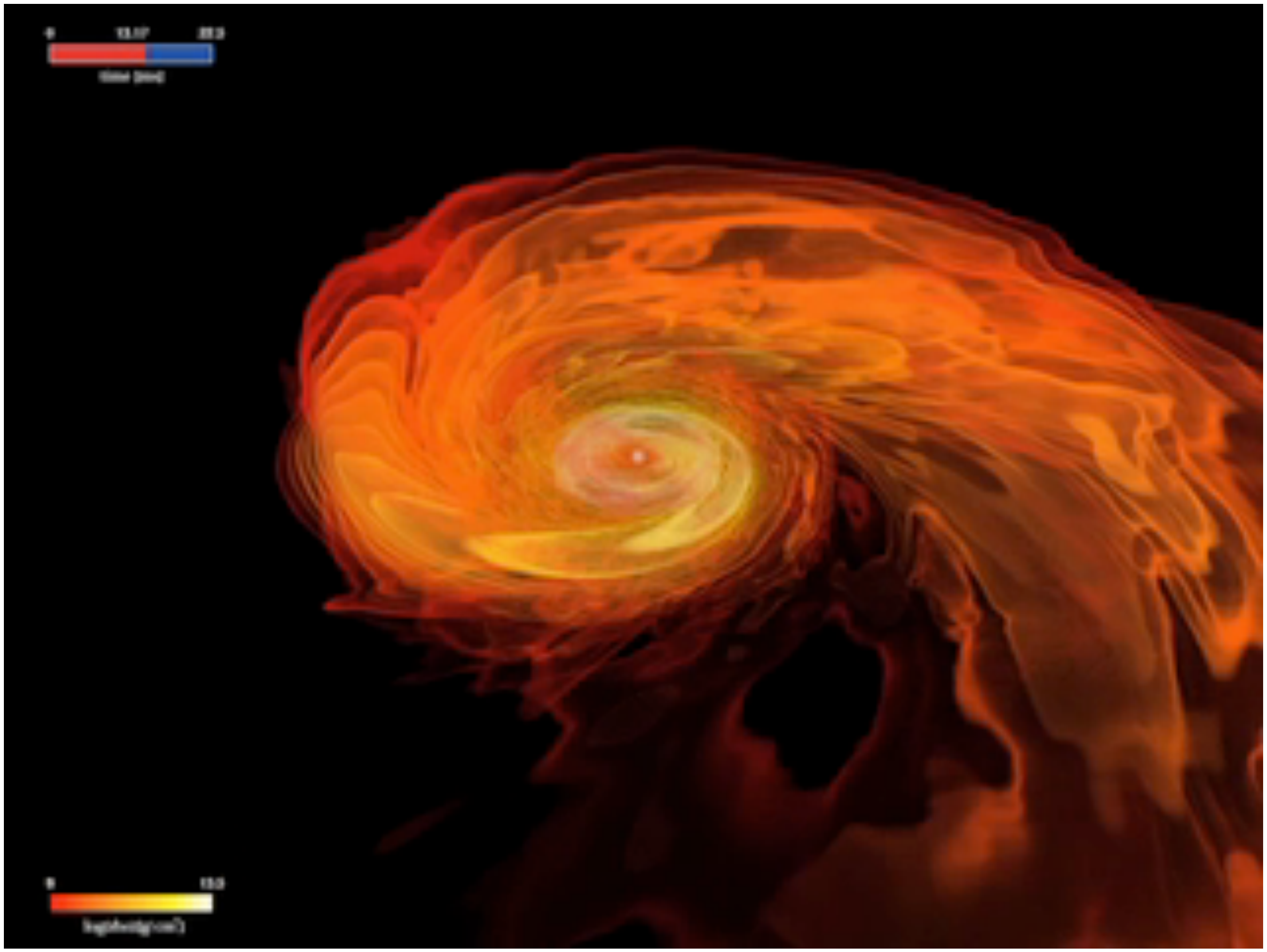
Neutron Star Mergers



RF & Metzger (2016)

NS mergers dynamics

Unequal mass NS-NS merger:



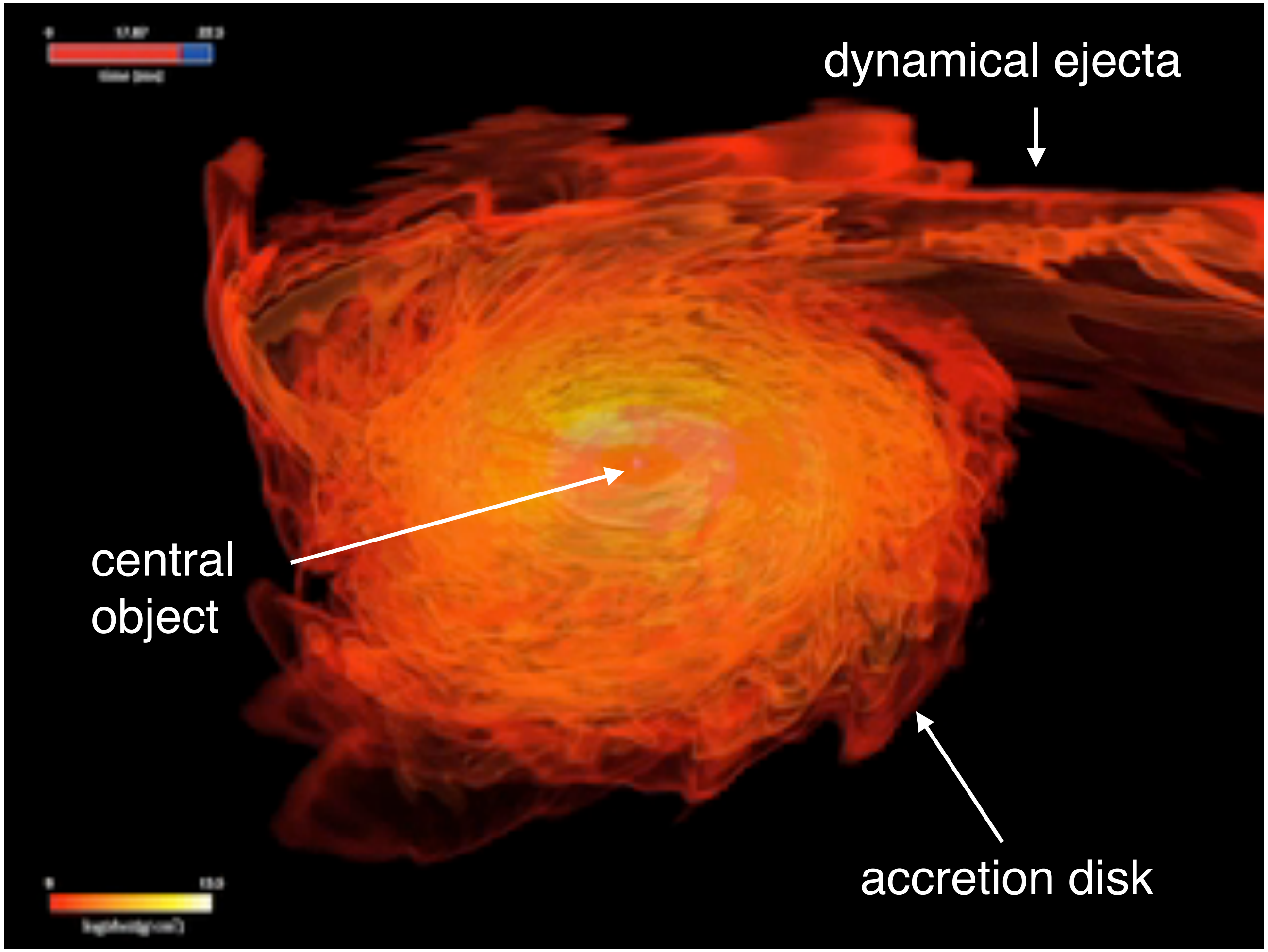
Rezzolla+ (2010)

Phases:

- inspiral
- merger
- remnant + ejecta

NS mergers: Basic Elements

Unequal mass NS-NS merger:



Rezzolla+ (2010)

Phases:

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

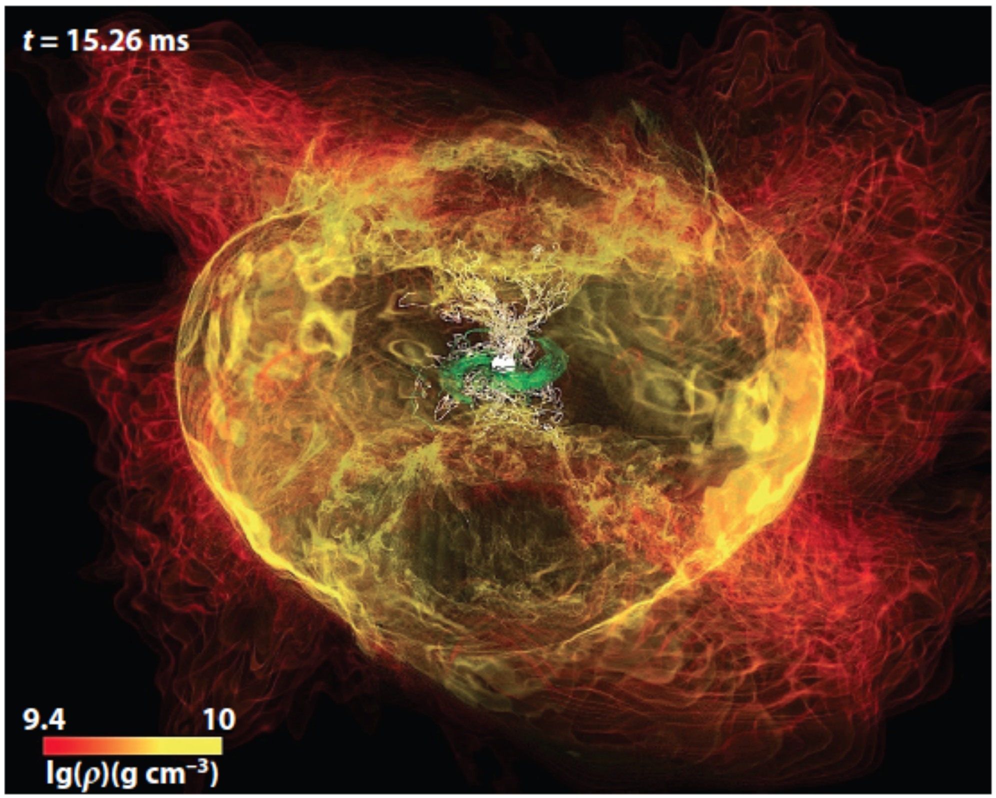
Large body of work:

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

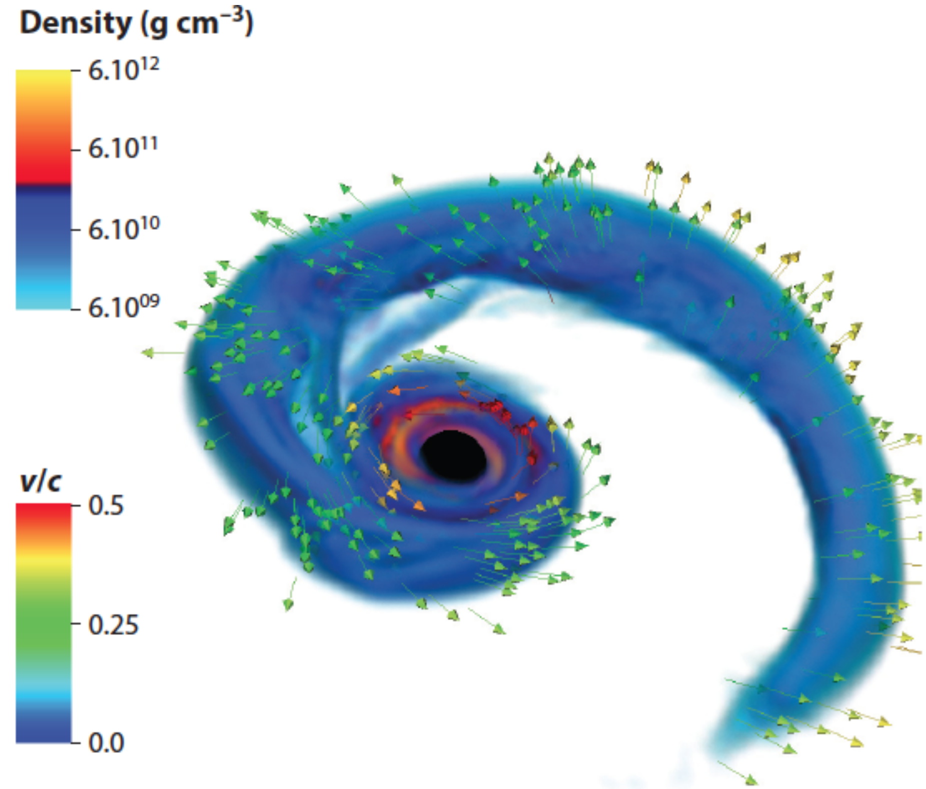
Ejecta Geometry depends on Binary Type

NS-NS mergers

NS-BH mergers



Rezzolla+ (2011)



Foucart+ (2015)

NS mergers: EM emission

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

Paczynski (1986), Eichler+ (1989)

2) Orphan afterglow $(10° \lesssim \theta_j \lesssim 20°)$

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

3) Magnetospheric precursor

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

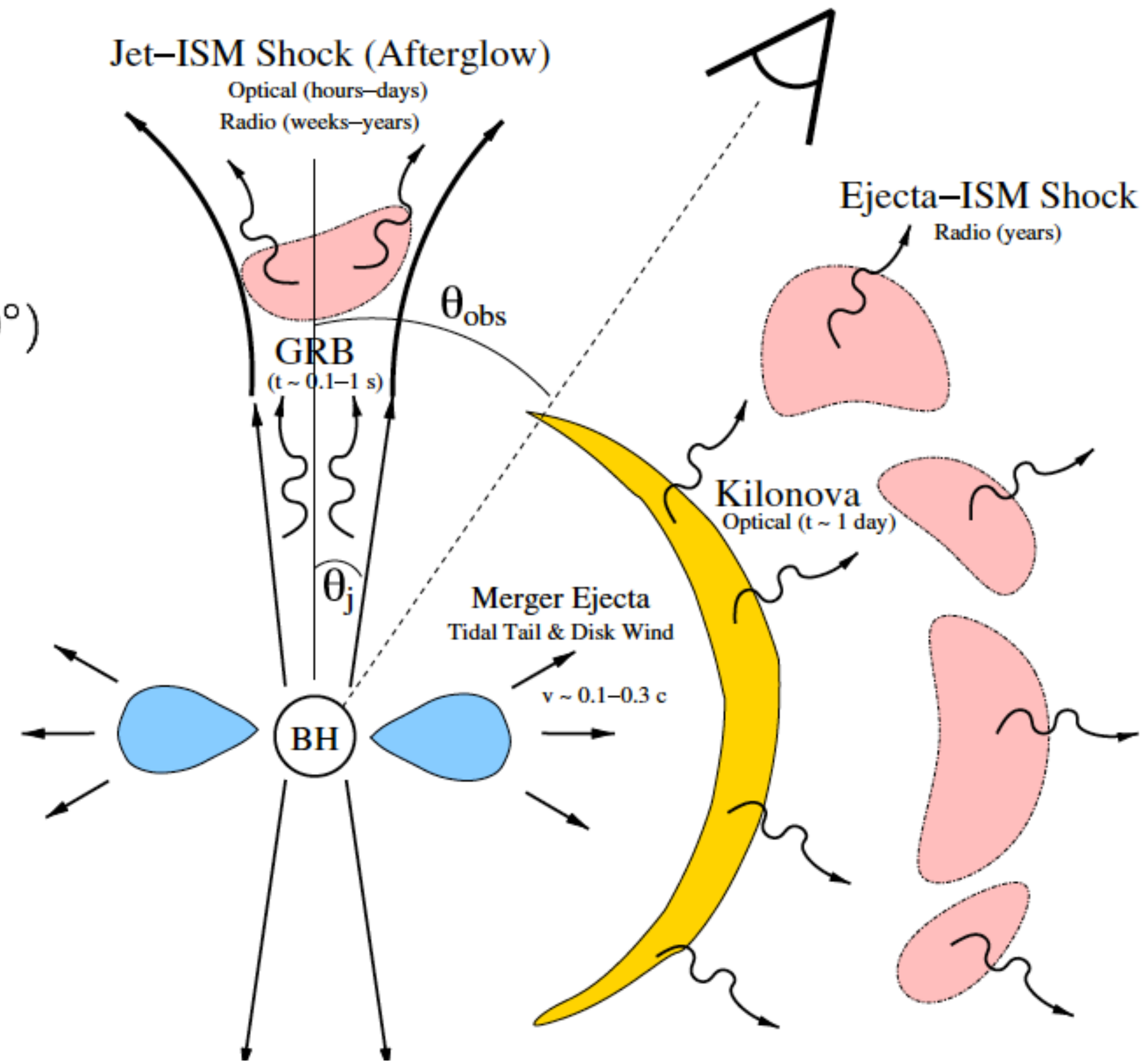
4) **Kilonova**

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

Reviews: Rosswog (2015), Tanaka (2016), Metzger (2016)

5) Late-time radio transient

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



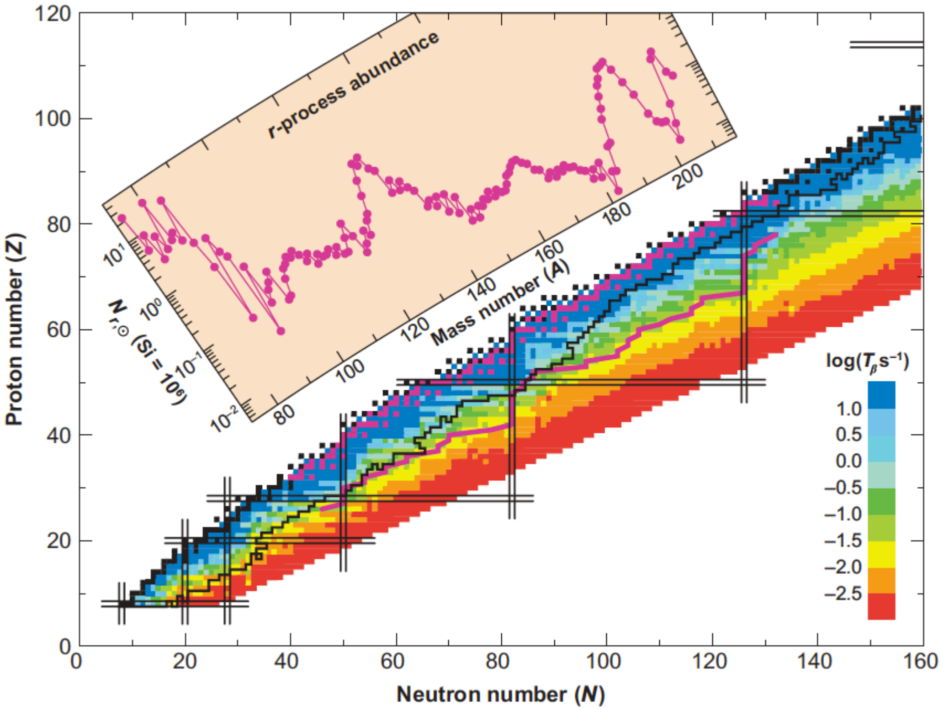
Metzger & Berger (2012)

r-Process Nucleosynthesis

~50% of elements heavier than Zinc (Z=30) require formation by ‘rapid’ neutron capture (r-process)

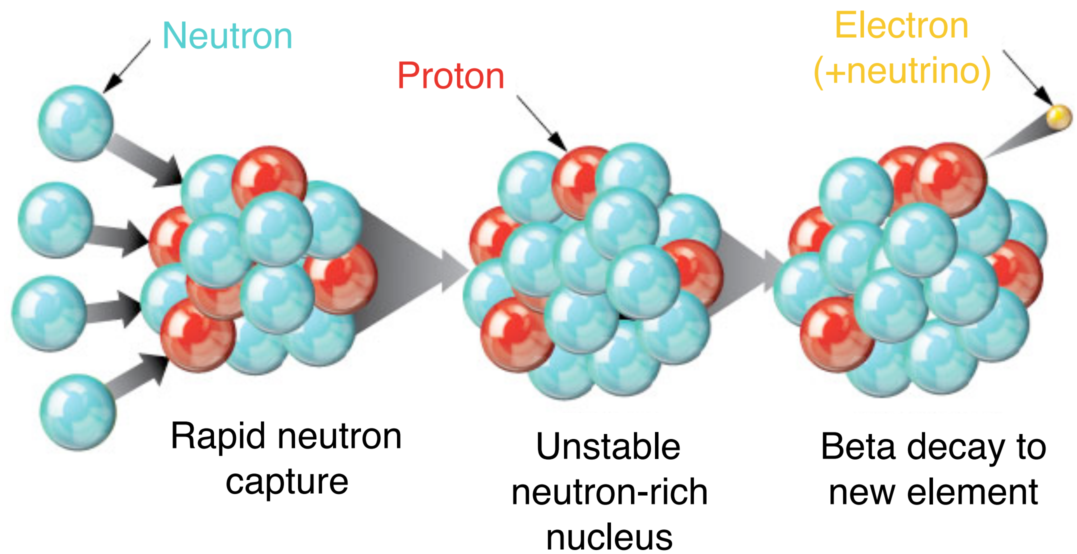
Burbidge et al. (1957), Cameron (1957)

Nuclear Chart & Solar System abundances:



Möller, Nix, & Kratz (1997)

$$t_{\mathrm{n-capture}} \ll t_{\beta-\mathrm{decay}}$$



llnl.gov

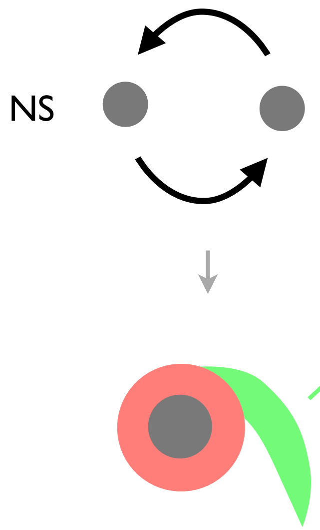
Astrophysical site not determined yet.

Candidate sites:

1) Neutron Star Mergers

2) Core-Collapse Supernovae

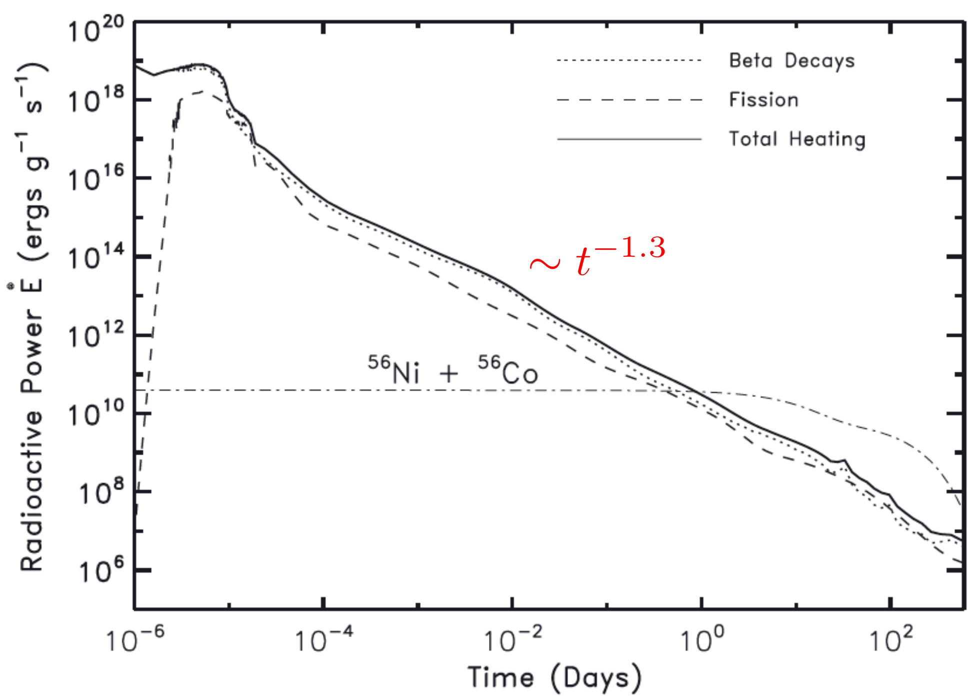
NS mergers: Sub-Relativistic Ejecta



HMNS or BH
+ Disk
+ Dynamical
Ejecta

Merger outcome:

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



Metzger+(2010)

Neutron-rich ejecta undergoes radioactive decay: power-law

Metzger+(2010), Roberts+(2011), Korobkin+ (2012), Tanaka et al. (2014), Grossman+ (2014), Hotokezaka+(2016), Barnes+(2016), Rosswog+(2017)

Kilonova (aka Macronova)

(see also Kulkarni 2005)

Supernova-like transient, but:

1) smaller ejecta mass → 1) shorter duration

2) higher velocity → 2) dimmer

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

(Arnett's rule)

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

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

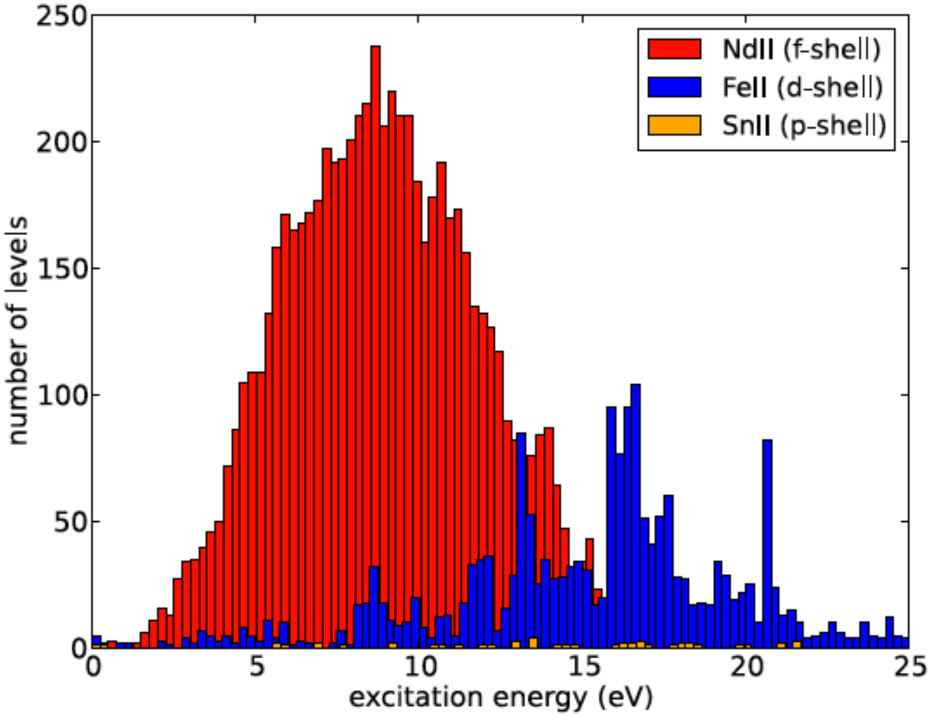
$\kappa \sim 10 - 100\ {\rm cm^2\ g^{-1}}$ (Kasen)

$100 - 10^4\ {\rm cm^2\ g^{-1}}$ (Fontes)

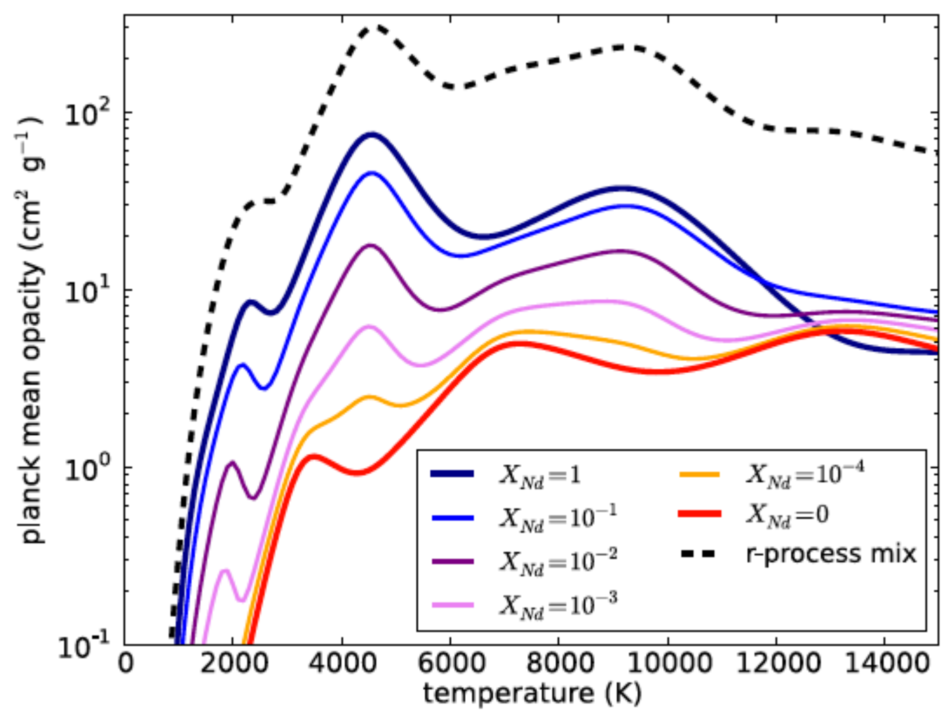
(r-process A > 130)

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:

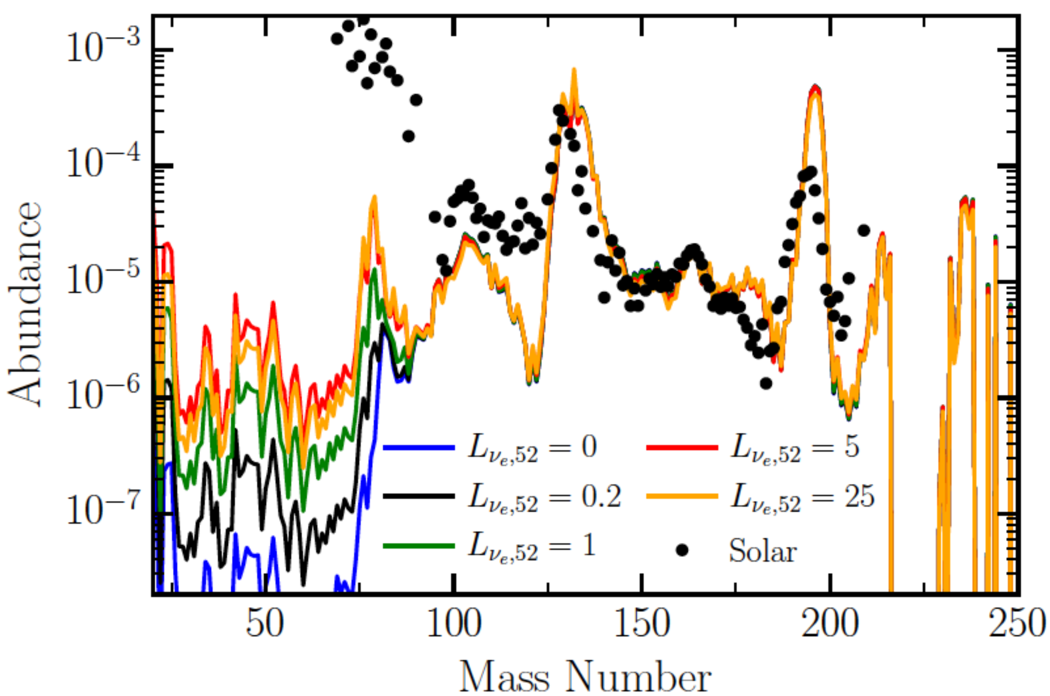
Tanaka & Hotokezaka (2013)

Fontes+ (2015)

Fontes+ (2017)

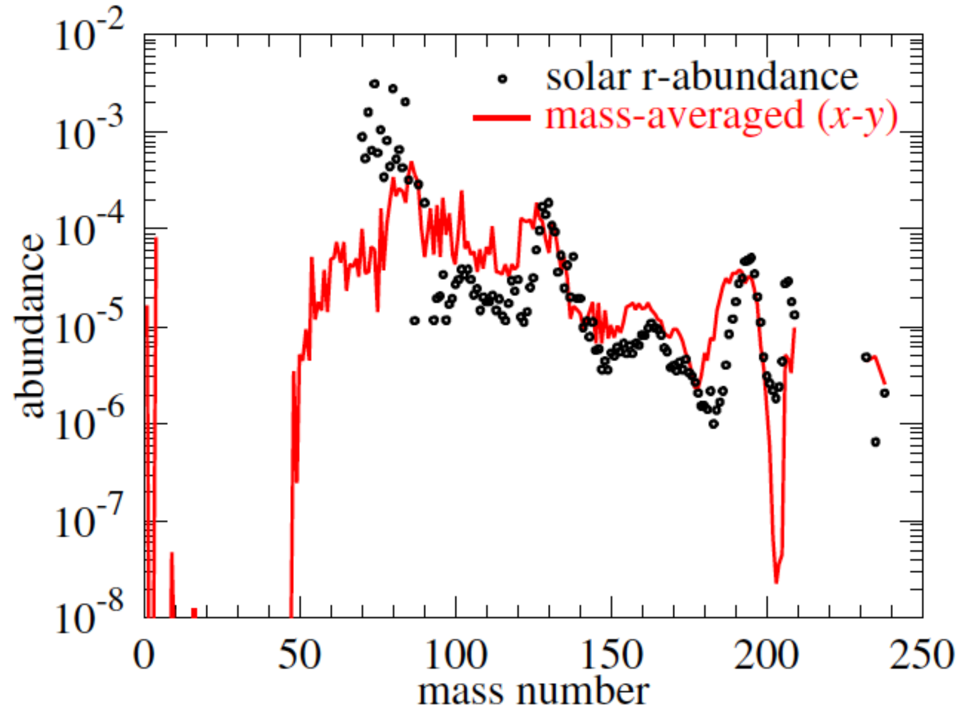
Dynamical Ejecta

Composition dominated by heavy r-process (BH-NS)



Roberts+ (2017)

NS-NS



Wanajo+ (2014)

See also:

Korobkin+ (2012)

Goriely+ (2013)

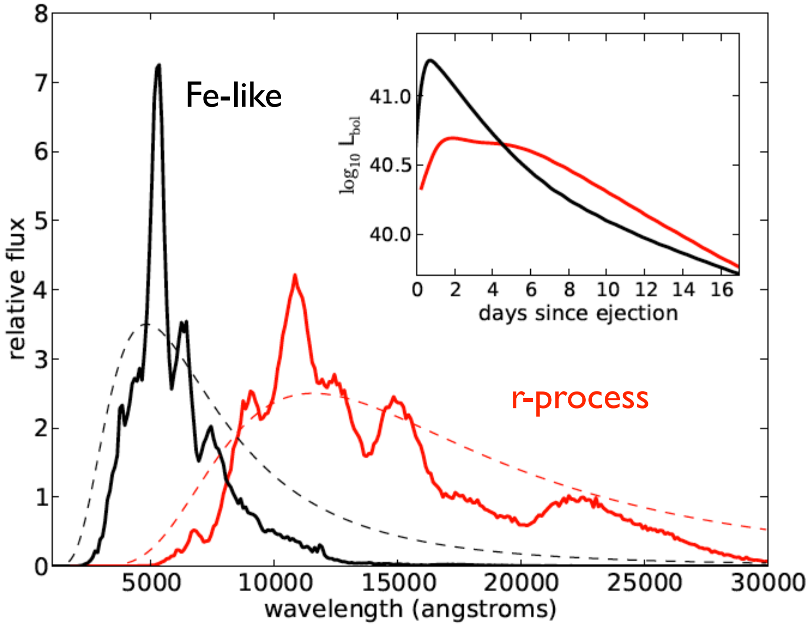
Radice+ (2016)

Bauswein+ (2013)

Sekiguchi+ (2016)

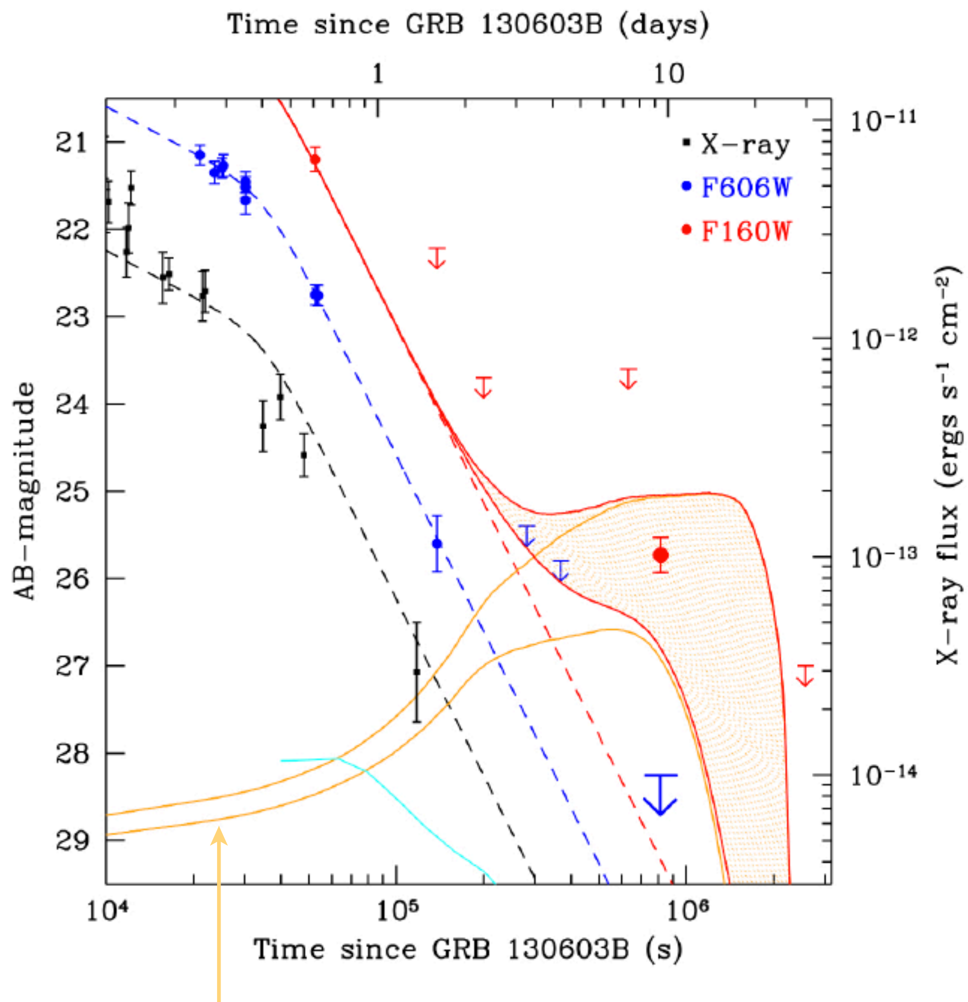
Dynamical Ejecta: r-process kilonova

Theoretical kilonova spectra & light curves:



r-process-dominated material generates IR transient

(large number of lines in optical)

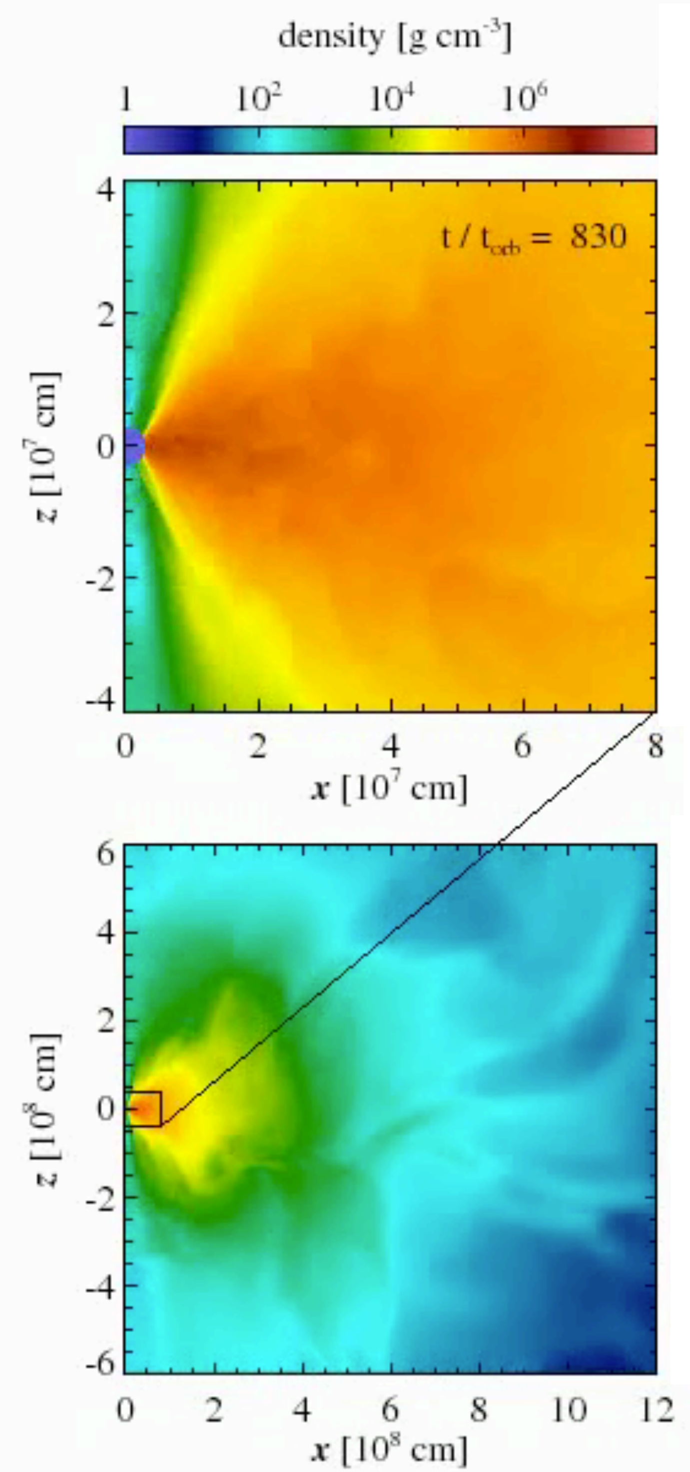


Kilonova models
from Barnes & Kasen (2013)
(dynamical ejecta)

Tanvir+ (2013)

Berger+ (2013)

see also Tanaka & Hotokezaka (2013)



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

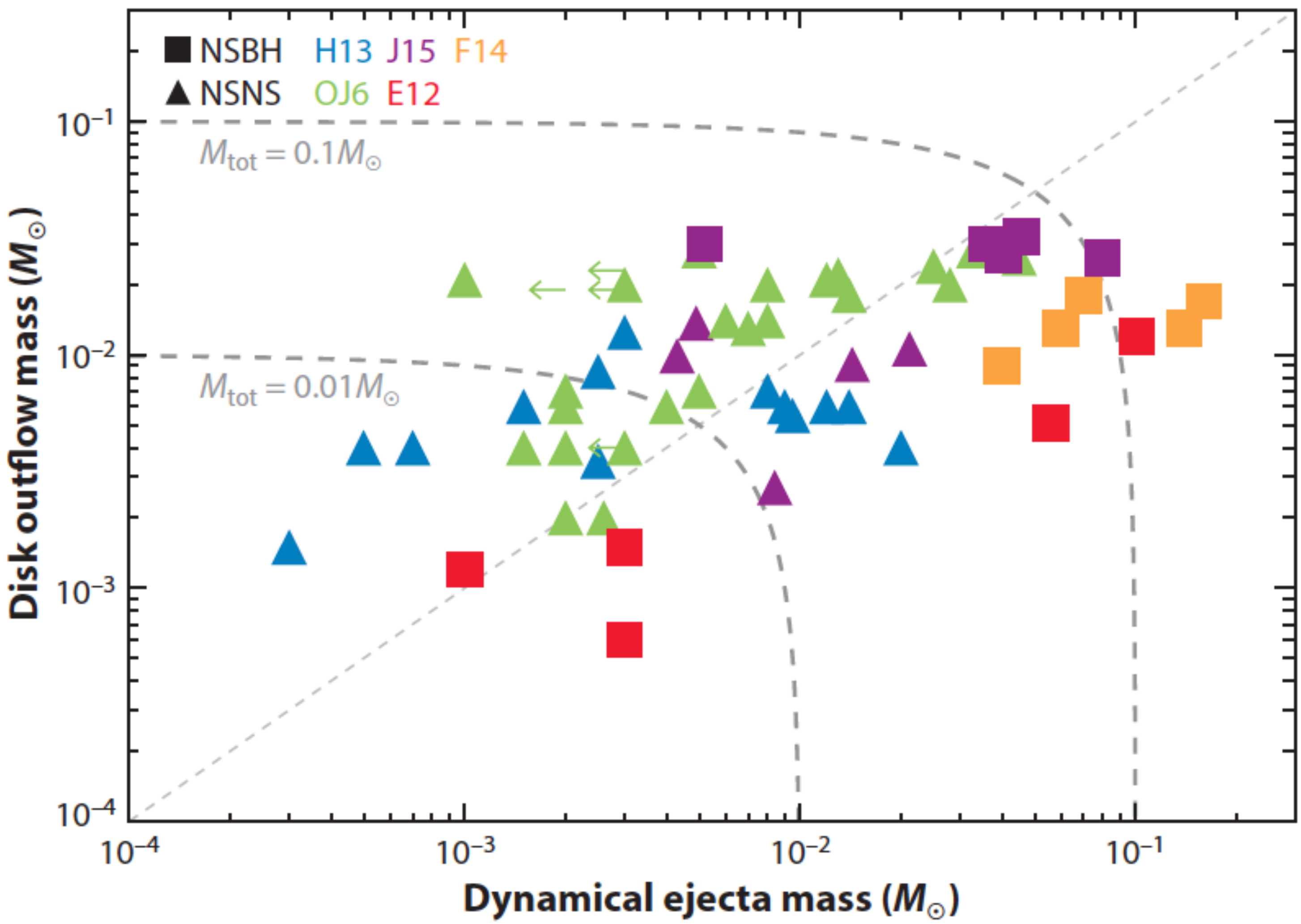
RF et al. (2015), MNRAS

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

Metzger (2009)

Siegel & Metzger (2017), arXiv: 1705.05473 (GRMHD)

Disk wind vs. Dynamical Ejecta



Hotokezaka+ (2013)

Oechslin & Janka (2006)

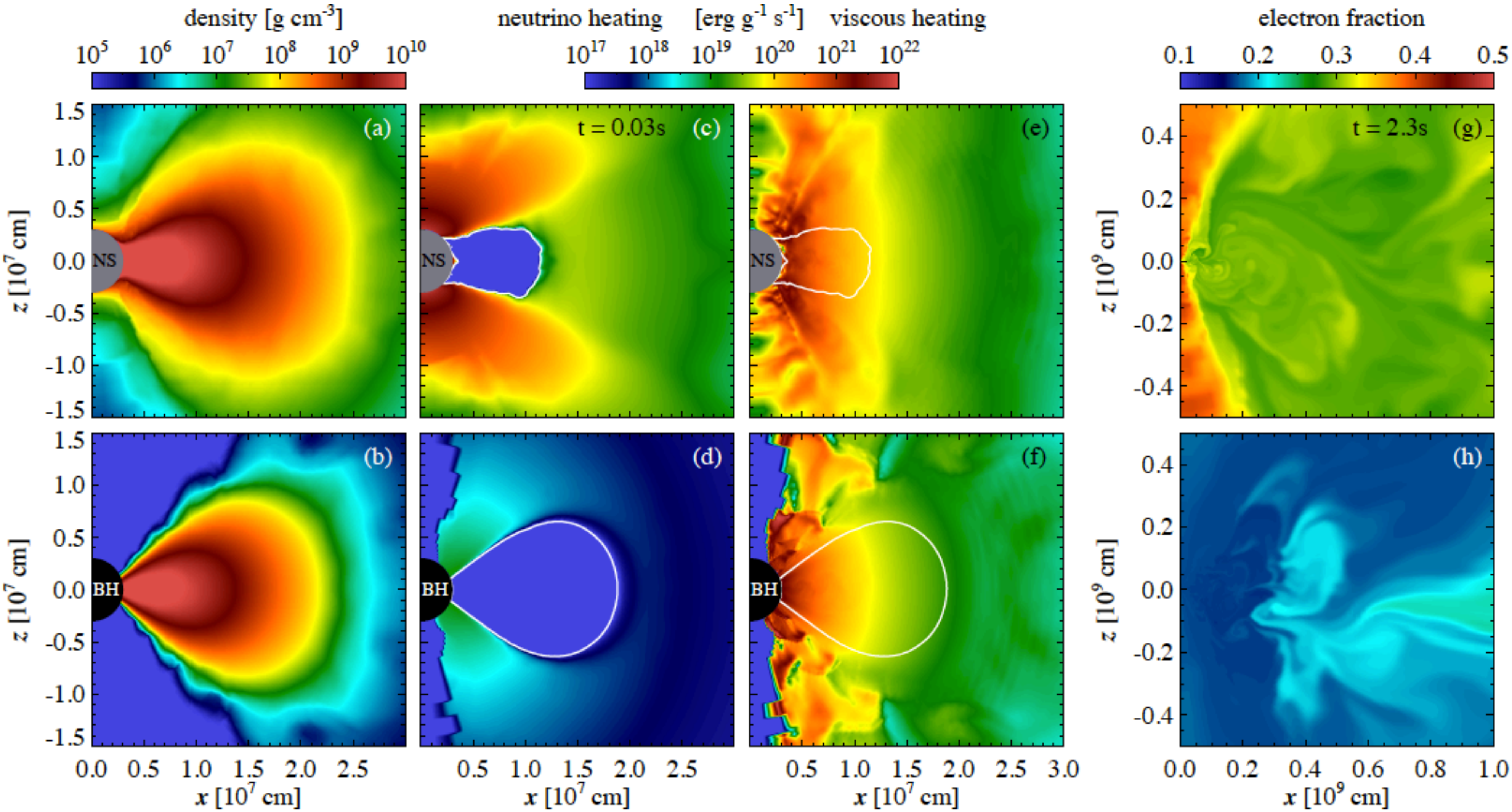
Just+ (2015)

East+ (2012)

Foucart+ (2014)

RF & Metzger (2016)

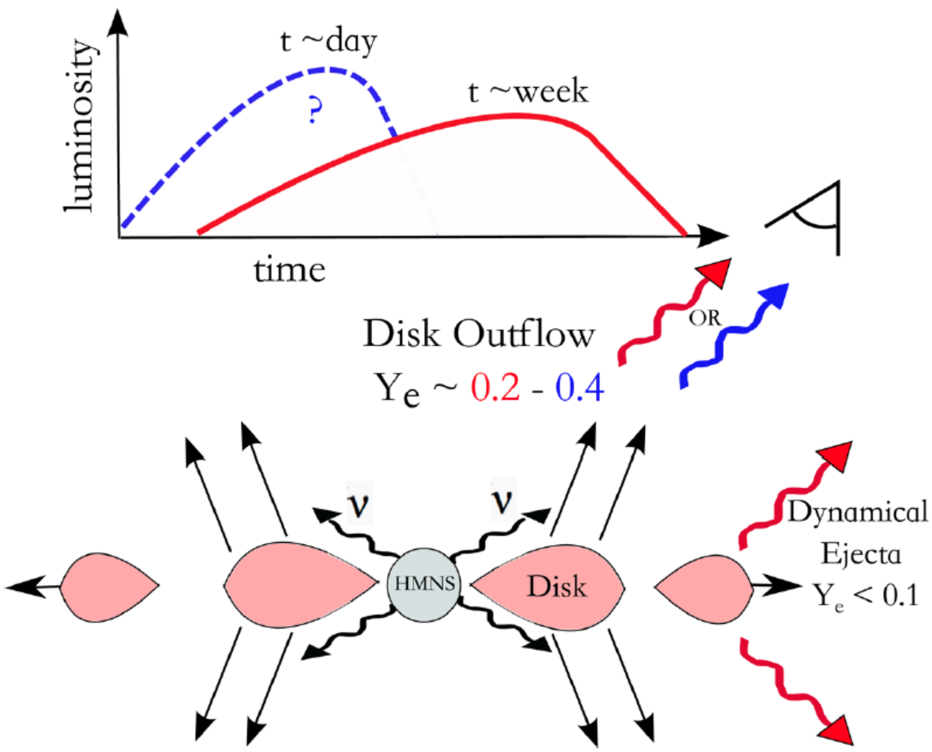
Hypermassive NS versus BH



Metzger & RF (2014)

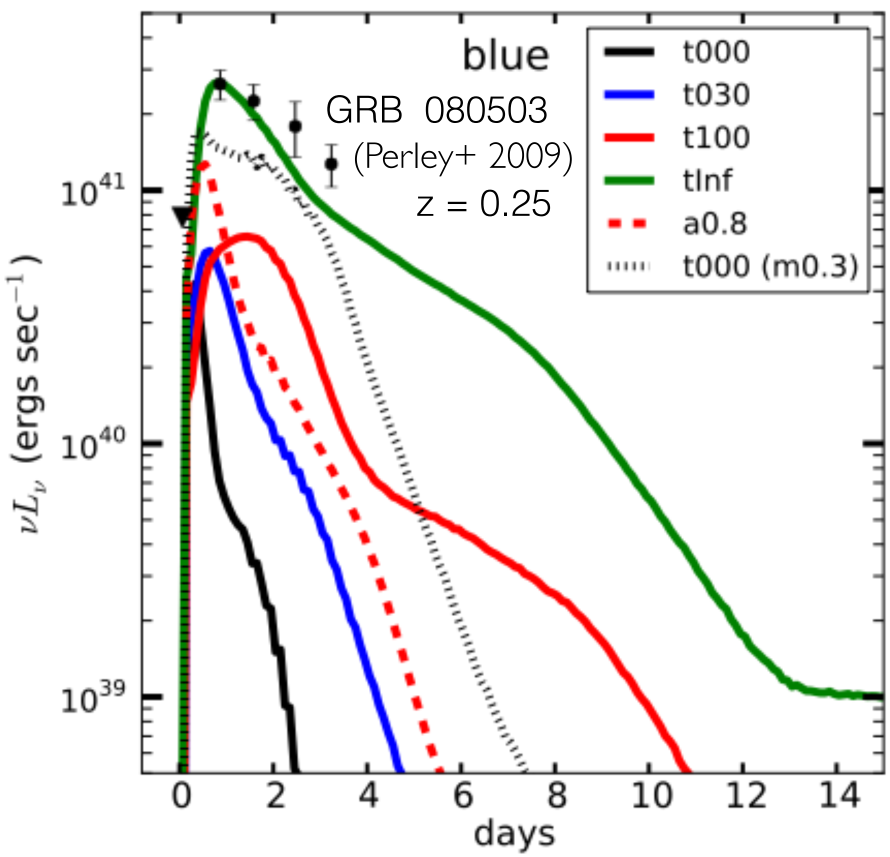
HMNS lifetime and kilonova

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



Metzger & RF (2014)

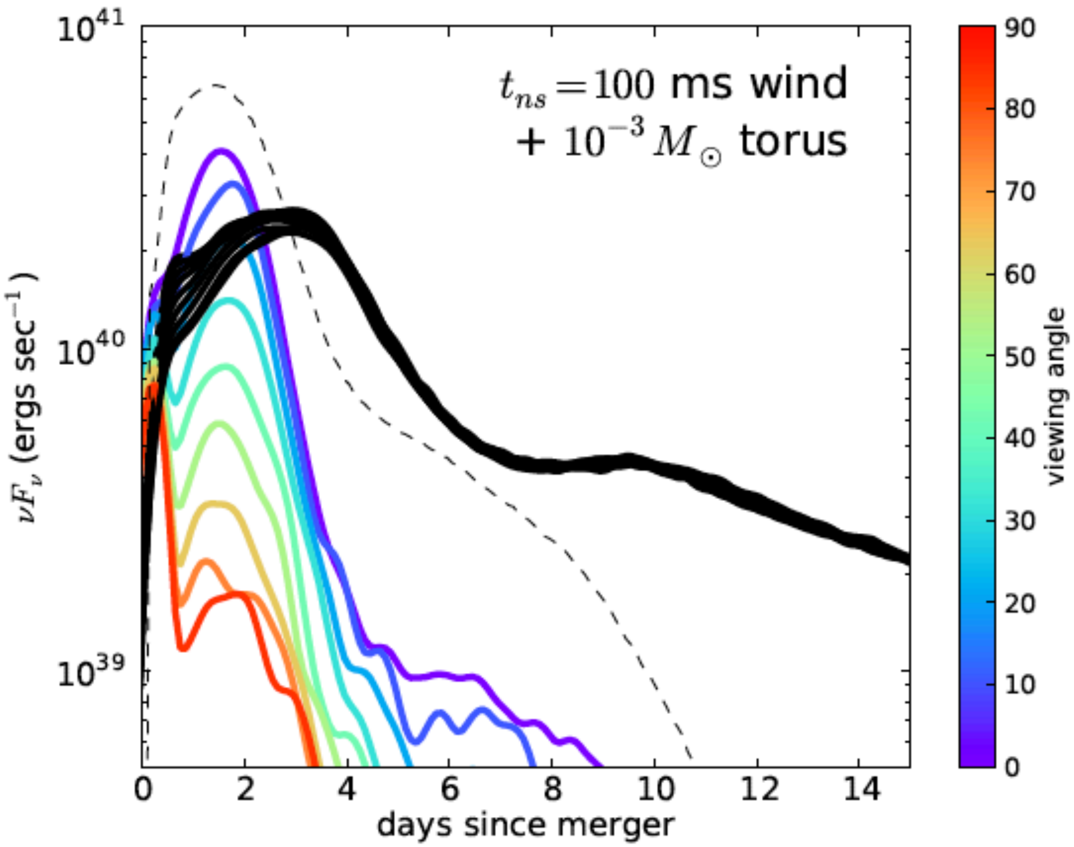
Light curve in 3500-5000 A filter



Kasen, RF, & Metzger (2015)

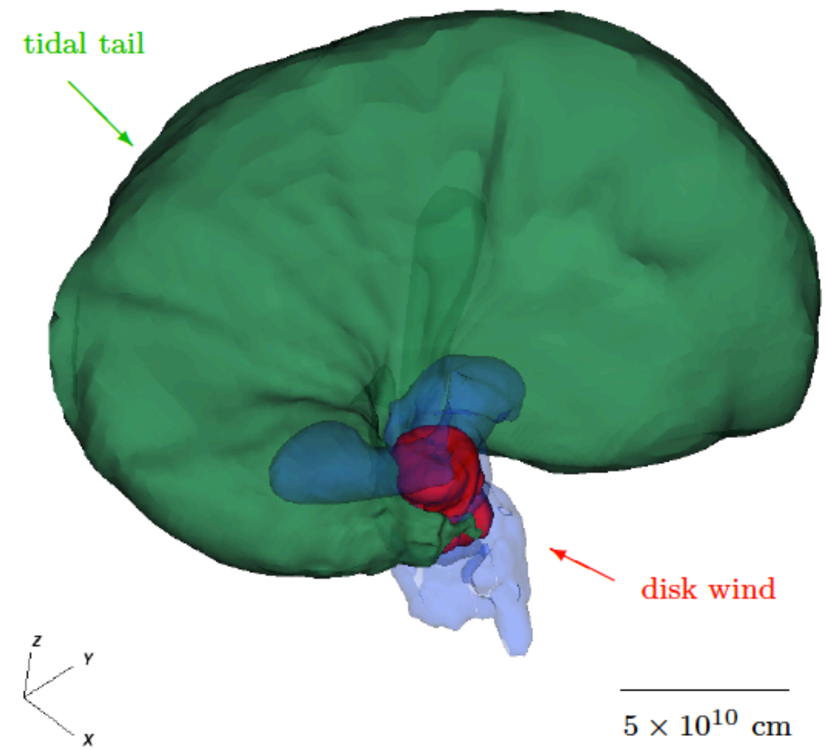
Viewing angle dependence

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



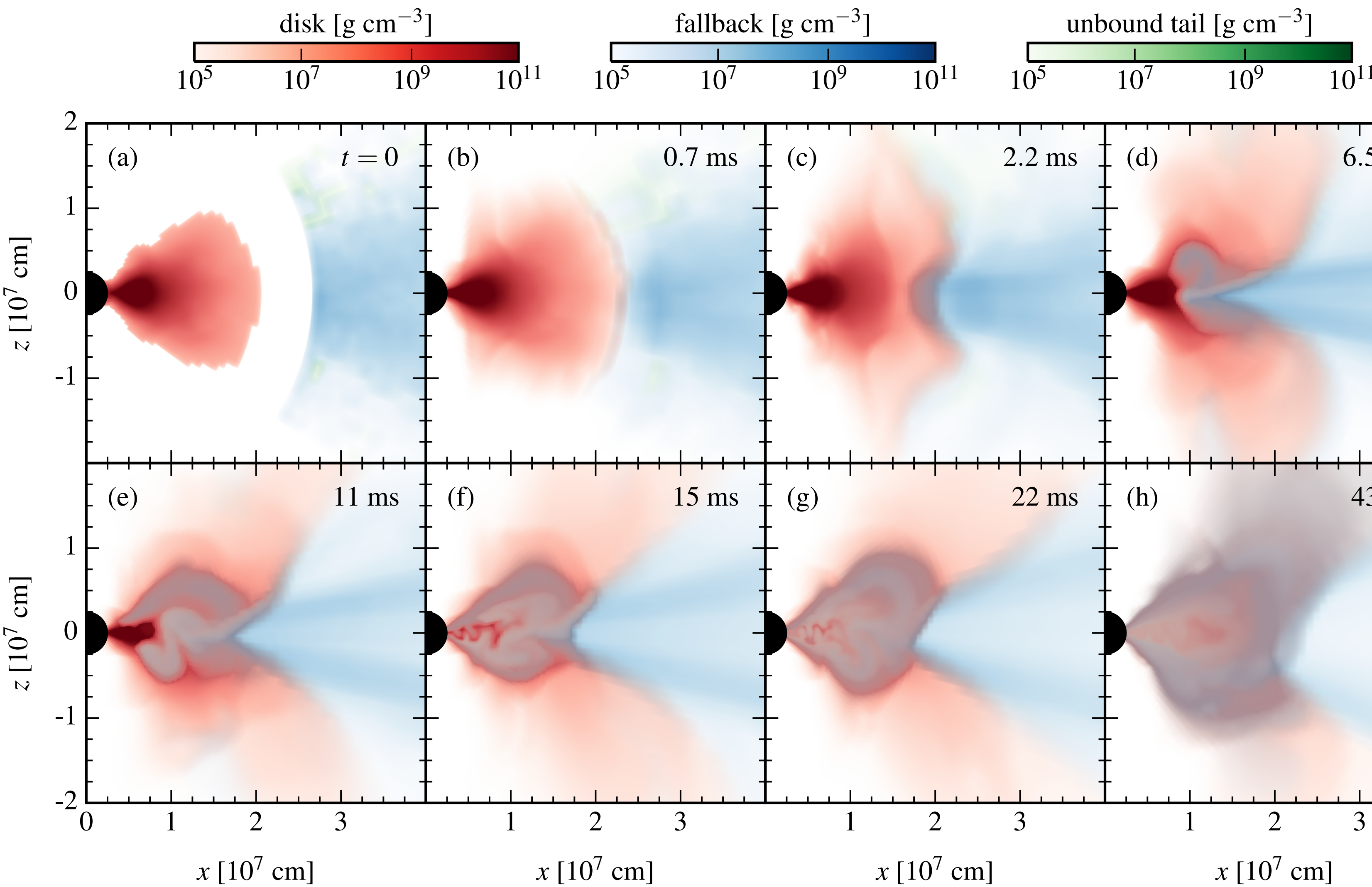
Kasen, RF, & Metzger (2015)

BH-NS merger remnant:



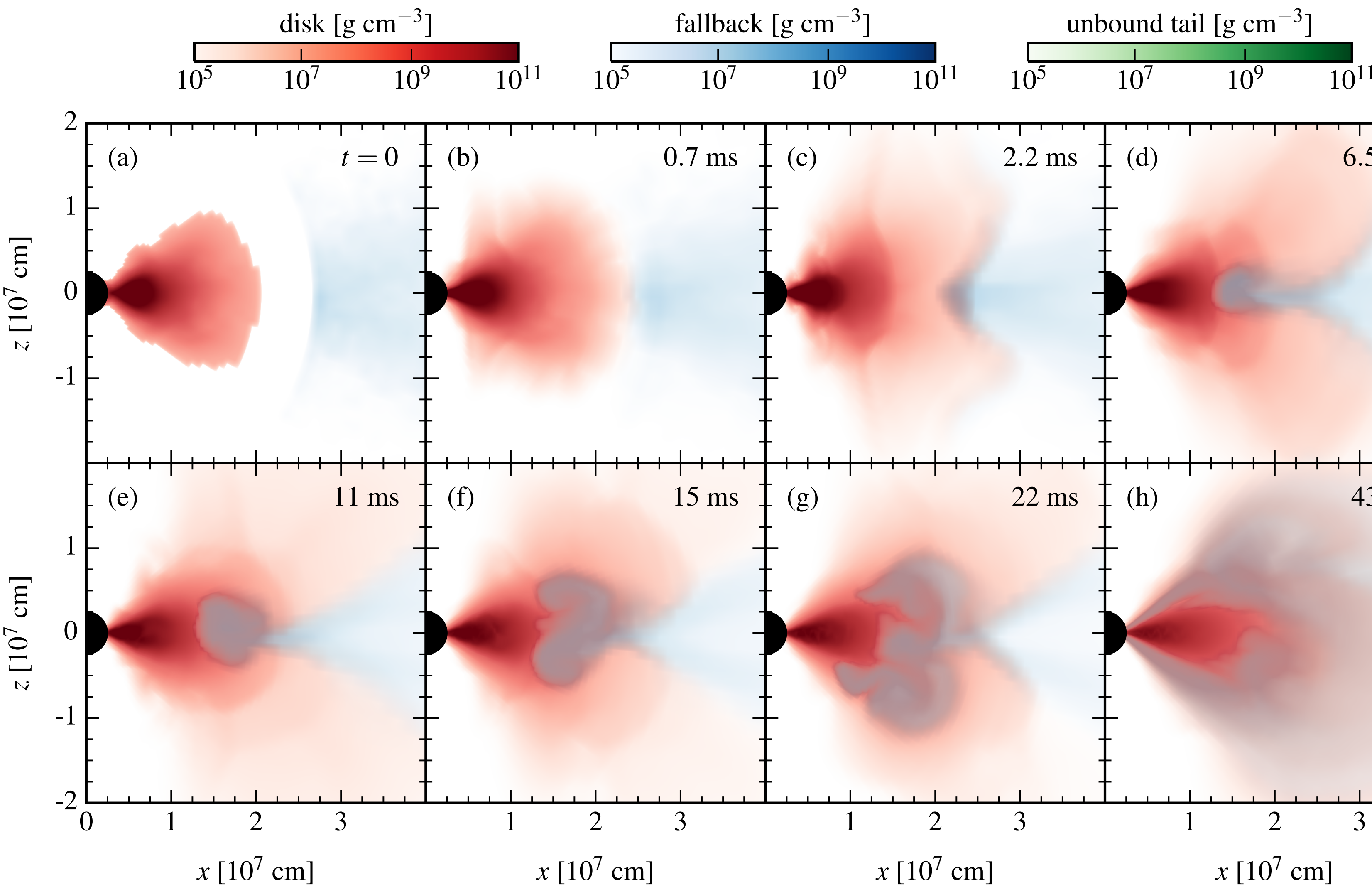
RF, Quataert, Schwab, Kasen & Rosswog (2015)

Interplay of disk wind and dynamical ejecta



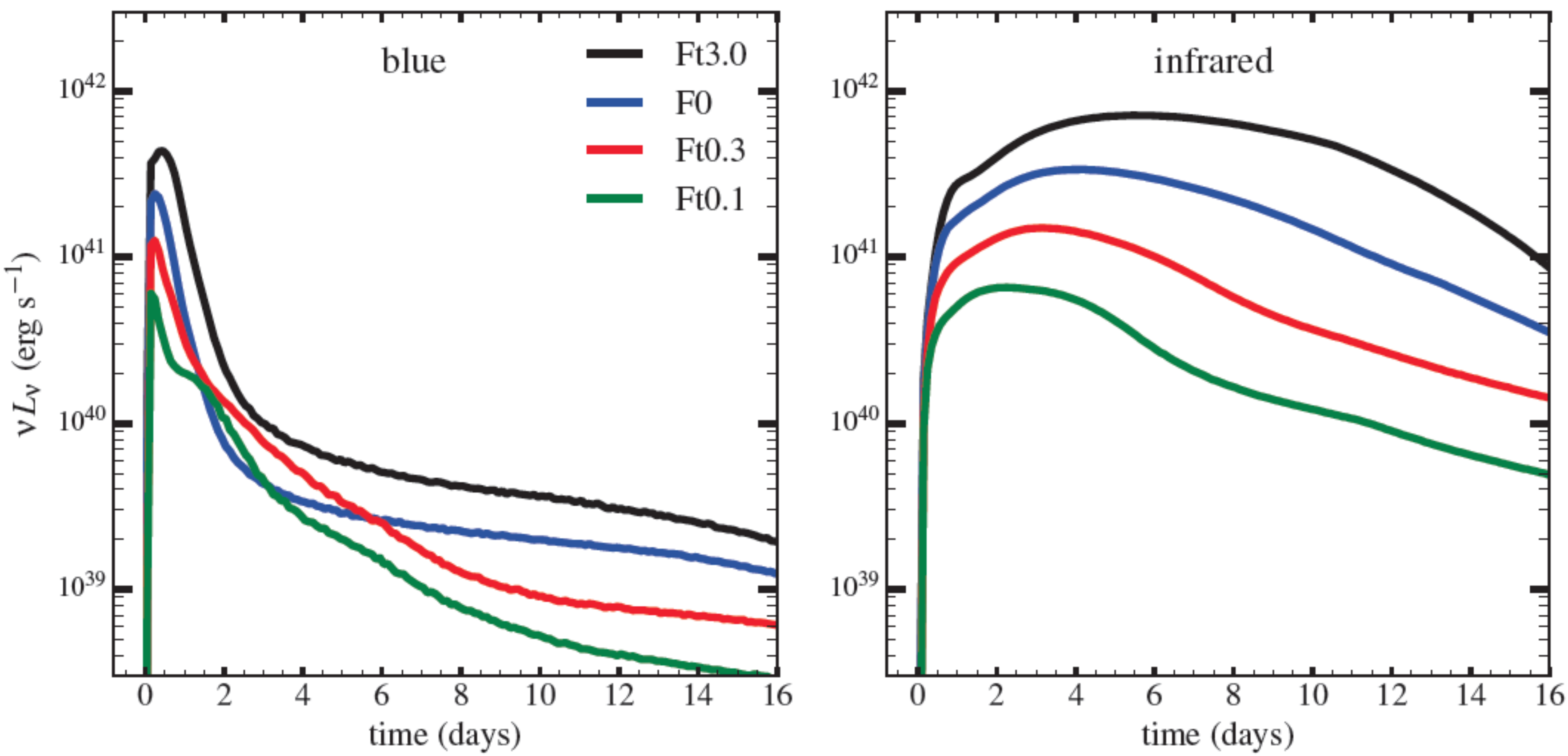
RF, Foucart, Kasen, Lippuner, et al. (2016)

Interplay of disk wind and dynamical ejecta



RF, Foucart, Kasen, Lippuner, et al. (2016)

Early Optical Emission even for Dynamical Ejecta dominated kilo nova



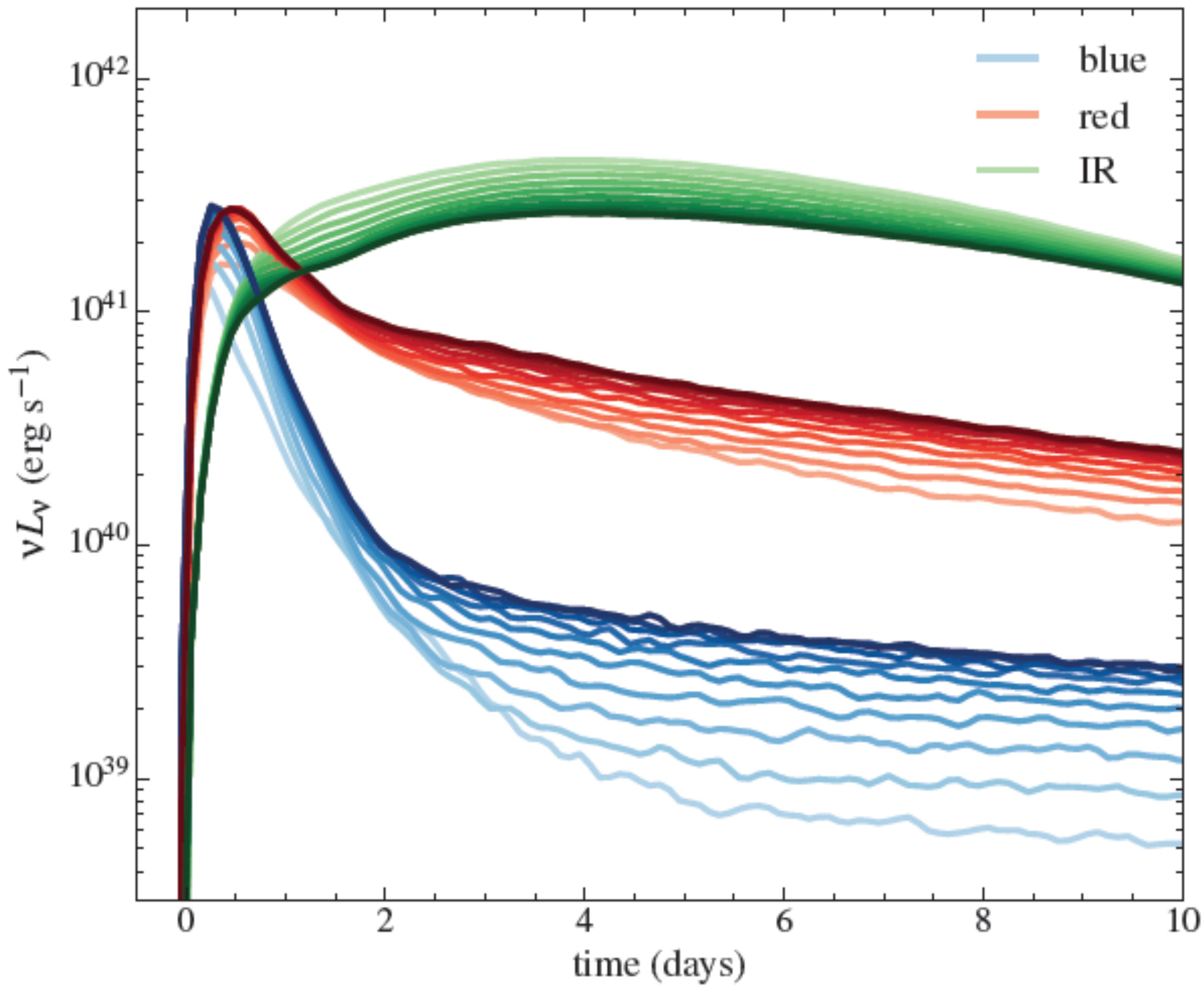
RF, Foucart, Kasen, Lippuner et al. (2016)

effect also discussed in Kasen+ (2013)

See also: Barnes & Kasen (2013) Grossman+ (2014) Wollaeger+ (2017)

Tanaka & Hotokezaka (2013) Rosswog+ (2017)

Effect of viewing angle

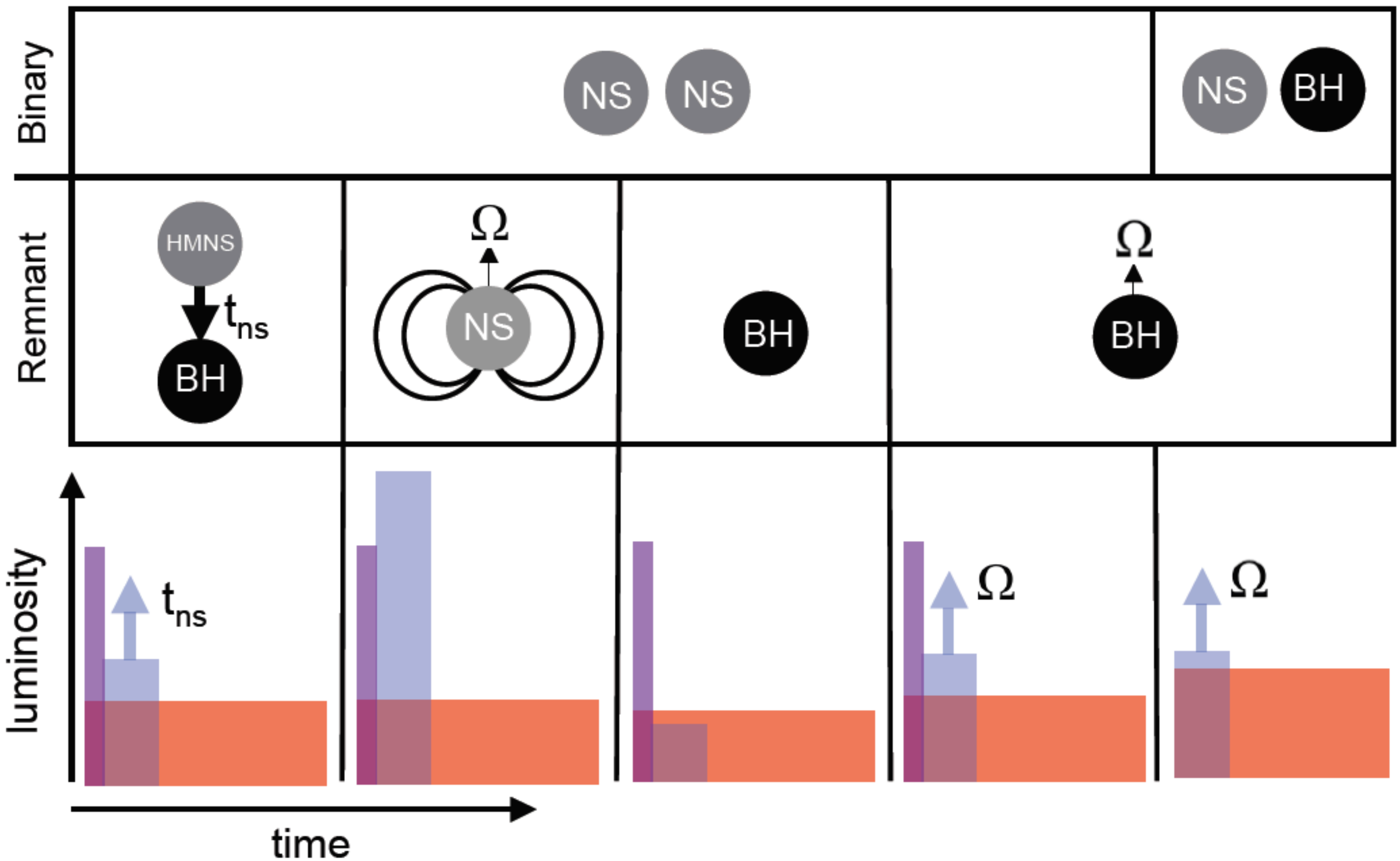


RF, Foucart, Kasen, Lippuner et al. (2016)

Diversity of Outcomes & Transients

(Metzger+ 2015)

UV (n-precursor) optical (disk wind) infrared (disk wind + dynamical)



Kasen, RF, & Metzger (2015)

Future Kilonova Issues (Theory)

1. Optical & IR opacities of r-process elements

2. MHD & neutrino transport in merger/remnant simulations

3. Improved r-process calculations: abundances & opacities

4. Interplay with jet & SGRB

5. Other sources of energy? Kisaka, Ioka, & Nakar (2016)

Summary

1. The Kilonova is the most easily detectable EM counterpart from a NS merger. The transient is powered by the radioactive decay of r-process elements made in the merger ejecta.

2. The optical opacity is very sensitive to the composition of the ejecta, in particular if heavy r-process elements are made: this can make the difference between an optical or infrared transient

3. The dynamical ejecta and the disk outflow contribute to the Kilonova with different compositions. The resulting differences can be used to diagnose the physical conditions in the system.

Thanks to: UNIVERSITY OF ALBERTA NSERC CRSNG NERSC U.S. DEPARTMENT OF ENERGY Office of Science