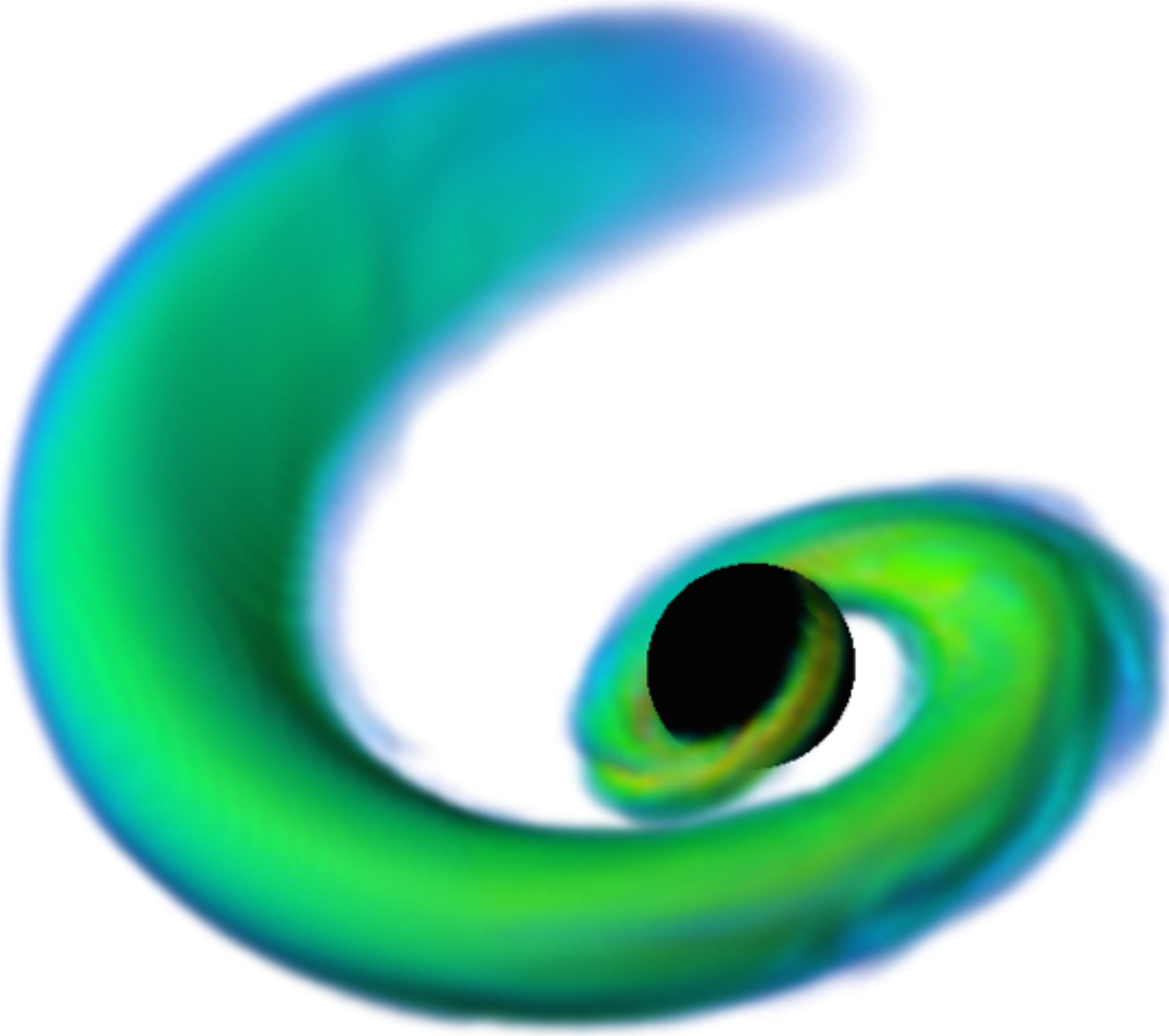
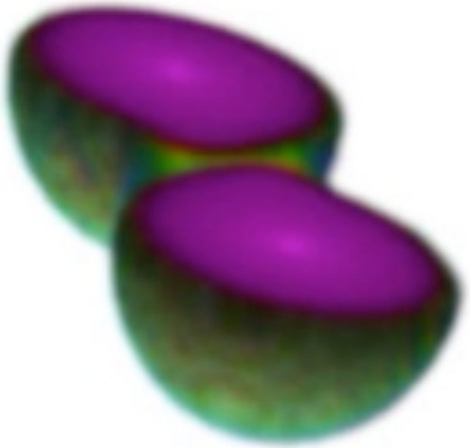
Merging Black Holes and Neutron Stars



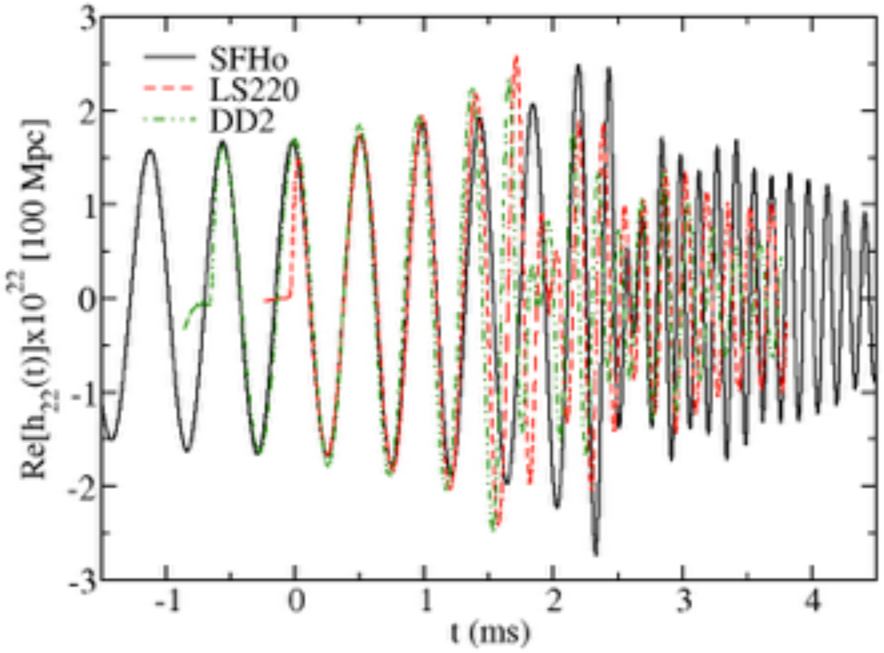
Francois Foucart (LBNL, Einstein Fellow)
SxS Collaboration

KITP, August 5th 2016

Neutron Star Mergers



Gravitational Waves



Short Gamma-ray bursts

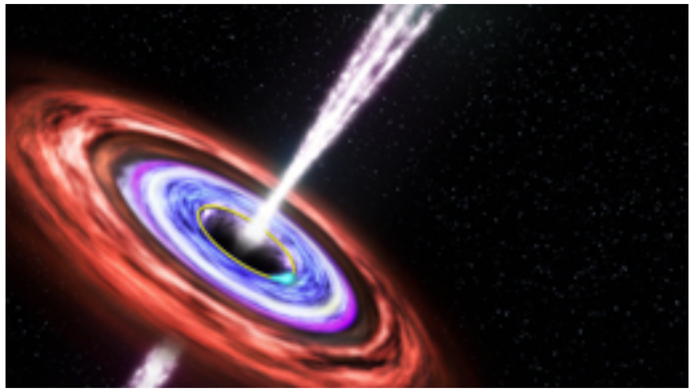


Image: Nasa

r-process / IR transients

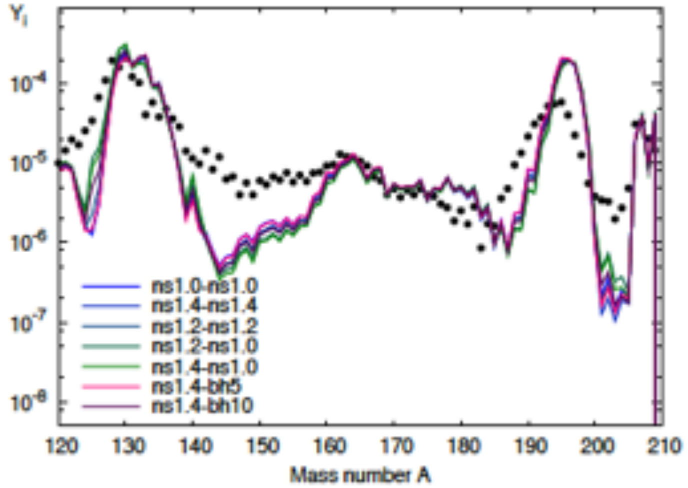
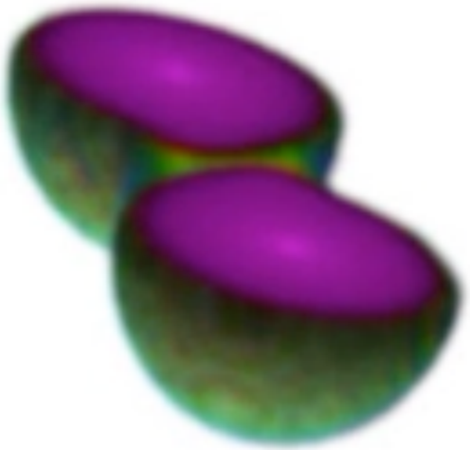
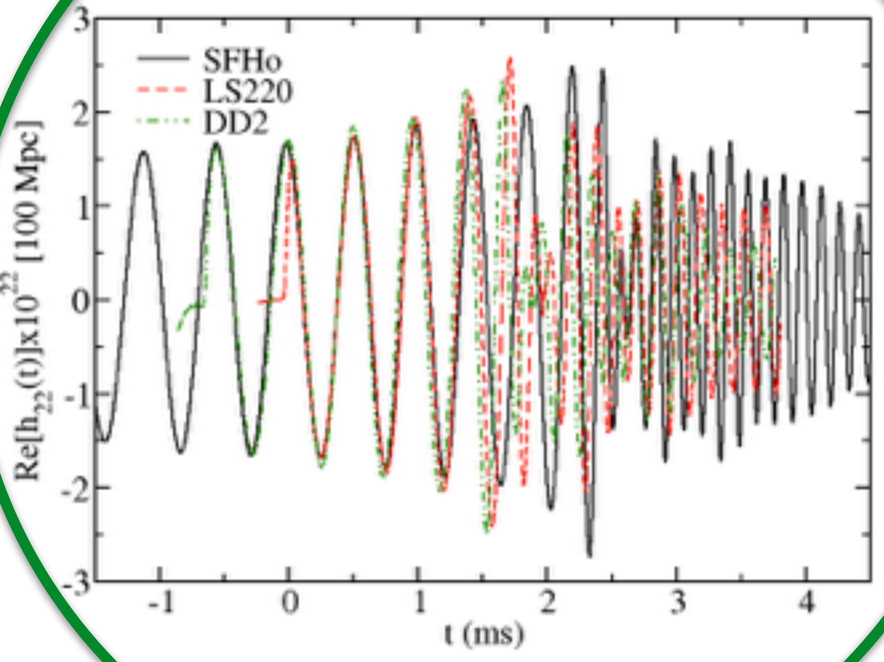


Image: Korobkin et al. 2012

Neutron Star Mergers

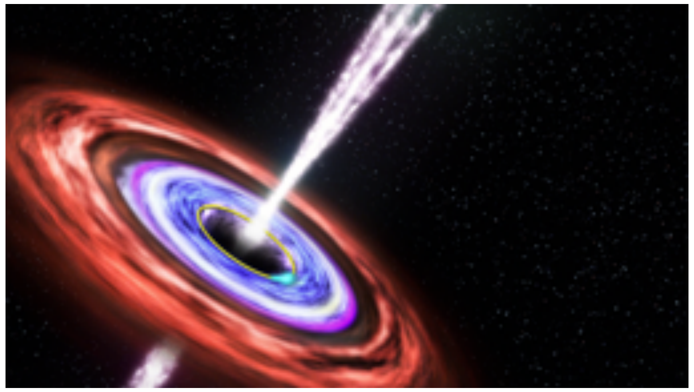


Gravitational Waves



Inspiral &
Post-Merger Signal

Short Gamma-ray bursts



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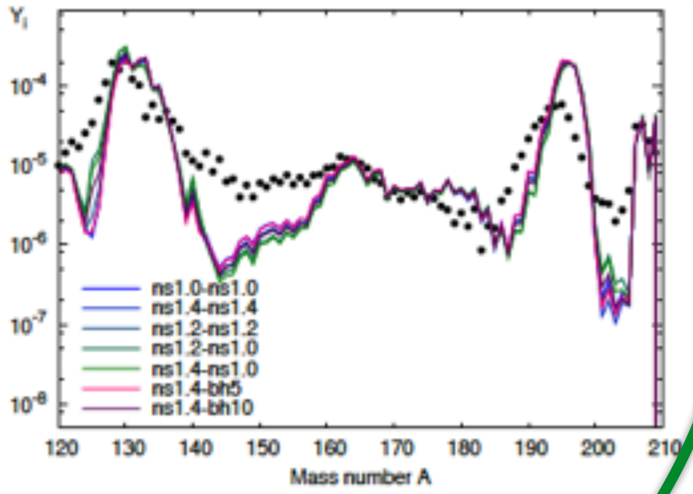


Image: Korobkin et al. 2012

r-process /
kilonovae

Qualitative Merger Results

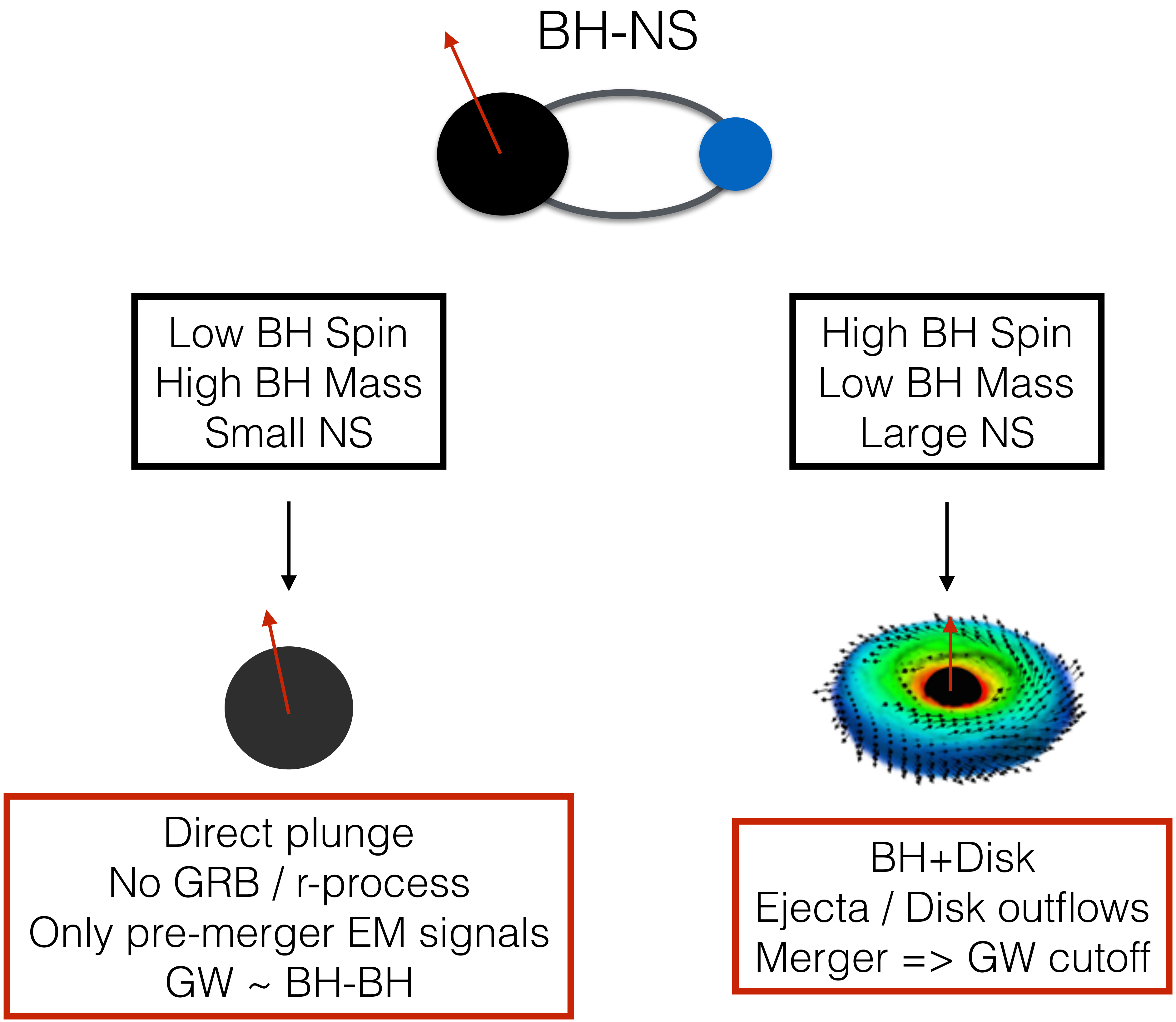
Merger outcome : BH-NS binaries

Simulations from Foucart et al. 2013; Hinderer, ..FF et al. 2016

Merger outcome : BH-NS binaries

Simulations from Foucart et al. 2013; Hinderer, ..FF et al. 2016

Merger Outcomes



BH-NS

Low BH Spin
High BH Mass
Small NS

Direct plunge
No GRB / r-process
Only pre-merger EM signals
GW ~ BH-BH

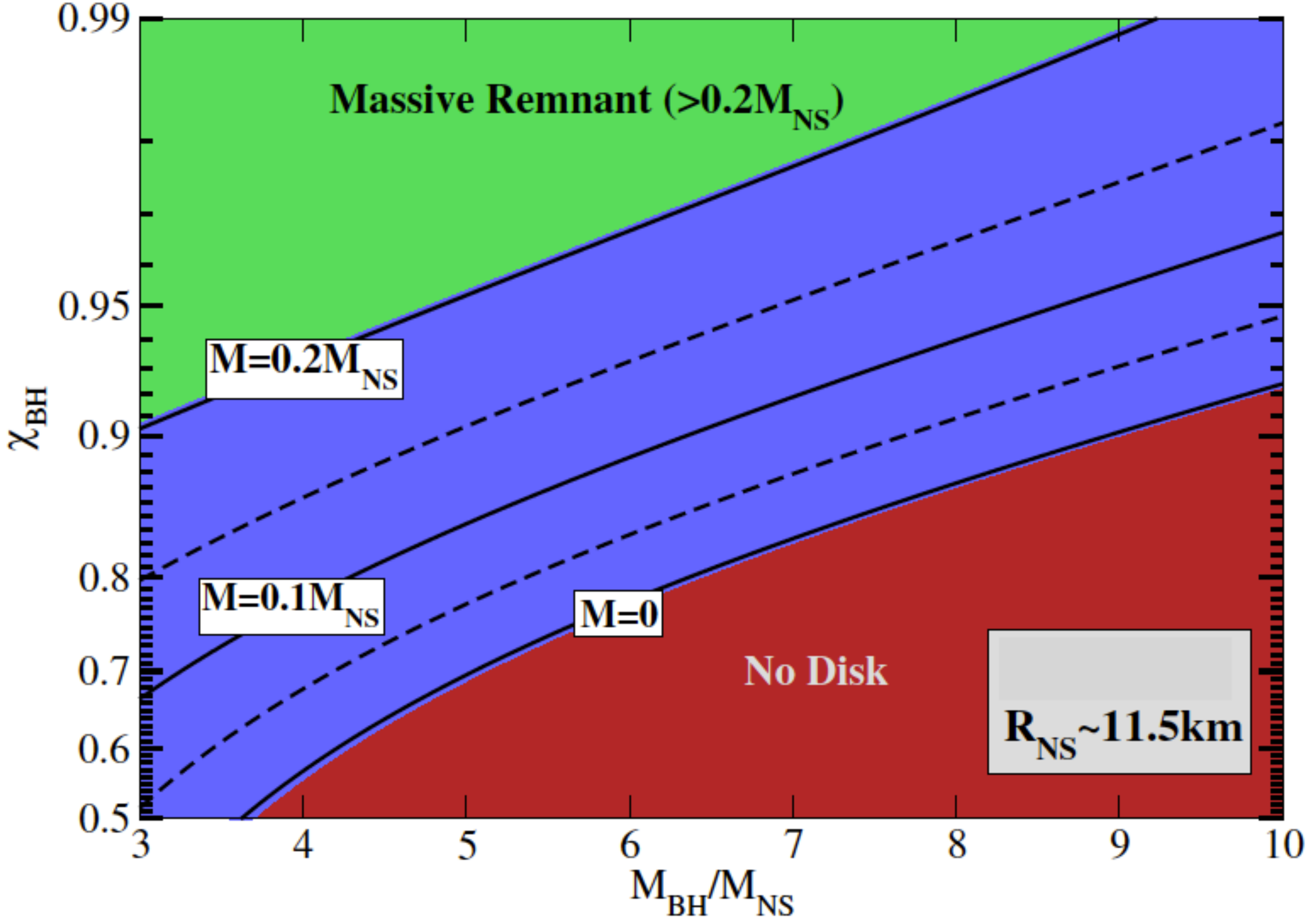
High BH Spin
Low BH Mass
Large NS

BH+Disk
Ejecta / Disk outflows
Merger => GW cutoff

Merger outcome : BH-NS binaries

BH-NS “Disruption Line”

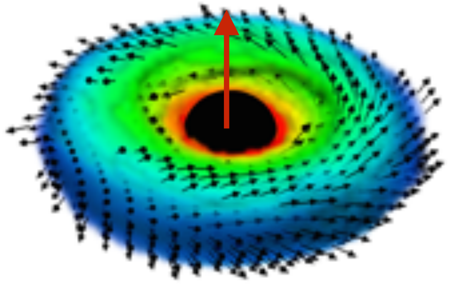
Foucart 2012



Merger Outcomes

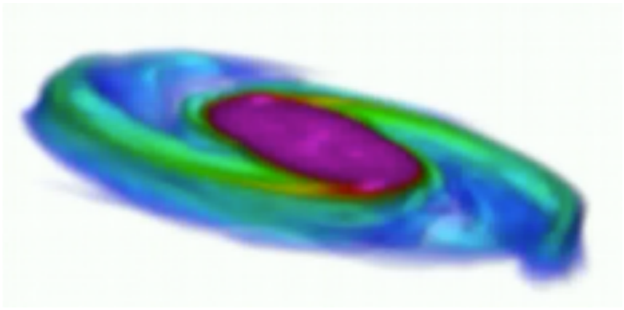
NS-NS

High Mass Binary



BH+Disk
Ejecta / Disk outflows
Merger => GW cutoff

Low Mass Binary



NS+Disk
Ejecta / Disk outflows
Post-merger GW signal

Gravitational Waves

Nuclear physics and the neutron star equation of state

Equation of state
(Mass-radius)

→

Nuclear Physics
Constraints

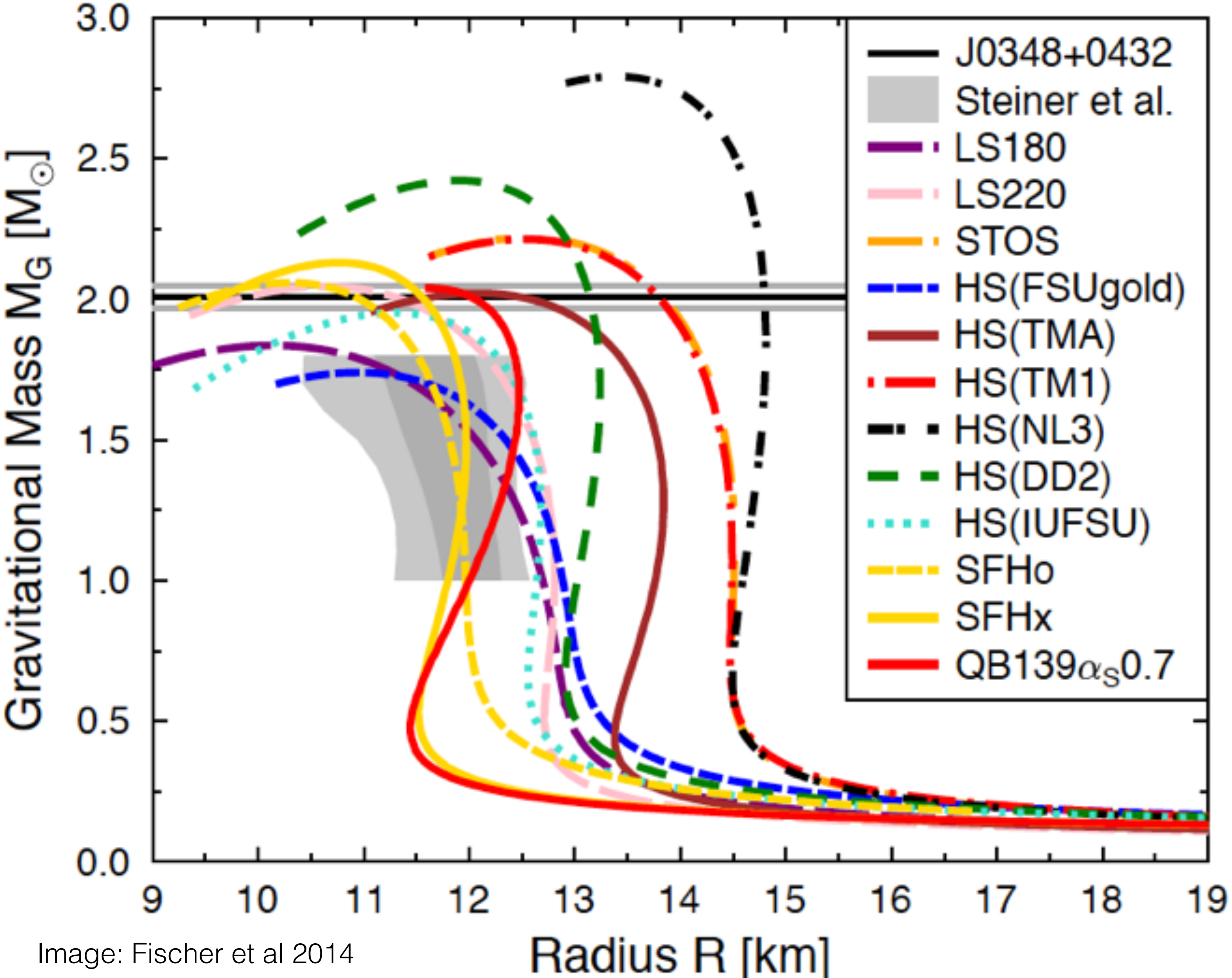


Image: Fischer et al 2014

Equation of State measurements with LIGO

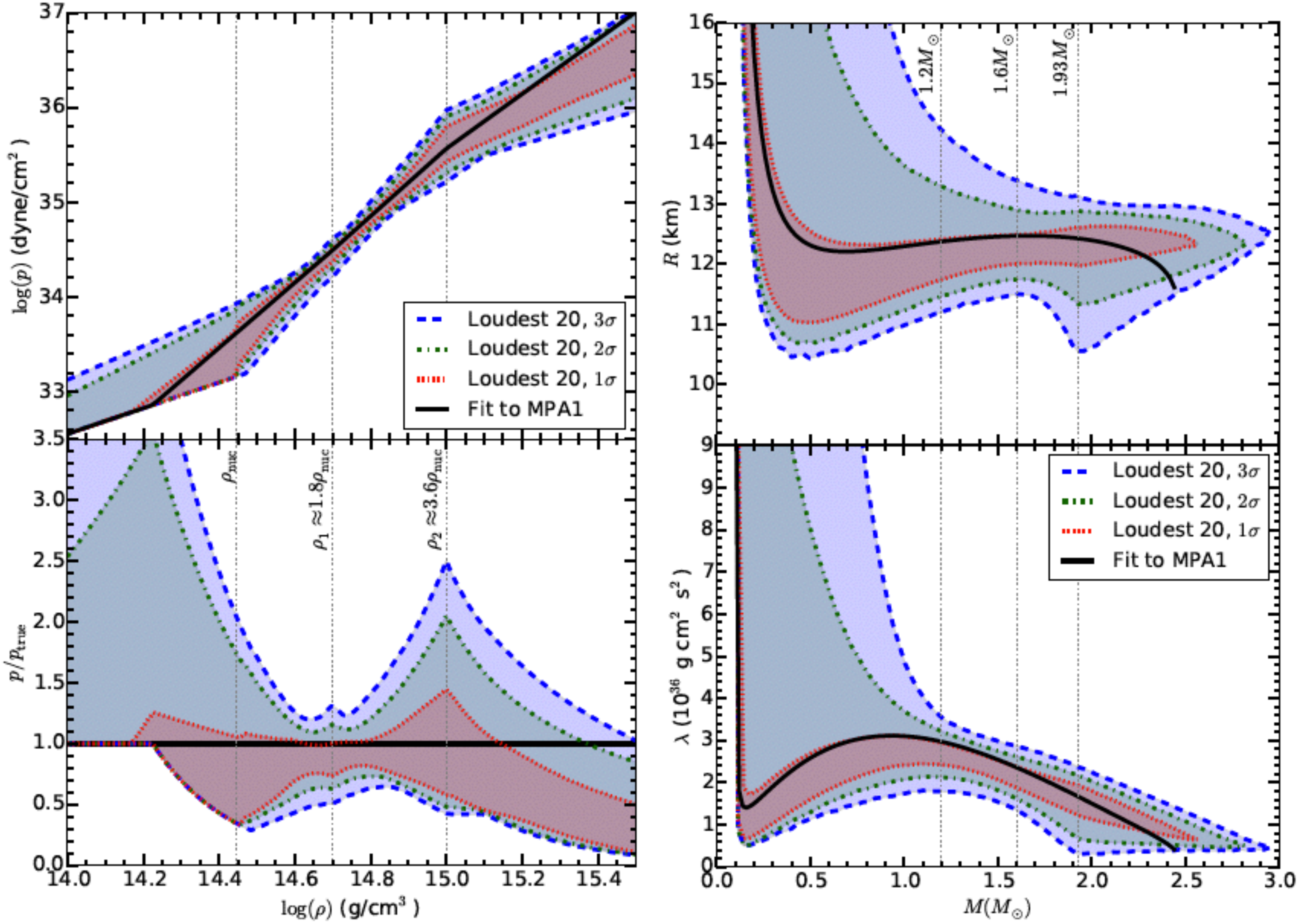
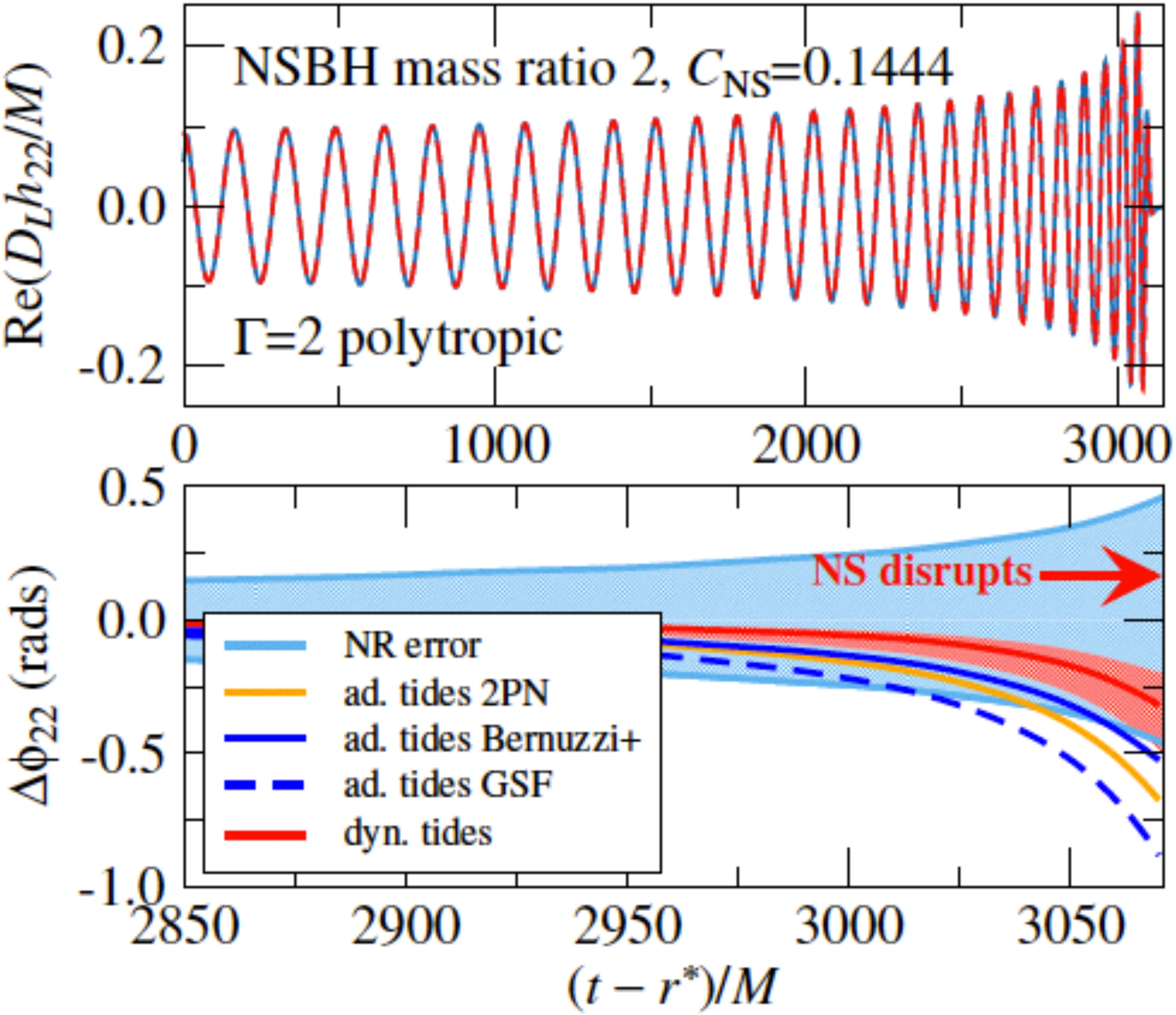


Image: Lackey & Wade 2015, see also Del'Pozzo et al. 2013

Gravitational wave modeling : Inspiral

Image: T. Hinderer, …, FF et al. (2016)



Theory: Could measure radii to <1km

Issue: Need very accurate templates. Simulations required to reliably measure NS radius!

Status: Significant progress, but simulations & models still need to improve!

See also Bernuzzi et al 2015

Finite size effects: ~ 2 rad for this system

Gravitational waves : Merger and Post-Merger

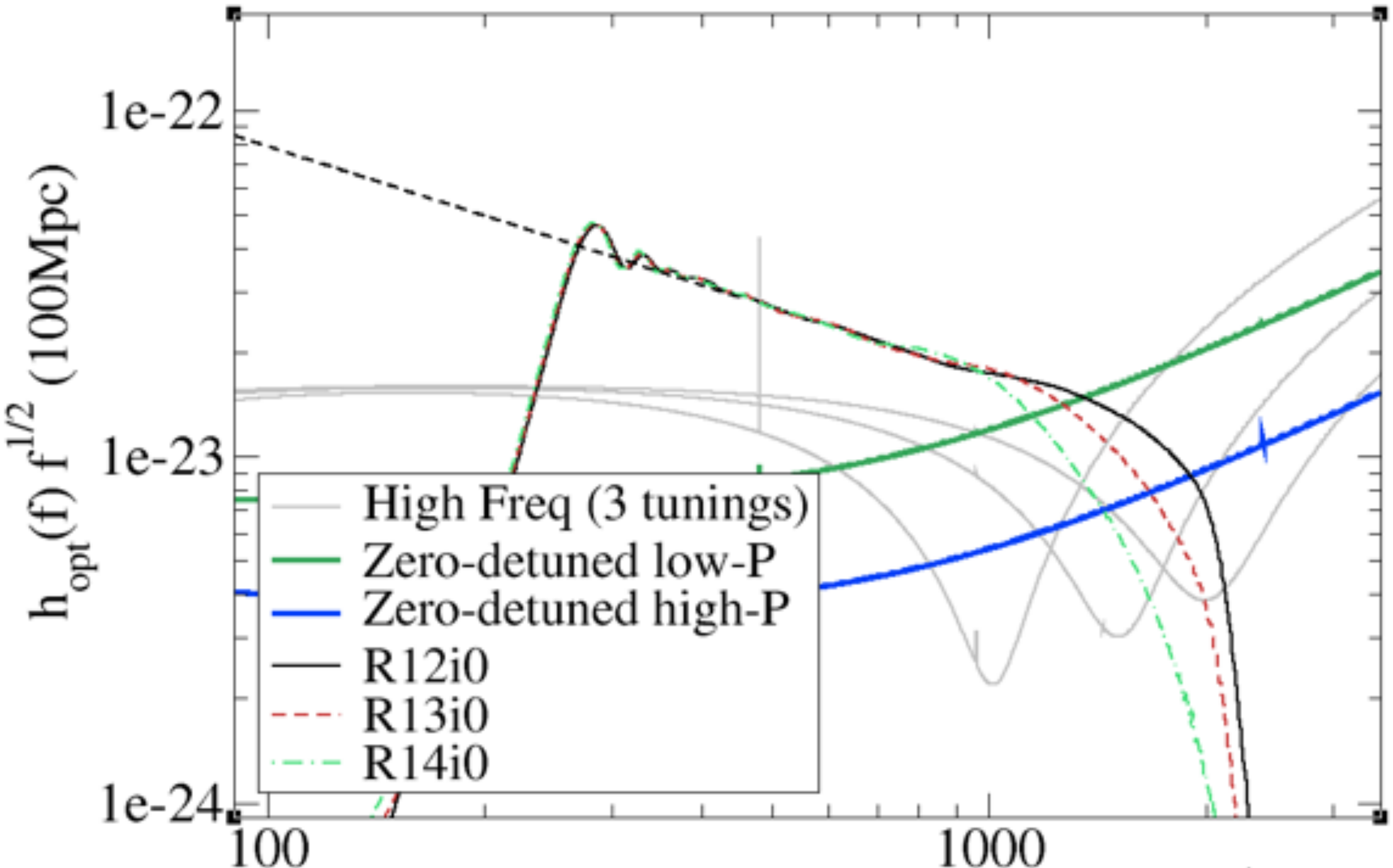


Image: Foucart et al. 2013

$$f_{\text{disrupt}} \sim f^{\text{surf}}_{\text{Kepler}} \sim 1.6\,\text{kHz} \left(\frac{M_{\text{NS}}}{1.4 M_\odot}\right)^{1/2} \left(\frac{R_{\text{NS}}}{12\,\text{km}}\right)^{-3/2}$$

Prediction:

Disruption at EoS-dependent frequency

Ringdown / QNM for weak/no disruption

Practically:

Disruption very difficult to detect

See also Lackey et al. 2012/2013, Kyuotoku et al. 2010/2012/2013, Pannarale et al. 2013

Gravitational waves : Merger and Post-Merger

Prediction:

NS-NS : Clear peaks in post-merger spectrum

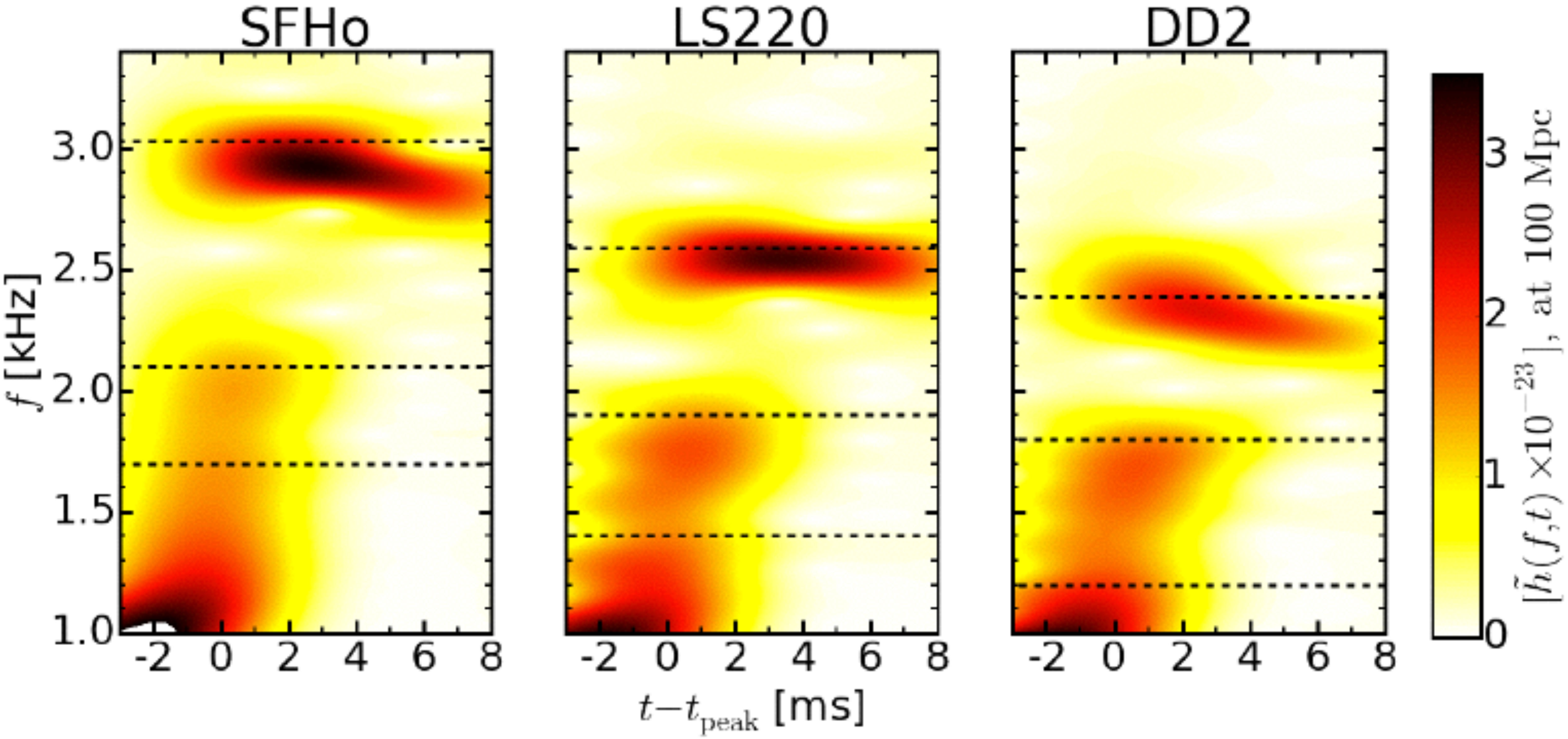
Practically:

Low systematic errors, Low SNR

See also Bauswein & Stergoulias 2015, Takami et al. 2015, Bernuzzi et al. 2015, Lehner et al. 2016

Gravitational waves : Merger and Post-Merger

Image: Foucart et al., 2016.



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Ejecta & r-process

r-process nucleosynthesis

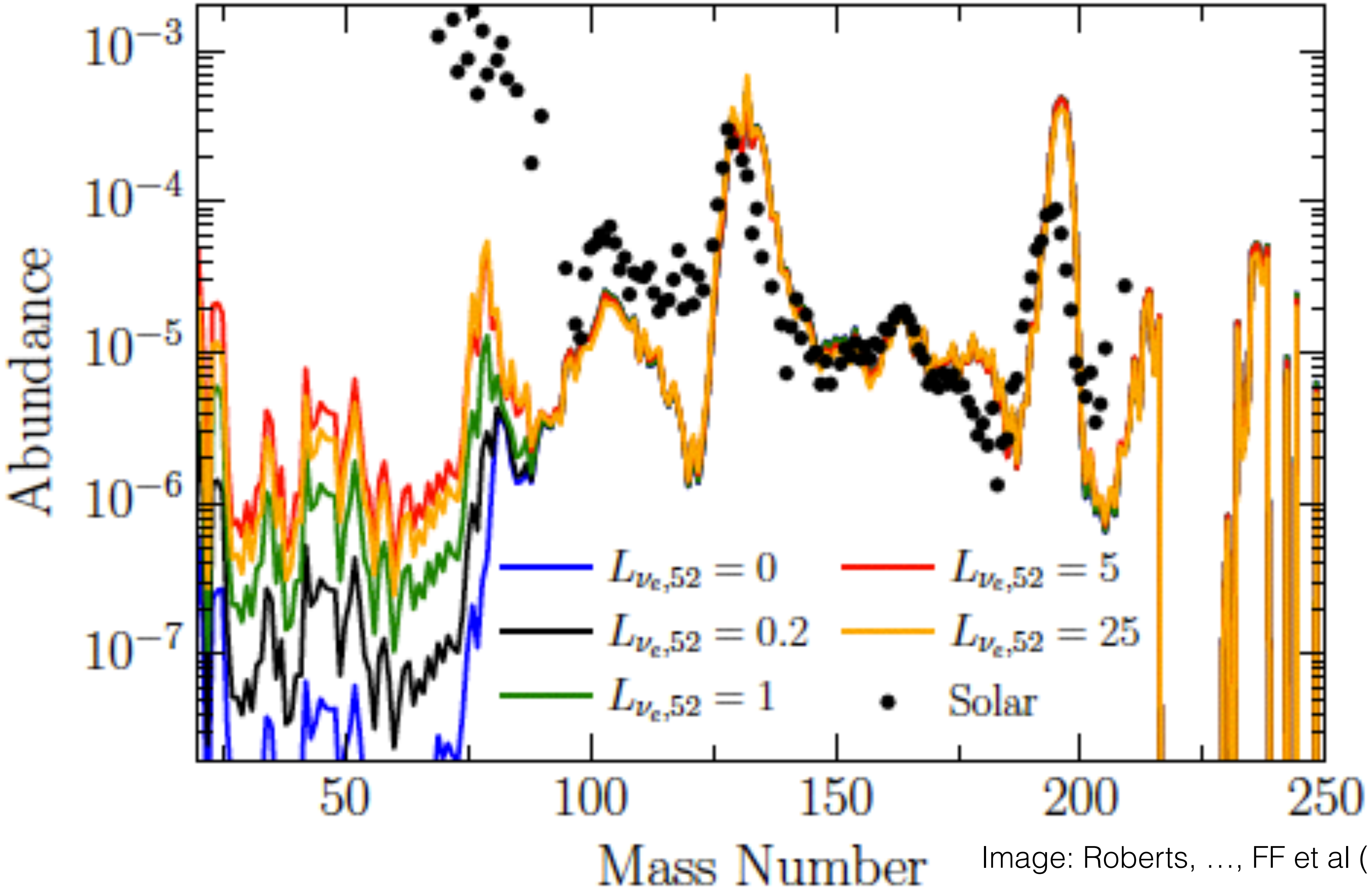
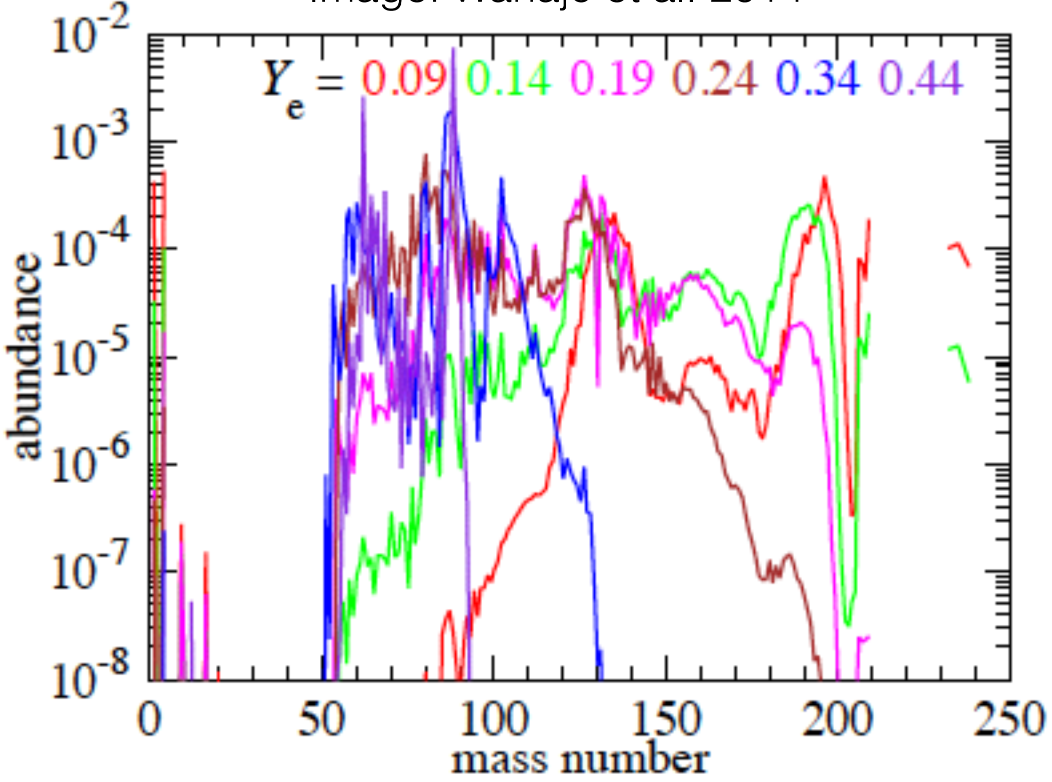


Image: Roberts, …, FF et al (subm.)

- Where are r-process elements produced?
- Robust r-process occurs in NS mergers. What about supernovae?
- How much r-process do NS mergers produce?

Outflows : r-process nucleosynthesis

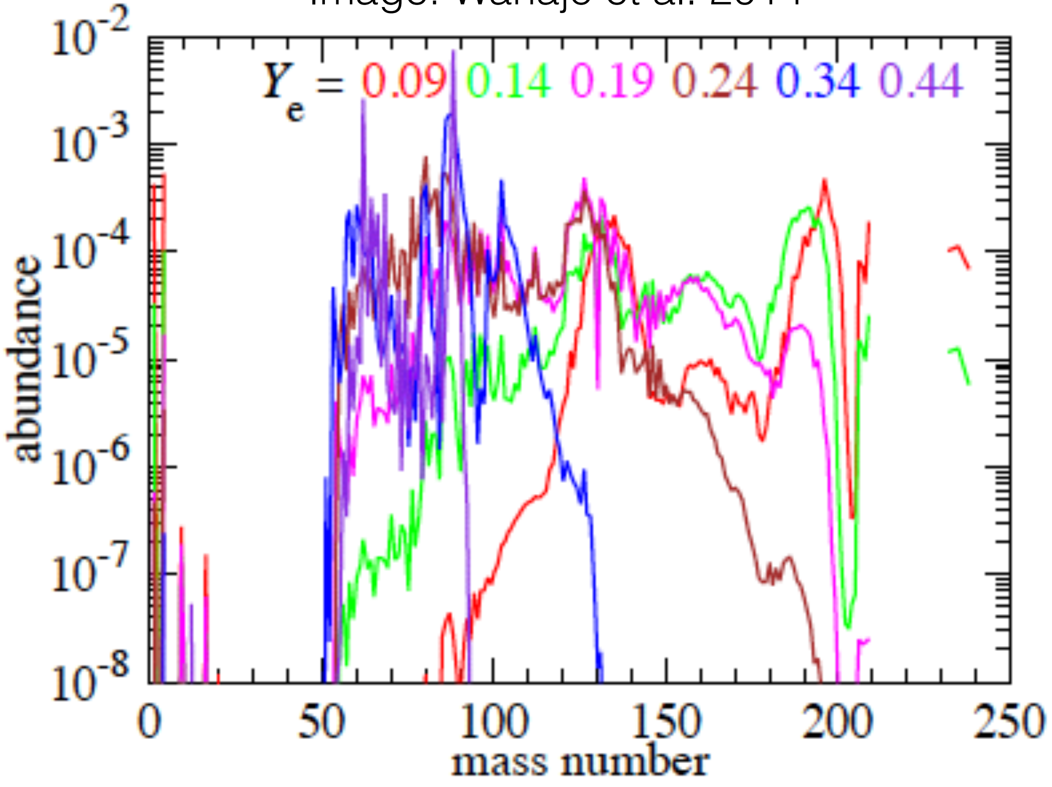
Image: Wanajo et al. 2014



Nucleosynthesis outcome determined by:
Outflow electron fraction
Outflow entropy
Outflow velocity

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

Outflows : r-process nucleosynthesis



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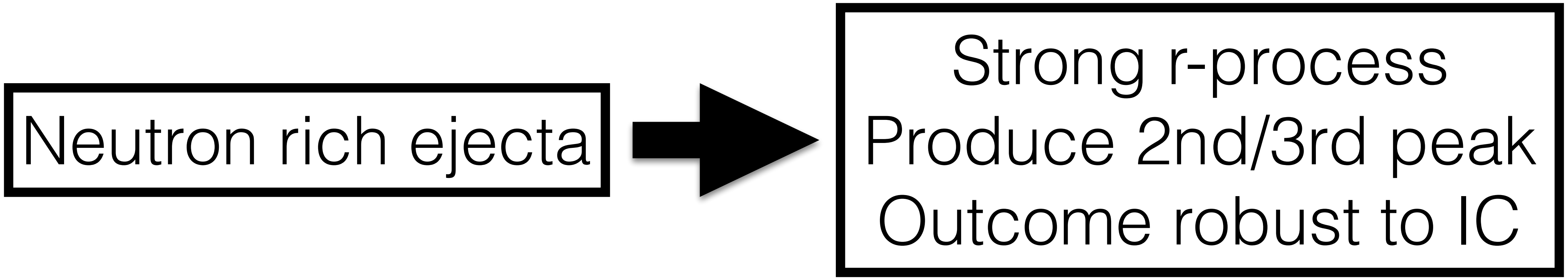
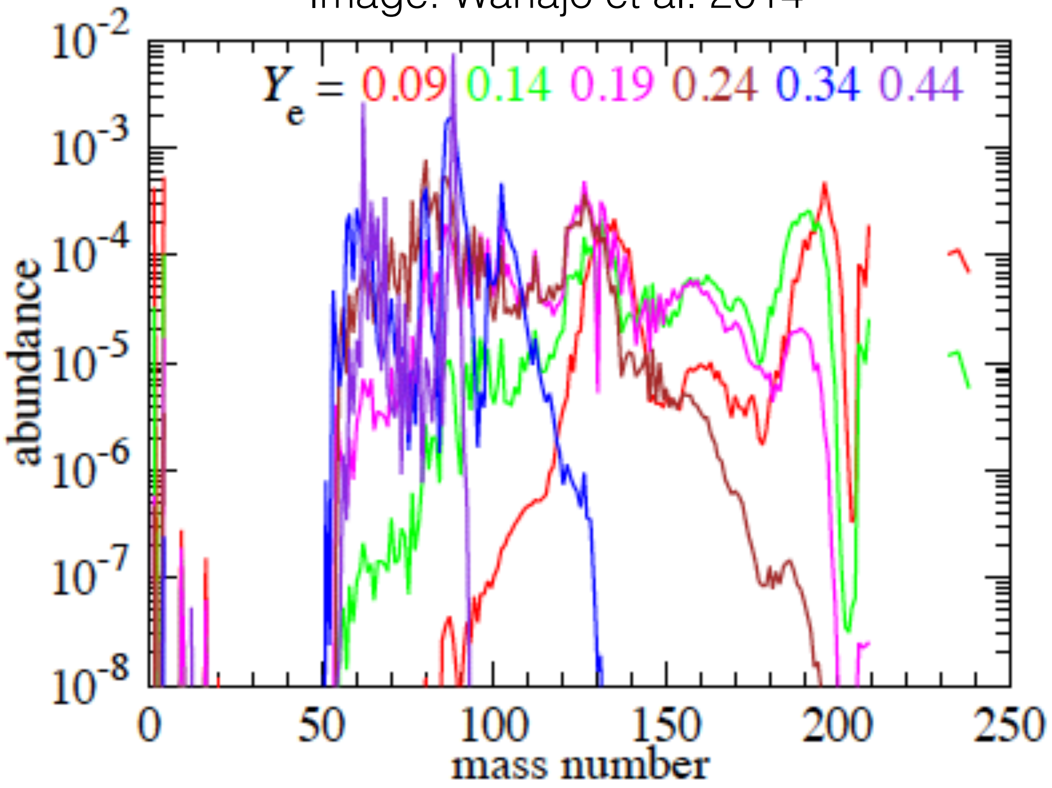


Neutron rich ejecta

Strong r-process
Produce 2nd/3rd peak
Outcome robust to IC

Outflows : r-process nucleosynthesis

Image: Wanajo et al. 2014



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Neutron rich ejecta → Strong r-process
Produce 2nd/3rd peak
Outcome robust to IC

Ye > 0.2-0.3 → Weak r-process
Produce lighter nuclei

Outflows : r-process nucleosynthesis

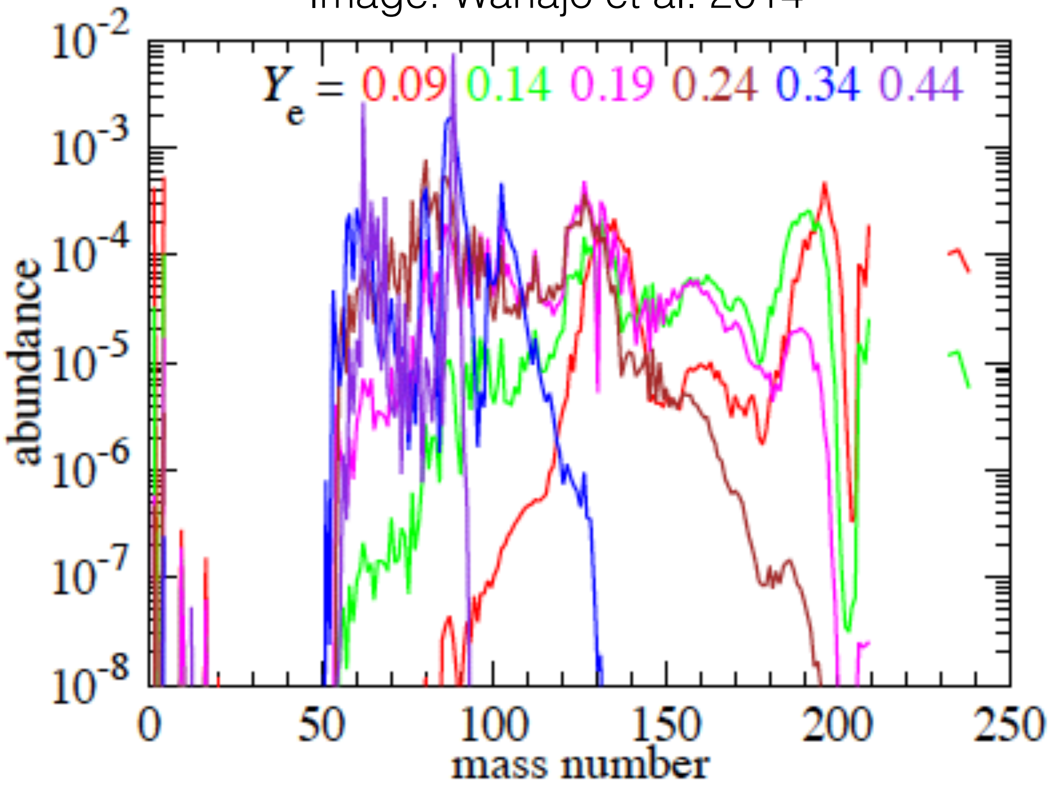
Image: Wanajo et al. 2014

Nucleosynthesis outcome determined by:
Outflow electron fraction
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$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

Neutron rich ejecta →

Strong r-process
Produce 2nd/3rd peak
Outcome robust to IC

Ye > 0.2-0.3 →

Weak r-process
Produce lighter nuclei

Electron fraction set by neutrino-matter interactions!!

Outflows : radioactively powered transients

Strong r-process creates high-opacity lanthanides

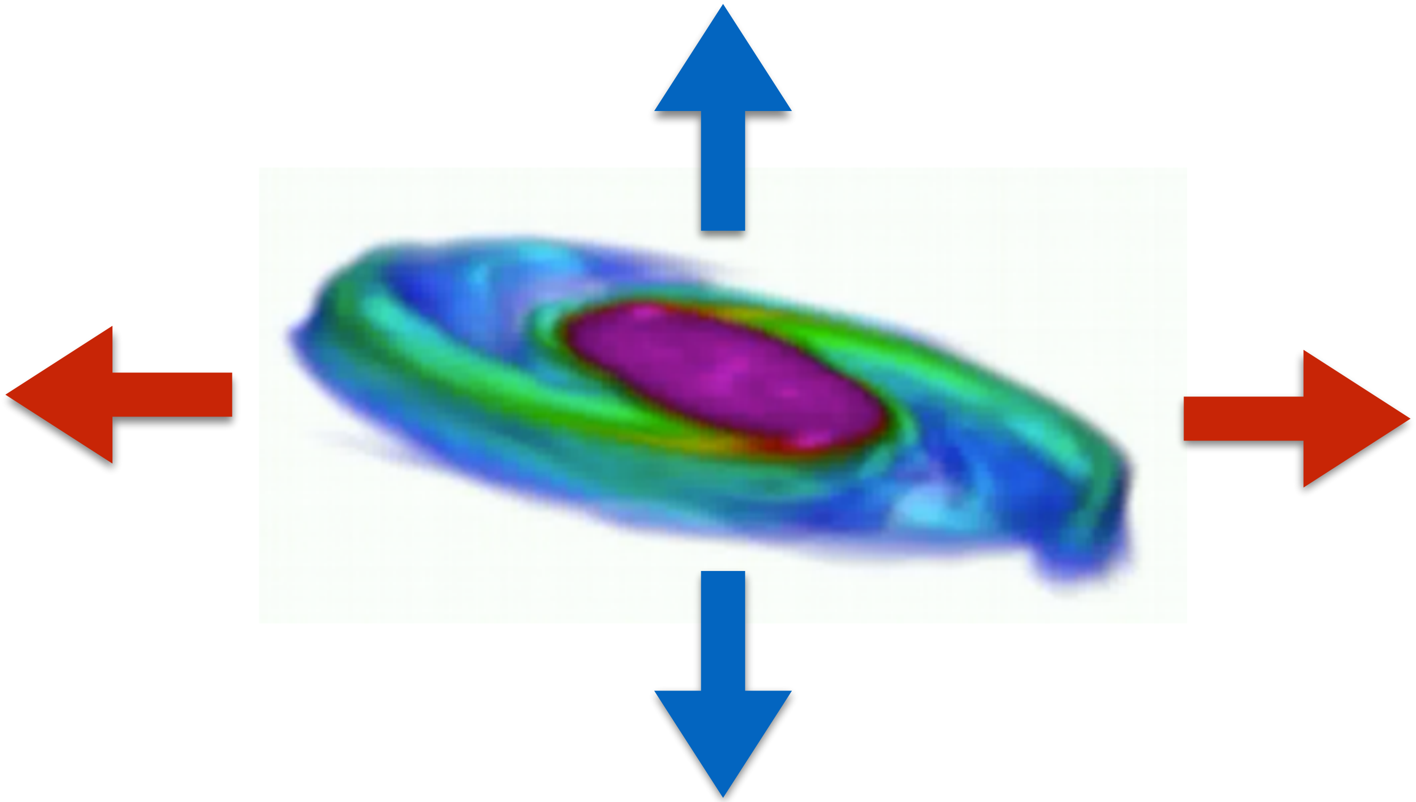
EM signal significantly affected by nucleosynthesis results

Weak r-process:
Day-long transient
Optical wavelength

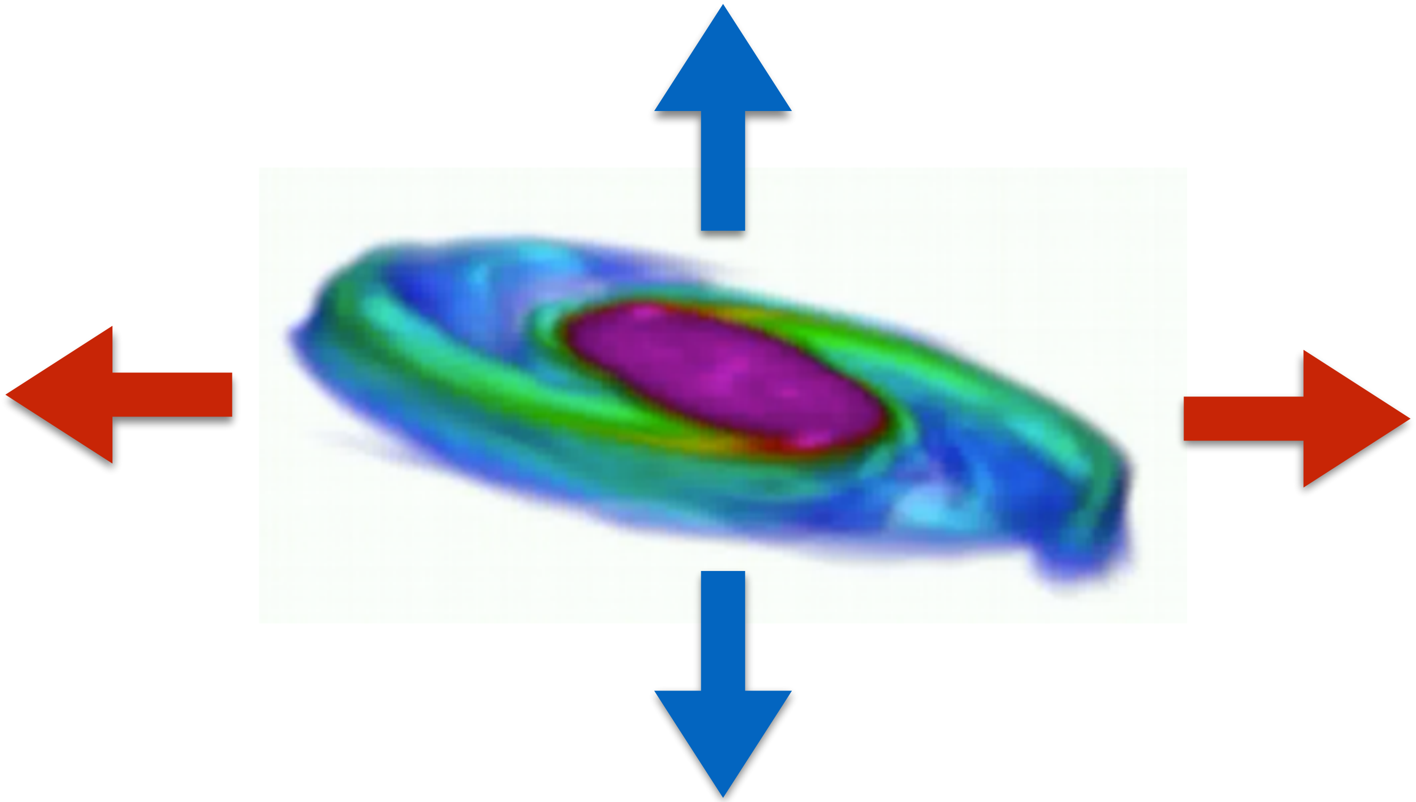
Strong r-process:
Week-long transient
Infrared wavelength

See Kasen et al. 2013, Barnes & Kasen 2013

Dynamical Outflows : Numerical Results



Dynamical Outflows : Numerical Results



Tidal Ejecta

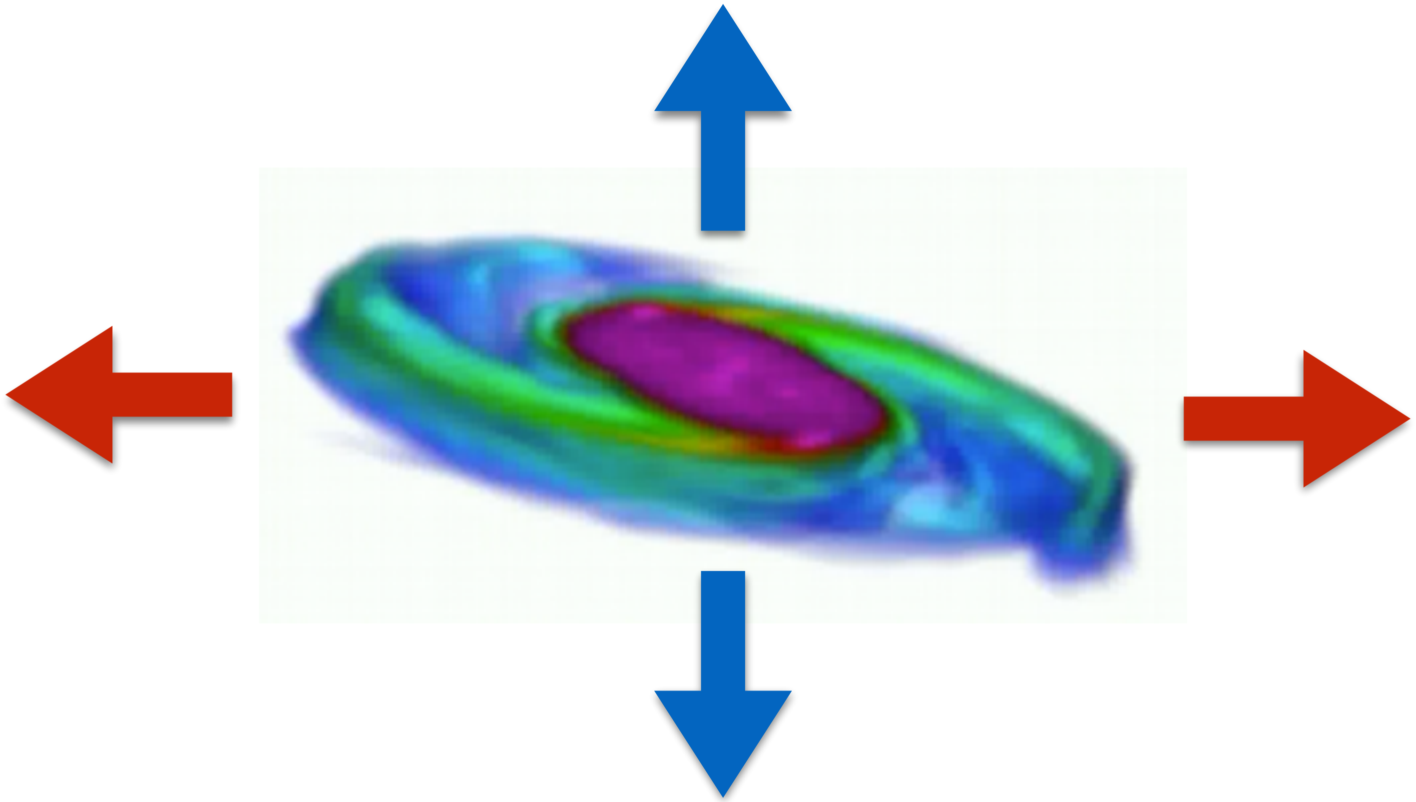
Cold / Neutron-rich

Favored by:

Large stars

Asymmetric mergers

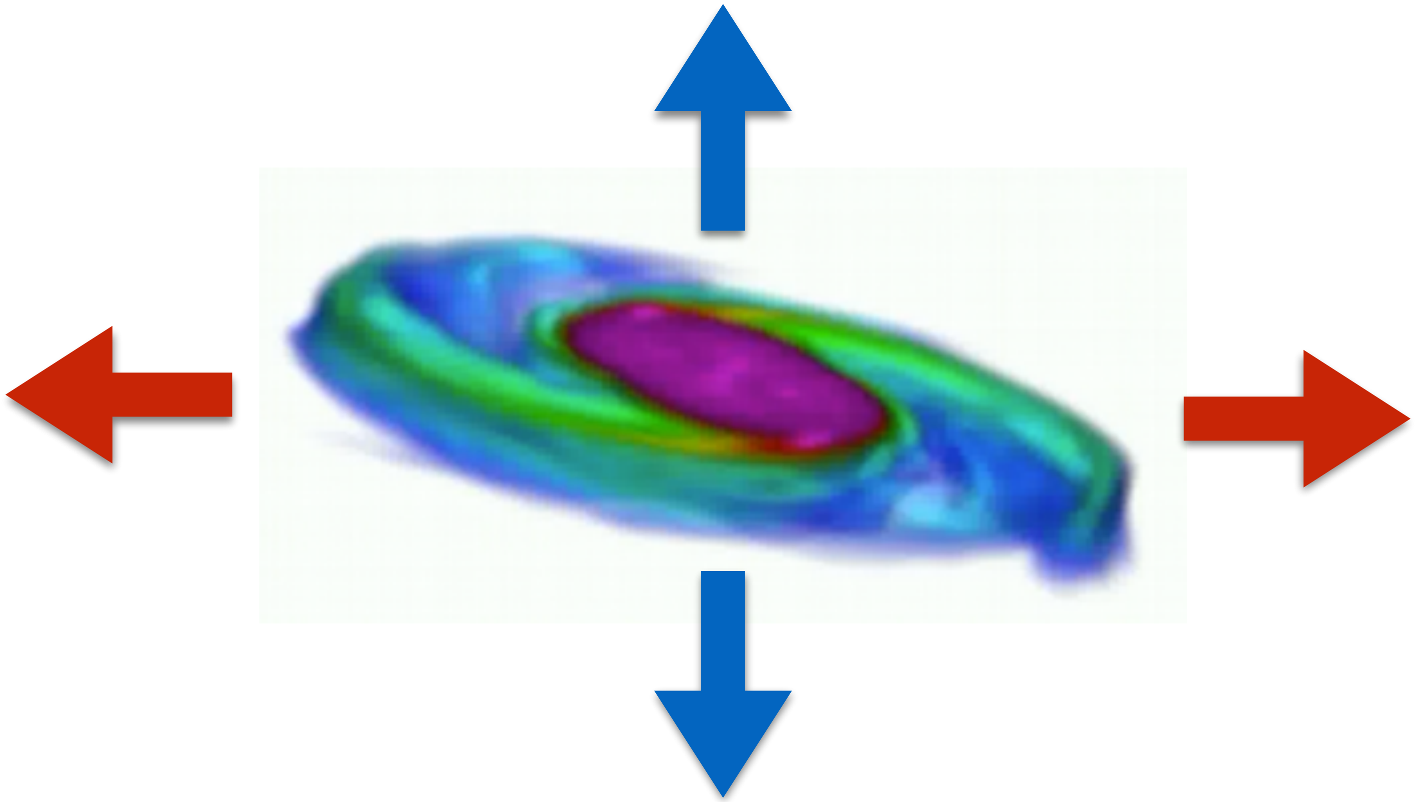
Dynamical Outflows : Numerical Results



Tidal Ejecta
Cold / Neutron-rich
Favored by:
Large stars
Asymmetric mergers

Shocked Ejecta
Hot / Less neutrons
Only for NS-NS
Favors small radii

Dynamical Outflows : Numerical Results



<u>Tidal Ejecta</u>
Cold / Neutron-rich
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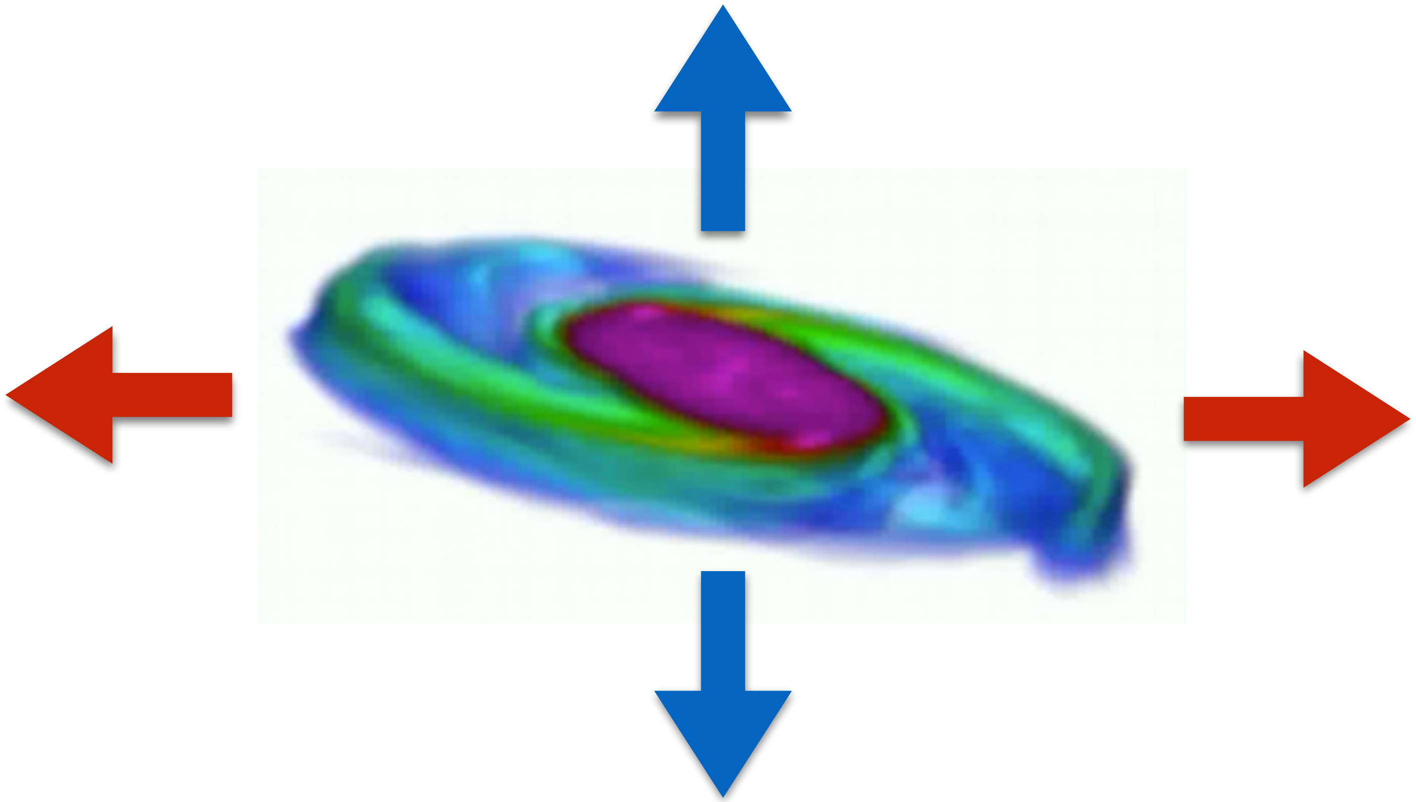
<u>Shocked Ejecta</u>
Hot / Less neutrons
Only for NS-NS
Favors small radii

<u>Post-Merger Disks:</u>
Winds (B-fields, v)
Strong v effects

Dynamical Outflows : Numerical Results



Tidal Ejecta
Cold / Neutron-rich
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Hot / Less neutrons
Only for NS-NS
Favors small radii

Post-Merger Disks:
Winds (B-fields, v)
Strong v effects

General relativistic simulations with neutrino transport critical to predict EM transients and nucleosynthesis yields!

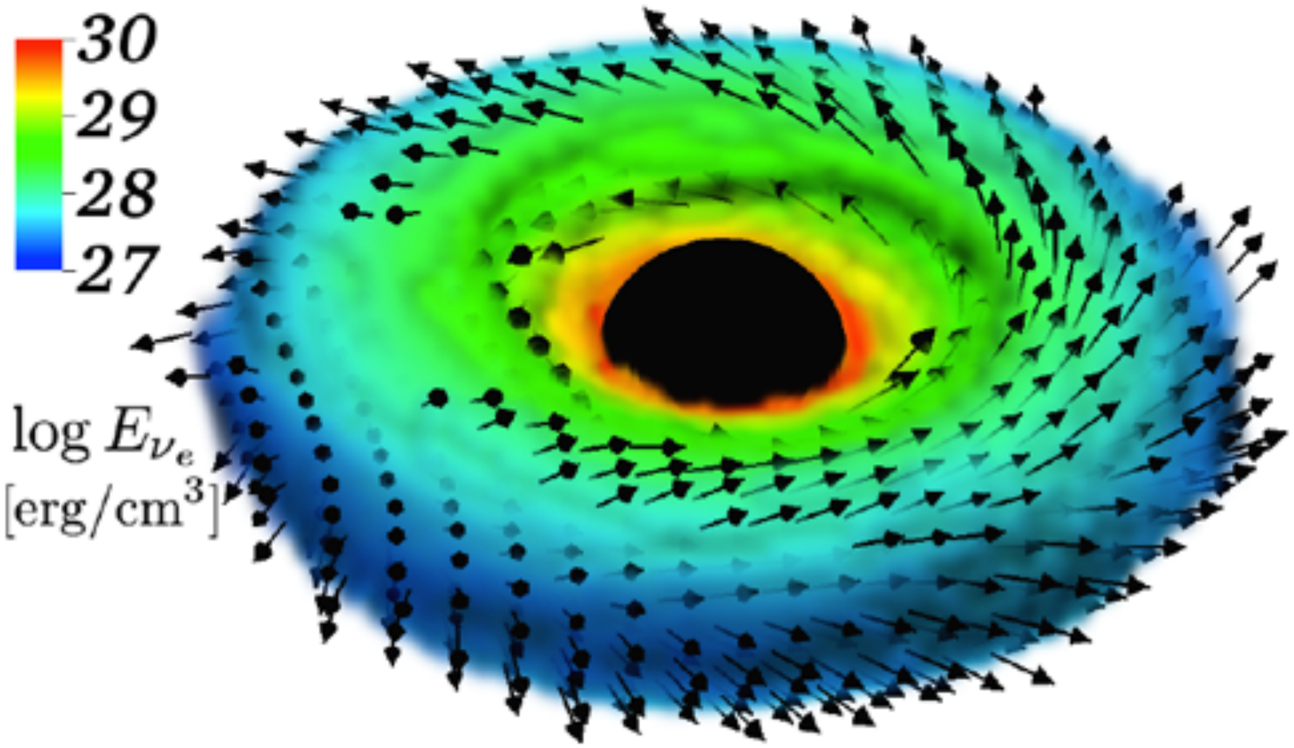
Neutrino emission

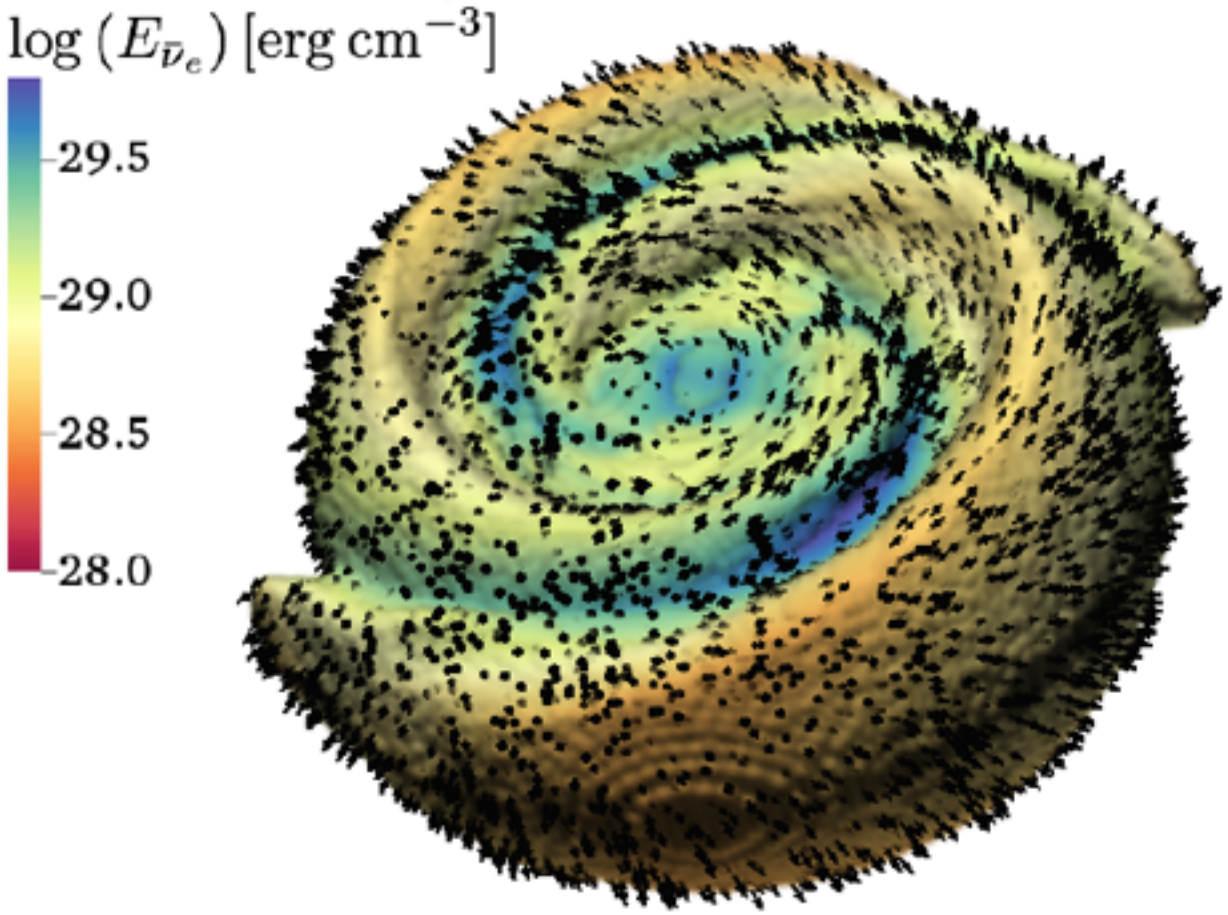
Moment formalism: Evolve neutrino energy and flux density (gray scheme)

Consider 3 species: $\nu_e,\ \bar{\nu}_e,\ \nu_x = (\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau)$

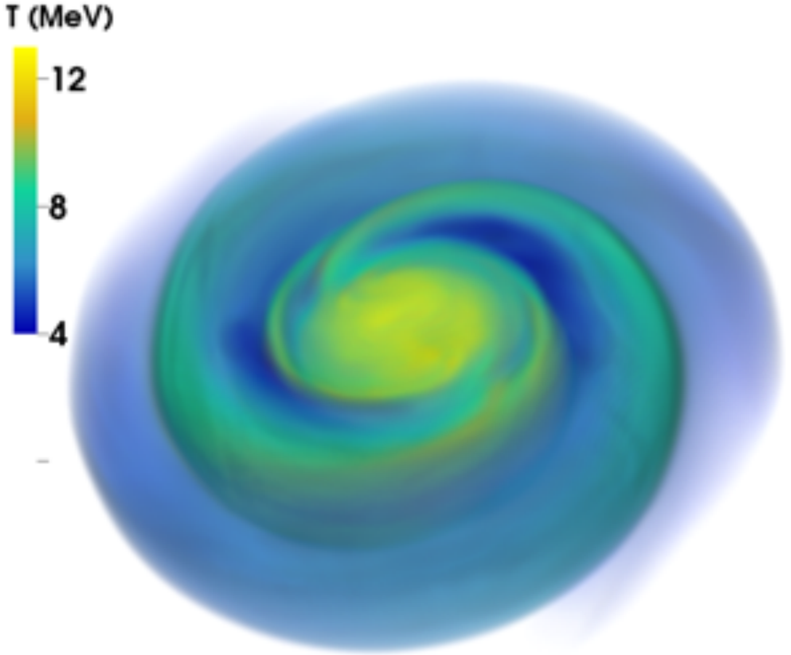
Case I:
BH-NS / High mass NS-NS
Emission from heated disk

Case II:
Low mass NS-NS
Emission from NS + disk

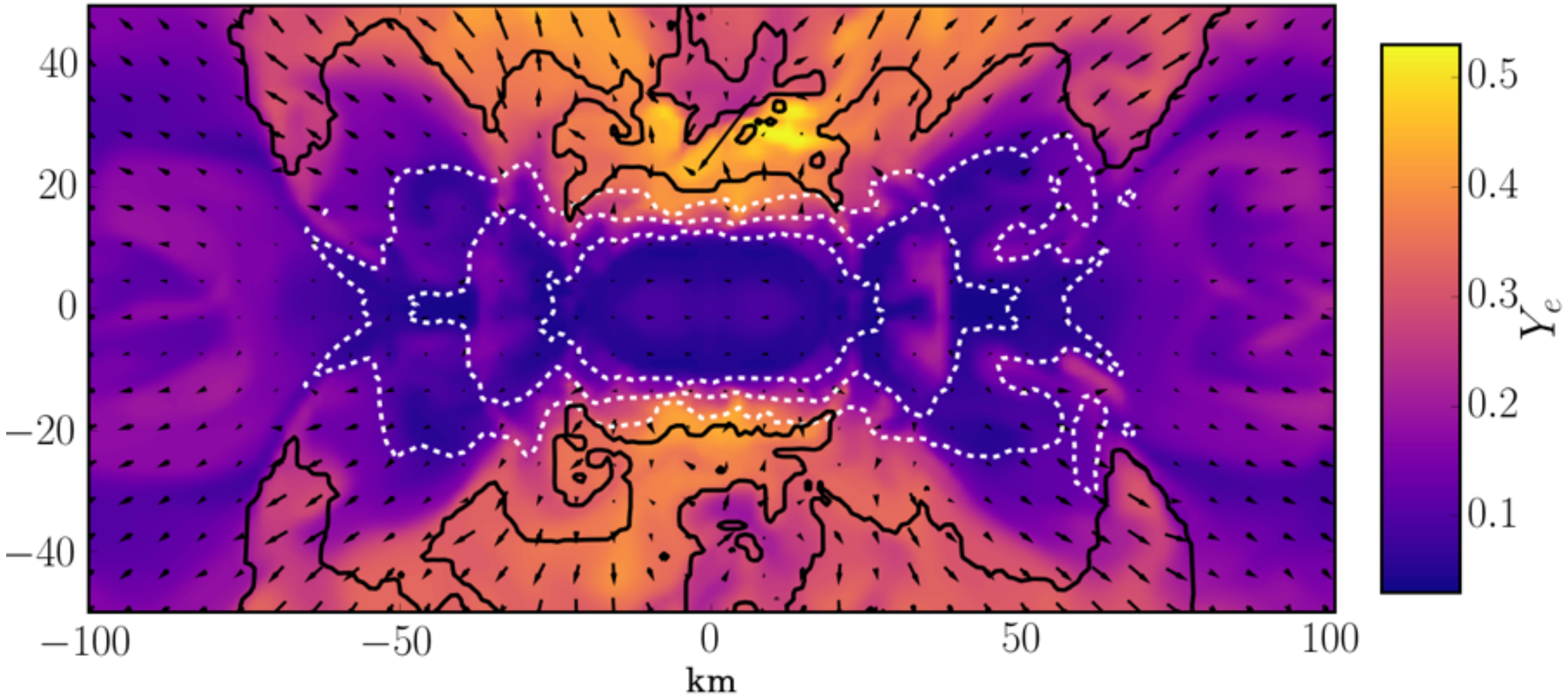




NS-NS Outflows Simulation Results



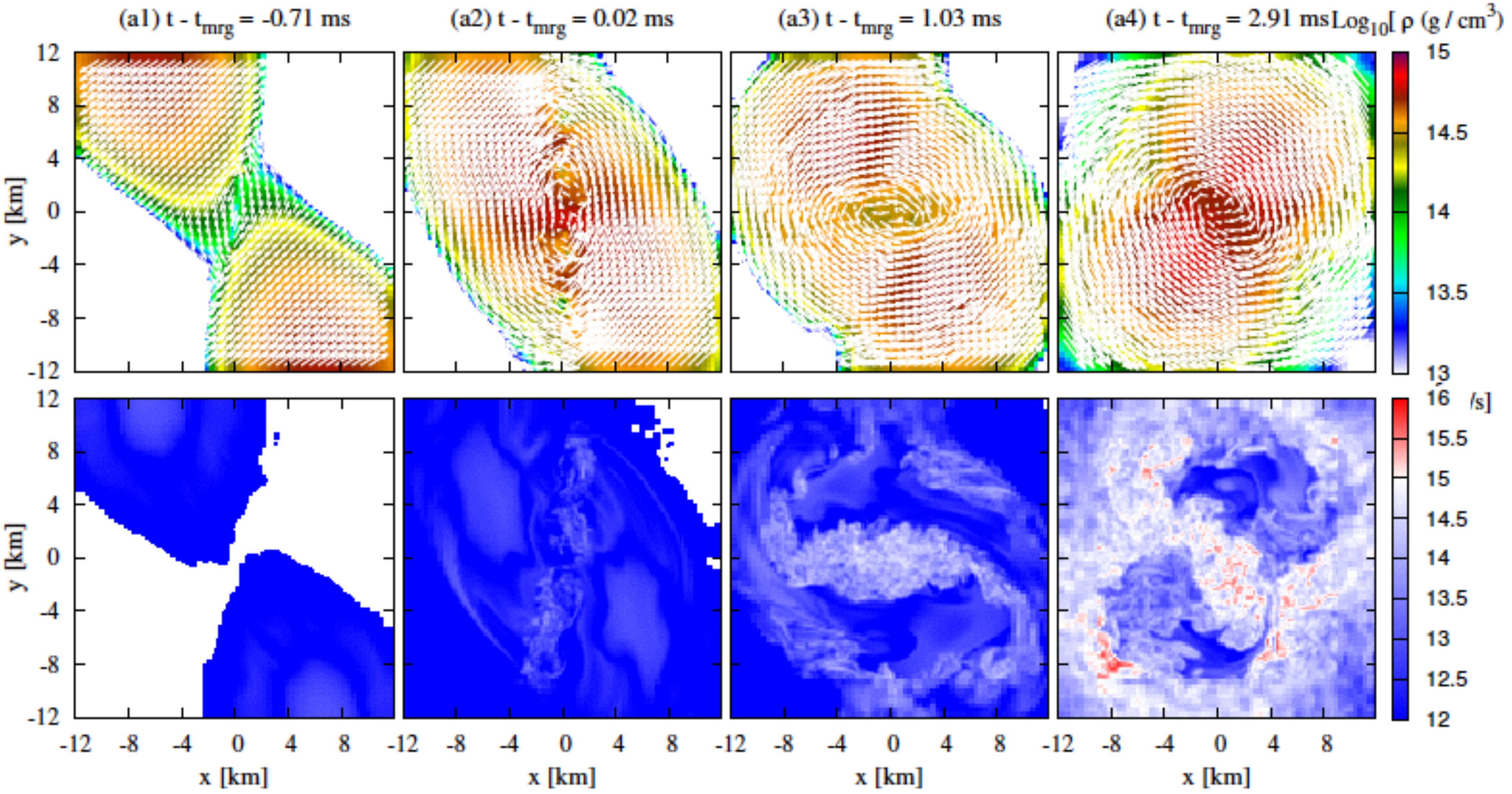
Images: Foucart et al, 2016



Neutron poor polar ejecta
Neutron rich equatorial ejecta

Magnetic effects

Disks unstable to magnetorotational instability
Contact regions in NS-NS mergers Kelvin-Helmholtz unstable



Images: Kiuchi et al. 2015

Very expensive to resolve - no convergent results yet for KH
Large scale B-field?

Magnetic effects - Jets ?

Image: Dionysopoulou et al. 2015

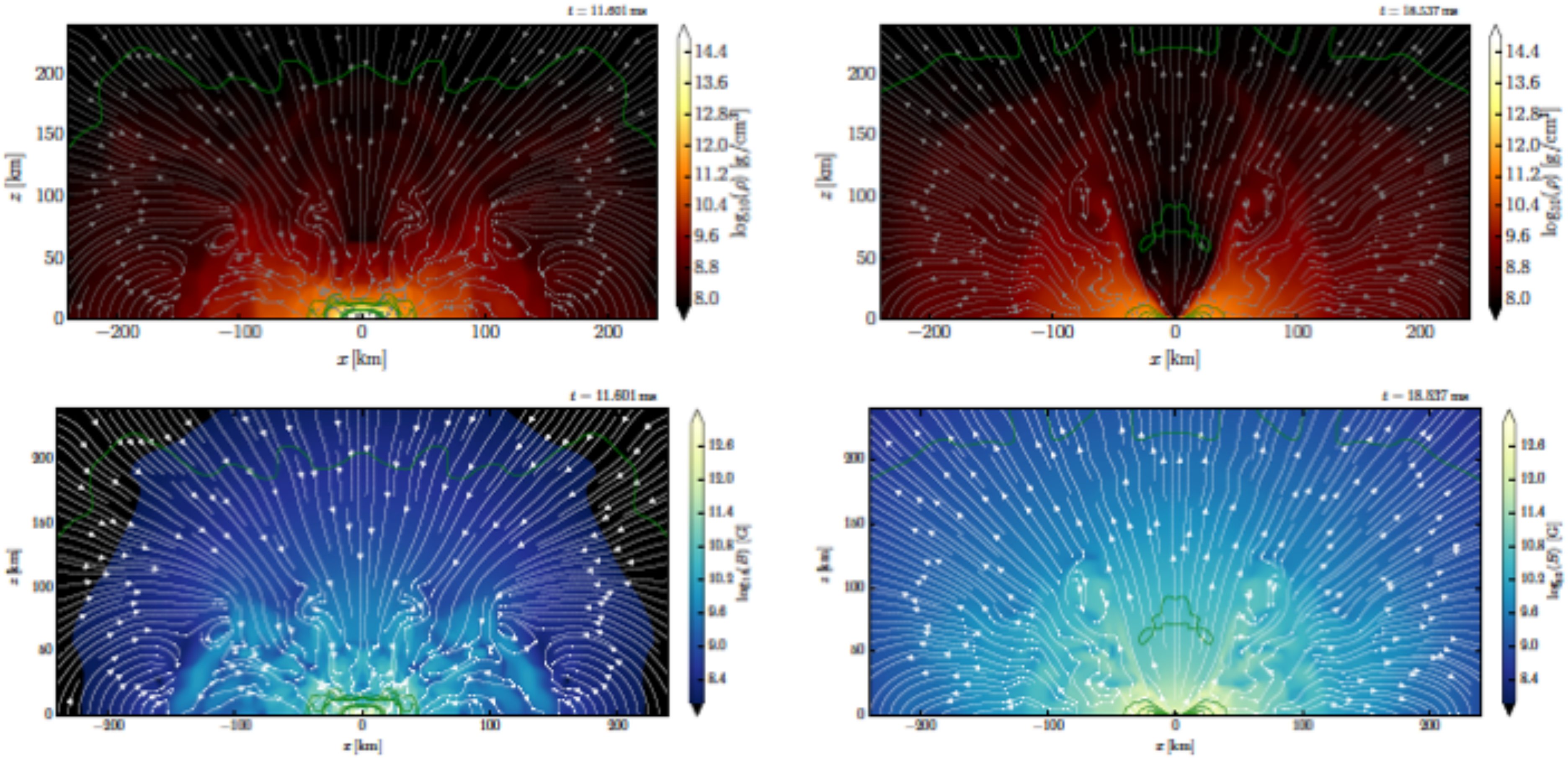
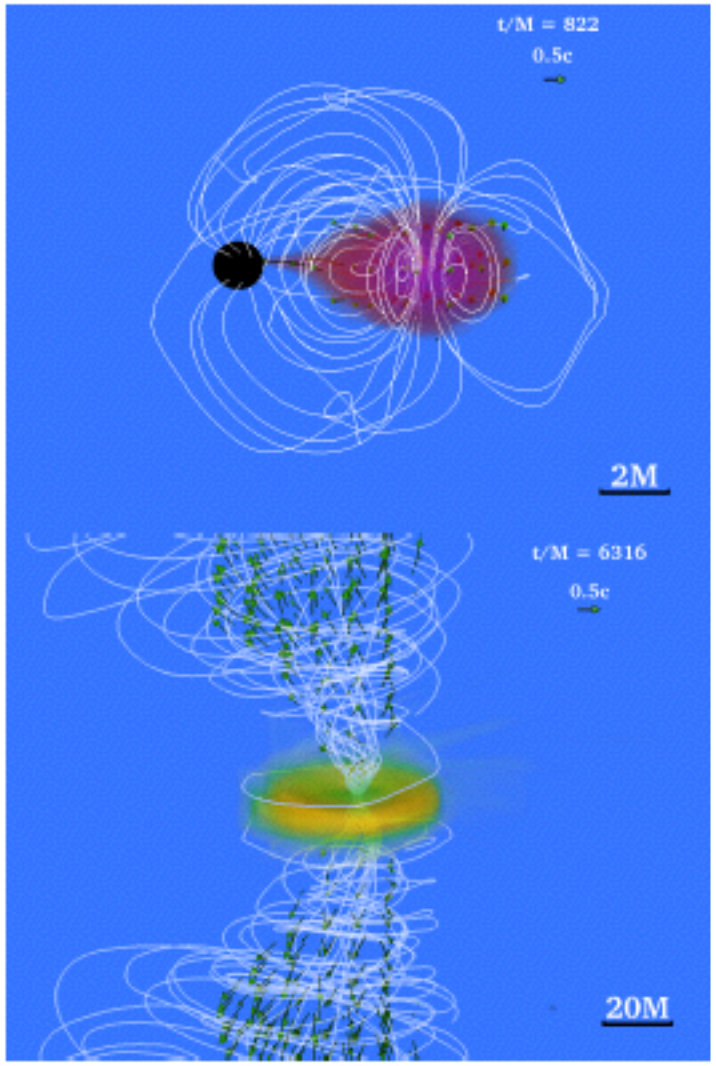


Image: Paschalidis et al. 2015



- Baryon free, jet-like structures observed in some simulations
- Numerical methods do not allow very relativistic jets
- Robustness (to initial conditions / neutrinos / …) of the jet formation still an important open question!
- Other possibility: jet from non-collimated engine [Duffel et al 2015]

Critical to understand SRGBs!!

Post-merger disks

- From 2D simulations, with artificial viscosity: (5-20)% of disk mass unbound
- Outflow properties impacted by
    - Disk compactness (BH mass in BH-NS mergers)
    - NS lifetime (NS-NS merger)
    - Neutrino modeling
- Y_e~0.1-0.4, with higher Y_e in polar regions
- See e.g. Fernandez et al., Just et al.

What’s missing?

- **Inspiral:** Waveform models accurate to <10% of tidal effects
- **Merger:** Resolved magnetic field growth + neutrino transport
- **Post-Merger:** Magnetically driven turbulence + neutrino transport + realistic initial data
- **Nuclear Physics:** NS equation of state, properties of neutron-rich nuclei