Title: Neutron star mergers and the cosmic origin of the heavy elements

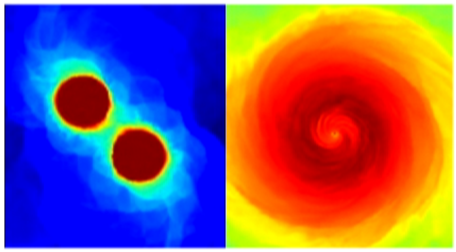
Date: Feb 15, 2018 01:30 PM

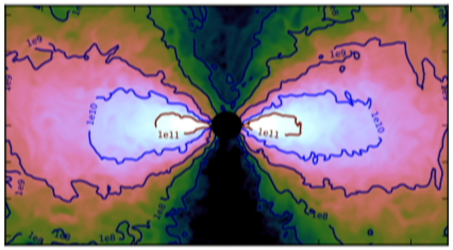
URL: http://pirsa.org/18020093

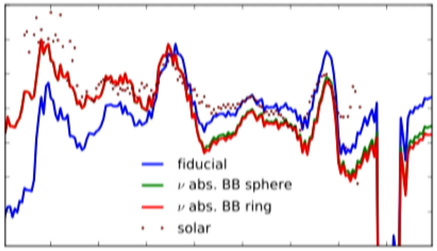
Abstract: <p>The recent detection of the binary neutron star merger GW170817 by LIGO and Virgo was followed by a firework of electromagnetic counterparts across the entire electromagnetic spectrum. In particular, the ultraviolet, optical, and near-infrared emission is consistent with a kilonova that provided strong evidence for the formation of heavy elements in the merger ejecta by the rapid neutron capture process (r-process). In this talk, I will discuss the state of the art in modeling neutron star mergers from first principles, which represents a multi-physics challenge involving all four fundamental forces and petascale computing. I will present recent results from general-relativistic magnetohydrodynamic simulations and discuss possible scenarios and mass ejection mechanisms that can give rise to the observed kilonova features. In particular, I will argue that massive winds from neutrino-cooled post-merger accretion disks most likely synthesized the heavy r-process elements in GW170817. I will show how this finding (at least partially) concludes the quest for the cosmic origin of the heavy elements, which has been an enduring mystery for more than 70 years.</p>

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Neutron star mergers and the cosmic origin of the heavy elements







Daniel M. Siegel

NASA Einstein Fellow

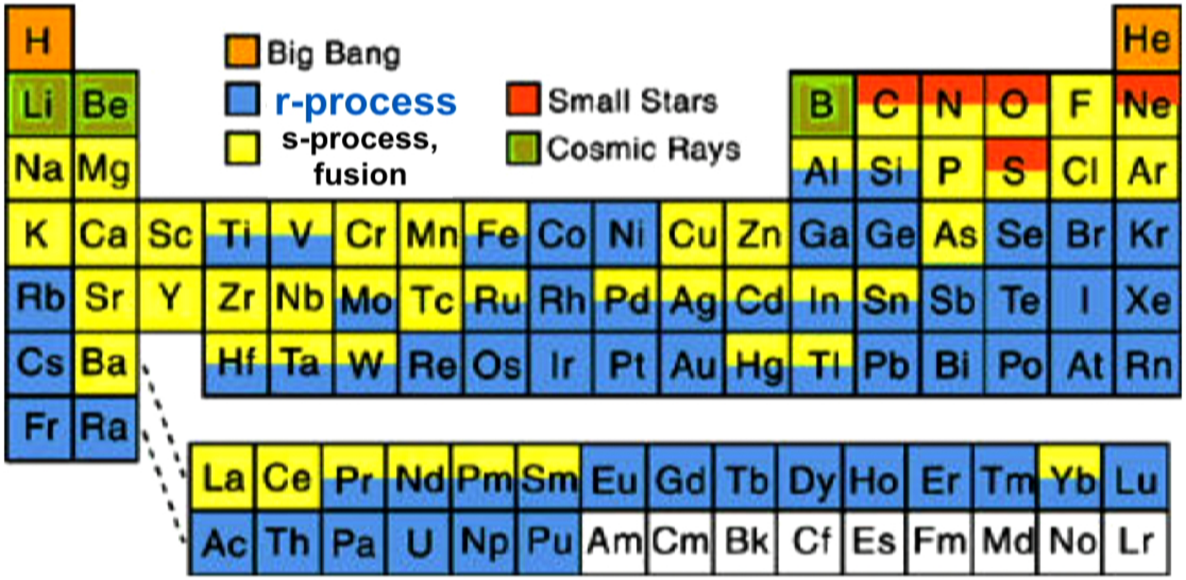
Center for Theoretical Physics & Columbia Astrophysics Laboratory, Columbia University

Perimeter Institute for Theoretical Physics, Feb. 15, 2018

Overview

- ☑ The r-process
- ☑ Modeling NS mergers
- ☑ Mass ejection: kilonovae
- ☑ The site of the r-process
- ☑ Conclusions & Outlook

The origin of the elements

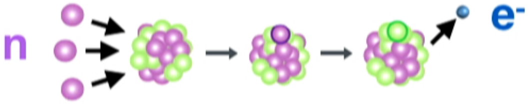


How are the *heavy* elements formed?

The r-process and s-process

Burbidge, Burbidge, Fowler, Hoyle (1957), Cameron (1957):

The heavy elements (A > 62) are formed by neutron capture onto seed nuclei



Burbidge, Burbidge, Fowler, Hoyle ("B²FH")

slow neutron capture (**s**-process):

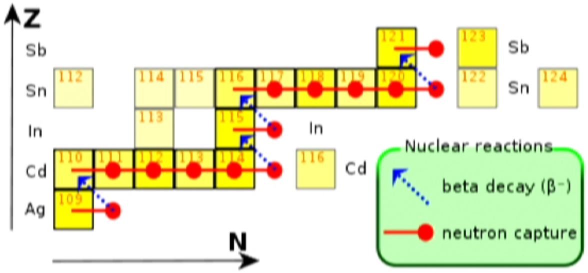
timescale for neutron capture longer than for β-decay

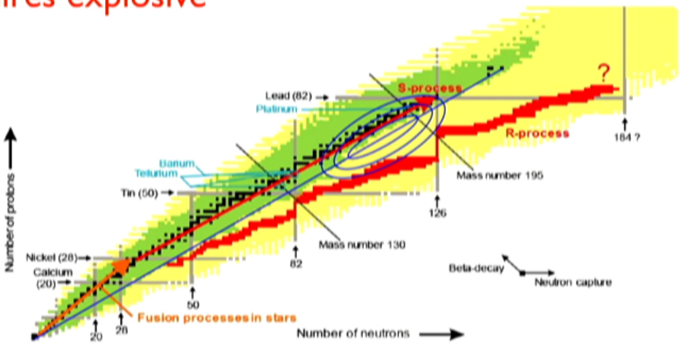
rapid neutron capture (**r**-process):

timescale for neutron capture shorter than for β-decay

→ speculated that r-process requires explosive environment of supernovae

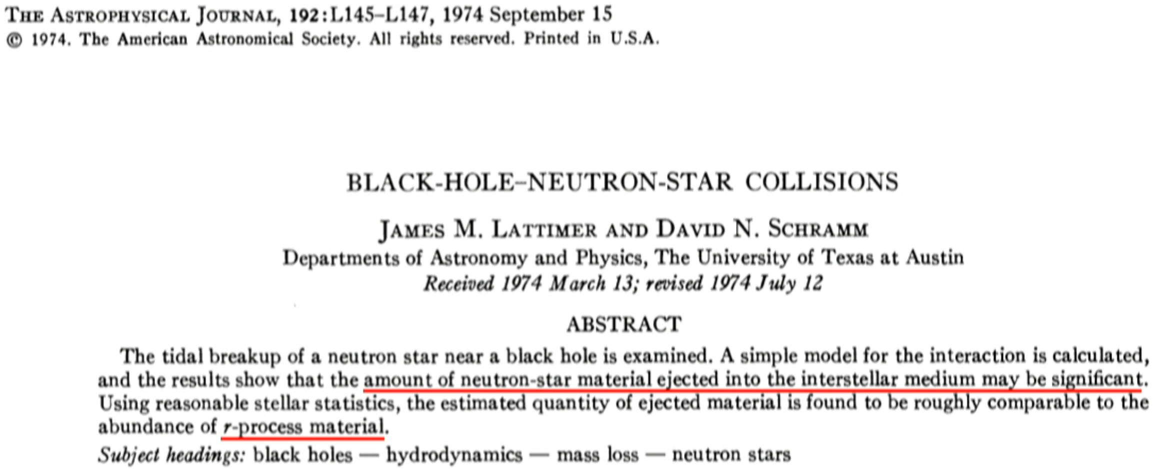
Cameron





Neutron star mergers and r-process

Lattimer & Schramm (1974):



THE ASTROPHYSICAL JOURNAL, 192:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

JAMES M. LATTIMER AND DAVID N. SCHRAMM
Departments of Astronomy and Physics, The University of Texas at Austin

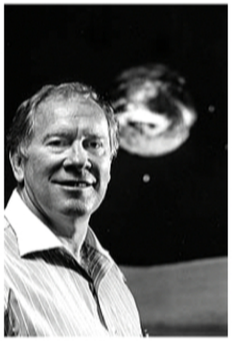
Received 1974 March 13; revised 1974 July 12

ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

Subject headings: black holes — hydrodynamics — mass loss — neutron stars

Lattimer

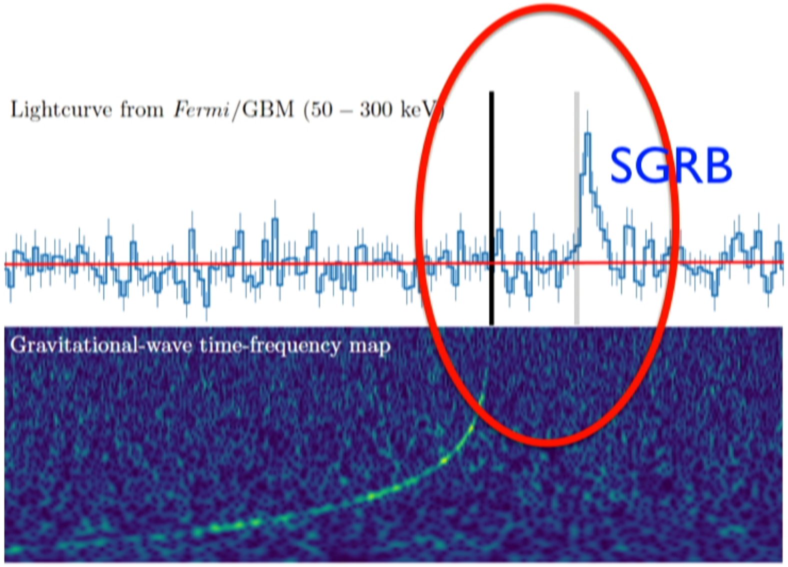


Schramm

- dynamical expansion of n-rich matter provides a natural r-process site
- though predicted 40 years ago, this idea for the r-process had not been favored until very recently

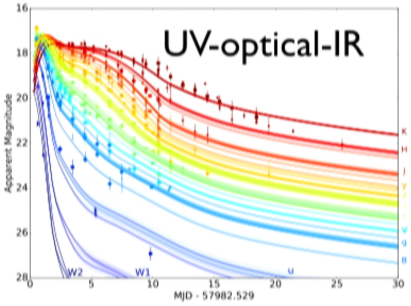
The recent LIGO discovery GW170817 has provided strong evidence that NS mergers can indeed form r-process elements

GW170817 and the firework of EM counterparts

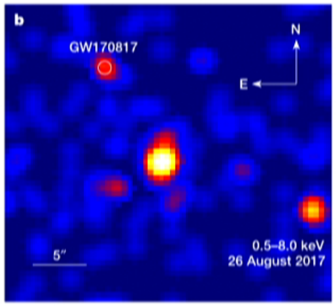


- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material

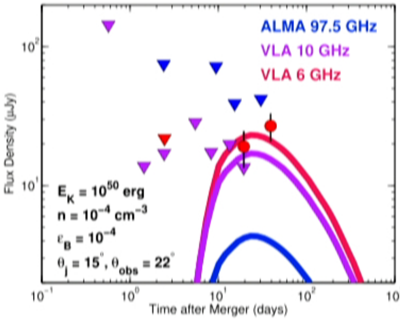
kilonova



X-rays

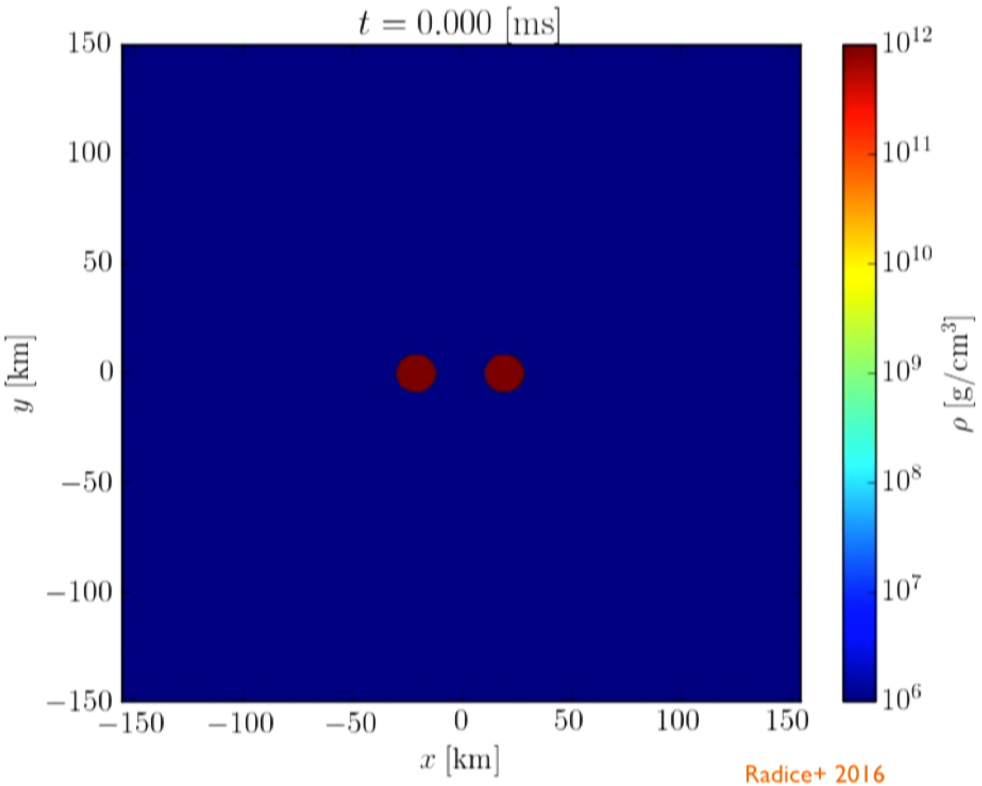


radio



The state of the art in modeling NS mergers from first principles

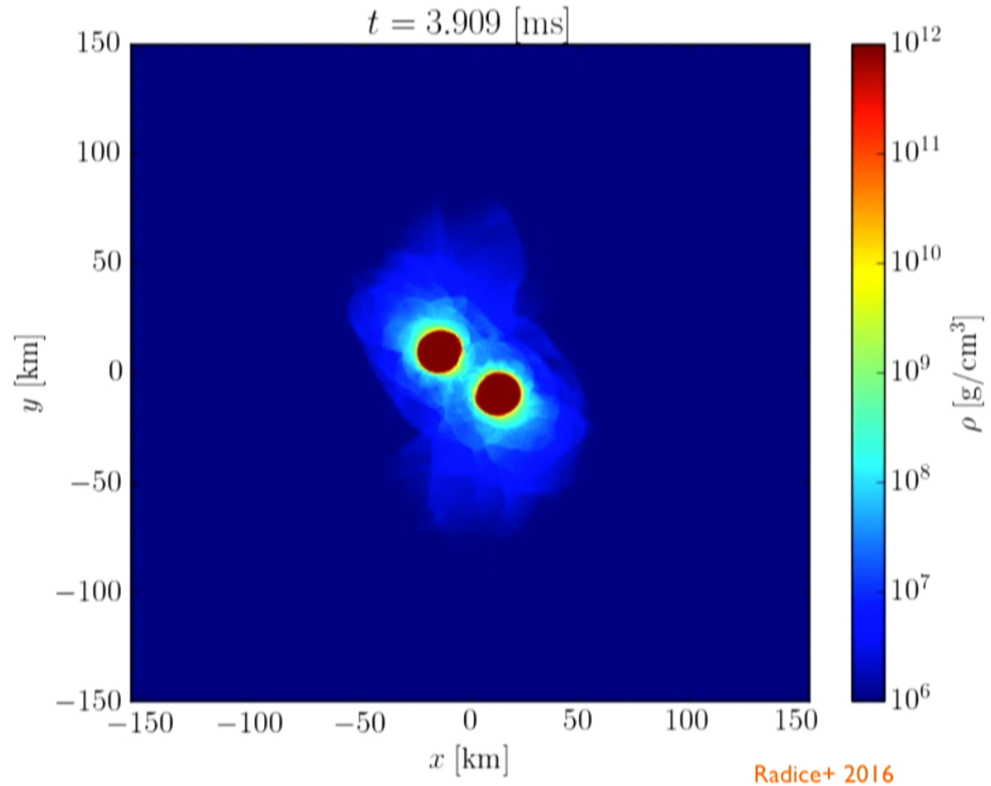
BNS merger ➡ black hole: numerical simulation



Radice+ 2016

Movie: BNS merger with prompt black-hole formation, showing dynamical ejecta and disk formation

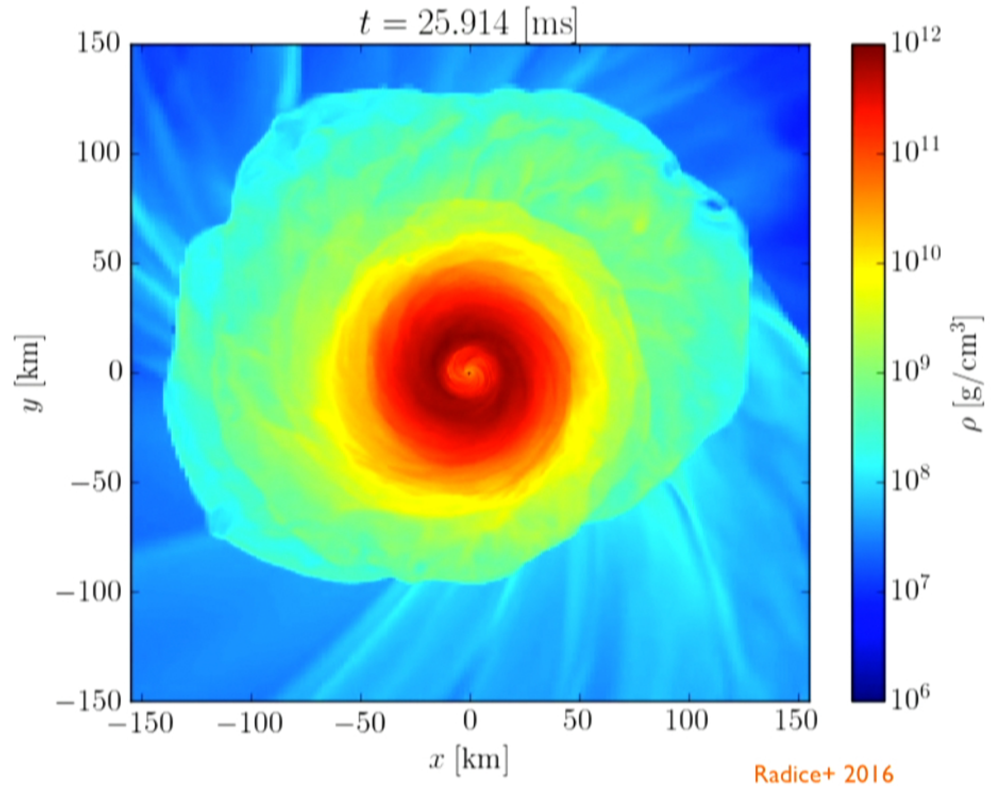
BNS merger ➡ black hole: numerical simulation



Radice+ 2016

Movie: BNS merger with prompt black-hole formation, showing dynamical ejecta and disk formation

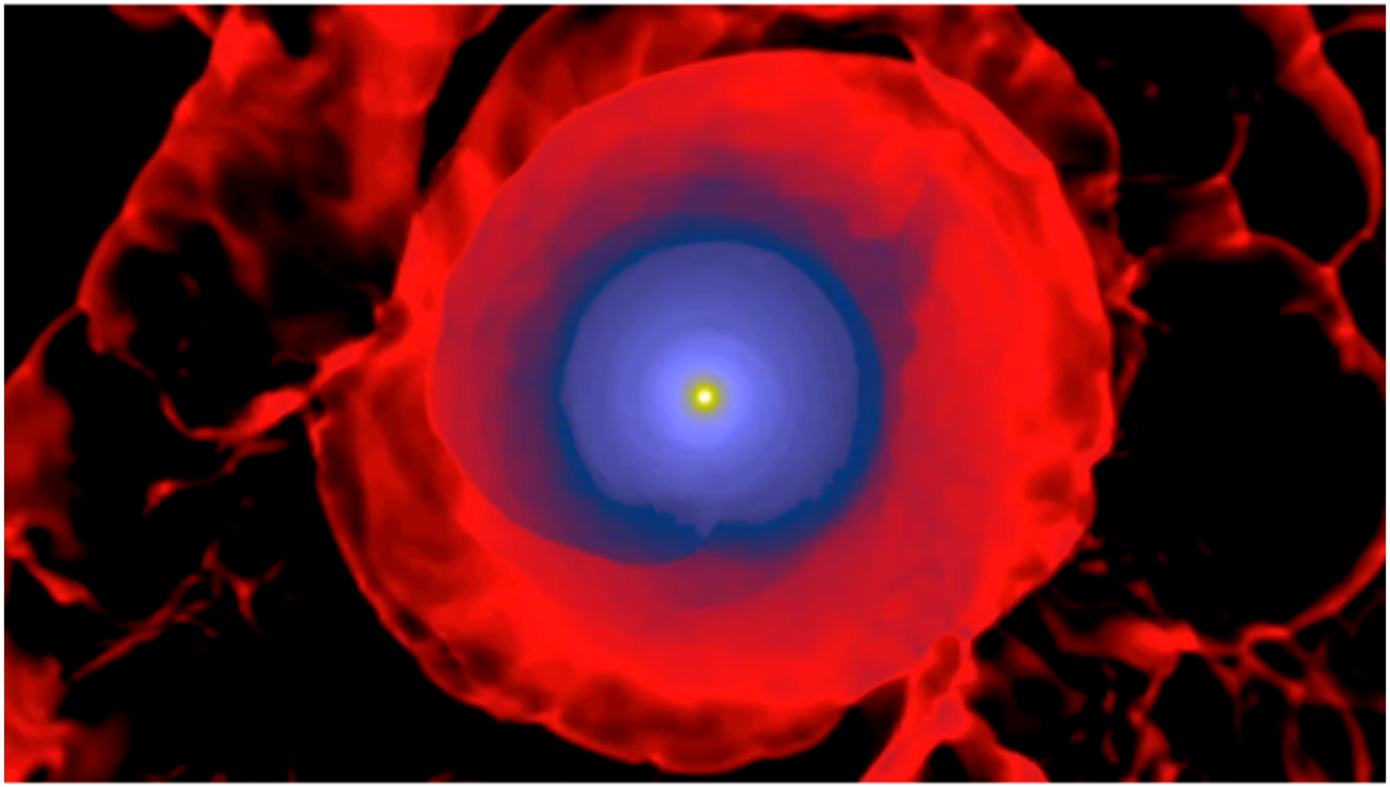
BNS merger ➡ black hole: numerical simulation



Radice+ 2016

Movie: BNS merger with prompt black-hole formation,
showing dynamical ejecta and disk formation

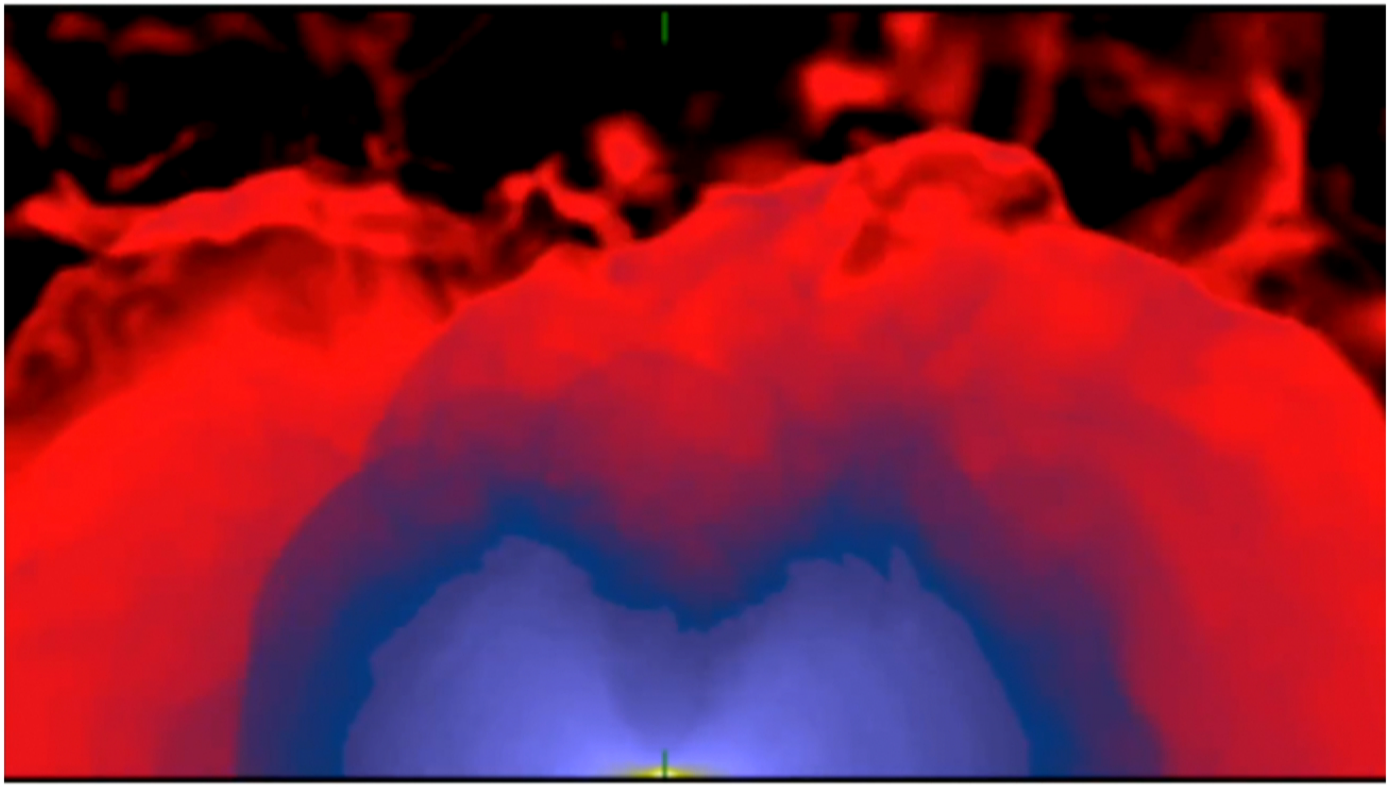
BNS merger ➡ neutron star: numerical simulation



Movie: BNS merger showing dynamical ejecta and winds from remnant neutron star

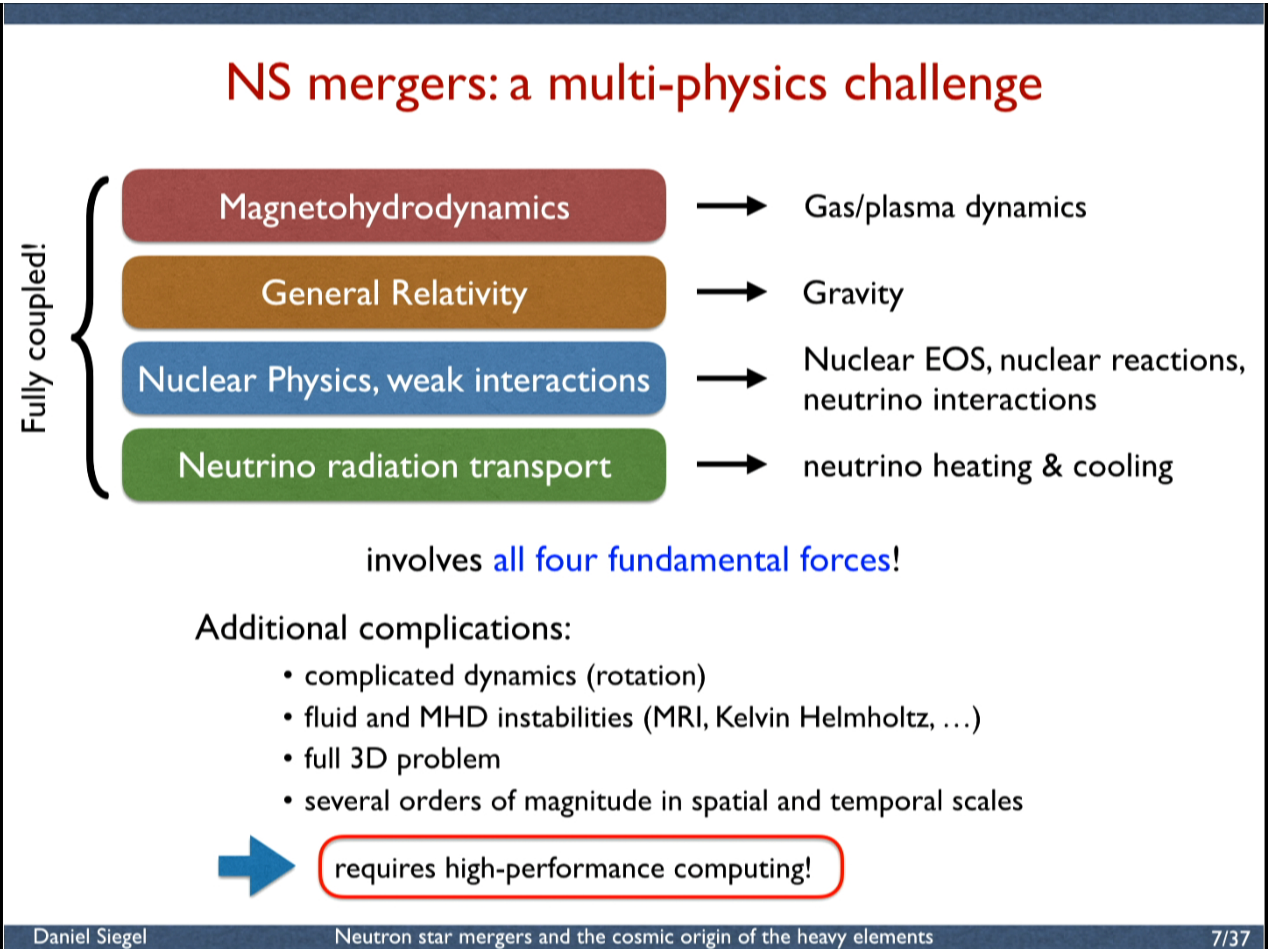
Ciolfi, Siegel+2017

BNS merger → neutron star: numerical simulation



Movie: BNS merger showing dynamical ejecta and winds from remnant neutron star

Ciolfi, Siegel+2017



NS mergers: a multi-physics challenge

Fully coupled!

- Magnetohydrodynamics → Gas/plasma dynamics
- General Relativity → Gravity
- Nuclear Physics, weak interactions → Nuclear EOS, nuclear reactions, neutrino interactions
- Neutrino radiation transport → neutrino heating & cooling

involves all four fundamental forces!

Additional complications:

- complicated dynamics (rotation)
- fluid and MHD instabilities (MRI, Kelvin Helmholtz, …)
- full 3D problem
- several orders of magnitude in spatial and temporal scales

→ requires high-performance computing!

NS mergers: a multi-physics challenge

Einstein's equations

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

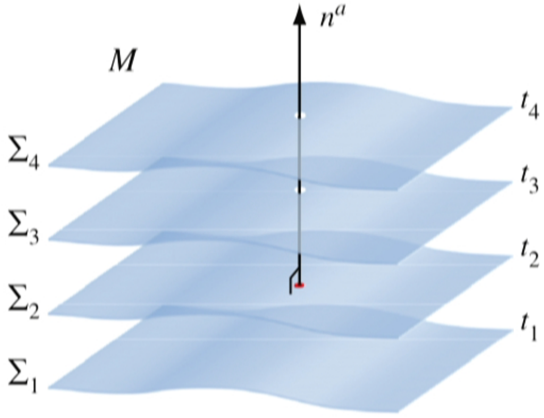
Matter (GRMHD), weak interactions

$$\boxed{\begin{aligned} \nabla_\mu T^{\mu\nu} &= \Psi^\nu \\ \nabla_\mu {}^\star F^{\mu\nu} &= 0 \\ \nabla_\mu (n_\mathrm{b} u^\mu) &= 0 \\ \nabla_\mu (n_\mathrm{e} u^\mu) &= \mathcal{R} \end{aligned}}$$

$$T^{\mu\nu} = T^{\mu\nu}_\mathrm{mat} + T^{\mu\nu}_\mathrm{EM} + T^{\mu\nu}_\mathrm{neu}$$

Equation of state (EOS):

$$p = p(\rho, T, Y_e, \ldots)$$

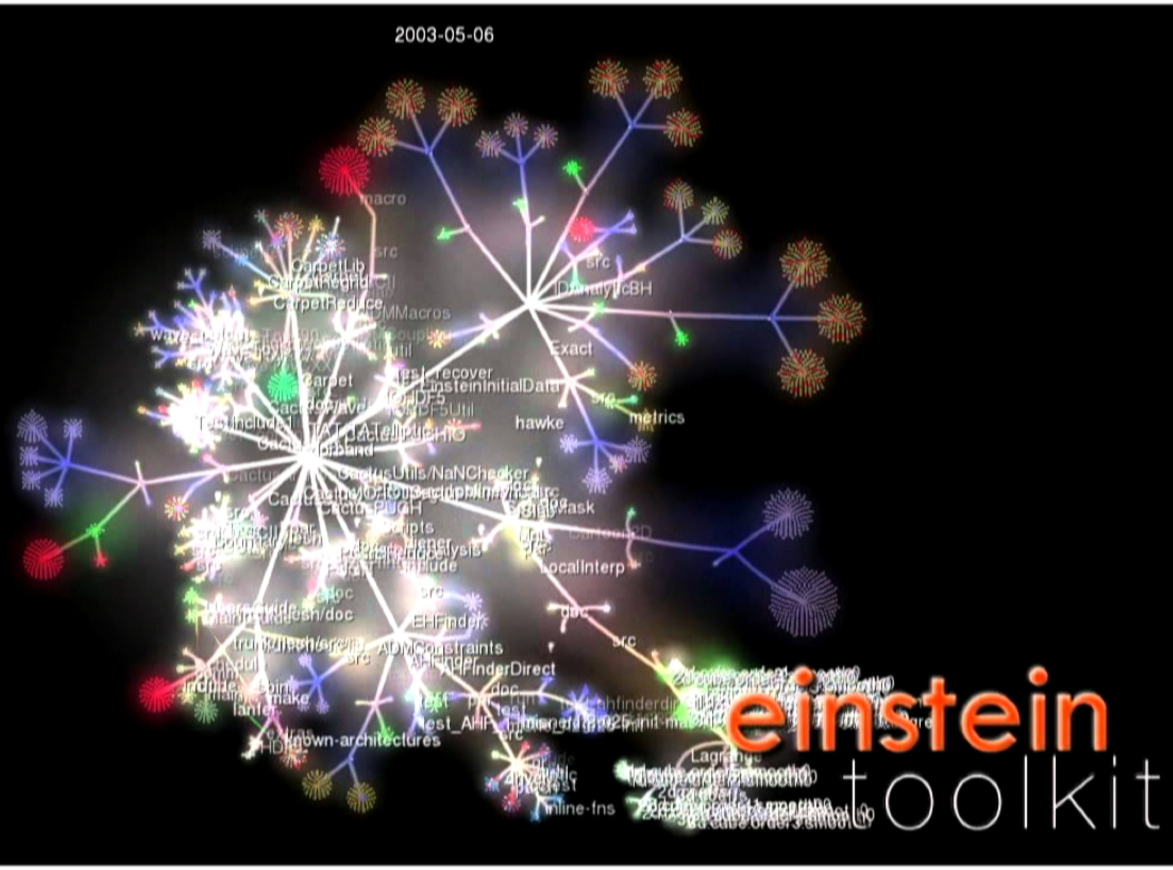


3+1 split of spacetime:
reformulation as an initial value problem

Weak interactions (neutrinos):

$$\begin{aligned} &e^+ + n \leftrightarrow p + \bar{\nu}_e \\ &e^- + p \leftrightarrow n + \nu_e \\ &e^+ + e^- \rightarrow \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau} \\ &\gamma \rightarrow \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau} \end{aligned} \quad \Rightarrow \quad \Psi^\nu,\ \mathcal{R}$$

High performance computing infrastructure



GRHydro: defining the state-of-the-art of GRMHD

GRHydro+

Siegel & Metzger 2017b
Siegel+ 2017

- evolved version of original GRHydro Moesta+ 2014
- ideal GRMHD
- dynamic and fixed spacetimes
- now supports realistic (tabulated) 3-parameter (nuclear) EOS
- new enhanced methods for primitive recovery to support evolved microphysics
- new implementation of weak interactions & approximate neutrino transport
- benefits from the *Einstein Toolkit*
  - ⟶ provides spacetime solver, AMR (nested, moving boxes), multi-patch spherical grids, general infrastructure for HPC

➡ most advanced code for NS mergers!

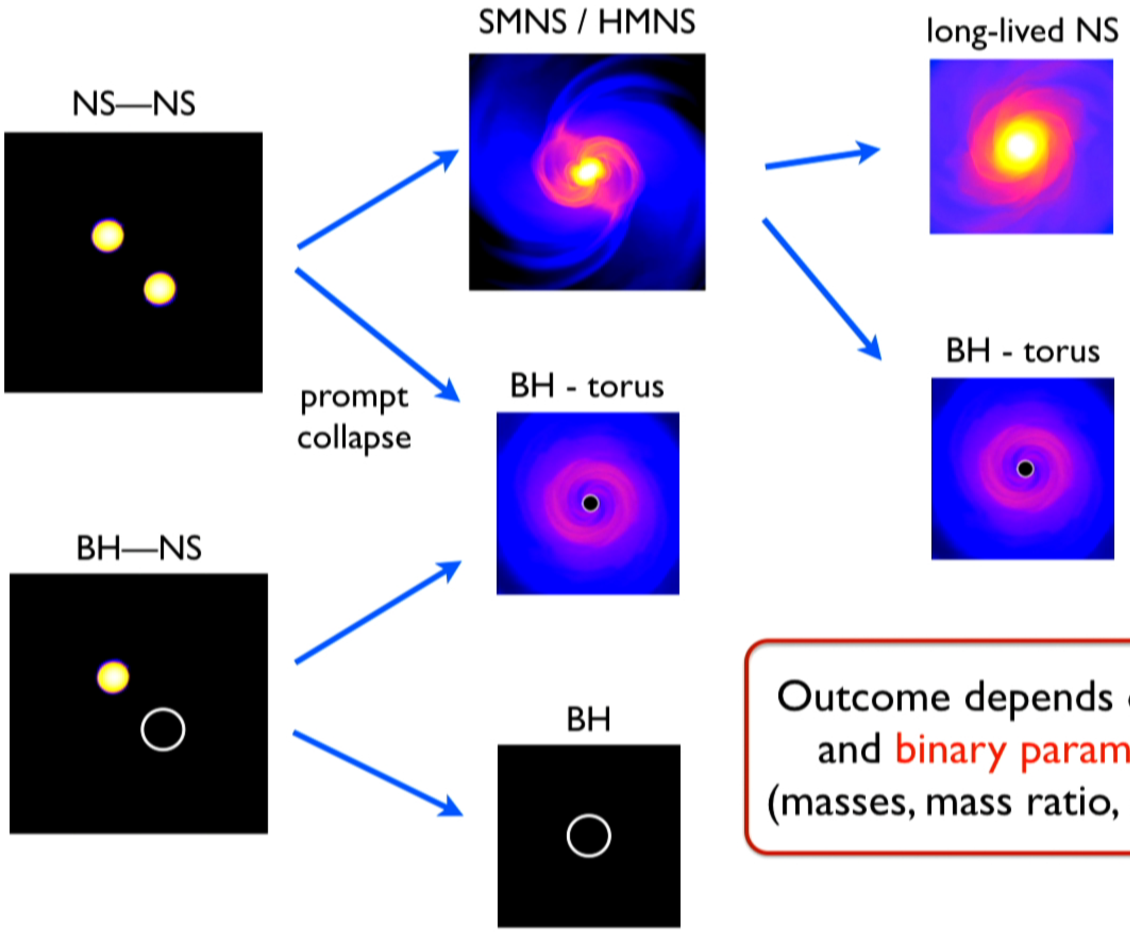
High Performance Computing (HPC)

Pleiades, NASA: 246048 CPUs, 7.25 Pflop/s

SuperMUC, LRZ, Germany: 241000 CPUs, 6.8 Pflop/s

NS merger phenomenology and mass ejection

NS merger phenomenology



NS—NS

BH—NS

prompt
collapse

SMNS / HMNS

BH - torus

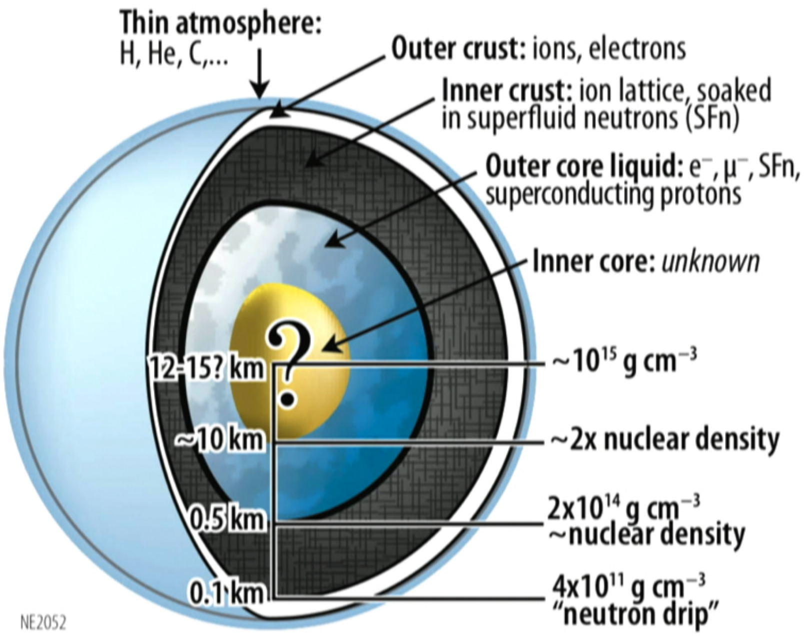
BH

long-lived NS

BH - torus

Outcome depends on EOS
and binary parameters
(masses, mass ratio, spin, …)

Inferring nuclear matter at high densities



credit: NASA

Hyperons, quarks, QCD phase transitions, …?

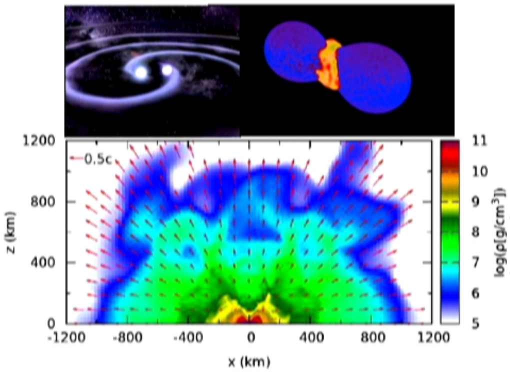
NS mergers provide a laboratory to explore properties of nuclear matter at densities inaccessible on Earth!

Sources of ejecta in NS mergers

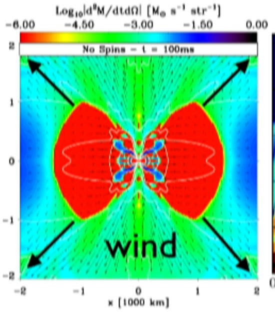
dynamical ejecta (~ms)

winds from NS remnant (~10ms-1s)

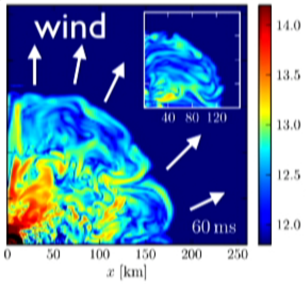
accretion disk (~10ms-1s)



Hotokezaka+ 2013, Bauswein+ 2013

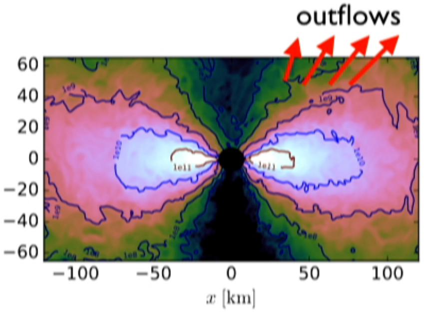


Dessart+ 2009



Siegel+ 2014

Ciolfi, Siegel+ 2017



Siegel & Metzger 2017 a,b

tidal ejecta

shock-heated ejecta

$M_{\rm tot} \lesssim 10^{-3} {\rm M}_\odot$

$v \gtrsim 0.2c$

neutrino-driven wind

$\dot{M}_{\rm in} \sim (10^{-4} - 10^{-3}) {\rm M}_\odot {\rm s}^{-1}$

magnetically driven wind

$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$

thermal outflows

$M_{\rm tot} \gtrsim 0.3 - 0.4 M_{\rm disk}$

$v \sim 0.1c$

Overall ejecta mass per event:

$$\lesssim 10^{-3} - 10^{-2}\, M_\odot$$

strongly depends on EOS and mass ratio

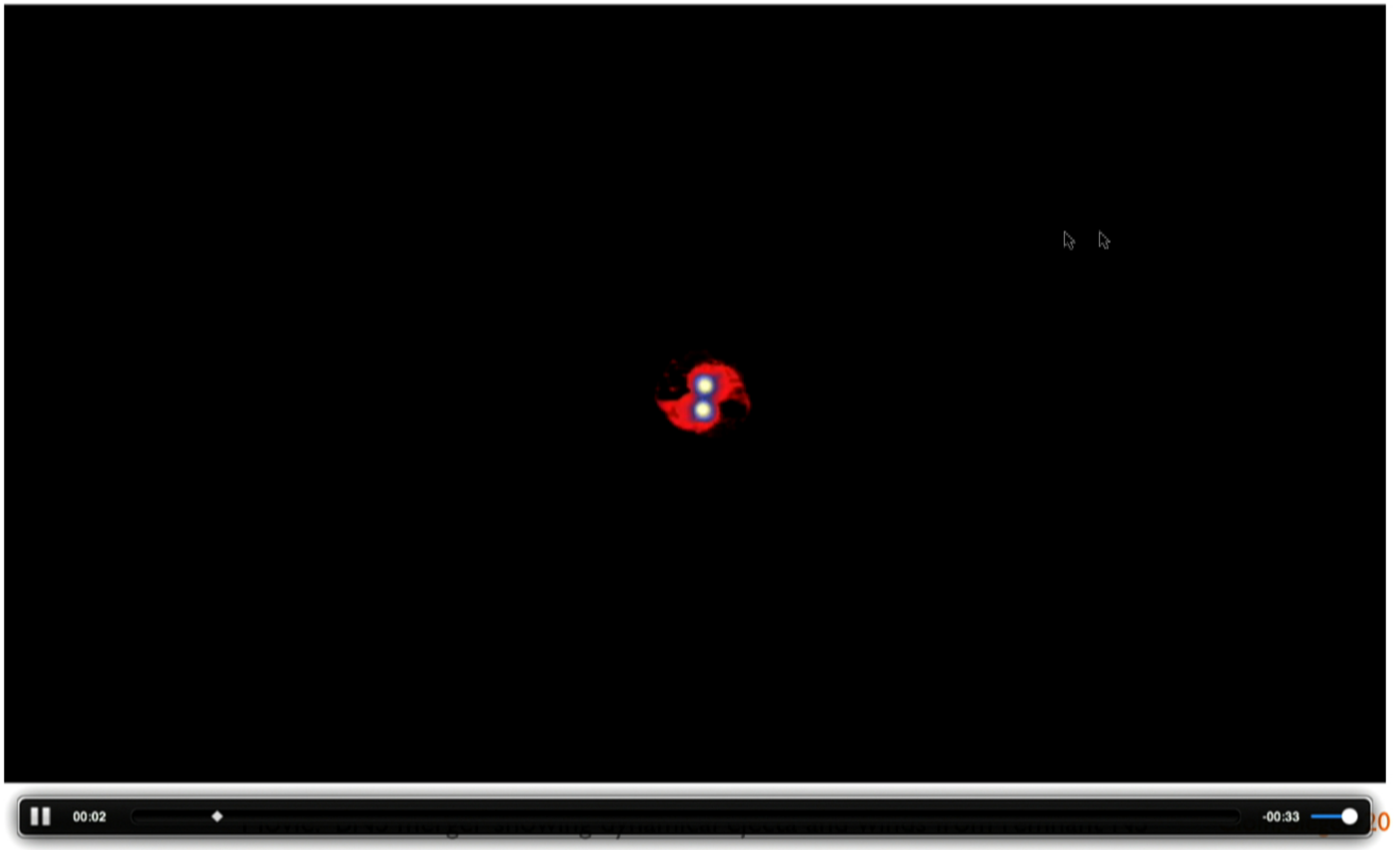
Bauswein+ 2013
Radice+ 2016, 2017
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Ciolfi, Siegel+2017

Siegel & Metzger 2017 a,b

$$\gtrsim 10^{-2} M_\odot$$

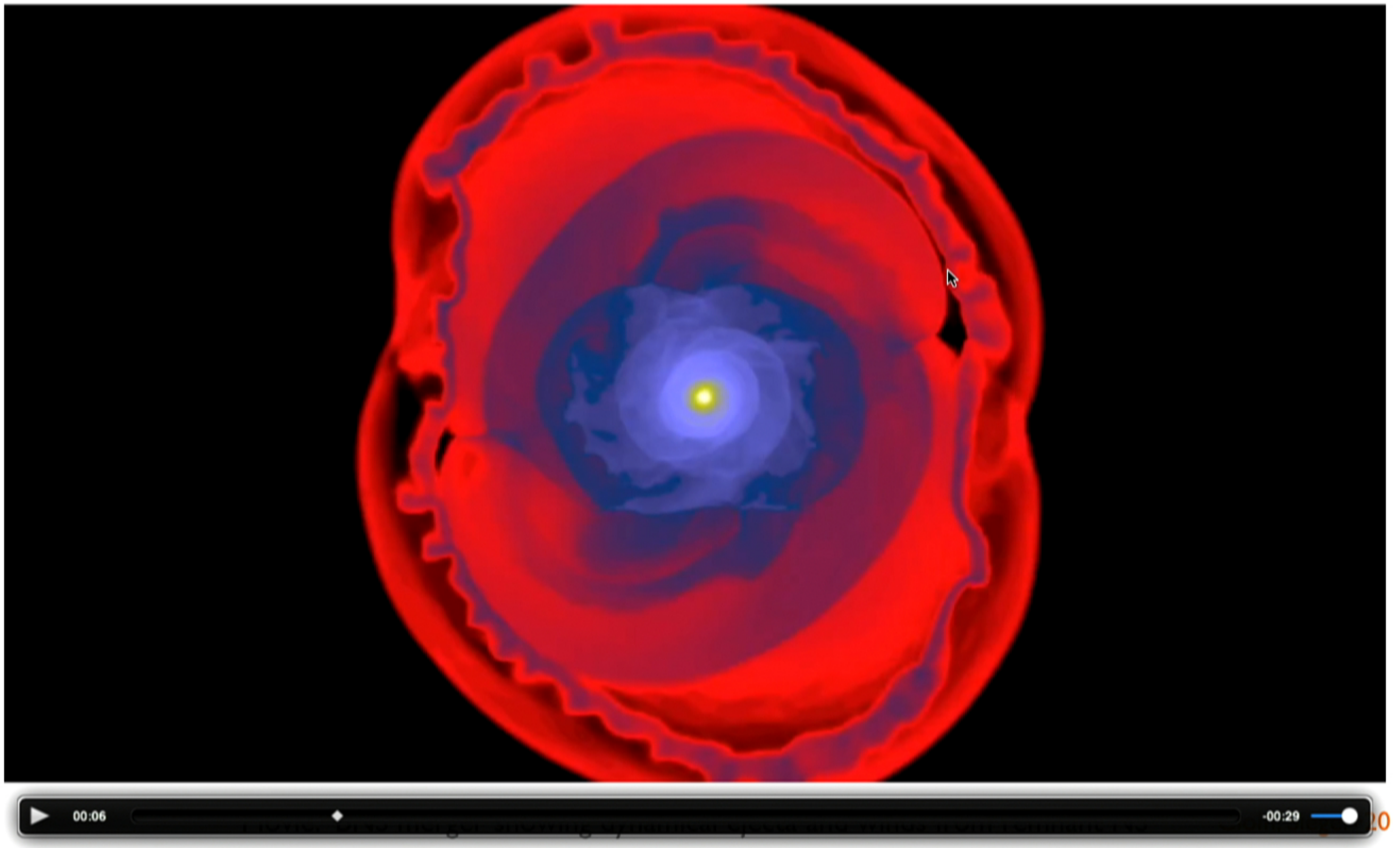
lower limit

Dynamical ejecta and winds



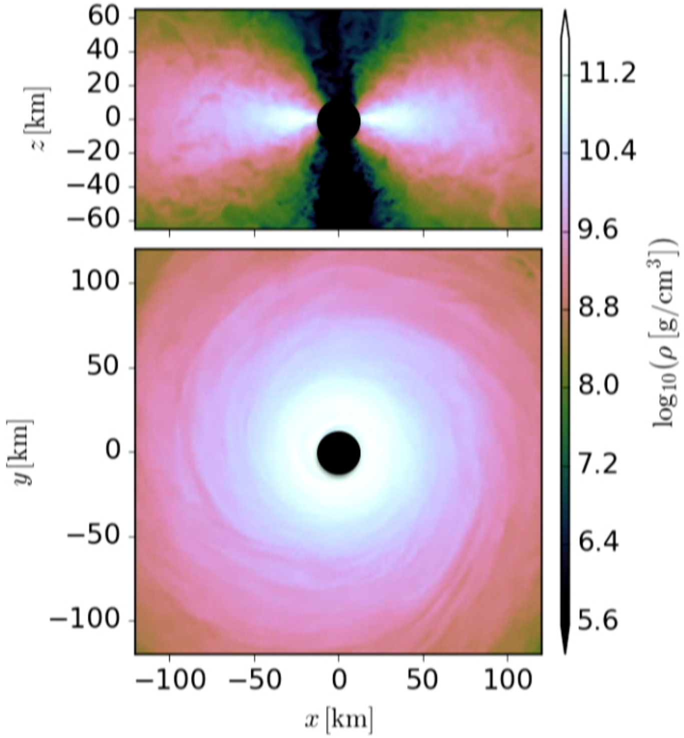
2017

Dynamical ejecta and winds



017

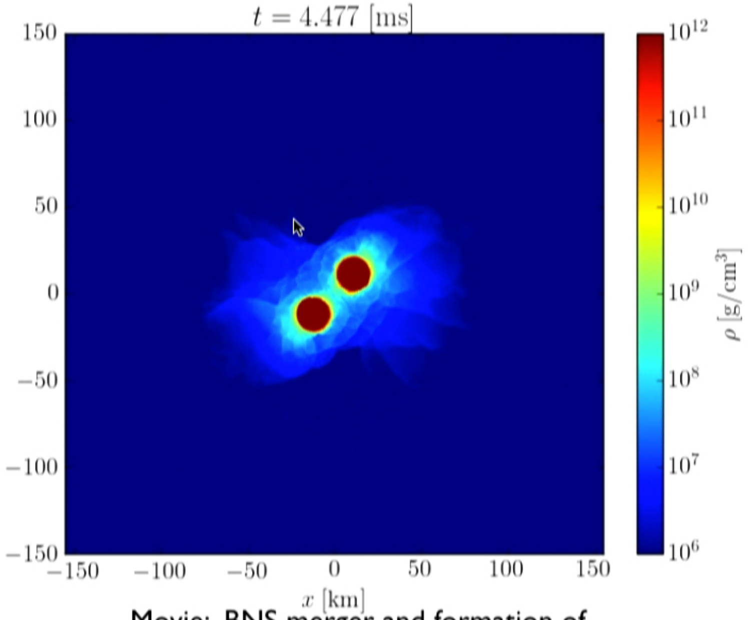
Accretion disk outflows



$t = 32.547\,\mathrm{ms}$

Movie: long-term evolution of post-merger accretion disk, M_{BH}=3Msun (spin: 0.8), M_{disk}=0.02Msun

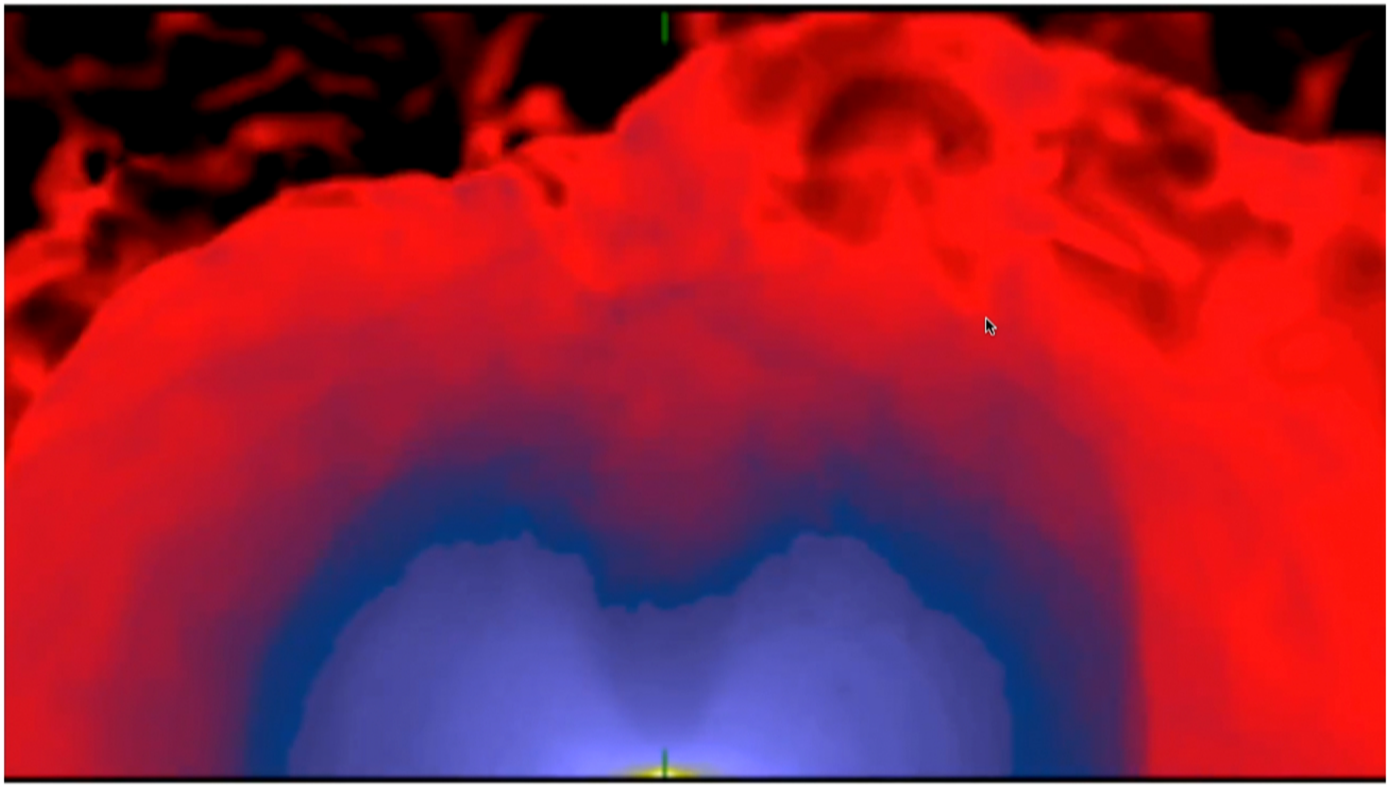
Siegel & Metzger 2017a, PRL   Siegel & Metzger 2017b



Movie: BNS merger and formation of post-merger accretion disk

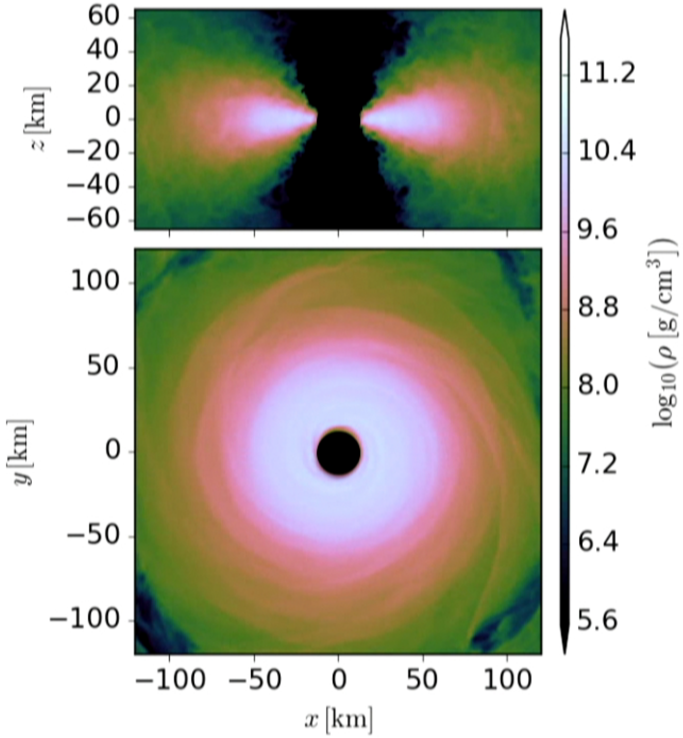
Radice+ 2016

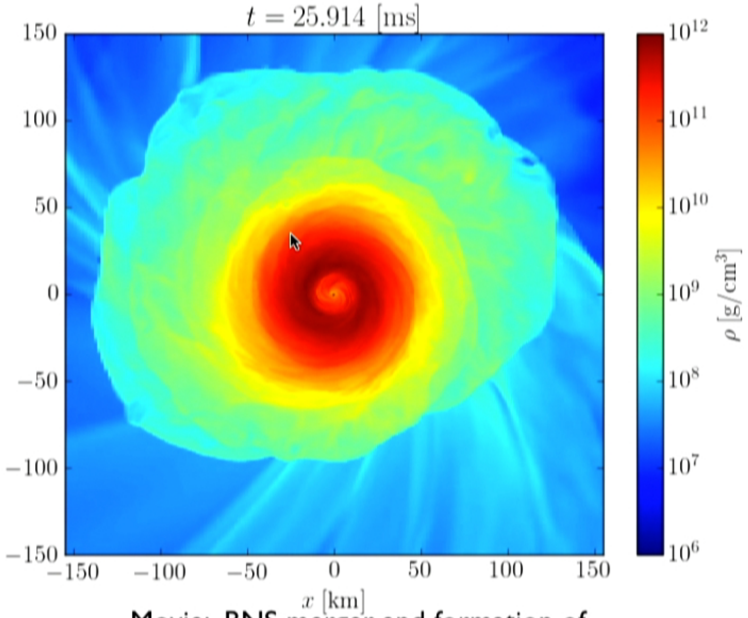
Dynamical ejecta and winds



Movie: BNS merger showing dynamical ejecta and winds from remnant NS Ciolfi, Siegel+2017

Accretion disk outflows





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Radice+ 2016

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Siegel & Metzger 2017a, PRL   Siegel & Metzger 2017b

Mass ejection generates kilonovae

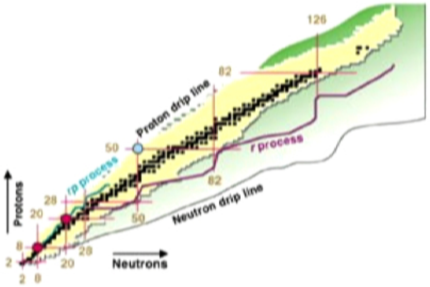
neutron rich ejecta from NS-NS or NS-BH mergers (Y_e~0.1-0.4)

~1s — decompression, rapid neutron capture (r-process)

heavy radioactive elements

~ days — alpha, beta decay, nuclear fission, further expansion

thermal emission (kilonova)
(quasi isotropic, long lasting: ~days)



Most simple kilonova model:

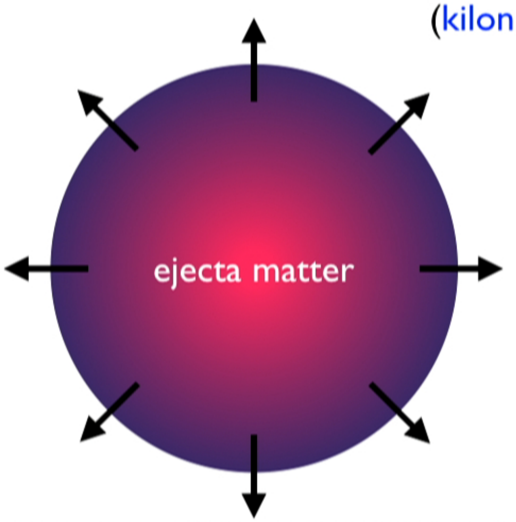
Piran+ 2013, Metzger+ 2017

$$\frac{dE_v}{dt} = -\frac{E_v}{t} - \frac{E_v}{t_{\rm diff}} + \dot{Q}_v$$

adiabatic losses

radiative luminosity (kilonova)

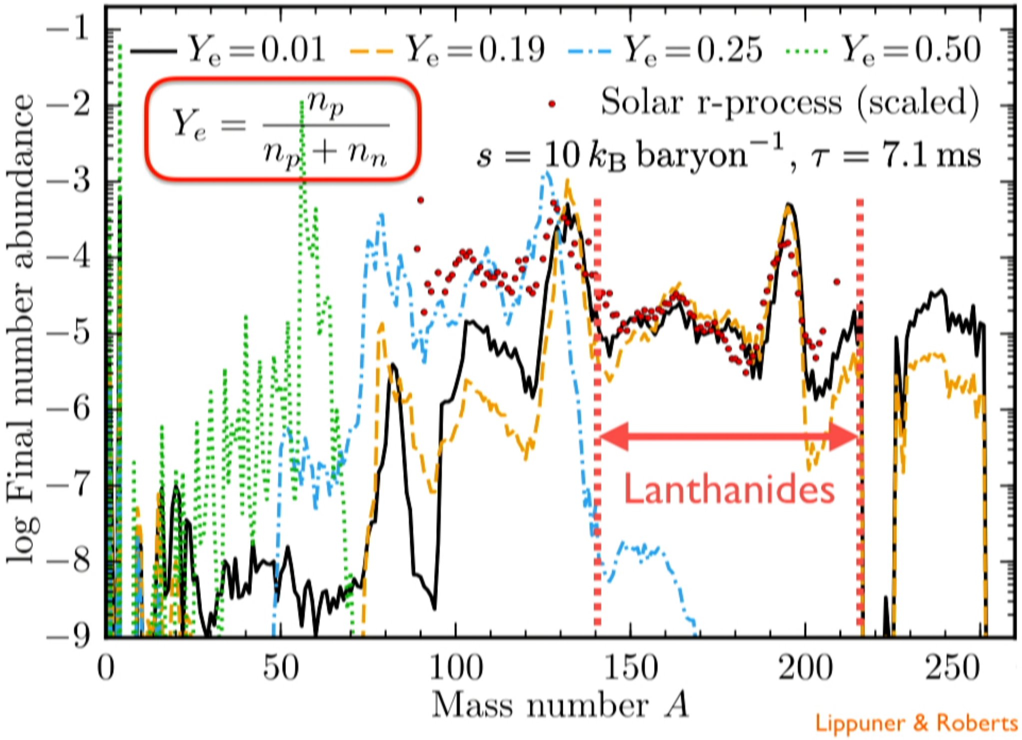
radioactive heating (r-process)



homologous expansion

r-process: strongly dependent on composition

fewer free n per seed ⟷ more free n per seed



Lippuner & Roberts 2015

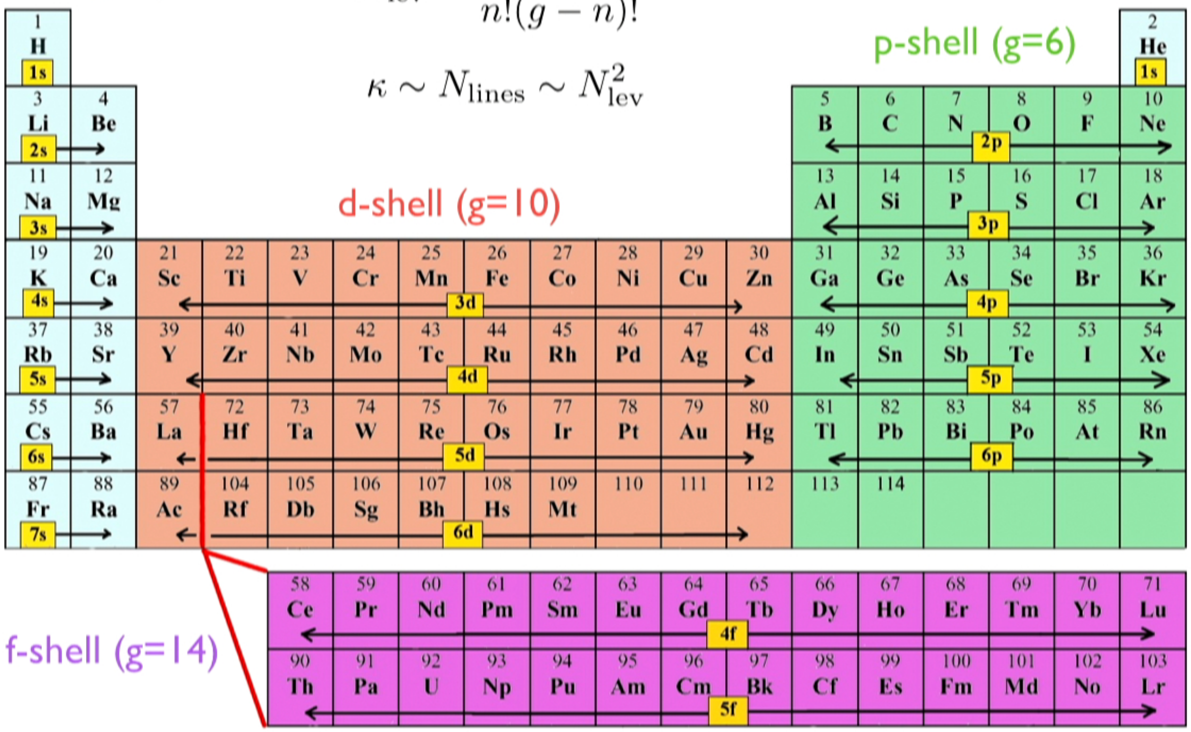
→ importance of accurate neutrino physics in simulations!

High opacities of the Lanthanides

Kasen+ 2013, Barnes & Kasen 2013

$$N_{\rm lev} \sim \frac{g!}{n!(g-n)!}$$

$$\kappa \sim N_{\rm lines} \sim N_{\rm lev}^2$$



s-shell (g=2)

p-shell (g=6)

d-shell (g=10)

f-shell (g=14)

1 H 1s																	2 He 1s
3 Li 2s	4 Be											5 B	6 C	7 N	8 O 2p	9 F	10 Ne
11 Na 3s	12 Mg											13 Al	14 Si	15 P 3p	16 S	17 Cl	18 Ar
19 K 4s	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe 3d	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As 4p	34 Se	35 Br	36 Kr
37 Rb 5s	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru 4d	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb 5p	52 Te	53 I	54 Xe
55 Cs 6s	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os 5d	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po 6p	85 At	86 Rn
87 Fr 7s	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs 6d	109 Mt	110	111	112	113	114				
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb 4f	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk 5f	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

High opacities of the Lanthanides

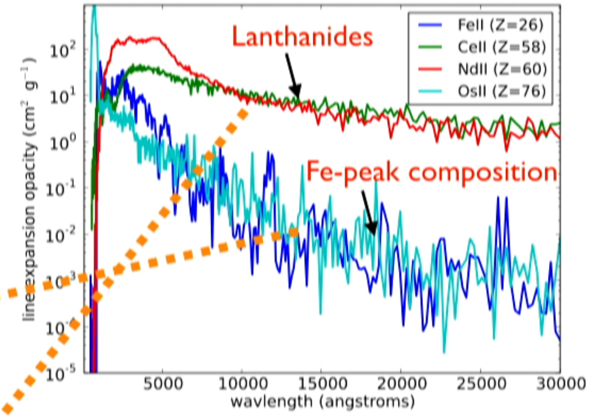
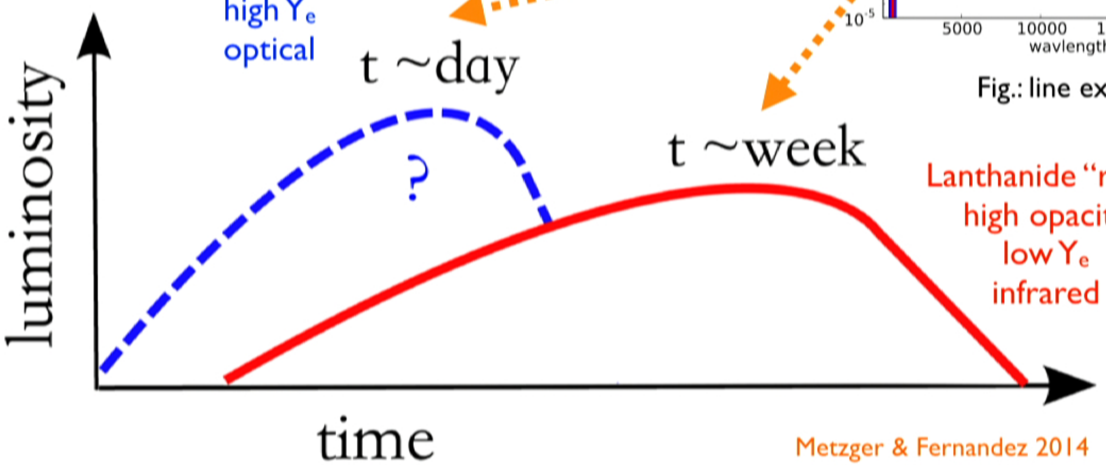


Fig.: line expansion opacities

Kasen+ 2013

Lanthanide "free"
low opacity
high Y_e
optical



Lanthanide "rich"
high opacity
low Y_e
infrared

Metzger & Fernandez 2014

Fig.: kilonova lightcurves probe composition (Lanthanide mass fraction).

The kilonova of GW170817

- blue kilonova properties:

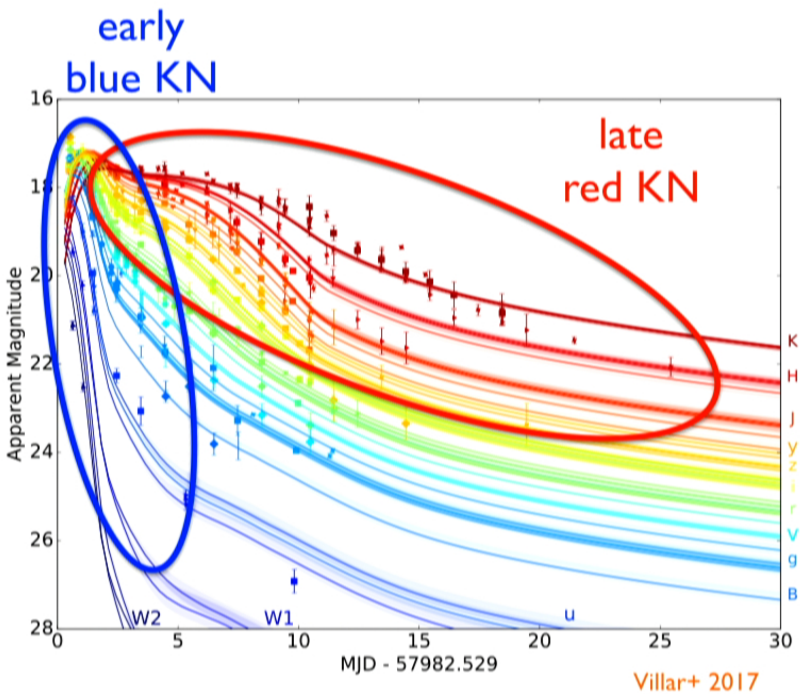
  $M_{ej} \sim 10^{-2} M_{sun}$
  $v_{ej} \sim 0.2\text{-}0.3c$
  $Y_e > 0.25$
  $X_{La} < 10^{-4}$
  low opacity

  Kilpatrick+ 2017
  Kasen+ 2017
  Nicholl+ 2017
  Villar+ 2017

- red kilonova properties:

  $M_{ej} \sim 4\text{-}5 \times 10^{-2} M_{sun}$
  $v_{ej} \sim 0.08\text{-}0.14c$
  $Y_e < 0.25$
  $X_{La} \sim 0.01$
  high opacity

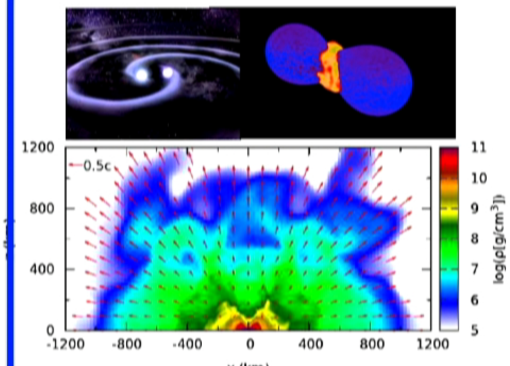
  Kilpatrick+ 2017
  Kasen+ 2017
  Kasliwal+ 2017
  Drout+ 2017
  Cowperthwaite+ 2017
  Chornock+ 2017
  Villar+ 2017



Villar+ 2017

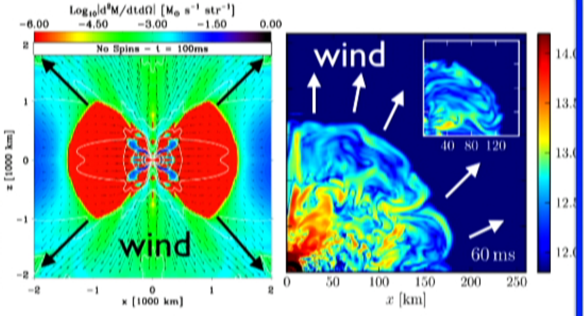
Sources of ejecta for kilonova in GW170817

dynamical ejecta (~ms)



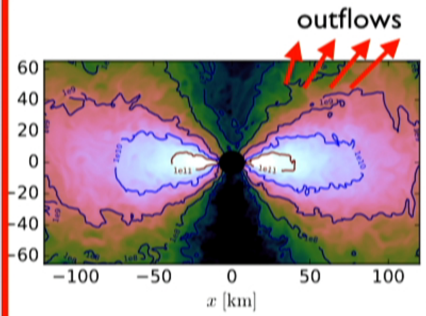
$$M_{\rm tot} \lesssim 10^{-3} {\rm M}_\odot$$
$$v \gtrsim 0.2c$$

winds from NS remnant (~ms-1s)



$$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$$
$$v \lesssim 0.1c$$

accretion disk (~10ms-1s)



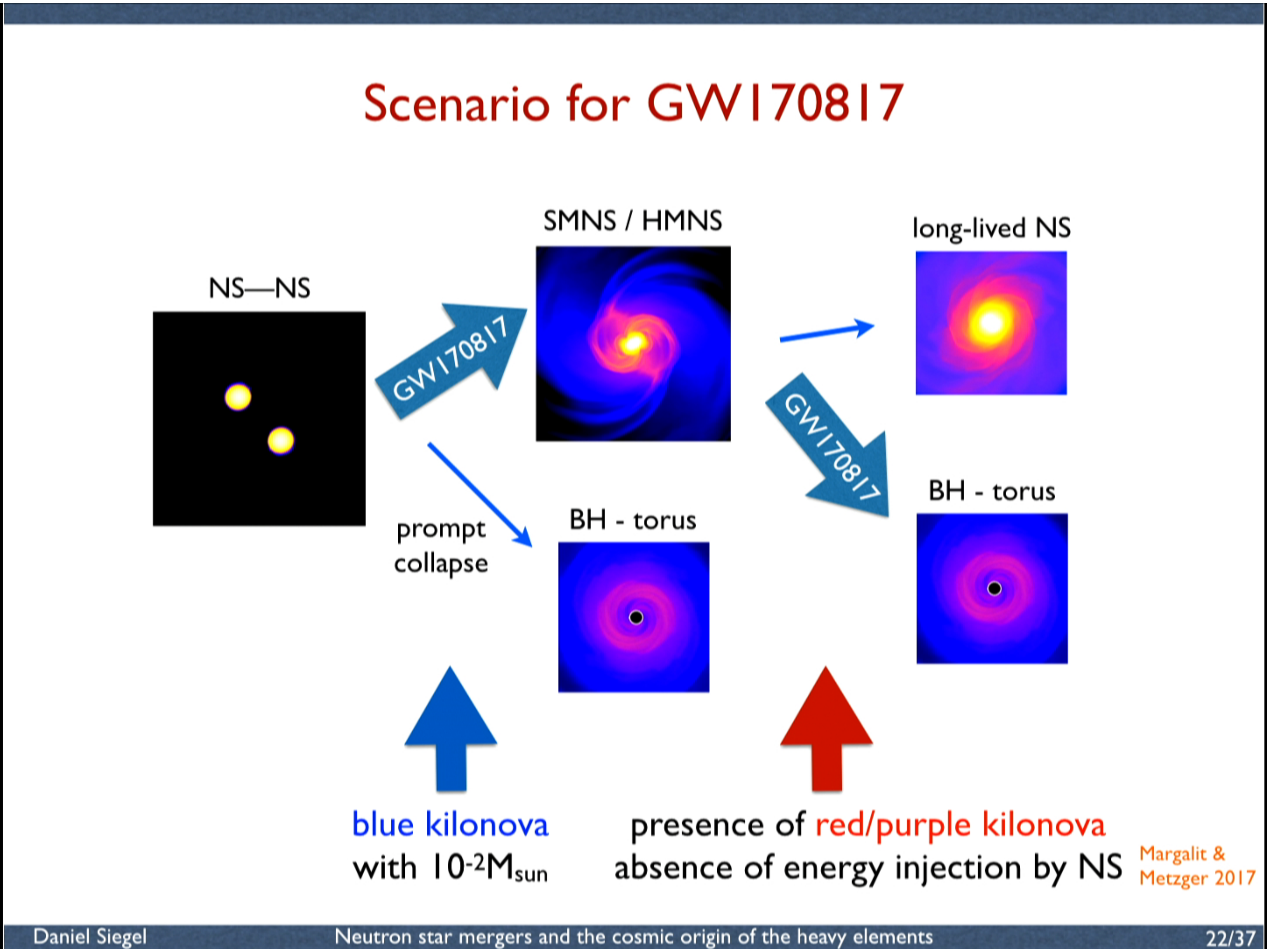
$$M_{\rm tot} \gtrsim 10^{-2} M_\odot$$
$$v \sim 0.1c$$

blue KN in GW170817

- → requires large amount of shock heated ejecta to obtain high $Y_e > 0.25$
- → requires metastable NS phase
- → requires EOS with small NS radius (~12 km)

red KN in GW170817

- → produces the heavy r-process elements in GW170817 (Y_e<0.25)



Scenario for GW170817

NS—NS

SMNS / HMNS

long-lived NS

GW170817

prompt collapse

BH - torus

GW170817

BH - torus

blue kilonova
with $10^{-2} M_{sun}$

presence of red/purple kilonova
absence of energy injection by NS

Margalit & Metzger 2017

What is the physical site that produces the heavy elements?

Post-merger accretion disks

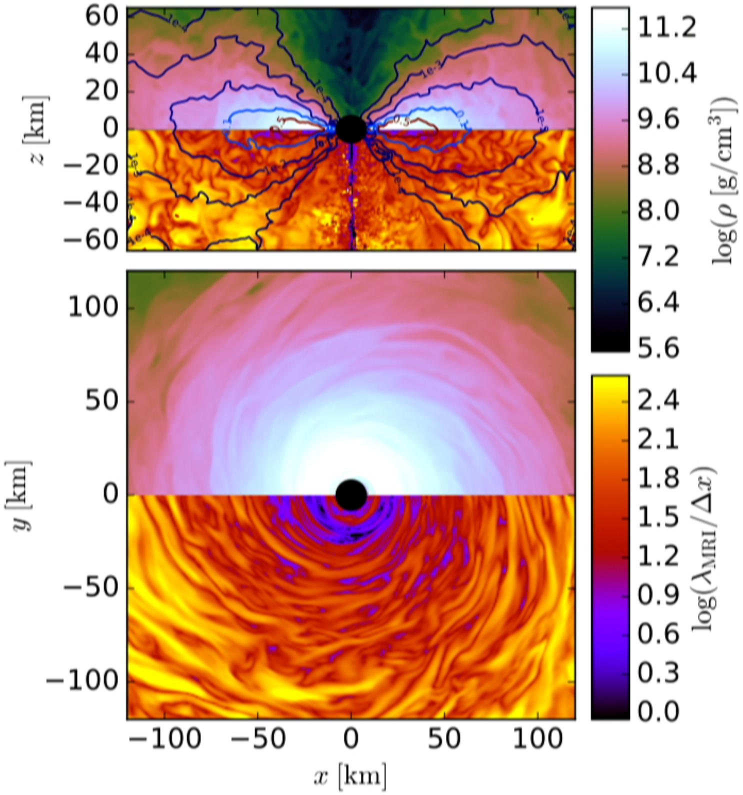


Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017a, PRL   Siegel & Metzger 2017b

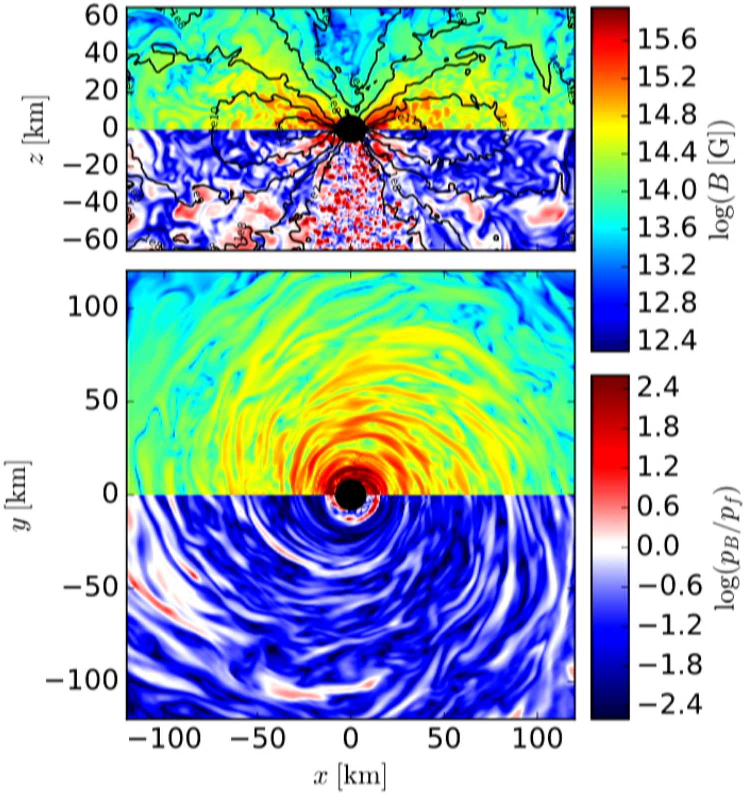
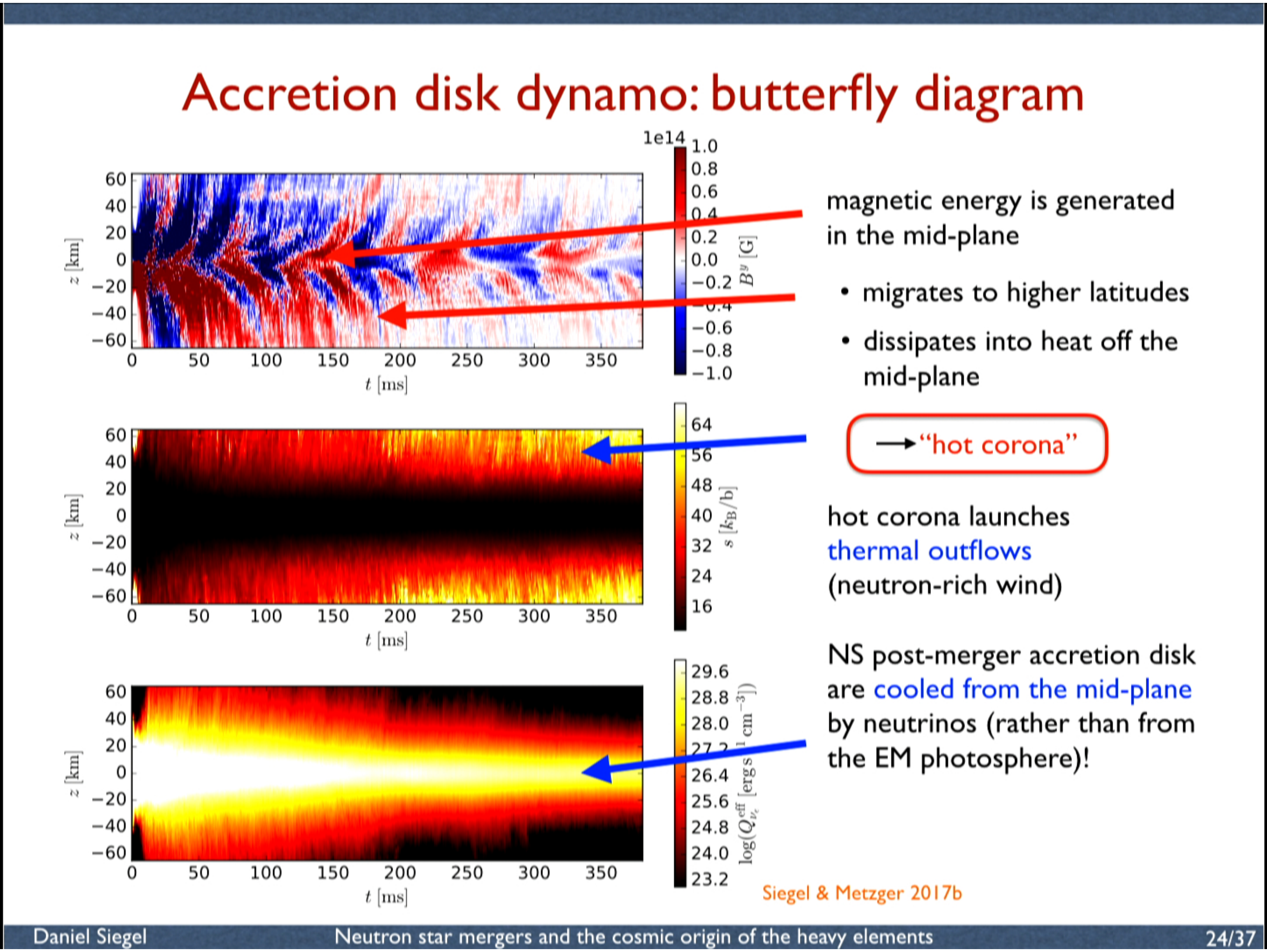


Fig.: magnetic fields in the disk; contours: rest-mass density

magnetic properties very similar to Ciolfi+ 2017, Kiuchi+ 2015



Accretion disk dynamo: butterfly diagram

magnetic energy is generated in the mid-plane

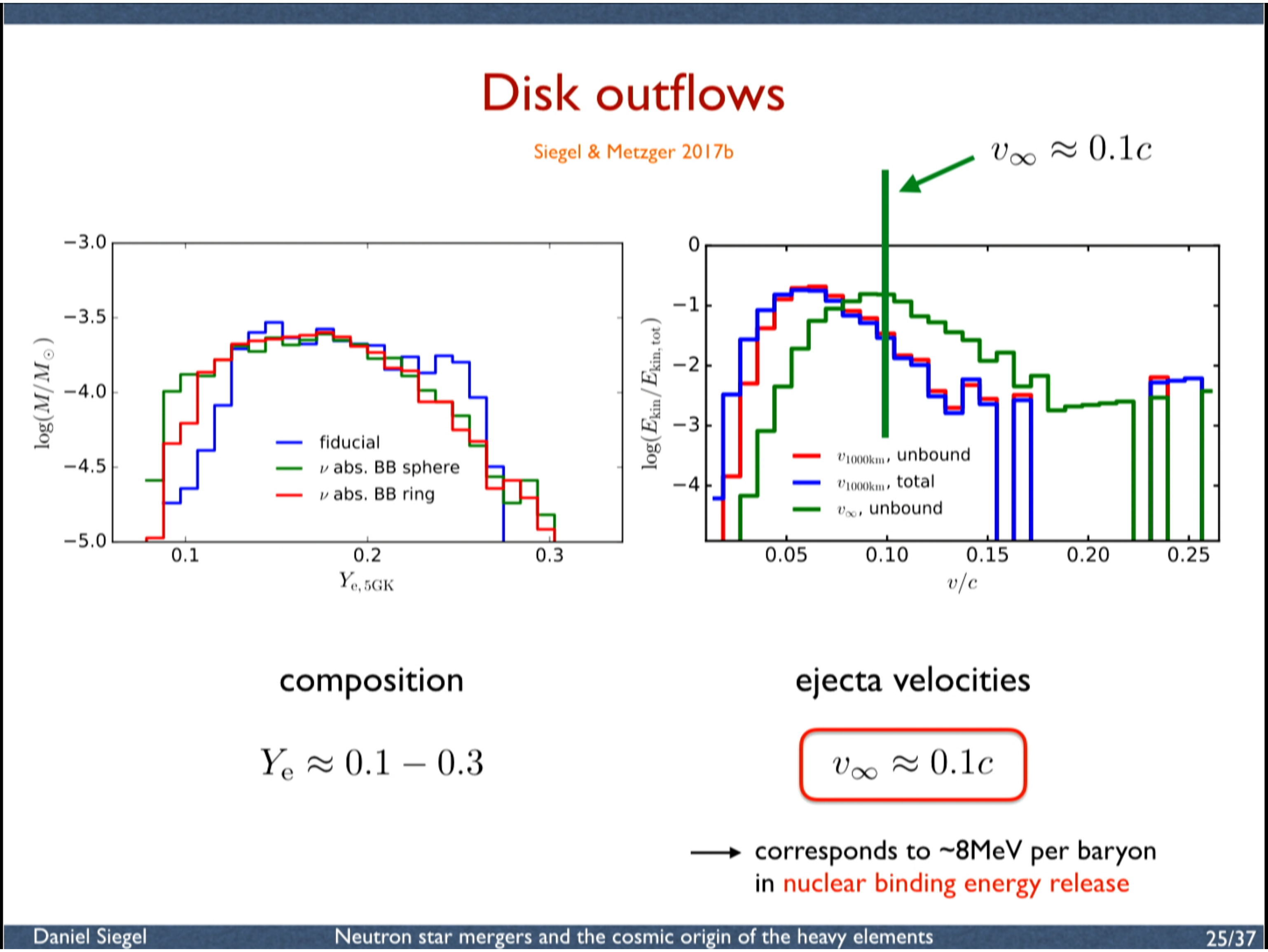
- migrates to higher latitudes
- dissipates into heat off the mid-plane

→ "hot corona"

hot corona launches thermal outflows (neutron-rich wind)

NS post-merger accretion disk are cooled from the mid-plane by neutrinos (rather than from the EM photosphere)!

Siegel & Metzger 2017b



Disk outflows

Siegel & Metzger 2017b

$v_\infty \approx 0.1c$

composition

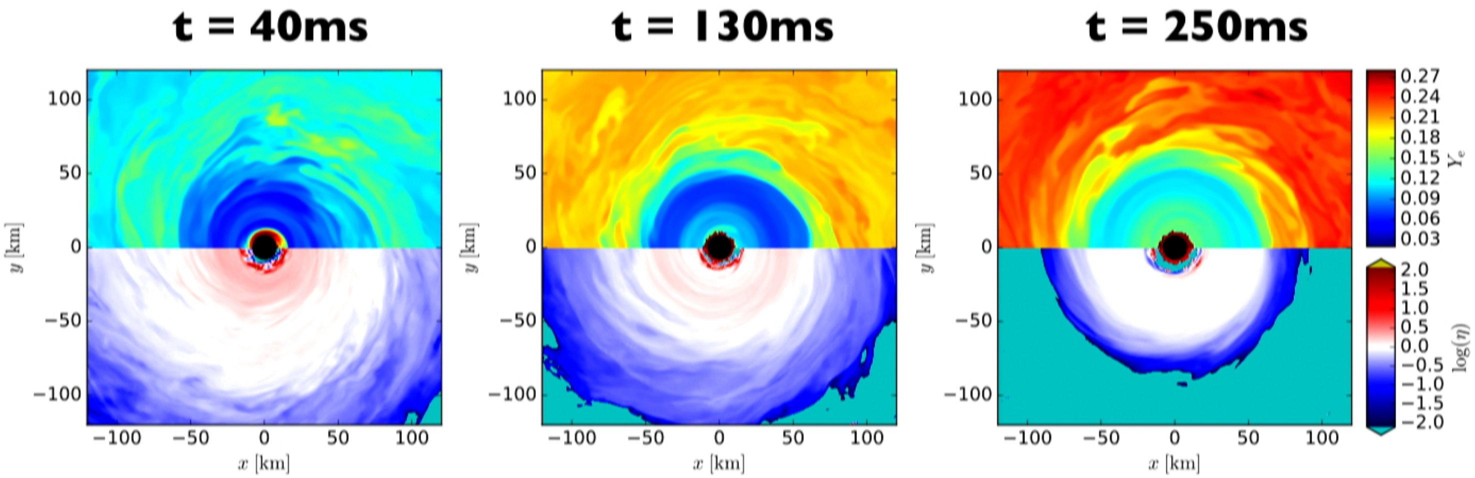
$Y_\mathrm{e} \approx 0.1 - 0.3$

ejecta velocities

$\boxed{v_\infty \approx 0.1c}$

→ corresponds to ~8MeV per baryon in nuclear binding energy release

Why are the disk outflows neutron-rich?



Siegel & Metzger 2017b

Neutron-rich conditions favor:

$$e^+ + n \to p + \bar{\nu}_e$$

How can the overall Y_e of the outflow stay low (~0.1-0.2)?

(and produce 3rd peak r-process elements?)

Self-regulation: keeping a neutron-rich reservoir

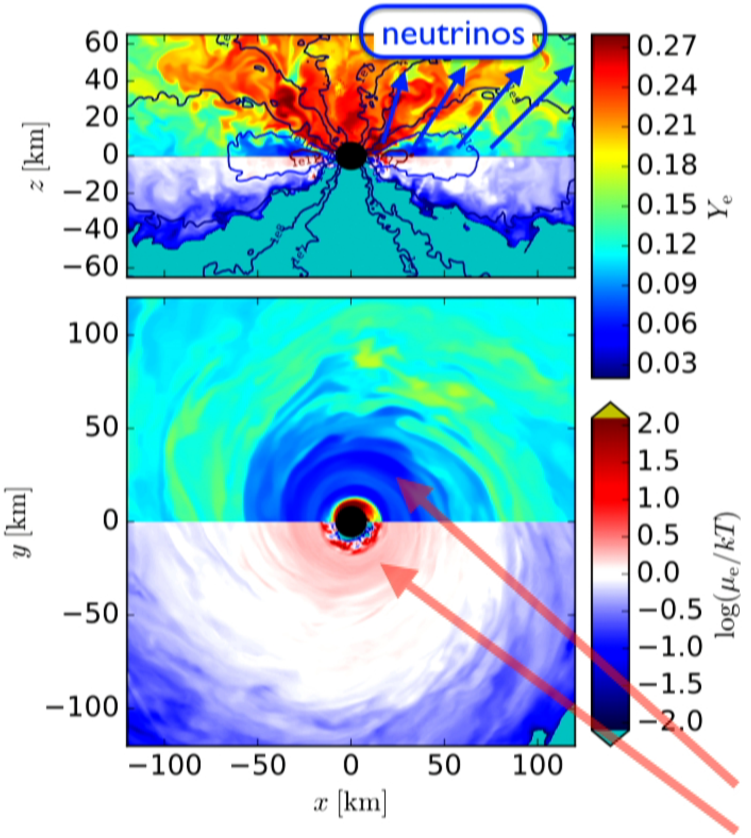


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017a, PRL Siegel & Metzger 2017b

Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low Y_e matter):

Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009

- viscous heating via magnetic turbulence
- neutrino cooling

→ charged-current processes:

$e^- + p \to n + \nu_e$

$e^+ + n \to p + \bar{\nu}_e$

pair annihilation:

$e^- + e^+ \to \nu_e + \bar{\nu}_e$

$e^- + e^+ \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

plasmon decay:

$\gamma \to \nu_e + \bar{\nu}_e$

$\gamma \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

→ balance with feedback mechanism:

higher degeneracy μ_e/kT

fewer e^-, e^+ (lower Y_e)

less neutrino emission, i.e., cooling

higher temperatures

lower degeneracy μ_e/kT

direct evidence of self-regulation

Self-regulation: keeping a neutron-rich reservoir

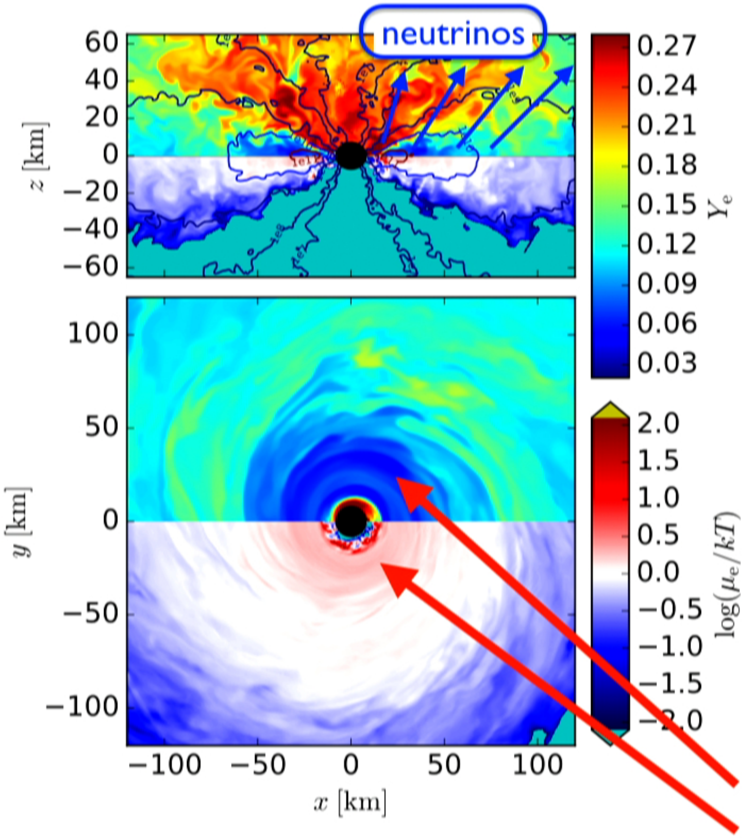


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017a, PRL Siegel & Metzger 2017b

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higher degeneracy μ_e/kT

↓

fewer e^-, e^+ (lower Y_e)

↓

less neutrino emission, i.e., cooling

↓

higher temperatures

↓

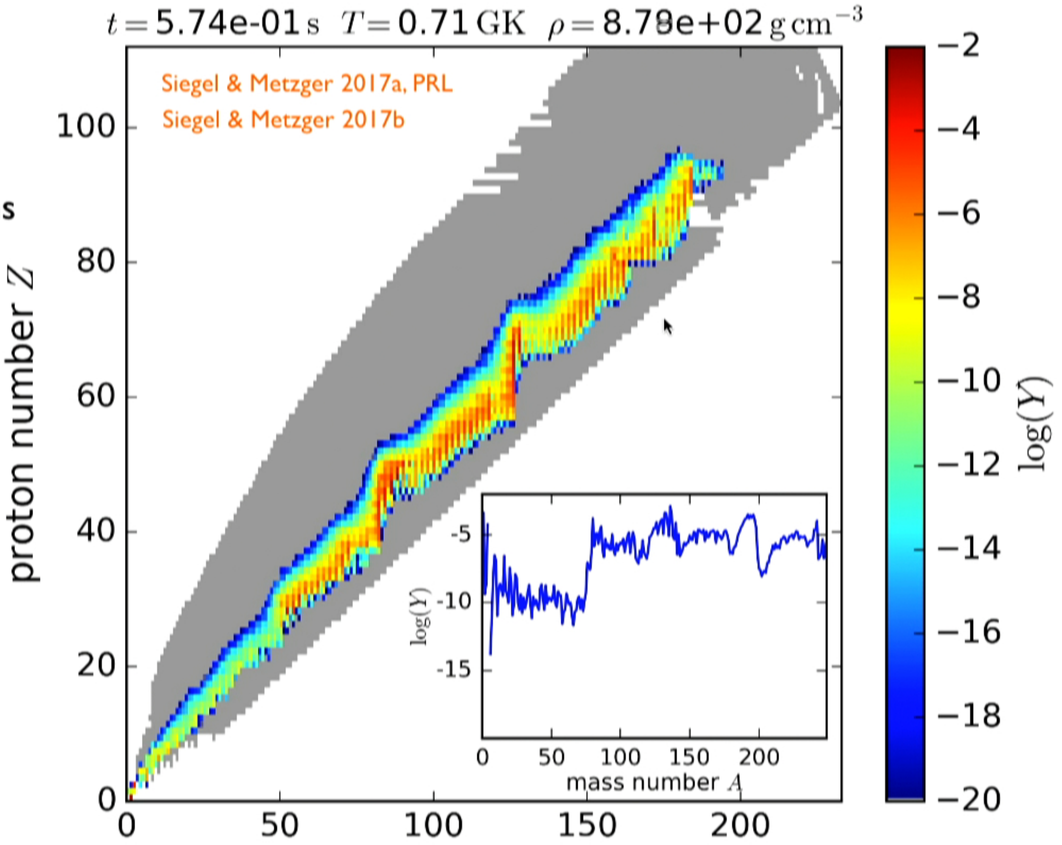
lower degeneracy μ_e/kT

direct evidence of self-regulation

r-process nucleosynthesis in disk outflows

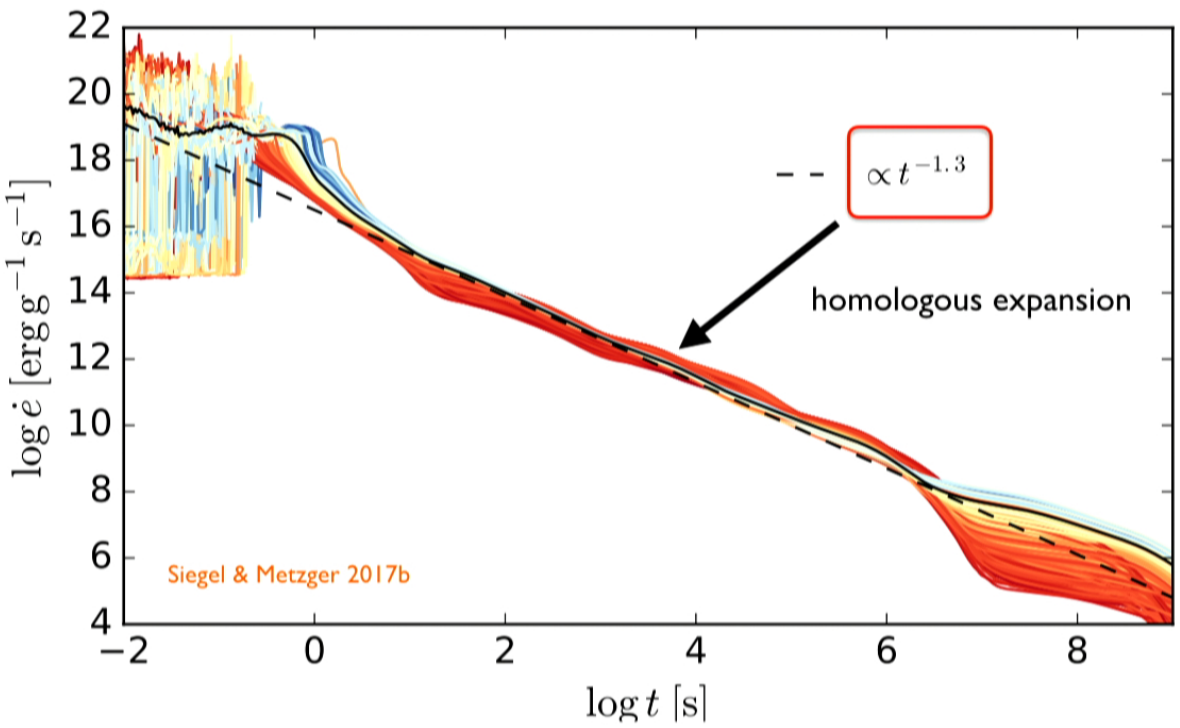
nuclear reaction network (*SkyNet*)

- neutron captures
- photo-dissociations
- α-, β-decays
- fission



Movie: r-process nucleosynthesis from NS merger remnant disks

r-process heating rates



$\propto t^{-1.3}$

homologous expansion

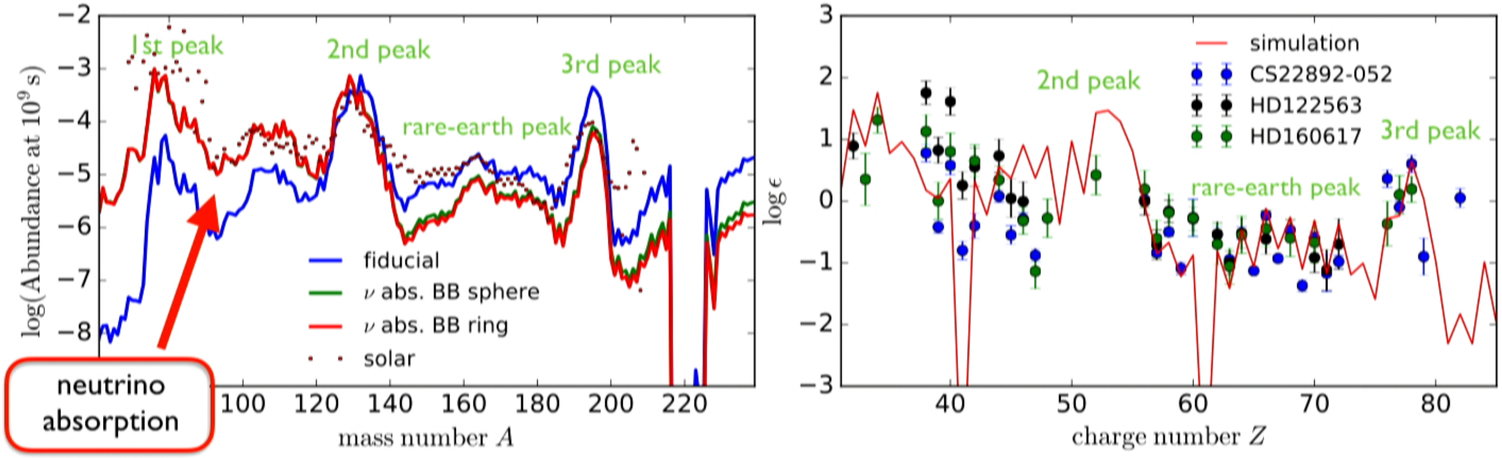
Siegel & Metzger 2017b

Fig: heating rates from r-process nucleosynthesis in disk outflows

→ powers the kilonova!

r-process nucleosynthesis in disk outflows

Siegel & Metzger 2017a, PRL
Siegel & Metzger 2017b

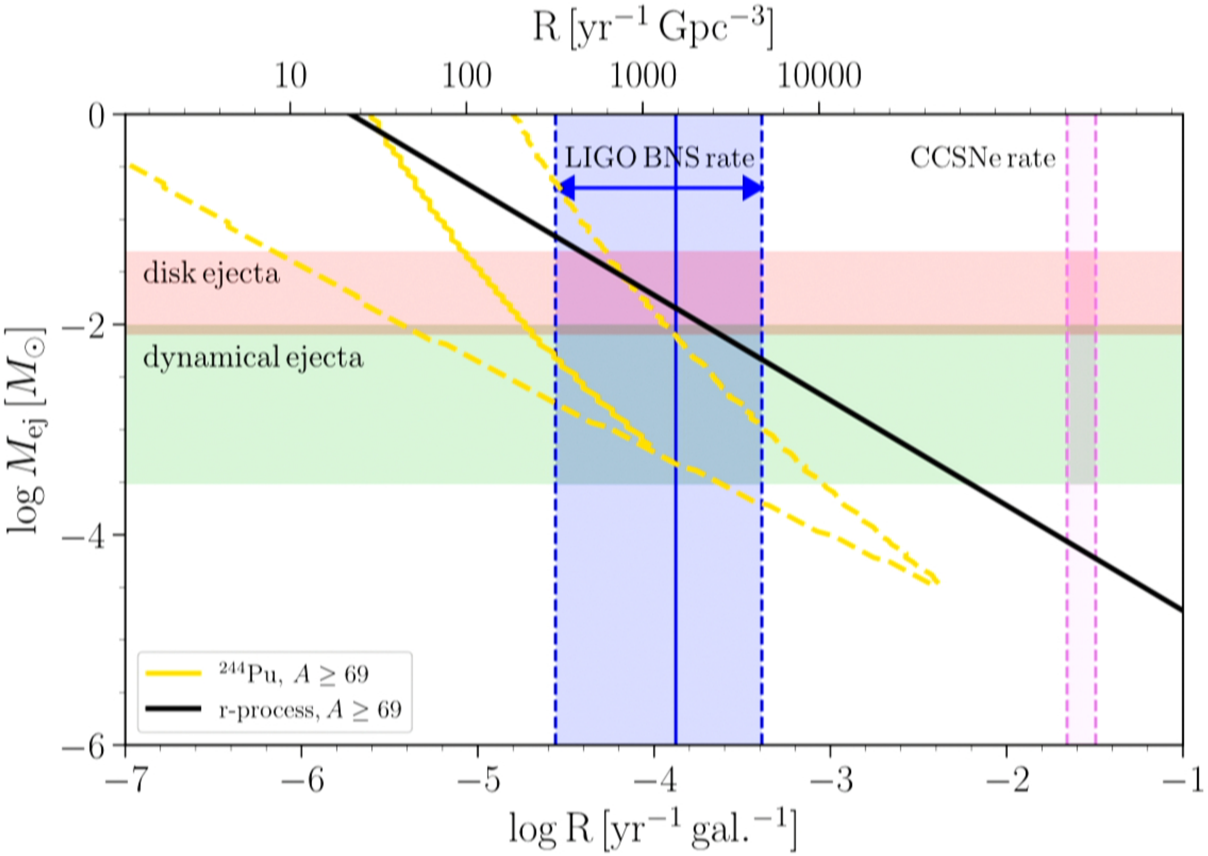


neutrino absorption

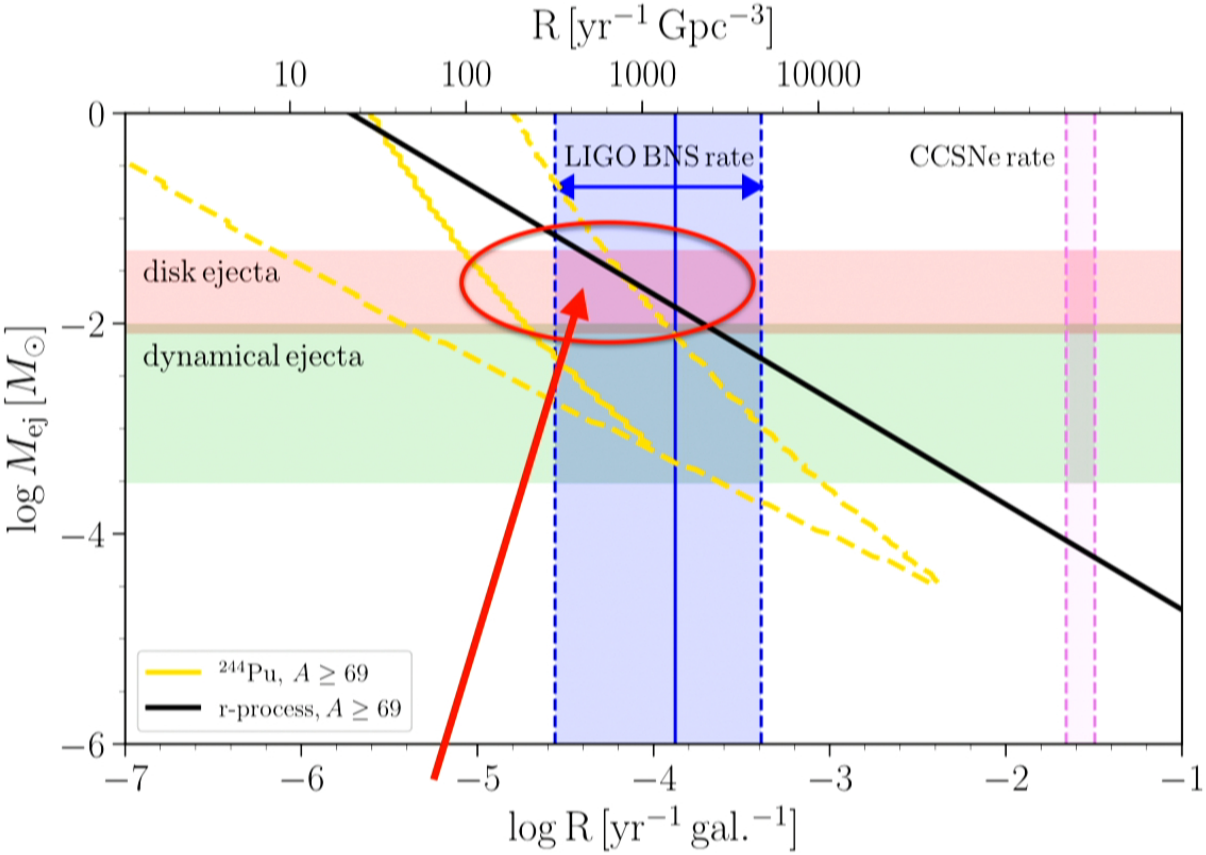
- robust 2nd and 3rd peak r-process!
- including neutrino absorption: additional good fit to 1st & 2nd peak elements

→ production of all r-process elements!

Constraints on r-process nucleosynthesis

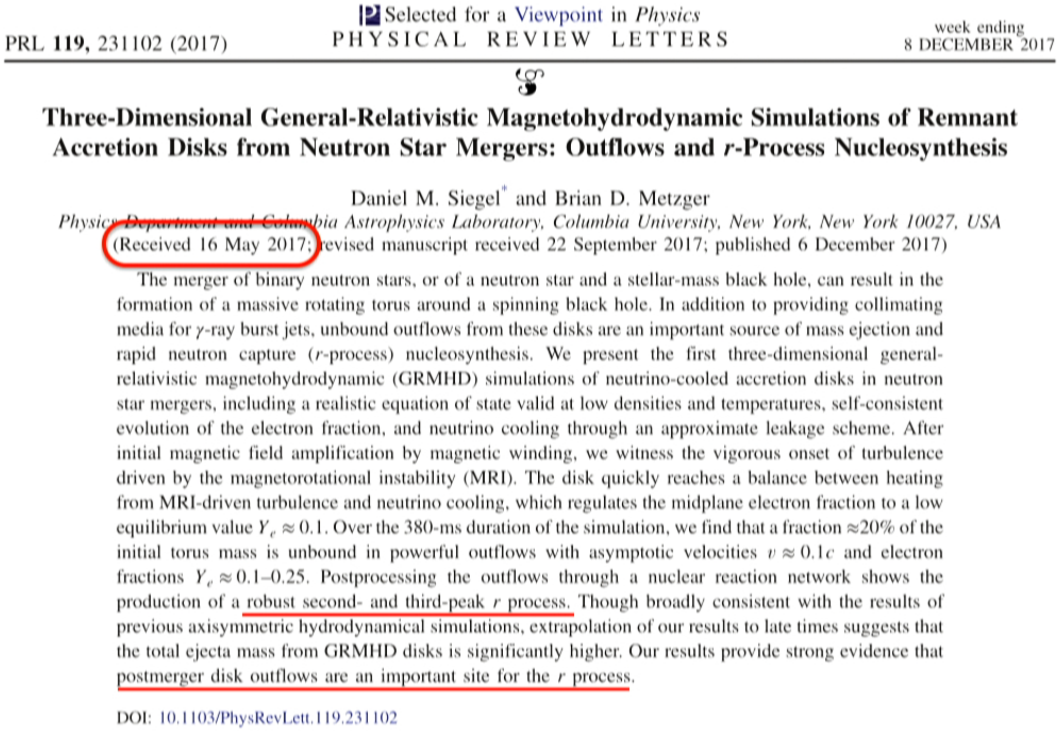


Constraints on r-process nucleosynthesis



post-merger disk outflows are a promising site for the r-process!

A first-principles prediction…



Selected for a Viewpoint in *Physics*
PRL **119,** 231102 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

Three-Dimensional General-Relativistic Magnetohydrodynamic Simulations of Remnant Accretion Disks from Neutron Star Mergers: Outflows and *r*-Process Nucleosynthesis

Daniel M. Siegel* and Brian D. Metzger
Physics Department and Columbia Astrophysics Laboratory, Columbia University, New York, New York 10027, USA

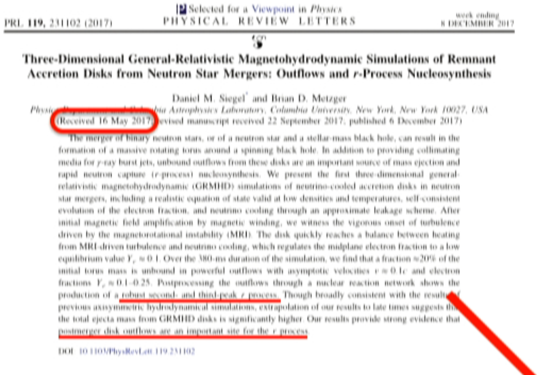
(Received 16 May 2017; revised manuscript received 22 September 2017; published 6 December 2017)

The merger of binary neutron stars, or of a neutron star and a stellar-mass black hole, can result in the formation of a massive rotating torus around a spinning black hole. In addition to providing collimating media for γ-ray burst jets, unbound outflows from these disks are an important source of mass ejection and rapid neutron capture (r-process) nucleosynthesis. We present the first three-dimensional general-relativistic magnetohydrodynamic (GRMHD) simulations of neutrino-cooled accretion disks in neutron star mergers, including a realistic equation of state valid at low densities and temperatures, self-consistent evolution of the electron fraction, and neutrino cooling through an approximate leakage scheme. After initial magnetic field amplification by magnetic winding, we witness the vigorous onset of turbulence driven by the magnetorotational instability (MRI). The disk quickly reaches a balance between heating from MRI-driven turbulence and neutrino cooling, which regulates the midplane electron fraction to a low equilibrium value $Y_e \approx 0.1$. Over the 380-ms duration of the simulation, we find that a fraction $\approx$20% of the initial torus mass is unbound in powerful outflows with asymptotic velocities $v \approx 0.1c$ and electron fractions $Y_e \approx 0.1$–0.25. Postprocessing the outflows through a nuclear reaction network shows the production of a robust second- and third-peak r process. Though broadly consistent with the results of previous axisymmetric hydrodynamical simulations, extrapolation of our results to late times suggests that the total ejecta mass from GRMHD disks is significantly higher. Our results provide strong evidence that postmerger disk outflows are an important site for the r process.

DOI: 10.1103/PhysRevLett.119.231102

post-merger accretion disks as potential main site of r-process nucleosynthesis in NS mergers shortly predicted before GW170817

A first-principles prediction…



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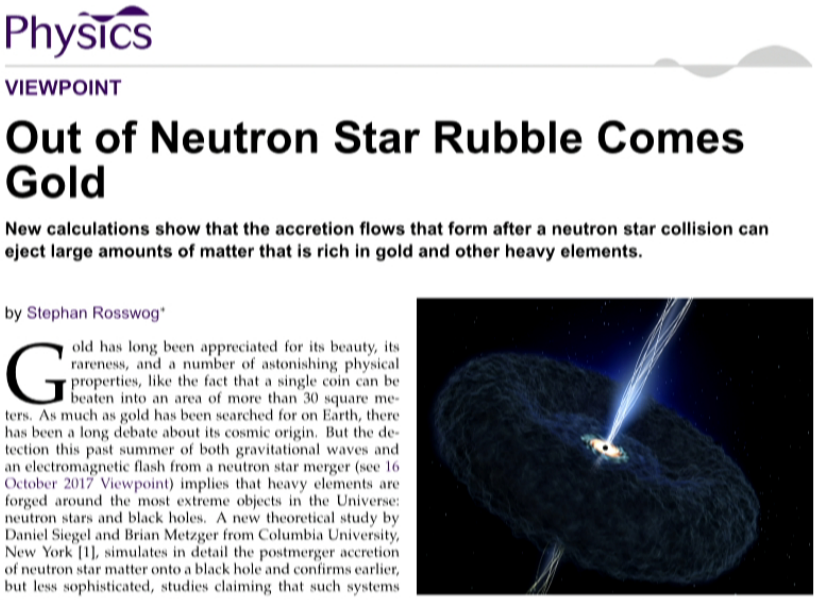
Viewpoint article by Stephan Rosswog



Physics

VIEWPOINT

Out of Neutron Star Rubble Comes Gold

New calculations show that the accretion flows that form after a neutron star collision can eject large amounts of matter that is rich in gold and other heavy elements.

by Stephan Rosswog*

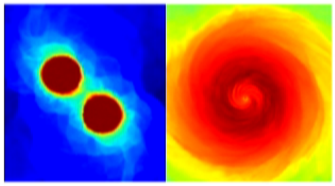
Gold has long been appreciated for its beauty, its rareness, and a number of astonishing physical properties, like the fact that a single coin can be beaten into an area of more than 30 square meters. As much as gold has been searched for on Earth, there has been a long debate about its cosmic origin. But the detection this past summer of both gravitational waves and an electromagnetic flash from a neutron star merger (see 16 October 2017 Viewpoint) implies that heavy elements are forged around the most extreme objects in the Universe: neutron stars and black holes. A new theoretical study by Daniel Siegel and Brian Metzger from Columbia University, New York [1], simulates in detail the postmerger accretion of neutron star matter onto a black hole and confirms earlier, but less sophisticated, studies claiming that such systems

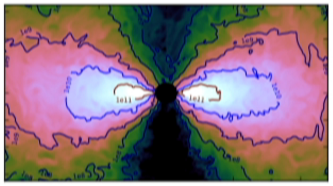
Conclusions

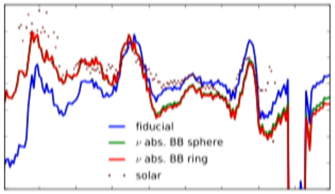
- The origin of the heavy elements has been an enduring mystery for more than 70 years
- First-principle simulations key to understand their formation (identify the site, production processes, abundance pattern etc.)
- Simulations + GW170817 + EM (kilonova) point to post-merger accretion disk winds as promising site (ubiquitous phenomenon!)

→ red KN in GW170817 consistent with winds from post-merger accretion disk

  - hot corona launches thermal outflows
  - likely dominant source of ejecta in NS mergers
  - slower than dynamical ejecta

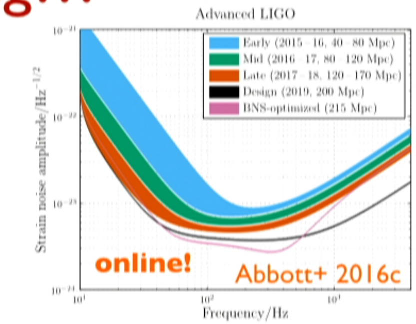






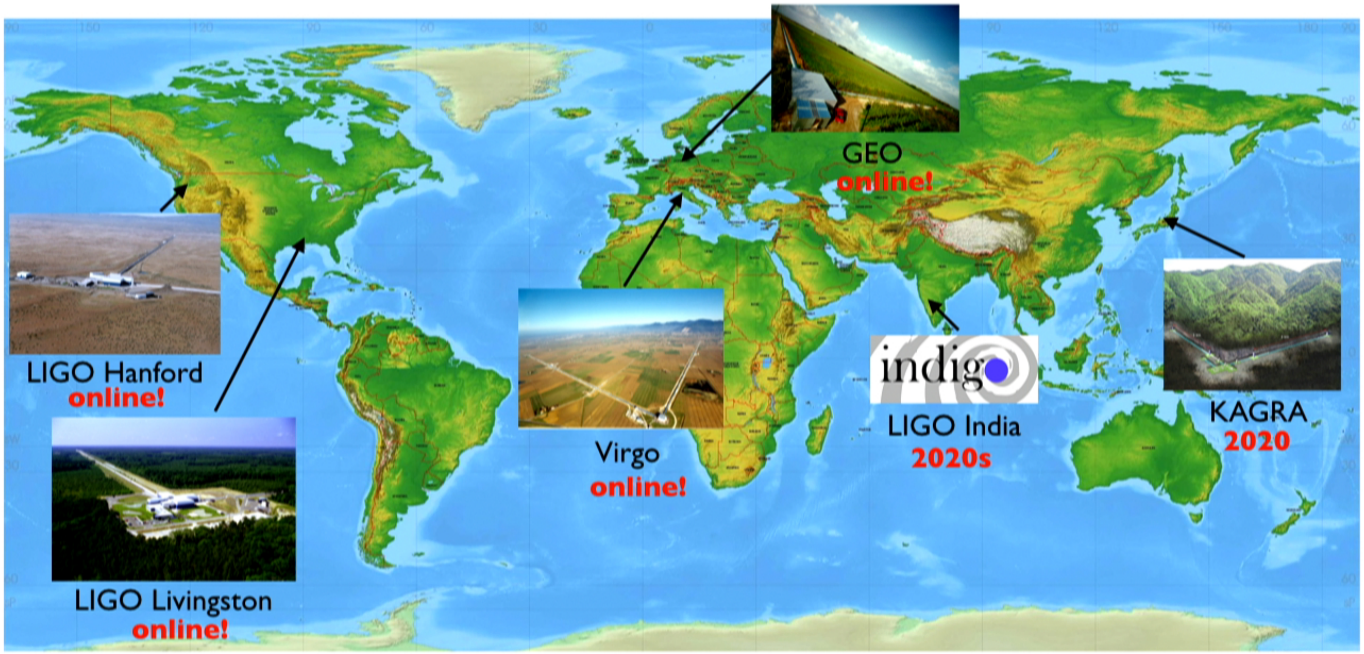
Relative abundances, total ejecta mass, measured BNS merger rate provide yet strongest evidence for NS mergers being the prime production site for the r-process

Outlook: this is just the beginning…



next 5-10 years: revolution in time-domain astronomy

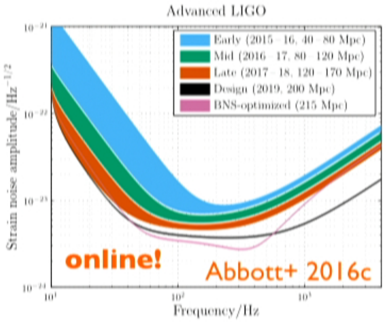
- ~ 6-120 BNS detections per year once LIGO has reached design sensitivity by 2020, *improved Sky localization* with 4 and 5 detector network (*LIGO-India, KAGRA*)

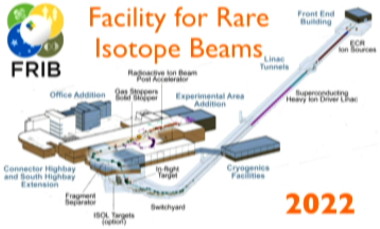


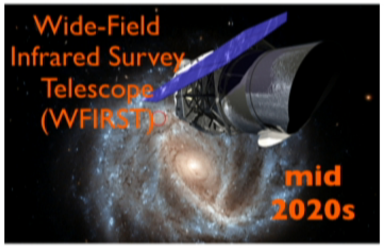
Outlook: this is just the beginning…

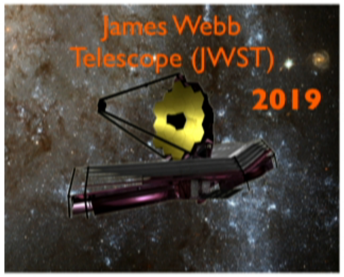
next 5-10 years: what I hope to learn (nucleosynthesis)

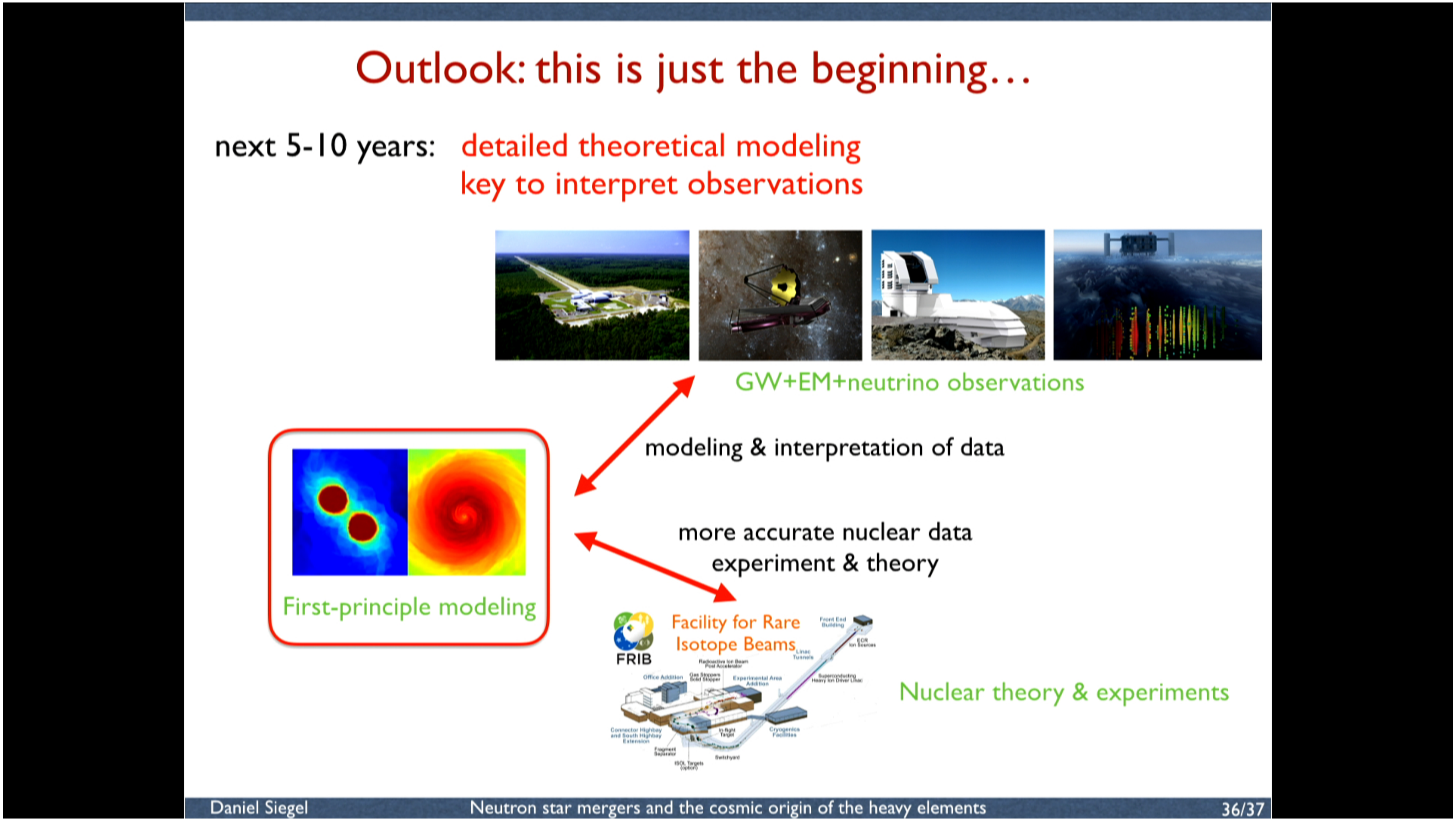
- Are NS mergers the dominant source of r-process elements in the Universe?
- Contribution of NS-BH mergers?
- Range/diversity of synthesized elements? (solar composition?)
- Can we "see" (spectroscopically) the synthesis of specific elements?
- Can we prove whether/how Actinides are formed? Observational signatures, processes? Actinide-boost stars?
- What is the geometry of the nucleosynthesis products? Observational consequences?
- How are the nucleosynthesis products mixed into the galaxies? Chemical evolution?











Outlook: this is just the beginning…

next 5-10 years: detailed theoretical modeling
key to interpret observations

GW+EM+neutrino observations

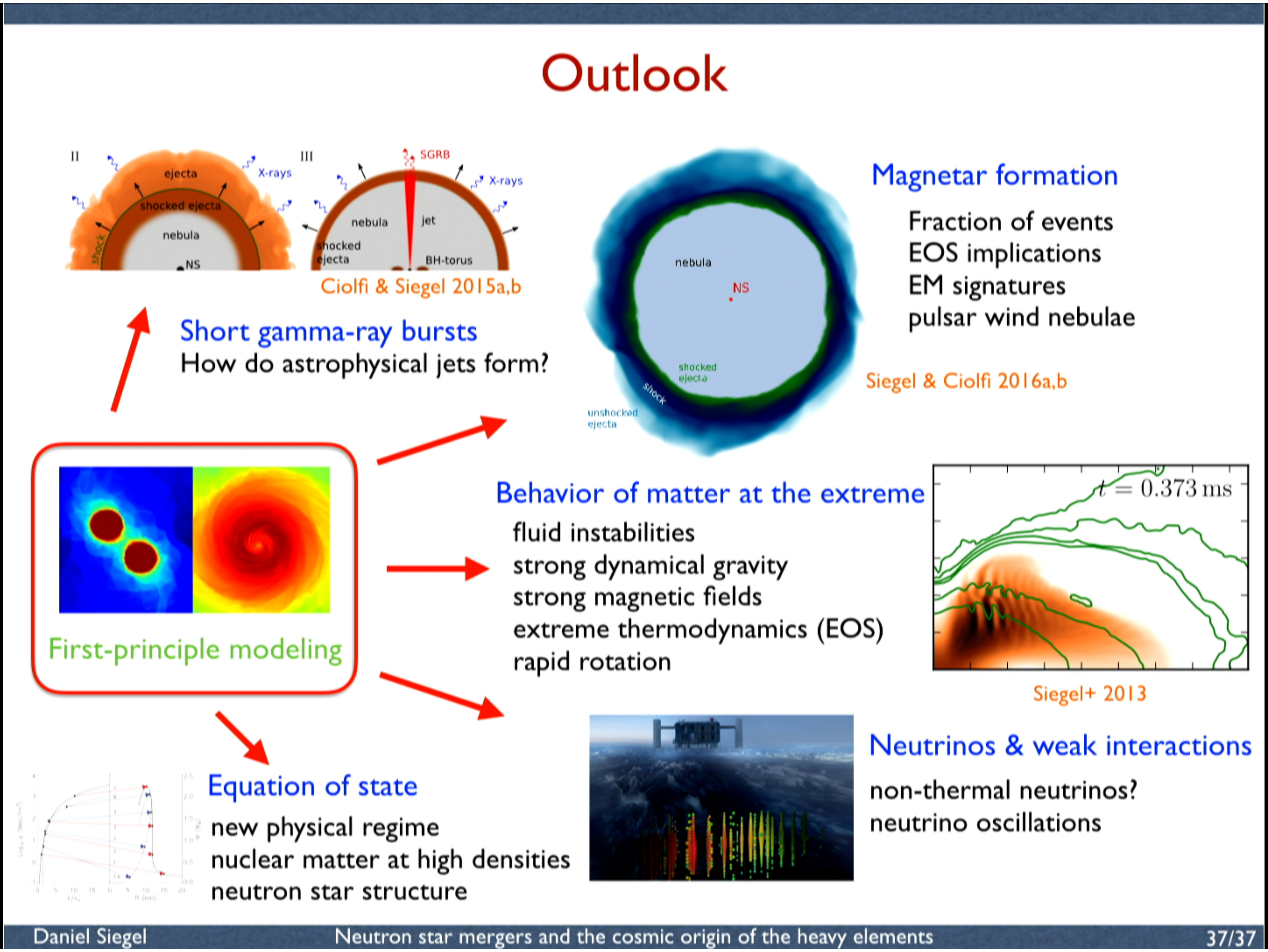
modeling & interpretation of data

First-principle modeling

more accurate nuclear data
experiment & theory

Facility for Rare Isotope Beams

Nuclear theory & experiments



Outlook

Ciolfi & Siegel 2015a,b

Short gamma-ray bursts

How do astrophysical jets form?

Magnetar formation

- Fraction of events
- EOS implications
- EM signatures
- pulsar wind nebulae

Siegel & Ciolfi 2016a,b

First-principle modeling

Behavior of matter at the extreme

- fluid instabilities
- strong dynamical gravity
- strong magnetic fields
- extreme thermodynamics (EOS)
- rapid rotation

Siegel+ 2013

Equation of state

- new physical regime
- nuclear matter at high densities
- neutron star structure

Neutrinos & weak interactions

- non-thermal neutrinos?
- neutrino oscillations