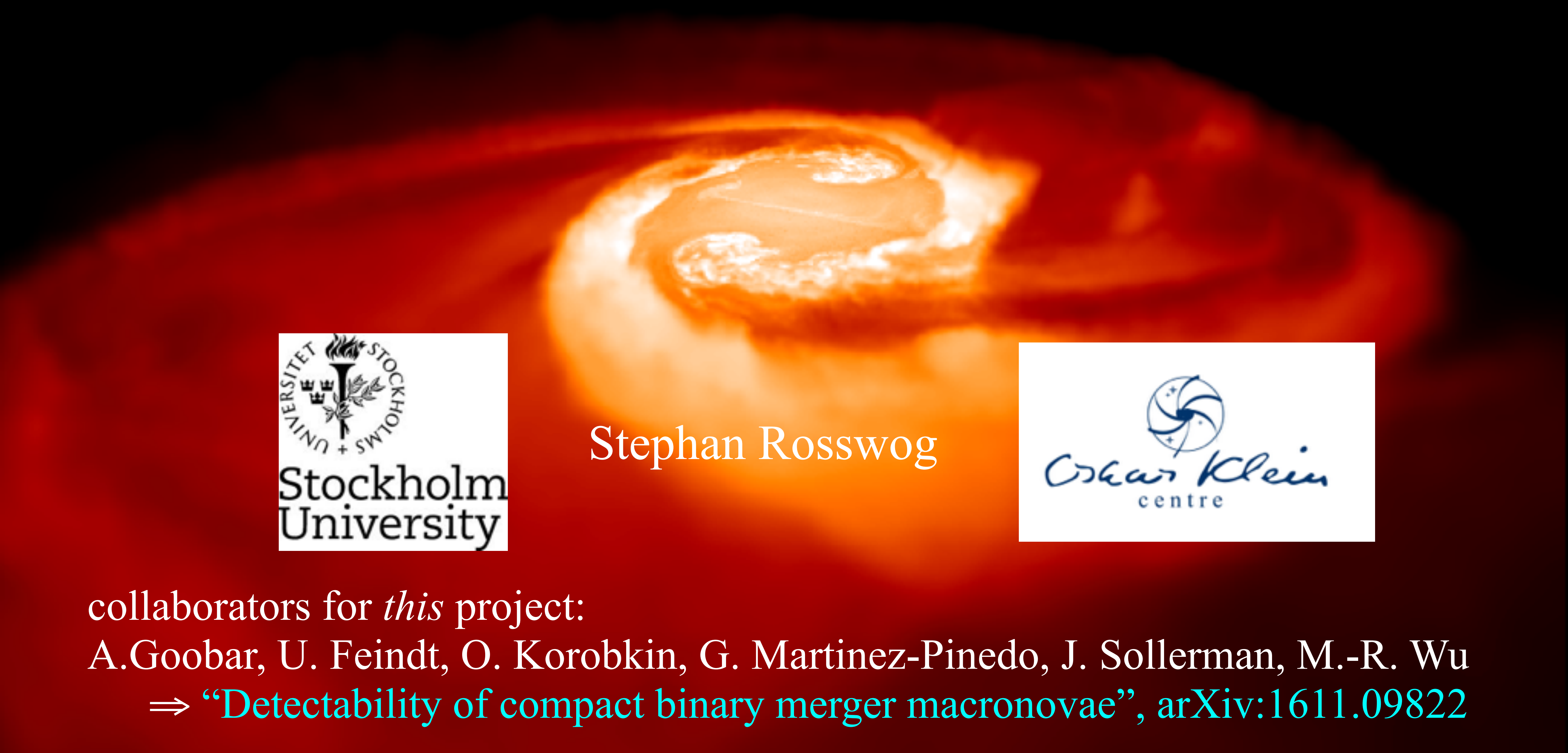
Hirschegg, 17.01.2017

Compact binary mergers: what else apart from gravitational waves?



Stockholm University

Stephan Rosswog

Oskar Klein centre

collaborators for *this* project:
A.Goobar, U. Feindt, O. Korobkin, G. Martinez-Pinedo, J. Sollerman, M.-R. Wu
⇒ “Detectability of compact binary merger macronovae”, arXiv:1611.09822

Outline

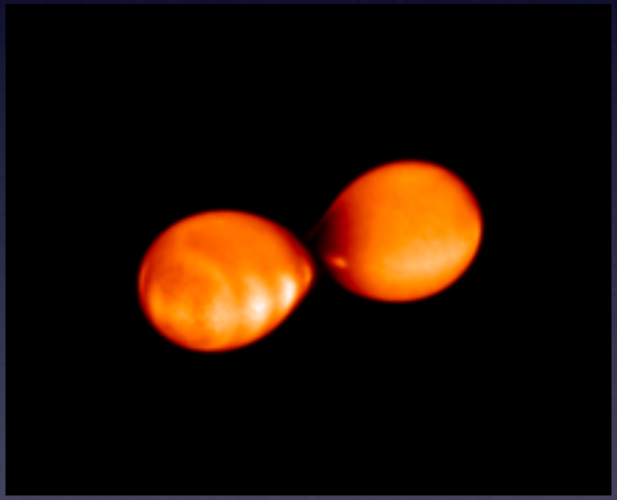
- I. Introduction
    - Glueing fields together
    - GWs: EM needed
    - Types of expected EM

- II. Overview mass loss and nucleosynthesis
    - Mechanisms
    - Dynamic ejection + nucleo
    - ν-winds + nucleo
    - Other types of “winds”
    - Rate constraints from nucleo
        - a) mass in Galaxy
        - b) constraints nucleo + sGRB + GW

- III. Macronovae
    - Our model
    - Explored parameter space
    - Impact of mass formula
    - Detection prospects
    - “Tanvir+ event”

- IV. Summary

I.1 Neutron star mergers: “glueing together separate fields”



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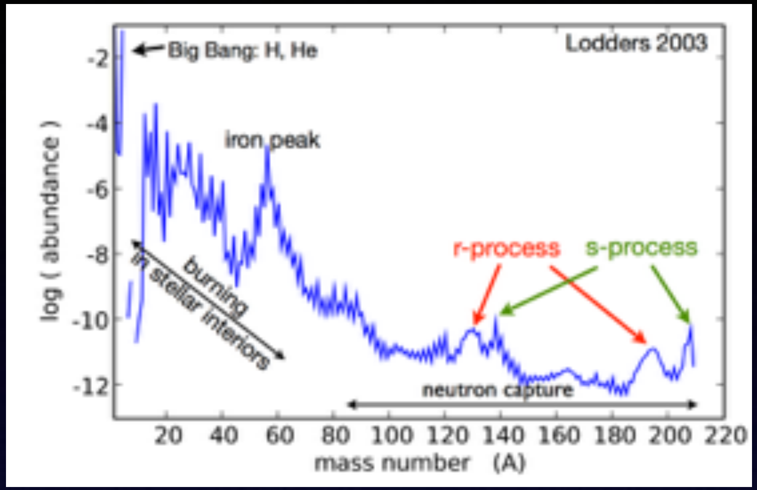
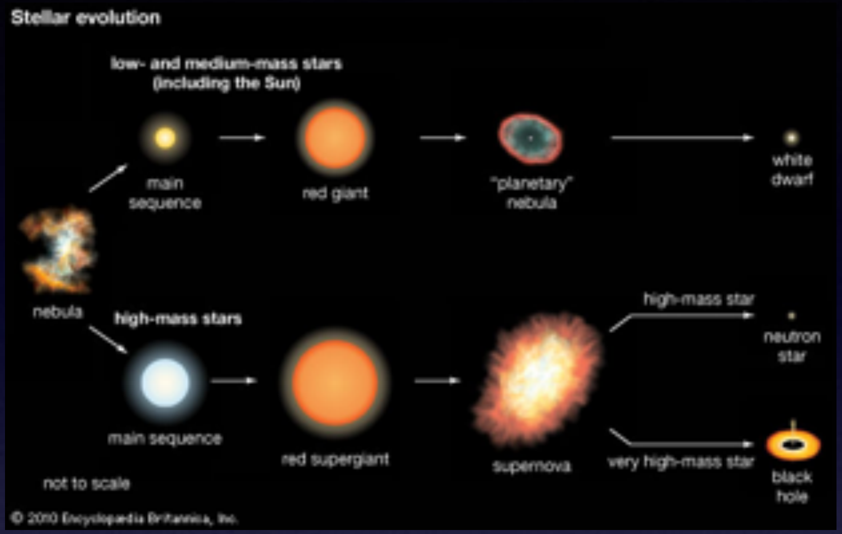
nucleosynthesis



Stellar (binary) evolution



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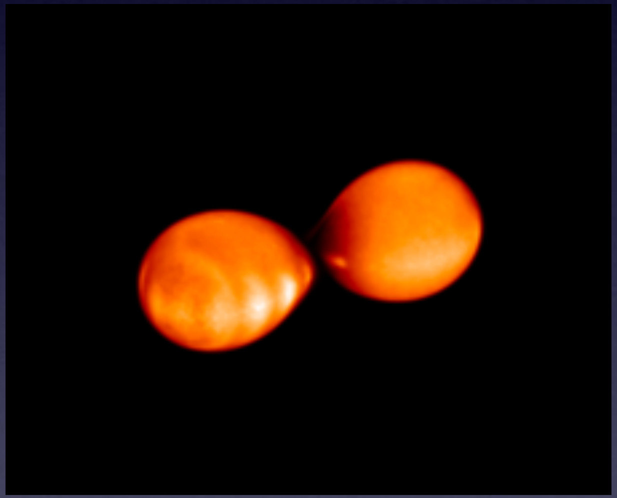
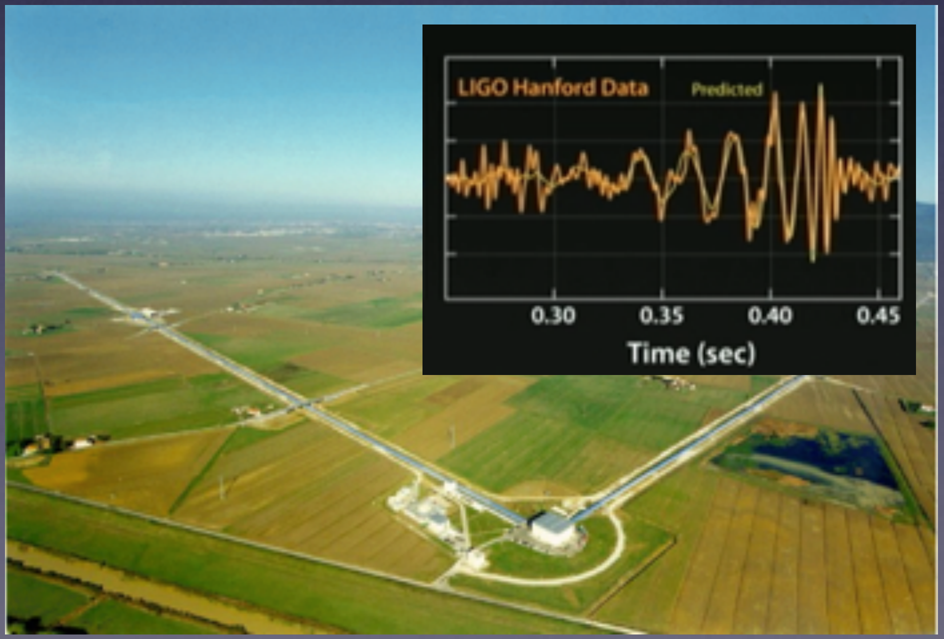
Chemical enrichment of the Cosmos



Gravitational wave detection

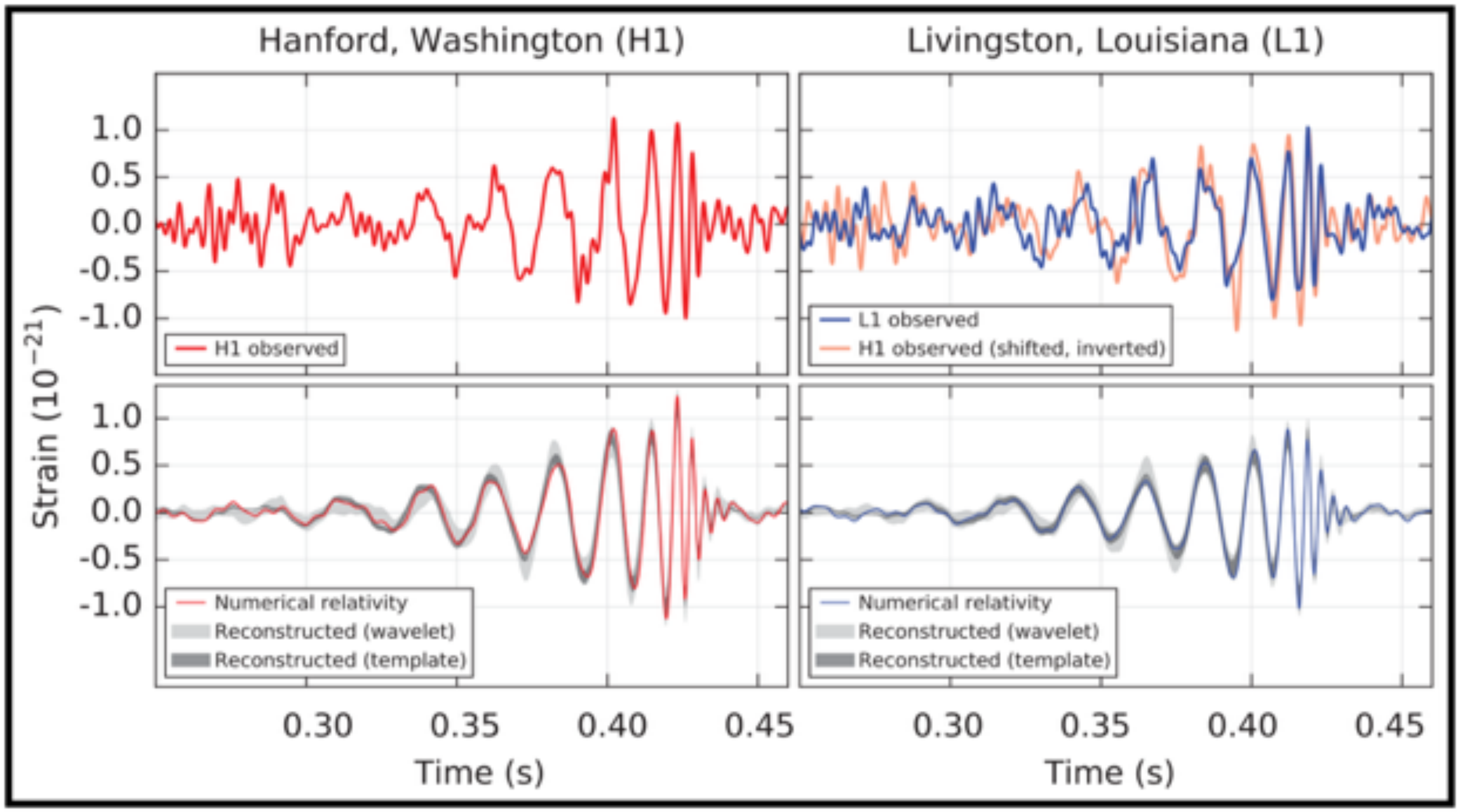


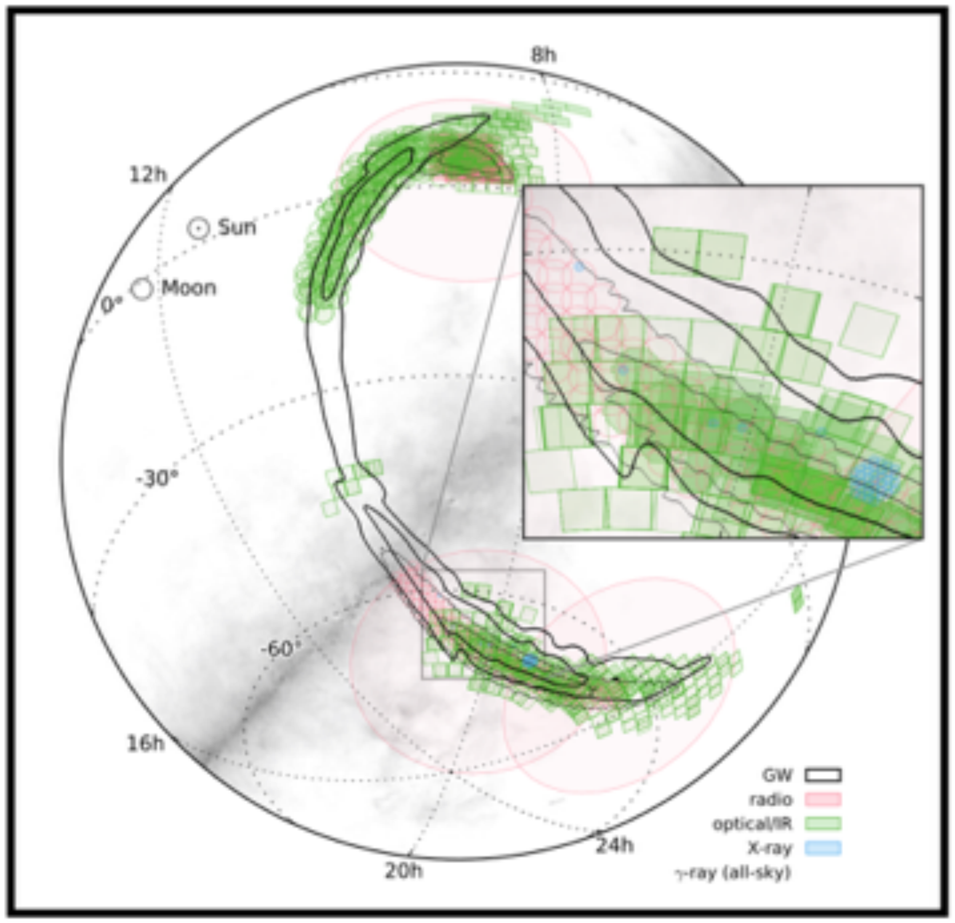
Radioactively powered transients (“macronovae”)

(short) Gamma-Ray Bursts

I.2 Gravitational wave astronomy

The first gravitational wave detection GW150914



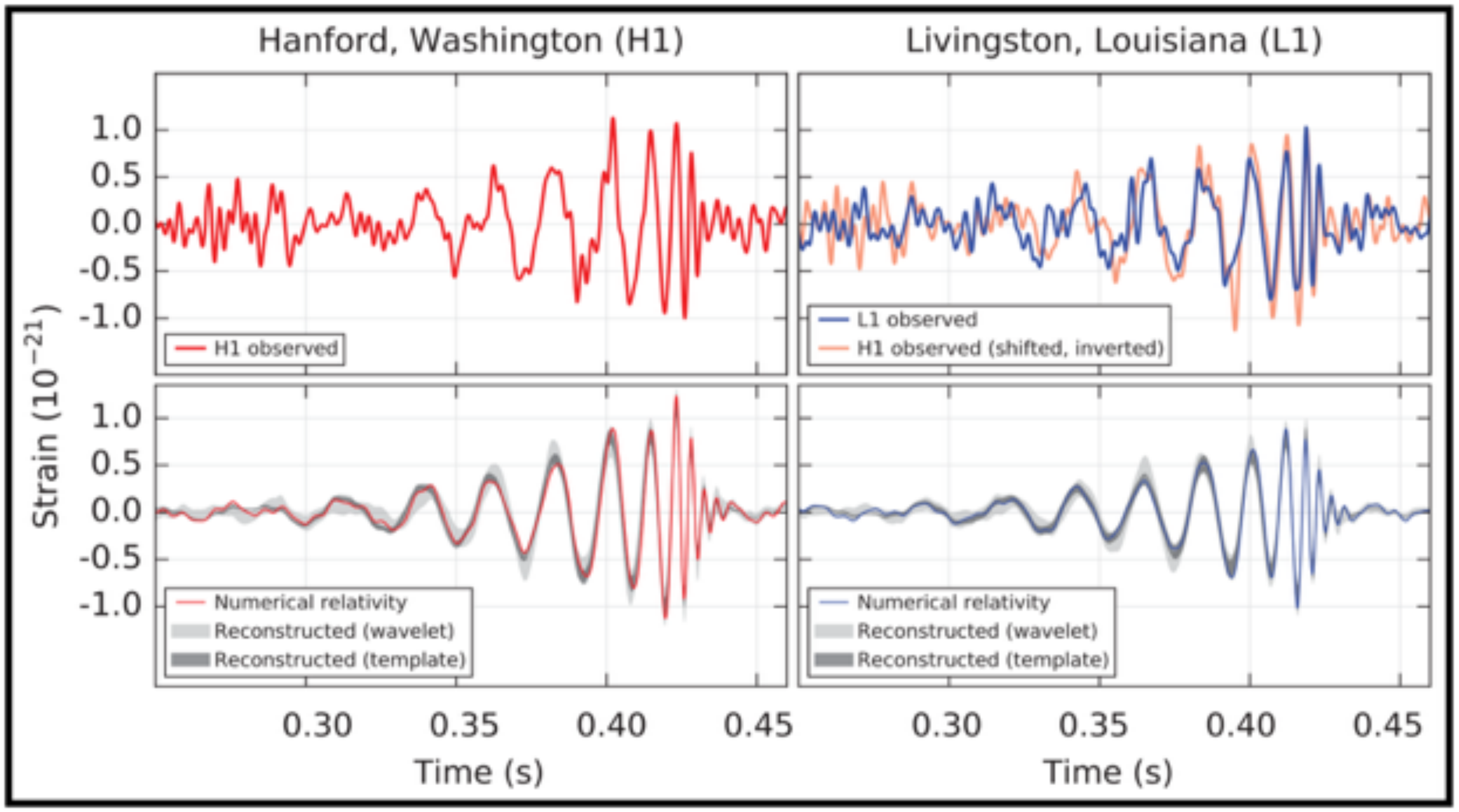


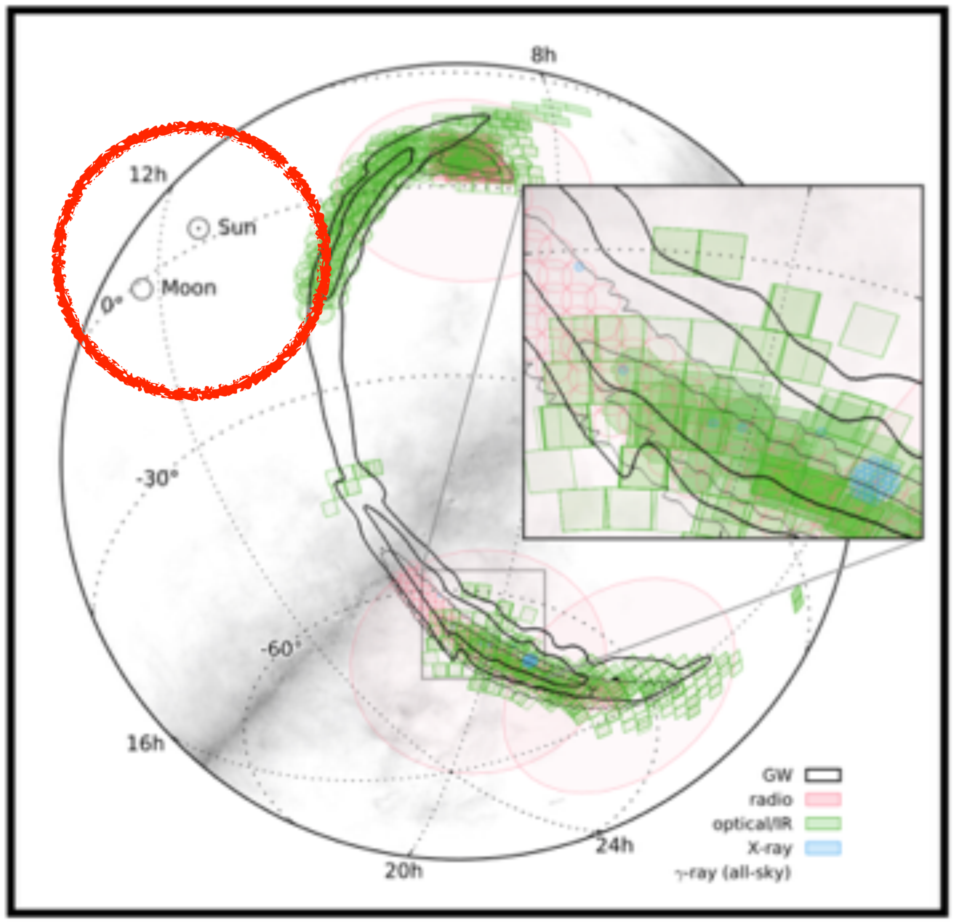
⇒ “physics from gravitational wave signal”

⇒ “astronomy/astrophysics from the electromagnetic (EM) transient”

I.2 Gravitational wave astronomy

The first gravitational wave detection GW150914





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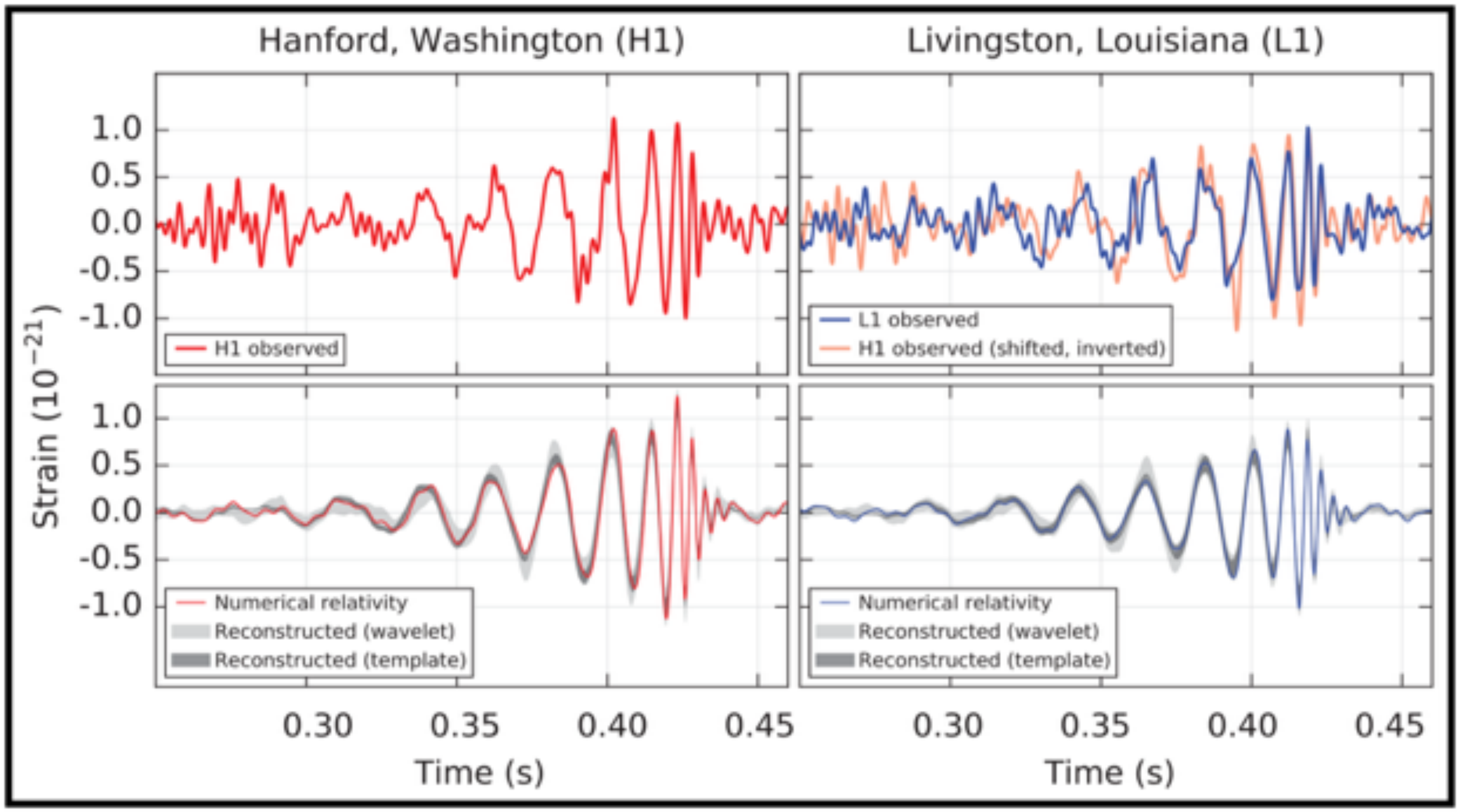
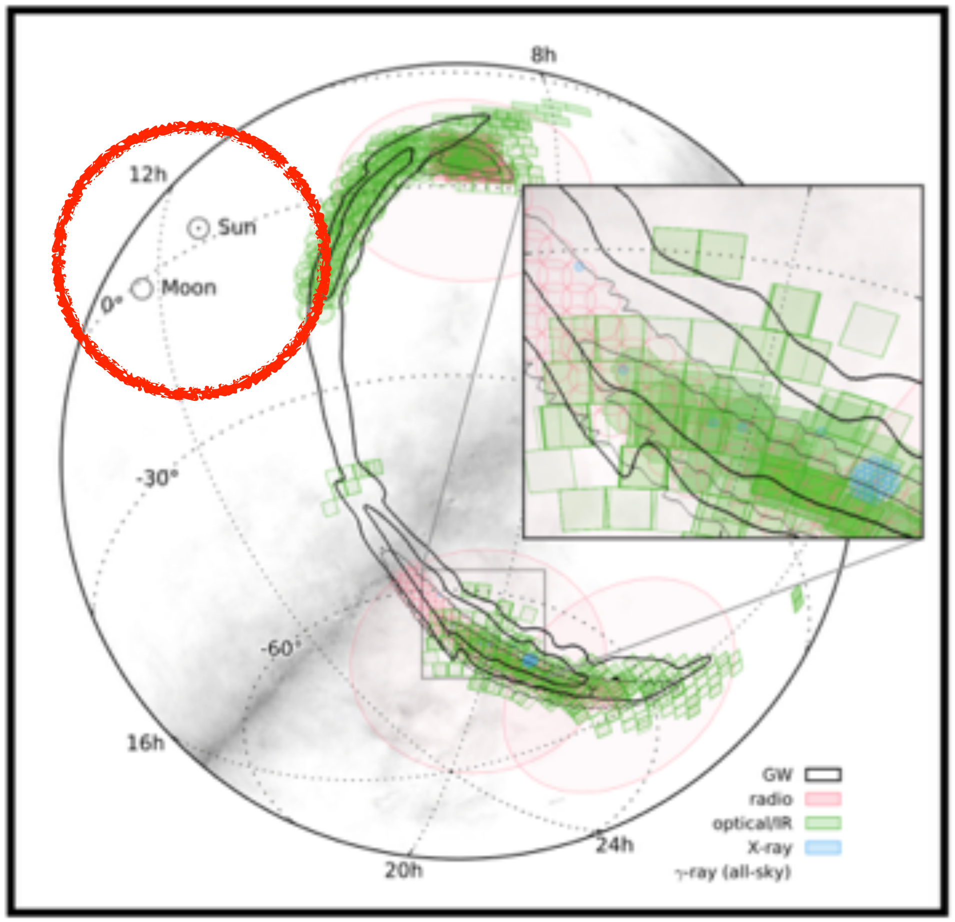




⇒ “physics from gravitational wave signal”

⇒ “astronomy/astrophysics from the electromagnetic (EM) transient”

location in the sky essentially unknown,
~ 600 deg^2 error region

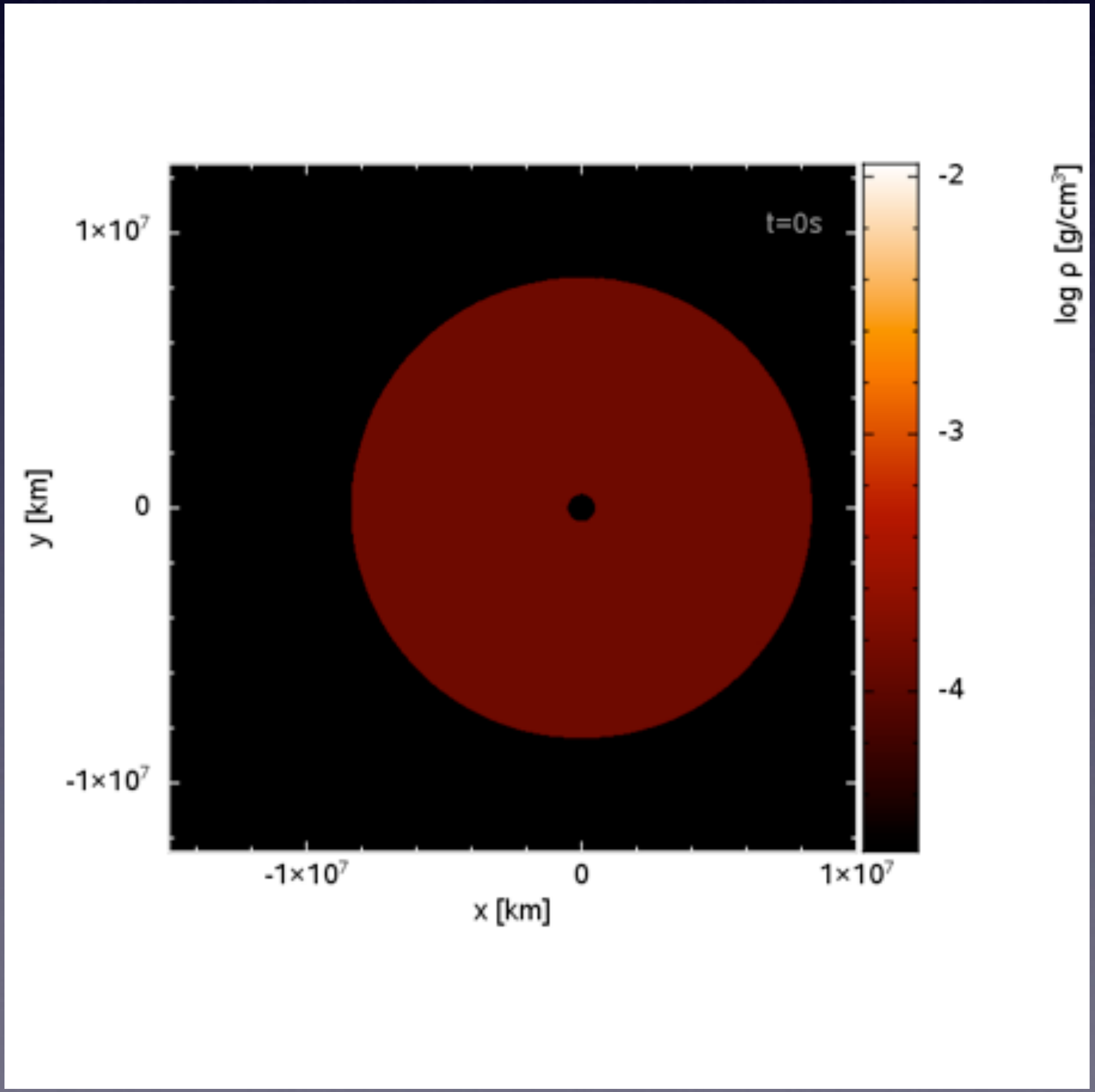
==> electromagnetic (EM)-transient
needed for sky location!

I.3 Which EM-transients can we expect to accompany a gravitational wave chirp?

for binary black holes:

- IF the merger occurs in gaseous environment:
  post-merger black hole has mass reduced by △m, has received "kick"

S.R. 2017



"BH kicked through disk"

parameters of this illustrative example:

- $m_1 = 29\ M_\odot$ & $m_2 = 36\ M_\odot$
- $\triangle m = 3\ M_\odot$
- $m_{disk} = 0.01\ M_\odot$
- $v_{\_kick} = 500$ km/s

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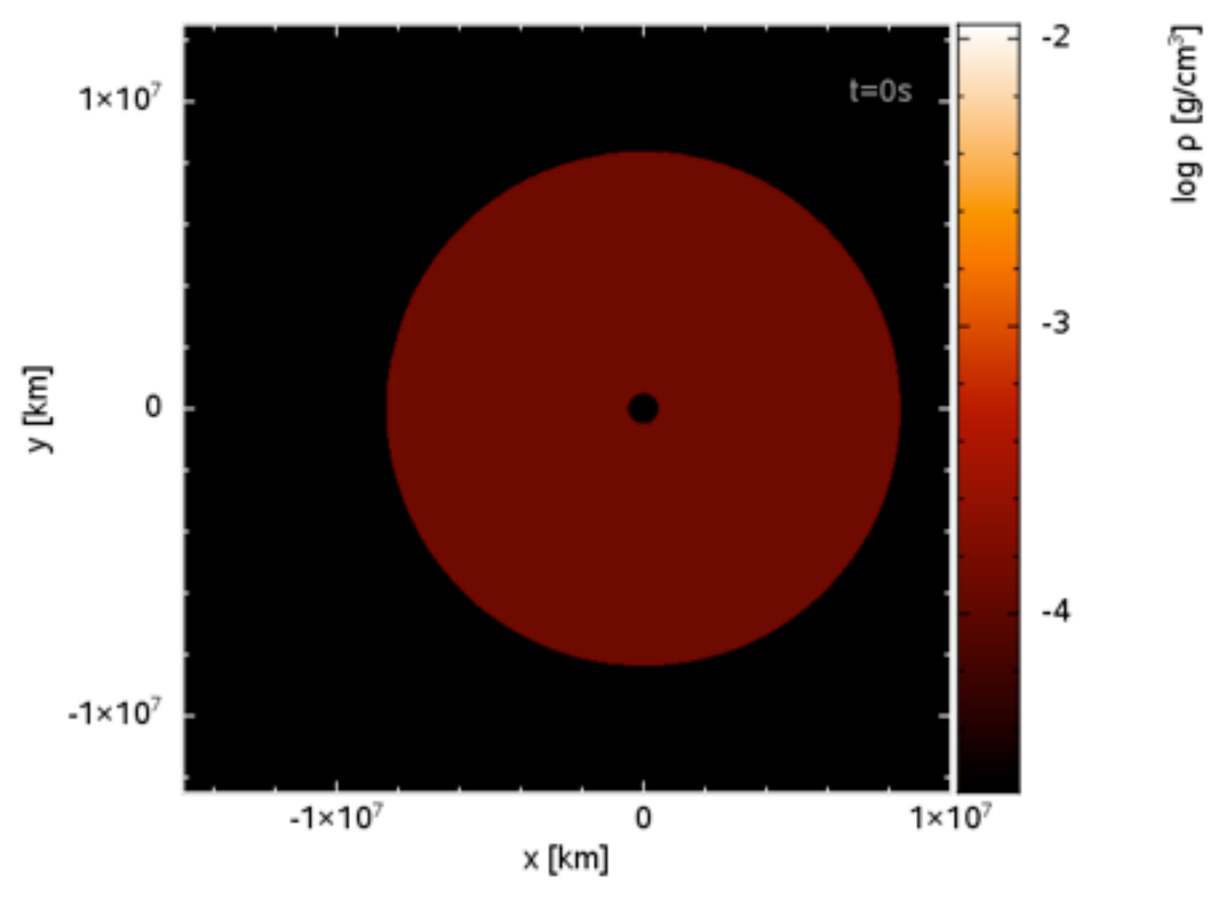

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for compact binaries involving neutron stars:

(1) Short Gamma-Ray Bursts

- collimated into ~8° ⇒ detect ~ 1 out of 70 bursts

time scales ~ second

(2) Radioactively powered transients ("macronovae")

- de-compressed neutron star matter forms heavy nuclei
- "cloud of radioactive, expanding matter"
- isotropic emission

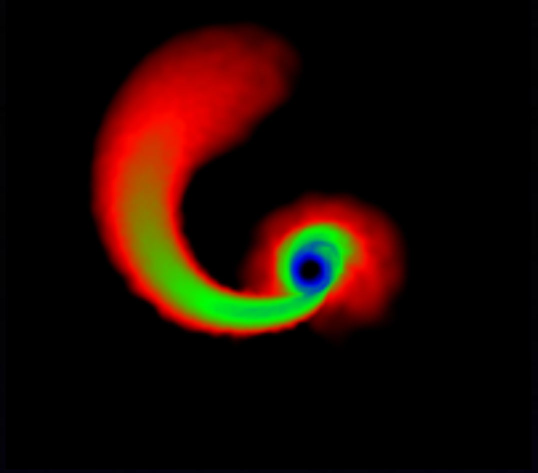
time scales ~ days

(3) Radio flares

- from dissipation of kinetic energy in ambient medium

time scales ~ months

II. Mass loss and nucleosynthesis

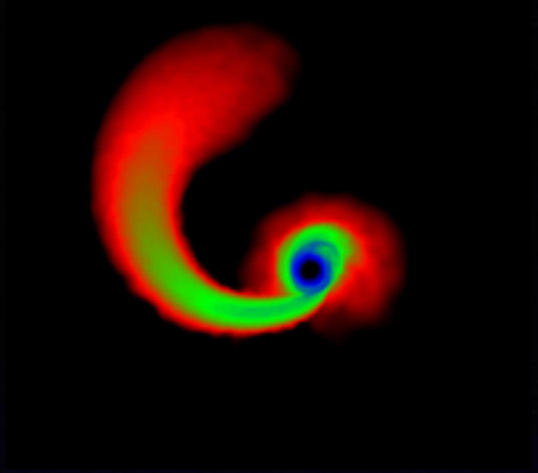


II.1 Mass loss channels for NSNS and NSBH:

- dynamic ejecta: by hydrodynamics and gravitational torques

nsns: few 10^{-3} to few 10^{-2} $M_\odot$ (mass ratio!)
nsbh: up to ~0.2 $M_\odot$ (mass ratio, bh spin χ)

II. Mass loss and nucleosynthesis



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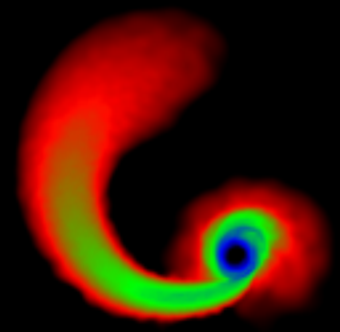

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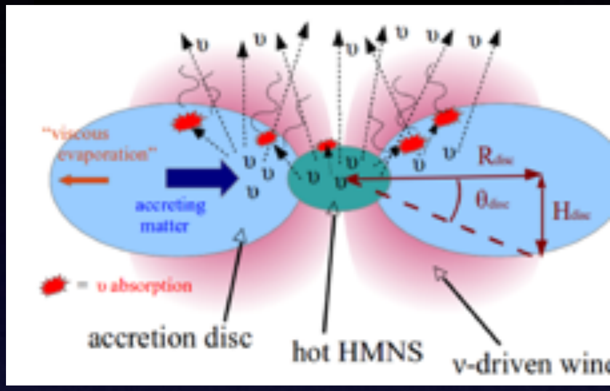
- ν-driven winds: massive neutron star present: ~0.01 $M_\odot$

  bh + torus: ≪ ~0.01 $M_\odot$

$L_\nu \sim 10^{53}$ erg/s $\langle E_\nu \rangle \sim 15$ MeV



(from Perego et al. 2014)

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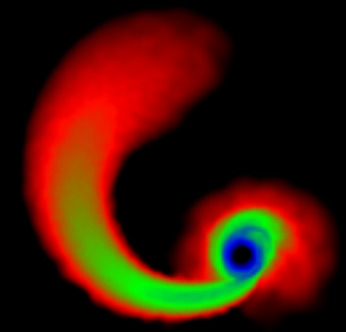

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  either from disks and/or massive “neutron star”

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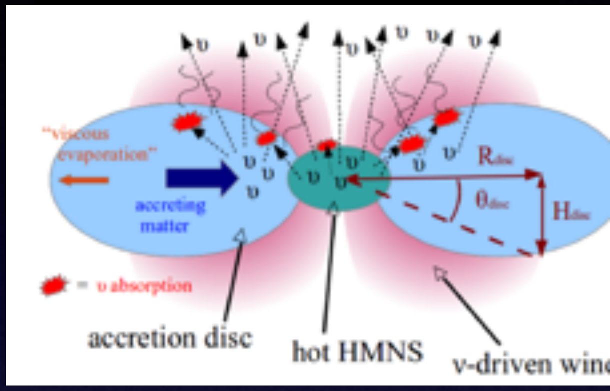

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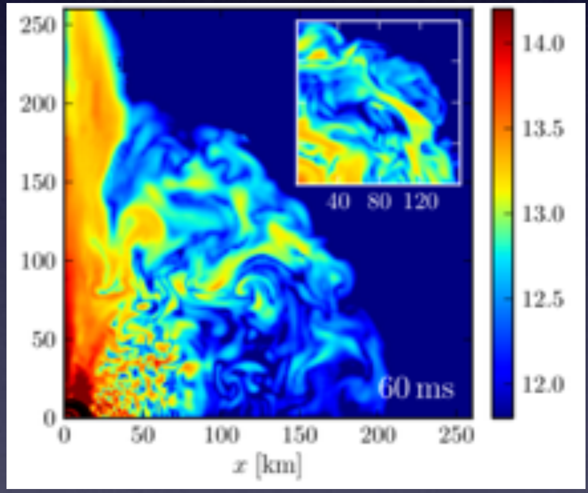

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  bh + torus: ≪ ~0.01 M⊙

- **magnetically-driven winds:**

  either from disks and/or massive “neutron star”

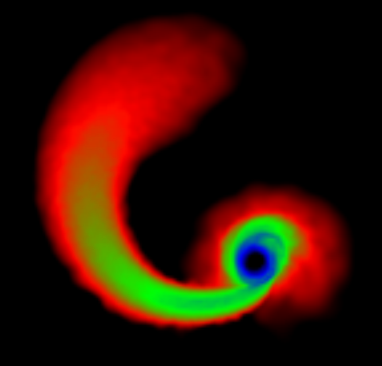
- **torus unbinding** (viscous diss., nuclear recomb.):

  ~ 20% of initial torus mass

  (Fernandez & Metzger 13, Just+ 15)

- **initial torus mass can be large!**

  ⇒ could plausibly unbind ~0.02 … 0.1 M⊙



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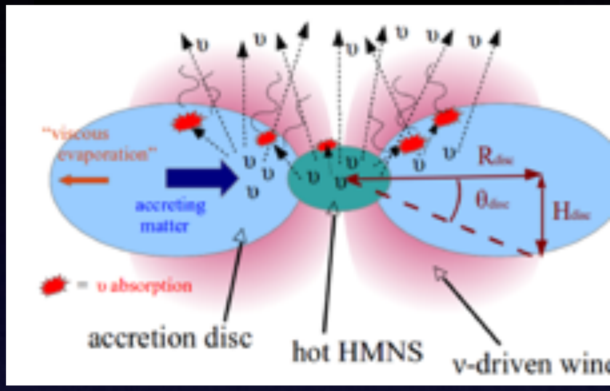

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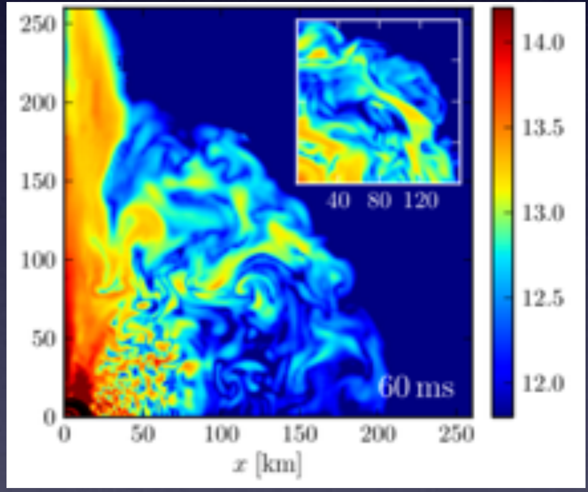

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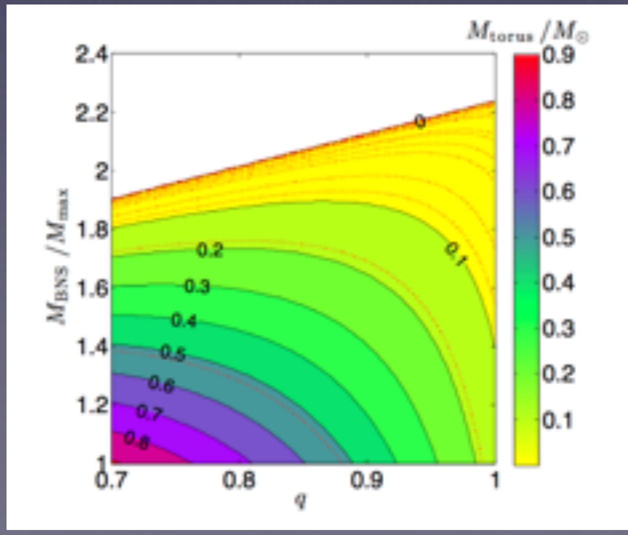

(from Giacomazzo et al. 2013)

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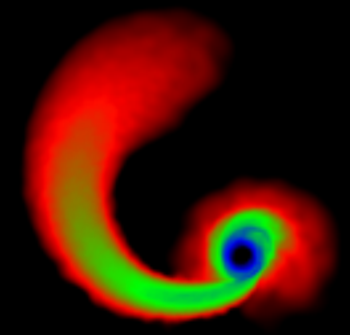

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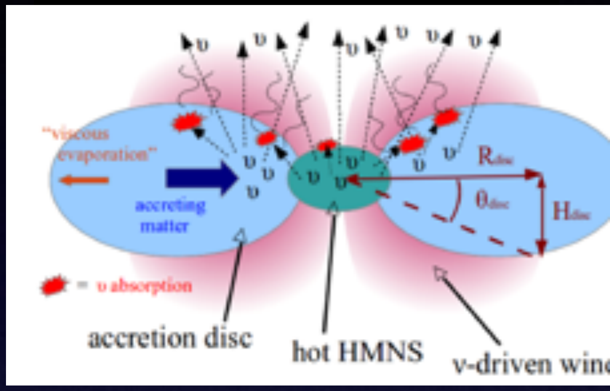


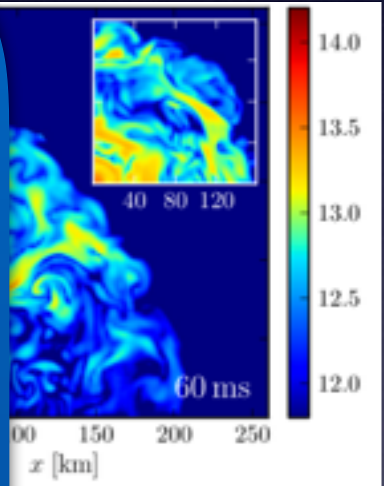
m Perego et al. 2014)

- ν-driven winds: massive neutron star present: ~0.01 M☉

“winds”: - stay longer closer the central neutrino source
⇒ electron fraction driven towards equilibrium
(Qian & Woosley 96)

$$Y_e^{\mathrm{fin,wind}} \approx \left(1 + \frac{L_{\bar\nu_e}}{L_{\nu_e}} \frac{\epsilon_{\bar\nu_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar\nu_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1} \sim 0.3$$

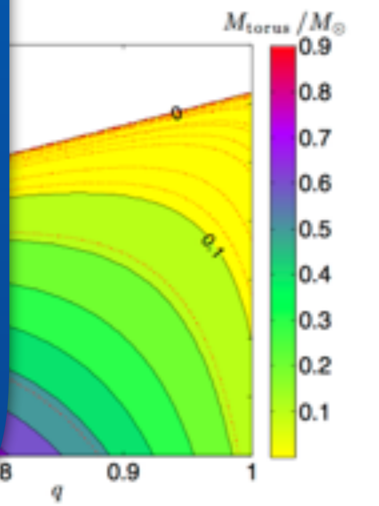
- ma



el et al. 2014)

- toru

- different velocities



- init

⇒ different nucleosynthesis

⇒ different EM-transients

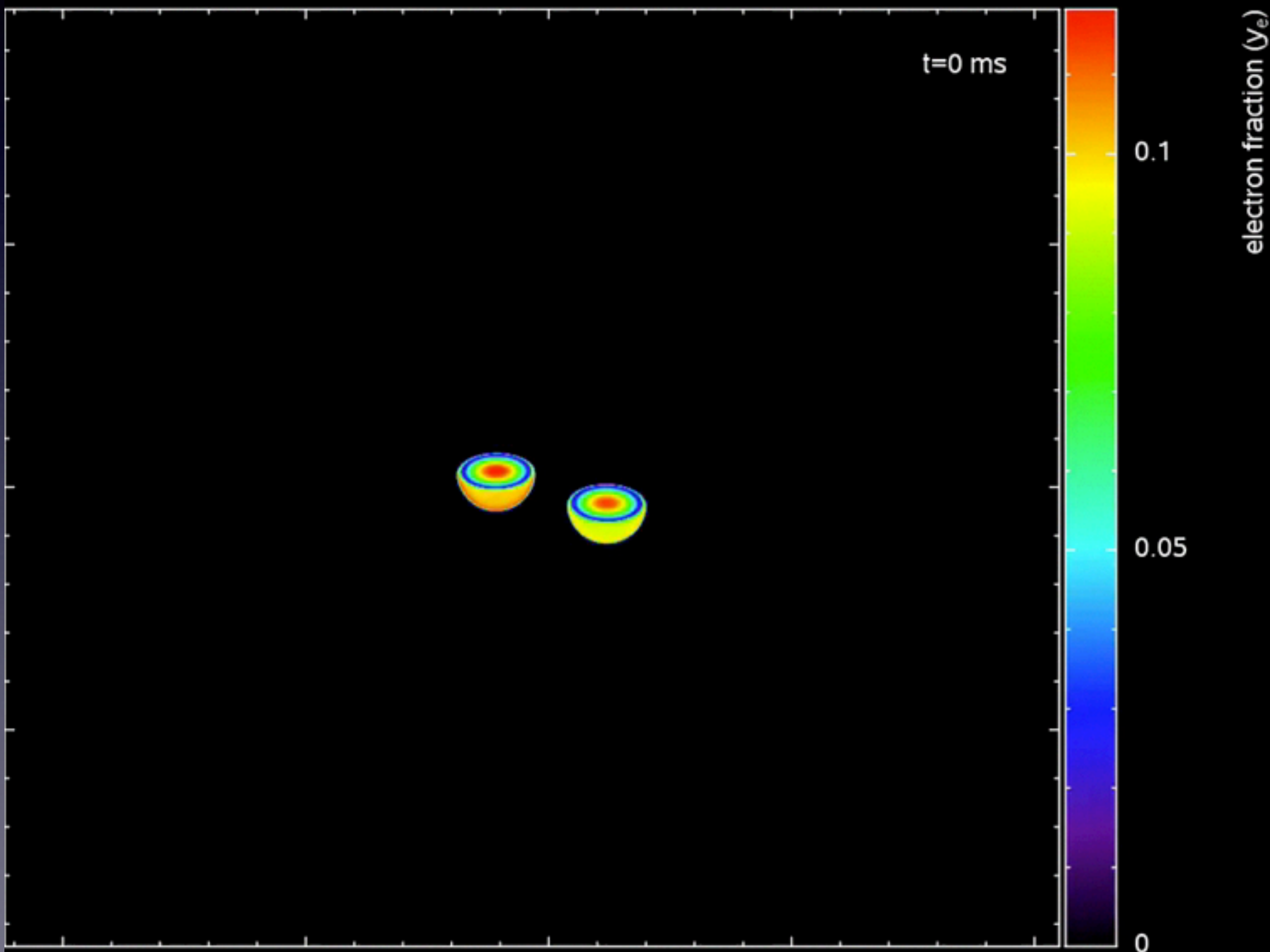
(from Giacomazzo et al. 2013)

II.2 Nucleosynthesis for dynamic ejecta

Example: neutron star binary (1.4 and 1.5 M_{sol}, no stellar spins)

Modelled Physics

- 3D Lagrangian hydrodynamics; SPH with 6 million particles (e.g. S.R. 2016)
- Newtonian self-gravity
- GW-backreaction force
- Nuclear equation of state (Shen et al. 1998)
- opacity-depent neutrino cooling and weak interactions/change of composition (S.R. & Liebendoerfer 2003)



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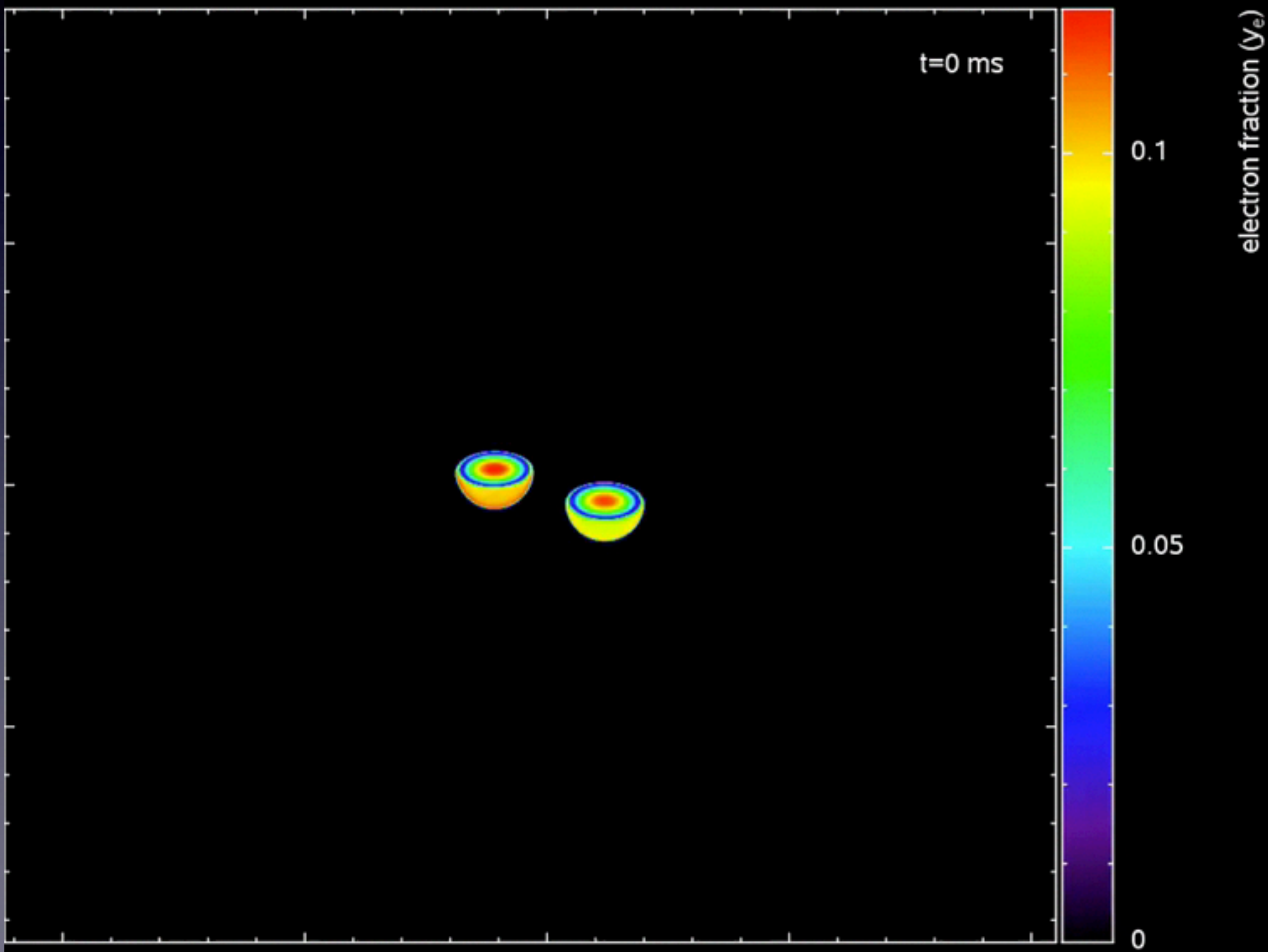

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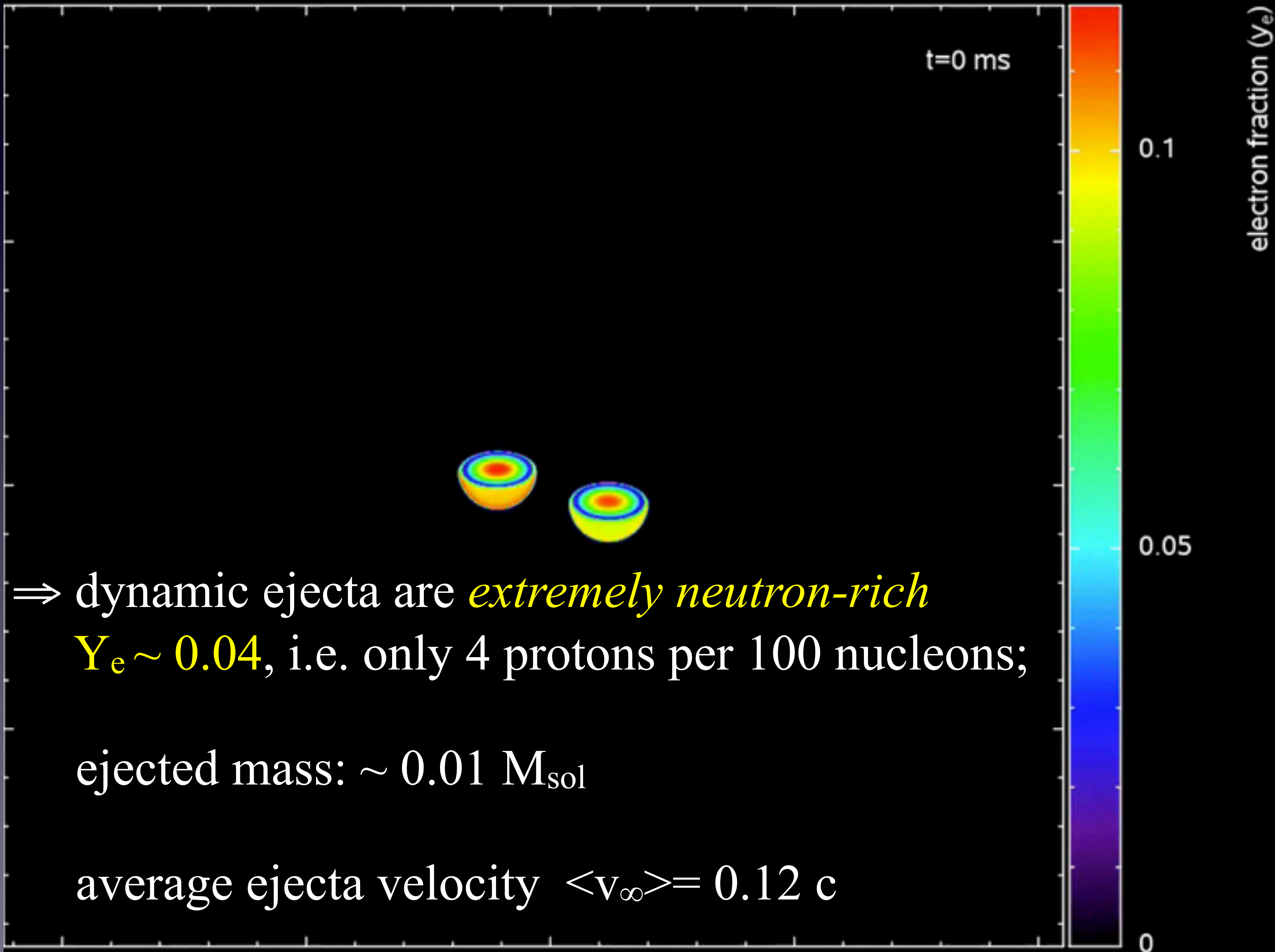

⇒ dynamic ejecta are *extremely neutron-rich*

$Y_e \sim 0.04$, i.e. only 4 protons per 100 nucleons;

ejected mass: ~ 0.01 M_{sol}

average ejecta velocity $\langle v_\infty \rangle = 0.12$ c

r-process calculations for dynamic ejecta

(Korobkin, S.R, Arcones, Winteler, MNRAS 426, 1940 (2012))

T_9

$\rho[\mathrm{g/cm^3}]$

Winnet network
(Winteler 2012)

5 831 isotopes

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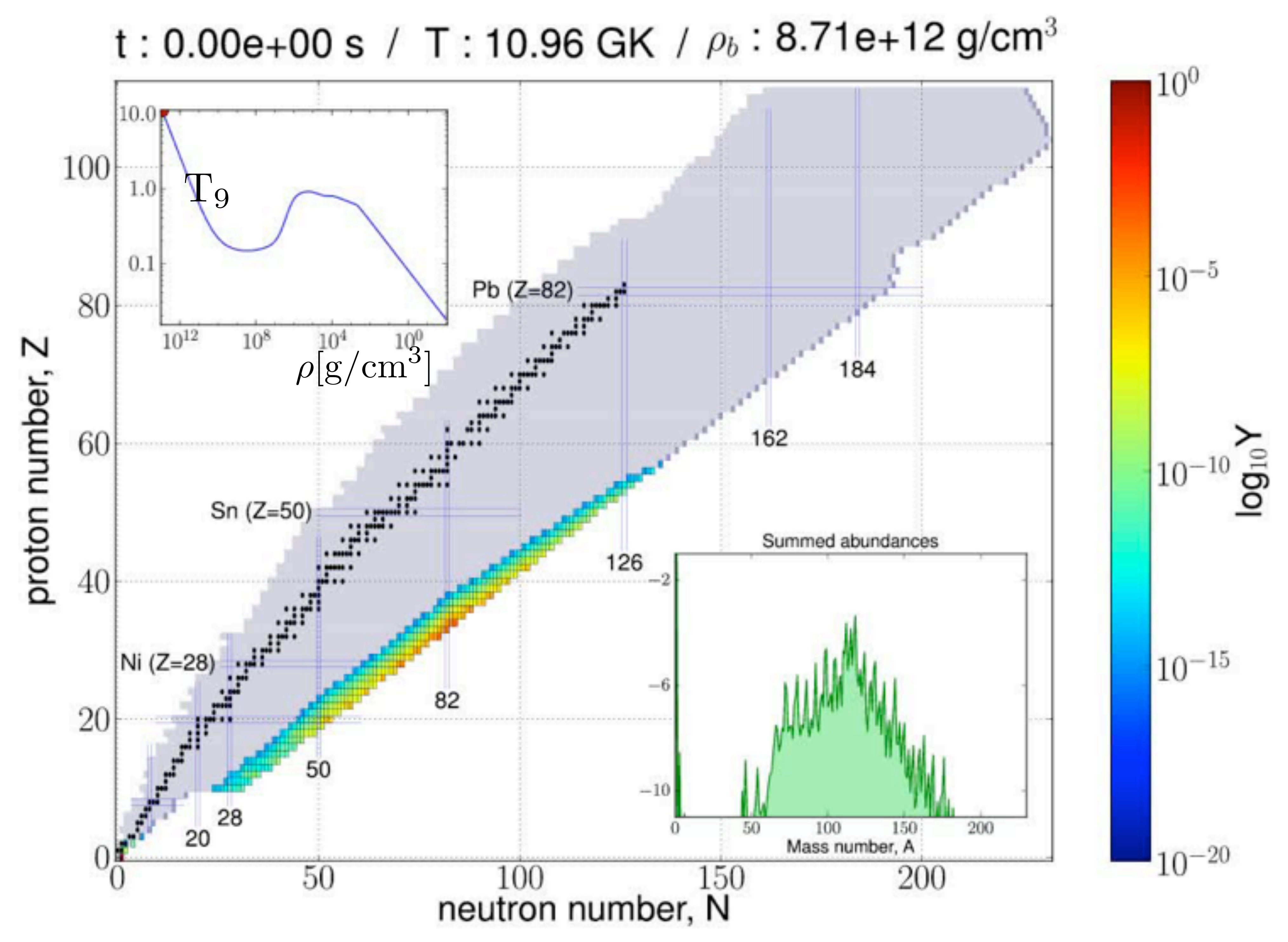


Winnet network
(Winteler 2012)

5 831 isotopes

Resulting abundances

- "Punchlines"

1. all binaries reach the "platinum peak" (A=195) without any tuning, not much below A ~ 130

2. the abundance pattern is extremely robust with respect to astrophysics:
   A. all mass ratios (even NSBH-systems) deliver the same pattern
   B. Ye ≲ 0.25 needed for 3rd r-process peak ("platinum peak")

3. sensitivity to nuclear physics ⇒ e.g. talks Eichler, Giuliani, Surman, Wu

4. tidal dynamic ejecta component delivers very low-Y_e material ($Y_e \sim 0.04$), likely complemented by higher Y_e components (ν-driven wind, disk evaporation etc.)

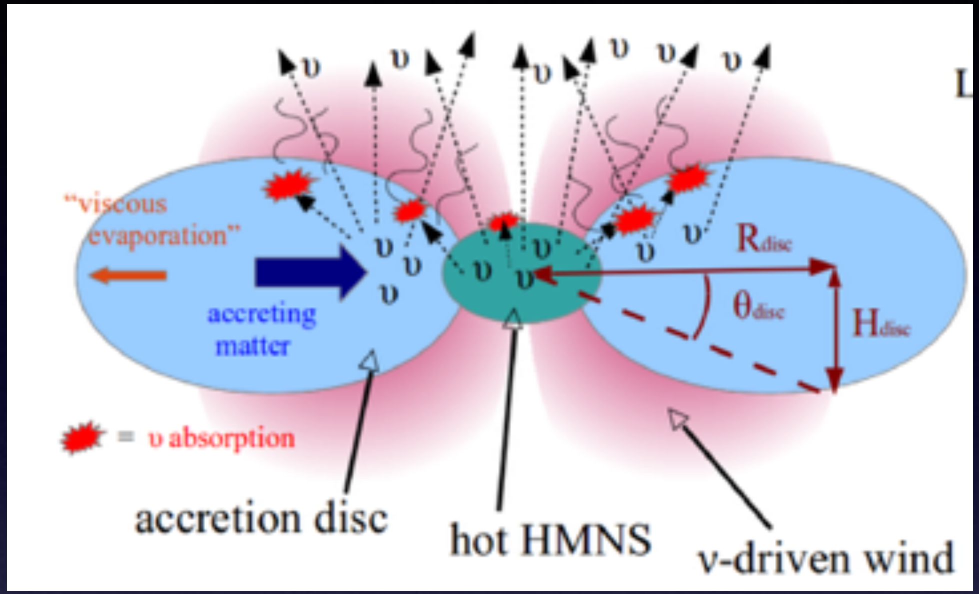
II.3 Nucleosynthesis neutrino-driven winds

(Perego, et al. 2014, Martin, et al. 2015)

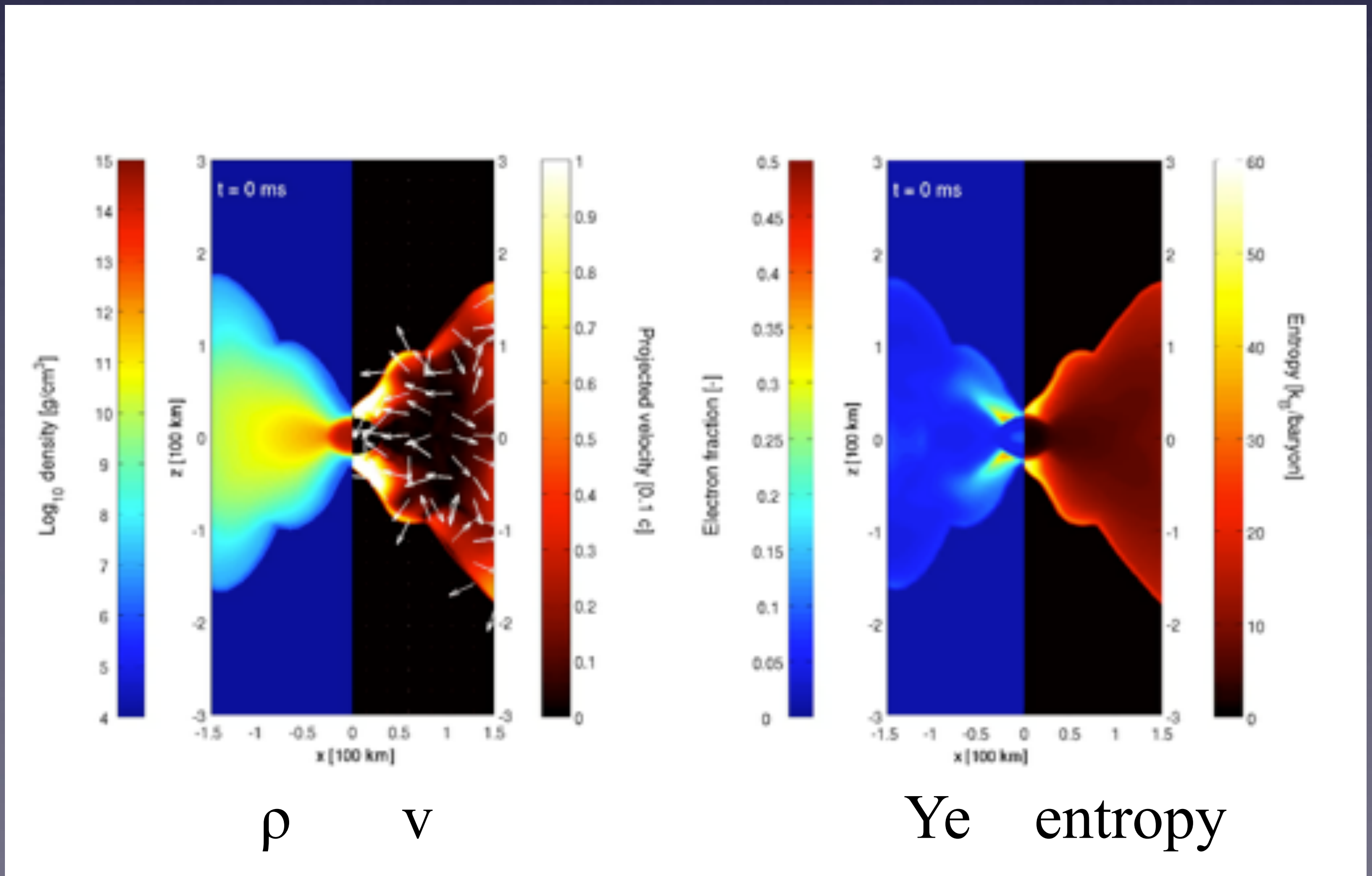
Questions:

- neutrino properties?
- impact ν-oscillations ⇒ talk Gail McLaughlin
- neutrino-driven winds:
  - mass loss?
  - geometry?
  - nucleosynthesis?
  - resulting radioactively powered transients?

$L_\nu \sim 10^{53}$ erg/s $\langle E_\nu \rangle \sim 15$ MeV



(from Perego et al. 2014)



$\Rightarrow$ $0.2 \lesssim Y_e \lesssim 0.4$

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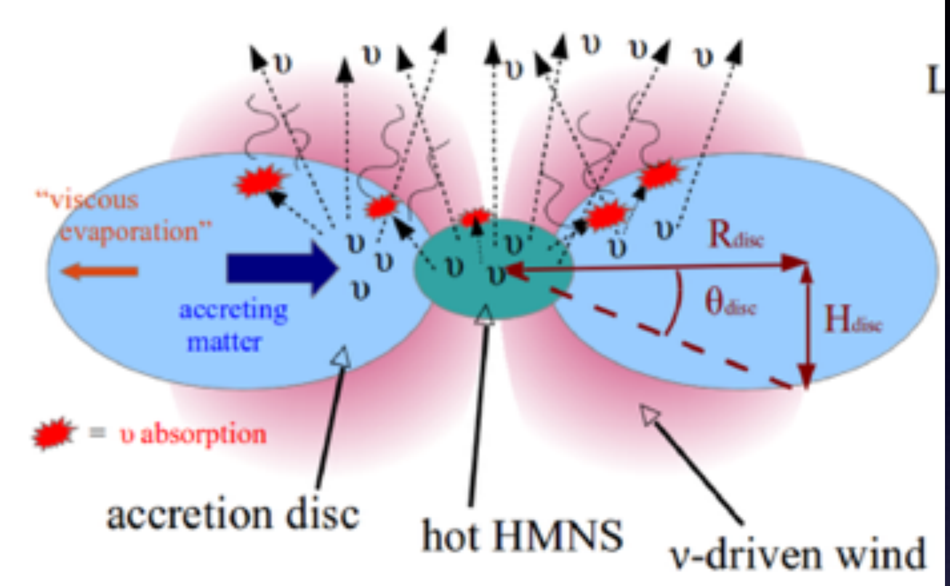

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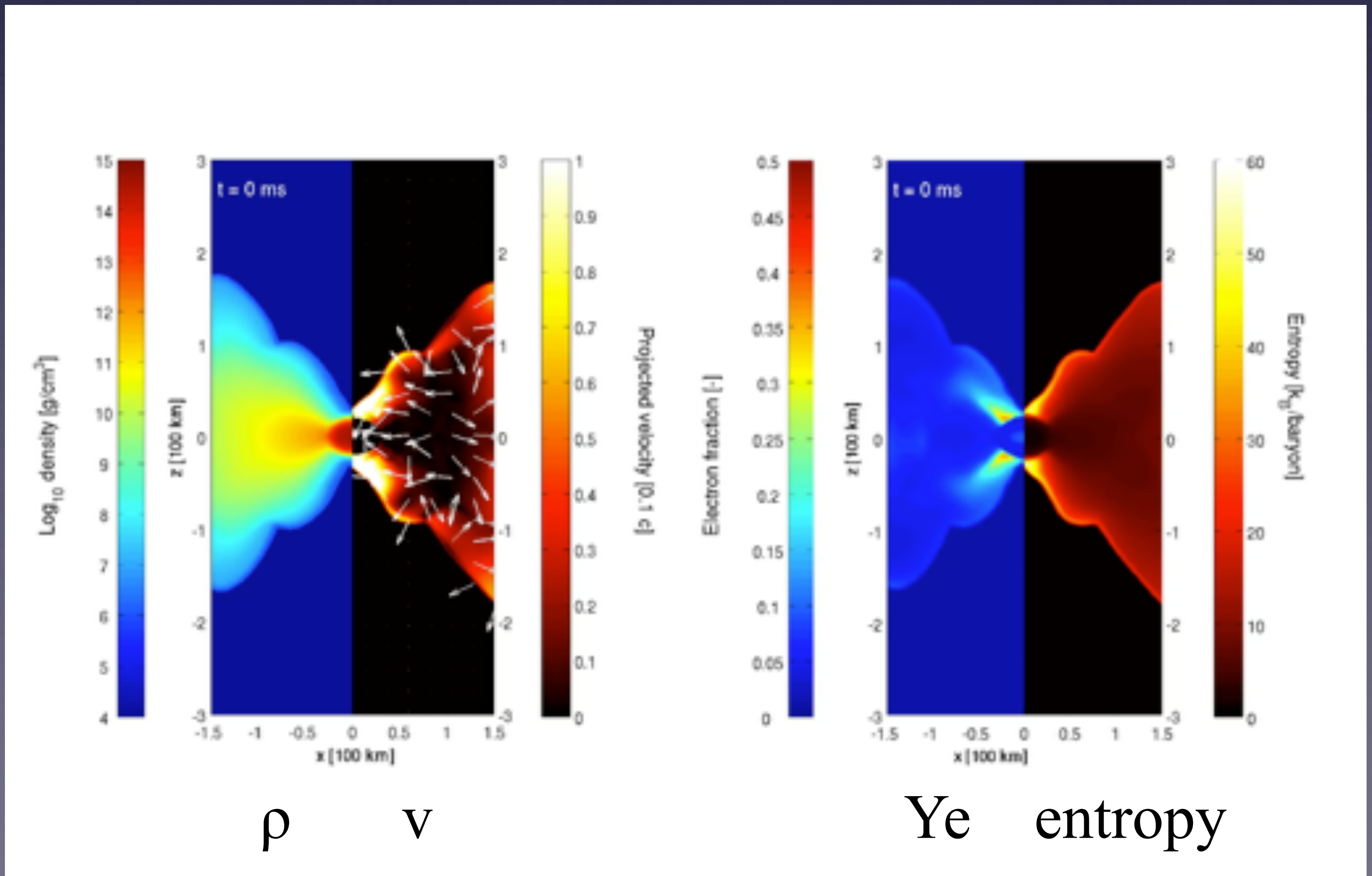

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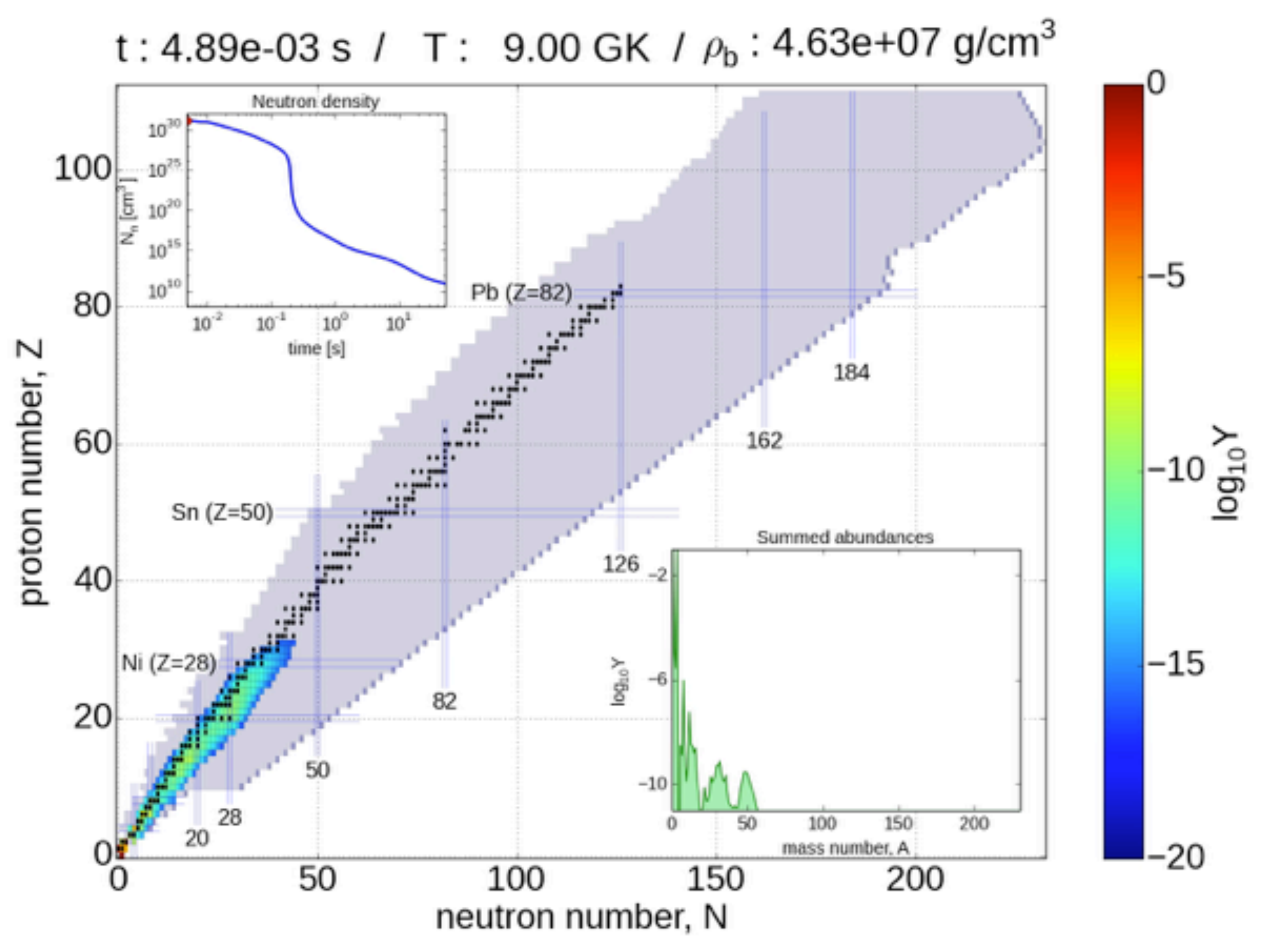
nucleosynthesis in neutrino-driven winds

(Martin, Perego, Arcones, Thielemann, Korobkin, S.R. (2015))



Winnet network

(Winteler 2012, 5831 isotopes)

complementary r-process in the range 80 ≲ A ≲ 130

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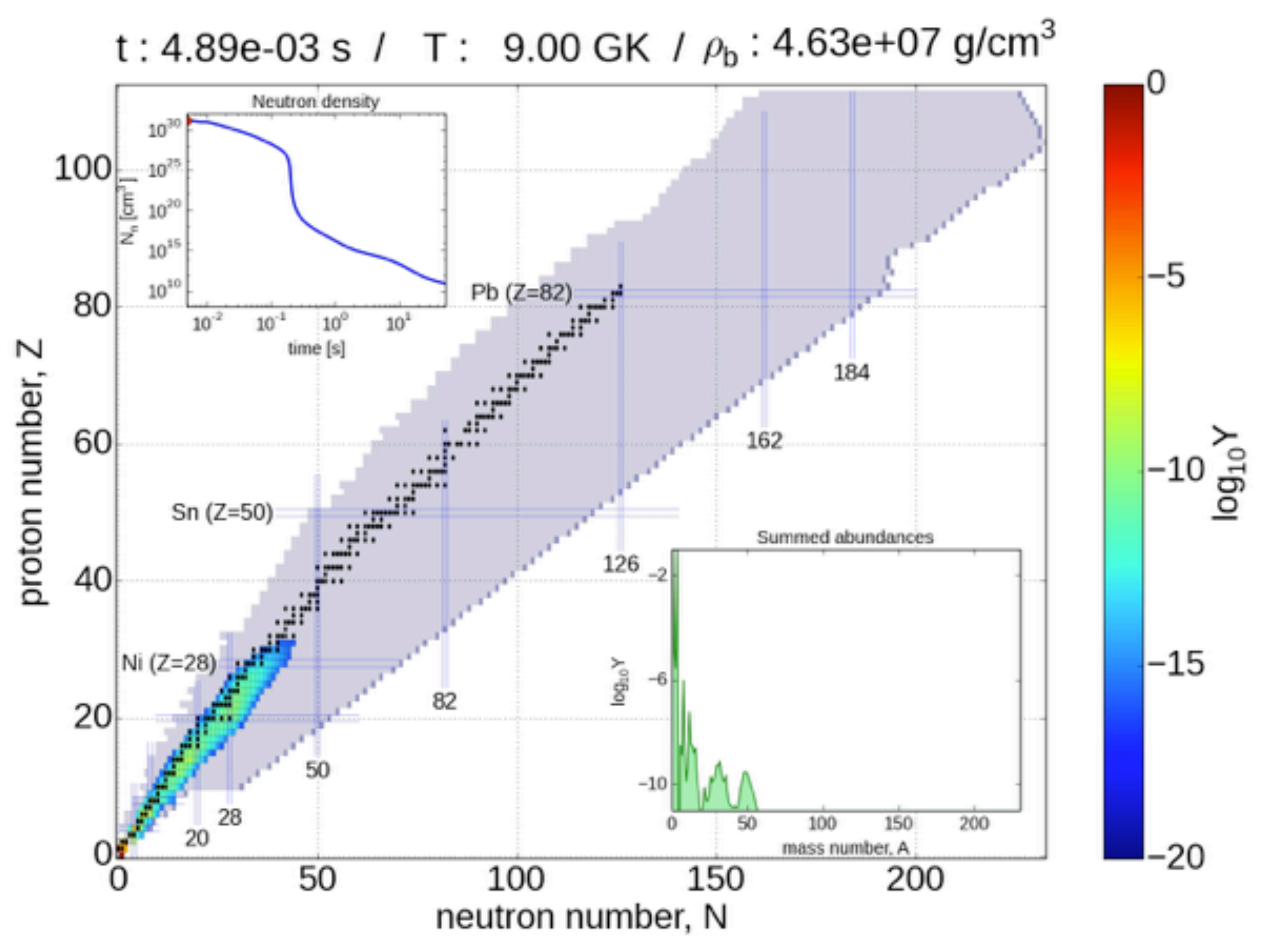

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II.4 Rate constraints

In the Milky Way:

all r-process: $19\,000 M_\odot$ r-process A $>$ 80: $14\,000\ M_\odot$ r-process A $>$ 130: $2530\ M_\odot$

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What does this imply for the production rate?

$$\boxed{M_r = m_{\rm ej} \times \mathcal{R} \times \tau_{\rm Gal}}$$

total r-mass   typical ejecta mass   average rate   age of Galaxy

- degeneracy $m_{\rm ej} \times \mathcal{R} = \frac{\rm M_r}{\tau_{\rm Gal}}$

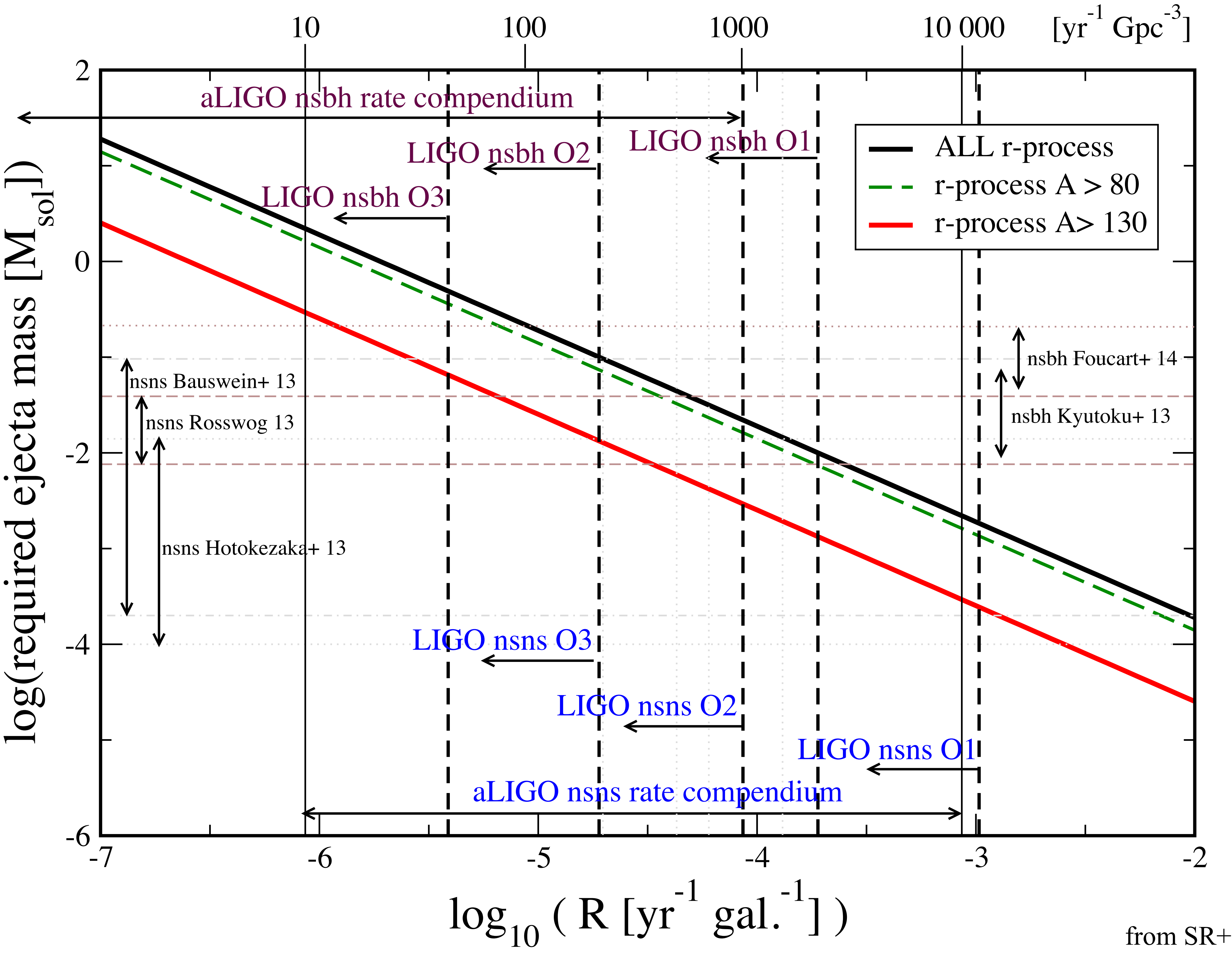
all r-process: $1.9 \times 10^{-6} \frac{\rm M_\odot}{\rm yr}$

r-process A > 80: $1.4 \times 10^{-6} \frac{\rm M_\odot}{\rm yr}$

r-process A > 130: $2.5 \times 10^{-7} \frac{\rm M_\odot}{\rm yr}$

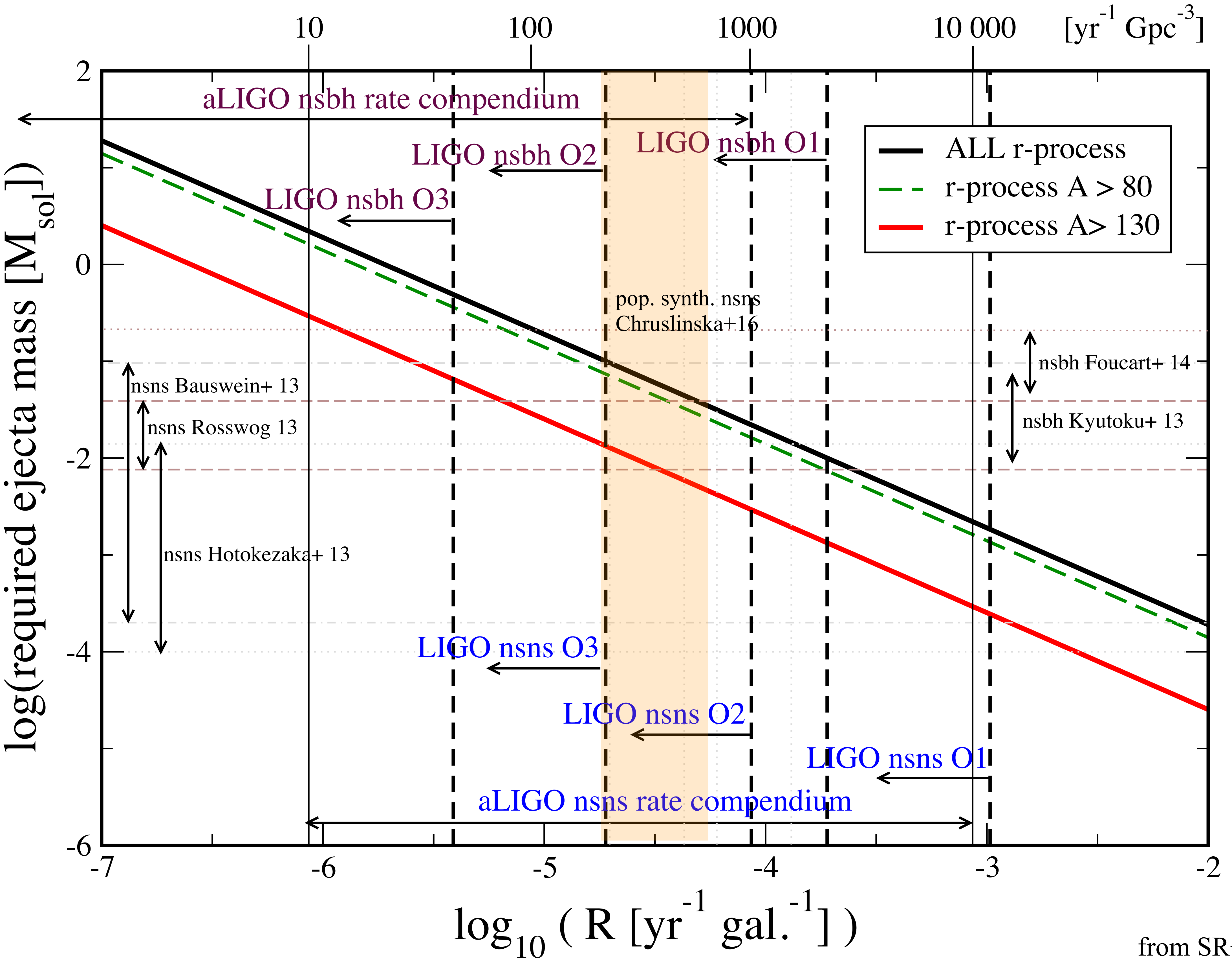
$\Rightarrow$ "rare high-mass (e.g. NSNS merger) or frequent low-mass events (like supernovae) ?"

Rate constraints



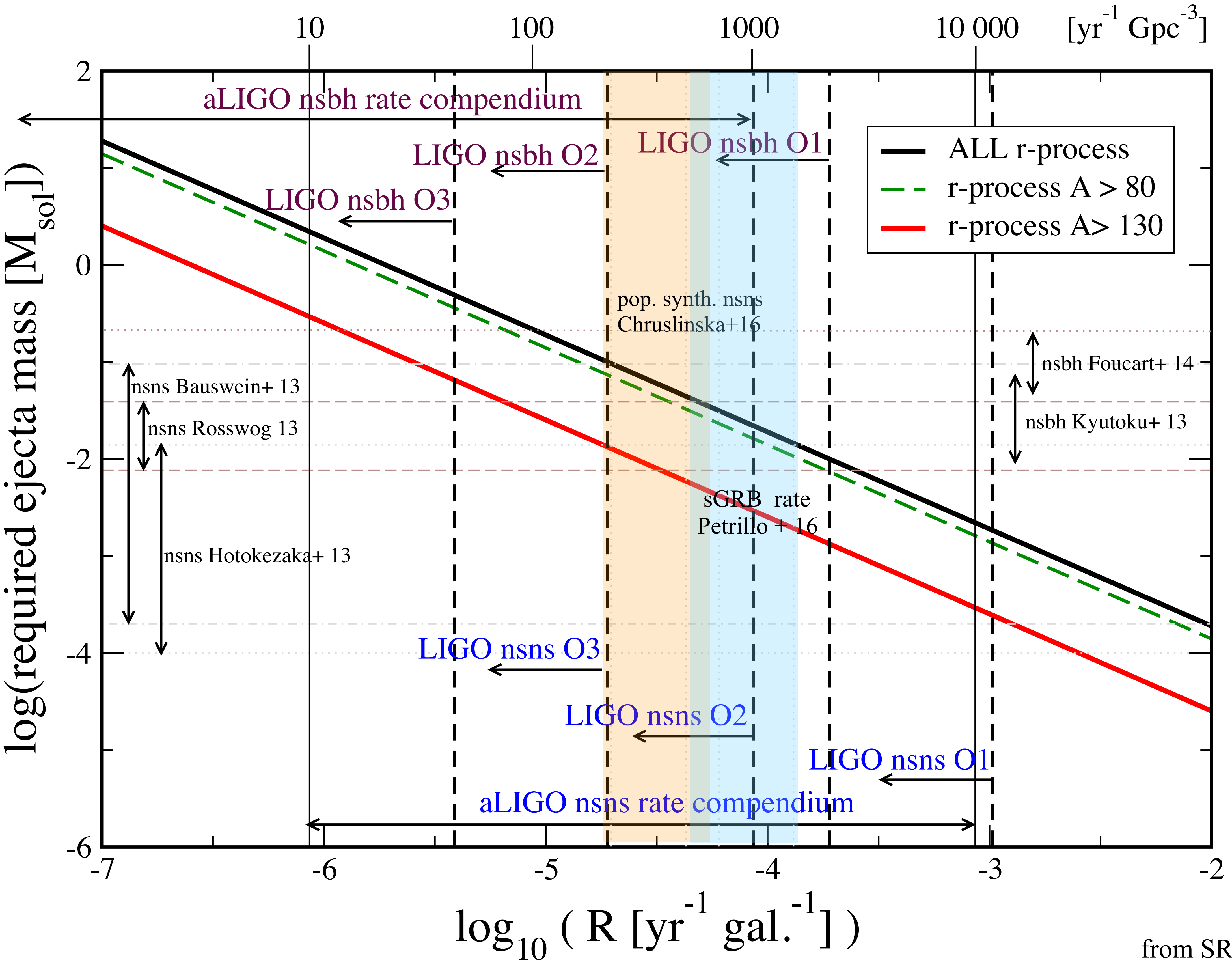
from SR++ (2016)

Rate constraints



from SR++ (2016)

Rate constraints



from SR++ (2016)

III. Macronovae (MN)

use here two simple models, i.e. no full radiative transfer (⇒ talk Ryan Wollager):

macronova model I:

(Grossman++ 14)

- spher. symmetric, homologously expanding ρ-profile
- "radiating volume": above "diffusion surface" ($\tau_{\rm dyn} = \tau_{\rm diff}$)
- nuclear heating rate direct from nuclear network
- "Finite Range Droplet Model" (FRDM) for nuclear mass (Moeller++ 95)
- constant thermalization used f= 0.5
- BB-spectrum with effective temperature of the photosphere ($\tau_{\rm ph}$=2/3)
- opacities:
  - dynamic ejecta: κ= 10 cm^2/g (Kasen+13, Barnes+13)
  - "wind" ejecta: κ= 1 cm^2/g (Grossman+14)

macronova model II:

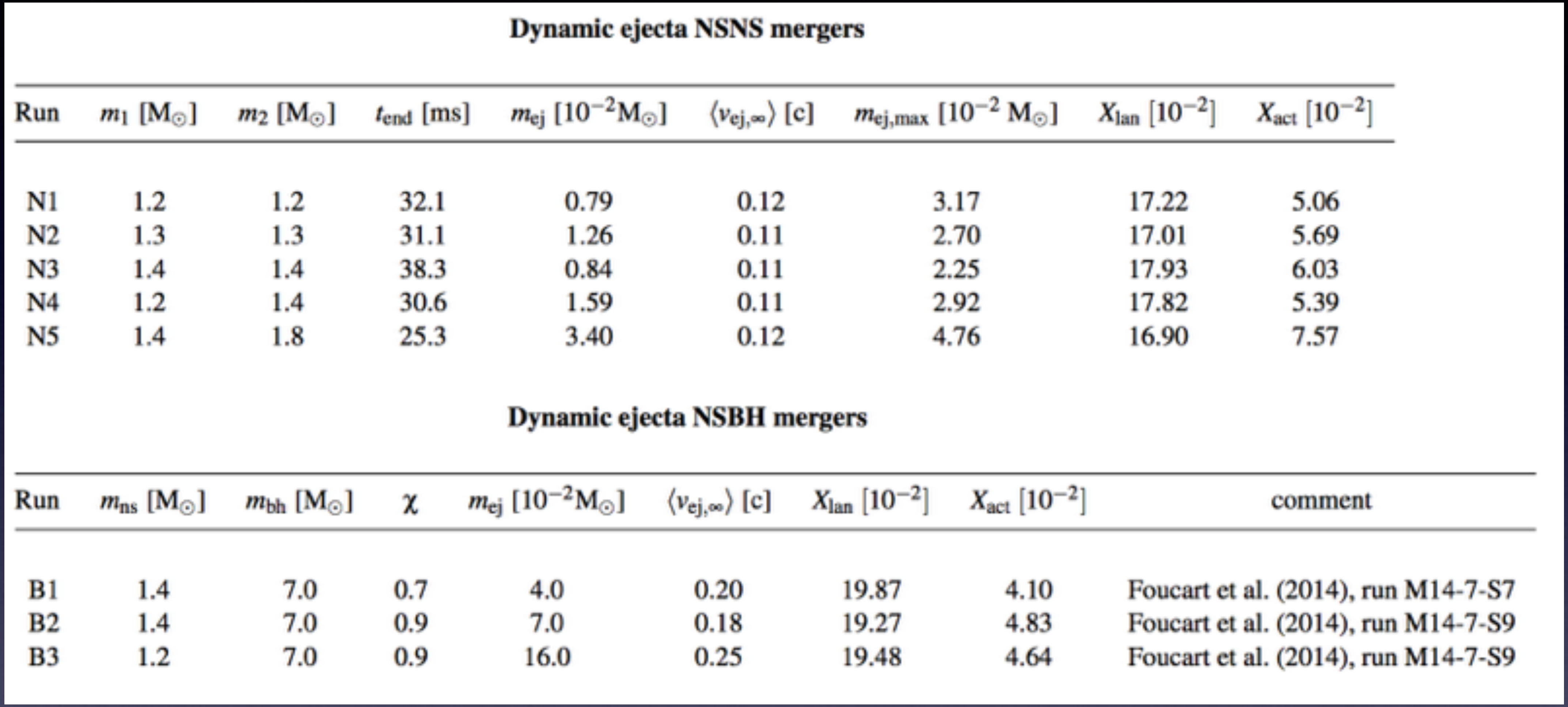
like model I, BUT:

- either FRDM mass model or Duflo-Zuker (DZ31, Duflo-Zuker 95)
- time-dependent thermalization efficiencies for each species according to the model developed by Barnes et al. 16

III.2 Explored parameter space

Dynamic ejecta nsns- & nsbh mergers

lanthanide + actinides > 20% of mass



Dynamic ejecta NSNS mergers

Run	m_1 [$M_\odot$]	m_2 [$M_\odot$]	t_{end} [ms]	m_{ej} [$10^{-2} M_\odot$]	$\langle v_{ej,\infty} \rangle$ [c]	$m_{ej,max}$ [$10^{-2} M_\odot$]	X_{lan} [10^{-2}]	X_{act} [10^{-2}]
N1	1.2	1.2	32.1	0.79	0.12	3.17	17.22	5.06
N2	1.3	1.3	31.1	1.26	0.11	2.70	17.01	5.69
N3	1.4	1.4	38.3	0.84	0.11	2.25	17.93	6.03
N4	1.2	1.4	30.6	1.59	0.11	2.92	17.82	5.39
N5	1.4	1.8	25.3	3.40	0.12	4.76	16.90	7.57

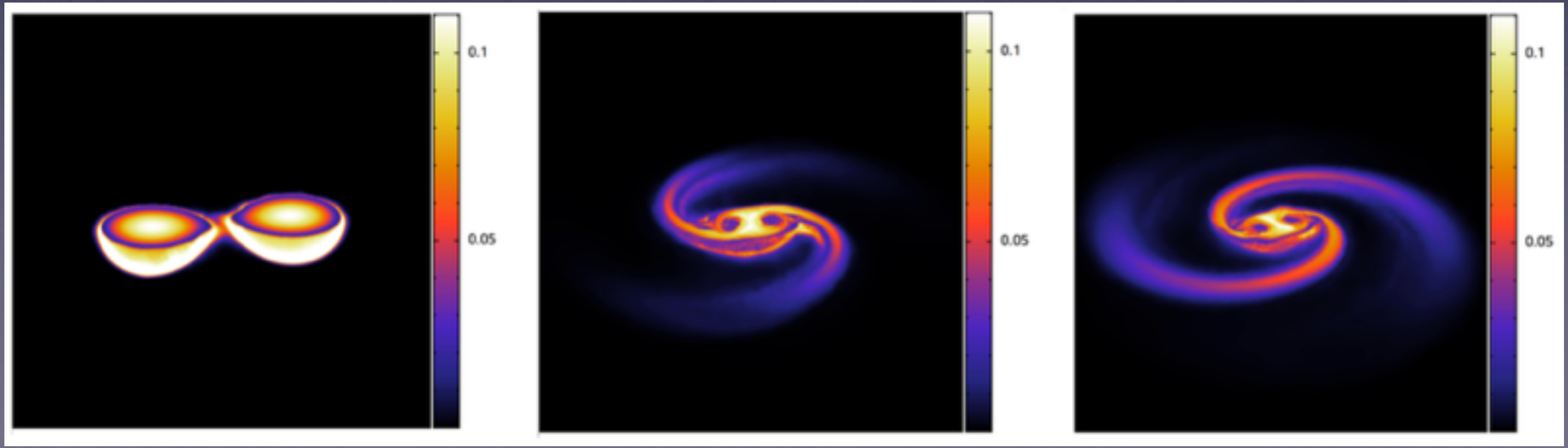
Dynamic ejecta NSBH mergers

Run	m_{ns} [$M_\odot$]	m_{bh} [$M_\odot$]	χ	m_{ej} [$10^{-2} M_\odot$]	$\langle v_{ej,\infty} \rangle$ [c]	X_{lan} [10^{-2}]	X_{act} [10^{-2}]	comment
B1	1.4	7.0	0.7	4.0	0.20	19.87	4.10	Foucart et al. (2014), run M14-7-S7
B2	1.4	7.0	0.9	7.0	0.18	19.27	4.83	Foucart et al. (2014), run M14-7-S9
B3	1.2	7.0	0.9	16.0	0.25	19.48	4.64	Foucart et al. (2014), run M14-7-S9

m_{ej} up to ~0.04 $M_\odot$

q=0.78
compare with
J0453+1559: q= 0.75

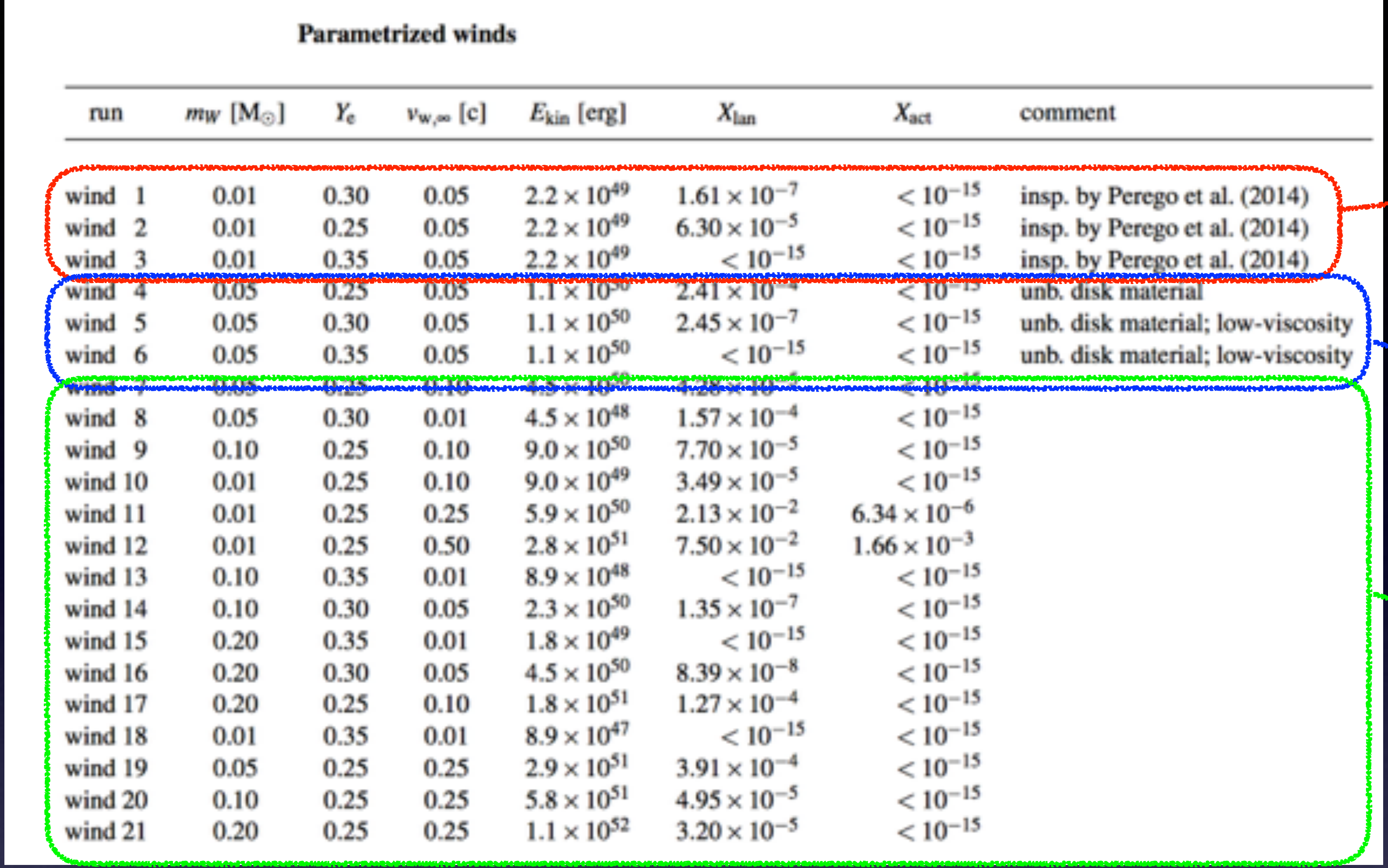
m_{ej} up to ~0.16 $M_\odot$



ns13ns13

from SR++ (2016)

(parametrized) winds



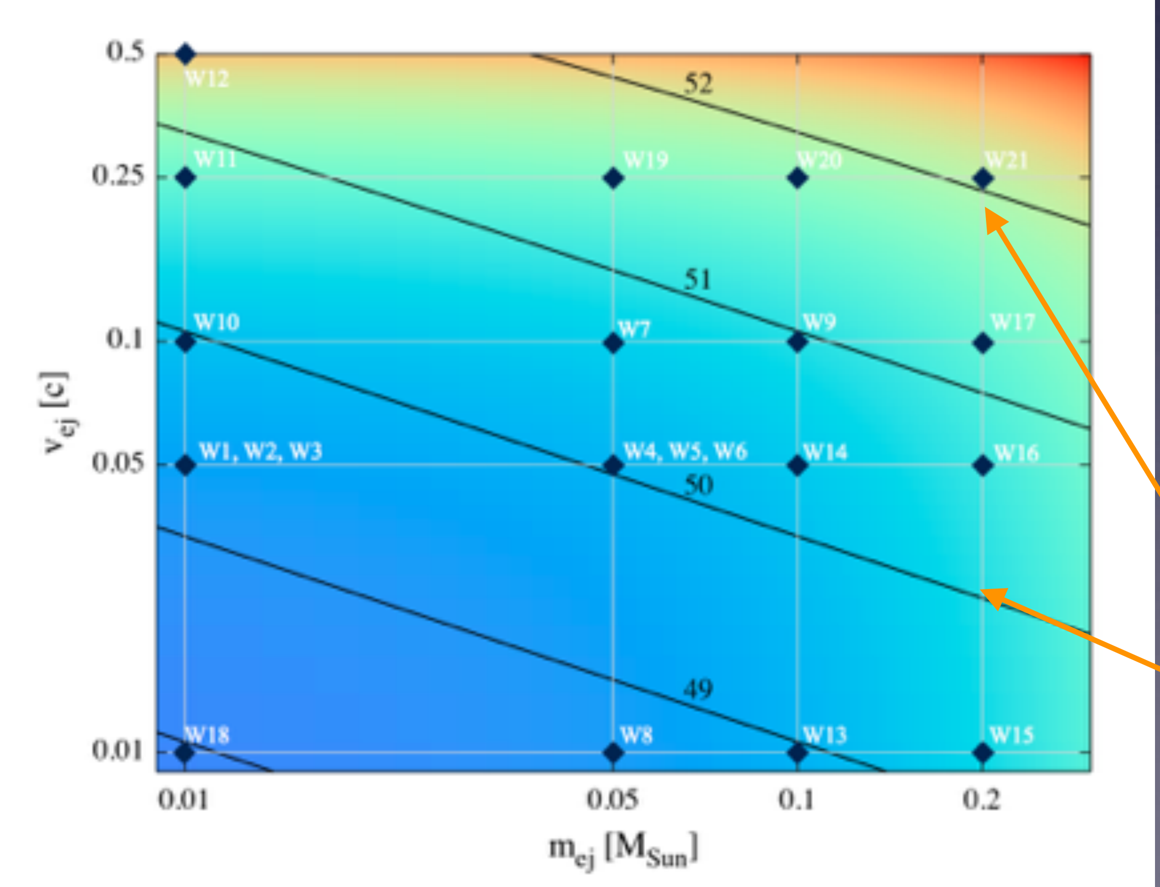
Parametrized winds

run	m_W [$M_\odot$]	Y_e	$v_{w,\infty}$ [c]	E_{kin} [erg]	X_{lan}	X_{act}	comment
wind 1	0.01	0.30	0.05	2.2×10^{49}	1.61×10^{-7}	$< 10^{-15}$	insp. by Perego et al. (2014)
wind 2	0.01	0.25	0.05	2.2×10^{49}	6.30×10^{-5}	$< 10^{-15}$	insp. by Perego et al. (2014)
wind 3	0.01	0.35	0.05	2.2×10^{49}	$< 10^{-15}$	$< 10^{-15}$	insp. by Perego et al. (2014)
wind 4	0.05	0.25	0.05	1.1×10^{50}	2.41×10^{-4}	$< 10^{-15}$	unb. disk material
wind 5	0.05	0.30	0.05	1.1×10^{50}	2.45×10^{-7}	$< 10^{-15}$	unb. disk material; low-viscosity
wind 6	0.05	0.35	0.05	1.1×10^{50}	$< 10^{-15}$	$< 10^{-15}$	unb. disk material; low-viscosity
wind 7	0.05	0.25	0.10	4.5×10^{50}	4.28×10^{-5}	$< 10^{-15}$	
wind 8	0.05	0.30	0.01	4.5×10^{48}	1.57×10^{-4}	$< 10^{-15}$	
wind 9	0.10	0.25	0.10	9.0×10^{50}	7.70×10^{-5}	$< 10^{-15}$	
wind 10	0.01	0.25	0.10	9.0×10^{49}	3.49×10^{-5}	$< 10^{-15}$	
wind 11	0.01	0.25	0.25	5.9×10^{50}	2.13×10^{-2}	6.34×10^{-6}	
wind 12	0.01	0.25	0.50	2.8×10^{51}	7.50×10^{-2}	1.66×10^{-3}	
wind 13	0.10	0.35	0.01	8.9×10^{48}	$< 10^{-15}$	$< 10^{-15}$	
wind 14	0.10	0.30	0.05	2.3×10^{50}	1.35×10^{-7}	$< 10^{-15}$	
wind 15	0.20	0.35	0.01	1.8×10^{49}	$< 10^{-15}$	$< 10^{-15}$	
wind 16	0.20	0.30	0.05	4.5×10^{50}	8.39×10^{-8}	$< 10^{-15}$	
wind 17	0.20	0.25	0.10	1.8×10^{51}	1.27×10^{-4}	$< 10^{-15}$	
wind 18	0.01	0.35	0.01	8.9×10^{47}	$< 10^{-15}$	$< 10^{-15}$	
wind 19	0.05	0.25	0.25	2.9×10^{51}	3.91×10^{-4}	$< 10^{-15}$	
wind 20	0.10	0.25	0.25	5.8×10^{51}	4.95×10^{-5}	$< 10^{-15}$	
wind 21	0.20	0.25	0.25	1.1×10^{52}	3.20×10^{-5}	$< 10^{-15}$	

“ν-wind inspired”

“disk evaporation inspired”

explore “unknown” parameter space



parameters of wind model:

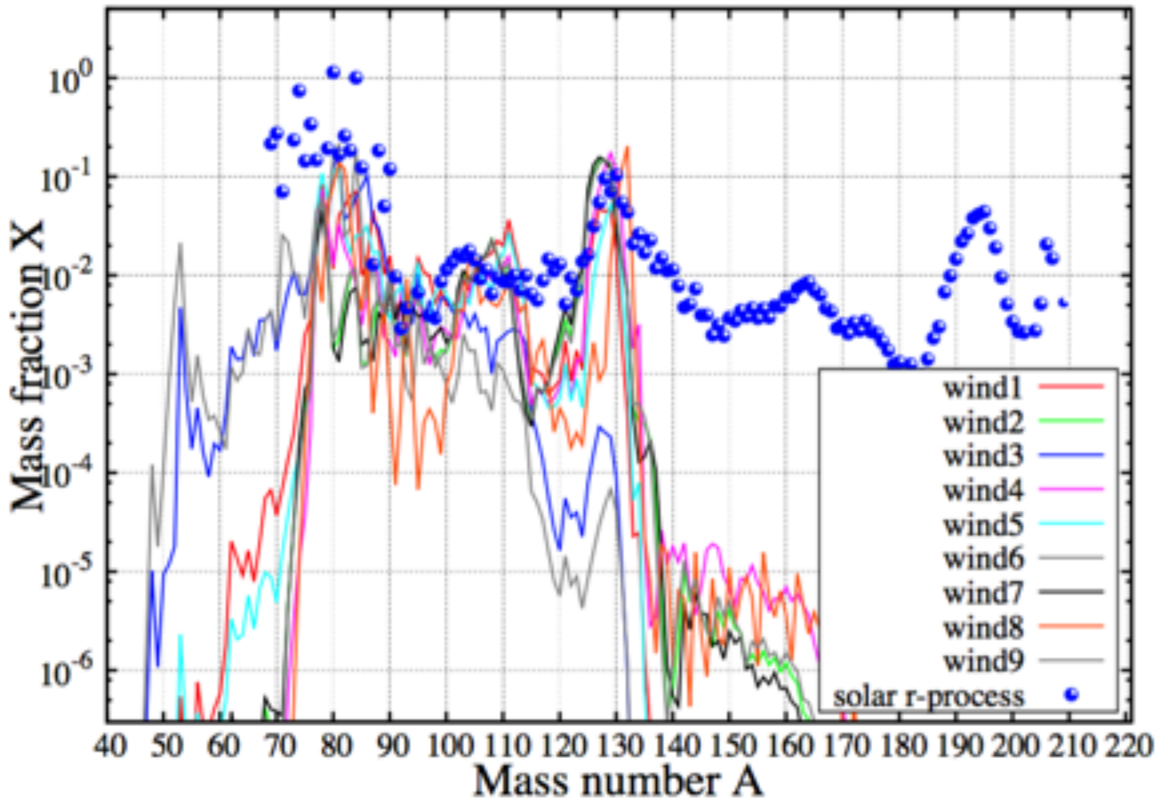
- mass: 0.01 … 0.2 M☉
- velocity: 0.01 … 0.50 c
- electron fraction: 0.25 … 0.35
- entropy: 15 kB/bar.

Log(kinetic energy)

from SR++ (2016)

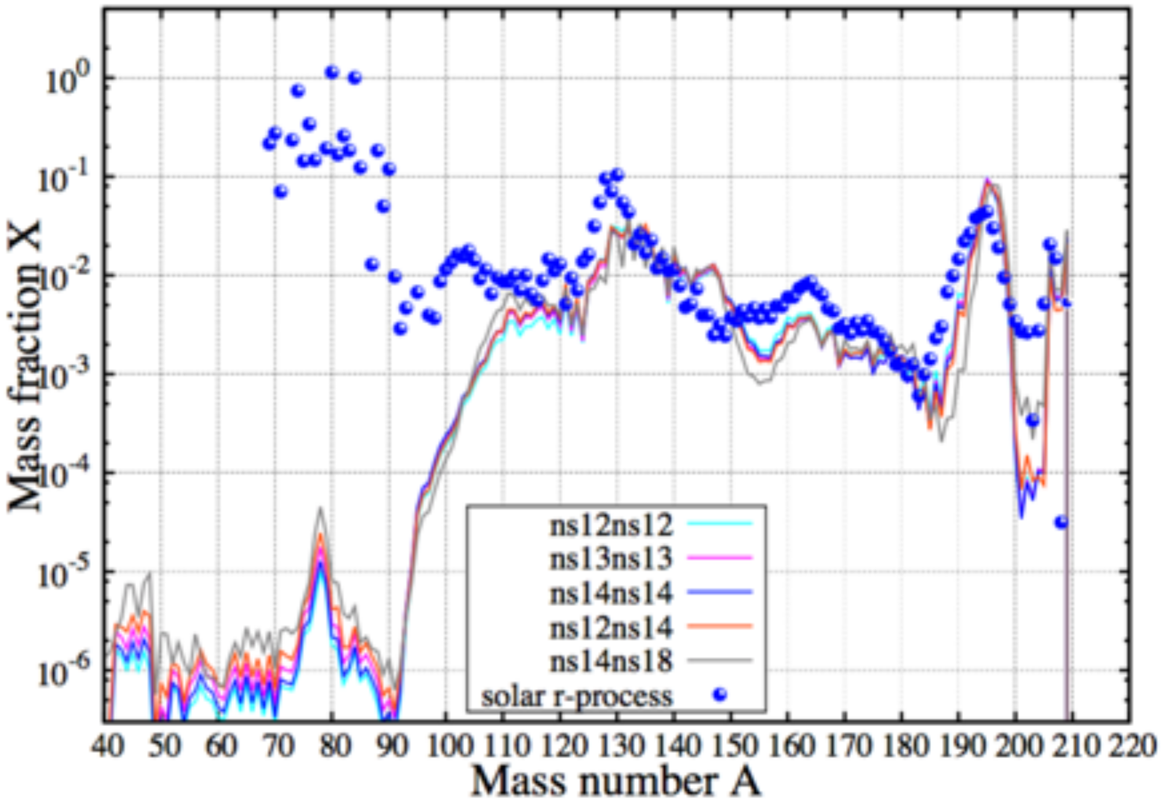
(broad-brush) nucleosynthesis:

“winds”



“weak r-process, A ≲ 130”

“dynamic ejecta”



“strong r-process, A ≳ 130”

III.3 How big is the impact of nuclear physics on potential observability?

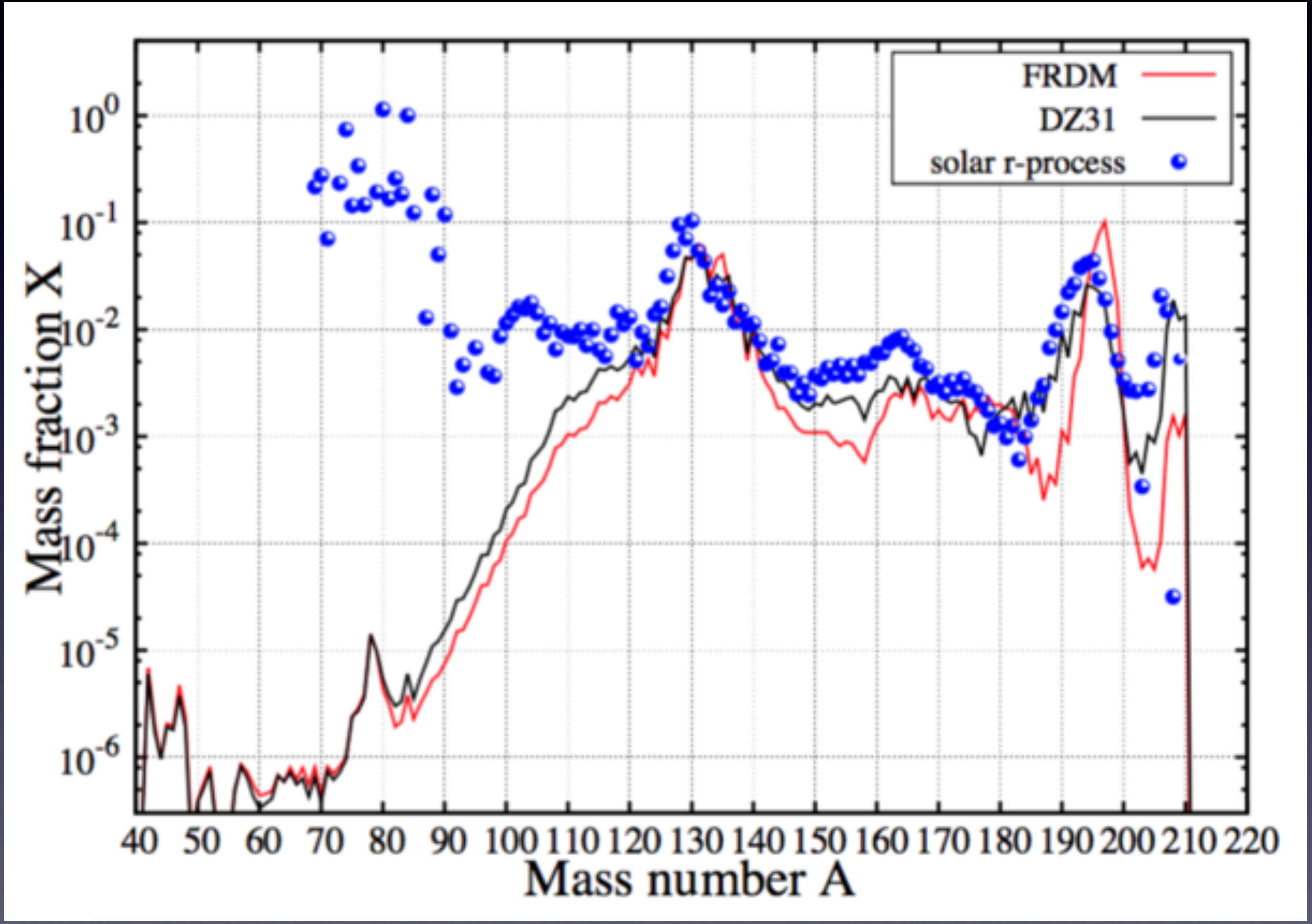
from SR++ (2016)

comparison nuclear mass formulae:

Finite Range Droplet Model (FRDM)

vs.

Duflo Zuker 31 param. (DZ31)

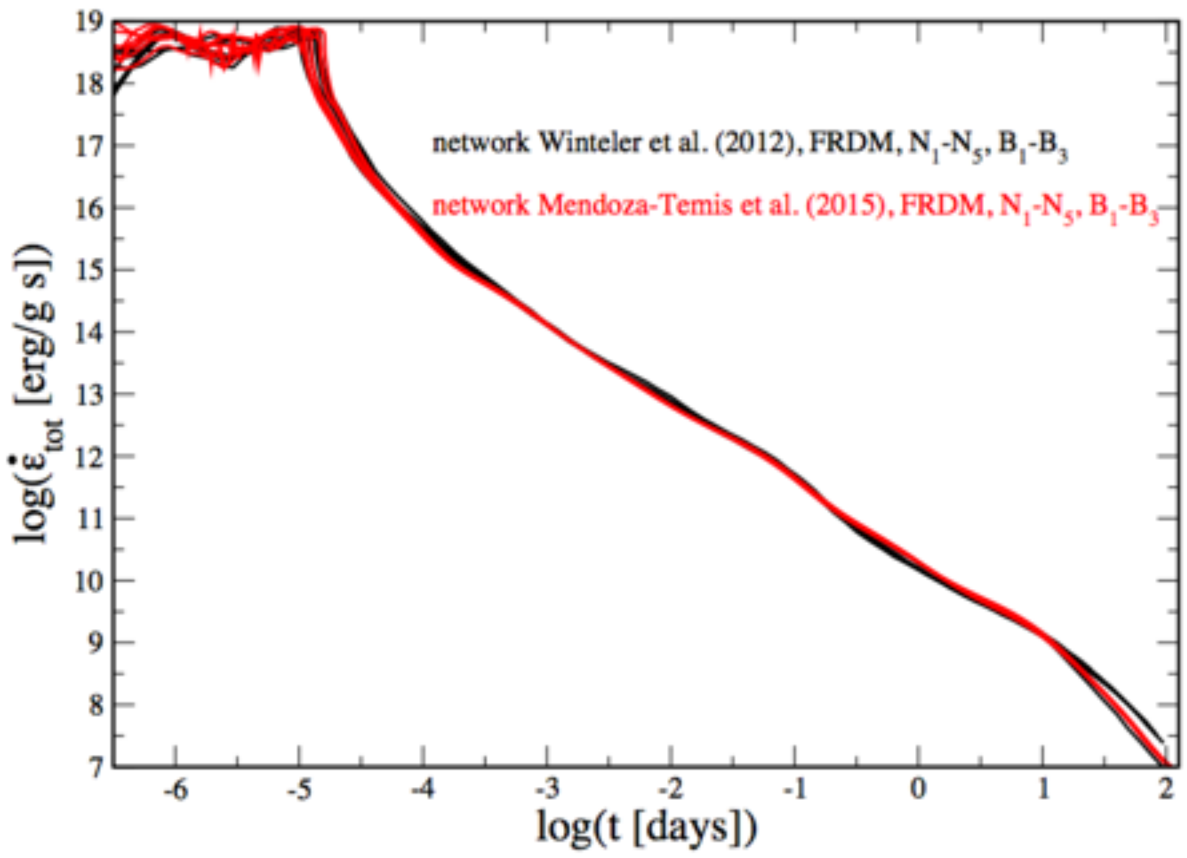


(at example ns12 + ns14 at t= 100 days)

⇒ substantially larger amounts of trans-lead elements for Duflo Zuker 31 (as first discussed in Barnes et al. (2016) ⇒ talk Jennifer Barnes)

comparison networks:

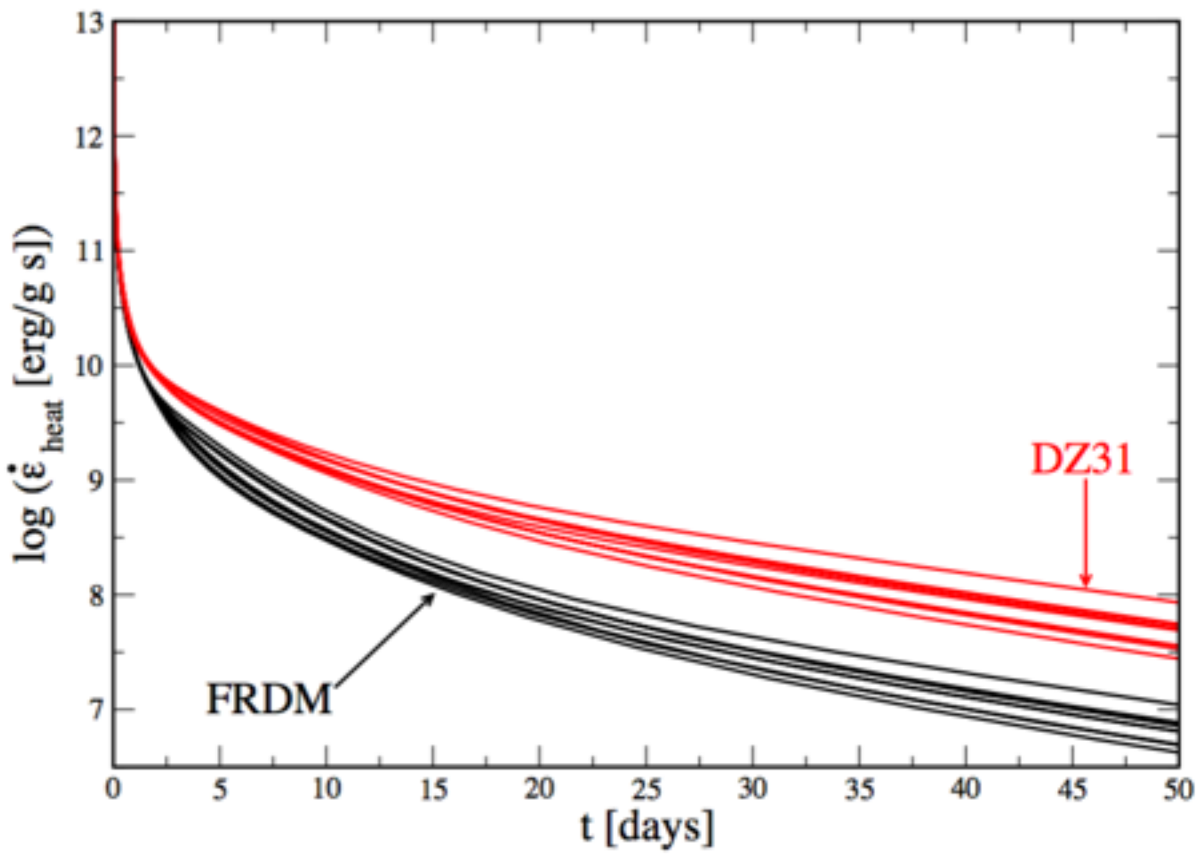
heating rate for same mass formula



comparison of mass formulae:

heating rate for FRDM vs DZ31

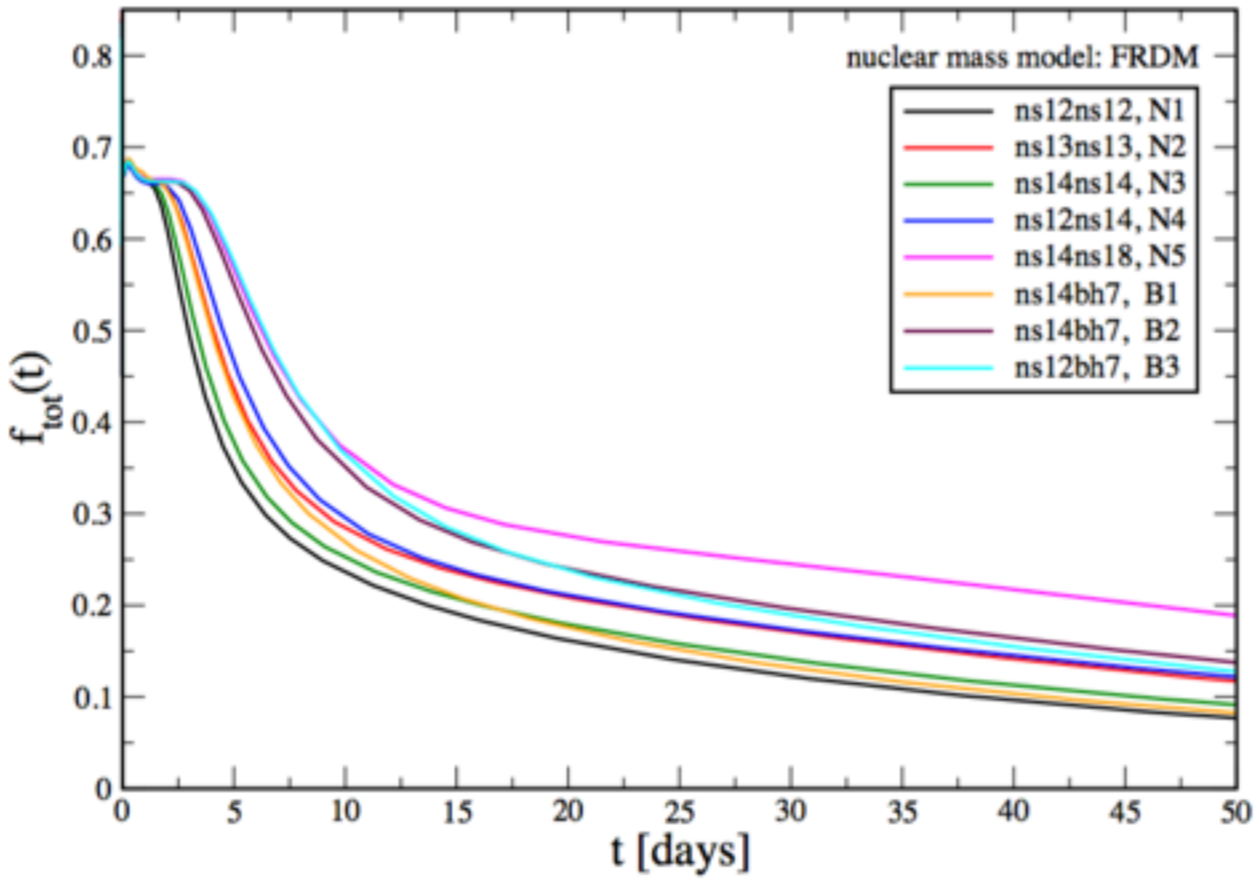
(for same network (Mendoza-Temis++ 2015))



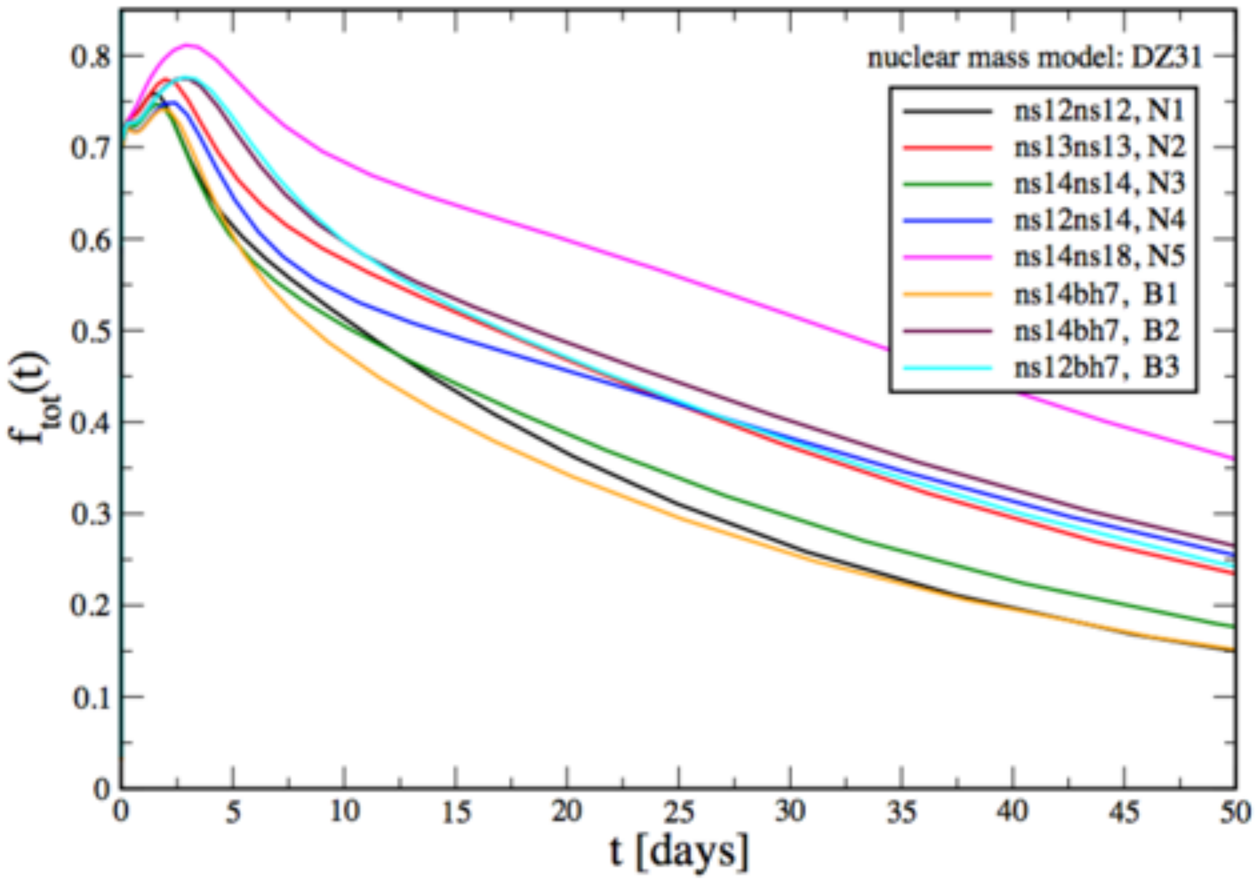
from SR++ (2016)

⇒ at relevant times (days): ~ order of magnitude larger heating rate due to α-decays of trans-lead elements for Duflo Zuker 31

thermalization efficiency FRDM



thermalization efficiency DZ31

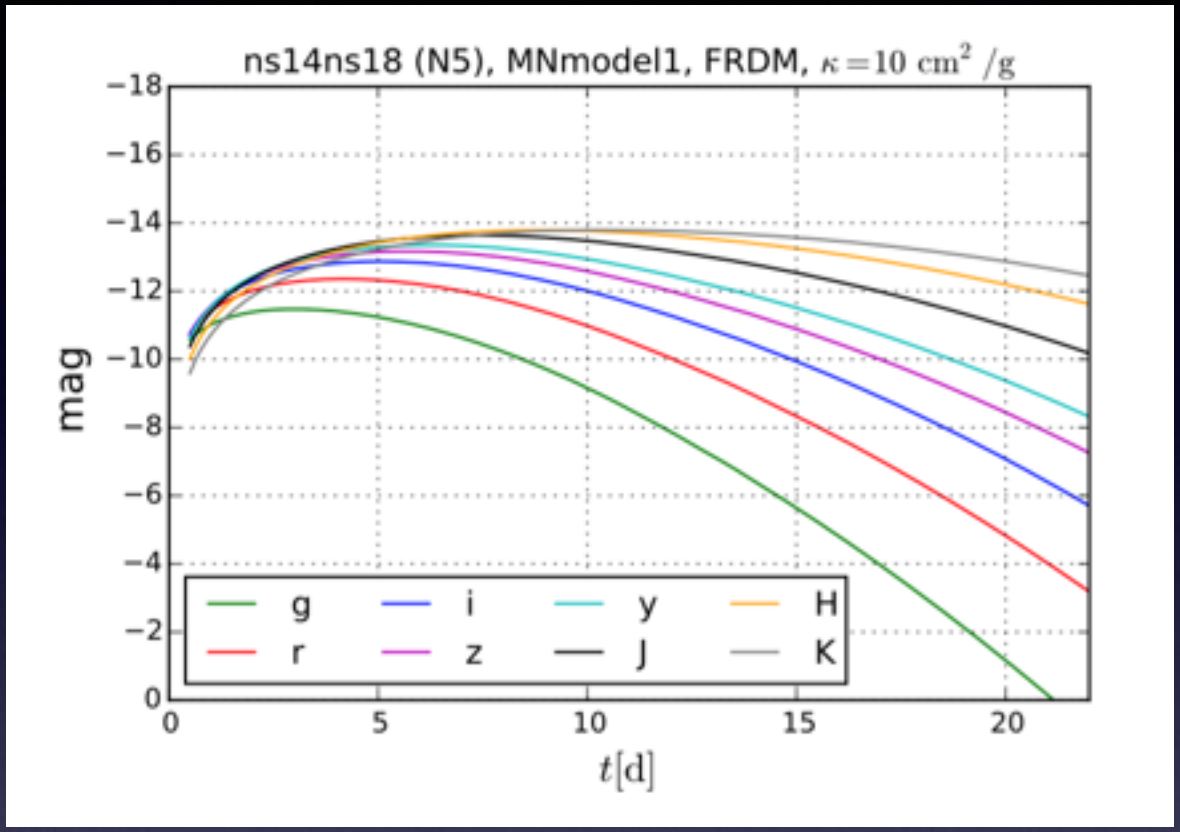


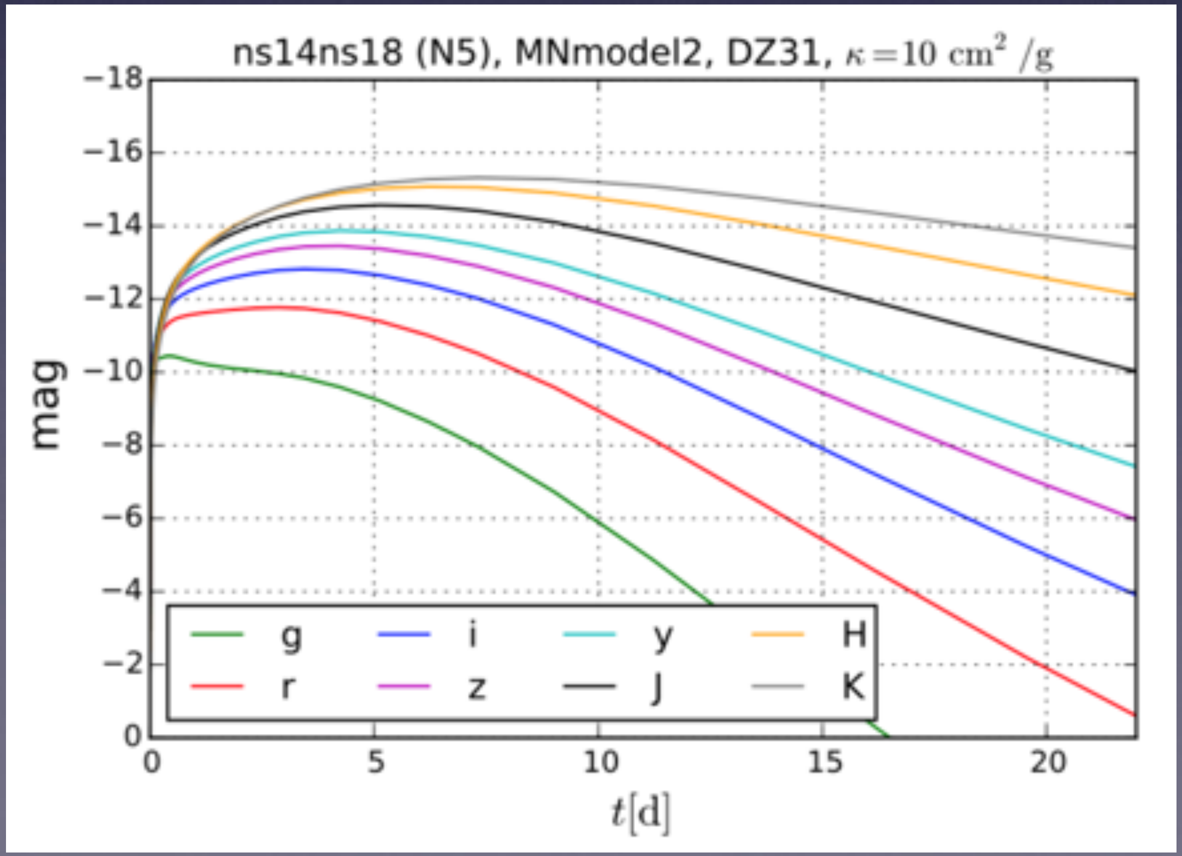
from SR++ (2016)

⇒ at ~ 10 days ~factor of two larger for Duflo Zuker 31

impact on optical/near IR light-curves:

our brightest nsns-example: 1.4 $M_\odot$ + 1.8 $M_\odot$





broadband filters

LSST

g	~380 - 580 nm
r	~520 - 700 nm
i	~650 - 850 nm
z	~780 - 950 nm
y	~950 - 1050 nm

2MASS

J	~1.1 - 1.4 micron
H	~1.5 - 1.8 micron
K	~2.0 - 2.4 micron

Macronova model 1:

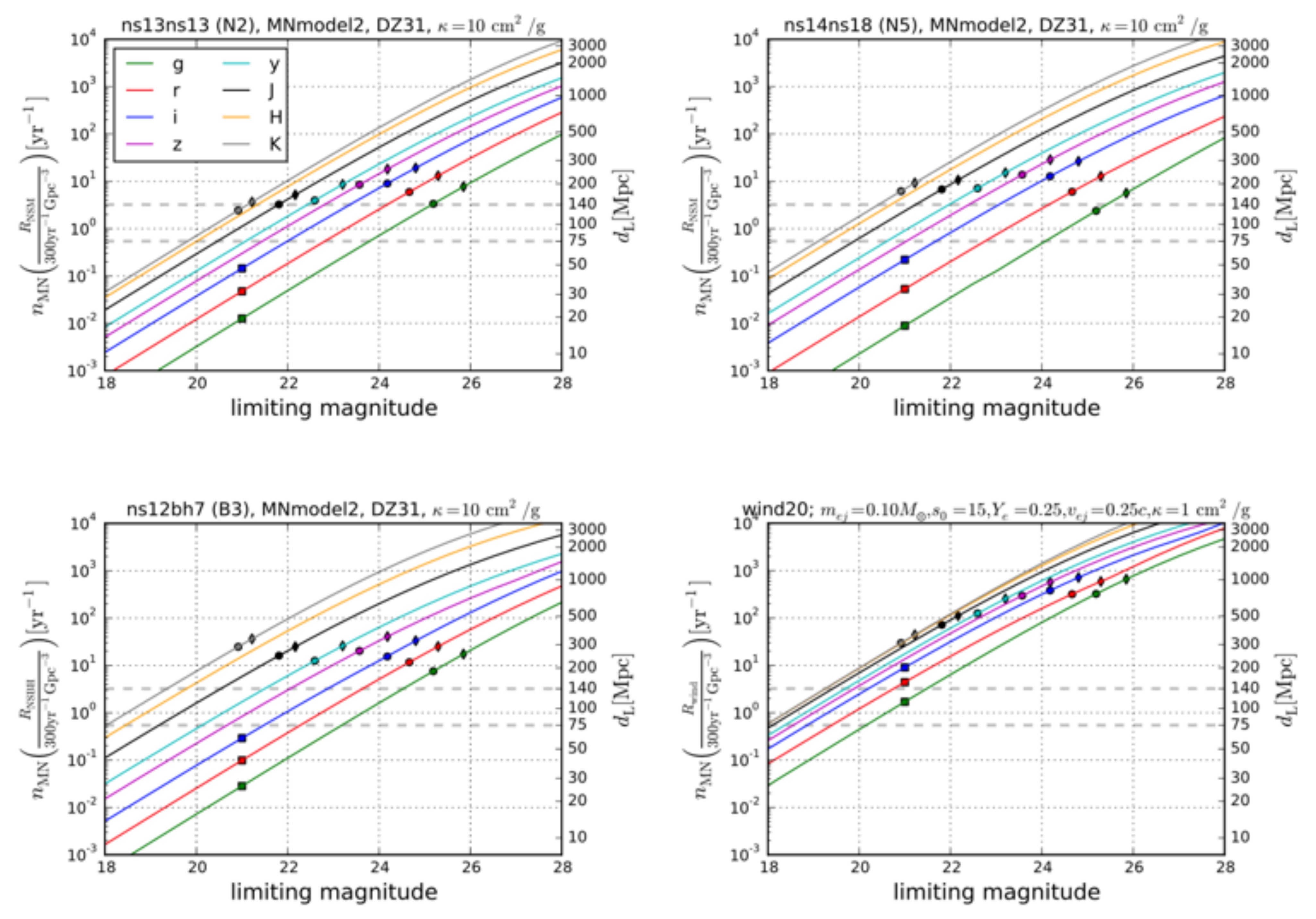
- original Grossman++(2014)
- FRDM mass model
- efficiency = 0.5 = const.

Macronova model 2:

like model 1, but
- DZ31
- time-dep. efficiencies

- “faint and fast in blue”
- “bright in NIR for weeks”
- “up to a magnitude brighter for DZ 31”

III.4 What are the detection prospects?



~ 10 detections per year VISTA/LSST

from SR++ (2016)

squares: Zwicky Transient Facility (ZTF; for depth 21 mag)
circles: 60 second exposures VISTA (J & K band) and LSST (grizy)
diamonds: 180 second exposures VISTA (J & K band) and LSST (grizy)

III.5 Comparison with "macronova candidate" GRB130603B

- possibly first detection of "macronova" in the aftermath of short GRB 130603B

9 days 30 days after burst

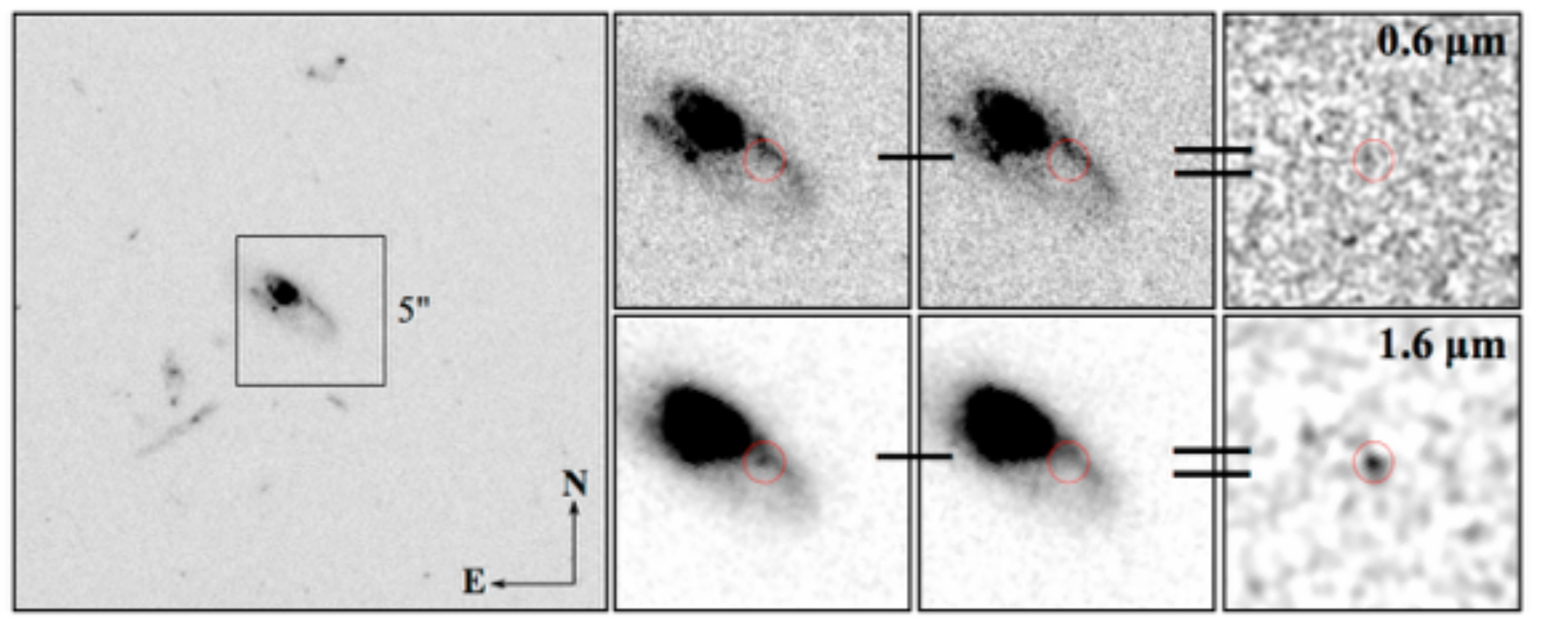


Figure 1 HST imaging of the location of SGRB 130603B. The host is well resolved

optical

nIR

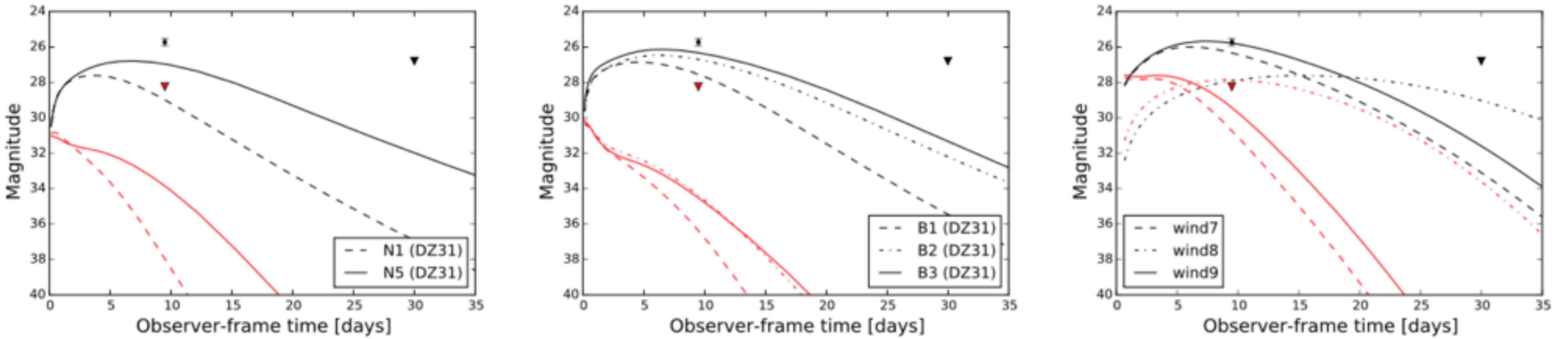
sGRB130603B (Tanvir et al. 2013):

- $T_{90} \approx 0.18$ s, z= 0.356
- nIR-transient, present at ≈9 days, but faded away after 30 days

- If interpretation correct:
  - short Gamma-ray Bursts caused by compact binary mergers
  - compact binary mergers are a major source of rapid neutron capture elements
  - isotropic macronovae promising accompanying signature for "chirp" GW signals

black: HST-band F160W (1.5 μm)   red: HST-band F606W (peak: 5.9 μm)

nsns   nsbh   wind



N1: dimmest nsns (1.2 +1.2 $M_\odot$)

N5: brightest nsns (1.4+1.8 $M_\odot$)

B1: nsbh (1.4 +7.0 $M_\odot$, χ= 0.7)
B2: nsbh (1.4 +7.0 $M_\odot$, χ= 0.9)
B3: nsbh (1.2 +7.0 $M_\odot$, χ= 0.9)

wind7: m_{ej}= 0.05 $M_\odot$, v_{ej}= 0.05 c, Y_e= 0.25
wind8: m_{ej}= 0.05 $M_\odot$, v_{ej}= 0.01 c, Y_e= 0.30
wind9: m_{ej}= 0.10 $M_\odot$, v_{ej}= 0.10 c, Y_e= 0.25

⇒ several models are “near” the observed properties

(e.g. nsns 1.4 + 1.8 $M_\odot$,
nsbh 1.2 $M_\odot$ + 7.0 $M_\odot$, χ= 0.9,
wind m_{ej}= 0.10 $M_\odot$, v_{ej}= 0.10 c, Y_e= 0.25)

many models much dimmer

V. Summary

- EM-transients crucial for GW-source localization

- EM-transients ⇔ matter ejection ⇔ r-process nucleo. ⇔ sGRBs

- various ejection channels:
  - dynamic (very low Ye component ⇒ "strong r-process" ⇒ large opacities ⇒ "late + red")
  - various types of "winds" (higher Ye ⇒ "weak" r-process ⇒ lower opacities ⇒ "early + blue")

- nuclear physics has substantial impact on observability, e.g. α-decaying trans-lead nuclei (DZ31) impacts on
  - heating rates
  - thermalization efficiencies

    ⇒ substantially brighter lightcurves

- detection prospects: LSST could see ~10 nsns-events yr^{-1}

- several of our dyn. ejecta and wind models are good candidates for "Tanvir-event" (prov. DZ31, trans-lead α-decay, standard opacities), but many will be very difficult to observe

- caveats of current MN model:

  I) opacities

  II) wait for full radiative transfer