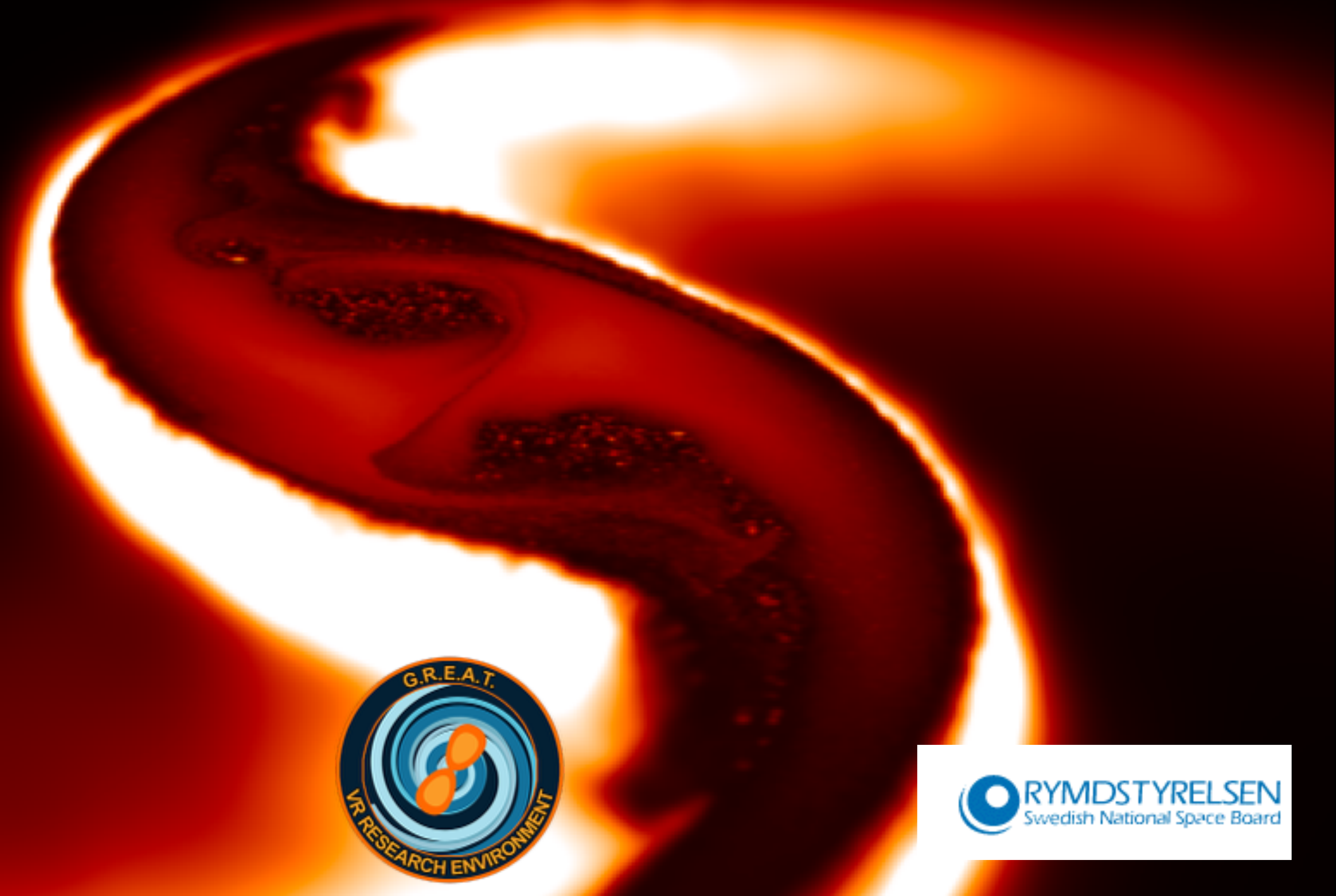
Sackler Conference, Harvard, May 08 2018

Neutron star mergers as cosmic factories of heavy elements

Stephan Rosswog
Stockholm University



Vetenskapsrådet

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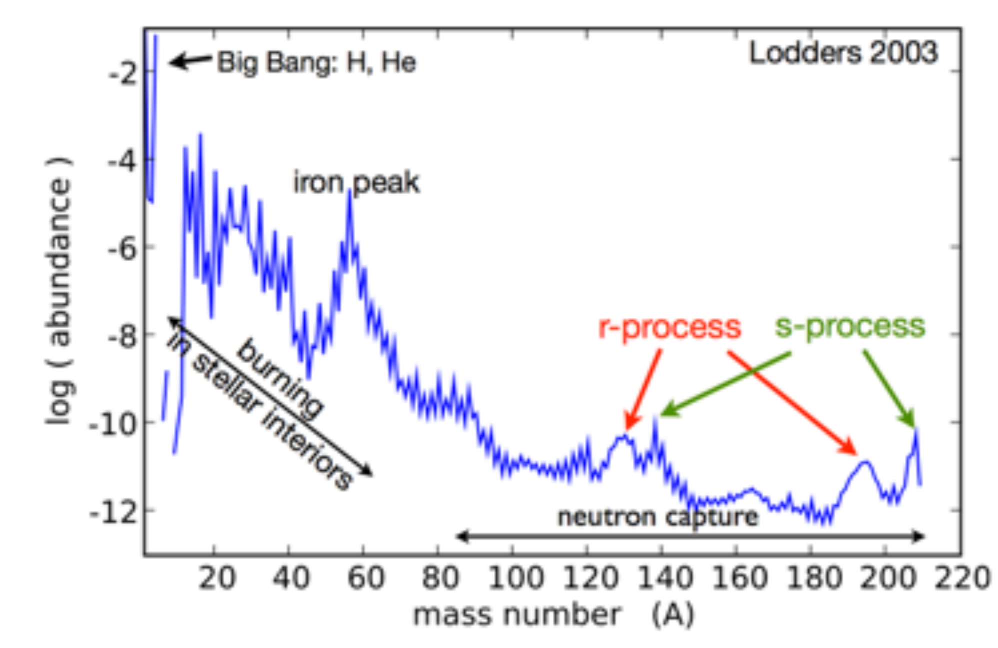
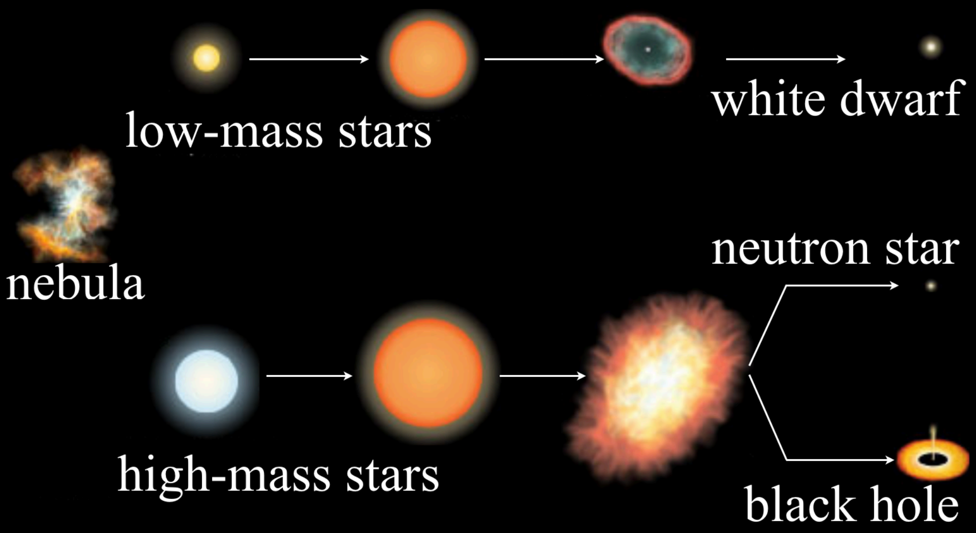
Swedish National Space Board

Nucleosynthesis

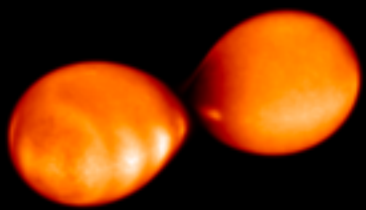


Chemical enrichment of the Cosmos

Binary stellar evolution

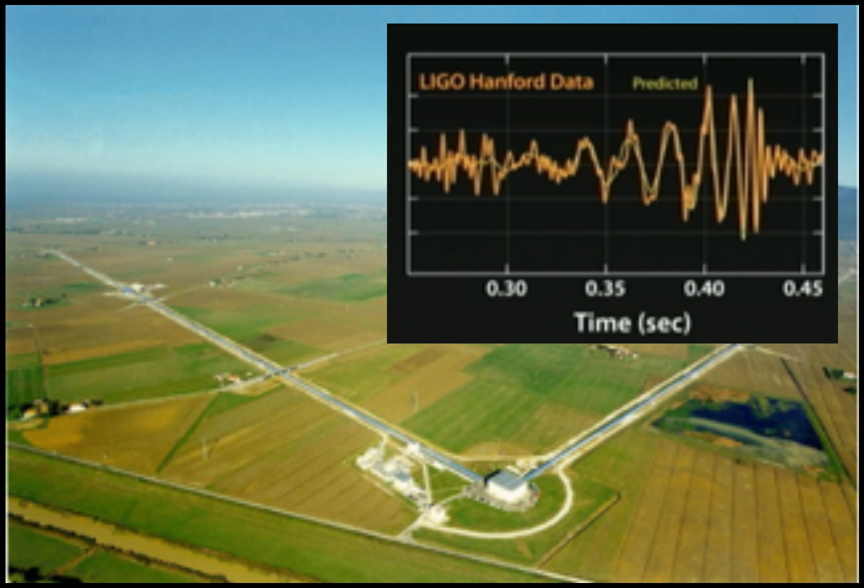


Radioactively powered flashes

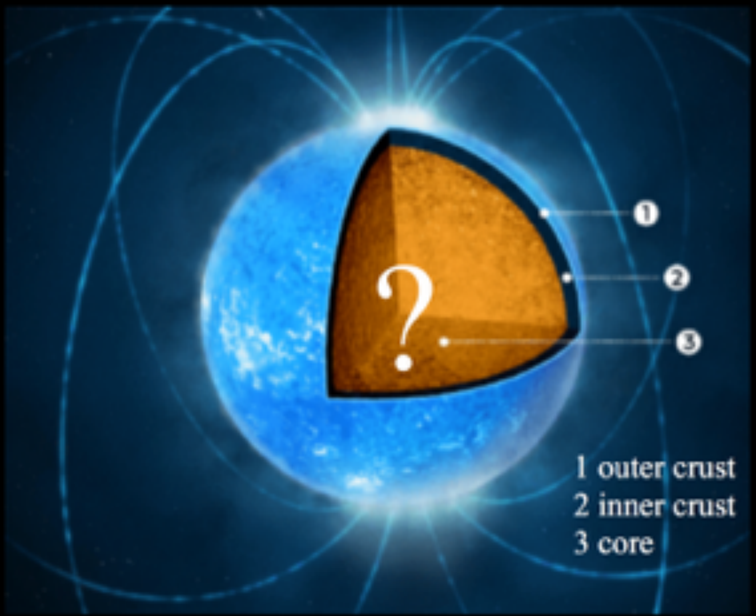


ns-ns mergers

Gravitational wave detection



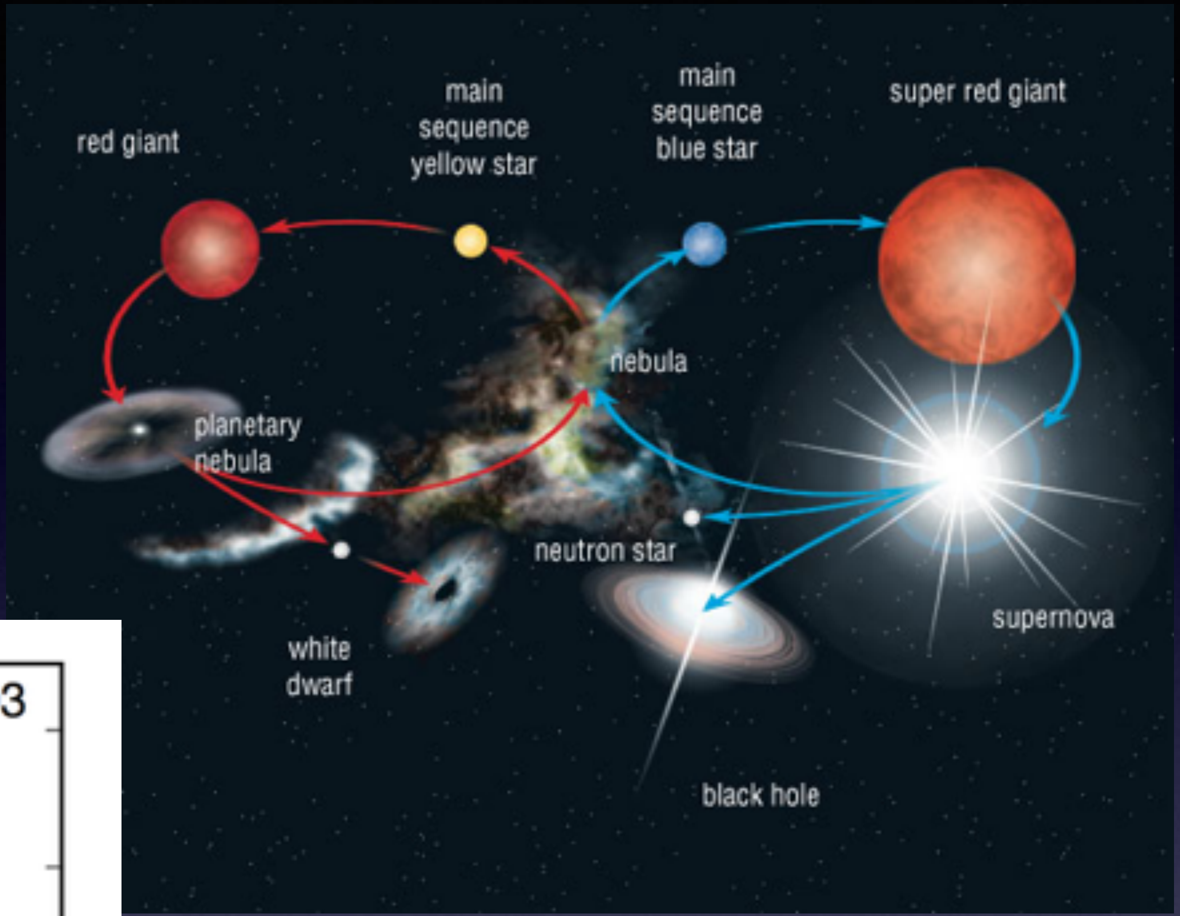
Nuclear matter properties



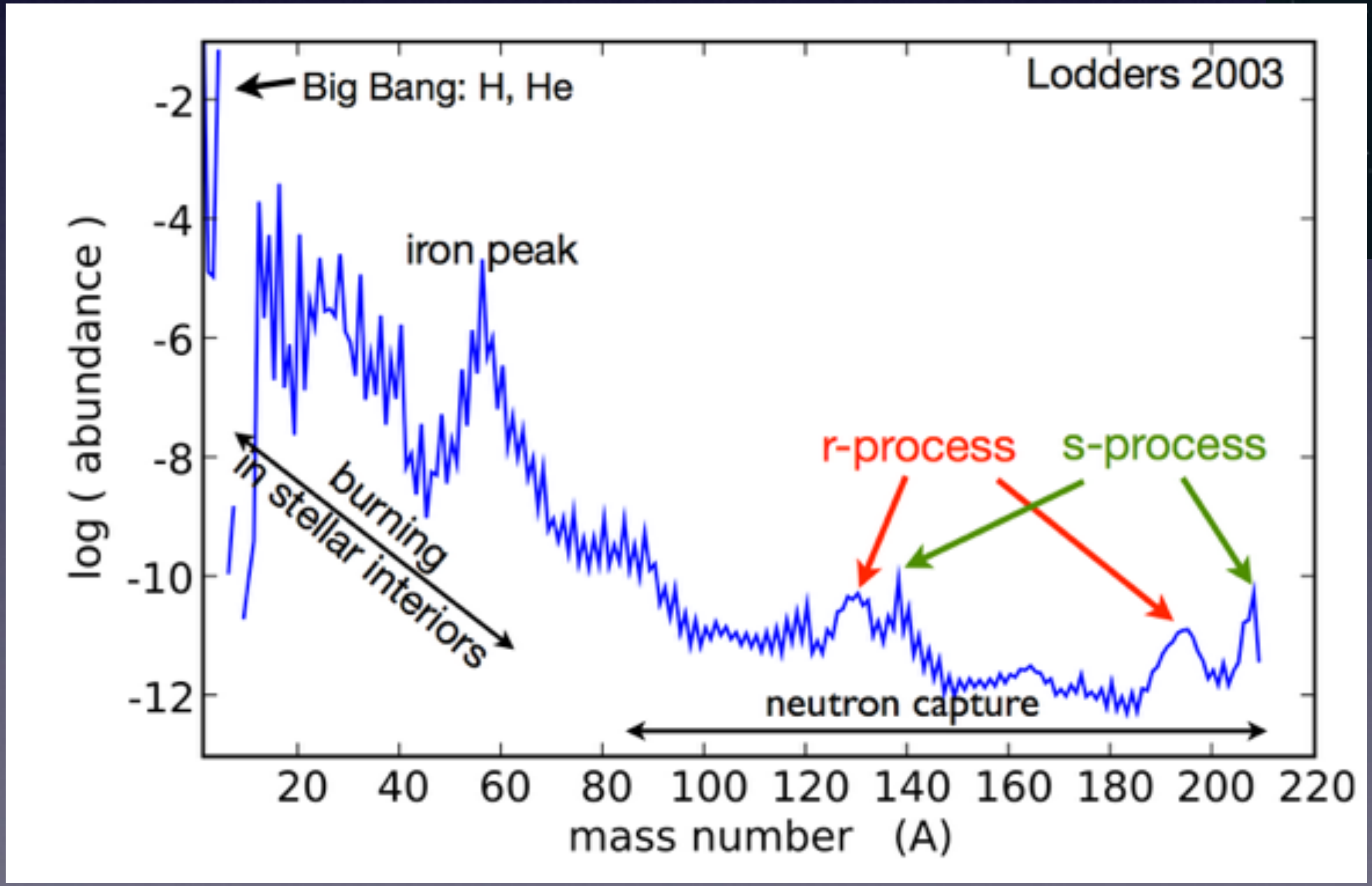
(short) Gamma-Ray Bursts

R-process nucleosynthesis

cosmic life cycle



Solar system abundances



"Big Bang" "stellar burning" "neutron captures"

two neutron capture processes:

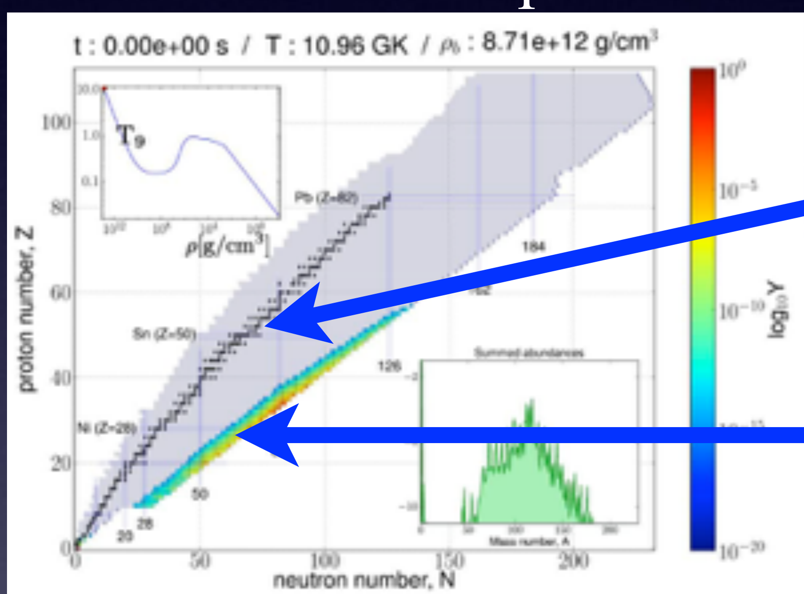
- slow n-capture ("s-process")
- rapid n-capture ("r-process")

$\Rightarrow$ ~50% of elements heavier than iron

Electron fraction Y_e plays decisive role!

- "electron fraction" $Y_e = \text{"}\,\frac{\#\ \text{protons}}{\#\ \text{nucleons}} = \frac{\#\ \text{electrons}}{\#\ \text{nucleons}}\,\text{"}$

- effect on reaction path:



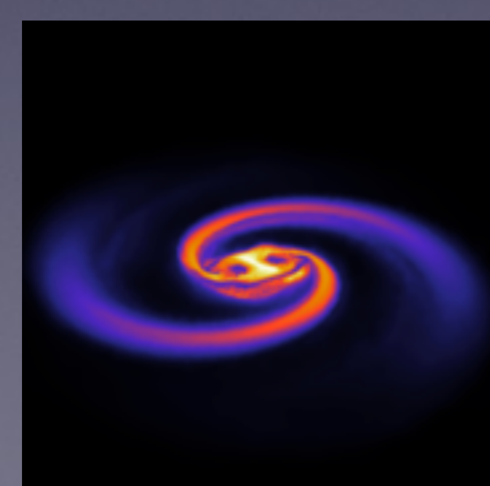
high Ye:
- close to valley of β-stability
- nuclear properties from experiments

low Ye:
- close to neutron drip line
- nuclear properties from models

- astrophysical realization

Supernova:

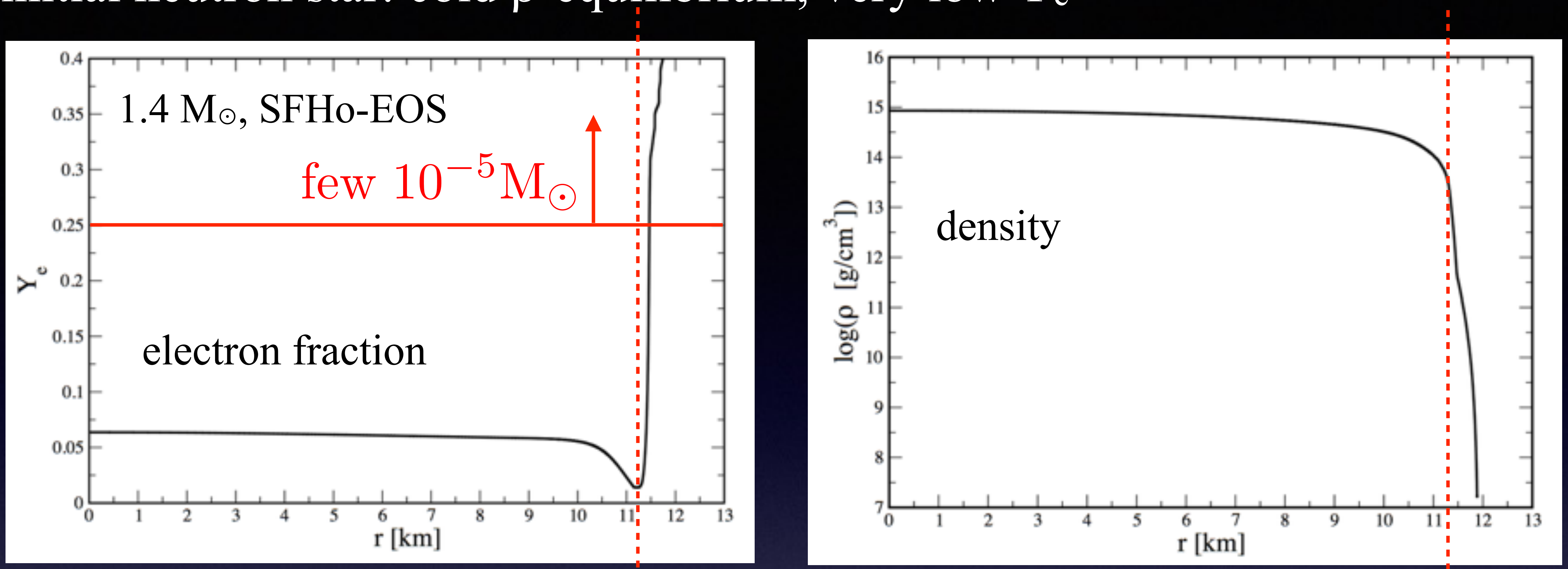
"de-leptonizing" from 0.5 down to Ye~ 0.3



NS mergers:

"re-protonizing" starting from Ye~ 0.1

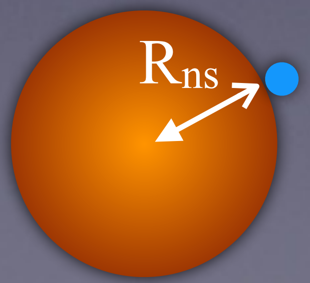
• initial neutron star: cold β-equilibrium, very low Y_e



• increasing Y_e via β-reactions $e^+ + n \rightarrow p + \bar{\nu}_e$ ⇒ ejecta history?

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

• BUT: unbinding matter from a neutron star is non-trivial!



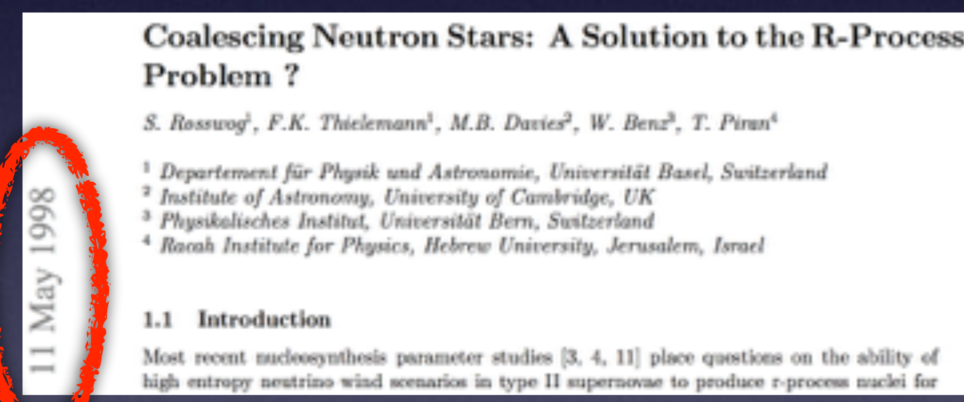
$$|E_{\rm grav}| \approx 150 \text{ MeV} \gg E_{\rm nuc} \leq 8 \text{ MeV}$$

Discussion of the r-process production site

- One of the "11 science questions for the new century"
  (Nat. Res. Counc. 2003)

- Supernovae traditionally favored since the 1950ies
  (Burbidge et al. 1957, Cameron 1957)

- Neutron star mergers
  - 1974:
    - idea discussed in NSBH context (Lattimer & Schramm 1974)
    - ejecta amounts unknown ("~0.05 ± 0.05 M_{ns}") ⇒ relevance?
  - 1989:
    - discussion " ns-ns merger: r-process, neutrino bursts & gamma-ray bursts" (Eichler+ 1989)
  - 1998:
    - first nucleosynthesis for nsns-mergers (S.R.+1998, Freiburghaus+ 1999, S.R.+ 1999):
      - "eject enough to explain all Galactic r-process"
      - "reproduce solar r-process up to platinum peak without any tuning"
    - "radioactive decay from r-process should power EM transient" (Li & Paczynski 1998)



11 May 1998

Coalescing Neutron Stars: A Solution to the R-Process Problem ?

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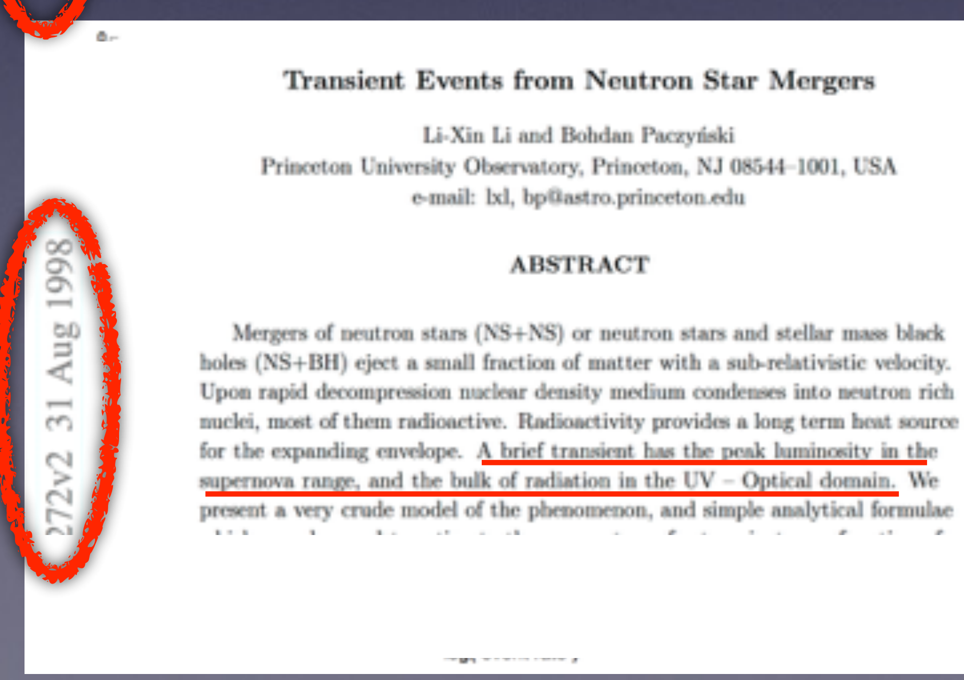
1.1 Introduction

Most recent nucleosynthesis parameter studies [3, 4, 11] place questions on the ability of high entropy neutrino wind scenarios in type II supernovae to produce r-process nuclei for



272v2 31 Aug 1998

Transient Events from Neutron Star Mergers

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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 sub-relativistic 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 the 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

Ejecta types

i) "dynamic"

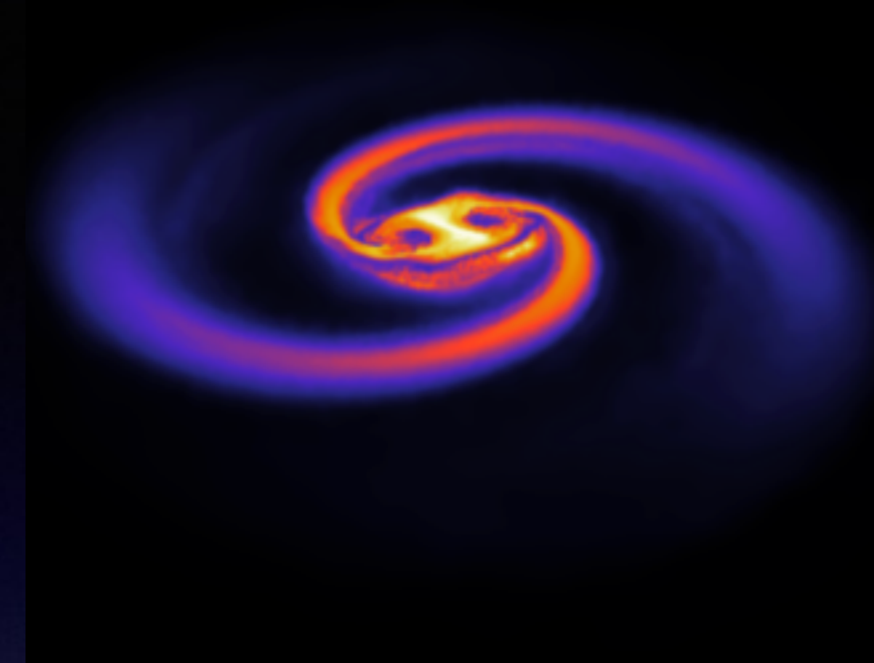
a) "tidal":

- equatorial
- low Ye ~0.1
- ~1% M$_\odot$

b) "contact":

- "polar"
- higher Ye > 0.1
- ~1% M$_\odot$

~ 1 ms

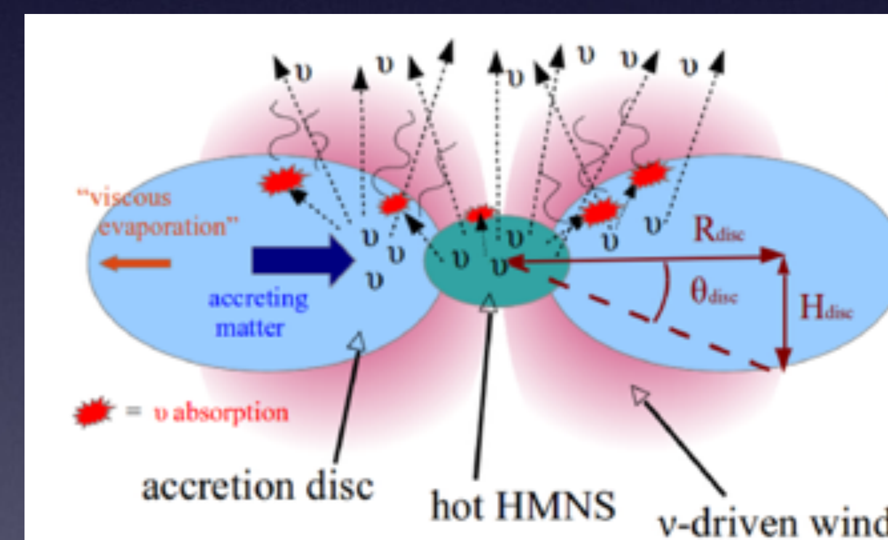


(from S.R. et al. 2017)

ii) neutrino-driven winds

- polar
- mass: ~1% M$_\odot$
- broader range of Ye

~ 10 - 100 ms

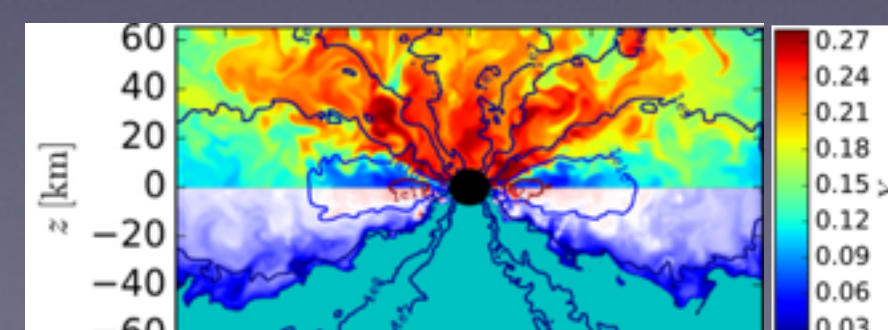


(from Perego et al. 2014)

iii) "secular"

- viscosity/MRI
- recombination nucleons into α-particles
- ~ 30% initial torus mass

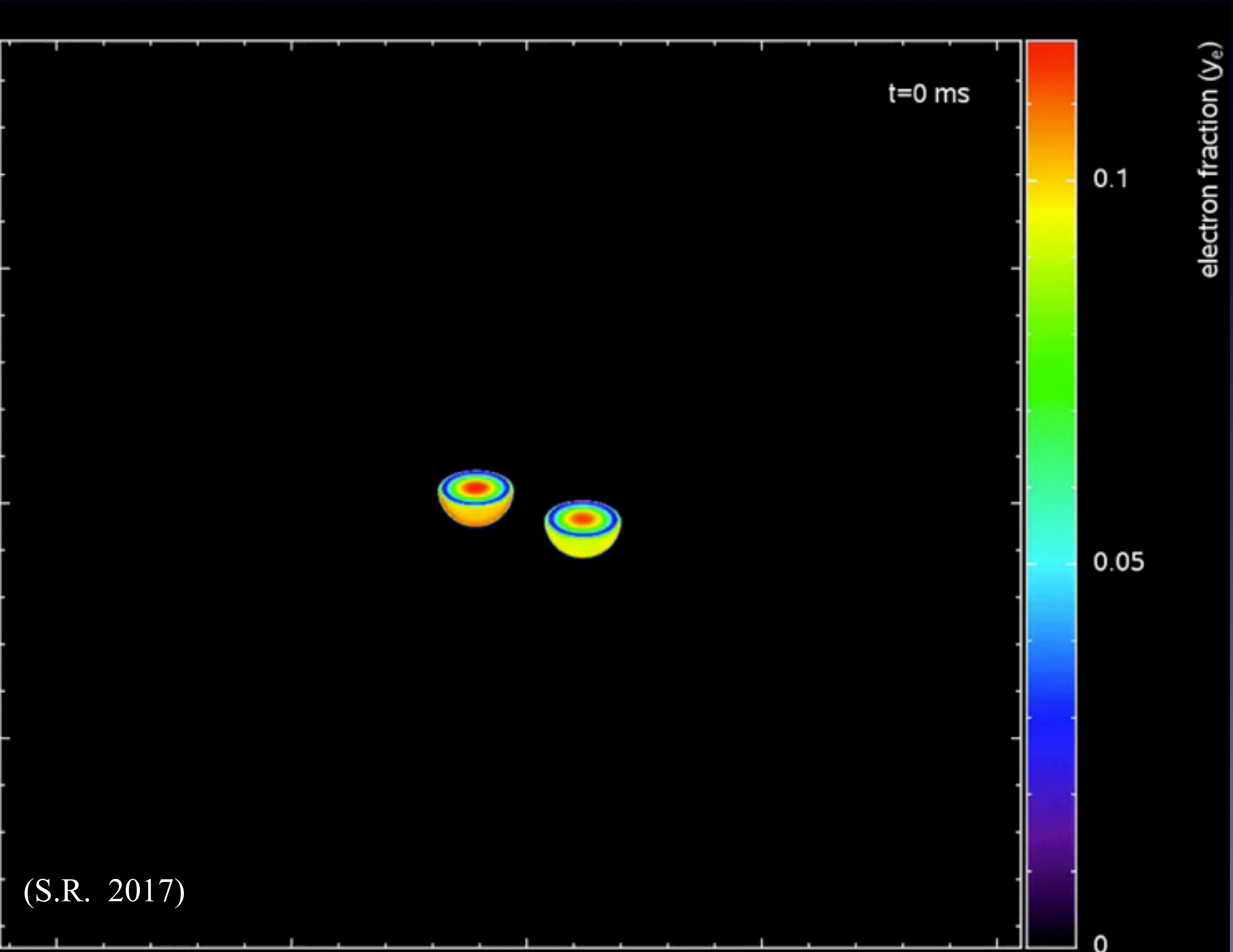
~ 1 s



(from Siegel & Metzger 2017)

i) Dynamic ejecta, tidal component

1.4 and 1.5 M_{sol} , no stellar spins

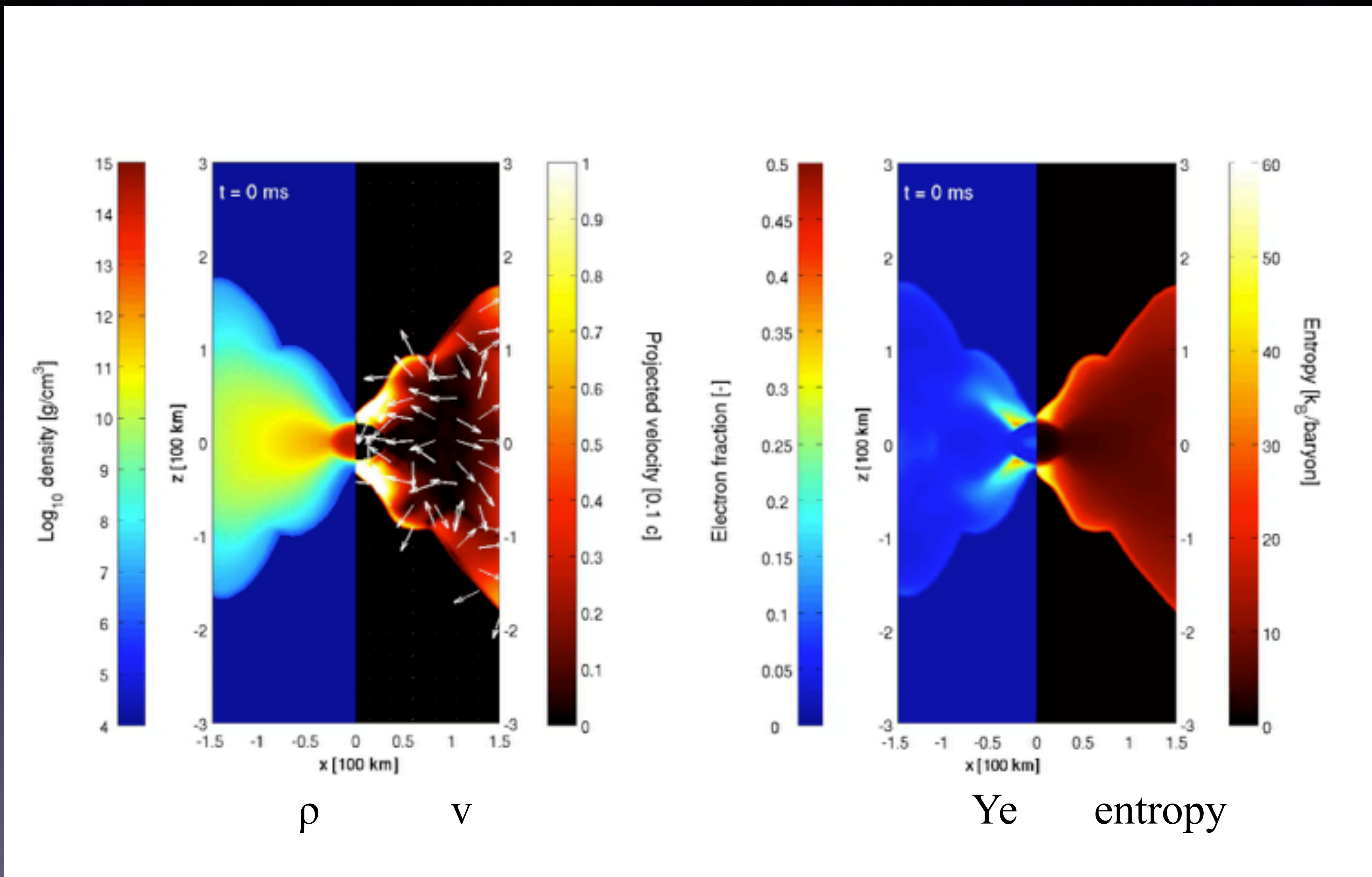


(S.R. 2017)

typical numbers:

- mass:
  ~0.005 … 0.02 $M_\odot$
- velocity:
  ~ 0.15c
- electron fraction:
  - "tidal": ~0.05
  - "interaction": ~0.2

ii) Neutrino-driven winds



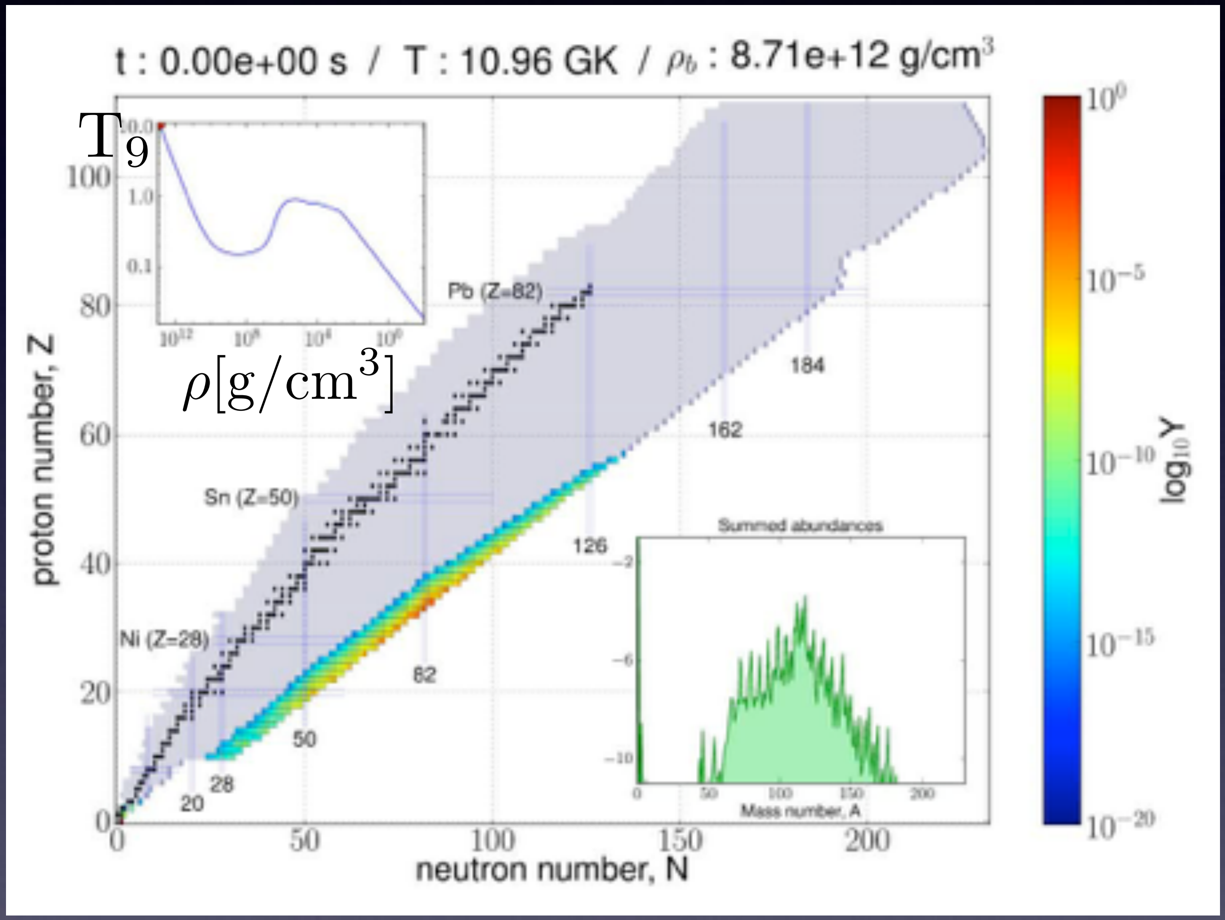
typical numbers:

- mass: ~0.01 M☉
- velocity: ~ 0.05c
- electron fraction: ~0.2 … 0.4

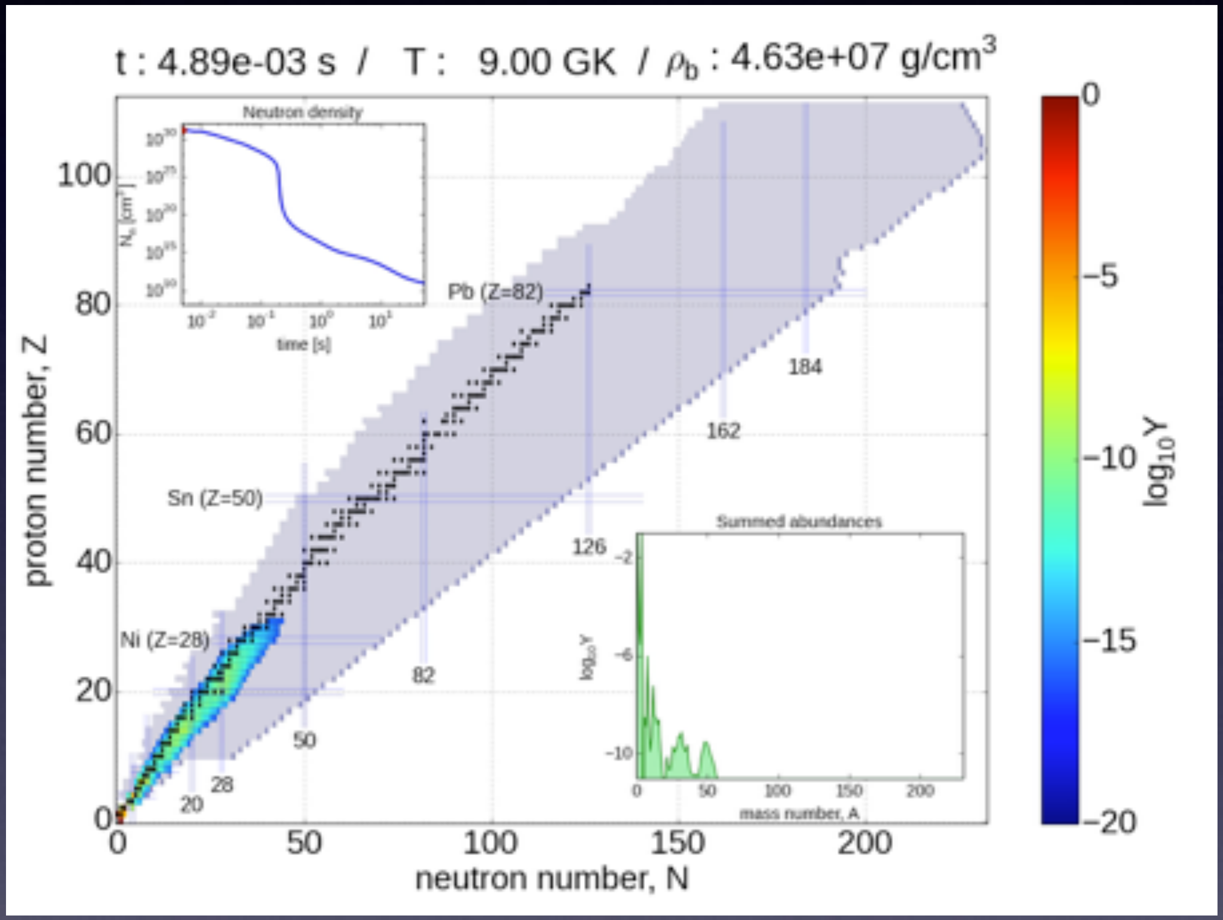
(Perego, S.R., Cabezon … 2014)

Nucleosynthesis

Winnet network
(Winteler 2012)
5 831 isotopes



(Korobkin, Rosswog, Arcones, Winteler 2012)



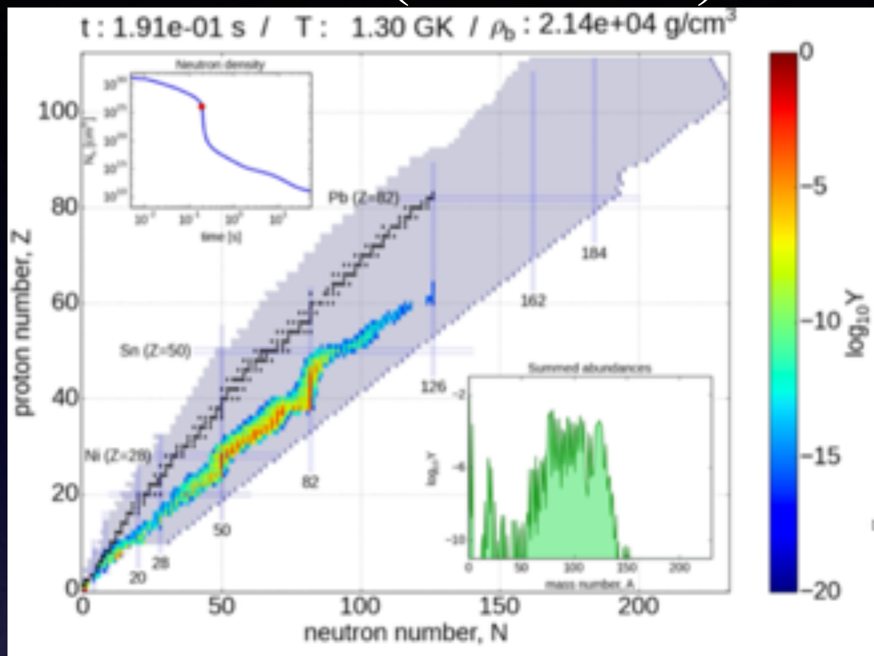
(Martin, Perego, Arcones, Thielemann, Korobkin, Rosswog 2014)

very low Ye (= 0.05),
dynamic ejecta

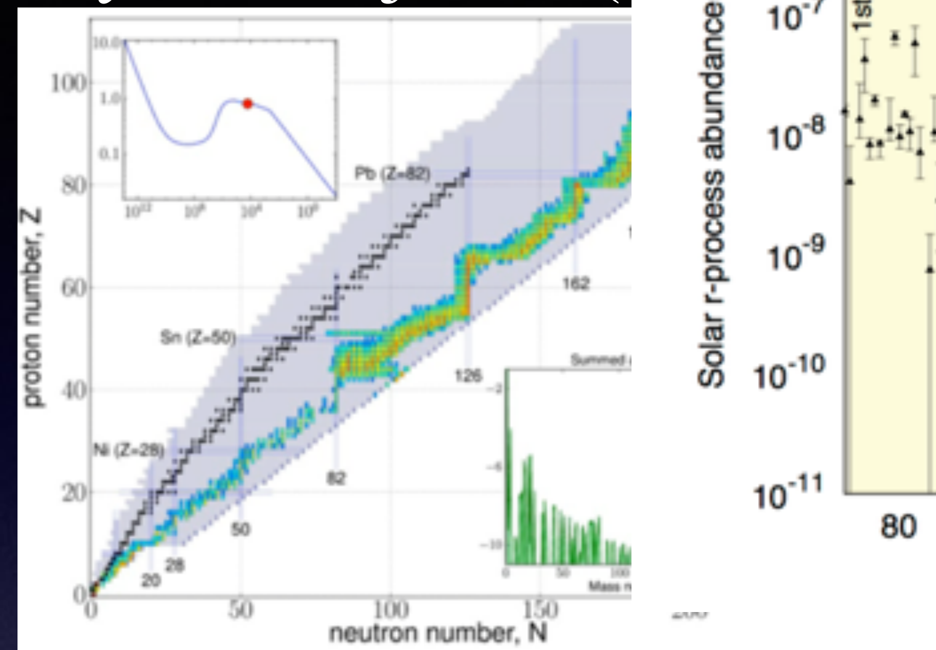
moderately high Ye (= 0.3),
ν-driven wind ejecta

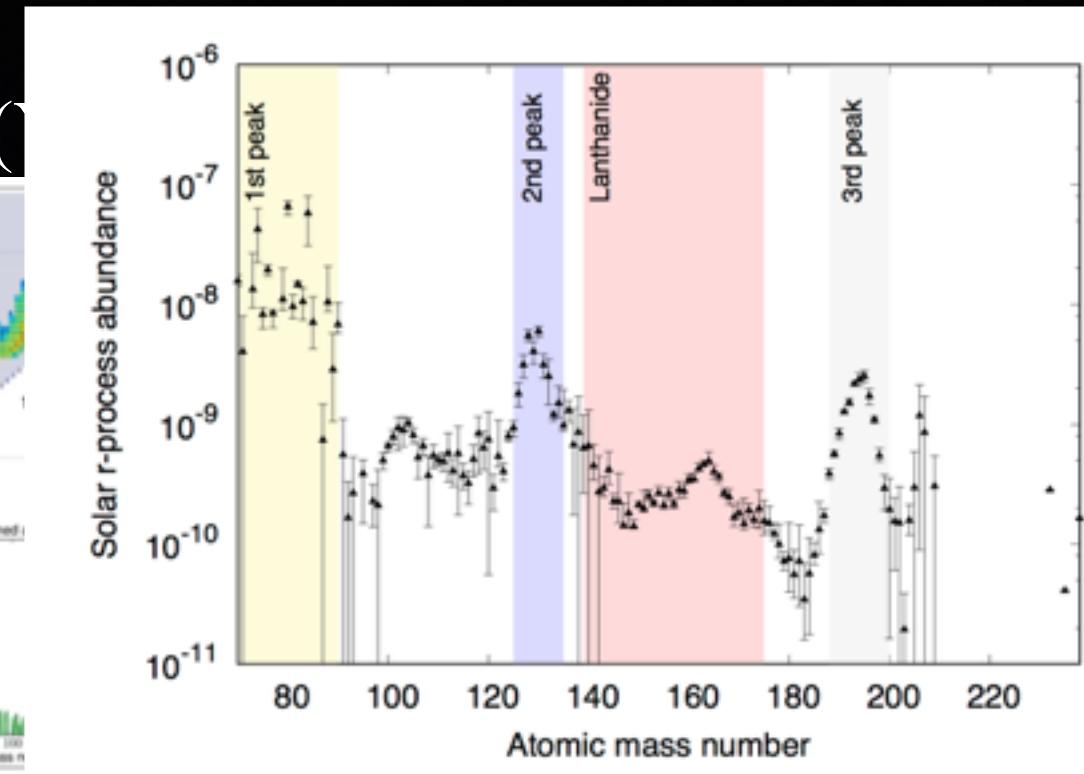
critical value for producing lanthanide-rich ejecta: $Y_e \approx 0.25$

"winds" ($Y_e \gtrsim 0.25$)

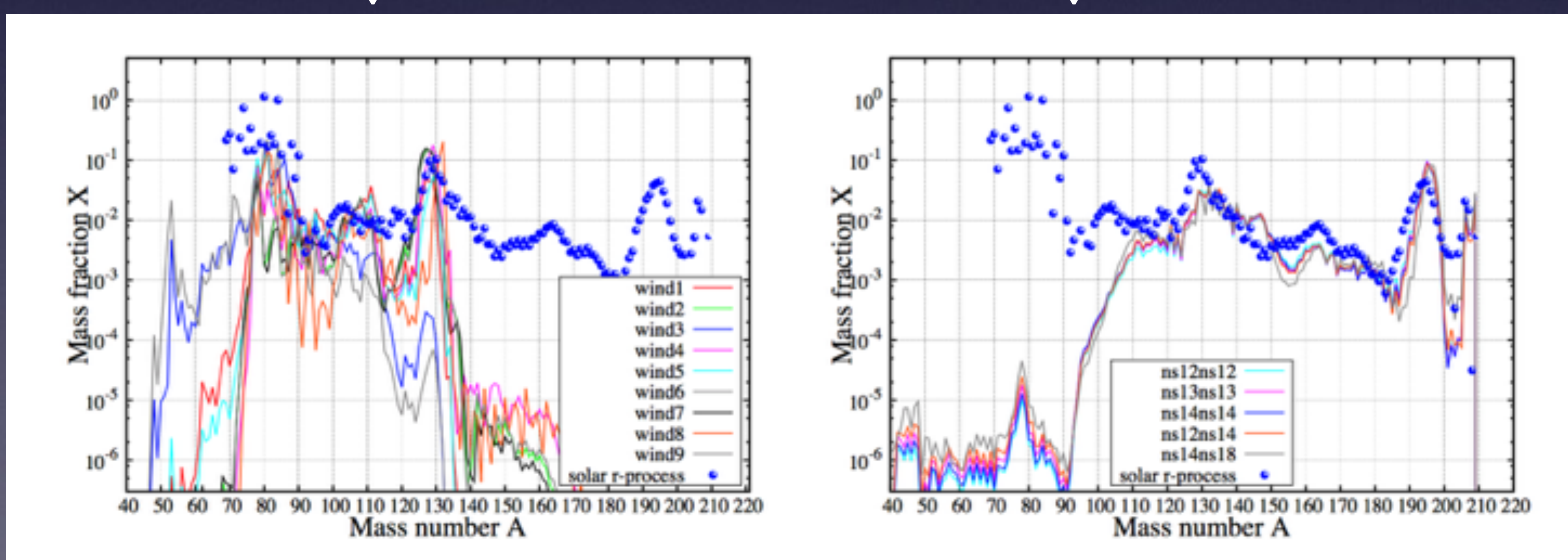


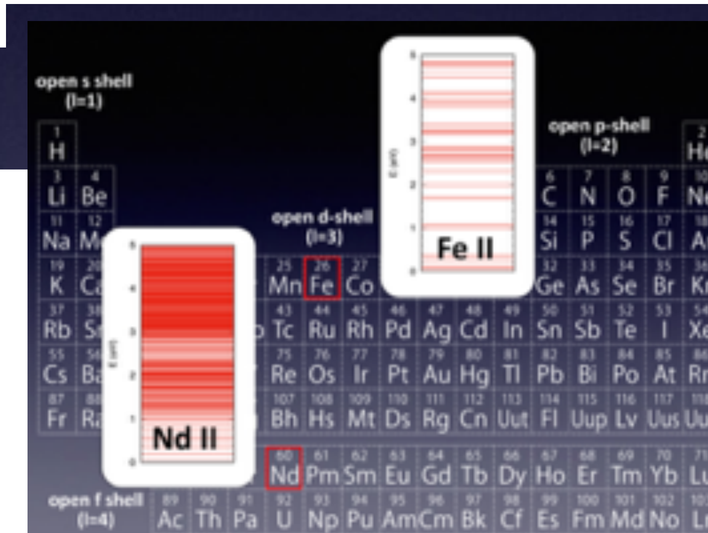
"dynamic ejecta" (Y





⇓ ⇓





courtesy M. Tanaka

"weak r-process, A ≲ 130"

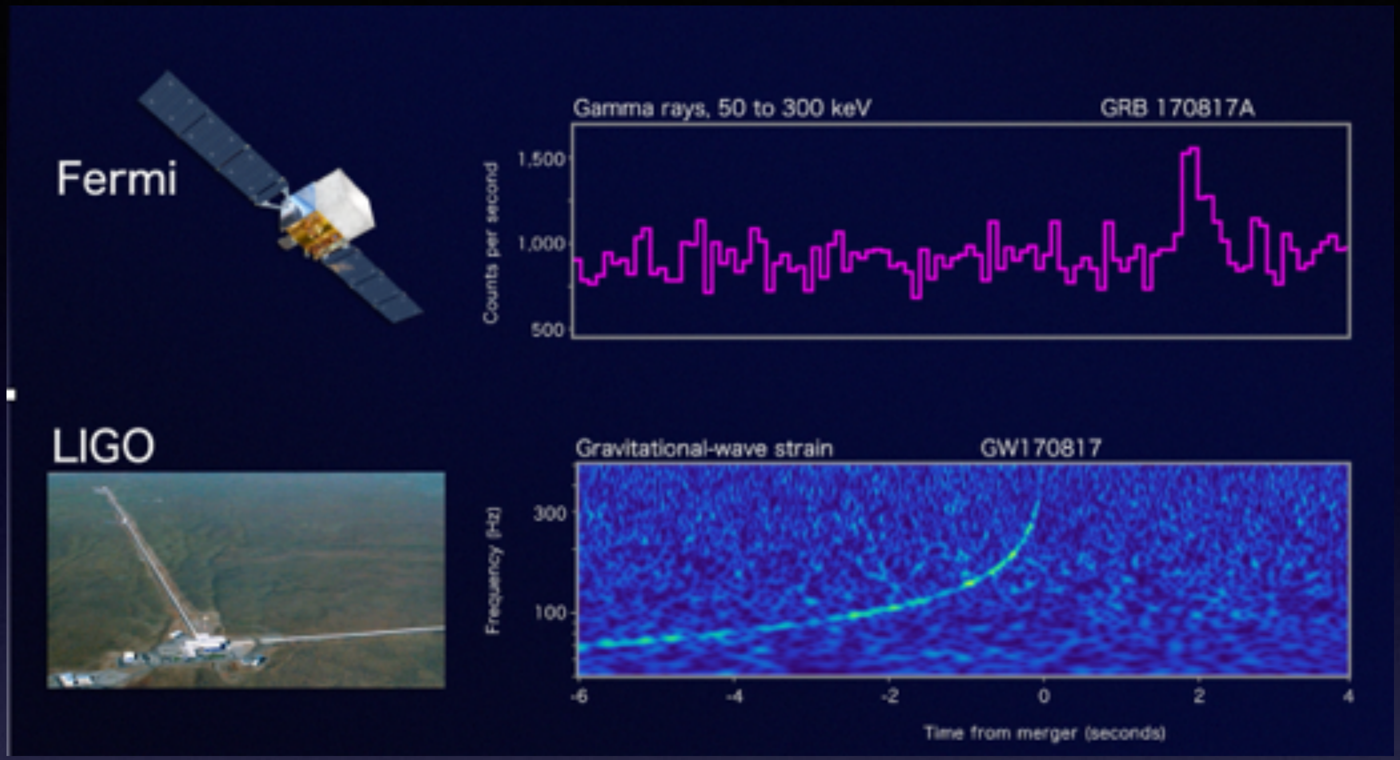
"strong r-process, A ≳ 130"

⇒ complementary nucleosynthesis

large number bound-bound line transitions

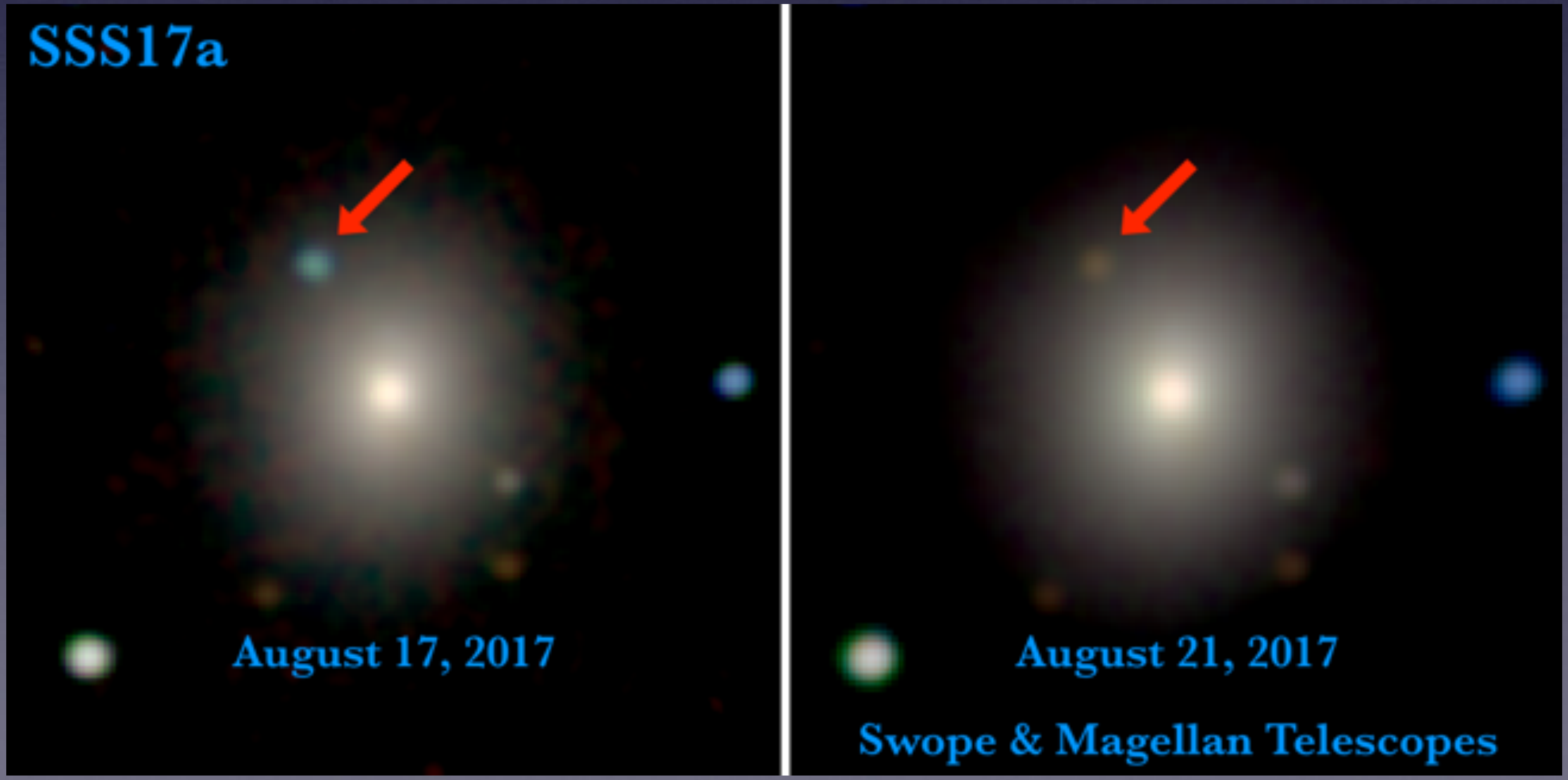
⇒very large opacities

IV. GW/EM 170817: Beginning of the Multi-Messenger era



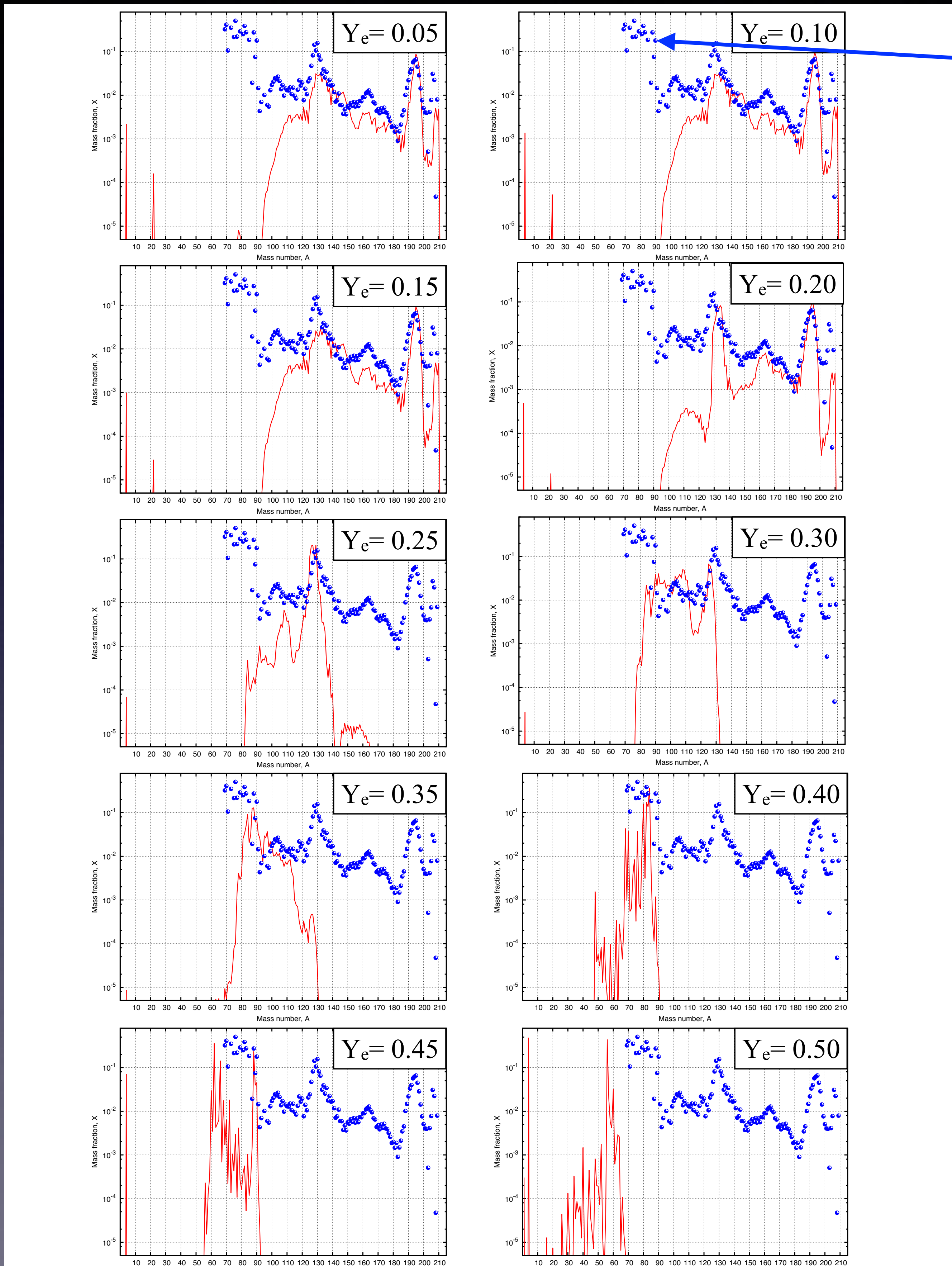
γ-rays

gravitational waves



evolution from
blue to red

IV.1 Really r-process?



(from S.R.++ 2018, arXiv:1710.05445)

solar-system r-process

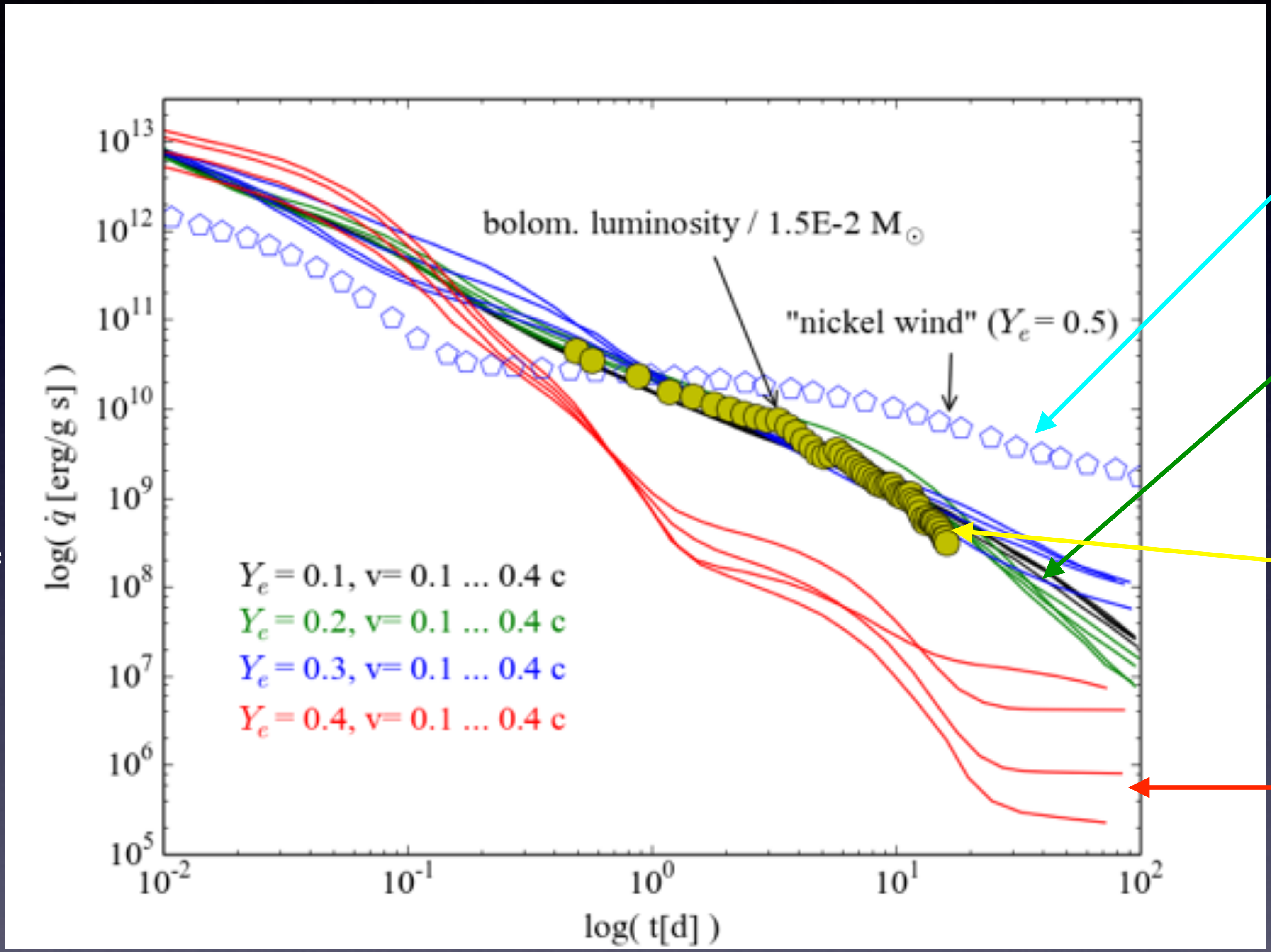
experiment:

- v_{ej}= 0.25c, WinNet
- vary electron fraction Y_e

- threshold value $Y_e^{crit} \approx 0.25$:
  - $Y_e < Y_e^{crit}$:
    - "strong/heavy" r-process A ≳ 130
    - insensitive to details of trajectory
  - $Y_e > Y_e^{crit}$:
    - A ≲ 130
    - sensitive to details of trajectory
- substantial Nickel production only near Ye≈ 0.5

- numerical experiment: (from S.R++ 2018, A&A in press)
  - nuclear reaction network different conditions (v ∈ [0.1,0.4], Y_e ∈ [0.1, 0.4])
  - nuclear heating rate ⇔ bolometric luminosity

observed luminosity/ nuclear heating rate



"nickel wind" (Y_e= 0.5)

low electron fraction (Ye ≲ 0.3) ⇒ r-process

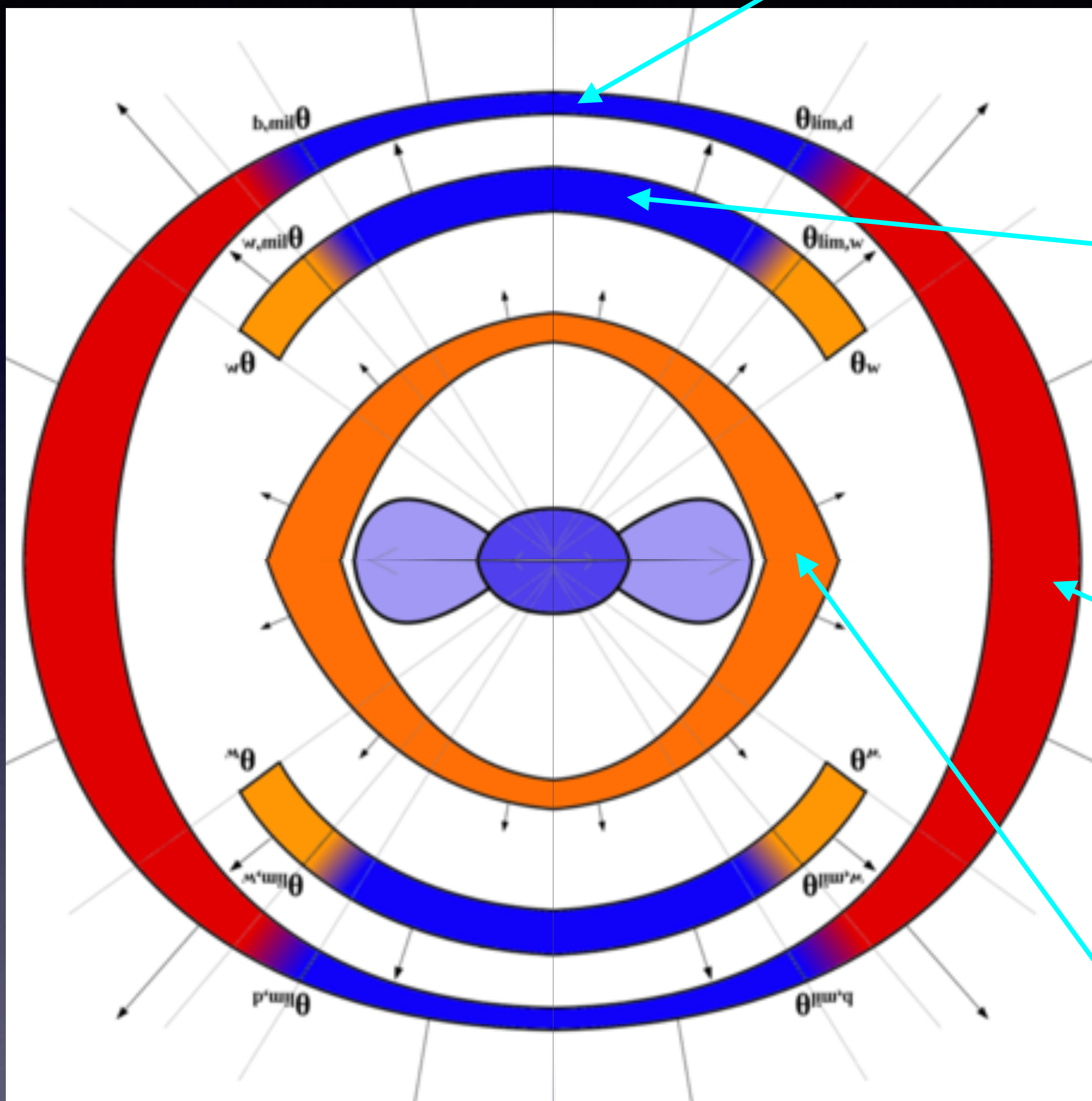
(scaled) observed luminosity

higher electron fraction (Y_e= 0.4)

- lessons:
  - decay of luminosity consistent with r-process nucleosynthesis
  - either with (more likely) or without lanthanides
  - ejecta mass > 0.015 $M_\odot$

e.g. Kilpatrick+ 17
Kasen+ 17
Perego+ 17

"blue":
m ~ 0.025 M⊙
v ~ 0.25 c



(after Perego+ 2017)

dynamic ejecta, "interaction component":
- early, ~1 ms
- "polar"
- higher Y_e
- 'blue'

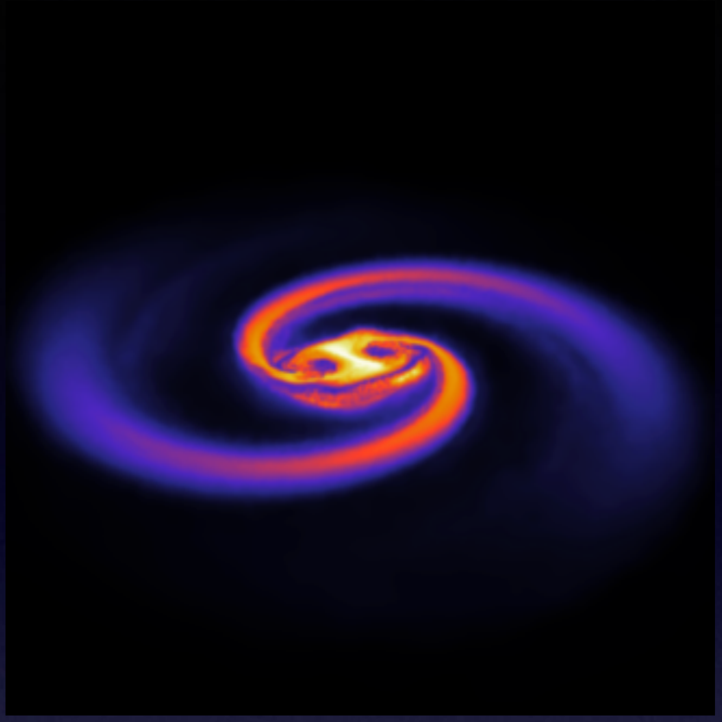
winds (ν-driven, magnetic, etc):
- early, ~10s of ms
- higher Y_e
- 'blue'

dynamic ejecta, "tidal component":
- early, ~ 1 ms
- equatorial
- low Y_e
- 'red'

"red":
m ~ 0.035 M⊙
v ~ 0.15 c

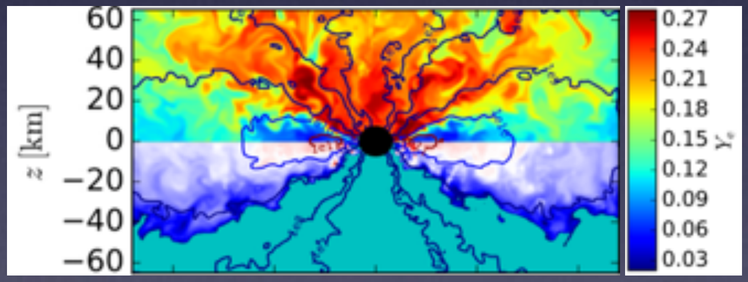
"secular", "tidal component":
- late, ~ 1 s
- ~ isotropic
- broad range Y_e

Implications



(from S.R.+ 2017)

- “large mass in red component” (~0.04 $M_\odot$)
  - very difficult for tidal dynamic ejecta
  - additional ejection mechanism (?):
    - secular/disk ejecta:
      - large mass reservoir
      - BUT: a) exp. velocities only ~0.05 c < 0.15 c
        b) really red/$Y_e < 0.25$?



(from Siegel & Metzger 2017)

- stresses need for relevant physics:
  - nuclear recombination
  - magnetic fields/MRI
  - weak interactions/neutrino transport

- “large mass in blue component” (~0.02 $M_\odot$)
  - keep in mind: original mass with $Y_e > 0.25$ only ~$5\mathrm{x}10^{-5}$ $M_\odot$

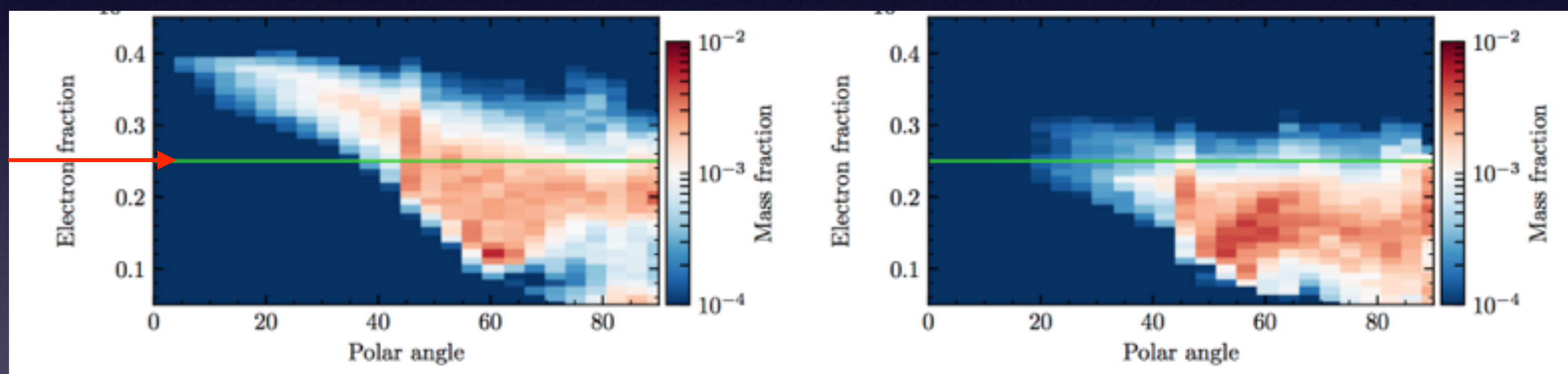
    ⇒ large amounts of mass have undergone e^+/ν_e-captures

    ⇒ weak interaction/neutrino physics plays key role

  - example: ejecta from 1.35 + 1.35 $M_\odot$; SFHO-EOS (Perego+ 2017)

WITH ν-absorption — WITHOUT ν-absorption

Y_e^{crit}



⇒ need accurate ν-treatment

- likely merger outcome: temporarily stable neutron star

  evolution driven by (e.g. Radice+ 2017)

  a) turbulent viscosity

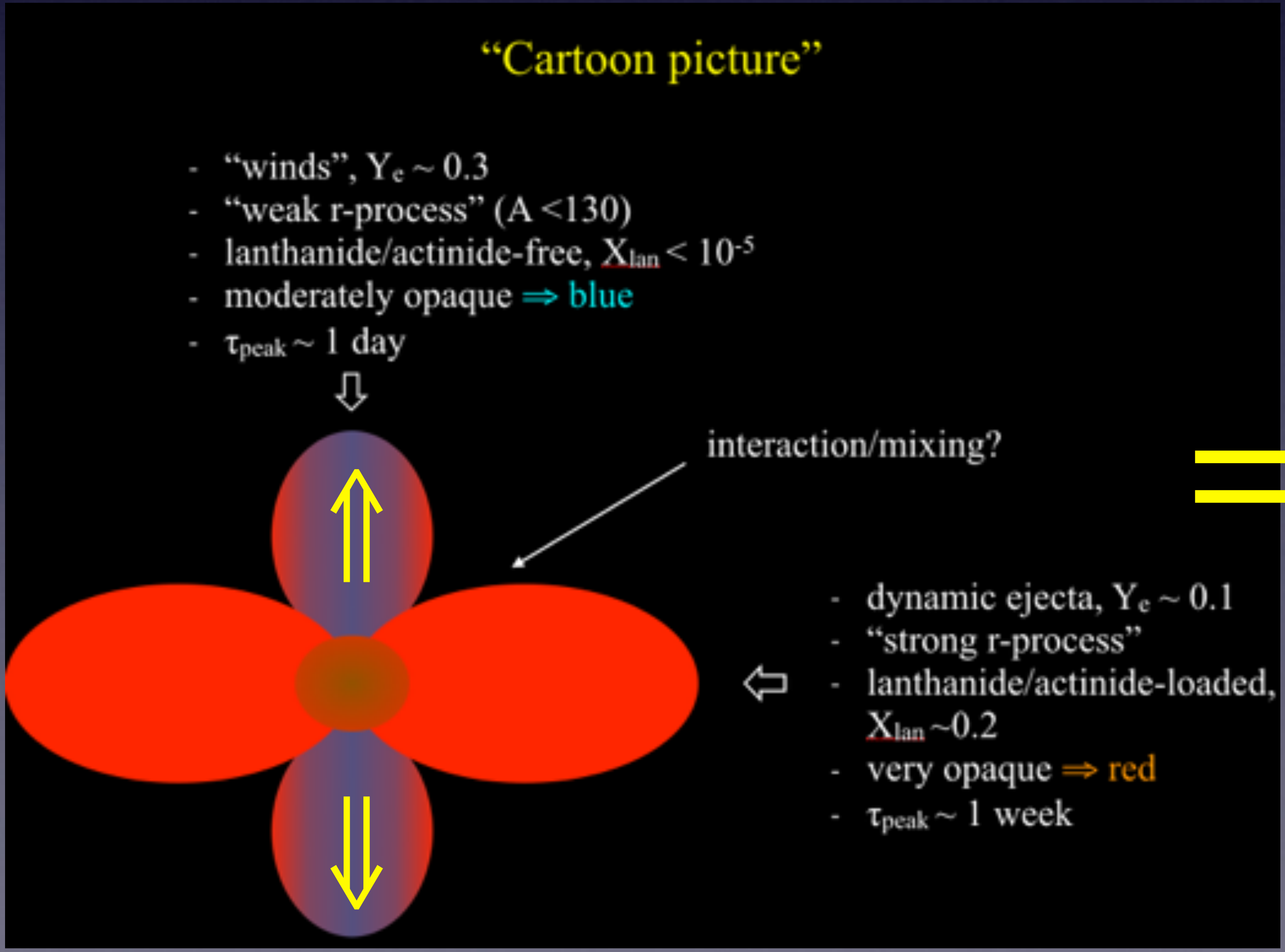
  b) neutrino processes

  } ⇒ could plausibly enhance blue component

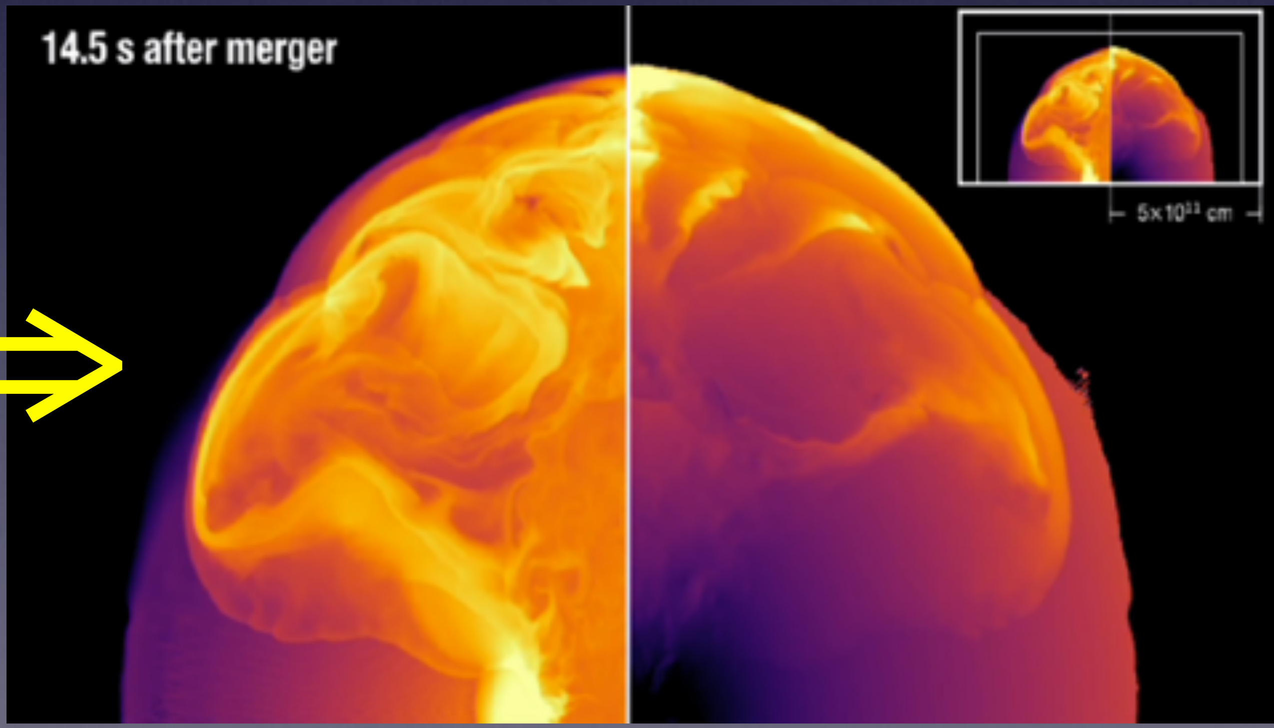
• where do high velocities come from?

a) B-field-enhanced ν-winds (Thompson 2003)?

b) interaction with jet? ⇒ re-distribute/mix ejecta priperties



⇒

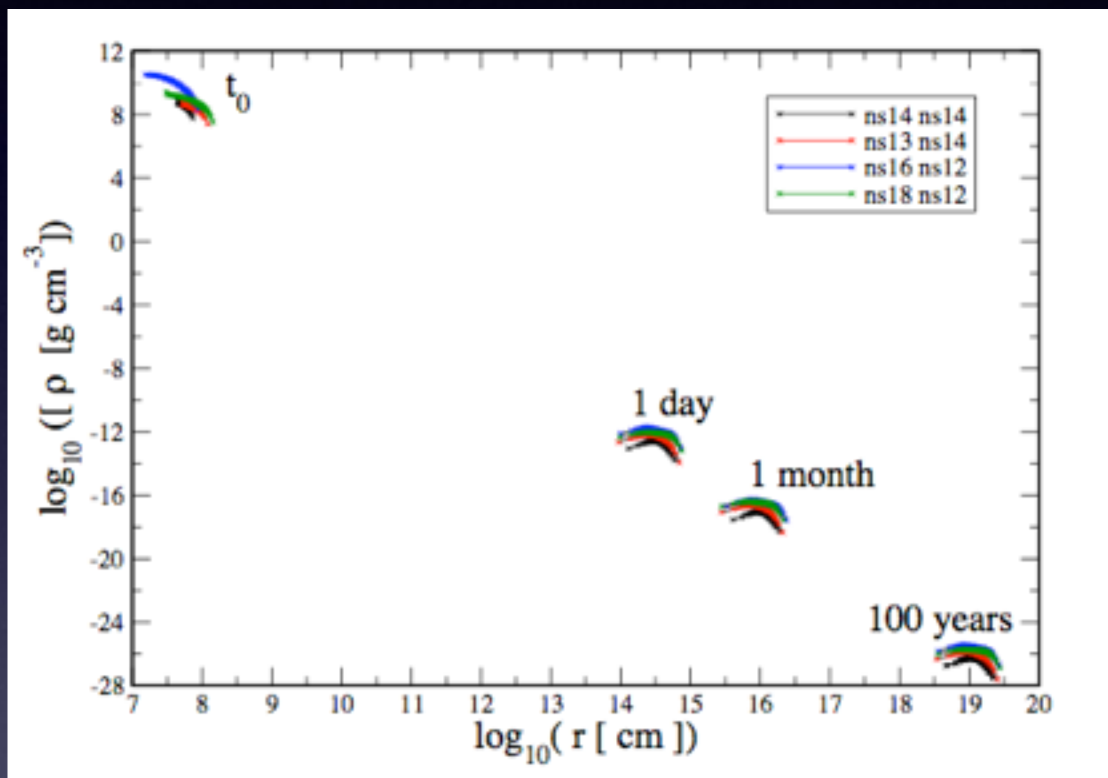


e.g. Kasliwal + 2017
Gottlieb+ 2017
Lazzati+ 2017

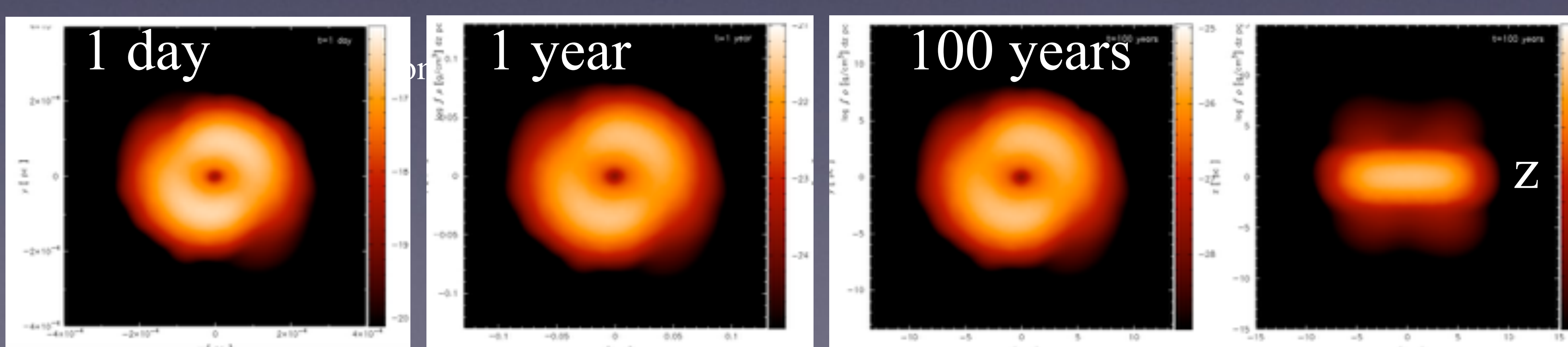
Further modelling challenge: scales!

- length/time scales: t_{peak} (~10^5 s) >> physical/numerical time scales (10^{-6}s)

- remnant structure at time of peak emission?



⇒ densities drop by ~30 orders of magnitude in ~ week



5×10^{-4} pc 0.15 pc 15 pc x

2 x1.4 $M_\odot$

Summary

- strong case for r-process material powering EM emission
- ejecta amounts are large $\gtrsim 0.04\ M_\odot$:
  additional/enhanced ejection channels?
- winds and secular ejecta are likely crucial
- implications on the range of physics that needs to be modelled:
  - accurate weak interactions/neutrino-transport
  - magnetic fields/MRI
  - nuclear recombination
- How particular was this event?
  $\Rightarrow$waiting for LIGO/VIRGO O3