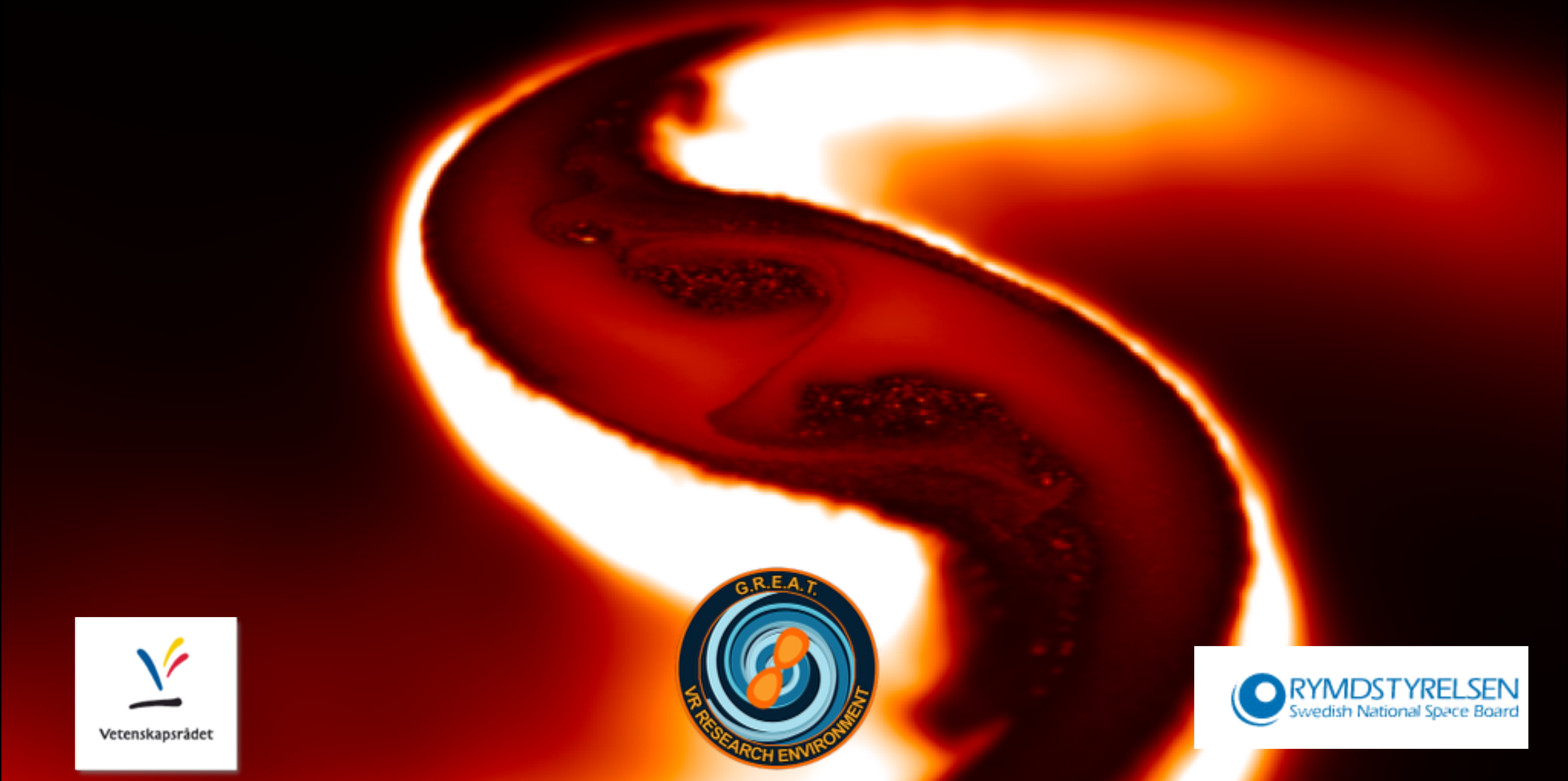
Marcel Grossmann Meeting, July 3, 2018

Neutron star mergers as heavy element production site

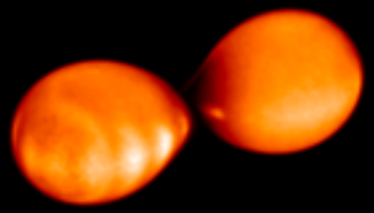
Stephan Rosswog
Astronomy & Oskar Klein Centre
Stockholm University



Vetenskapsrådet

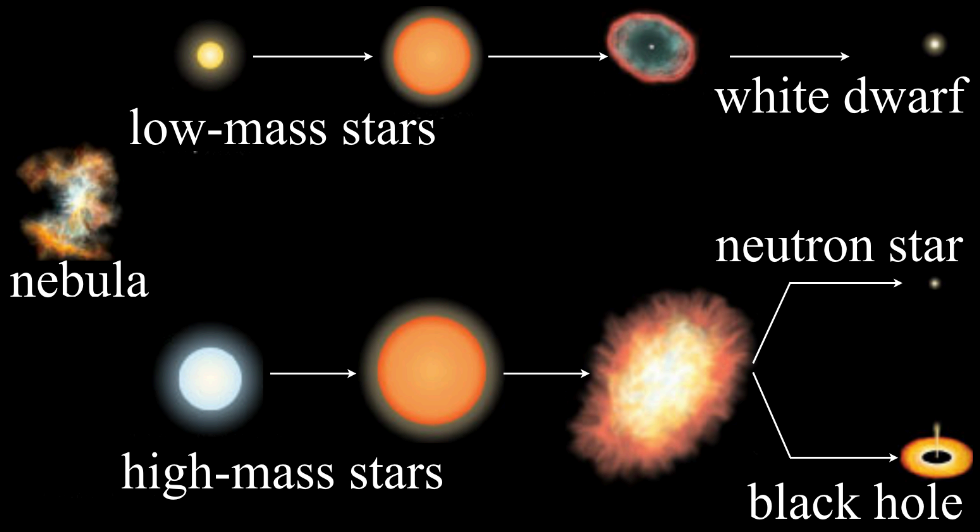
G.R.E.A.T.
VR RESEARCH ENVIRONMENT

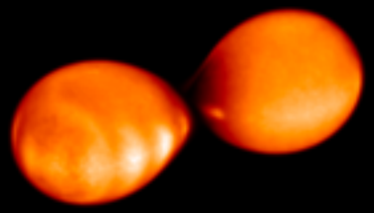
RYMDSTYRELSEN
Swedish National Space Board



ns-ns mergers

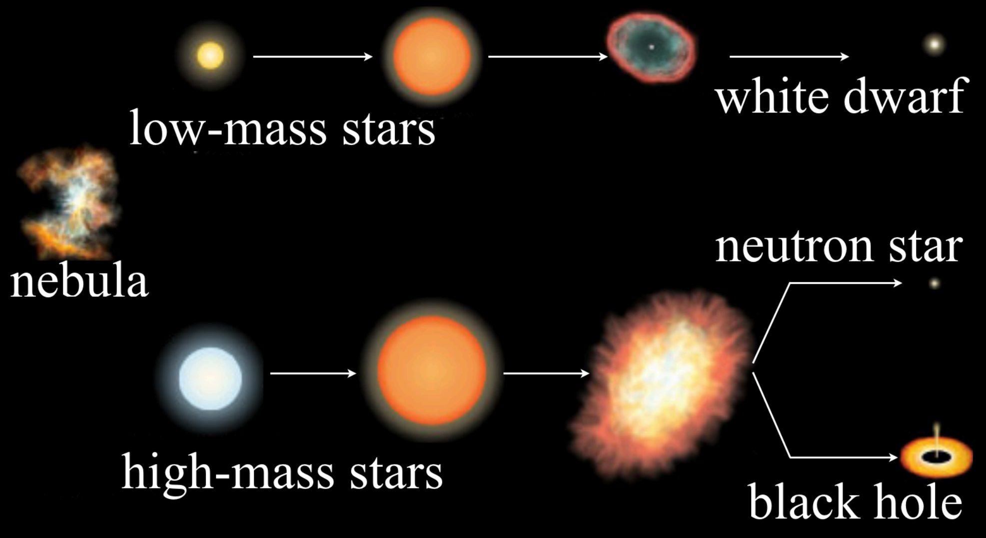
Binary stellar evolution





ns-ns mergers

Binary stellar evolution


low-mass stars

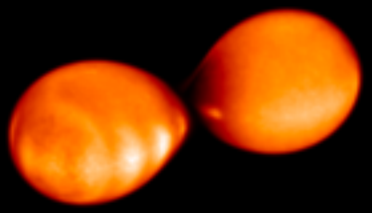
white dwarf

nebula

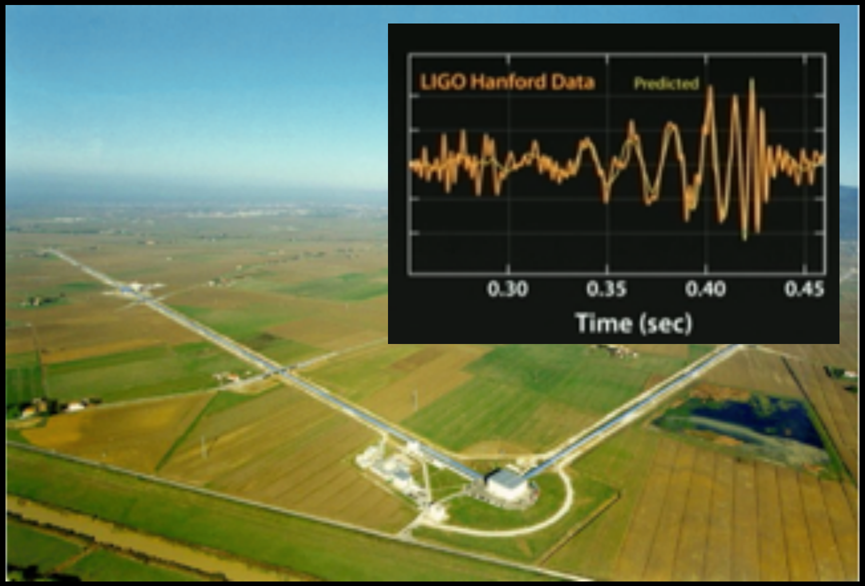
neutron star

high-mass stars

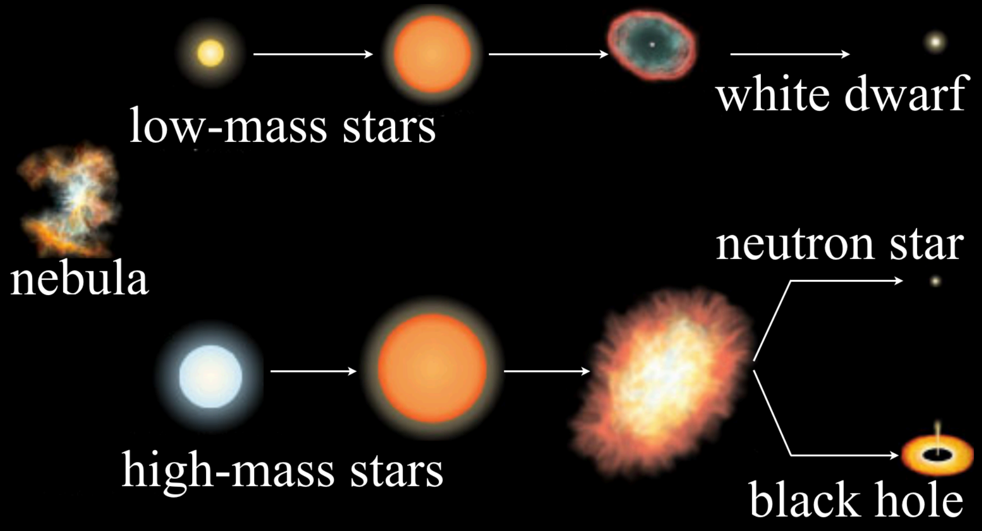
black hole


ns-ns mergers

Gravitational wave detection



Binary stellar evolution



low-mass stars

white dwarf

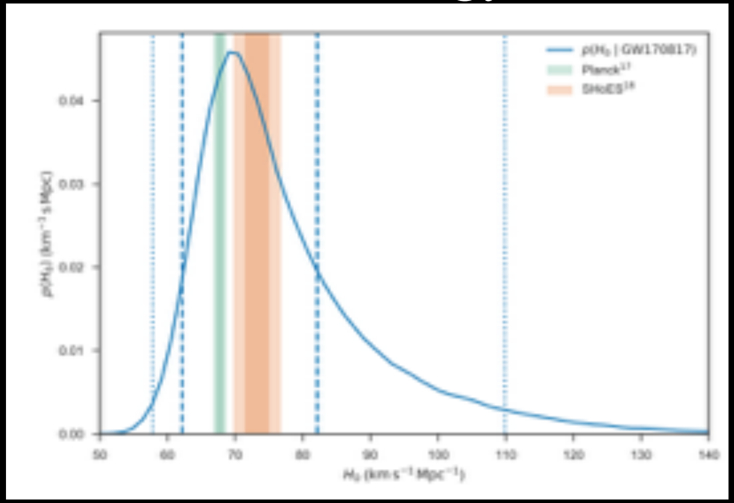
nebula

neutron star

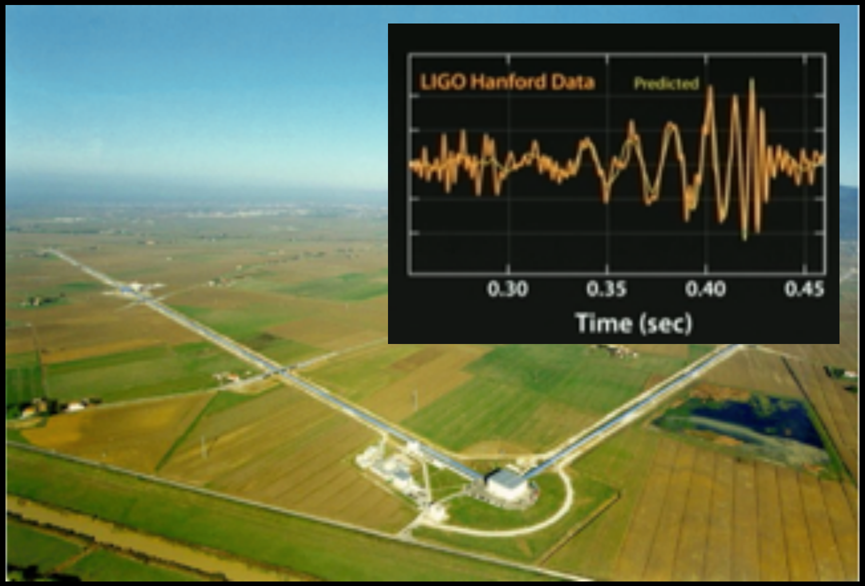
high-mass stars

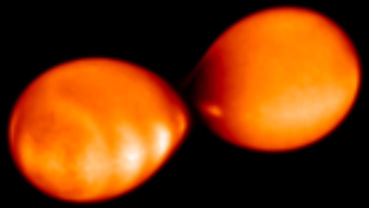
black hole

Cosmology



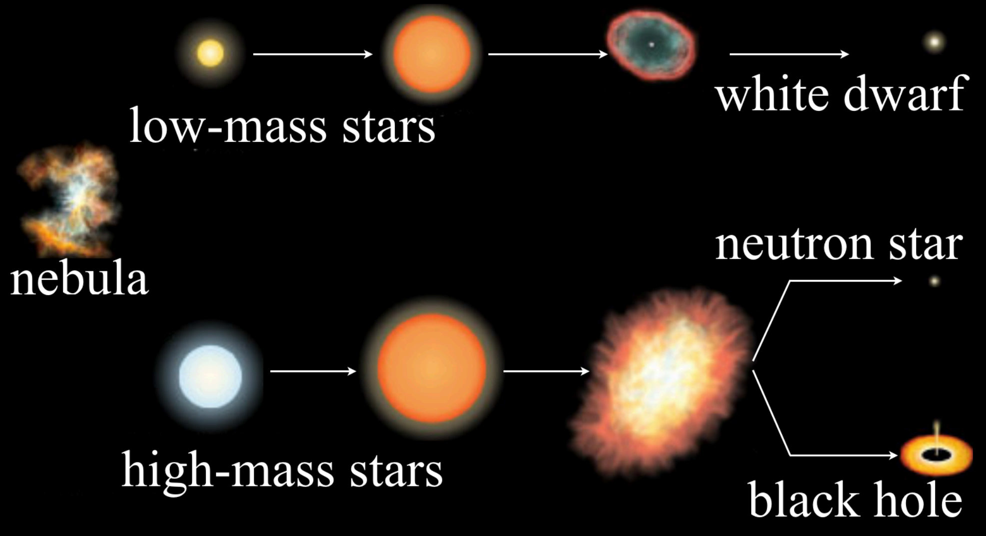
Gravitational wave detection





ns-ns mergers

Binary stellar evolution



low-mass stars

white dwarf

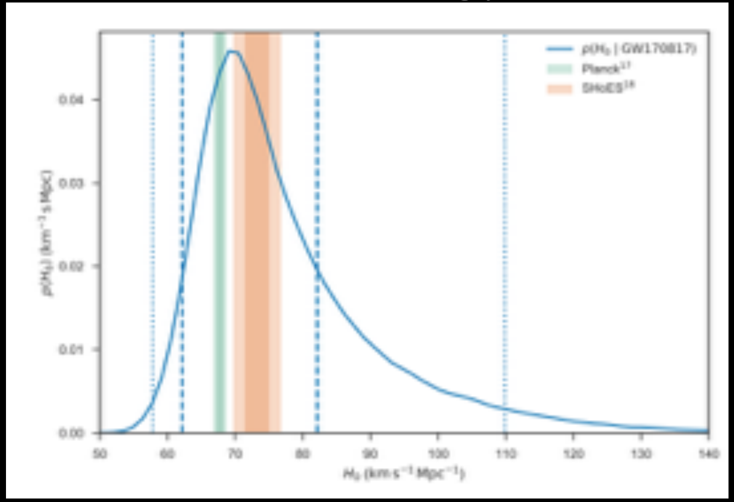
nebula

neutron star

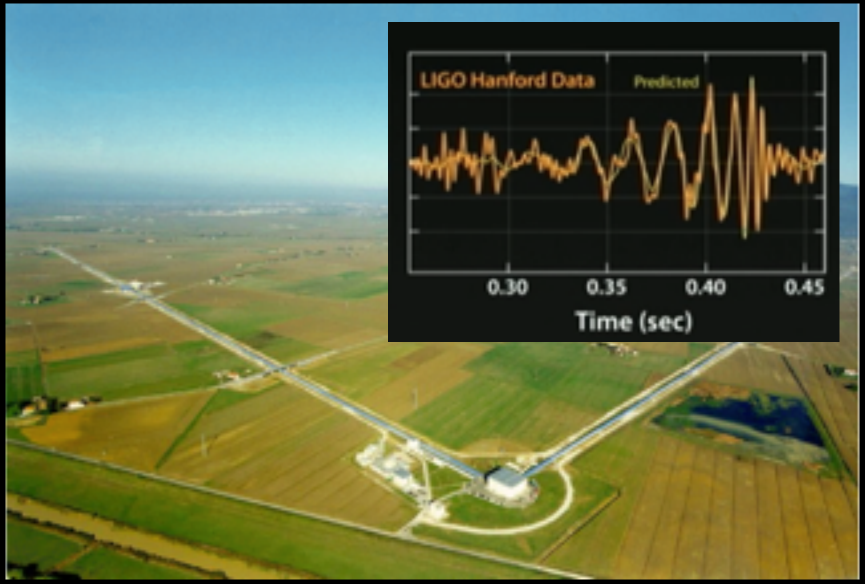
high-mass stars

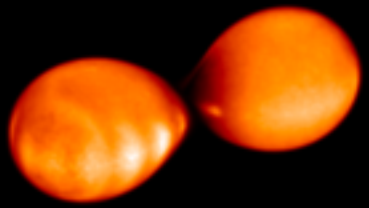
black hole

Cosmology



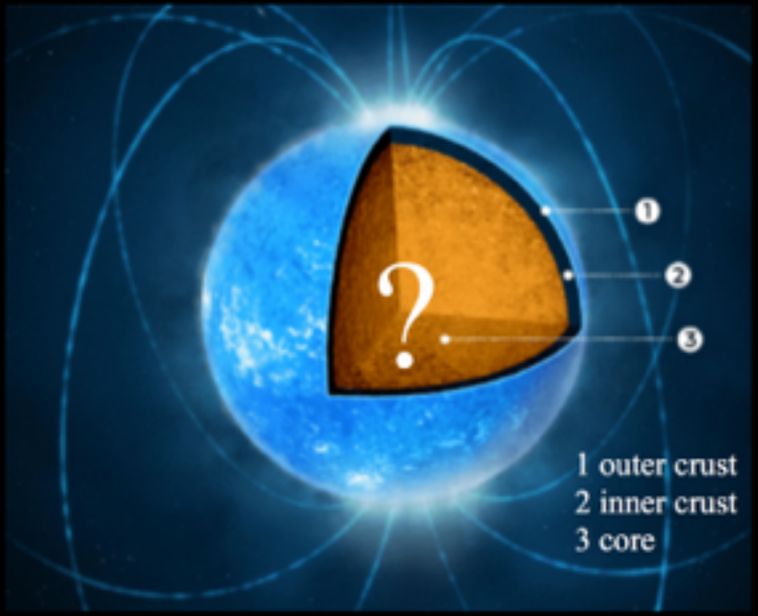
Gravitational wave detection



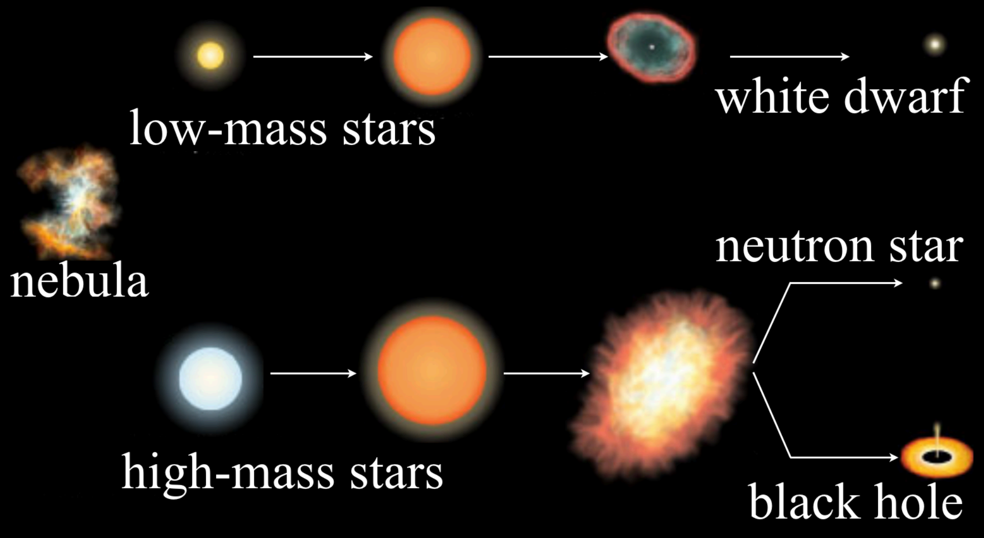


ns-ns mergers

Nuclear matter properties



Binary stellar evolution



low-mass stars

white dwarf

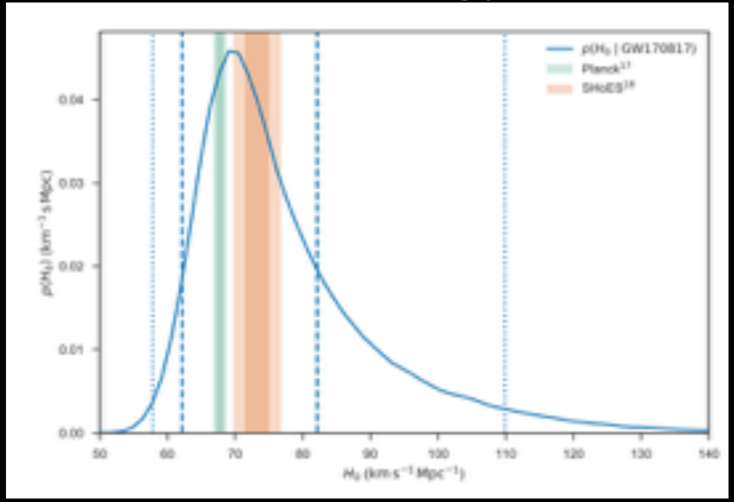
nebula

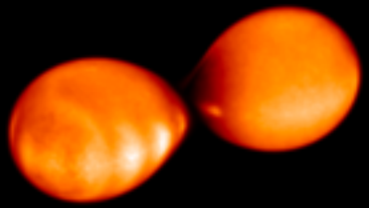
neutron star

high-mass stars

black hole

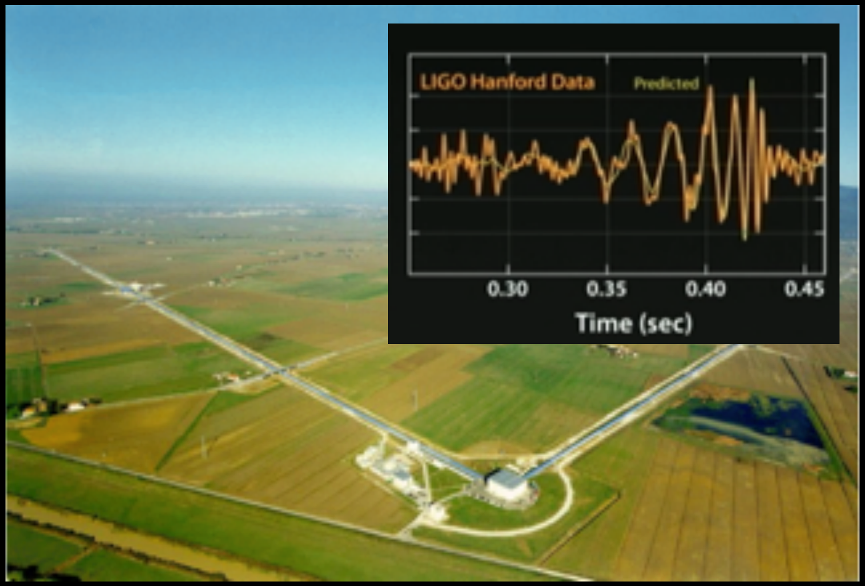
Cosmology



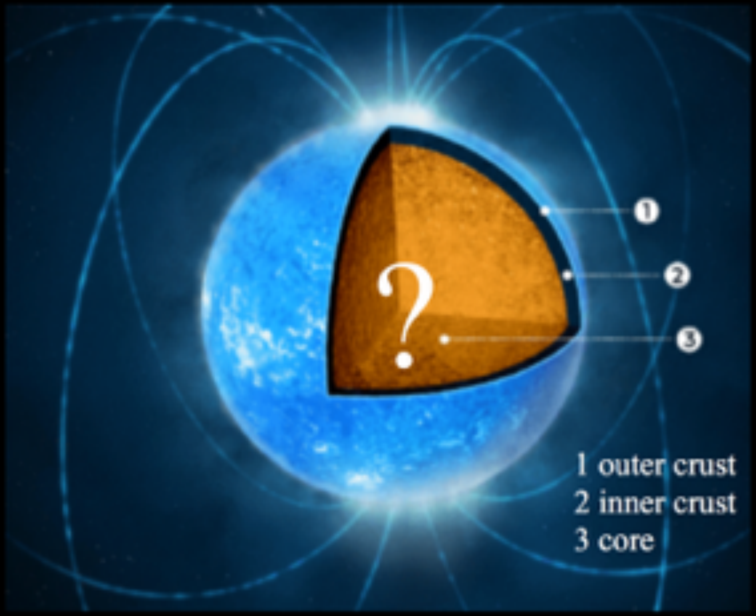


ns-ns mergers

Gravitational wave detection

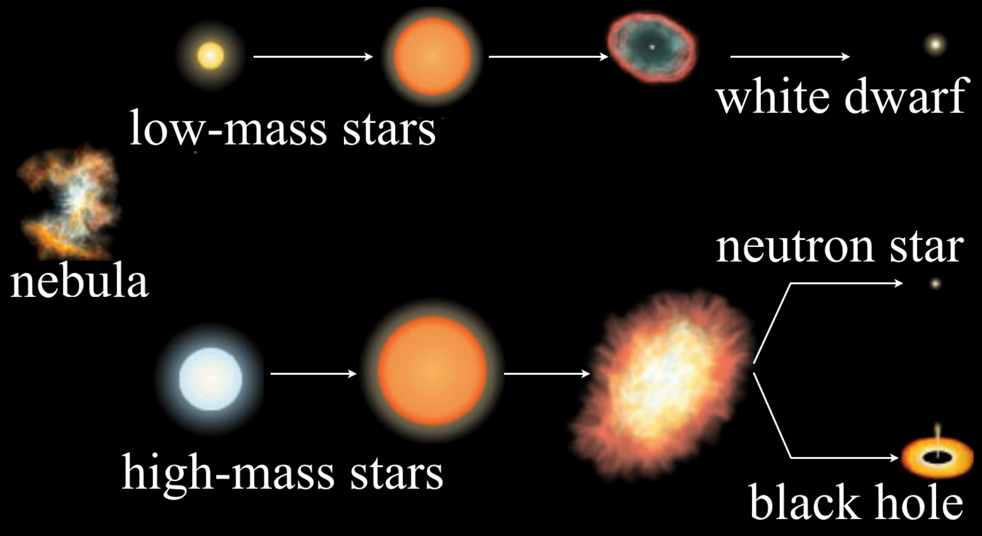


Nuclear matter properties



(short) Gamma-Ray Bursts

Binary stellar evolution



low-mass stars

white dwarf

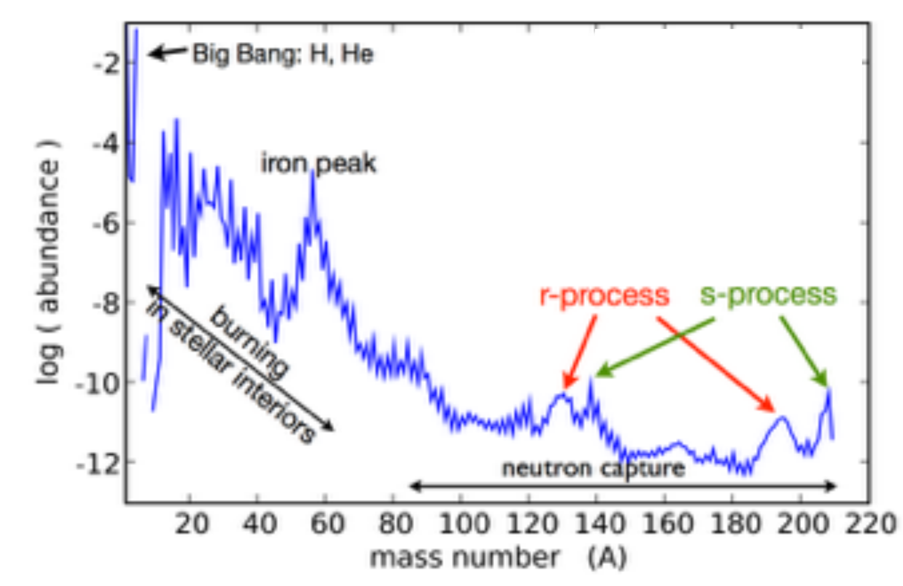
nebula

neutron star

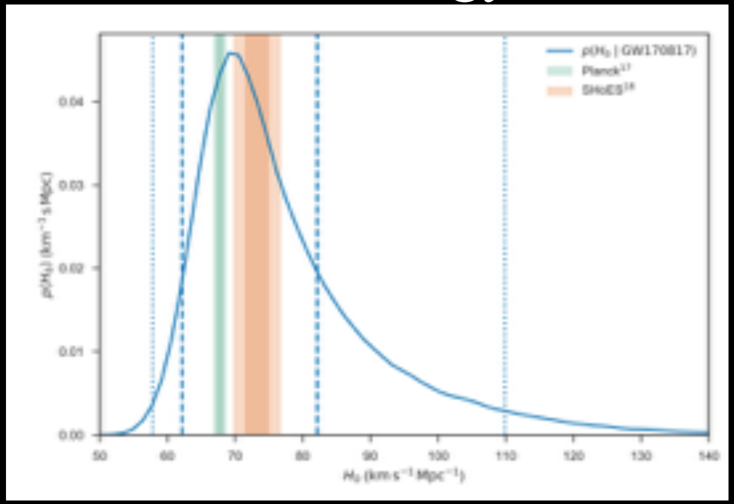
high-mass stars

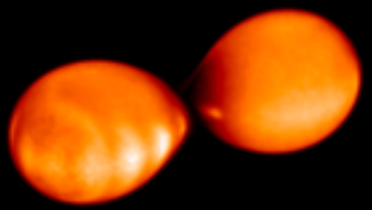
black hole

Nucleosynthesis



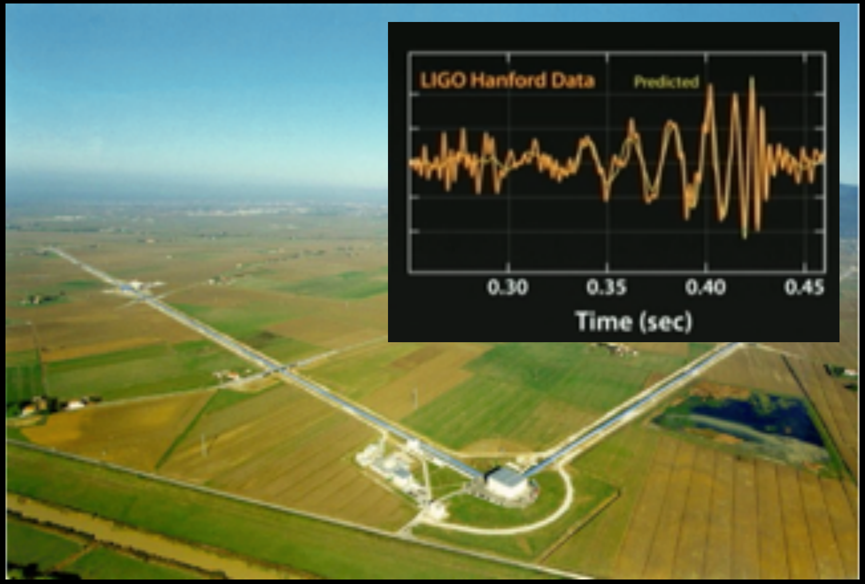
Cosmology



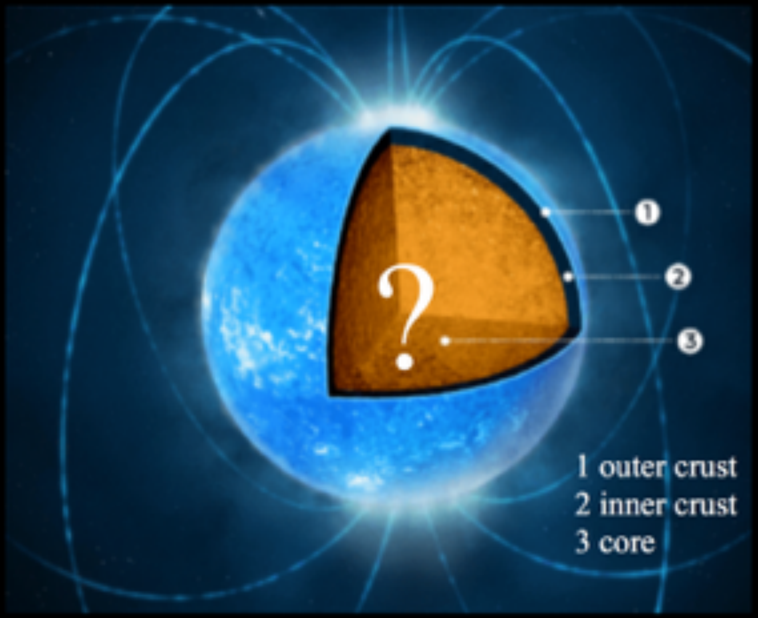


ns-ns mergers

Gravitational wave detection



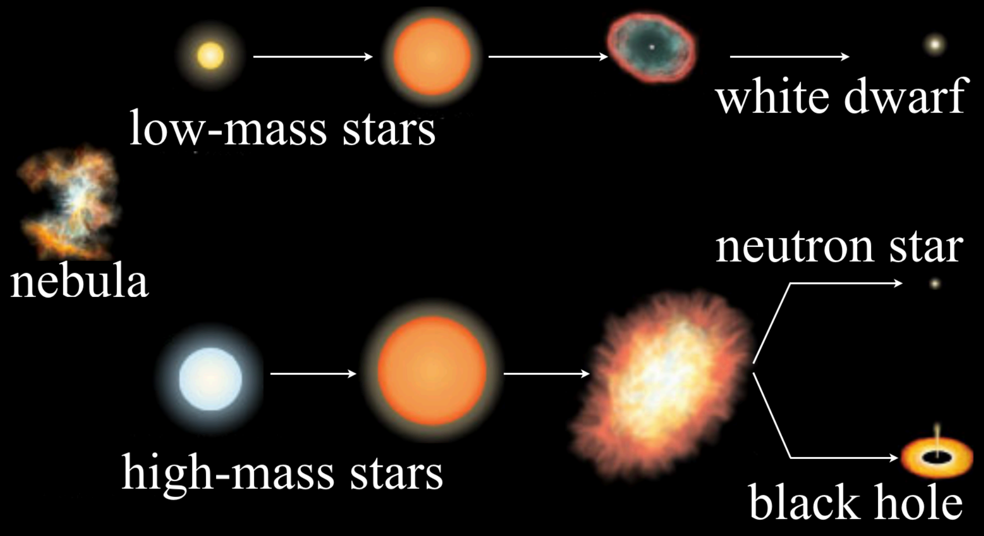
Nuclear matter properties



1 outer crust
2 inner crust
3 core

(short) Gamma-Ray Bursts

Binary stellar evolution



low-mass stars

white dwarf

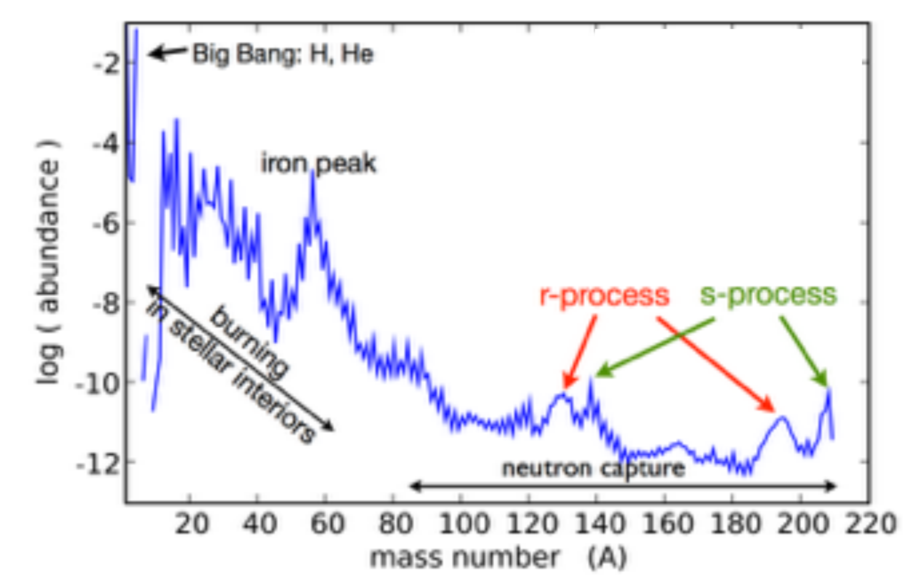
nebula

neutron star

high-mass stars

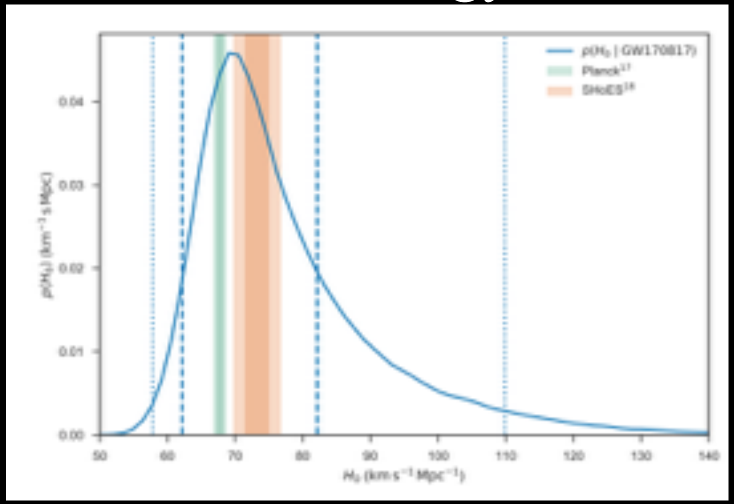
black hole

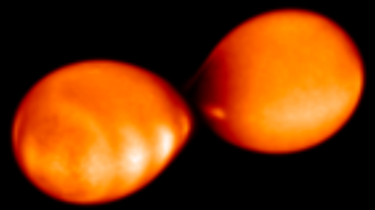
Nucleosynthesis



Elemental evolution of the Cosmos

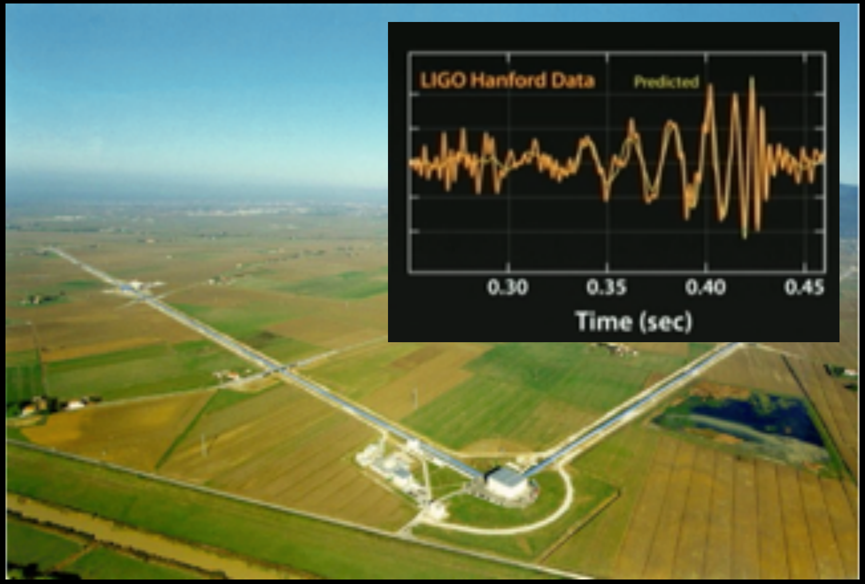
Cosmology



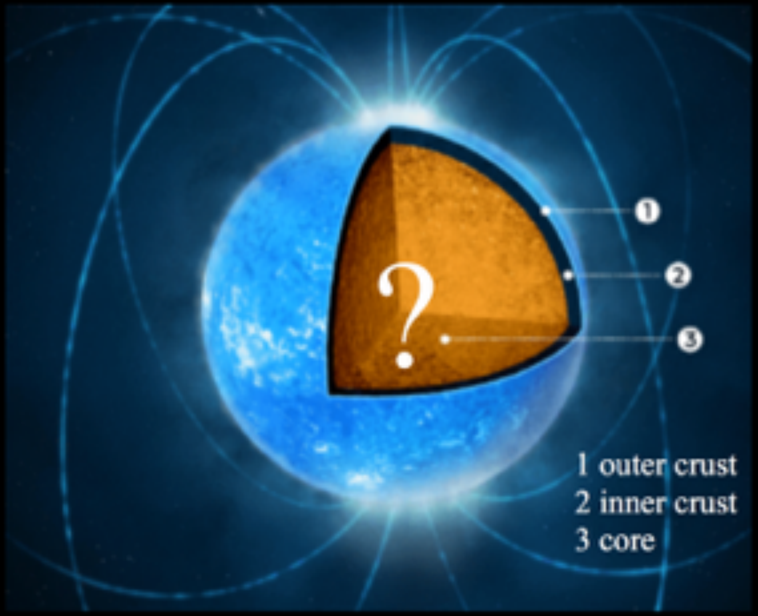


ns-ns mergers

Gravitational wave detection



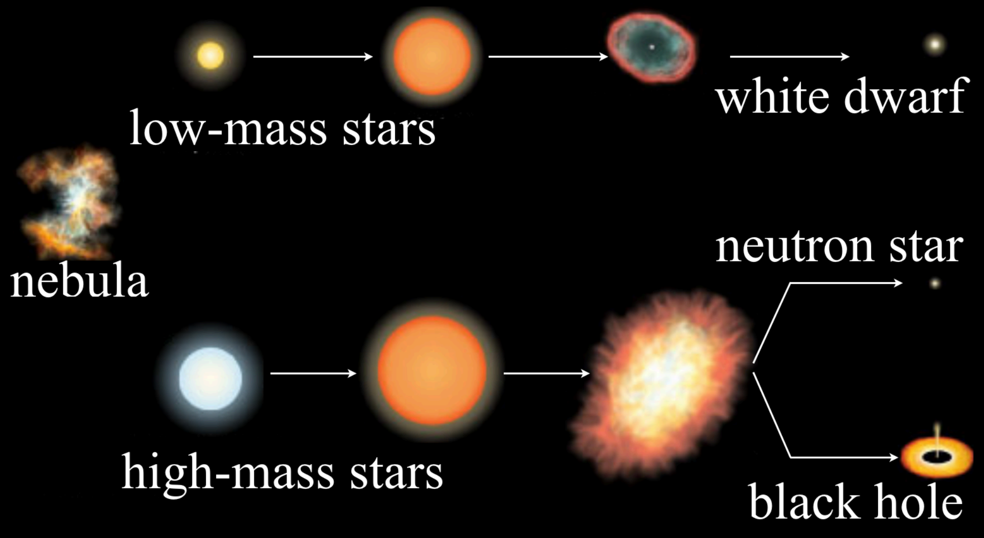
Nuclear matter properties



1 outer crust
2 inner crust
3 core

(short) Gamma-Ray Bursts

Binary stellar evolution



low-mass stars

white dwarf

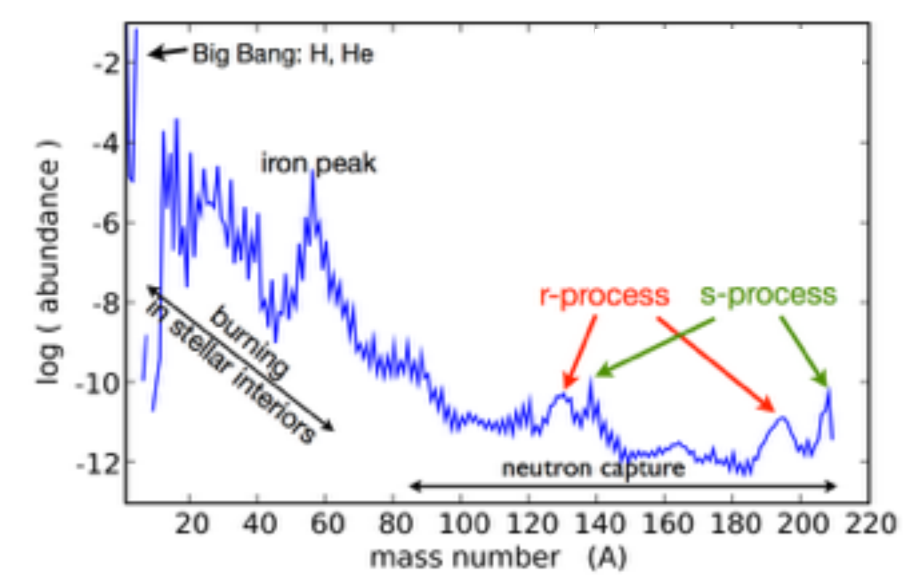
nebula

neutron star

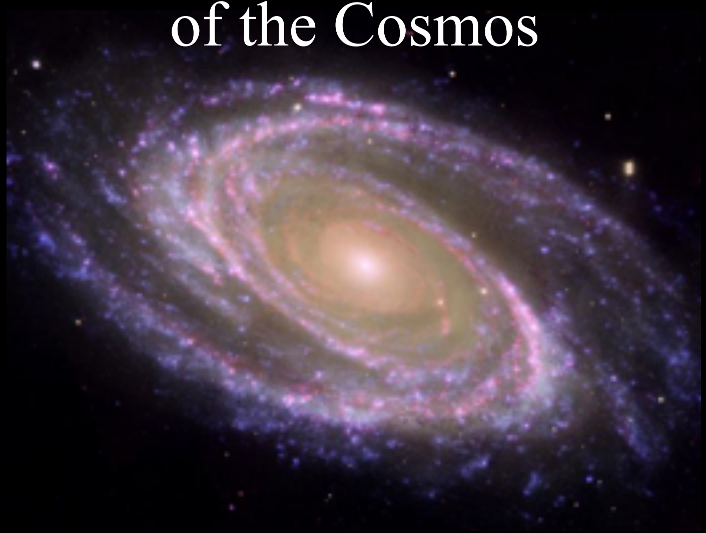
high-mass stars

black hole

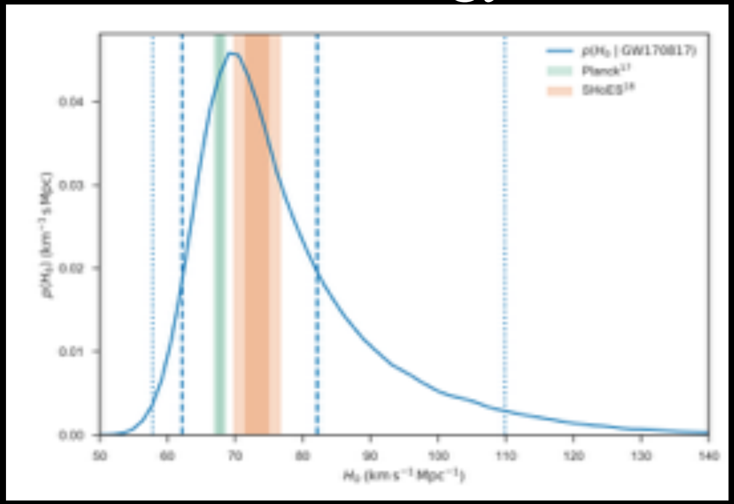
Nucleosynthesis

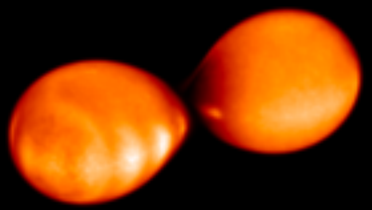


Elemental evolution of the Cosmos



Cosmology

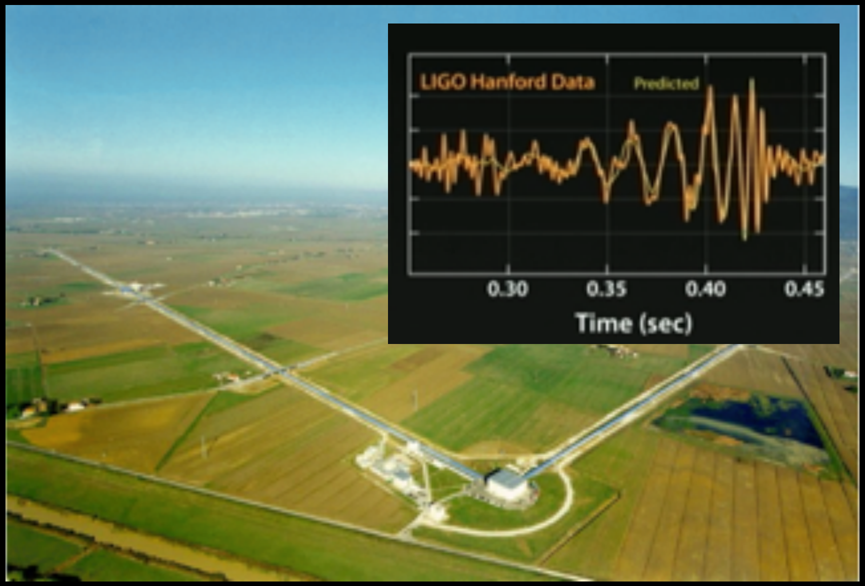




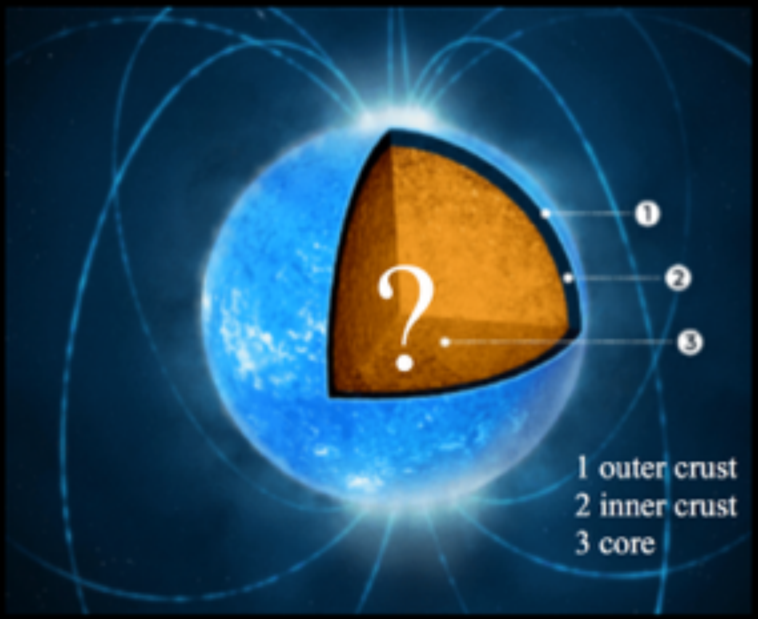
ns-ns mergers

Radioactive electromag. flashes

Gravitational wave detection

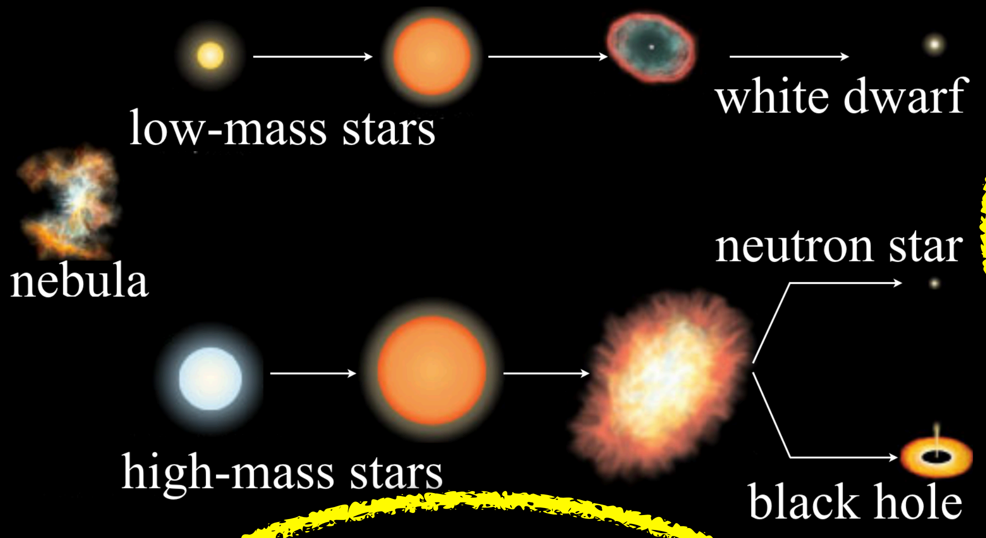


Nuclear matter properties



(short) Gamma-Ray Bursts

Binary stellar evolution



low-mass stars

white dwarf

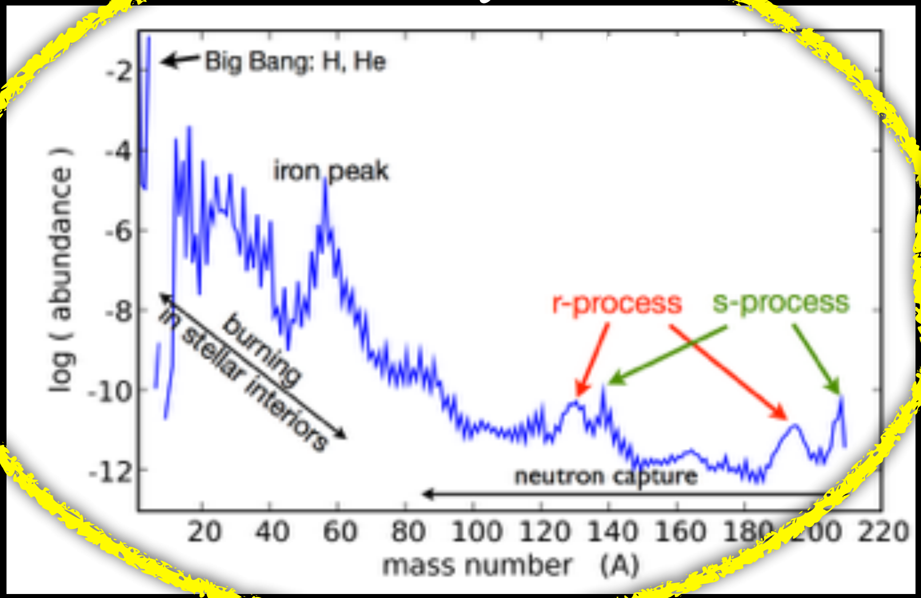
nebula

neutron star

high-mass stars

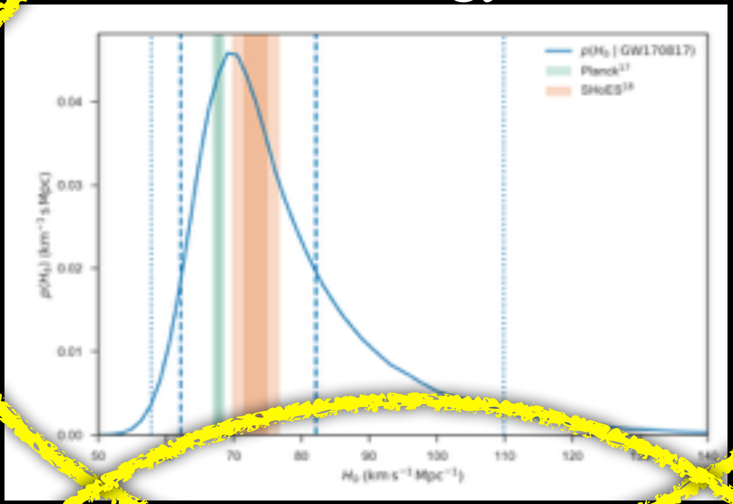
black hole

Nucleosynthesis

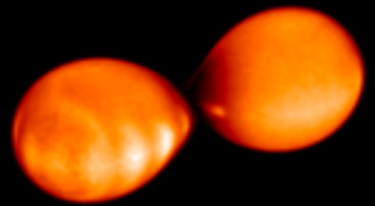


Elemental evolution of the Cosmos

Cosmology

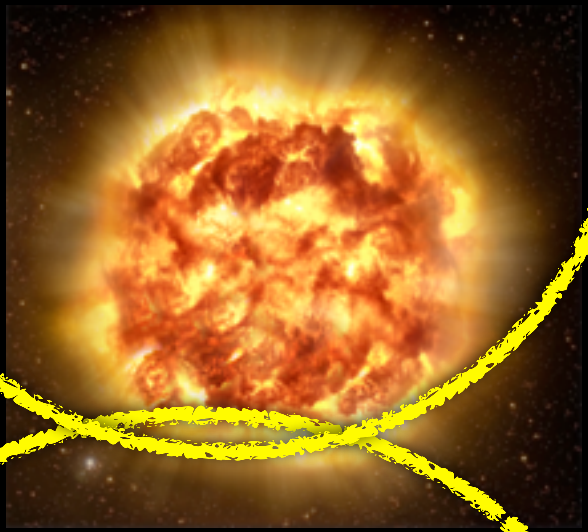


GW170817

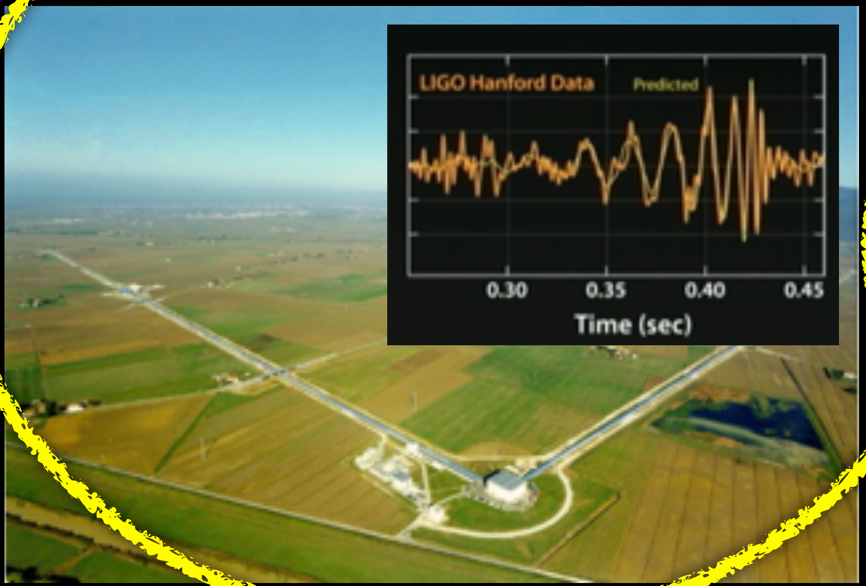


ns-ns mergers

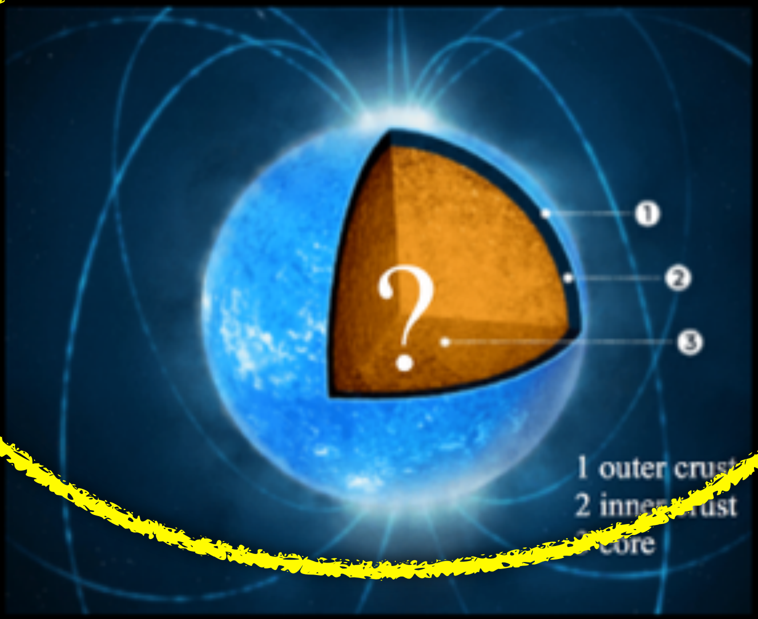
Radioactive electromag. flashes



Gravitational wave detection



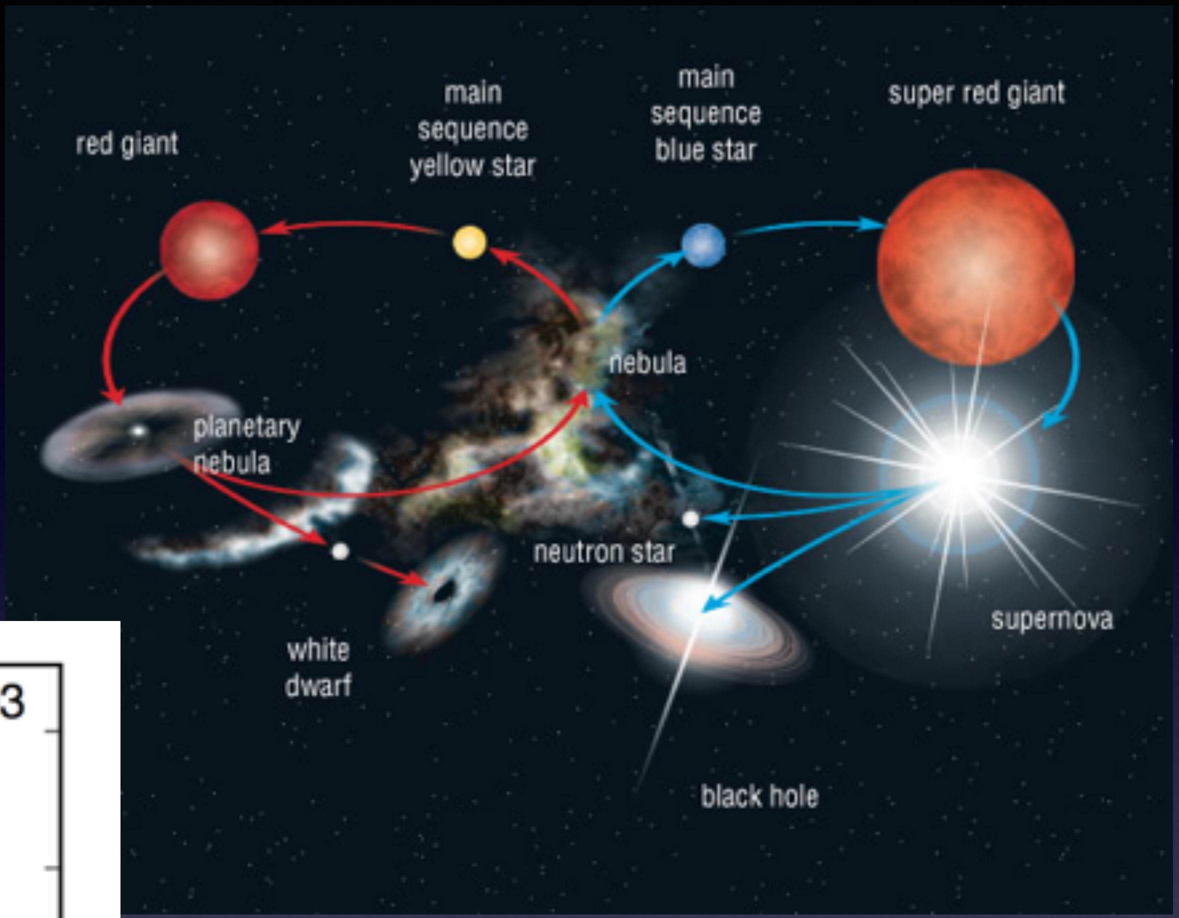
Nuclear matter properties



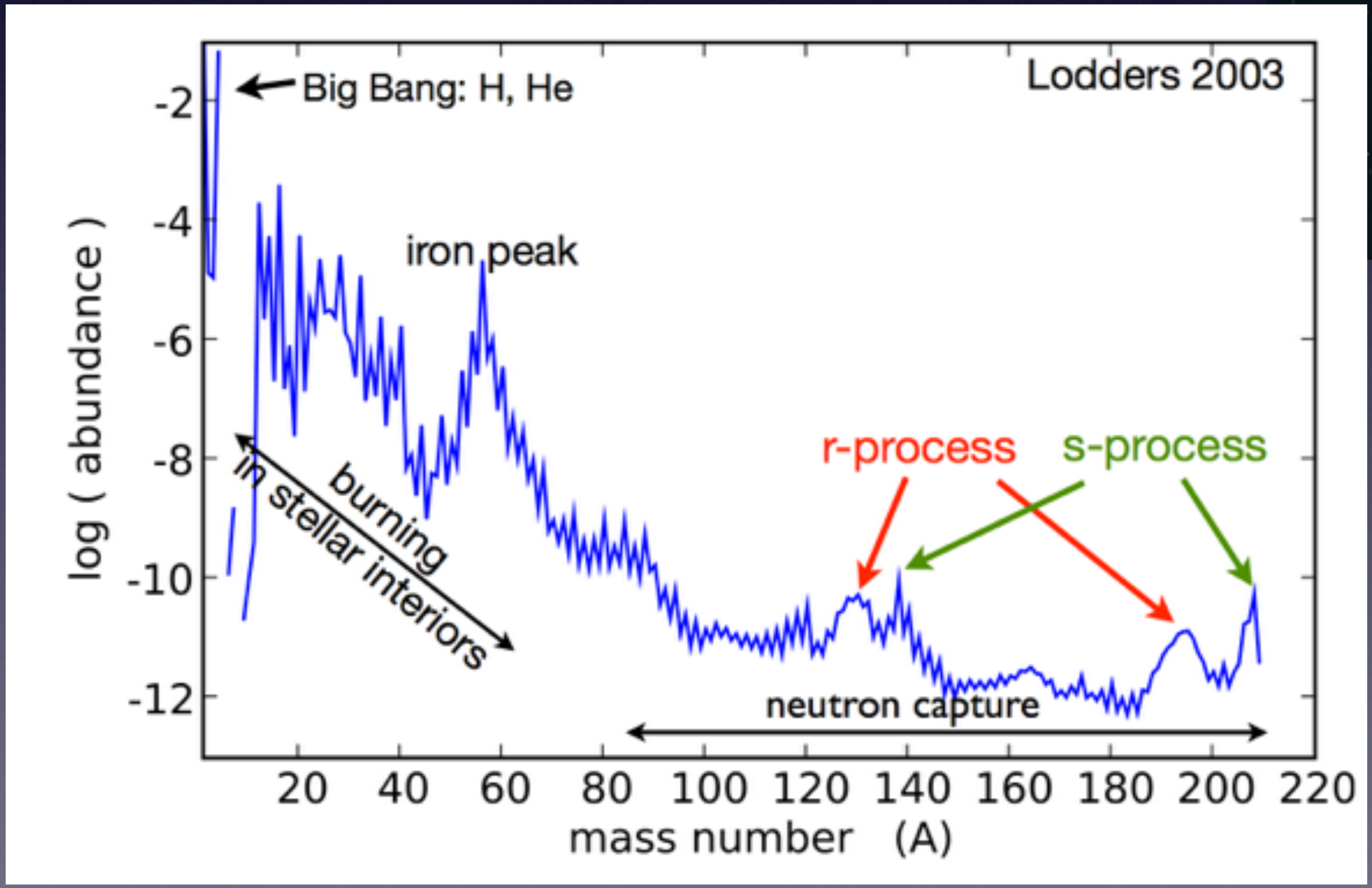
(short) Gamma-Ray Bursts

R-process nucleosynthesis

cosmic life cycle



Solar system abundances



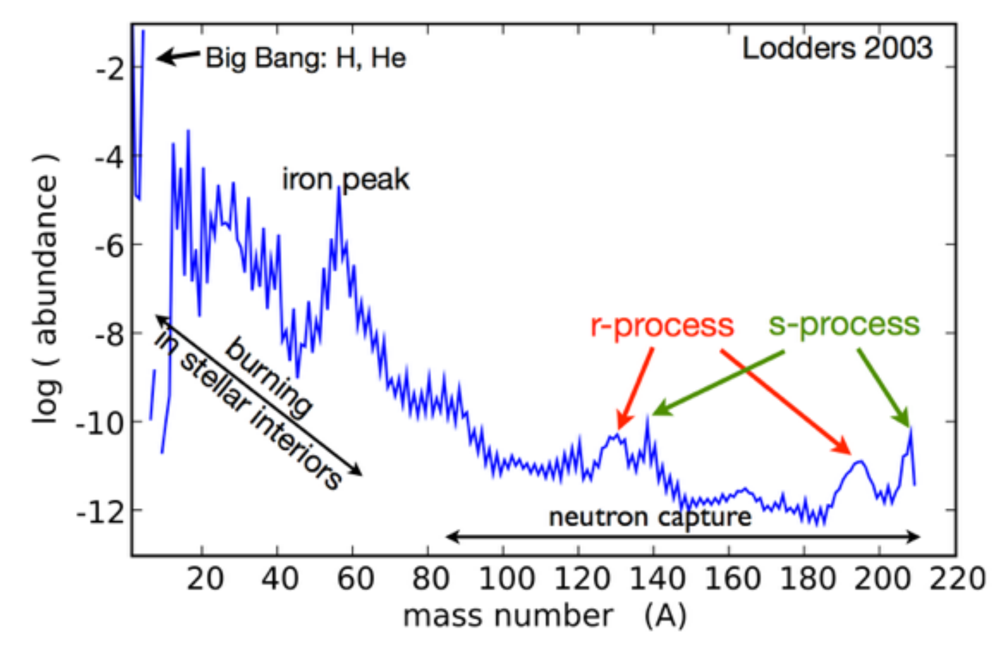
"Big Bang""stellar burning" "neutron captures"

two neutron capture processes:

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

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

Examples of r-process elements



Iridium, Z= 77, A= 192

Platinum, Z= 78, A= 195

Gold, Z= 79, A= 197

Lead, Z= 82, A= 207

Where does the r-process happen?

- One of the “11 science questions for the new century”
  (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies
  (Burbidge et al. 1957, Cameron 1957)

Where does the r-process happen?

- One of the “11 science questions for the new century”
  (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies
  (Burbidge et al. 1957, Cameron 1957)
- Neutron star mergers (selection)
  - 1974:
    - idea discussed in NSBH context (Lattimer & Schramm 1974)
    - ejecta amounts unknown (“~$0.05 \pm 0.05\ M_{ns}$”) ⇒ relevance?

Where does the r-process happen?

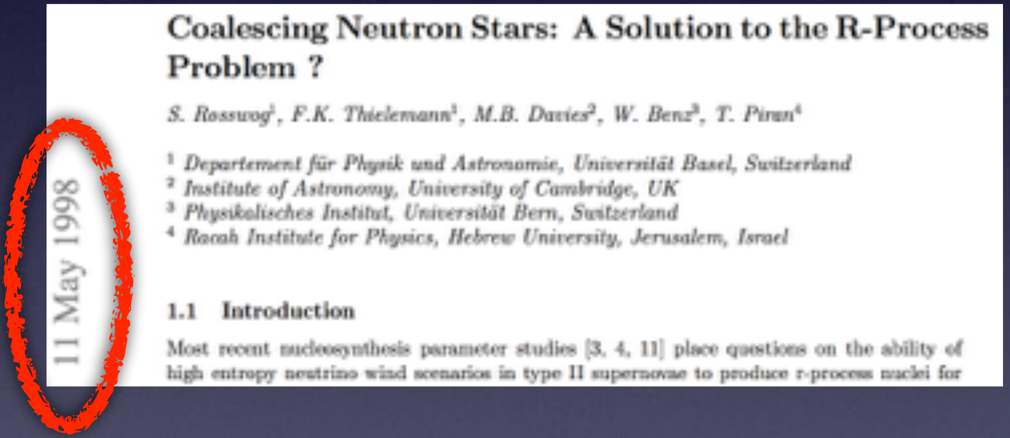
- One of the "11 science questions for the new century"
  (National Research Council 2003)

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

- Neutron star mergers (selection)
  - 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)

Where does the r-process happen?

- One of the "11 science questions for the new century" (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies (Burbidge et al. 1957, Cameron 1957)
- Neutron star mergers (selection)
  - 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 (Rosswog+1998, Freiburghaus+ 1999, Rosswog+ 1999):



11 May 1998

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

S. Rosswog[1], F.K. Thielemann[1], M.B. Davies[2], W. Benz[3], T. Piran[4]

[1] *Departement für Physik und Astronomie, Universität Basel, Switzerland*
[2] *Institute of Astronomy, University of Cambridge, UK*
[3] *Physikalisches Institut, Universität Bern, Switzerland*
[4] *Racah Institute for Physics, Hebrew University, Jerusalem, Israel*

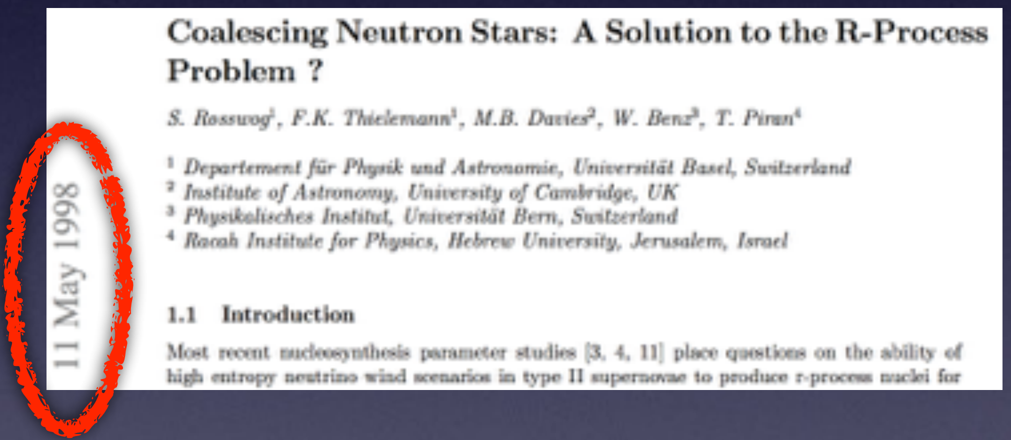
1.1 Introduction

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

Where does the r-process happen?

- One of the “11 science questions for the new century”
  (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies
  (Burbidge et al. 1957, Cameron 1957)

- Neutron star mergers (selection)
  - 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
      (Rosswog+1998, Freiburghaus+ 1999, Rosswog+ 1999):
      - “eject enough to explain all Galactic r-process”



11 May 1998

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

S. Rosswog[1], F.K. Thielemann[1], M.B. Davies[2], W. Benz[3], T. Piran[4]

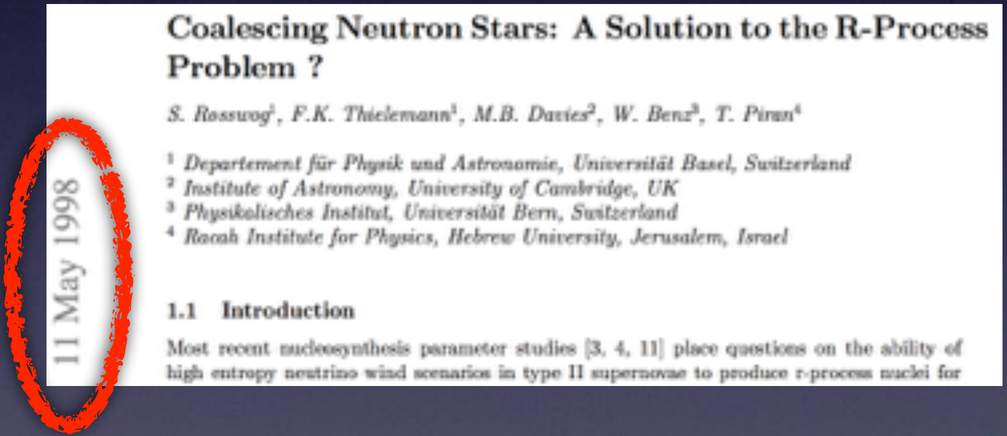
[1] *Departement für Physik und Astronomie, Universität Basel, Switzerland*
[2] *Institute of Astronomy, University of Cambridge, UK*
[3] *Physikalisches Institut, Universität Bern, Switzerland*
[4] *Racah Institute for Physics, Hebrew University, Jerusalem, Israel*

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

Where does the r-process happen?

- One of the "11 science questions for the new century" (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies (Burbidge et al. 1957, Cameron 1957)
- Neutron star mergers (selection)
  - 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 (Rosswog+1998, Freiburghaus+ 1999, Rosswog+ 1999):
      - "eject enough to explain all Galactic r-process"
      - "reproduce solar r-process up to platinum peak without any tuning"



11 May 1998

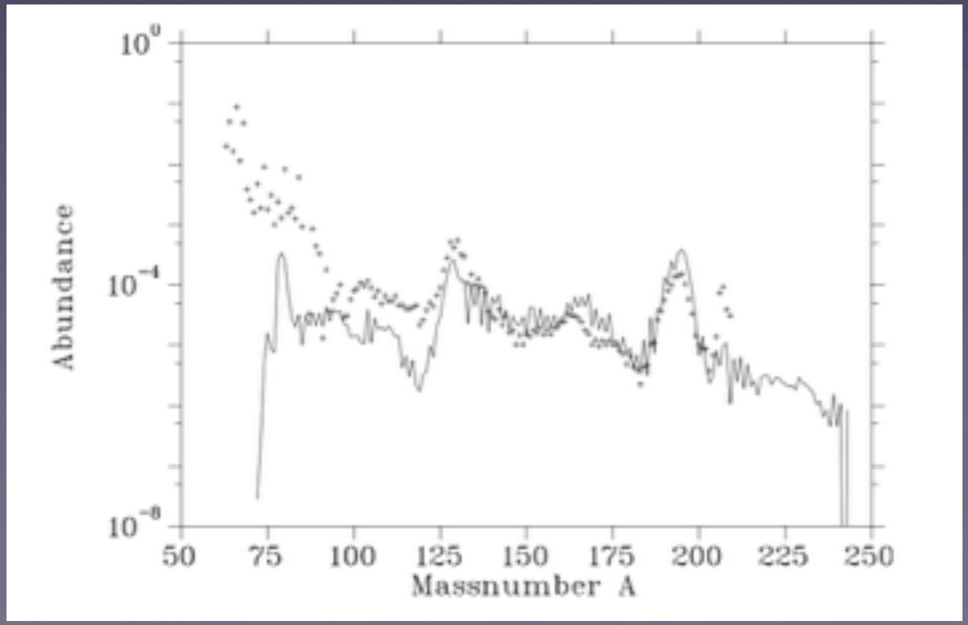
Coalescing Neutron Stars: A Solution to the R-Process Problem ?

S. Rosswog[1], F.K. Thielemann[1], M.B. Davies[2], W. Benz[3], T. Piran[4]

[1] *Departement für Physik und Astronomie, Universität Basel, Switzerland*
[2] *Institute of Astronomy, University of Cambridge, UK*
[3] *Physikalisches Institut, Universität Bern, Switzerland*
[4] *Racah Institute for Physics, Hebrew University, Jerusalem, Israel*

1.1 Introduction

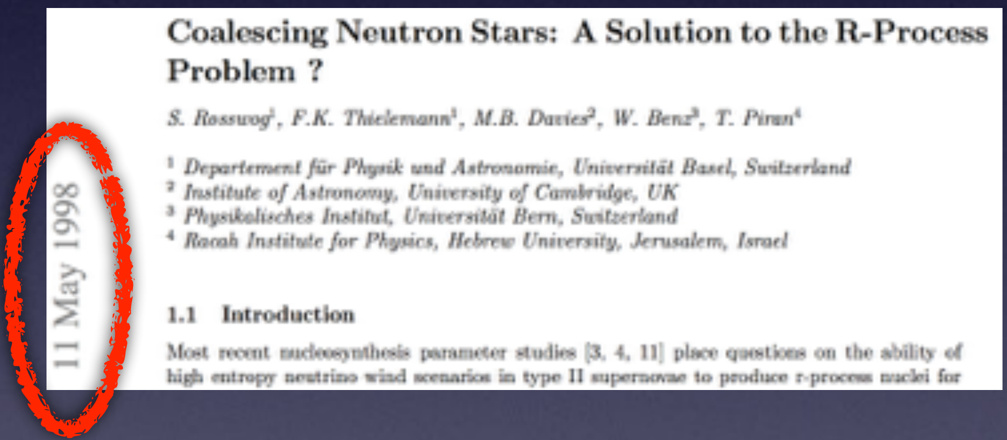
Most recent nucleosynthesis parameter studies [3, 4, 11] place questions on the ability of high entropy neutrino wind scenarios in type II supernovae to produce r-process nuclei for



Where does the r-process happen?

- One of the "11 science questions for the new century"
  (National Research Council 2003)
- Supernovae traditionally favored since the 1950ies
  (Burbidge et al. 1957, Cameron 1957)

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



11 May 1998

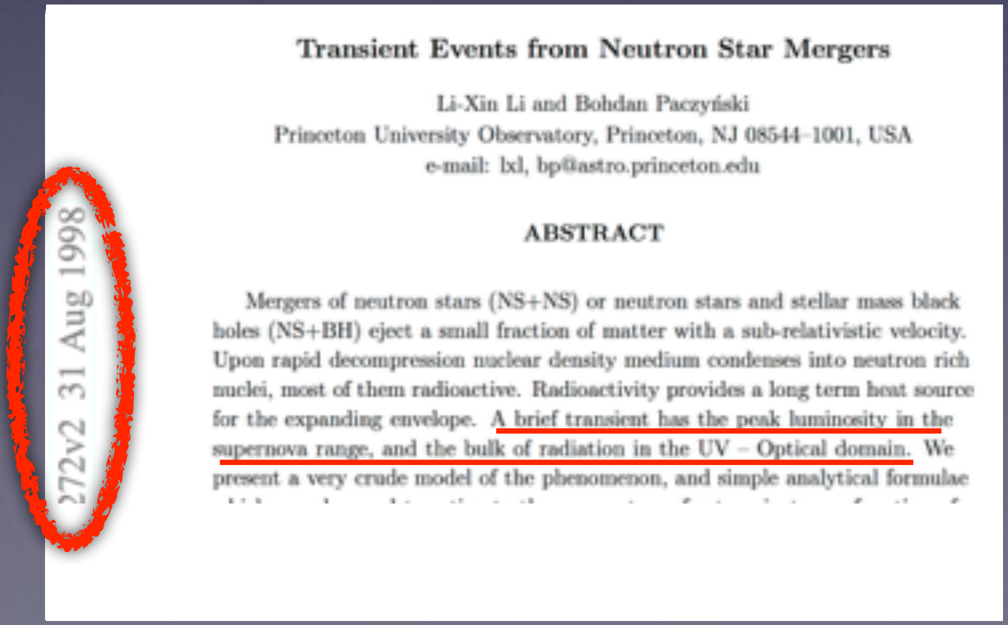
Coalescing Neutron Stars: A Solution to the R-Process Problem ?

S. Rosswog^1, F.K. Thielemann^1, M.B. Davies^2, W. Benz^3, T. Piran^4

^{1} Departement für Physik und Astronomie, Universität Basel, Switzerland
^{2} Institute of Astronomy, University of Cambridge, UK
^{3} Physikalisches Institut, Universität Bern, Switzerland
^{4} Racah Institute for Physics, Hebrew University, Jerusalem, Israel

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

Li-Xin Li and Bohdan Paczyński
Princeton University Observatory, Princeton, NJ 08544–1001, USA
e-mail: lxl, bp@astro.princeton.edu

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

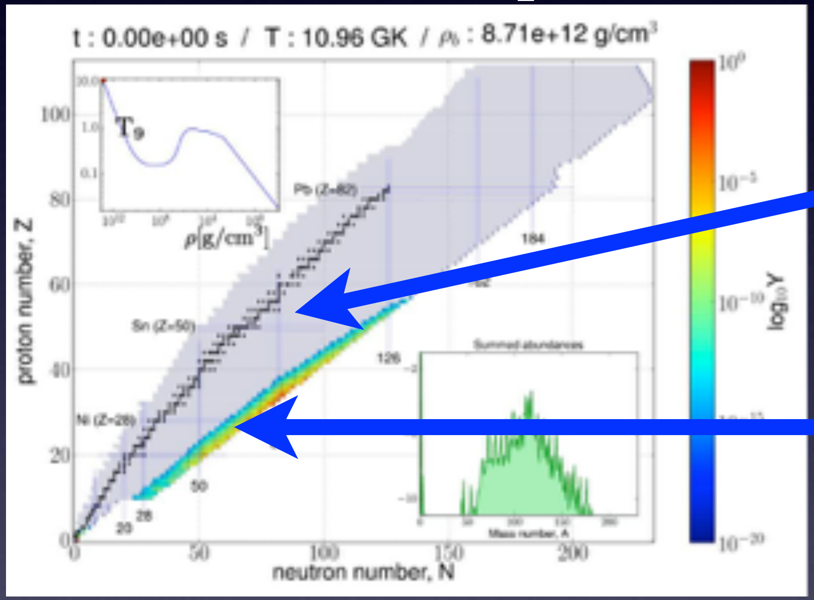
R-process: electron fraction Y_e plays decisive role!

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

R-process: electron fraction Y_e plays decisive role!

- “electron fraction” $Y_e = ”\frac{\#\ \text{protons}}{\#\ \text{nucleons}} = \frac{\#\ \text{electrons}}{\#\ \text{nucleons}}”$

- effect on reaction path:



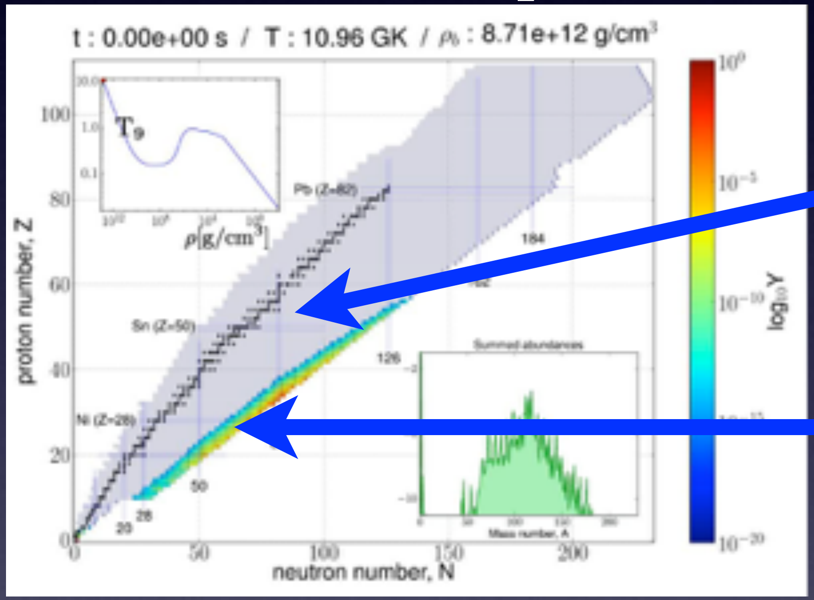
high Ye:
- closer to valley of β-stability
- nuclear properties from experiments

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

R-process: electron fraction Y_e plays decisive role!

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

- effect on reaction path:



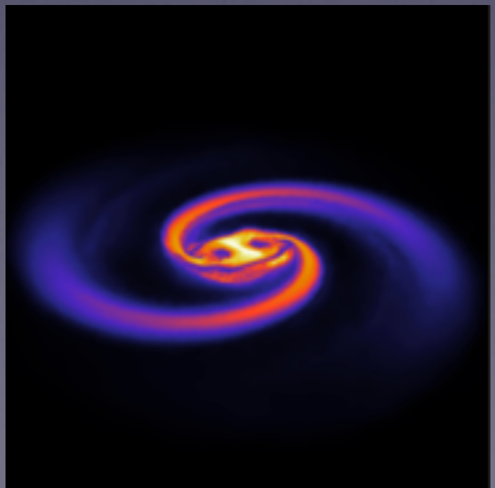
high Ye:
- closer to valley of β-stability
- nuclear properties from experiments

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

- astrophysical realization

Supernova:

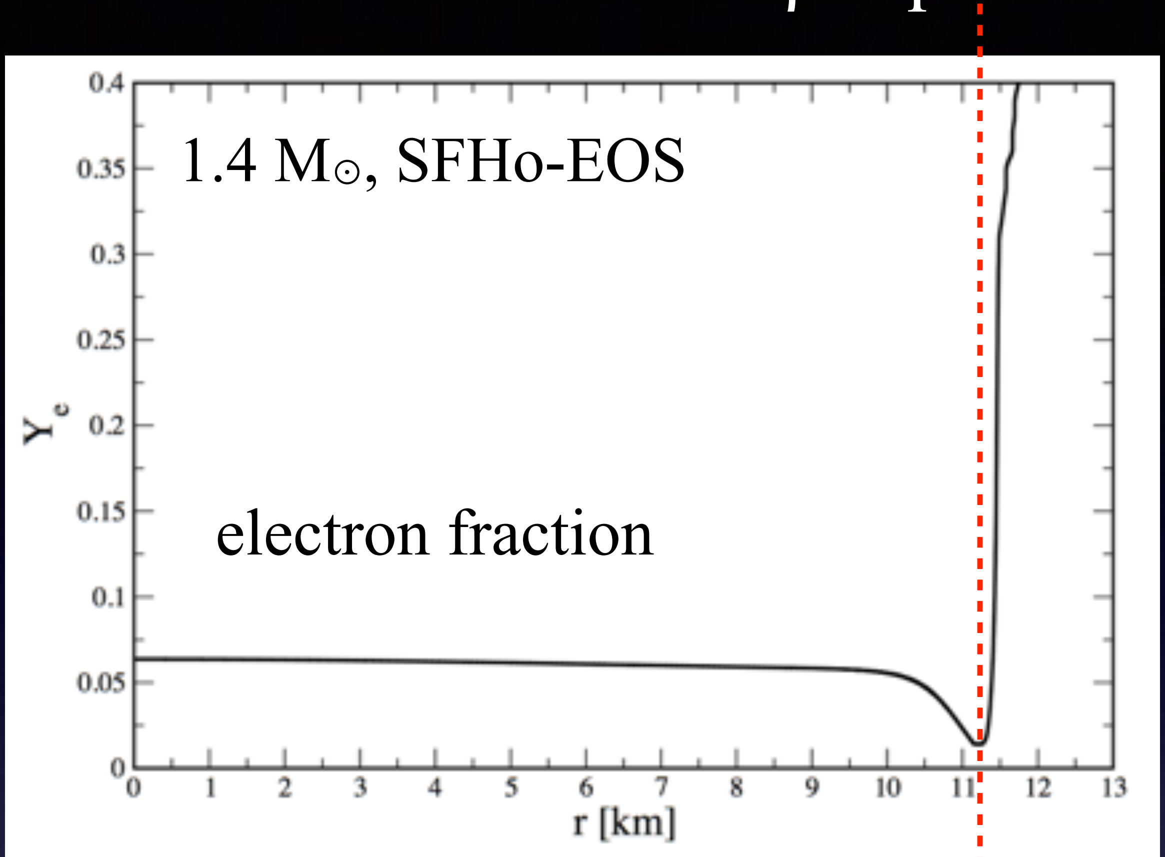
“de-leptonizing”
from 0.5 down
to Ye~ 0.3

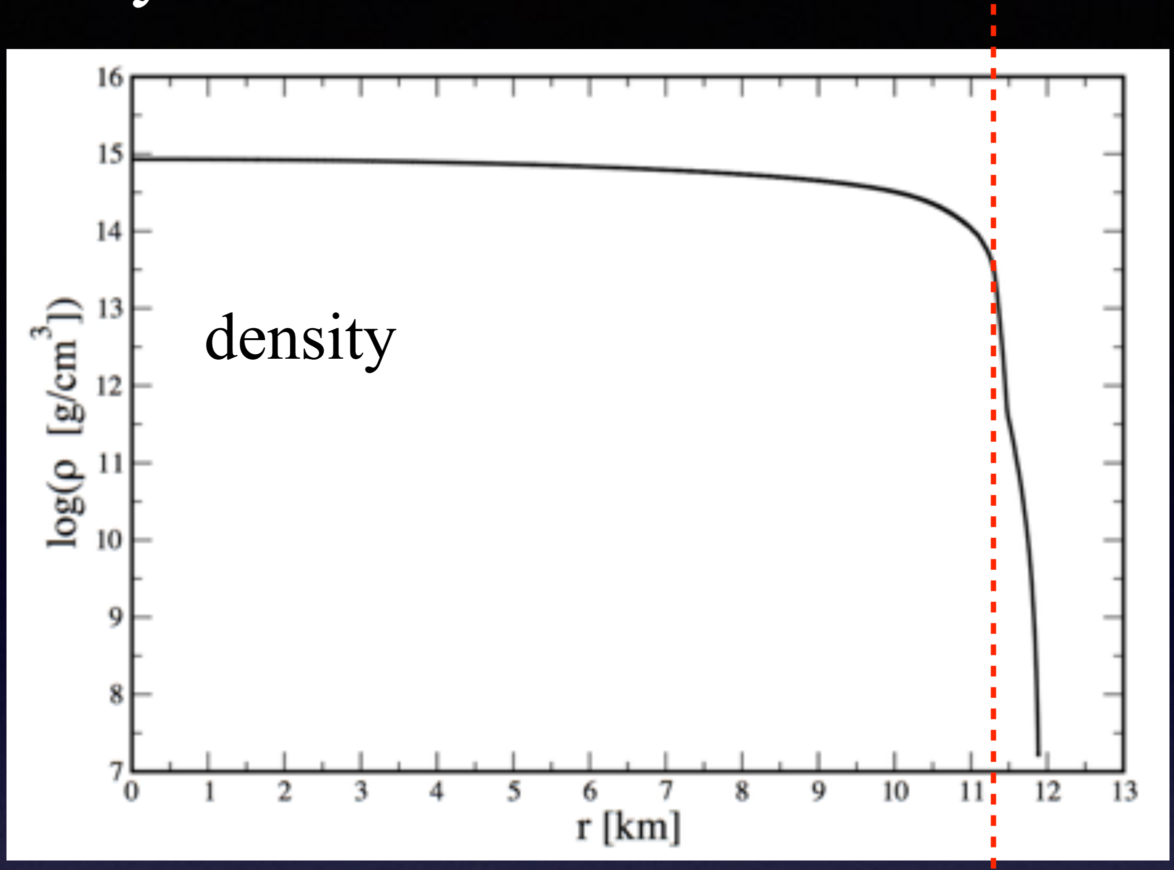


NS mergers:

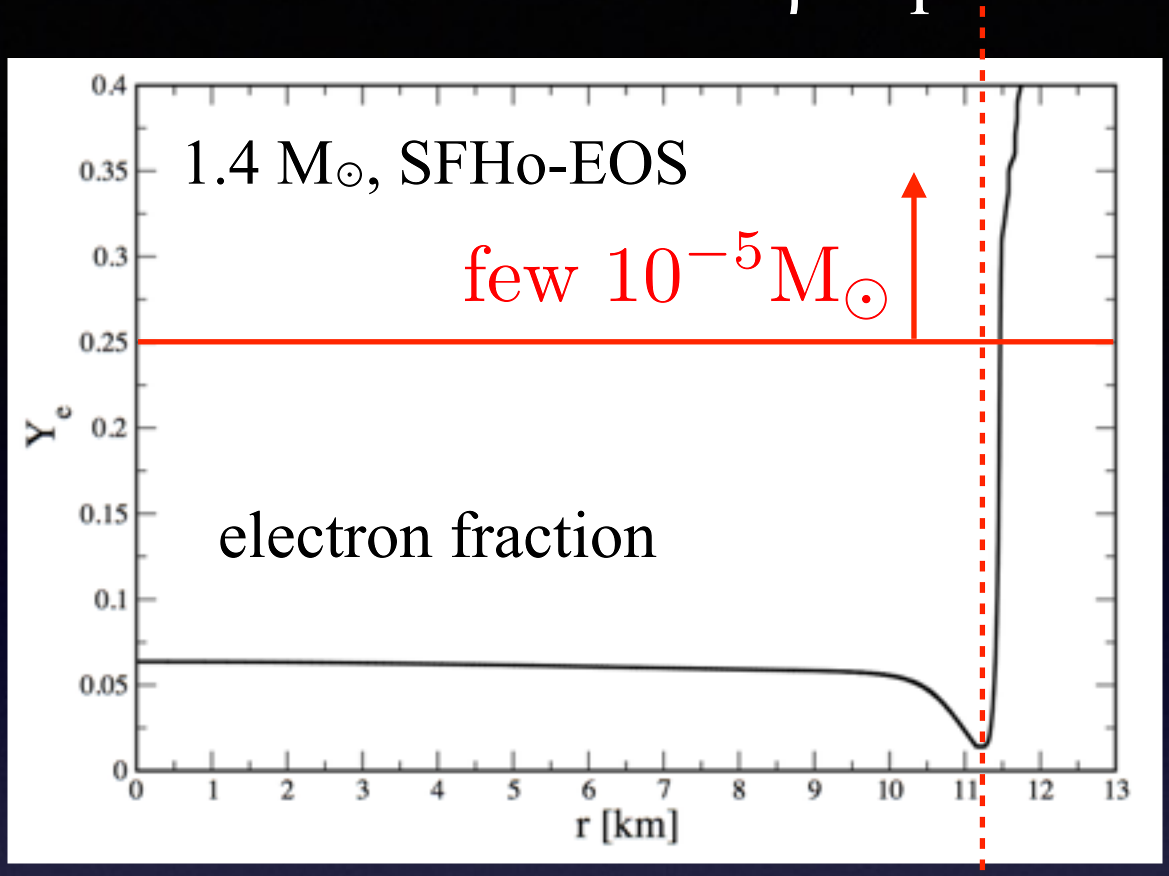
“re-protonizing”
starting from
Ye~ 0.1

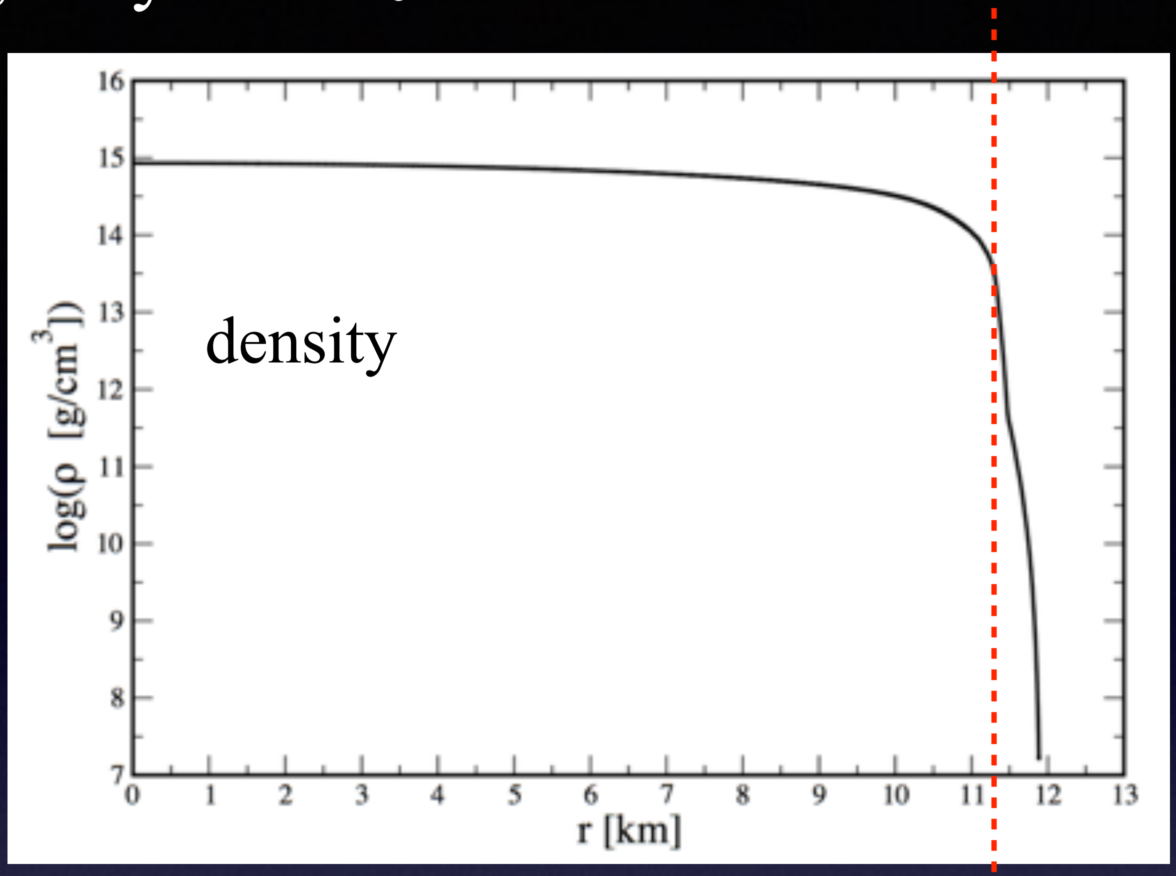
- initial neutron star: cold β-equilibrium, very low Y_e



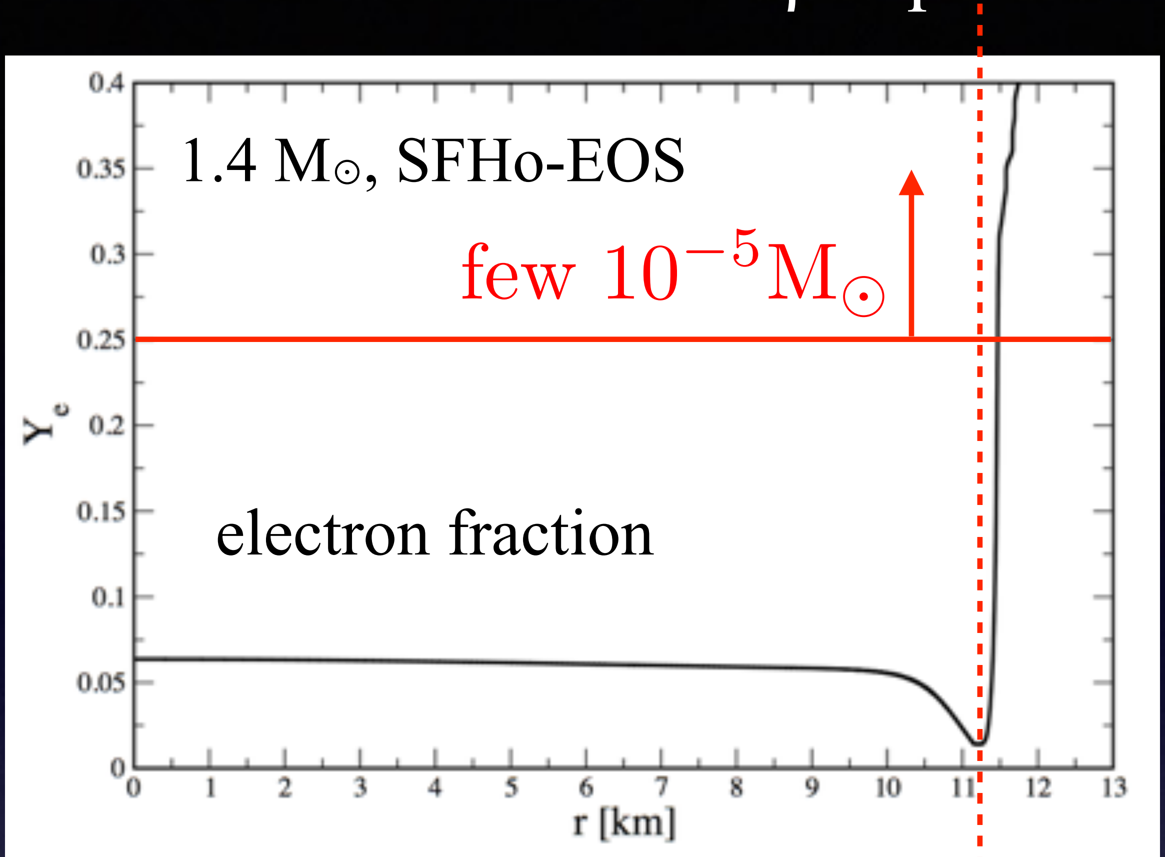


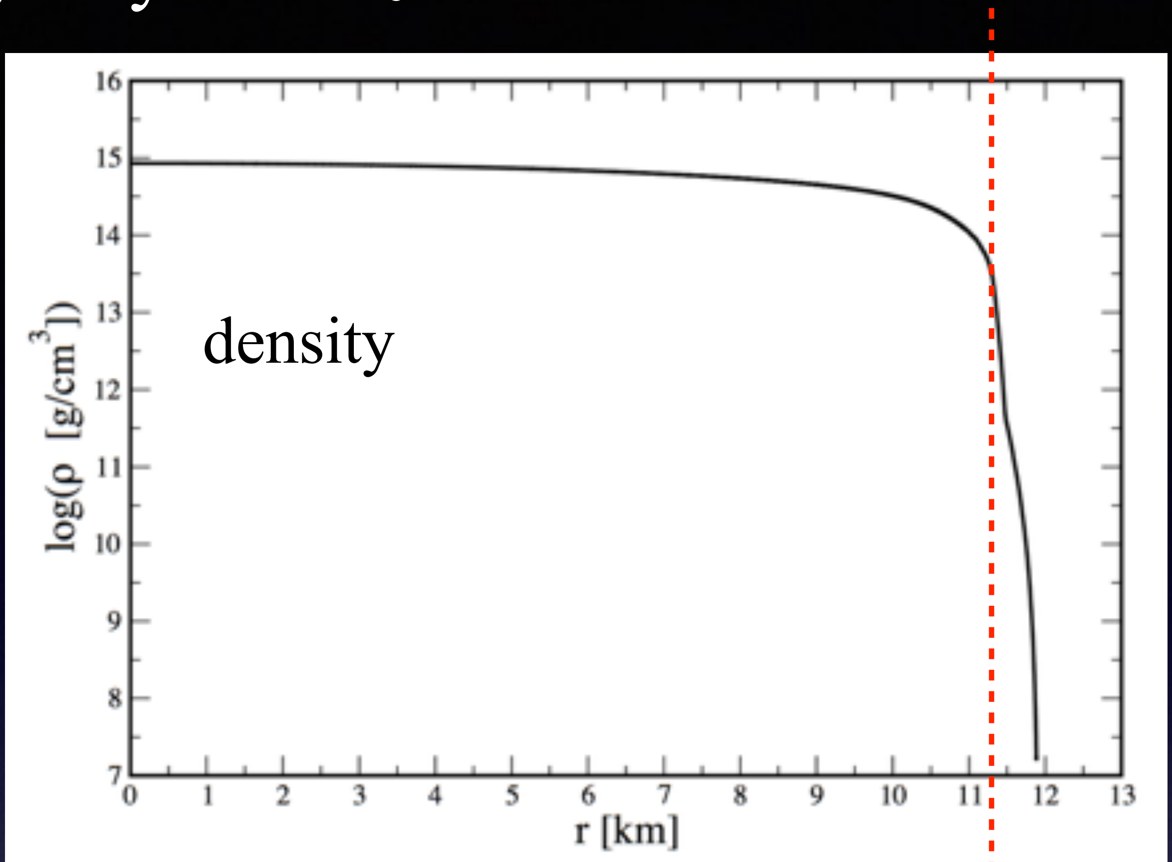
- initial neutron star: cold β-equilibrium, very low Y_e





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





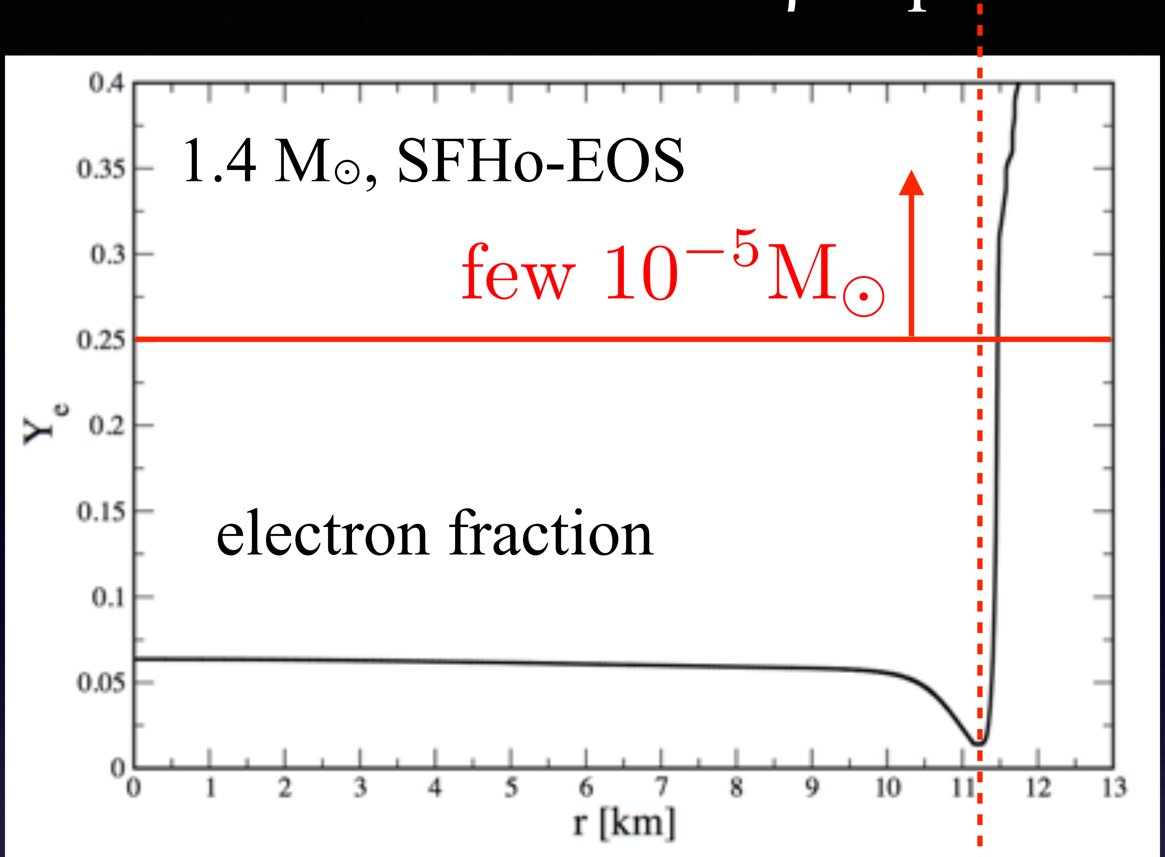
- increasing Y_e via β-reactions

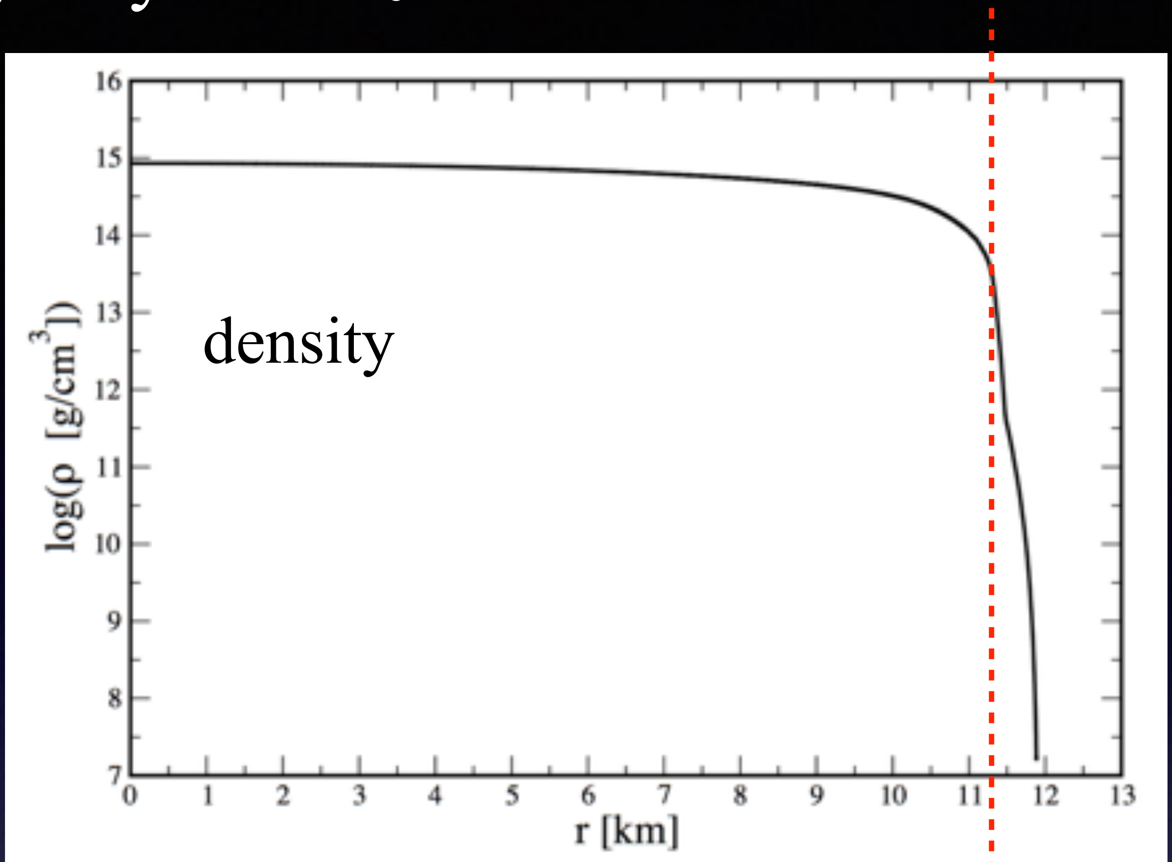
$$e^+ + n \rightarrow p + \bar{\nu}_e$$

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

⇒ ejecta history?

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

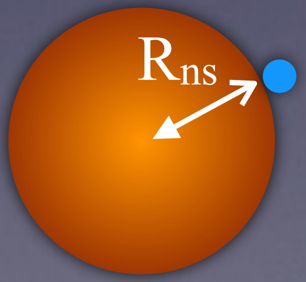




- increasing Y_e via β-reactions $e^+ + n \to p + \bar{\nu}_e$ ⇒ ejecta history?

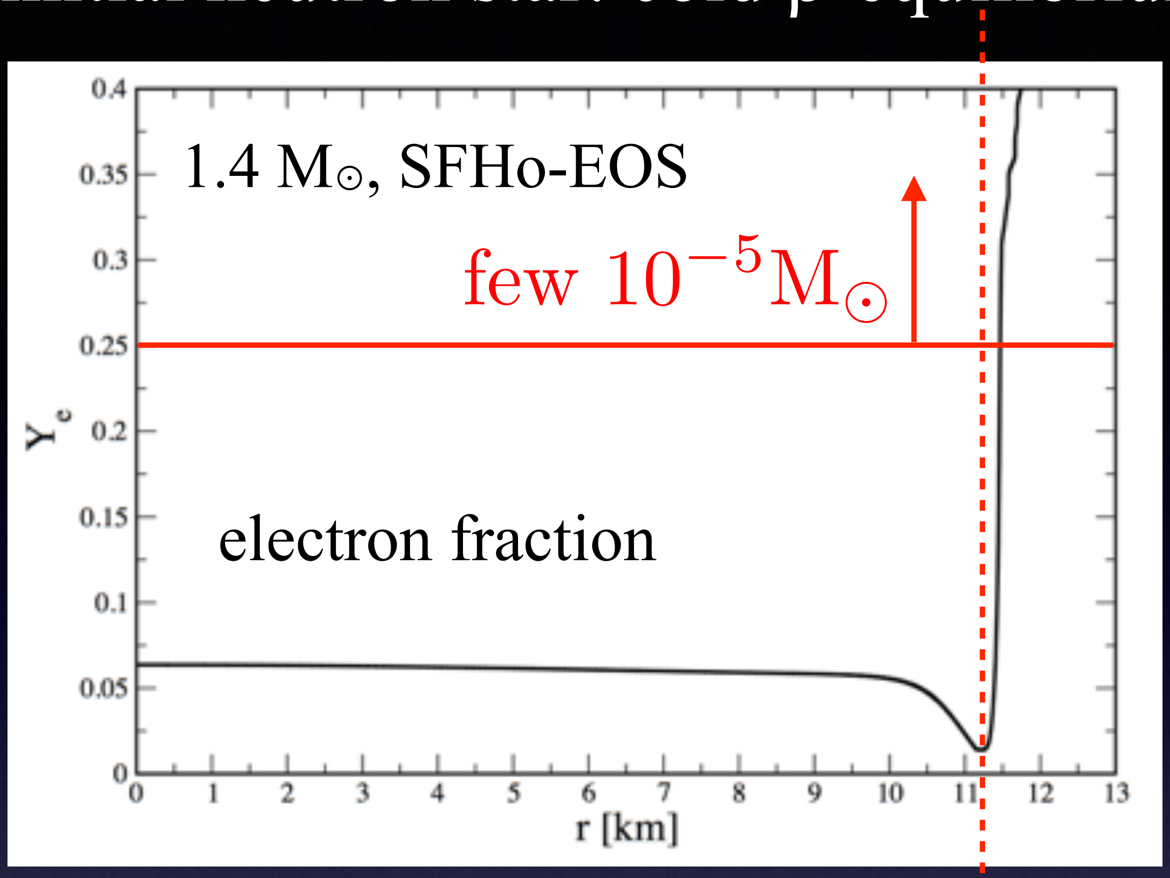
$$\nu_e + n \to p + e^-$$

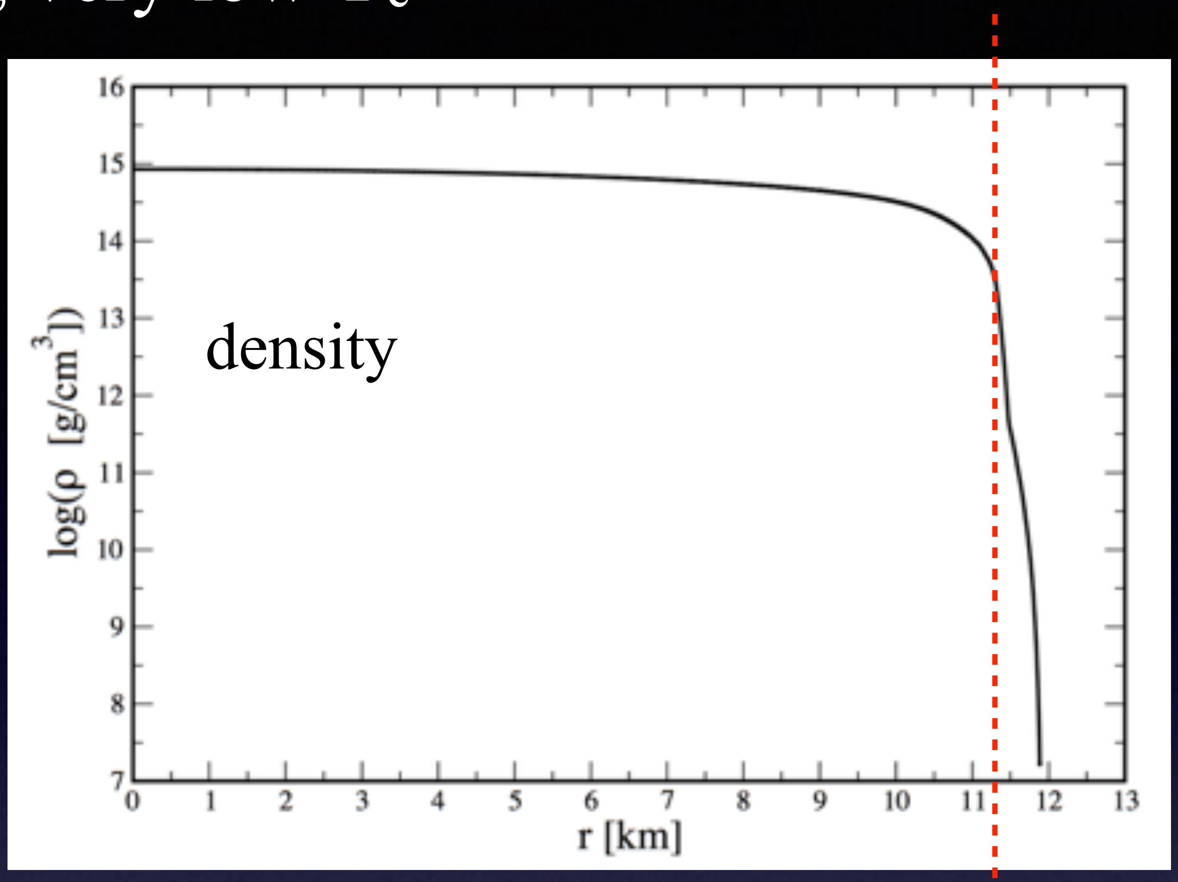
- BUT: unbinding matter from a neutron star is non-trivial!



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

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

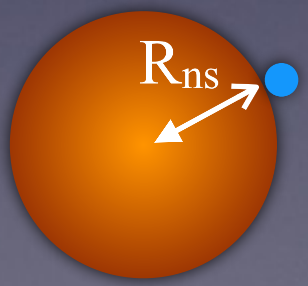




- increasing Y_e via β-reactions $e^+ + n \rightarrow p + \bar{\nu}_e$ ⇒ ejecta history?

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

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



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

⇒ need extreme conditions: merger with ns or bh

Ejecta types

i) “dynamic”

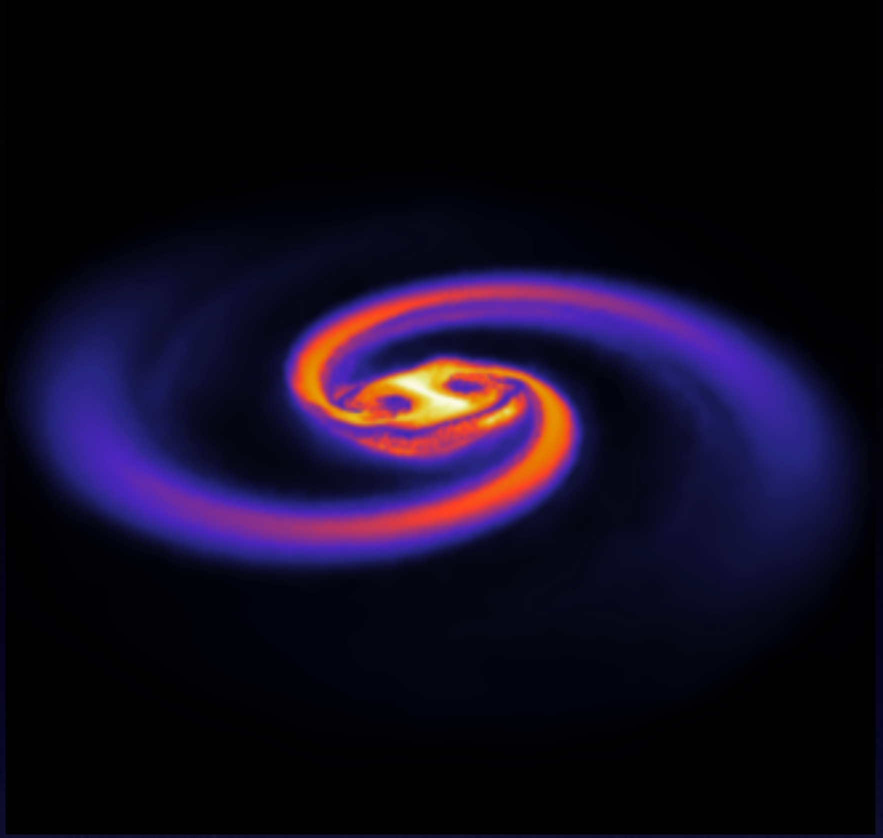
a) “tidal”:

- equatorial
- “cold”
- low Ye ~0.1
- ~1% $M_{\odot}$

~ 1 ms

b) “contact”:

- “polar”
- “hot”
- higher Ye > 0.1
- ~1% $M_{\odot}$

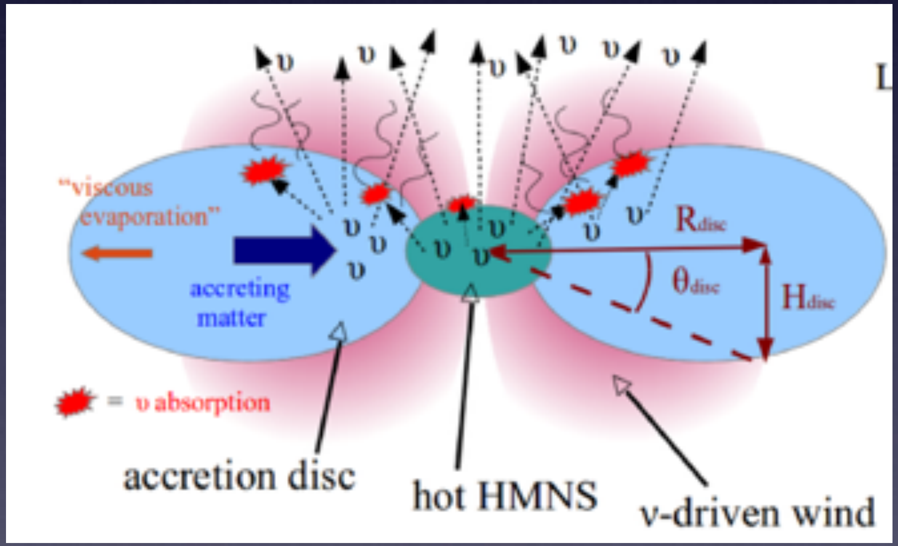


(from S.R. et al. 2017)

ii) neutrino-driven winds

- polar
- mass: ~1% $M_{\odot}$
- broader range of Ye

~ 10 - 100 ms

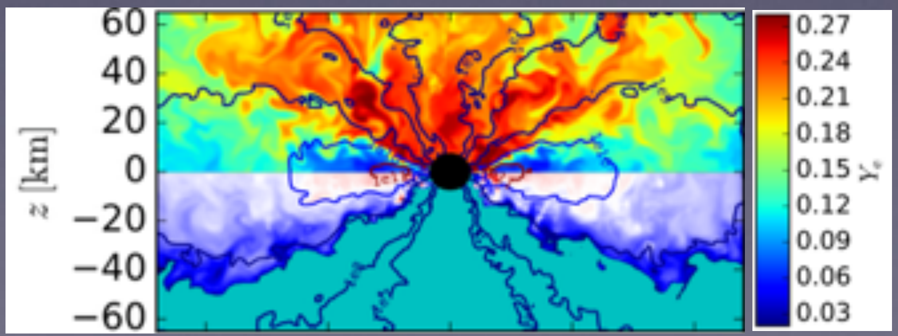


(from Perego et al. 2014)

iii) “secular”

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

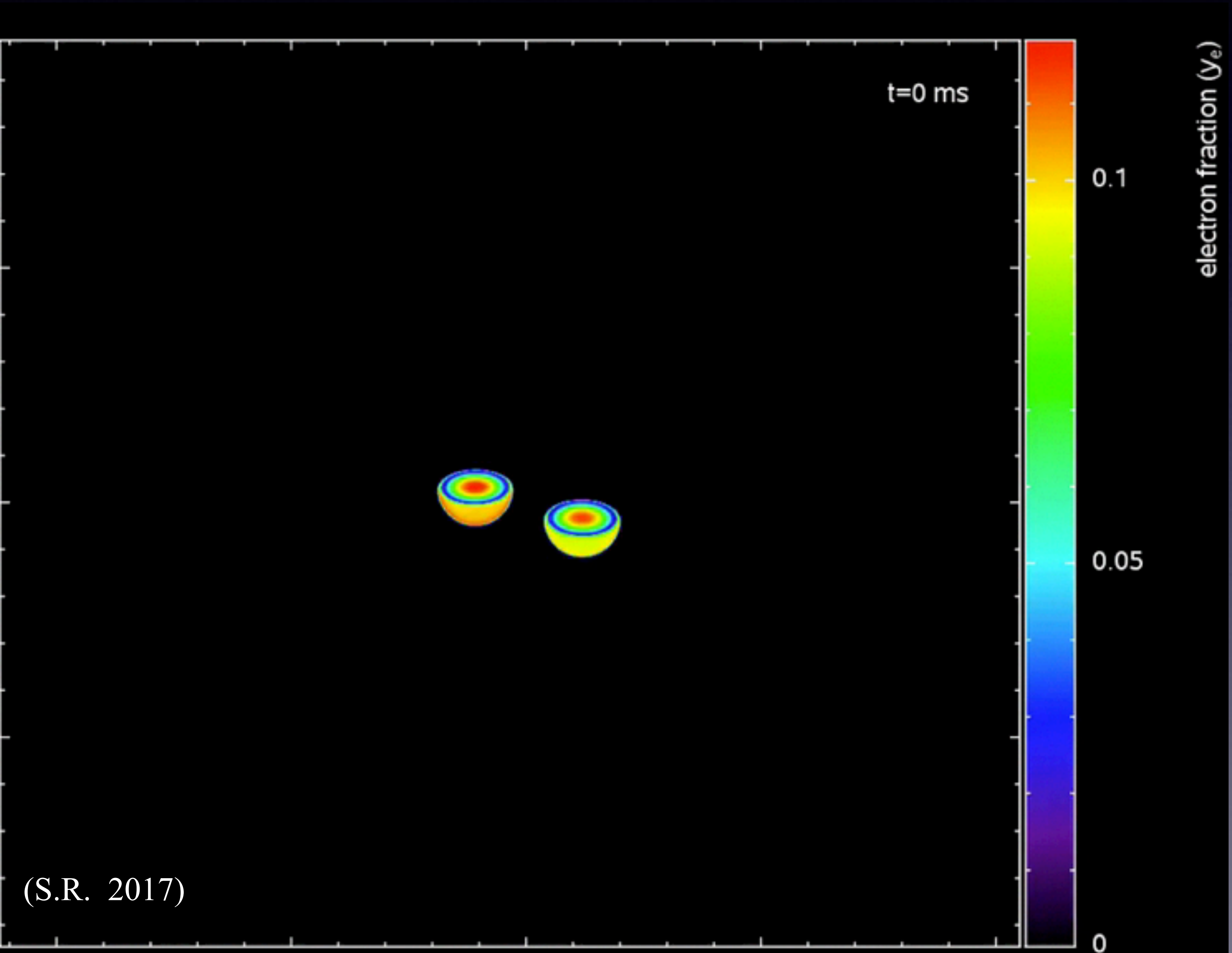
~ 1 s



(from Siegel & Metzger 2017)

i) Dynamic ejecta, tidal component

1.4 and 1.5 M_{sol} , no stellar spins



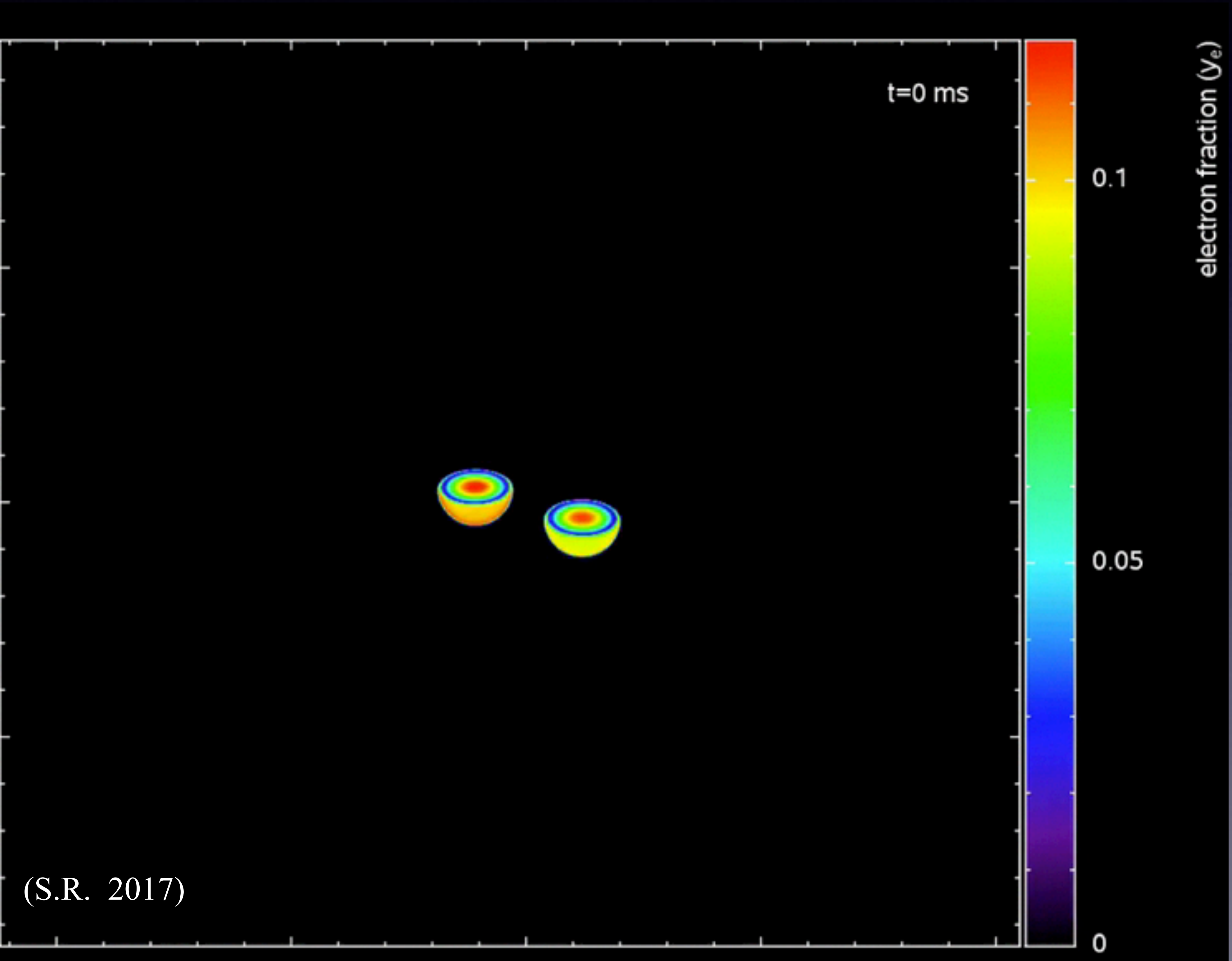
(S.R. 2017)

typical numbers:

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

i) Dynamic ejecta, tidal component

1.4 and 1.5 M_{sol} , no stellar spins

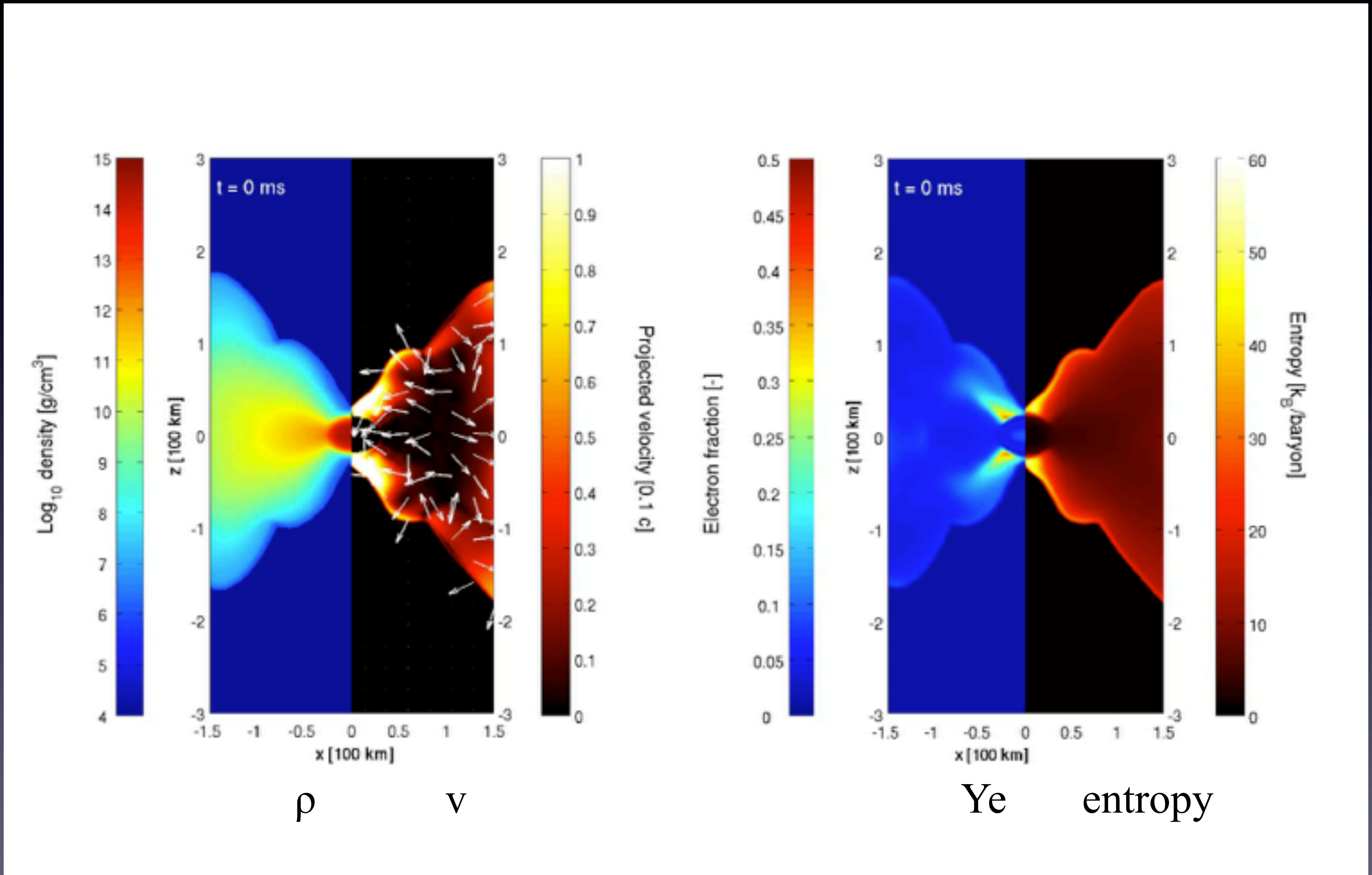


(S.R. 2017)

typical numbers:

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

ii) Neutrino-driven winds

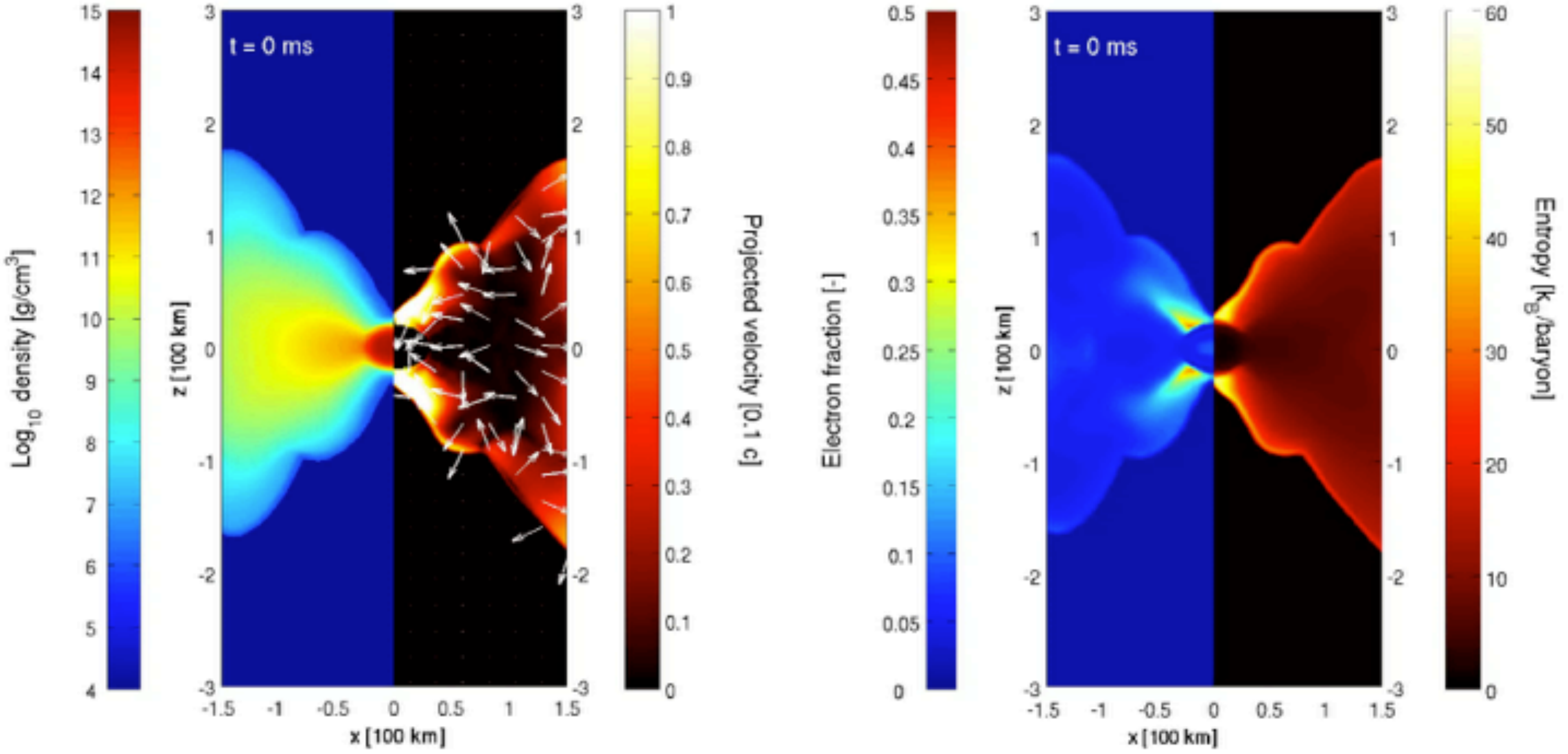


(Perego, S.R., Cabezon … 2014)

typical numbers:

- mass:
  ~0.01 $M_\odot$
- velocity:
  ~ 0.05c
- electron fraction:
  ~0.2 … 0.4

ii) Neutrino-driven winds



ρ v Ye entropy

(Perego, S.R., Cabezon … 2014)

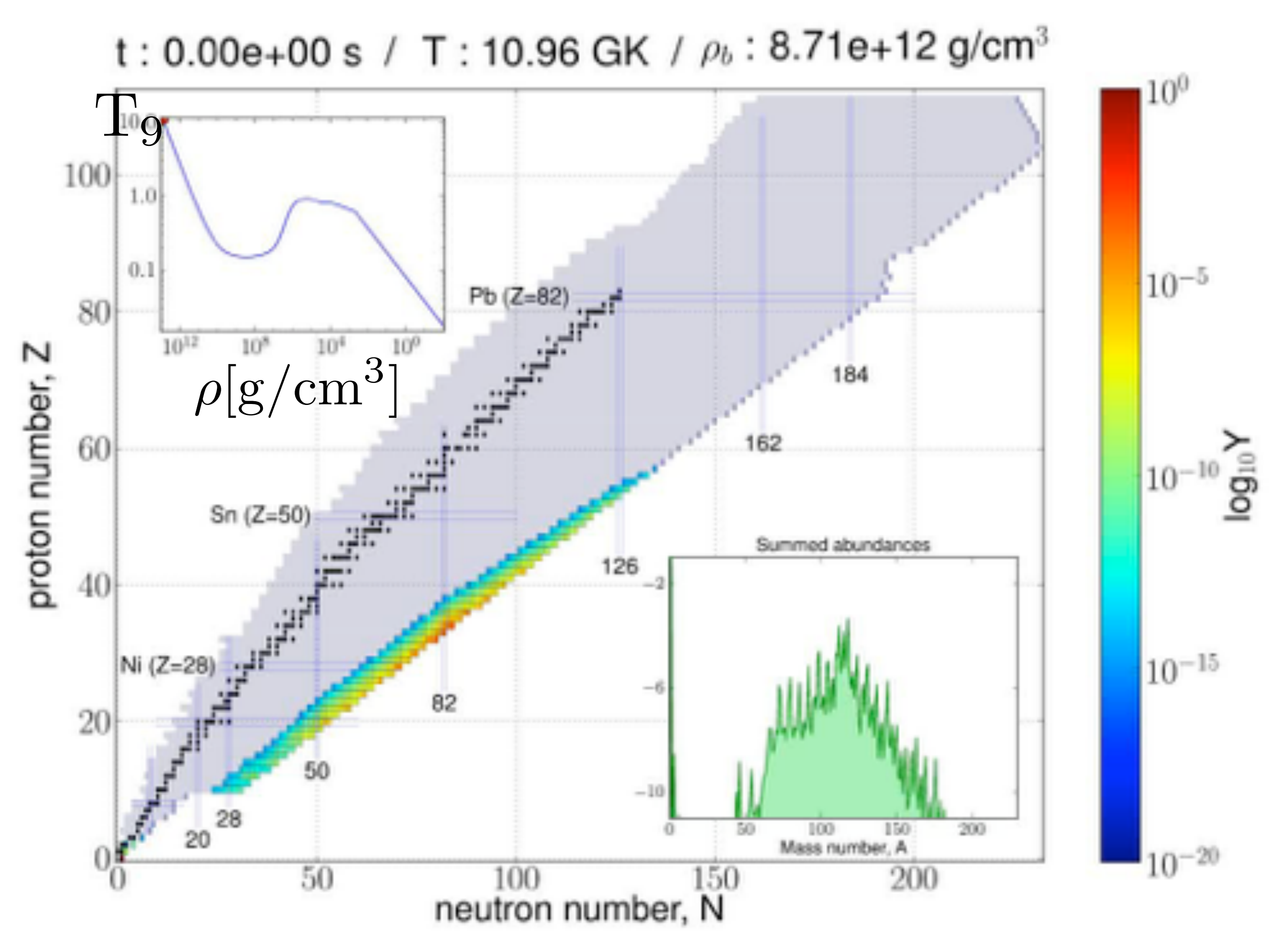
typical numbers:

- mass: ~0.01 $M_\odot$
- velocity: ~ 0.05c
- electron fraction: ~0.2 … 0.4

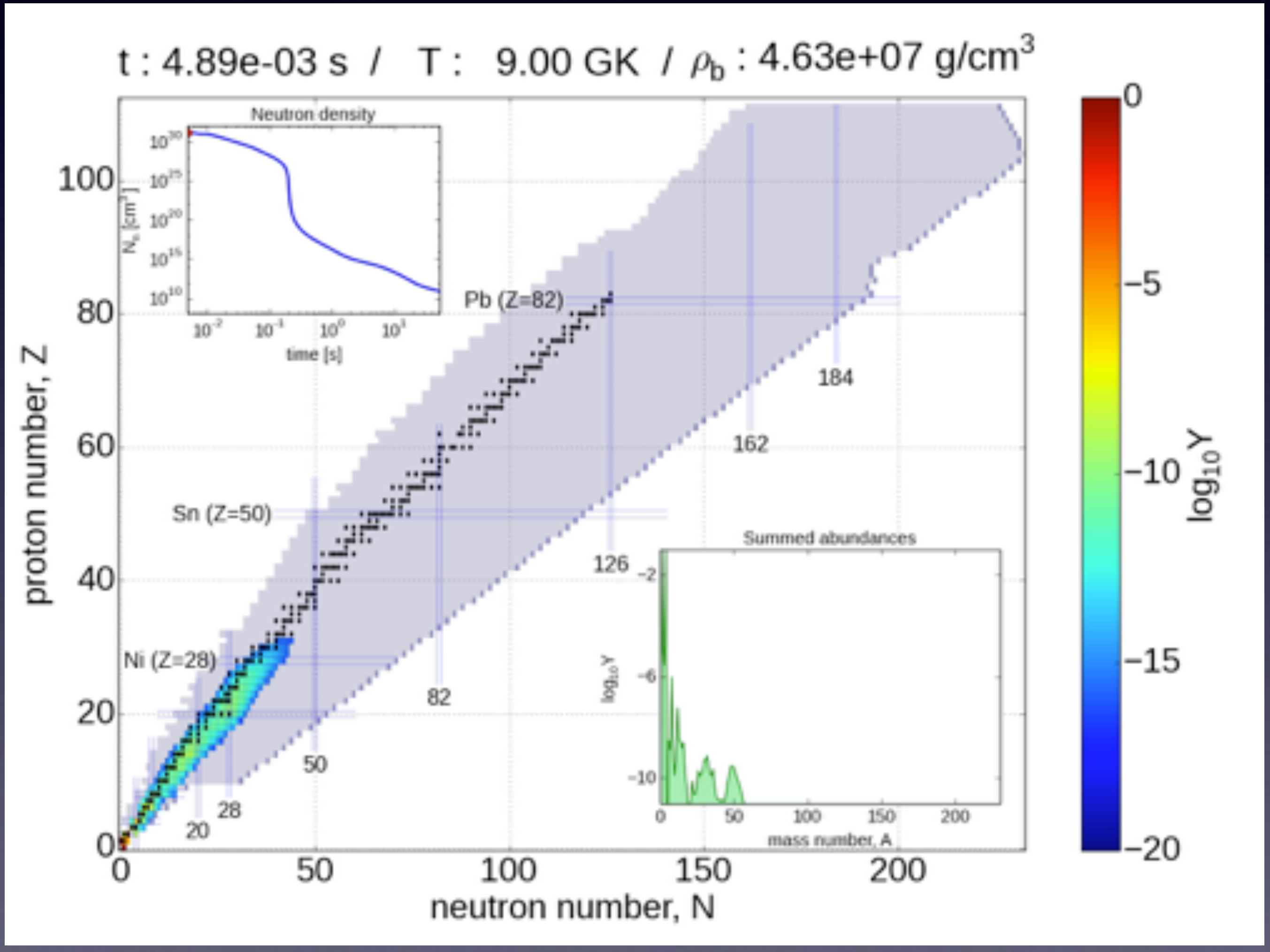
Nucleosynthesis (Winnet network, Winteler 2012; 5 831 isotopes)

very low Ye (= 0.05),
dynamic ejecta

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



(Korobkin, S.R., Arcones, Winteler 2012)

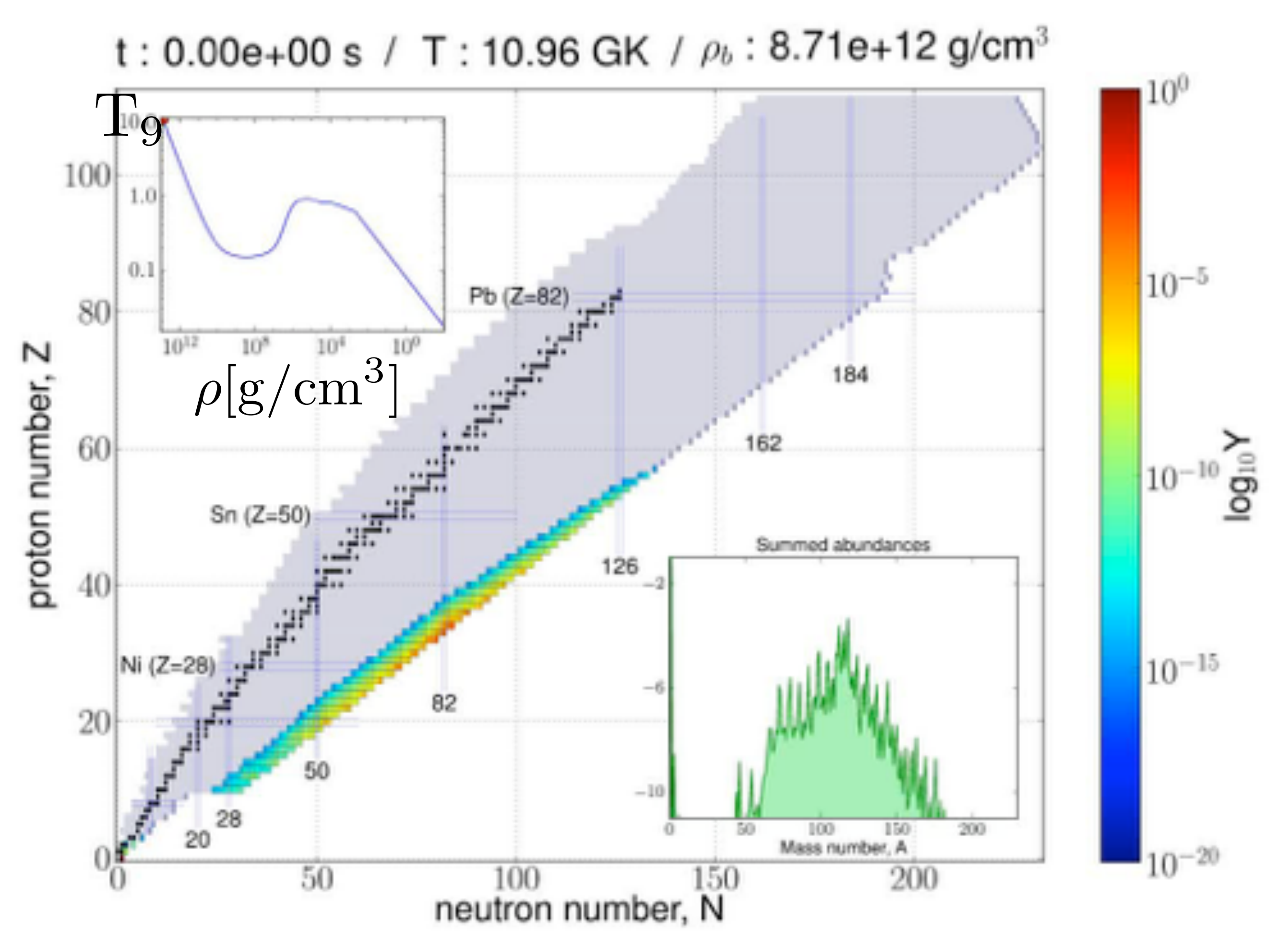


(Martin, Perego, Arcones, Thielemann, Korobkin, S.R. 2014)

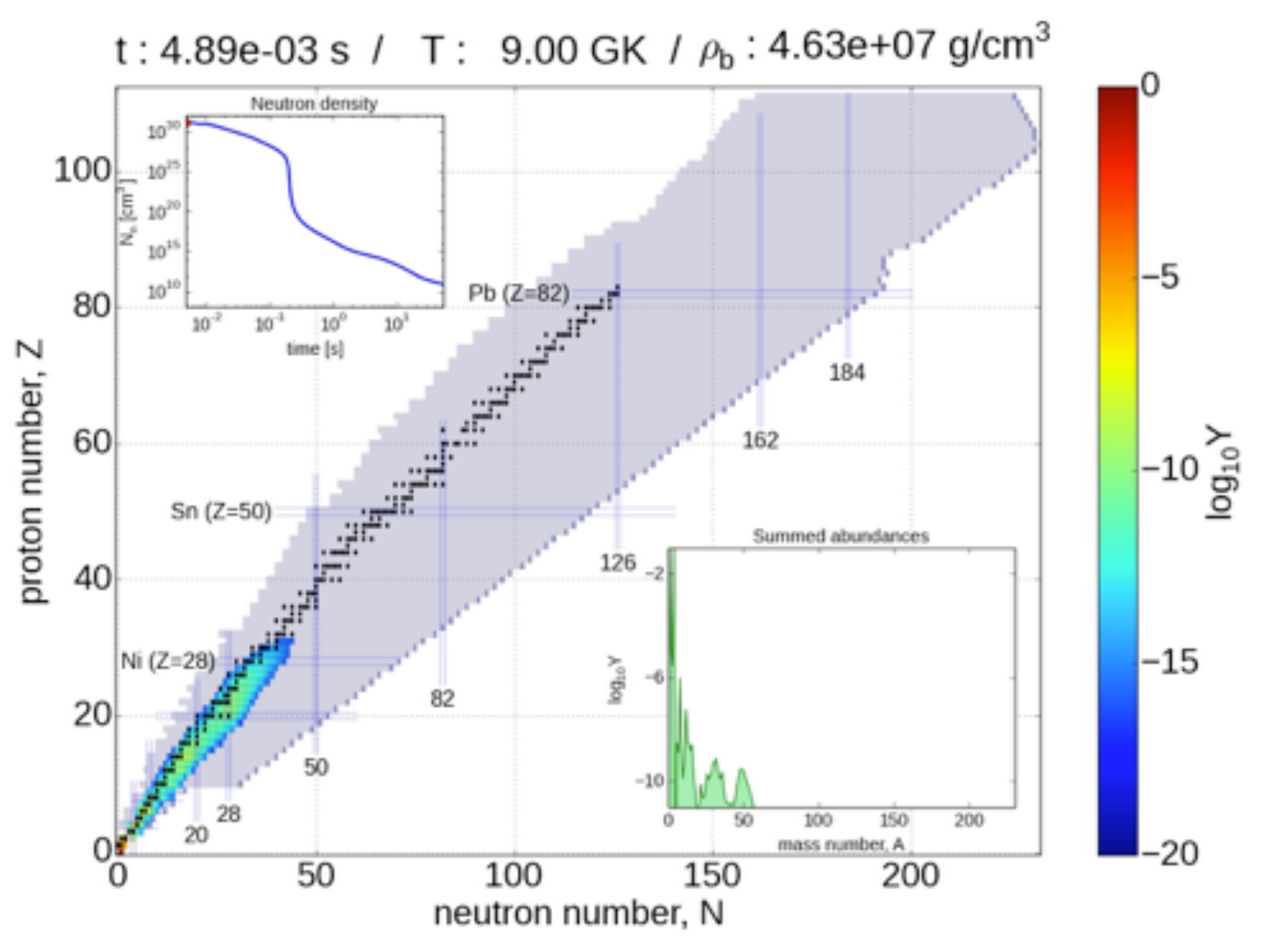
Nucleosynthesis (Winnet network, Winteler 2012; 5 831 isotopes)

very low Ye (= 0.05),
dynamic ejecta

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



(Korobkin, S.R., Arcones, Winteler 2012)

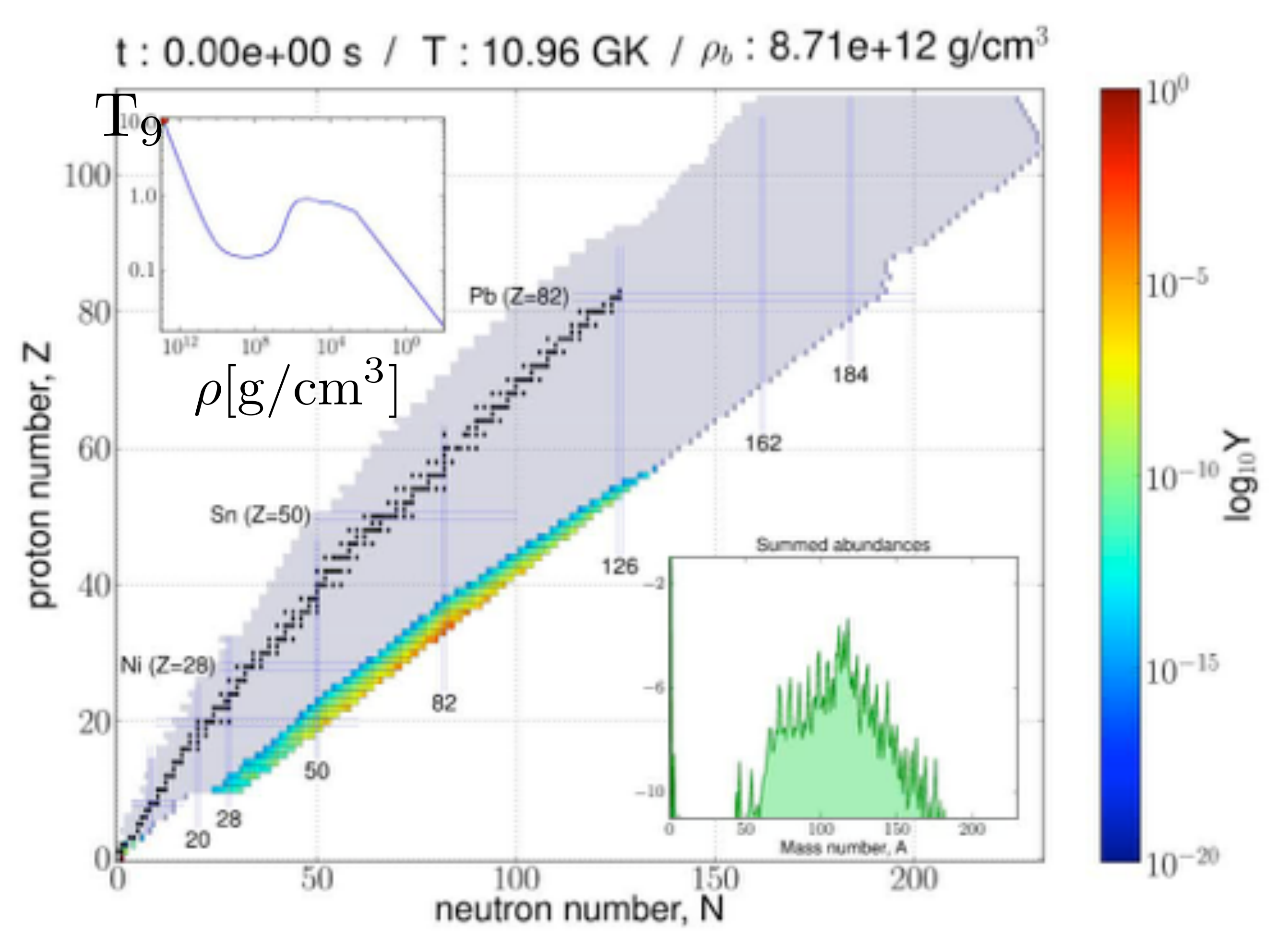


(Martin, Perego, Arcones, Thielemann, Korobkin, S.R. 2014)

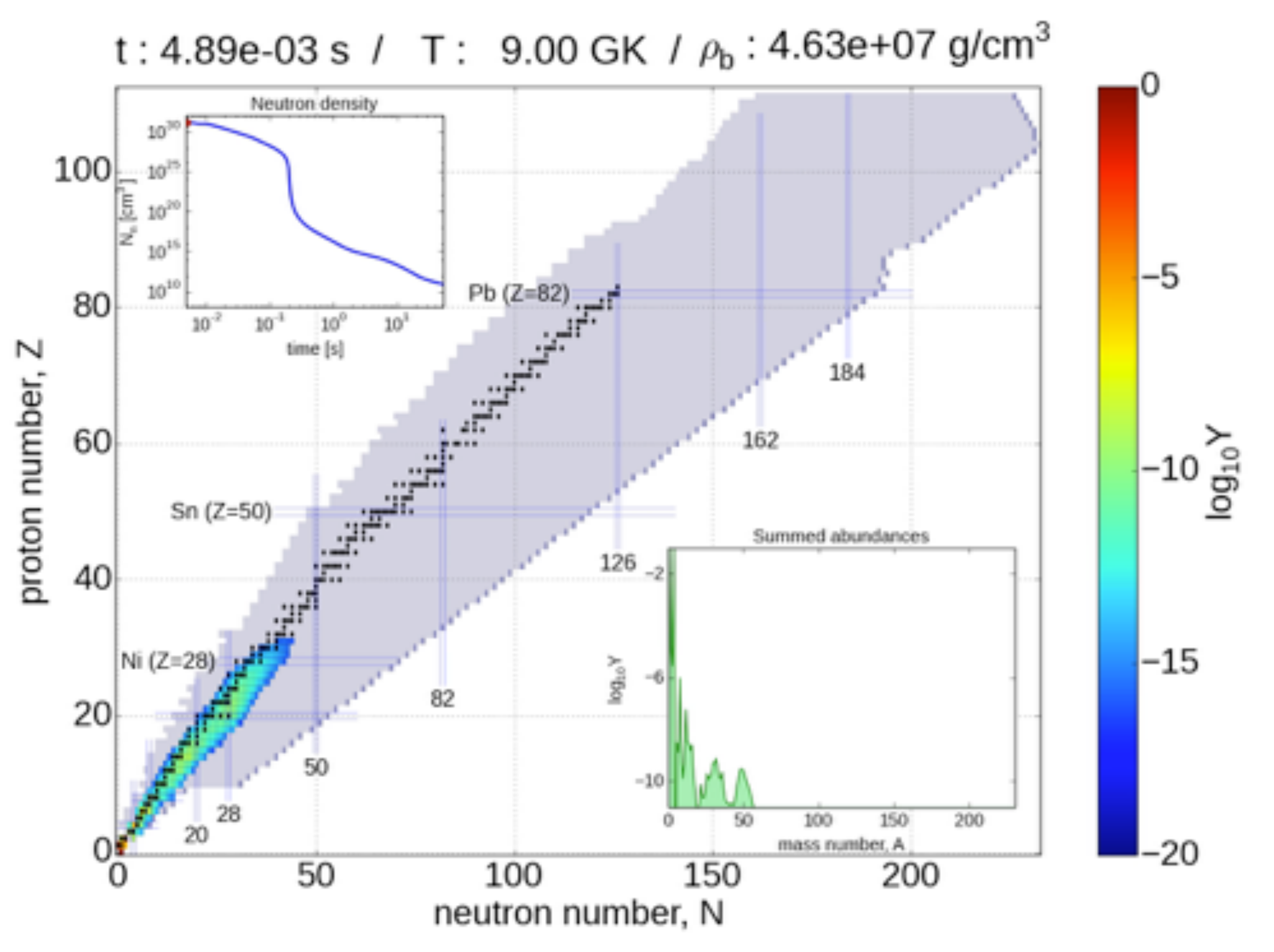
Nucleosynthesis (Winnet network, Winteler 2012; 5 831 isotopes)

very low Ye (= 0.05),
dynamic ejecta

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

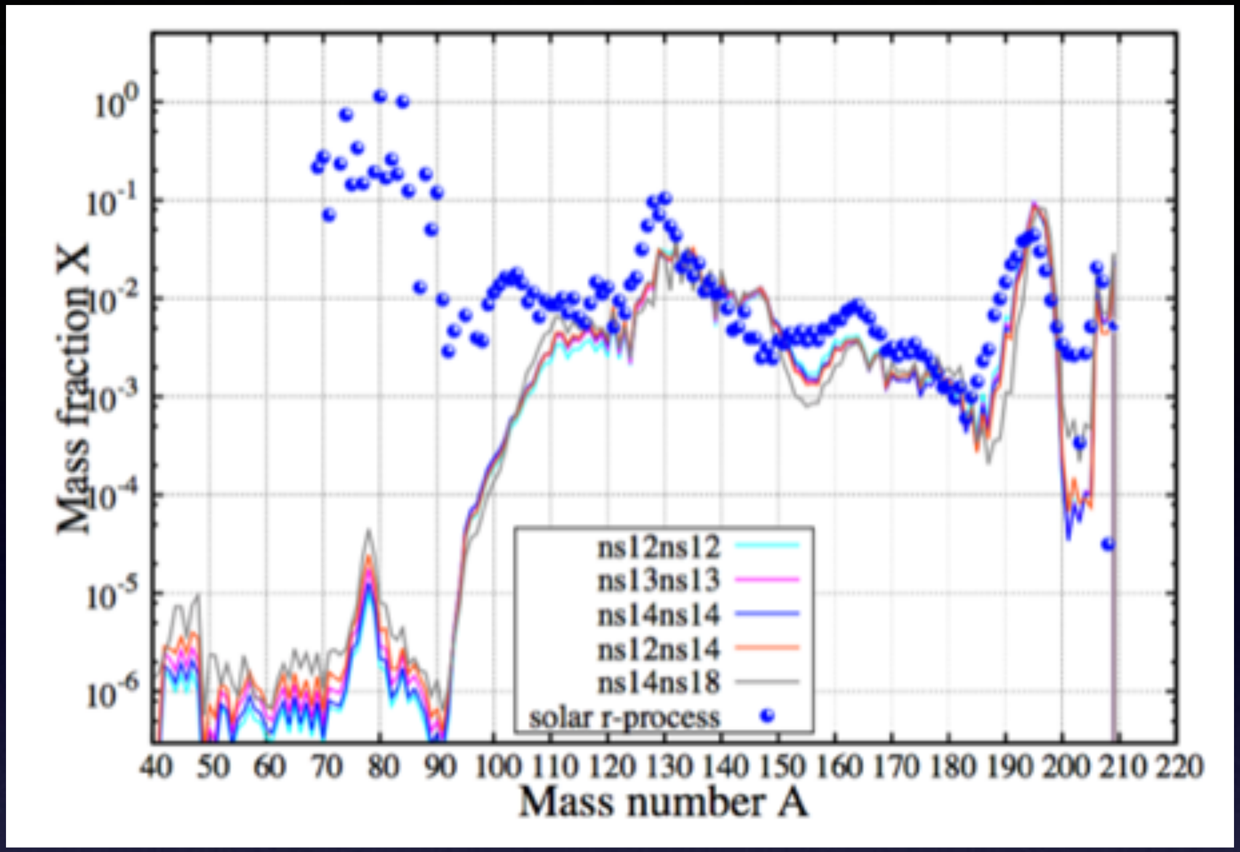


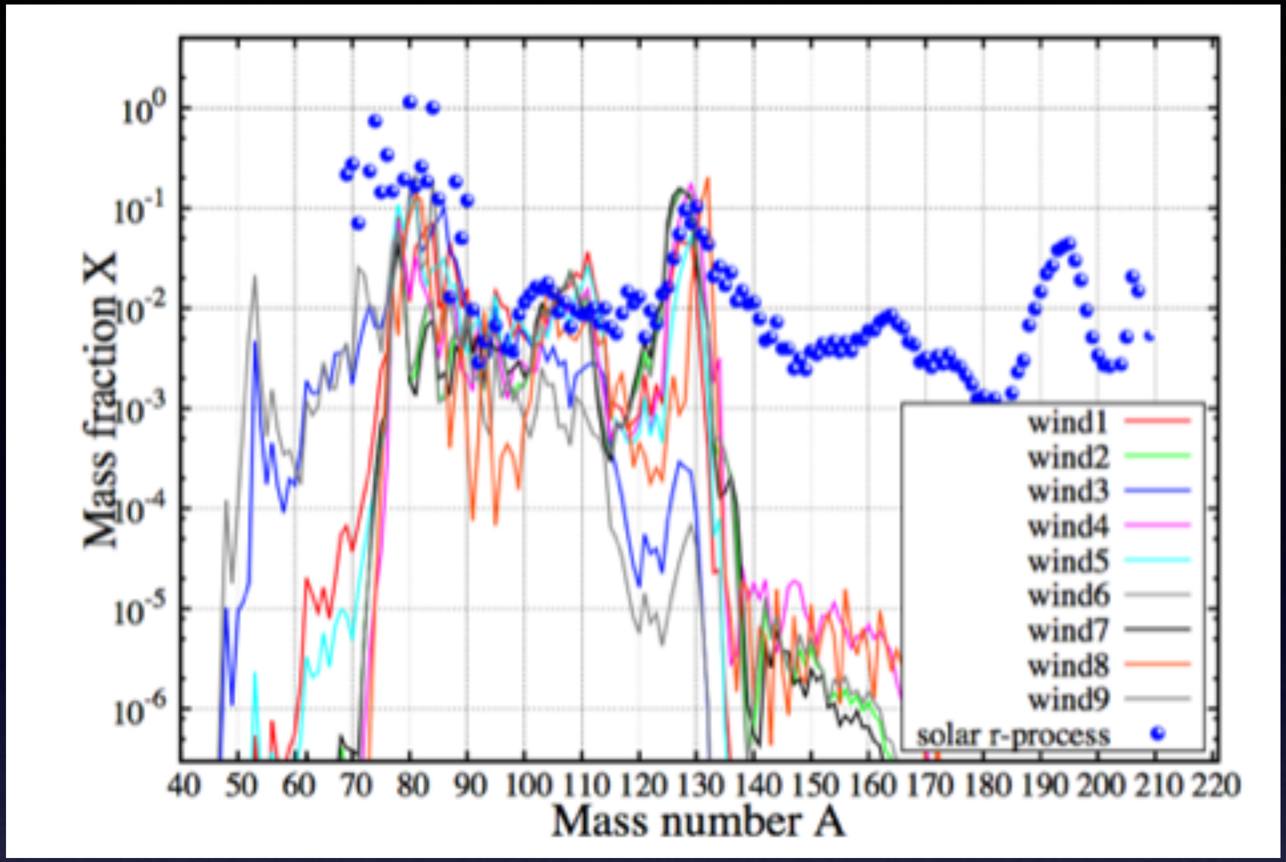
(Korobkin, S.R., Arcones, Winteler 2012)



(Martin, Perego, Arcones, Thielemann, Korobkin, S.R. 2014)

low-Ye dynamic ejecta $Y_e^{\mathrm{crit}} \approx 0.25$ moderately high Ye wind ejecta



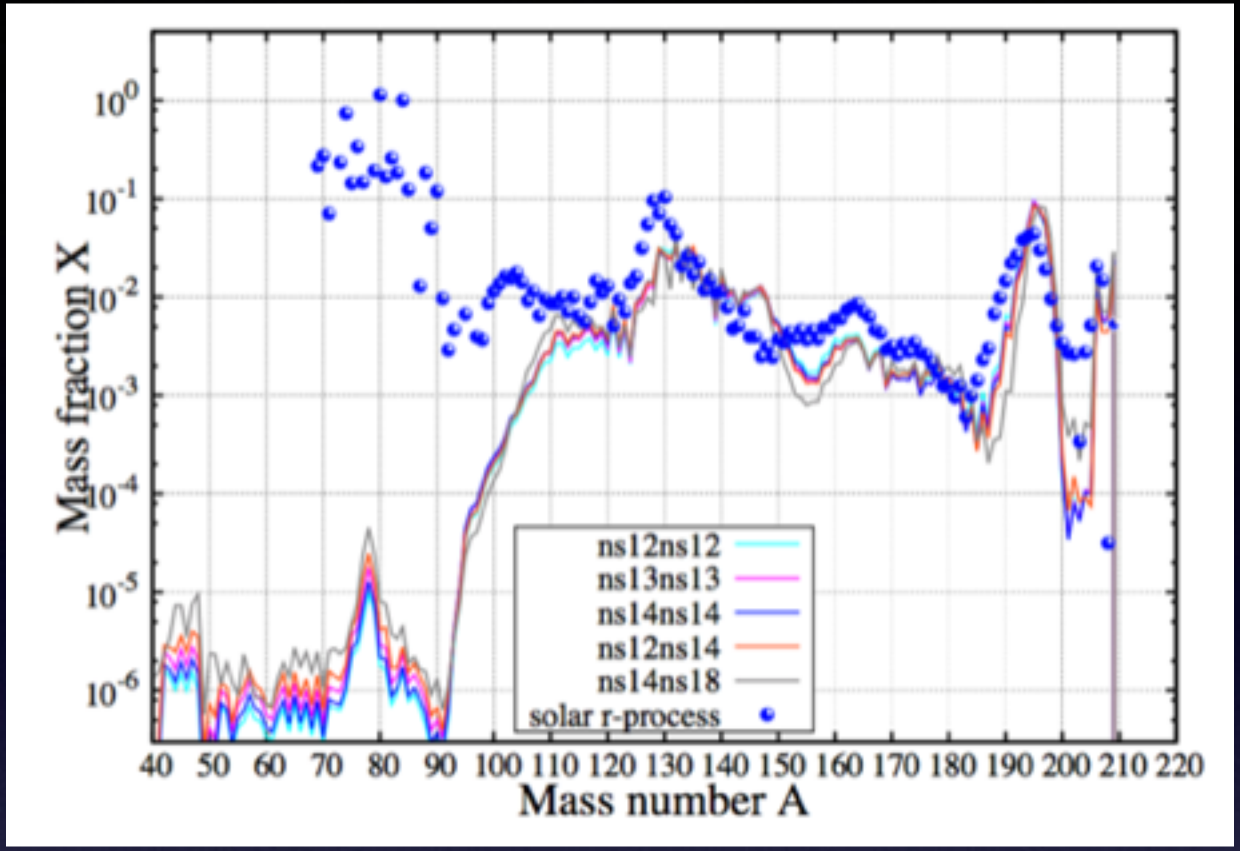


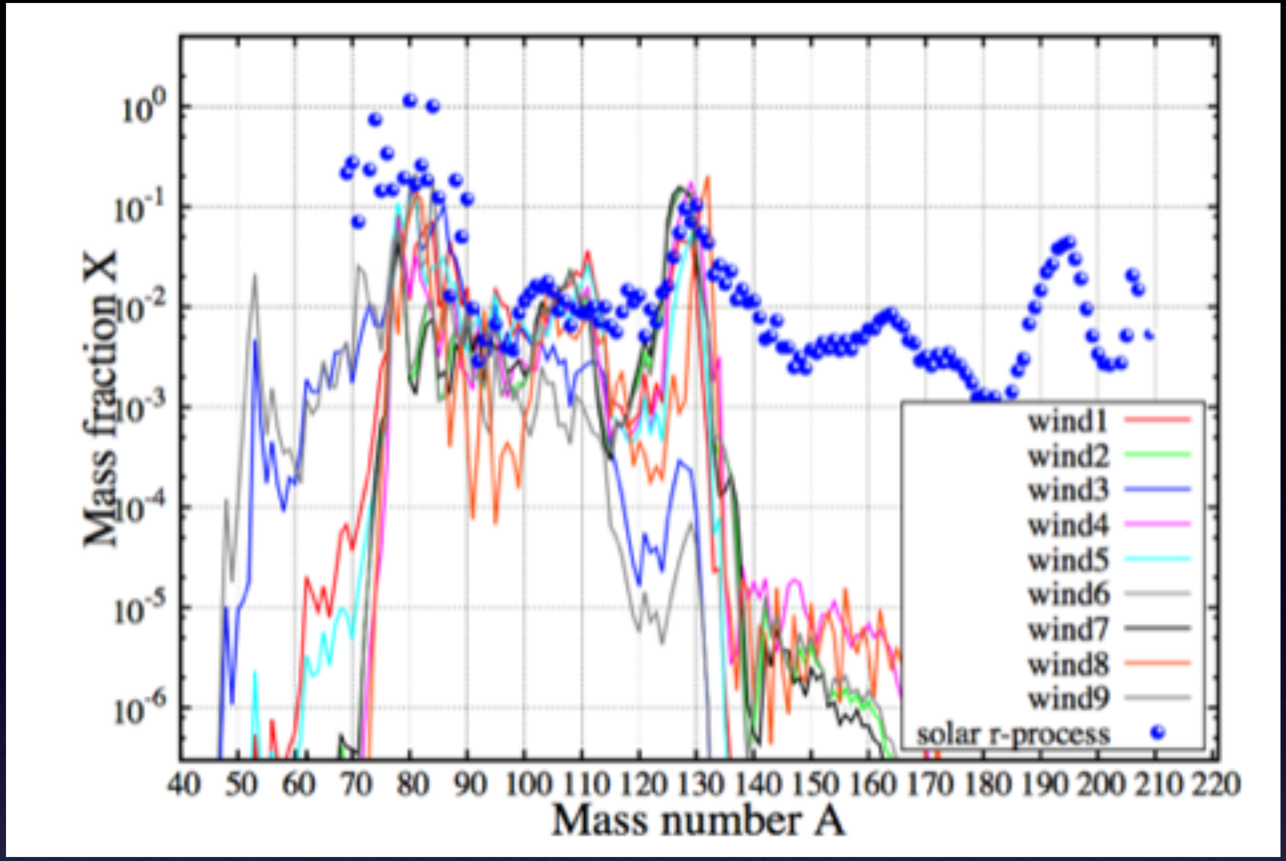
(from S.R.+ 2014)

- (astrophysically) “robust”
- (but not with resp. to nuclear physics)
- “strong”, A ≳ 130
- this robustness is observed in stellar spectra

- sensitive to detailed trajectory
- “weak”, A ≲ 130

low-Ye dynamic ejecta $Y_e^{crit} \approx 0.25$ moderately high Ye wind ejecta





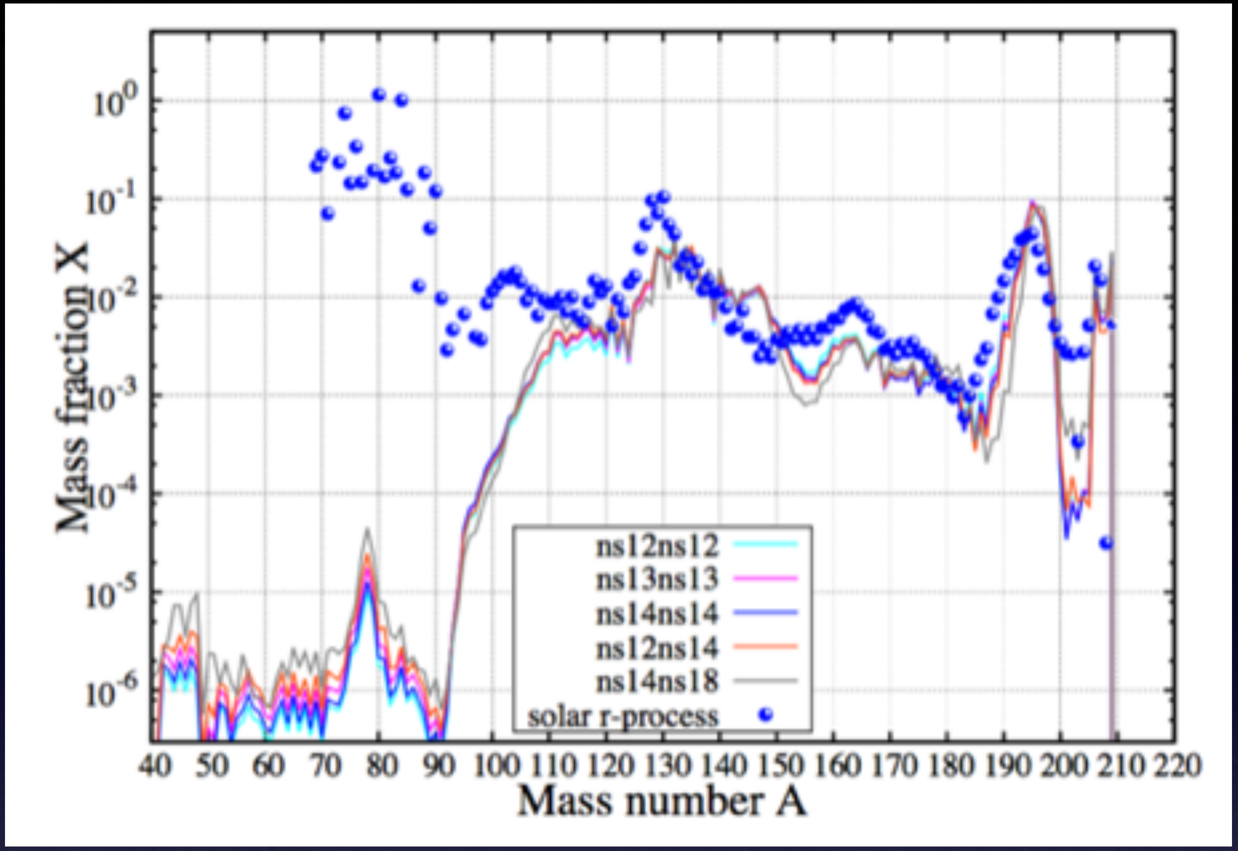
(from S.R.+ 2014)

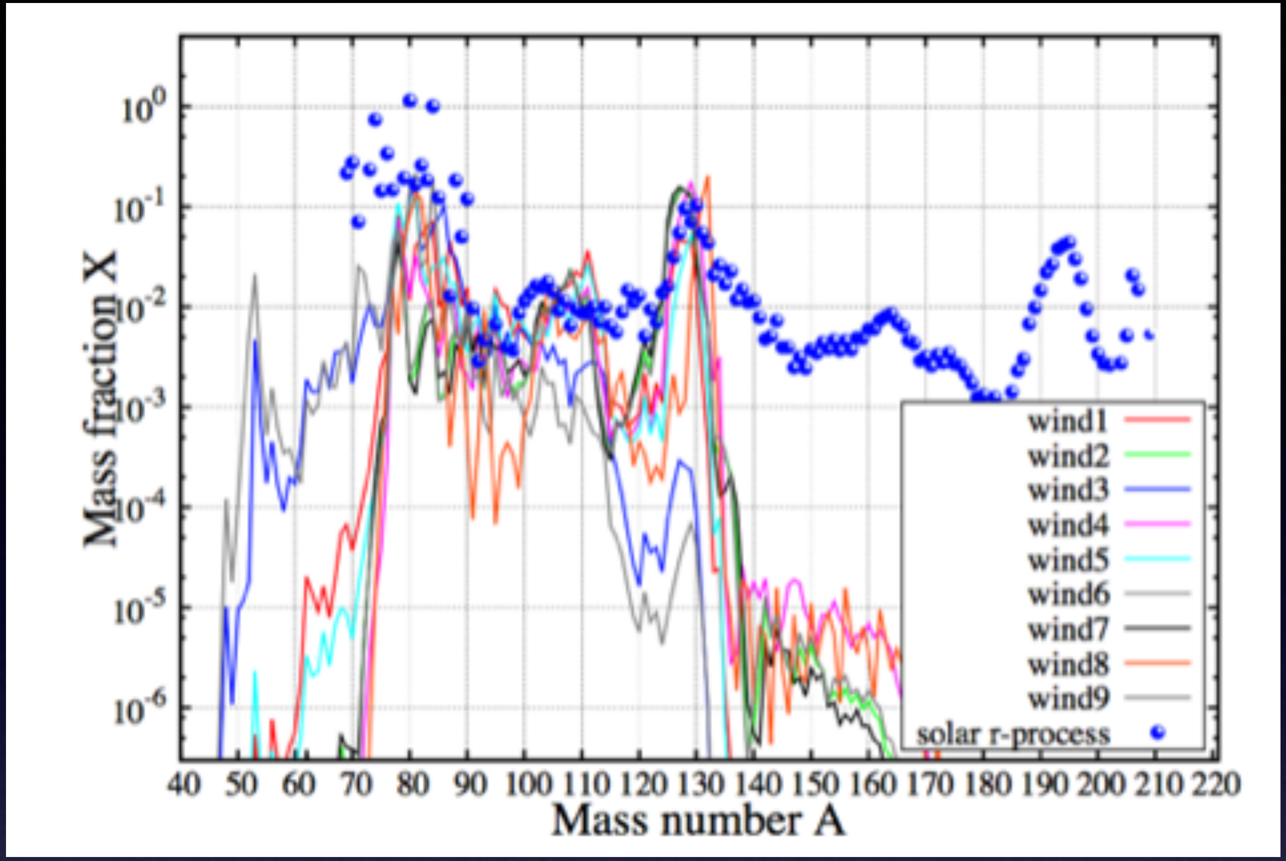
- (astrophysically) “robust”
- (but not with resp. to nuclear physics)
- “strong”, $A \gtrsim 130$
- this robustness is observed in stellar spectra

- sensitive to detailed trajectory
- “weak”, $A \lesssim 130$

⇒ complementary nucleosynthesis

low-Ye dynamic ejecta $Y_e^{crit} \approx 0.25$ moderately high Ye wind ejecta





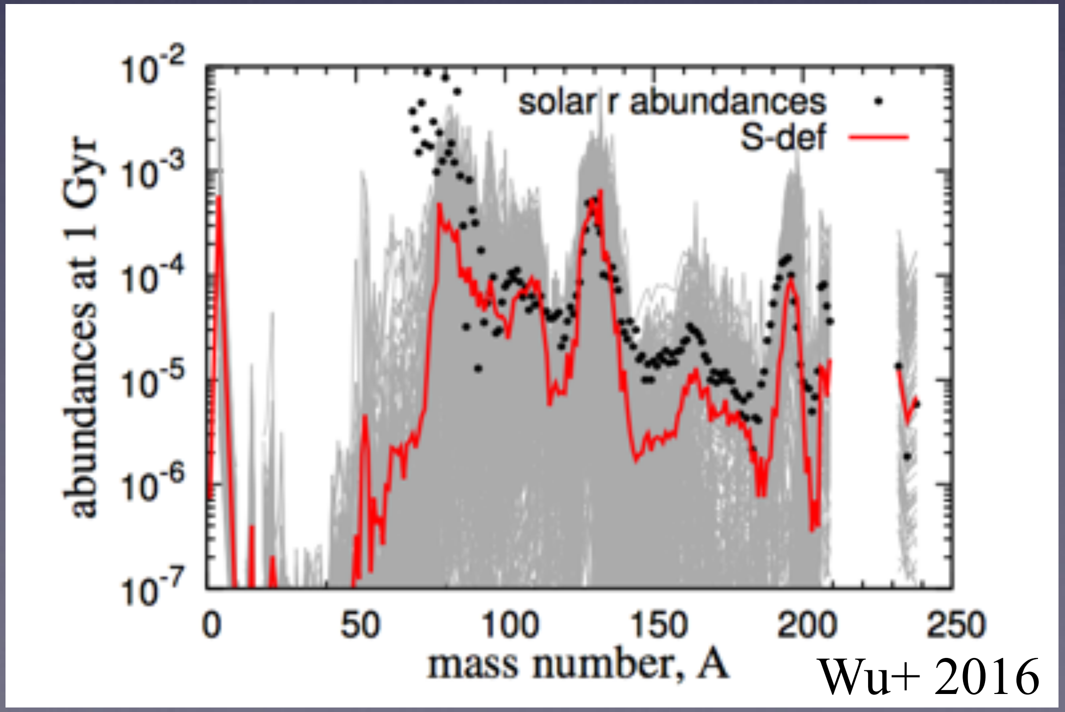
(from S.R.+ 2014)

- (astrophysically) “robust”
- (but not with resp. to nuclear physics)
- “strong”, A ≳ 130
- this robustness is observed in stellar spectra

- sensitive to detailed trajectory
- “weak”, A ≲ 130

⇒ complementary nucleosynthesis

- also found for BH+torus systems
  (e.g. Just+ 15, Wu+ 16, Siegel+17)

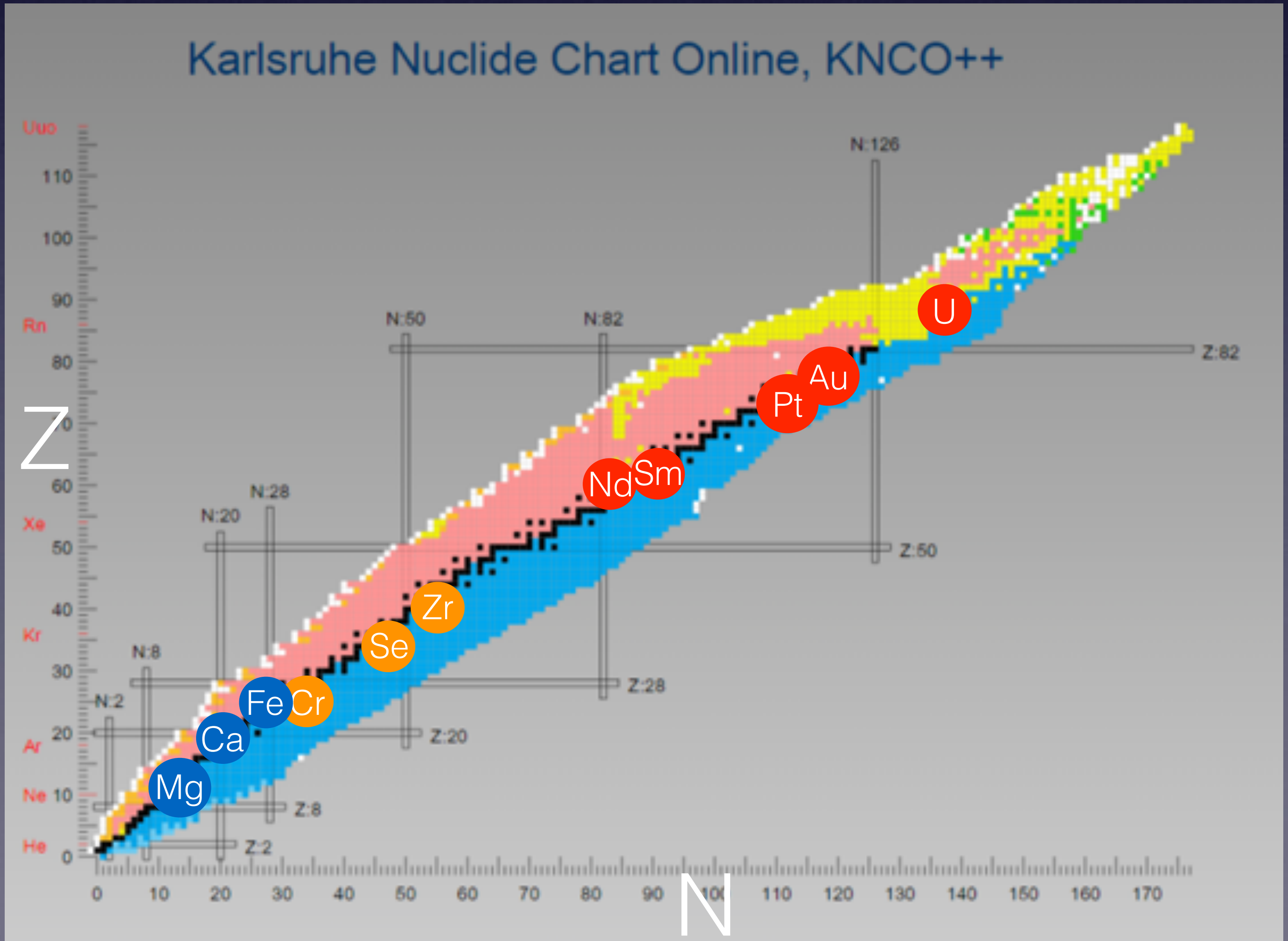


Wu+ 2016

Radioactive decay: macronovae

- similarities to supernovae:
  - expanding, radioactive material

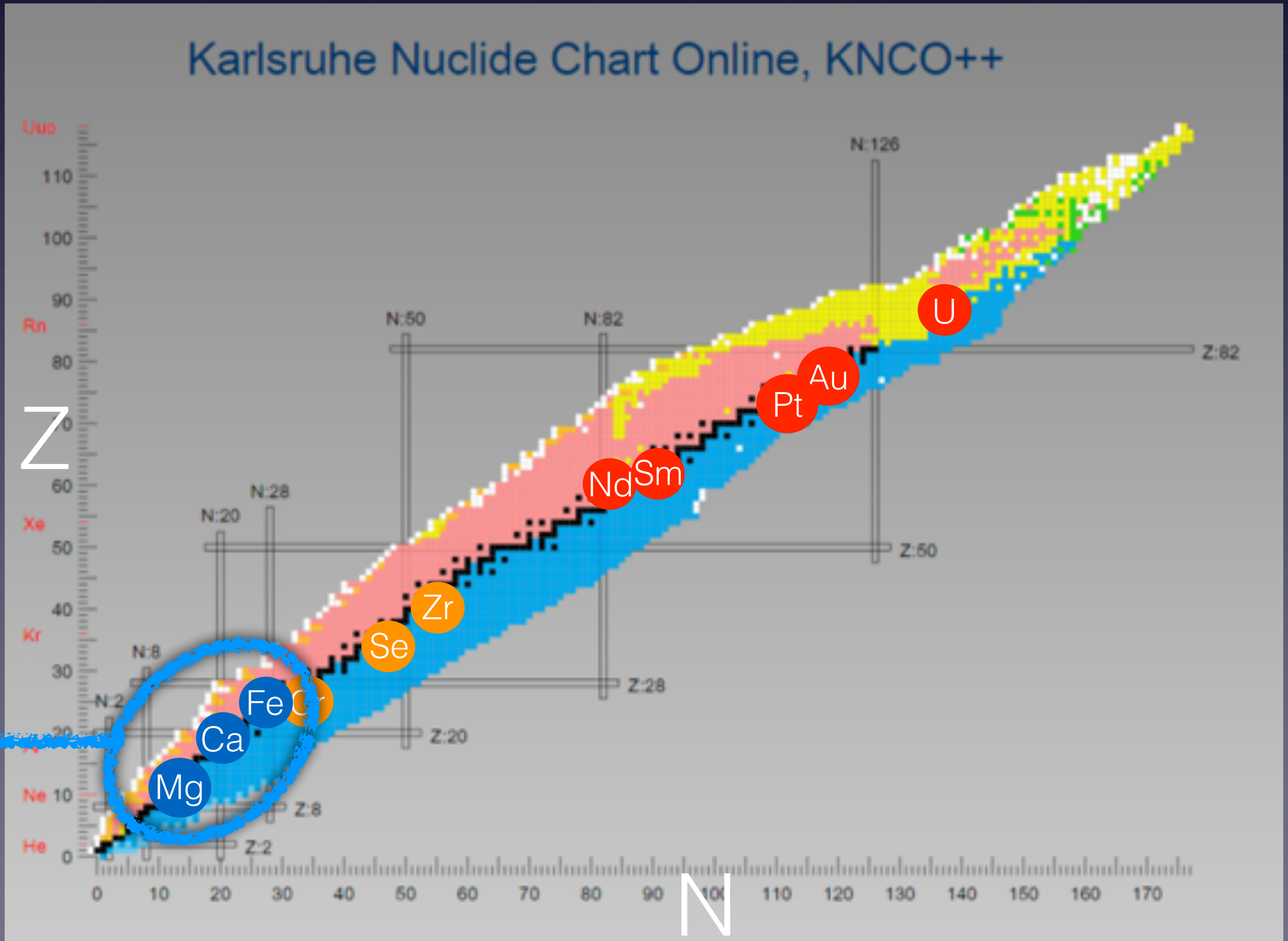
- BUT:
  - less material, ~0.01 $M_\odot$
  - higher velocities, ~0.1 c
  - very different composition:



Radioactive decay: macronovae

- similarities to supernovae:
  - expanding, radioactive material

- BUT:
  - less material, ~0.01 $M_\odot$
  - higher velocities, ~0.1 c
  - very different composition:

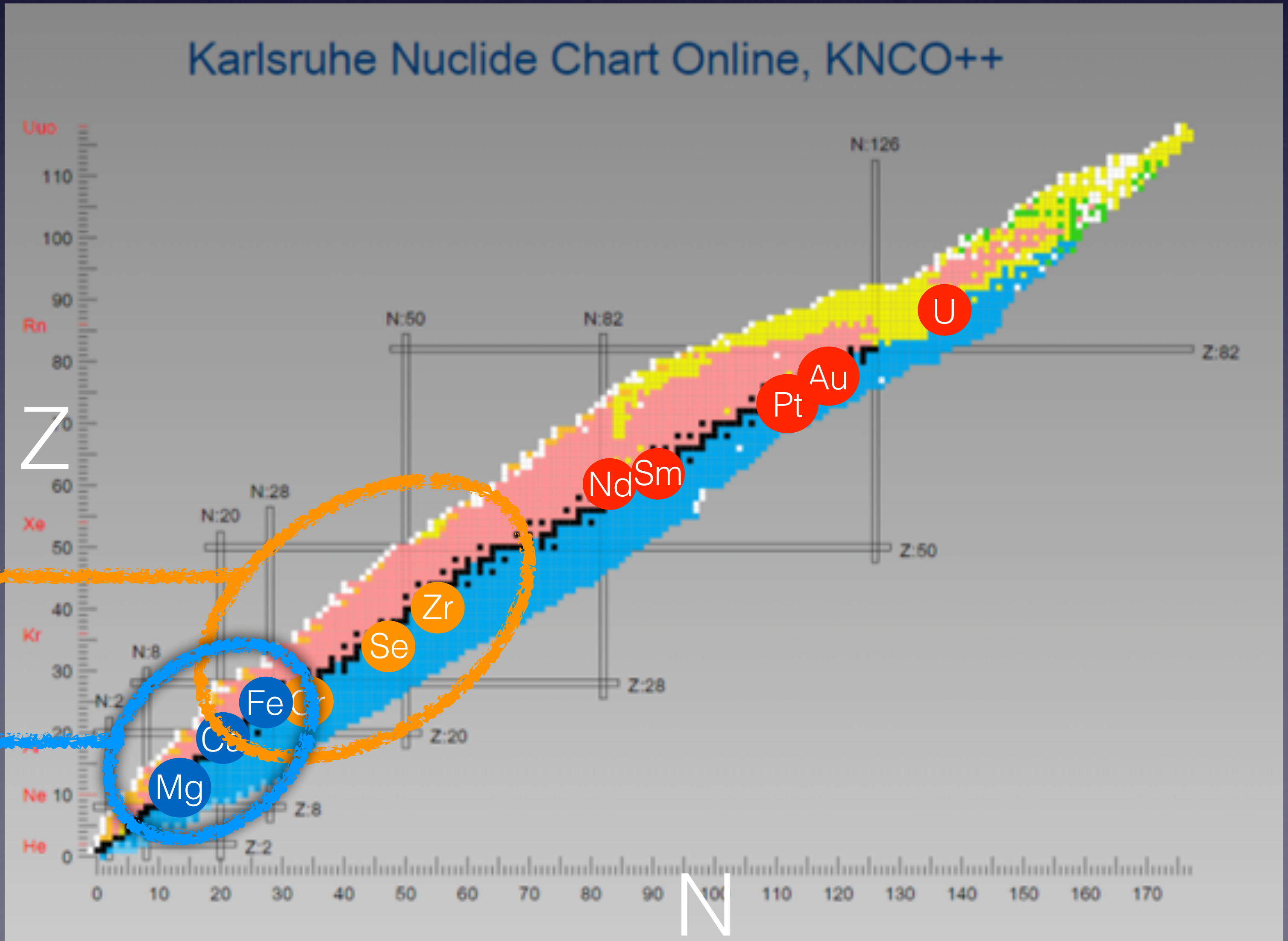


supernovae

Radioactive decay: macronovae

- similarities to supernovae:
  - expanding, radioactive material

- BUT:
  - less material, ~0.01 M☉
  - higher velocities, ~0.1 c
  - very different composition:



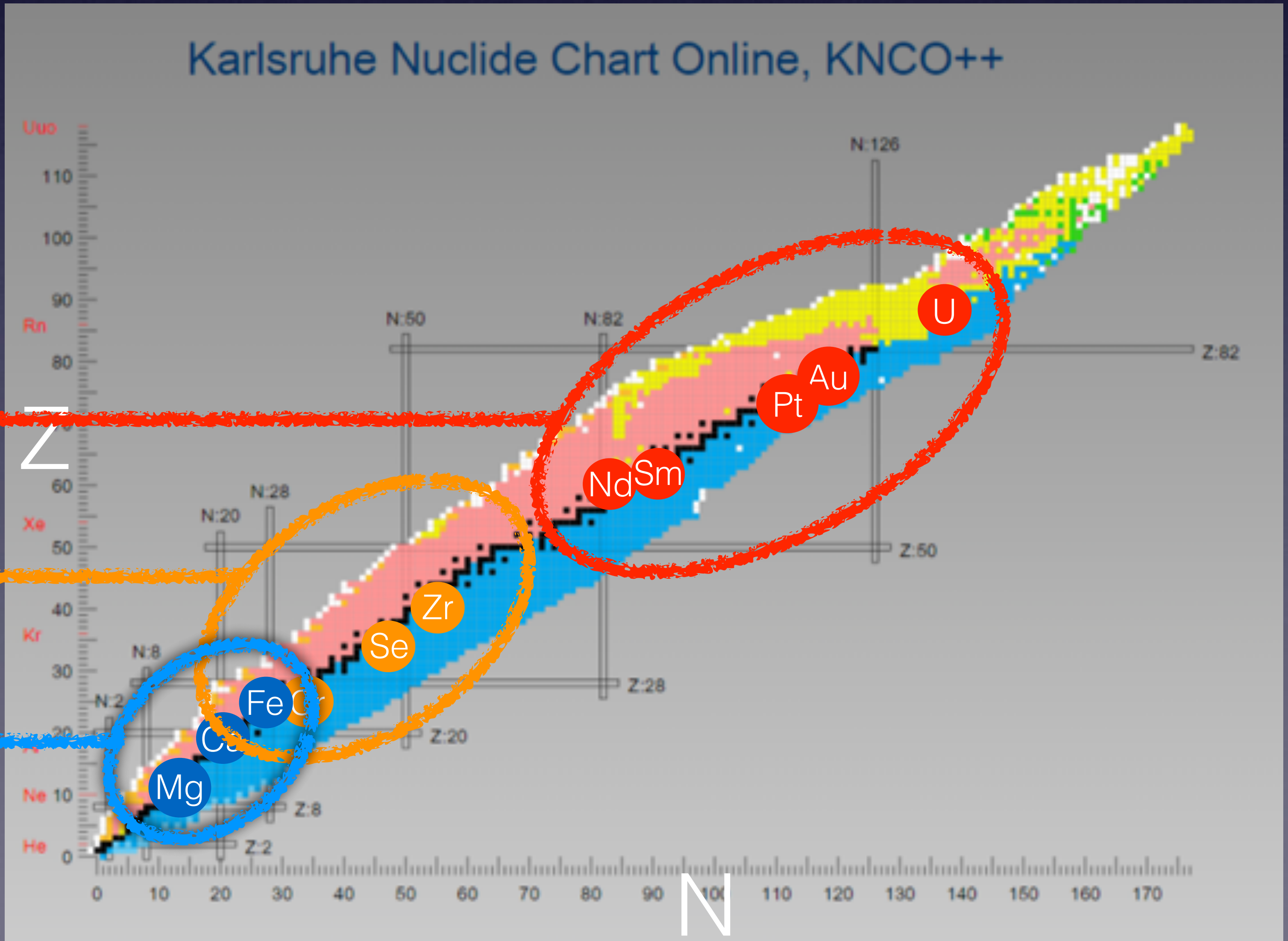
“winds”

supernovae

Radioactive decay: macronovae

- similarities to supernovae:
  - expanding, radioactive material

- BUT:
  - less material, ~0.01 M⊙
  - higher velocities, ~0.1 c
  - very different composition:



“dynamic ejecta”

“winds”

supernovae

Scaling relations

M

v (free expansion: $R= v\, t$)

κ opacity, assumed const.

Scaling relations

M

v (free expansion: R= v t)

κ opacity, assumed const.

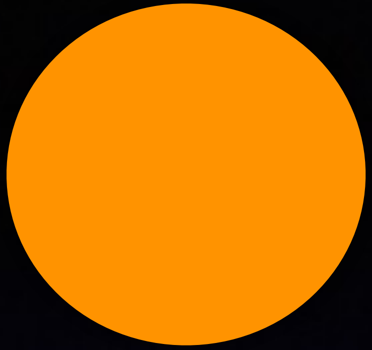
- optical depth: $\tau = R\kappa\rho$
- diffusion time: $t_{\rm diff} = \frac{R}{c}\,\tau$
- peak emission when $t_{\rm diff} = t_{\rm expansion}$ yields
  (Arnett 1980)

$$t_{\rm peak} = \left[\frac{3}{4\pi}\,\frac{M\kappa}{vc}\right]^{\frac{1}{2}}$$

- photospheric temperature evolution

$$T(t) \approx \left[\frac{fM\dot{Q}}{\sigma_{\rm SB}v^2t^2}\right]^{1/4}$$

Scaling relations



M

v (free expansion: R= v t)

κ opacity, assumed const.

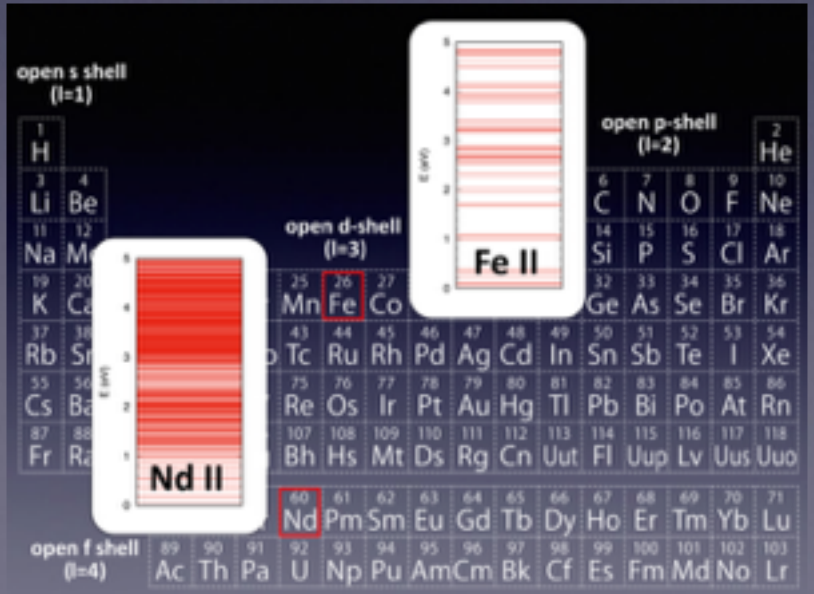
- optical depth: $\tau = R\kappa\rho$
- diffusion time: $t_{\rm diff} = \frac{R}{c}\tau$
- peak emission when $t_{\rm diff} = t_{\rm expansion}$ yields
  (Arnett 1980)

$$t_{\rm peak} = \left[\frac{3}{4\pi}\,\frac{M\kappa}{vc}\right]^{\frac{1}{2}}$$

- photospheric temperature evolution

$$T(t) \approx \left[\frac{f M \dot{Q}}{\sigma_{\rm SB} v^2 t^2}\right]^{1/4}$$

- opacities κ (e.g. Kasen 2013):
  - determined by density of lines
  - for SN-material: κ≈ 0.1 cm^2/g
  - for heavy r-process: κ≈ 10 cm^2/g



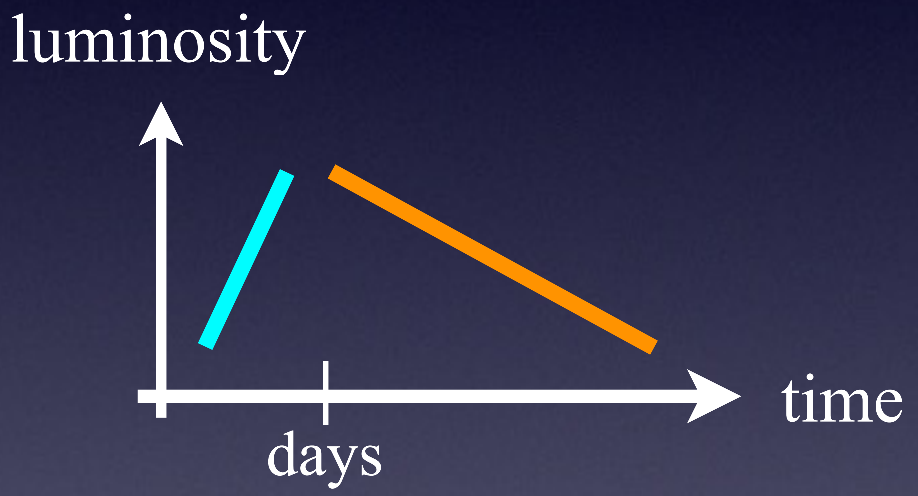
courtesy M. Tanaka

- expectation: $Y_e < 0.25$
  - “heavy r-process” (A>130)
  - “red transients” peaking after ~1 week

  $Y_e > 0.25$
  - “light r-process” (A<130)
  - “blue transients” peaking after ~1 day

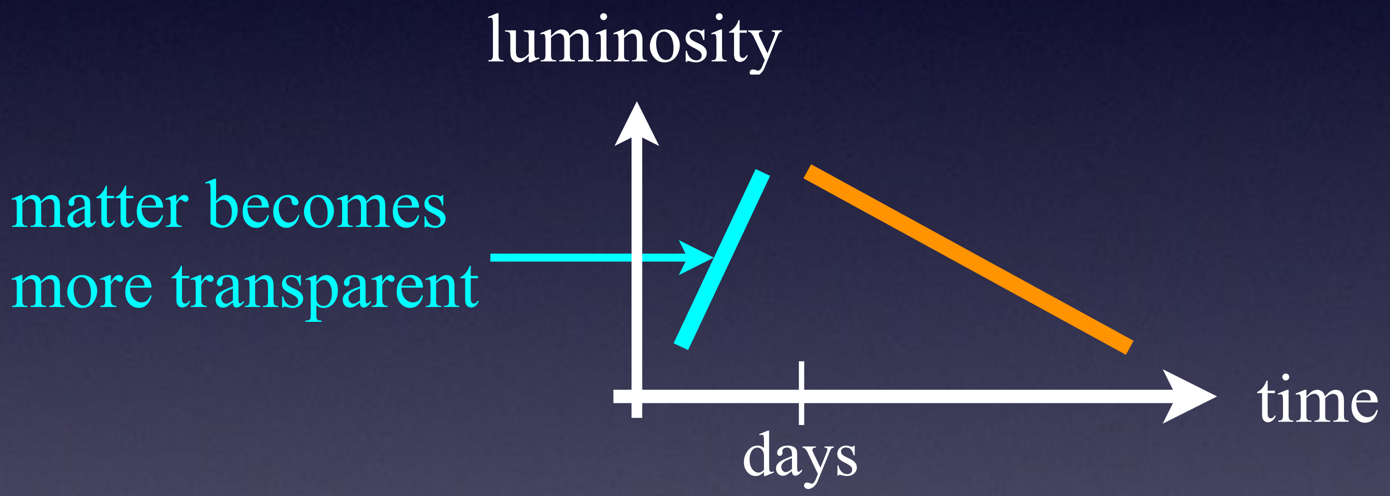
- expectation: $Y_e < 0.25$
  - “heavy r-process” (A>130)
  - “red transients” peaking after ~1 week

  $Y_e > 0.25$
  - “light r-process” (A<130)
  - “blue transients” peaking after ~1 day



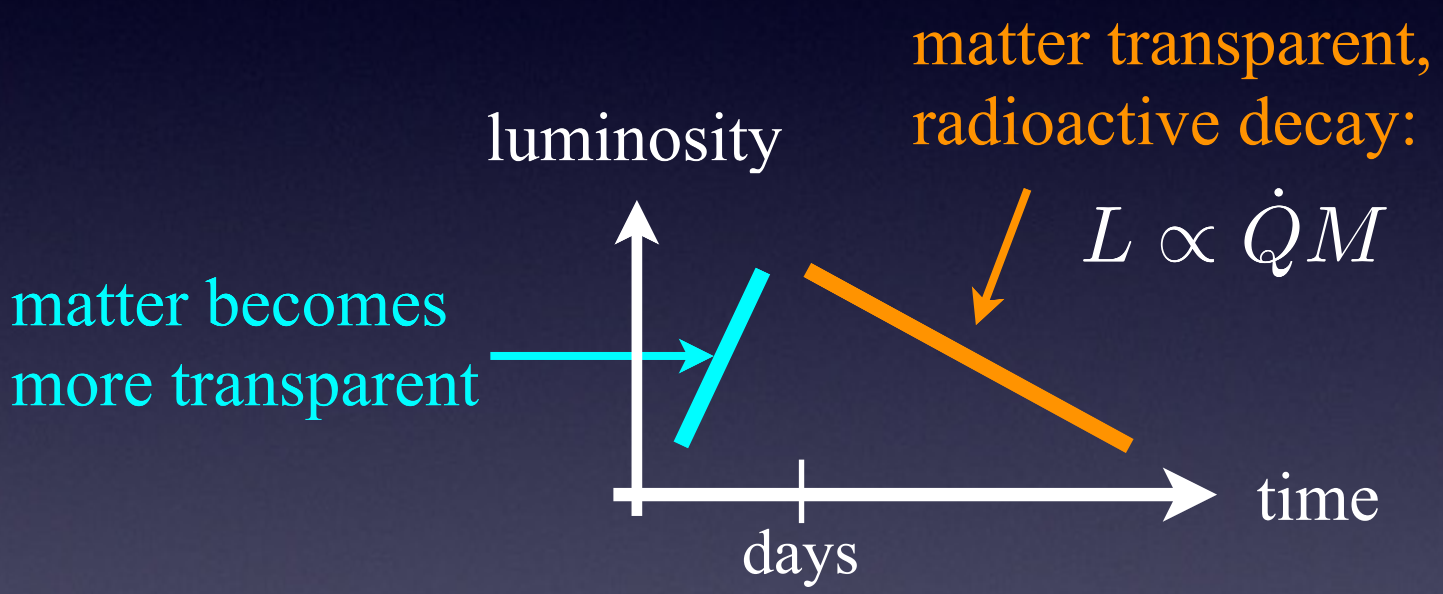
- expectation: $Y_e < 0.25$
  - “heavy r-process” ($A>130$)
  - “red transients” peaking after ~1 week

  $Y_e > 0.25$
  - “light r-process” ($A<130$)
  - “blue transients” peaking after ~1 day



matter becomes more transparent

- expectation:
  - $Y_e < 0.25$
    - “heavy r-process” ($A>130$)
    - “red transients” peaking after ~1 week
  - $Y_e > 0.25$
    - “light r-process” ($A<130$)
    - “blue transients” peaking after ~1 day



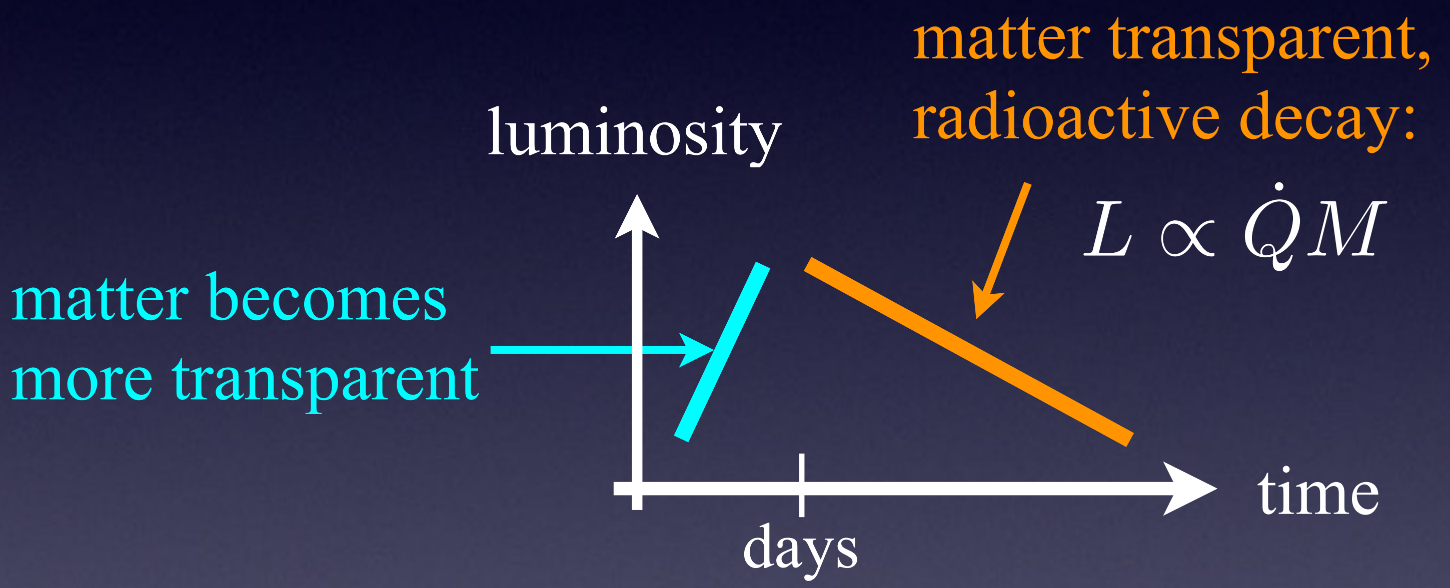
matter transparent,
radioactive decay:

$$L \propto \dot{Q} M$$

matter becomes
more transparent

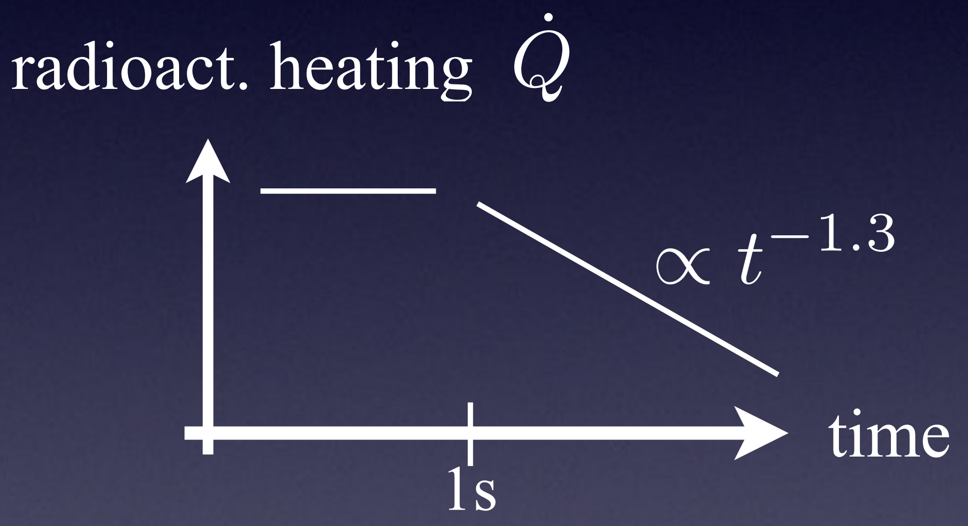
- expectation: $Y_e < 0.25$
  - “heavy r-process” (A>130)
  - “red transients” peaking after ~1 week

  $Y_e > 0.25$
  - “light r-process” (A<130)
  - “blue transients” peaking after ~1 day


matter transparent, radioactive decay:

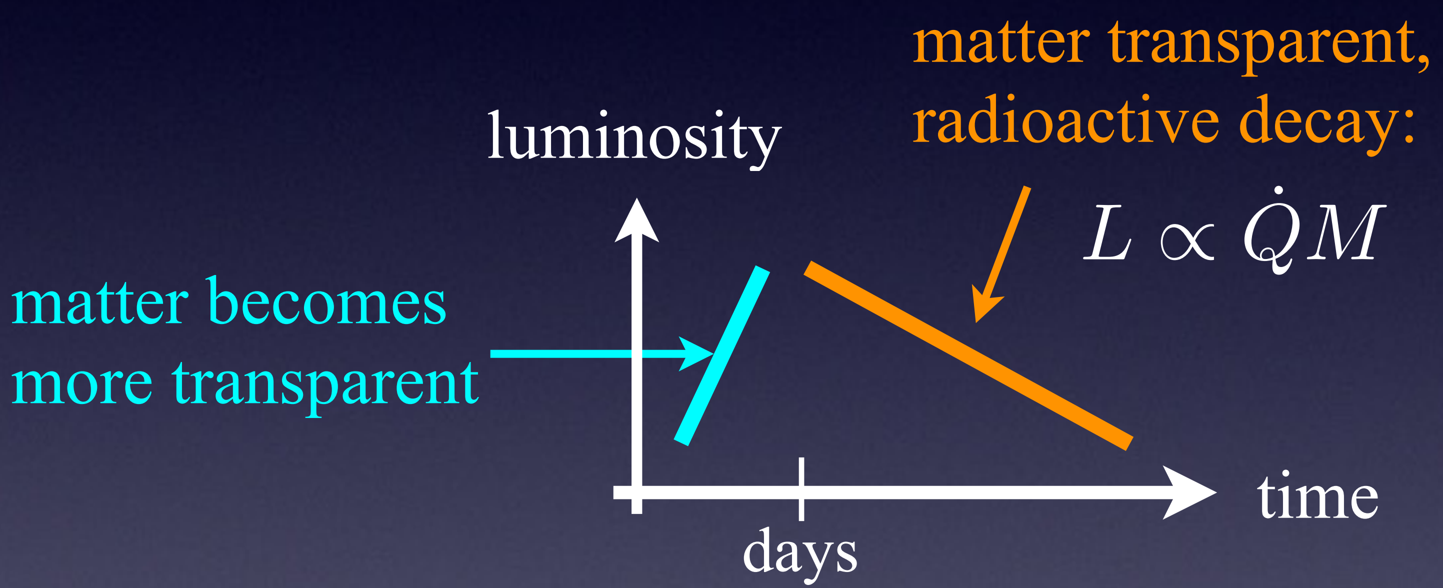
$L \propto \dot{Q} M$

matter becomes more transparent



- expectation: $Y_e < 0.25$
  - "heavy r-process" ($A>130$)
  - "red transients" peaking after $\sim$1 week

  $Y_e > 0.25$
  - "light r-process" ($A<130$)
  - "blue transients" peaking after $\sim$1 day



matter transparent,
radioactive decay:

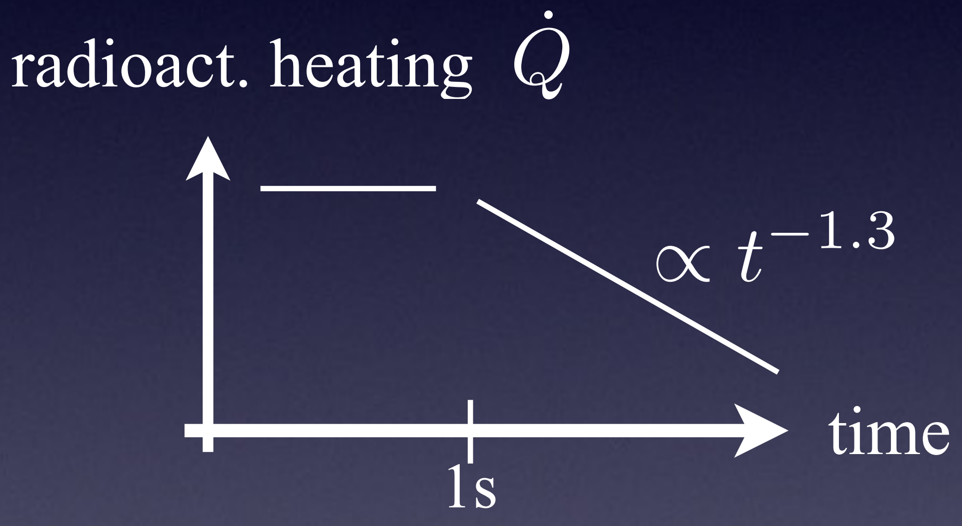
$L \propto \dot{Q} M$

luminosity

matter becomes
more transparent

time

days



radioact. heating $\dot{Q}$

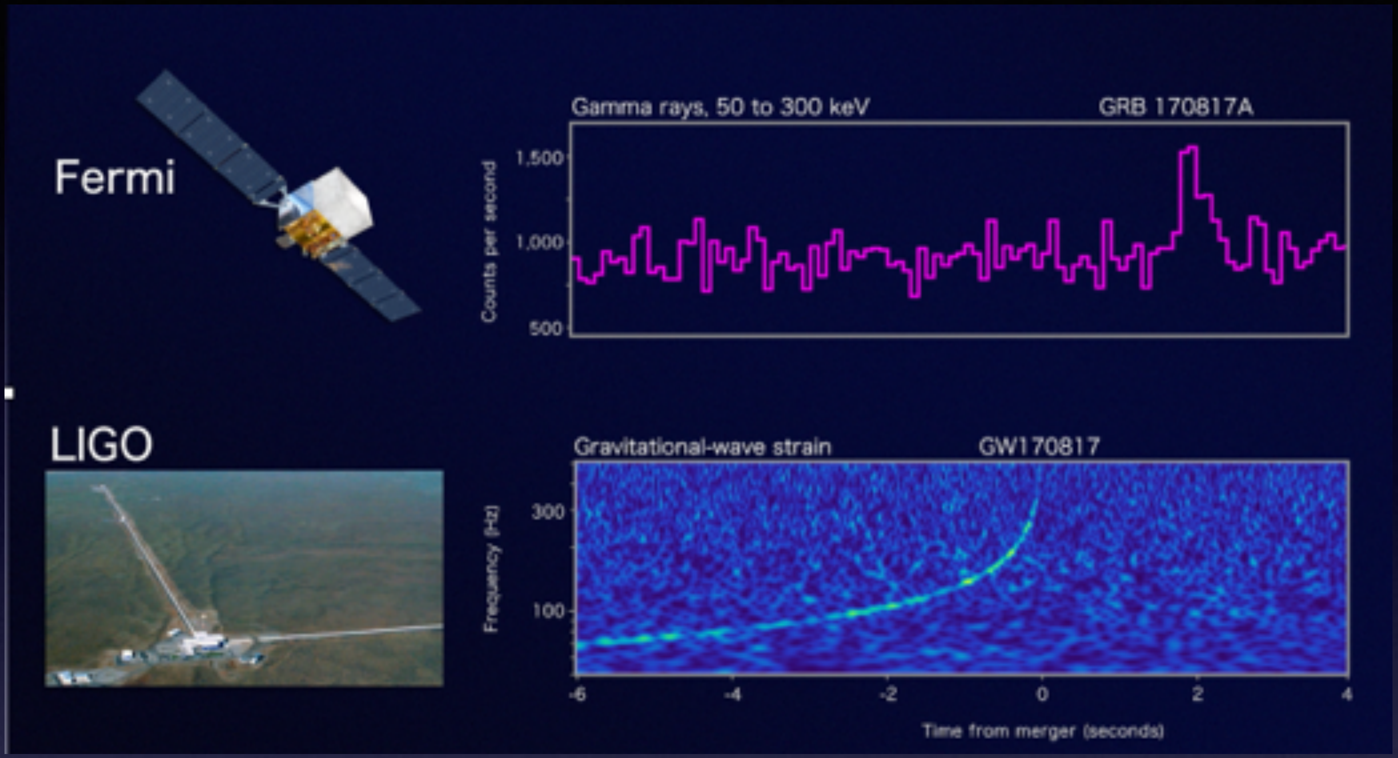
$\propto t^{-1.3}$

time

1s

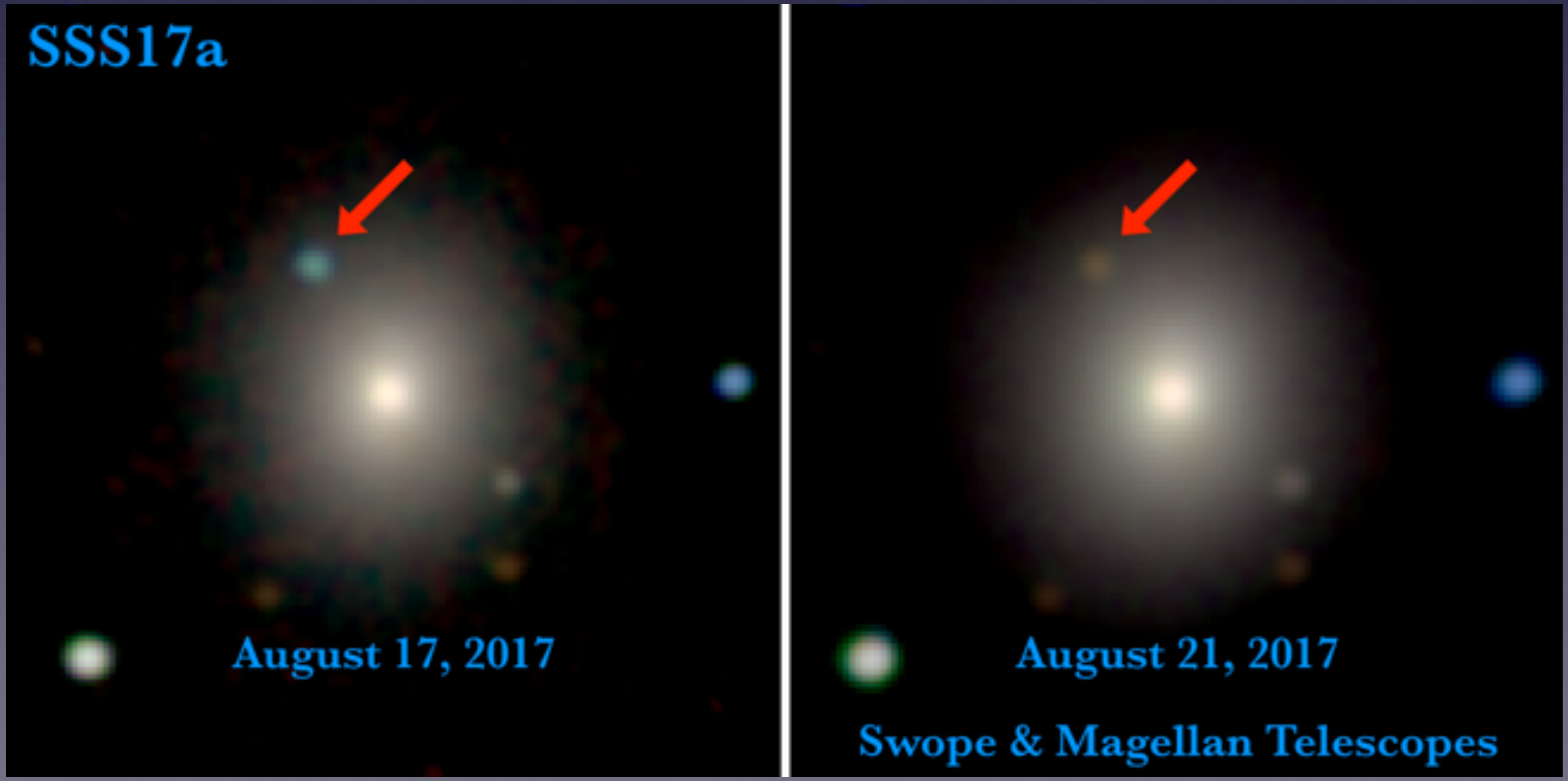
- key physics ingredients:
  - ejecta mass, velocity, Ye ⇒ astrophysics
  - opacity κ ⇒ atomic physics
  - radioactive heating rate $\dot{Q}$ ⇒ nuclear physics

GW/EM 170817: Beginning of the Multi-Messenger Era



γ-rays (“std. GRB” seen off-axis?)

gravitational waves

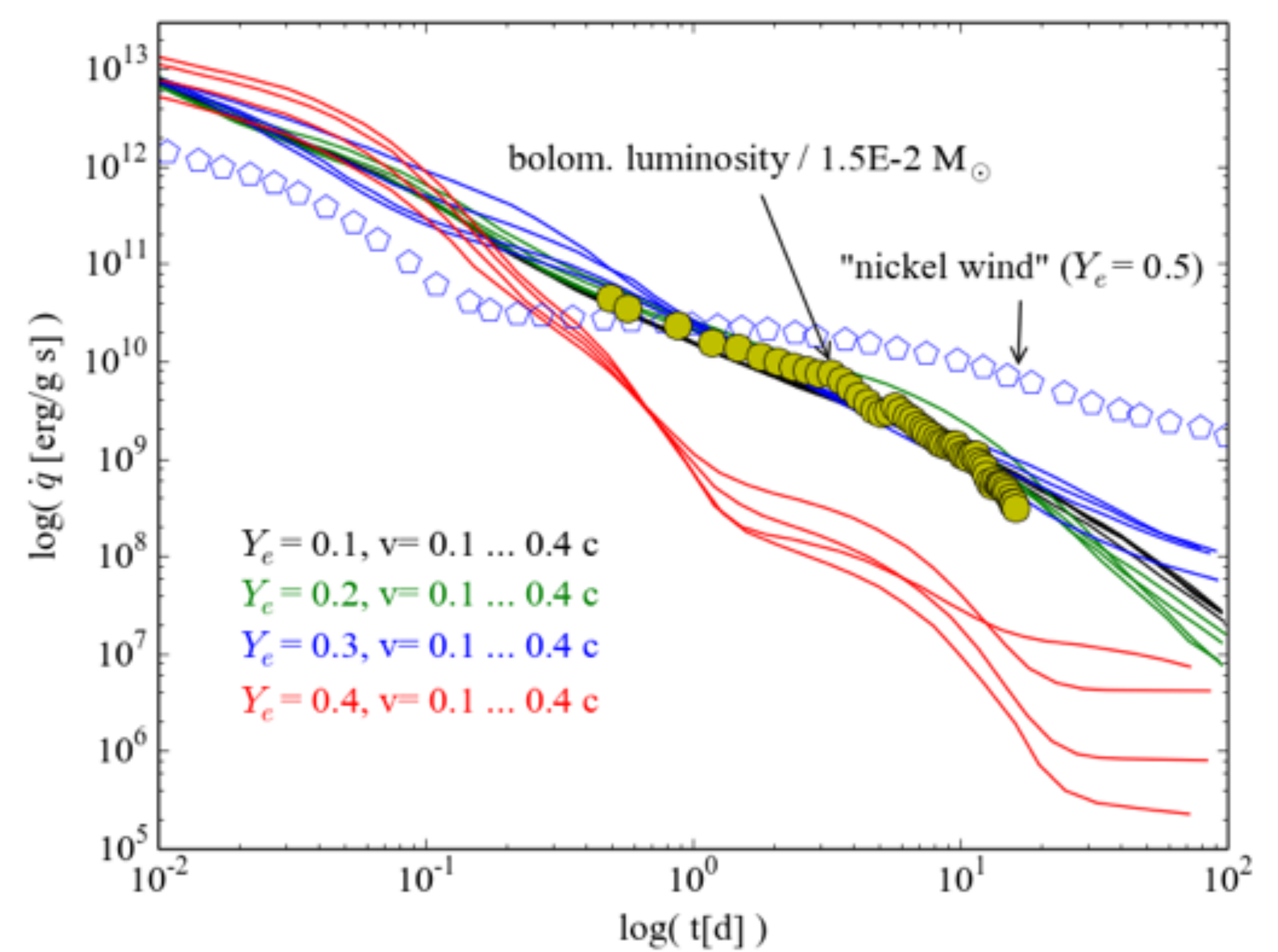


evolution from
blue to red

Really r-process?

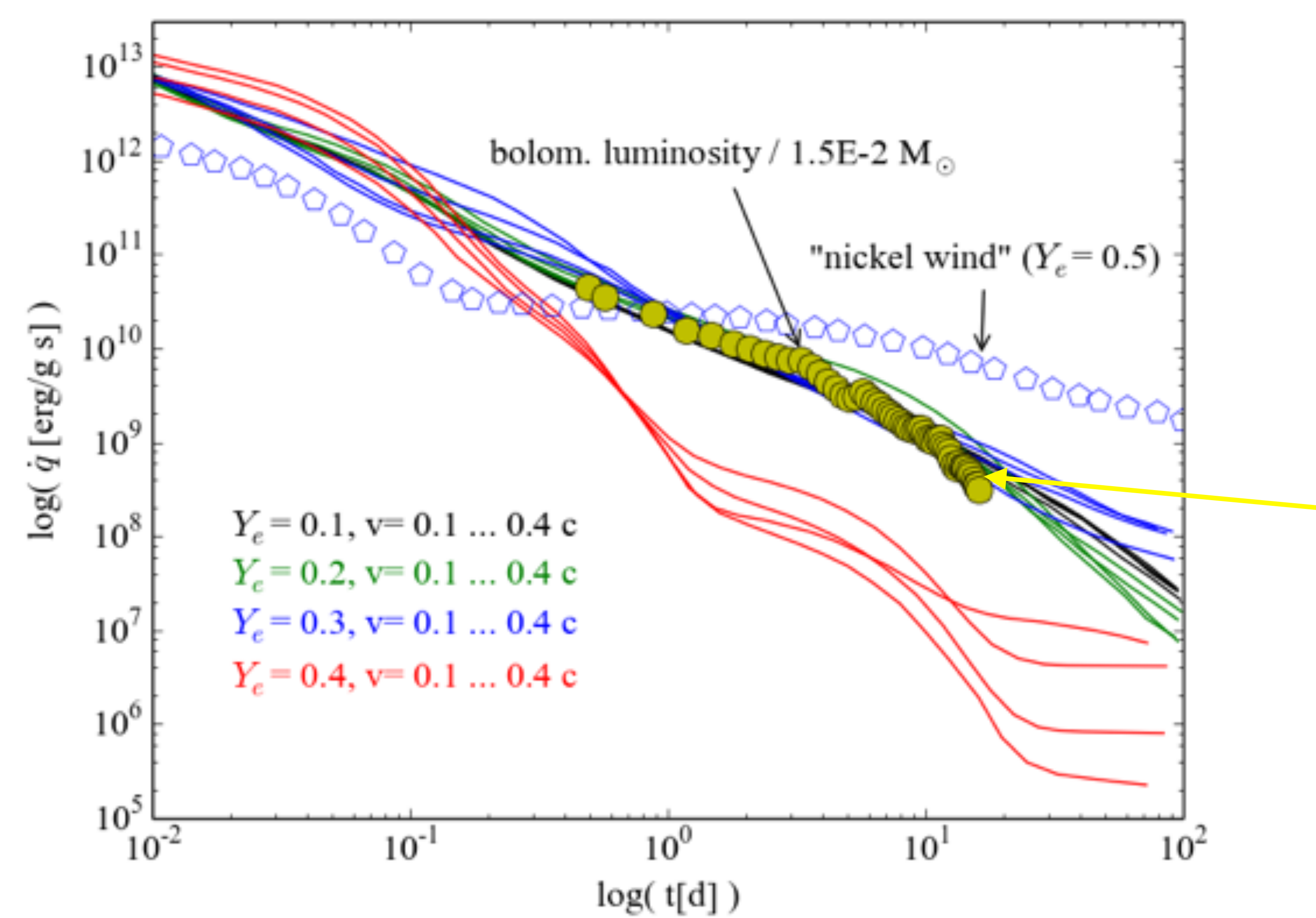
- numerical experiment: (from S.R++ 2018, A&A in press)
  - nuclear reaction network different conditions ($v \in [0.1,0.4]$, $Y_e \in [0.1, 0.4]$)
  - nuclear heating rate ⇔ bolometric luminosity

observed
luminosity/
nuclear
heating rate



Really r-process?

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

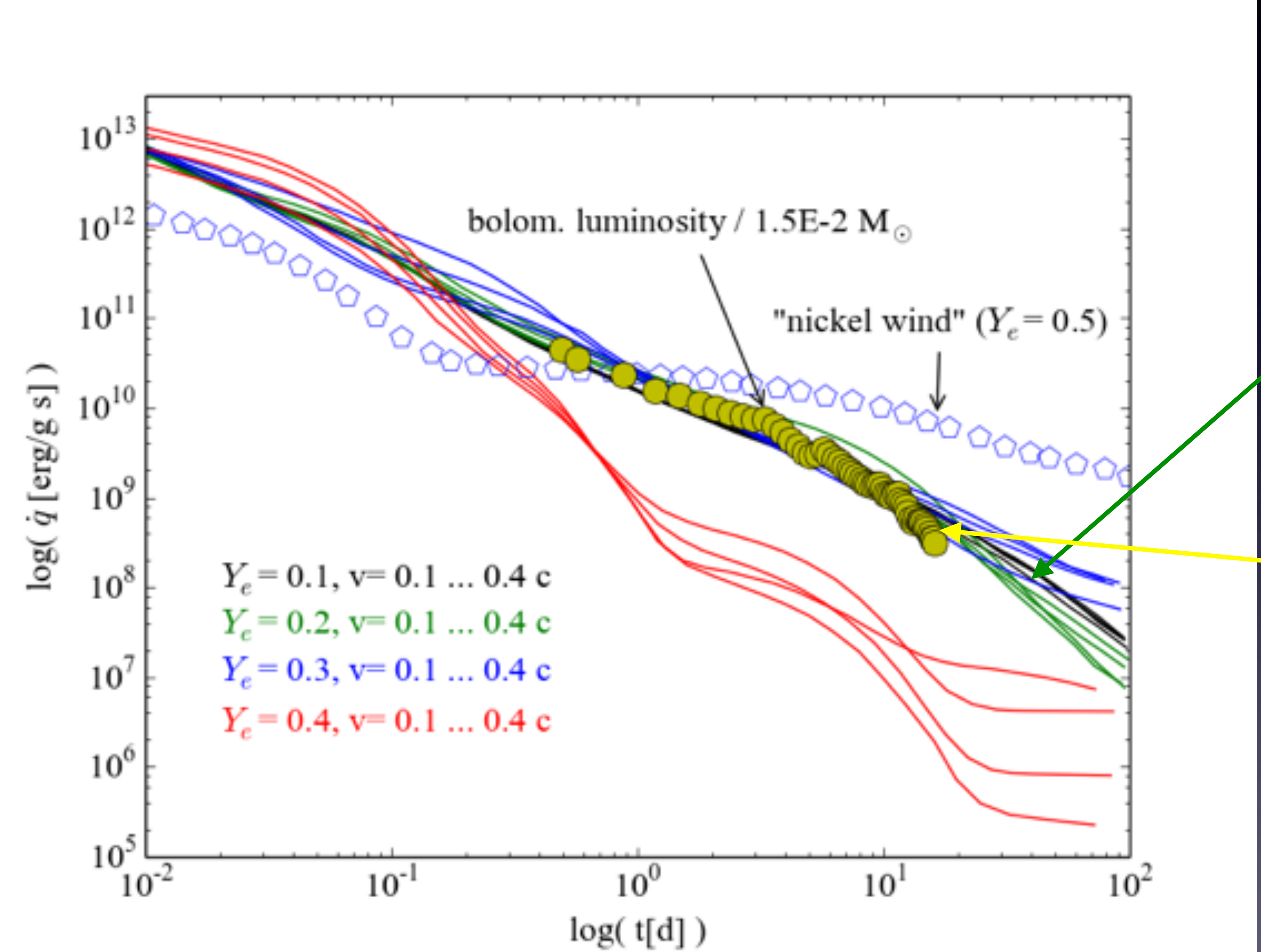


observed luminosity/ nuclear heating rate

(scaled) observed luminosity

Really r-process?

- 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

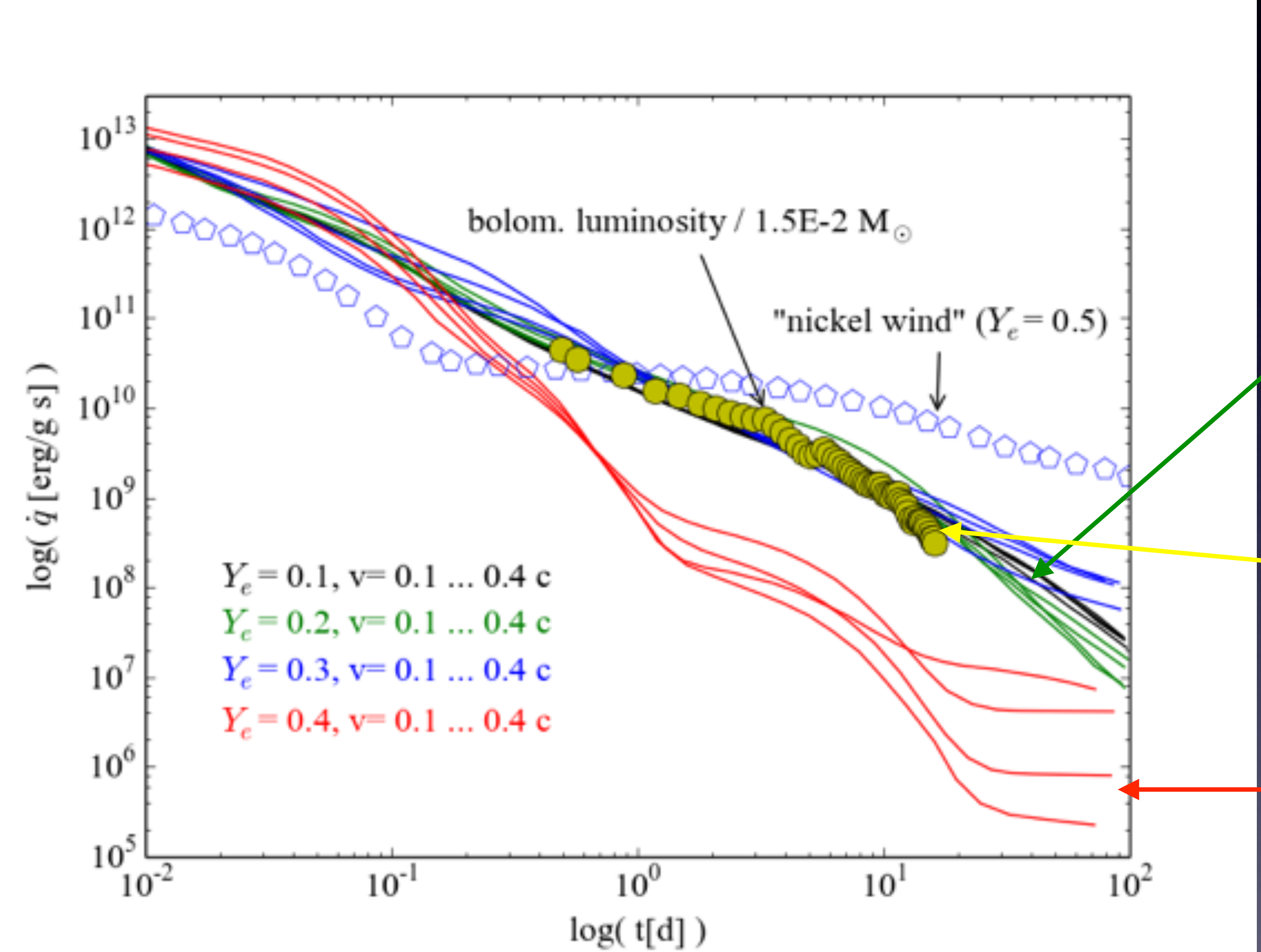
low electron fraction (Ye ≲ 0.3) ⇒ r-process

(scaled) observed luminosity

Really r-process?

- 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



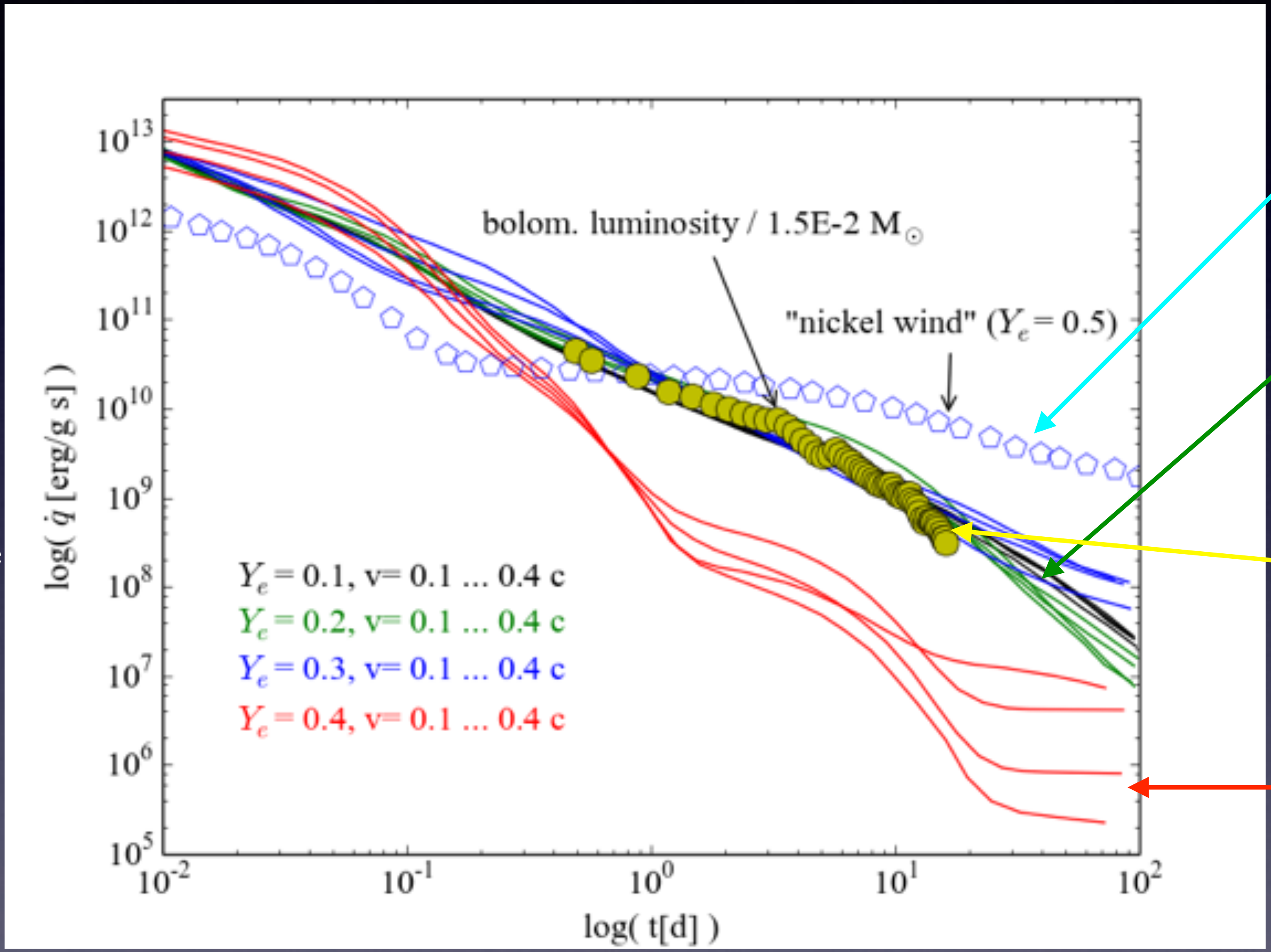
low electron fraction (Ye ≲ 0.3)
⇒ r-process

(scaled) observed luminosity

higher electron fraction (Y_e= 0.4)

Really r-process?

- 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)

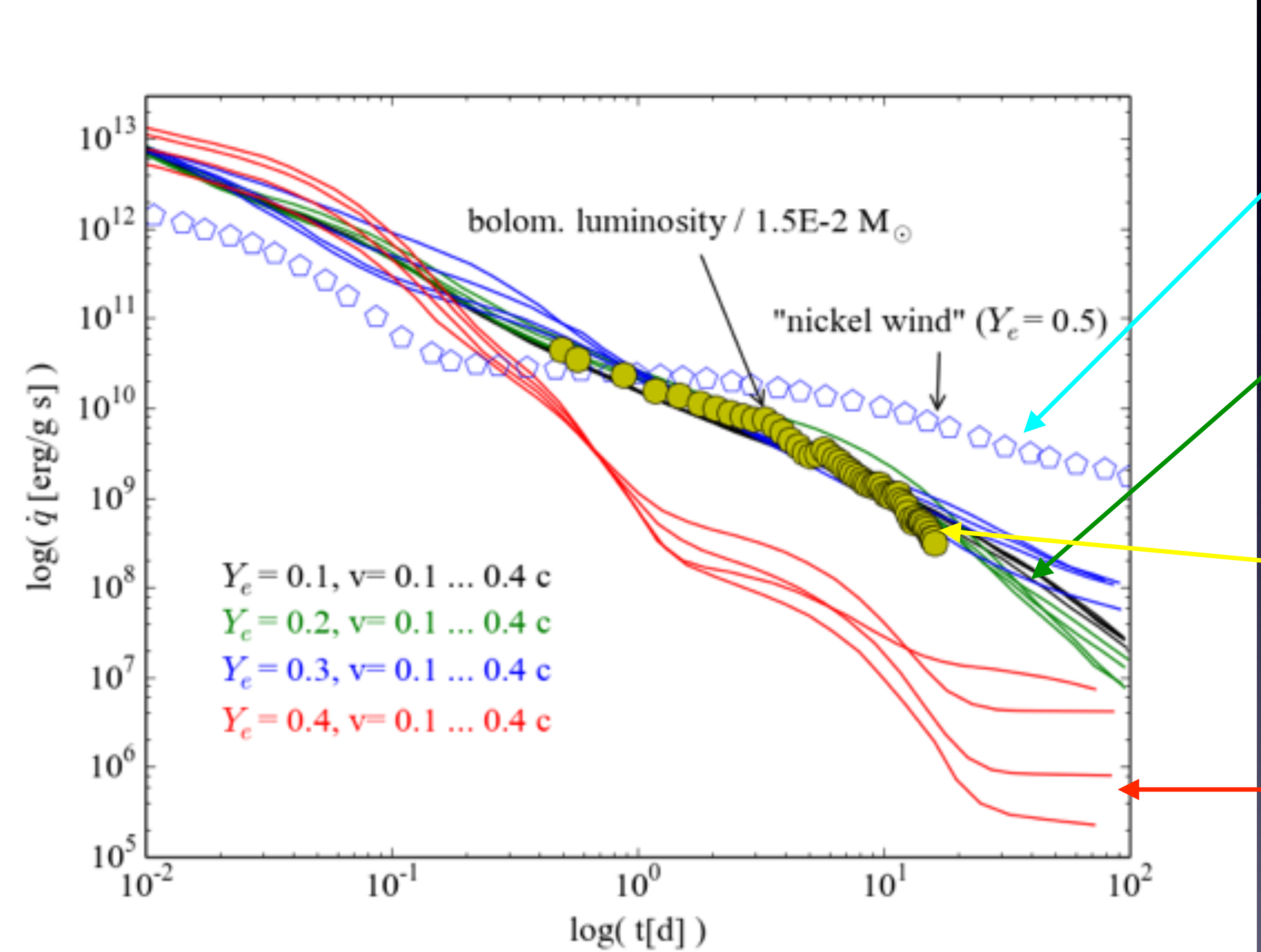
low electron fraction (Ye ≲ 0.3)
⇒ r-process

(scaled) observed luminosity

higher electron fraction (Y_e= 0.4)

Really r-process?

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



observed luminosity/ nuclear heating rate

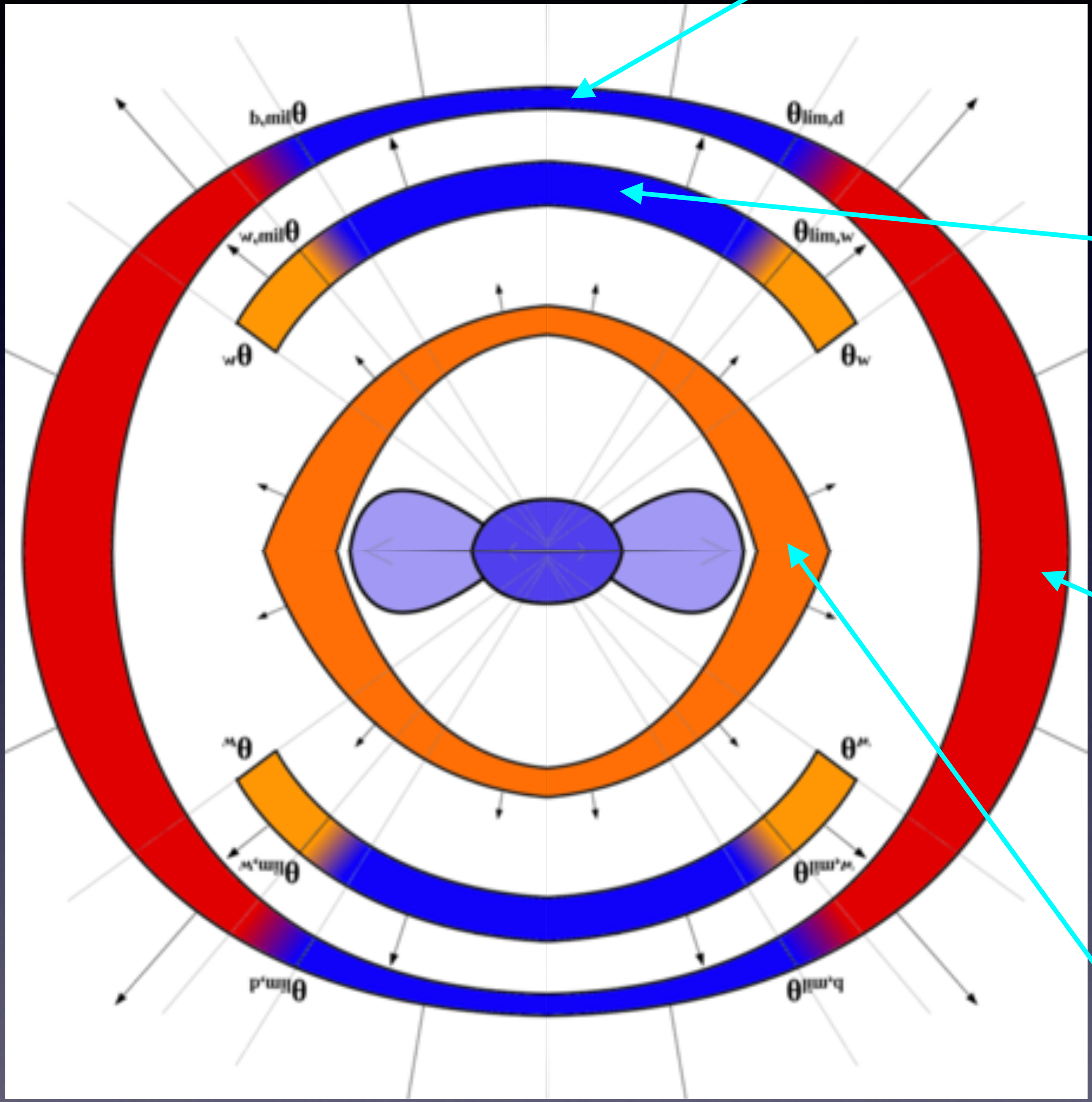
"nickel wind" (Y_e= 0.5)

low electron fraction ($Y_e \lesssim 0.3$)
⇒ 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 $M_\odot$



(Figure after Perego+ 2017)

dynamic ejecta, “interaction component”:
- early, ~1 ms
- “polar”
- higher Y_e
- ‘blue’

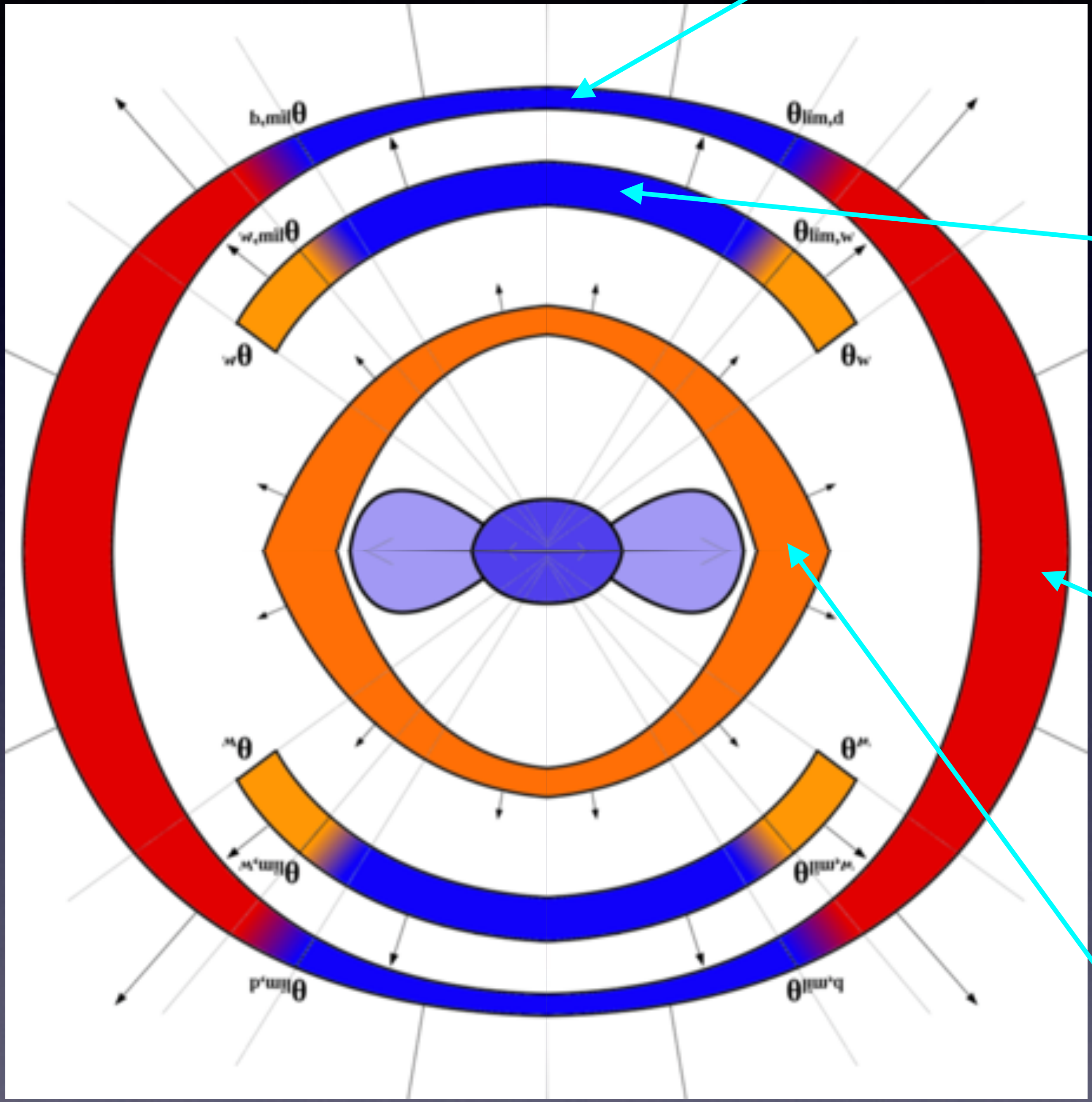
winds (ν-driven, magnetic, etc):
- early, ~10s of ms
- higher Y_e
- ‘blue’

dynamic ejecta, “tidal component”:
- early, ~ 1 ms
- equatorial
- low Y_e
- ‘red’

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

e.g. Kilpatrick+ 17
Kasen+ 17

“blue”:
$m \sim 0.025\ M_\odot$
$v \sim 0.25\ c$



(Figure 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’

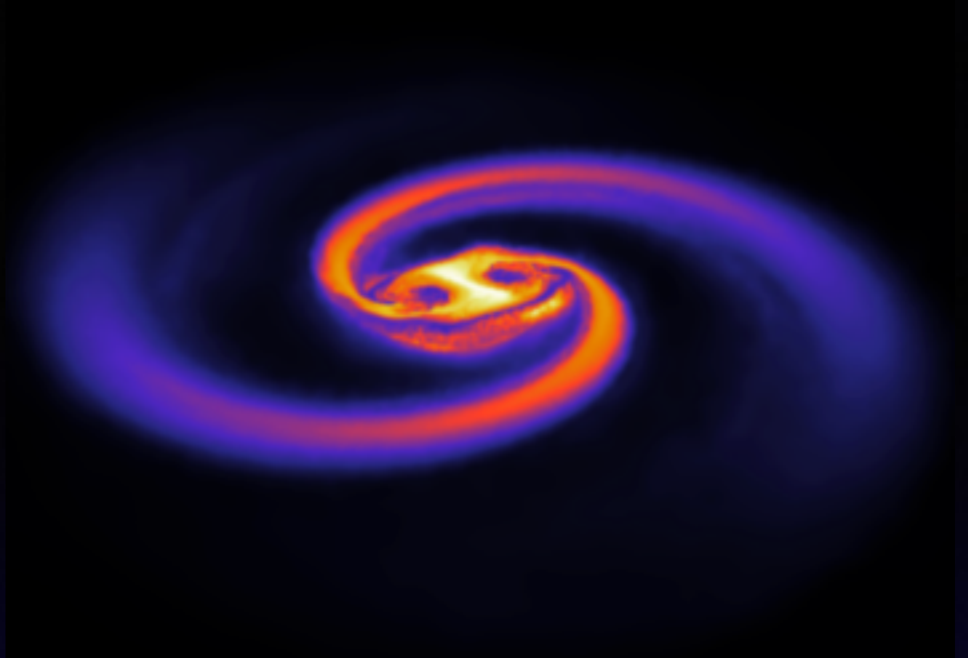
dynamic ejecta, “tidal component”:
- early, ~ 1 ms
- equatorial
- low Y_e
- ‘red’

“red”:
$m \sim 0.035\ M_\odot$
$v \sim 0.15\ c$

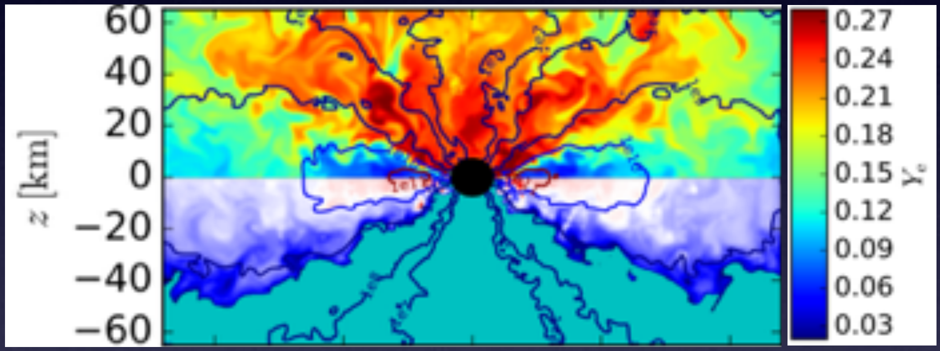
“secular”, “tidal component”:
- late, ~ 1 s
- ~ isotropic
- broad range Y_e

Implications

- “large mass in red component” (~0.04 M☉)
  - very difficult for tidal dynamic ejecta
  - secular/disk ejecta?



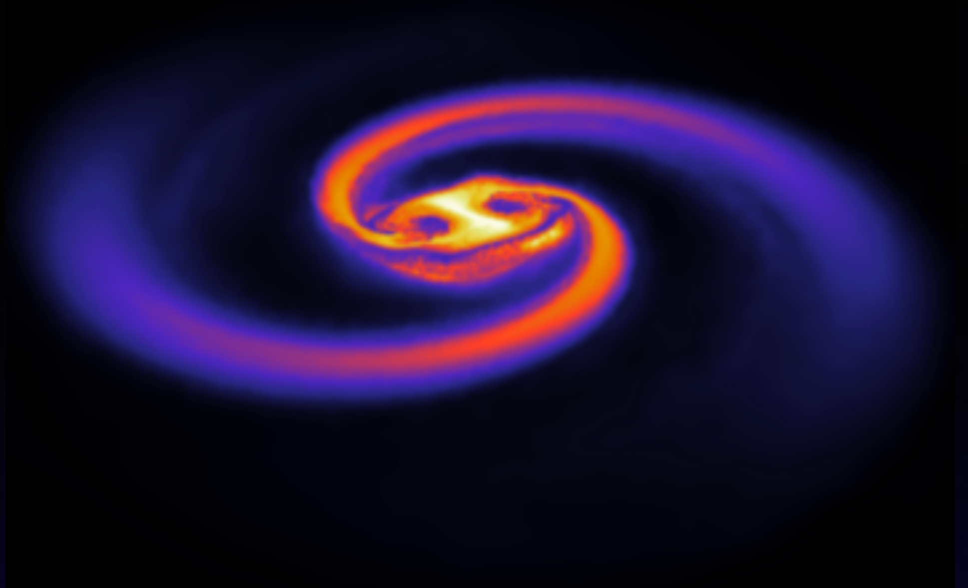
(from S.R.+ 2017)



(from Siegel & Metzger 2017)

Implications

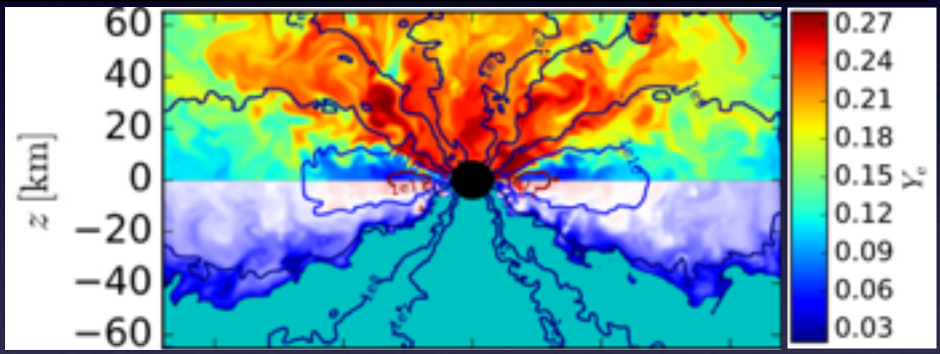
- “large mass in red component” (~0.04 $M_\odot$)
  - very difficult for tidal dynamic ejecta
  - secular/disk ejecta?



(from S.R.+ 2017)

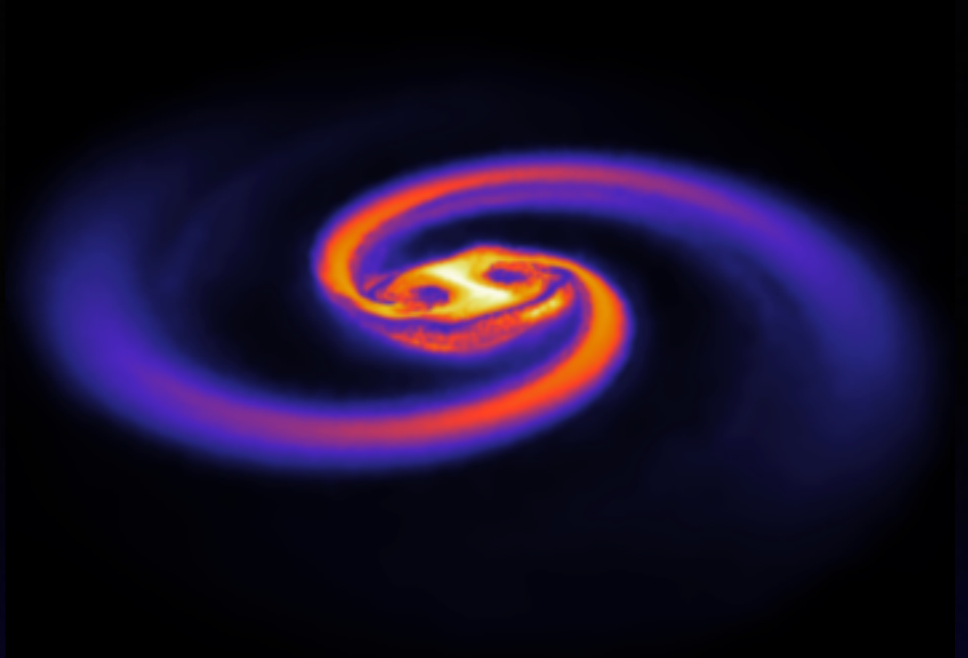
- “large mass in blue component” (~0.02 $M_\odot$)
  - original mass with $Y_e > 0.25$ only ~5×10^{-5} $M_\odot$

    $\Rightarrow$ weak interaction/neutrino physics plays key role!



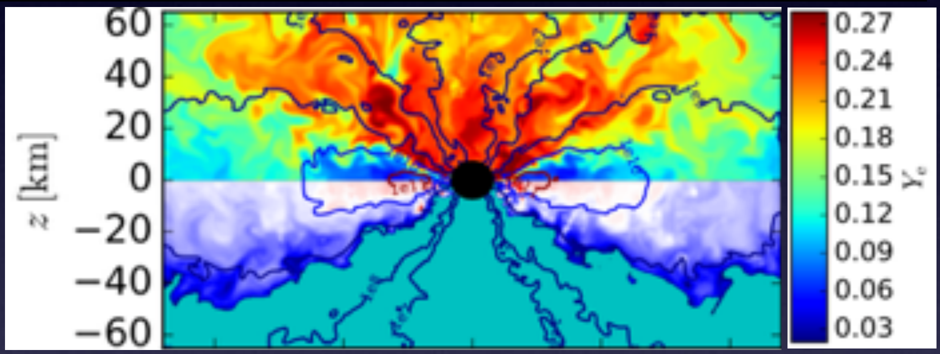
(from Siegel & Metzger 2017)

Implications



(from S.R.+ 2017)

- "large mass in red component" (~0.04 $M_\odot$)
  - very difficult for tidal dynamic ejecta
  - secular/disk ejecta?



(from Siegel & Metzger 2017)

- "large mass in blue component" (~0.02 $M_\odot$)
  - original mass with $Y_e > 0.25$ only ~$5\text{x}10^{-5}$ $M_\odot$

    ⇒ weak interaction/neutrino physics plays key role!

- expected, accumulated mass:

$$M_{\rm r,expected} \sim 17\,000\ {\rm M}_\odot \left(\frac{\mathcal{R}_{\rm nsns}}{500\ {\rm Gpc}^{-3}{\rm yr}^{-1}}\right)\left(\frac{\bar{m}_{\rm ej}}{0.03\ {\rm M}_\odot}\right)\left(\frac{\tau_{\rm Gal}}{1.3\times 10^{10}\ {\rm yr}}\right)$$

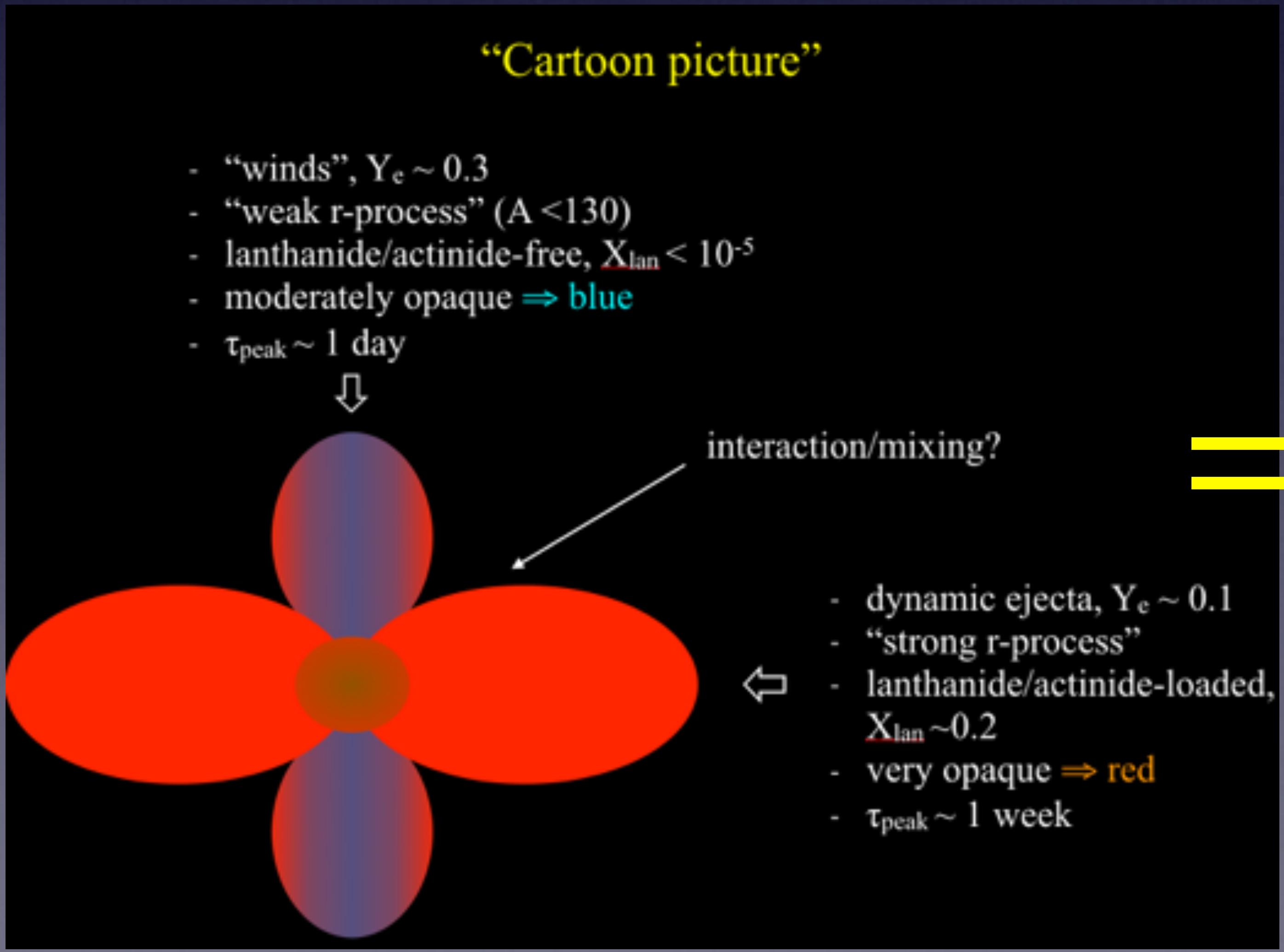
$$\sim M_{\rm r,MilkyWay}$$

⇒ very likely THE source of r-process elements in the Universe!

- velocities in blue component larger (~0.3c) than expected

  ⇒interaction with jet?

  ⇒ re-distribute/mix ejecta properties



"Cartoon picture"

- "winds", $Y_e \sim 0.3$
- "weak r-process" ($A < 130$)
- lanthanide/actinide-free, $X_{lan} < 10^{-5}$
- moderately opaque ⇒ blue
- $\tau_{peak} \sim 1$ day

⇩

interaction/mixing?

⇦

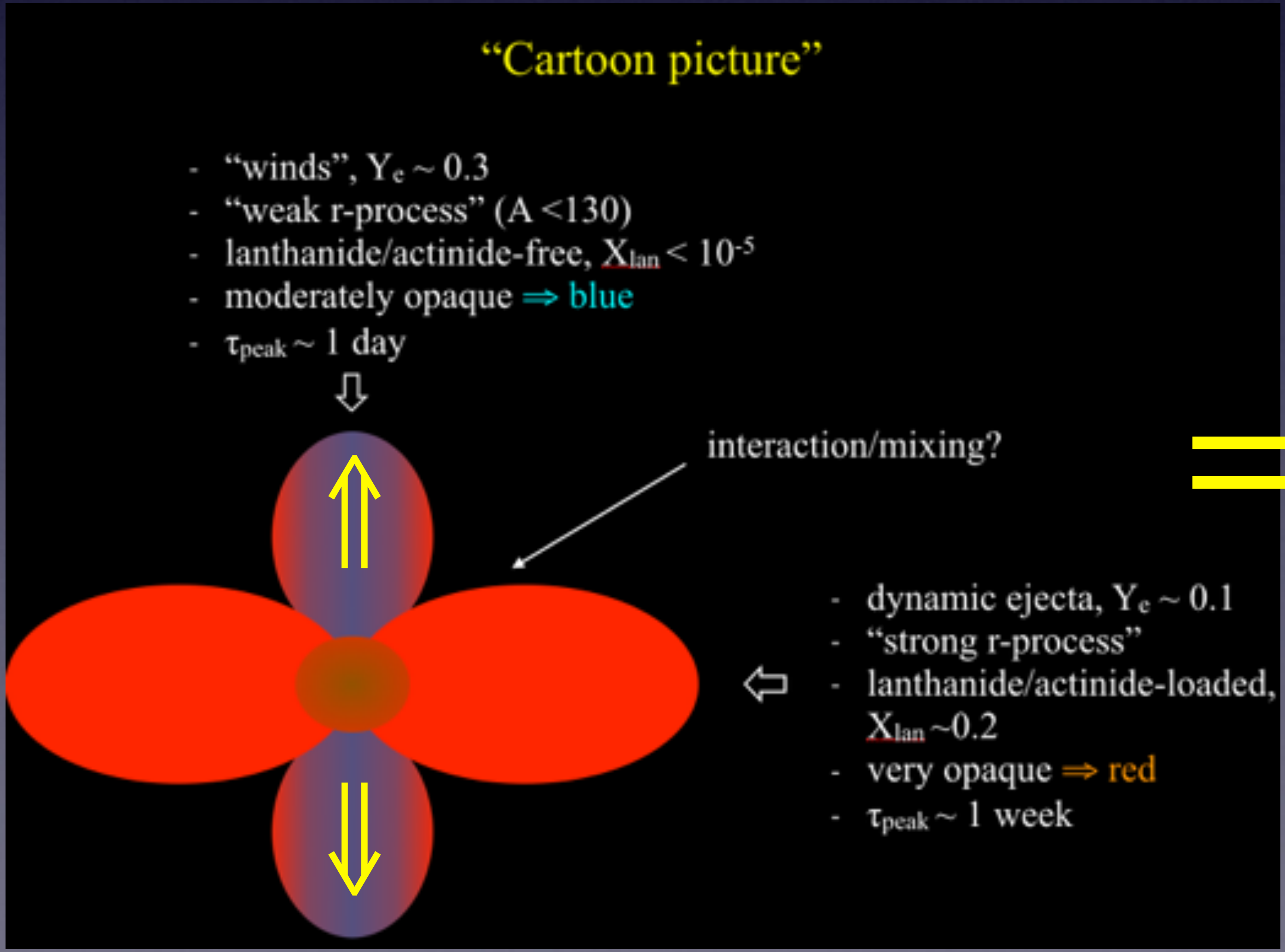
- dynamic ejecta, $Y_e \sim 0.1$
- "strong r-process"
- lanthanide/actinide-loaded, $X_{lan} \sim 0.2$
- very opaque ⇒ red
- $\tau_{peak} \sim 1$ week

⇒

- velocities in blue component larger (~0.3c) than expected

  ⇒interaction with jet?

  ⇒ re-distribute/mix ejecta properties



"Cartoon picture"

- "winds", $Y_e \sim 0.3$
- "weak r-process" ($A < 130$)
- lanthanide/actinide-free, $X_{lan} < 10^{-5}$
- moderately opaque ⇒ blue
- $\tau_{peak} \sim$ 1 day

interaction/mixing?

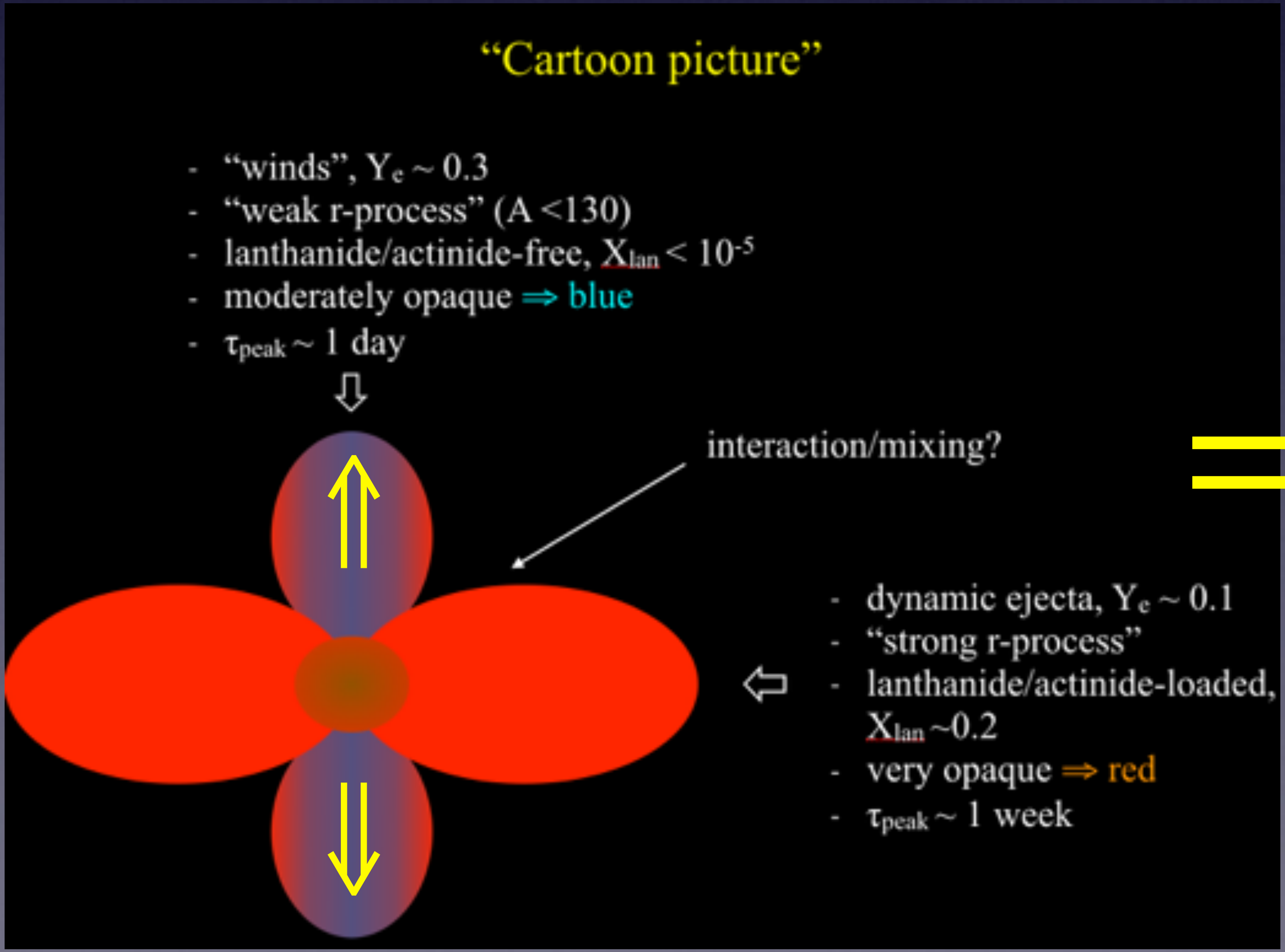
- dynamic ejecta, $Y_e \sim 0.1$
- "strong r-process"
- lanthanide/actinide-loaded, $X_{lan} \sim 0.2$
- very opaque ⇒ red
- $\tau_{peak} \sim$ 1 week

- velocities in blue component larger (~0.3c) than expected

⇒interaction with jet?

⇒ re-distribute/mix ejecta properties

Lorenzo Nativi



“Cartoon picture”

- “winds”, $Y_e \sim 0.3$
- “weak r-process” ($A < 130$)
- lanthanide/actinide-free, $X_{lan} < 10^{-5}$
- moderately opaque ⇒ blue
- $\tau_{peak} \sim 1$ day

interaction/mixing?

- dynamic ejecta, $Y_e \sim 0.1$
- “strong r-process”
- lanthanide/actinide-loaded, $X_{lan} \sim 0.2$
- very opaque ⇒ red
- $\tau_{peak} \sim 1$ week

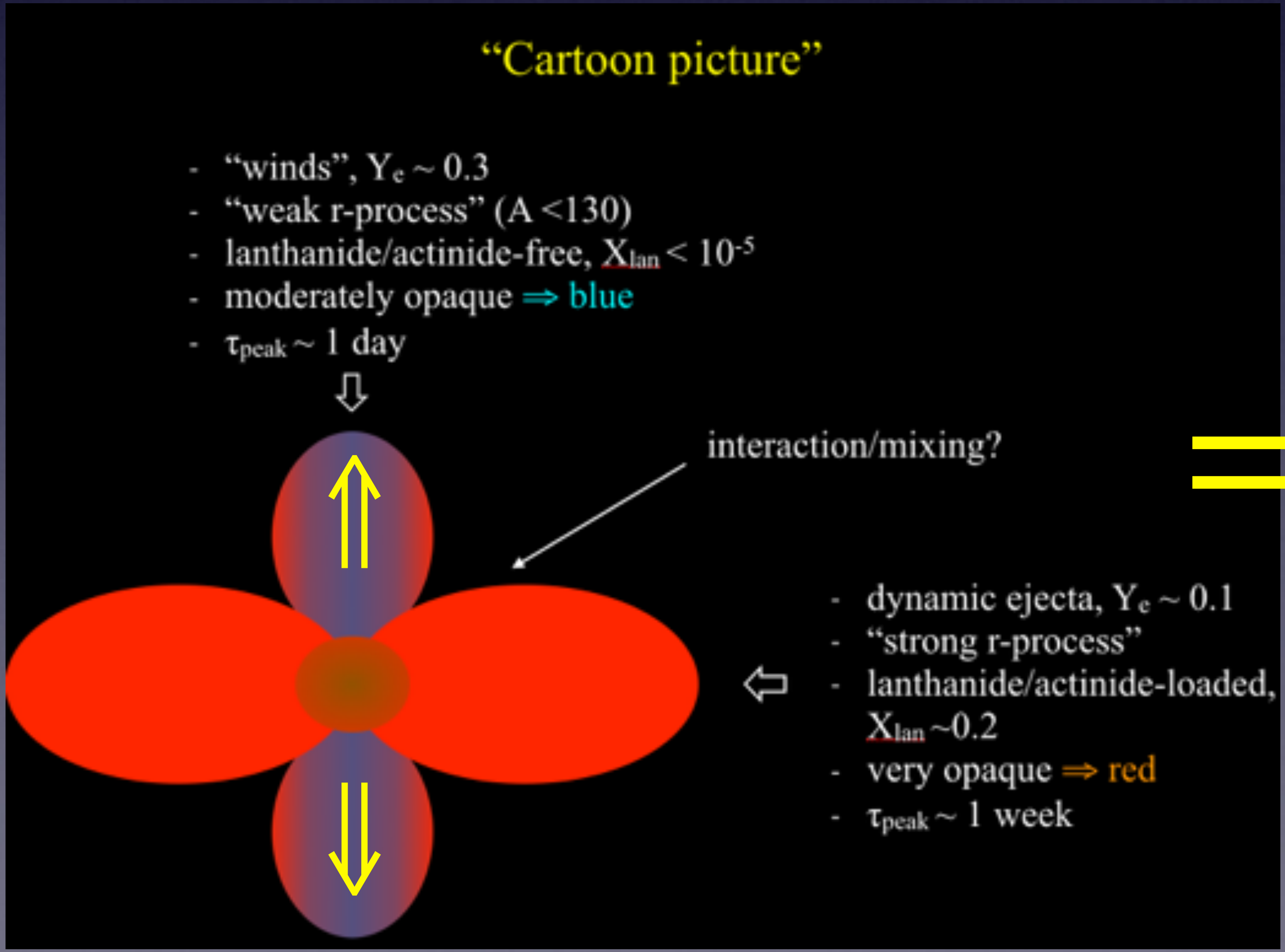
⇒

- velocities in blue component larger (~0.3c) than expected

⇒interaction with jet?

⇒ re-distribute/mix ejecta properties

Lorenzo Nativi



“Cartoon picture”

- “winds”, $Y_e \sim 0.3$
- “weak r-process” (A <130)
- lanthanide/actinide-free, $X_{lan} < 10^{-5}$
- moderately opaque ⇒ blue
- $\tau_{peak} \sim 1$ day

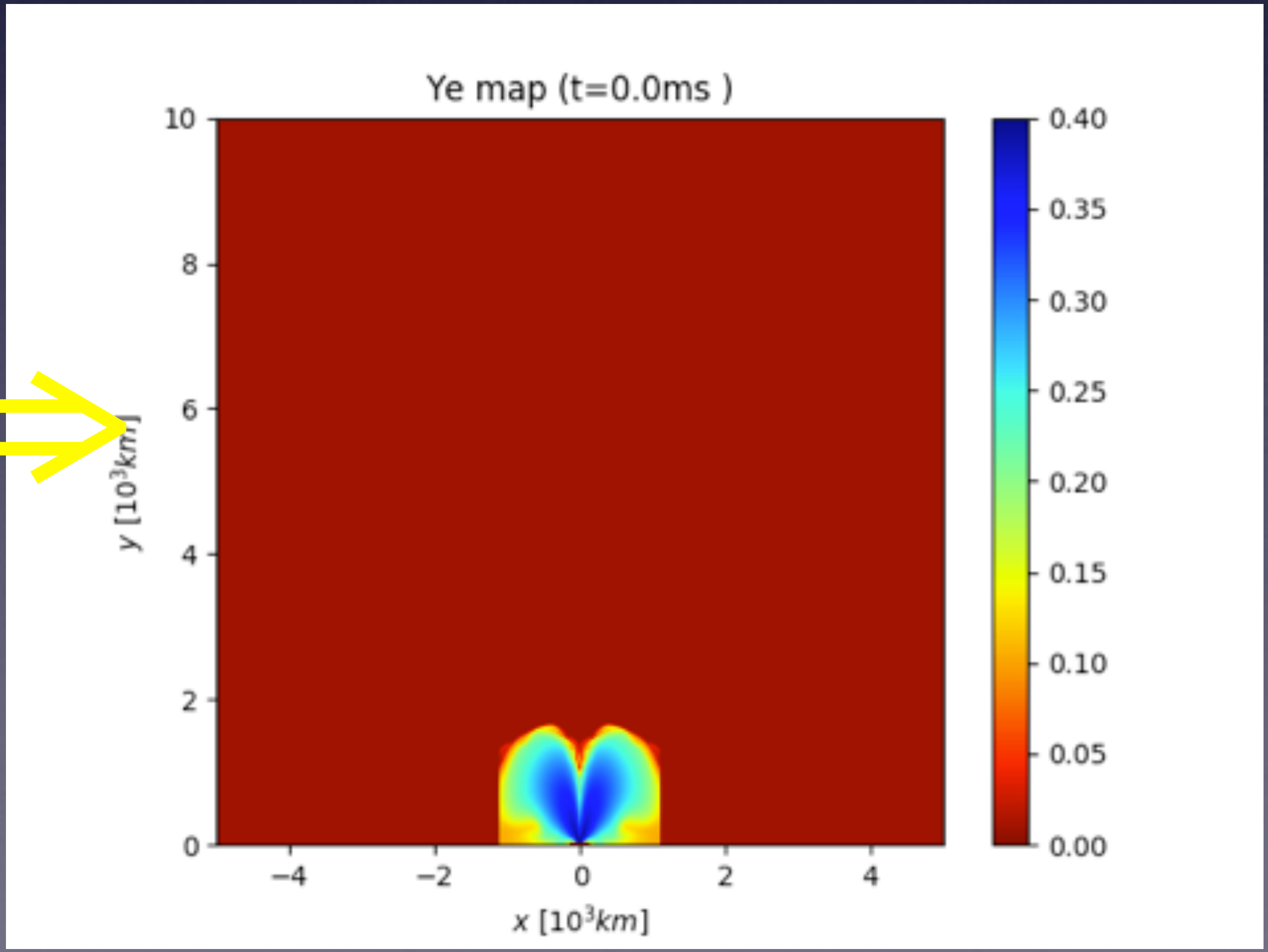
⇩

interaction/mixing?

⇦

- dynamic ejecta, $Y_e \sim 0.1$
- “strong r-process”
- lanthanide/actinide-loaded, $X_{lan} \sim 0.2$
- very opaque ⇒ red
- $\tau_{peak} \sim 1$ week

⇒



What have we learned from the first multi-messenger event?

What have we learned from the first multi-messenger event?

Gravitational Waves:

- “it was a neutron star neutron star merger with total mass ≈ 2.8 $M_\odot$”
- inspiral dynamics consistent with predictions from GR
- independent measure of the Hubble constant
- constraint on tidal deformability ⇒ nuclear EOS

What have we learned from the first multi-messenger event?

Gravitational Waves:

- “it was a neutron star neutron star merger with total mass ≈ 2.8 $M_\odot$”
- inspiral dynamics consistent with predictions from GR
- independent measure of the Hubble constant
- constraint on tidal deformability ⇒ nuclear EOS

Electromagnetic waves:

- “it happened in lenticular host galaxy at 42.5 Mpc, z= 0.0097”
- neutron star mergers produce short GRBs
- 1.7s delay GW vs. GRB: GWs travel at speed of light to within 1:10^{15}
- produced a “macronova”
- ***neutron stare mergers do produce r-process!***
    - likely broad range, light and heavy r-process nuclei
    - likely dominating r-process source in the Universe!

What have we learned from the first multi-messenger event?

Gravitational Waves:

- “it was a neutron star neutron star merger with total mass ≈ 2.8 $M_\odot$”
- inspiral dynamics consistent with predictions from GR
- independent measure of the Hubble constant
- constraint on ti

Electromagneti

- “it happened i
- neutron star m
- 1.7s delay GW vs. GRB: GWs travel at speed of light to within $1:10^{15}$
- produced a “macronova”
- ***neutron stare mergers do produce r-process!***
    - likely broad range, light and heavy r-process nuclei
    - likely dominating r-process source in the Universe!

The future is bright…

LIGO/VIRGO
Science Run O3,
exp. early 2019