

Annecy, 02.06.2017

# How do gravitational wave sources look electromagnetically?

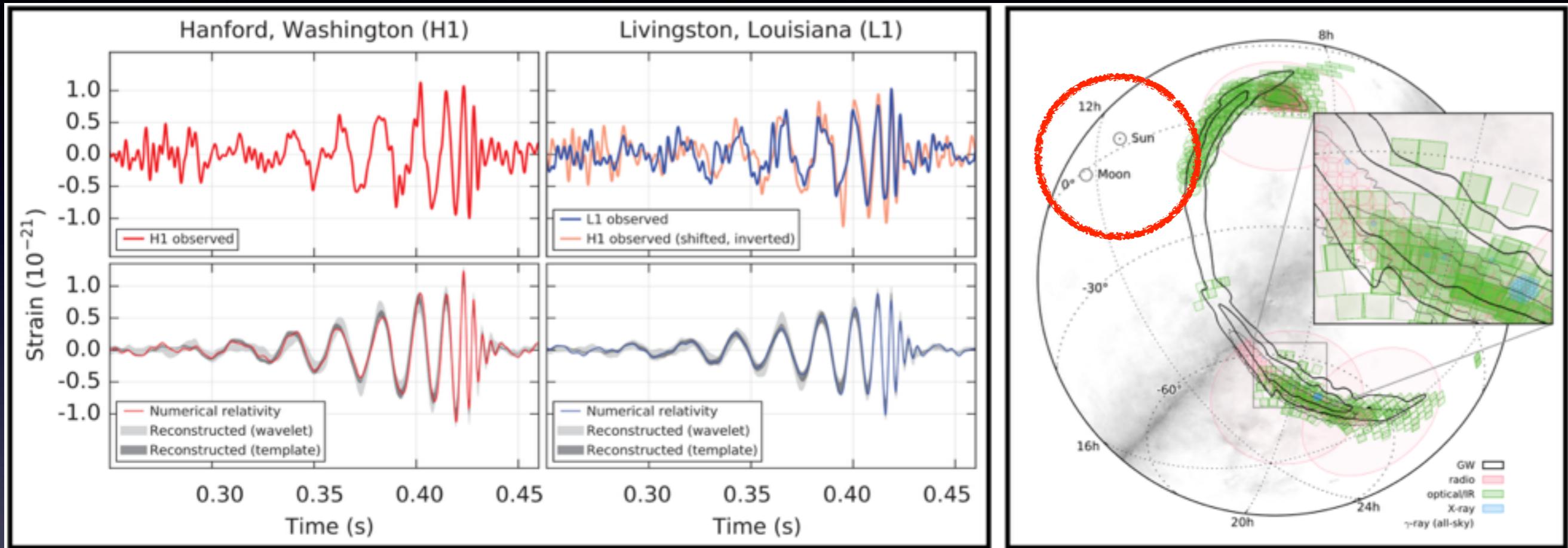


Stephan Rosswog



# I. Finally the new window has opened...

The first gravitational wave detection      GW150914



⇒ “physics from gravitational wave signal”

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

location in the sky essentially unknown,  
~ 600 deg<sup>2</sup> error region

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

for binary black holes:

- several channels suggested, no general consensus

for compact binaries involving neutron stars:

(1) Short Gamma-Ray Bursts

- collimated into  $\sim 8^\circ \Rightarrow$  detect  $\sim 1$  out of 70 bursts
- time scales  $\sim$  second



(2) Radioactively powered transients (“macronovae”)

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



time scales  $\sim$  days

(3) Radio flares

- from dissipation of kinetic energy in ambient medium
- time scales  $\sim$  months



Outline rest of talk:

(1) Compact binary mergers as factories for heavy elements

- r-process
- nucleosynthesis constraints on merger rate
- nucleosynthesis for dynamic ejecta and winds

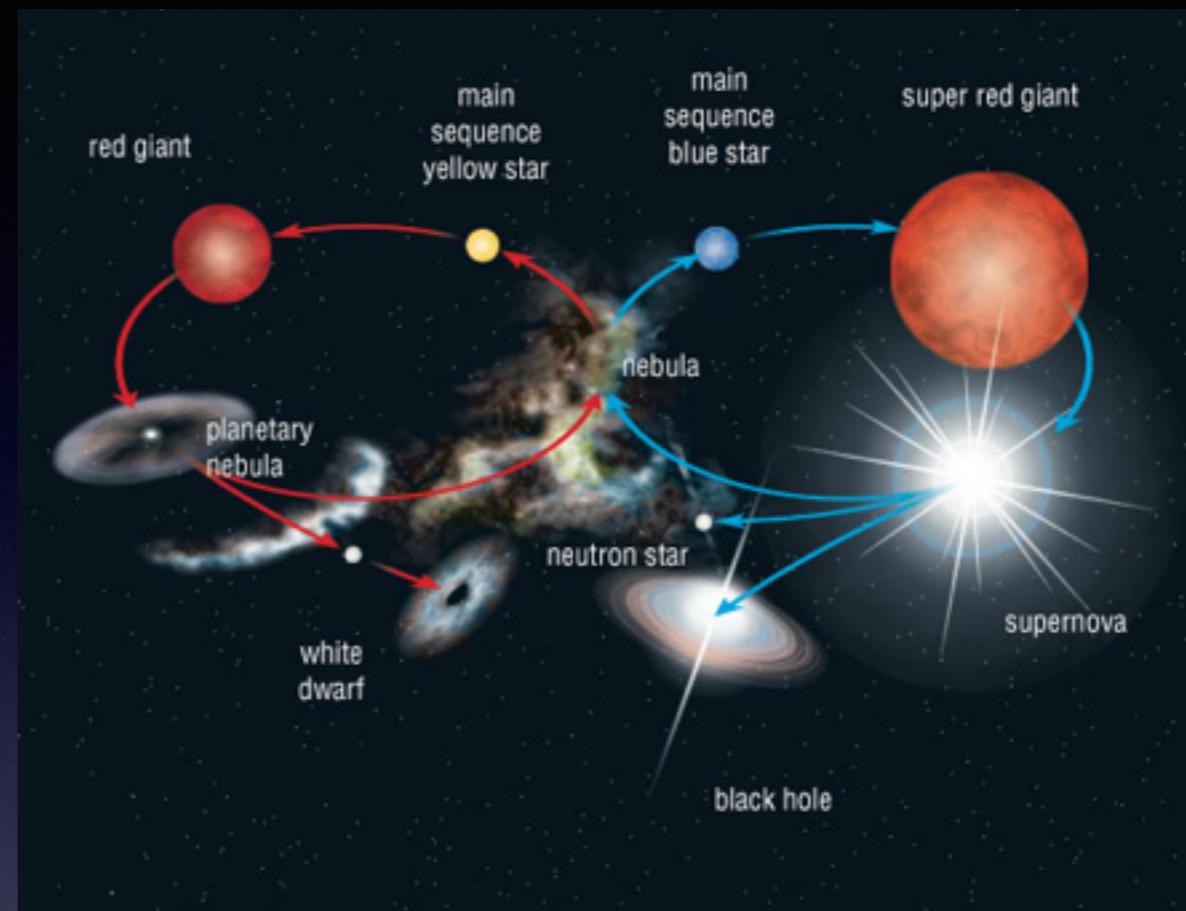
(2) Radioactively powered transients (“macronovae”)

- basics
- which ingredient has the biggest impact on observability?
- comparison with macronova candidate GRB130603B

references: a) SR et al., Class. Quant. Grav. 34, 104001 (2017)

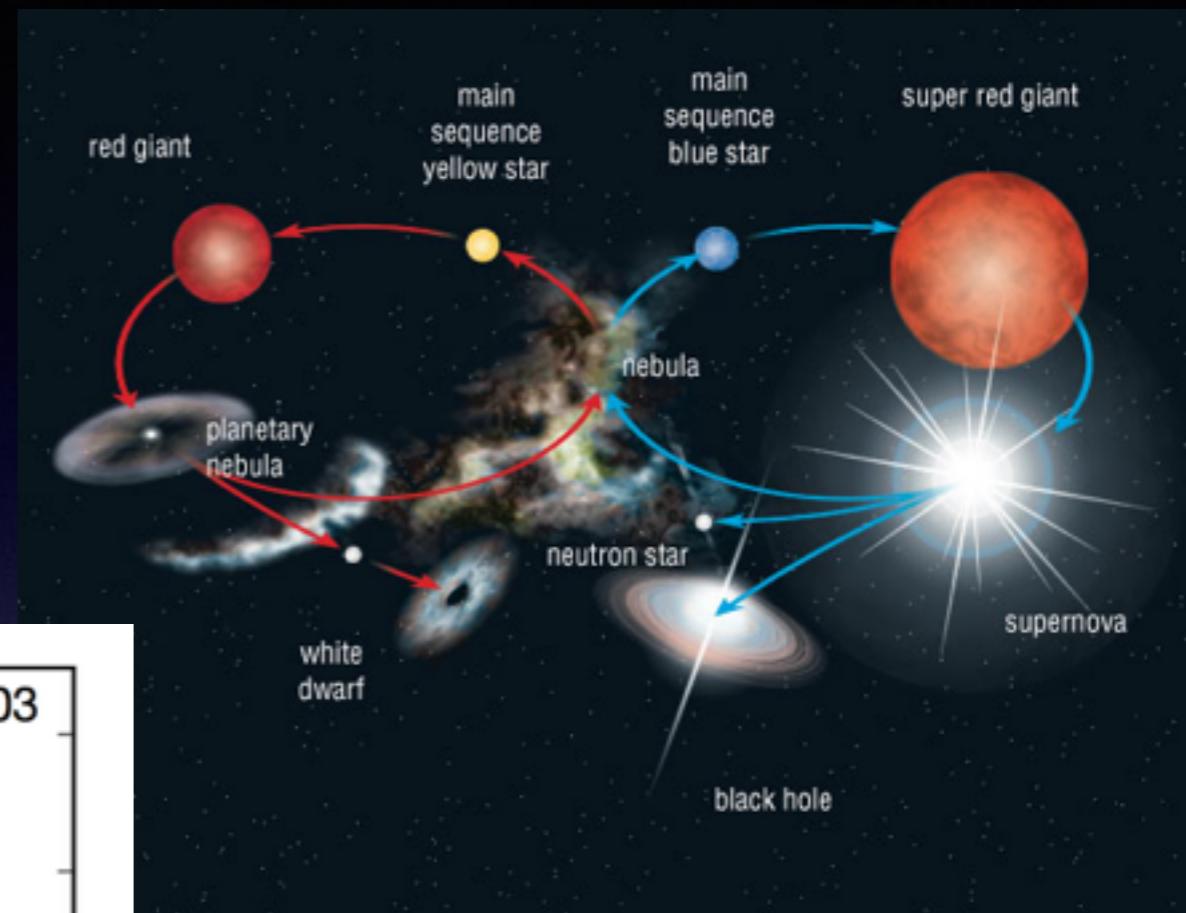
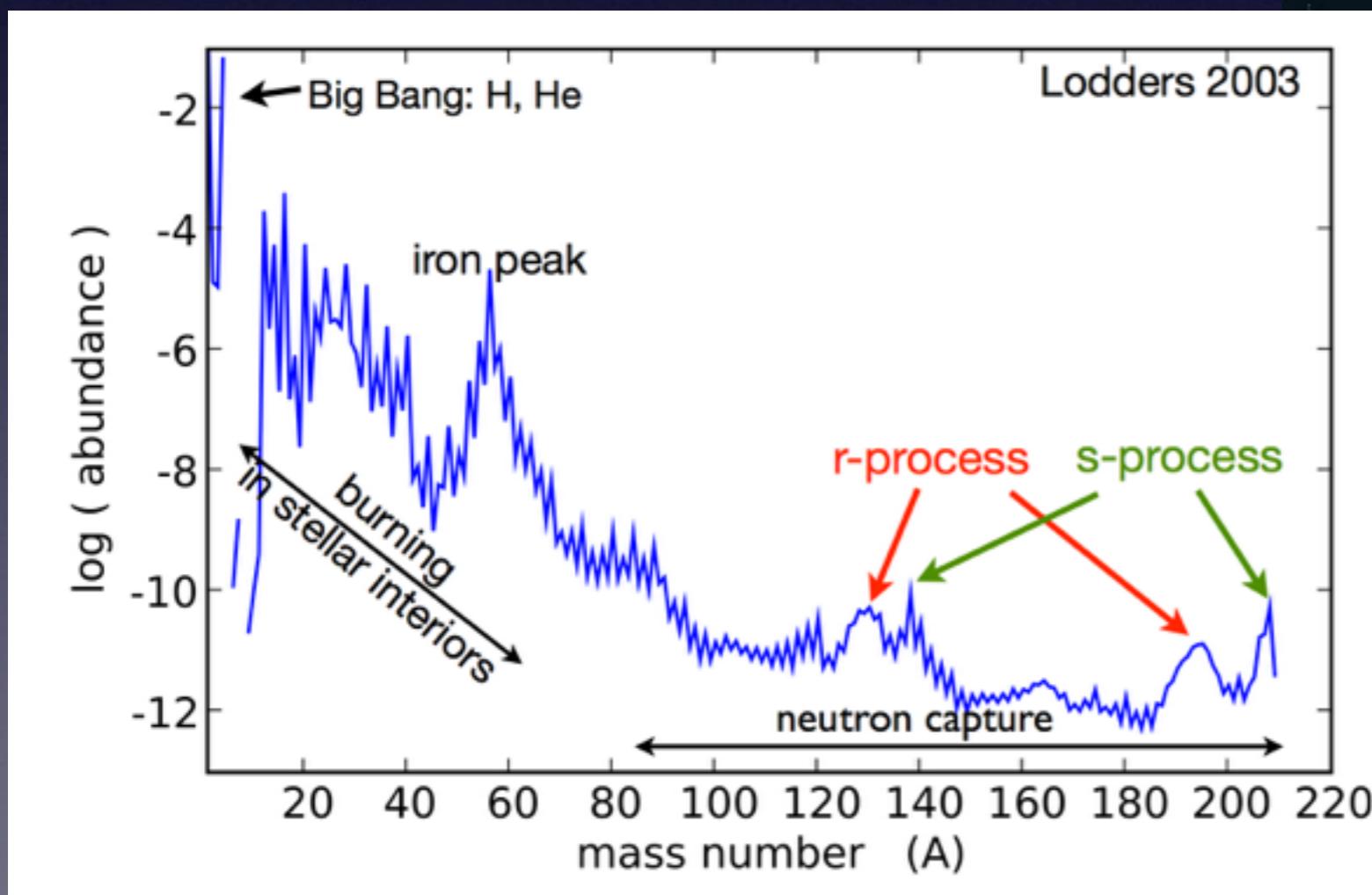
b) Wollaeger et al. 2017, arXiv:1705.07084

## II. Compact binary mergers as factories for heavy elements cosmic life cycle



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Solar system abundances

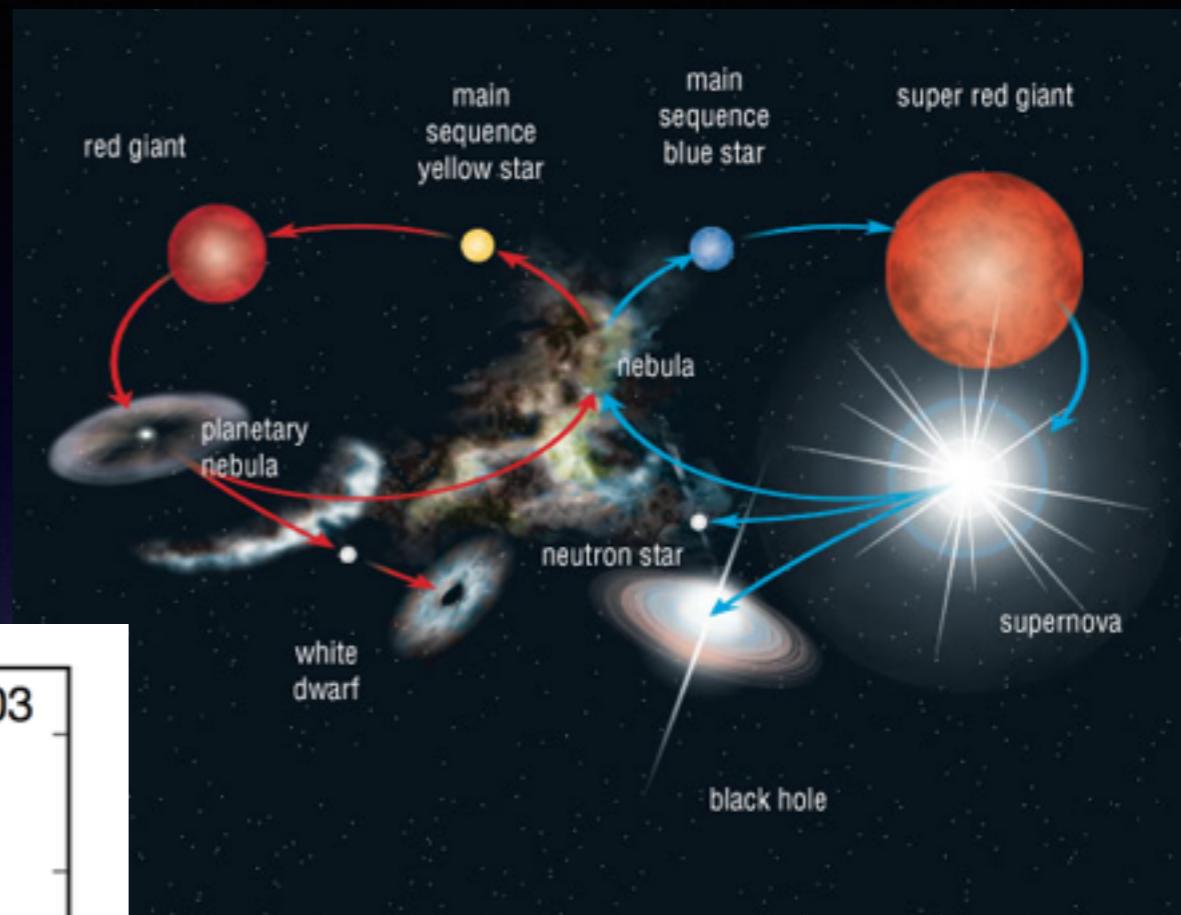
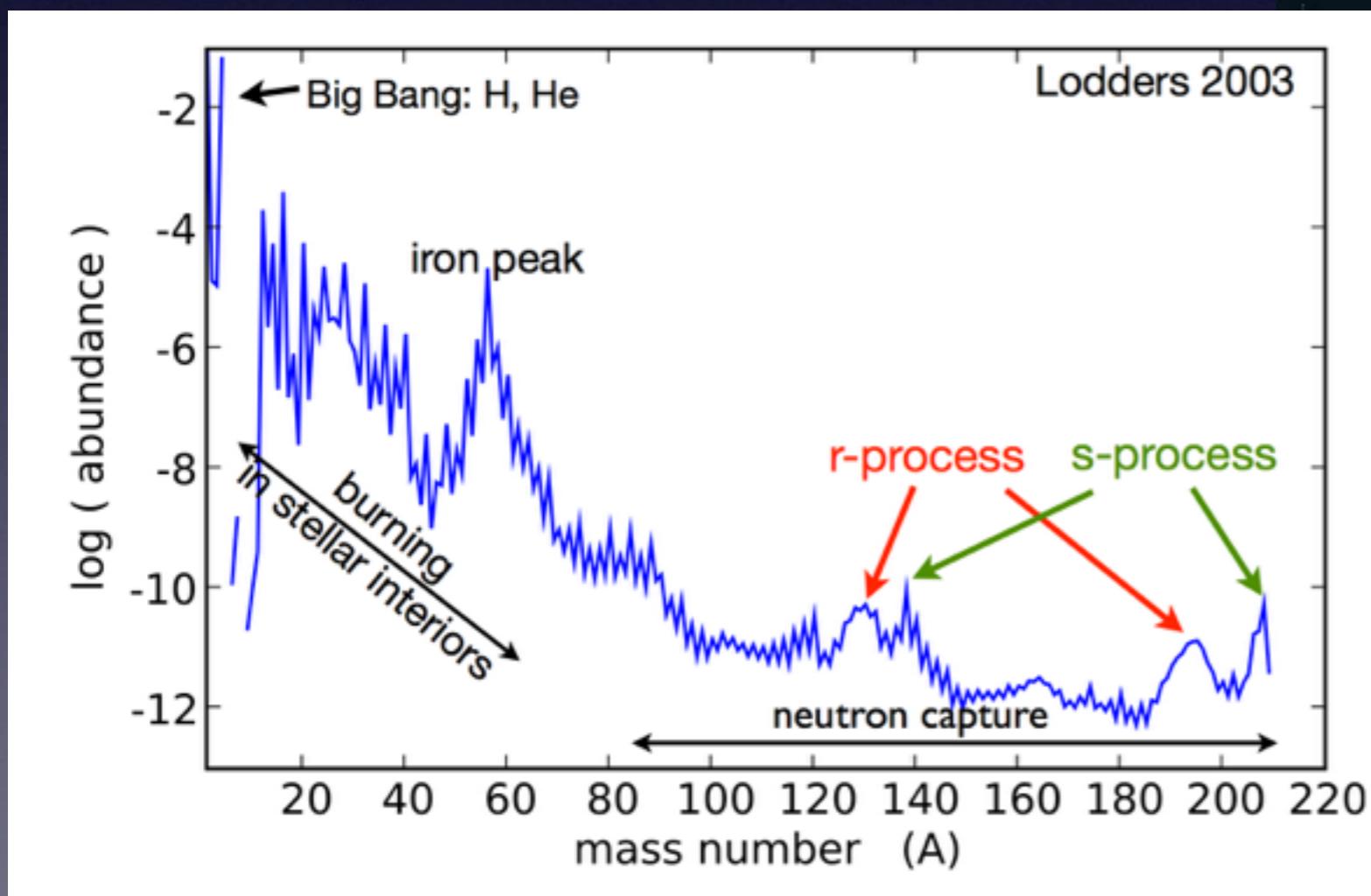


“Big Bang” “stellar burning” “neutron captures”

## II. Compact binary mergers as factories for heavy elements

cosmic life cycle

Solar system abundances



two neutron capture processes:

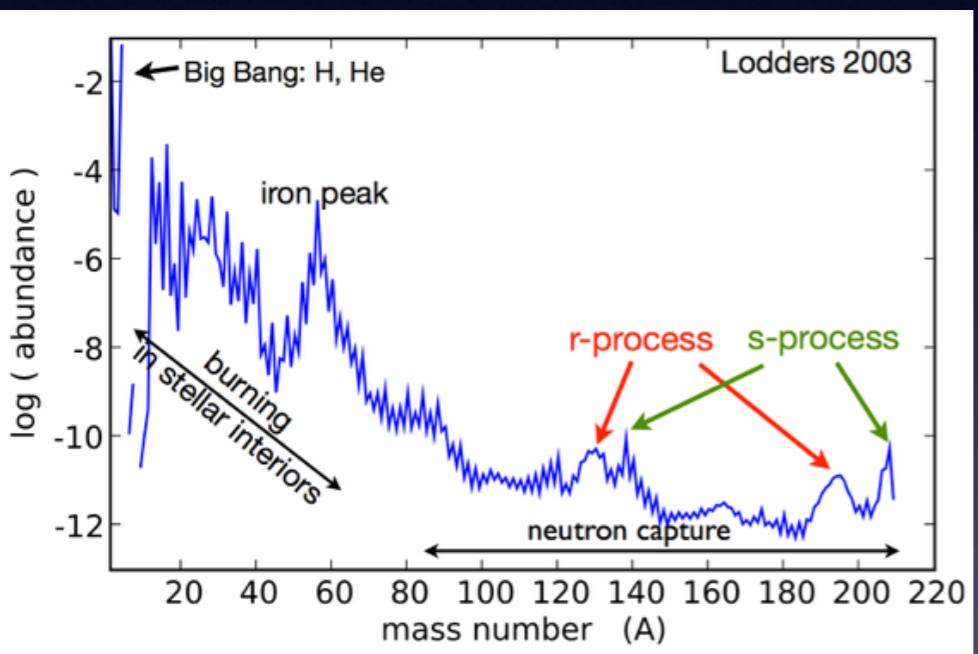
- slow n-capture (“s-process”)
- rapid n-capture (“r-process”)
 

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

“Big Bang” “stellar burning” “neutron captures”

# Examples of r-process elements

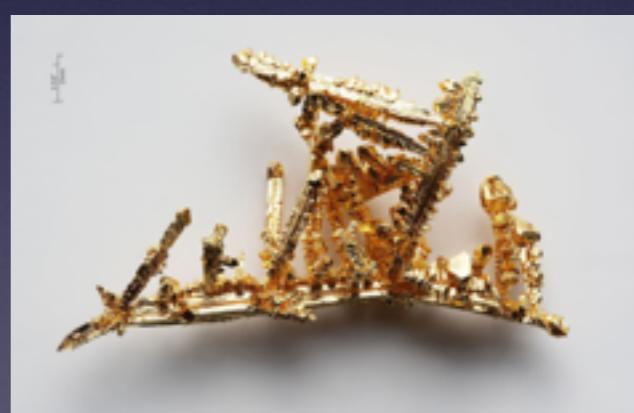
Iridium, Z= 77, A= 192



Platinum, Z= 78, A= 195



Gold, Z= 79, A= 197



Lead, Z= 82, A= 207

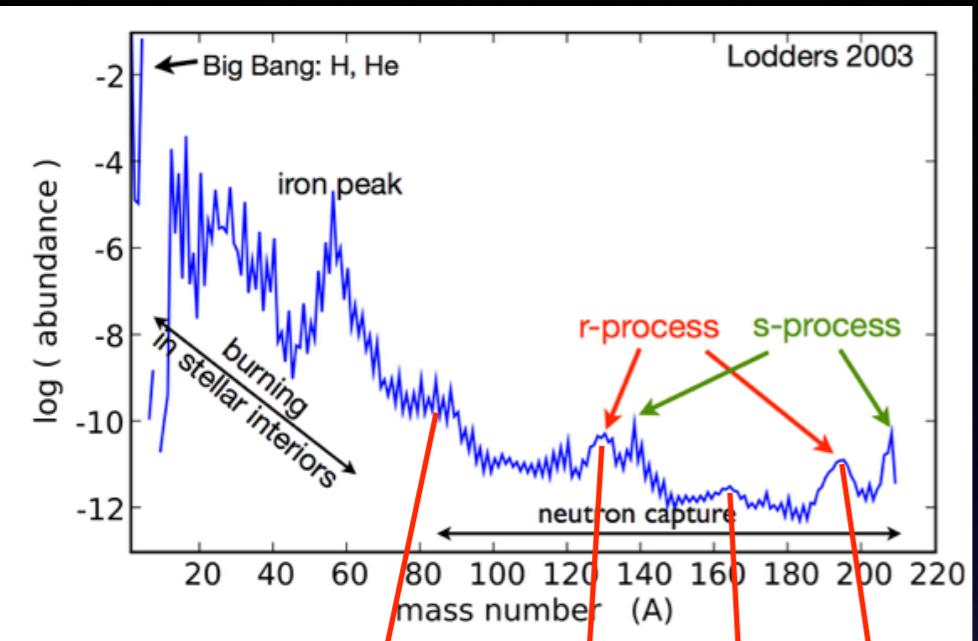


# How much r-process material in our Galaxy?

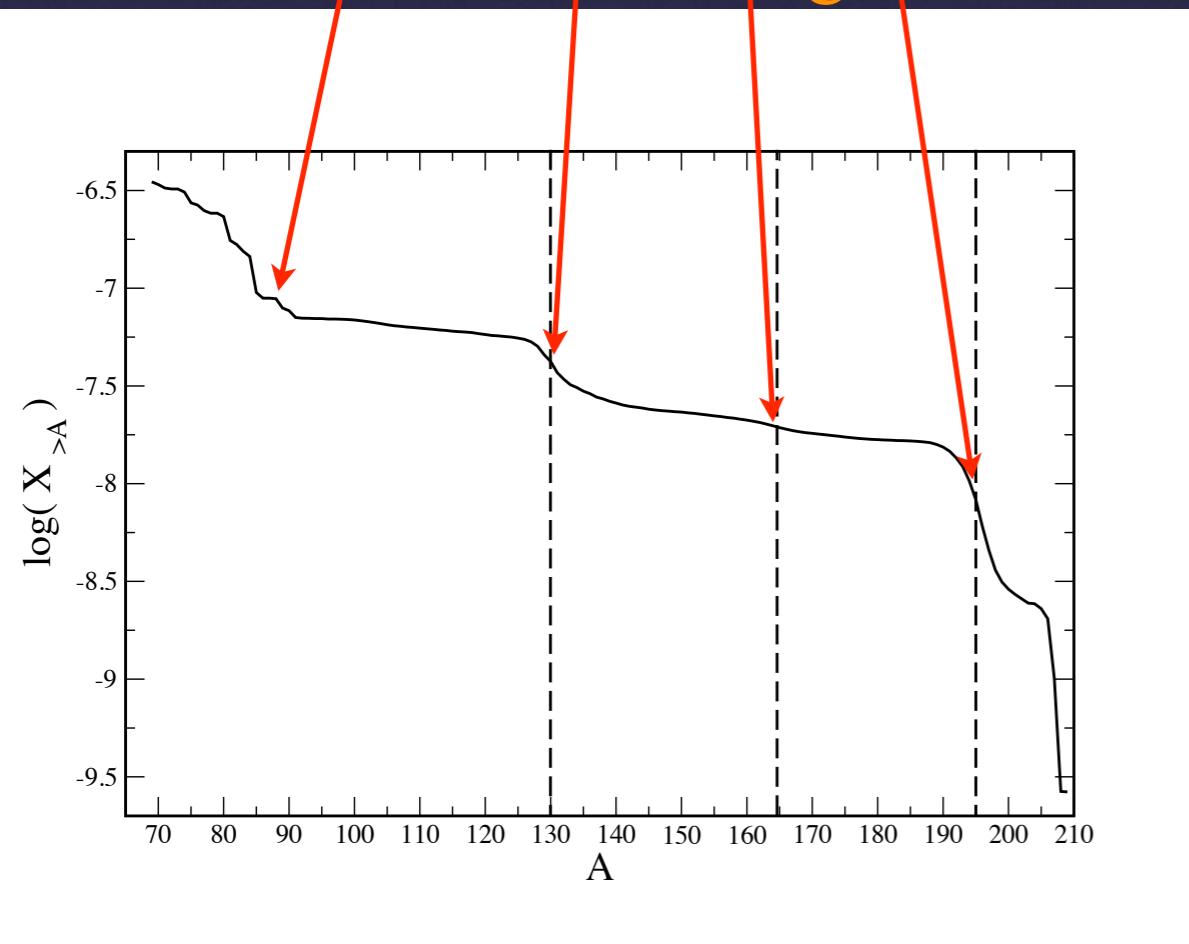
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Which fraction of r-process material  
has a nucleon number larger than A?

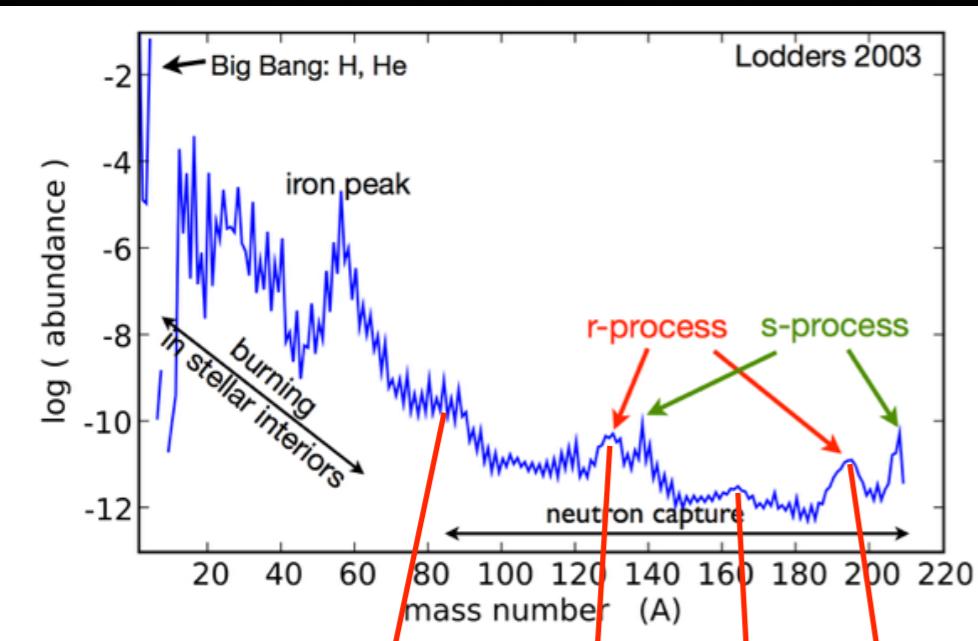
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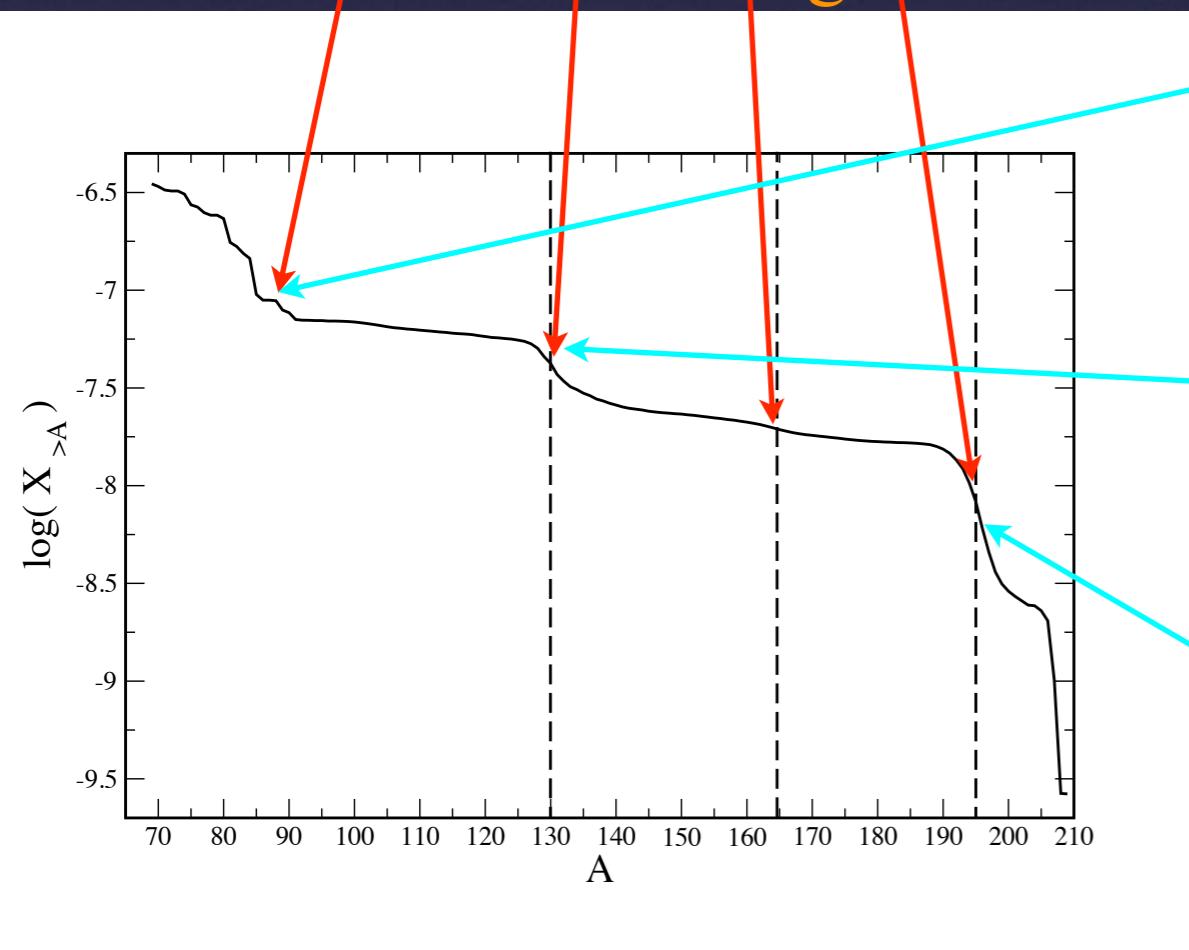
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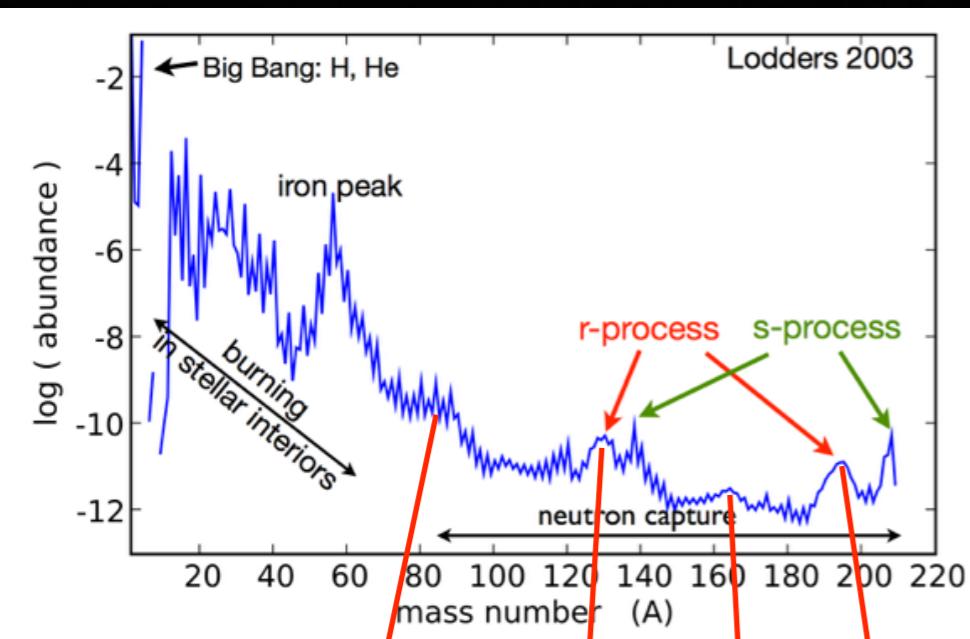


$2.4 \times 10^{-7}$  of nuclei beyond the  $A = 80$  peak

$4.2 \times 10^{-8}$  of nuclei beyond the  $A = 130$  peak

$8.3 \times 10^{-9}$  of nuclei beyond the “platinum peak” ( $A = 195$ )

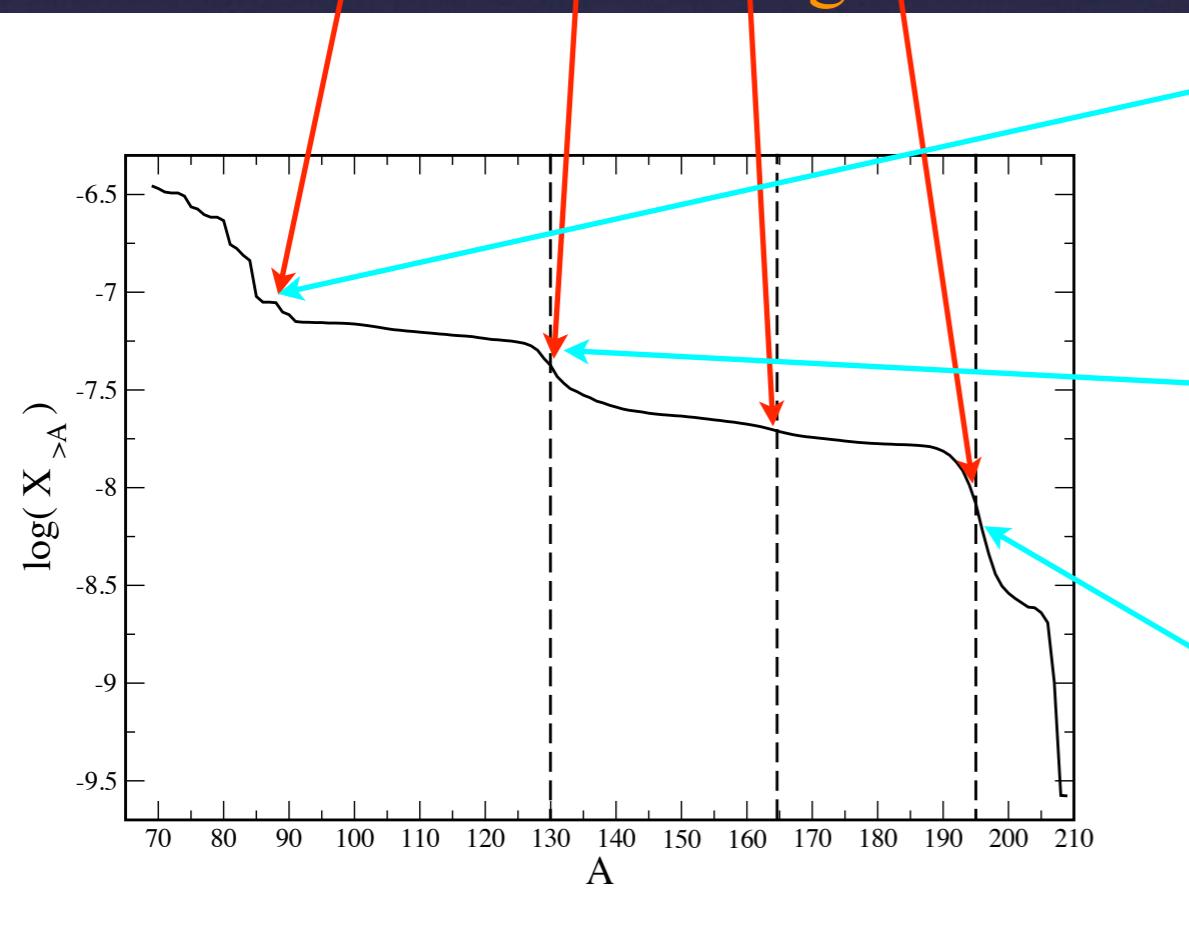
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Total amount Galaxy?  
 $(6 \times 10^{10} M_{\odot}$  baryonic;  
 McMillan+ 2011)

Which fraction of r-process material  
has a nucleon number larger than A?

total:  $19\,000 M_{\odot}$



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beyond the  $A = 80$  peak

$14\,000 M_{\odot}$

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$2530 M_{\odot}$

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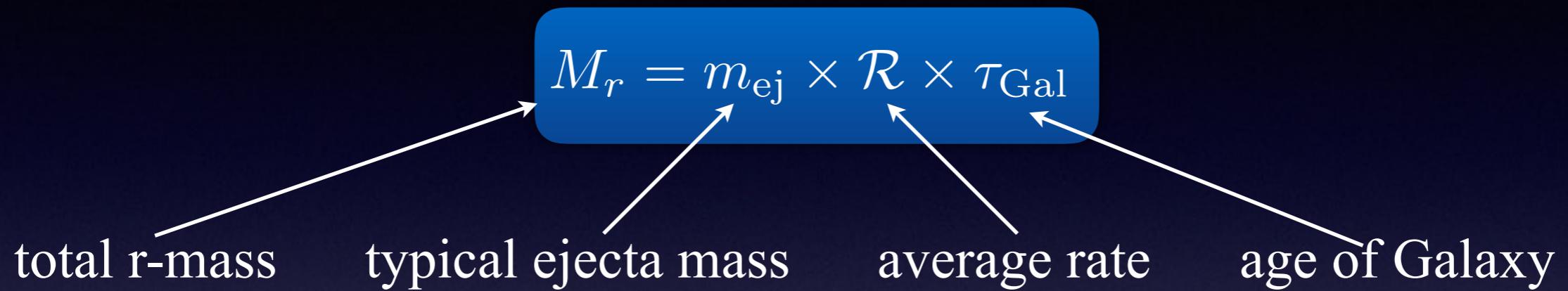
$500 M_{\odot}$

What does this imply for the production rate?

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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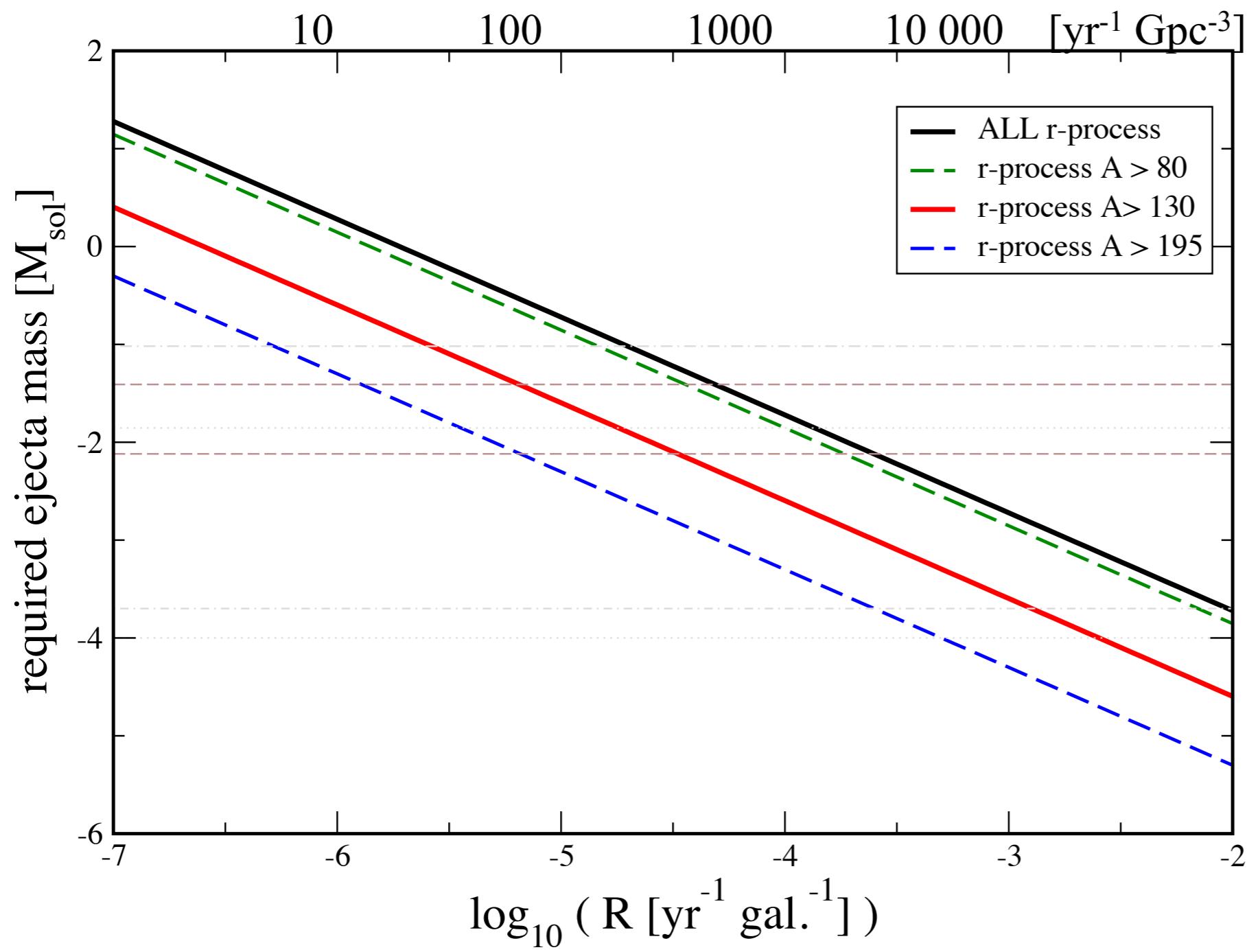
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- degeneracy  $m_{ej} \times \mathcal{R} = \frac{M_r}{\tau_{Gal}}$
- |                    |  |
|--------------------|--|
| all r-process:     | $1.9 \times 10^{-6} \frac{M_{\odot}}{\text{yr}}$ |
| r-process A > 80:  | $1.4 \times 10^{-6} \frac{M_{\odot}}{\text{yr}}$ |
| r-process A > 130: | $2.5 \times 10^{-7} \frac{M_{\odot}}{\text{yr}}$ |

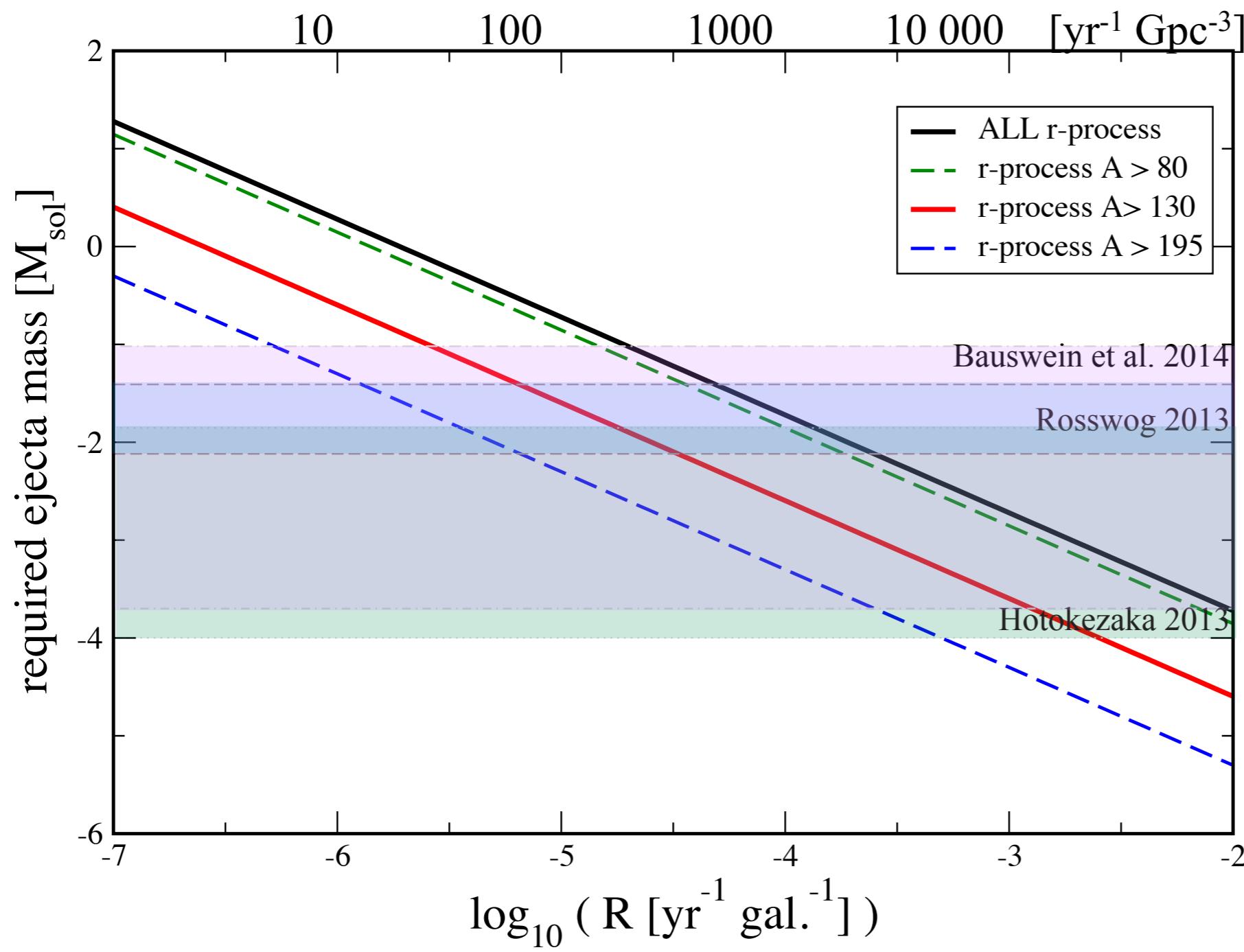
$\Rightarrow$  “rare high-mass (e.g. NSNS merger) or frequent low-mass events (like supernovae) ?”

# NSNS estimates only



LIGO O2: fall 2016  
LIGO O3: fall 2017  
LIGO limits from  
Abbott++ 2016

# NSNS estimates only



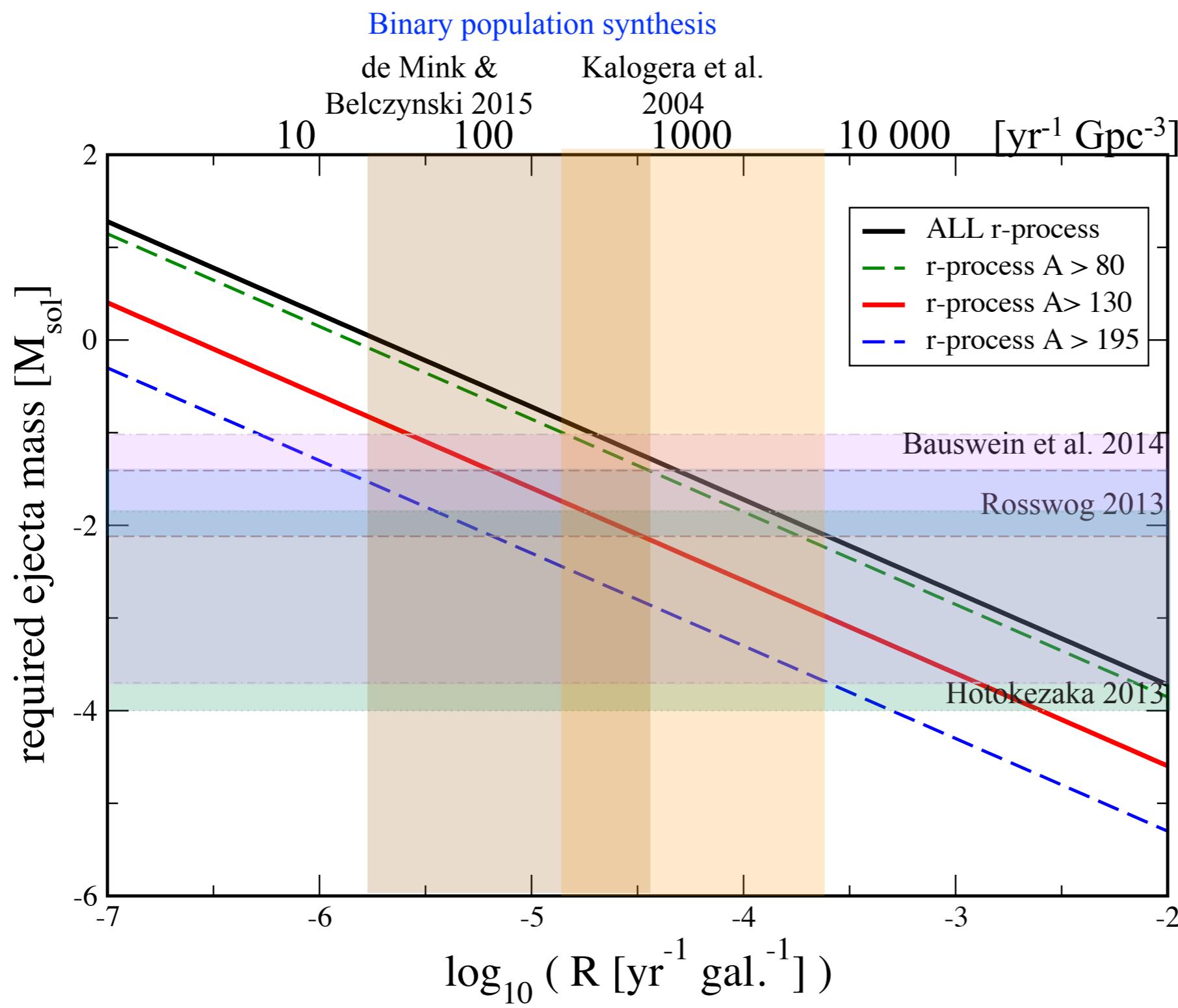
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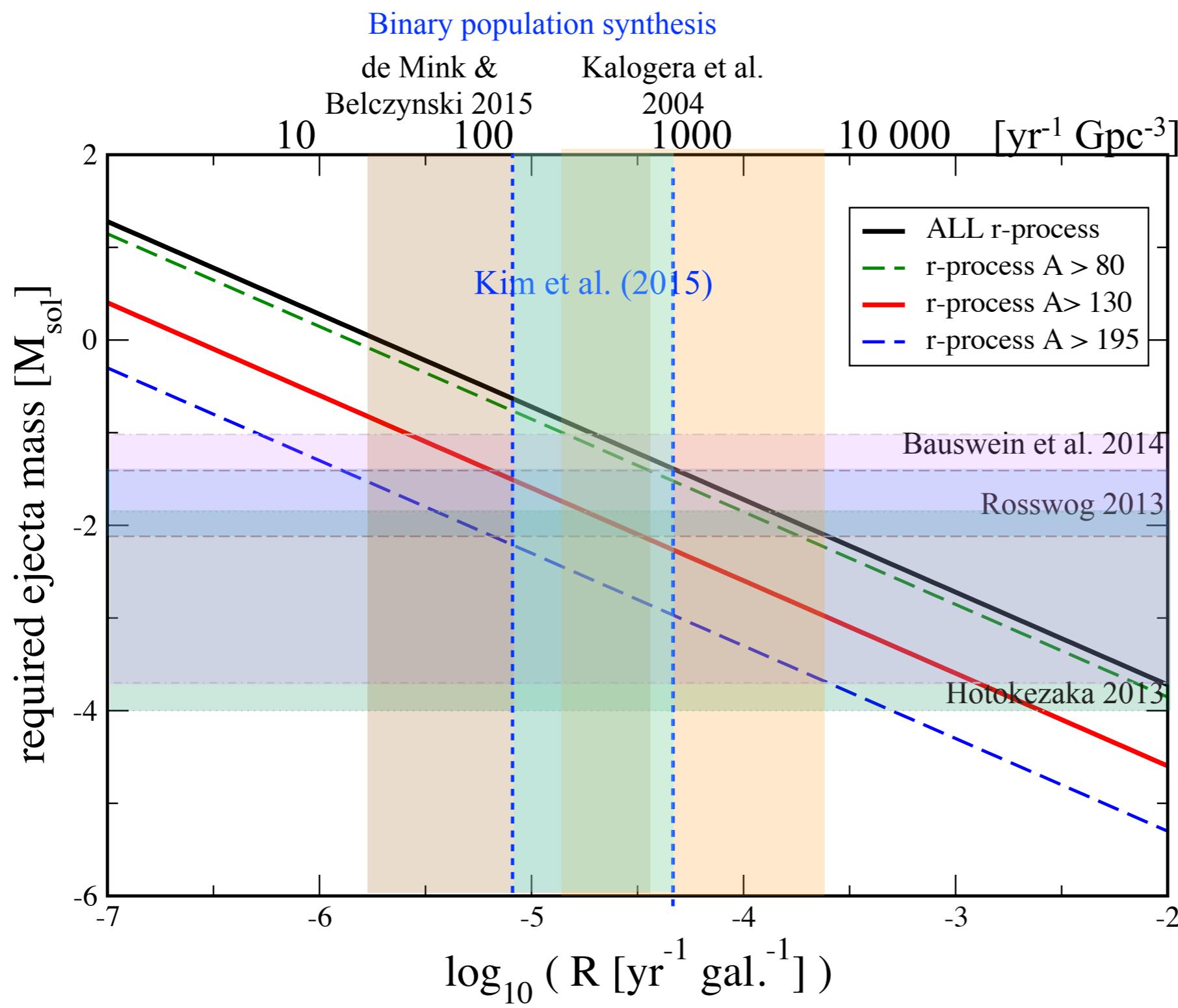
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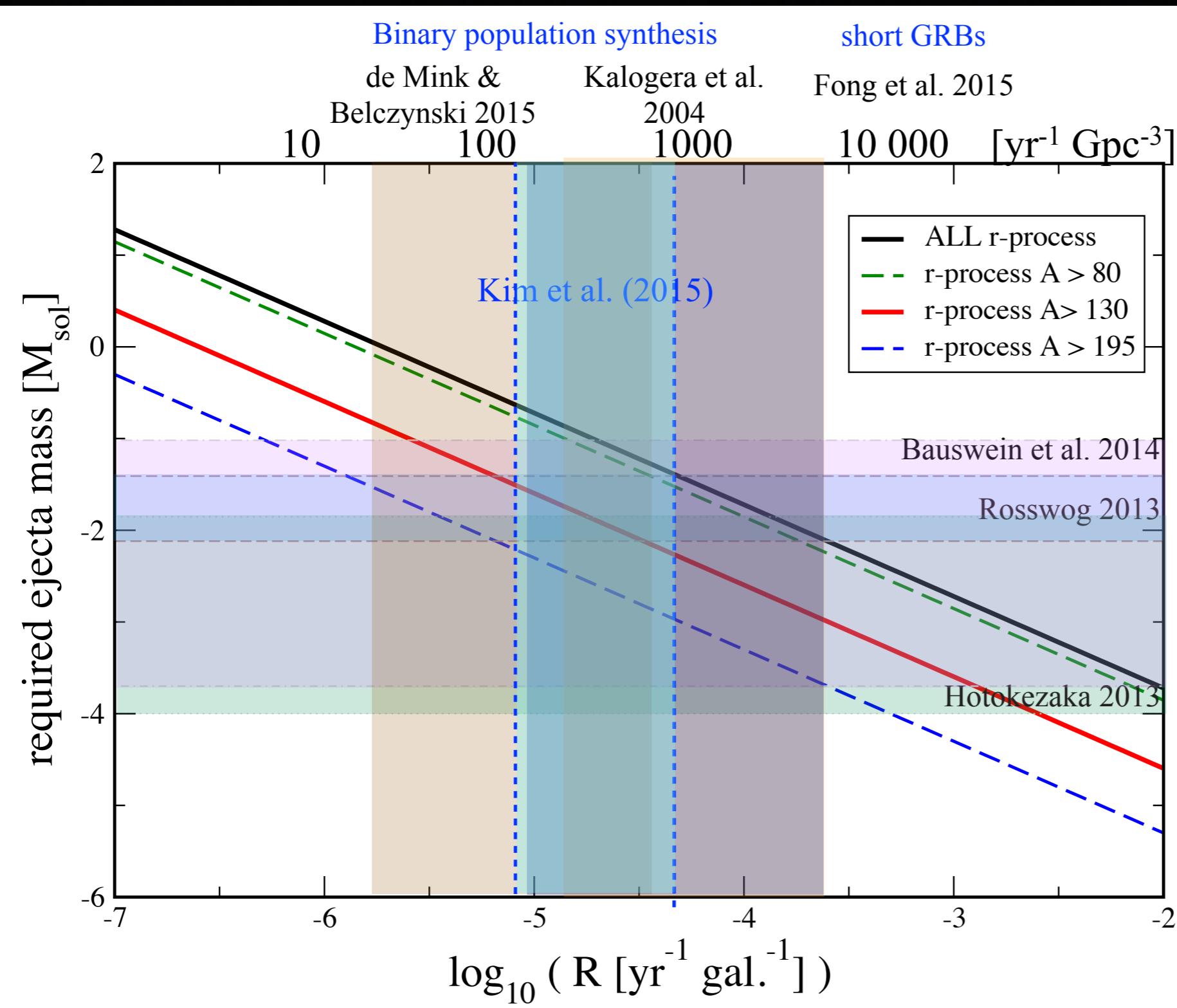
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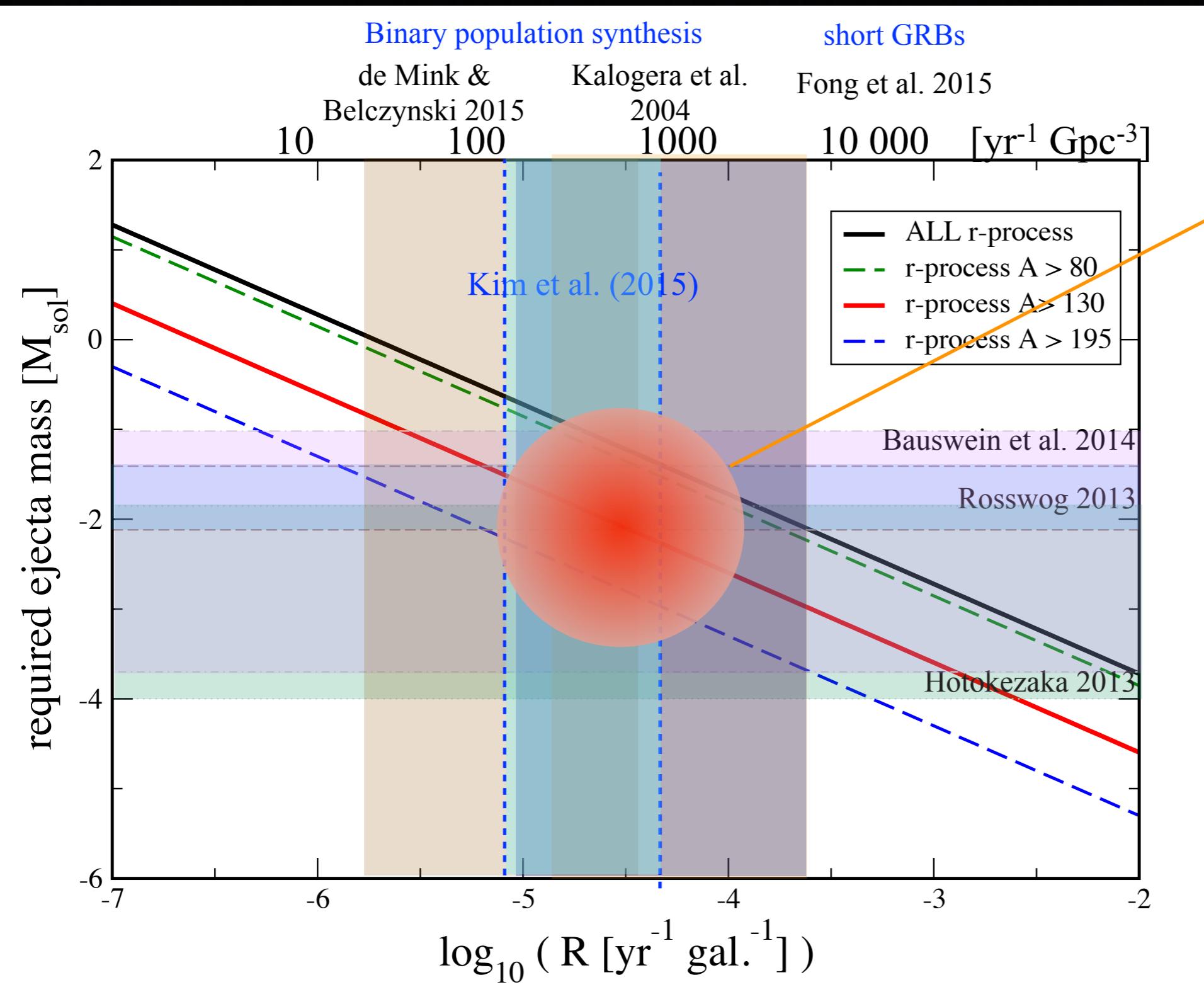
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“sweetspot” at  
 $\sim 300 \text{ yr}^{-1} \text{ Gpc}^{-3}$

= “informed best  
 guess” rate

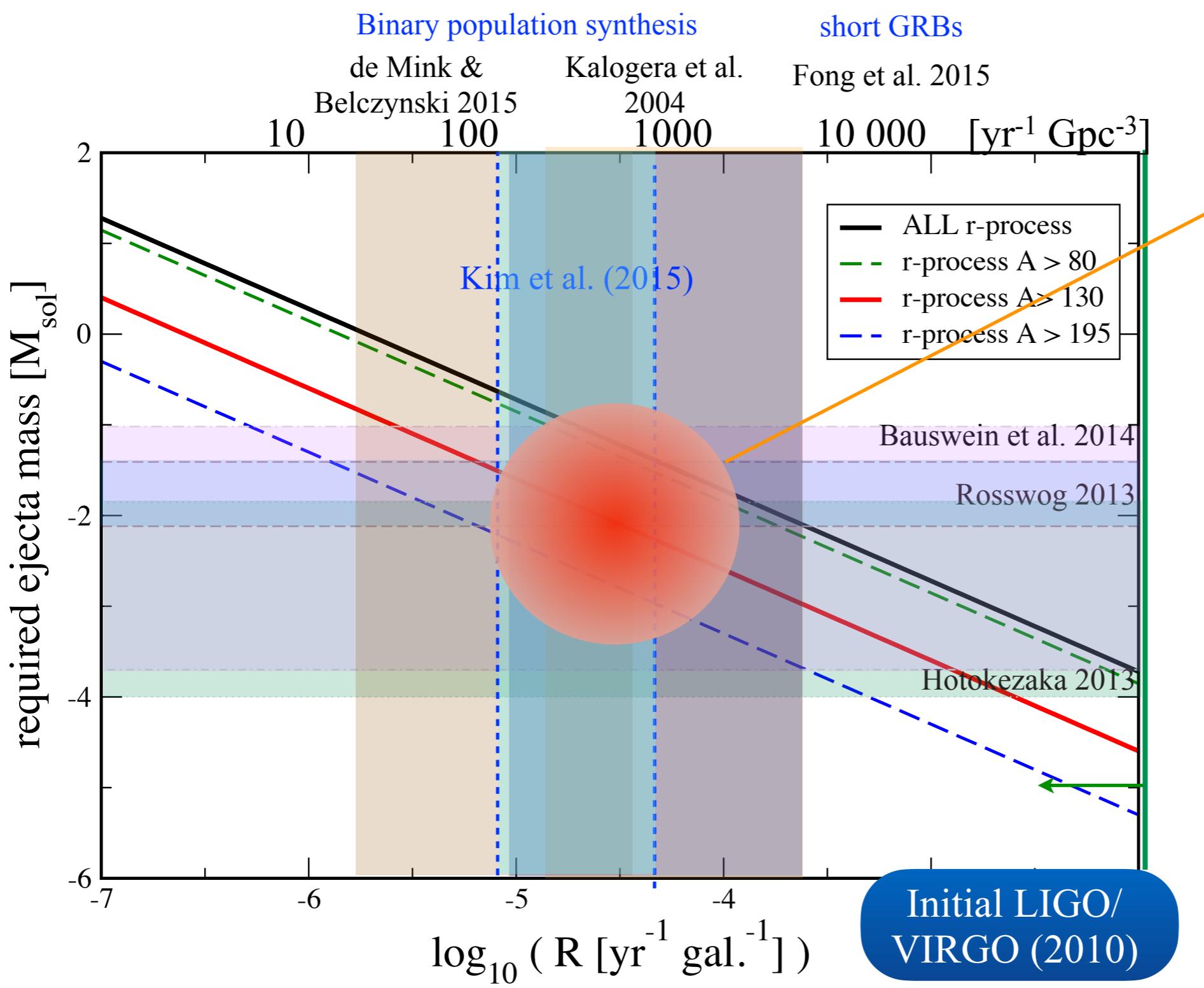
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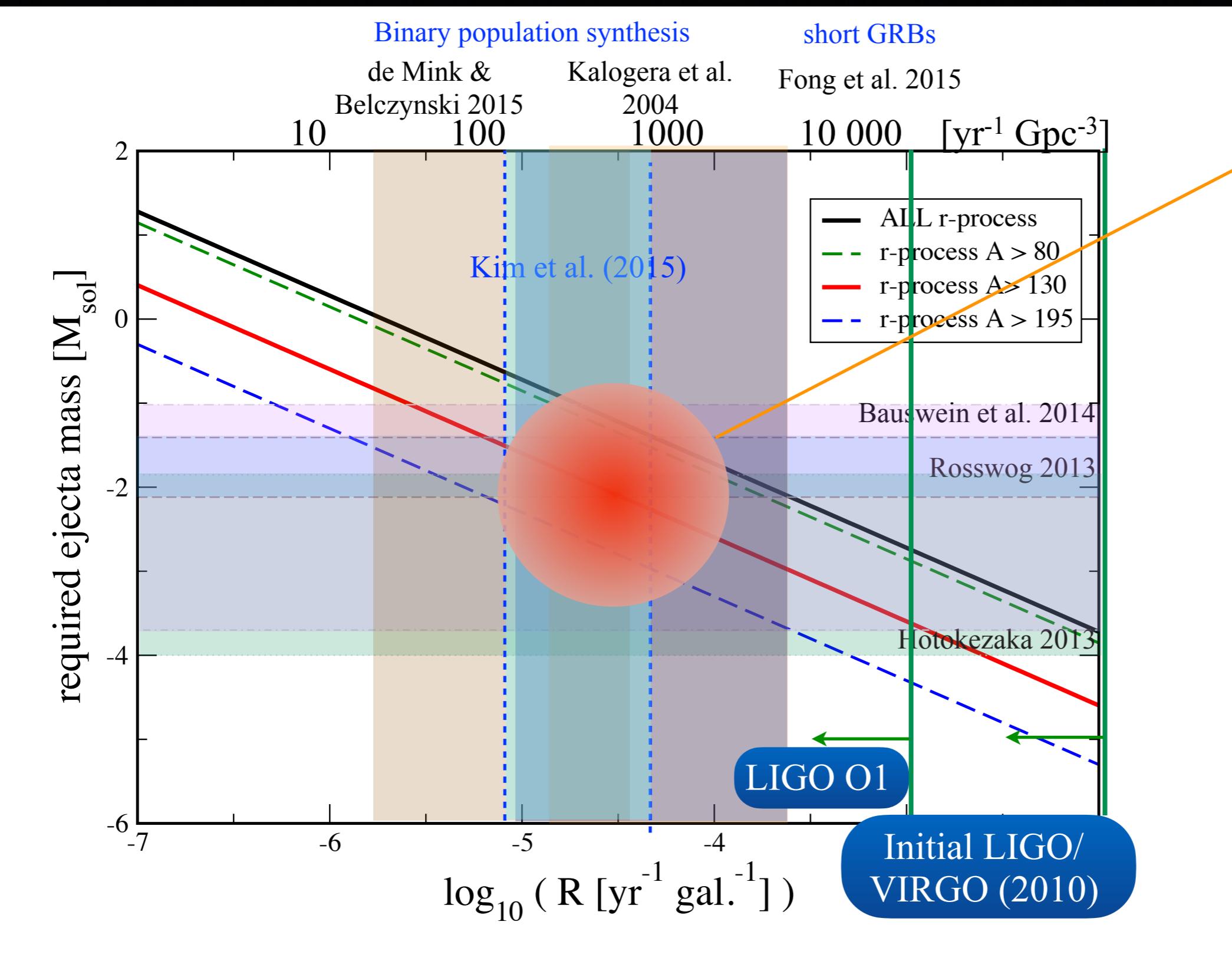
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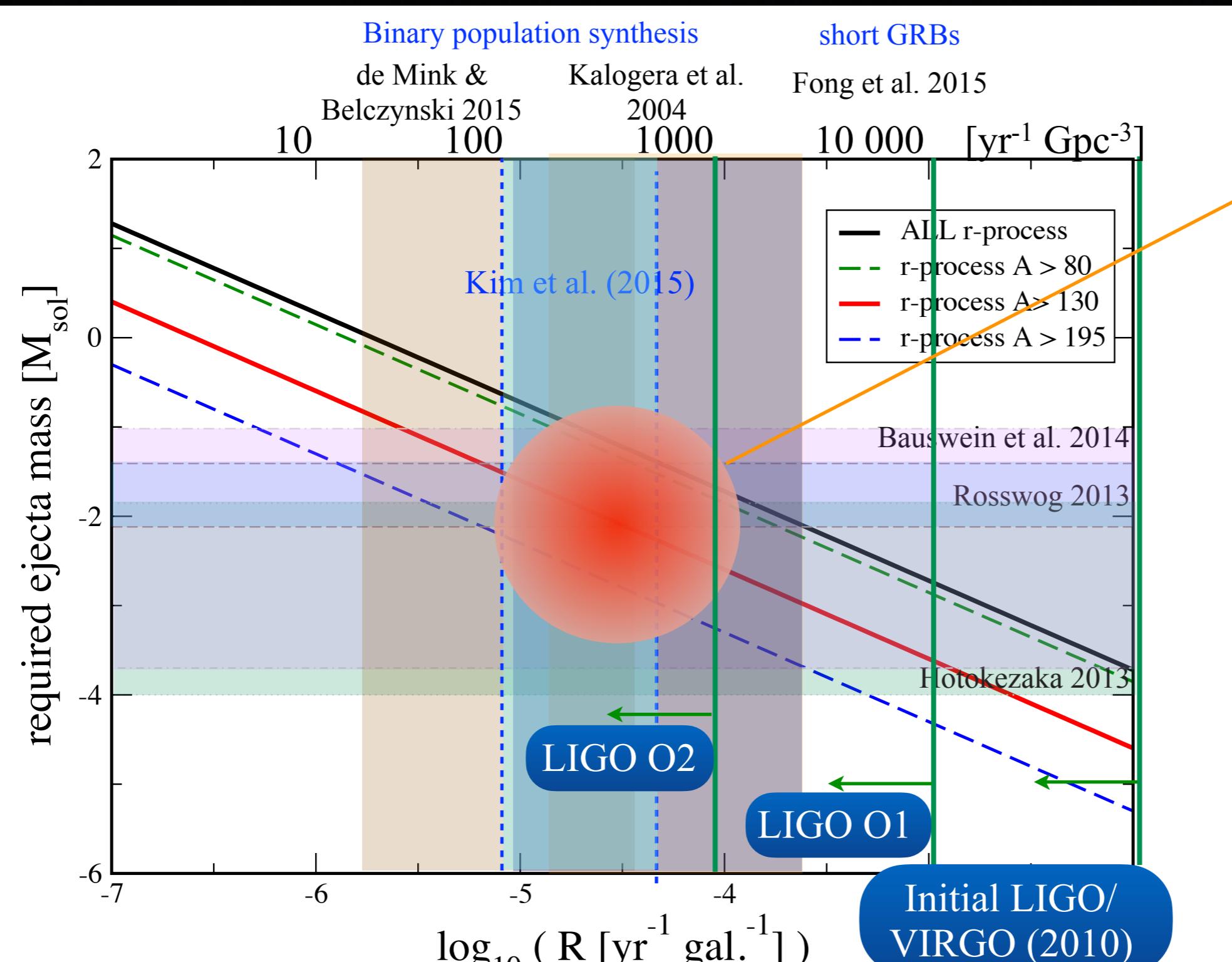
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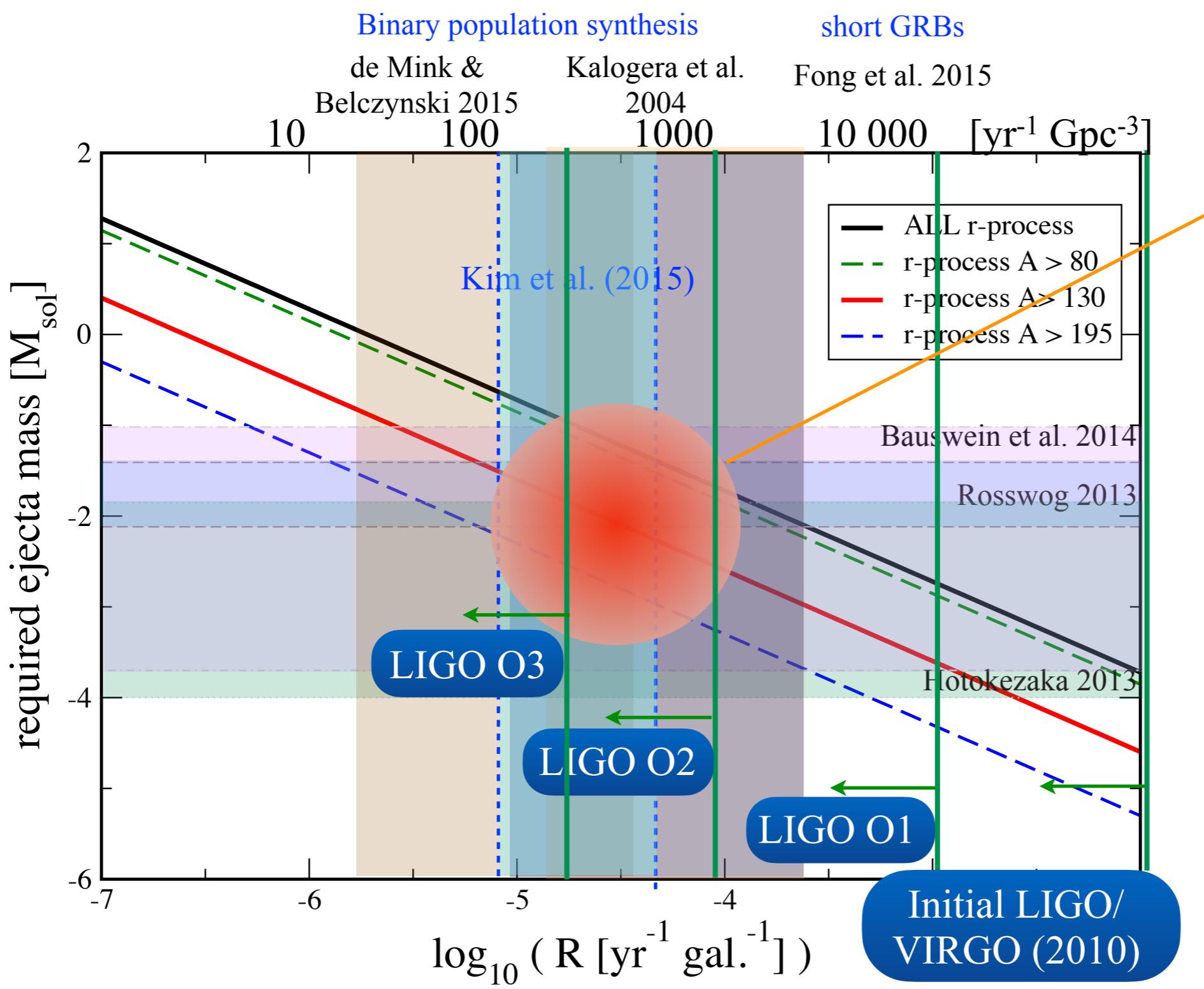
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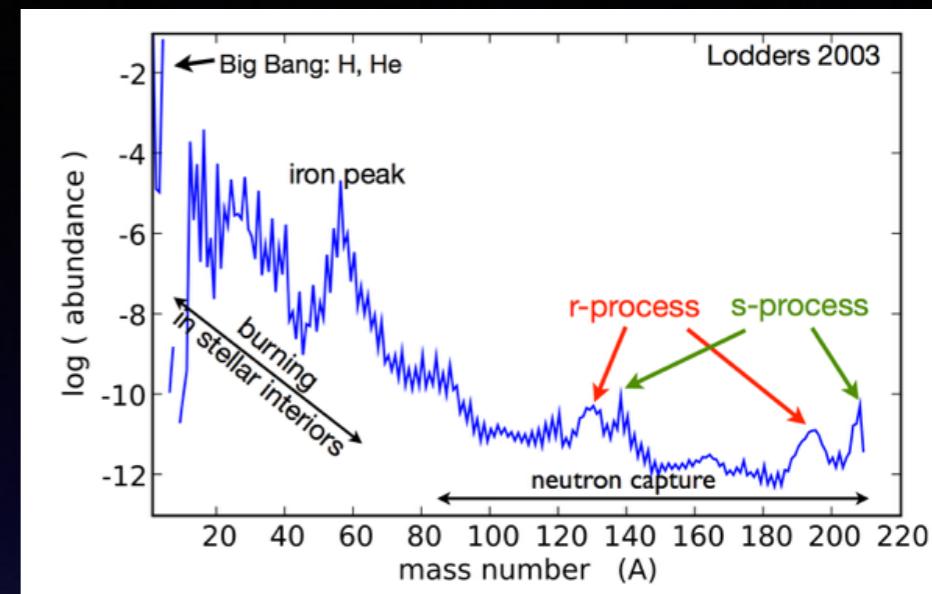
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# Role of electron fraction $Y_e$ play in heavy element nucleosynthesis?

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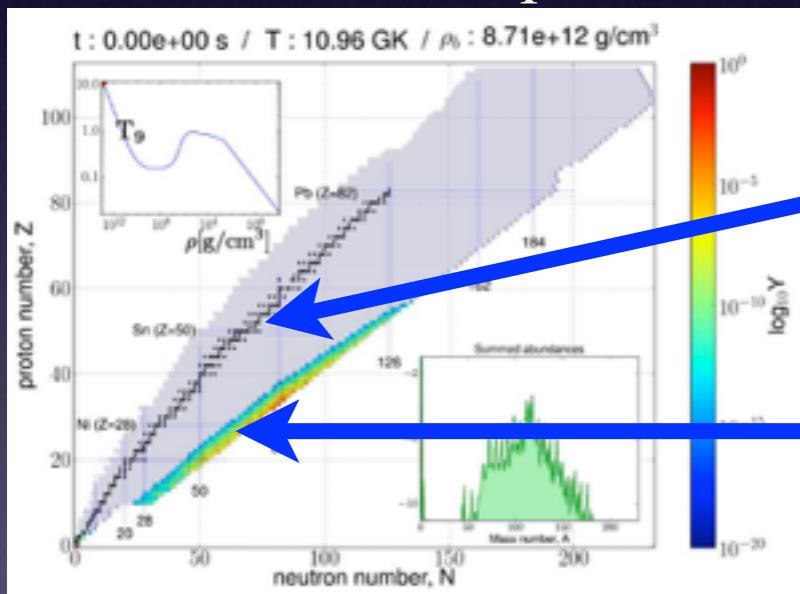
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 $\Rightarrow Y_e \sim 26/195 \sim 0.13$  very low!



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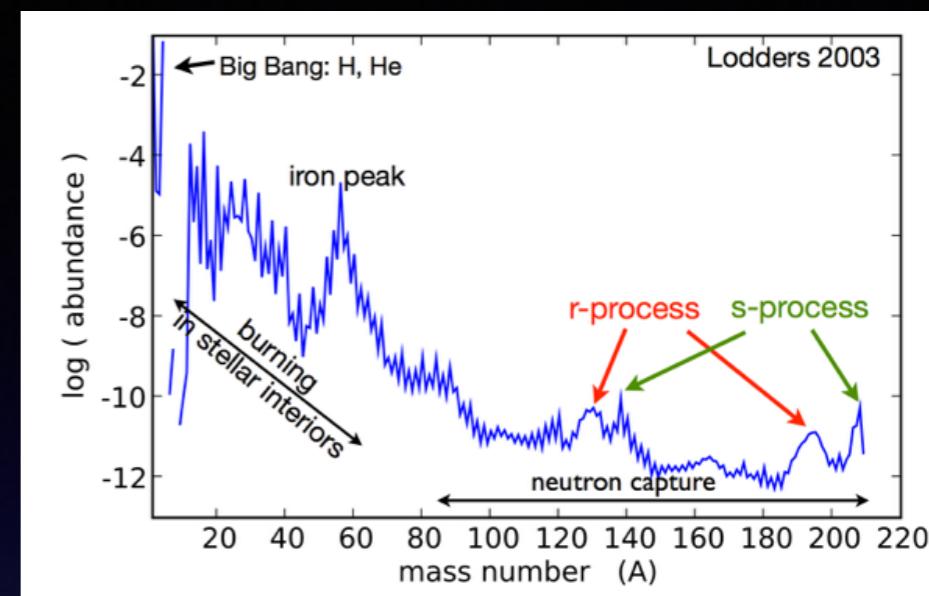


high  $Y_e$ :

- close to valley of  $\beta$ -stability
- nuclear properties from experiments

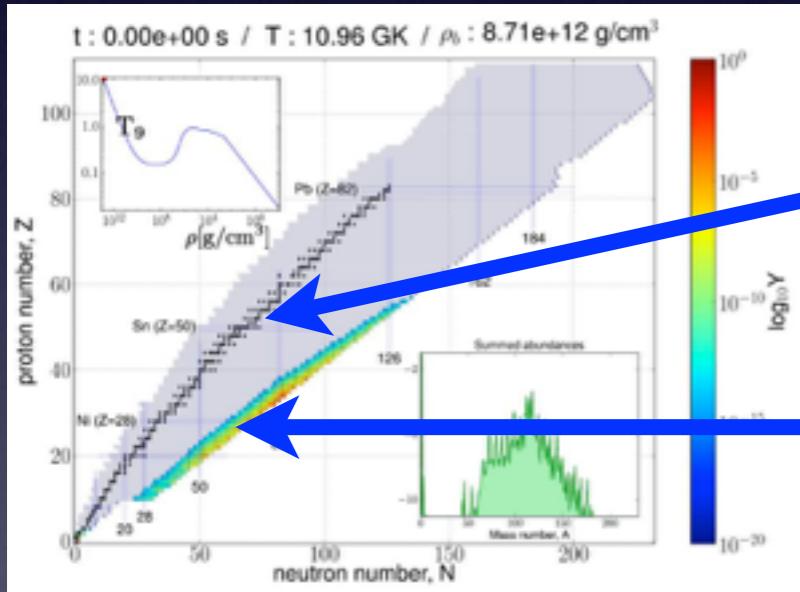
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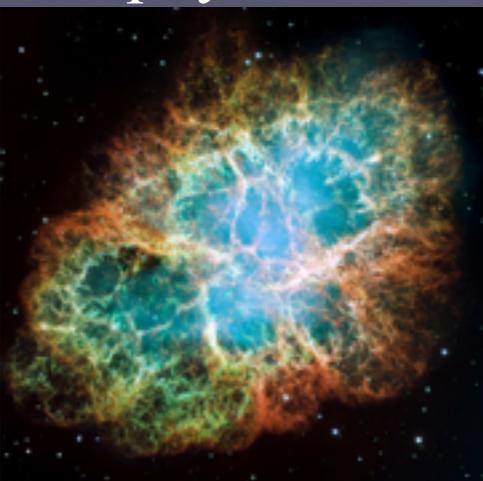
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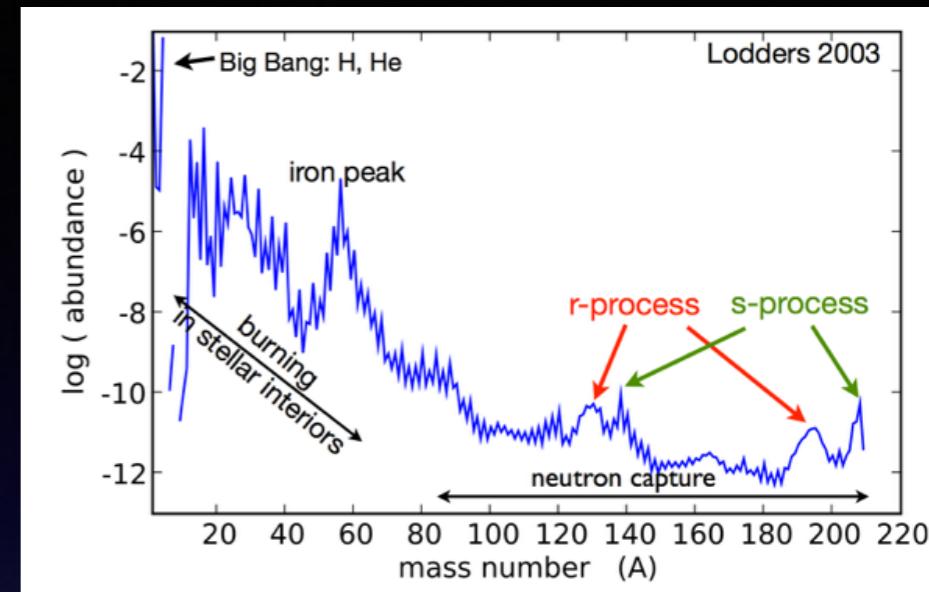
- close to neutron drip line
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- astrophysical realization



Supernova:

“de-leptonizing”  
from 0.5 down  
to  $Y_e \sim 0.3$

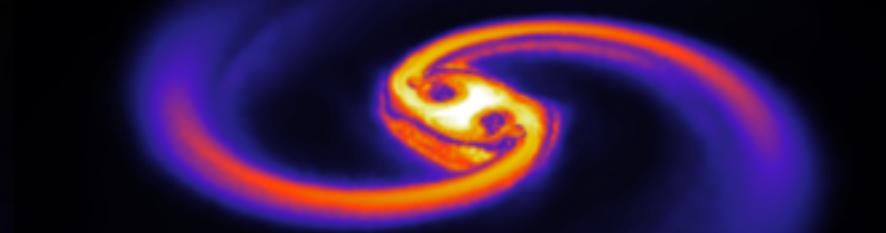


NS mergers:

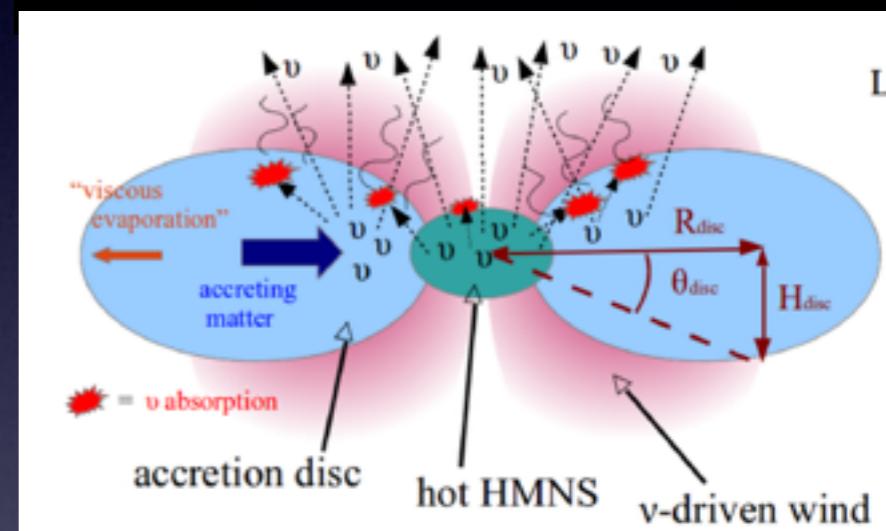
“re-protonizing”  
starting from  
 $Y_e \sim 0.1$

# Different mass loss channels

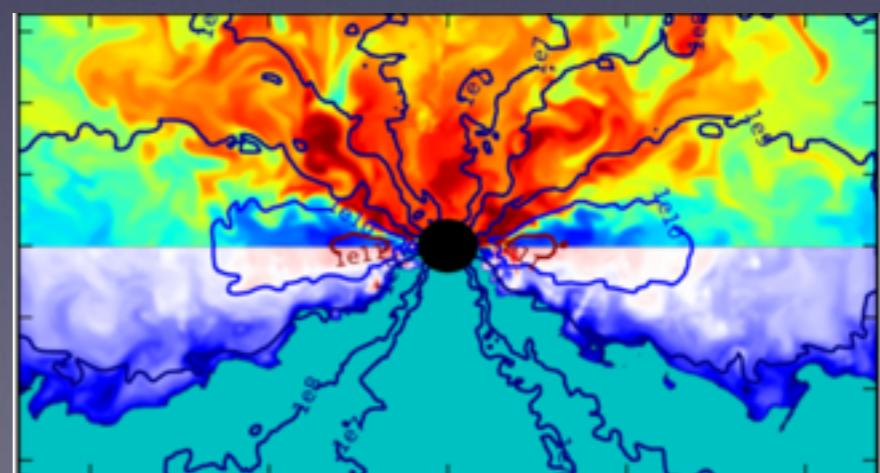
- “dynamic ejecta”:
  - “immediate”
  - via hydrodynamic interaction and grav. torques
  - typically  $\sim 0.01 M_{\odot}$
  - “low Ye”,  $Ye \sim 0.05$
- “winds”:
  - “delayed”
  - different origins,
    - e.g. neutrino-driven, or driven by Magneto-Rotational Instability (MRI)
  - typically  $\sim 25\%$  initial disk mass
  - “moderate Ye”,  $Ye \sim 0.25$



dynamic ejecta (SR+ 2017)



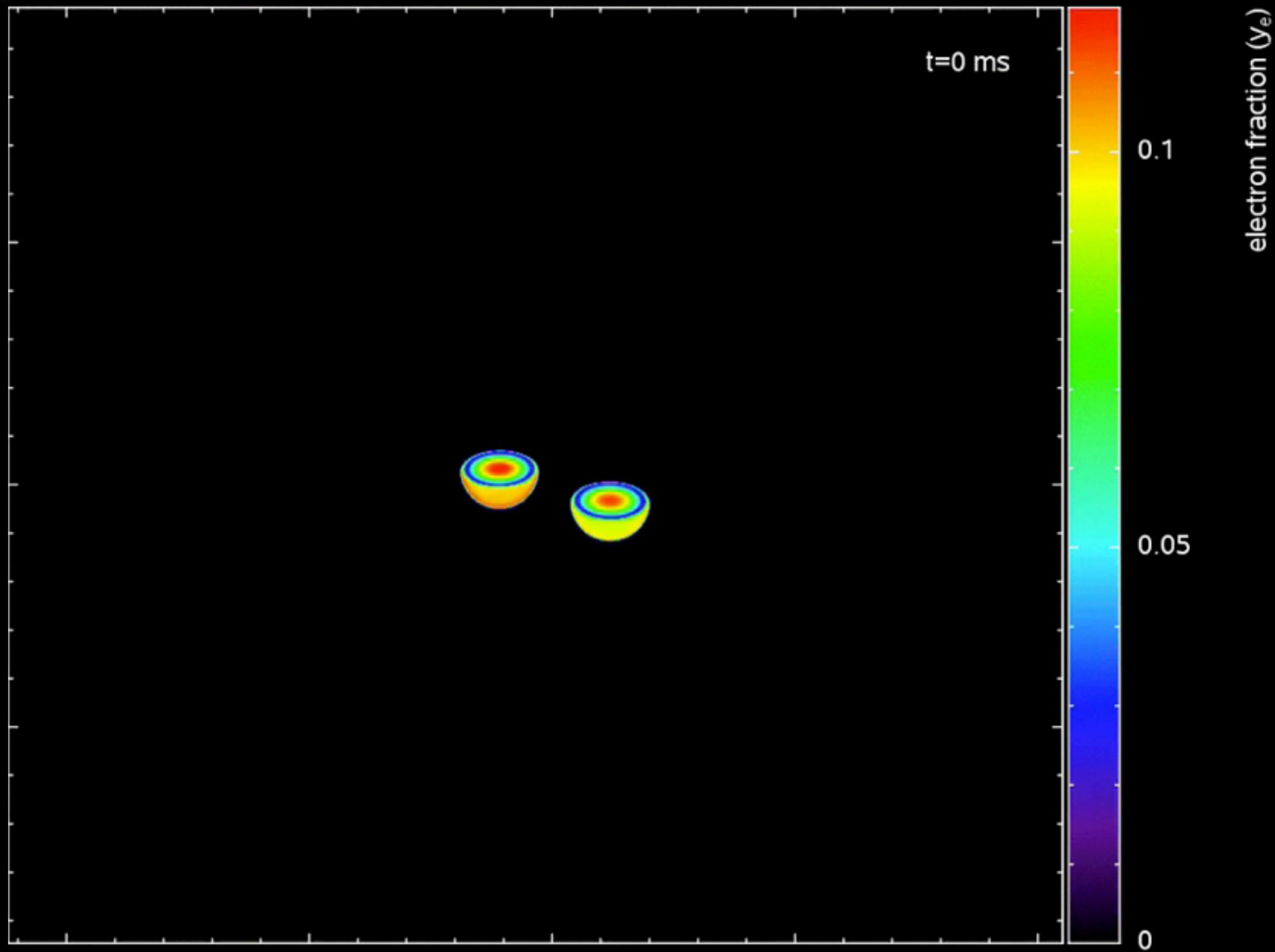
v-driven wind (Perego+ 2014)



MRI-driven wind  
(Siegel & Metzger 2017)

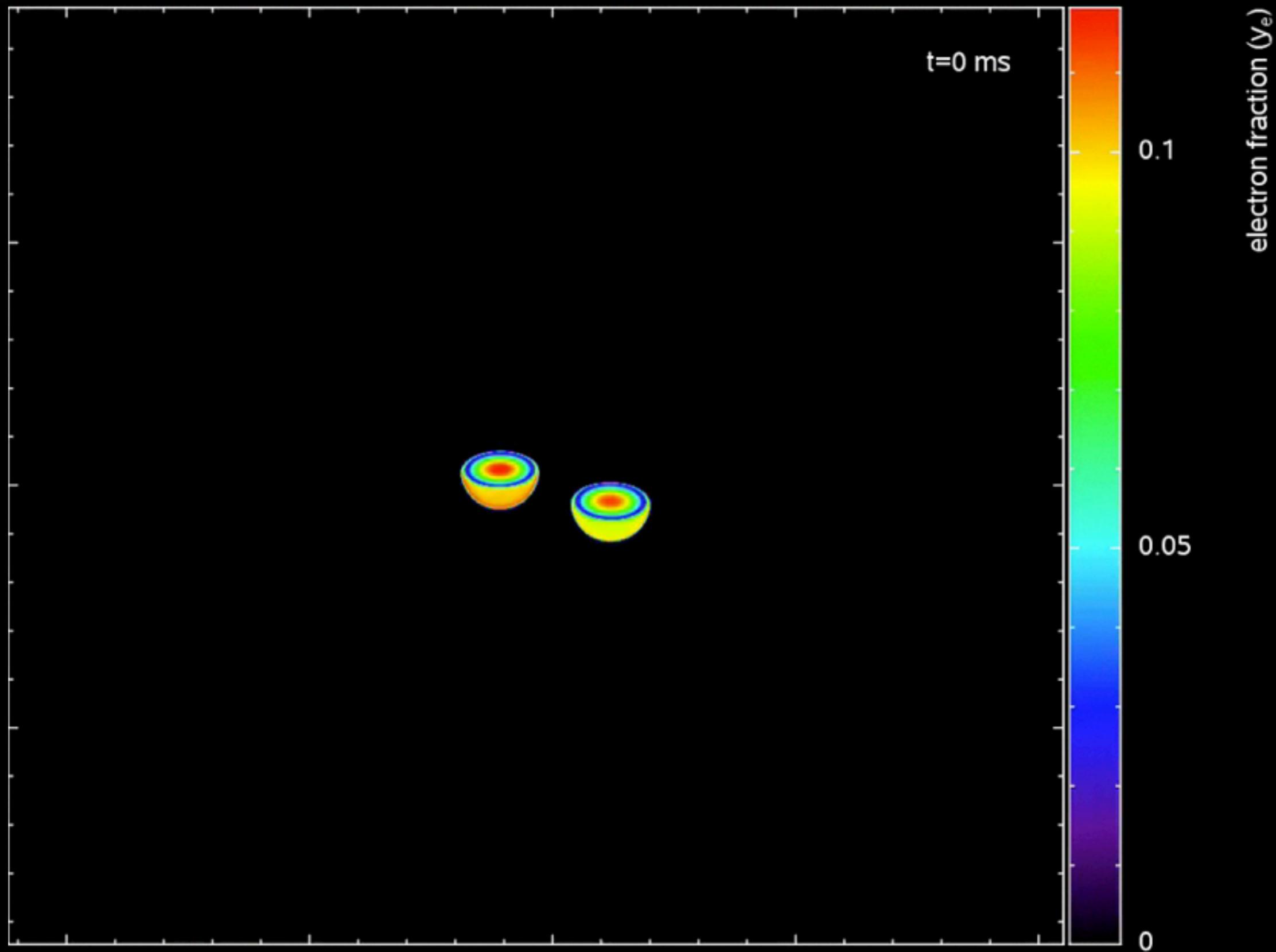
# Nucleosynthesis for dynamic ejecta

Example:  
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# r-process calculations for dynamic ejecta

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

T<sub>9</sub>

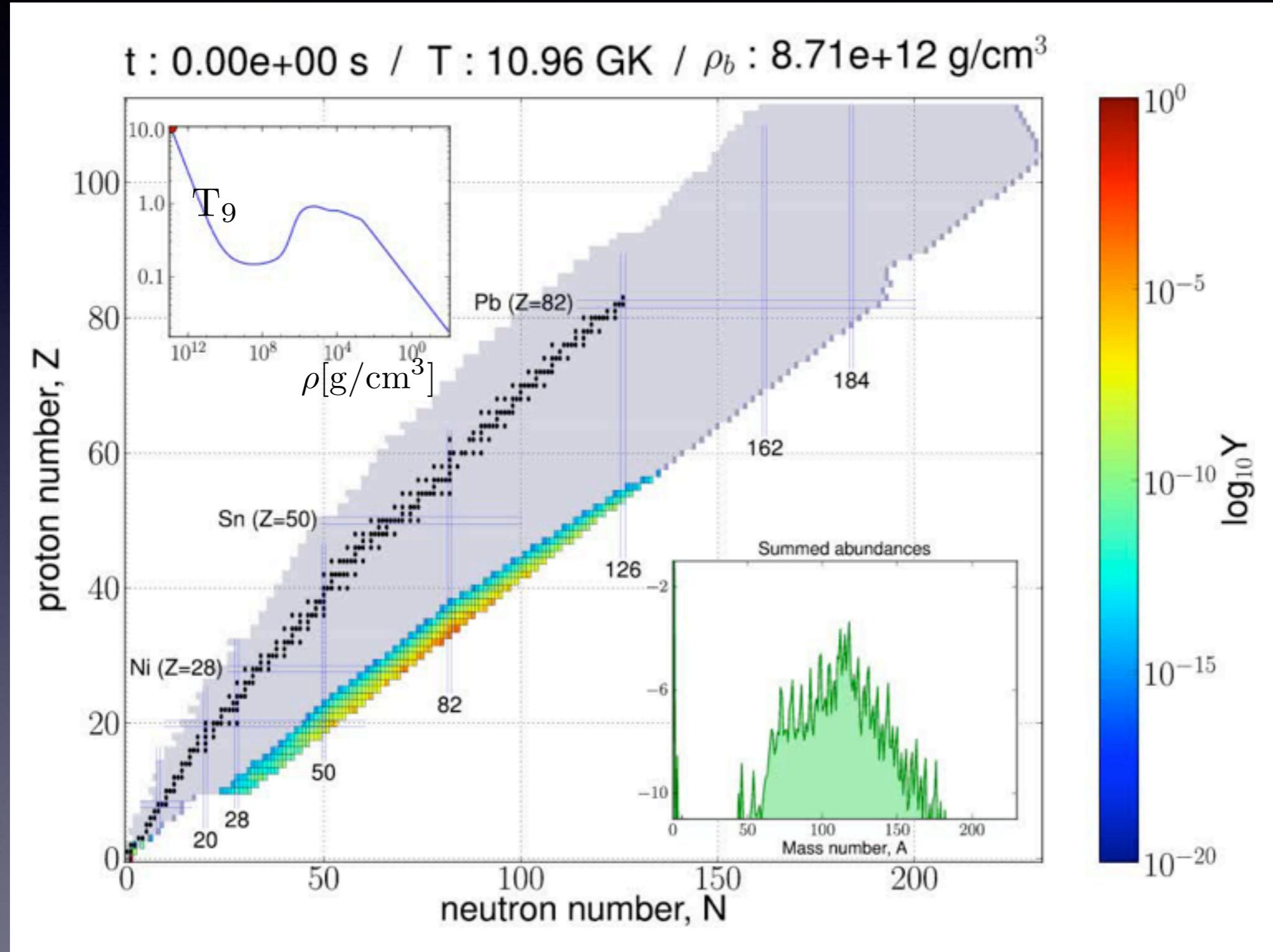
$\rho$ [g/cm<sup>3</sup>]

Winnet network  
(Winteler 2012)

5 831 isotopes

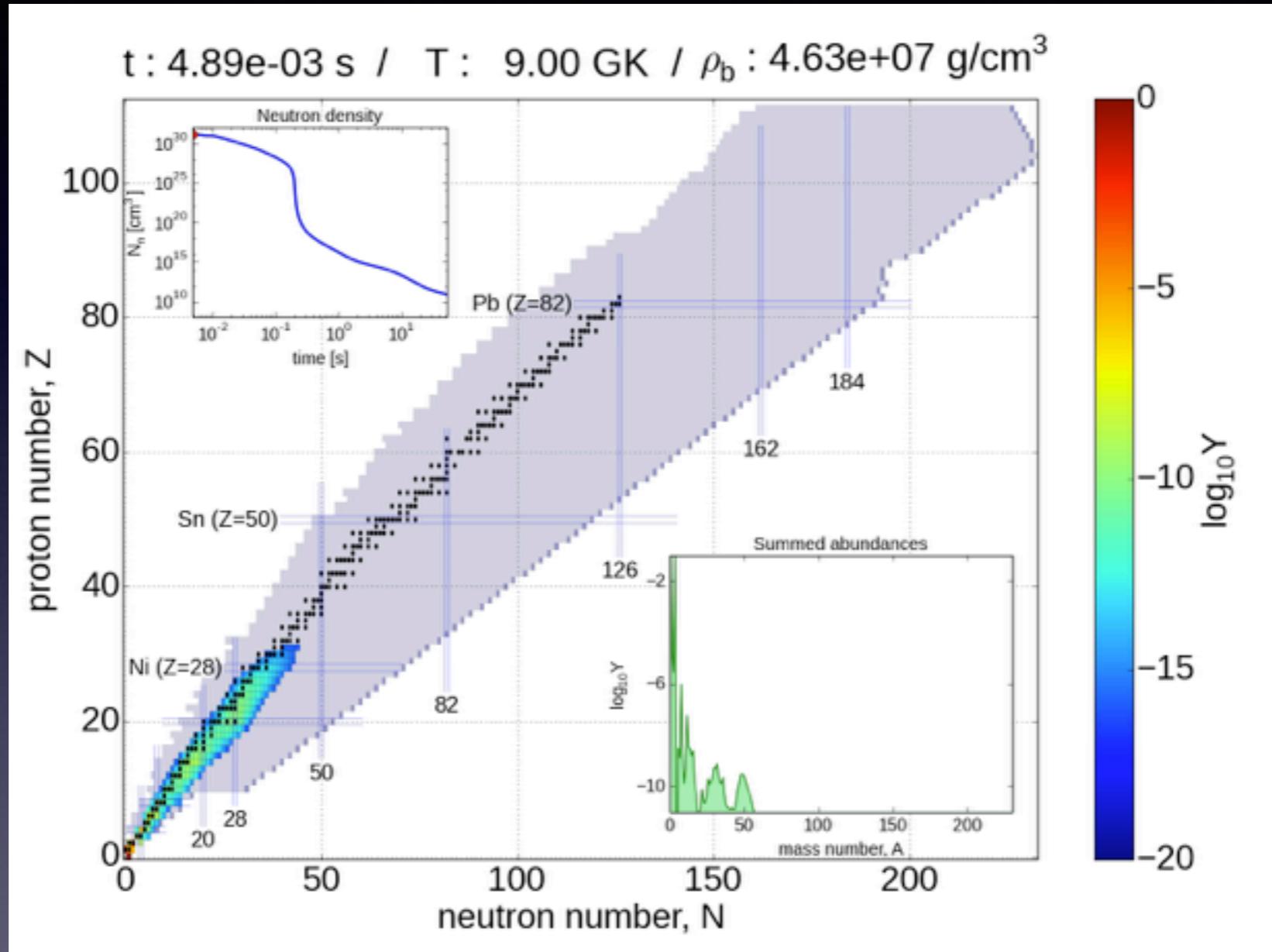
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# nucleosynthesis in neutrino-driven winds

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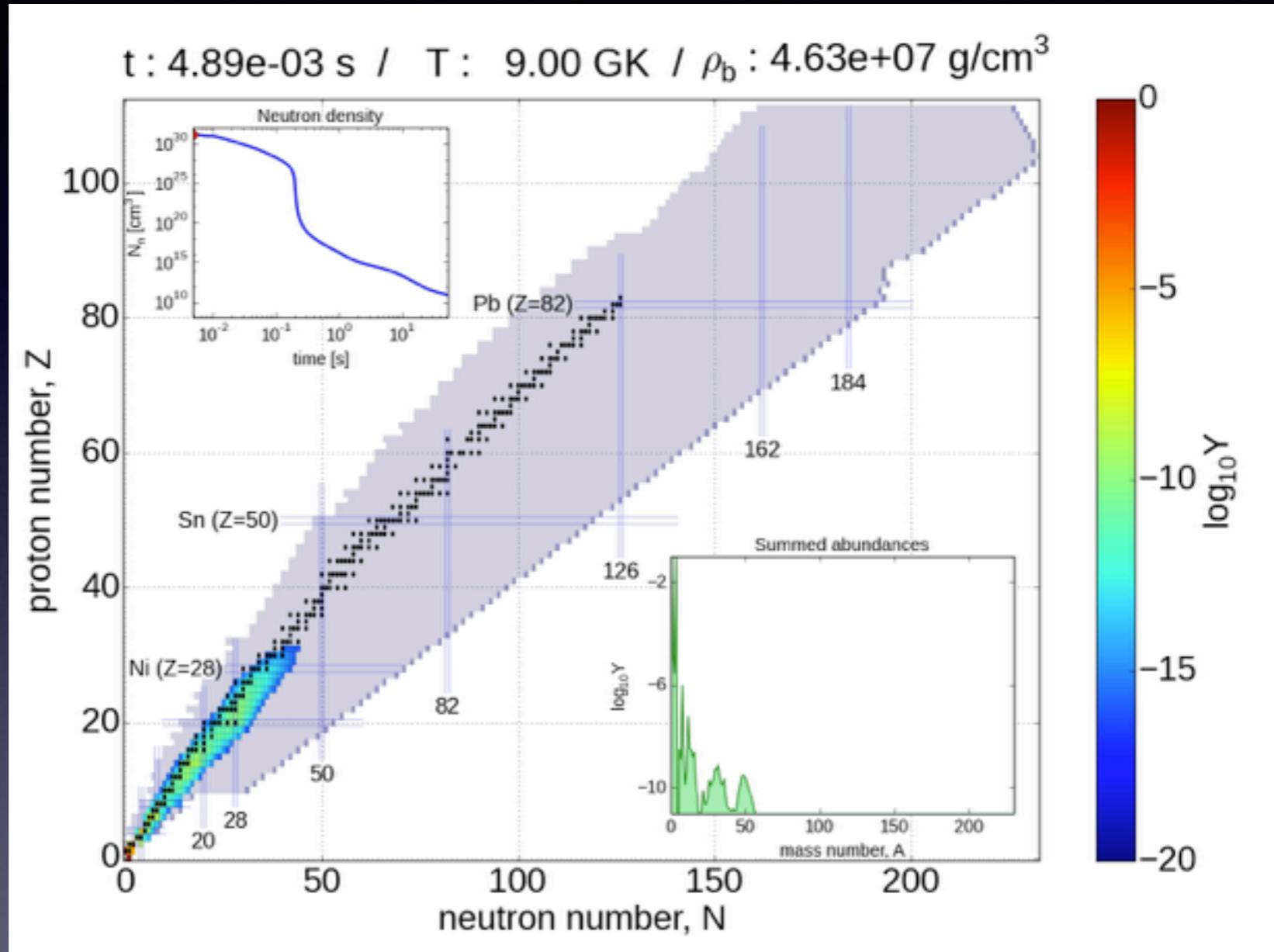


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complementary r-process in the range  $80 \leq A \leq 130$

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# nucleosynthesis dynamic ejecta $\leftrightarrow$ winds

## Dynamic ejecta

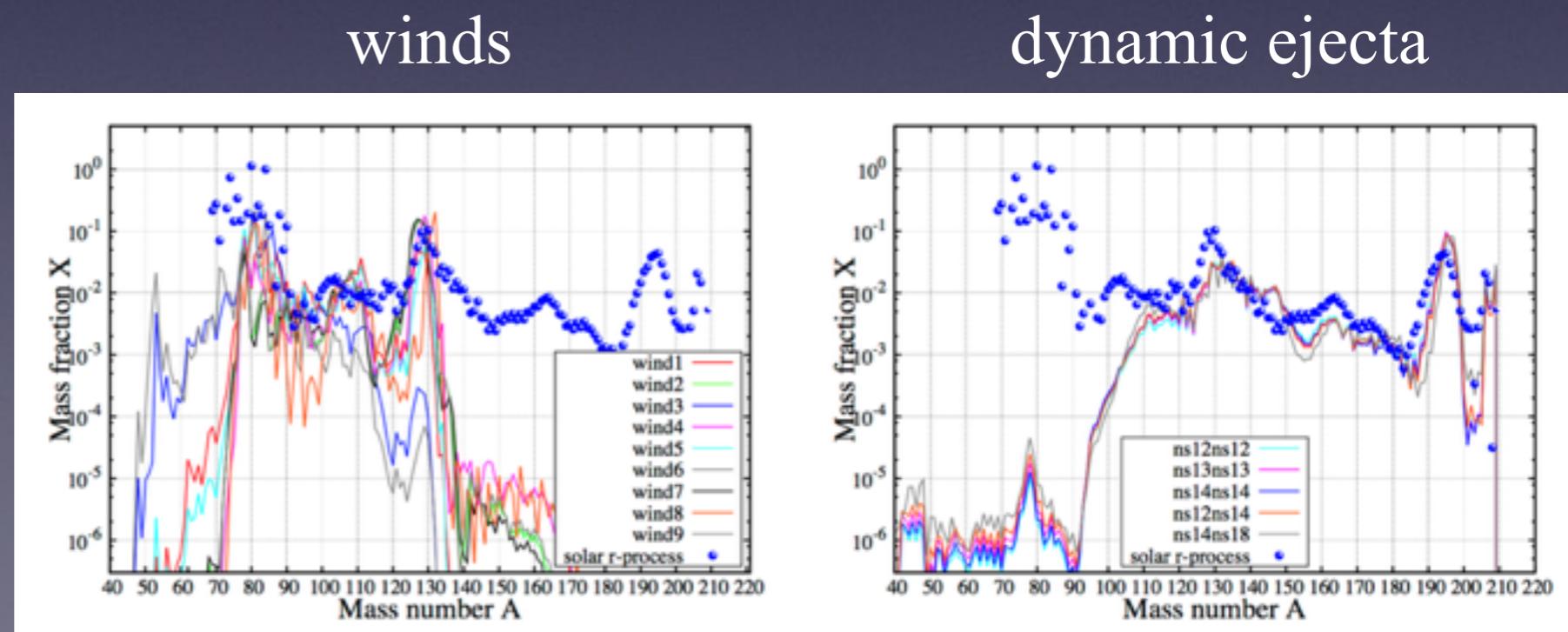
- all cases reach the “platinum peak” ( $A=195$ ) without any tuning
- not much below  $A=130$
- extremely (!) robust abundance pattern (same pattern for explored  $\sim 30$  binaries)

## “Winds”

- much more case-to-case variation
- mostly “weak r-process” ( $80 < A < 130$ )
- in cases full r-process range (e.g. Siegel & Metzger 2017)

## Together

- full r-process range in close-to-solar proportions



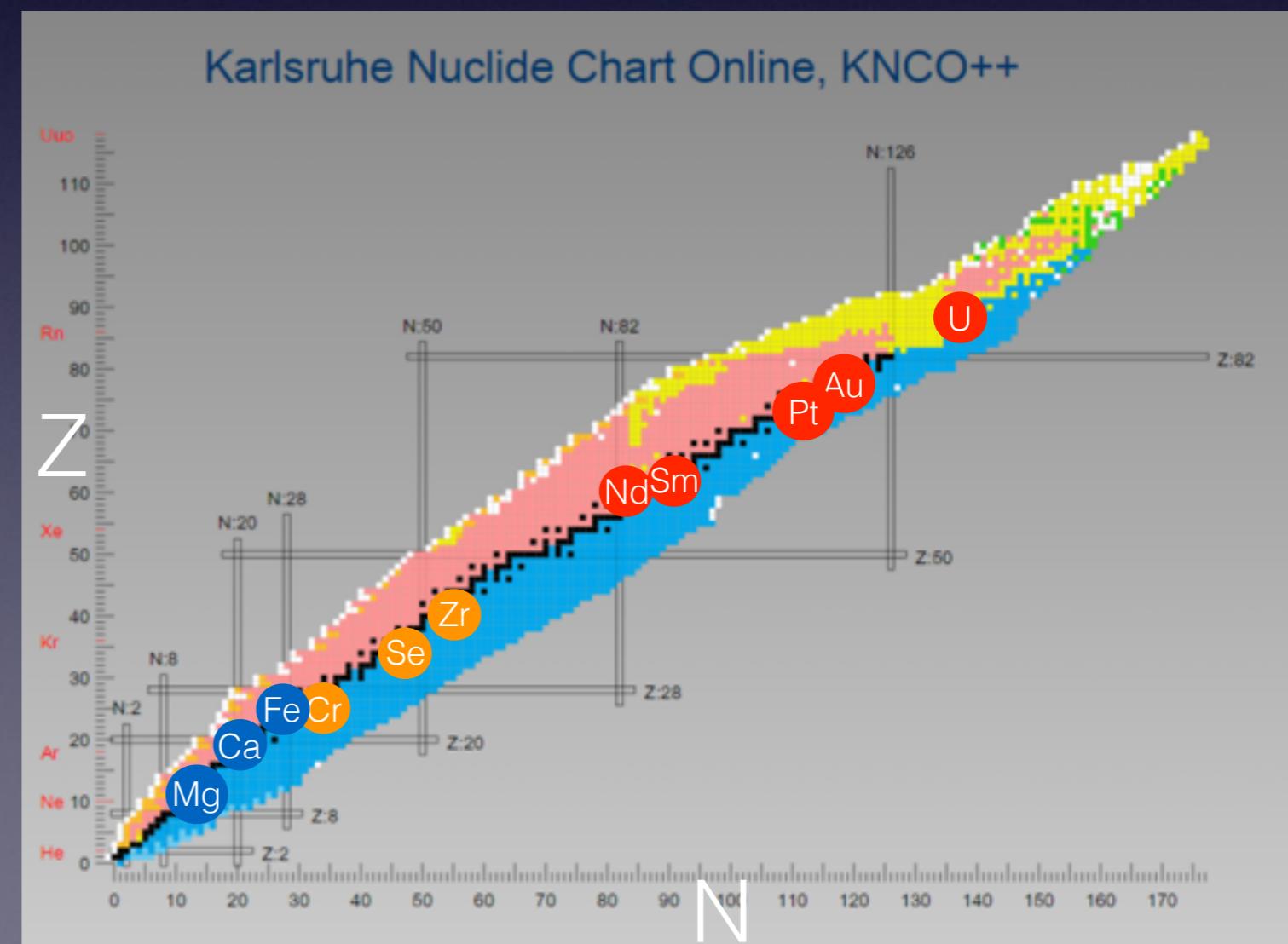
# “Macronovae”

Radioactively powered transients (“macronovae”)

- original suggestion Li & Paczynski (1998)

- similarities to supernovae:
  - expanding, radioactive material

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



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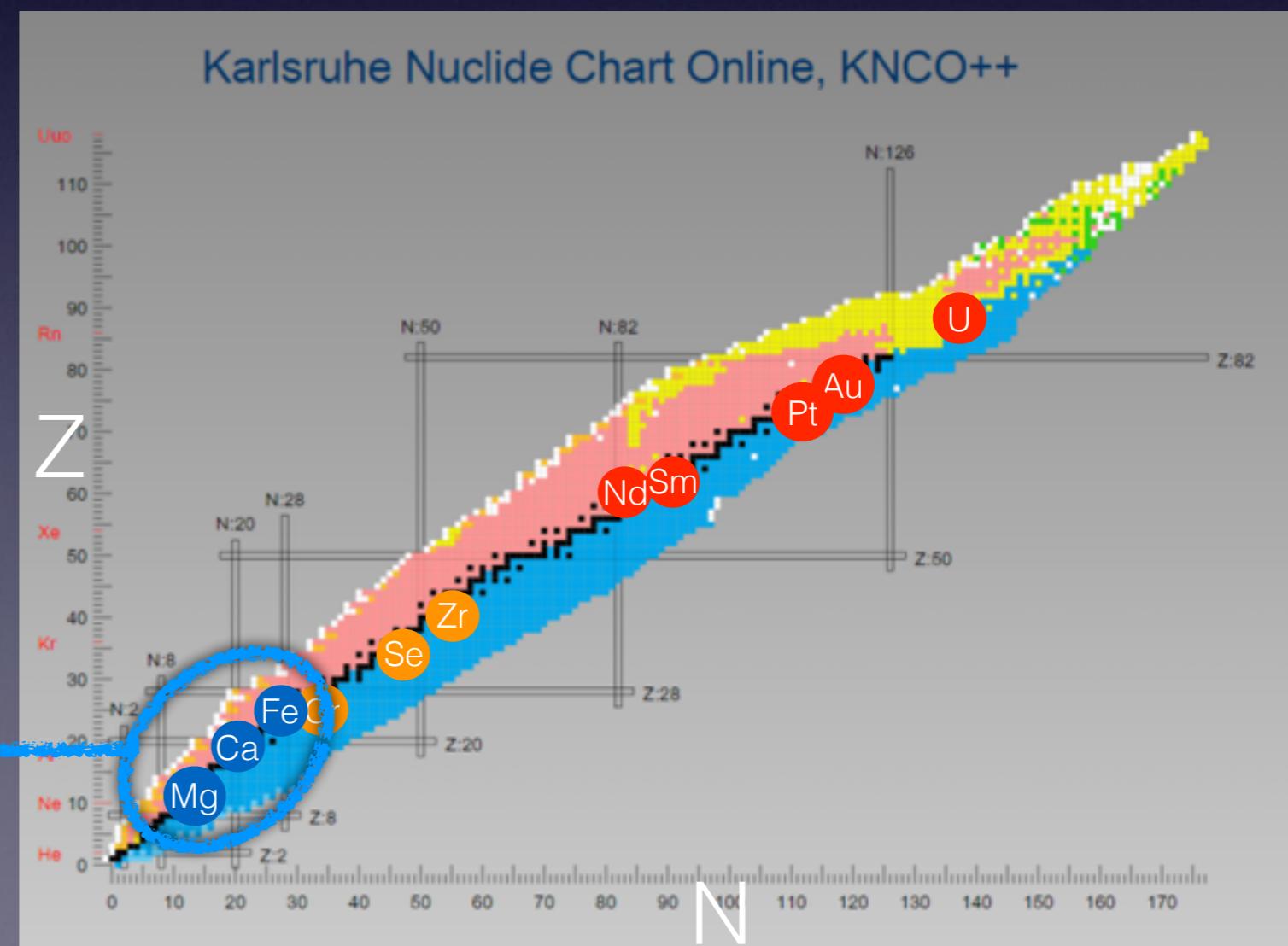
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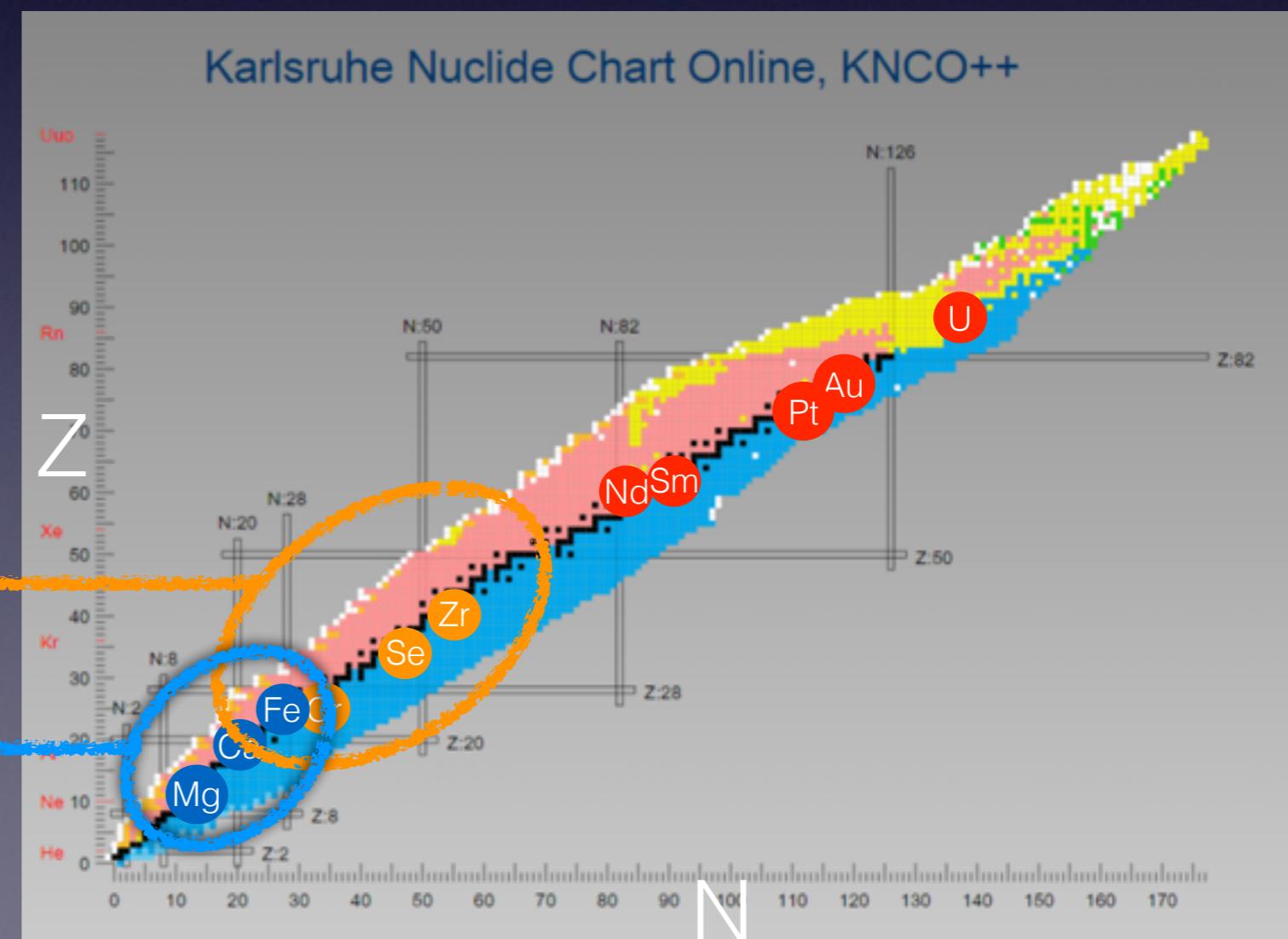
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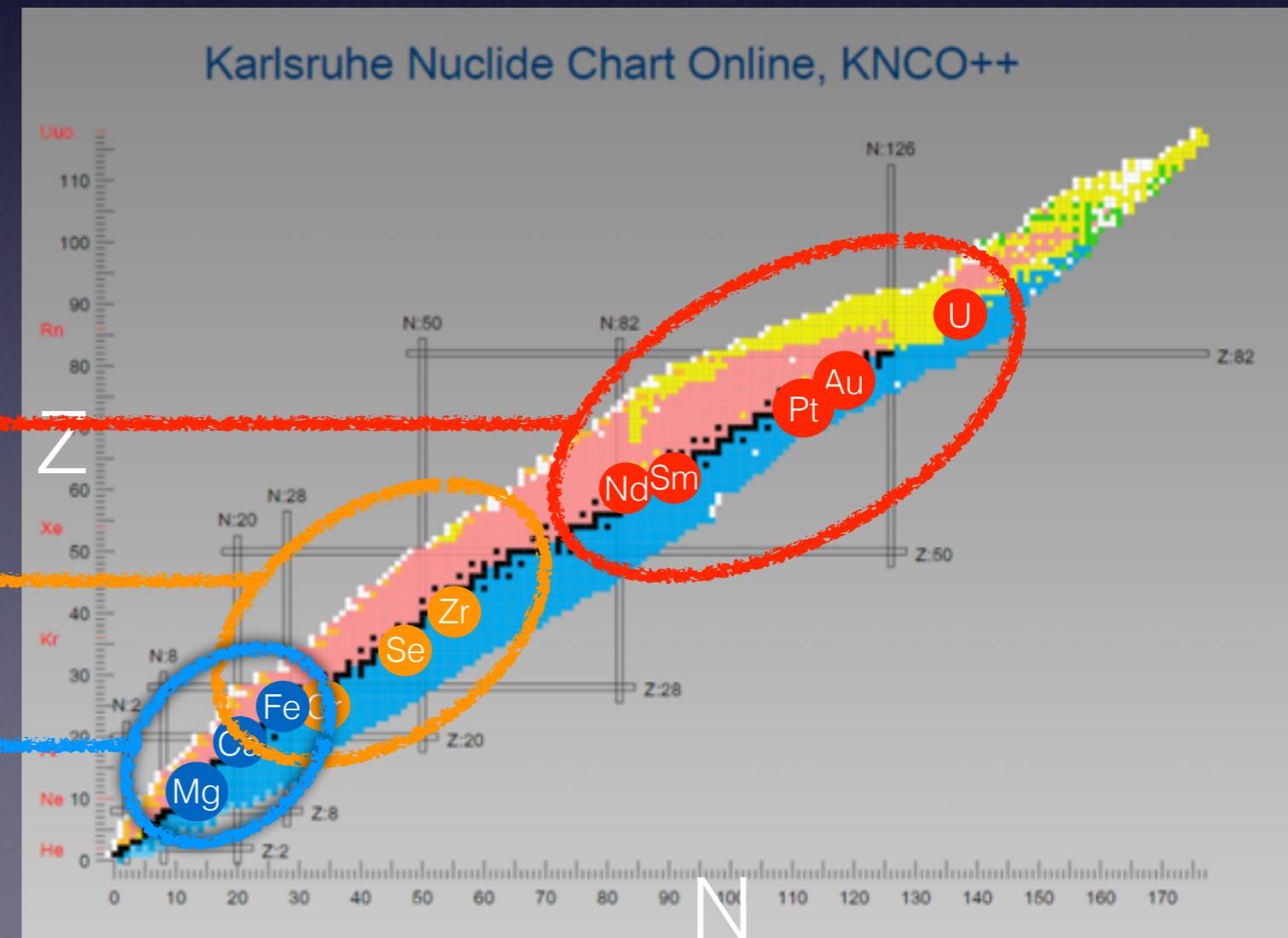
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“dynamic ejecta”

“winds”

supernovae



## 0-th order toy model: scaling relations

- expansion:  $R \sim v t$

- optical depth:  $\tau \sim \kappa \rho R \propto \frac{\kappa M}{v^2 t^2}$

- diffusion time:  $t_{\text{diff}} \sim \frac{R \tau}{c} \propto \frac{\kappa M}{cv t}$

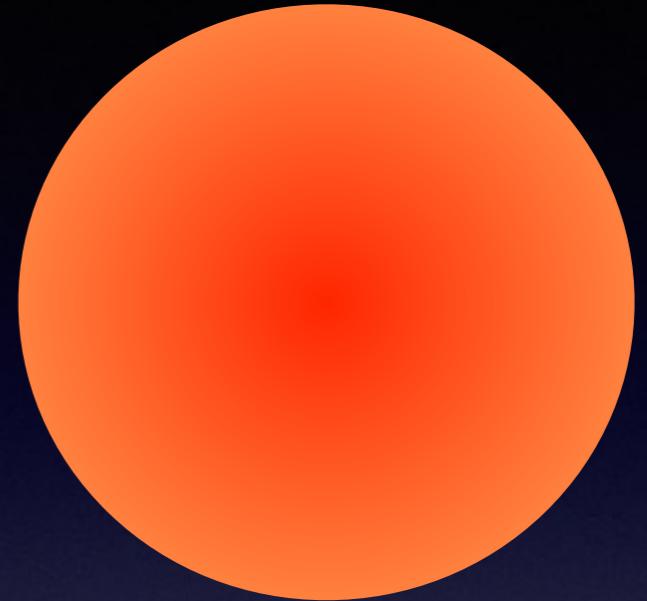
- further expansion:

- $t_{\text{diff}}$  decreases
- peak emission at  $t \approx t_{\text{diff}} \Rightarrow$   
(Arnett 1982)

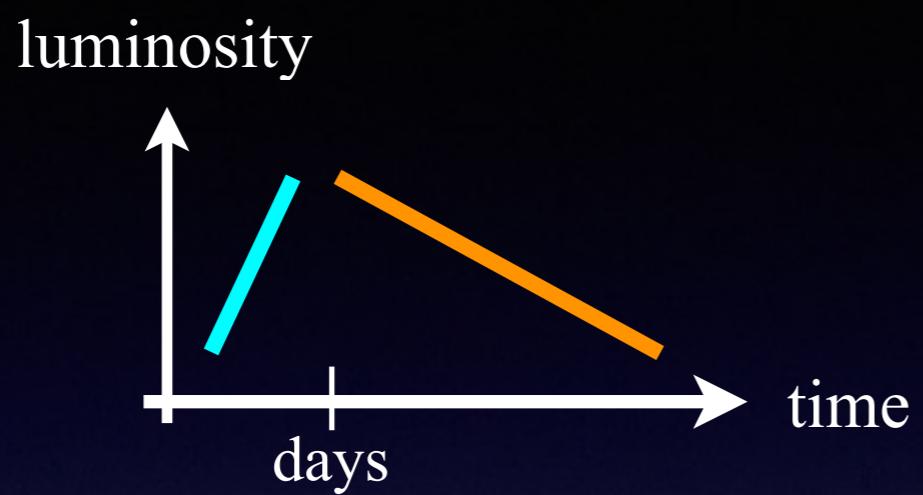
$$t_{\text{peak}} \approx 1.6 \text{ d} \left( \frac{M}{0.01 M_{\odot}} \right)^{1/2} \left( \frac{v}{0.1 c} \right)^{-1/2} \left( \frac{\kappa}{1 \text{ cm}^2/\text{g}} \right)^{1/2}$$

- at this time: thermal energy “used up for expansion”

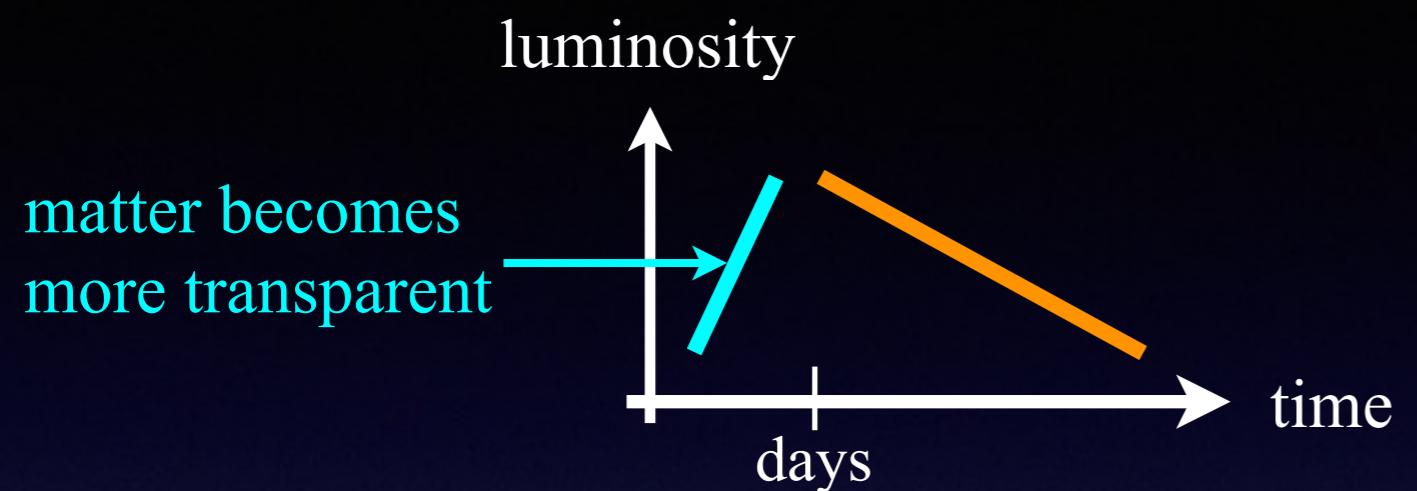
$\Rightarrow$  radioactivity needed for visibility



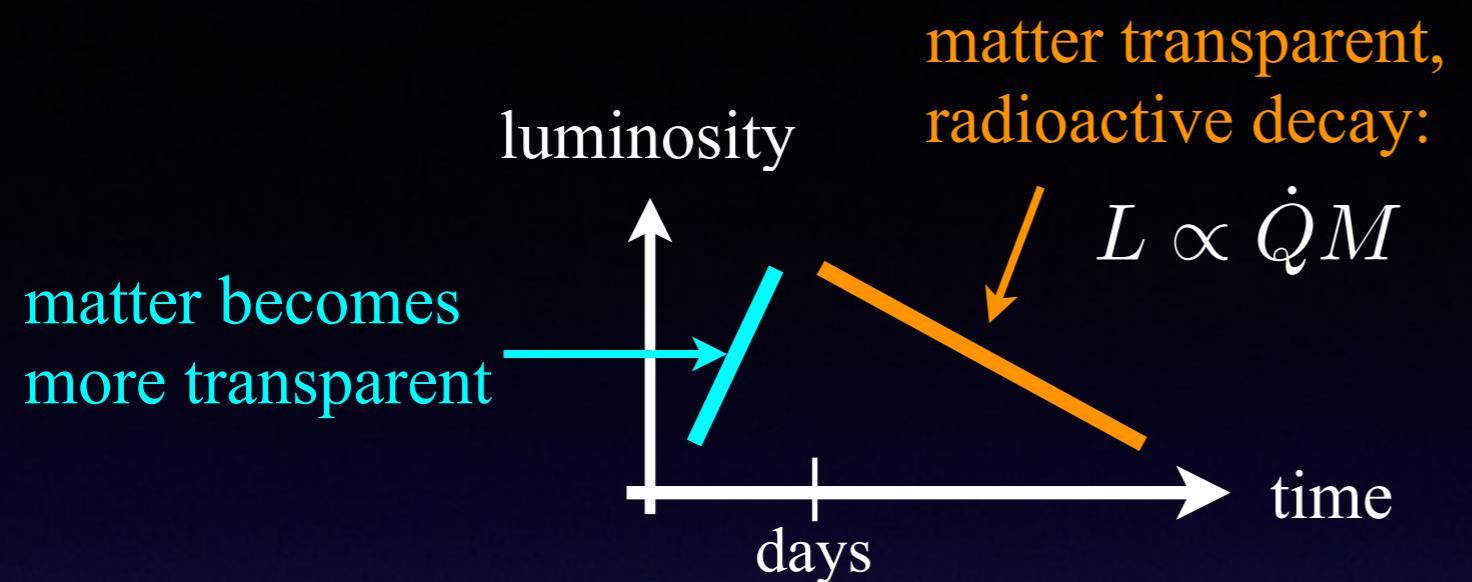
- qualitatively:



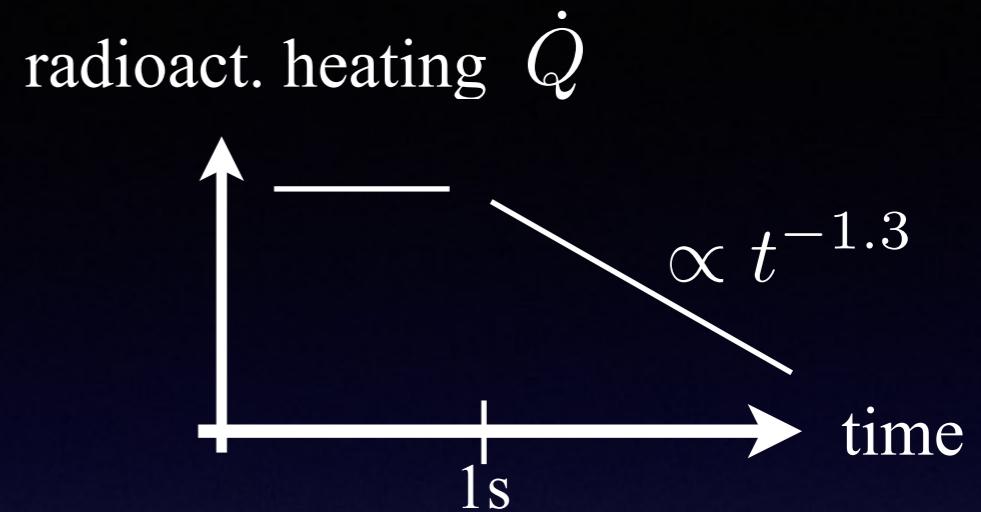
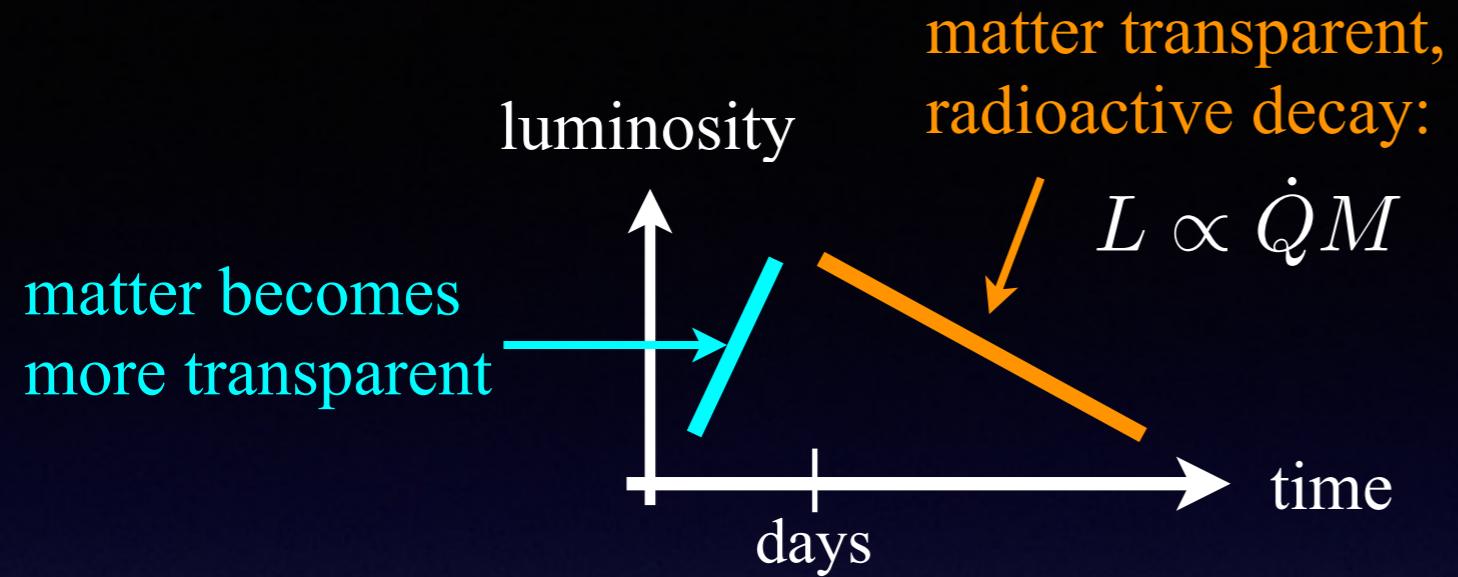
- qualitatively:



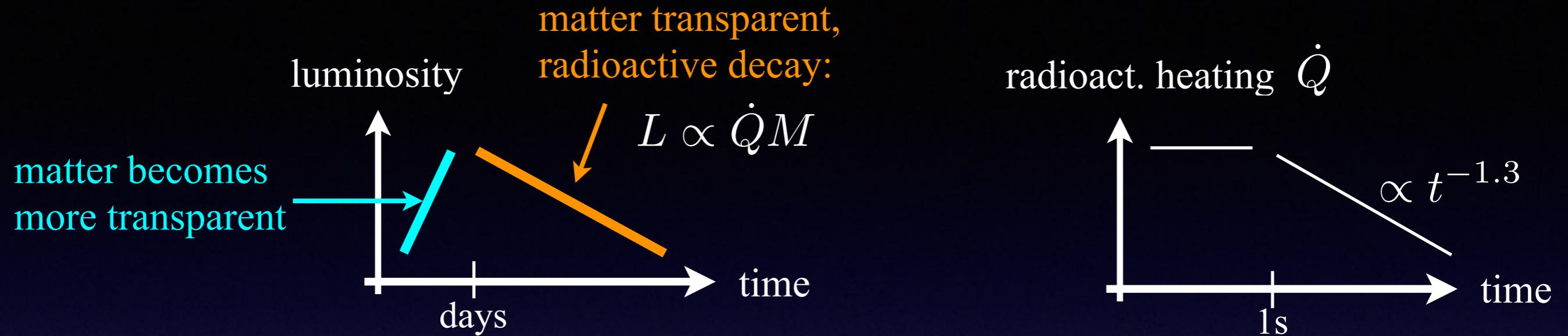
- qualitatively:



- qualitatively:



- qualitatively:



- key ingredients:

- ejecta mass and velocity  $\Rightarrow$  astrophysics
- opacity  $\kappa$   $\Rightarrow$  atomic physics
- radioactive heating rate  $\dot{Q}$   $\Rightarrow$  nuclear physics

“Which ingredient has the highest impact on brightness/observability?”

- more sophisticated, semi-analytic model (Grossman+ 2014):

- parametrized heating rate:  $\dot{Q} = \dot{Q}_0 \left( \frac{t}{t_0} \right)^{-\alpha}, \quad \alpha \approx 1.3$

- peak luminosity:

$$L_{\text{peak}} \propto \dot{Q} \kappa^{-\alpha/2} M^{1-\alpha/2} v^{\alpha/2}$$

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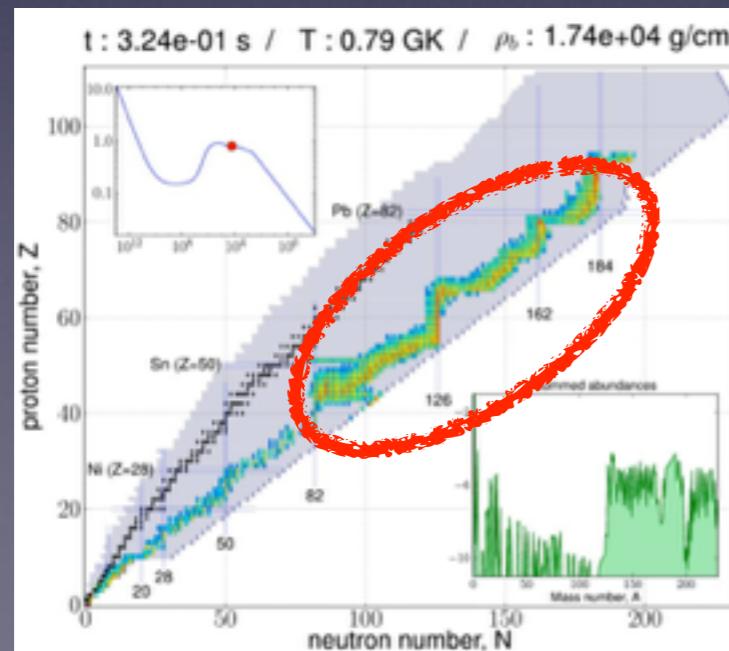
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⇒ How much variation can we expect from nuclear physics?



⇒ Nucleosynthesis occurs near  
“neutron dripline”  
⇒ no experimental information  
⇒ rely on theoretical nuclear mass models

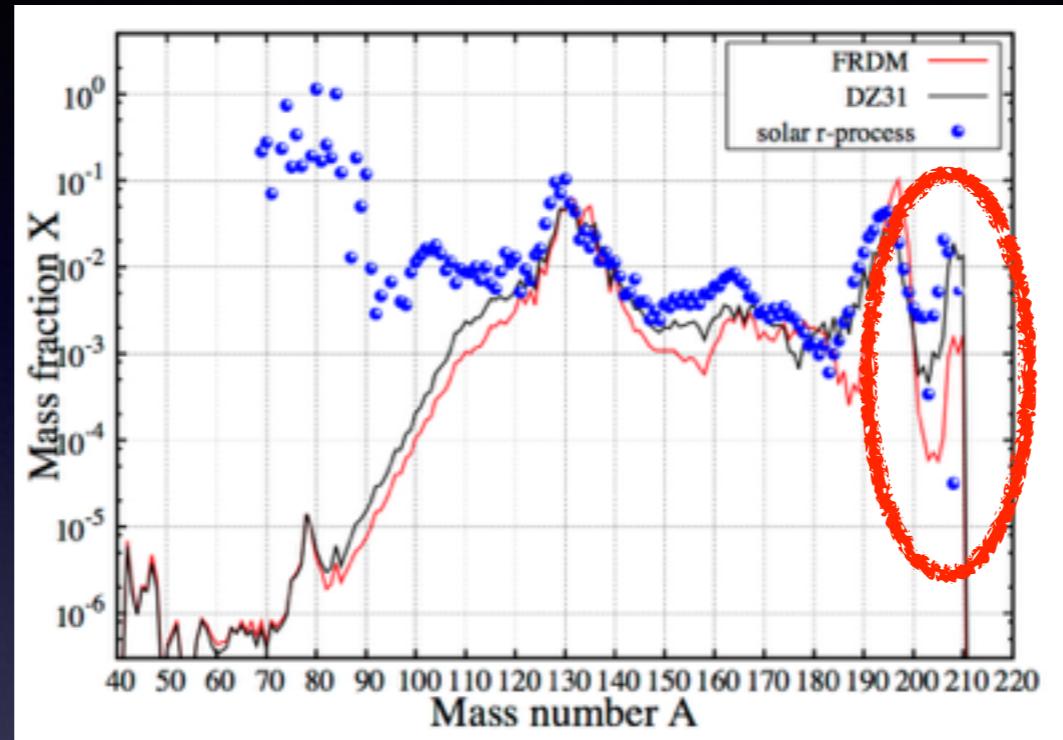
- compare two frequently used nuclear mass models:

- a) “Finite Range Droplet Model” (FRDM; Möller+ 1995)
- b) “Duflo Zuker Model” (DZ31; Duflo, Zuker 1995)

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most relevant for heating

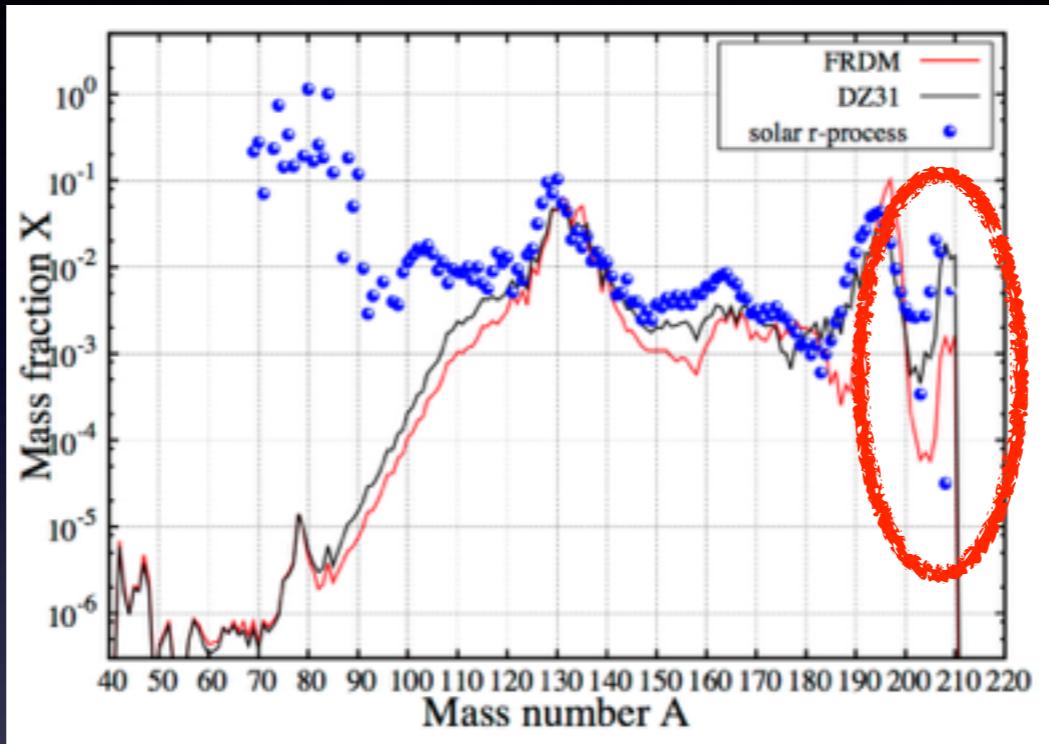
(first realized by Barnes et al. 2016):

- ⇒ “trans-lead” region
- ⇒  $\alpha$ -decays
- ⇒ important for:
  - heating rate
  - thermalization efficiency

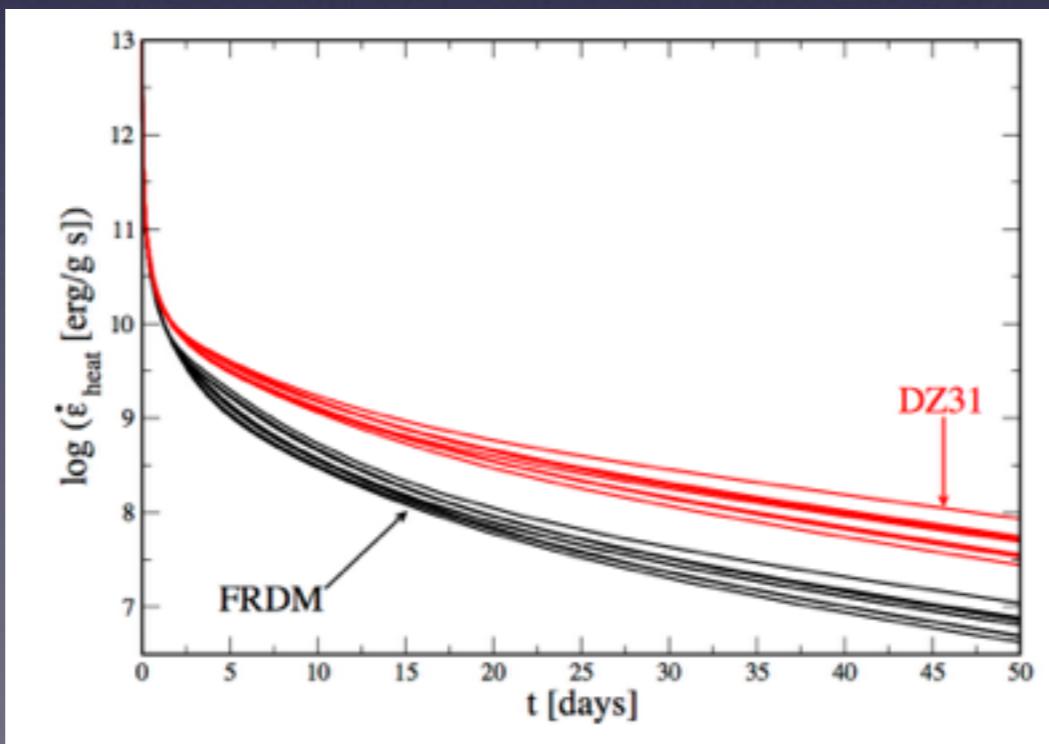
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at relevant times:  
one order of magnitude  
difference!!!

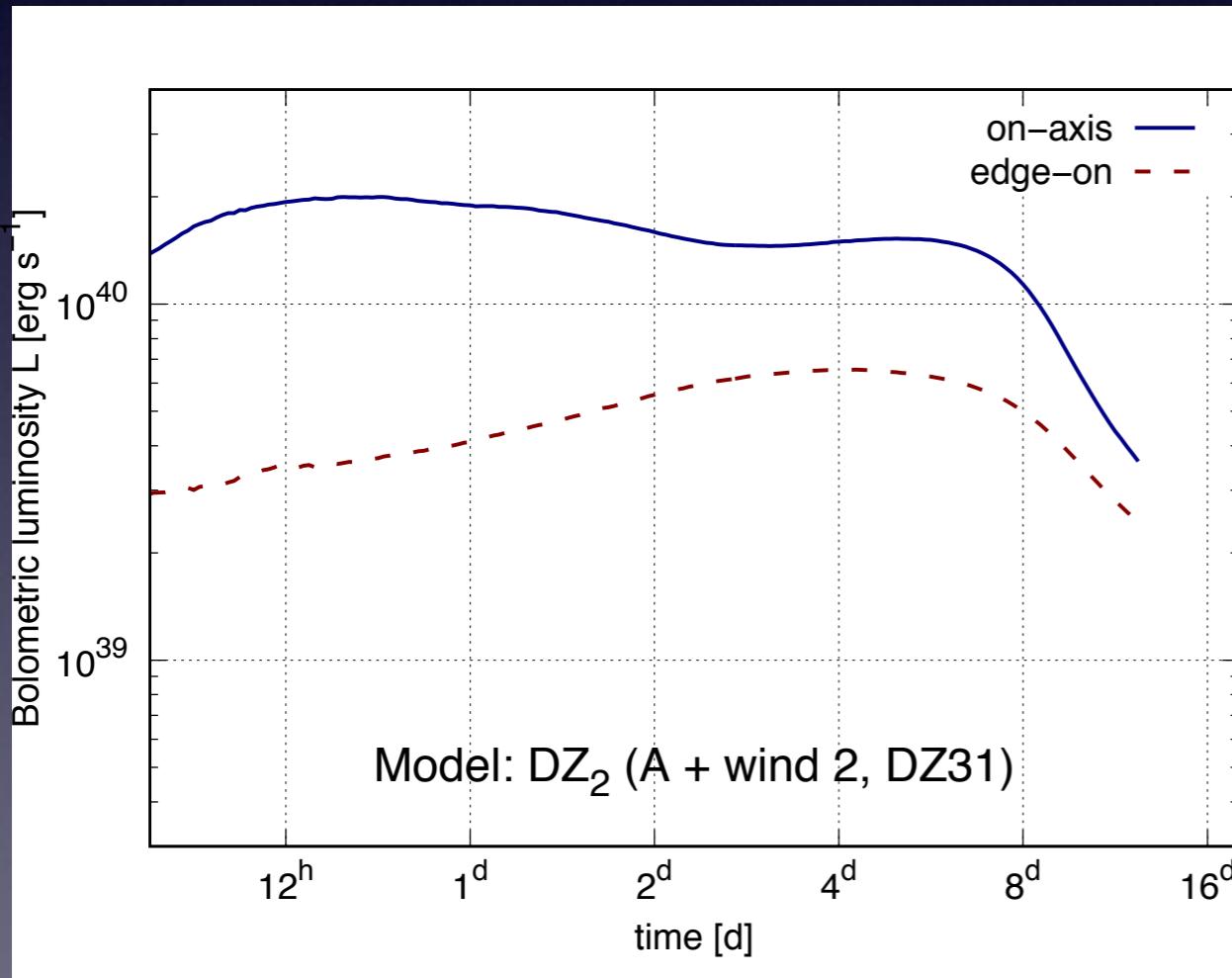
## studied system

- nsns binary  $2 \times 1.4 M_{\odot}$

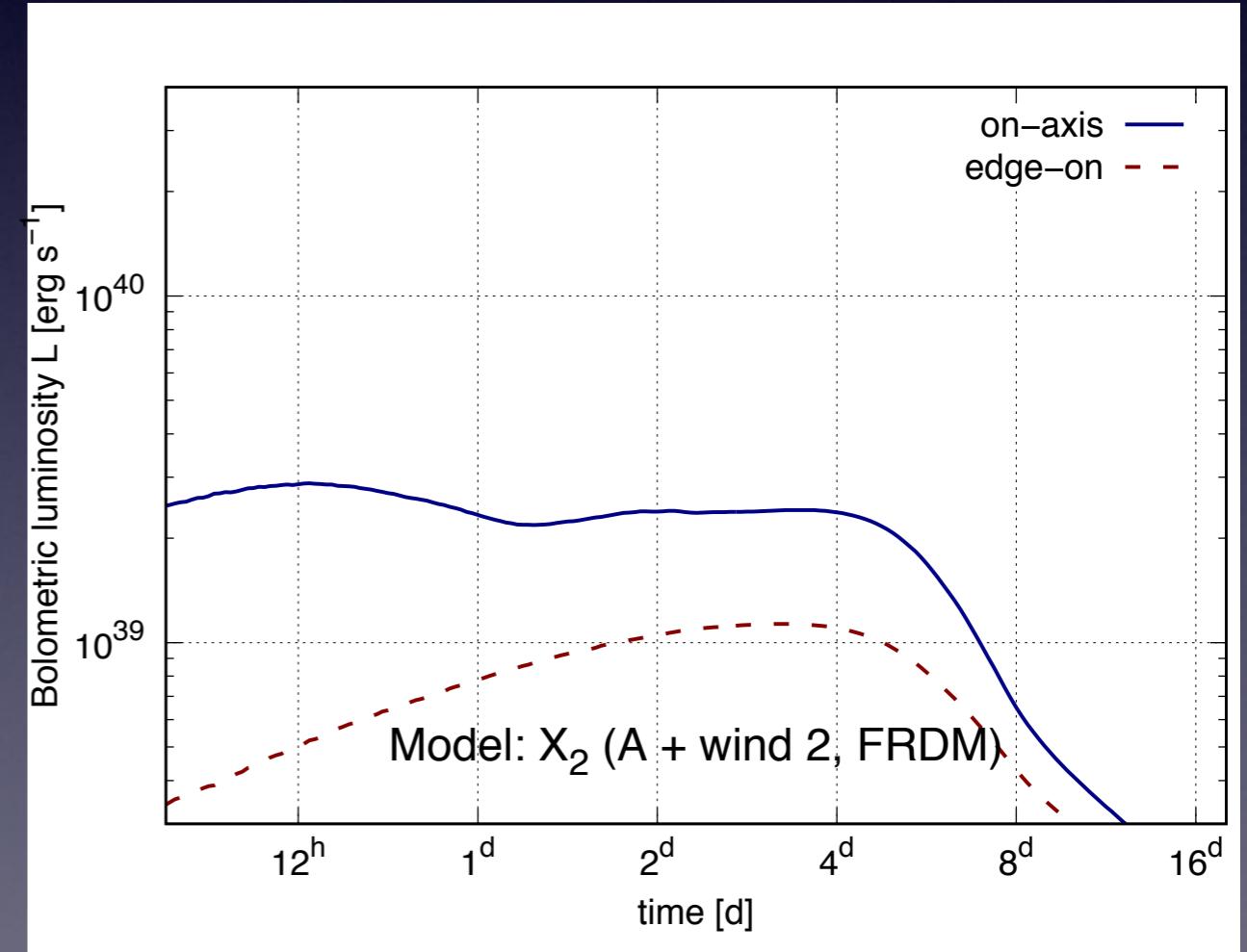
model (Wollaeger et al. 2017, arXiv:1705.07084)

- matter distribution from hydro simulations (SR+ 2014)
- dynamic ejecta + wind (ax.sym)
- full radiative transfer (SuperNu code)
- opacities from Los Alamos suite of atomic physics codes

## Duflo-Zuker mass formula heating

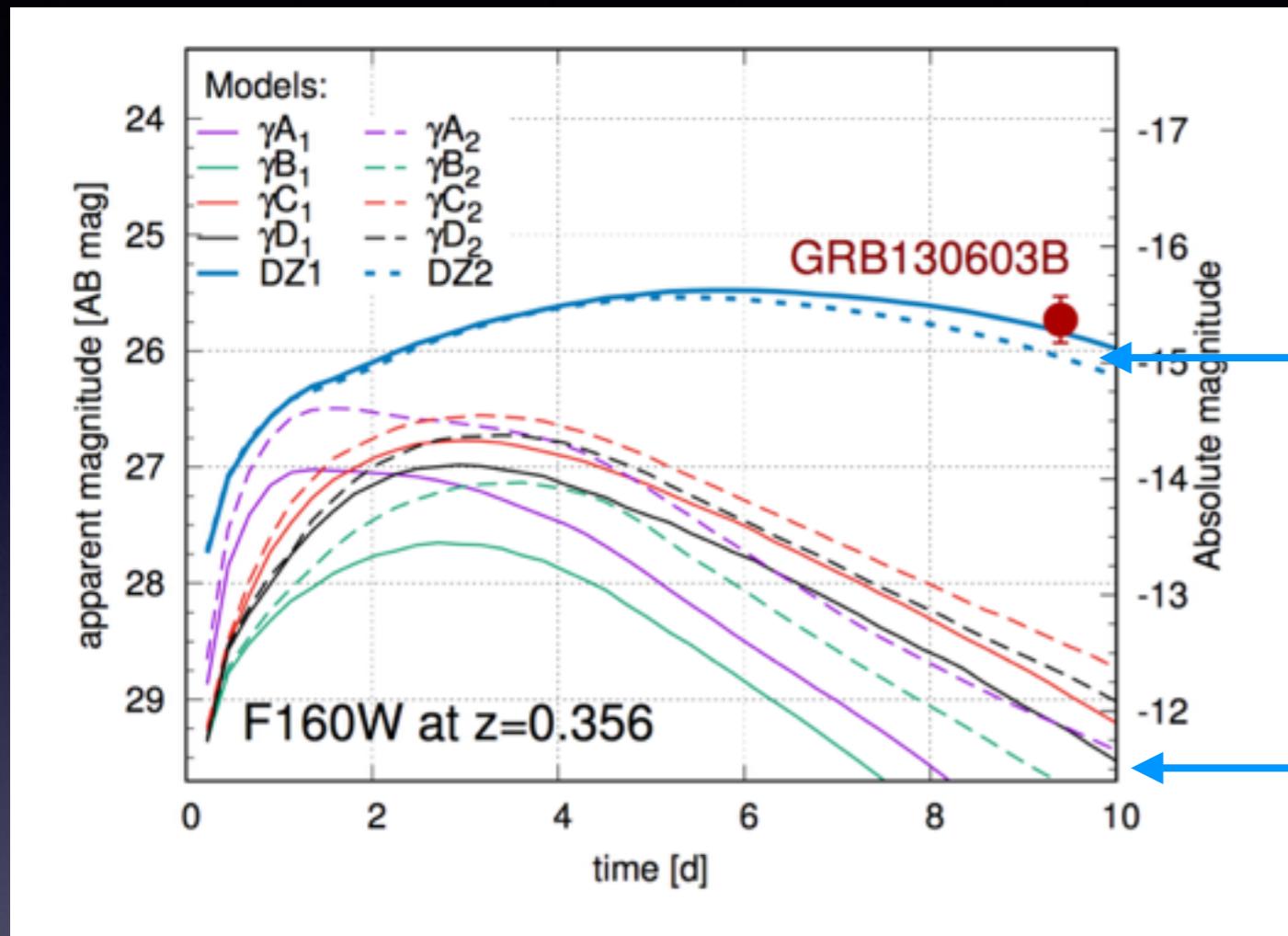


## FRDM mass formula heating



⇒ substantially brighter macronovae for DZ-mass formula

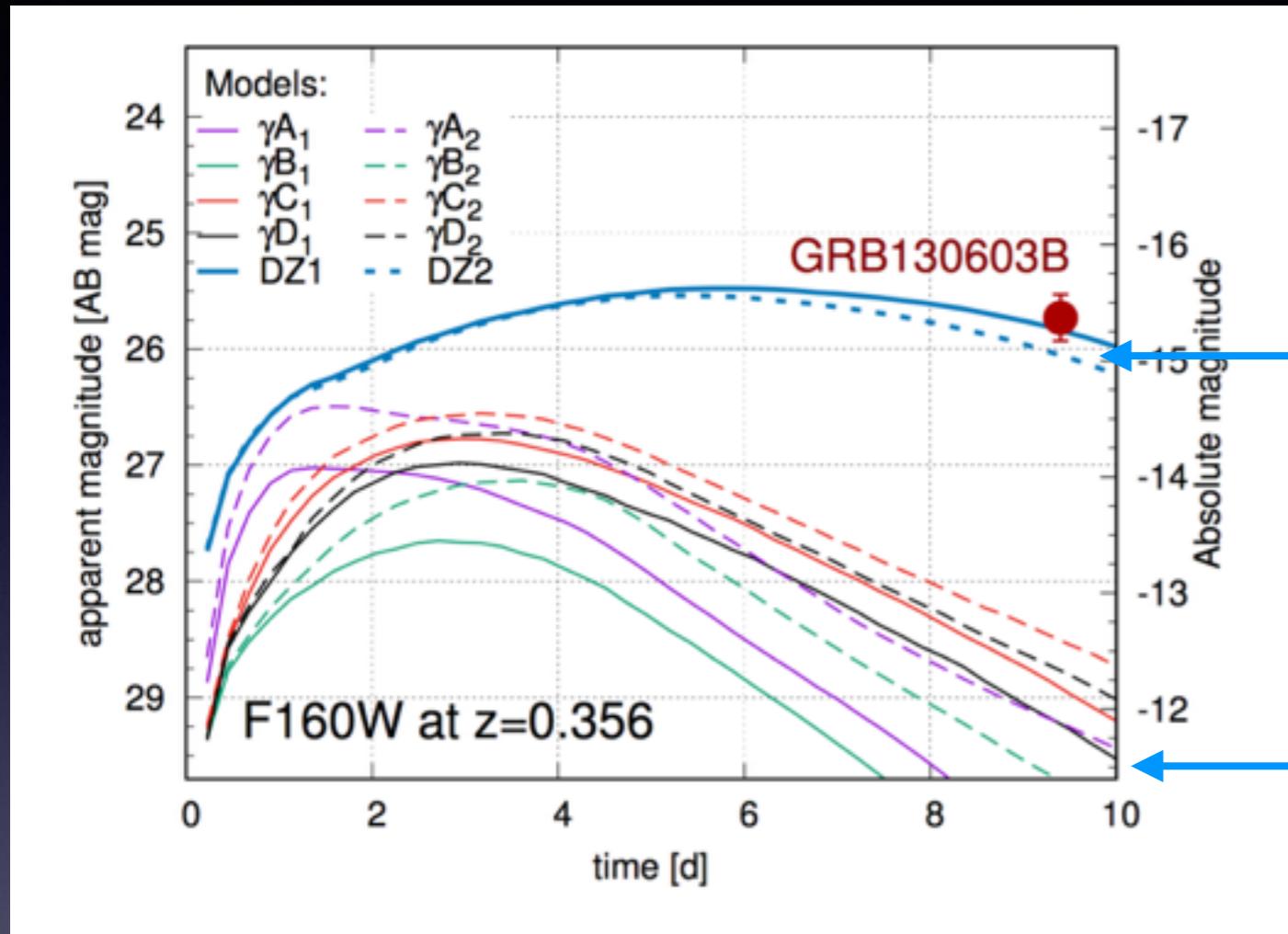
# Which models can explain macronova candidate GRB130603B?



Duflo-Zuker heating  
(nsns  $1.4 + 1.4 M_\odot$ , on-axis)

FRDM heating

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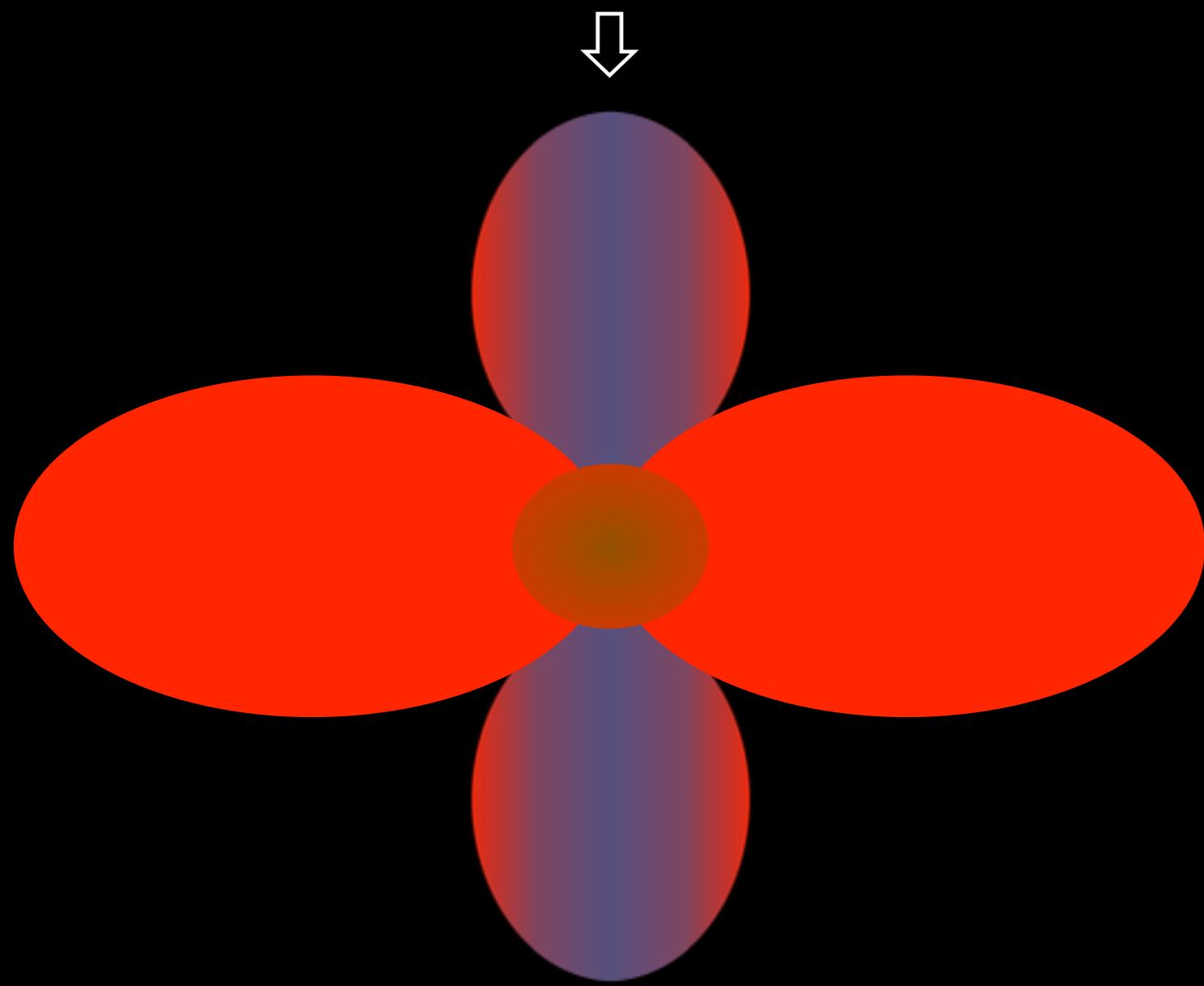
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FRDM heating

⇒ only Duflo-Zuker-type heating seem able to explain GRB130603B,

⇒ astrophysical parameters less important for detectability

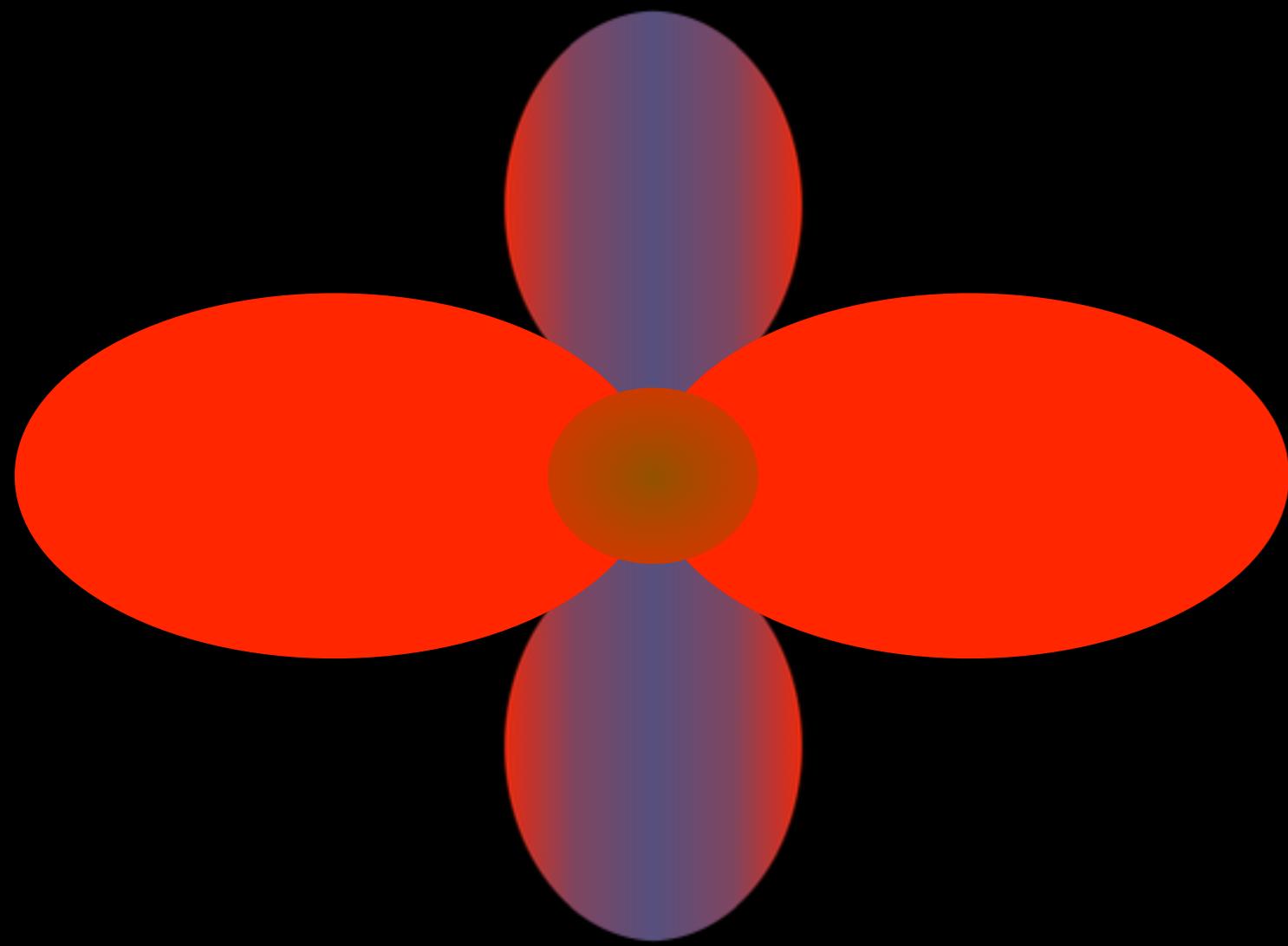
## “Cartoon picture”



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

# “Cartoon picture”

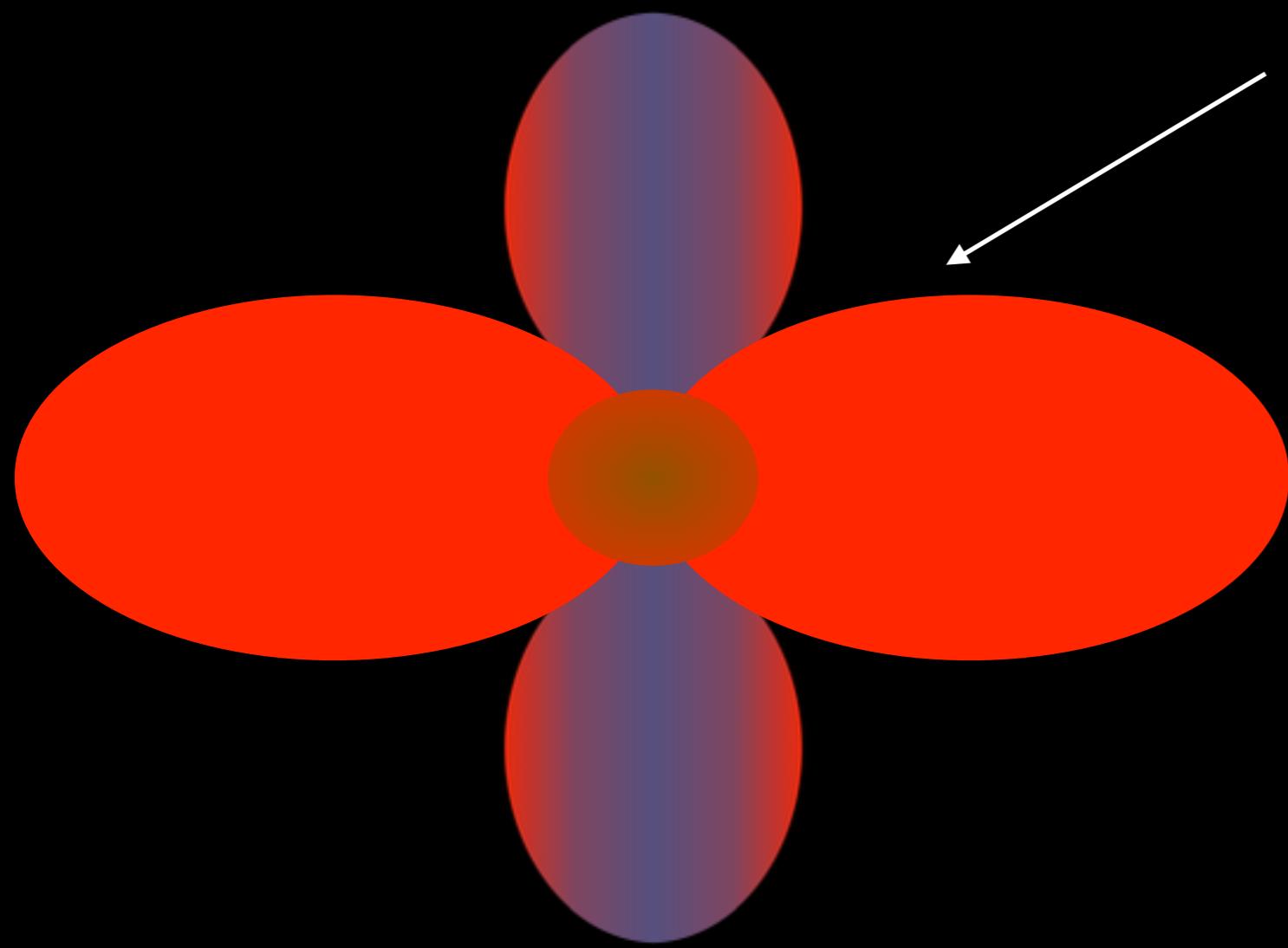
- “winds”,  $Y_e \sim 0.3$
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- lanthanide/actinide-free,  $X_{\text{lan}} < 10^{-5}$
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interaction/mixing?

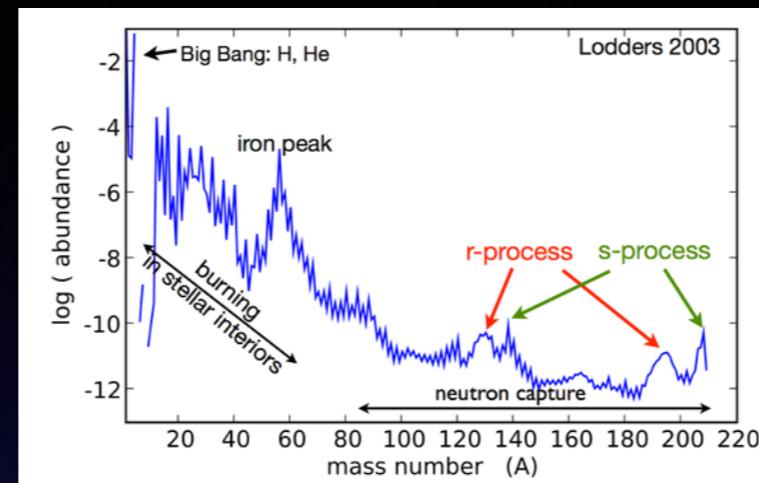
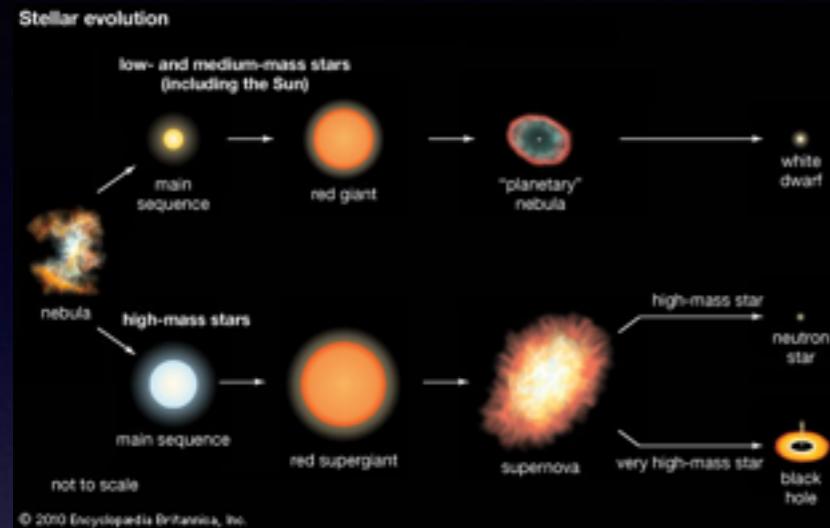


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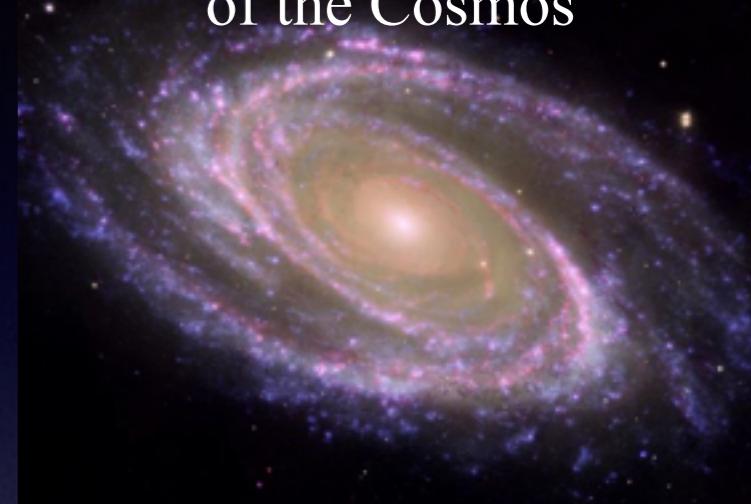
# “glueing together separate fields”

## nucleosynthesis

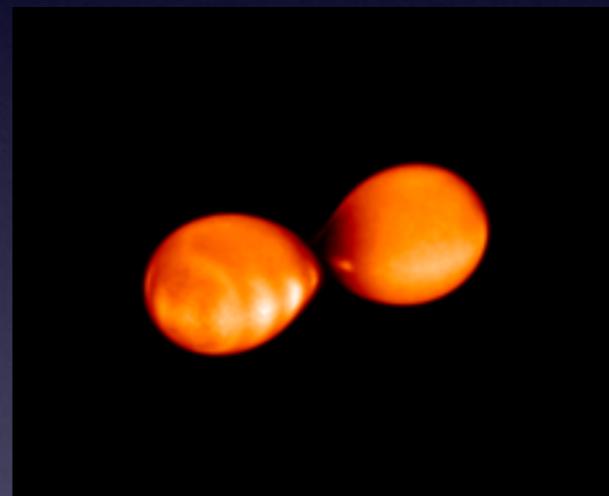
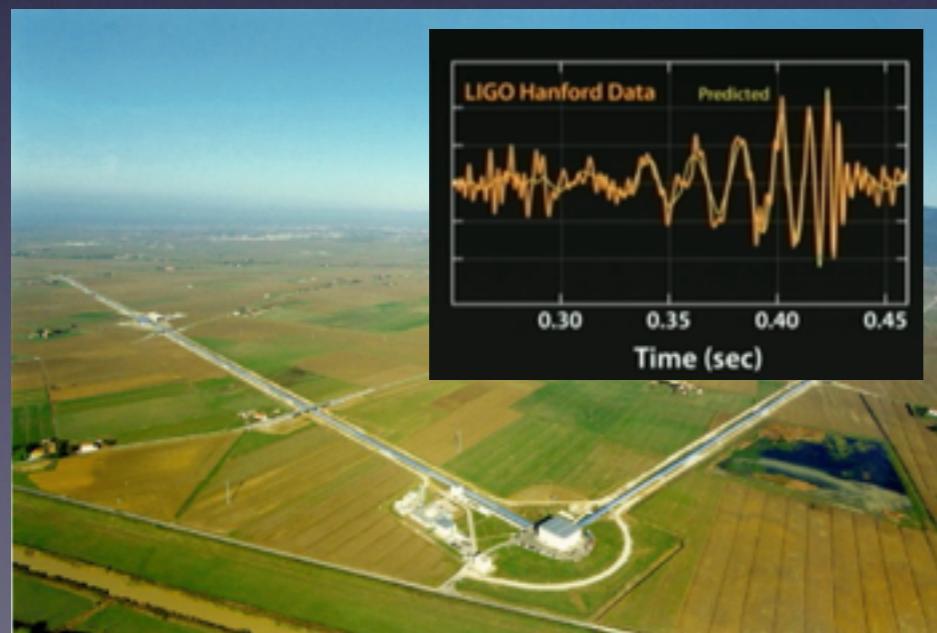
### Stellar (binary) evolution



### Chemical enrichment of the Cosmos



### Gravitational wave detection



(short) Gamma-Ray Bursts



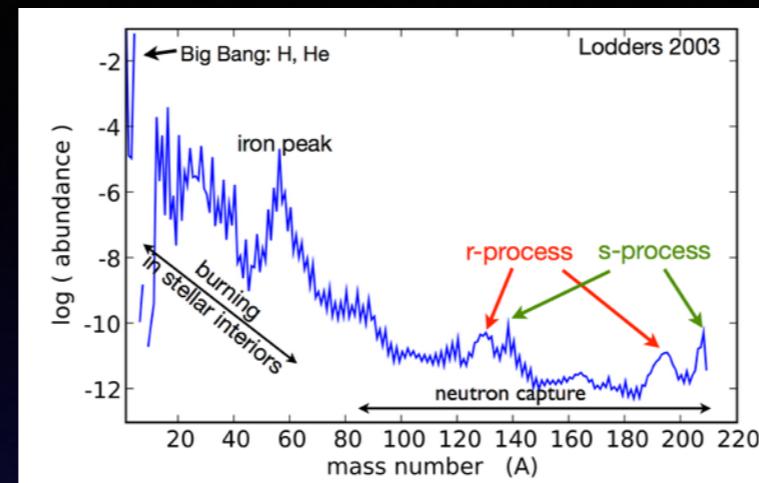
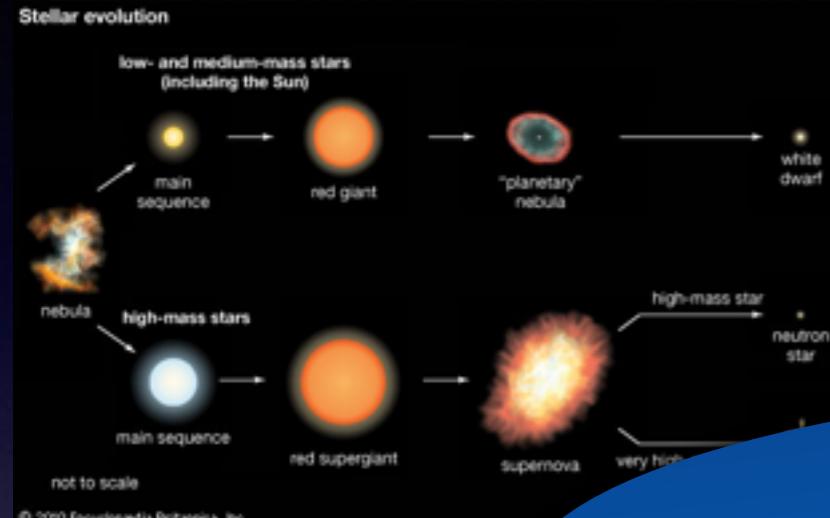
### Radioactively powered transients (“macronovae”)



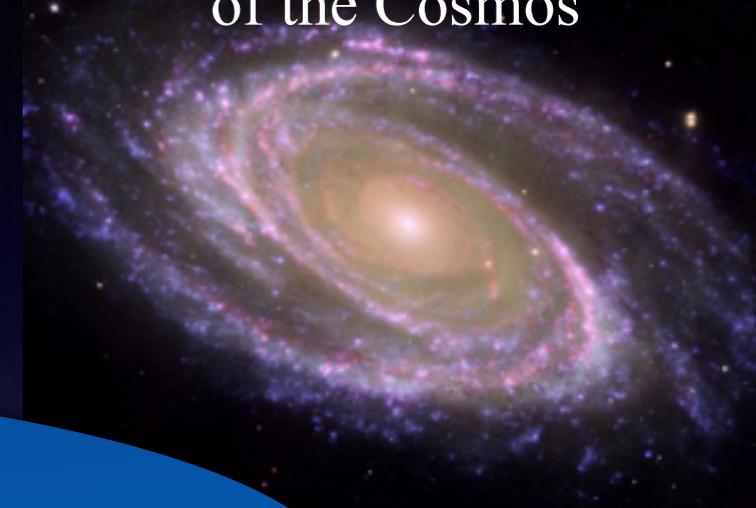
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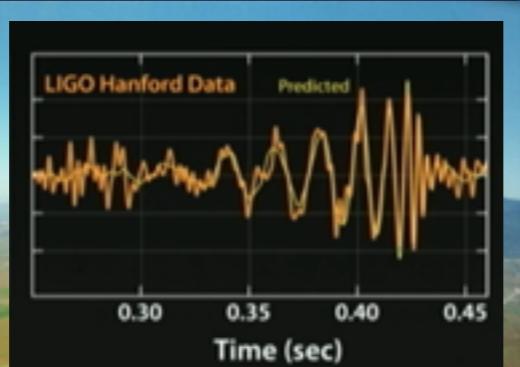


### Chemical enrichment of the Cosmos



Thank you!

### Gravitational wave detector



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