中性子星合体とrプロセス元素合成

Neutron star mergers and r-process nucleosynthesis

田中雅臣 (東北大学)

Masaomi Tanaka (Tohoku University)

チュートリアルの目標

- **rプロセス元素合成**
  - 天文観測からの要請：何がゴールか？
  - 基礎物理過程と起源天体の候補
- **中性子星合体**
  - 中性子星合体におけるrプロセス元素合成
  - 「キロノバ」: rプロセスによる突発天体現象
- **重力波天体の観測**
  - rプロセスに関して何がどこまで分かったか？
  - 何が分かっていないか

参考文献

- **天文月報 2014年1-2月 rプロセス特集**
  和南城 (rプロセス全般)、田中 (キロノバ)、
  西村・滝脇 (超新星)、青木 (天文観測)、
  本田 (天文観測)、石丸 (銀河の化学進化)
- **物理学会誌 2018年9月 中性子星合体GW170817特集**
  新井 (重力波)、柴田 (中性子星合体)、田中 (キロノバ)
- **Thielemann et al. 2018**, Annual Review of Nuclear and Particle Science, 67, 253-274 (arXiv:1710.02142)
  (天文観測、rプロセス、中性子星合体)
- **Arnould et al. 2007**, Physics Reports, 450, 97-213
  (天文観測、rプロセス、原子核物理、超新星)

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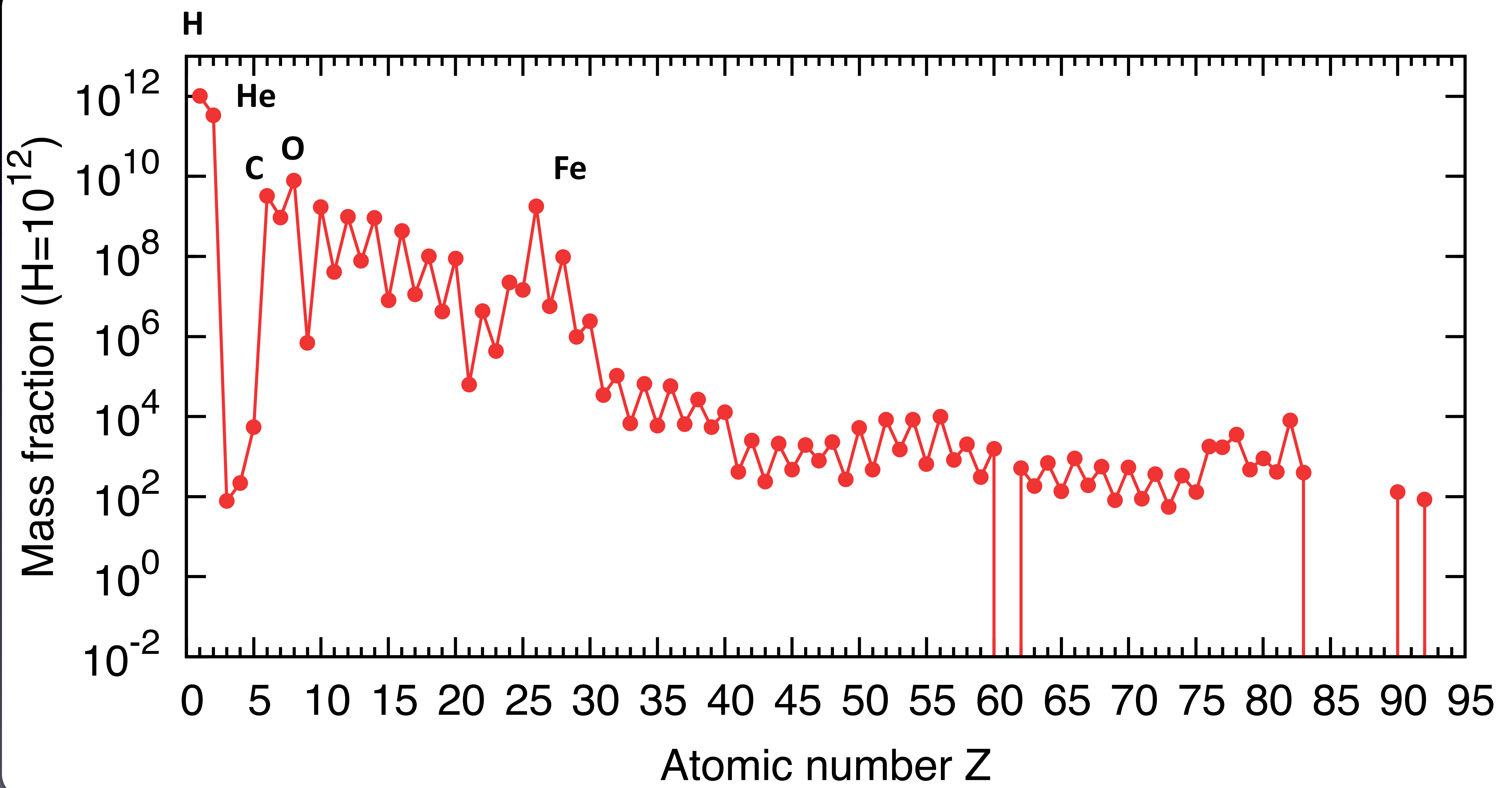
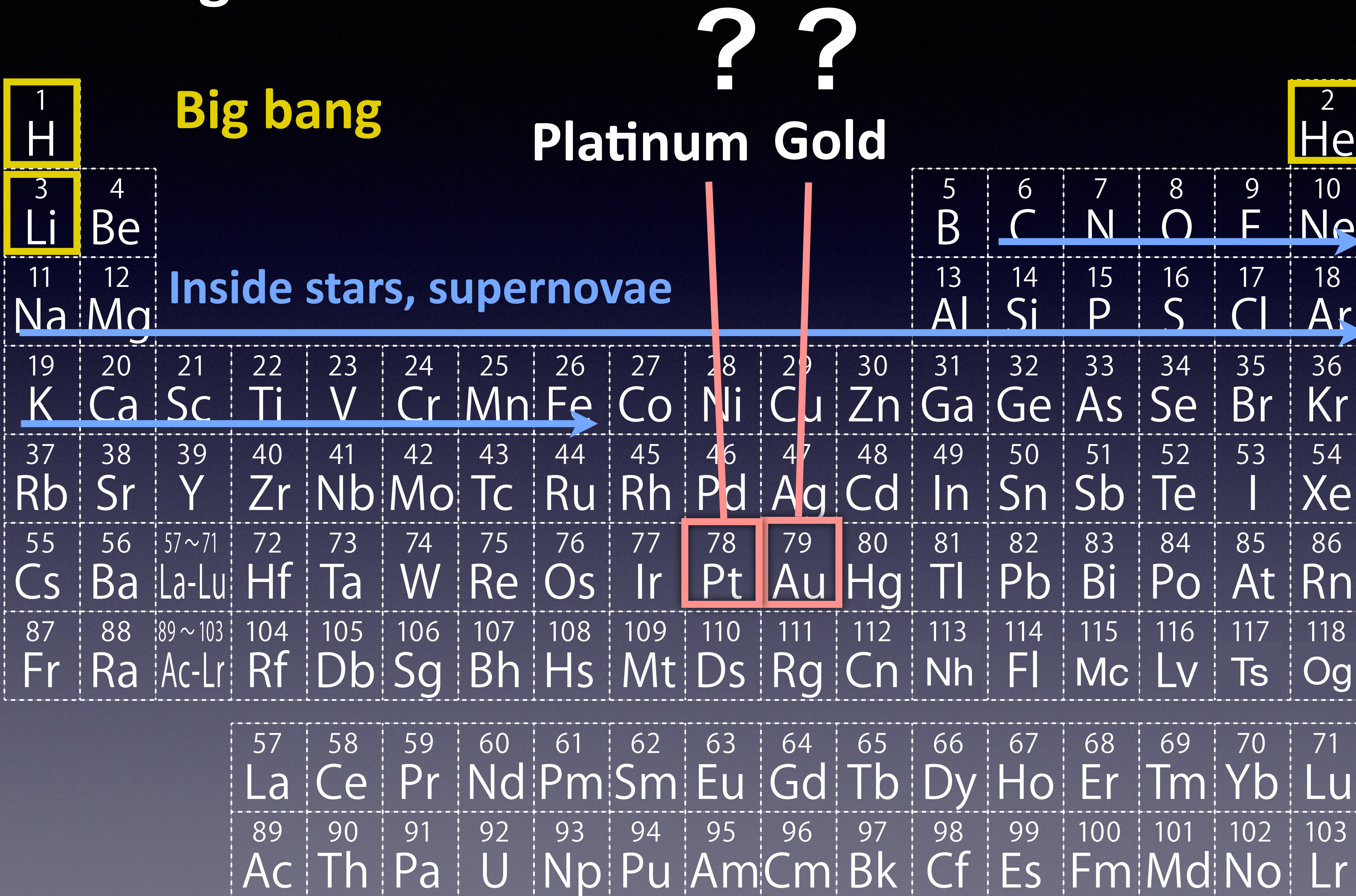
Cosmic abundances (atomic number)



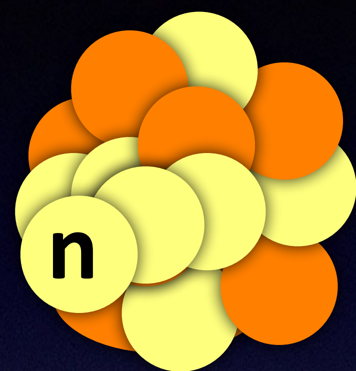
*mass fraction

The origin of elements

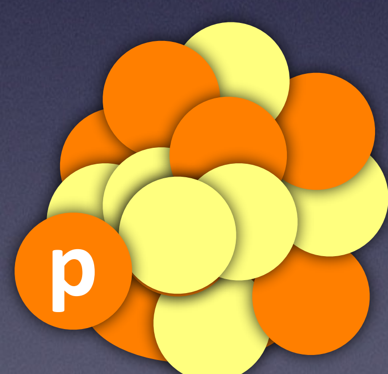


Neutron-capture nucleosynthesis

s (slow)-process



Decay

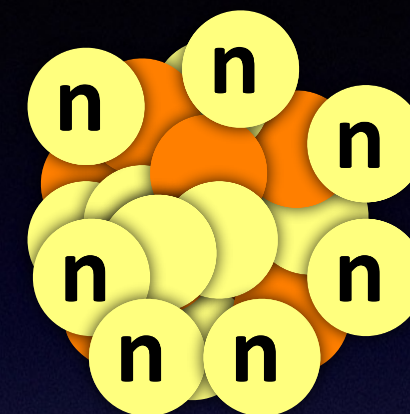


Ba, Pb, …

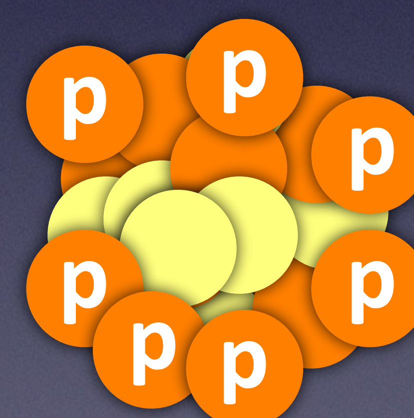
Inside of stars

$^{13}\mathrm{C}+{}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O}+\mathrm{n}$

r (rapid)-process



Decay



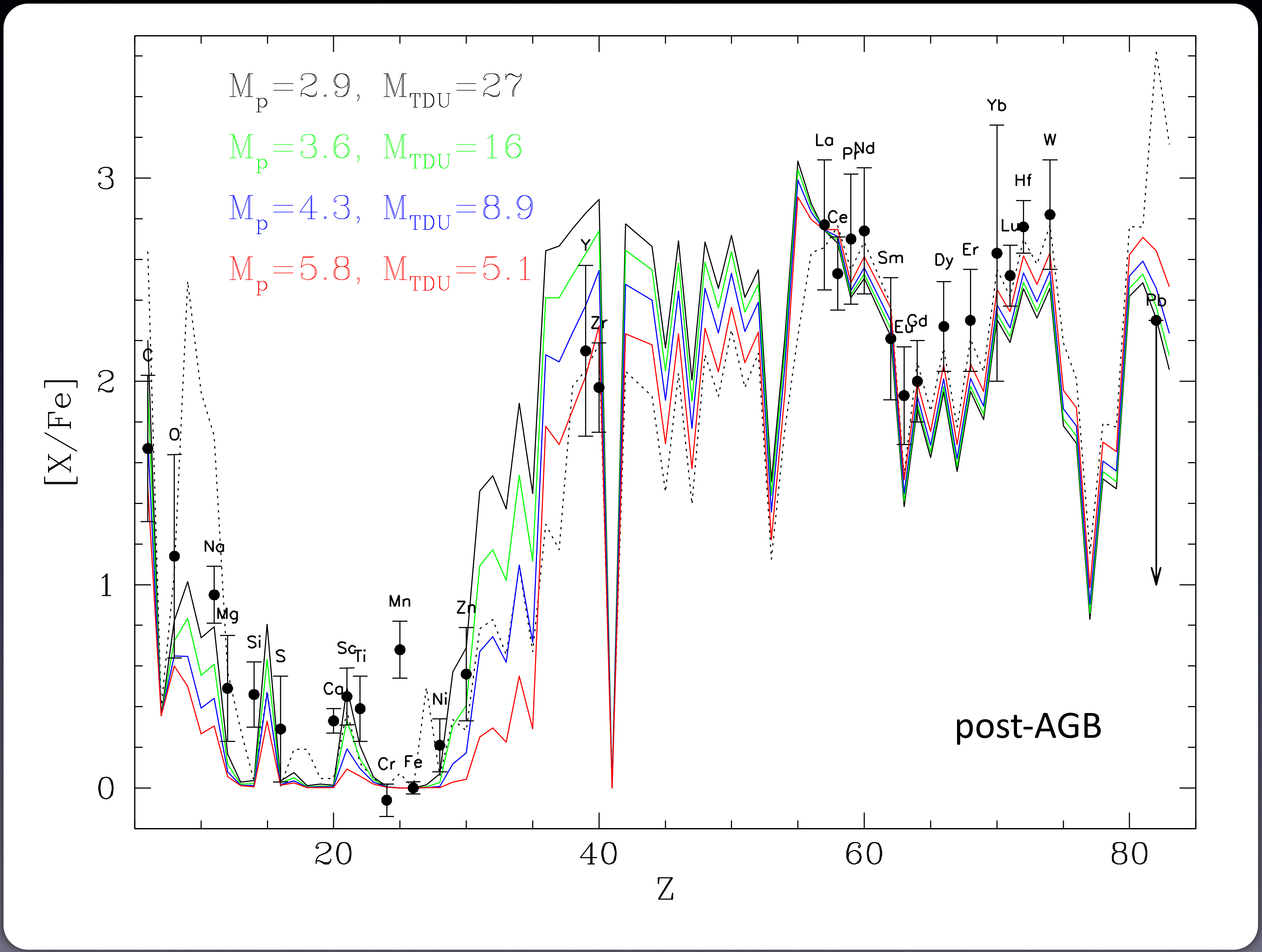
Au, Pt, U, …

??

s-process in evolved low-mass stars (asymptotic giant branch)

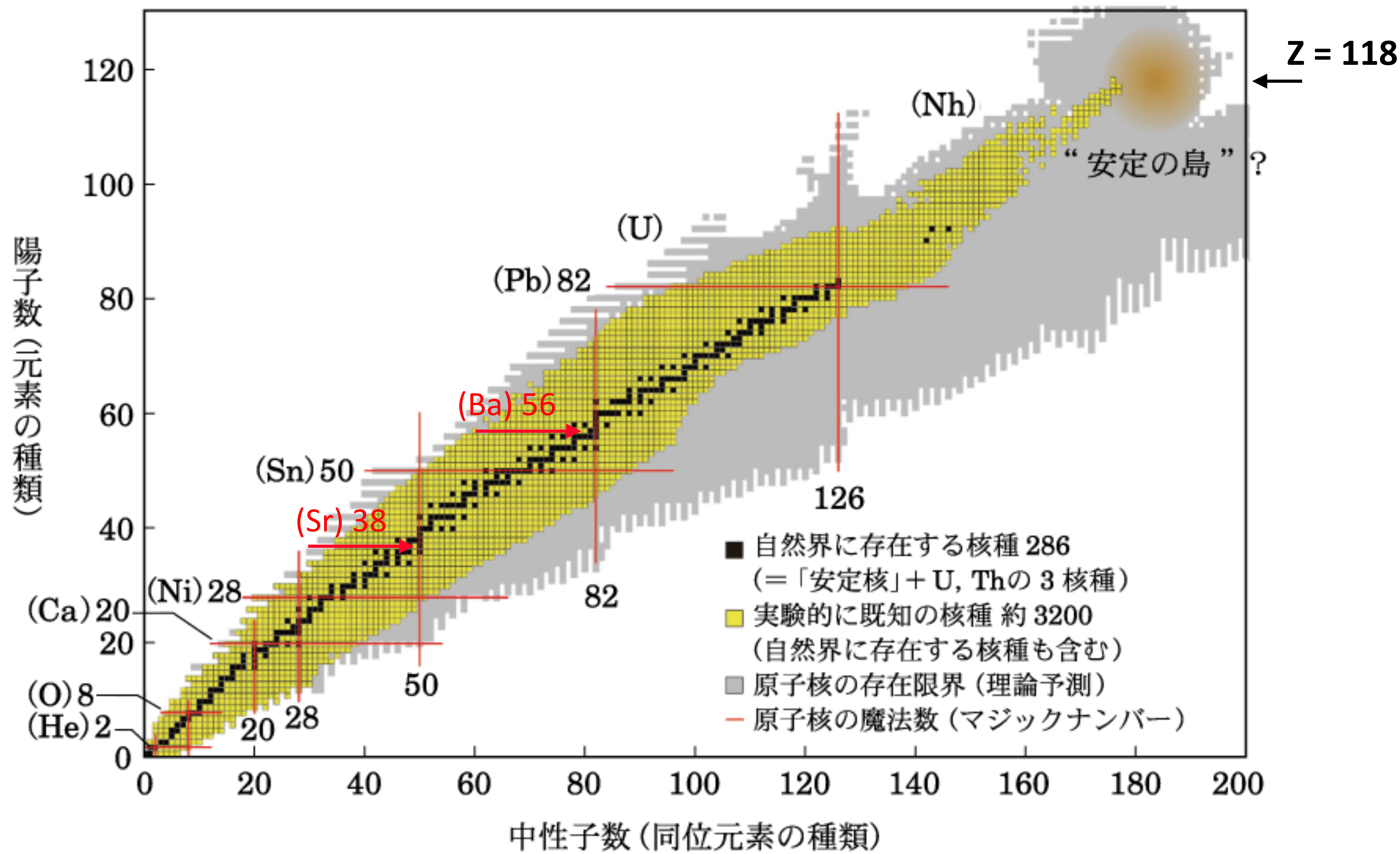
First evidence

Tc (Z = 43, no stable isotope) (Merrill 1952)



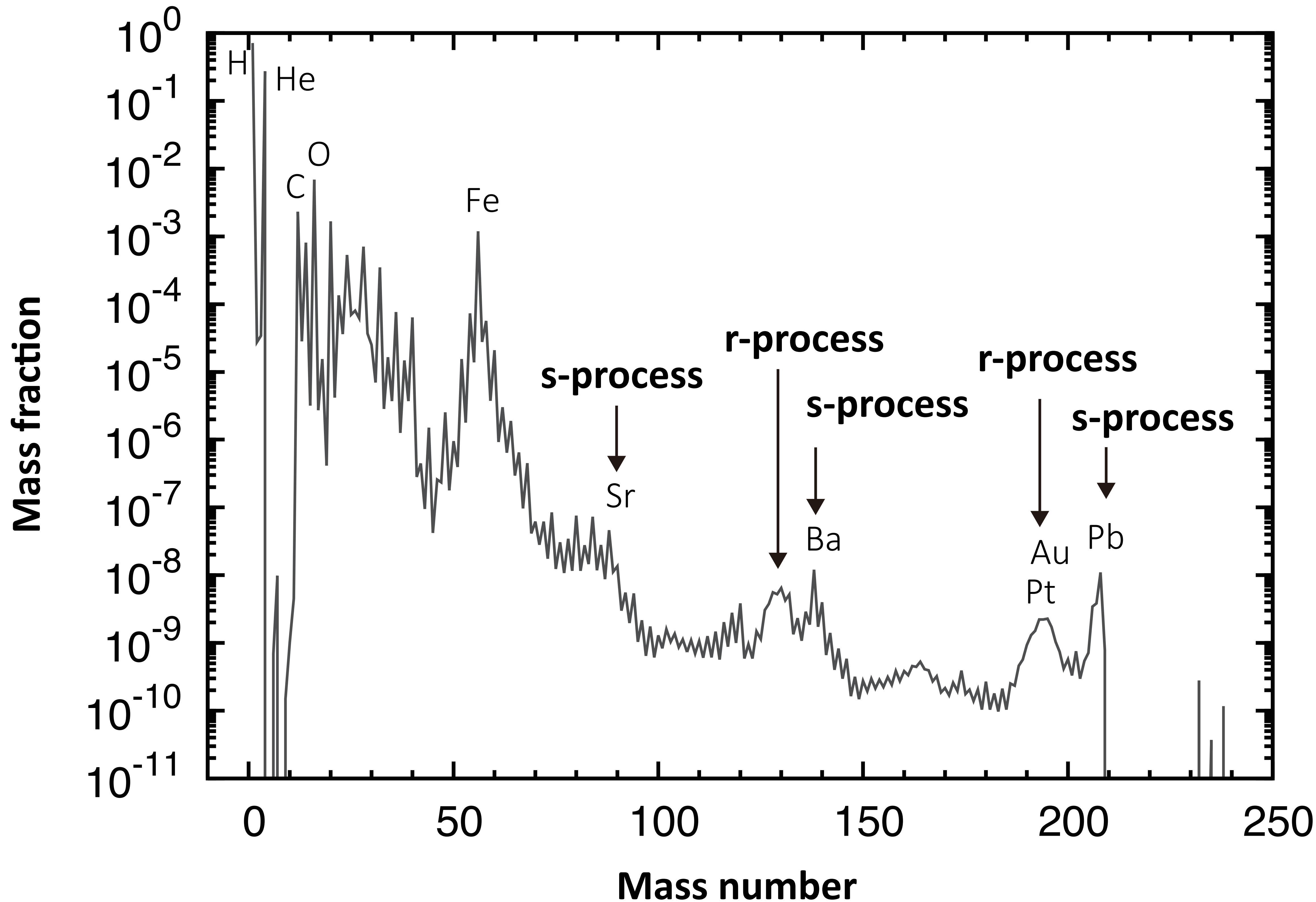
Lugaro+16

Chart of nuclides

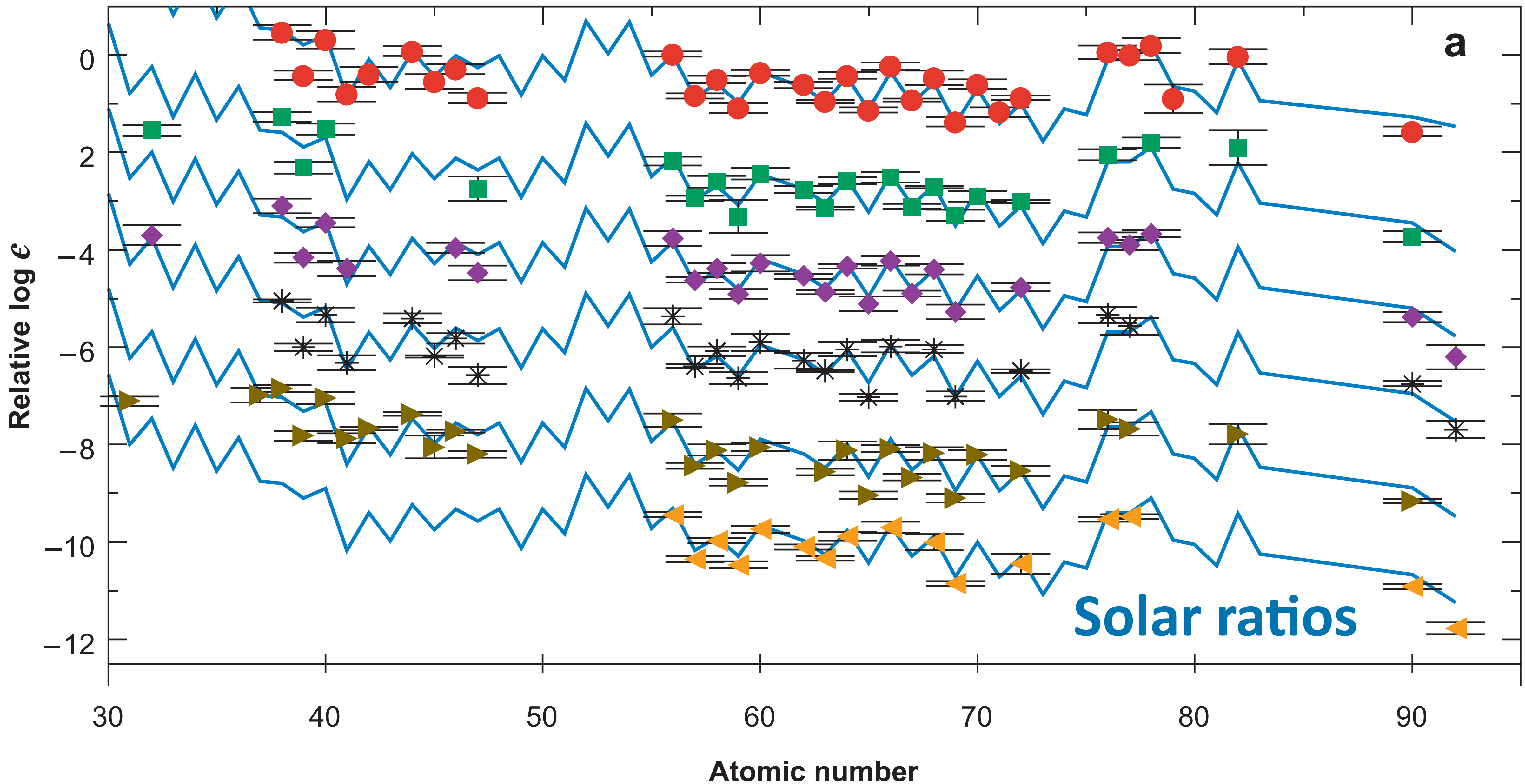


天文学辞典 http://astro-dic.jp

Cosmic abundances (mass number)



“Universality” of r-process abundances



Sneden+2008

=> (Probably) single origin

Conditions for r-process (1)

Neutron capture rate >> Beta decay rate

$$n_n \langle \sigma v \rangle \gg \frac{1}{\tau_\beta} \quad [s^{-1}]$$

$\langle \sigma v \rangle$ ~10^{-20} cm^3 s^{-1} $\qquad$ τ_β ~ 1 s

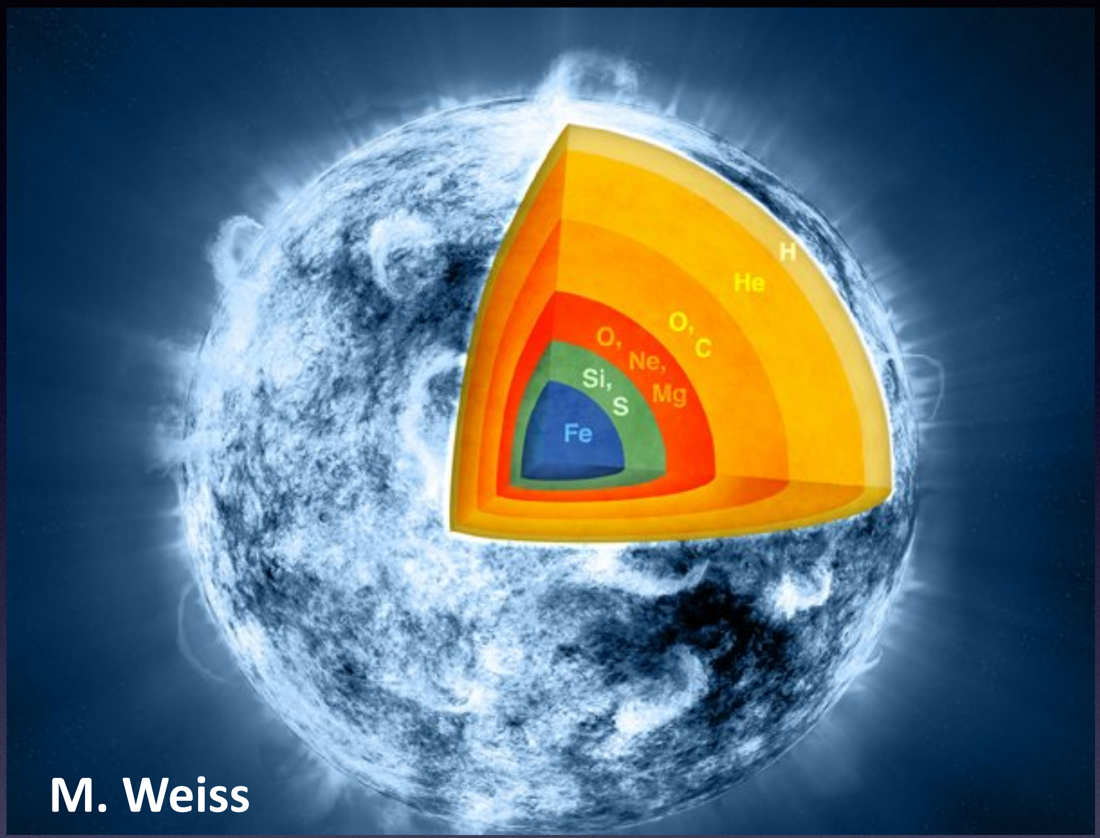
$n_n \gg 10^{20}$ cm^{-3} $\qquad$ ($n_n \sim 10^{5\text{-}7}$ cm^{-3} in s-process)

High neutron density (& rapid change of the system)

=> Explosive phenomena near the neutron star

Explosive phenomena near the neutron star

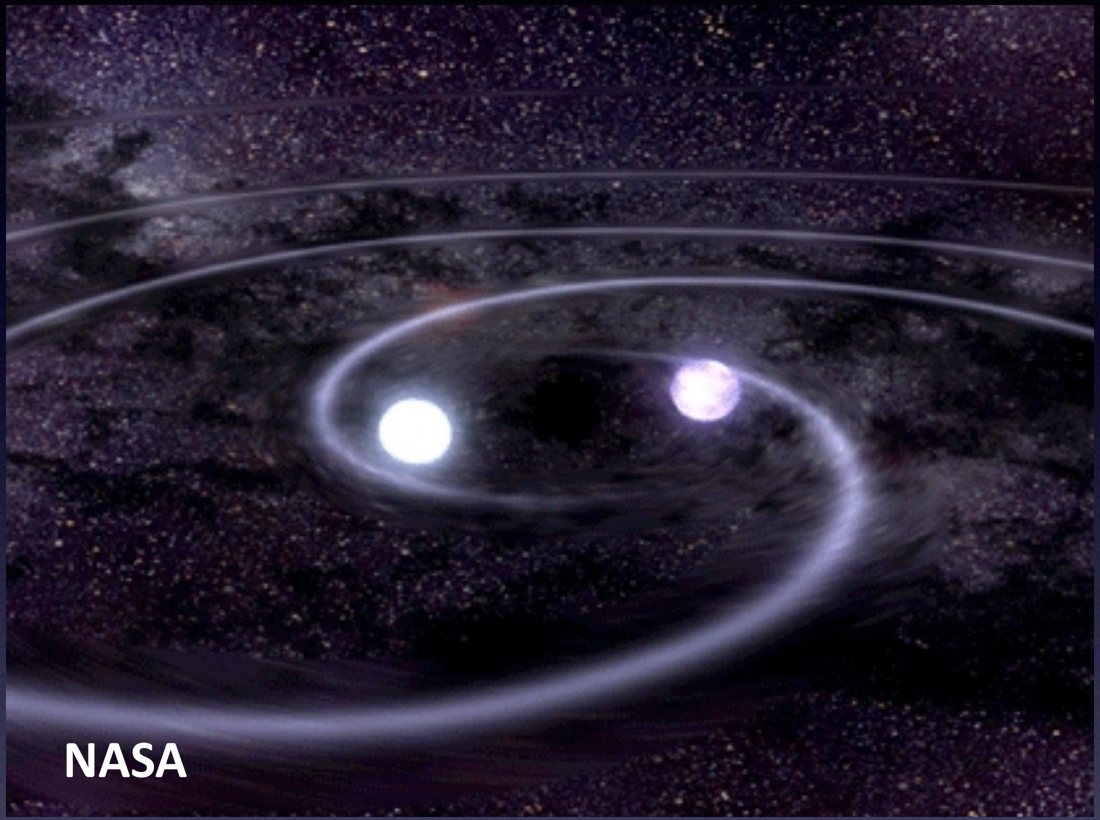
Core-collapse supernova



Moderately neutron rich

$Ye \sim 0.45$ ($n_n \sim 1.2 n_p$)

NS merger



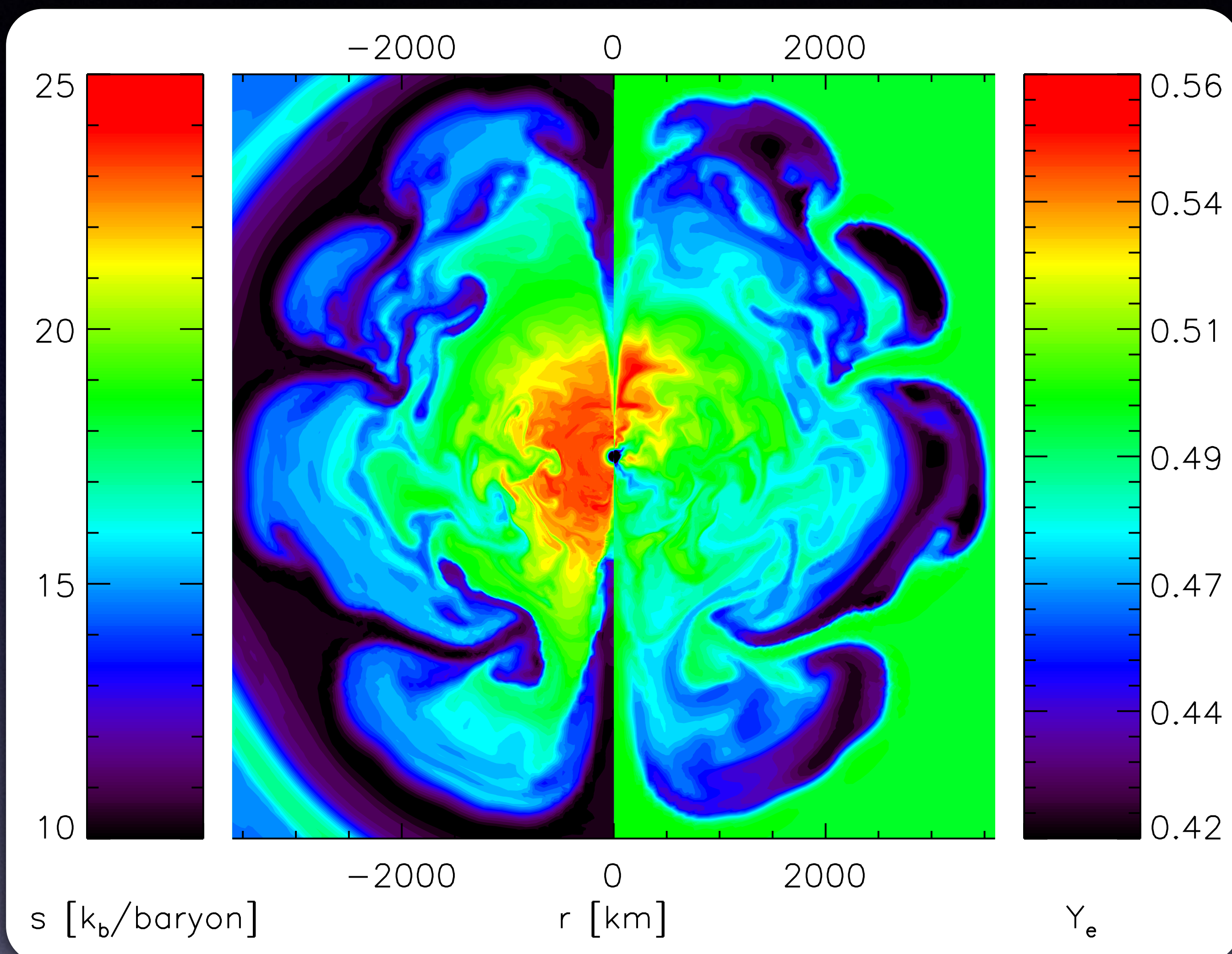
Very neutron rich

$Ye \sim 0.10$ ($n_n \sim 9\ n_p$)

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

$n_n = n_p$
for $Ye = 0.50$

Core-collapse supernovae



Wanajo+11, Wanajo 14

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

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

$$\epsilon_{\bar{\nu}_e} > \epsilon_{\nu_e}$$

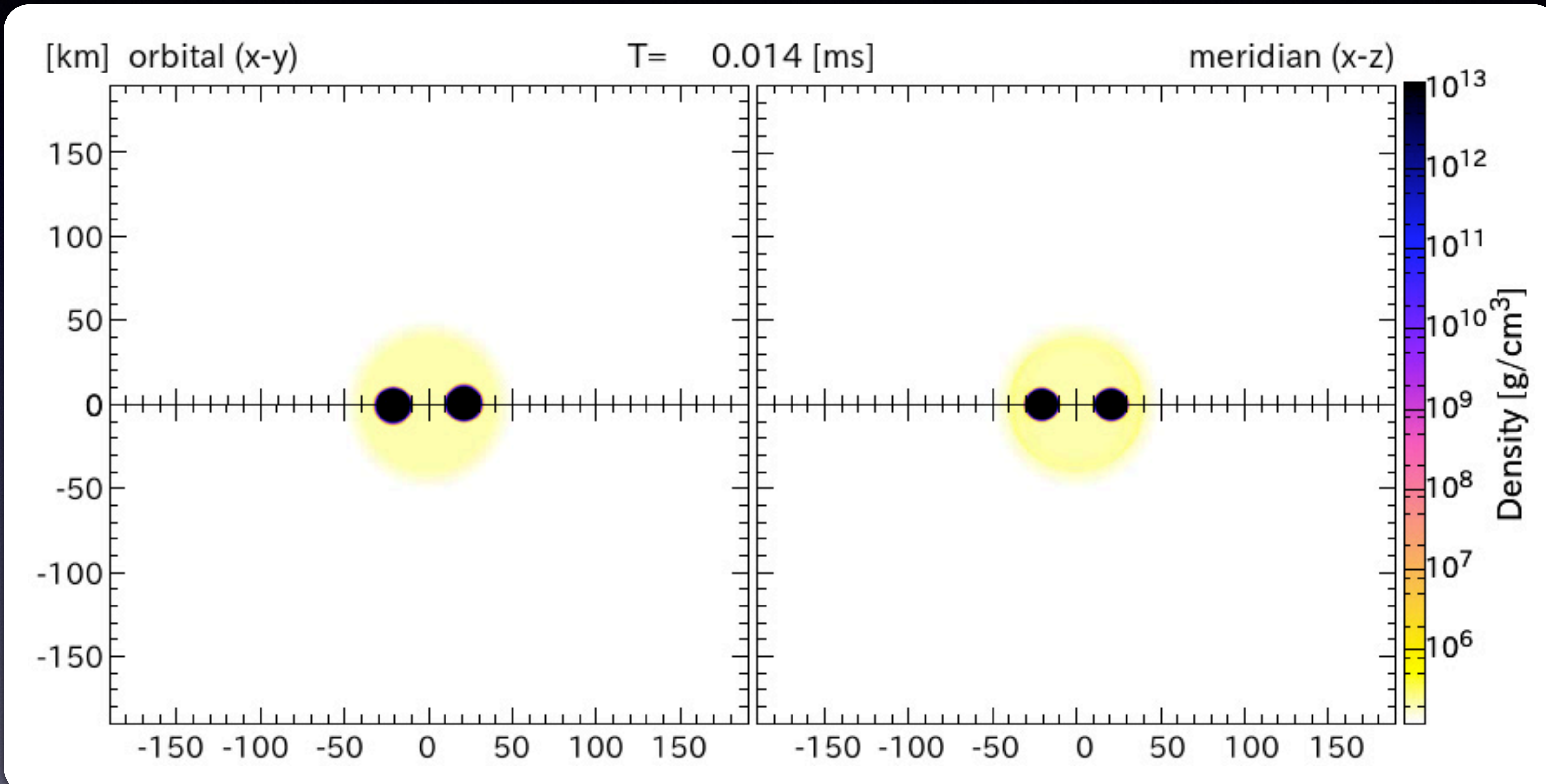
See Takiwaki-san's and Nakamura-san's Talks for more details

Probably neutron rich but only moderately

Ye ~ 0.45 ($n_n \sim 1.2 n_p$)

Neutron star merger

Top view **Side view**



Sekiguchi+15, 16

Very neutron rich (Composition of neutron star

Ye ~ 0.10 (n_n ~ 9 n_p)

3 steps of r-process in explosions

(MeV ~ 10^{10} K)

Temperature

~ 1 MeV

~ 0.5 MeV

~< 0.3 MeV

(A) Nuclear statistical equilibrium (NSE)

(B) NSE => breakdown of NSE

(C) neutron capture => decay

n, p, α

Fe-group elements +α

r-process elements

No more charged-particle reaction

Conditions for r-process (2)

High n/seed ratio after step (B)

$$A_{\mathrm{final}} = A_{\mathrm{seed}} + \mathrm{n/seed}$$

~200 ~50-100

n/seed ~> 100-150

High neutron abundance (low Ye) <= Neutron star merger

or

Low seed abundance <= Supernovae (neutrino driven wind)

Low Ye

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

(ex) Ye = 0.1 (n_n ~ 9 n_p)

1 seed ^{56}Ni (Z = 28, N = 28) + ~200 free neutron

=> n/seed ~ 200

Moderate Ye but high entropy (+ rapid expansion)

$$s \propto T^3/\rho$$

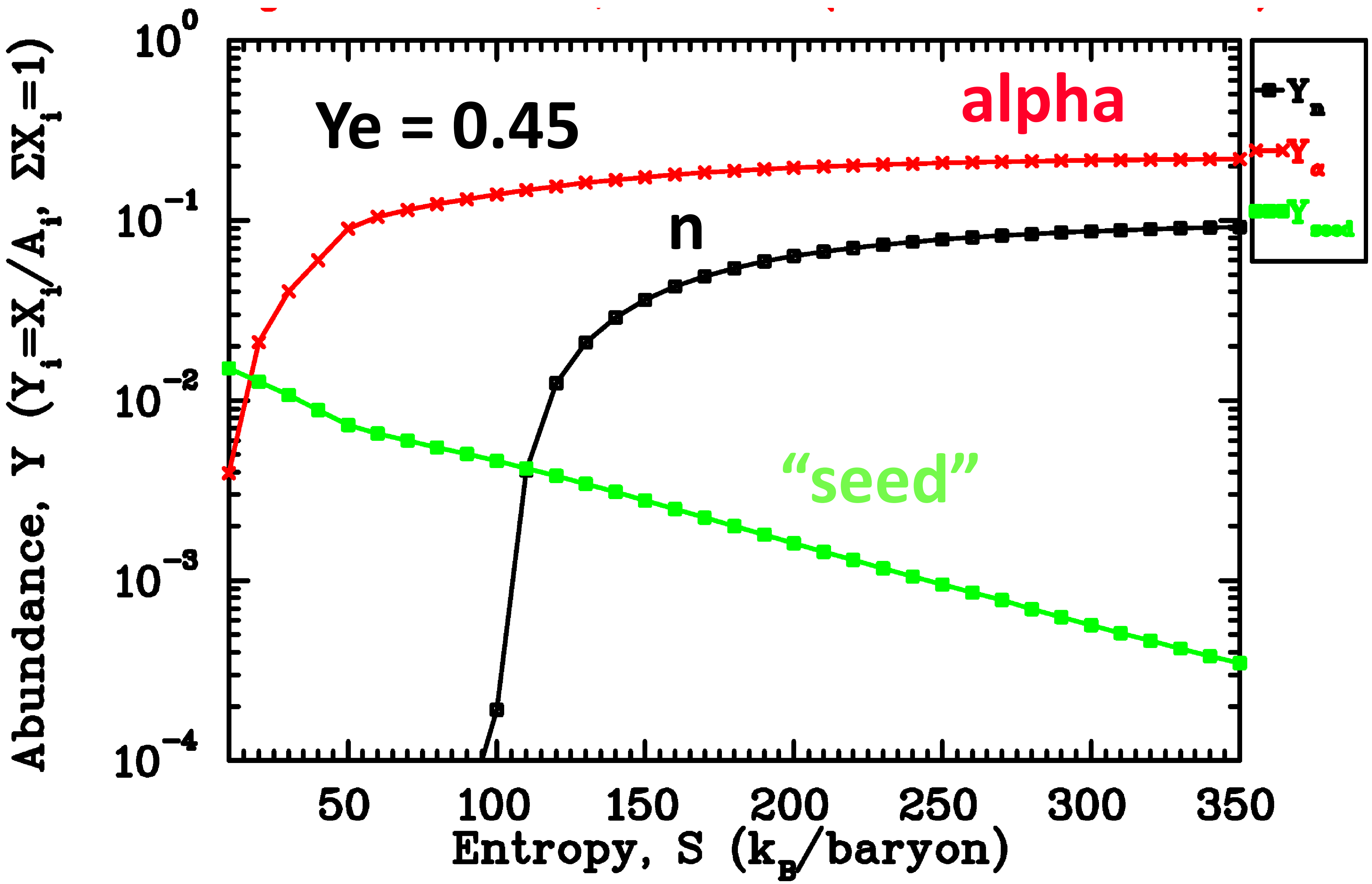
entropy/baryon (radiation dominated)

High temperature => preference for n, p, alpha
Low density => alpha remains at step (B)
=> low seed abundance

(B) Breakdown of NSE (w/ high entropy) = “alpha-rich” freeze-out

Bottle neck reactions (inefficient at low density)

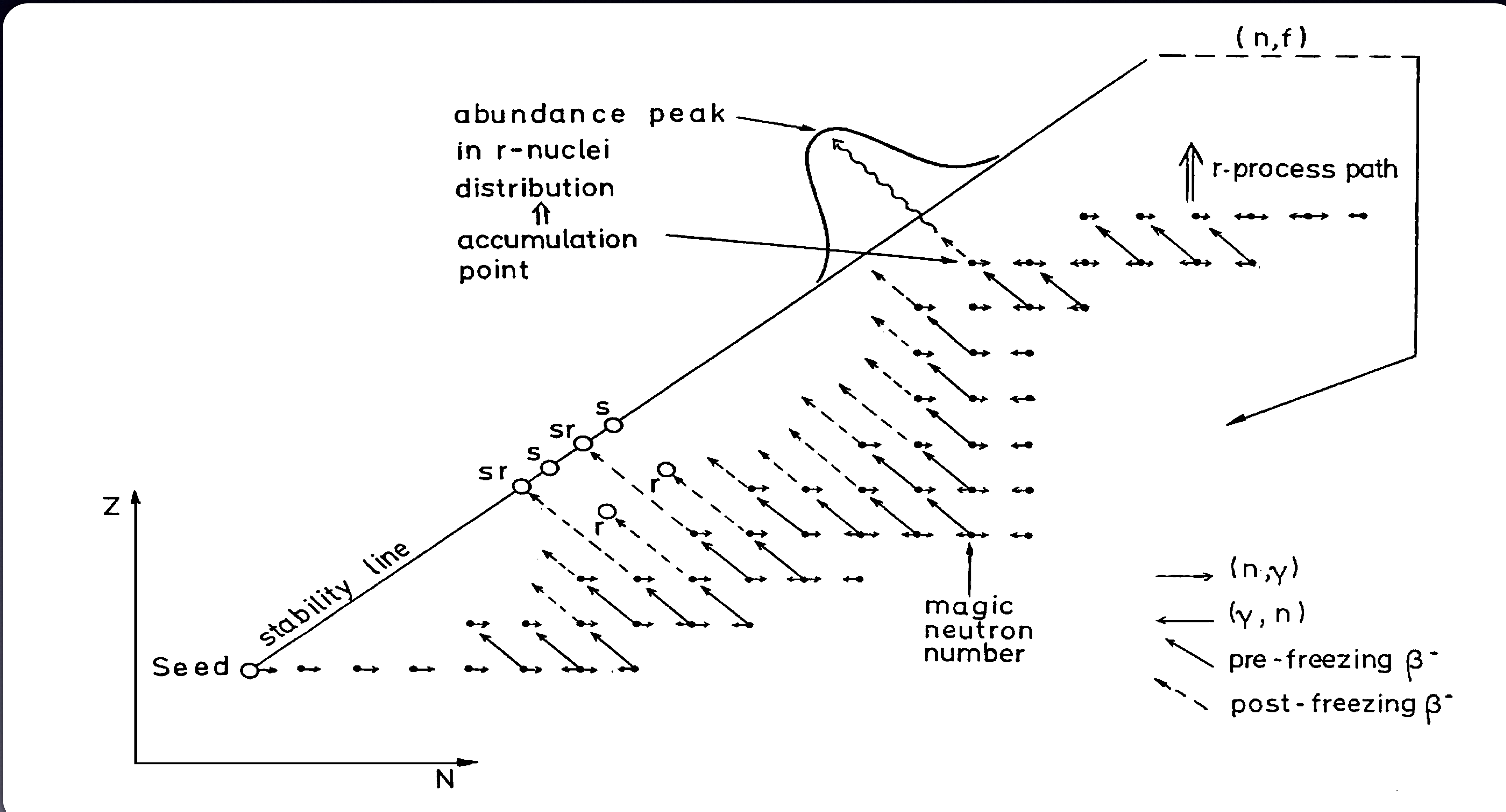
$$\alpha + \alpha + \mathrm{n} \rightarrow {}^{9}\mathrm{Be}$$
$${}^{9}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \mathrm{n}$$



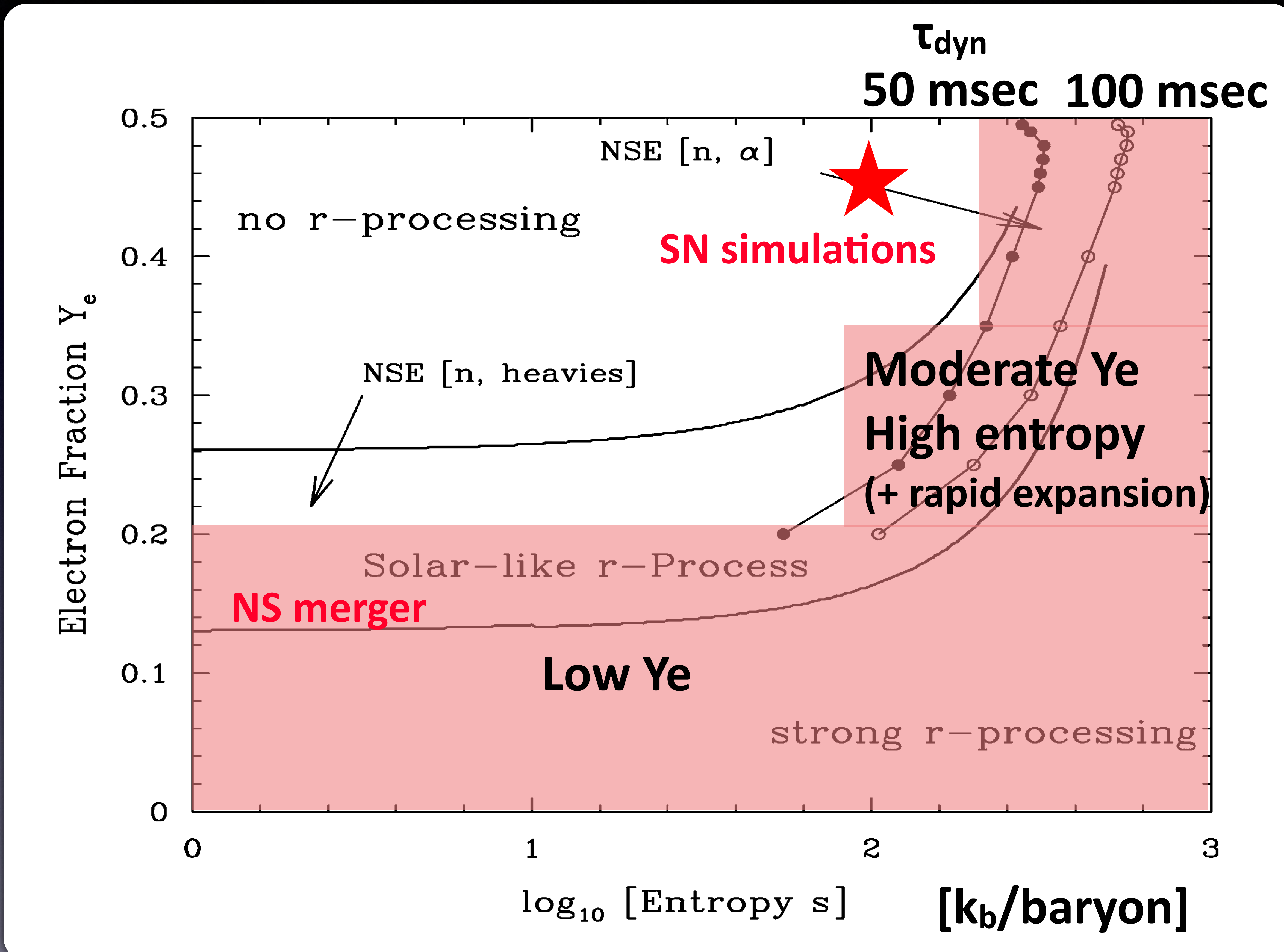
Thielemann+18

(C) Neutron capture (and beta decay)

$$n + (Z, A) \leftrightarrow (Z, A + 1) + \gamma$$



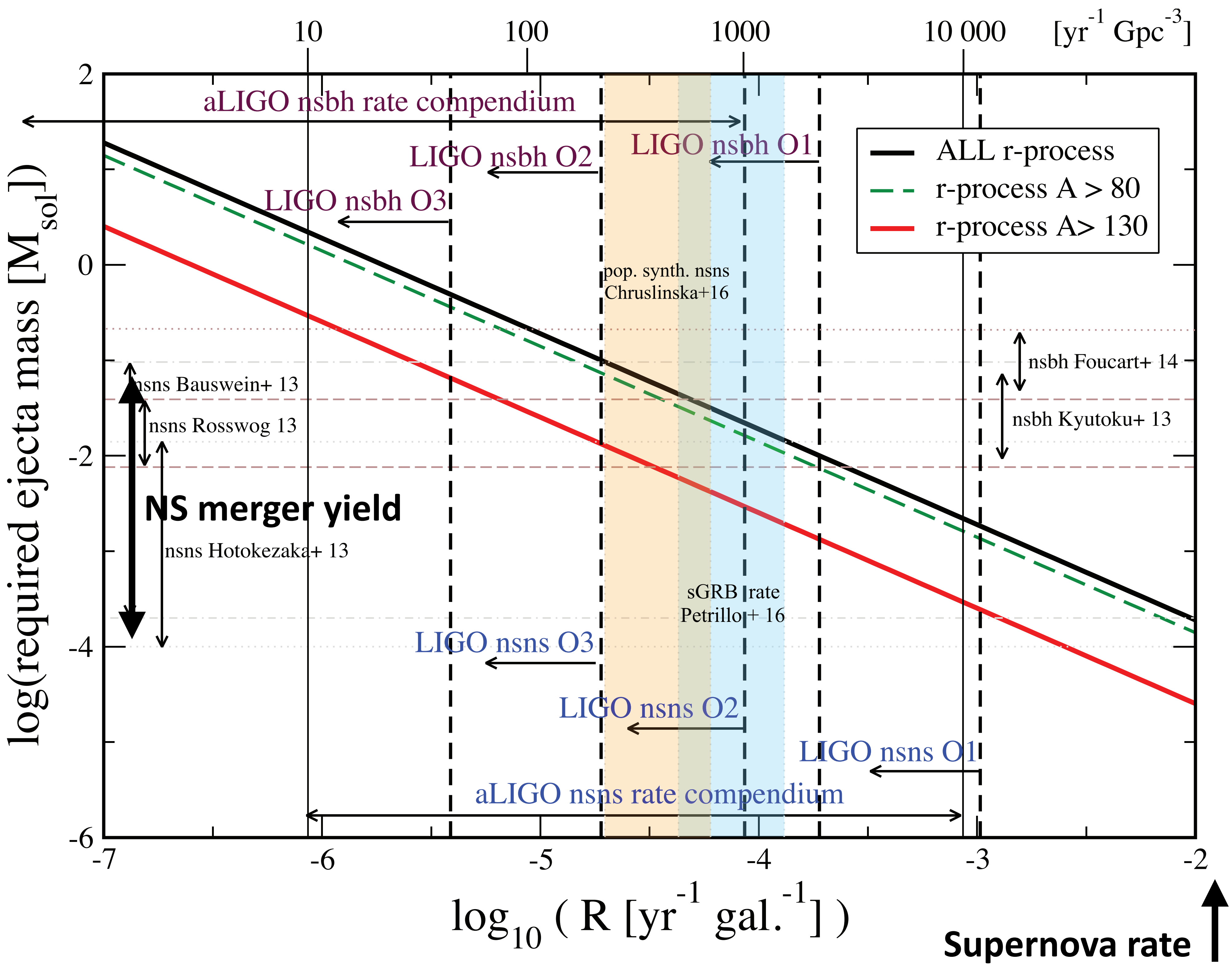
Arnould+07



τ_{dyn}
50 msec
100 msec
0.5
0.4
0.3
0.2
0.1
0
Electron Fraction Y_e
NSE [n, α]
no r−processing
SN simulations
NSE [n, heavies]
Moderate Ye
High entropy
(+ rapid expansion)
Solar−like r−Process
NS merger
Low Ye
strong r−processing
0
1
2
3
$\log_{10}$ [Entropy s]
[k_b/baryon]

Arnould+07

Constraints from the total amount in our Galaxy



See Tsujimoto-san's talk for more details

Rosswog+17, Hotokezaka+15, 18

まとめ (1/3): rプロセス元素合成

- **宇宙の元素組成**
  - sプロセス、rプロセスの両方が必要
  - rプロセスの元素組成パターンは「ユニバーサル」
  - 必要な産出量 10^{-4} Msun/Gal/100 yr = 10^{-2} Msun/Gal/10^4 yr
- **rプロセス元素合成と起源天体の候補**
  - 高い中性子密度 => 中性子星に関連した天体現象
  - 高いn/seed比 => 中性子過剰、高エントロピー
  - 中性子星合体：非常に中性子過剰
  - 超新星爆発 (ニュートリノ風)：
それなりに中性子過剰＆高エントロピー (難しいか？)

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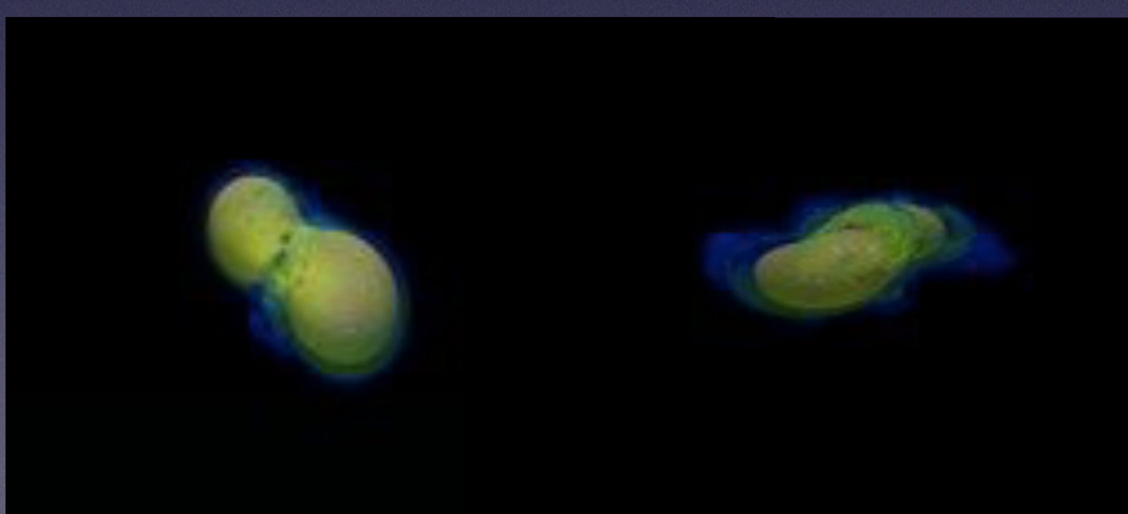
Merger → neutron-capture (r-process) nucleosynthesis → Radioactive decay => kilonova

Mass ejection

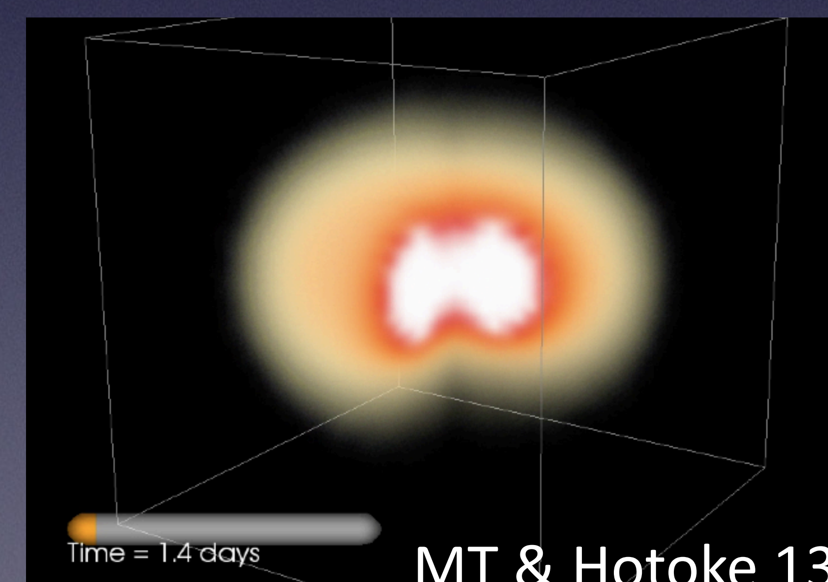
~< 100 ms

< 1 sec

~> days



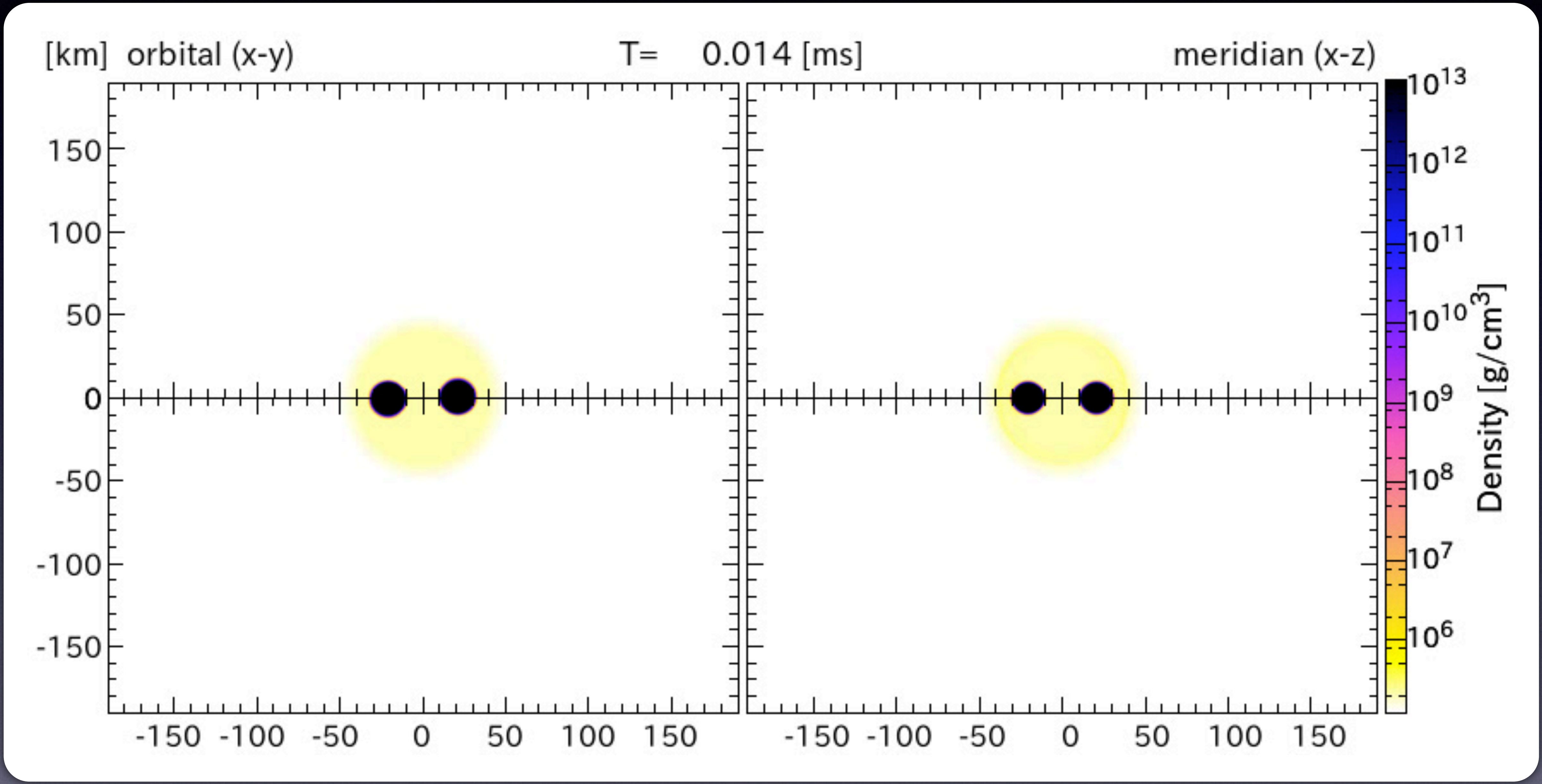
http://www.aei.mpg.de/comp-rel-astro



MT & Hotoke 13

Mass ejection from NS merger

Top view | **Side view**



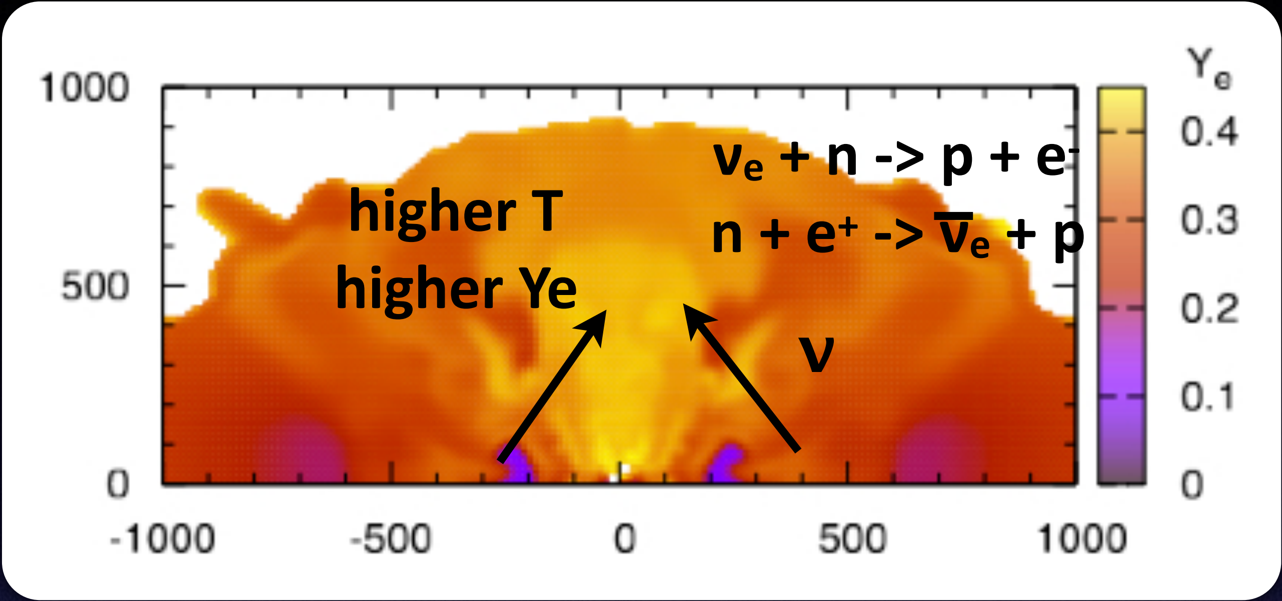
Sekiguchi+15, 16

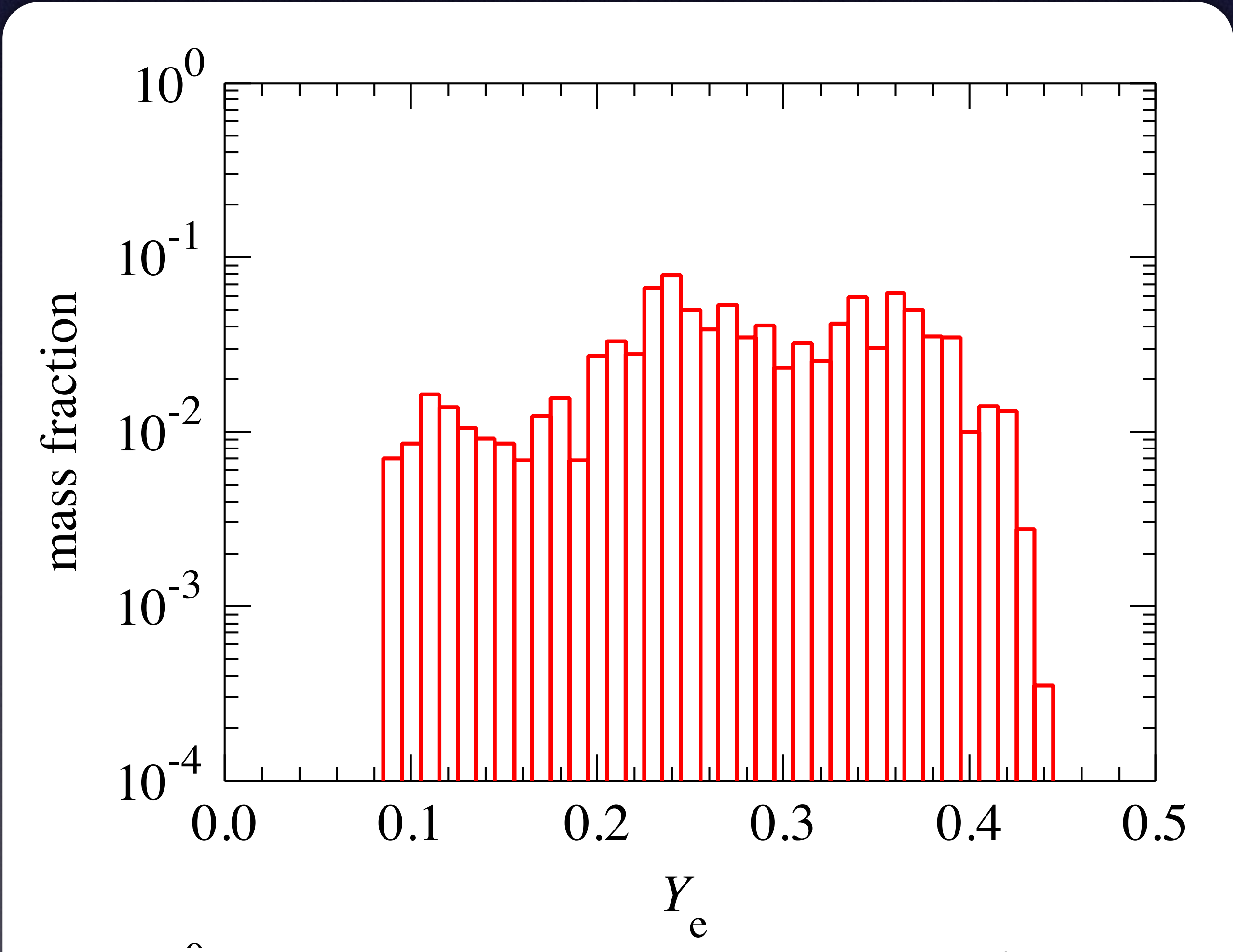
- Tidal disruption
- Shock heating

M ~ 10^{-3} - 10^{-2} Msun

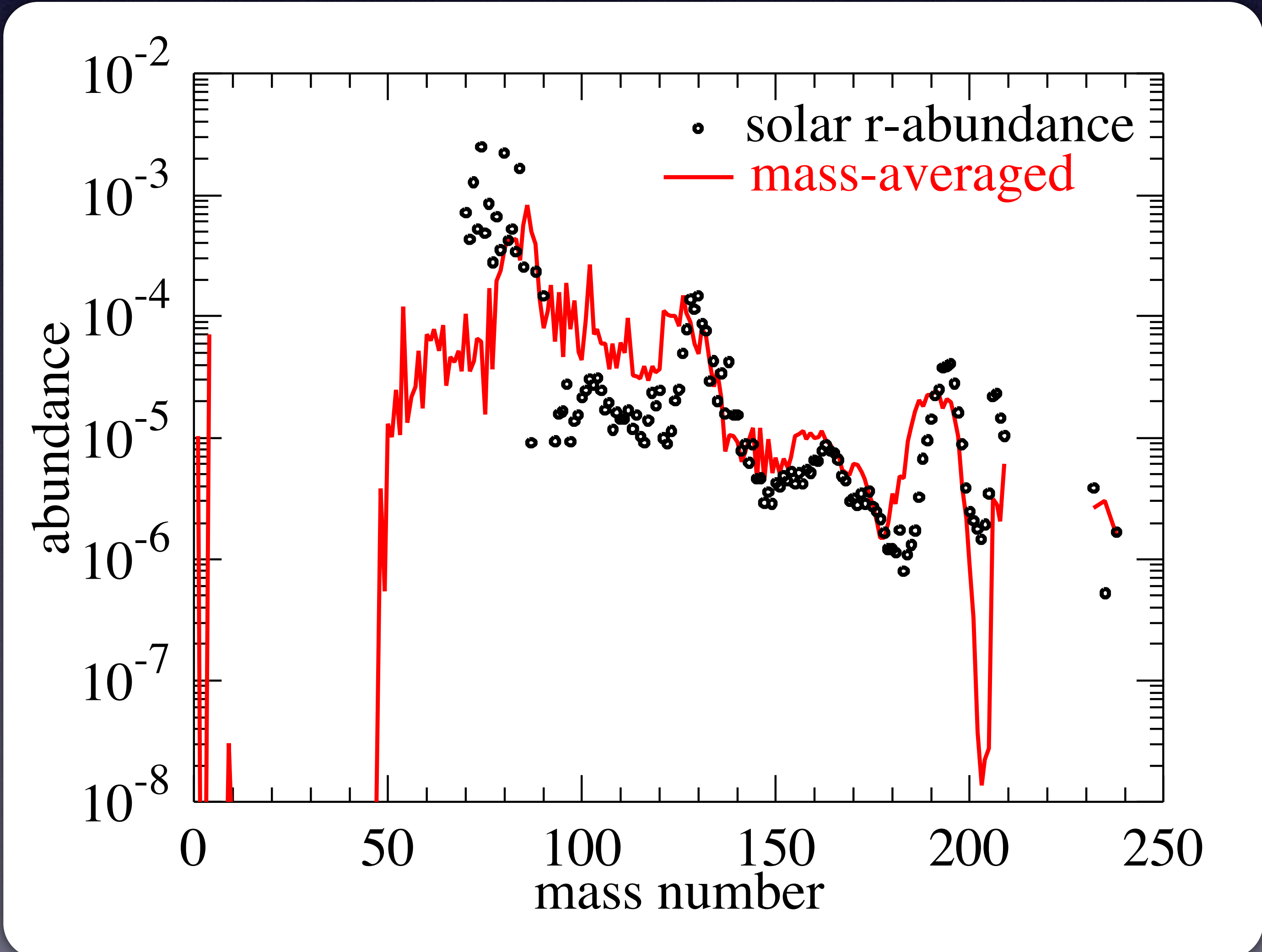
v ~ 0.1 - 0.2 c

r-process nucleosynthesis in the ejecta of NS mergers

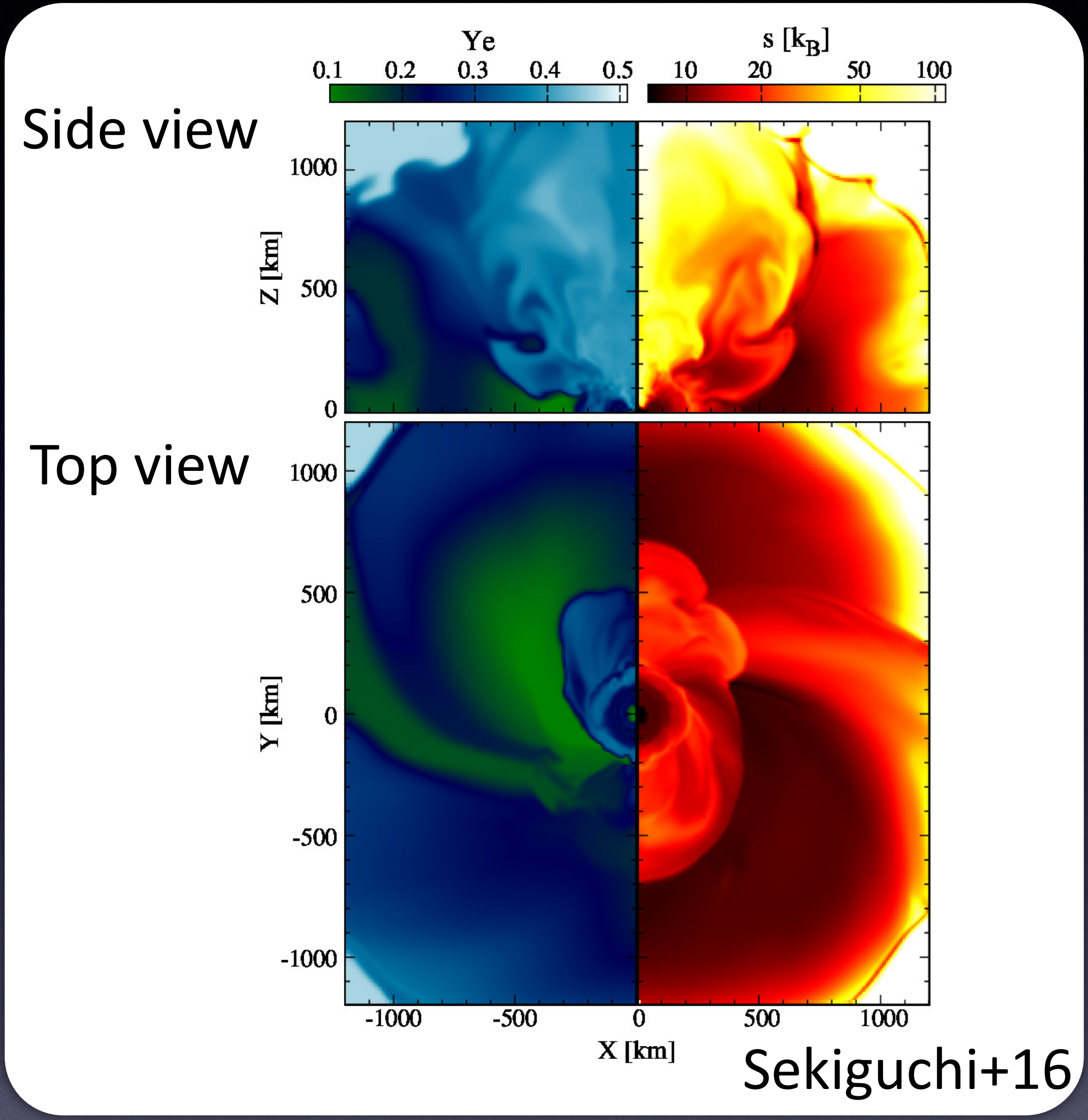




Wanajo+14

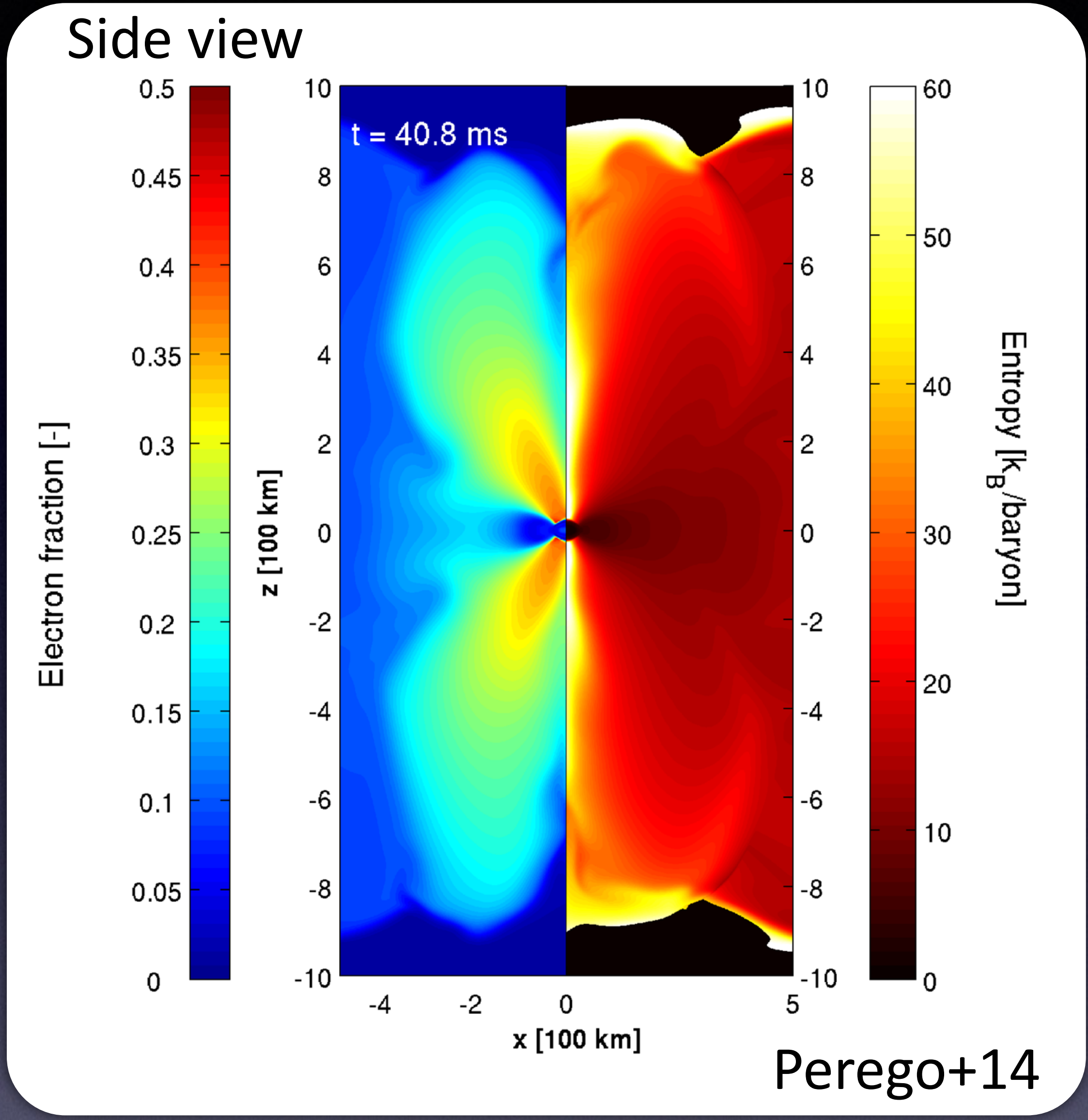


Dynamical ejecta (~< 10 ms)



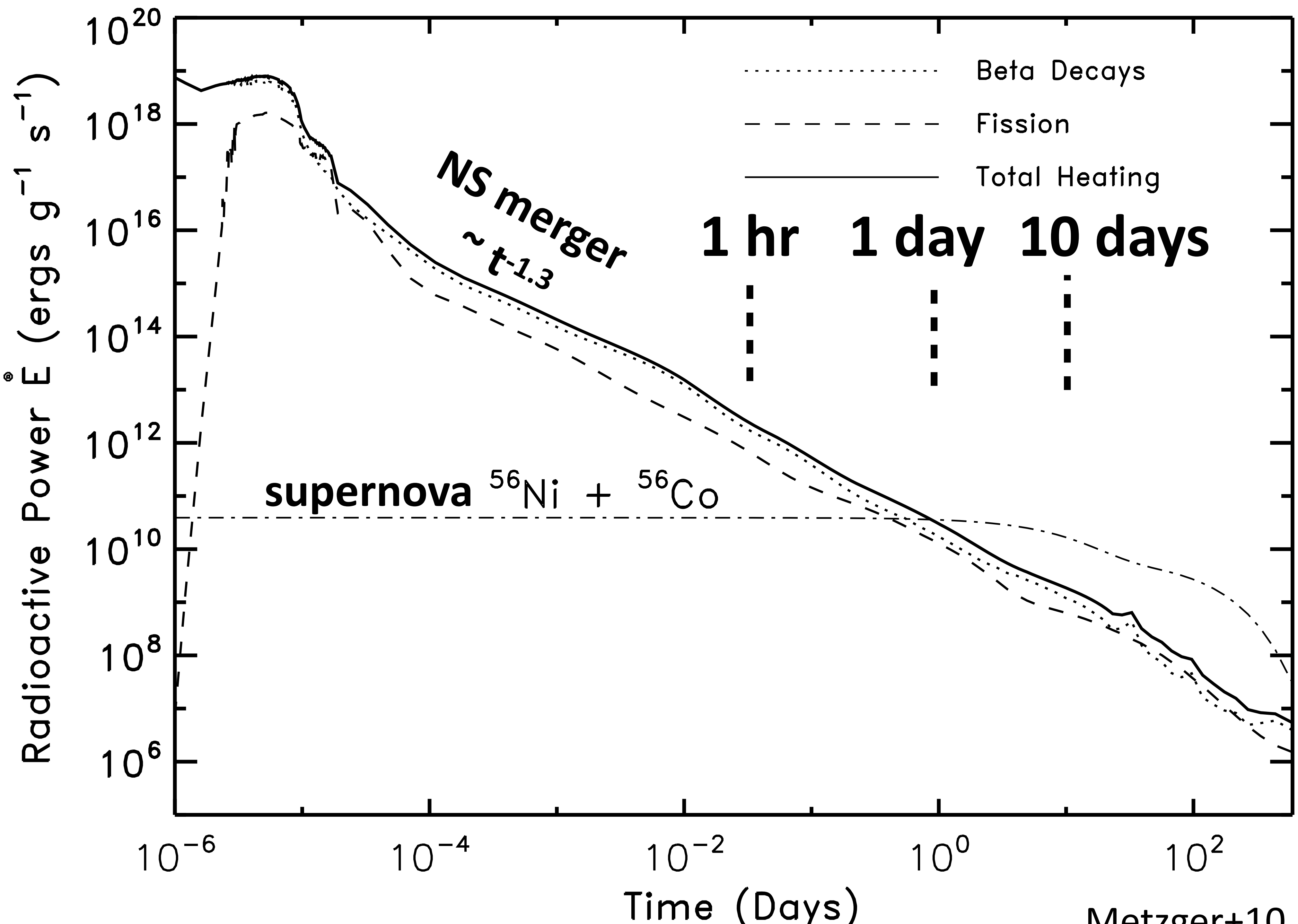
$M_{ej} \sim 10^{-3} - 10^{-2}$ Msun
v ~ 0.1-0.2 c
Low Ye (wide distribution)

Post-merger ejecta (~< 100 ms)



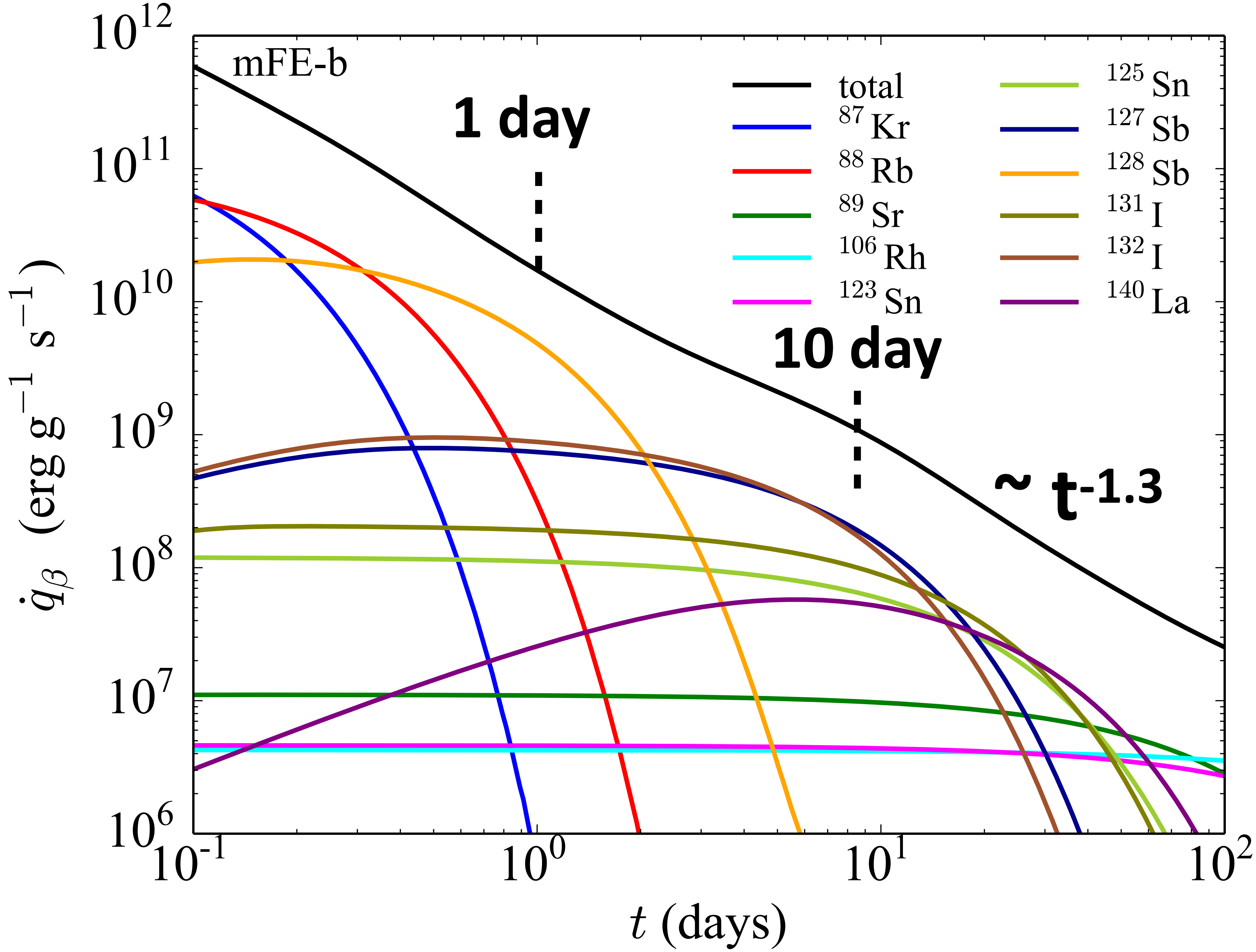
$M_{ej} >\sim 10^{-2}$ Msun
v ~ 0.05 c
Relatively high Ye

Radioactive decay luminosity



Metzger+10

Radioactive decay luminosity



Wanajo 18

Radioactive decays of r-process nuclei "heat up" the ejected material

β decay

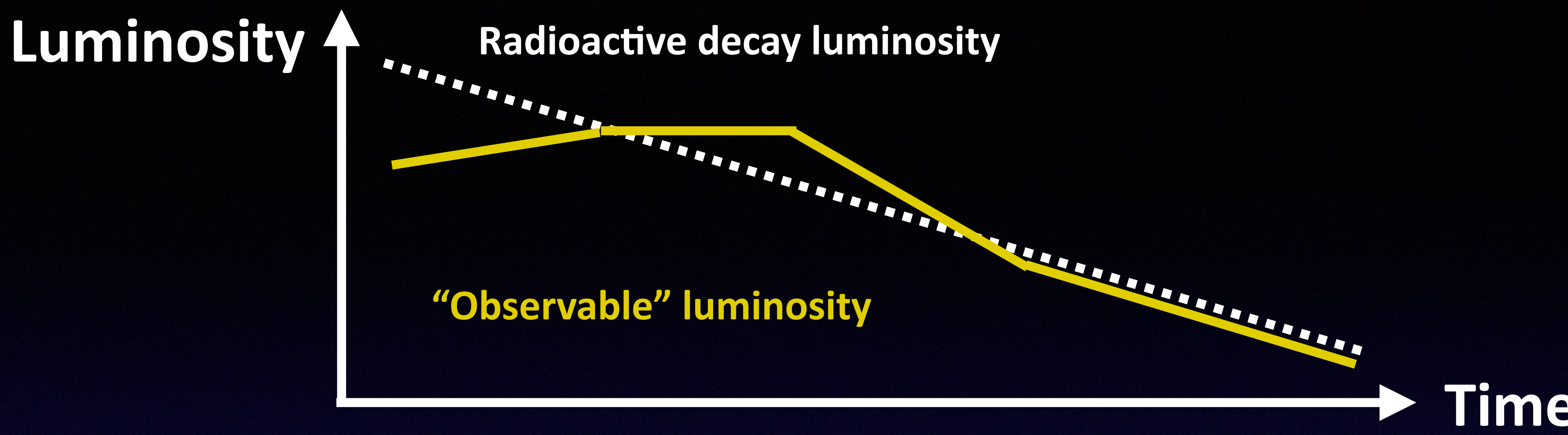
- γ-rays (~ 1 MeV) => Compton scat. & photo-absorption
- β particles (~1 MeV) => ionization/excitation

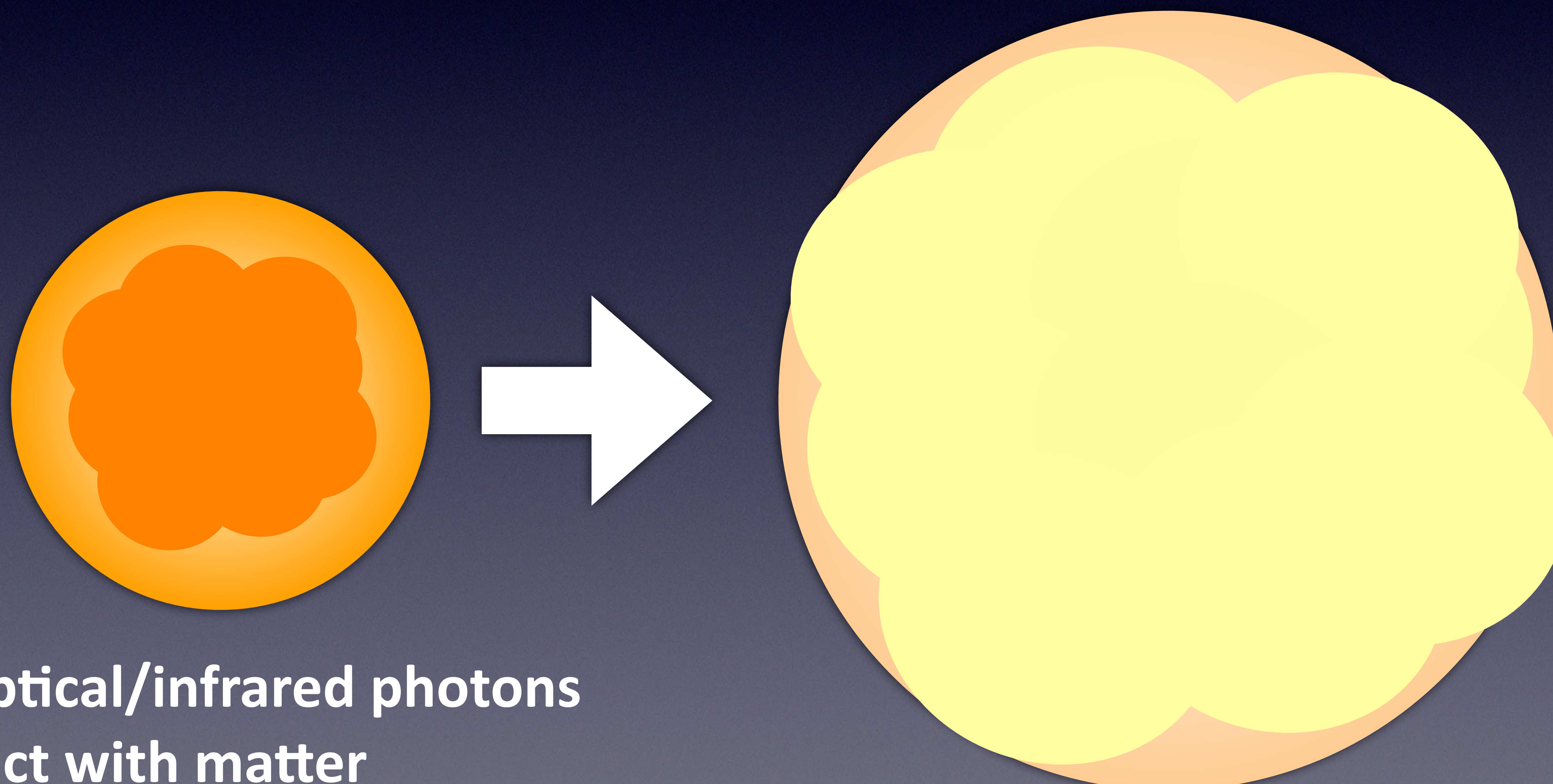
α decay

- α particles (~7 MeV) => ionization/excitation

Fission

- fission fragments (~100 MeV) => ionization/excitation

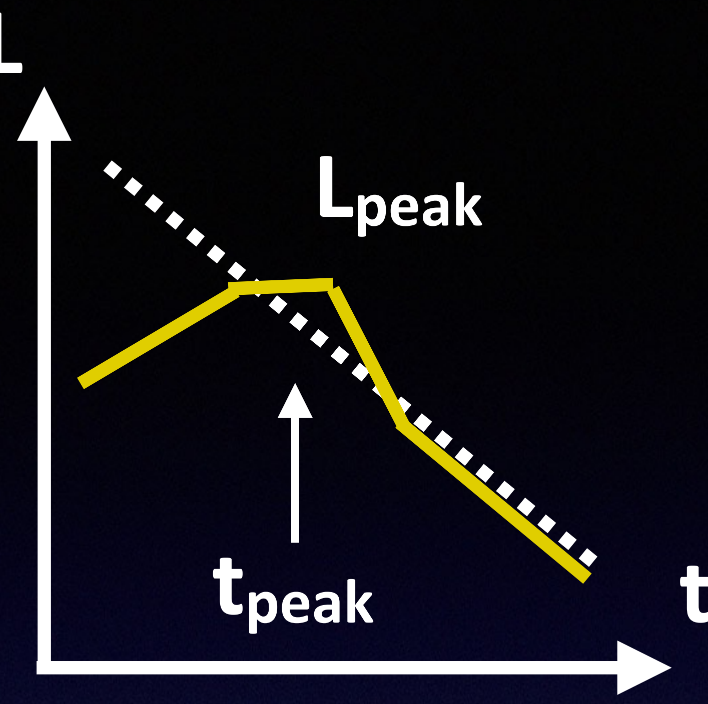




UV/optical/infrared photons
interact with matter
mainly via bound-bound transitions

“Kilonova/Macronova"

Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, …
High opacity: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, …



Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$
$$\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \boxed{\left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}}$$

Luminosity

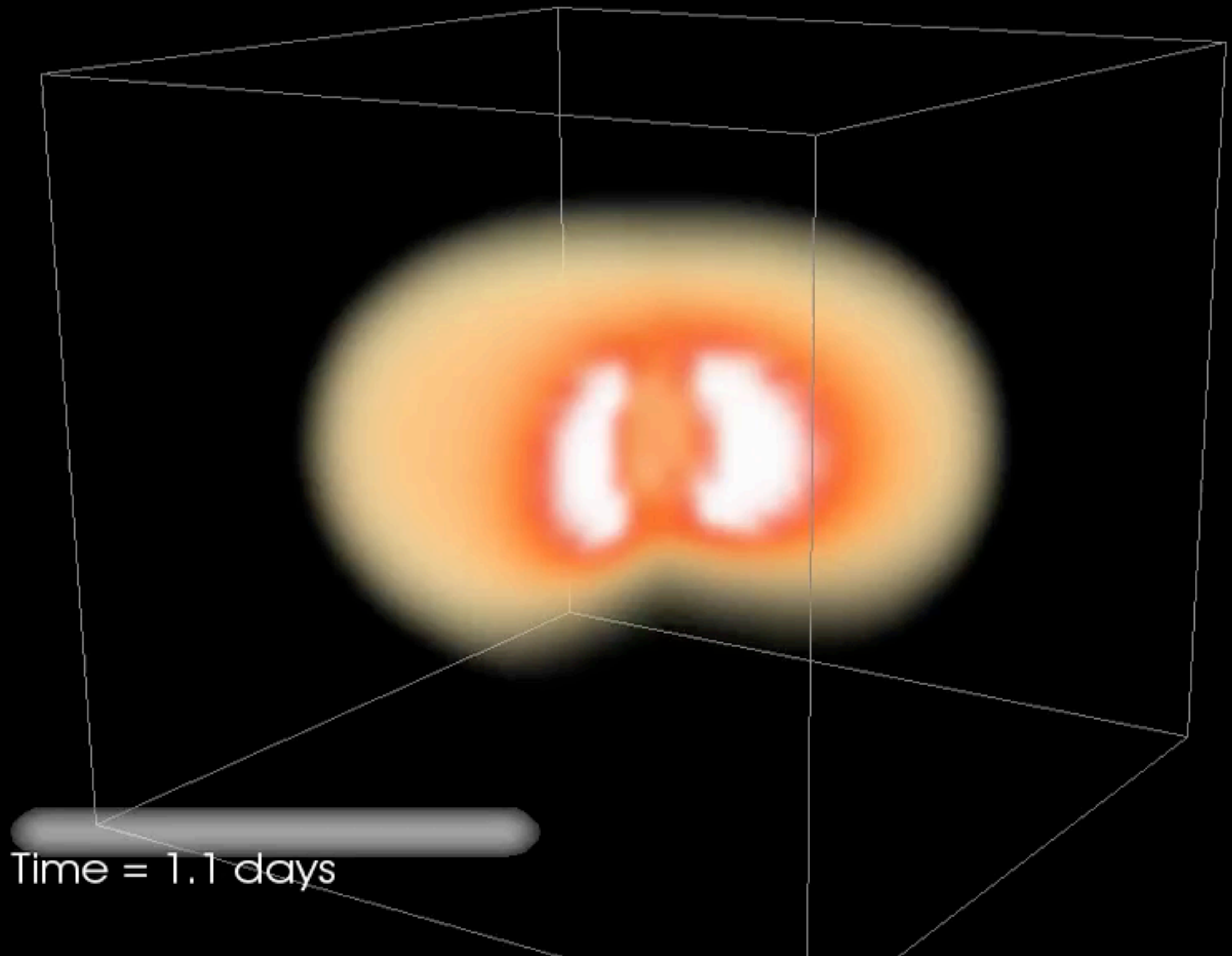
*assuming 50% thermalization

$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$
$$\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \boxed{\left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{-0.65}}$$

Temperature ~ 5000 K => Optical and infrared wavelengths

Radiation transfer simulations of kilonova

(MT & Hotokezaka 13, MT+14, MT 16)



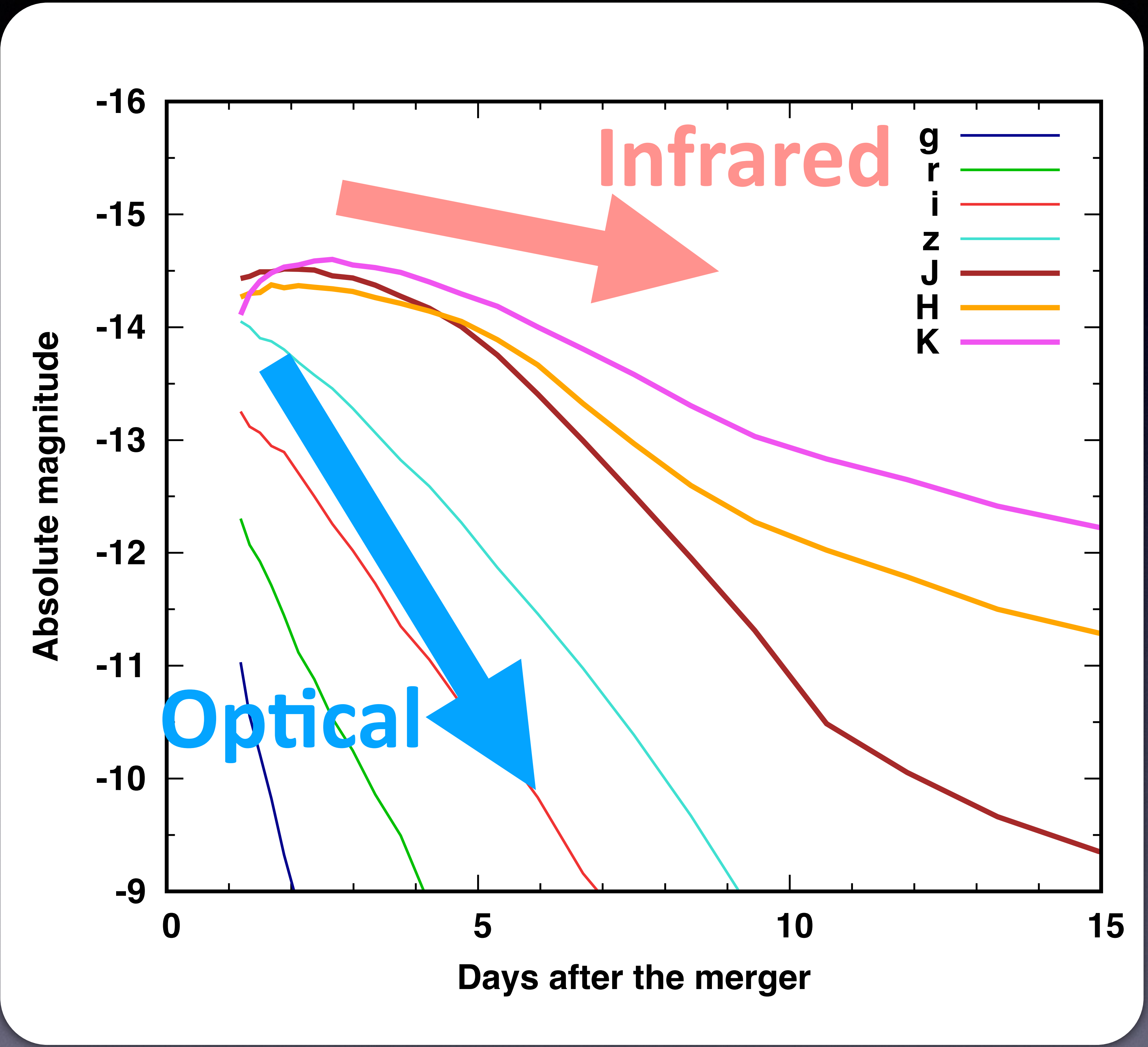
Light curves of kilonova

Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13

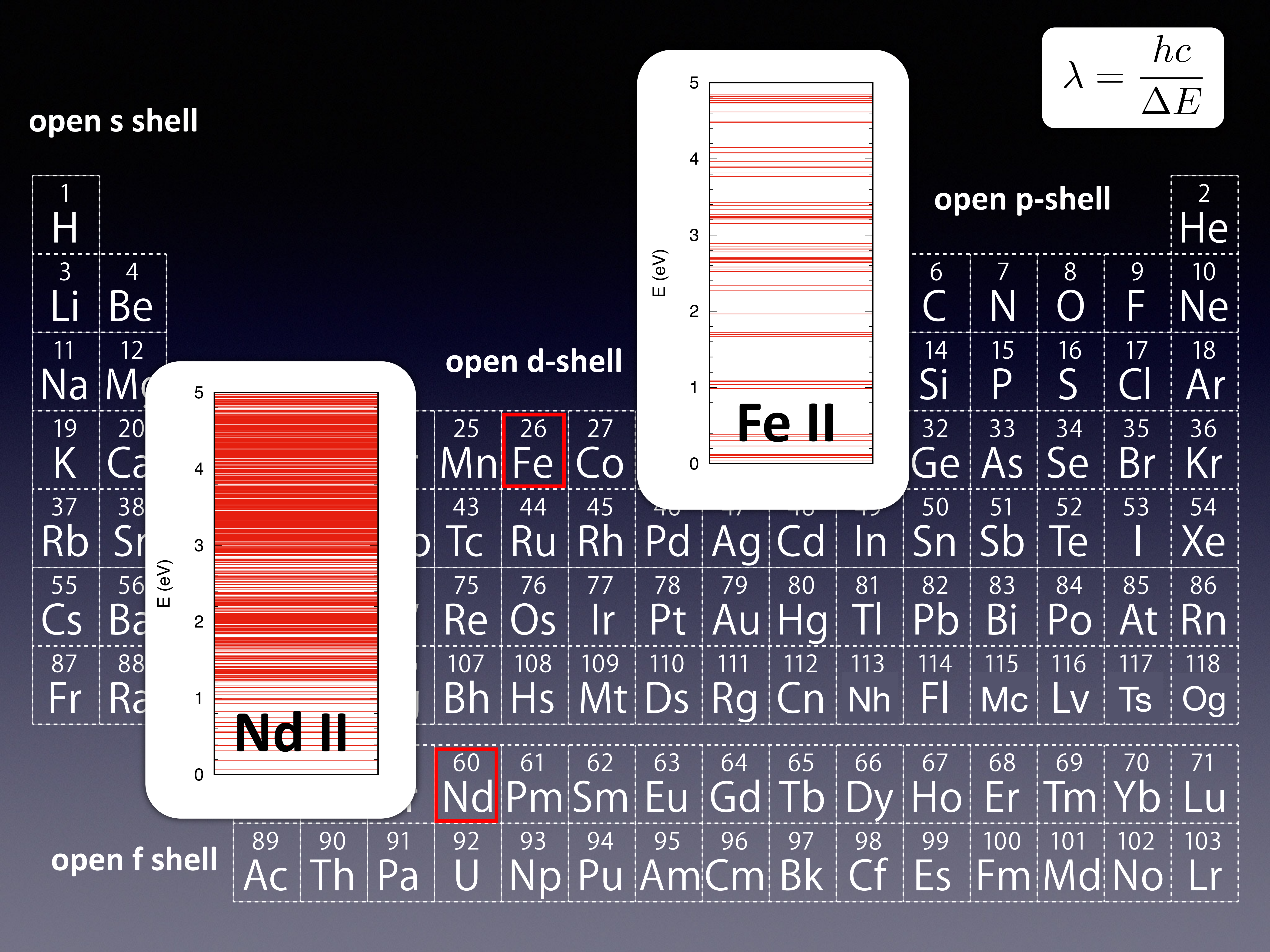
L ~ 10^{40}-10^{41} erg s^{-1}

t ~ weeks

NIR > Optical



Model: MT+17a



$\lambda = \frac{hc}{\Delta E}$
open s shell
open p-shell
open d-shell
open f shell
Fe II
E (eV)
Nd II
E (eV)

Number of state for a given l (1 electron)
(different combinations of m_l and m_z)

$$g = \underbrace{2}_{m_z\ \text{(spin)}}\underbrace{(2l+1)}_{m_l\ \text{(orbital)}}$$

g = 2 (l = 0, s shell)
g = 6 (l = 1, p shell)
g = 10 (l = 2, d shell)
g = 14 (l = 3, f shell)

Number of state per configuration (n electrons)

$$_gC_n = \frac{g!}{n!(g-n)!}$$

(ex)

Si I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$ $\quad$ **$_6C_2$ = 15**

Fe I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^6$ $\quad$ **$_{10}C_6$ = 219**

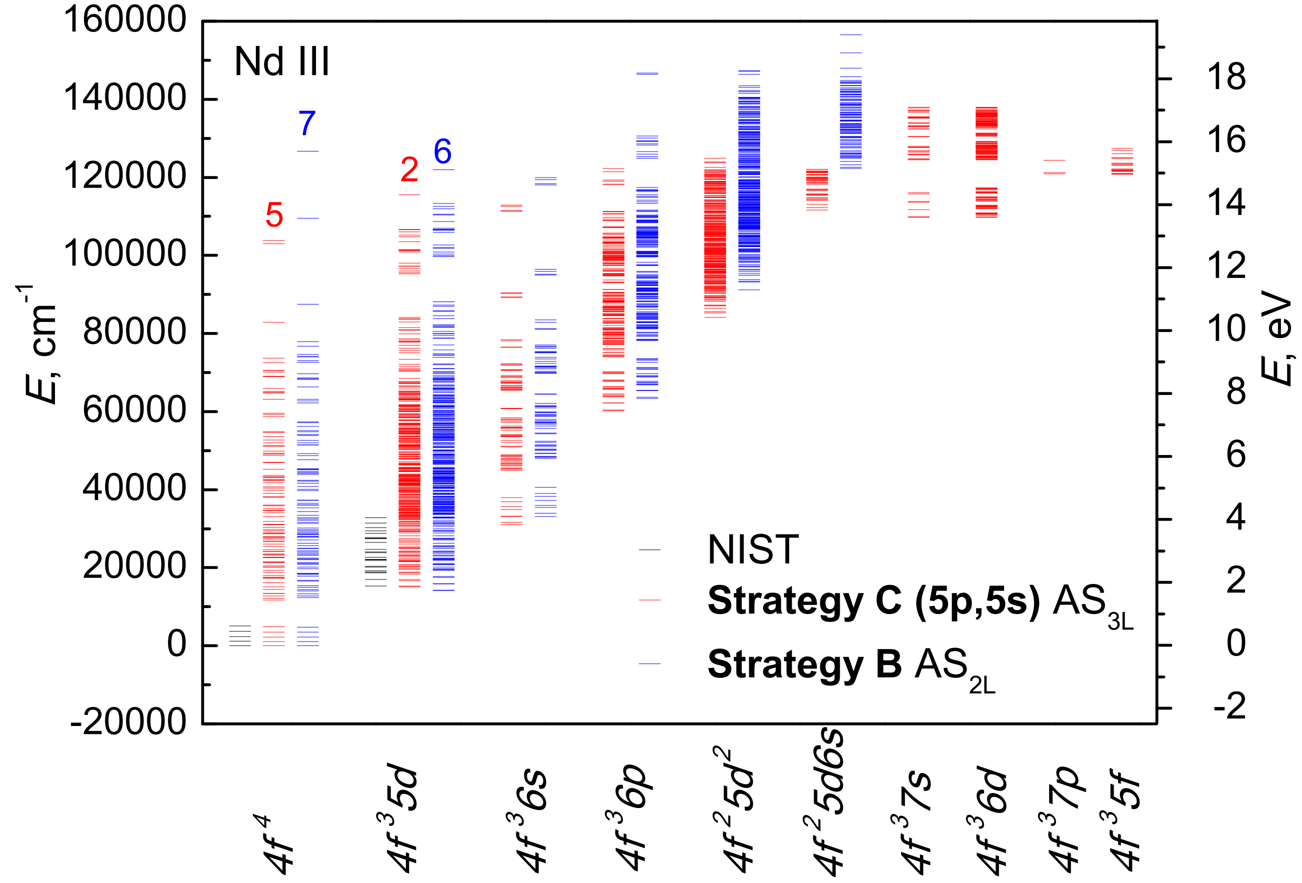
Nd I: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 4d^{10}\ 5s^2\ 4f^4$ $\quad$ **$_{14}C_4$ = 1001**

Atomic structure calculations for b-b transitions

Nd I-III
(Z=60, f)

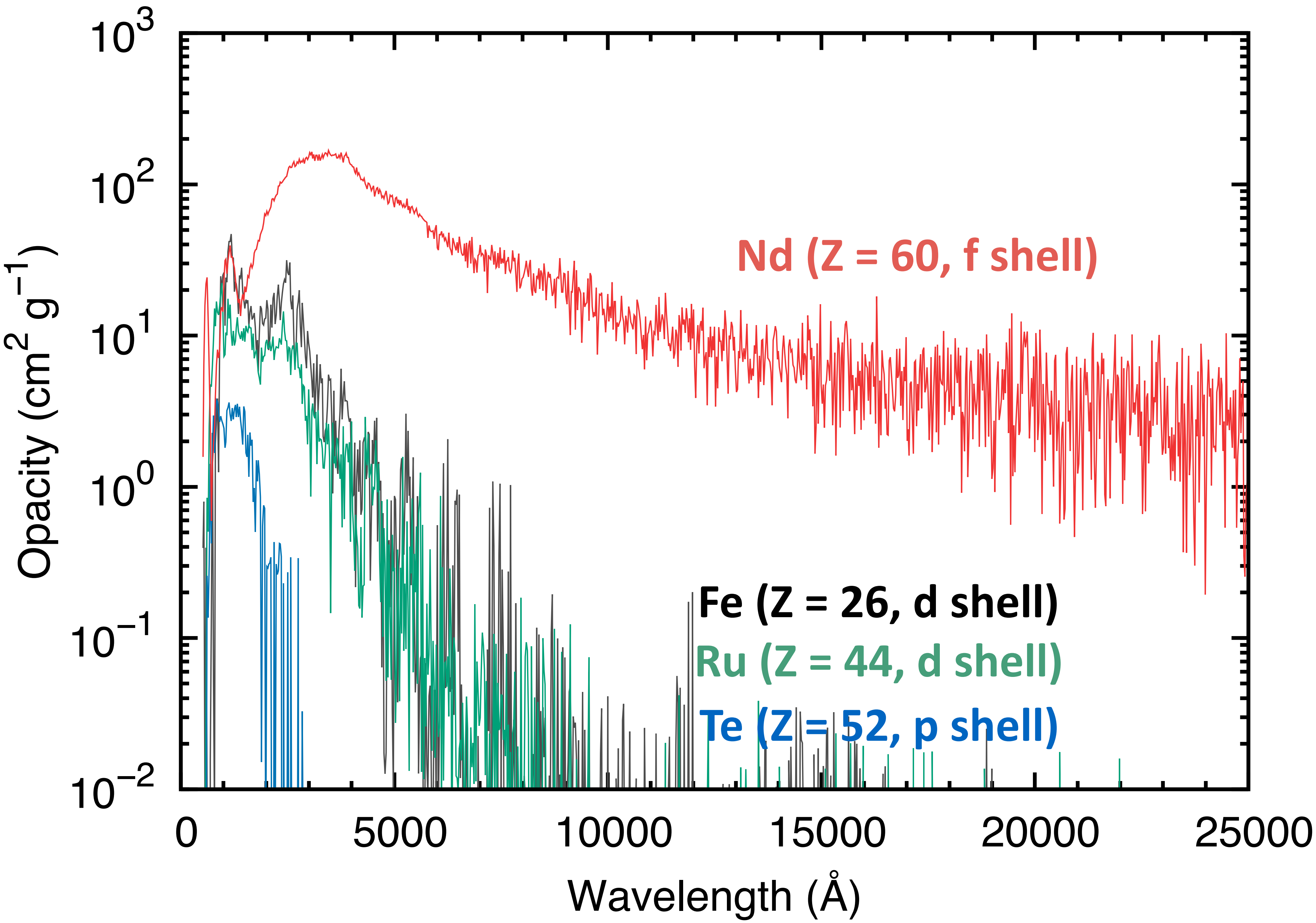
Er I-III
(Z=68, f)

Ion	Configurations	Number of levels	Number of lines
Nd I	$\mathbf{4f^46s^2}$, $\mathbf{4f^46s(5d,6p,7s)}$, $\mathbf{4f^45d^2}$, $\mathbf{4f^45d6p}$, $4f^35d6s^2$, $4f^35d^2(6s,6p)$, $4f^35d6s6p$	31,358	70,366,259
Nd II	$\mathbf{4f^46s}$, $\mathbf{4f^45d}$, $4f^46p$, $4f^36s(5d,6p)$, $4f^35d^2$, $4f^35d6p$	6,888	3,951,882
Nd III	$\mathbf{4f^4}$, $4f^3(5d,6s,6p)$, $4f^25d^2$, $4f^25d(6s,6p)$, $4f^26s6p$	2252	458,161
Er I	$\mathbf{4f^{12}6s^2}$, $\mathbf{4f^{12}6s(5d,6p,6d,7s,8s)}$, $4f^{11}6s^2(5d,6p)$, $4f^{11}5d^26s$, $4f^{11}5d6s(6p,7s)$	10,535	9,247,777
Er II	$\mathbf{4f^{12}6s}$, $4f^{12}(5d,6p)$, $4f^{11}6s^2$, $4f^{11}6s(5d,6p)$, $4f^{11}5d^2$, $4f^{11}5d6p$	5,333	2,432,665
Er III	$\mathbf{4f^{12}}$, $4f^{11}(5d,6s,6p)$	723	42,671



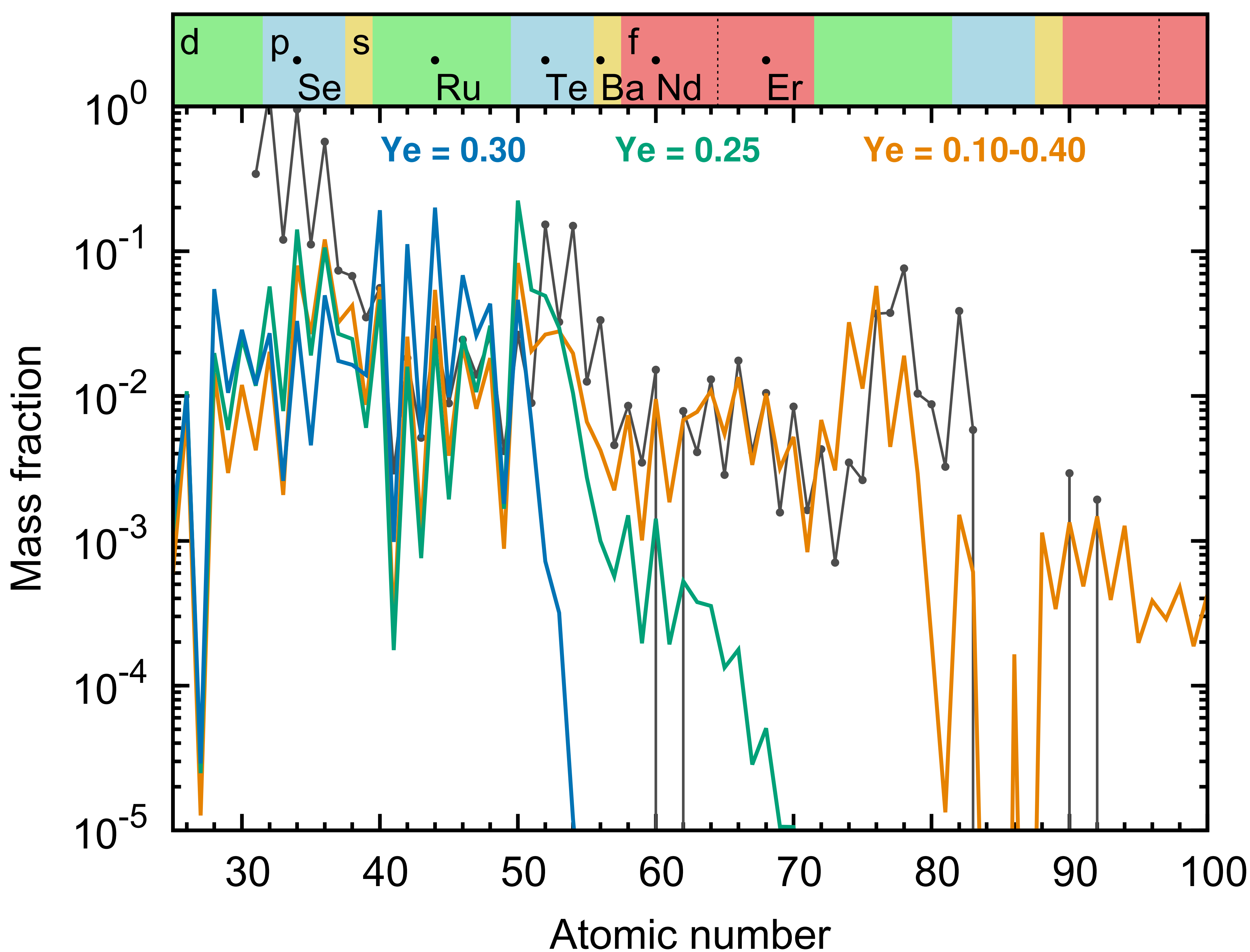
MT, Kato, Gaigalas+18

Bound-bound opacity



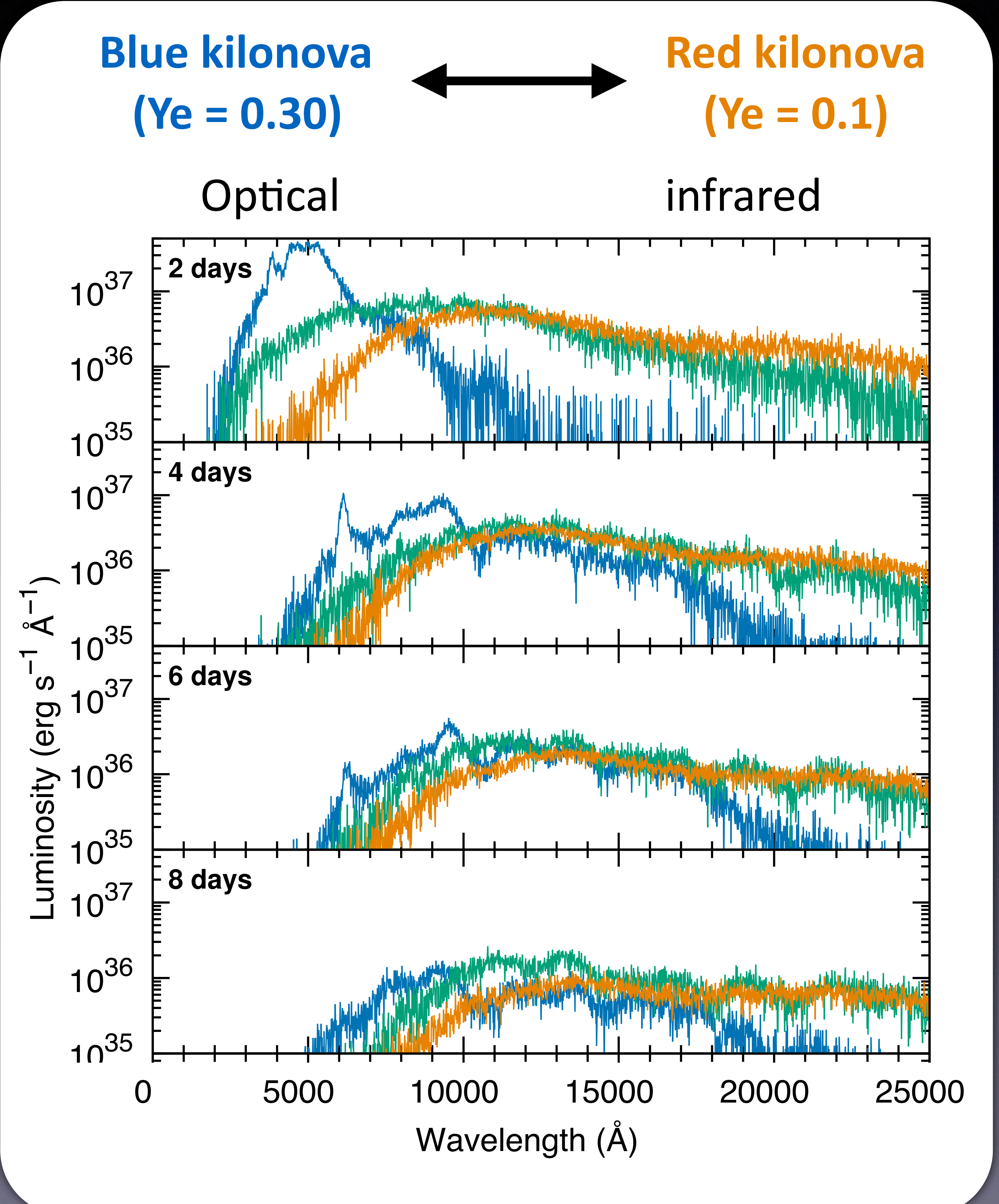
MT, Kato, Gaigalas+18

Little (or no) production of Lanthanide if Ye ~> 0.25



MT, Kato, Gaigalas+18

Nucleosynthesis is imprinted in the spectra



MT+18

Neutron star merger
Nucleosynthesis
Kilonova

Simulations

GW

Event rate of
NS merger

“Multi-messenger”
astronomy

EM

Mass ejection
per event

The origin of heavy (r-process) elements

まとめ (2/3): 中性子星合体とキロノバ

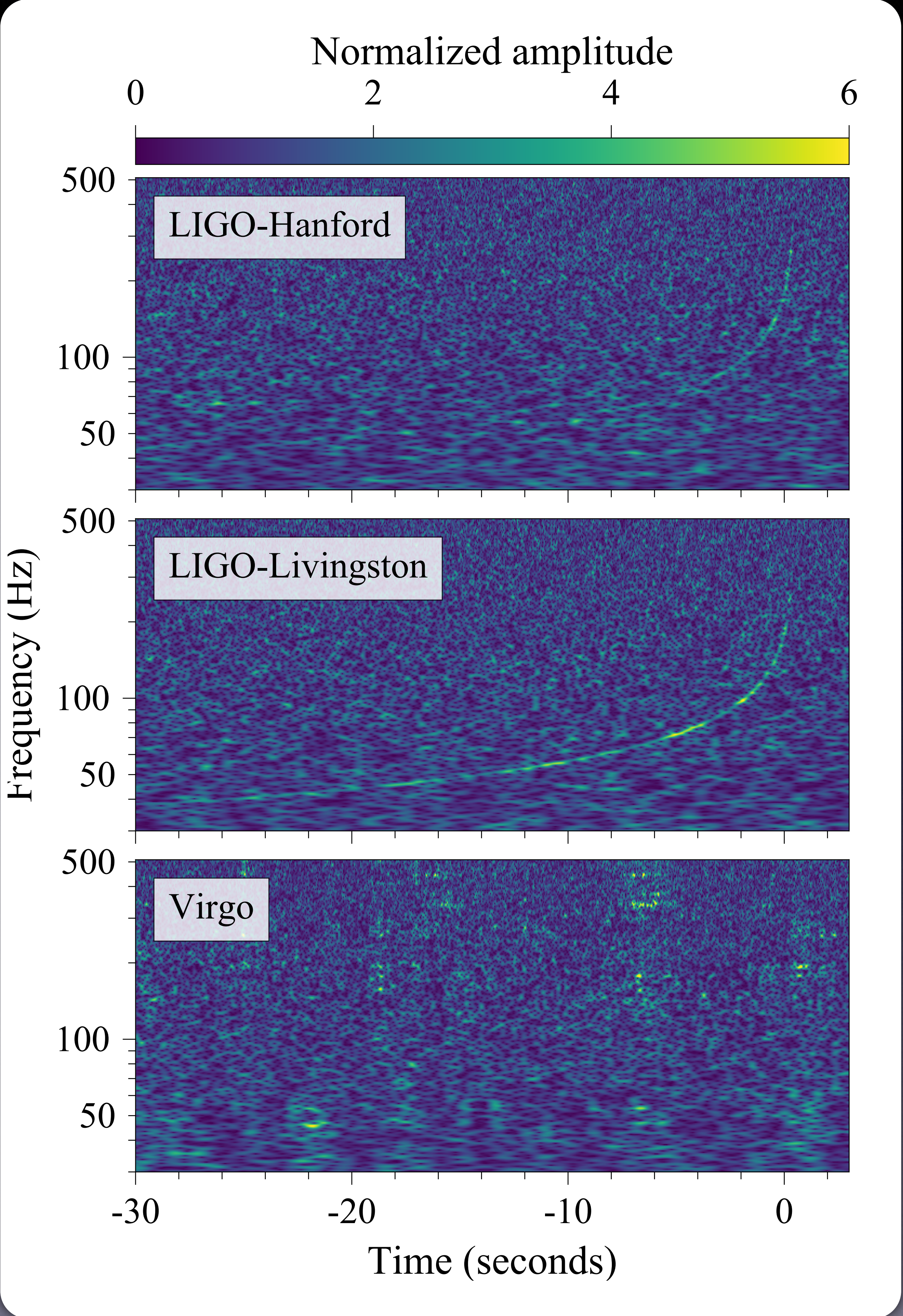
- **中性子星合体**
  - Dynamical ejecta: Ye低い (赤道面) Ye高い (上空方向)
  - Post-merger ejecta: Ye高い (ニュートリノの効果)
- **キロノバ**
  - rプロセス元素の放射性崩壊による電磁波放射
  - L ~ $10^{40\text{-}41}$ erg/s、T ~ 5000 K、timescale ~ week
  - Low Ye 赤外線 > 可視光 (ランタノイド元素の性質)
  - High Ye 可視光線 > 赤外線
  - 重力波 => event rate、電磁波 => 放出量 (+ Ye)

チュートリアルの目標

- **rプロセス元素合成**
  - 天文観測からの要請：何がゴールか？
  - 基礎物理過程と起源天体の候補
- **中性子星合体**
  - 中性子星合体におけるrプロセス元素合成
  - 「キロノバ」: rプロセスによる突発天体現象
- **重力波天体の観測**
  - rプロセスに関して何がどこまで分かったか？
  - 何が分かっていないか

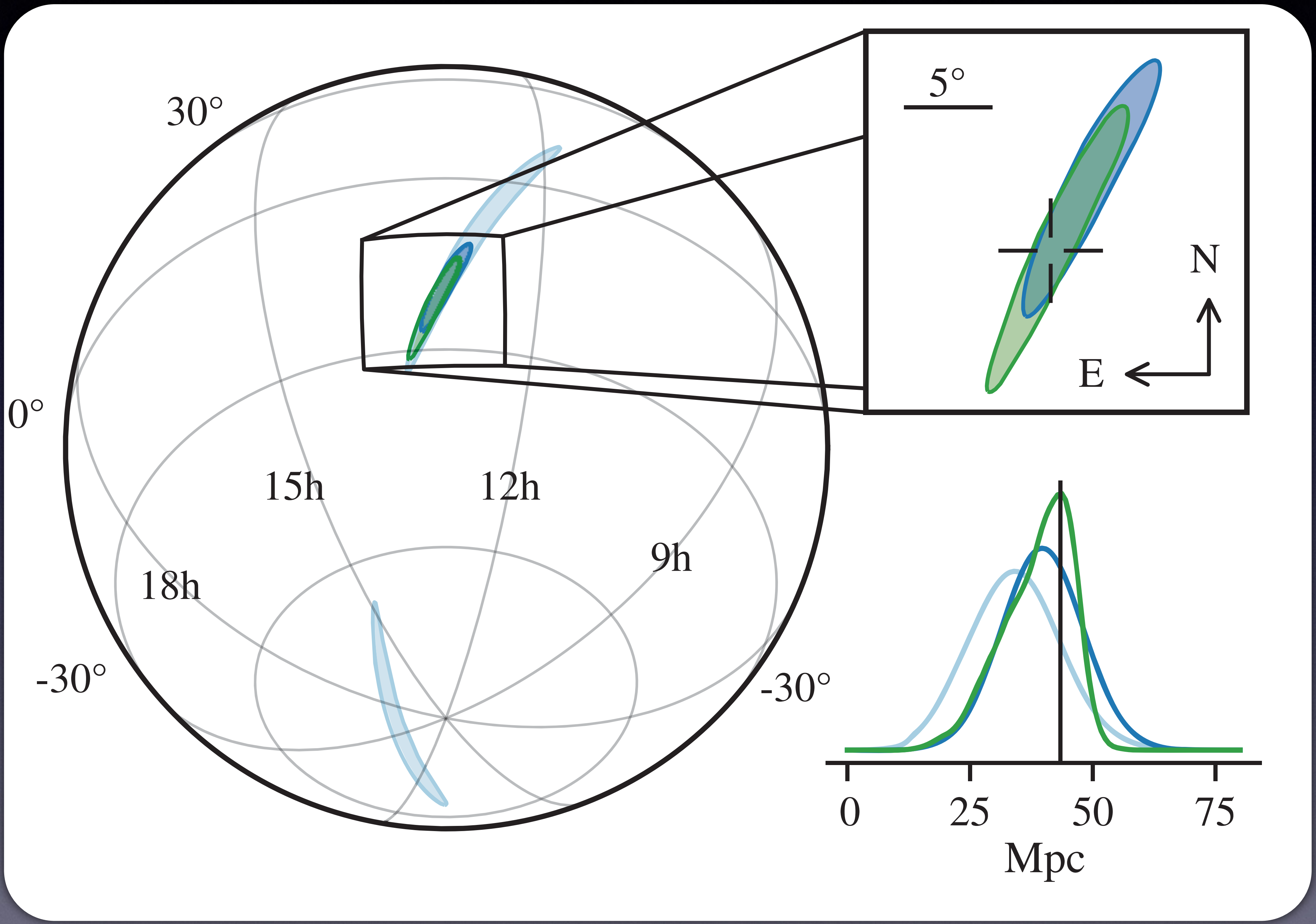
2017 Aug 17

GW170817:
The first detection of GWs from a NS merger



LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

Skymap from 3 detectors (LIGO x 2 + Virgo)
==> 30 deg² (~40 Mpc)

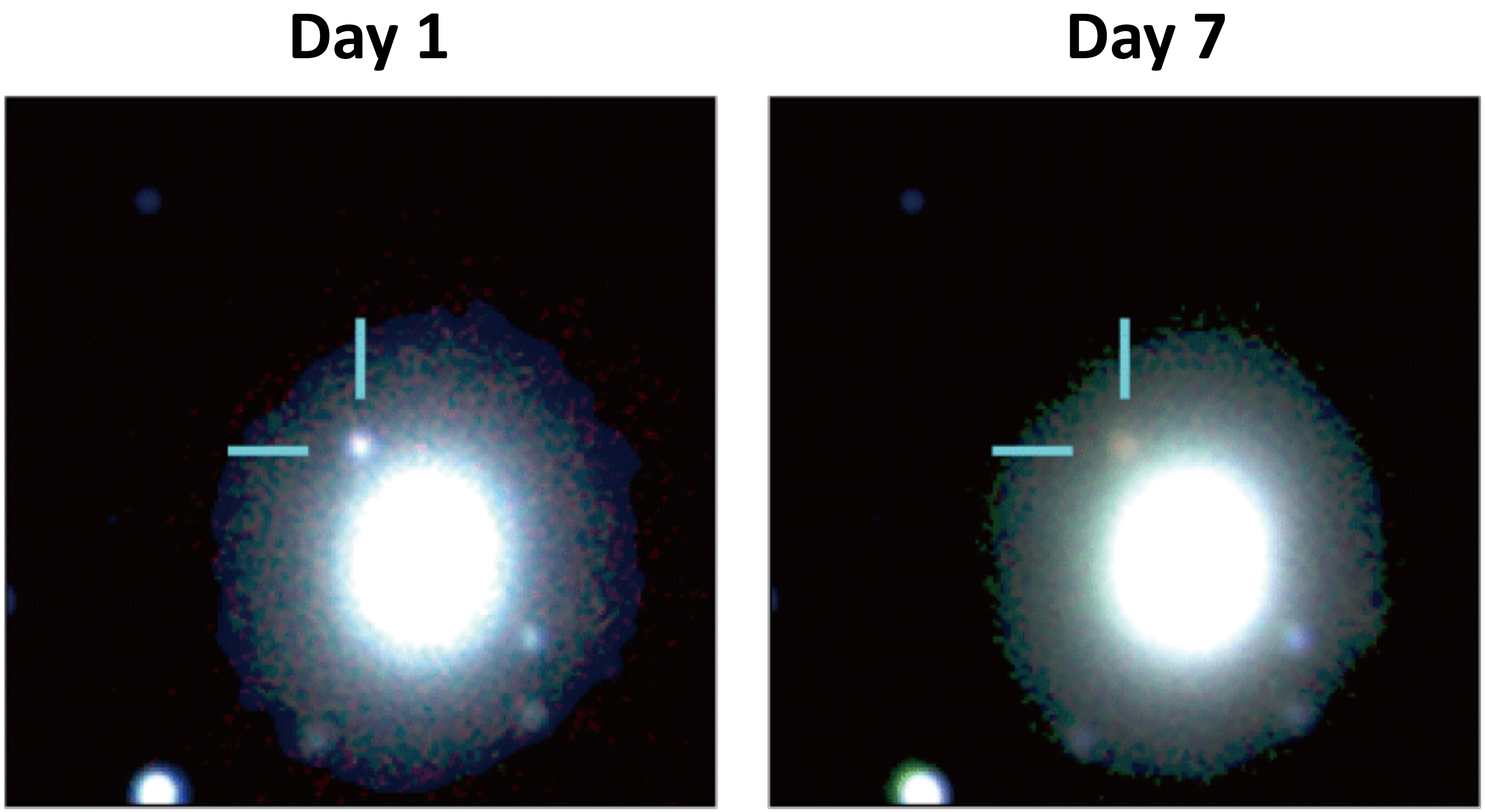


LIGO Scientific Collaboration and Virgo Collaboration, 2017

Coulter+17, Soares-Santos+17, Valenti+17, Arcavi+17, Tanvir+17, Lipunov+17

Movie: Utsumi, MT+17, Tominaga, MT+18

Electromagnetic counterpart of GW170817 @ 40 Mpc

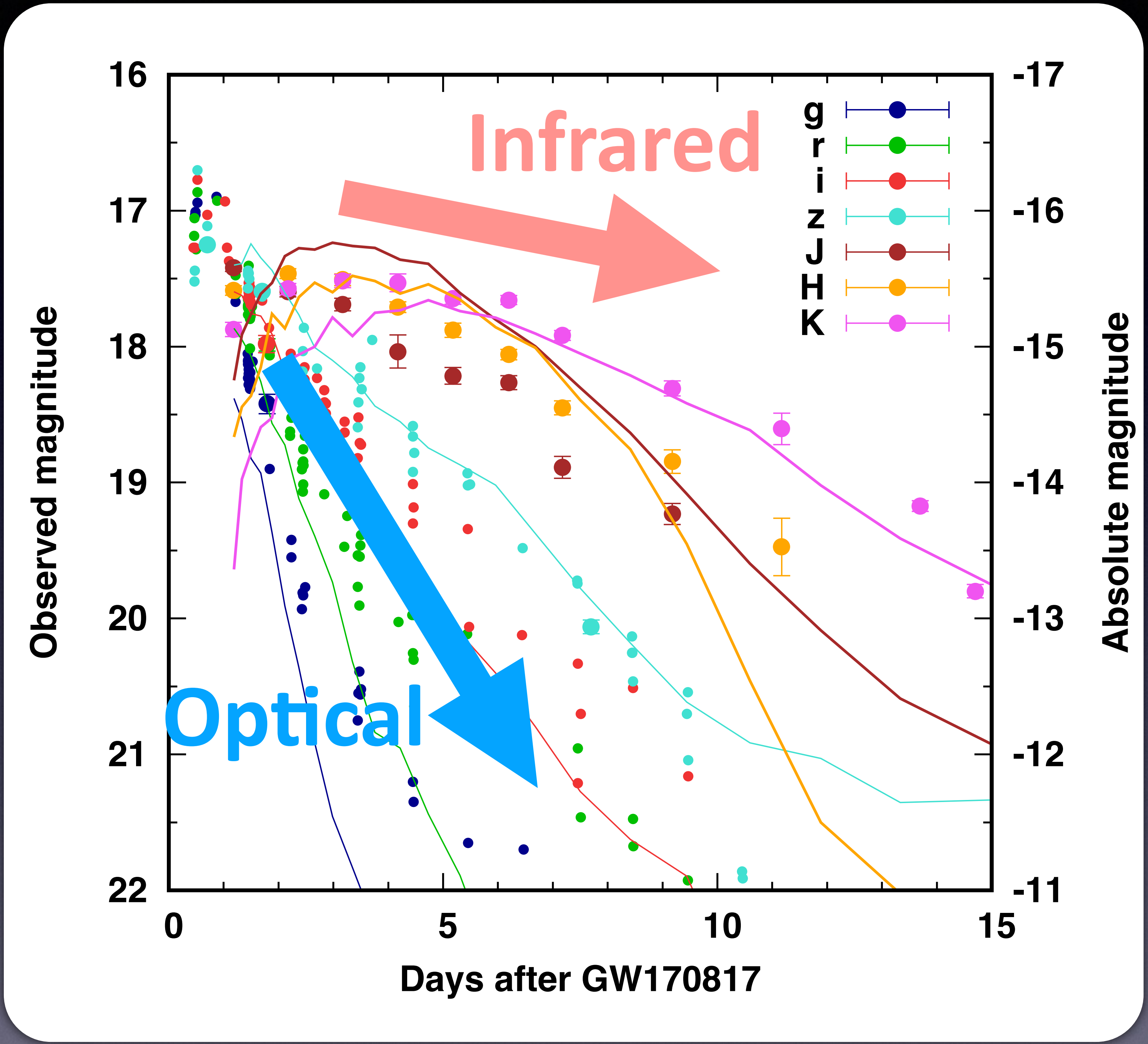


Optical (z) near IR (H) near IR (Ks)

Utsumi, MT+17

GW170817: optical/infrared light curves

Arcavi+17, Cowperthwaite+17, Diaz+17, Drout+17,Evans+17, Kasliwal+17,Pian+17, Smartt+17, Tanvir+17, Troja+17, Utsumi, MT+17, Valenti+17

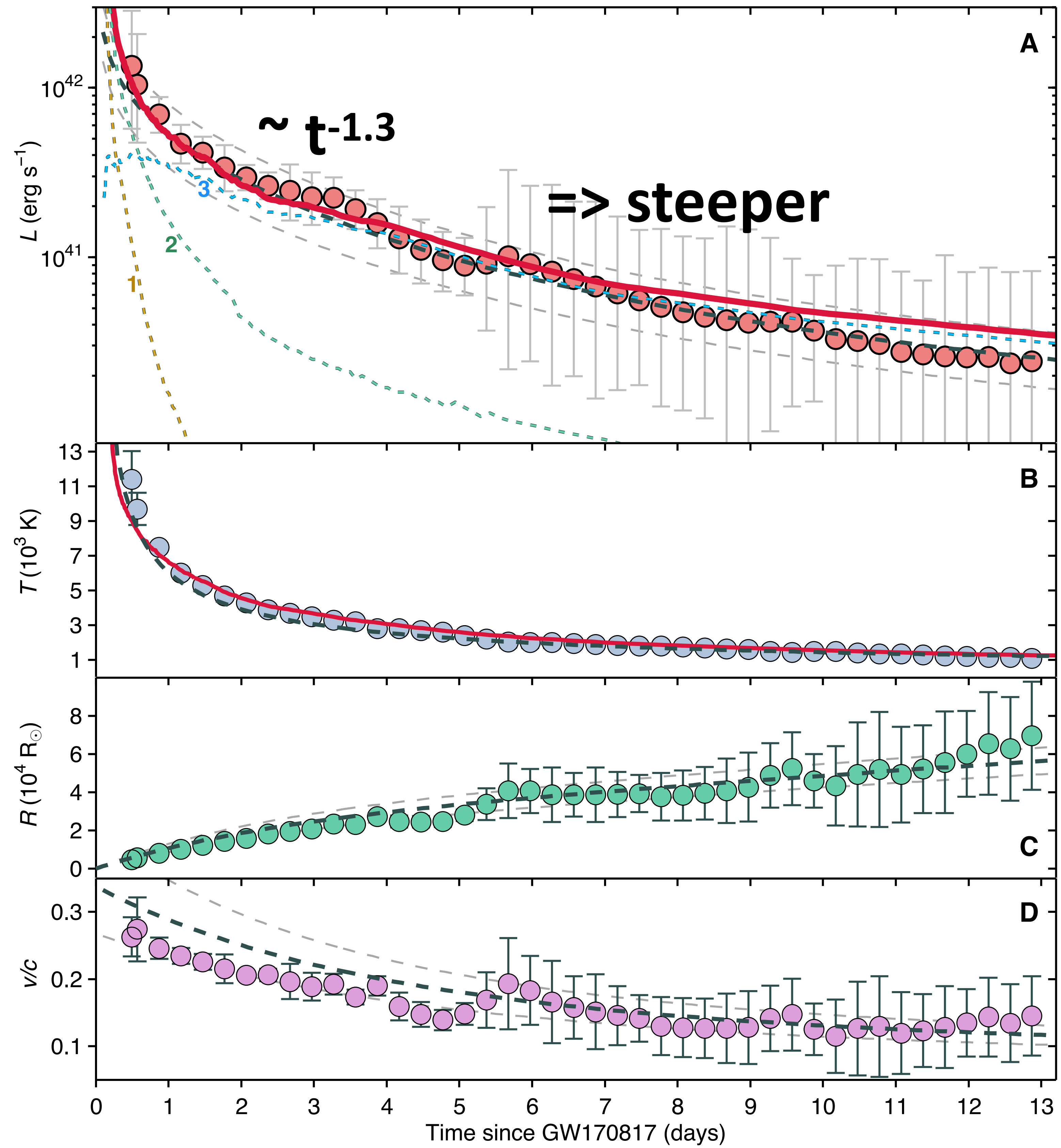


Signature of lanthanide elements

Ejecta mass ~0.03 Msun (w/ ~1% of lanthanides)

Bolometric light curves

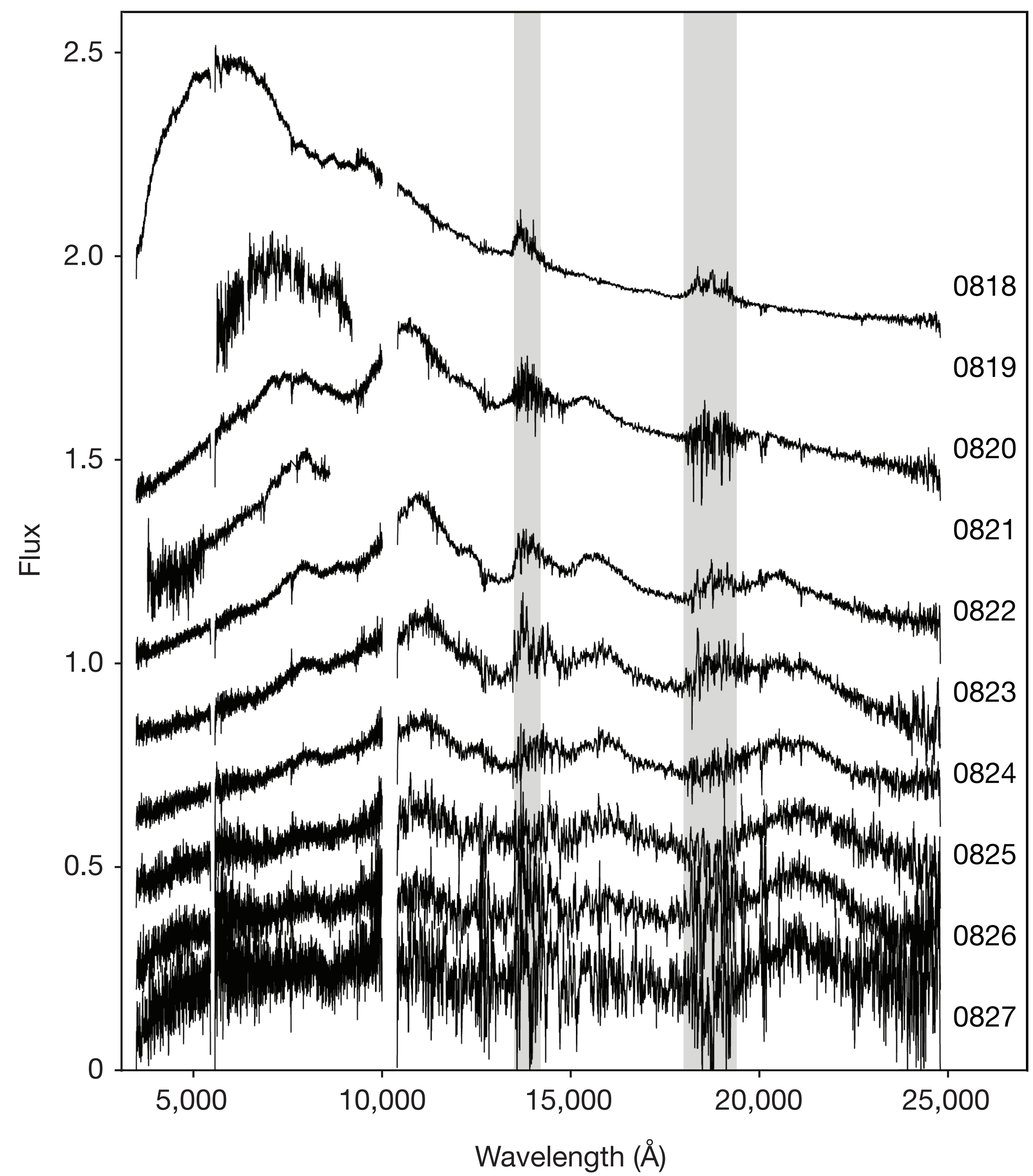
Heating rate ~ $t^{-1.3}$



Kasliwal+17

GW170817: Spectra

- Smooth spectra
  (high velocity)
- Not similar to
  known transients

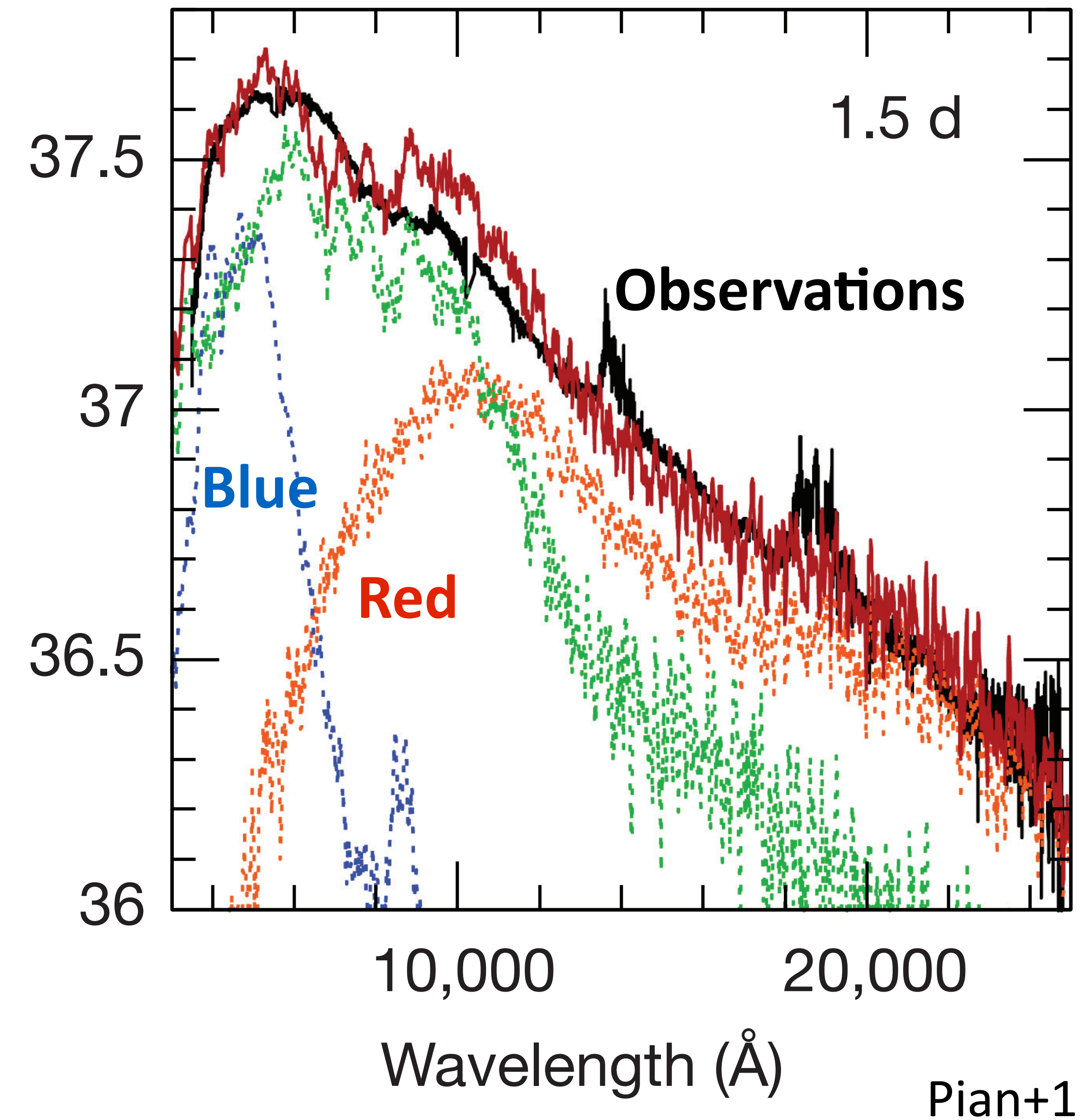


Andreoni+17, Chornock+17, Kilpatrick+17
McCully+17, Nicholl+17, Pian+17,
Shappee+17, Smartt+17

Pian+17

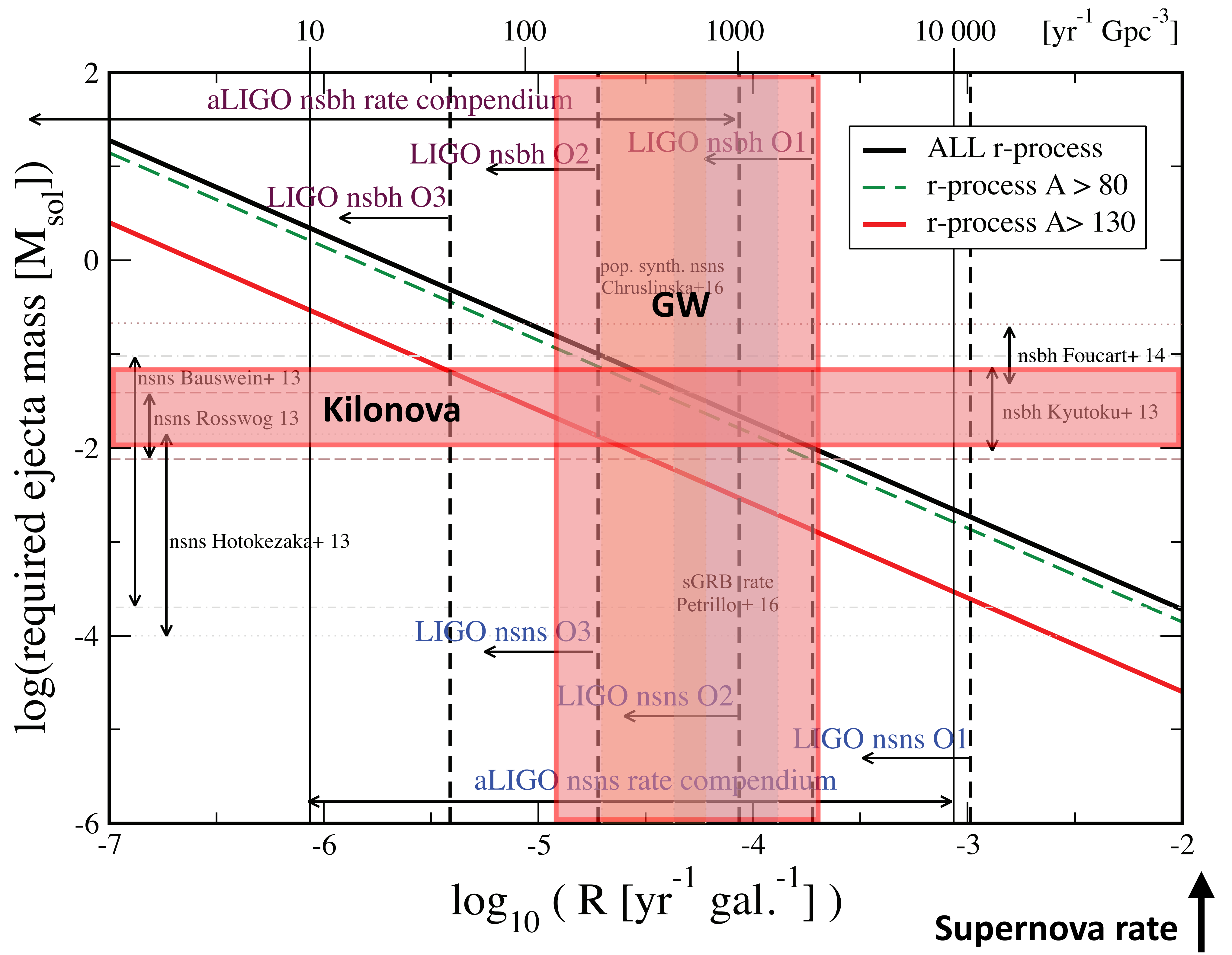
Presence of blue component

Kasen+17, Metzger 17, MT+17



Signature of lighter r-process elements
M ~ 0.02 Msun

Constraints from the total amount in our Galaxy



See Tsujimoto-san's talk for more details

Rosswog+17, Hotokezaka+15, 18

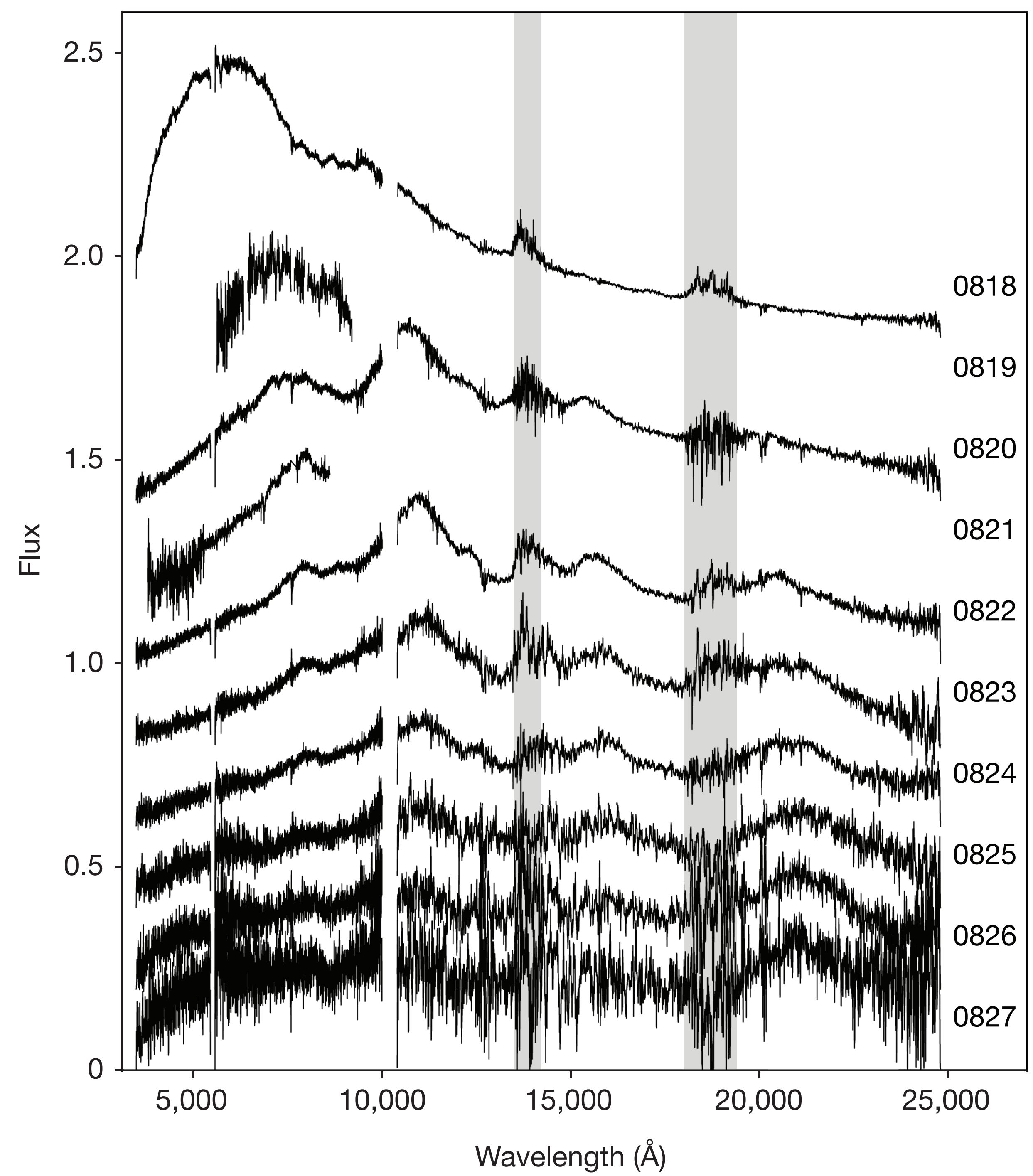
まとめ (3/3): 重力波天体の観測

- **GW170817のマルチメッセンジャー観測から分かったこと**
  - キロノバ (L ~ $t^{-1.3}$) => rプロセス元素合成
  - 「赤い」キロノバ => ランタノイド元素の合成
  - 「青い」キロノバ => ランタノイドより軽い元素の合成
  - 放出量 x rate => 今のところOK (不定性が大きい)
- **分かっていないこと**
  - どの元素がどれぐらいできたか？
太陽組成比に似ている？（「ユニバーサル」）
  - 超新星は不要？

Which elements are produced?
(similar to solar abundances??)

GW170817: Spectra

- Smooth spectra (high velocity)
- Not similar to known transients



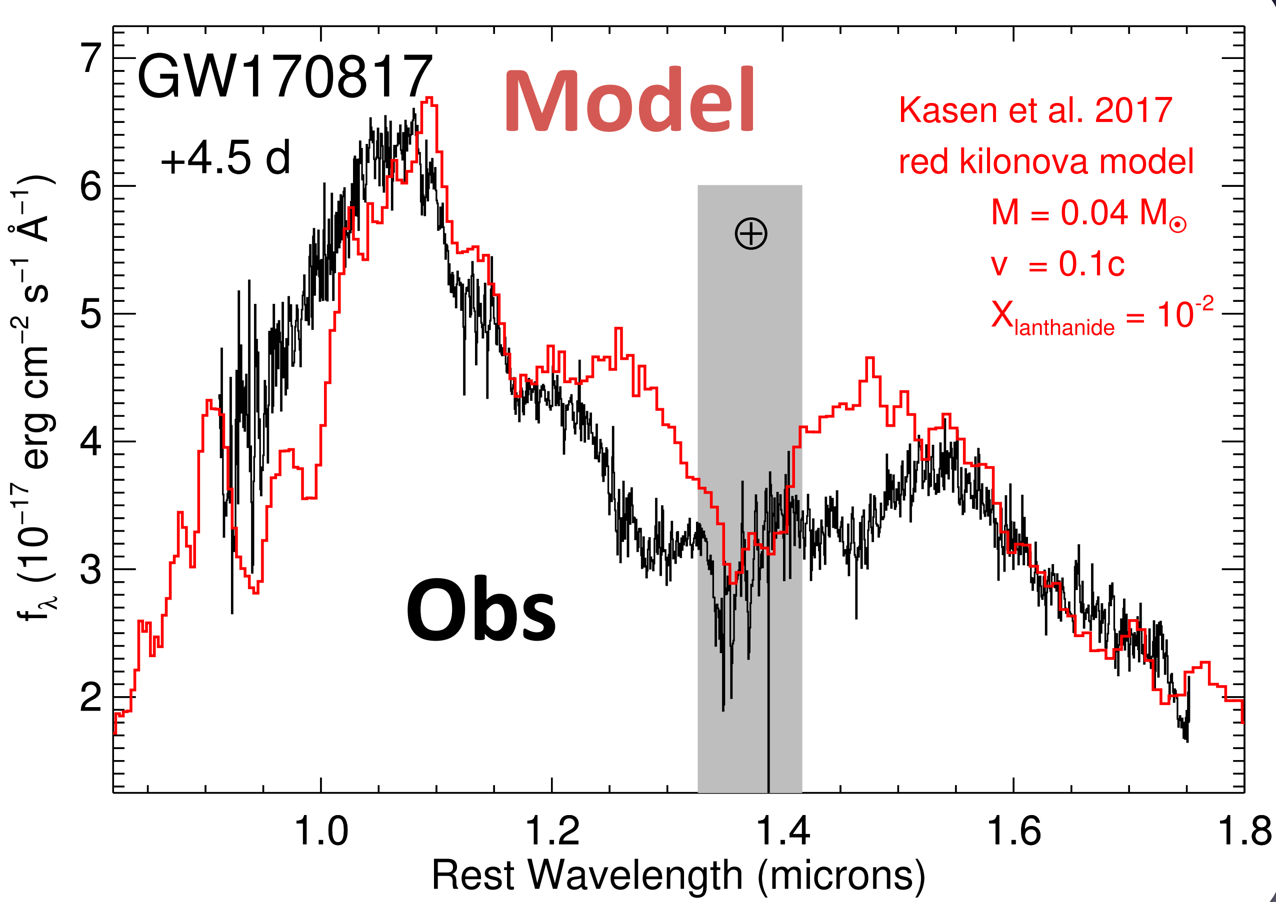
Andreoni+17, Chornock+17, Kilpatrick+17
McCully+17, Nicholl+17, Pian+17,
Shappee+17, Smartt+17

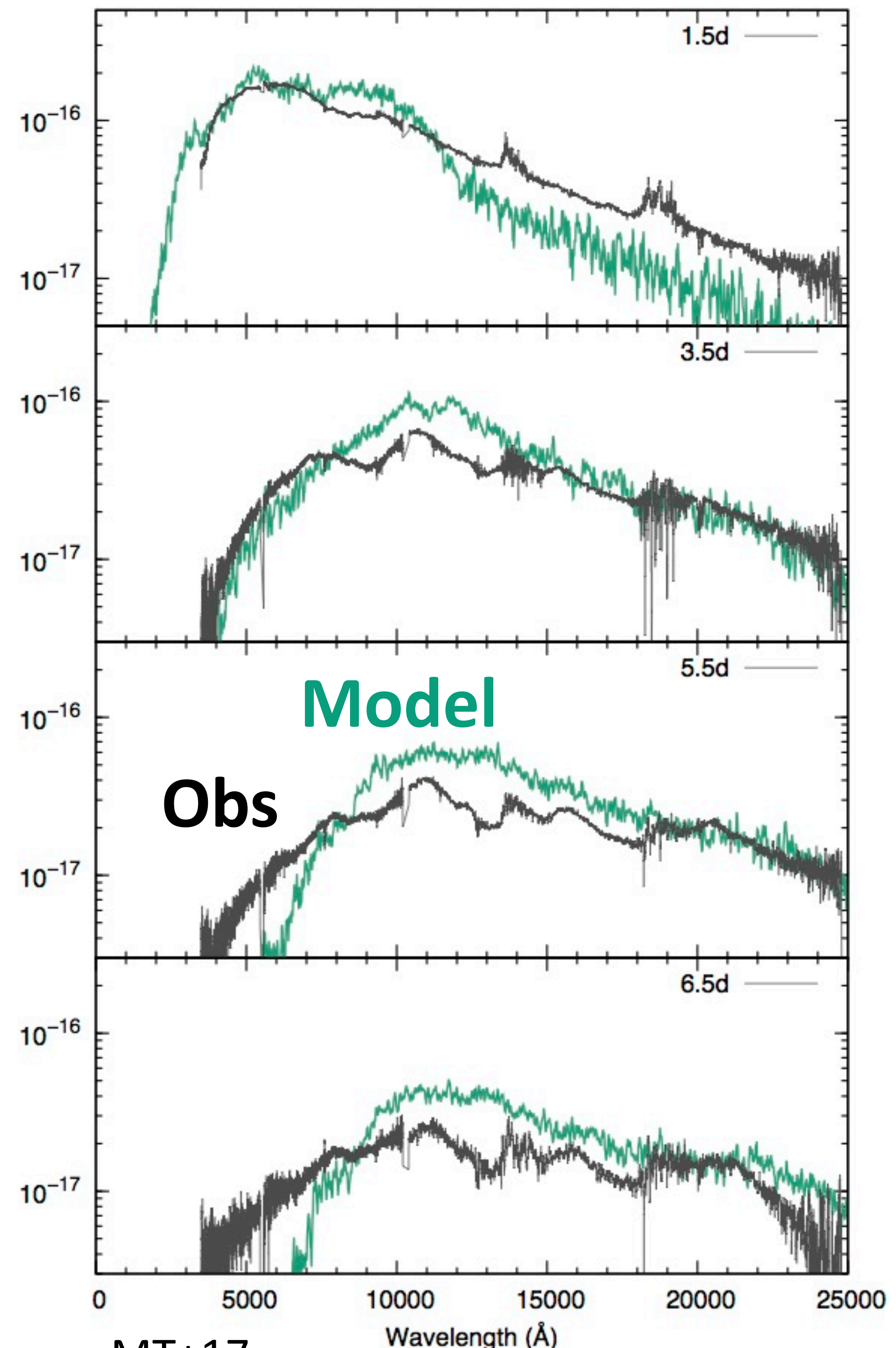
Pian+17

Approach from atomic physics

Possible element features
In the spectra??
=> Not conclusive yet
(lack of atomic data)

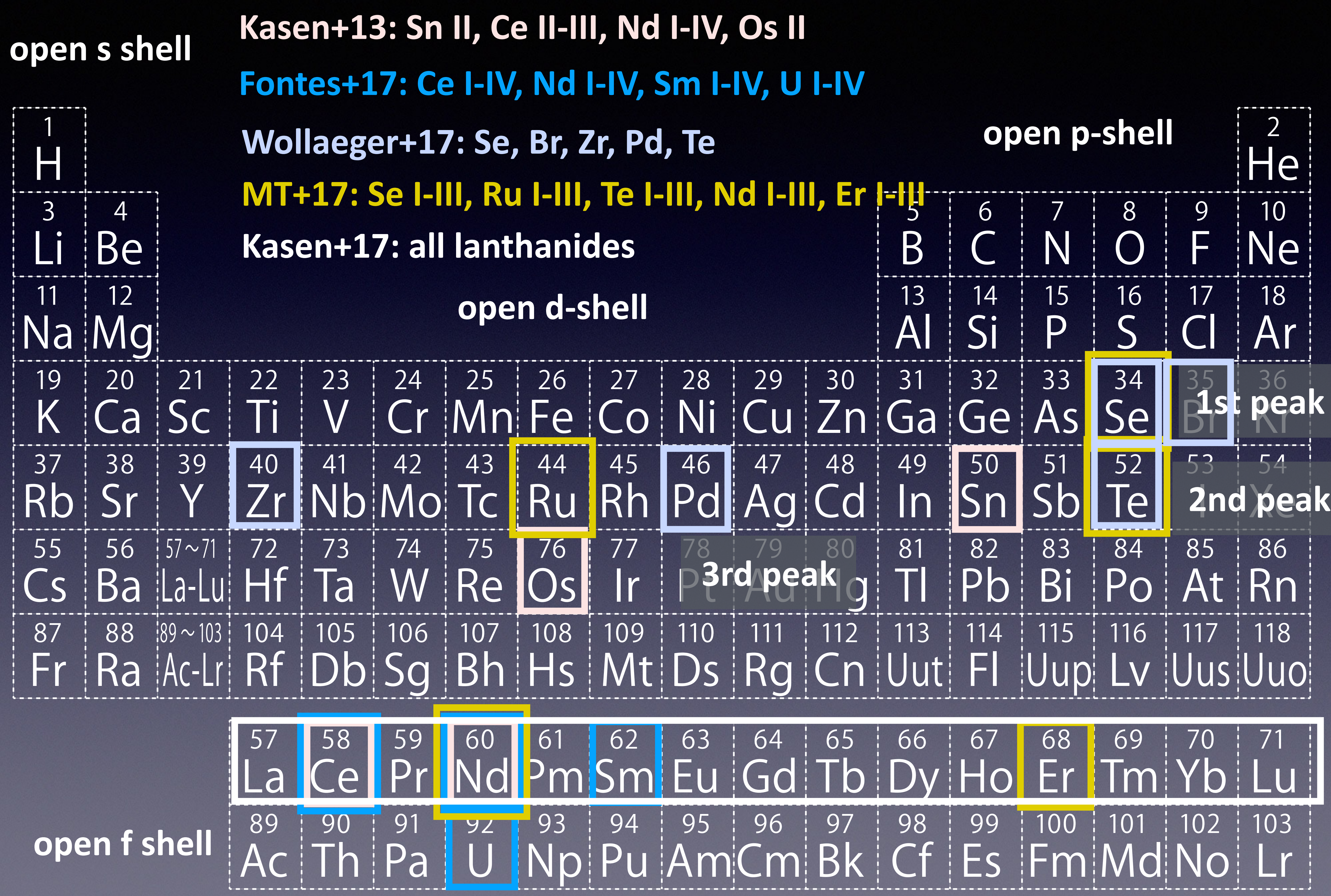
Chornock+17



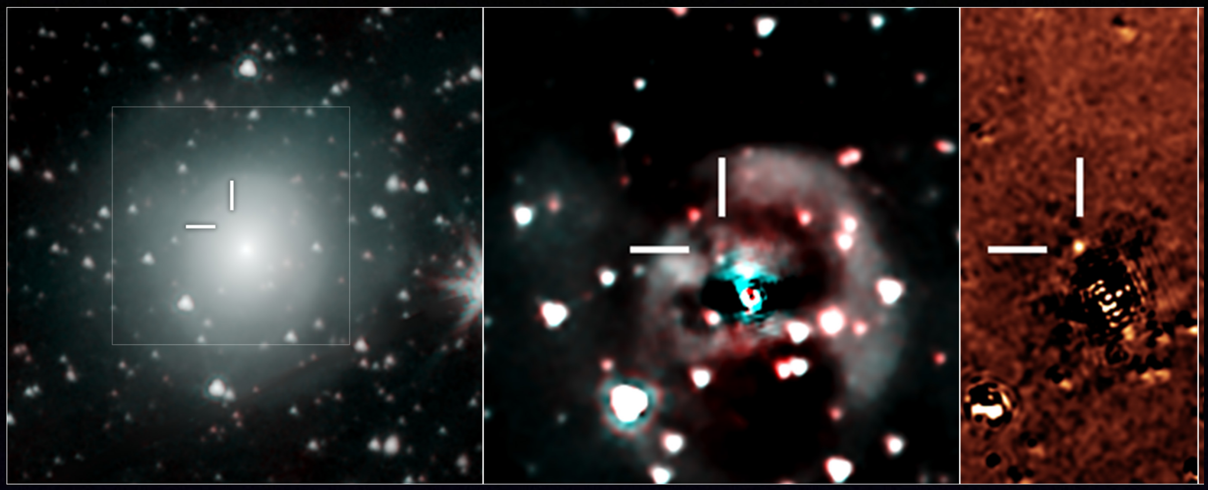


MT+17

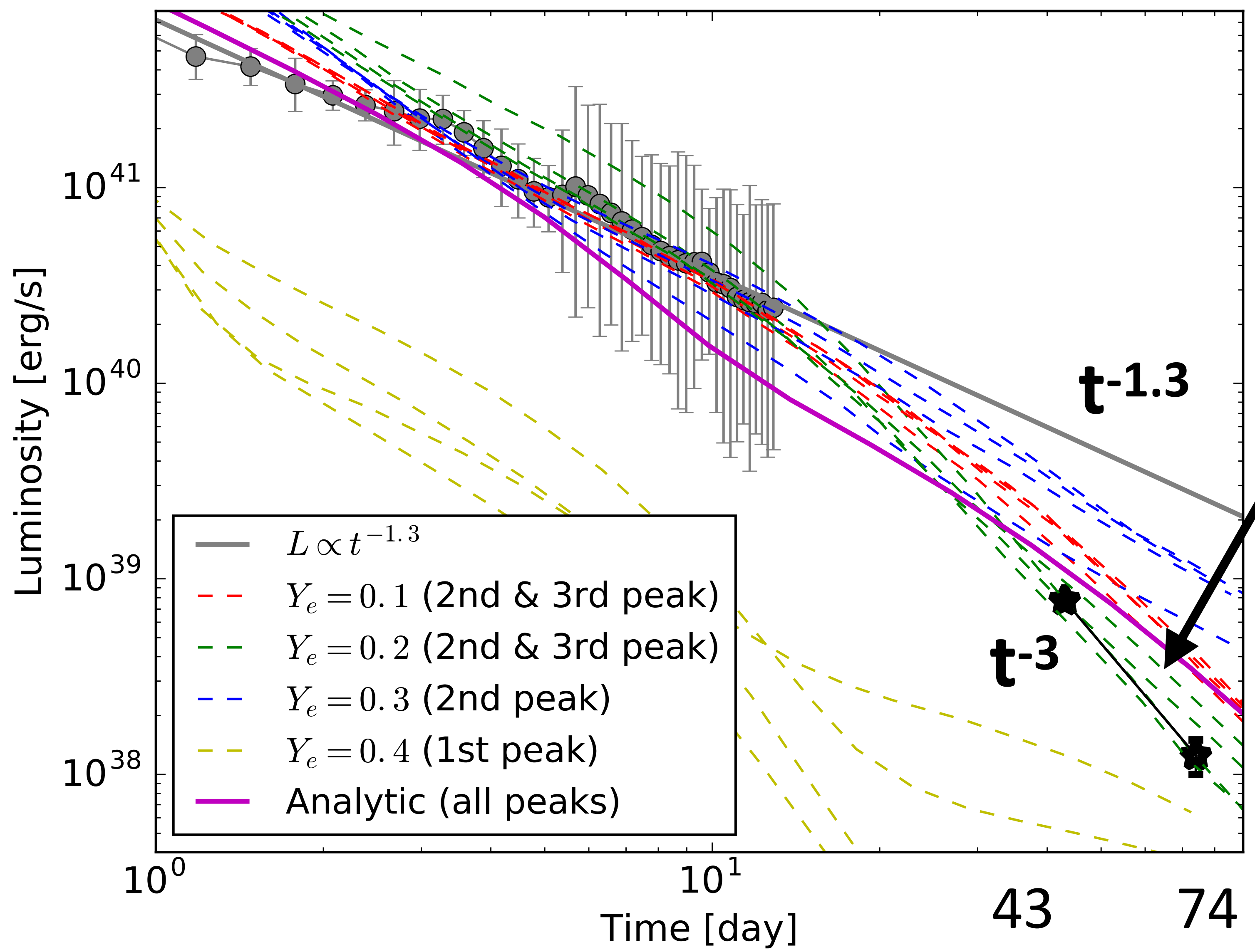
Status of atomic calculations



Approach from nuclear physics



Late-time follow-up in mid infrared (4 um)



steeper than $t^{-1.3}$

Dominated by several isotopes in the 3rd peak? (Ye ~ 0.1-0.2)

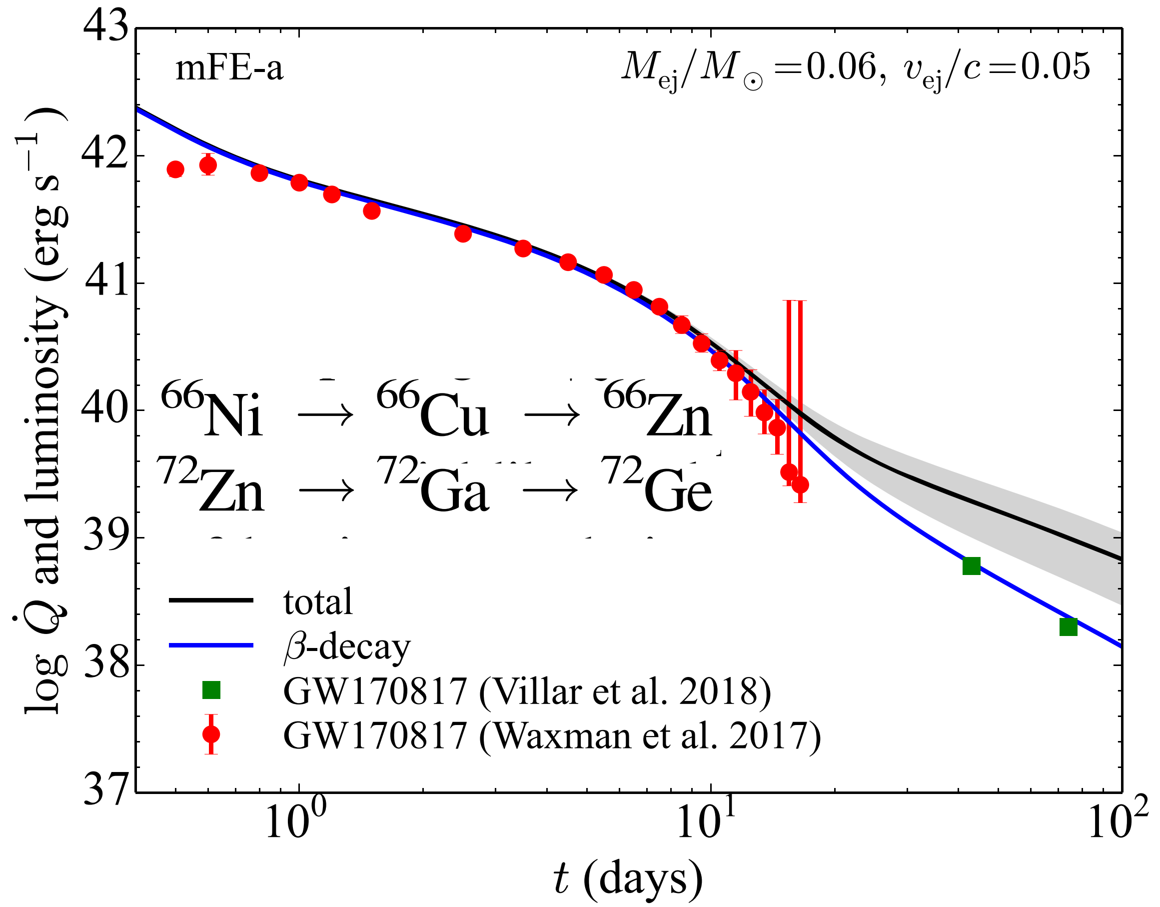
Kasliwal+18

Caveat: not total (bolometric) luminosity

Approach from nuclear physics

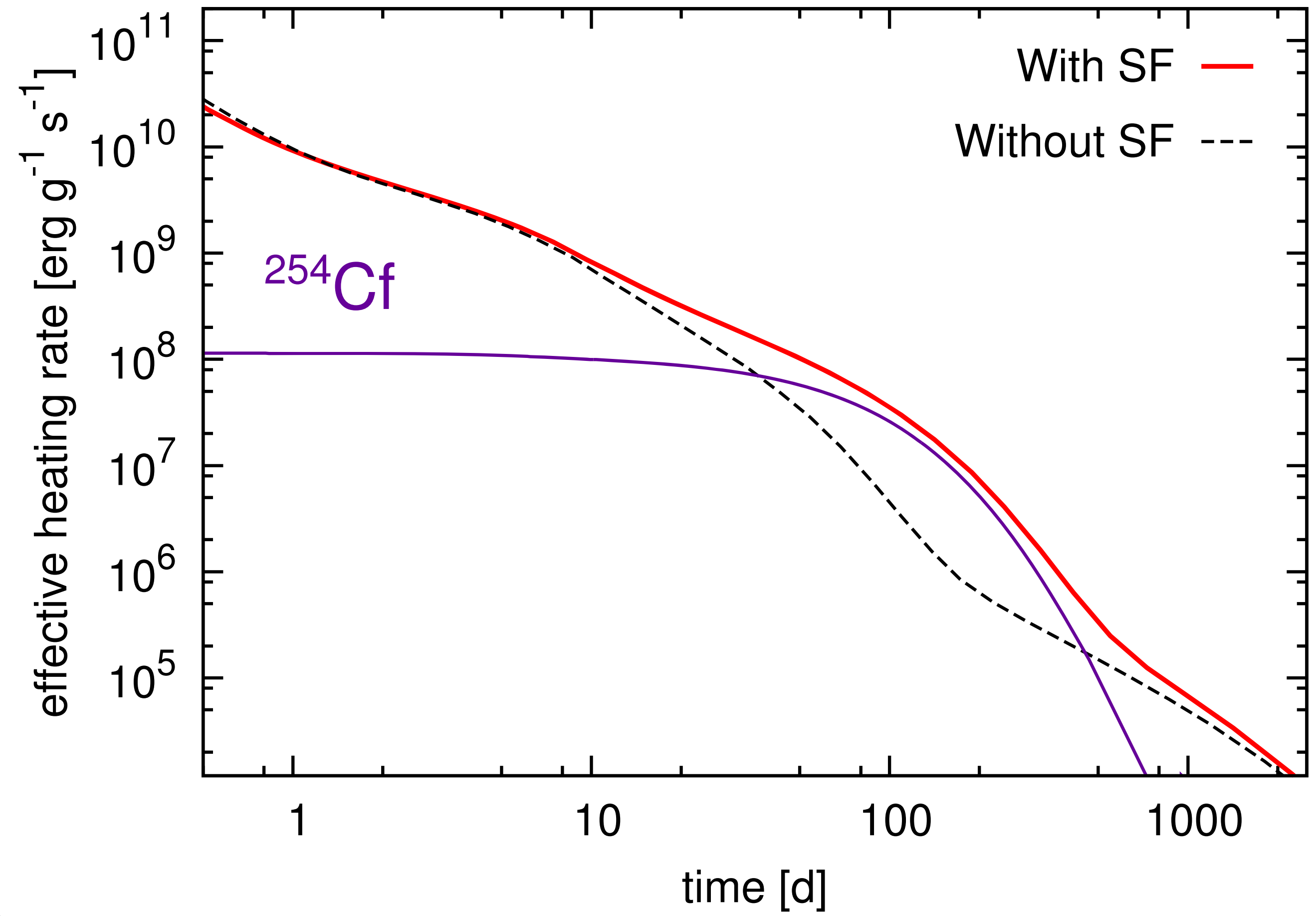
Wanajo 18, Wu+18, Zhu+18

Lighter r-process elements



Wanajo 18

Fission of heaviest elements



Zhu+18

*** Depends on nuclear models (Wu+18)**

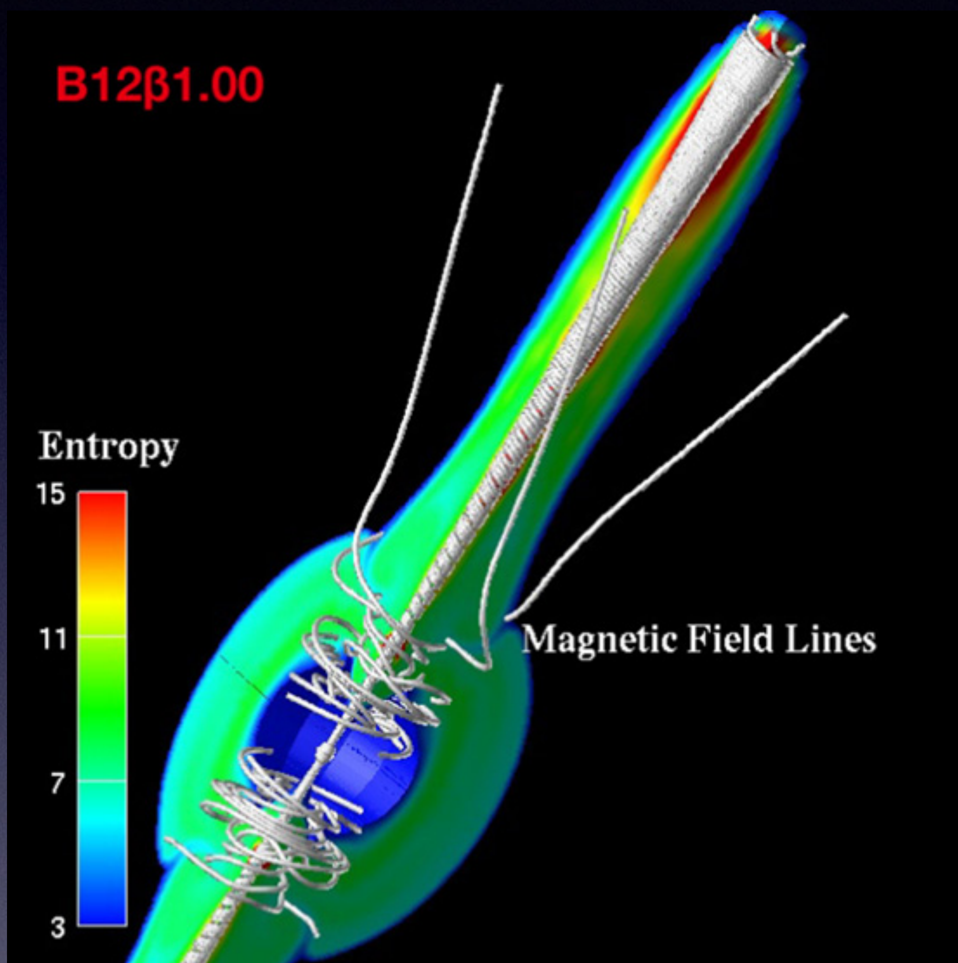
*** MIR data exclude enhanced 254Cf ? (Kasliwal+18)**

Key: total (bolometric) luminosity at late time

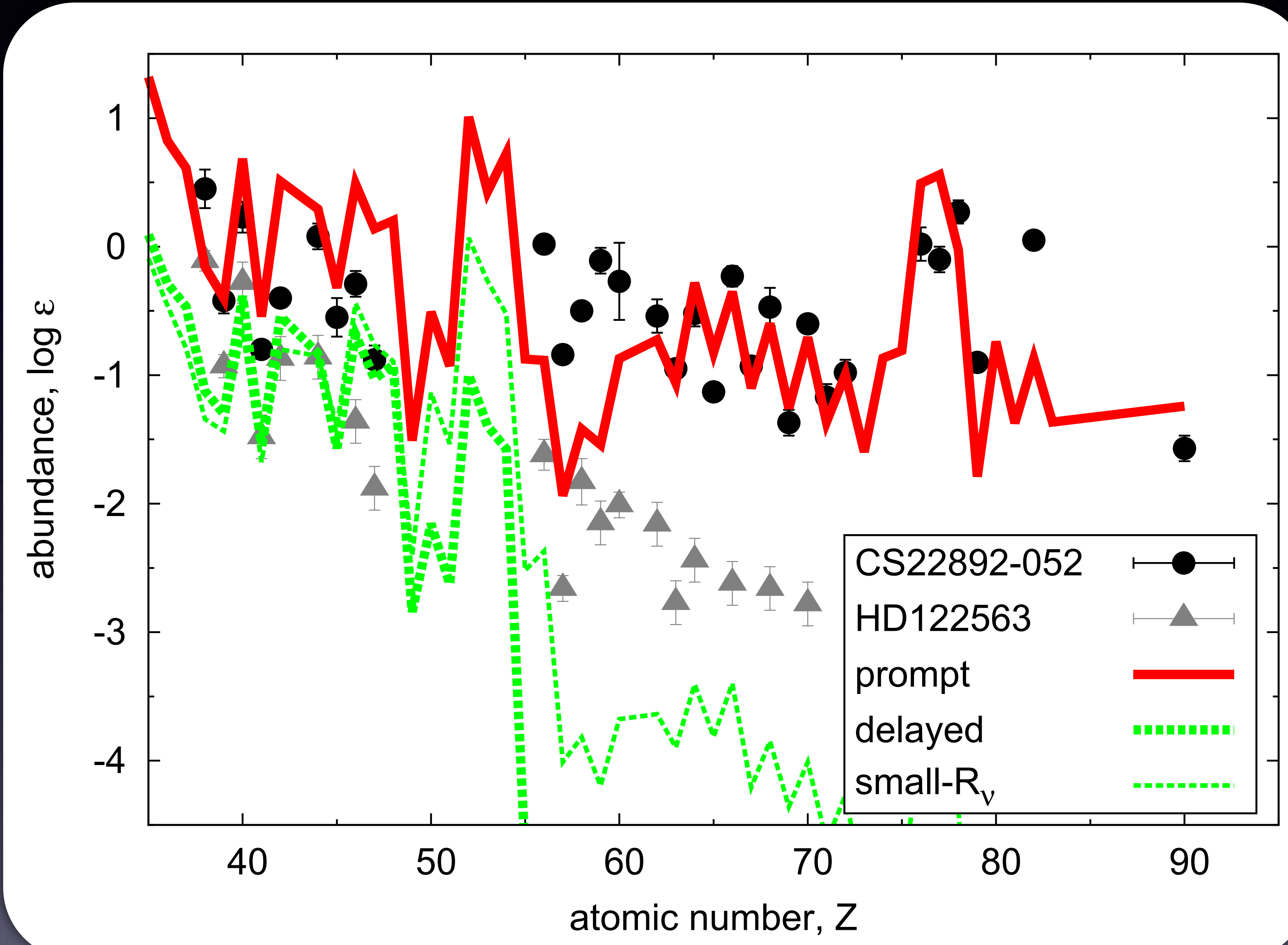
No need for supernovae??

See Tsujimoto-san's talk for chemical evolution of the Universe

r-process in magneto-rotational supernovae

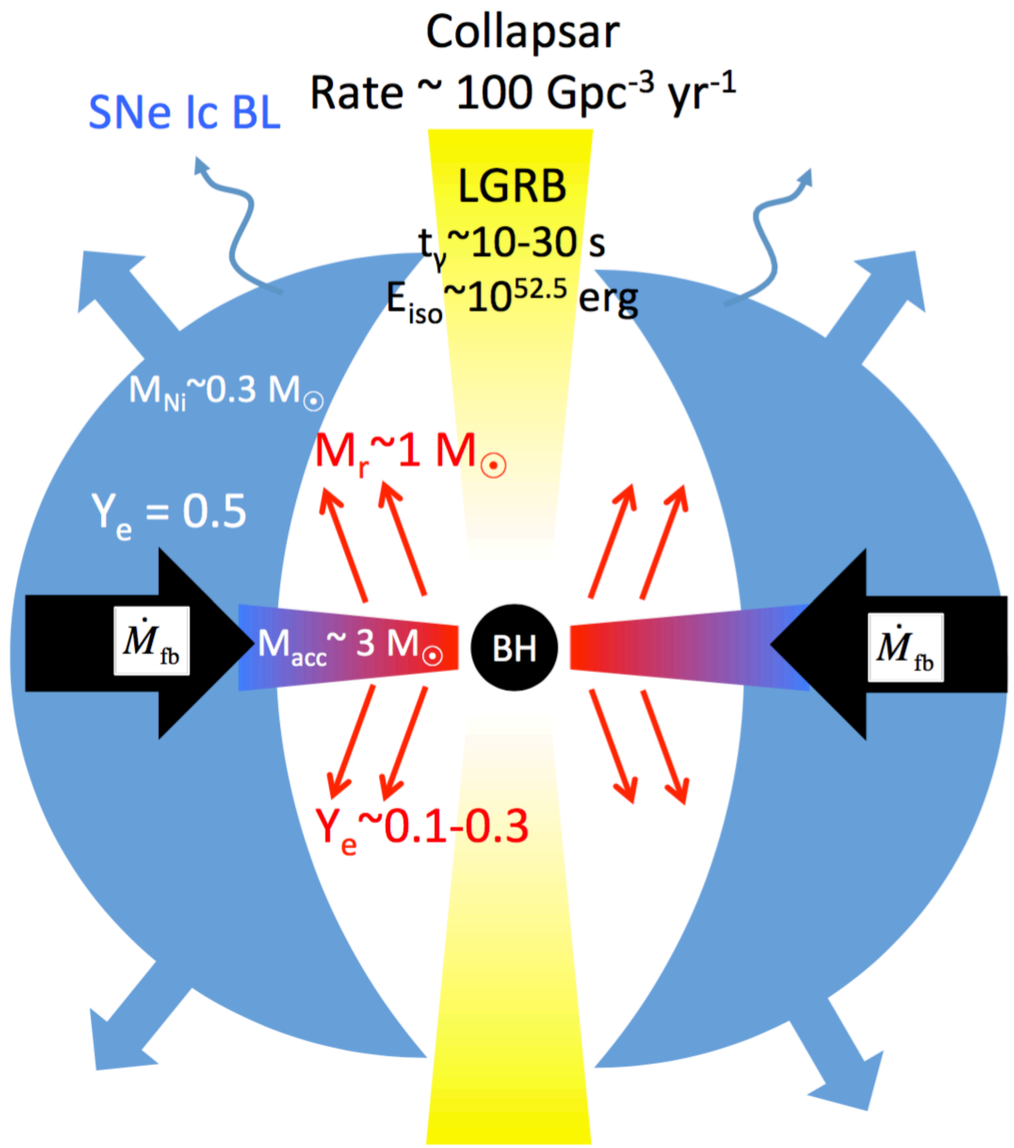


Nishimura, Takiwaki, Thielemann 15



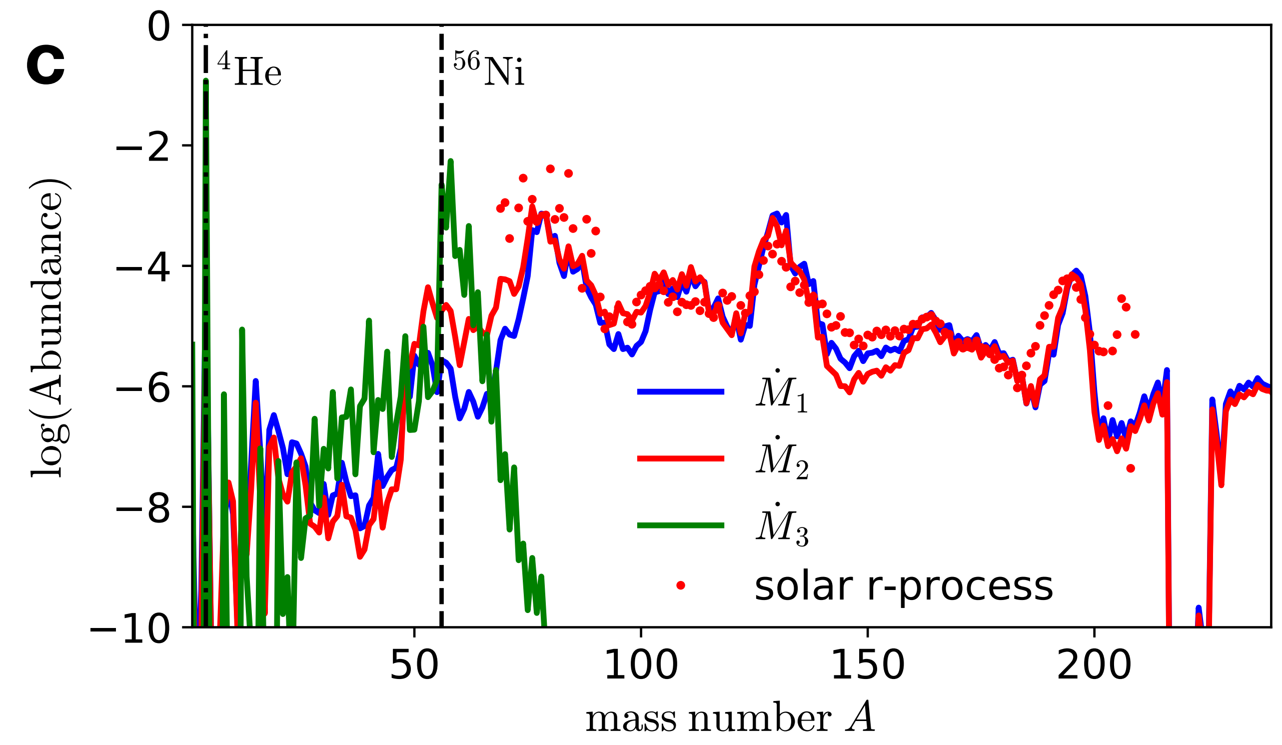
Successful r-process if explosion occurs early enough (depends on magnetic field/rotation)

r-process in "collapsar" (torus around BH => disk wind)



Similar to disk wind in NS merger

Siegel, Barnes, Metzger 18 (arXiv:1810.00098)



The neutron star merger GW170817 points to collapsars as the main *r*-process source

Daniel M. Siegel[1,2], Jennifer Barnes[1,2], Brian D. Metzger[1]

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