Compact Binary Mergers as Sources of r-process Nucleosynthesis

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Hirschegg Jan 2017

GRB ; TReX

1. Astronomical evidence for rate sources
    i. ^{244}Pu
    ii. Binary neutron star kicks and all that
    iii. Dwarf Galaxies

    Conclusion - Low rate high yield - SNe👎
2. Merger rates:
    i. Short GRBs
    ii. Binary NS

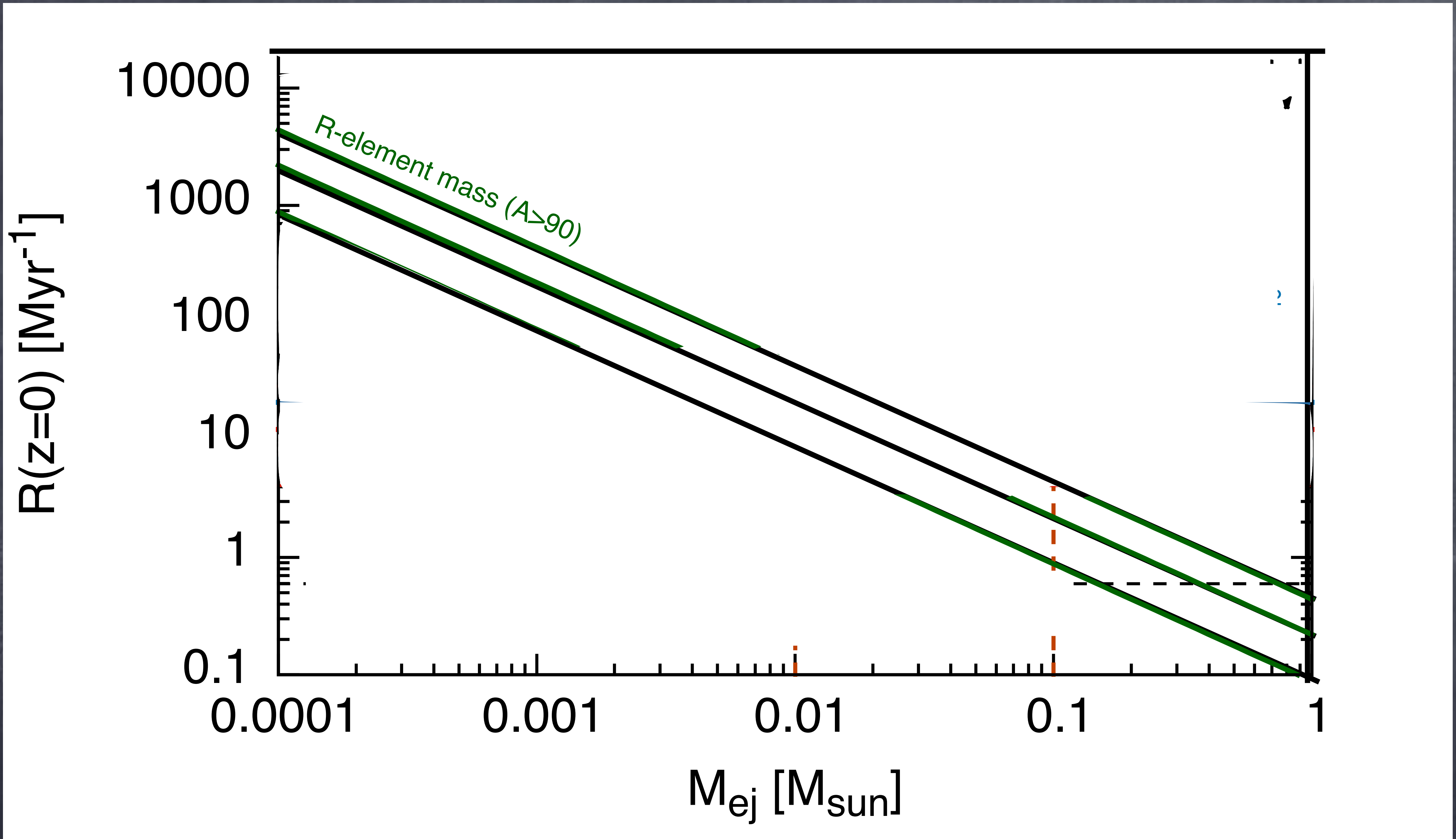
    Conclusion mergers - Mergers 👍
3. The Li-Paczynski Macronova (kilonova)
4. Macronove 130603b/060614/050709

    If correct sGRBs == Mergers 👍
5. Evidence for "stuff" around SGRBs 👍
6. Galactic Chemical Evolution 👍
7. * The cocoon's macronova - the strongest EM counterpart?

Some References

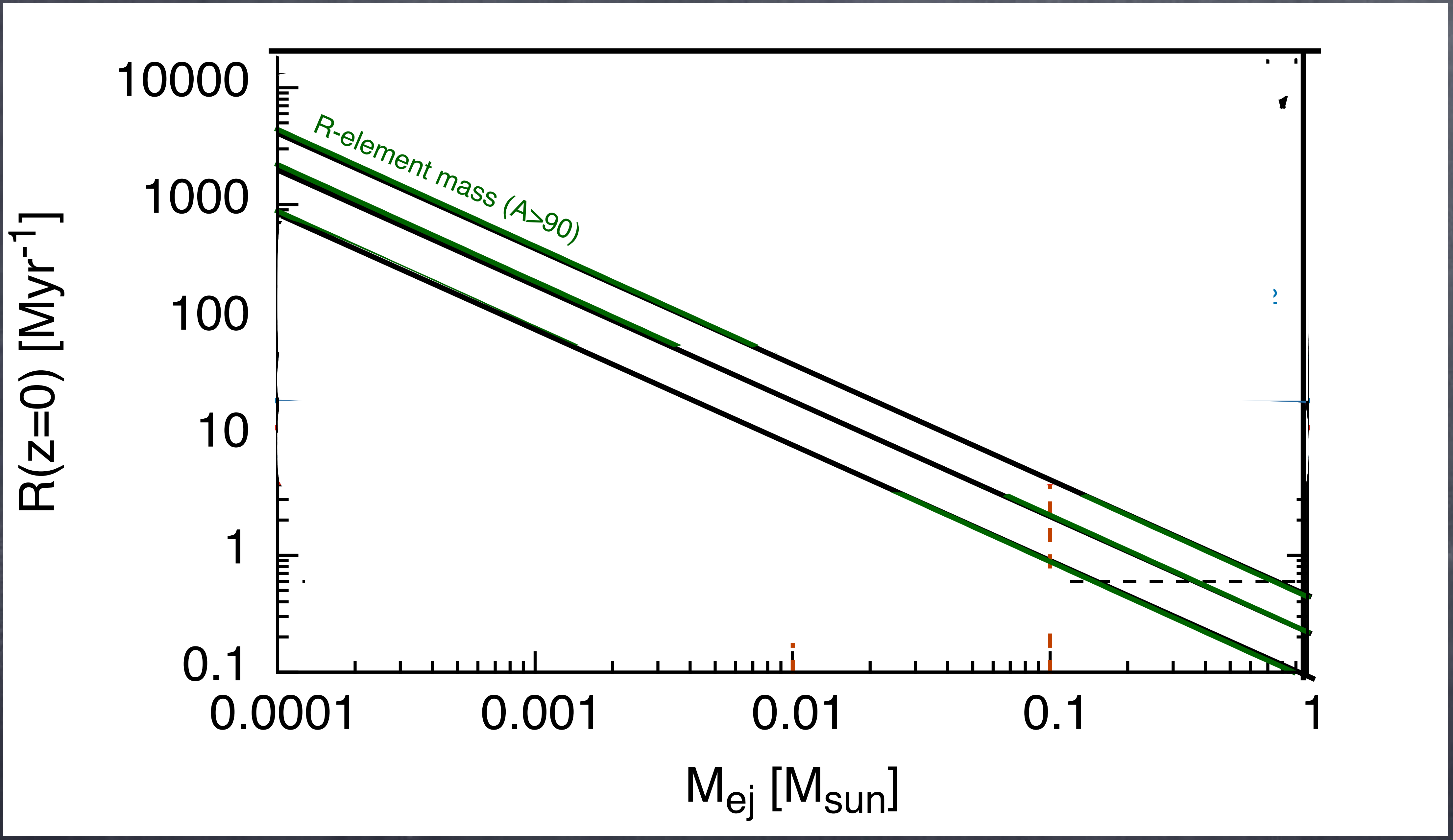
- Hotokezaka TP & Paul Nature Phys 2015- ^{244}Pu
- TP & Shaviv PRL2005; Dall'Osso, TP & Shaviv MNRAS, 2013, Beniamini & TP MNRAS 2015 - NS kicks
- Beniamini, Hotokezaka & TP 2016a,b - Dwarf Galaxies
- Wanderman & TP, MNRAS 2015 - sGRB rate
- Yang + Nature comm. 2015; Jin + Nature comm. 2016 - macronvoa candidates
- Moharana, + in prep 2017 - mass ejection evidence
- Hotokezaka & TP in prep 2017 - Chemical evolution
- Nakar & TP ApJ 2017; Gottelib, Nakar & TP in prep 2017 - Cocoon signature
- Nakar & TP Nature 2011; Hotokezaka & TP MNRAS 2014; Horesh + ApJ 2016 Hotokezaka + ApJ 2016 - Radio Flare

R-Process



lines of R-mass: Current event rate is lower than the average one by a factor of 5 (lower line), 3 (middle line).

R-Process



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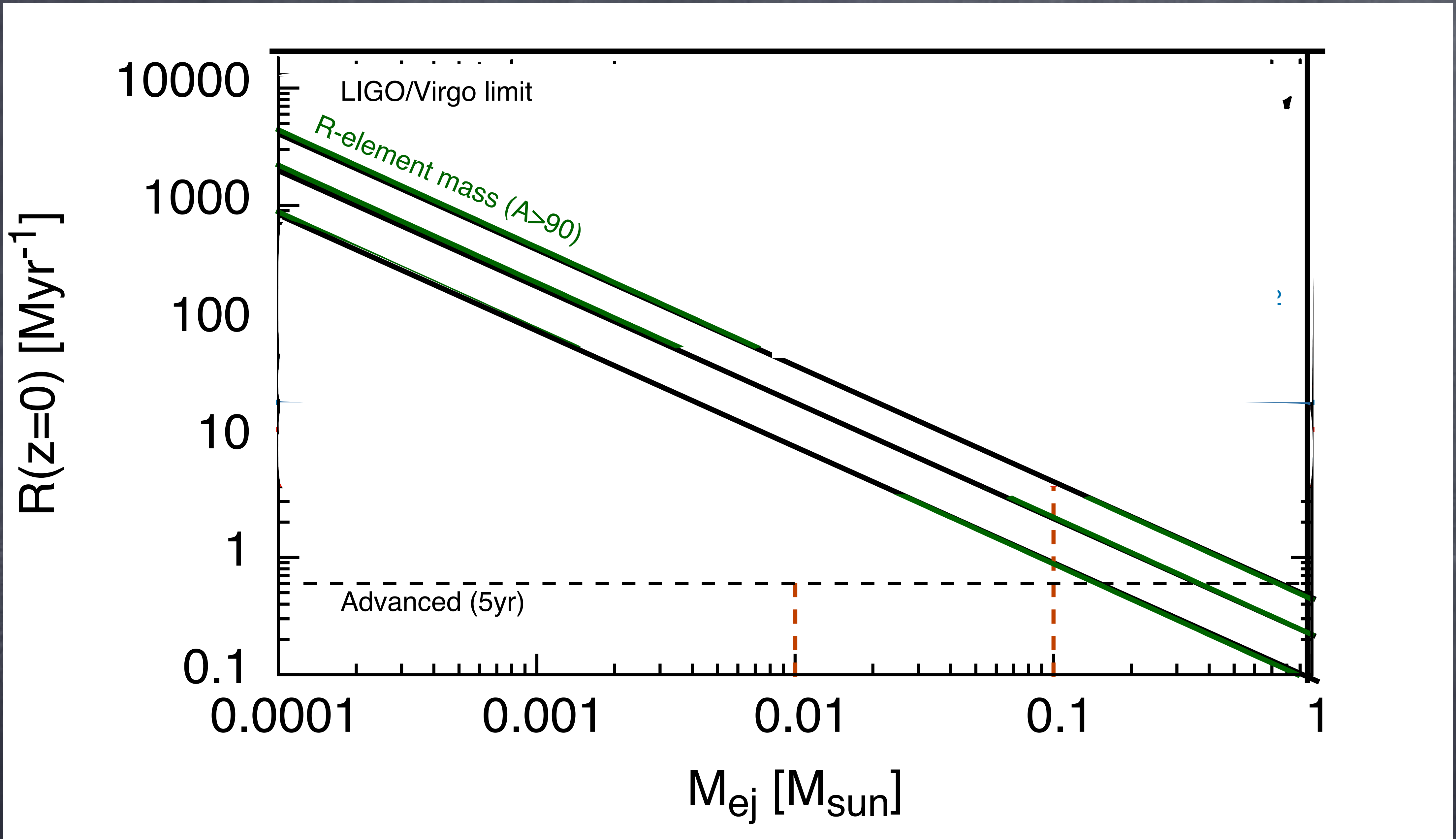
*

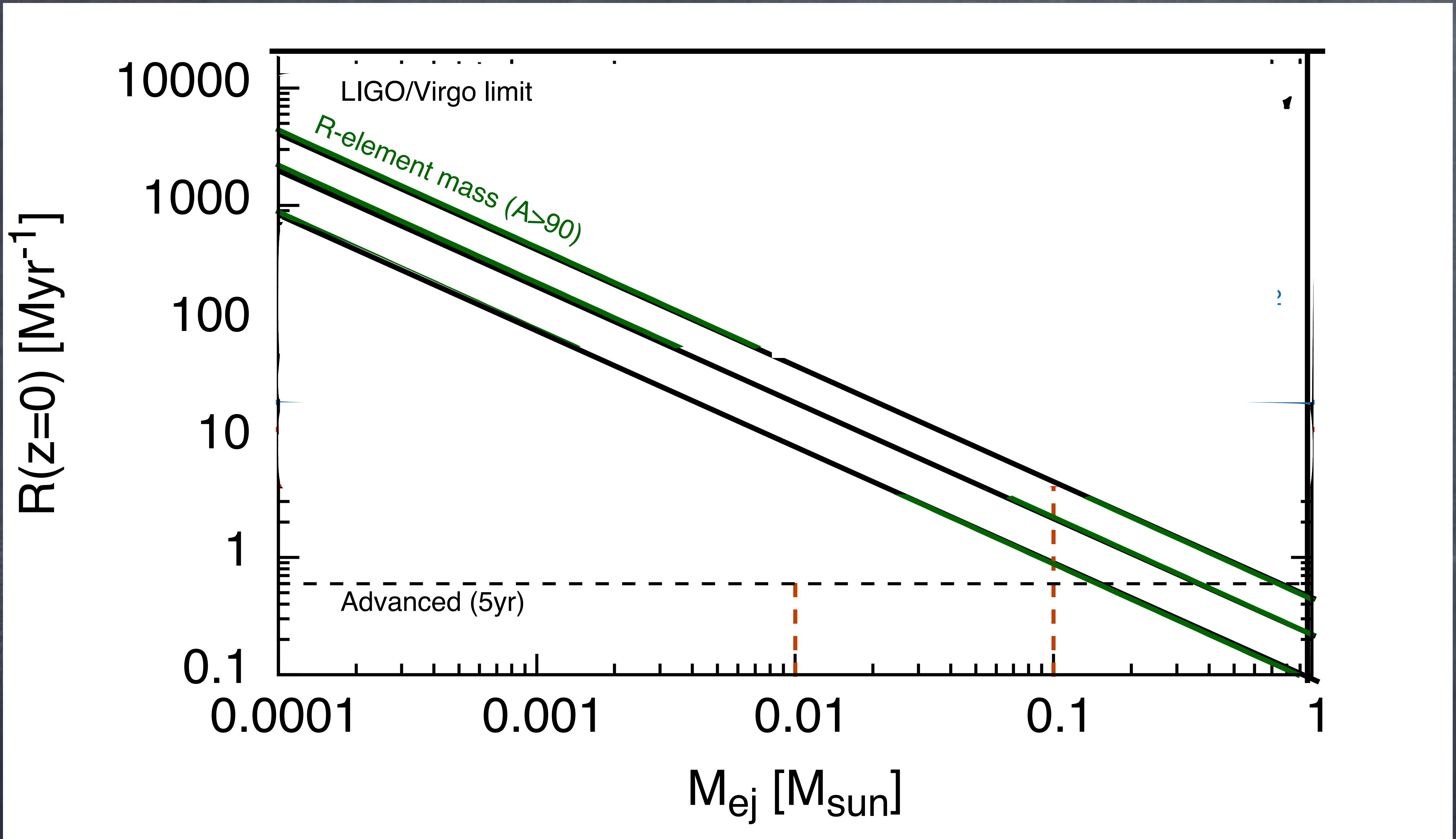
R-Process



Can we break the yield - rate degeneracy?

Hotokezaka, TP Paul, Nature Pays 2015

R-Process



Can we break the yield - rate degeneracy?

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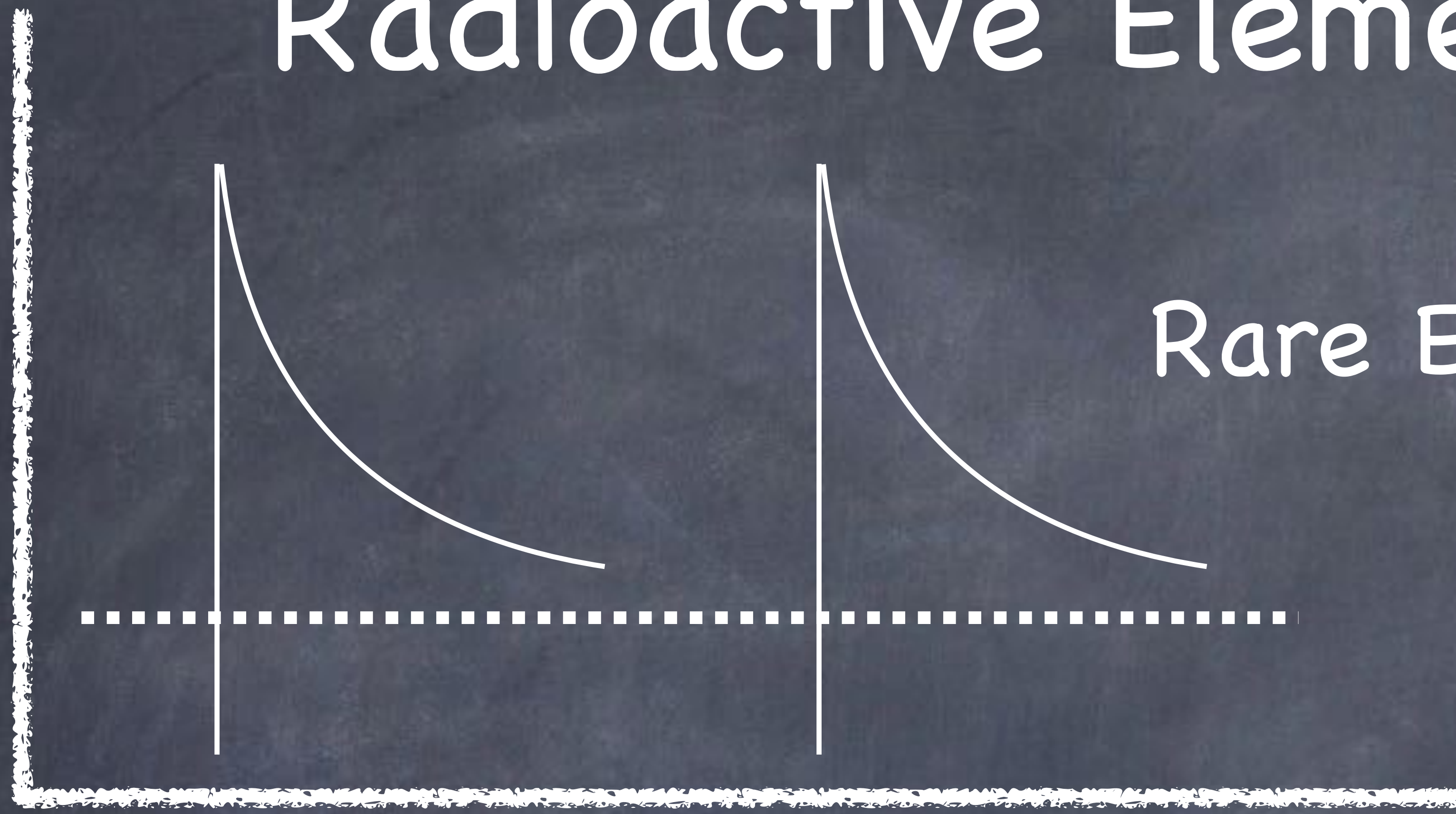
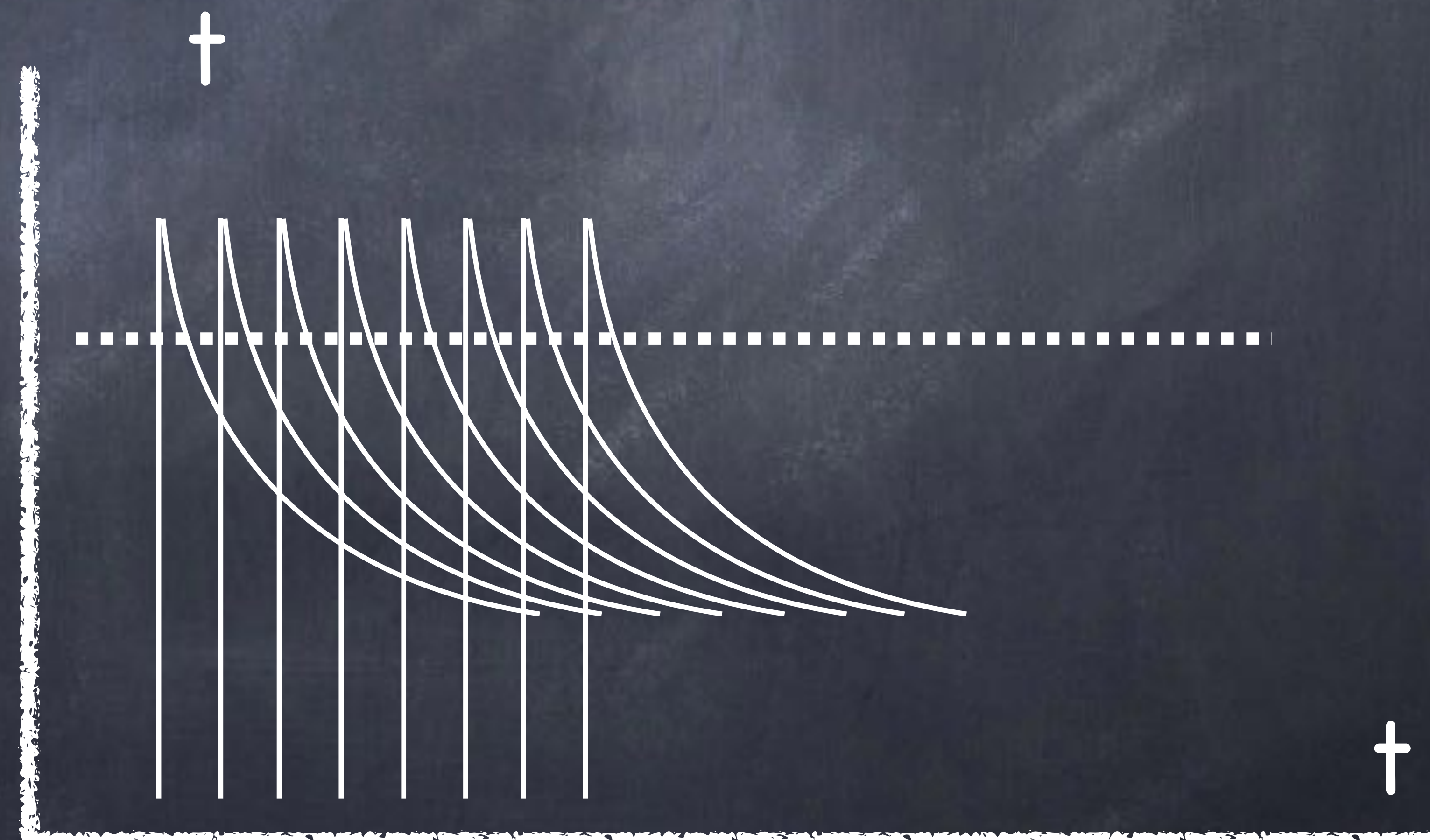
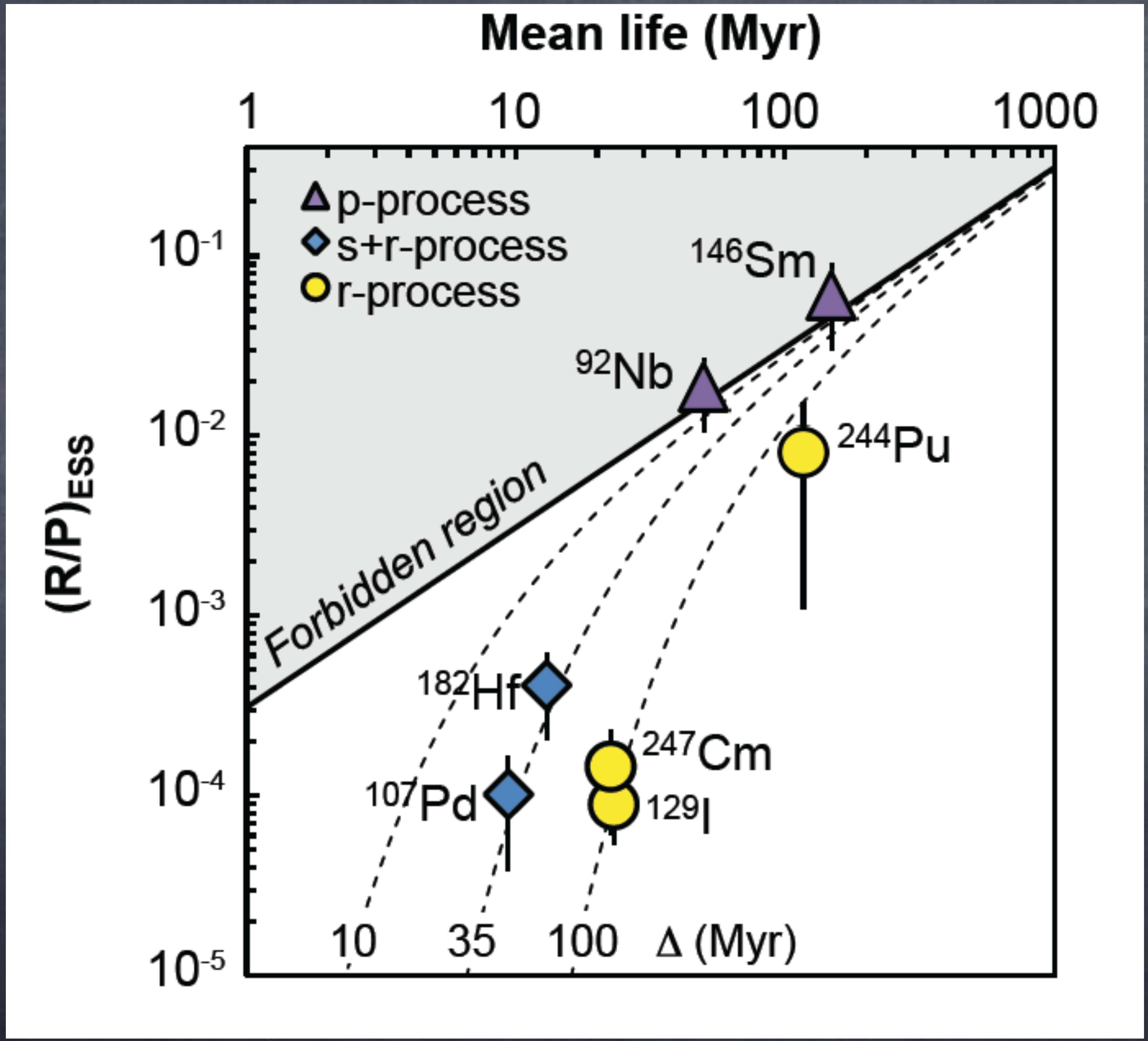
Radioactive Elements



Rare Events

Frequent events



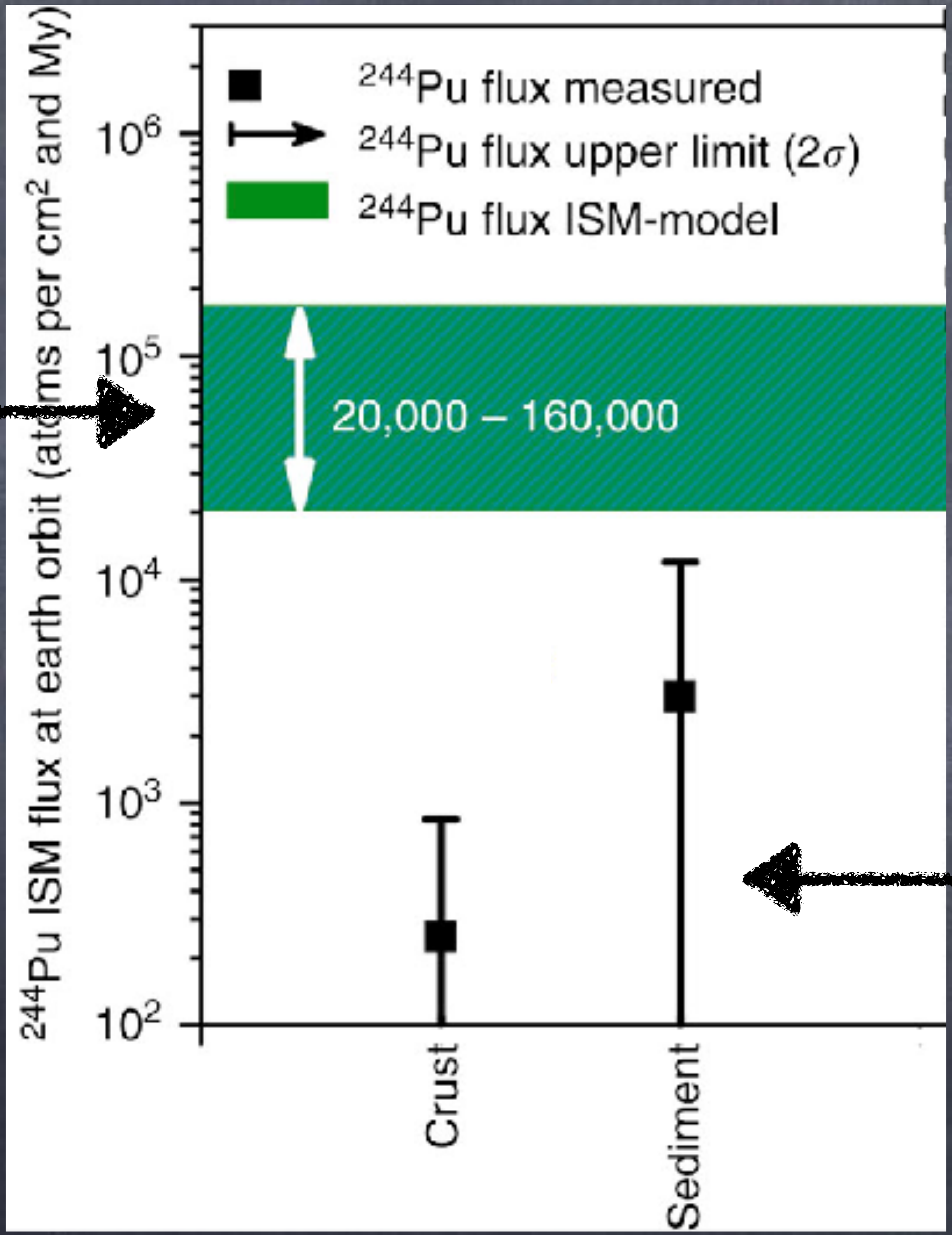


Mean life (Myr)
1
10
100
1000
p-process
s+r-process
r-process
146Sm
92Nb
244Pu
182Hf
247Cm
107Pd
129I
Forbidden region
(R/P)ESS
10-1
10-2
10-3
10-4
10-5
10
35
100
Δ (Myr)

Tissot + 16

^{244}Pu (half life 81Myr)

The early solar system



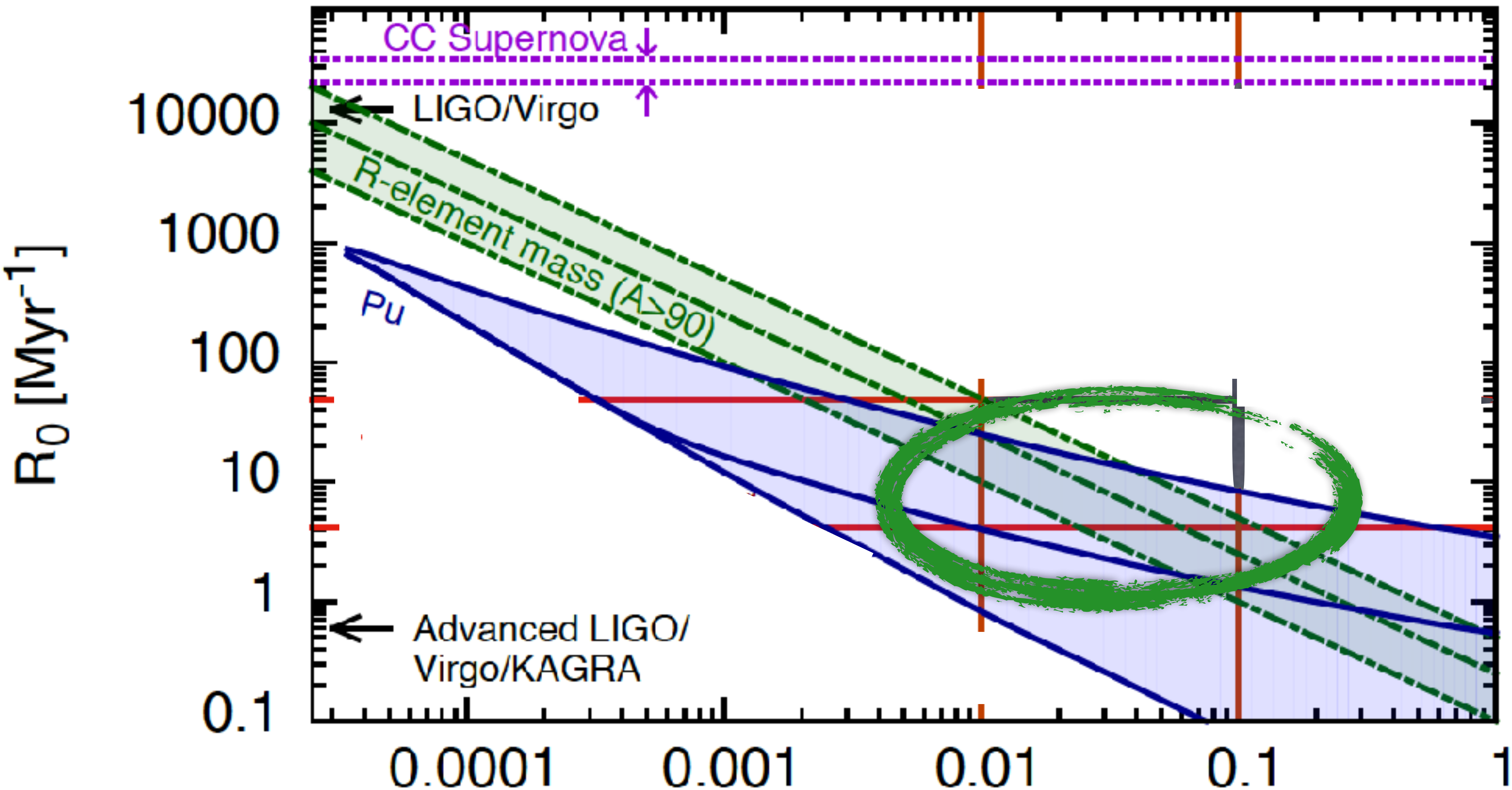
Current deposition rate

Wallner + 14

High ^{244}Pu at the early solar system =>

- ^{244}Pu Radioactive decay time ~ 100 Myear
- A nevent near the early solar system
- Mixing time < 150 Myr
- Large fluctuations possible => Event rate is low
- Lack of Cu => 10 Myr < Mixing time

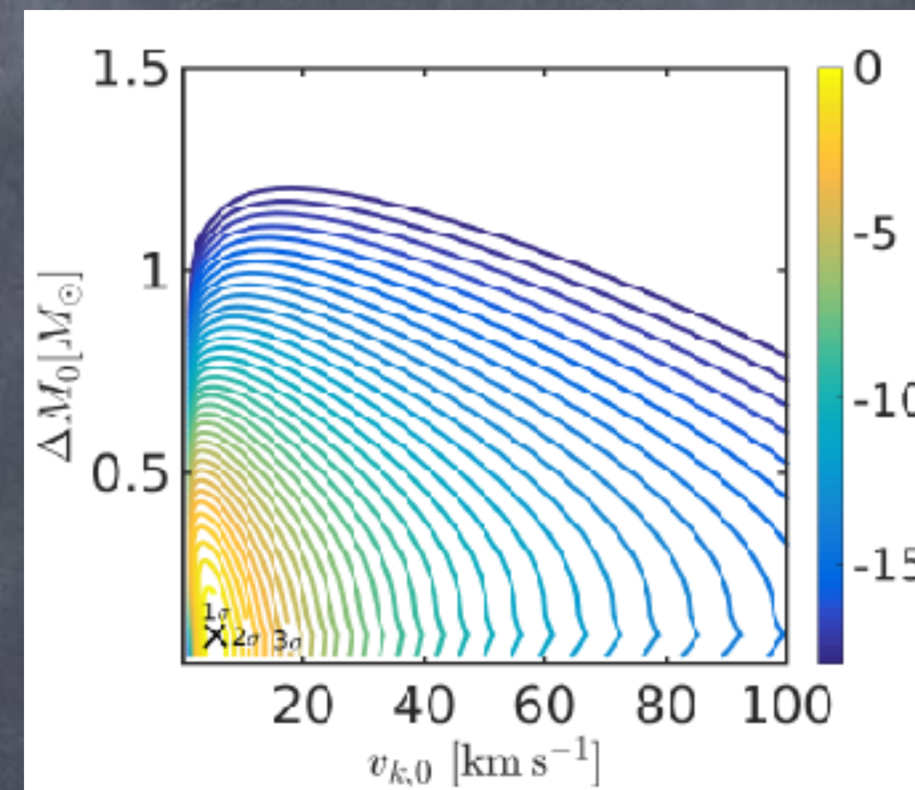
Rare and "massive" events



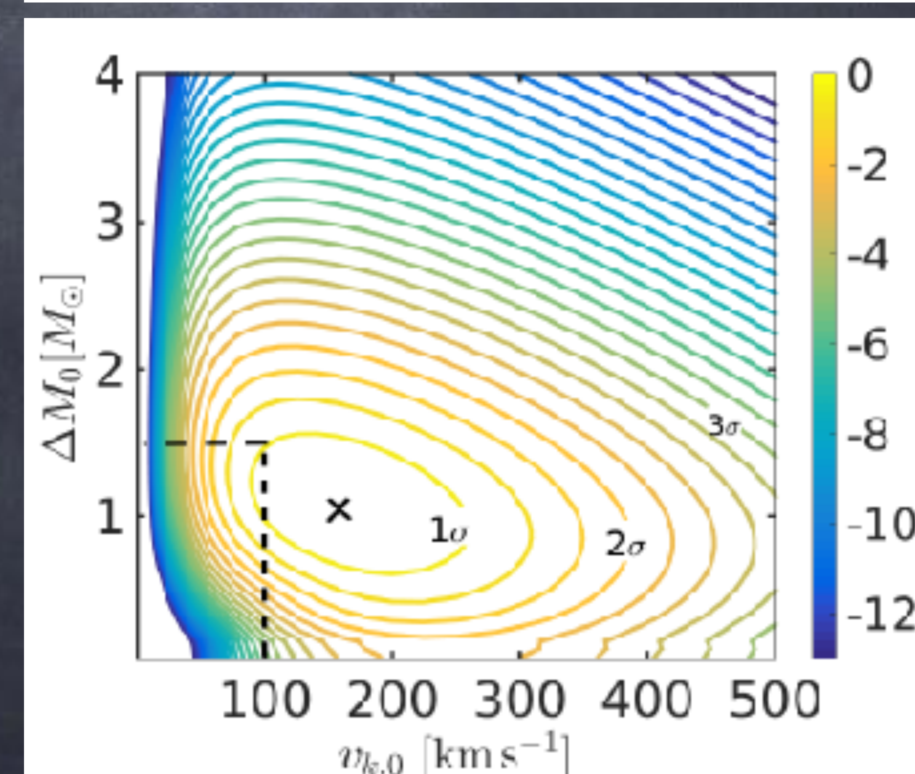
Hotokezaka, TP & Paul, Nature Pays, 2015

A remark about binary neutron stars

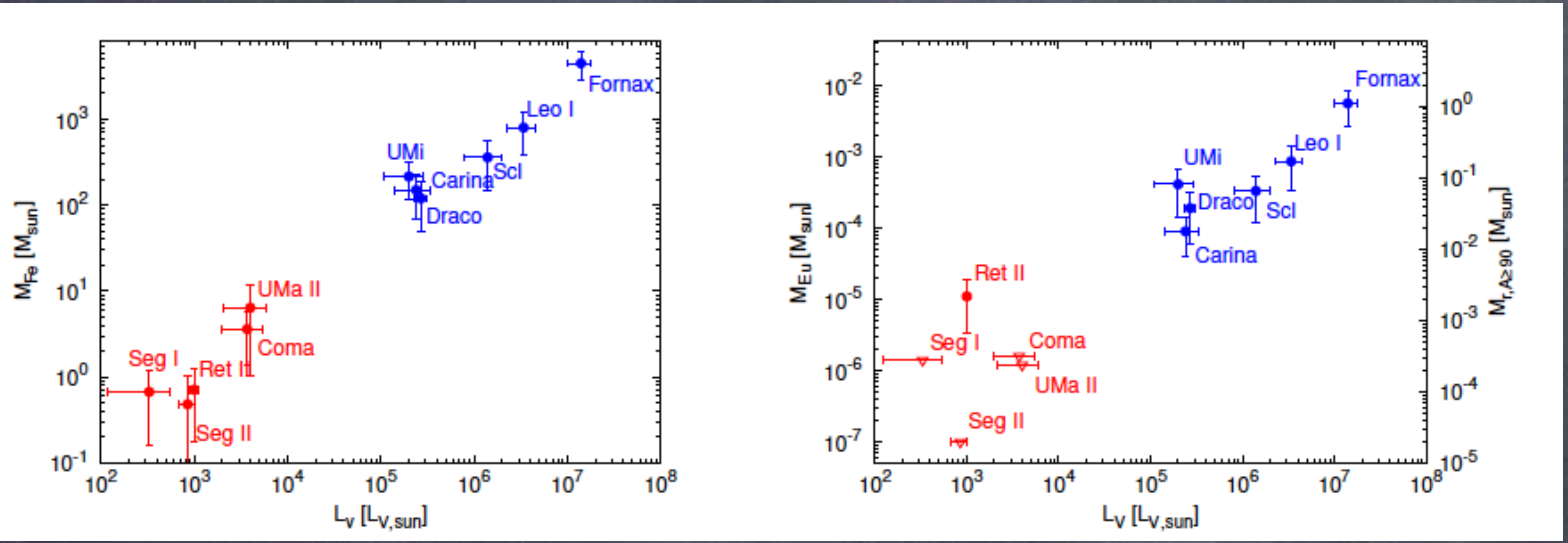
TP & Shaviv 2005; Dall'Osso, TP & Shaviv 2013, Beniamini & TP 2015

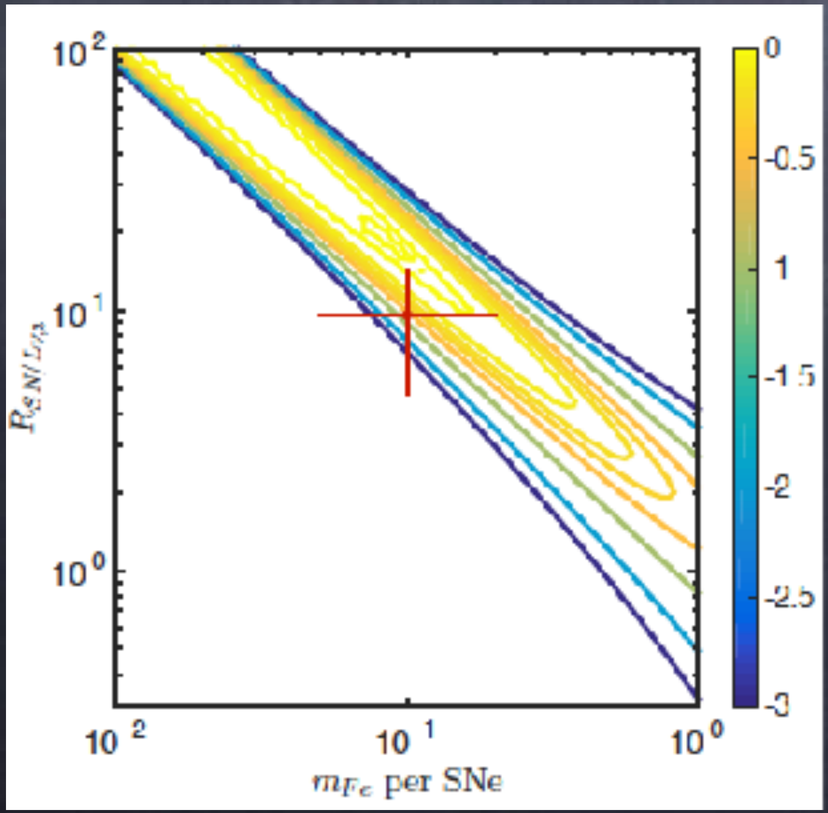


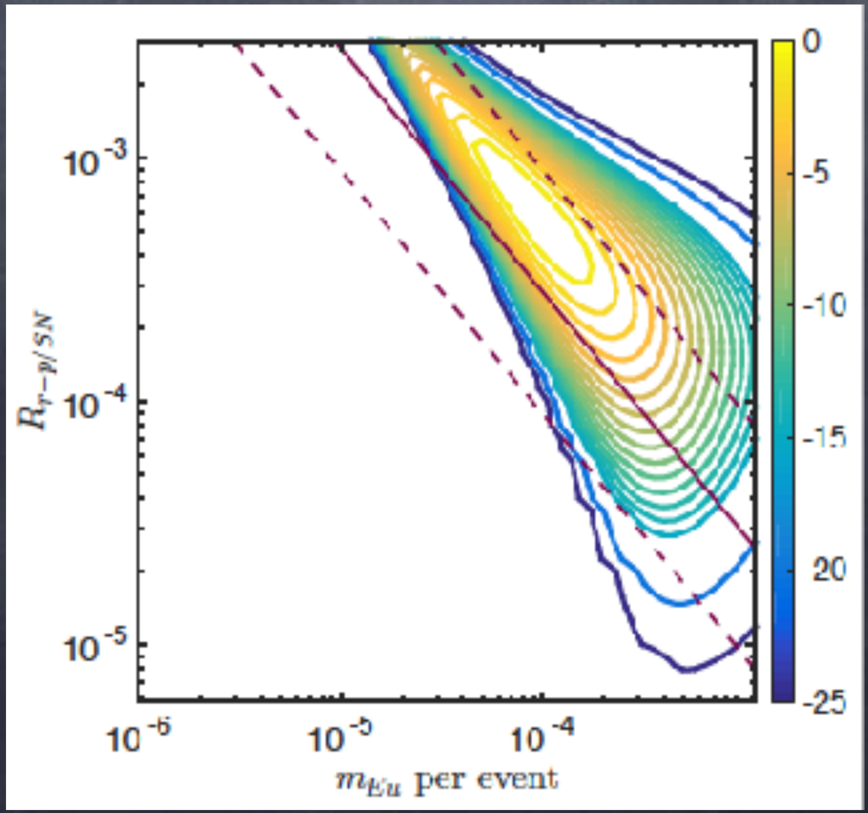
- ✳Most observed Galactic binary neutron stars have almost circular orbits and a low proper motion
- ➡Very low mass ejection (<0.1 M_{sun} for J0737-3039B)
- ➡NOT formed in a regular SNe
- ➡Most won't be ejected from a Dwarf Galaxy

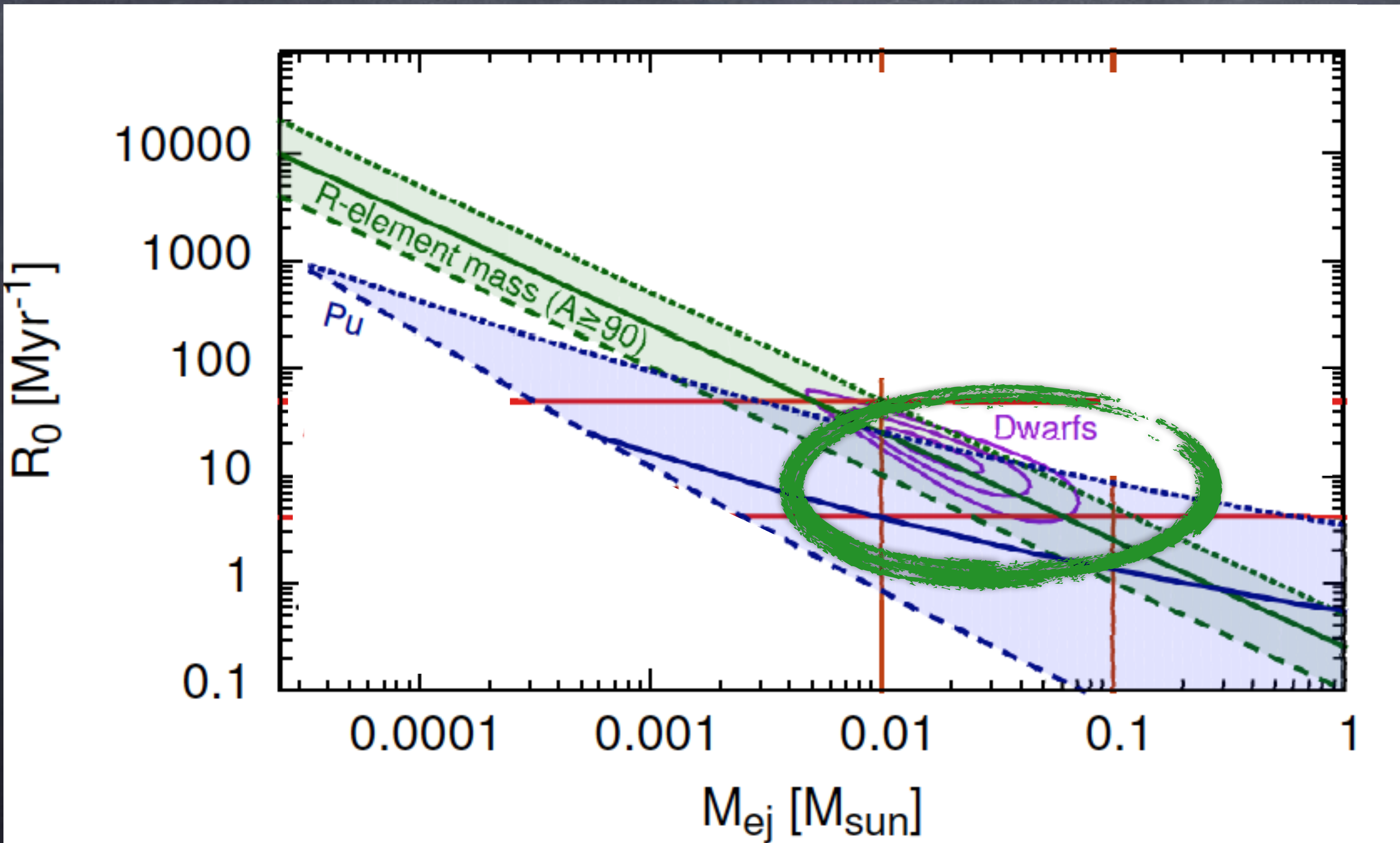


r-process material in Dwarf Galaxies (Beniamini, Hotokezaka & TP 16a,b)



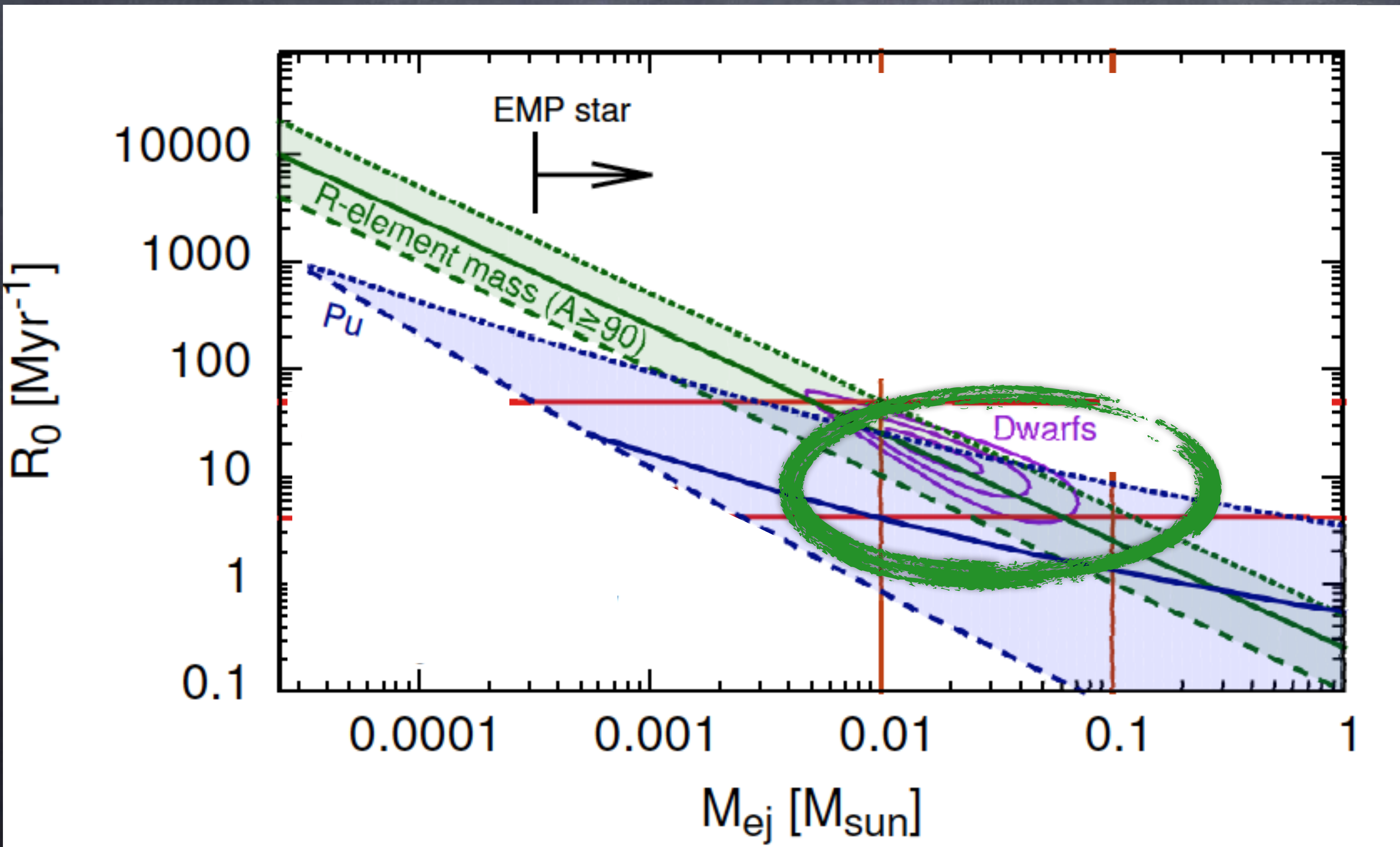




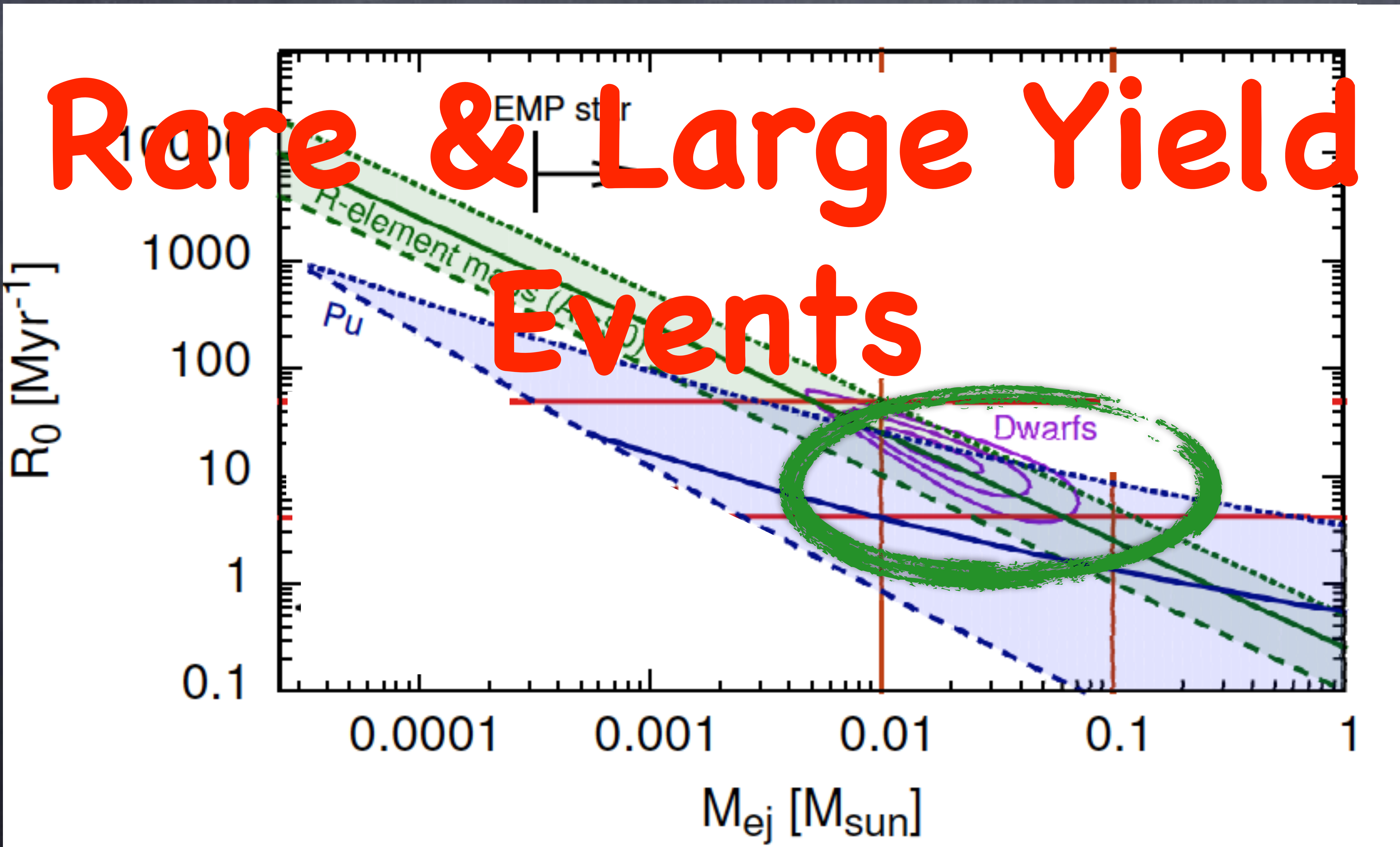


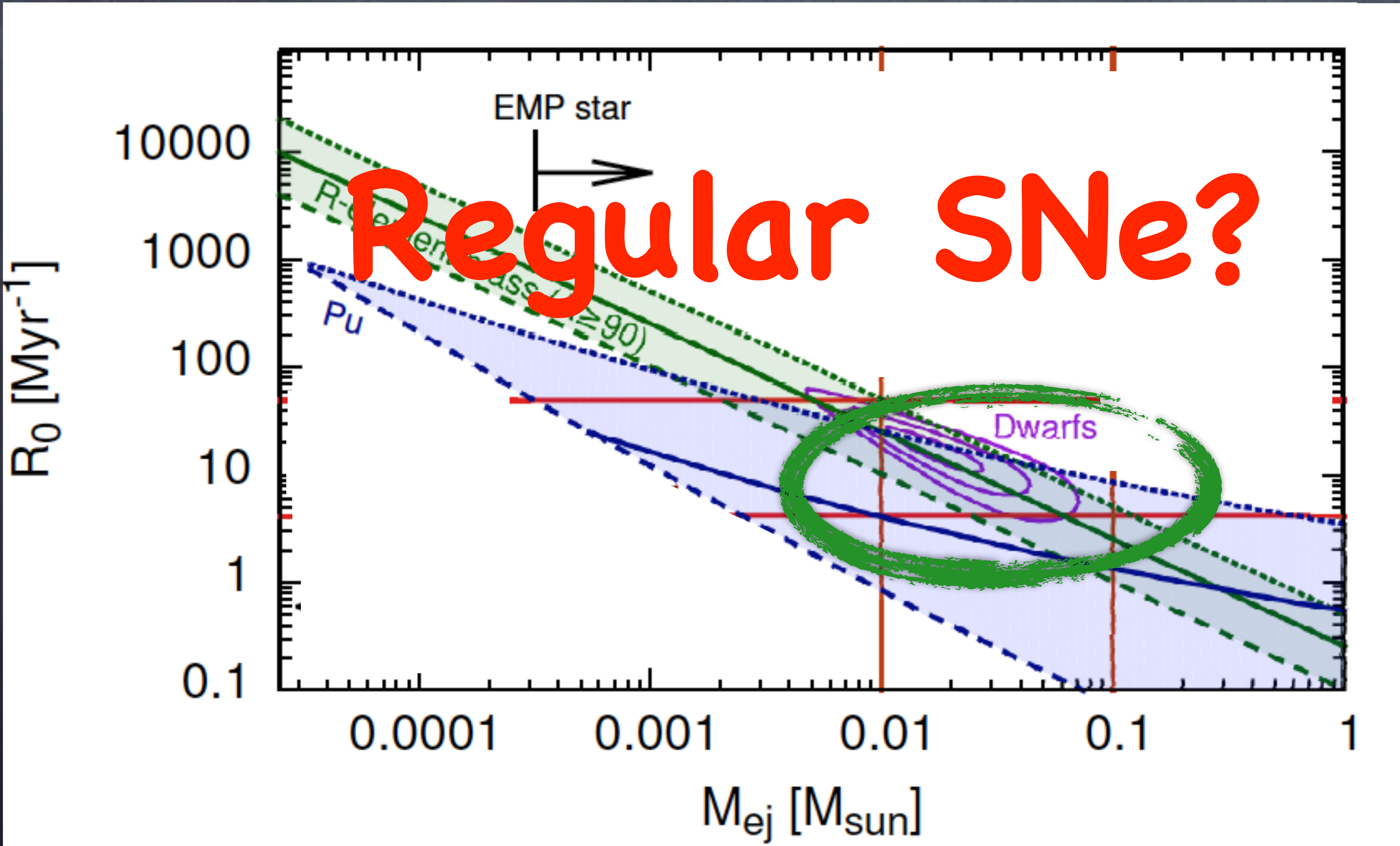
10000
1000
100
10
1
0.1
R_0 [Myr^{-1}]
R-element mass (A≥90)
Pu
Dwarfs
0.0001
0.001
0.01
0.1
1
M_{ej} [M_{sun}]

The most enriched Galactic low metallicity star (Macias & Ramirez Ruiz 2016)

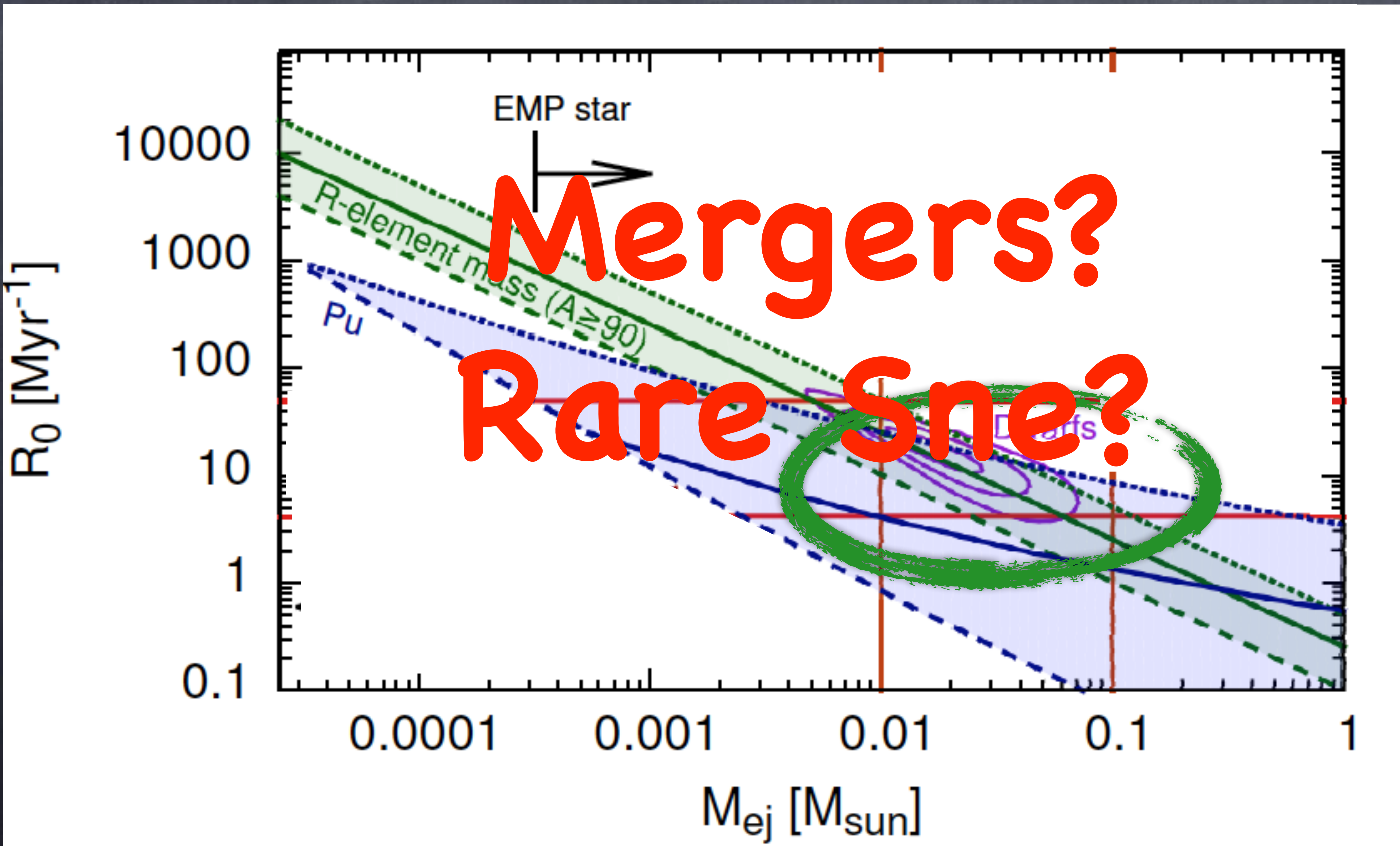


Rare & Large Yield Events





Regular SNe?
EMP star
R-element mass (A≥90)
Pu
Dwarfs
10000
1000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
R_0 [Myr^{-1}]
M_{ej} [M_{sun}]



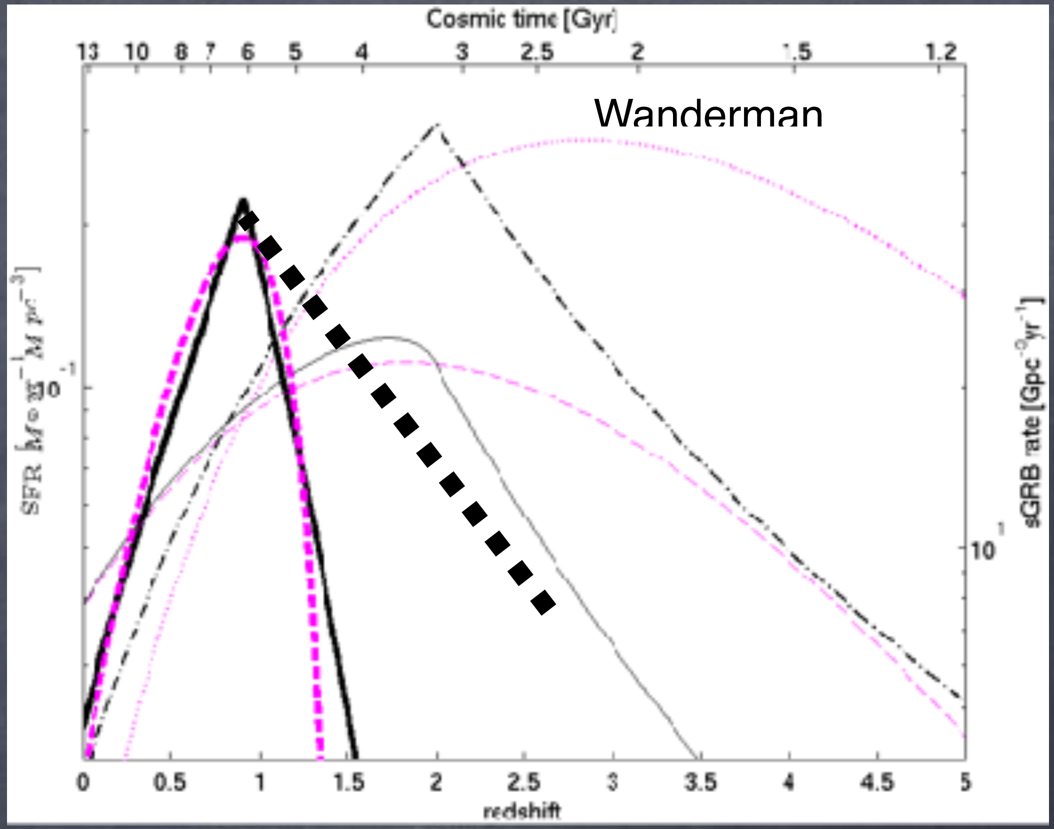
Mergers?
Rare Sne?
EMP star
R-element mass (A≥90)
Pu
Dwarfs
10000
1000
100
10
1
0.1
R0 [Myr-1]
0.0001
0.001
0.01
0.1
1
Mej [Msun]

Cnclusions so far

- ✴Rate ~20-30 Myr^{-1}
- ✴Yield ~0.01-0.1 m_{sun}
- ➡low rate high yield events
- ➡SNe👎
- ➡Mergers? or Rare SNe?

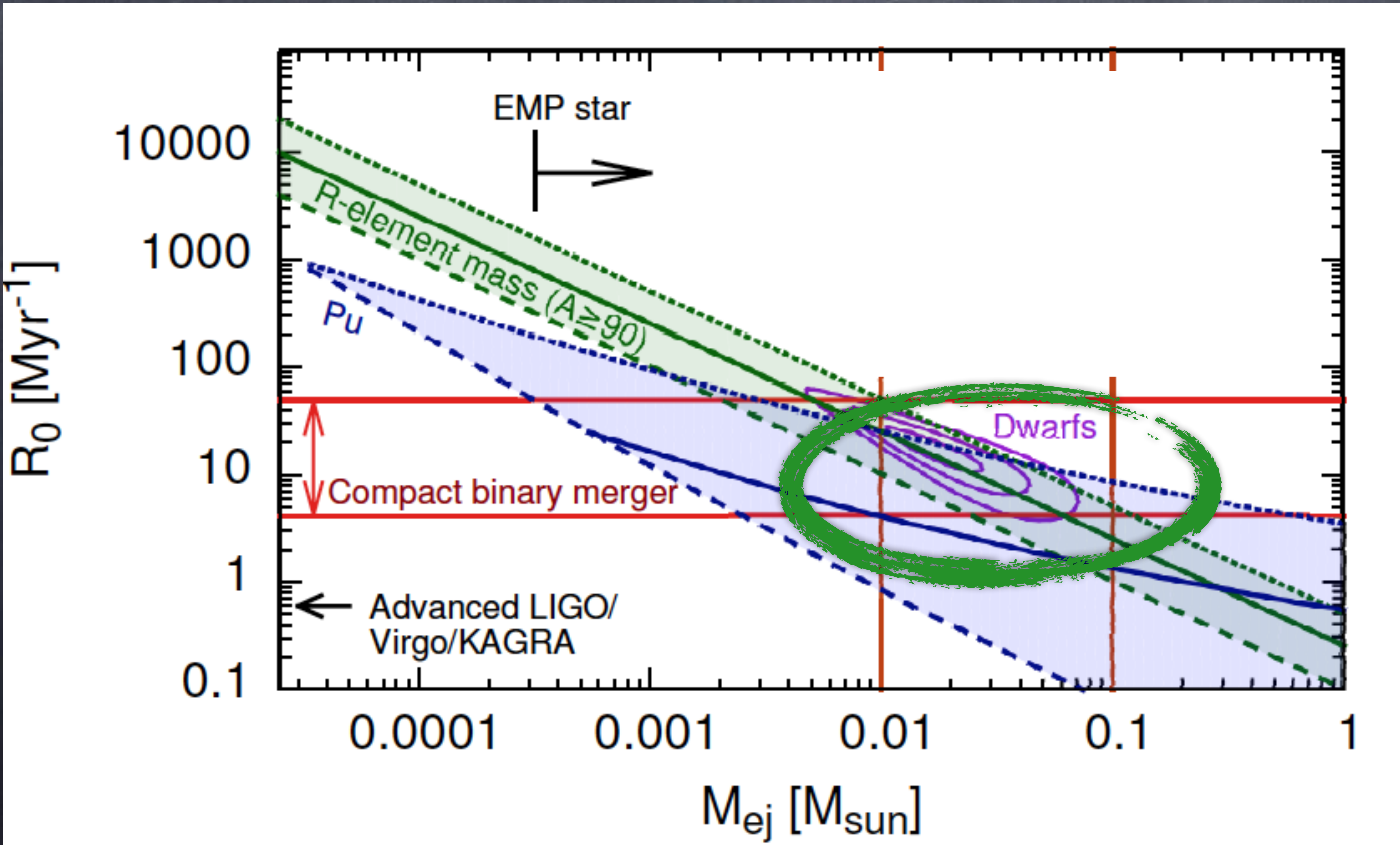
The Rate of short GRBs
(Wanderman & TP 2015)

- Current observed rate $\sim 5\ Gpc^{-3}\ yr^{-1} \sim 0.5\ Myr^{-1}$
- Earlier rate is larger
- Uncertainties
  - Short delay mergers (need high redshift sGRBs) can be ~20 Myr!!!
  - Lowest energy (rate can be higher)
  - Beaming factor x10-70 (Very uncertain)



- Galactic rate from binary pulsars $21_{-14}^{+28}\ My^{-1}$ (Kim + 15)

With estimates of the merger rate



Macronova* (Li & Paczynski 1997)

Bohdan Paczynski

- Radioactive decay of the neutron rich matter.
- $E_{radioactive} \approx 0.001\ Mc^2 \approx 10^{50}$ erg
- A weak short Supernova like event.

*Also called Kilonova

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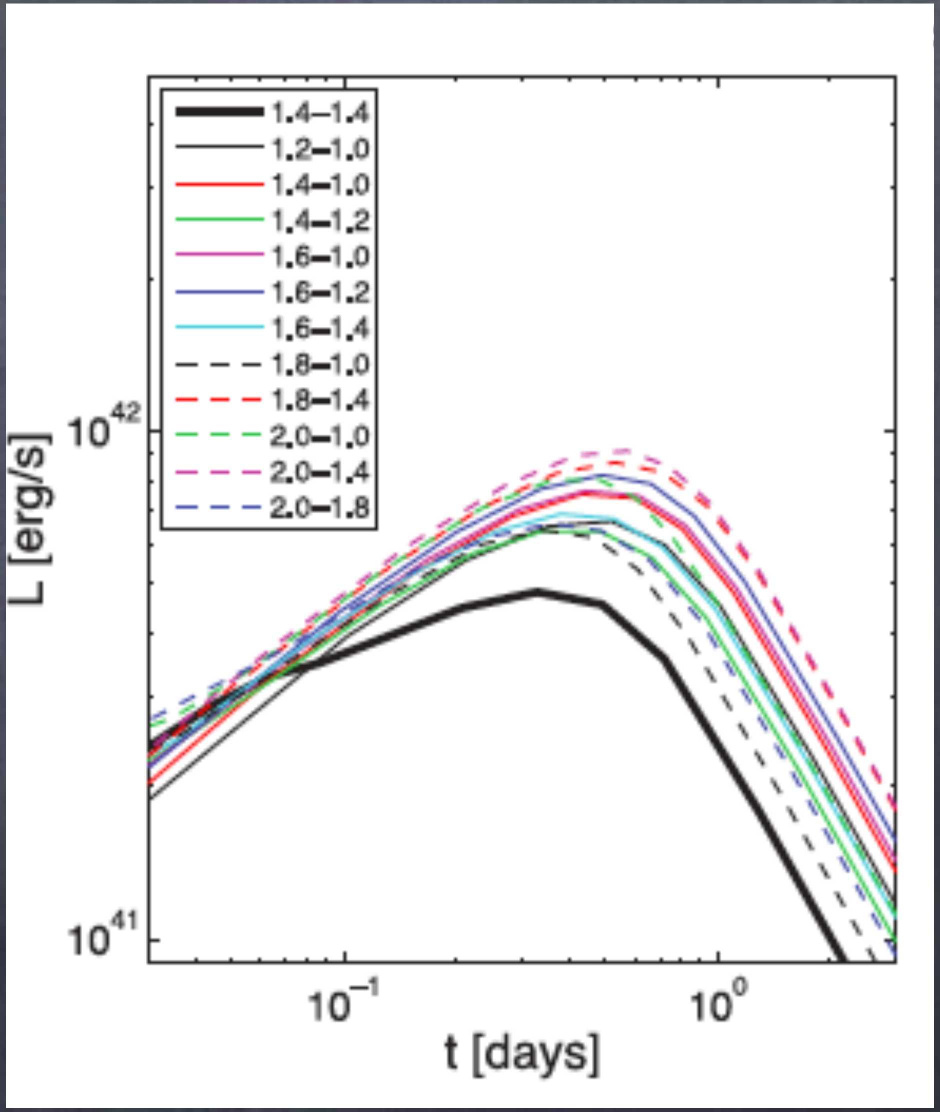
*Also called ~~Kilonova~~ ➔ ~~Hektanova~~ ➔ Decanova

Lanthanides dominate the opacity

(Kassen & Barnes 13, Tanaka & Hotokezaka 13))

- $\kappa = 10 cm^2/gm$
- $t_{max} \propto \kappa^{1/2}$ => l o n g e r
- $L_{max} \propto \kappa^{-0.65}$ => weaker
- $T \propto \kappa^{-0.4}$ => redder



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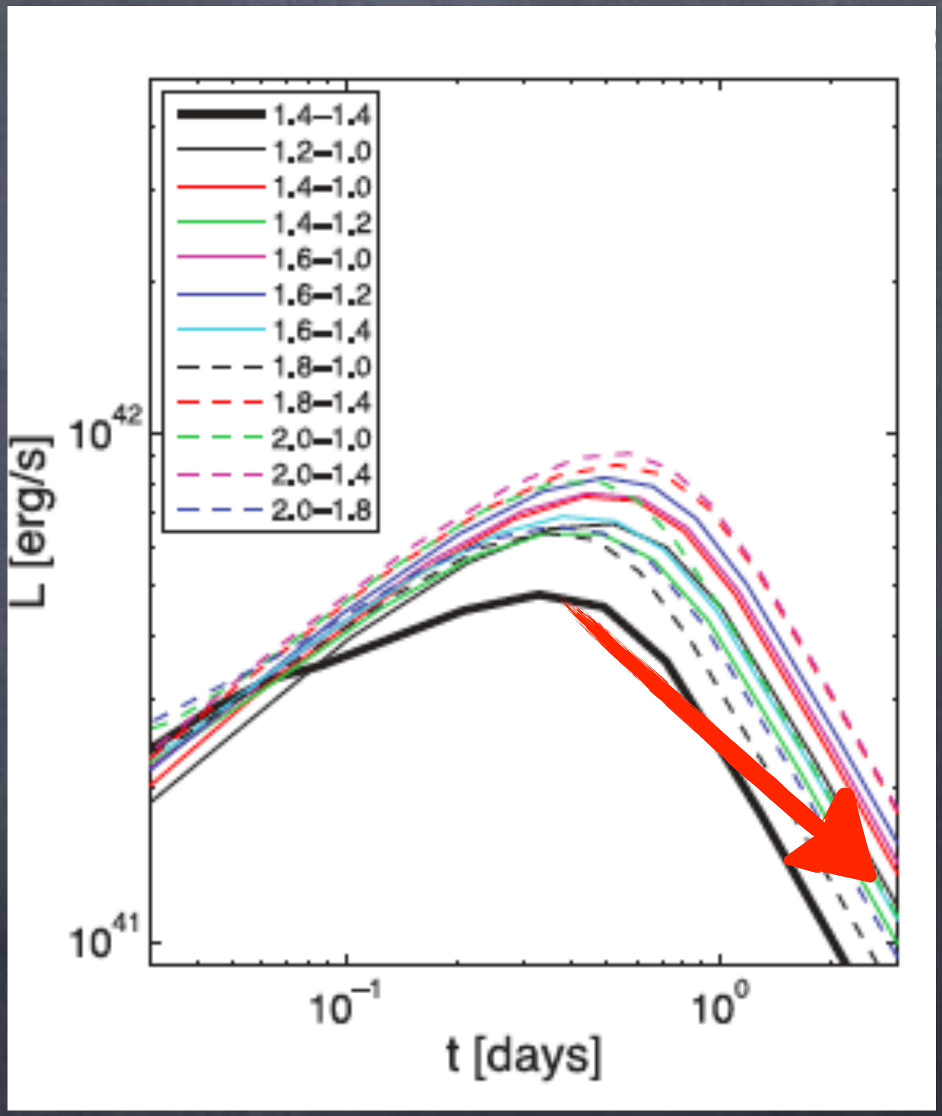

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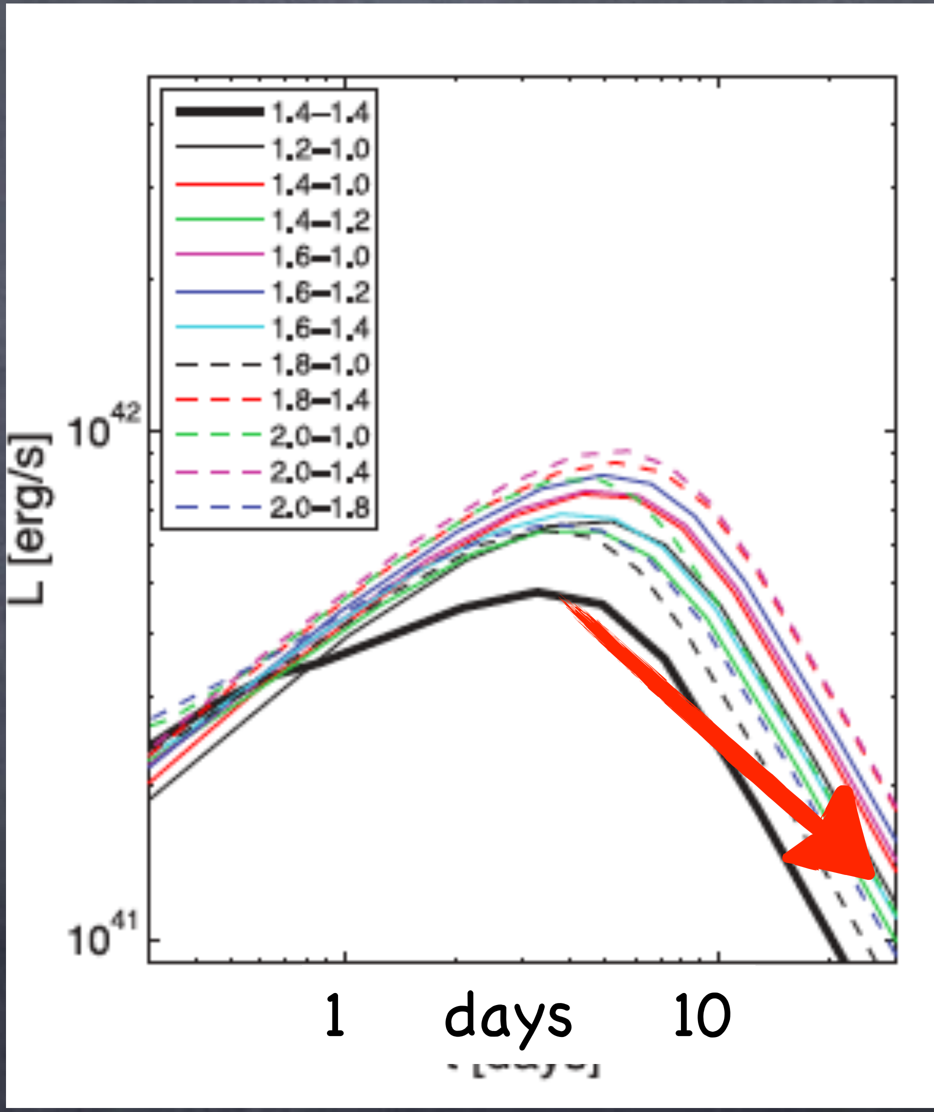

Lanthanides dominate the opacity

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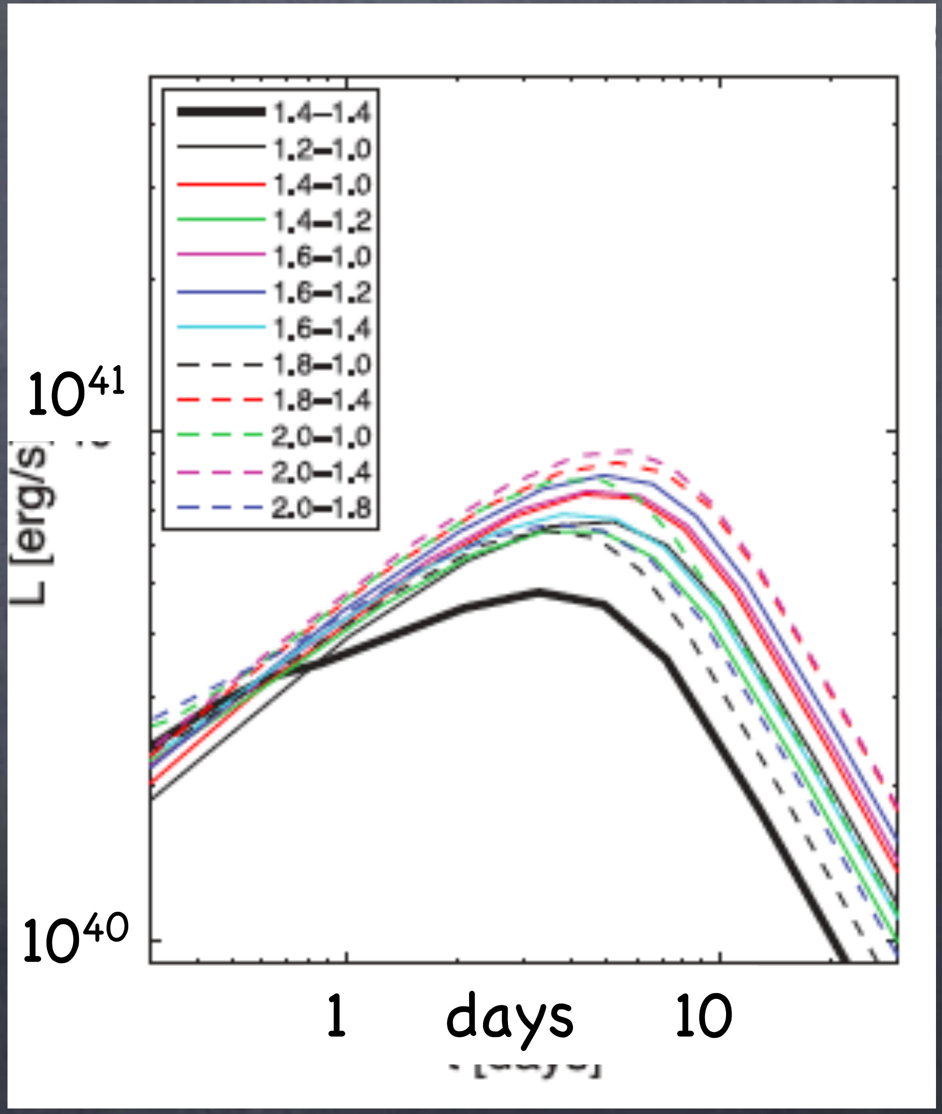

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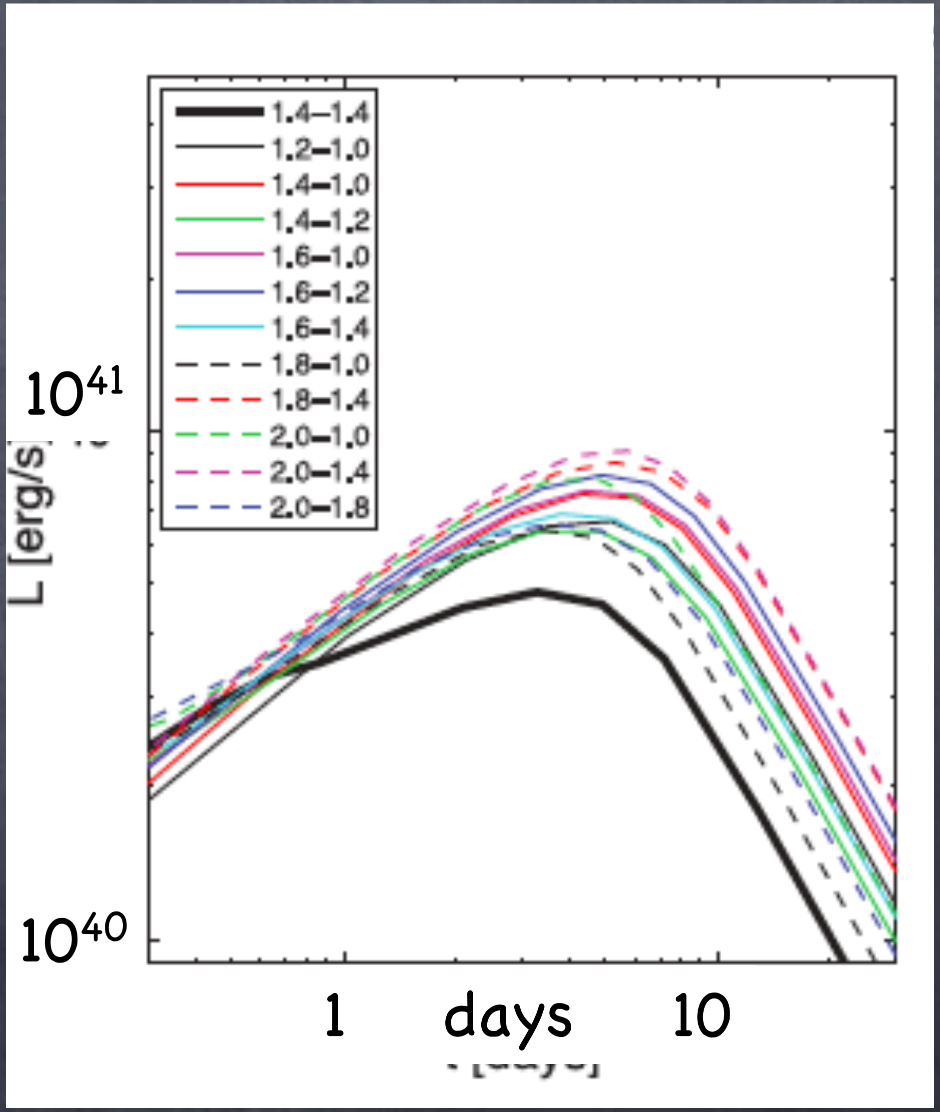
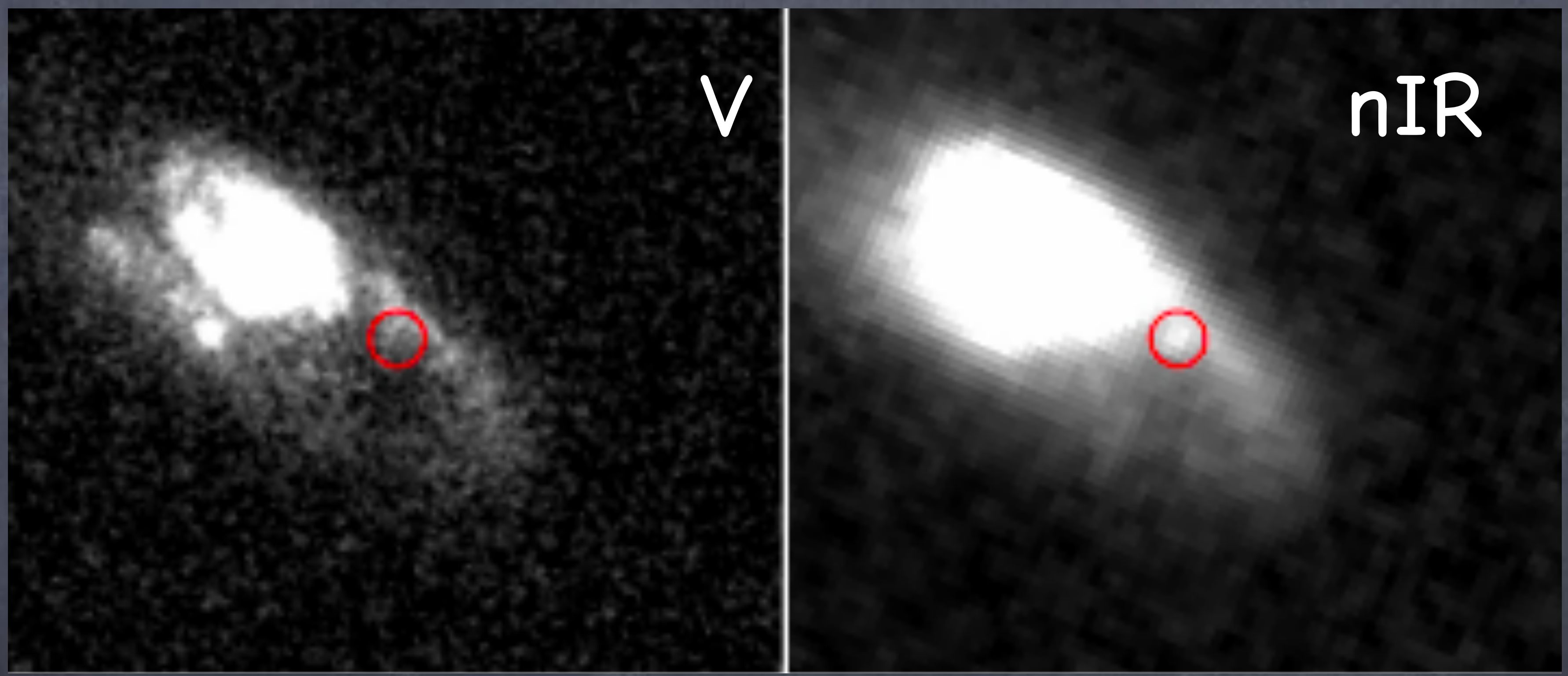


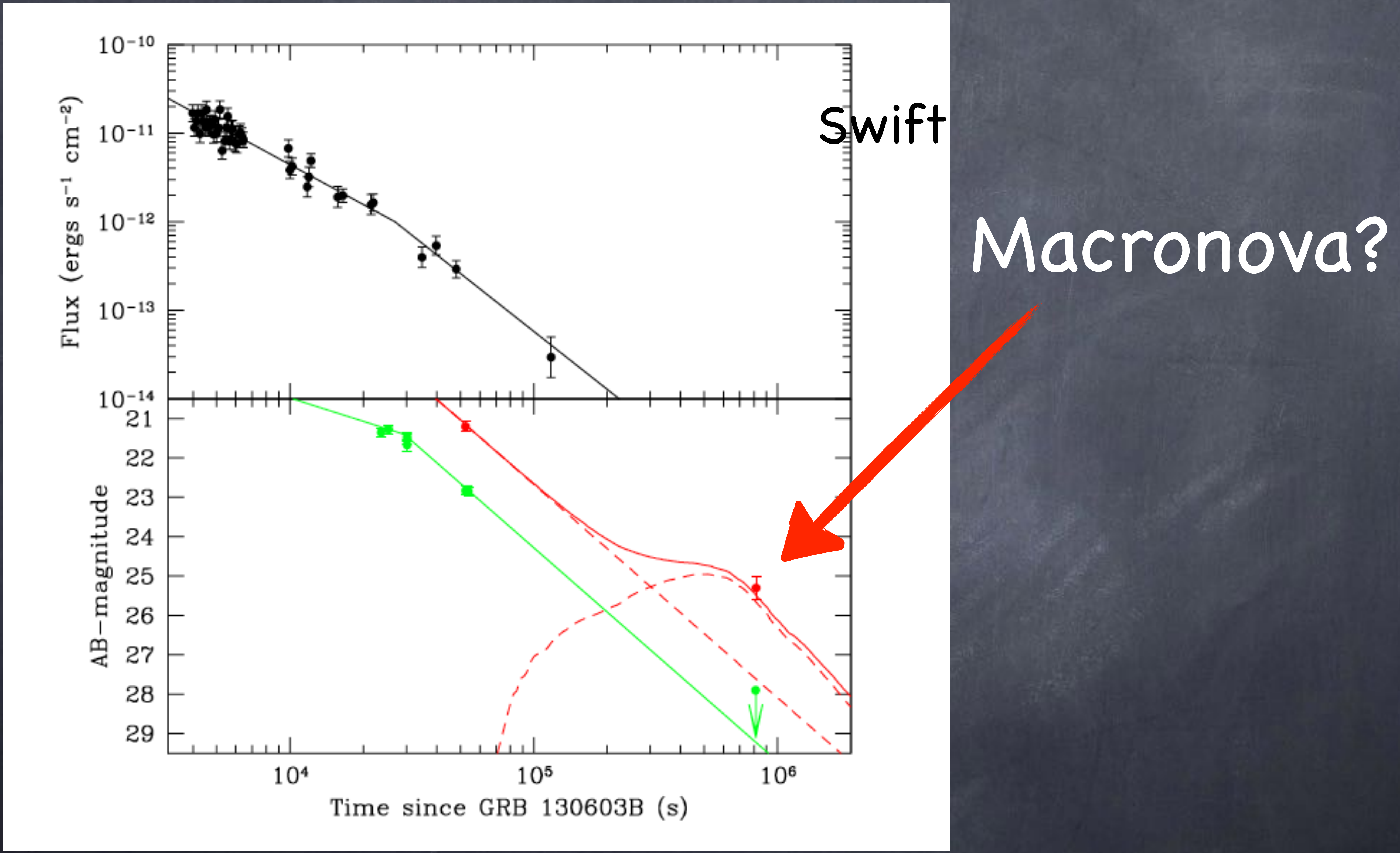
uv or optical -> IR

GRB130603B @ 9 days AB

(6.6 days at the source frame)



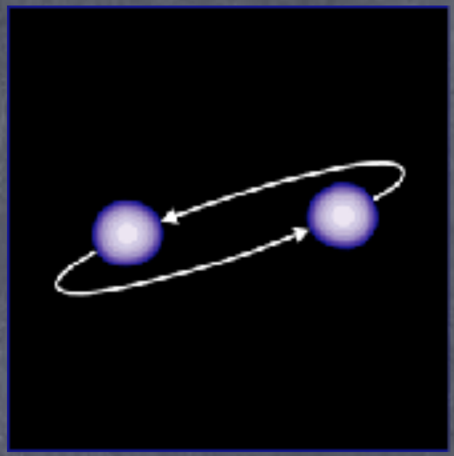
HST image (Tanvir + 13)



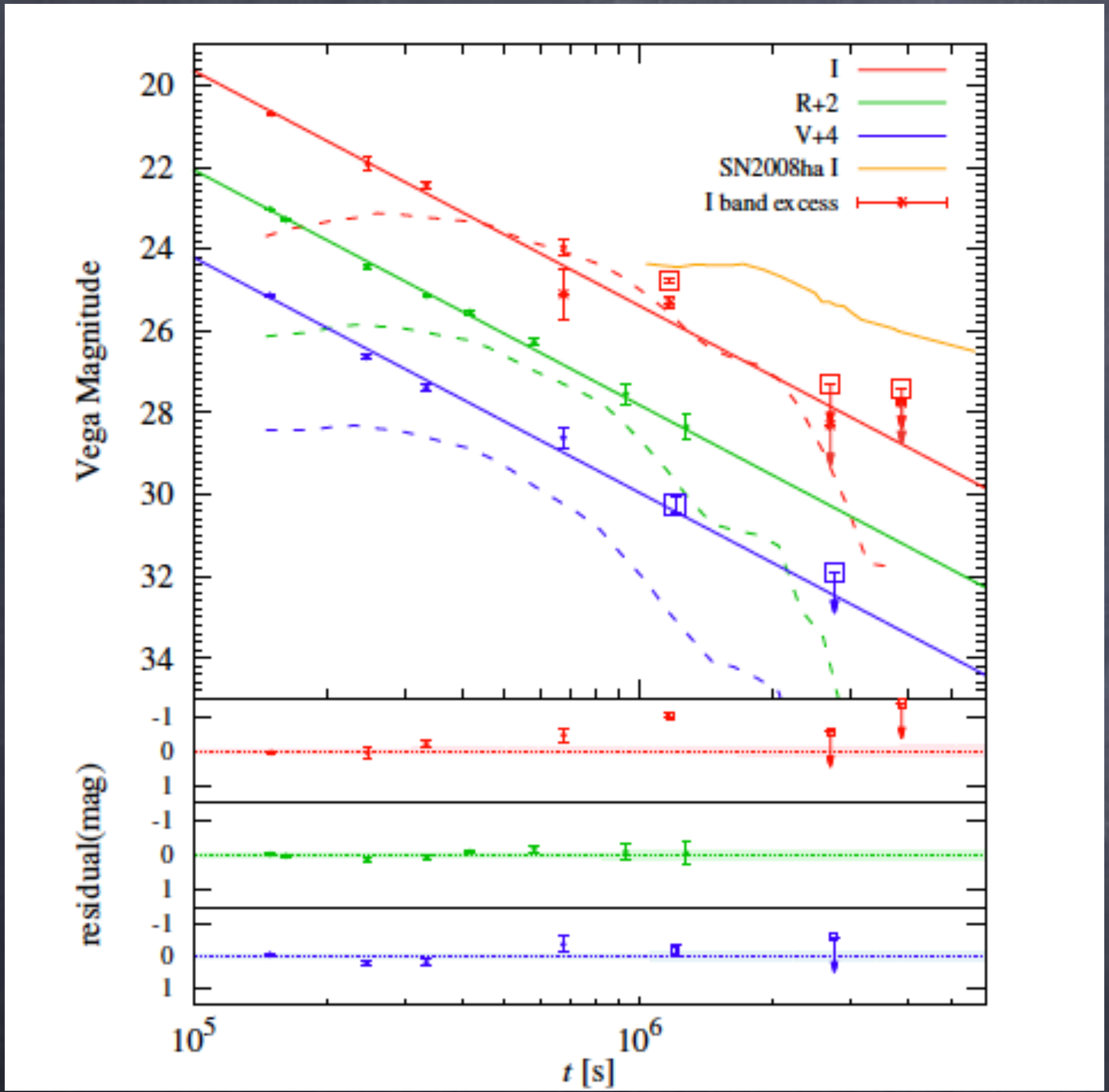
Tanvir + 13, Berger + 13

If correct

- Confirmaiton of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).
- Confirmation of the Li-Paczynski Macronova (Li-Paczynski 1997).
- Confirmation that compact binary mergers are the source of heavy (A>130) r-process material: Gold, Silver, Platinum, Plotonium, Uranium etc…(Lattimer & Schramm, 75).



GRB 060614



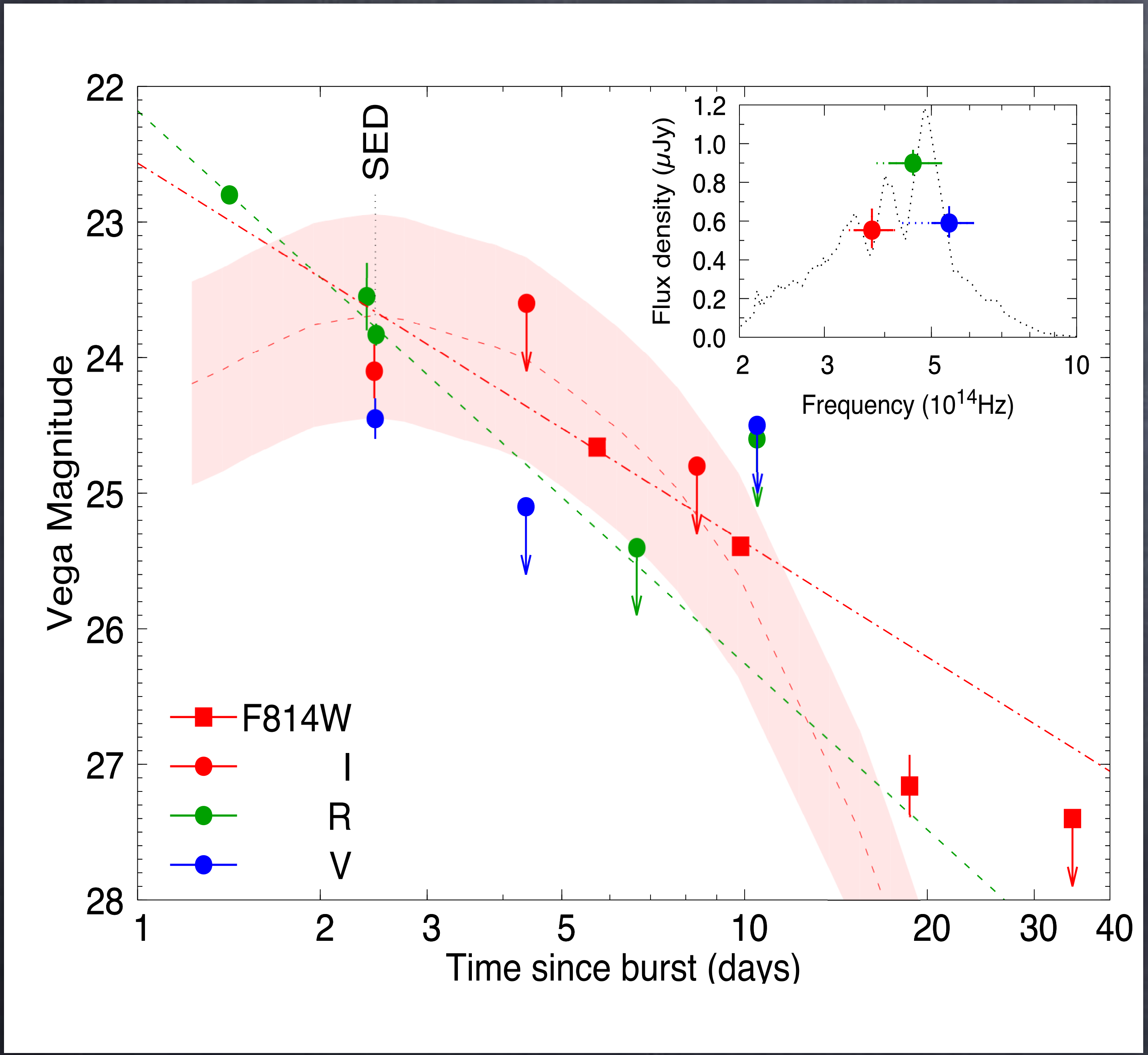
Need $M \simeq 0.1\ m_{sun}$ *

=> BH-NS ?

* mass estimate may increase (efficiency) BUT may decrease if additional energy source beyond radioactivity!

Yang et al., 2015

GRB 050709



Need $M \simeq 0.05 m_{sun}$ *

=> BH-NS ?

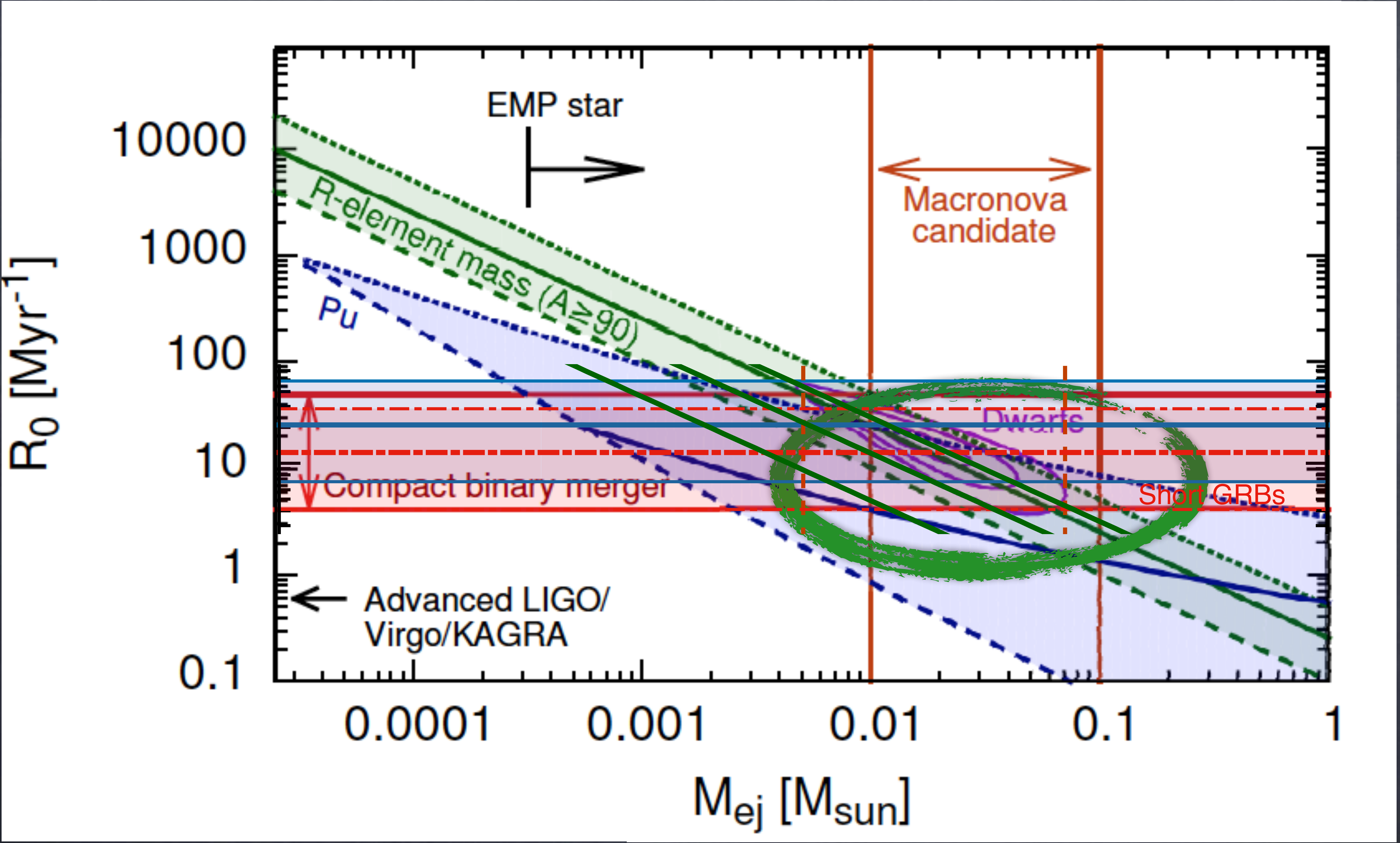
Jin et al., 2016

Are Macronova Frequent?

- There are 3 (6) possible (nearby) historical candidates with a good enough data
- In 3/3 (3/6) there are possible Macronovae

Macronova Mass estimates

- 0.02-0.1 m_{sun} * mass estimate may increase (efficiency) BUT may decrease if additional energy source beyond radioactivity! (see Kisaka, Nakar & Ioka 2016 for an additional energy source)

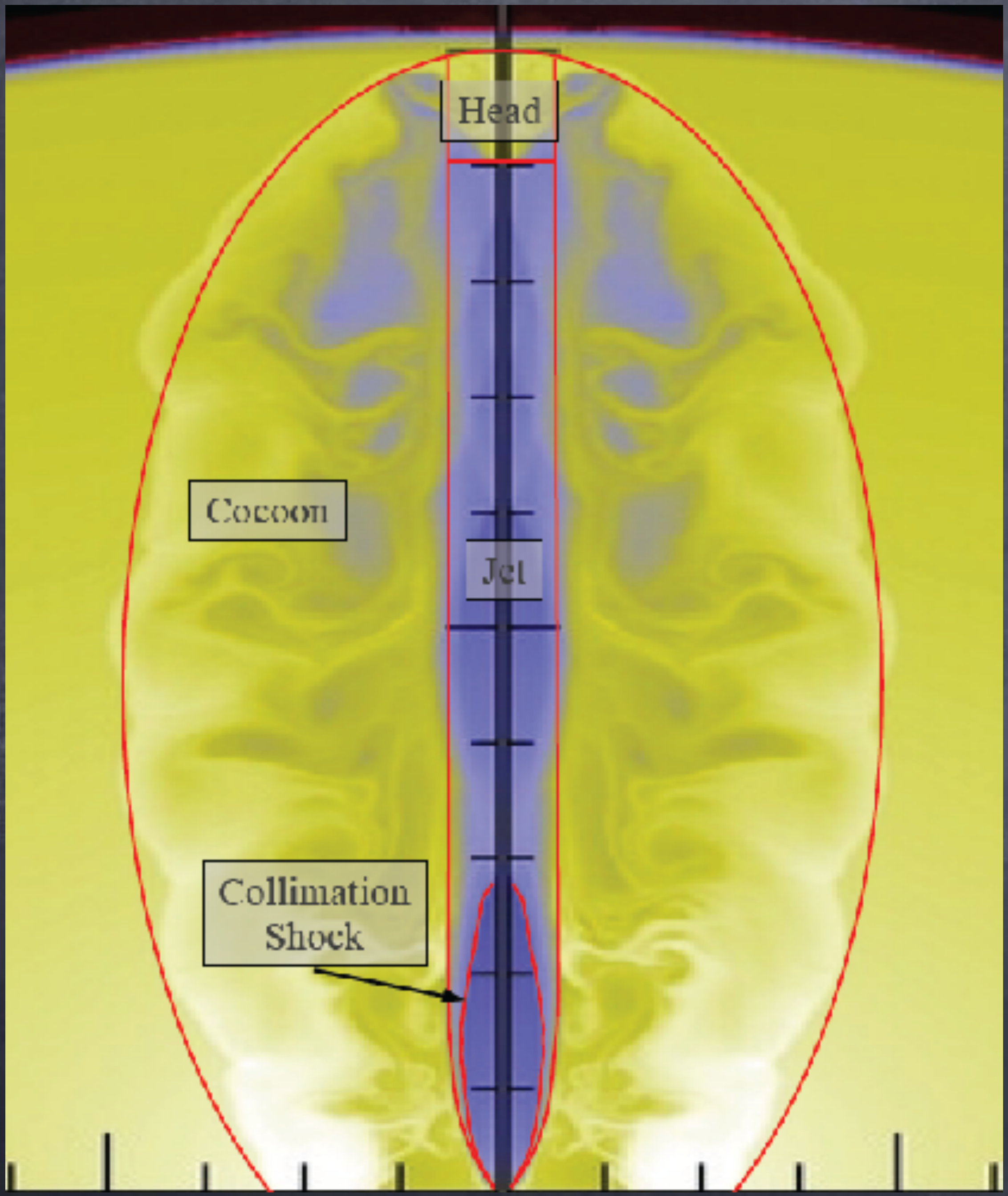


lines of R-mass: Current event rate is lower than the average one by a factor of 5 (lower line), 3 (middle line).

lines of SGRB: beaming factor f_b^-1 = 10, 30, 70 (Wanderman & Piran 2015)

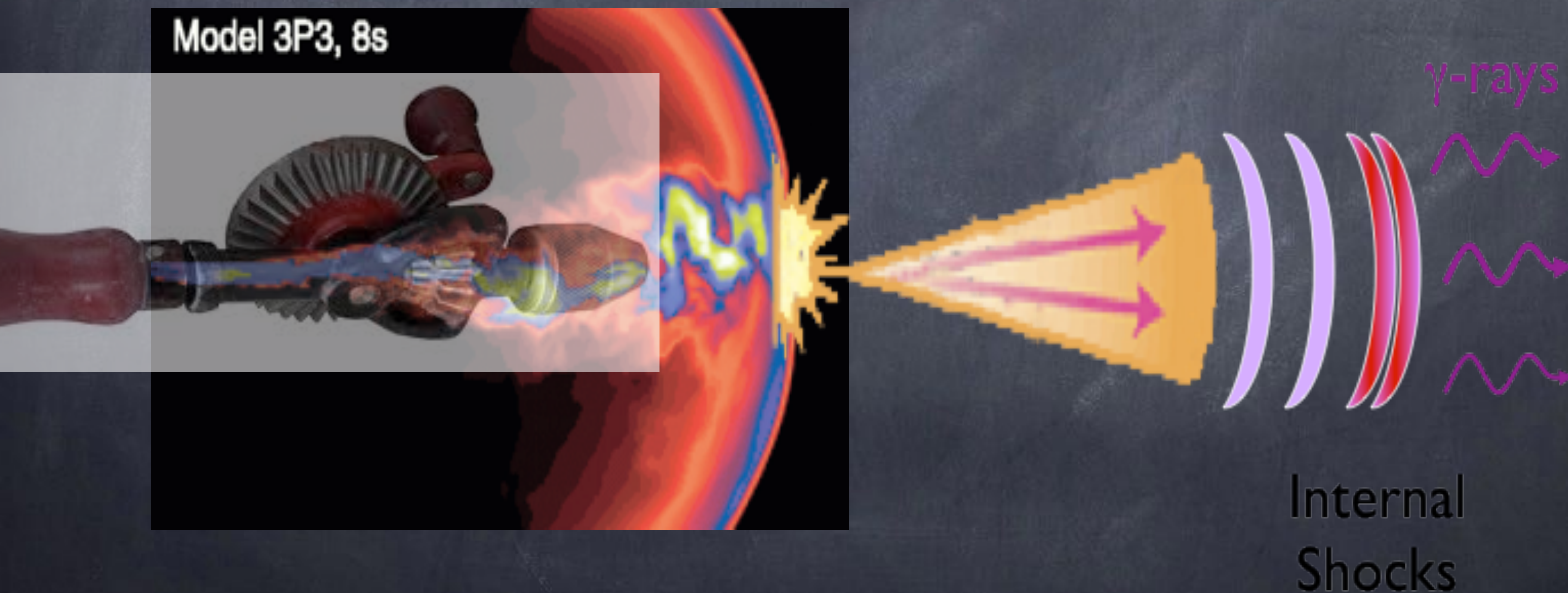
lines of NSNS: 95% confidence level (Kim et al 2015)

The Secret Signatures of GRB cocoons



Nakar & TP, ApJ 17

The Jet drills a hole in the star or in the surrounding ejecta



Jet breakout

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

LGRBs $$t_b \approx 8\ L_{51}^{-1/3} \theta_{10^o}^{4/3} R_{11}^{2/3} M_{10}^{1/3} \quad \mathrm{s}$$

sGRBs $$t_b \approx 0.37\ L_{49}^{-1/3} \theta_{10^o}^{4/3} R_9^{2/3} M_{0.1}^{1/3}\ s$$

The engine must be active until the jet's head breaks out!*

Jet breakout

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

sGRBs

$$t_b \approx 0.37\ L_{49}^{-1/3}\theta_{10^o}^{4/3}R_9^{2/3}M_{0.1}^{1/3}\ s$$

The engine must be active until the jet's head breaks out!*

3D simulation

4Msun, $R^*=4\times10^{10}$cm. $L_j = 10^{51}$erg/s, $\theta=8^o$ Using Pluto with high resolution $\Delta R=10^7$cm. Credit: Ore Gottlieb

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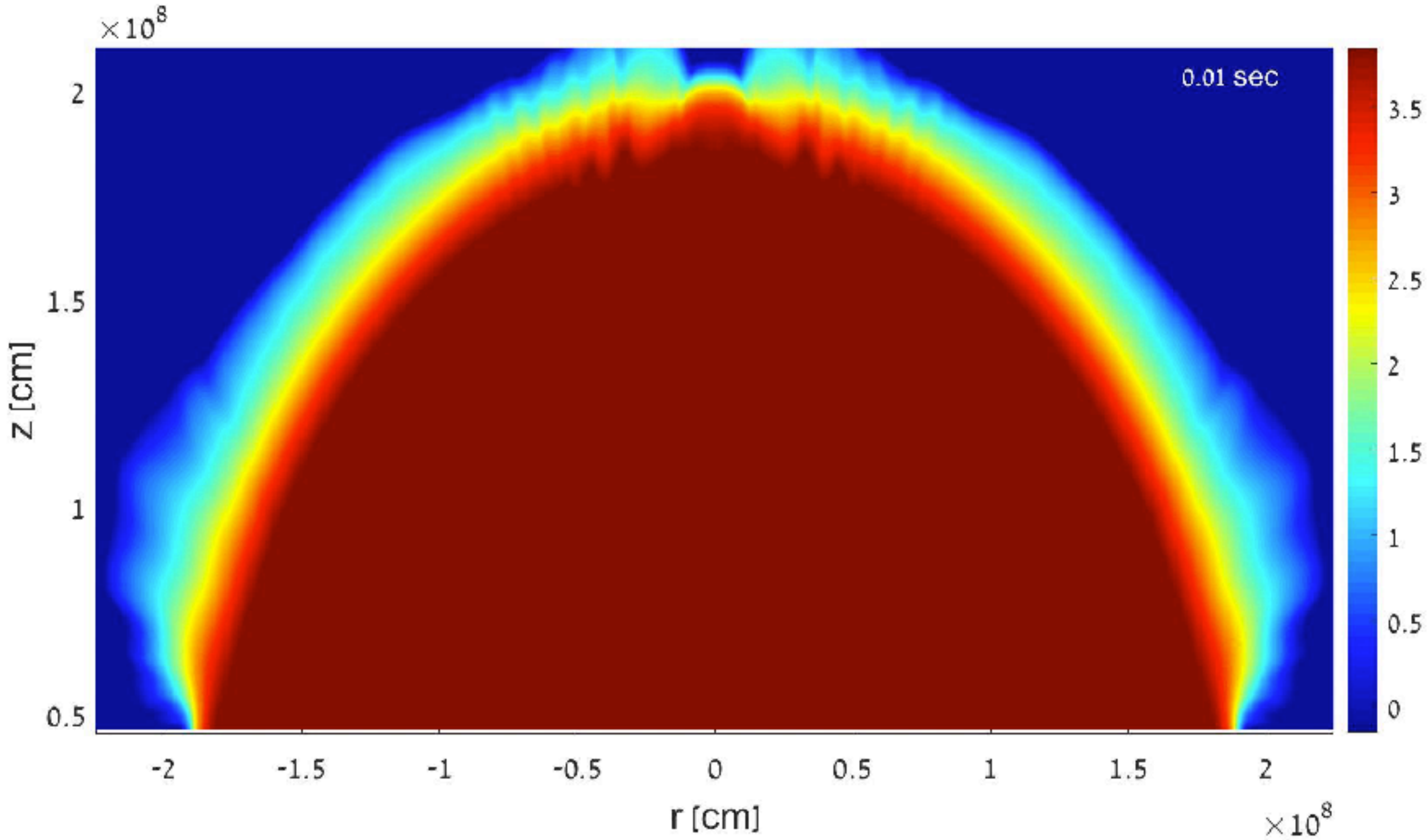
2D simulation



SGRB with a wind velocity of 0.2c. Credit: Ore Gottlieb

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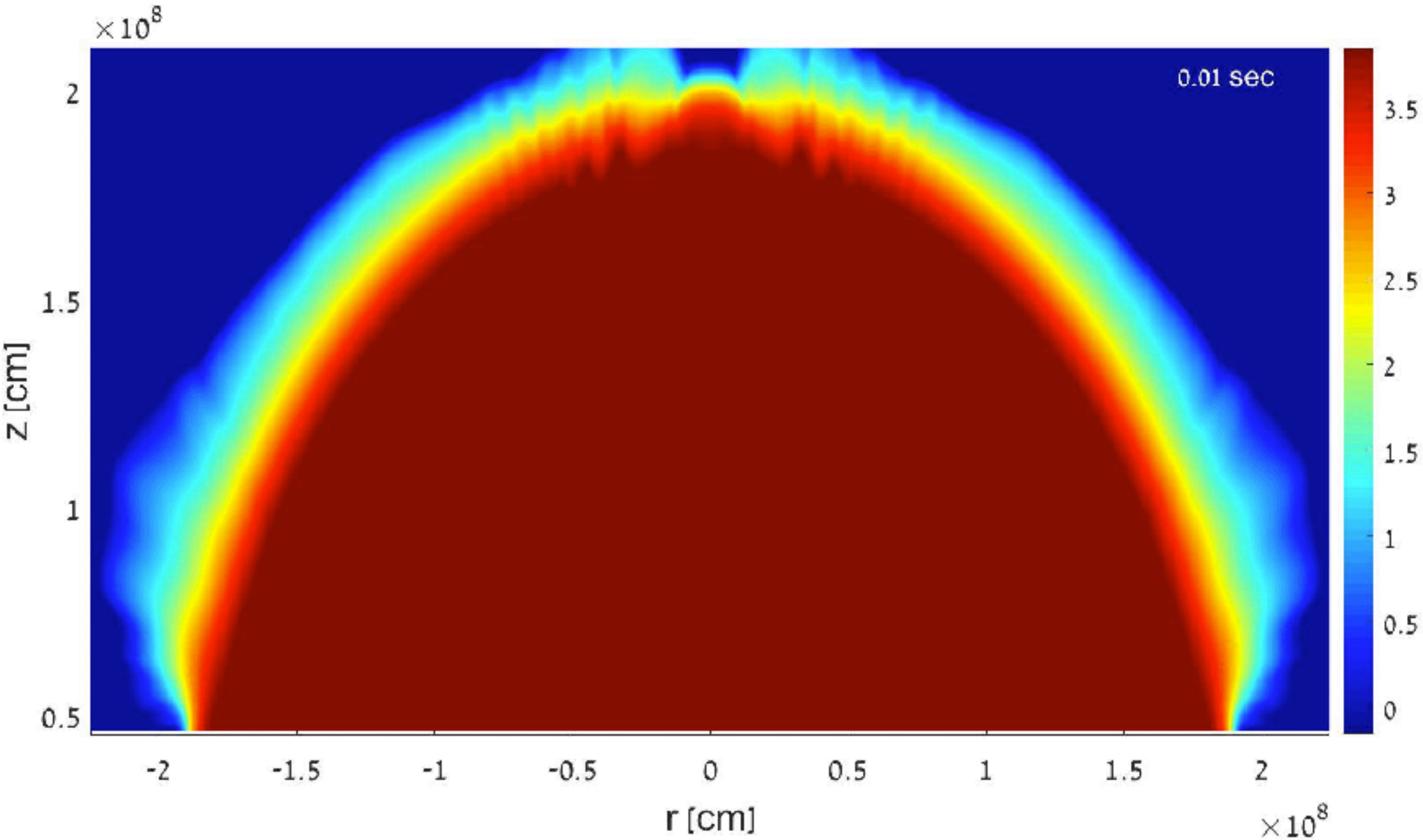


SGRB with a wind velocity of 0.2c. Credit: Ore Gottlieb

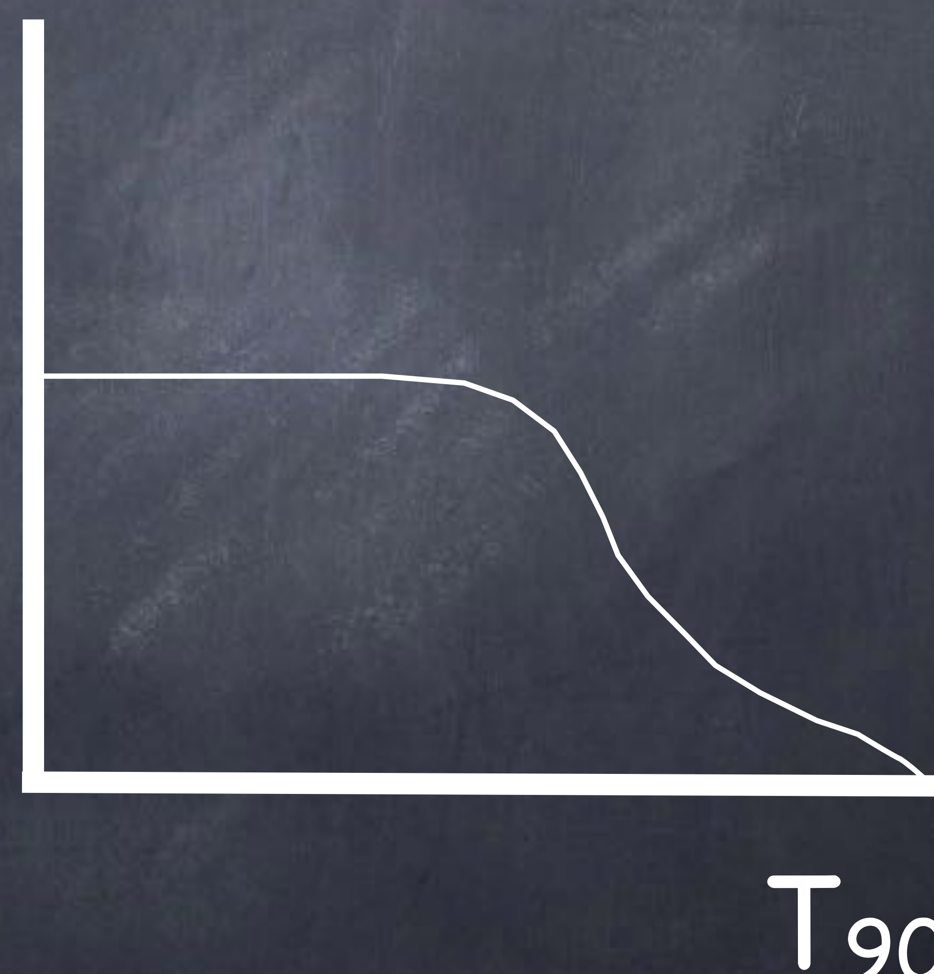
A prediction jet penetration model

Observed duration

$$T_{90} = T_e - T_B$$

Engine time

Break out time



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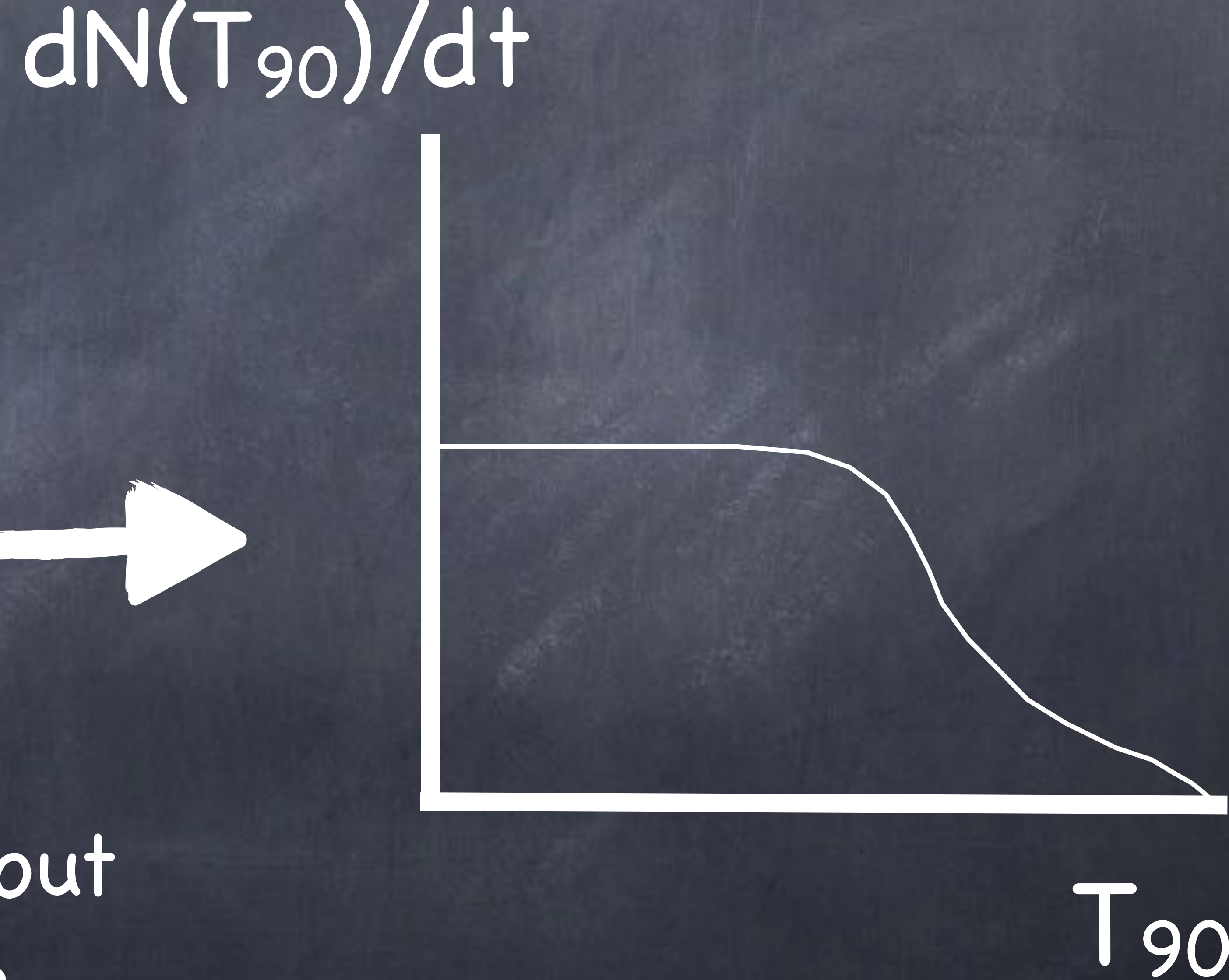

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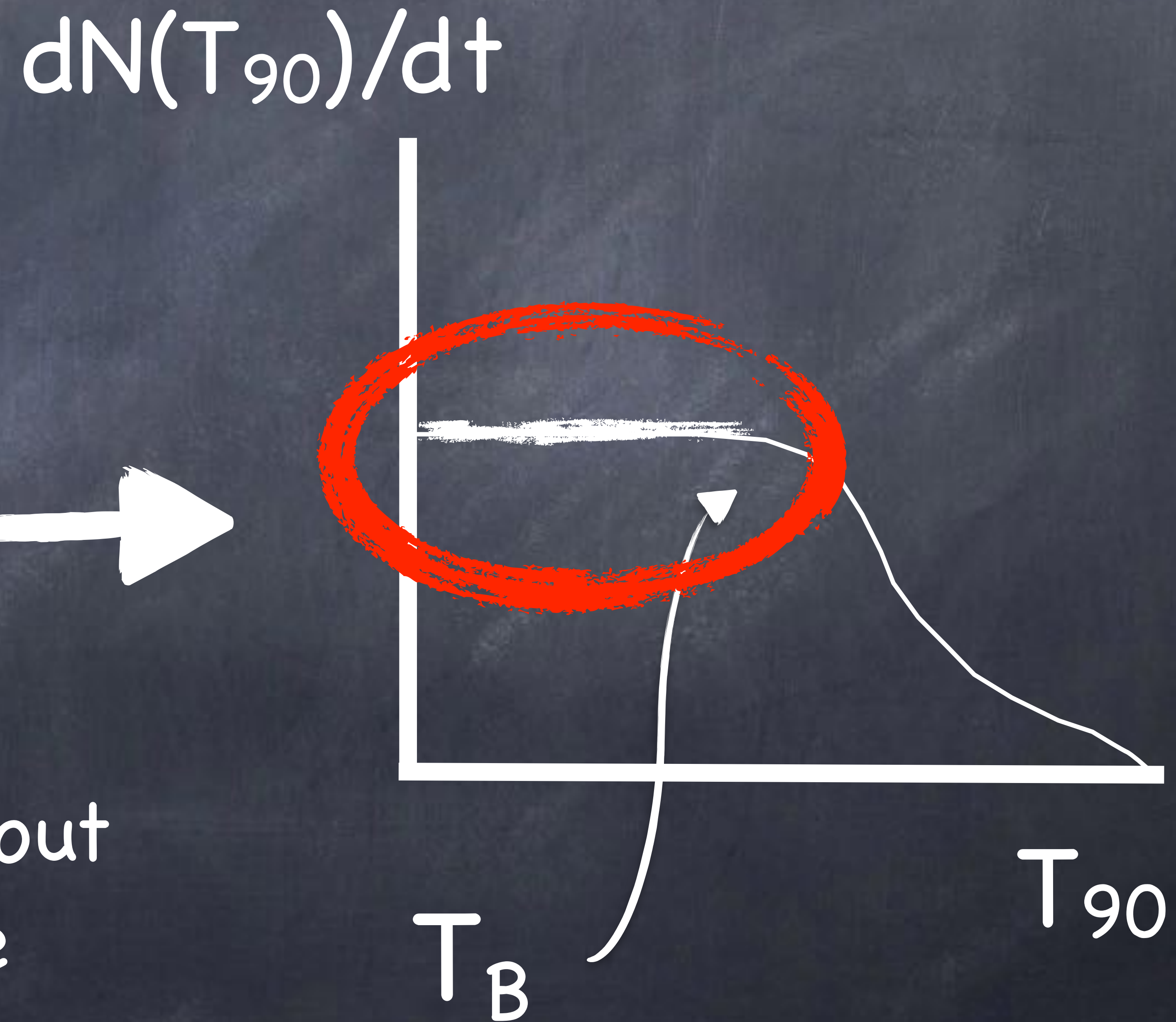
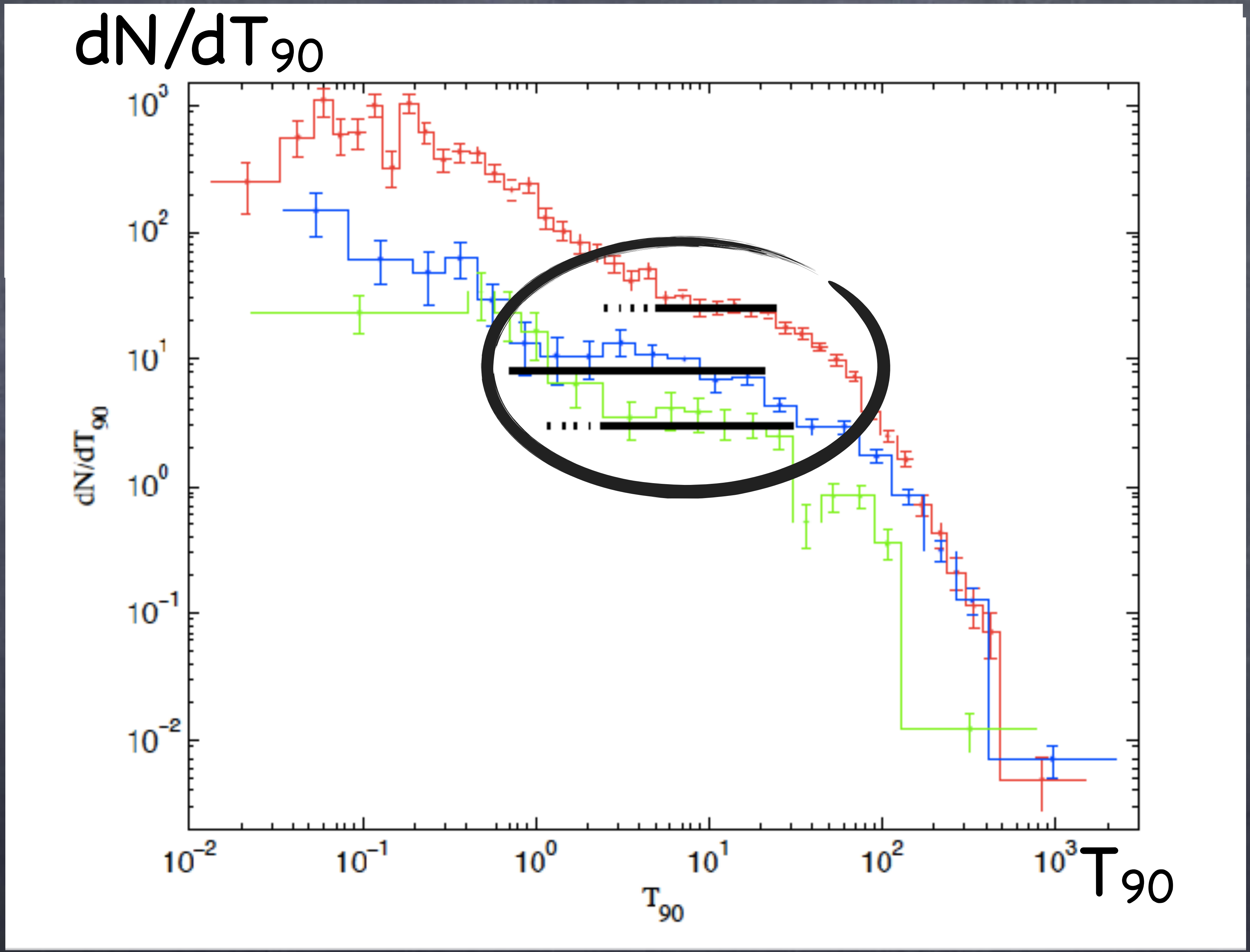


The Collapsar Plateau
(Bromberg Nakar, TP & Sari, 2011)



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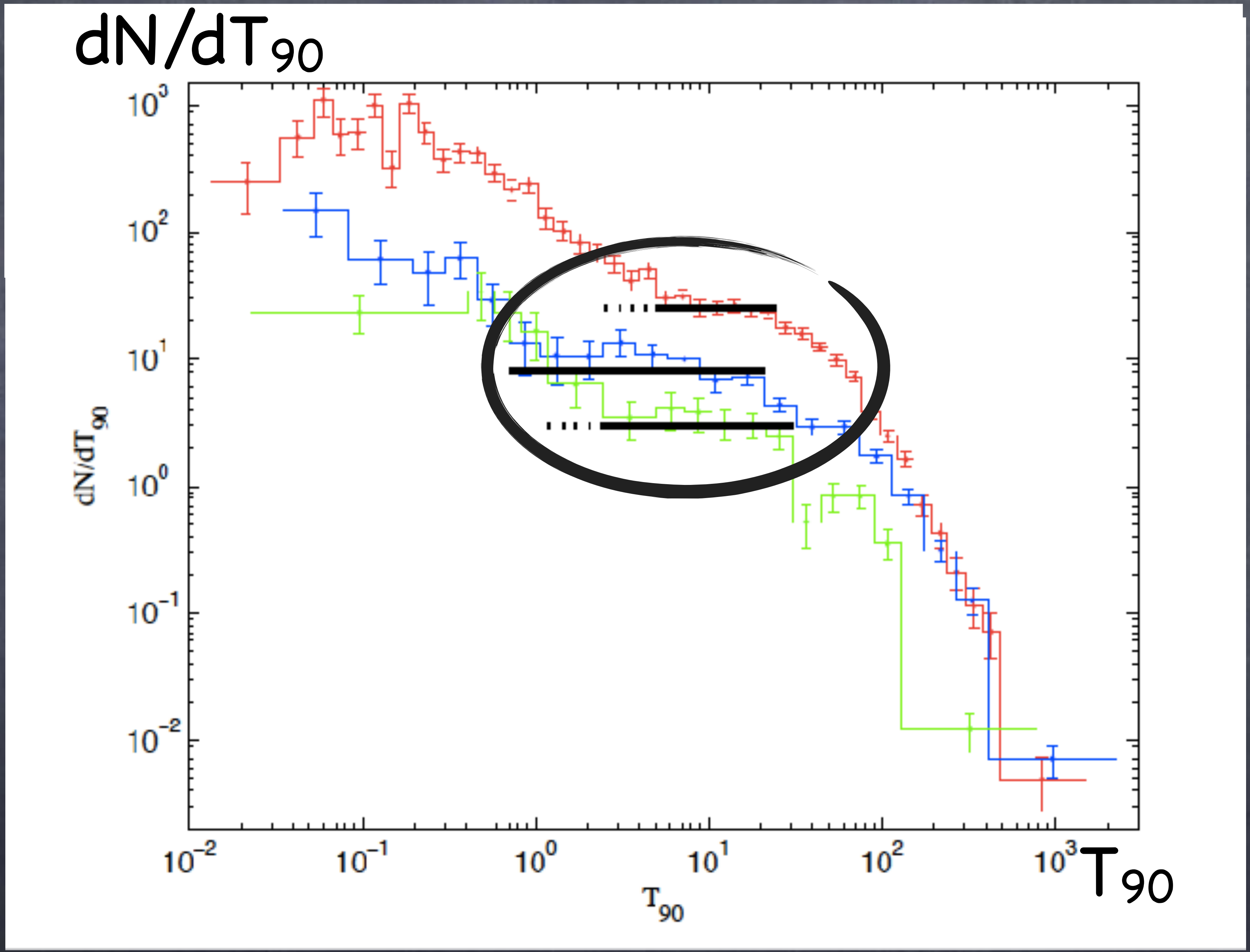
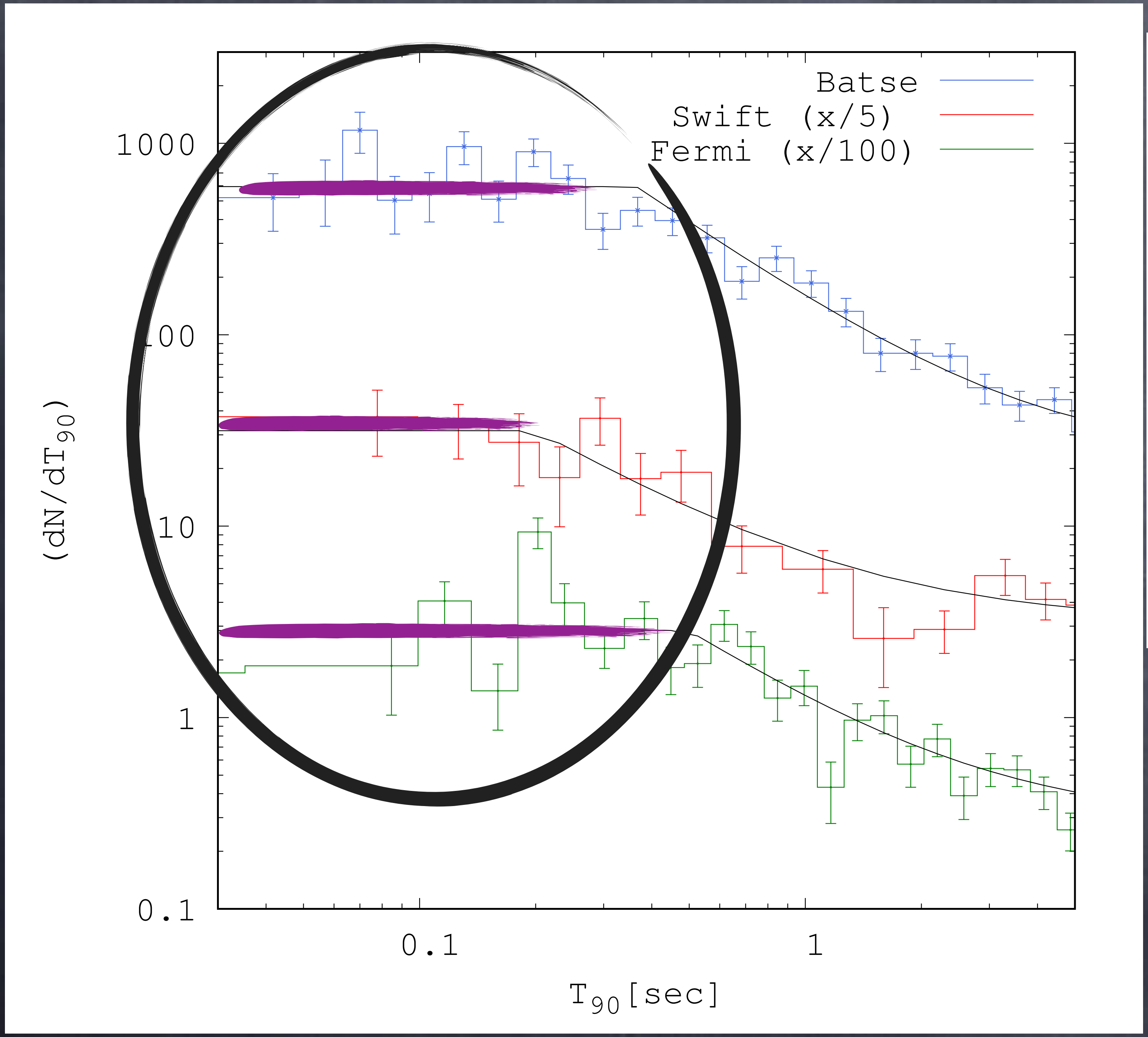
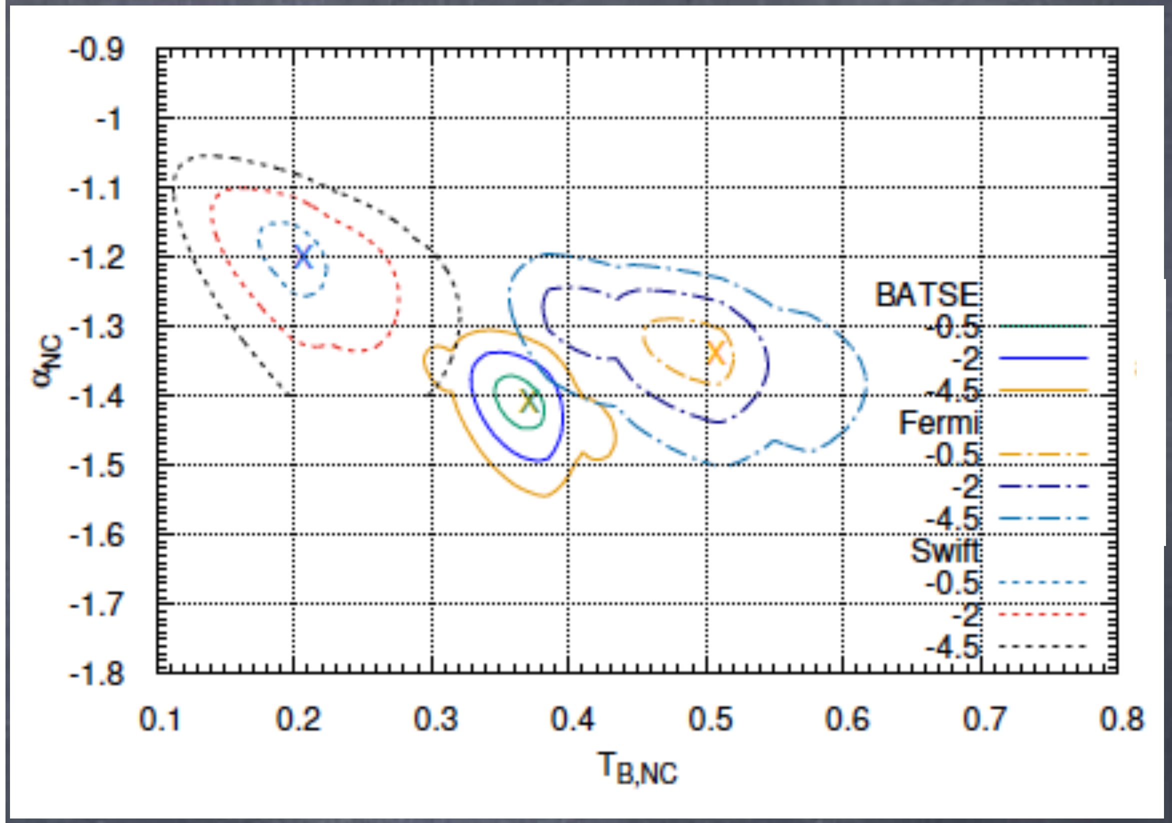


A direct observational proof of the Collapsar model.

The short GRB Plateau

(Moharana, Hotokezaka, Nakar & TP in prep2017)





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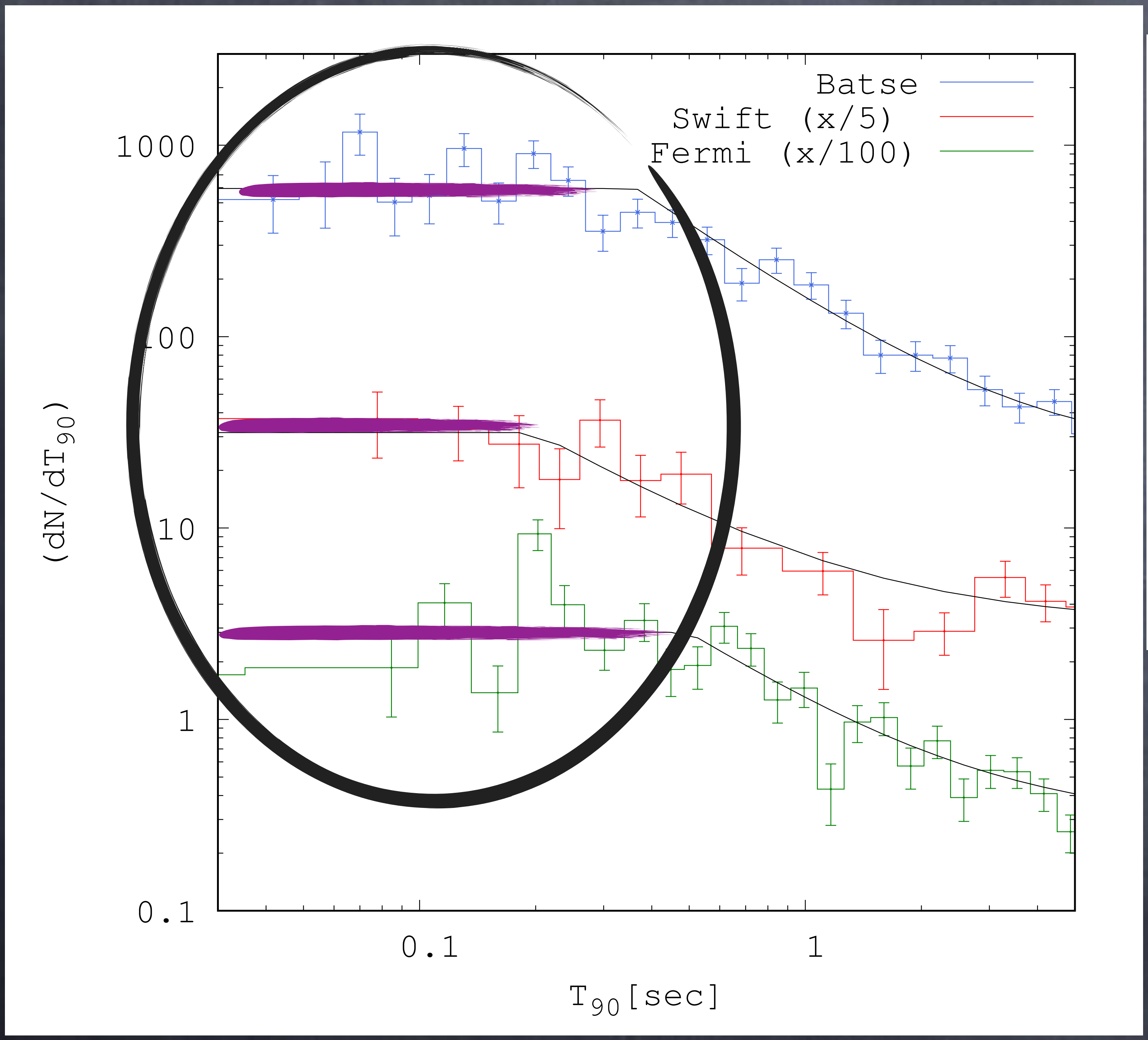
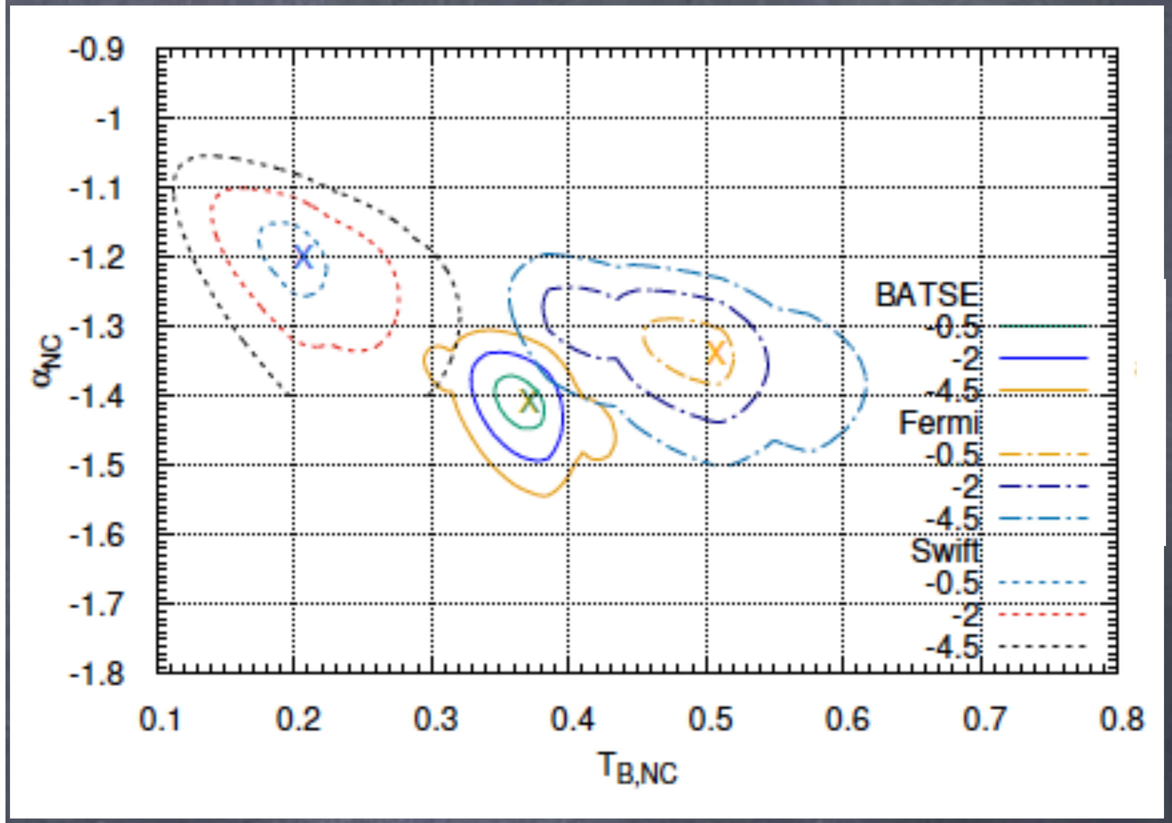




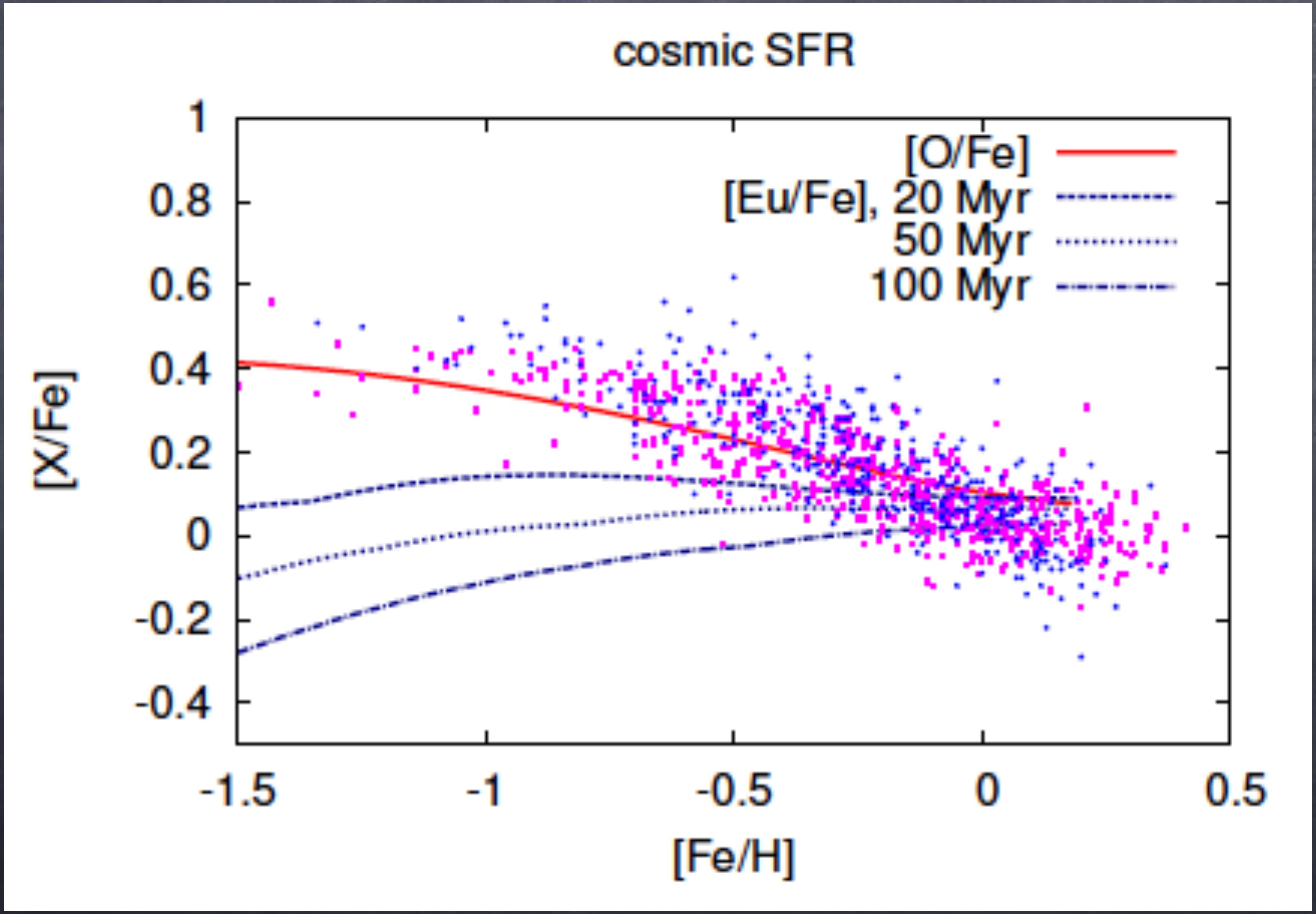
A direct observational evidence for ~0.05 m_{sun} ejecta around sGRB

Chemical Evolution
(Hotokezaka & TP 2017)

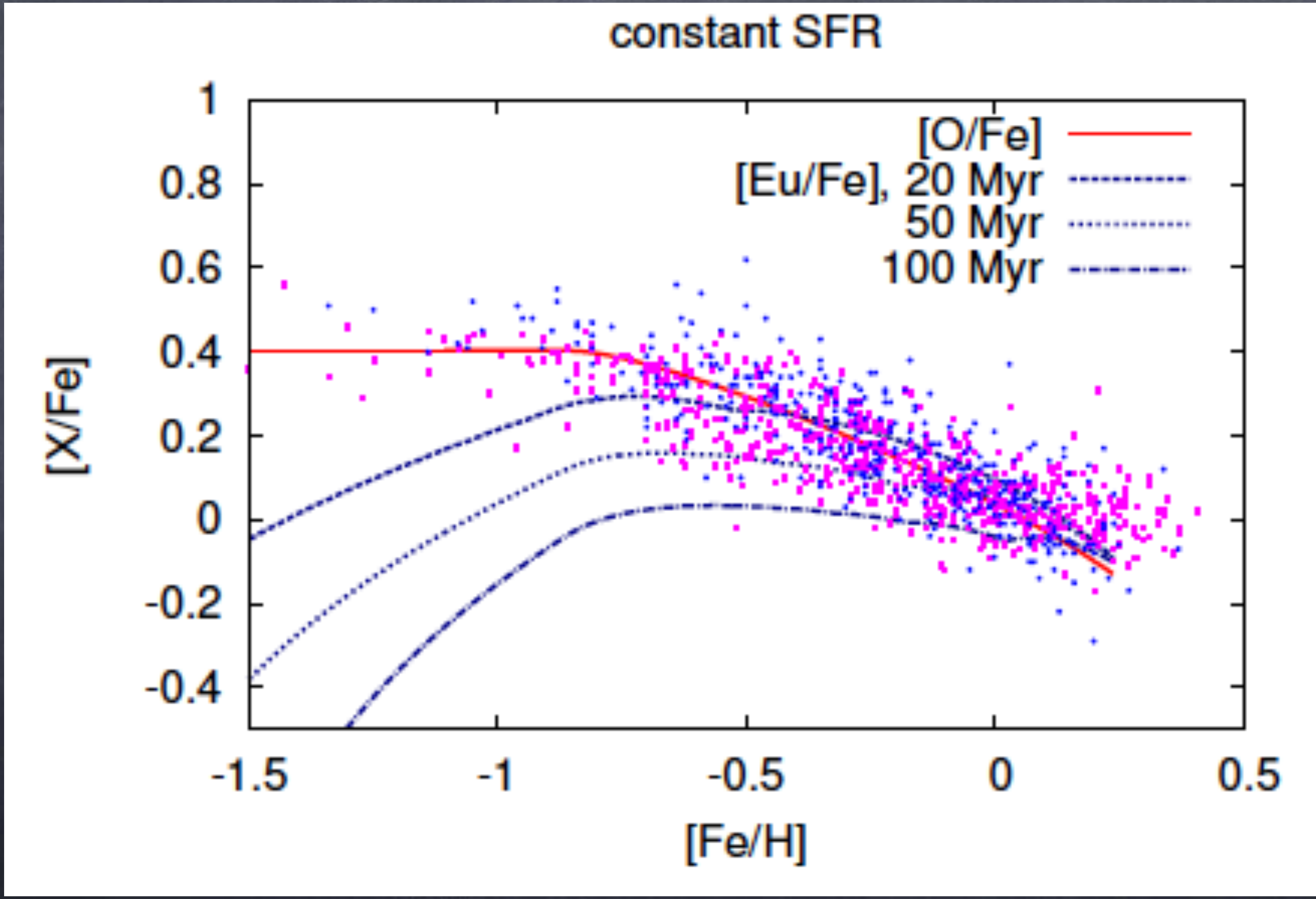
- Galactic low metallicity stars
- Argast + 2004 result ruling mergers is wrong! Unfortunately, they neglected turbulent and rotational mixing. There is good evidence for such mixing over a time scale of 20-100 Myr (from radioactive elements).
- The minimal time delay of a binary mergers is highly uncertain.

The late time evolution puzzle?

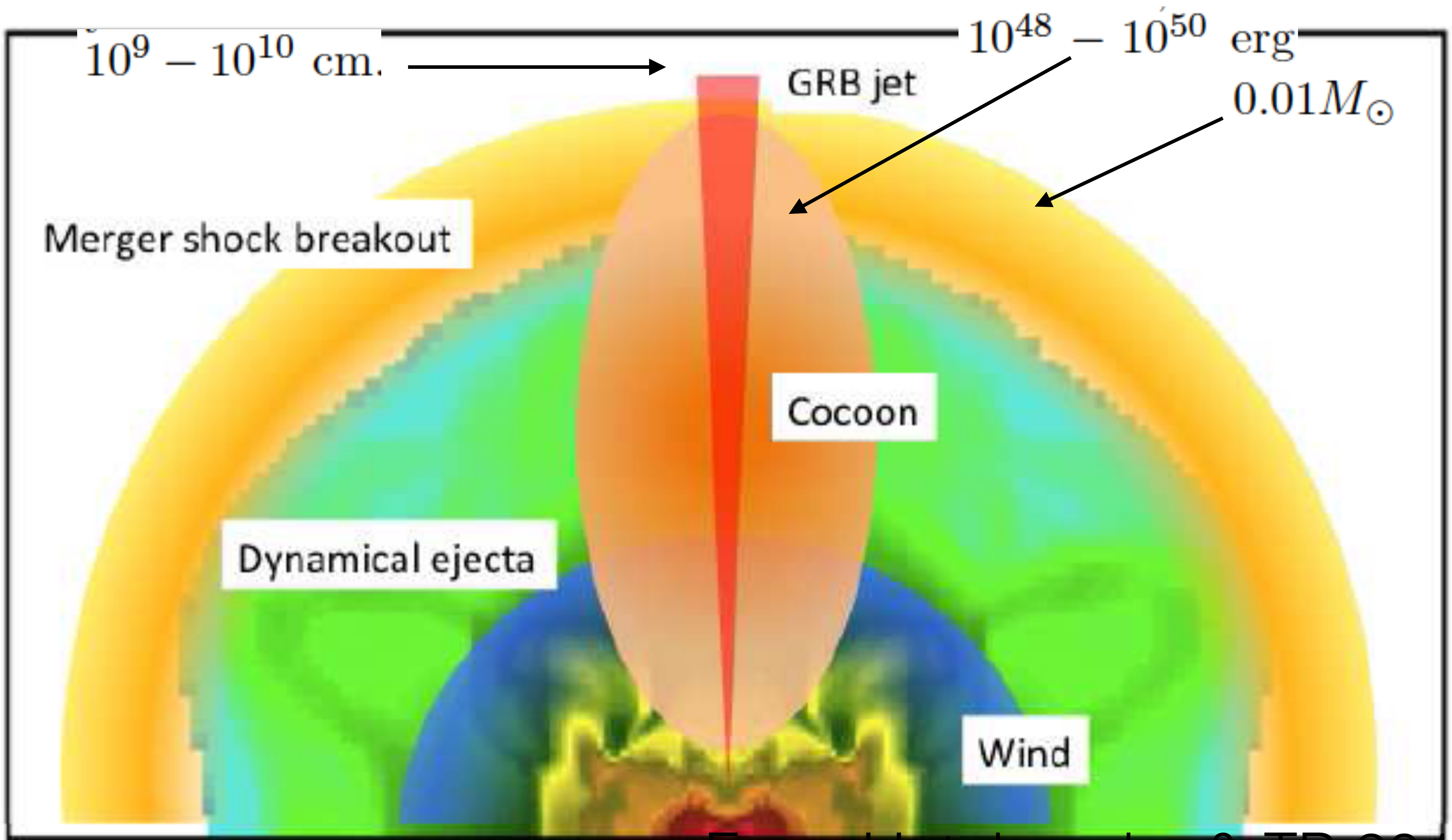
(Hotokezaka & TP 2017)



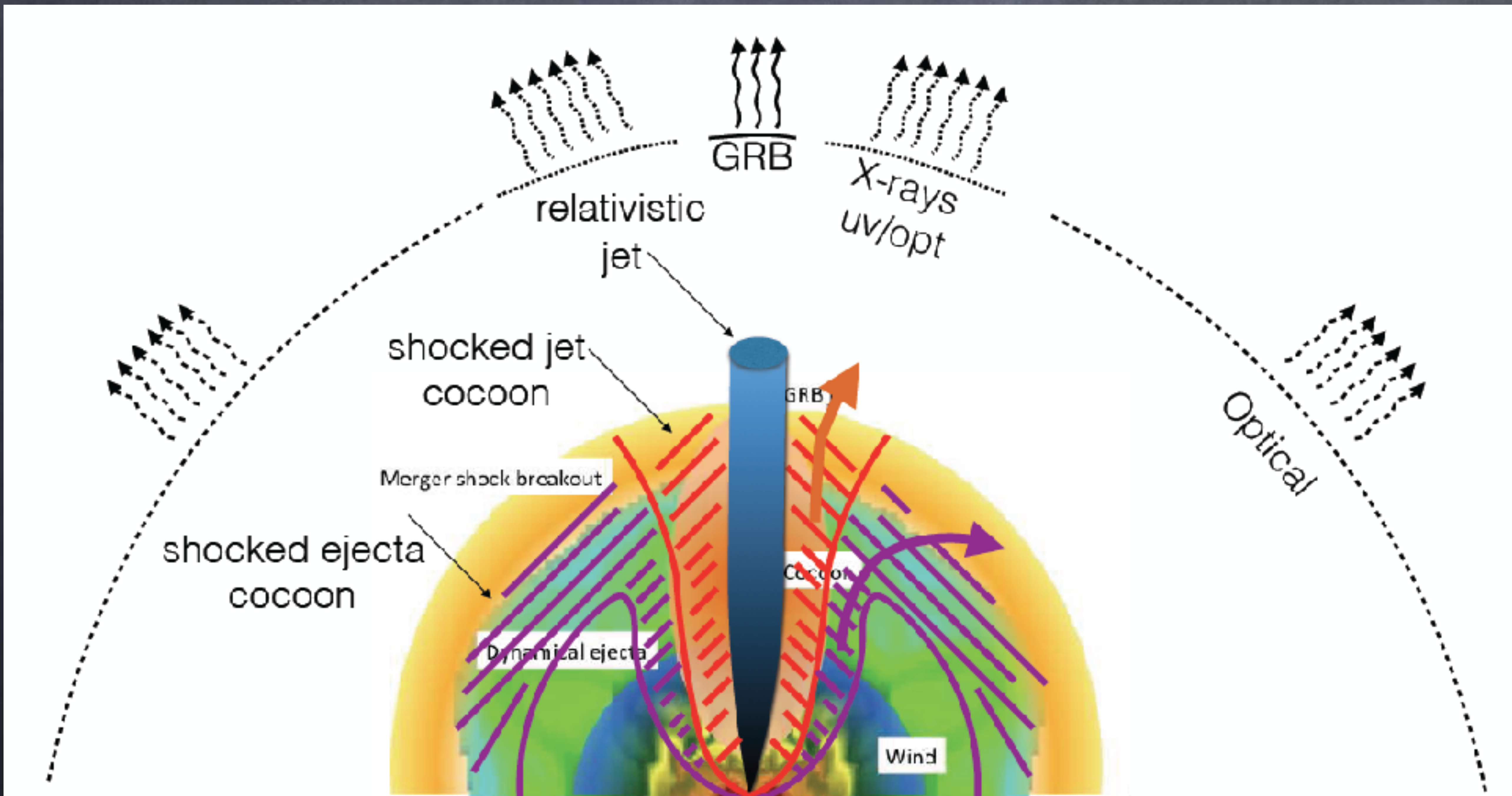
Resolved for a Galactic SFR (Hotokezaka & TP 2017)



Short GRBs Cocoons



From Hotokezaka & TP 2015



Nakar & TP 2017

SGRB cocoon signatures

Rel. Cocoon cooling

$E_c = 10^{50}$ + breakout radius of 10^{10} =>

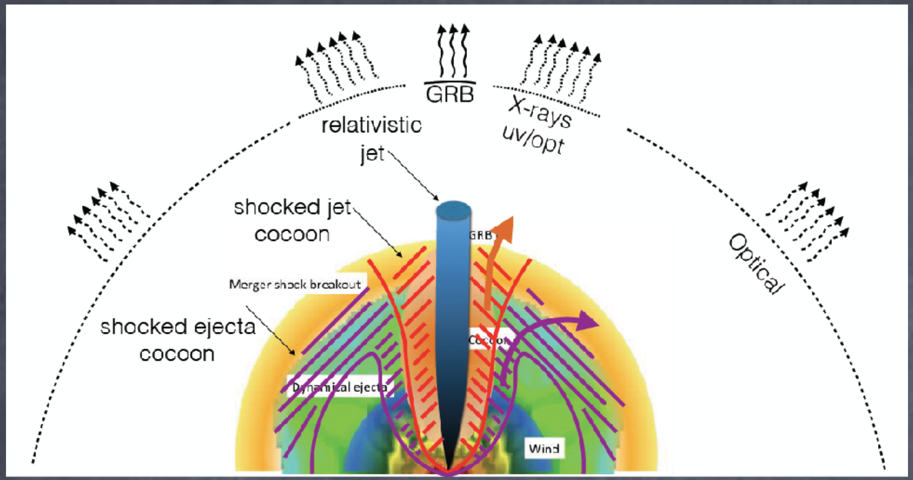
$\sim 10^{41}$ erg/s $\sim 10,000$ K. optical magnitude of about -14.

Rel. Cocoon Afterglow,
scaling from the regular SGRB afterglow

$\sim 10^{41}$ erg/s optical magnitude of about -14.

This is a wide angle signal 0.5 rad is stronger than typical SGRB orphan afterglow

Macronova cocoon signature



Heating due to radioactive decay

$$L_{MN} \sim 4 \times 10^{40}\ E_{49}^{0.325} \theta_{10}^{0.05} M_{ej,-2}^{0.025} \kappa_1^{-0.65} \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \frac{\mathrm{erg}}{\mathrm{s}},$$

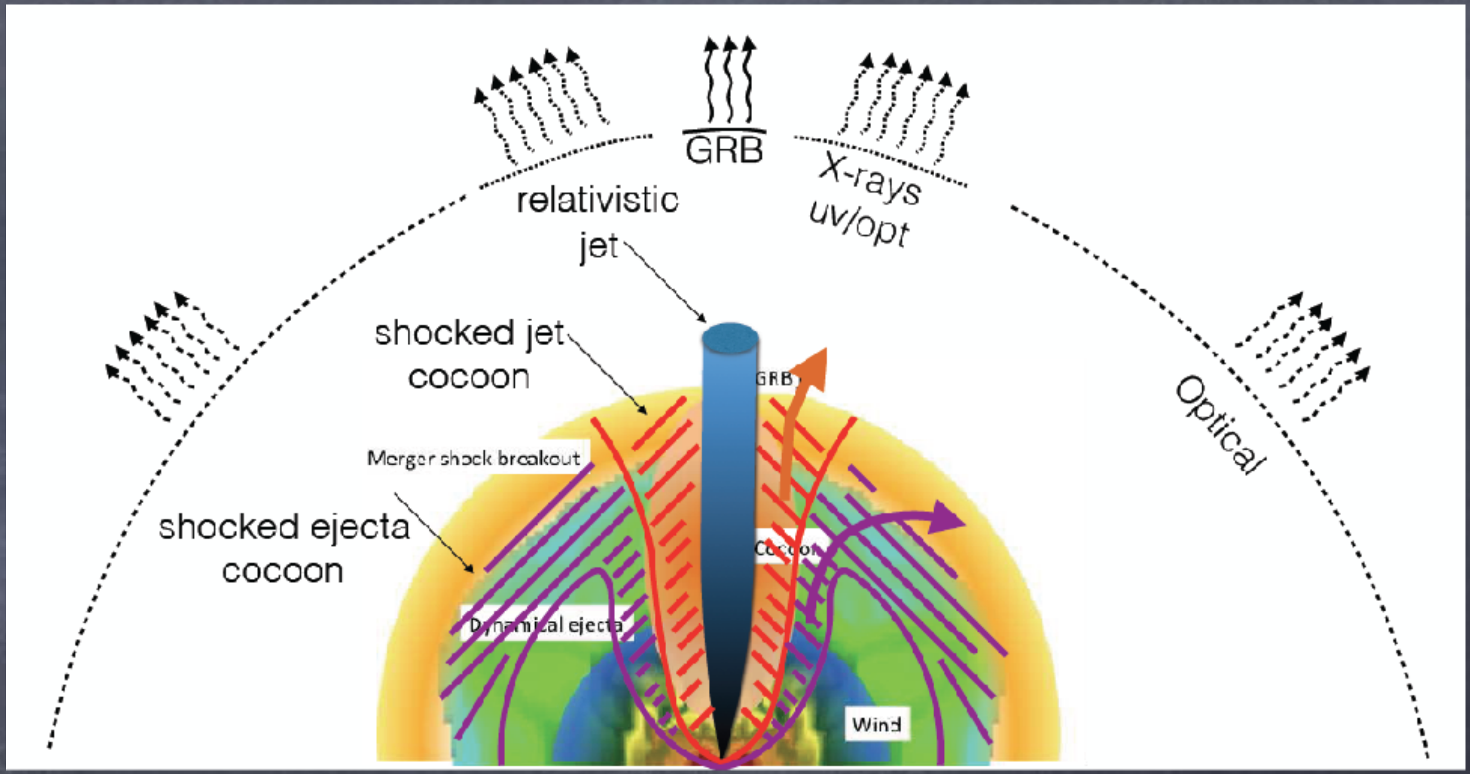
$$\dot{\epsilon}_0 = 10^{10} (t/day)^{-1.3}\ \mathrm{erg/gr/s}.$$

$$T_{MN} \sim 11{,}000\ E_{49}^{-0.04} \theta_{10}^{-0.24} M_{ej,-2}^{-0.12} \kappa_1^{-0.41} \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^{1/4} \mathrm{K}$$

Blue signal at around 0.5-1 day! Brighter or comparable to the classical Macronova

Summary

- Cocoons are the forgotten cousins in the GRB story. They carry a comparable amount of energy to the GRB and are wider than the GRBs.
- Short GRBs have their own cocoons whose signatures might be the best EM counterpart to



The radio - flare (Nakar & Piran 2011)
Testing the Macronova interpretation

A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.

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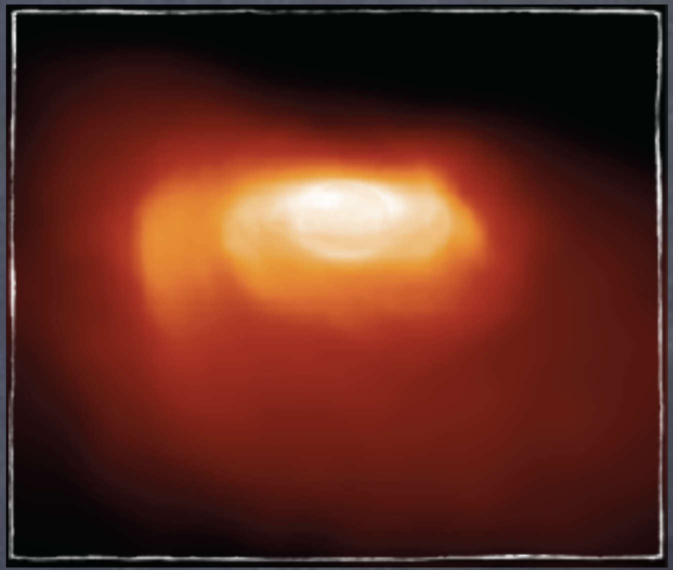

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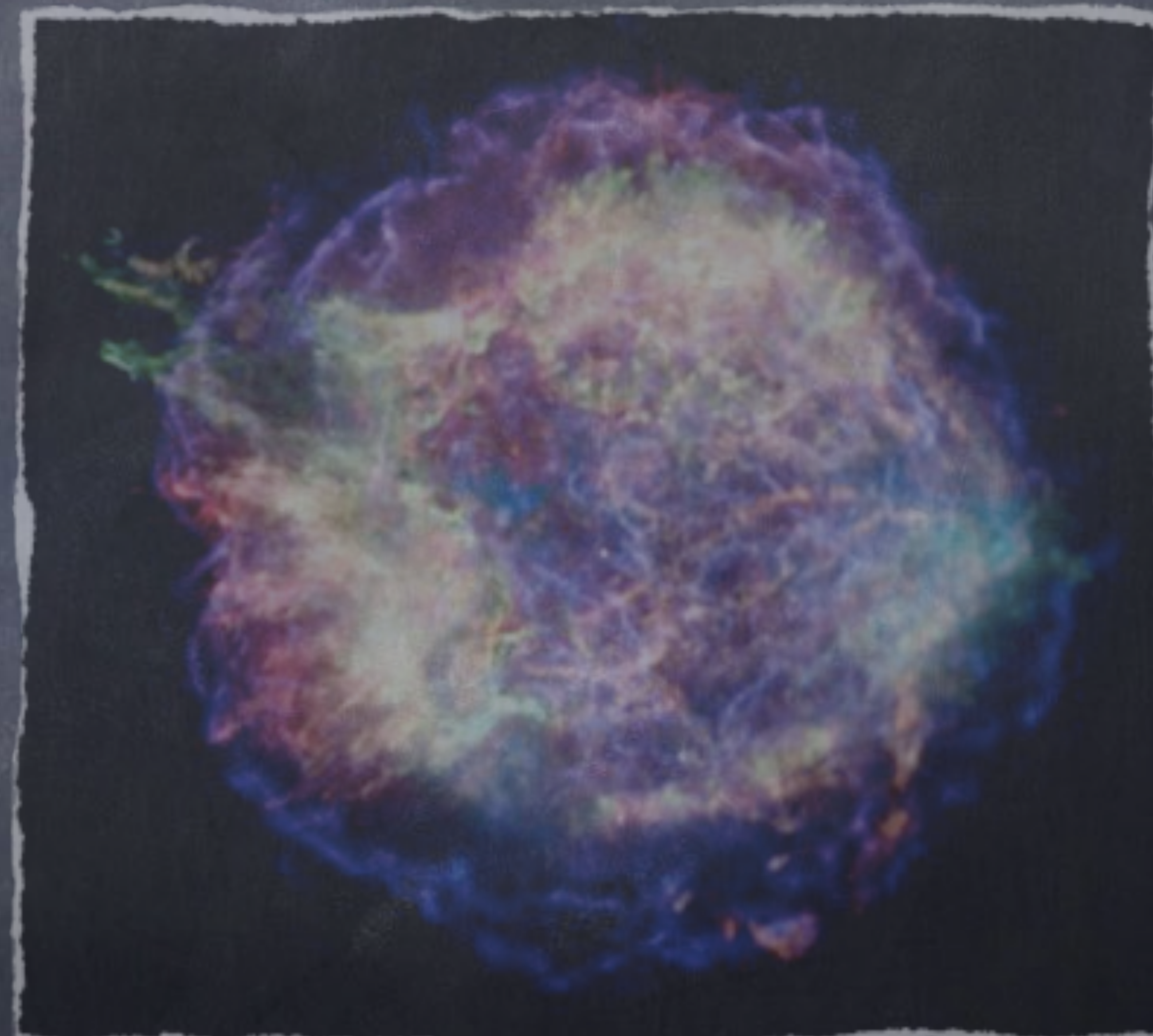

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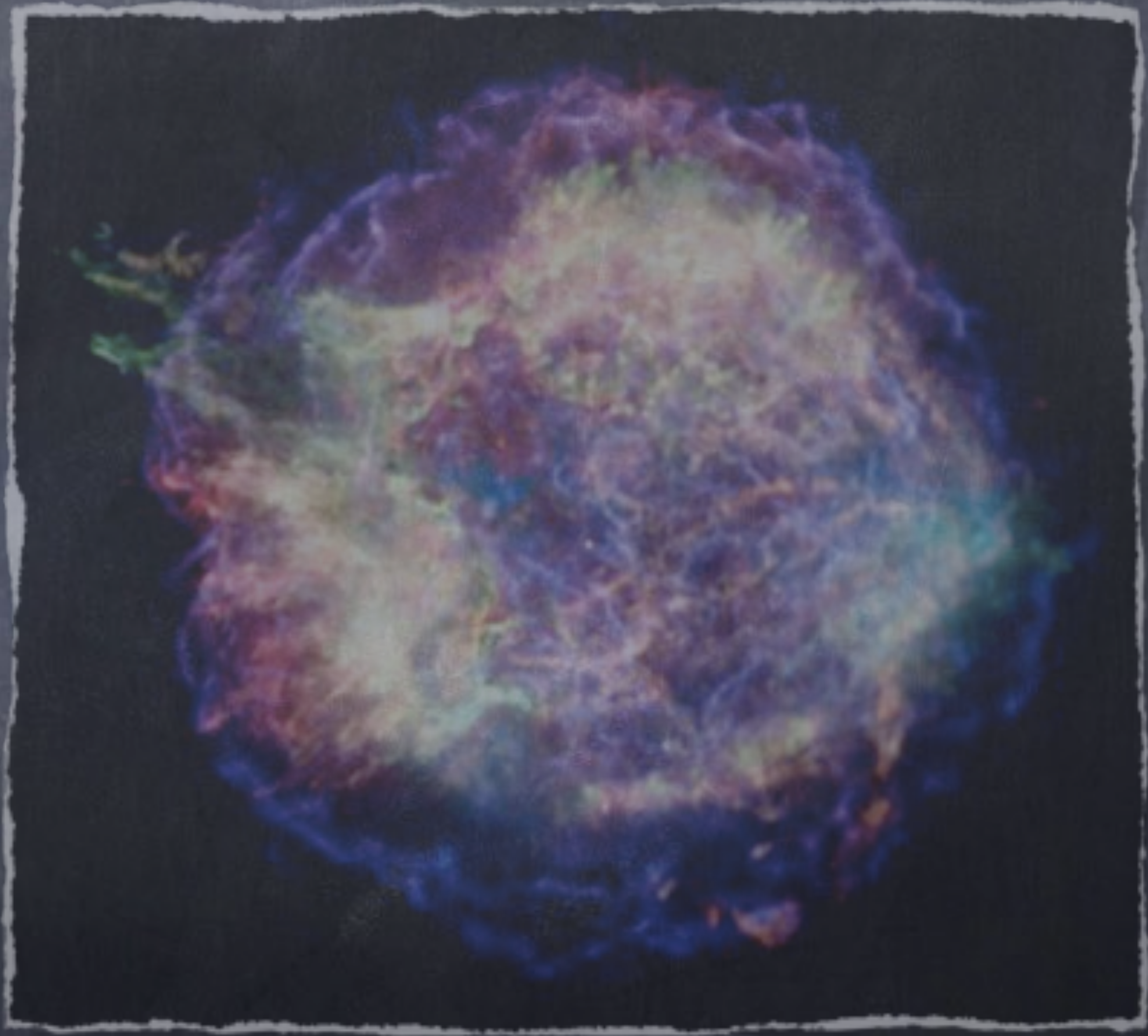

Supernova -> Supernova remnant

GRB -> Afterglow

Macronova -> Radio Flare

Summary

- Ample independent evidence for r-process production in rare events with large yield per event. => SNe 👎 Mergers 👍
- Macronovae ==> Merger - GRBs connection (even with GW).
- nIR Macronovae ==> r-process nucleosynthesis in Mergers.
- Chemical galactic evolution explained if the distribution of mergers time delay begins at ~20 Myr with a constant Galactic SFR

Advertisement - An postdoc opening under my TReX ERC!

Search for the flare from GRB 130603B by the EVLA

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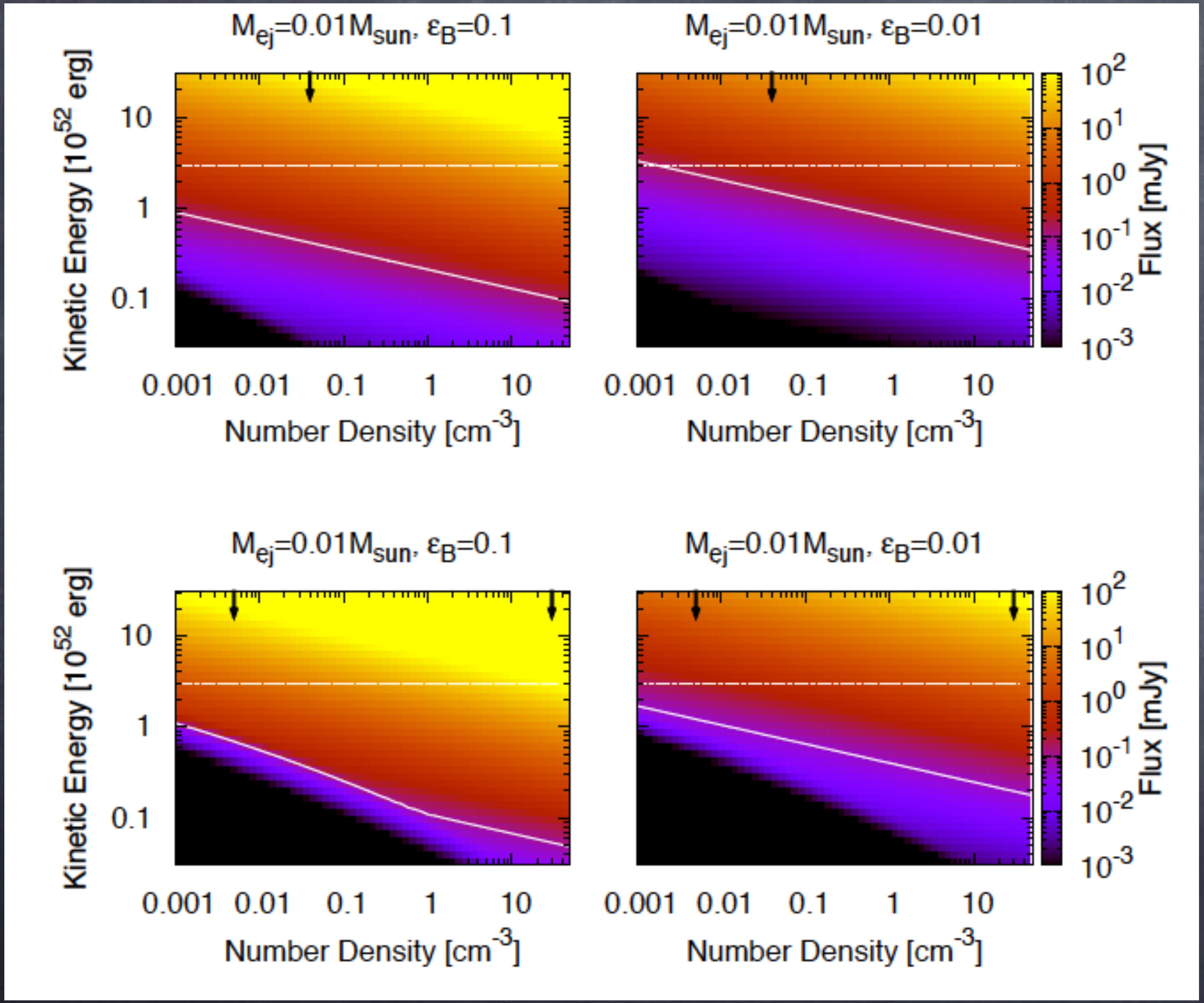
Radio limits on Magnetars



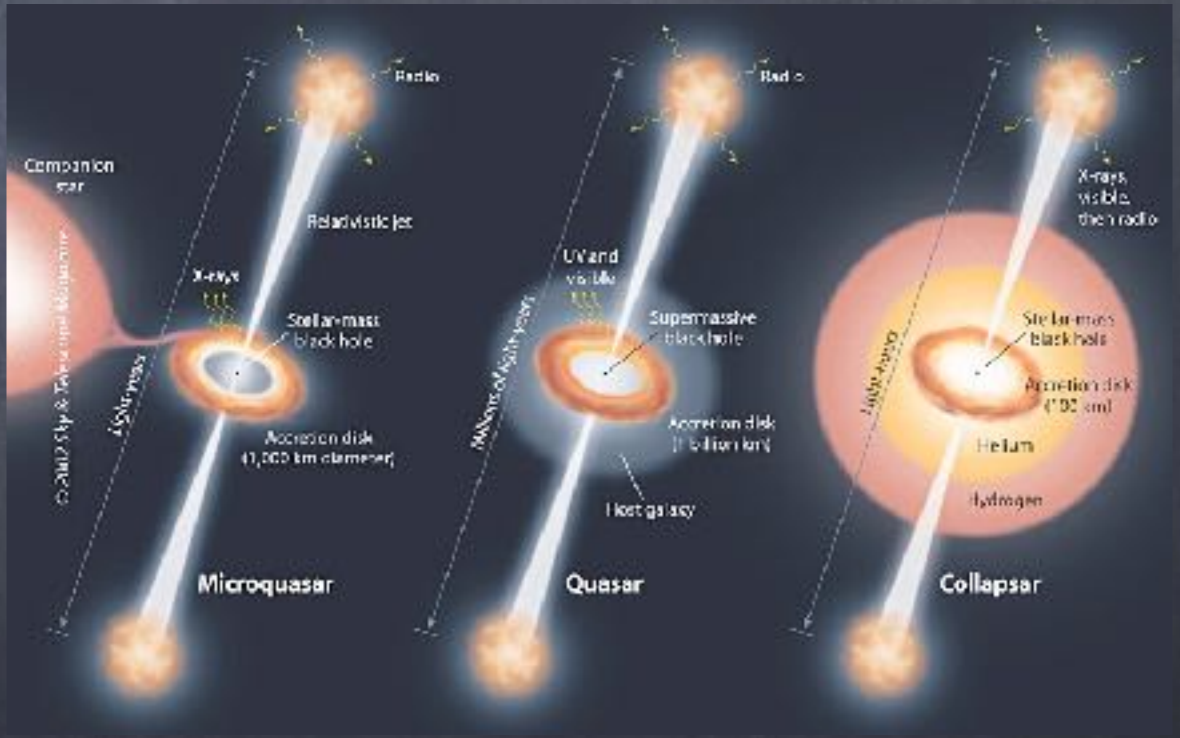
060614

130603B

Horesh + 16

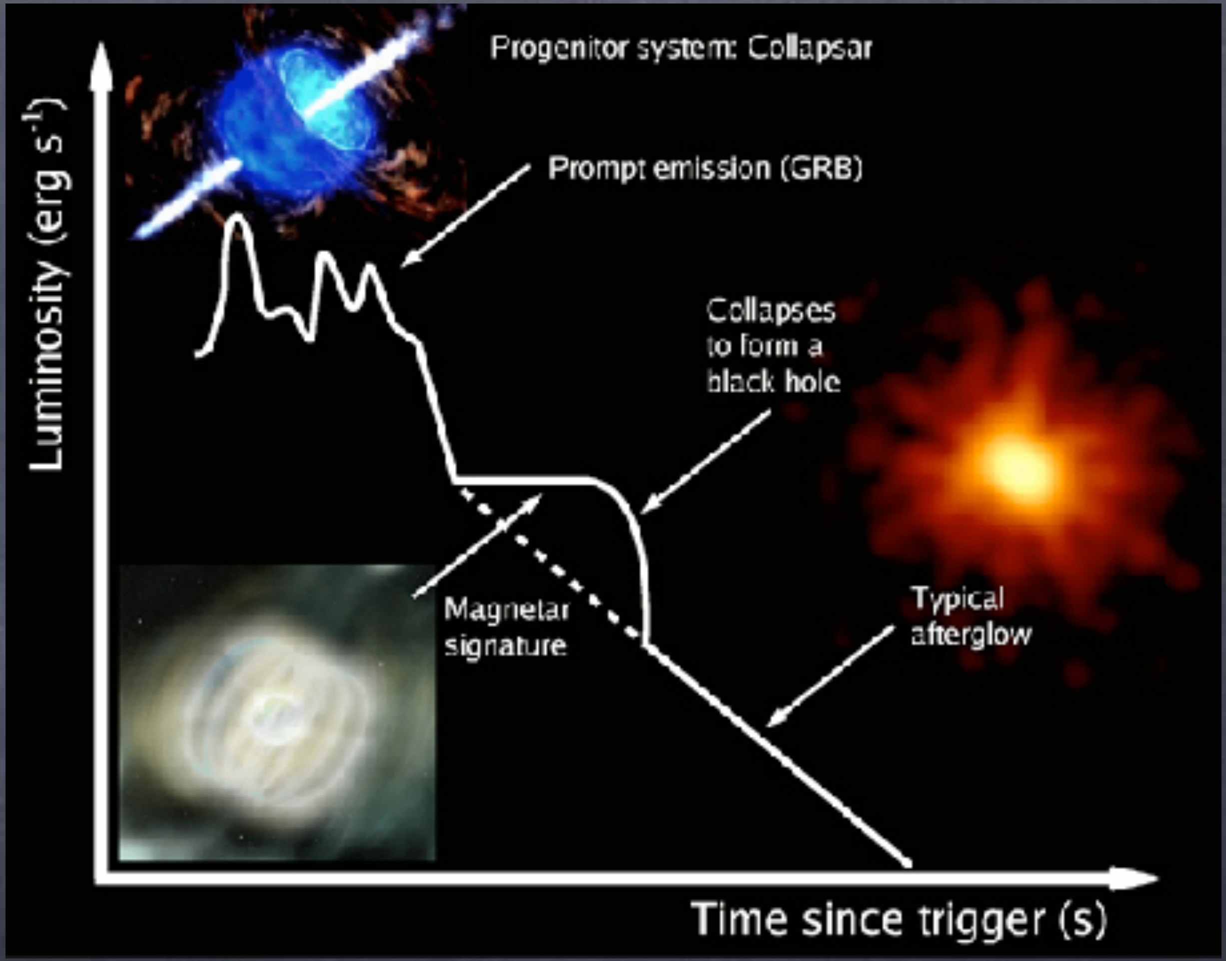
Do GRBs need magnetars?

- Quasars eject magnetic jets.
- => GRBs also have magnetic jets => Mangetars
- But quasars produce magnetic jets without magnetars



Where?

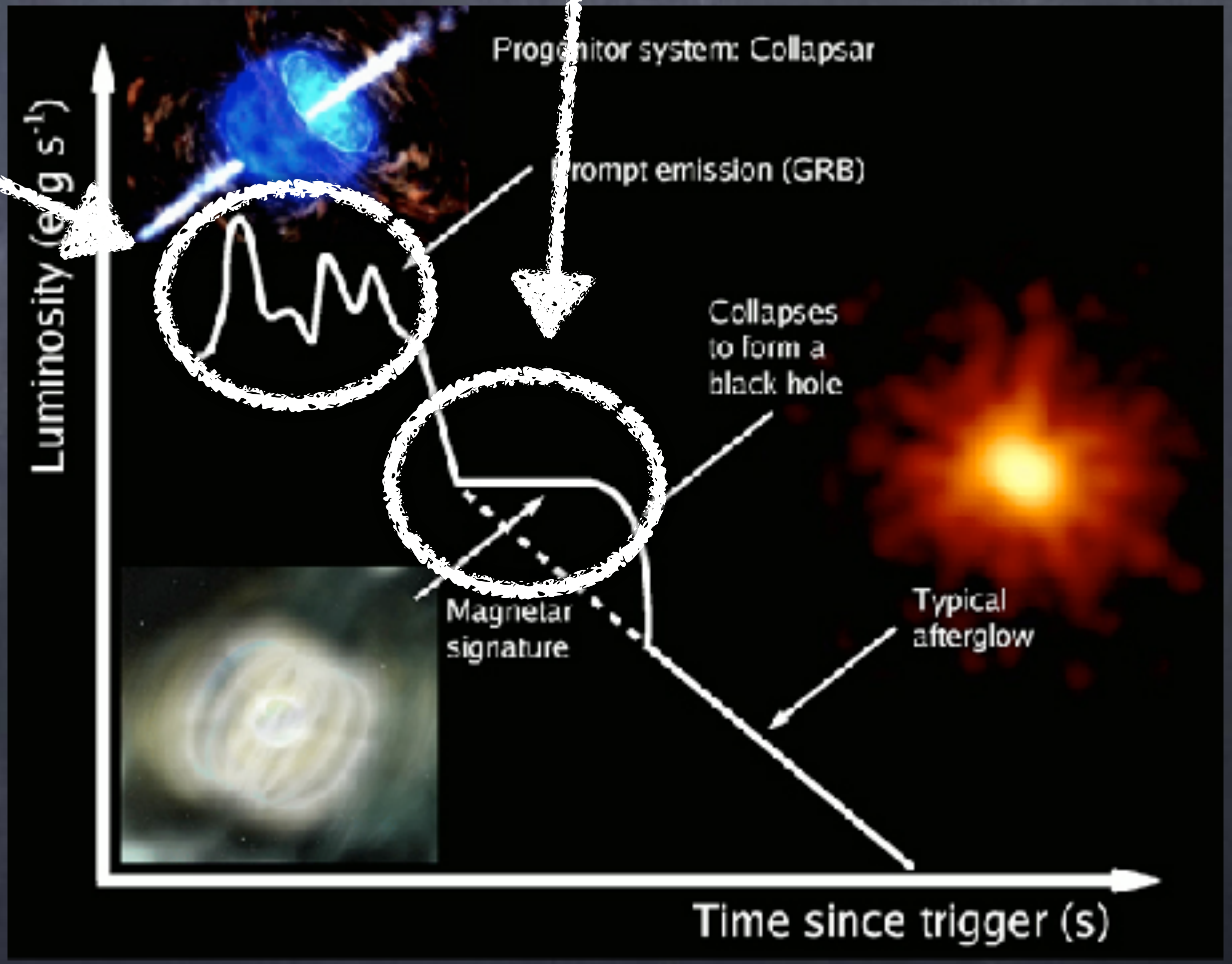
- Prompt?
- Afterglow?



Is impossible to have both from the same magnetar?

If a magnetar did this

What did that?



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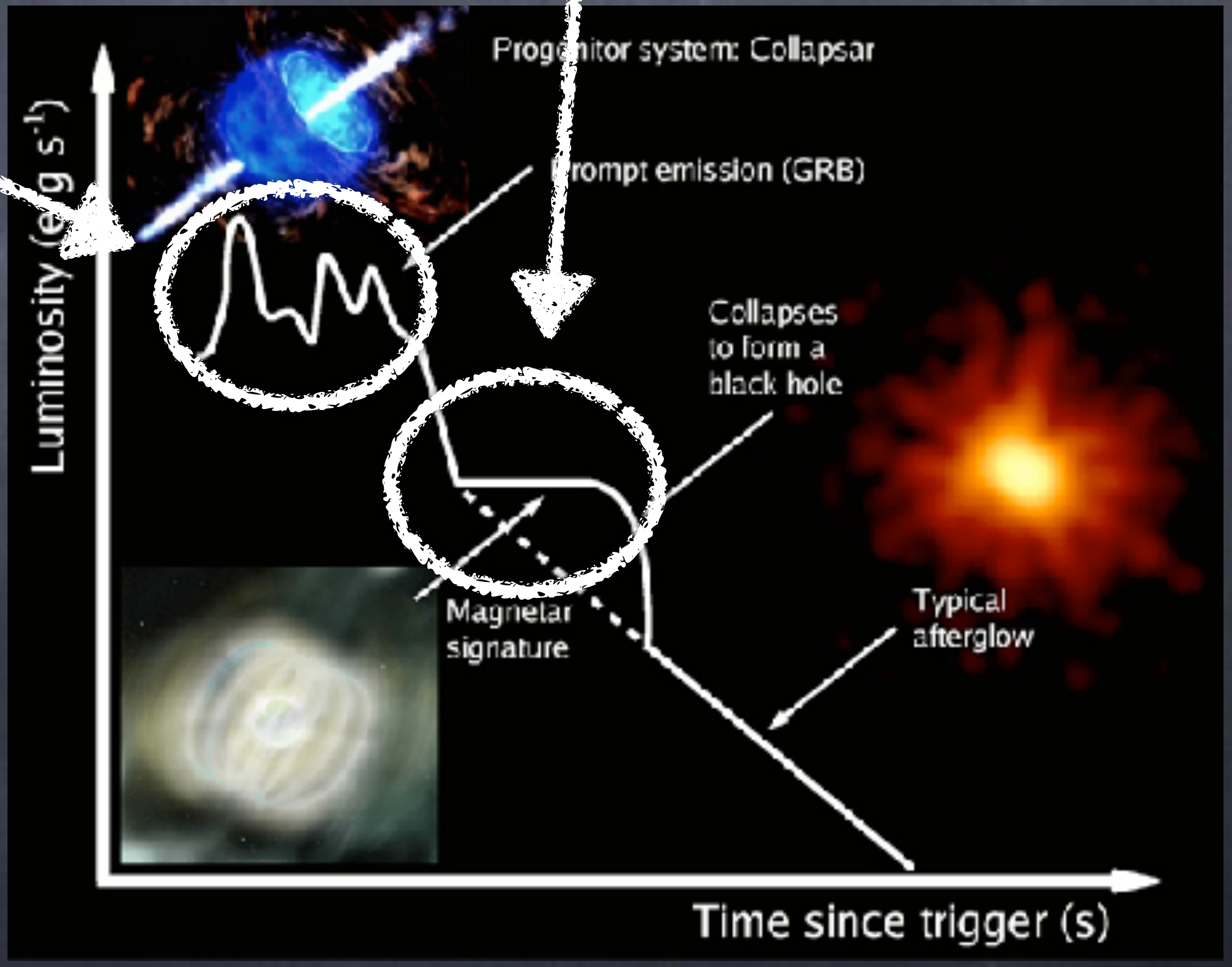
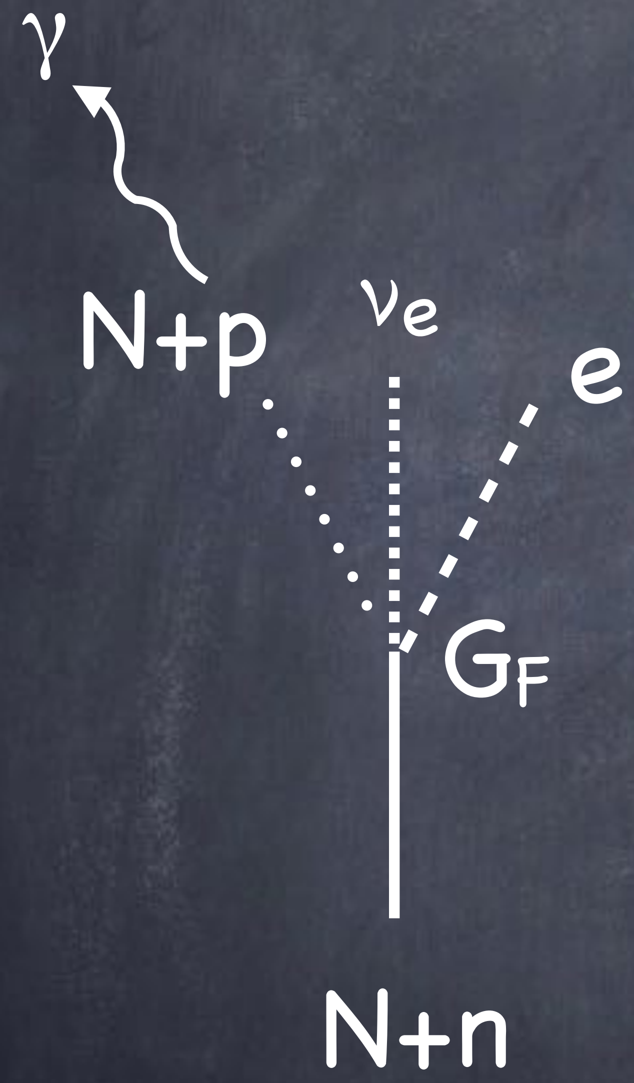


Energy Generation

Hotokezaka, Sari & TP + 16



$$t_f = \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 10^4 sec$$

$$\dot{E} = \epsilon_e \frac{m_e c^2}{t_f}\left(\frac{t}{t_F}\right)^{-\alpha}$$

$$\frac{1}{\tau} \propto \frac{d}{dE}\int d^3p_e \int d^3p_\nu$$

E^3 or $E^{3/2}$ E^3

Relativistic $\quad \frac{1}{\tau} \propto E^5 \quad \rightarrow \alpha = 6/5$

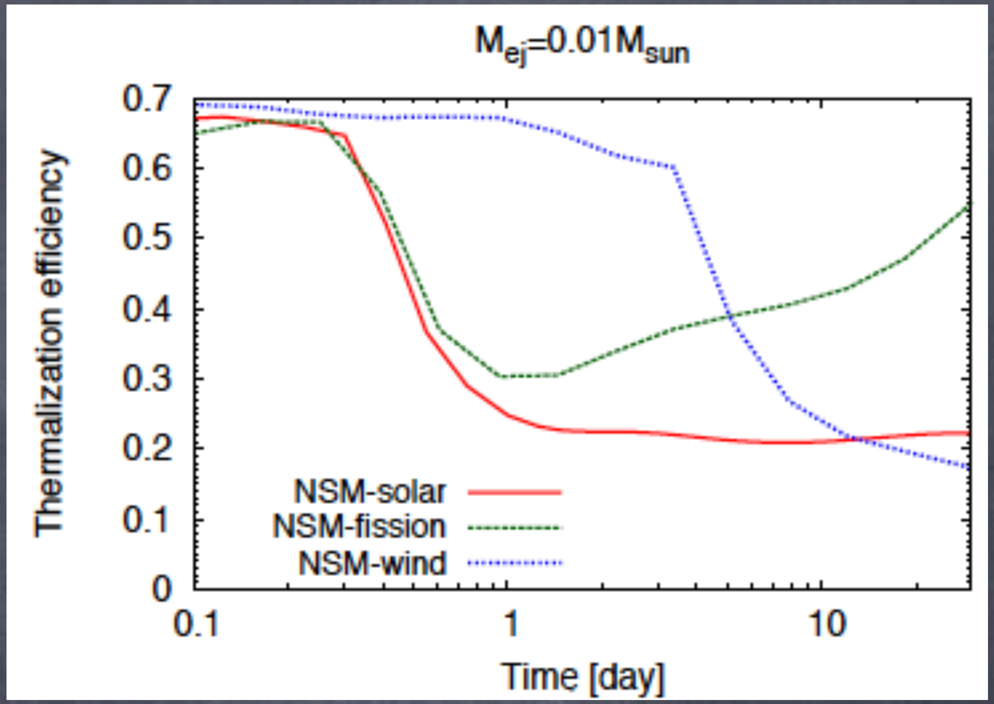
Newtonian $\quad \frac{1}{\tau} \propto E^{7/2} \quad \rightarrow \alpha = 9/7$

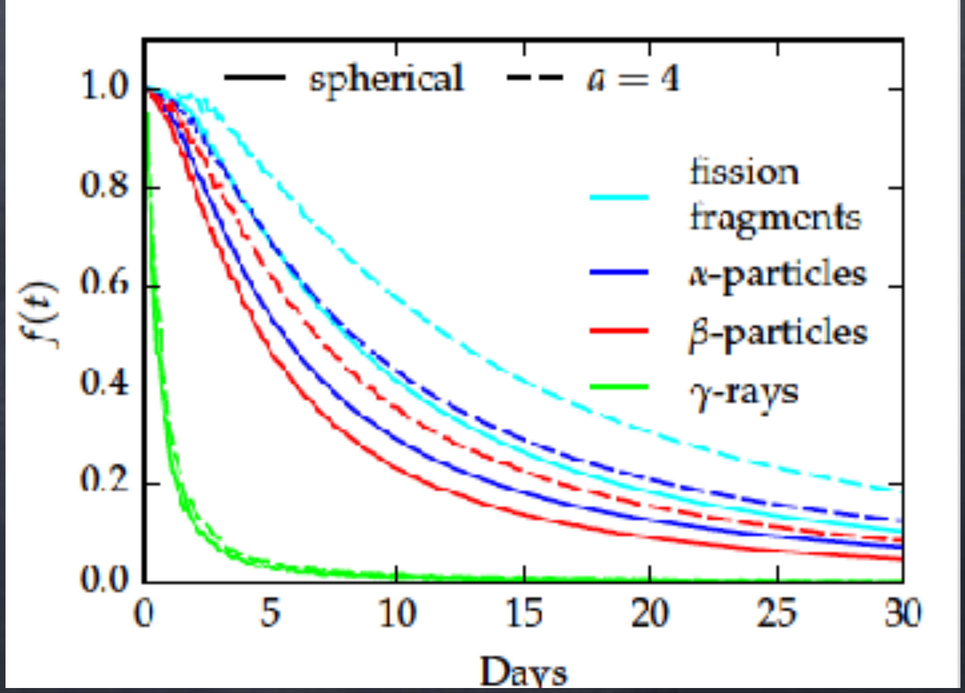
Efficiency

Hotokezaka, Wajano +...TP 16; Barnes +

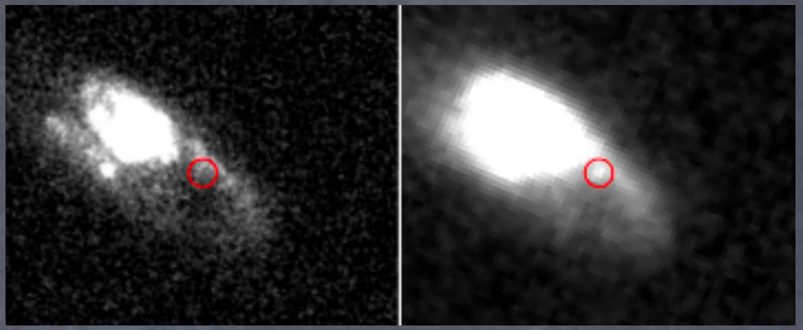
- Photon losses: The ejecta becomes optically thin to gamma-rays long before it becomes optically thin to optical/IR photons => photon leakage during the macronova peak (Hotokezaka + 16)

- Electron losses: Unlike previous believes not all the electrons energy is deposited (Barnes + 16)





Summary



- The nIR flare that followed the short GRB 130603B could have been a Macronova. If so than:
  - ✓ Short GRBs arise from mergers.
  - ✓ Gold and other A>130 elemets are produced in mergers. (But large m_{ej}).

- A radio flare may confirm this!
- A second & third Macronovae suggest a BH-NS merger
- ^{244}Pu suggests that R-process production is in rare events.

- Cocoon produces a short bright macronova
- We wait for the sGRB-GW coincidence

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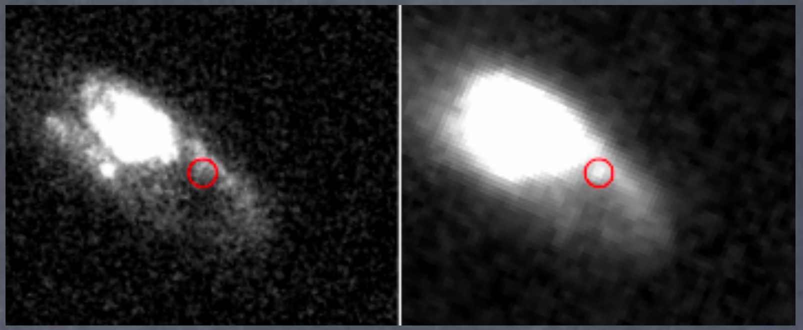

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