Mergers, Gamma-Ray Bursts and Gold

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The Hebrew University

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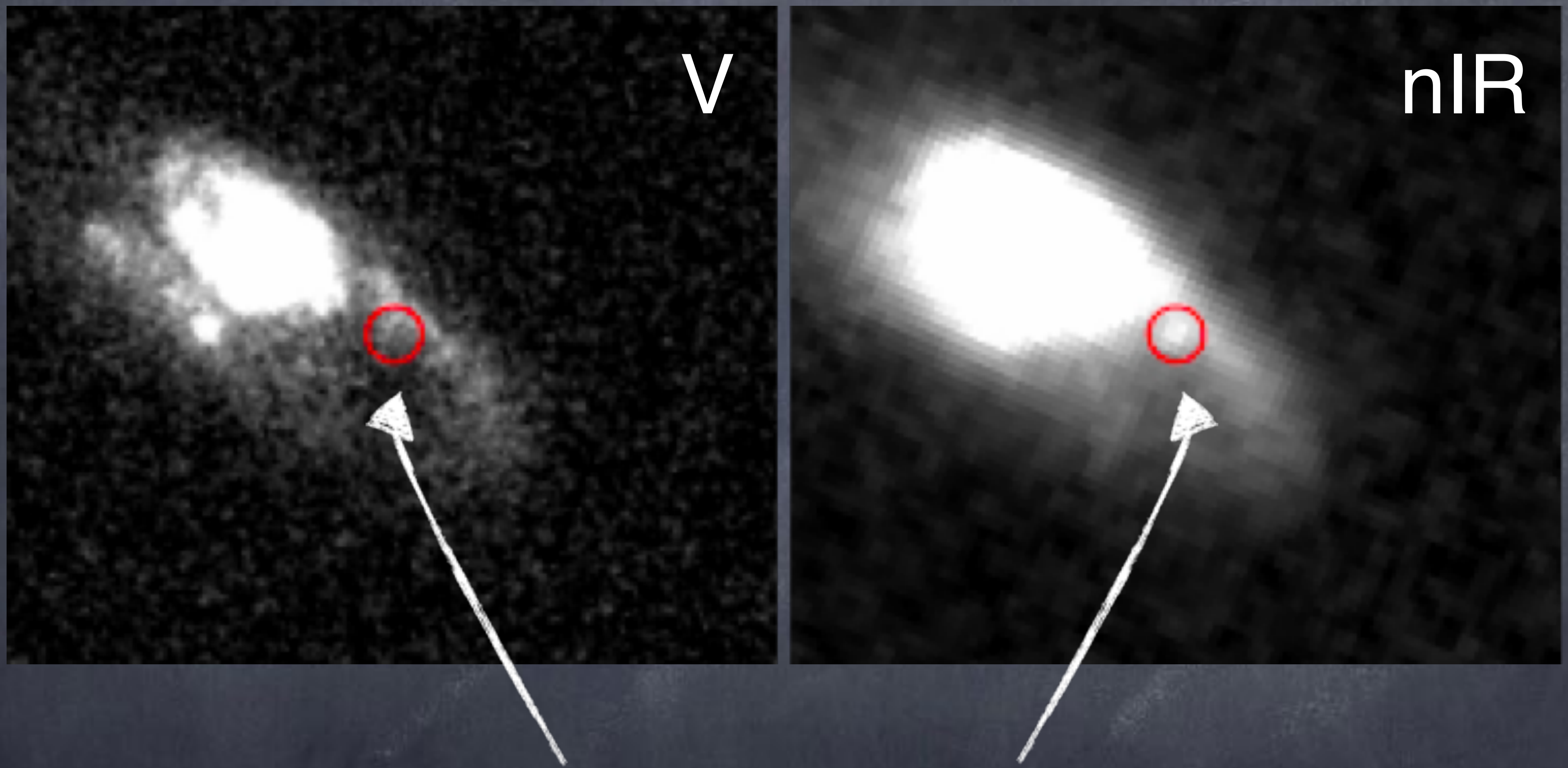
The Hubble Space Telescope June 13th 2013

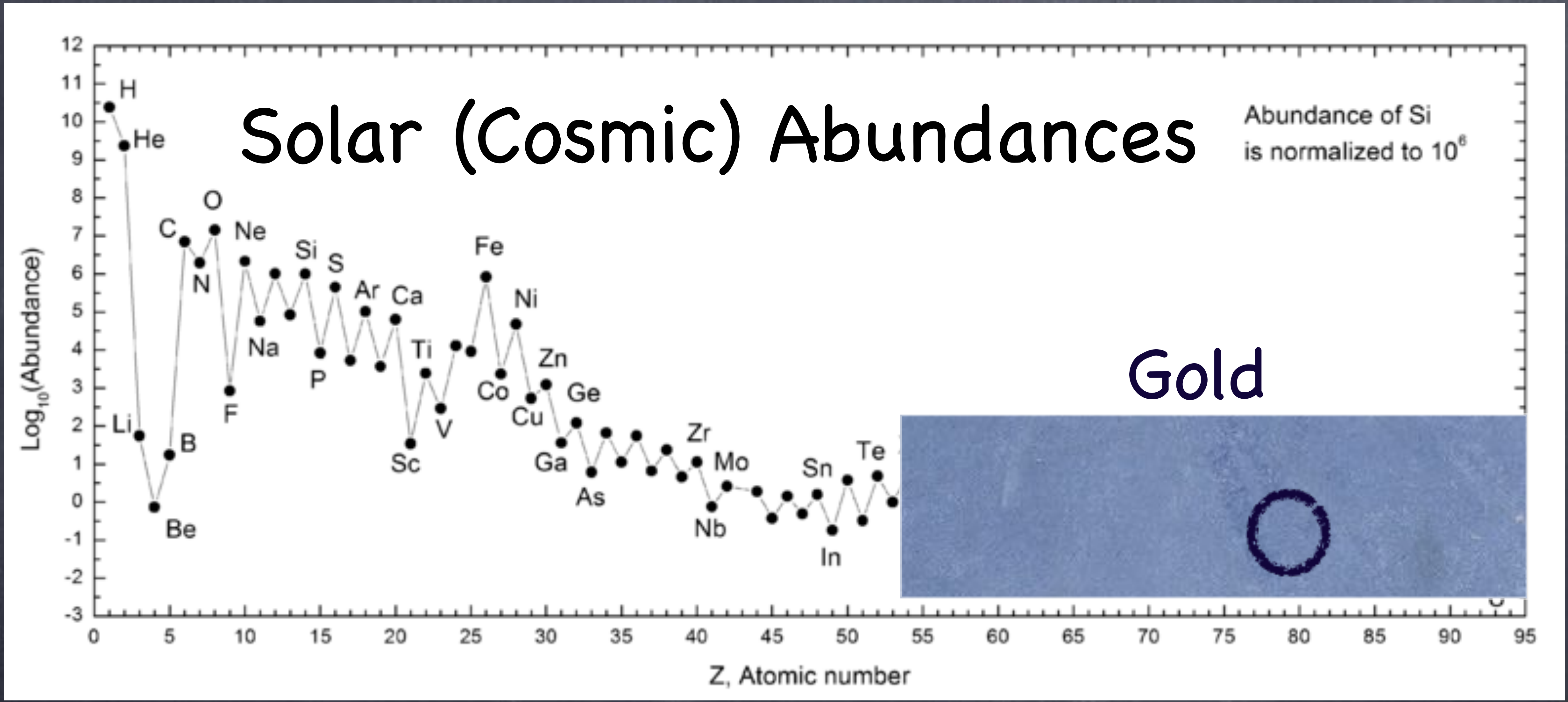


Is this the "smoking gun" proving the origin of Gold (and other heavy elemets) in the Universe?

Outline

1. Nucleosynthesis 101
2. Neutron Stars and Mergers
3. Gamma-Ray Bursts
4. The Li-Paczynski Macronova (kilonova)
5. Putting it all togather - GRB 130603B
6. Additional support
7. The origin of Gold

1. Nucleosynthesis 101

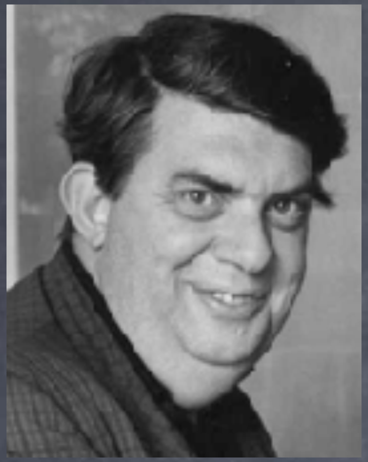
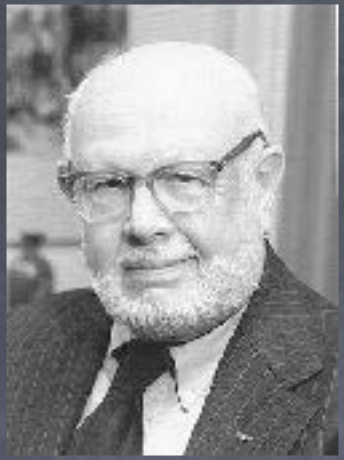


How are these elements produces?

BB (Big Bang) Nucleosynthesis

- 24% of the Universe is He.
- This He is produces in the big Bang.

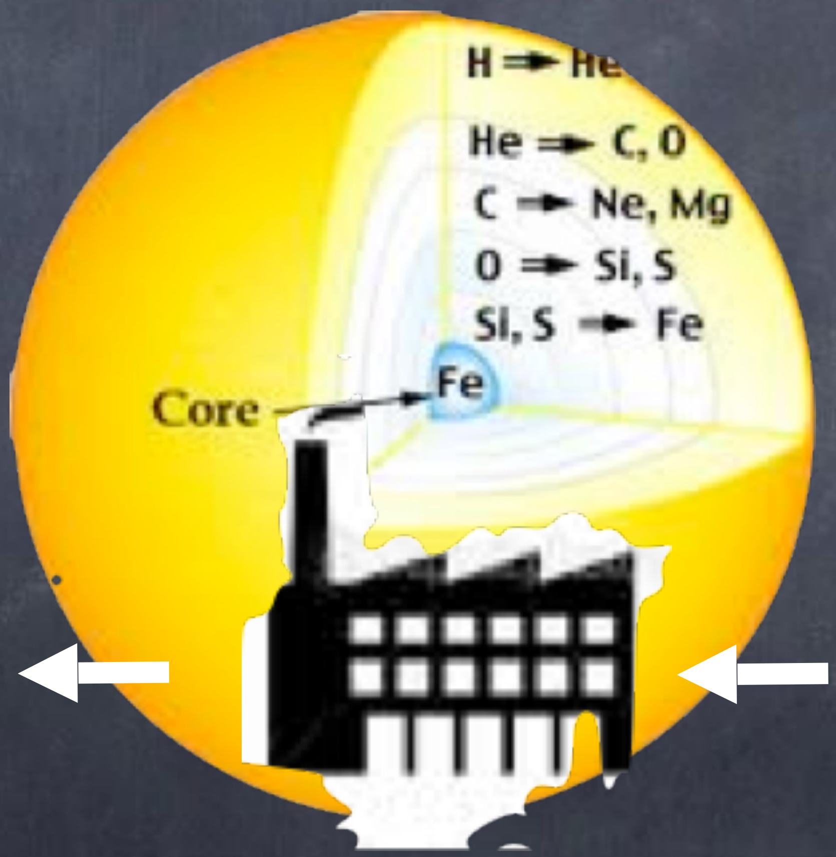
George Gammow

Burbidge, Burbidge, Fowler and Hoyle

B^2FH 1957

He,C,O,Ne,Mg
Si,S,Fe,Ni.....

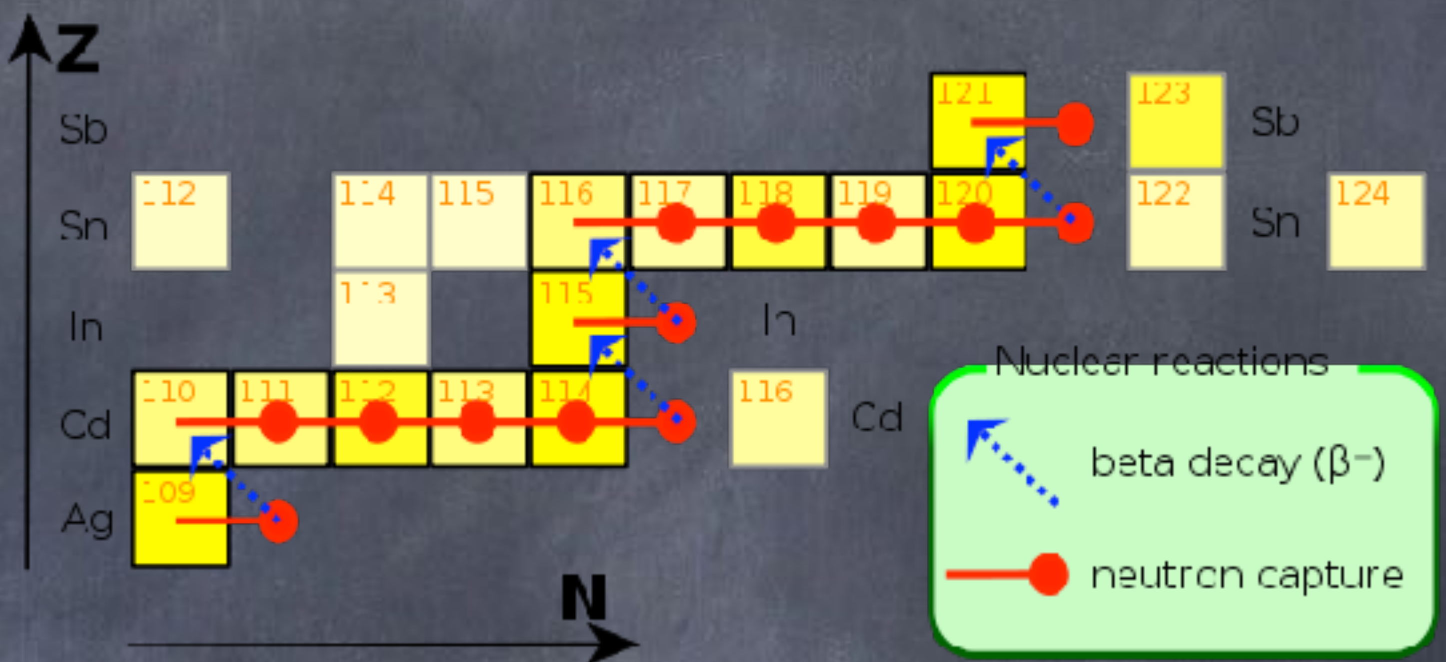


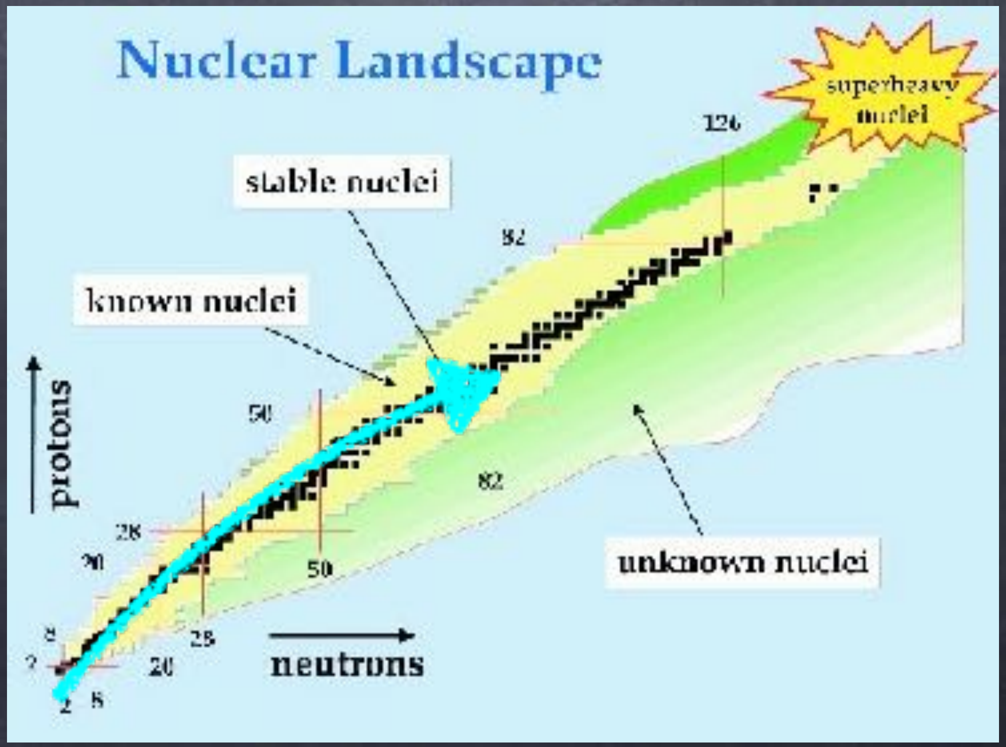
H

Elements up to Iron are produced in stars

S (slow) Process

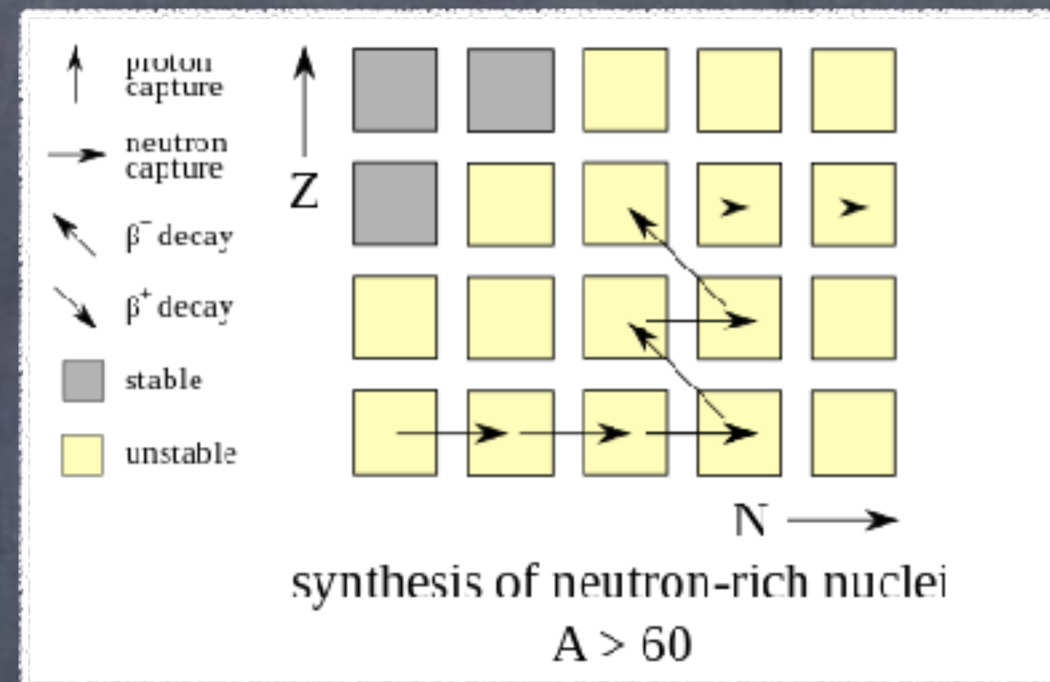
- Neutron capture slower than beta decay.
- Low neutron densities.
- time scale - years.
- Moves along the valley of nuclear stability.
- Final abundances depend on the conditions within the site.

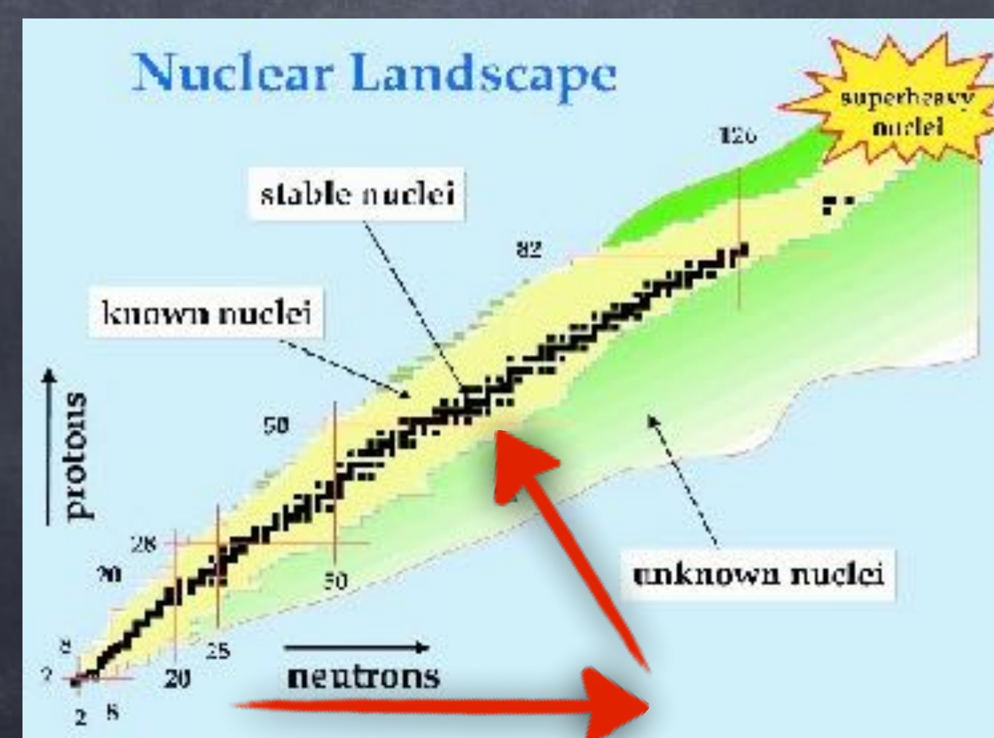




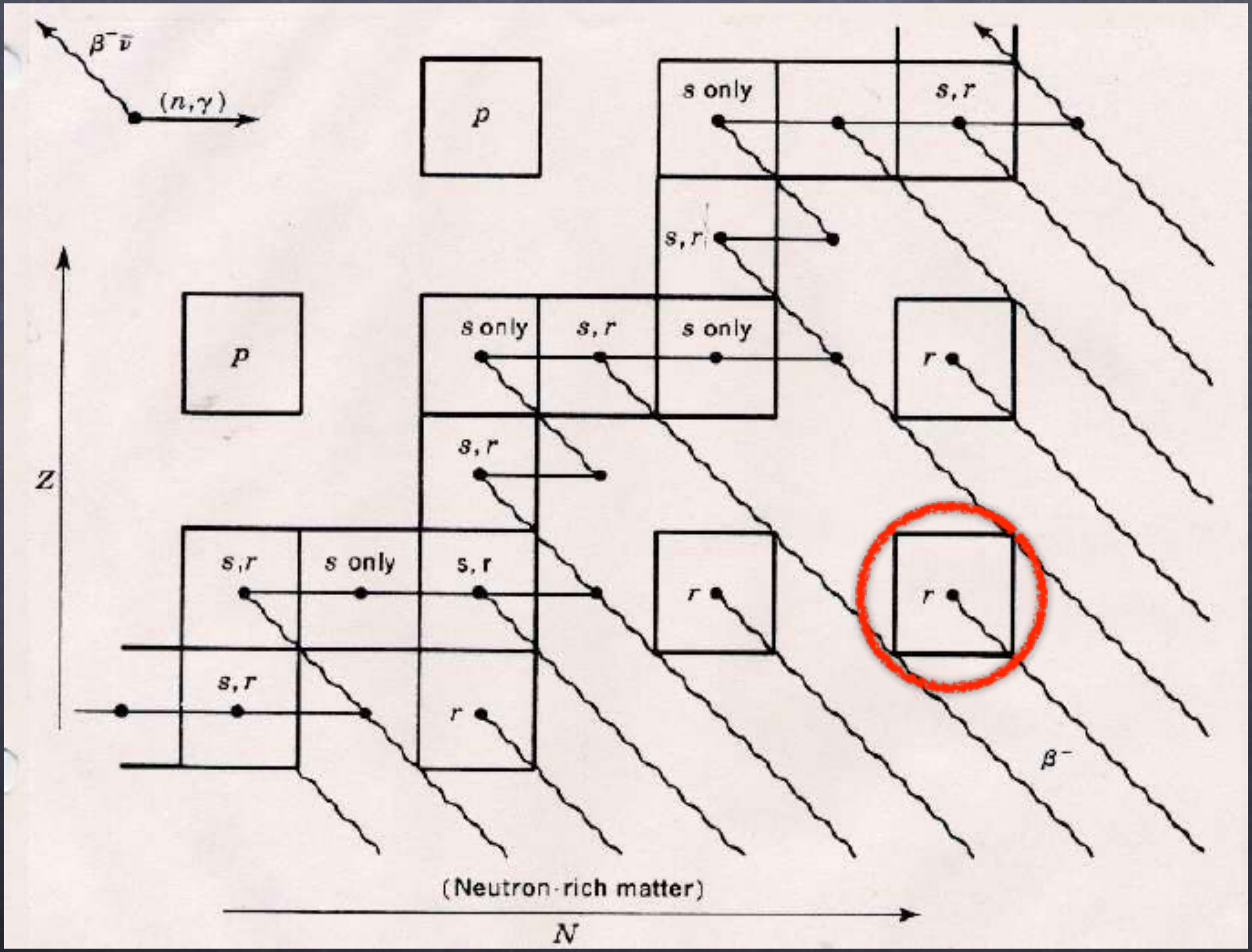
r (rapid) Process

- Neutron capture faster than beta decay.
- High neutron densities.
- Time scales - seconds.
- On the neutron rich side of nuclear stability.
- Uniform final abundances.





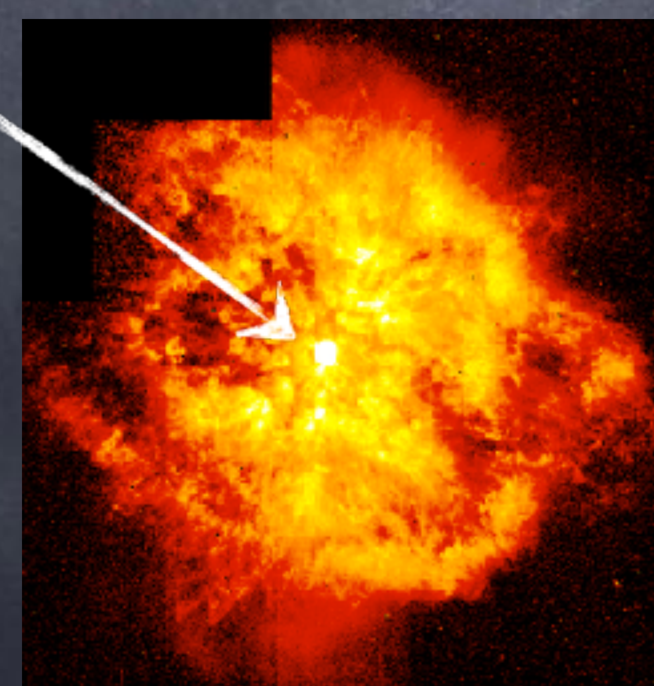
s and r processes



Explosive r-process

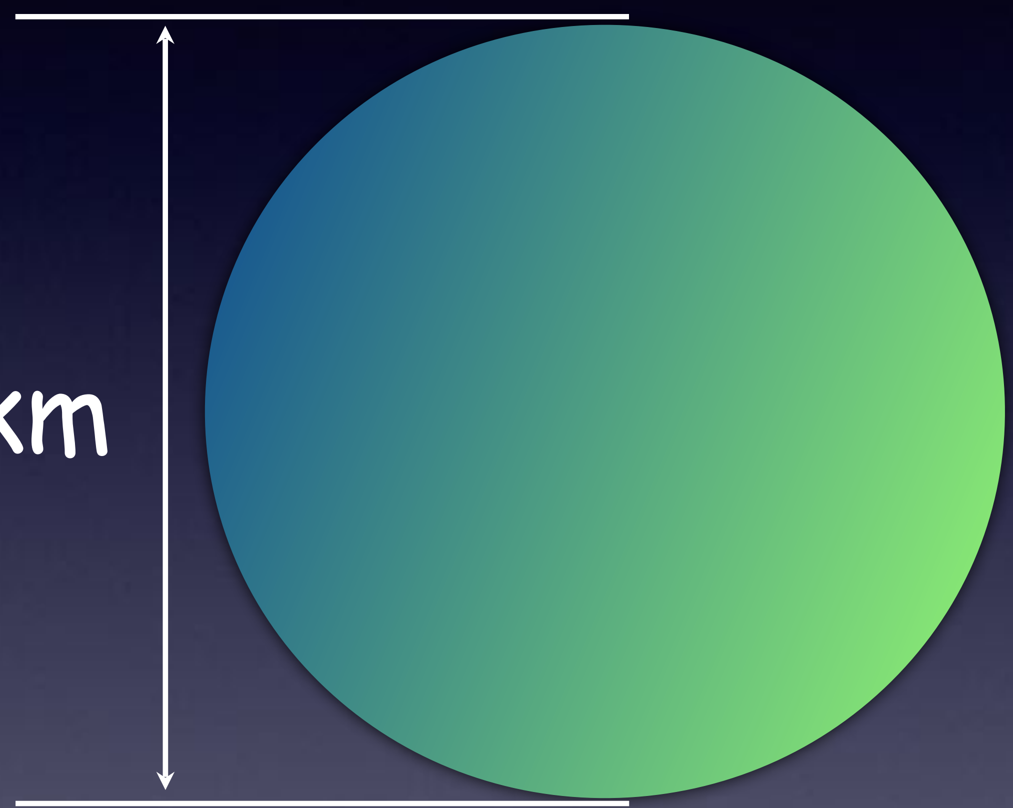
Supernova

- ν flux from the newborn neutron star produce excess of neutrons in **Supernova explosion.**

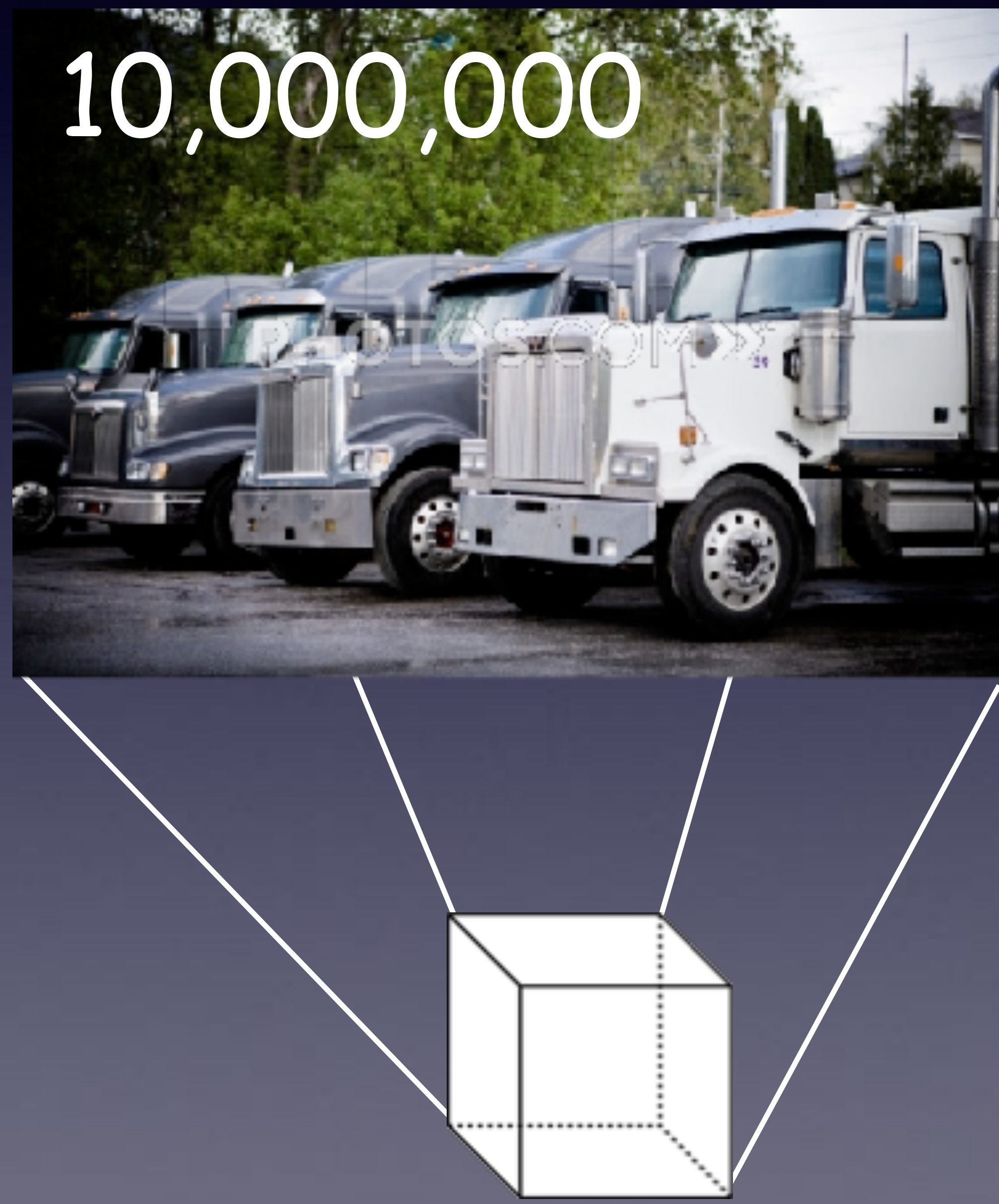


2. Neutron stars and mergers

24 km



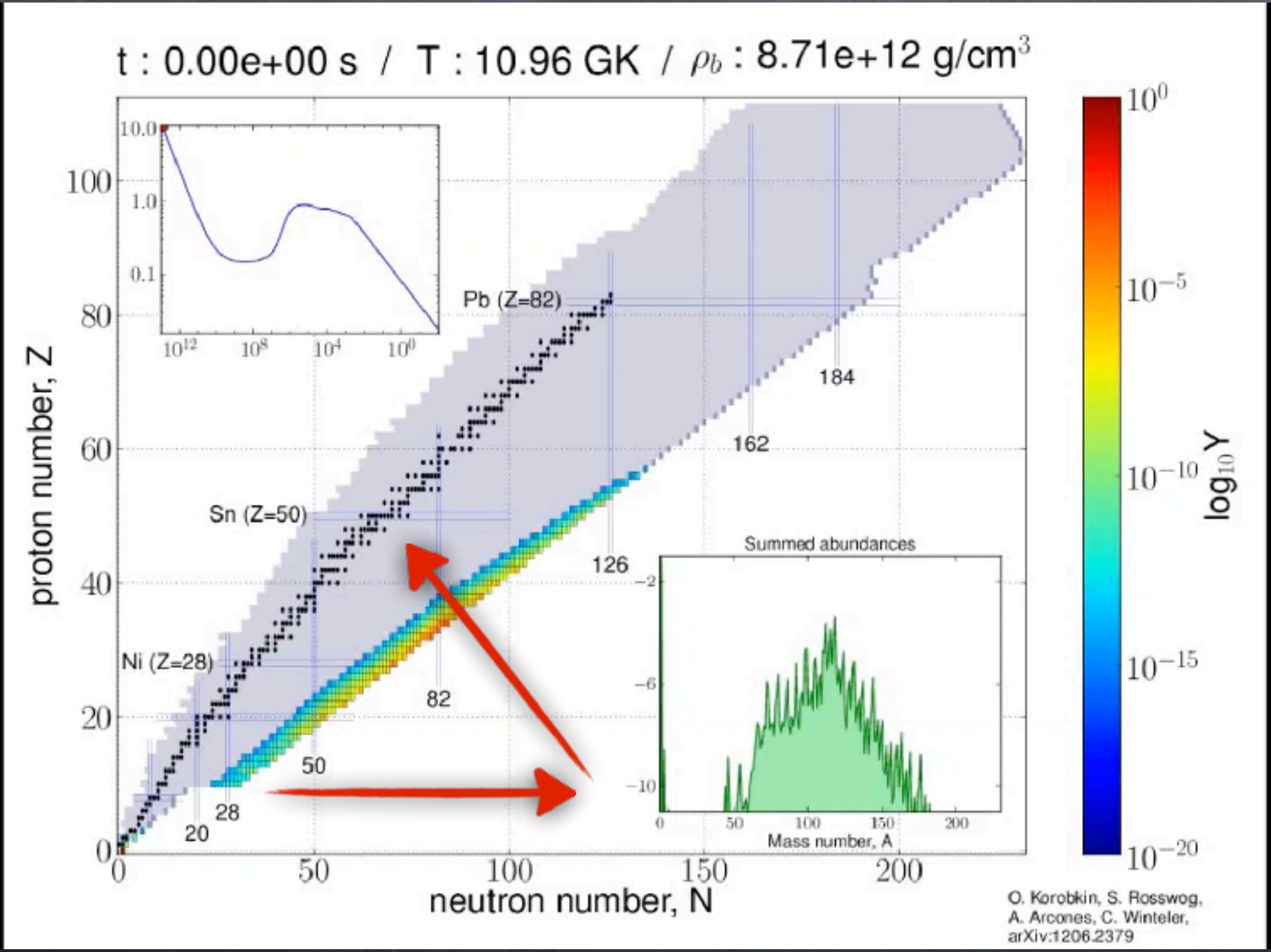
95% neutrons!



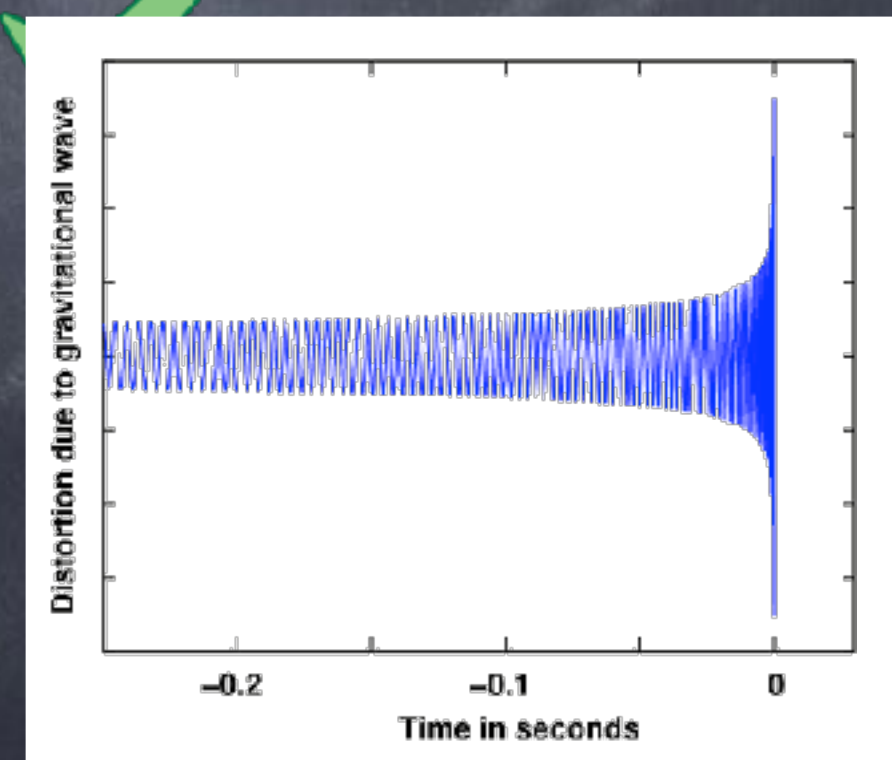
1 cc of neutron star material

$$n \rightarrow p + e + \nu$$

Decay of neutron star matter



Binary Neutron Stars

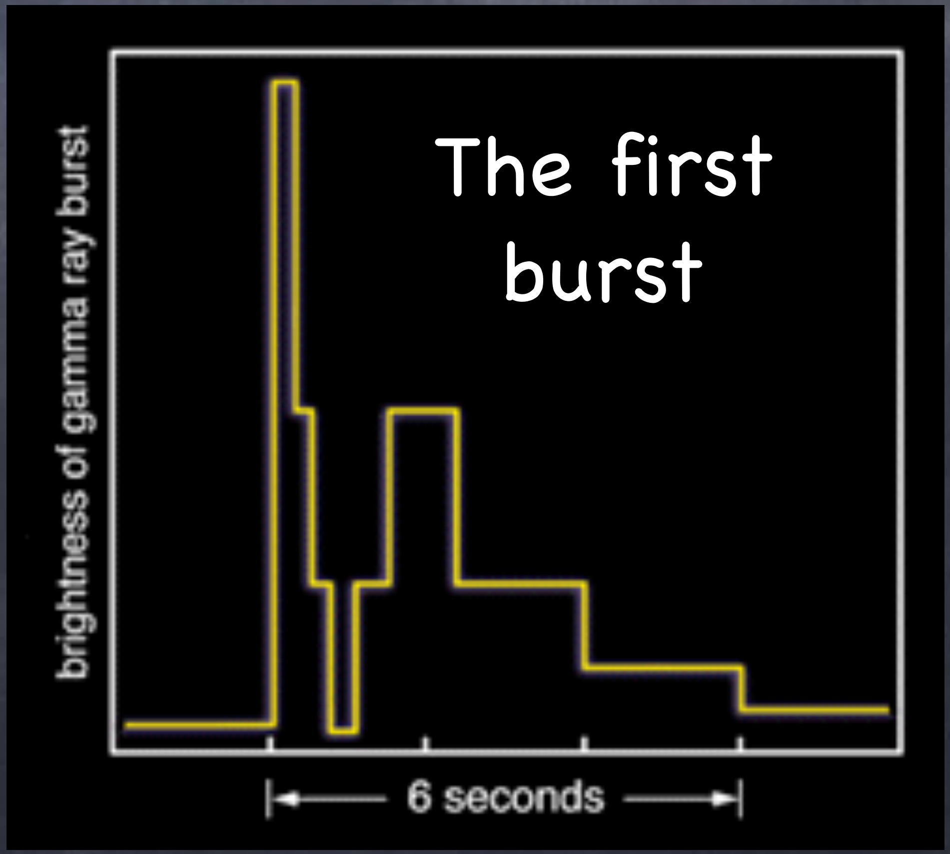


$$\frac{dr}{dt} = -\frac{64}{5}\frac{G^3}{c^5}\frac{(m_1 m_2)(m_1+m_2)}{r^3}$$

Neutron Star Mergers

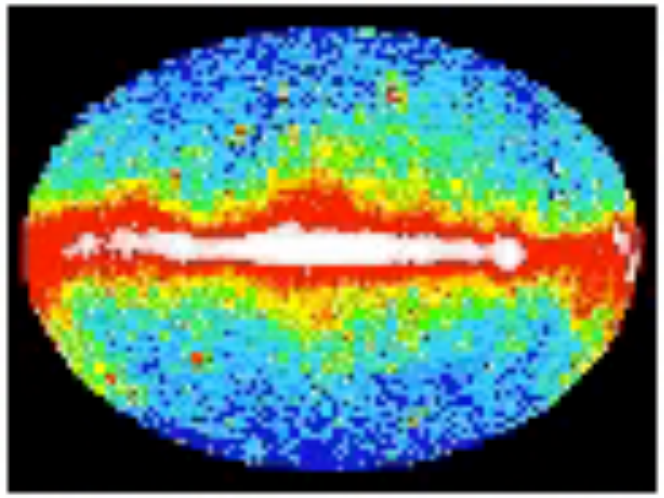
3. Gamma Ray Bursts

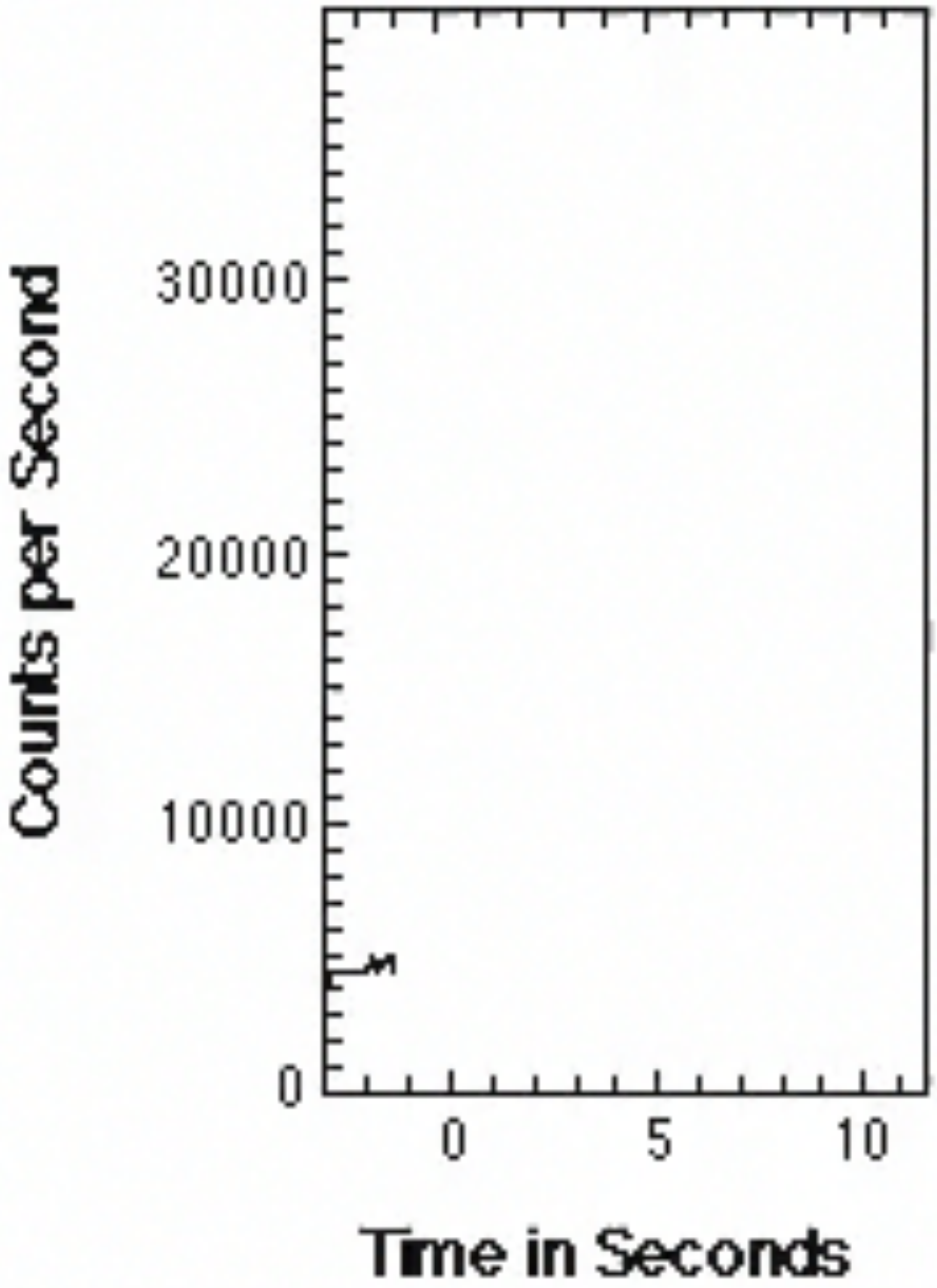
The Vela Satellites



Gamma-ray bursts

The sky in gamma-Rays

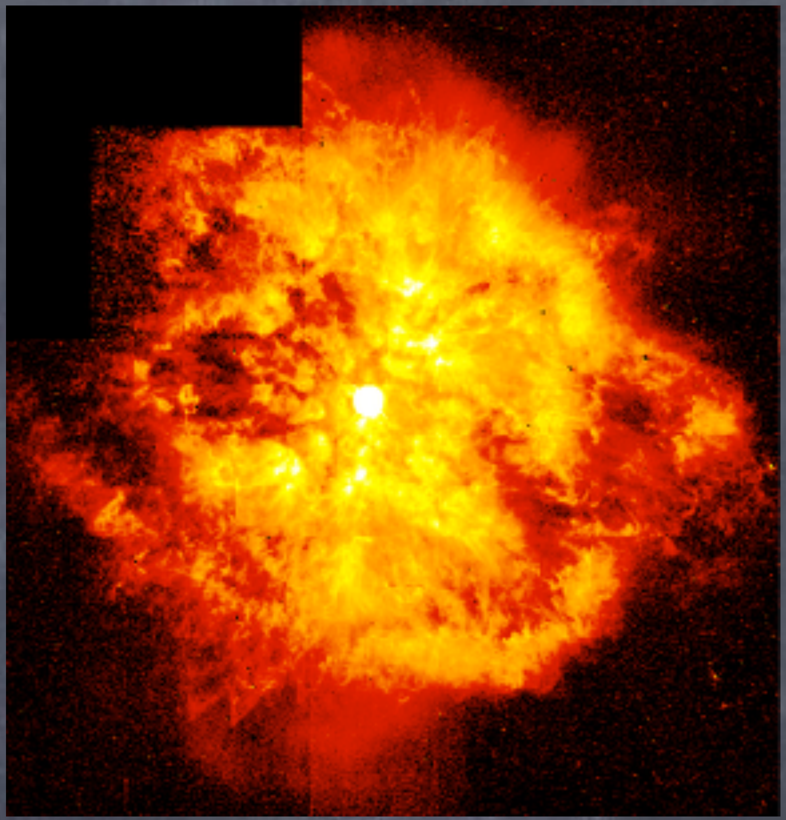




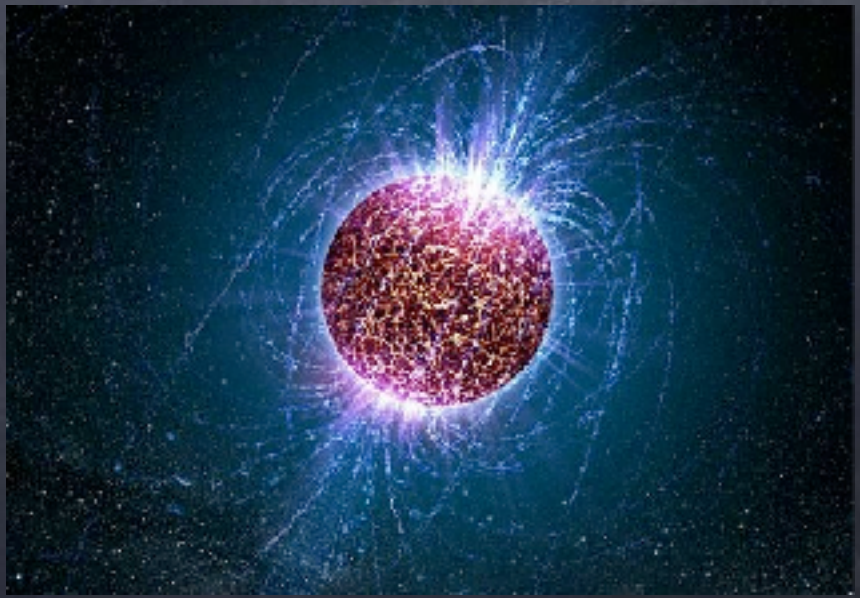
Gamma-ray bursts

The late 80ies

- r-process material from Supernovae



- GRBs from magnetic flares on galactic neutron stars ($E \sim 10^{40}$ ergs).



Gamma-ray bursts

Two provocative ideas

LETTERS TO NATURE

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

Gamma-ray bursts

Gravitational Waves

Gamma-Ray Bursts

Nucleosynthesis

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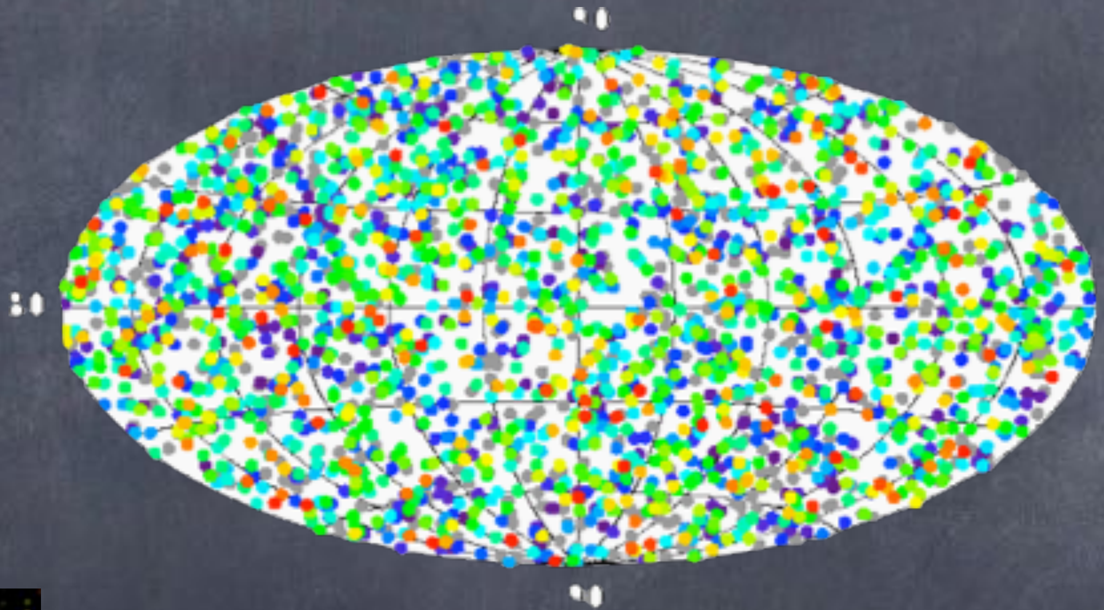
90ies: GRBs are cosmological

1992: BATSE - GRBs have a coslomogical distribution



Gamma-Ray Bursts

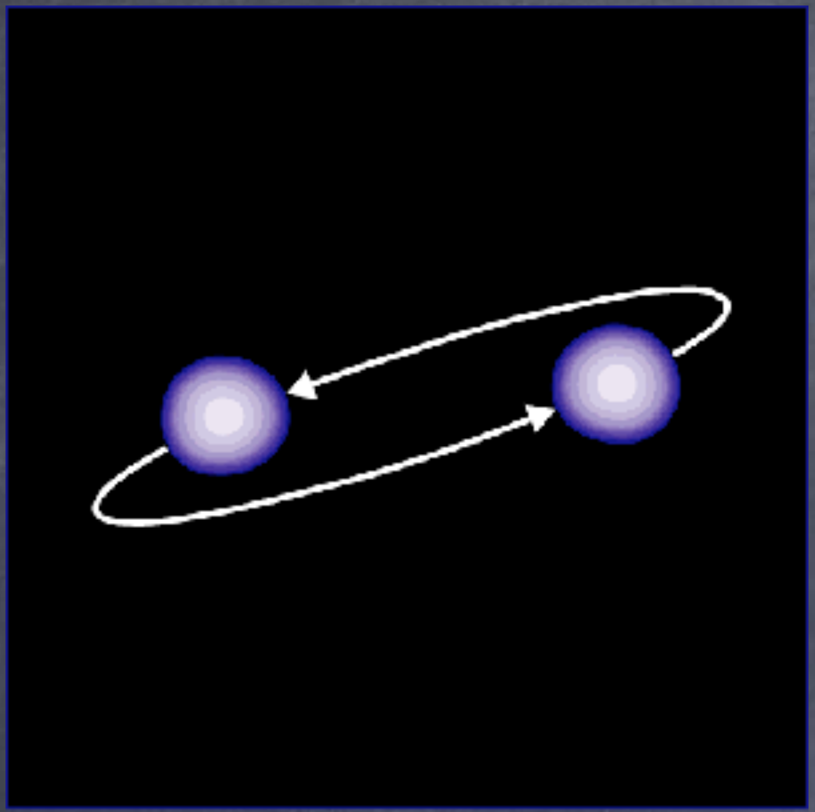
1997: BeppoSAX - GRBs' afterglow that enables redshift measurements confirming the coslomogical origin

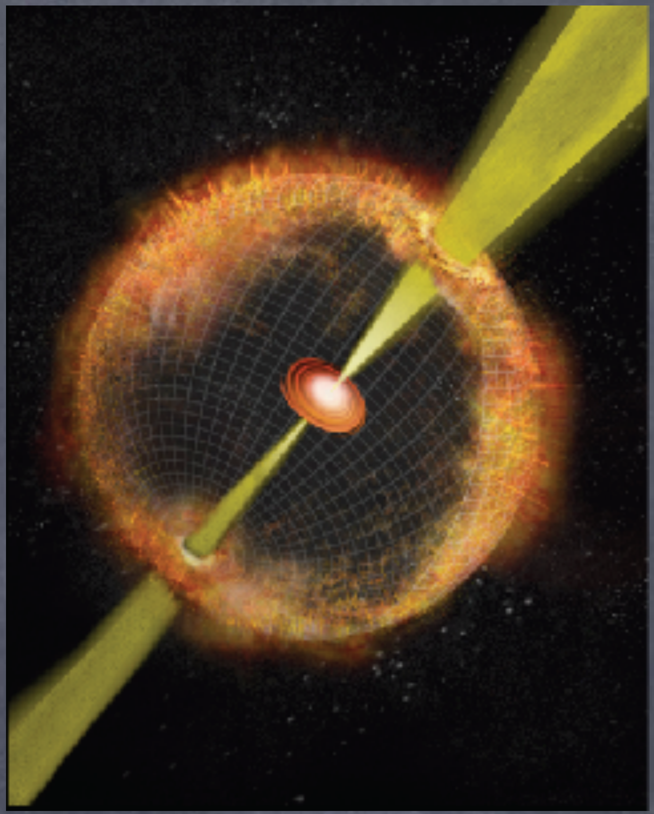
1988		2015
r-process from Supernovae	→	Supernovae cannot produce A>130
GRBs from magnetic flares on galactic neutron stars (E ~10^{40} ergs).	→	GRBs are cosmological (E ~10^{51} ergs).

Gamma-ray bursts

Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley, 98

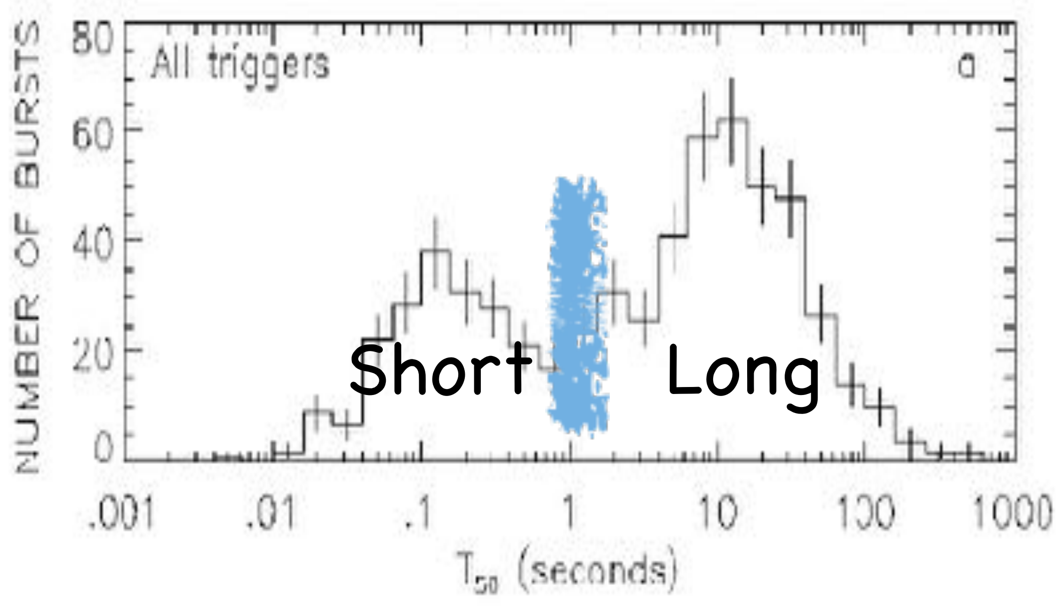




Indirect Evidence

NS mergers

Collapsars



Direct Evidence

Gamma-ray bursts

Mergers ejects 0.01–0.04M_{sun} with $E_k \sim 10^{50}$–10^{51} ergs

Stephan Rosswog

4. Macronova* (Li & Paczynski 1997)

Bohdan Paczynski

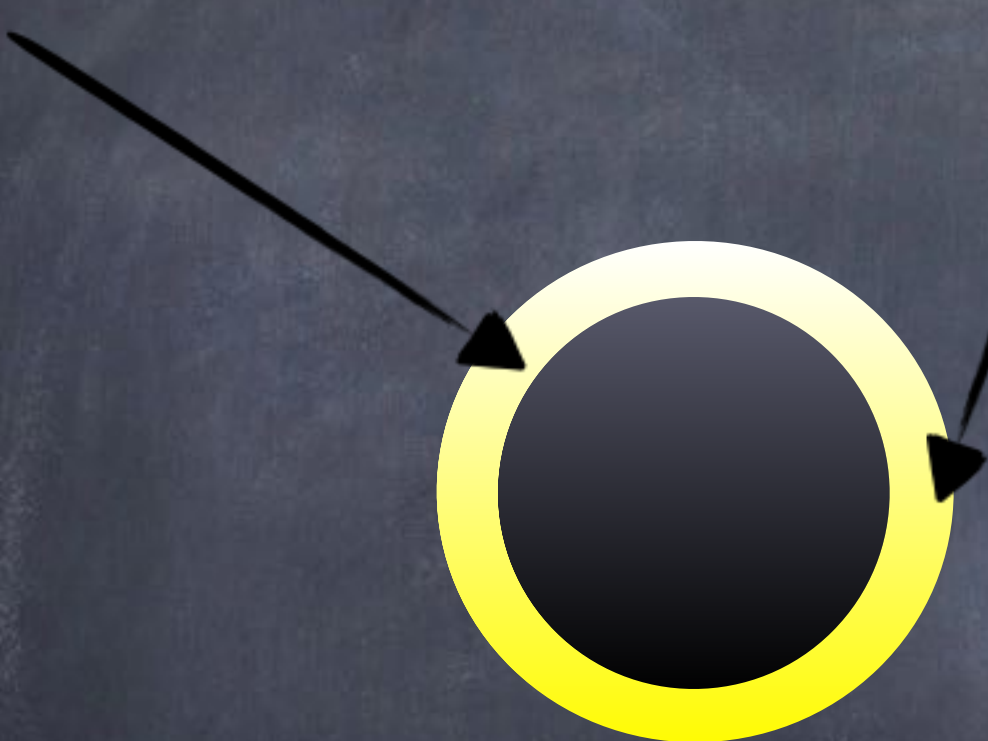
- Radioactive decay of the neutron rich matter.
- $E_{radioactive} \approx 0.001\ Mc^2 \approx 10^{50}$ erg
- A weak short Supernova like event.
- Macronovae follow short GRBs but could appear without a short GRB as those are beamed.

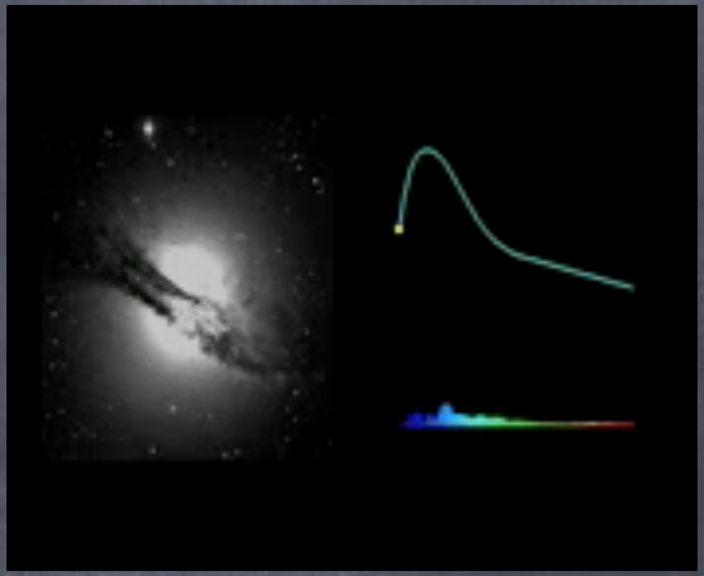
*Also called Kilonova

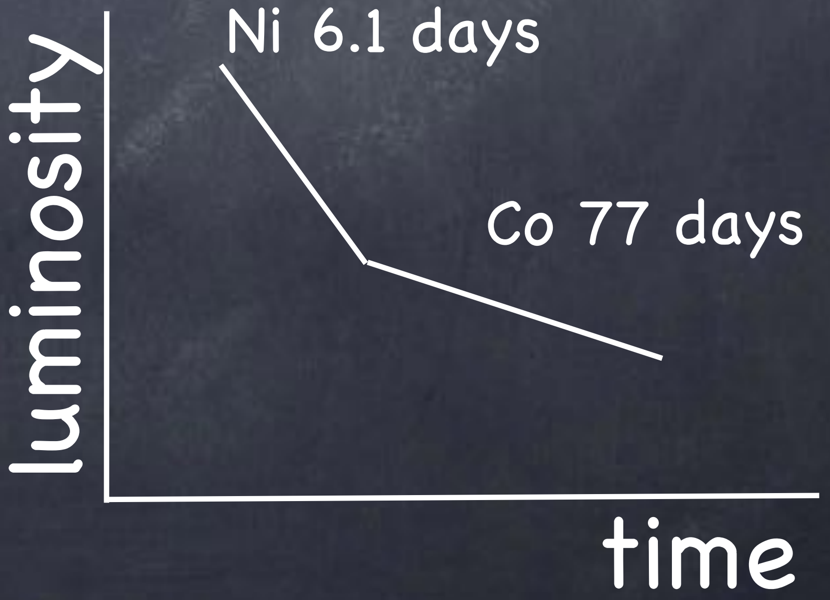
Supernova

Photosphere

Photons escape





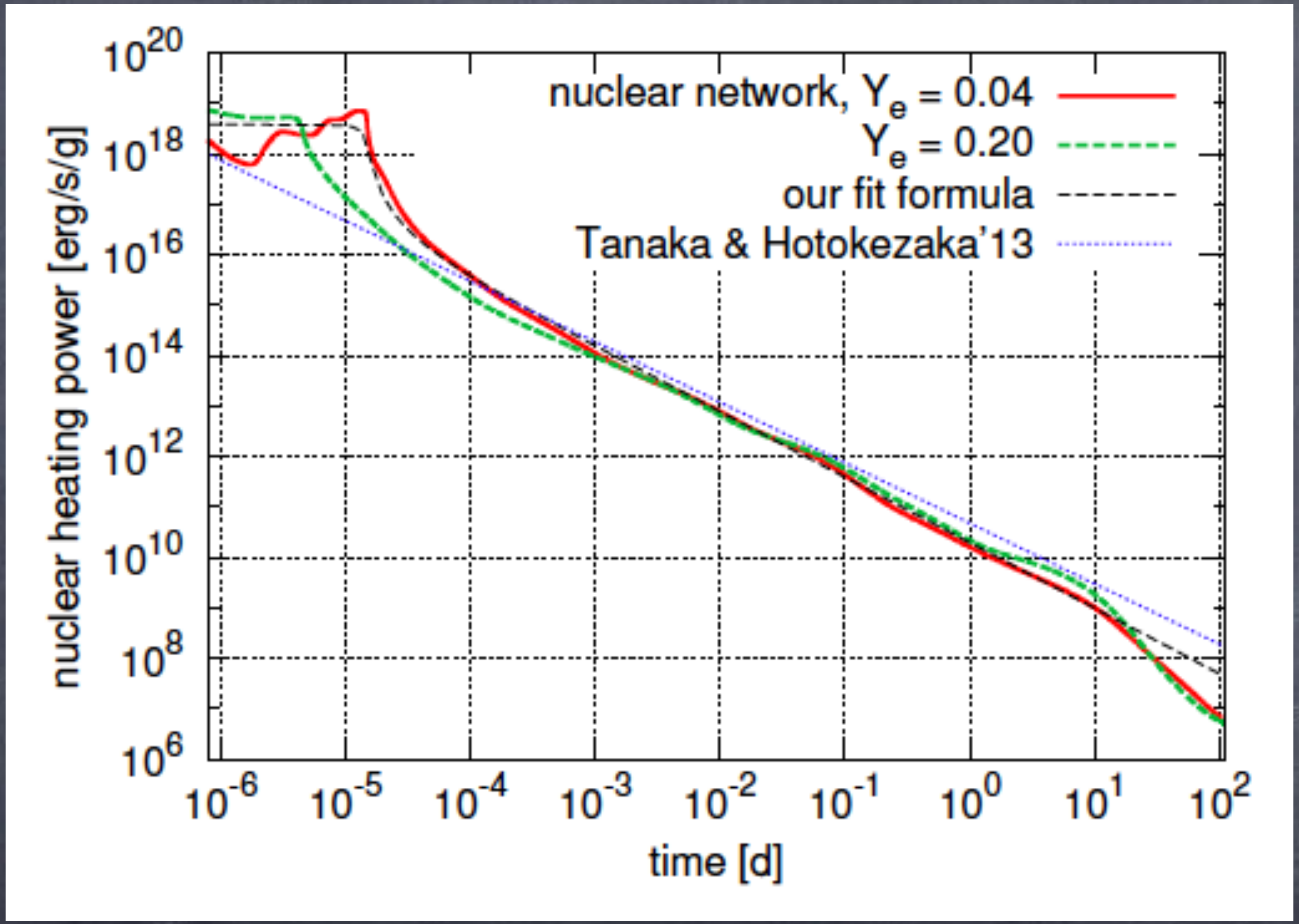


Powered by radioactive decay of $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

Macronova

Radioactive Decay

Korobkin + 13; Rosswog, Korobkin + 13

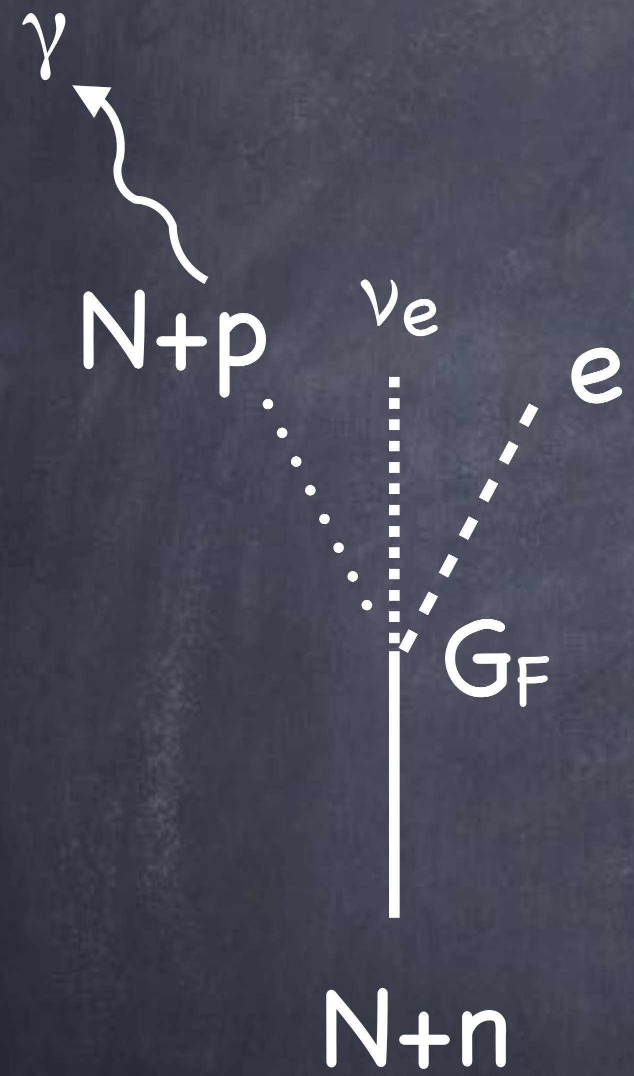


- After a second $dE/dt \propto t^{-1.3}$ (Freiburghaus+ 1999; Korobkin + 2013)

Macronova

Energy Generation

Hotokezaka, Sari & TP + 16



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

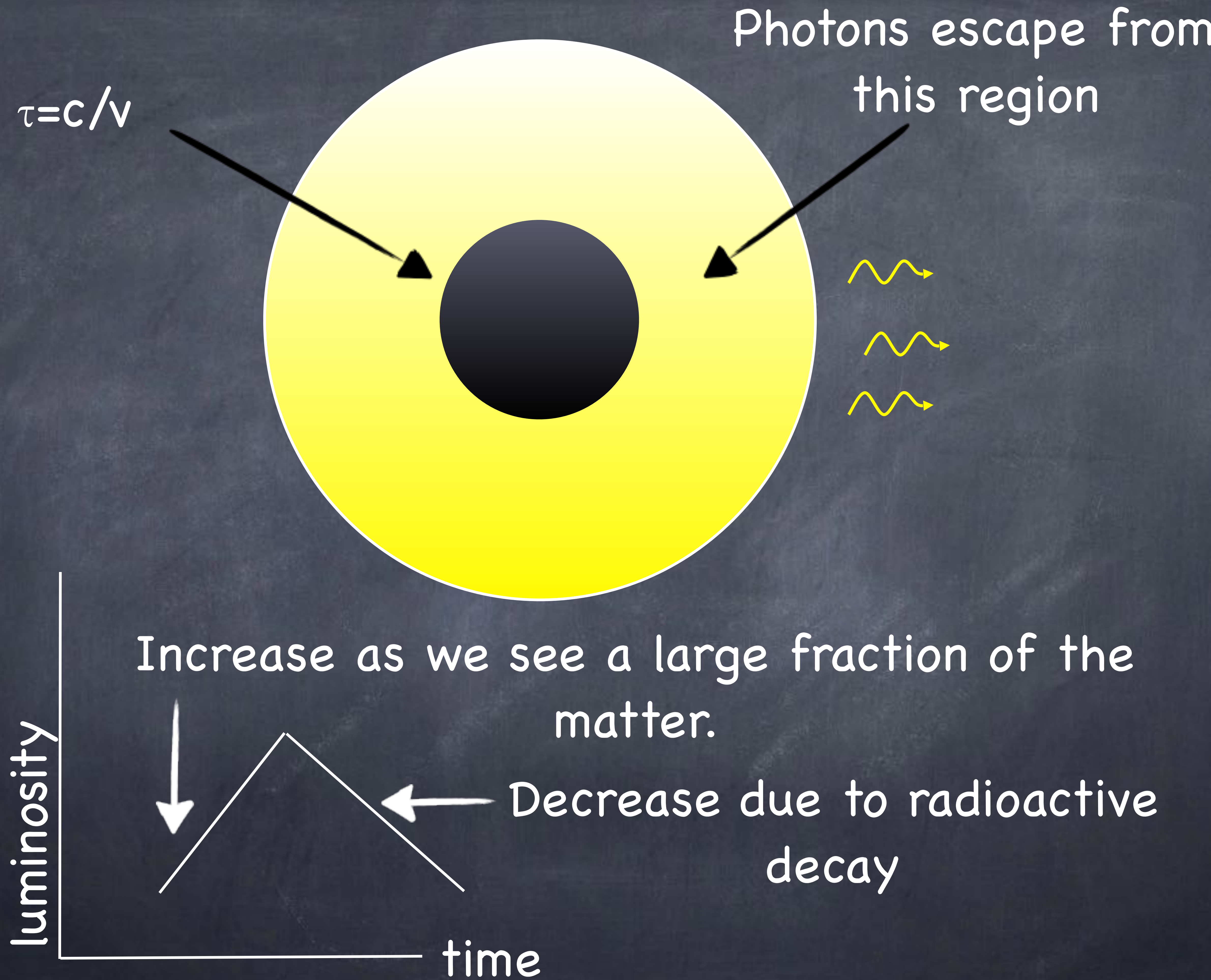
$$\dot{E} = \epsilon_e \frac{m_e c^2}{t_f}\left(\frac{t}{t_F}\right)^{-\alpha}$$

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

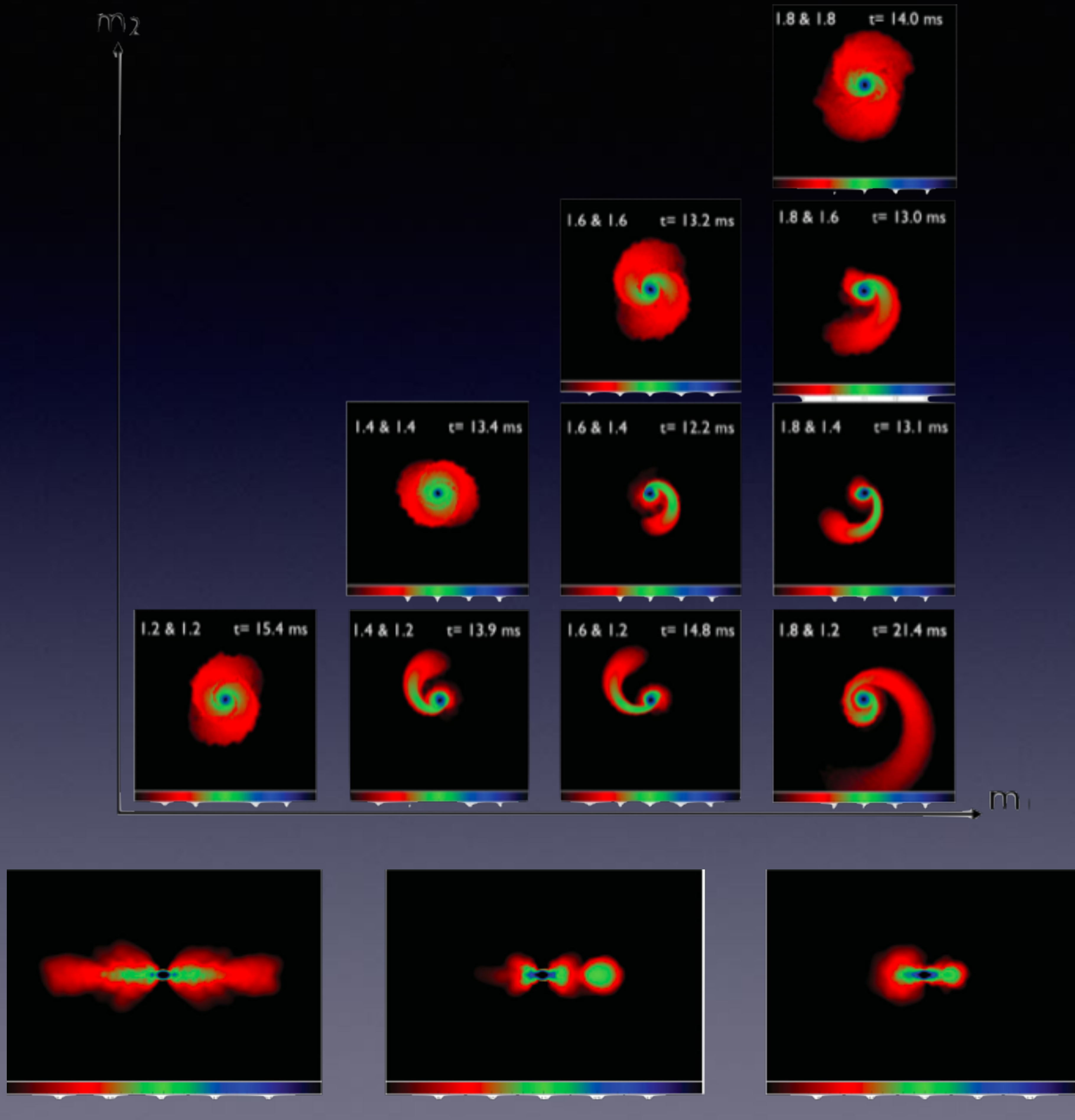
E^3 or $E^{3/2}$ (for $\int d^3p_e$) E^3 (for $\int d^3p_\nu$)

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

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


Photons escape from this region
τ=c/v
Increase as we see a large fraction of the matter.
Decrease due to radioactive decay
luminosity
time

Macronova


m2
1.8 & 1.8 t= 14.0 ms
1.6 & 1.6 t= 13.2 ms
1.8 & 1.6 t= 13.0 ms
1.4 & 1.4 t= 13.4 ms
1.6 & 1.4 t= 12.2 ms
1.8 & 1.4 t= 13.1 ms
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms
m1

Macronova

Peak time and peak luminosity

Diffusion time = expansion time <=>
Mass of the "emitting region"

$$\frac{m(v)}{v} = \frac{4\pi c t^2}{\kappa}$$

Luminosity

$$L(t) = \dot{\epsilon}(t) m(v) = \dot{\epsilon}_0 (t/t_0)^{-\alpha} m(v)$$

Radioactive heating rate

The peak time

$$\tilde{t}_p \approx \sqrt{\frac{\kappa m_{\rm ej}}{4\pi c \bar{v}}} = 4.9 \text{ days} \left(\frac{\kappa_{10} m_{{\rm ej},-2}}{\bar{v}_{-1}}\right)^{1/2}$$

The peak luminosity

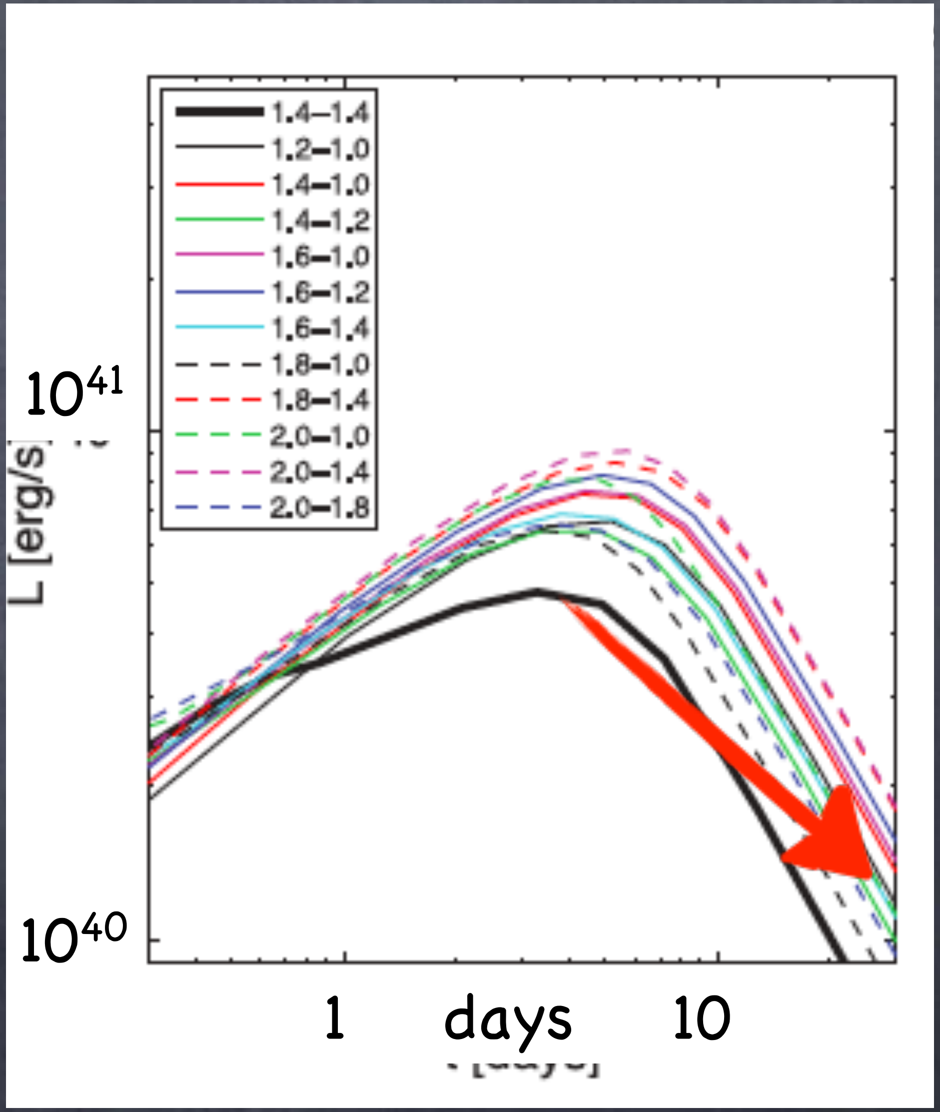
$$\tilde{L}_p \approx \dot{\epsilon}_0 m_{\rm ej} \left(\frac{\kappa m_{\rm ej}}{4\pi c \bar{v} t_0^2}\right)^{-\alpha/2} = 2.5 \times 10^{40} \frac{\rm erg}{\rm s} \left(\frac{\bar{v}_{-1}}{\kappa_{10}}\right)^{\alpha/2} m_{{\rm ej},-2}^{1-\alpha/2}$$

Macronova

Lanthanides dominate the Opacity

(Kassen & Barnes 13; Tanak & Hotokezaka 2013)

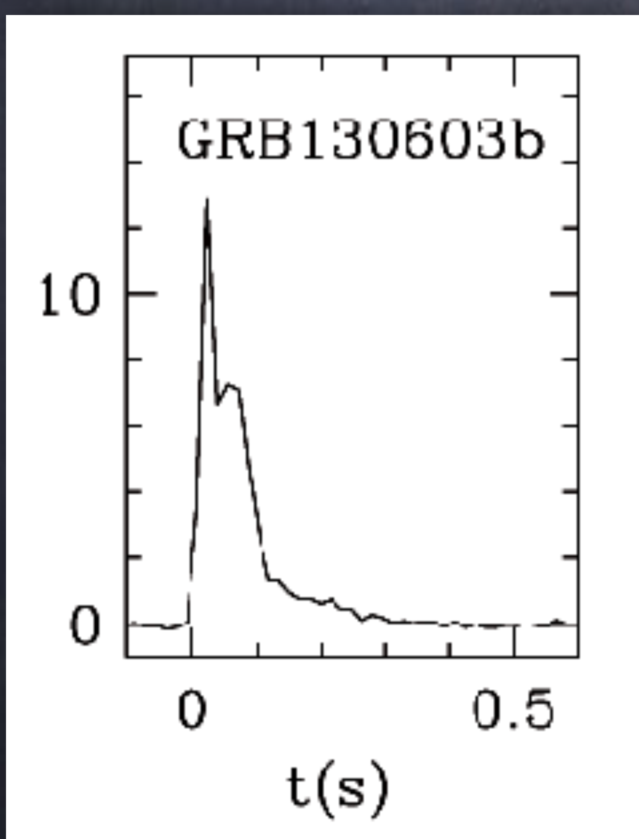
- $\varkappa = 10 \mathrm{cm}^2/\mathrm{gm}$
- $t_{max} \propto \varkappa^{1/2}$ => longer
- $L_{max} \propto \varkappa^{-0.65}$ => weaker
- $T \propto \varkappa^{-0.4}$ => redder

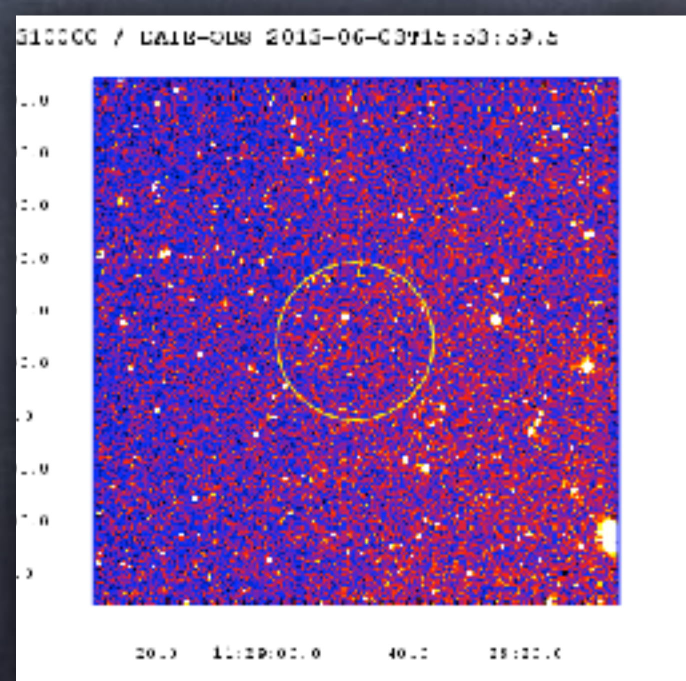


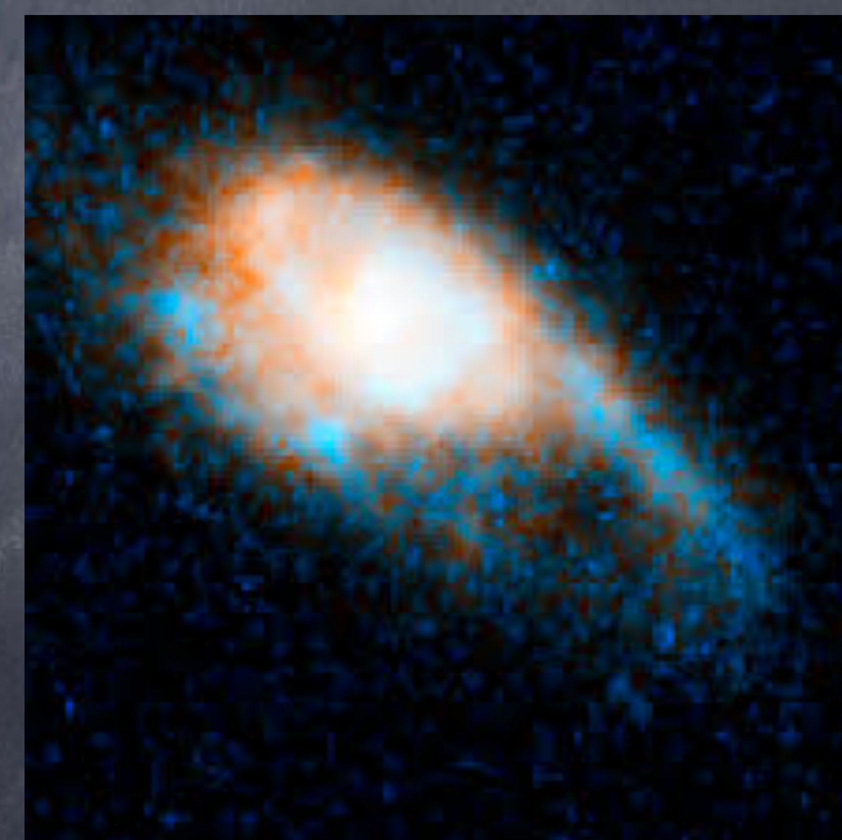
uv or optical -> IR

Macronova

Putting it all together
5. Gamma-Ray Burst (GRB) 130603B



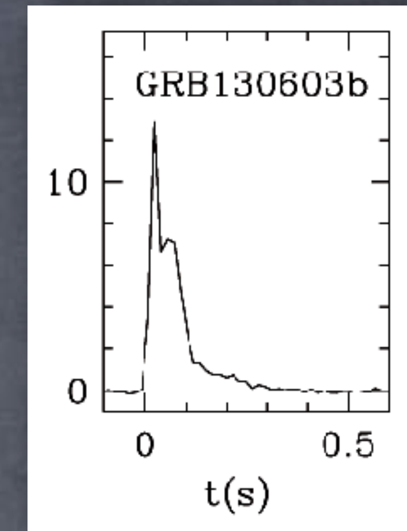




GRB 130603B

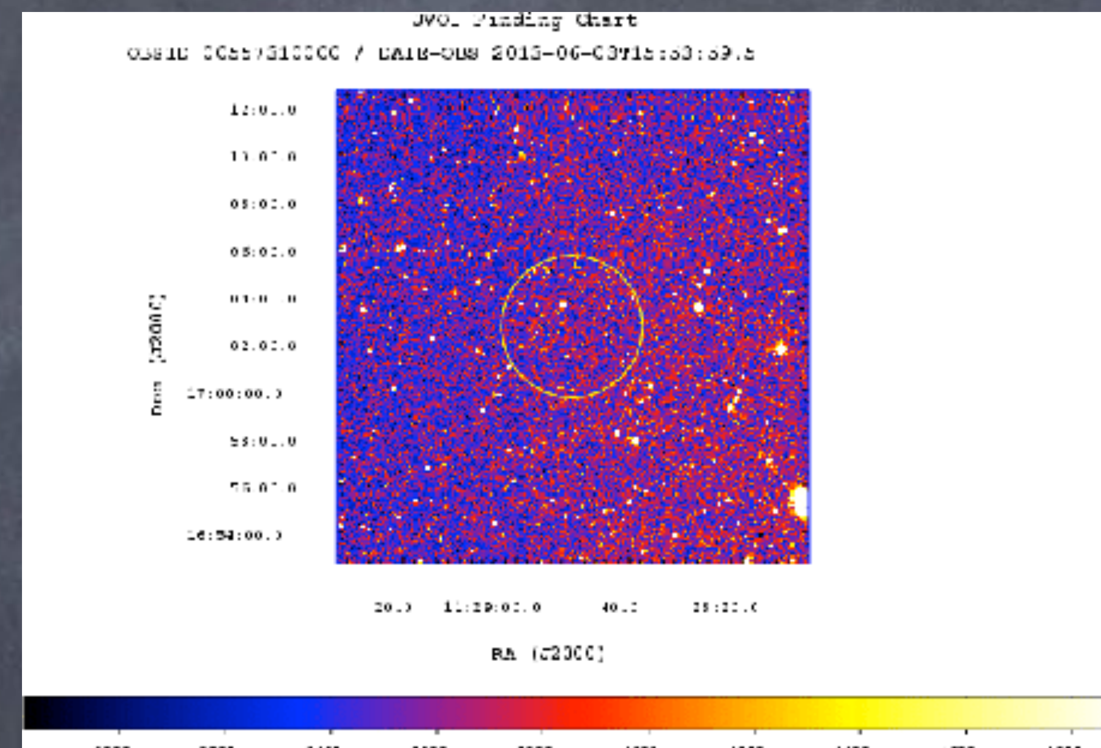
z=0.356 <=> 1 Gpc = 3 Glyr

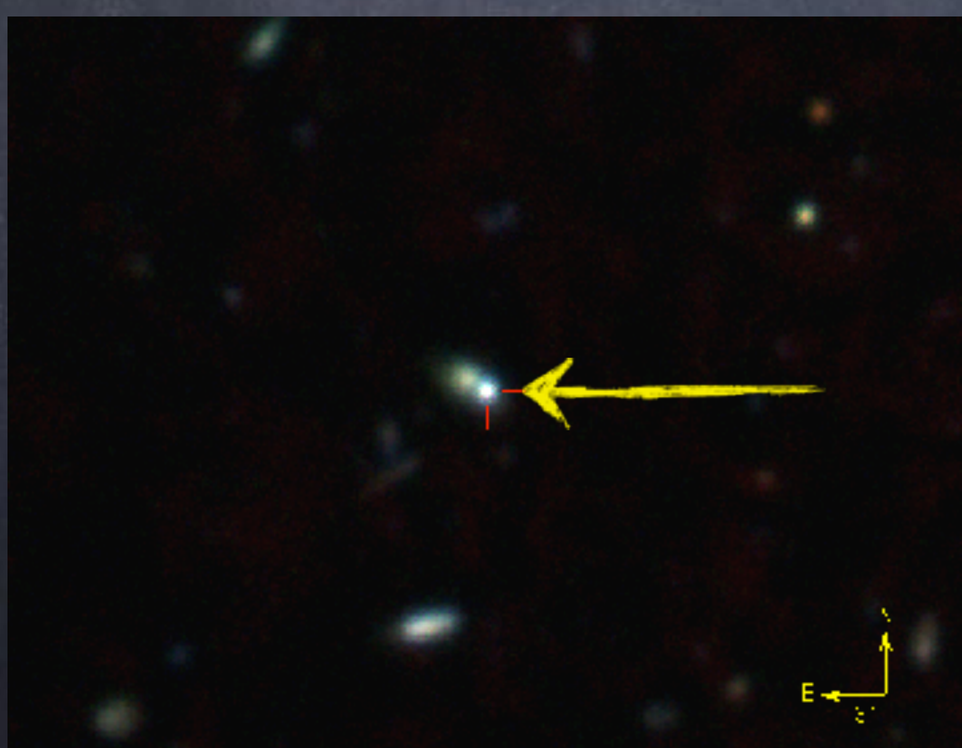
GRB 130603B



At 15:49:14 UT, the Swift Burst Alert Telescope (BAT) triggered and located GRB 130603B (trigger=557310). Swift slewed immediately to the burst.
The BAT on-board calculated location is
RA, Dec 172.209, +17.045 which is
RA(J2000) = 11h 28m 50s
Dec(J2000) = +17d 02' 42"
with an uncertainty of 3 arcmin (radius, 90% containment, including systematic uncertainty).
The BAT light curve showed a single spike structure with a duration of about 0.4 sec.
The peak count rate was 60000 counts/sec (15-350 keV), at ~0 sec after the trigger.

A short burst

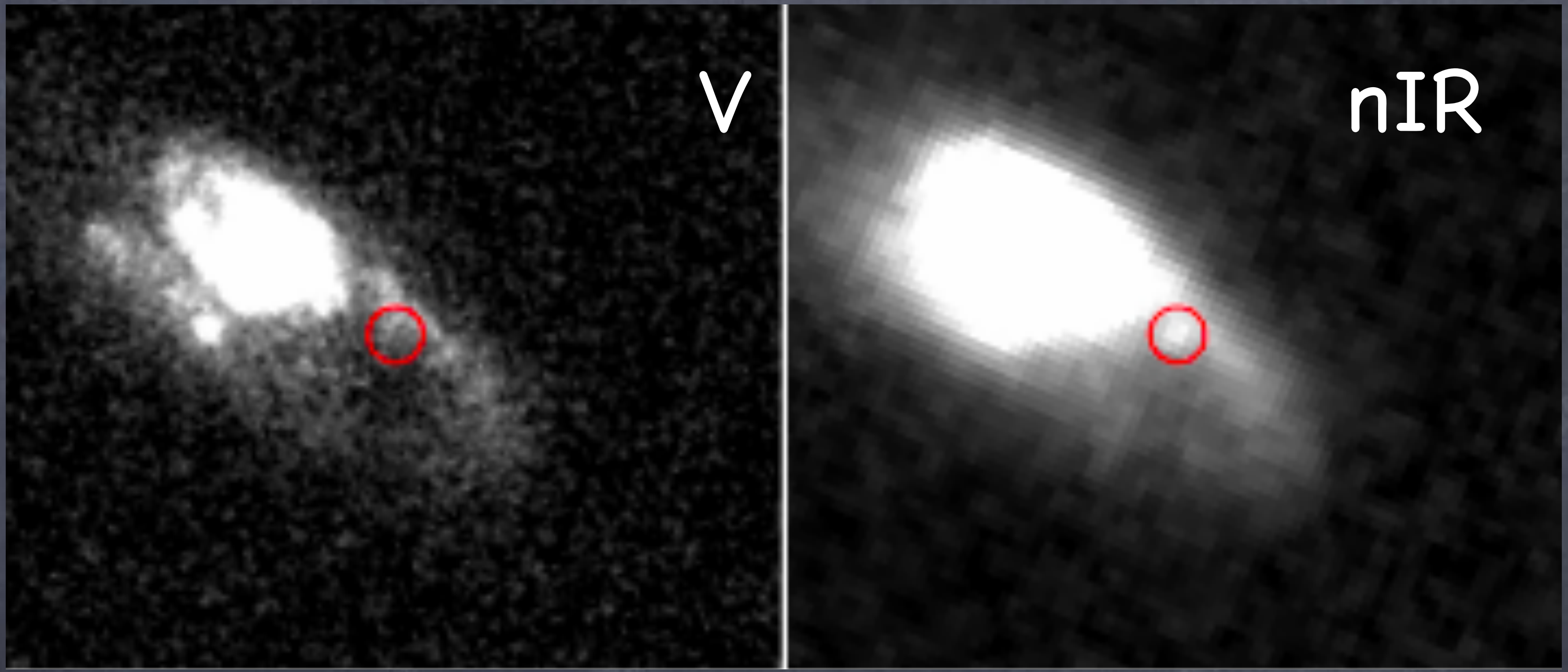




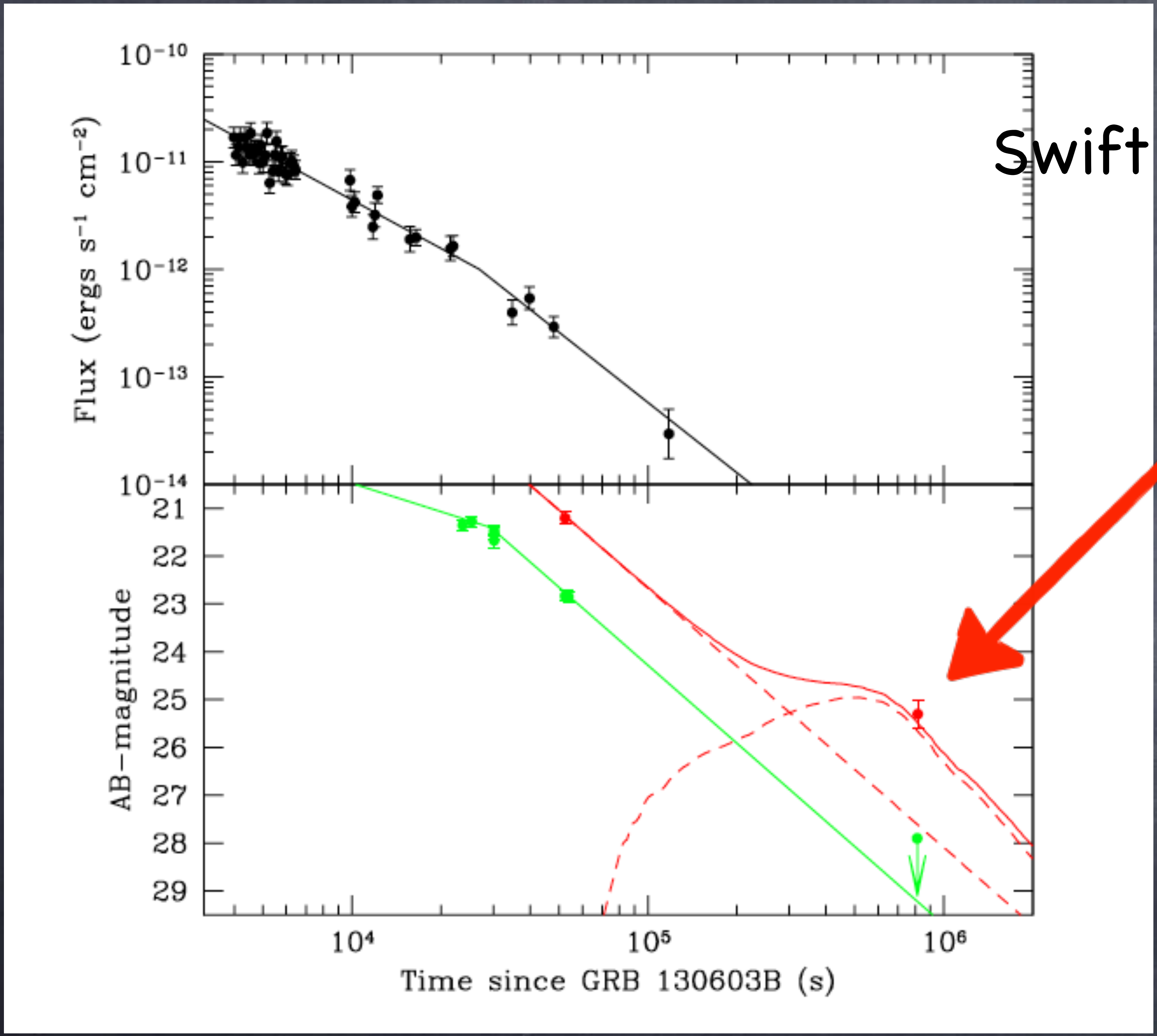
z=0.356 <=> 1 Gpc = 3 Glyr

GRB130603B @ 9 days AB

(6.6 days at the source frame)



HST image (Tanvir + 13)



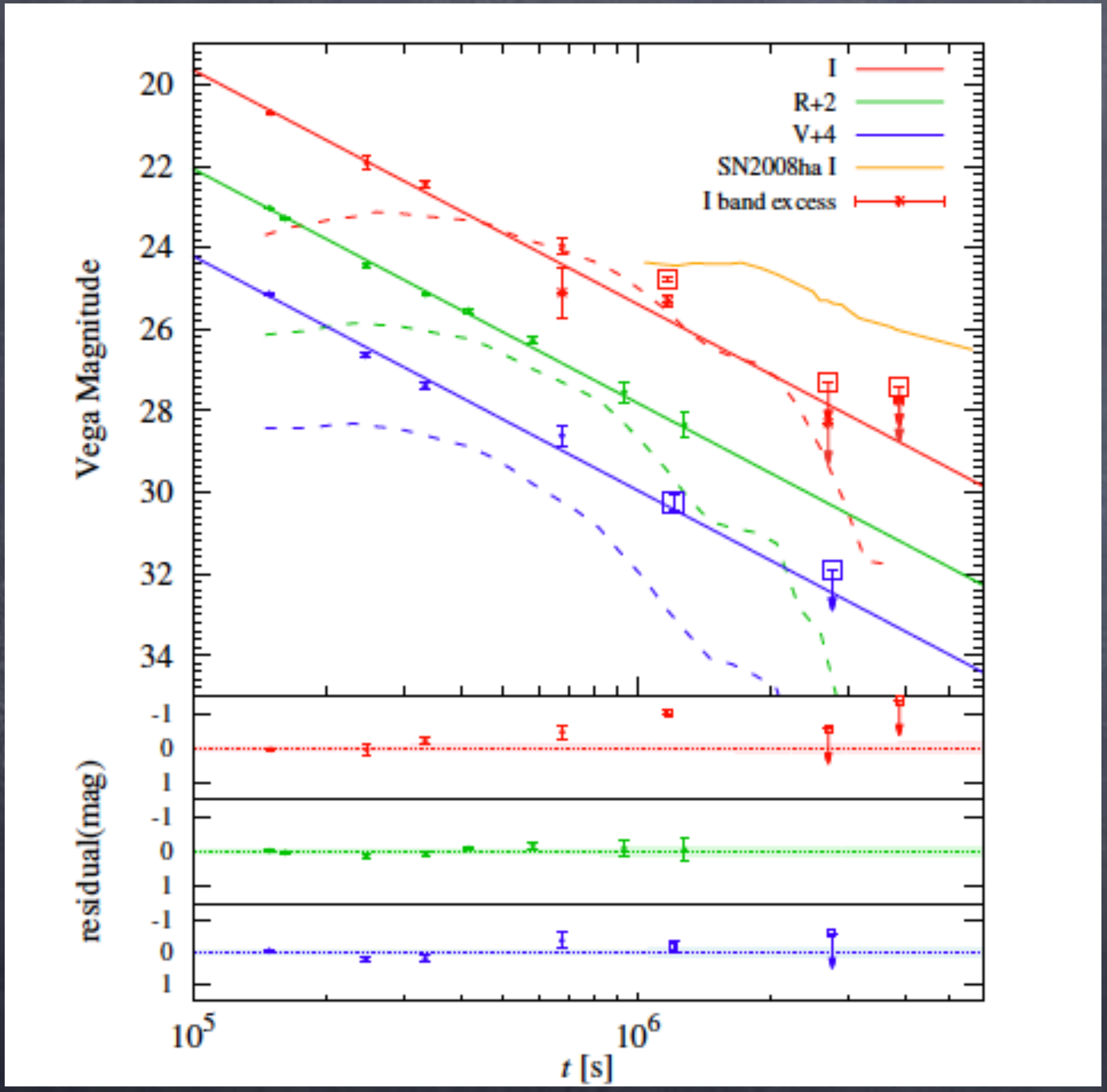
Macronova?

$0.01-0.05\ M_\odot$

Tanvir + 13 (see also Berger + 13)

GRB 130603B

6. Additional Evidence



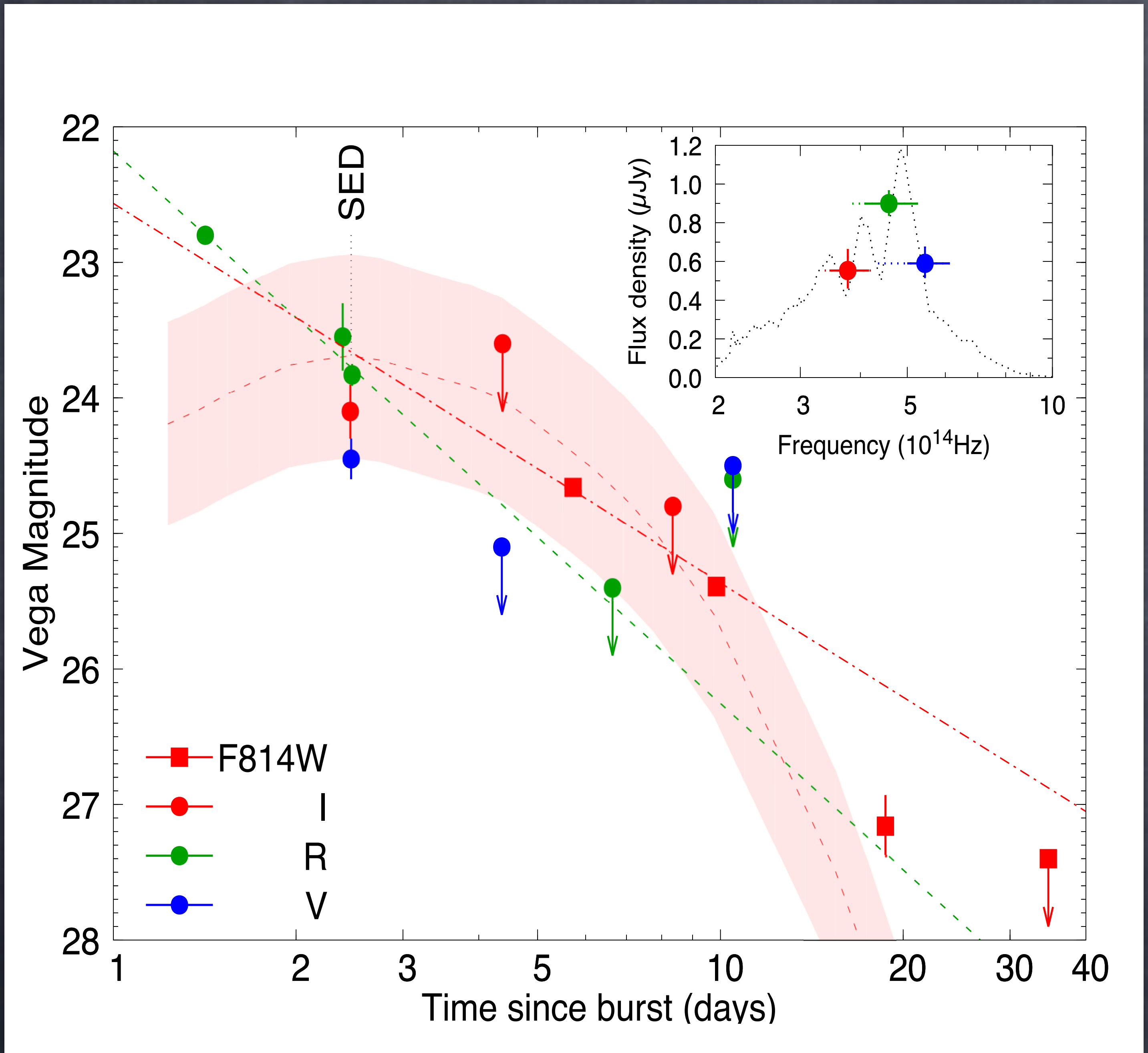
GRB 060614

Need $M \simeq 0.1 M_\odot$

=> BH-NS ?

Yang et al., 2015

Additional evidence



GRB 050709

Need M≃0.05M$_\odot$

=> BH-NS ?

Jin et al., 2016

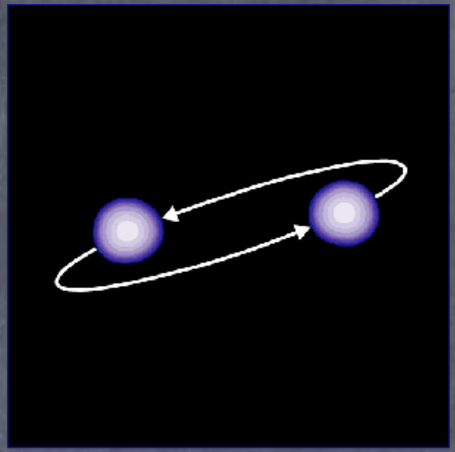
Additional evidence

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

Additional evidence

If correct



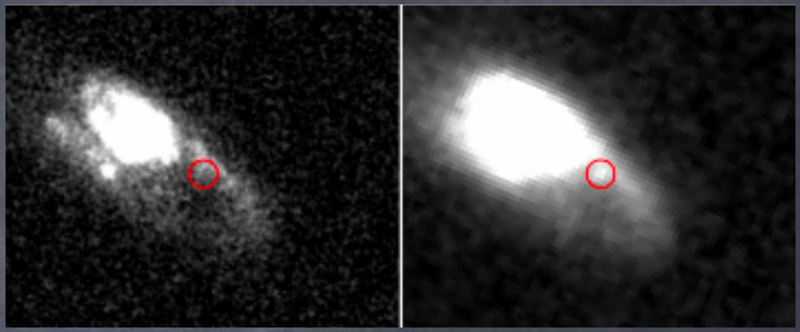
- Confirmaiton of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).

- Confirmation of the Li-Paczynski Macronova.

- Confirmation that compact binary mergers are the source of heavy (A>130) r-process material (Gold, Silver, Platinum, Plotonium, Uranium etc...).

Additional evidence

7. The Origin of GOLD



Implications

Mass ejected in a merger

Observed luminosity = 10^{41}erg/sec @ 6.6 days →

$$m_{ej} > 0.02(\epsilon/0.5)^{-1} m_{\odot}$$

# of mergers →

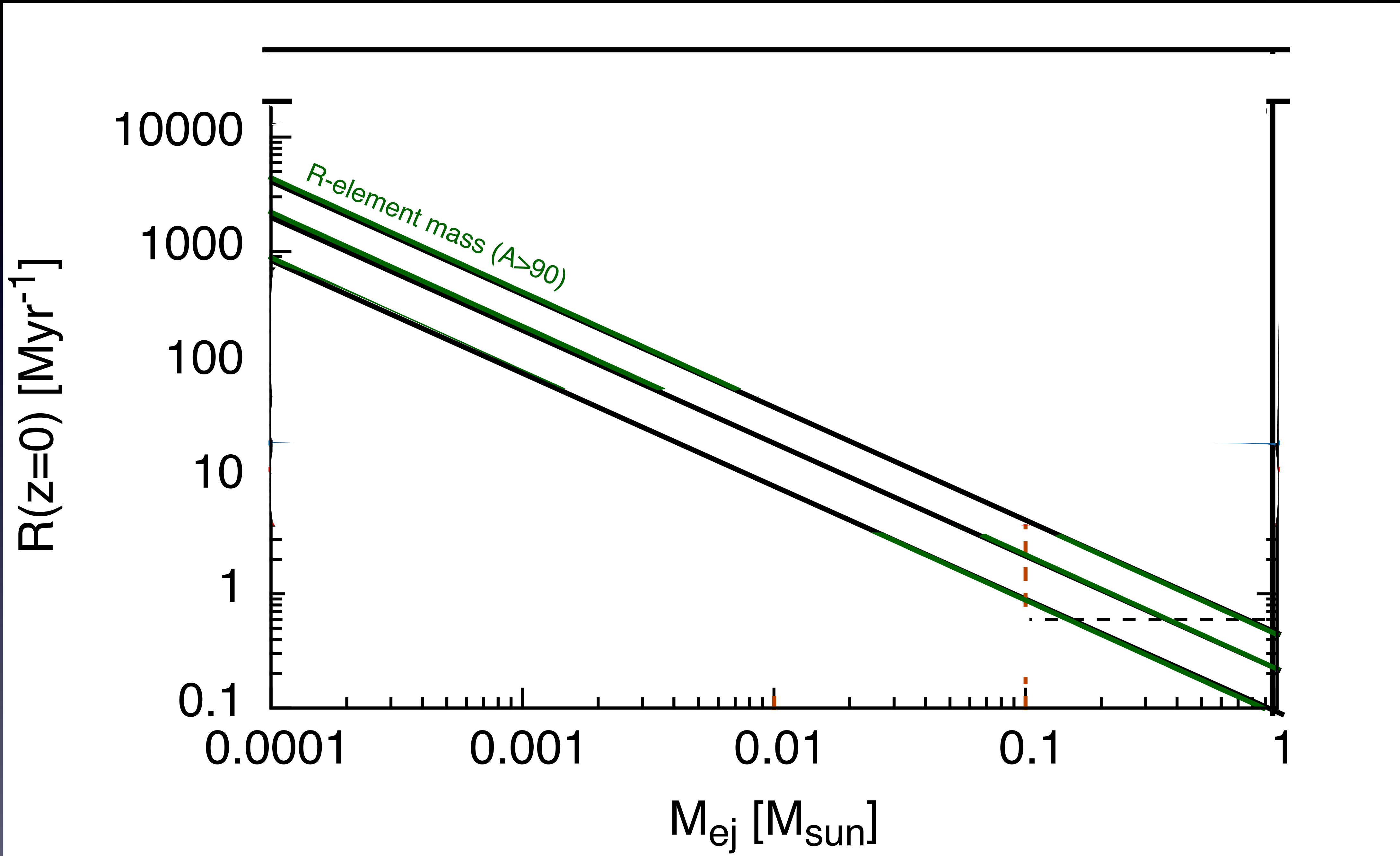
$$N = 2.5 \times 10^5 \left(\frac{M^{A>130}}{10^4 m_\odot}\right)\left(\frac{m_{ej}}{0.04 m_\odot}\right)^{-1}$$

A>130 r-process material in the Galaxy

Mergers' Rate

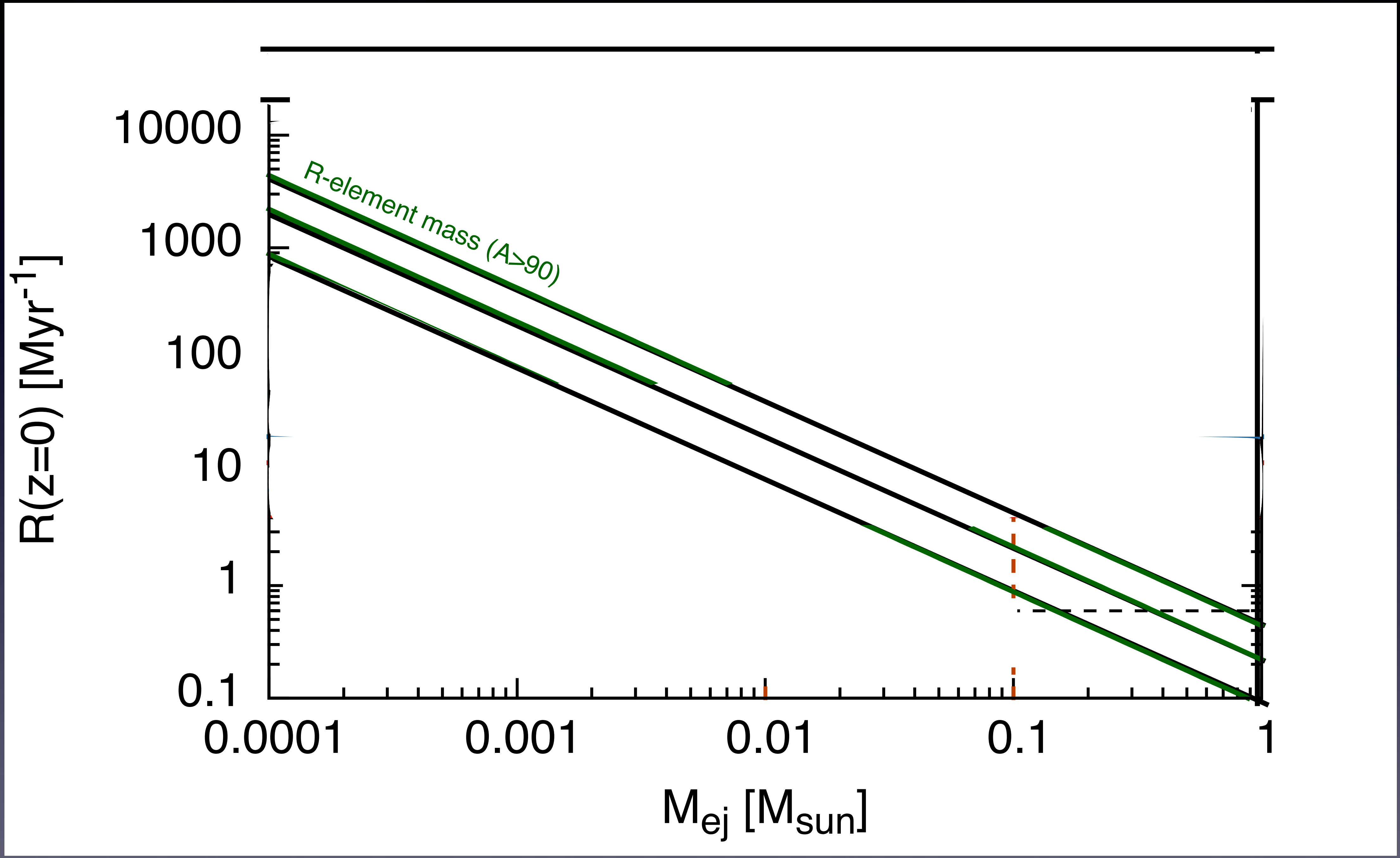
$$R_{merger} = 20 \left(\frac{m_{ej}}{0.04 m_\odot}\right)^{-1}\left(\frac{M^{A>130}}{10^4 m_\odot}\right) \text{Myr}^{-1}$$
$$= 200 \left(\frac{m_{ej}}{0.04 m_\odot}\right)^{-1}\left(\frac{M^{A>130}}{10^4 m_\odot}\right) \text{Gpc}^{-3}\text{yr}^{-1}$$

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).
lines of SGRB: beaming factor f_b^-1 = 10, 30, 70 (Wanderman & Piran 2015)
lines of NSNS: 95% confidence level (Kim et al 2015)

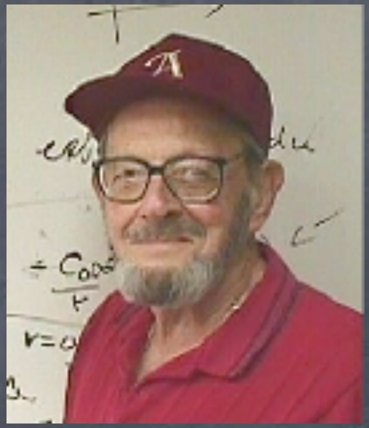
R-Process



Can we break the yield - rate degeneracy?
Hotokezaka, TP Paul, Nature Phys 2015

One cannot give a talk in Astronomy these days without a reference to the Solar System and life.

- The early Solar System had ^{244}Pu (τ= 117 Myr) Wasserburg et al, (2006).

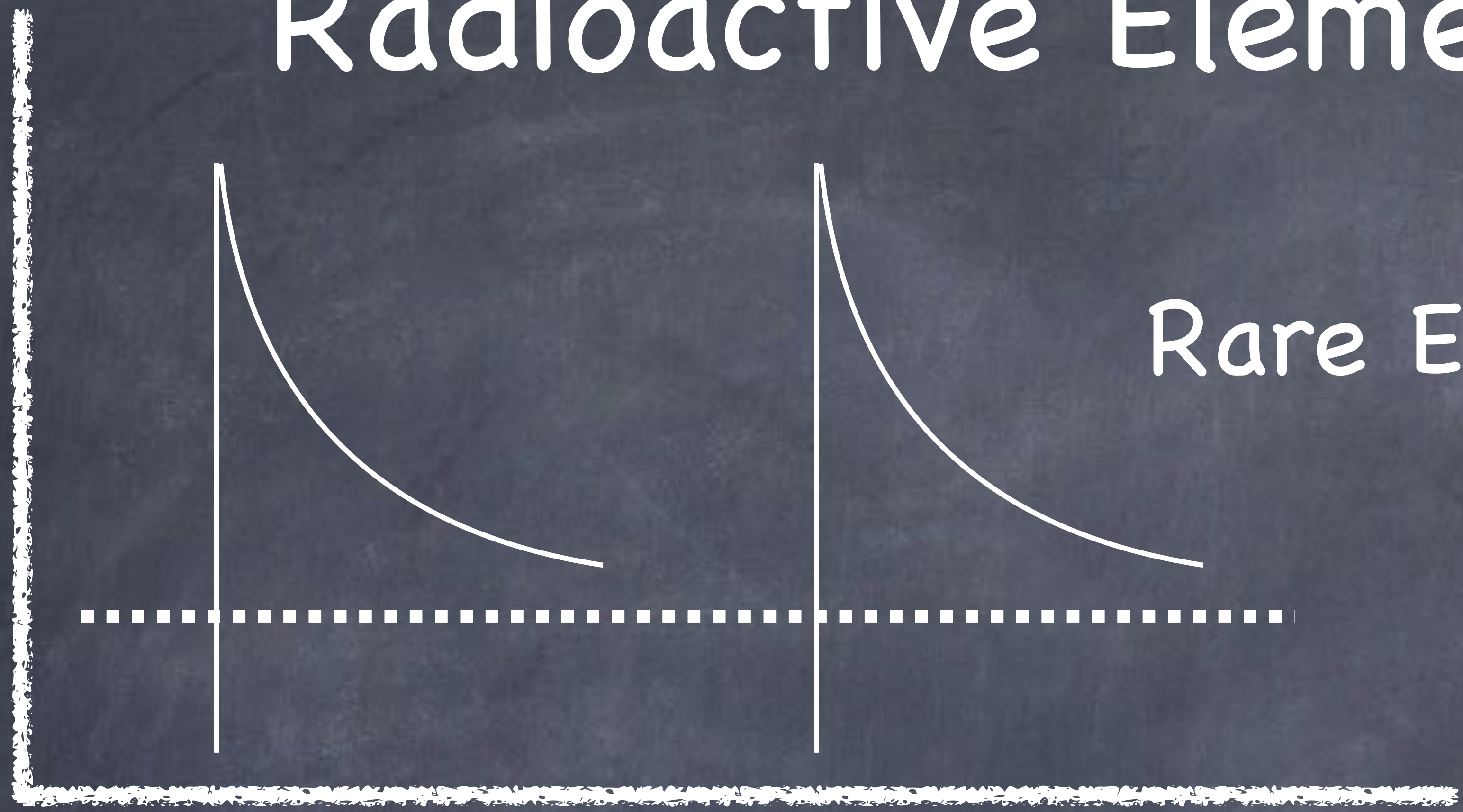


Gerry Wasserburg

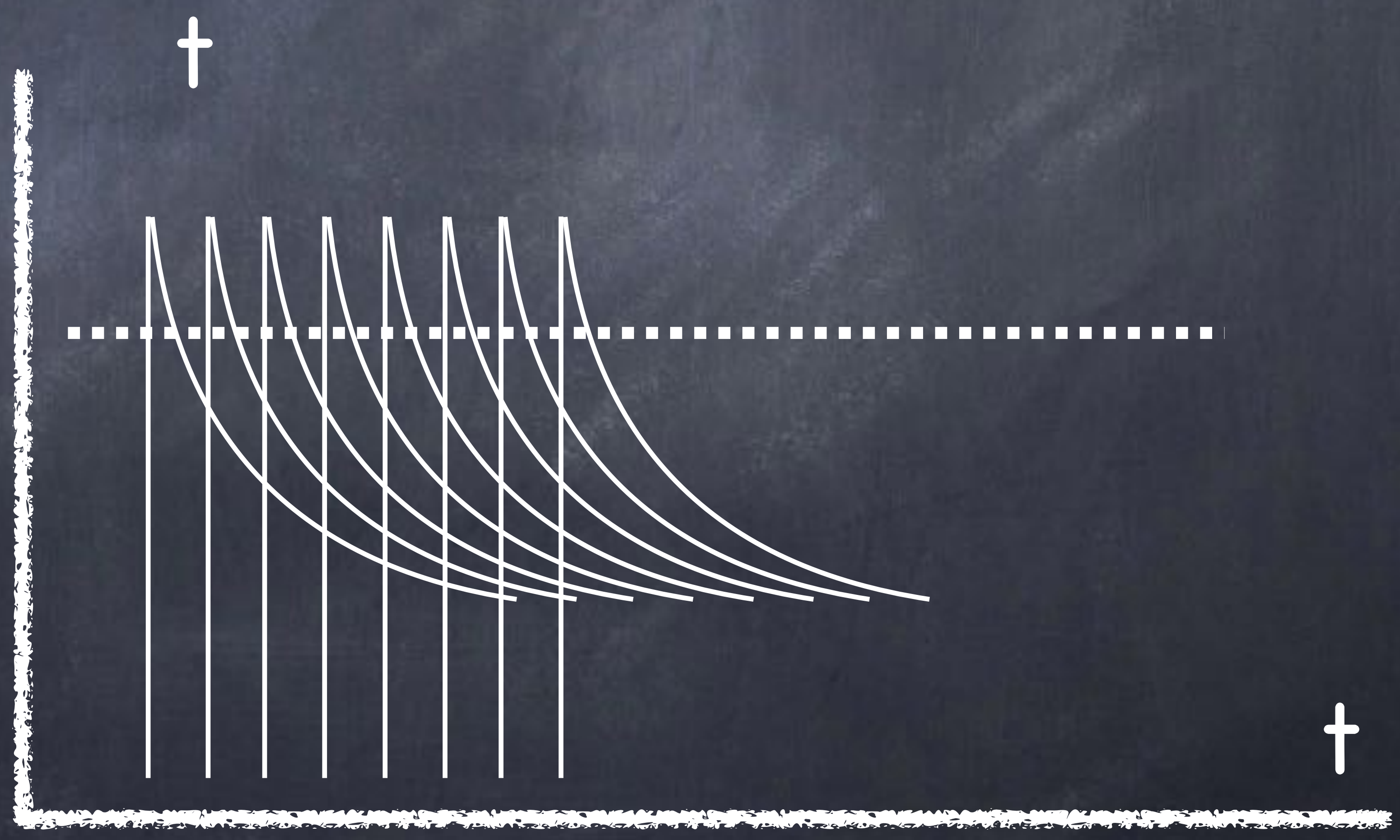
No evidence for ^{244}Pu deposition in deep-sea crust and sediment accumulated over the last ~25 Myr (M. Paul et al., 2001; A. Wallner et al., in preparation). =>
^{244}Pu is NOT from the Inter Stellar Medium! =>
Actinides production near the early Solar System just prior to formation.

- Irregular production from rare episodes.
  => E.g. a merger within <50 pc=150 lyr from the solar system just prior to its formation?

Radioactive Elements



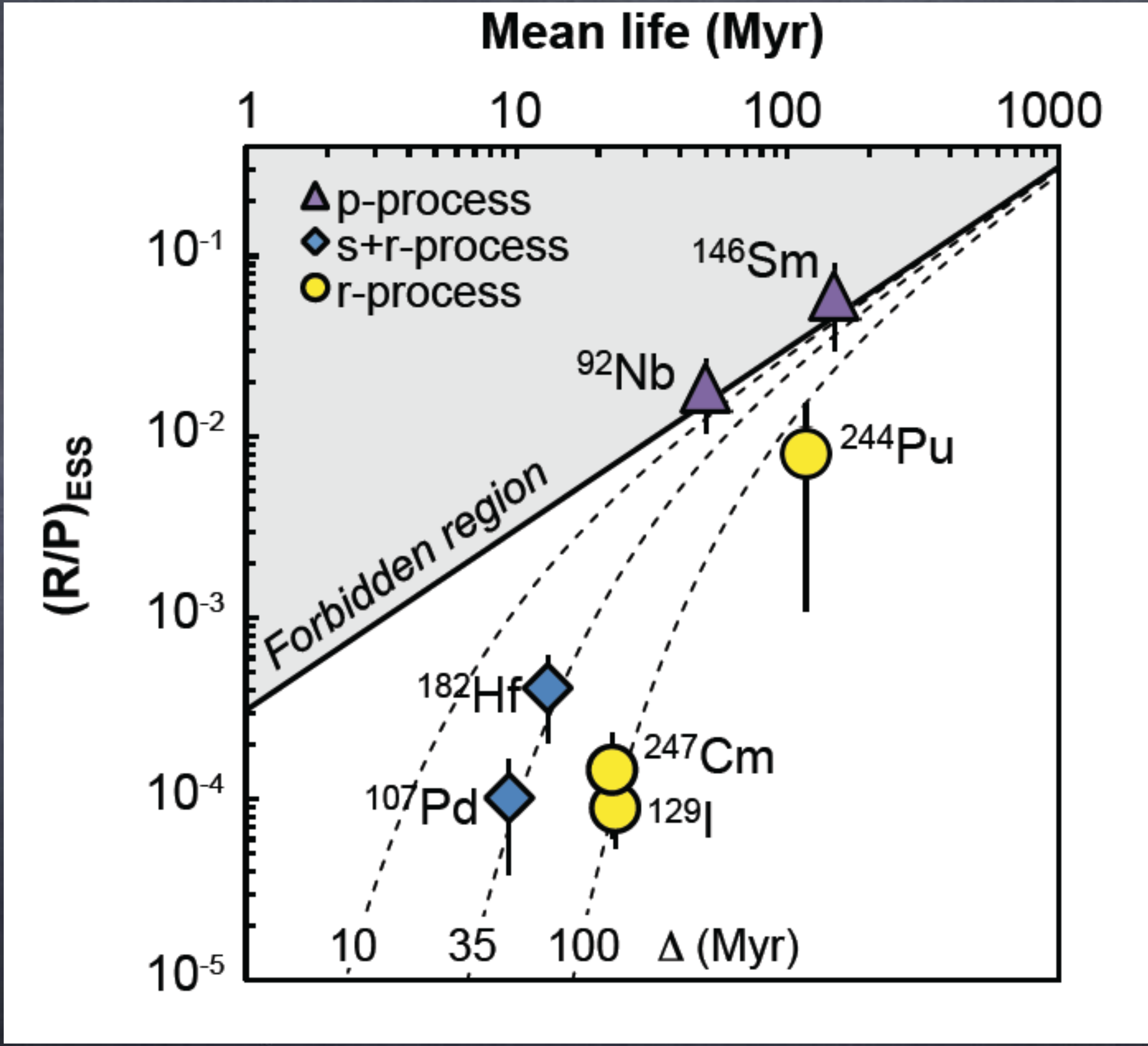
Rare Events



Frequent events

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

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

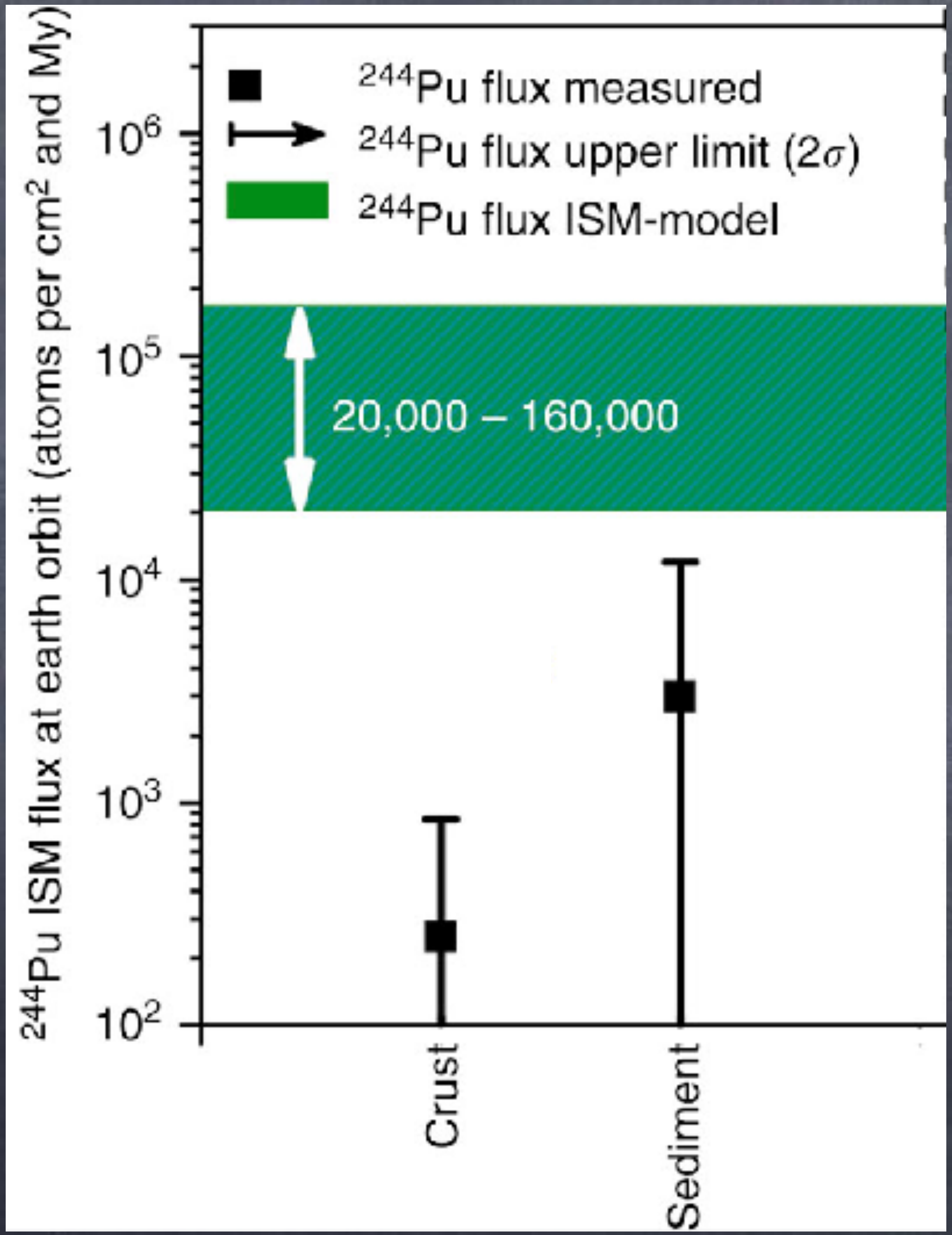


Mean life (Myr)
1
10
100
1000
p-process
s+r-process
r-process
146Sm
92Nb
244Pu
Forbidden region
182Hf
247Cm
107Pd
129I
10
35
100
Δ (Myr)
10-1
10-2
10-3
10-4
10-5
(R/P)ESS

Tissot + 16

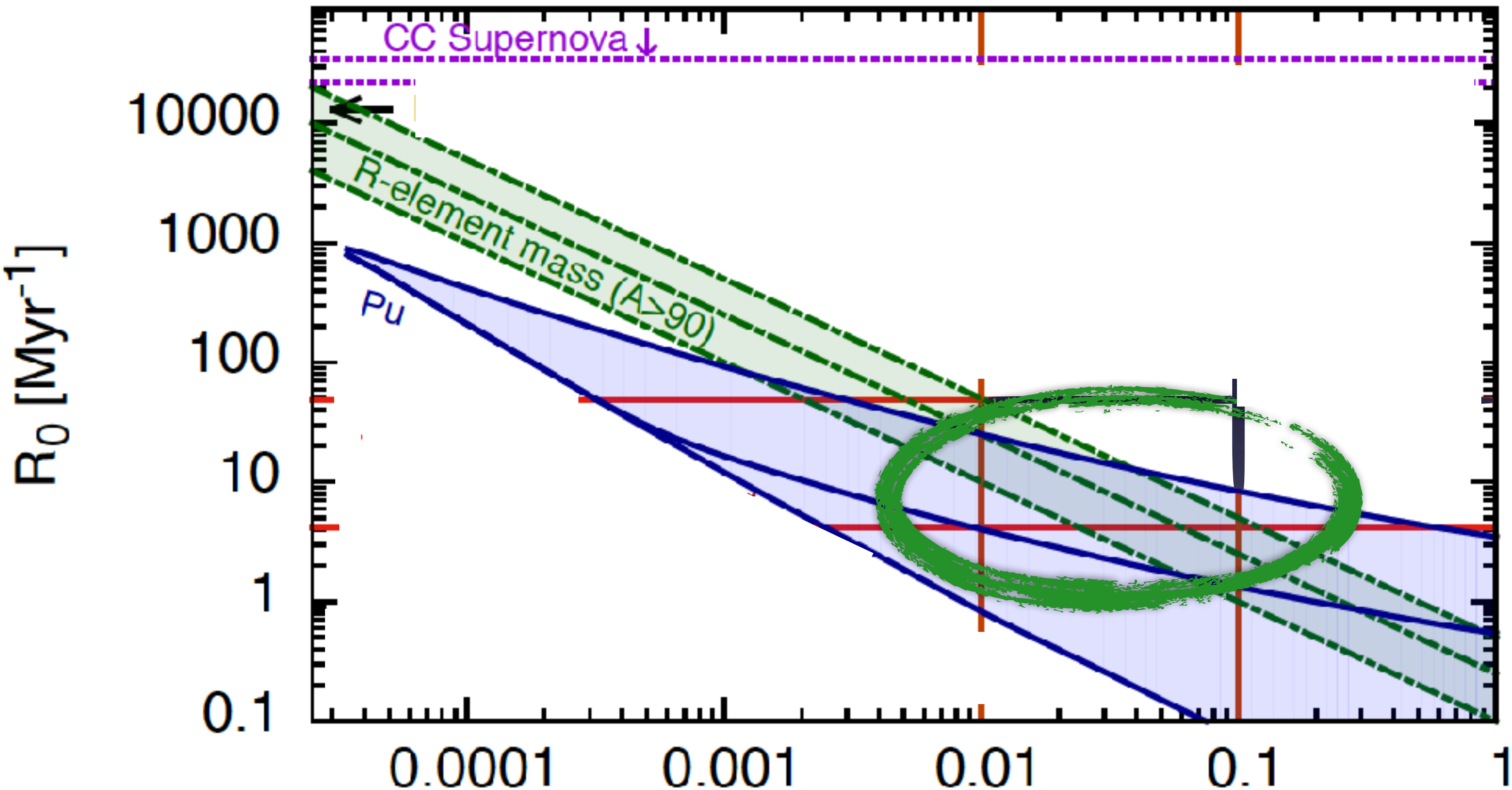
^{244}Pu (half life 81Myr)

The early solar system



Wallner + 14

Breaking the degeneracy: ^{244}Pu

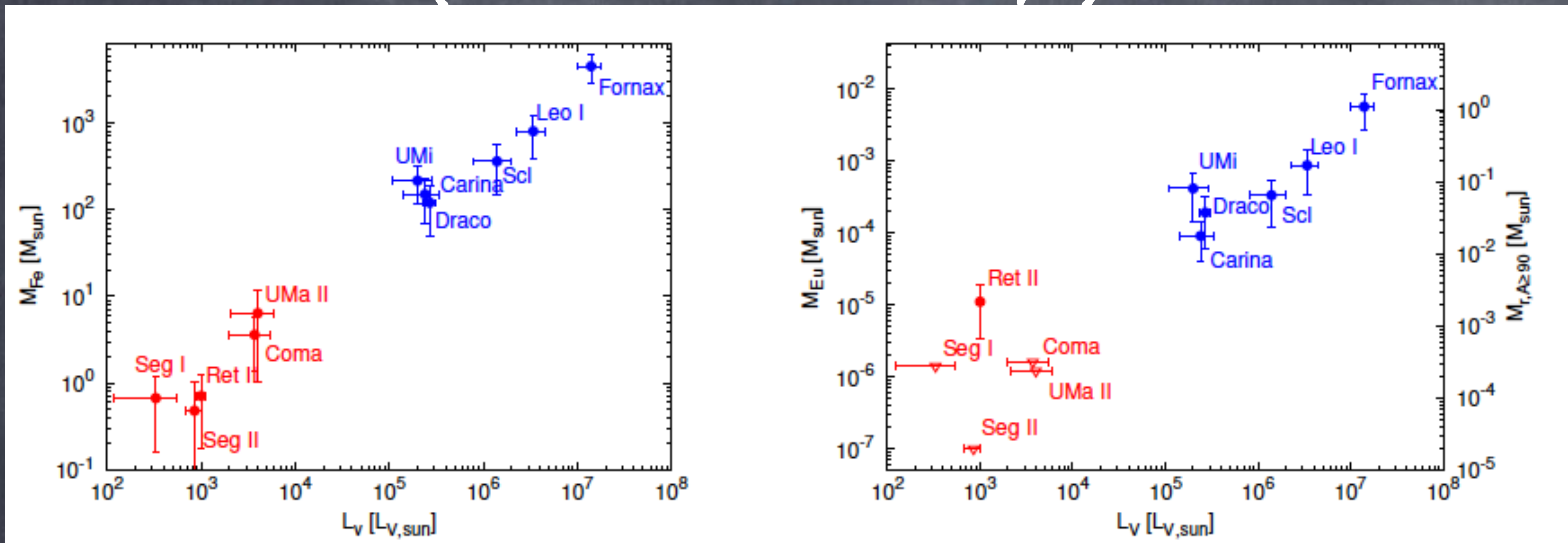


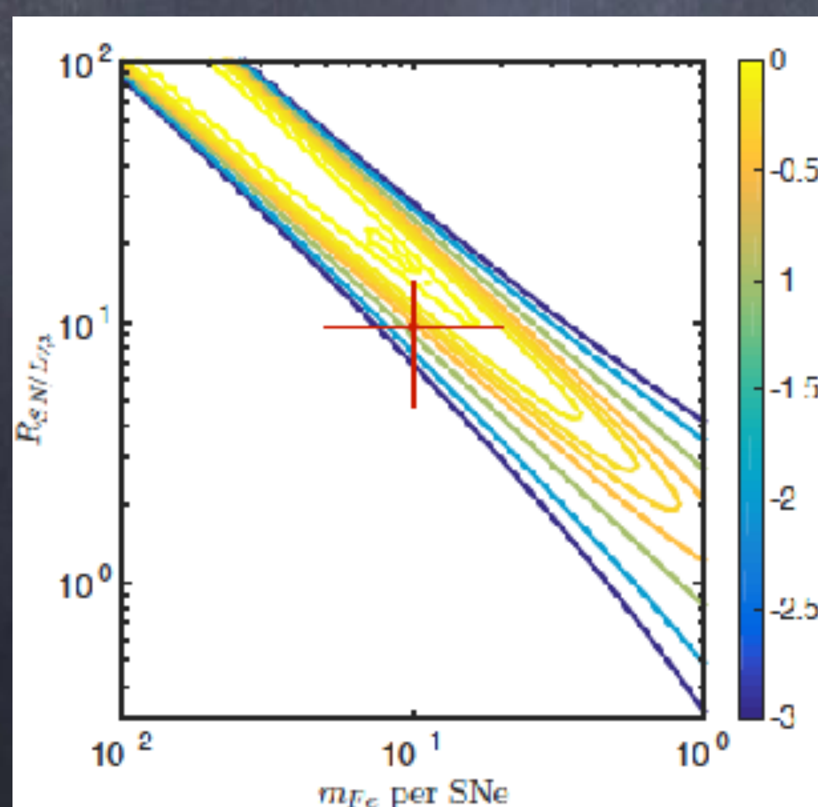
Rare and "massive" events

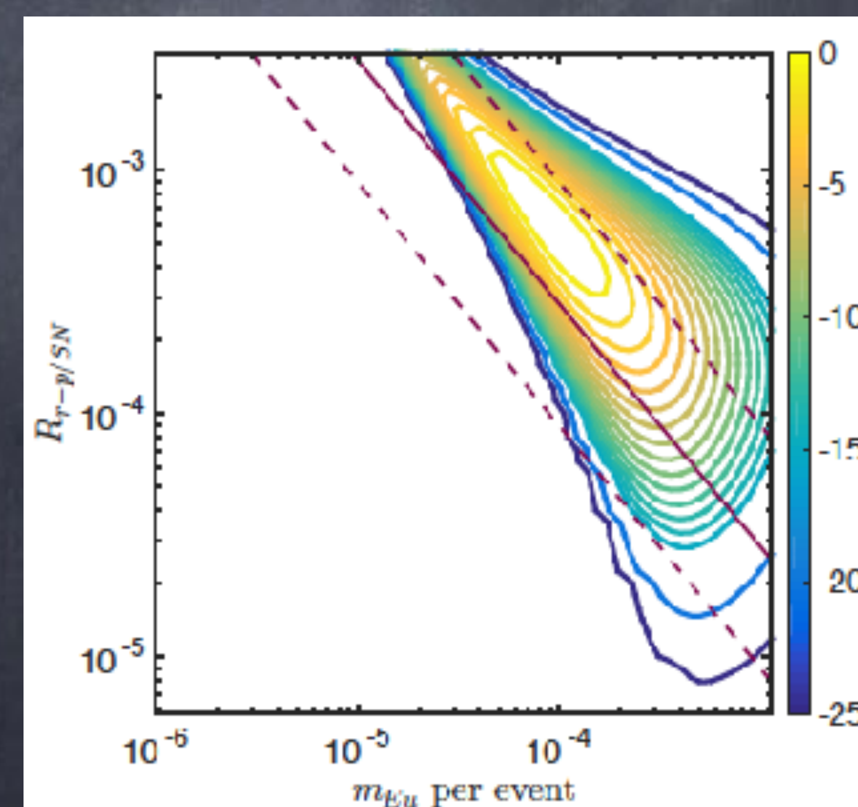
Hotokezaka, TP & Paul, Nature Pays 2015

r-process material in Dwarf Galaxies

(Beniamini+ 16a,b)



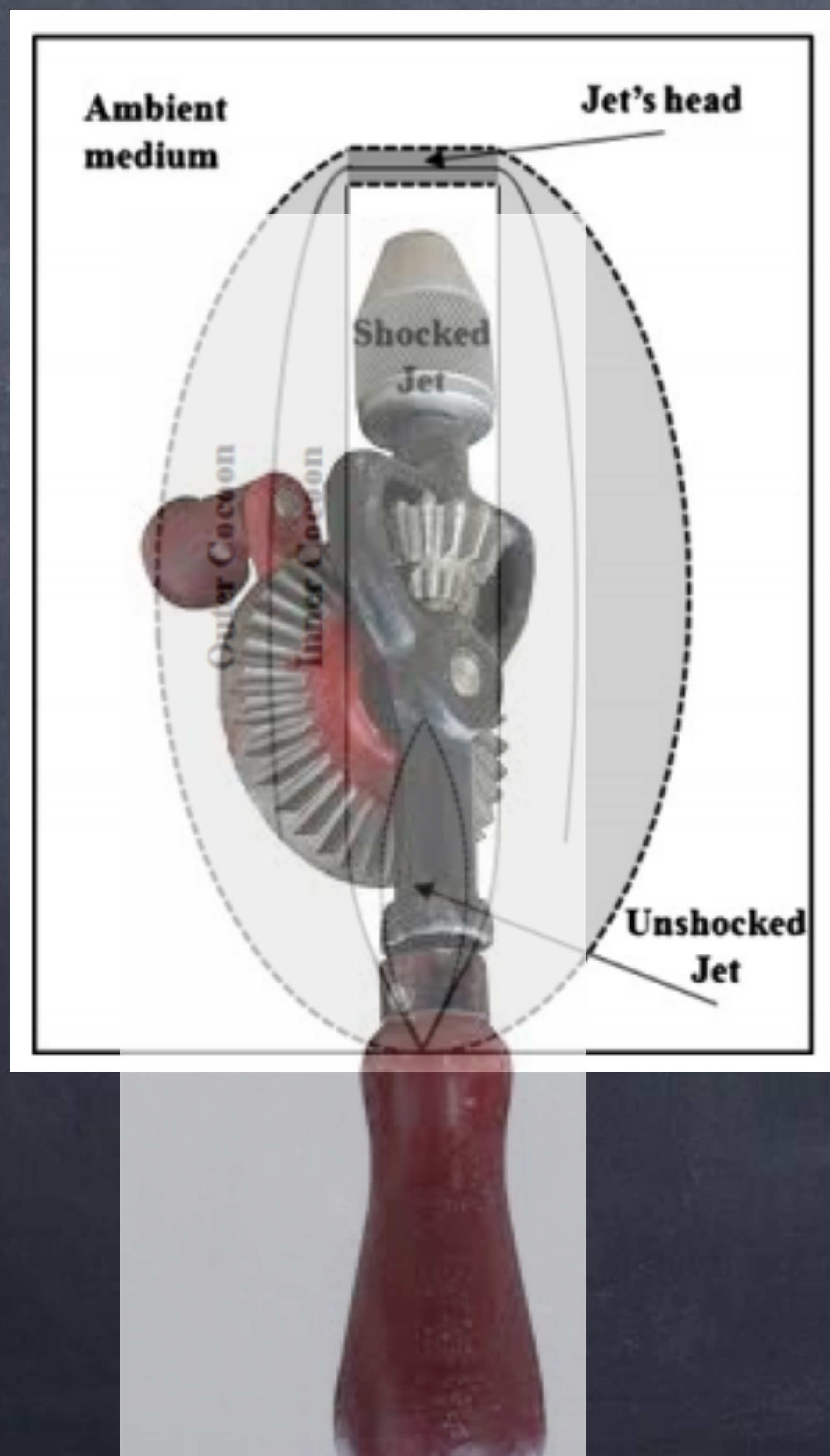


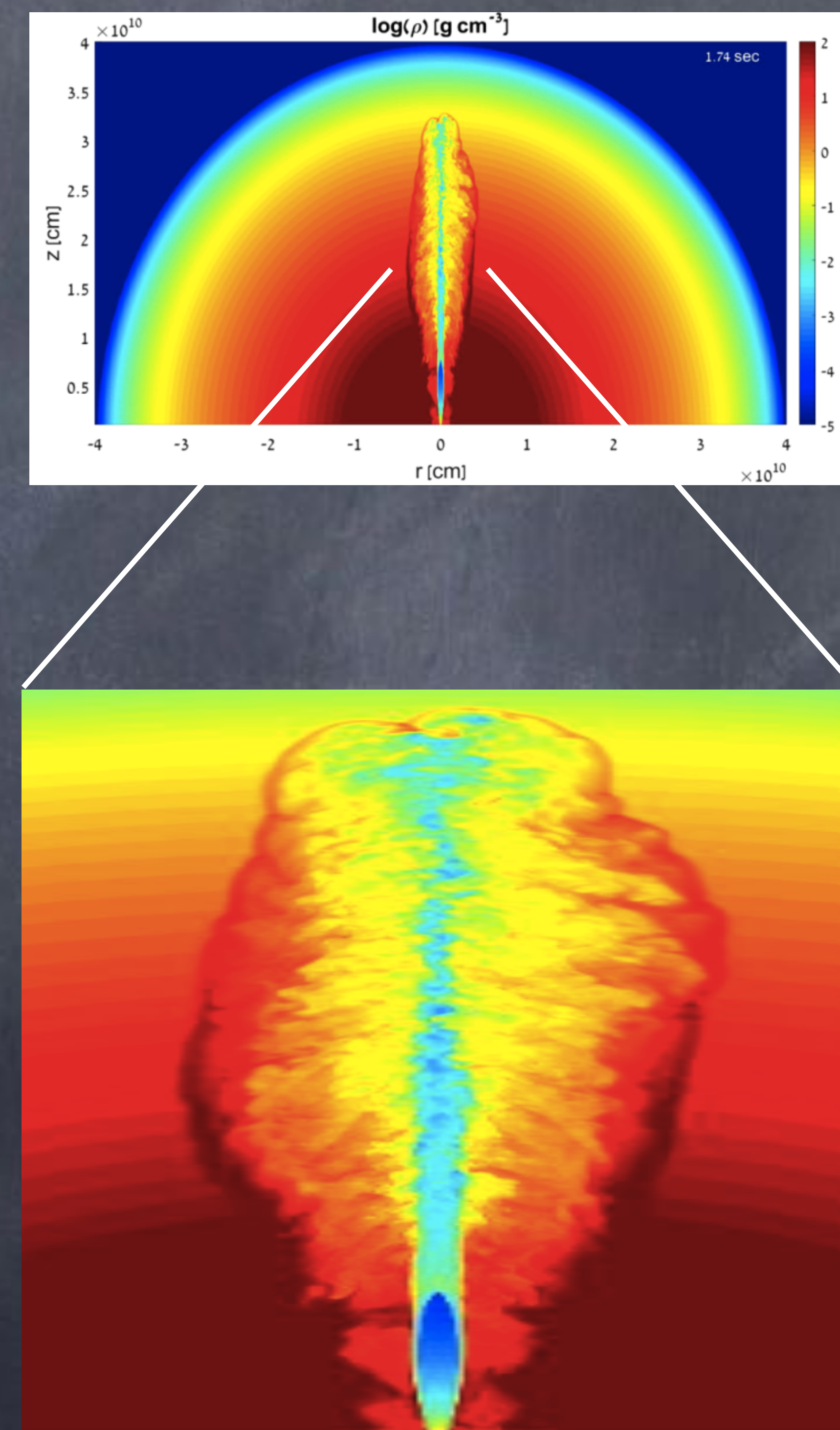


The Origin of Gold

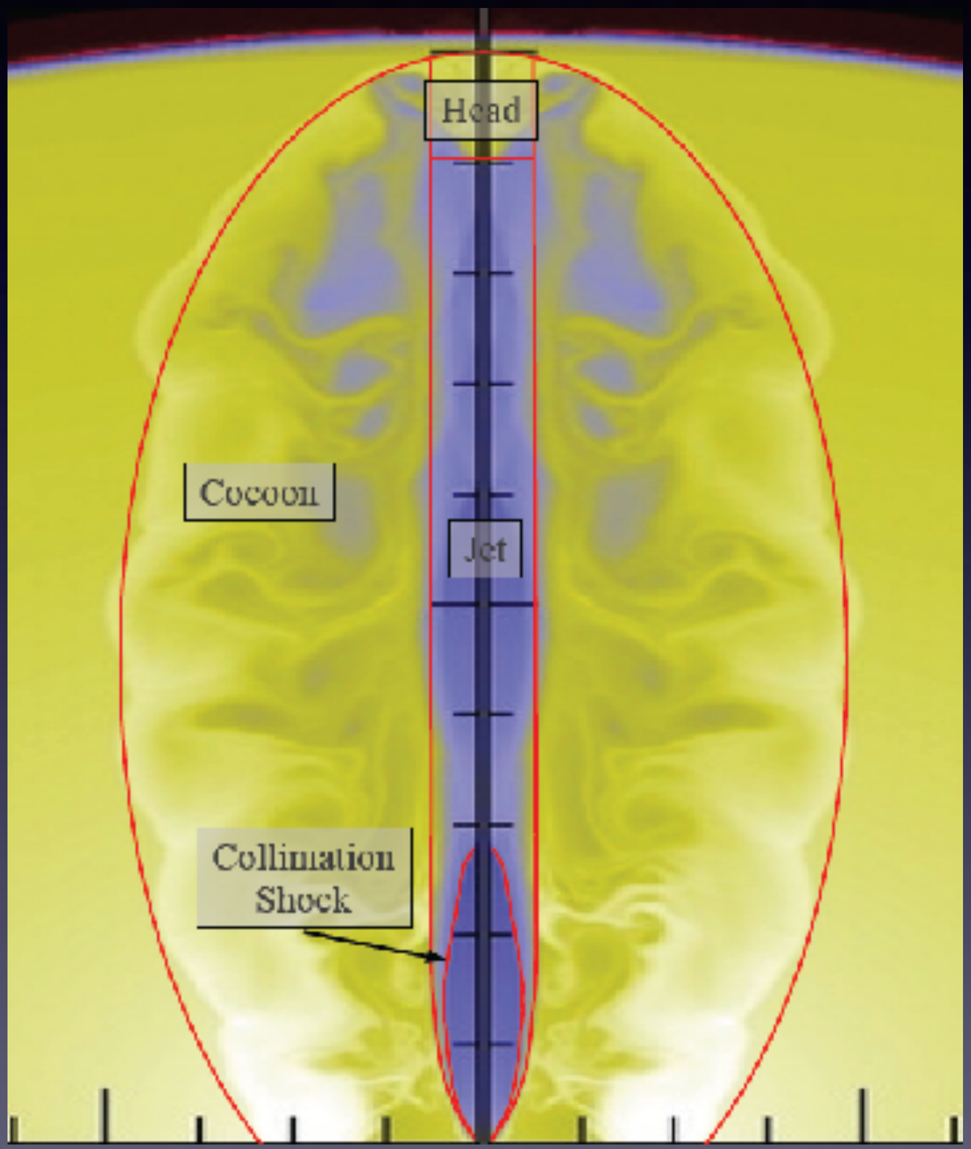
Jet Propagation

(MacFayden & Woosley 1998; Aloy+ 1999; Matzner 2003; Lazzati and Begelman,05; Bromberg + 2011….)





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



Observed duration

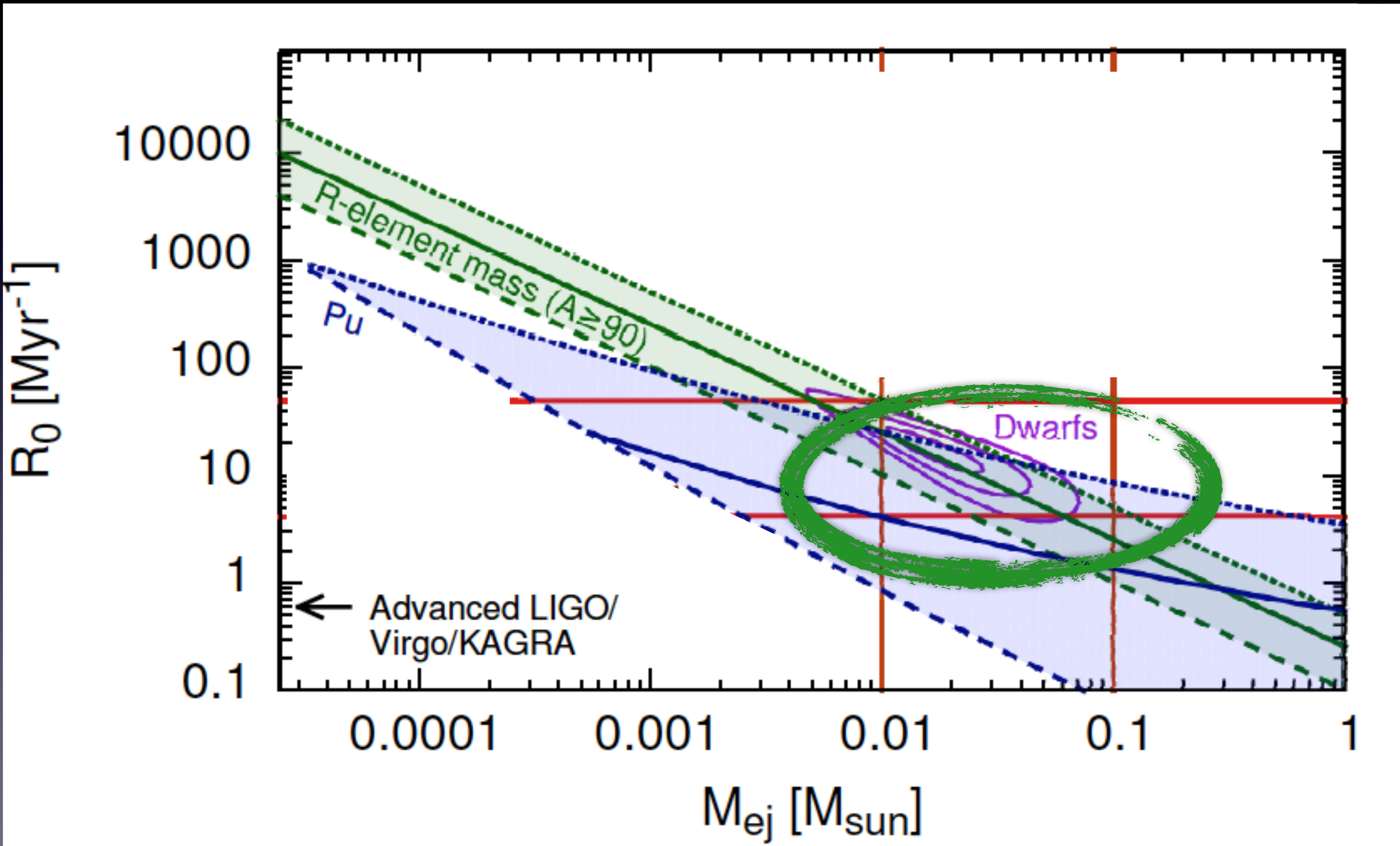
$T_{90} = T_e - T_B$

Engine time

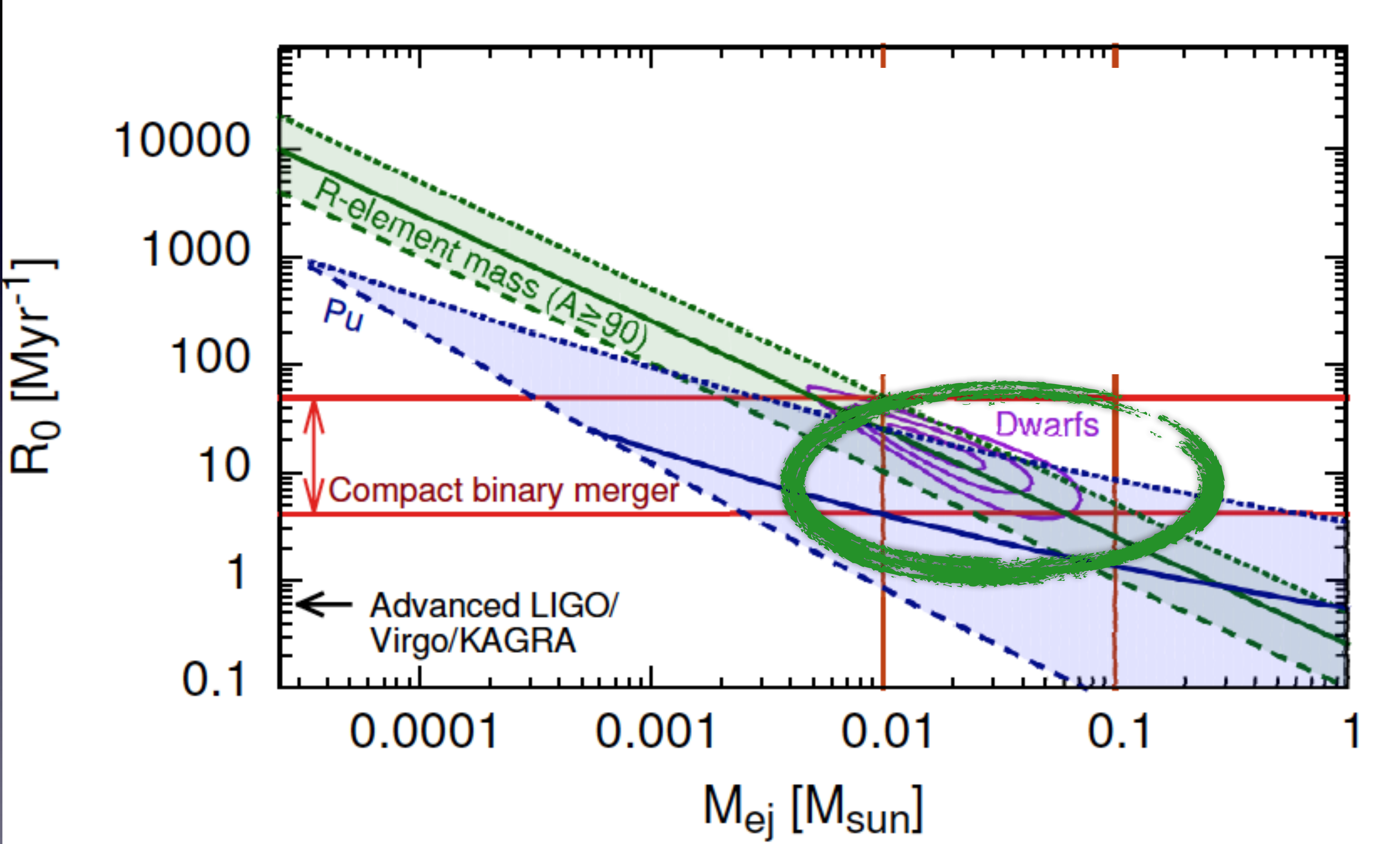
Break out time

$$t_b \simeq 15\ \mathrm{sec} \cdot \left(\frac{L_{iso}}{10^{51}\ \mathrm{erg/sec}}\right)^{-1/3} \left(\frac{\theta}{10^\circ}\right)^{2/3} \left(\frac{R_*}{5R_\odot}\right)^{2/3} \left(\frac{M_*}{15M_\odot}\right)^{1/3}$$

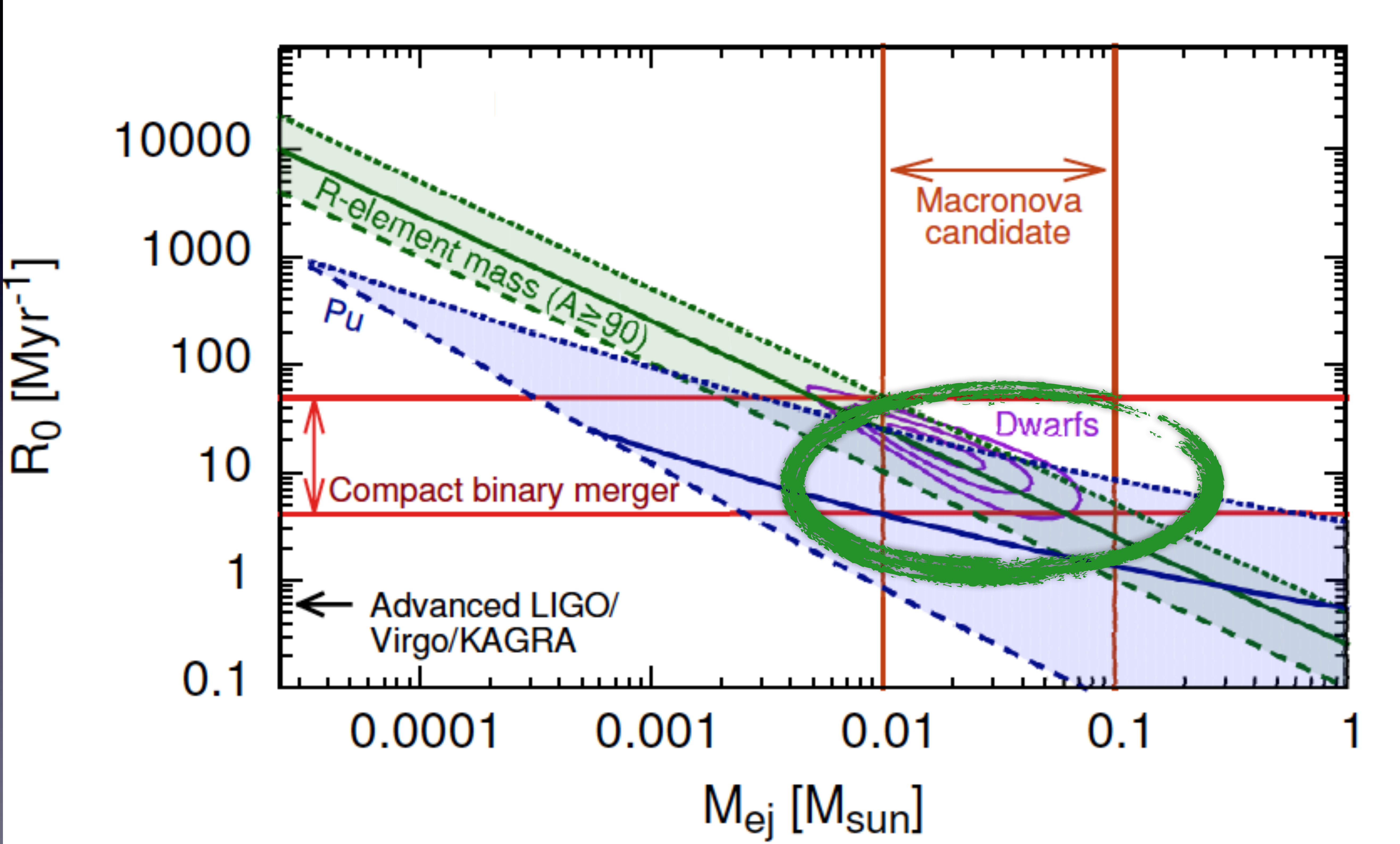
Dwarf Galaxies



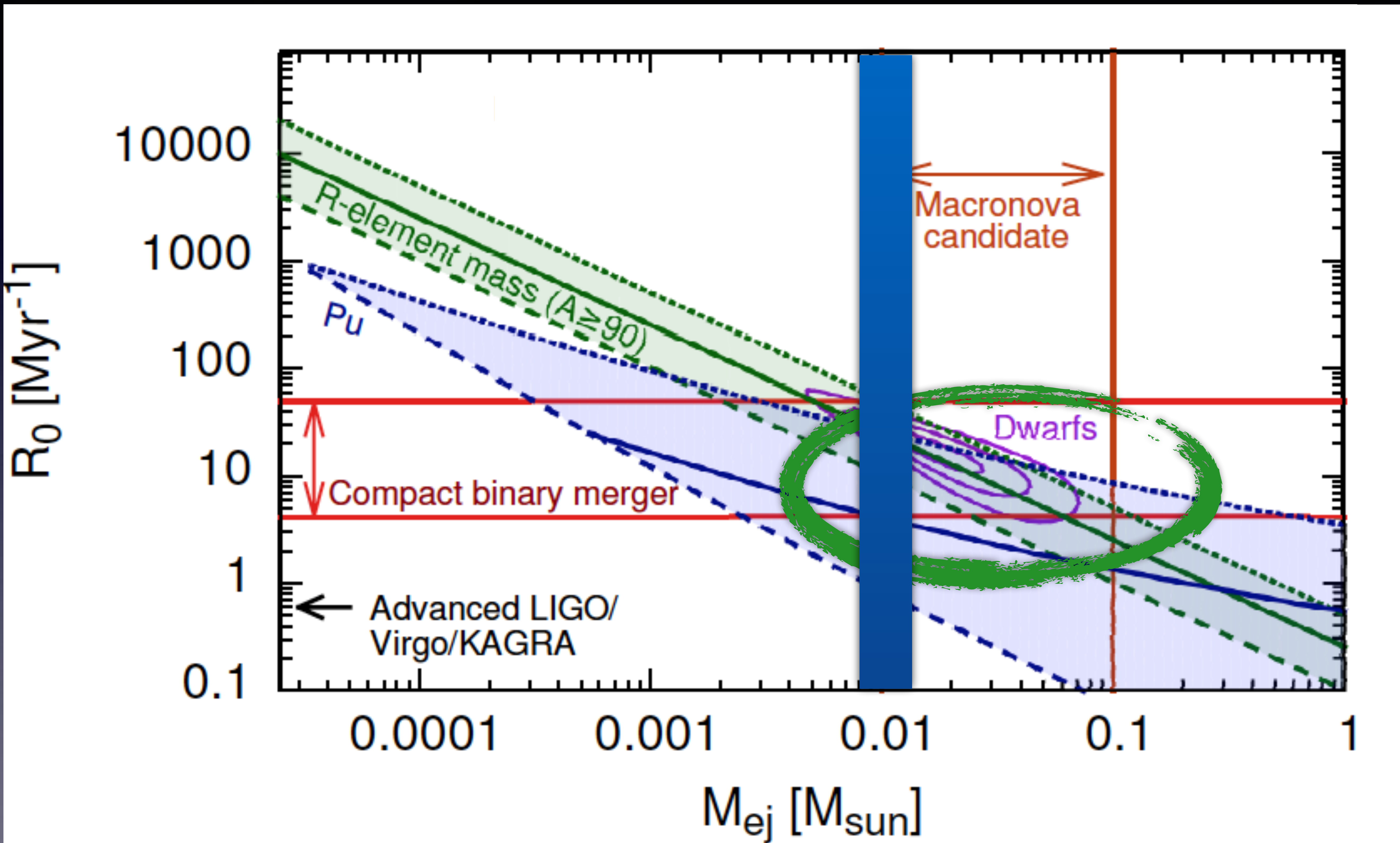
The Merger rate



r-process consistency



From SGRB Plateau



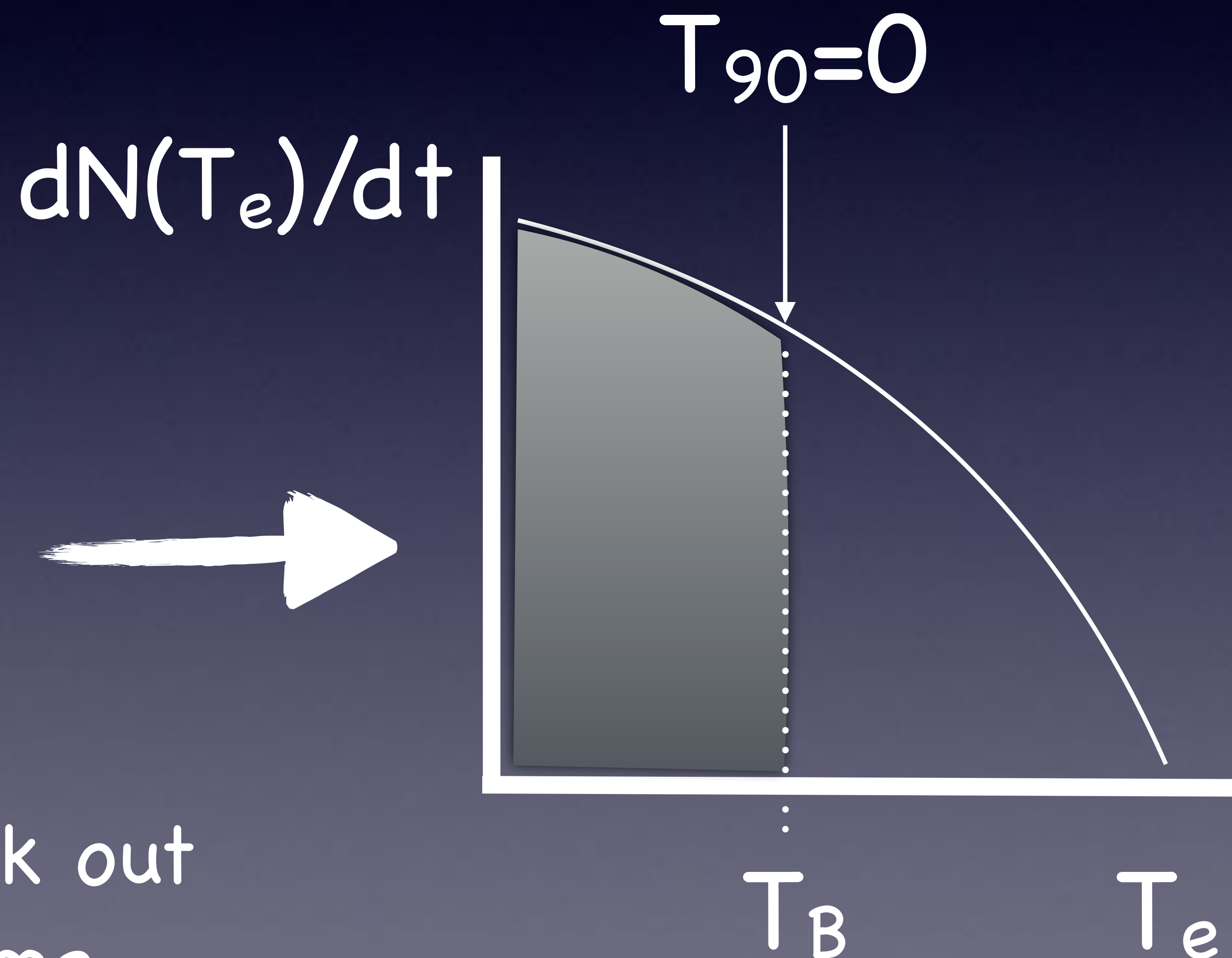
A prediction of the Collapsar model

Observed duration

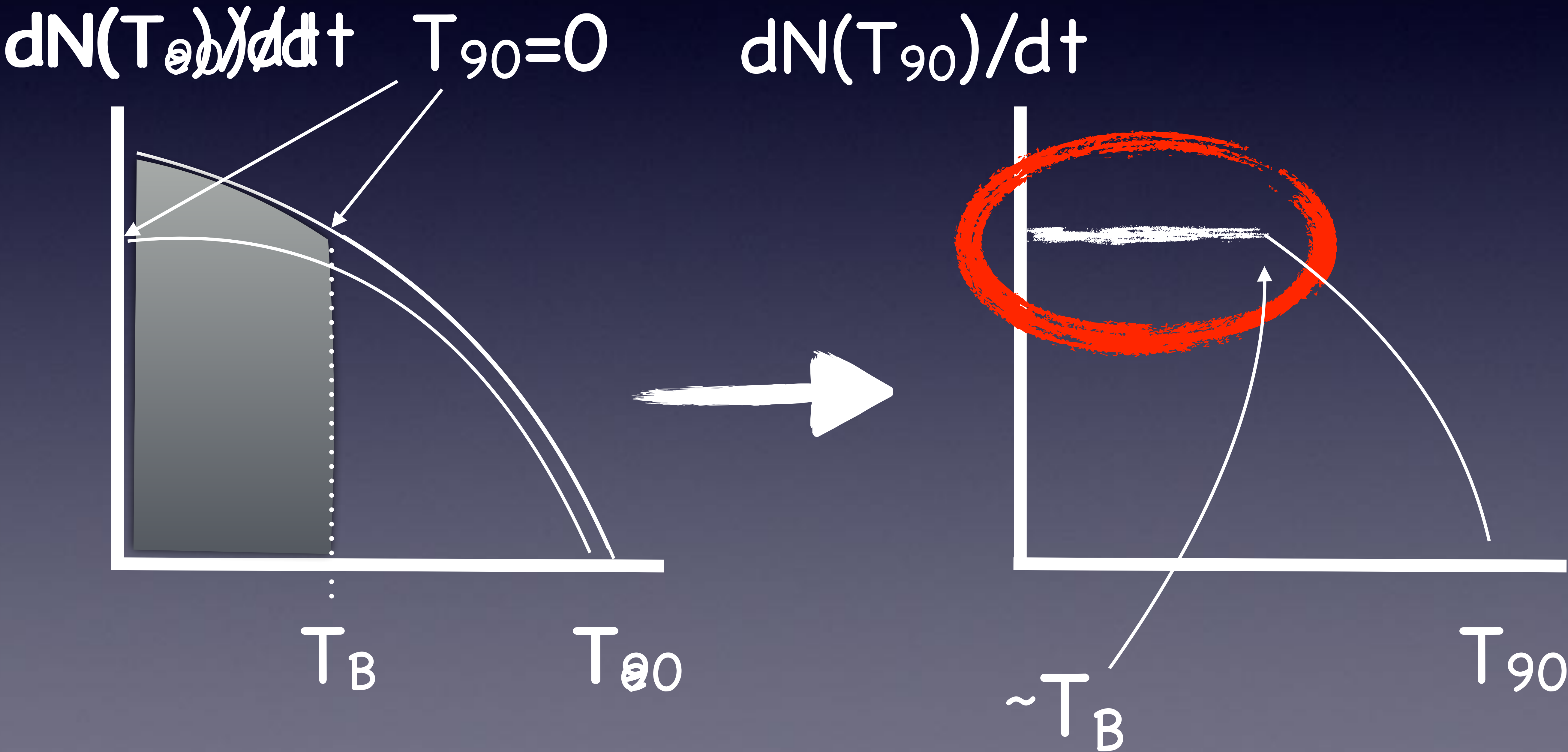
$$T_{90} = T_e - T_B$$

Engine time

Break out time

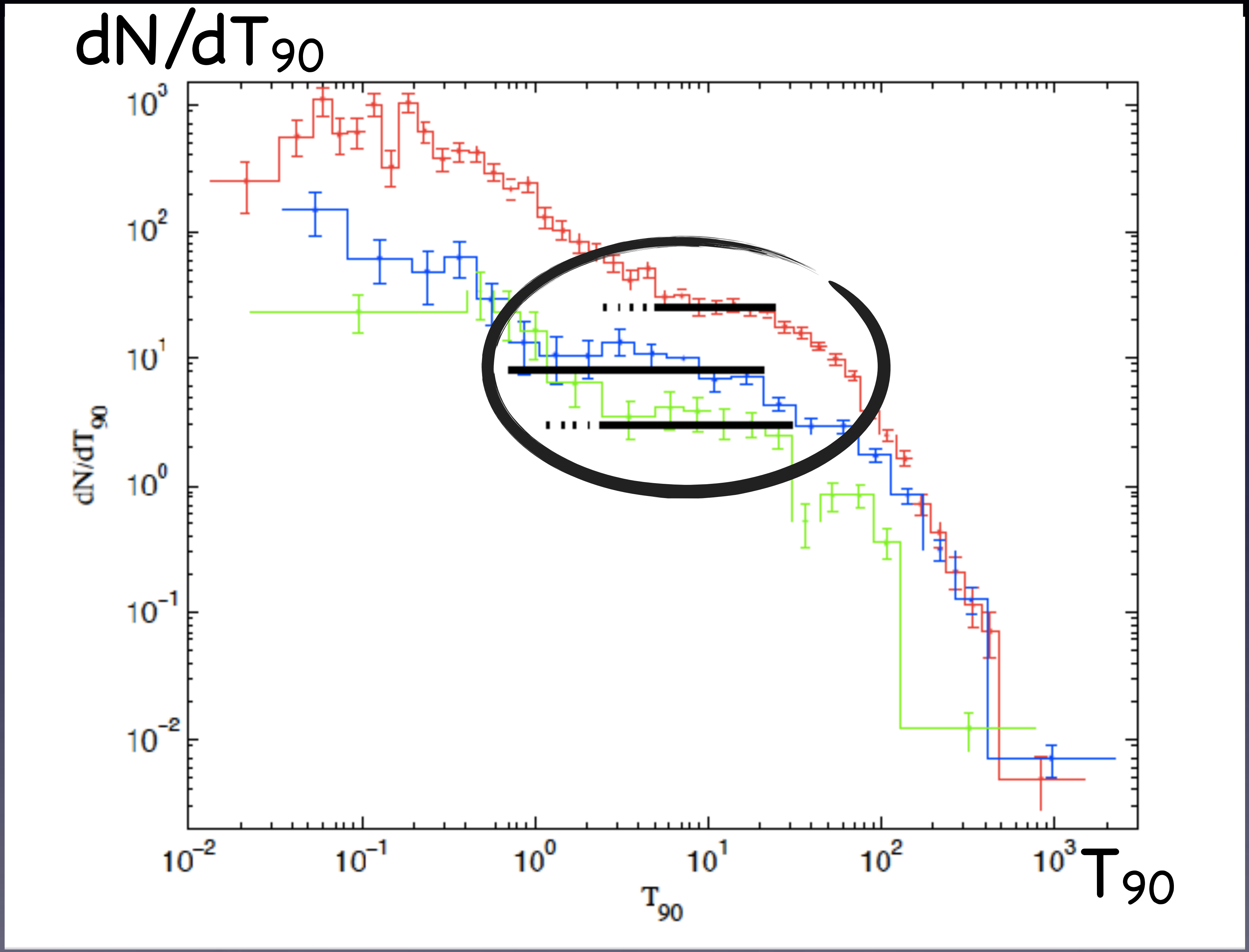


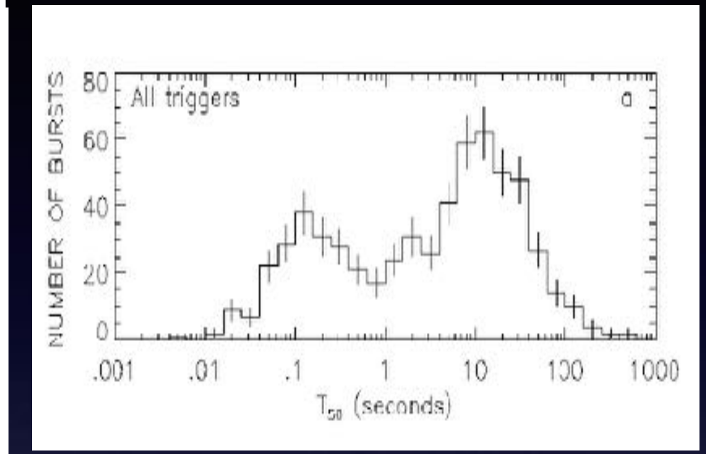
A prediction of the Collapsar model



The duration distribution

(Bromberg Nakar, TP & Sari, 2011)

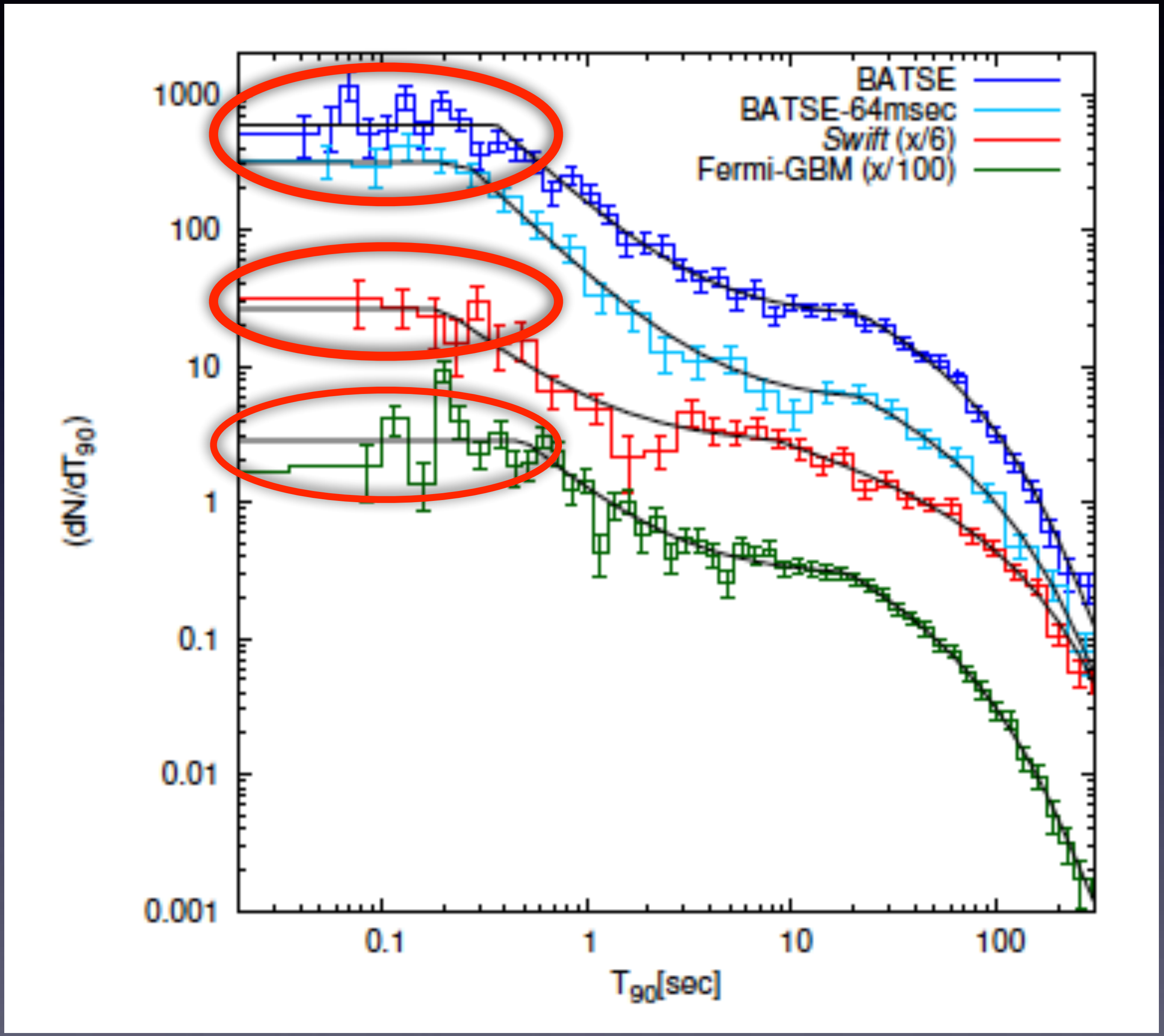


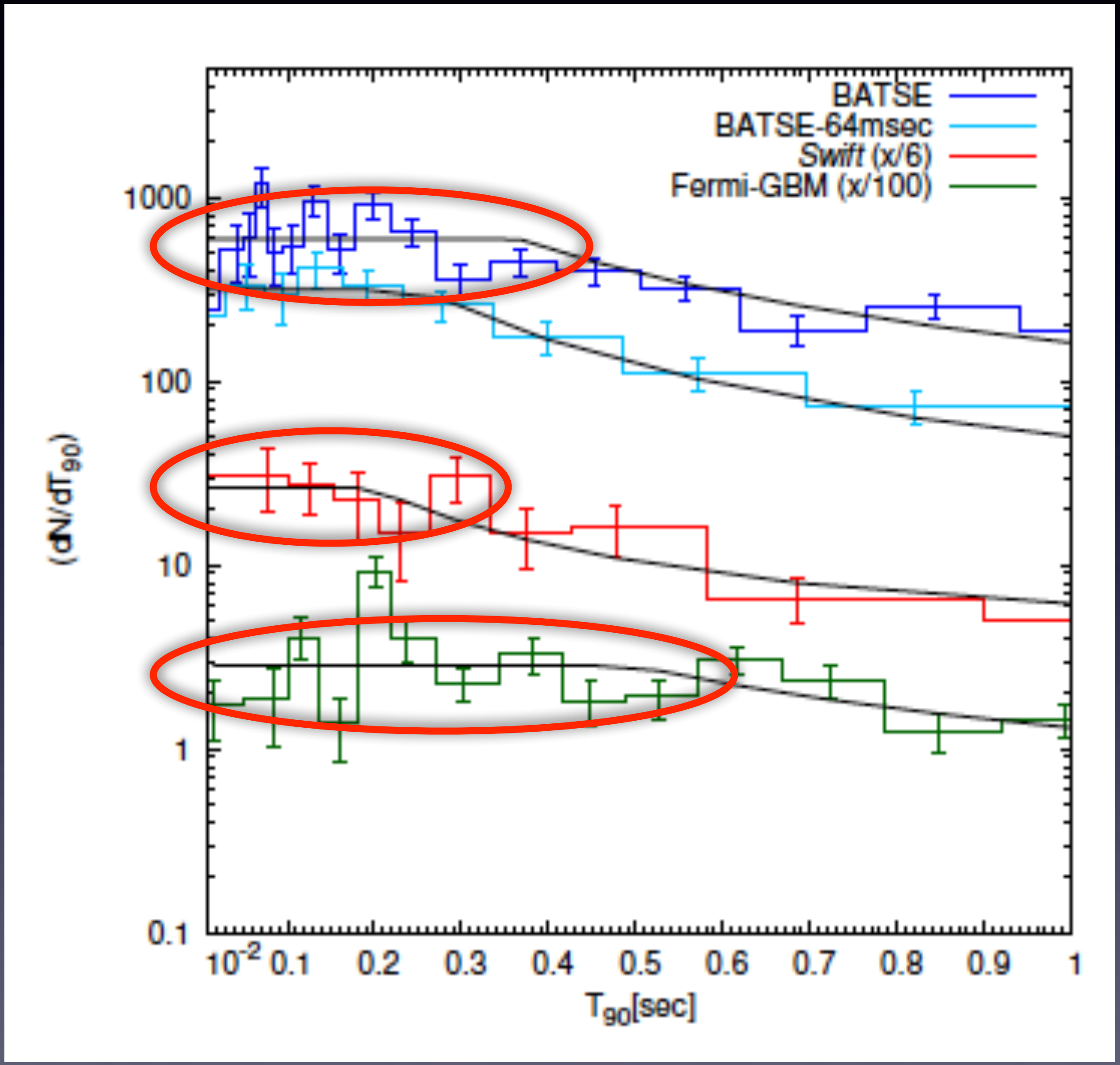


A direct observational proof of the Collapsar model.

The "short" plateau

Moharana & TP 17 arXiv170502598





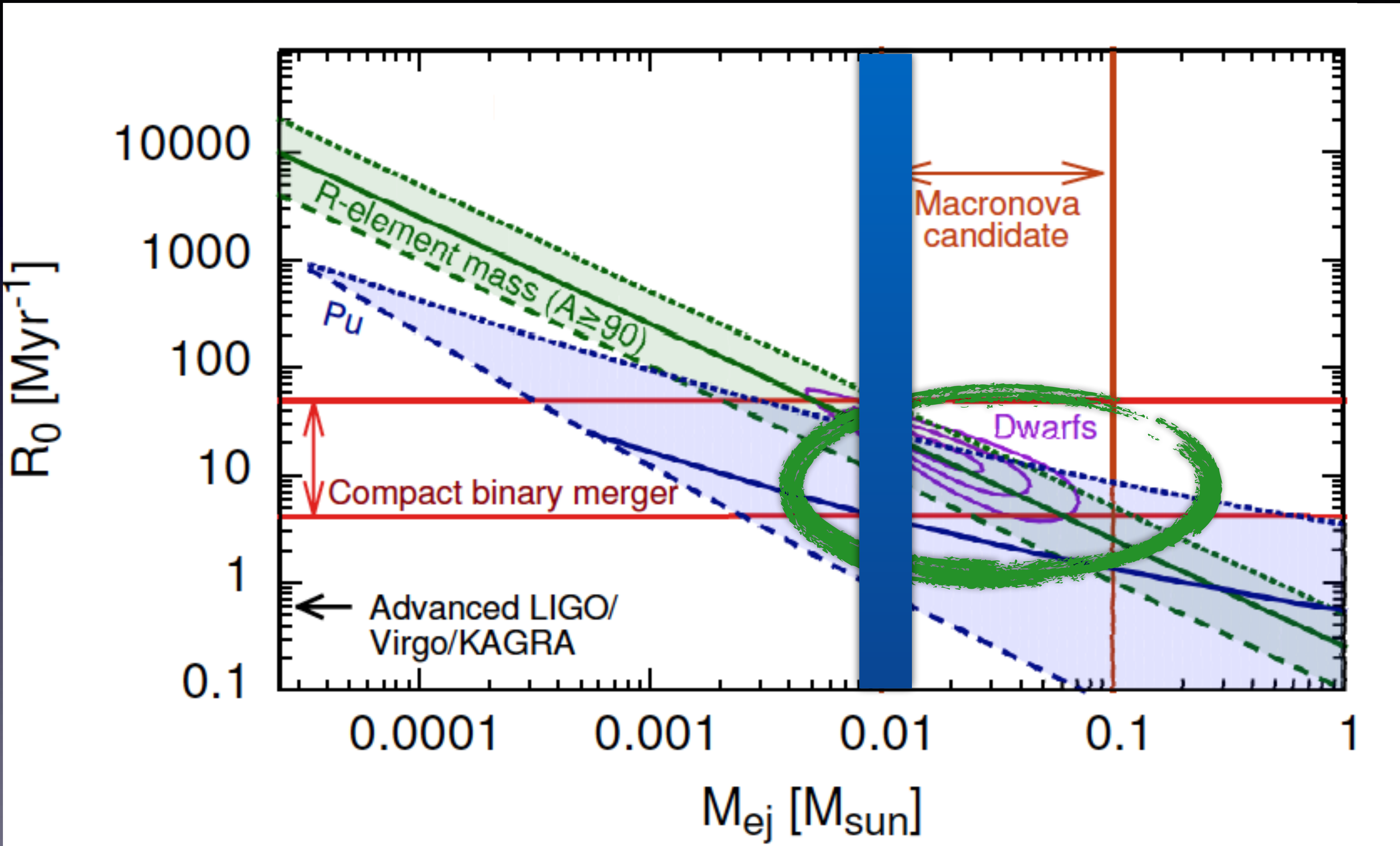
t_b~0.4 Sec

$$t_b = 0.4\,\mathrm{sec}\left(\frac{L_{iso,j}}{10^{51}\,\mathrm{ergs/sec}}\right)^{-1/3}\left(\frac{\theta_j}{15^\circ}\right)^{2/3}\left(\frac{R_e}{10^9\,\mathrm{cm}}\right)^{2/3}\left(\frac{M_e}{10^{-2}M_\odot}\right)^{1/3}$$

$$\int_0^{T_b}(\beta_h(t)-\beta_{max})dt = \beta_{max}\Delta t\,,$$

There are mergers in which the jet don't break out!

From SGRB Plateau



Early nucleosynthesis - a challenge

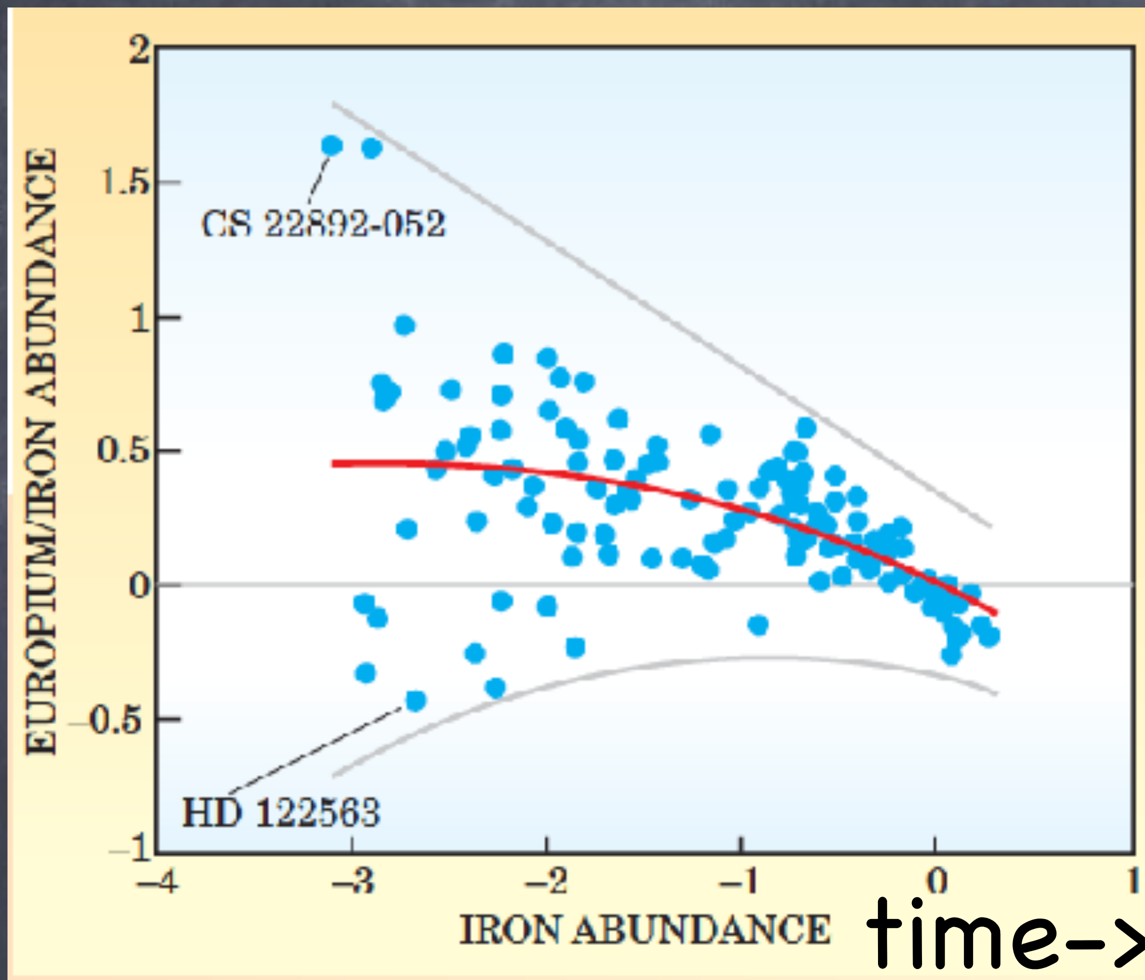


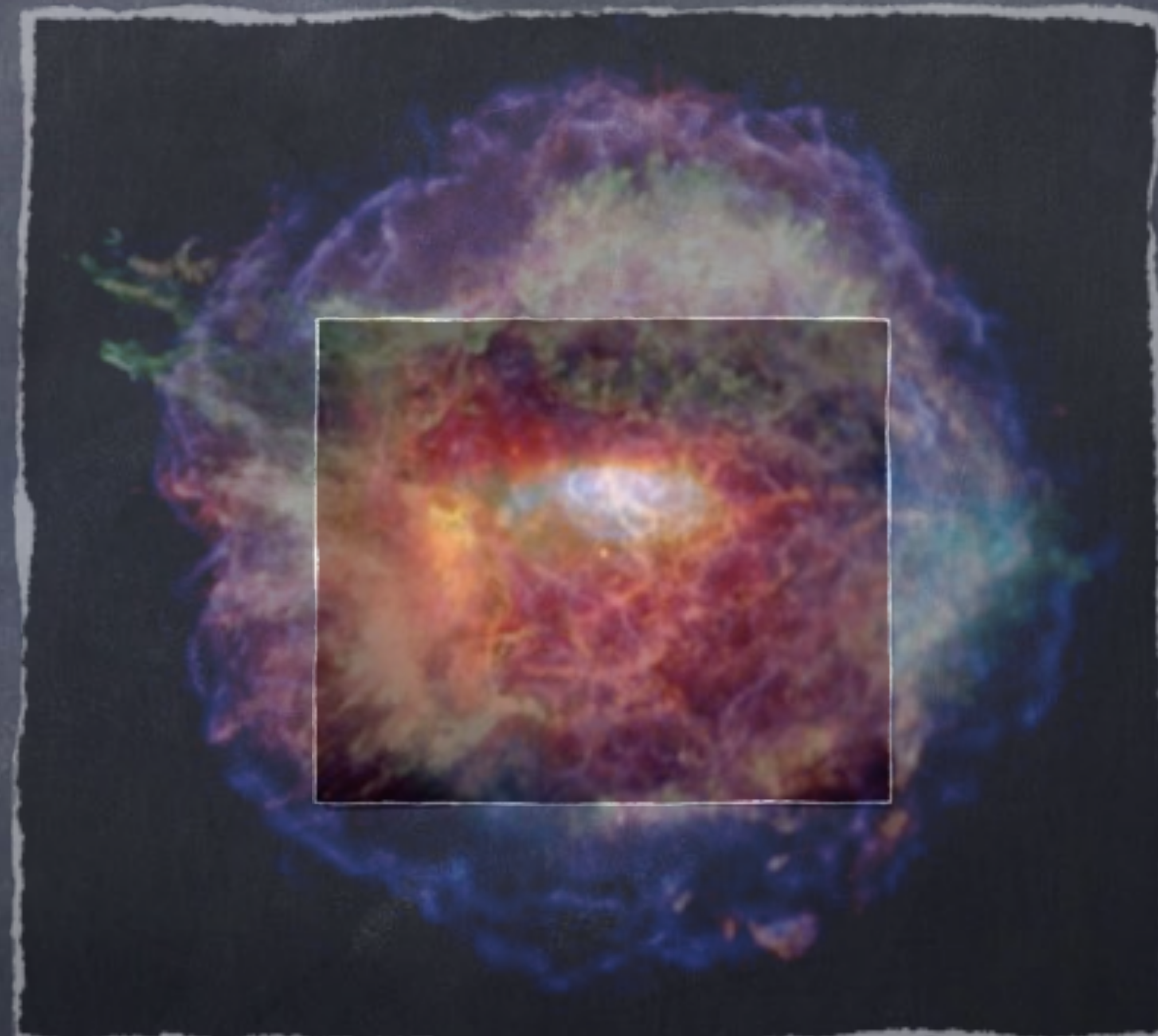
Figure 6. Europium abundance in a large sample of old and young stars, age being inferred from Fe abundance. The halo star HD 122563 is almost as Fe-poor as CS 22892-052, and therefore presumably just about as old, but it has much less Eu, an element made only in the r-process. The red line is a least-square-fit to the data, and the gray flanking curves indicate decreasing scatter in the data with increasing time. Numerical conventions are as in figure 5. Zero on the abscissa means Fe abundance like that of the 4.6-billion-year-old Sun.

A population of fast mergers?

From Cowan and Thielemann

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

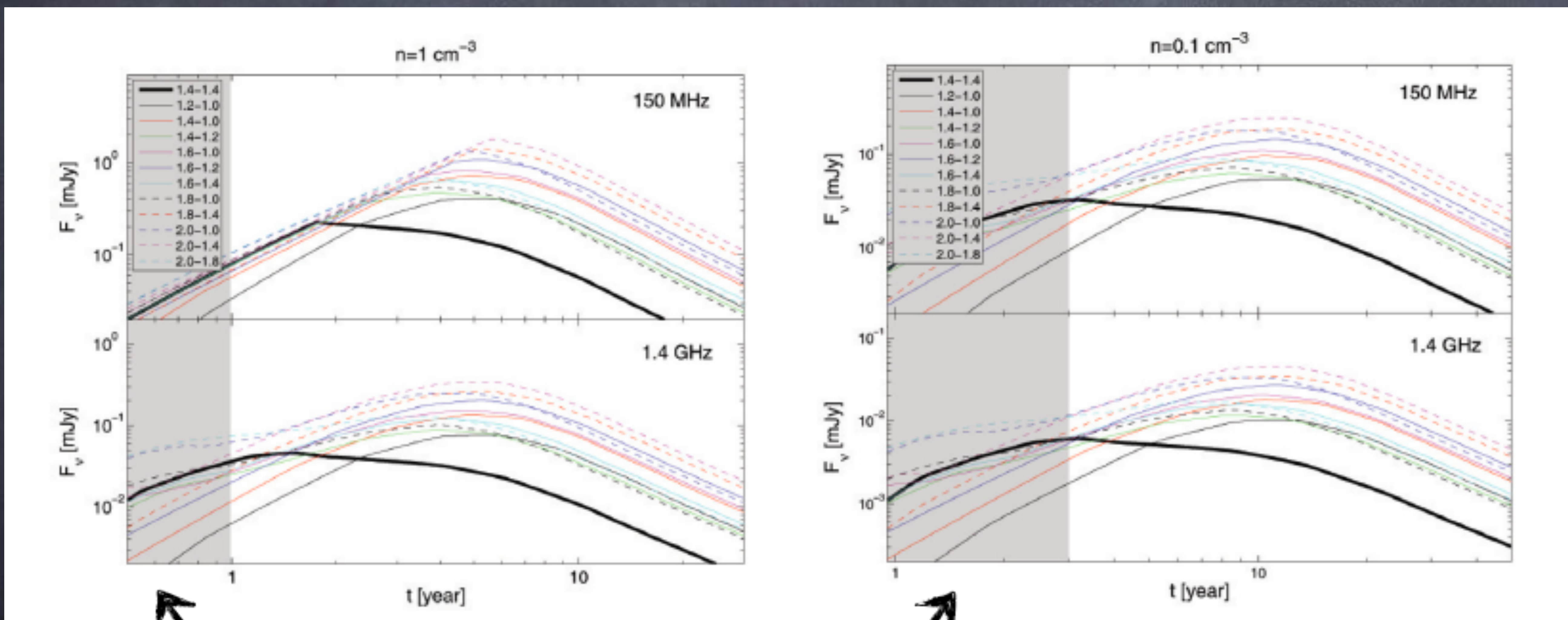
A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.



Supernova -> Supernova remnant

Macronova -> Radio Flare

Radio frlares from neutron star mergers

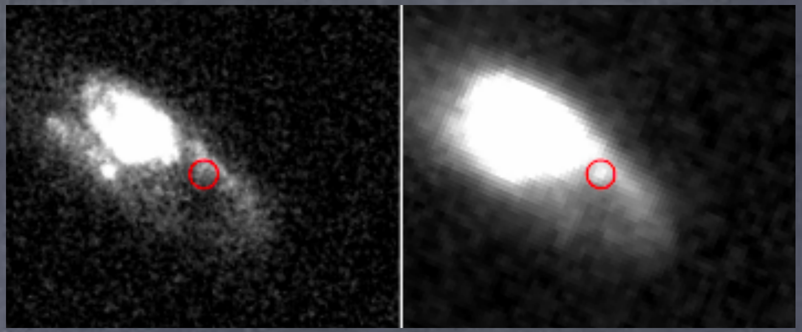


dominated by high velocity ejecta

A flare from GRB 130603B should be easily detected by the EVLA (if external density is not too small)

Summary

- **There are a few caveats** - But
- 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} and short time delay).

- A radio flare may confirm this!
- Another strong well localized short GRB is expected within a year or so.

- A GW signal + Merger + macronova (in 10 years)

The End ?