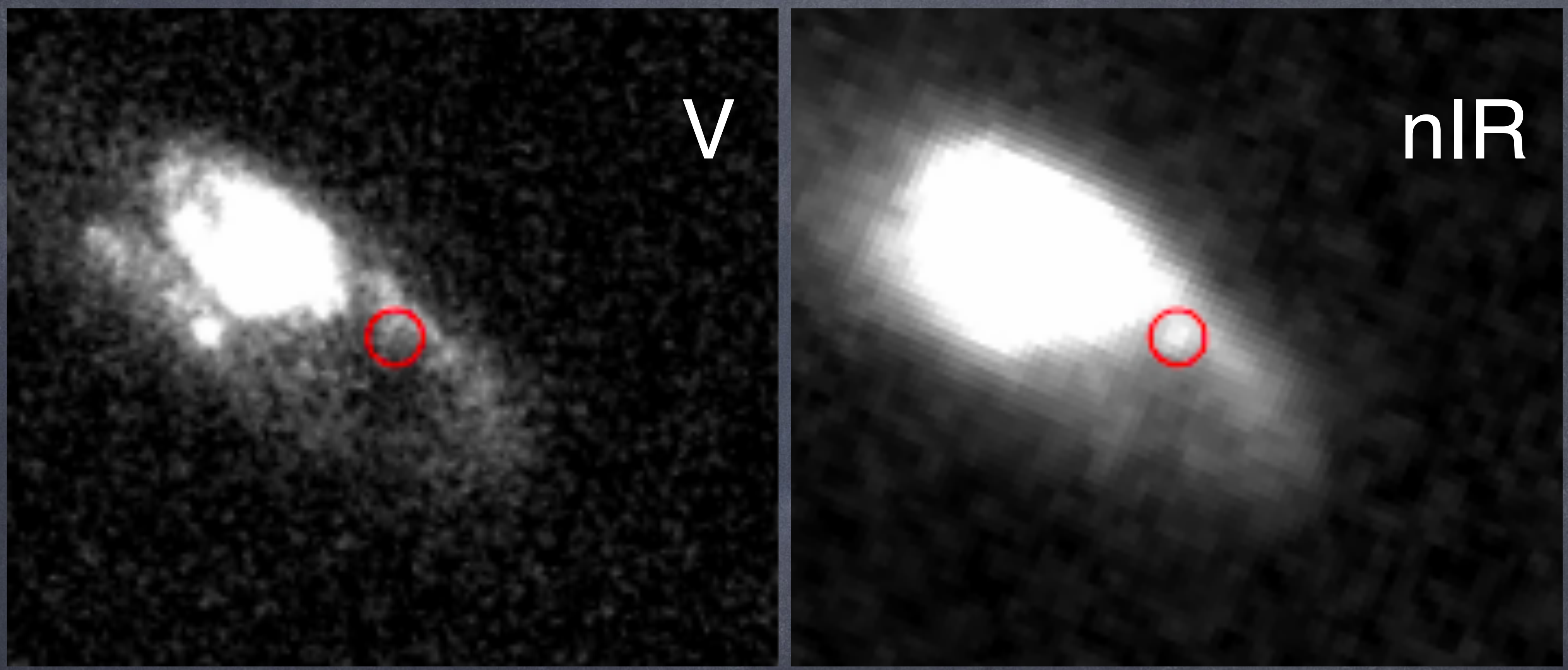
Neutron Star Mergers, Gravitaional Waves Gamma-Ray Bursts and the origin of Gold

Tsvi Piran

The Hebrew University

David Eichler, Mario Livio, David Schramm, Doron Grossmam,
Stephan Rosswog, Oleg Korobkin, Ehud Nakar,
David Wanderman Ben MargalitKenta Hoteokezaka

The Hubble Space Telescope
June 13th 2013



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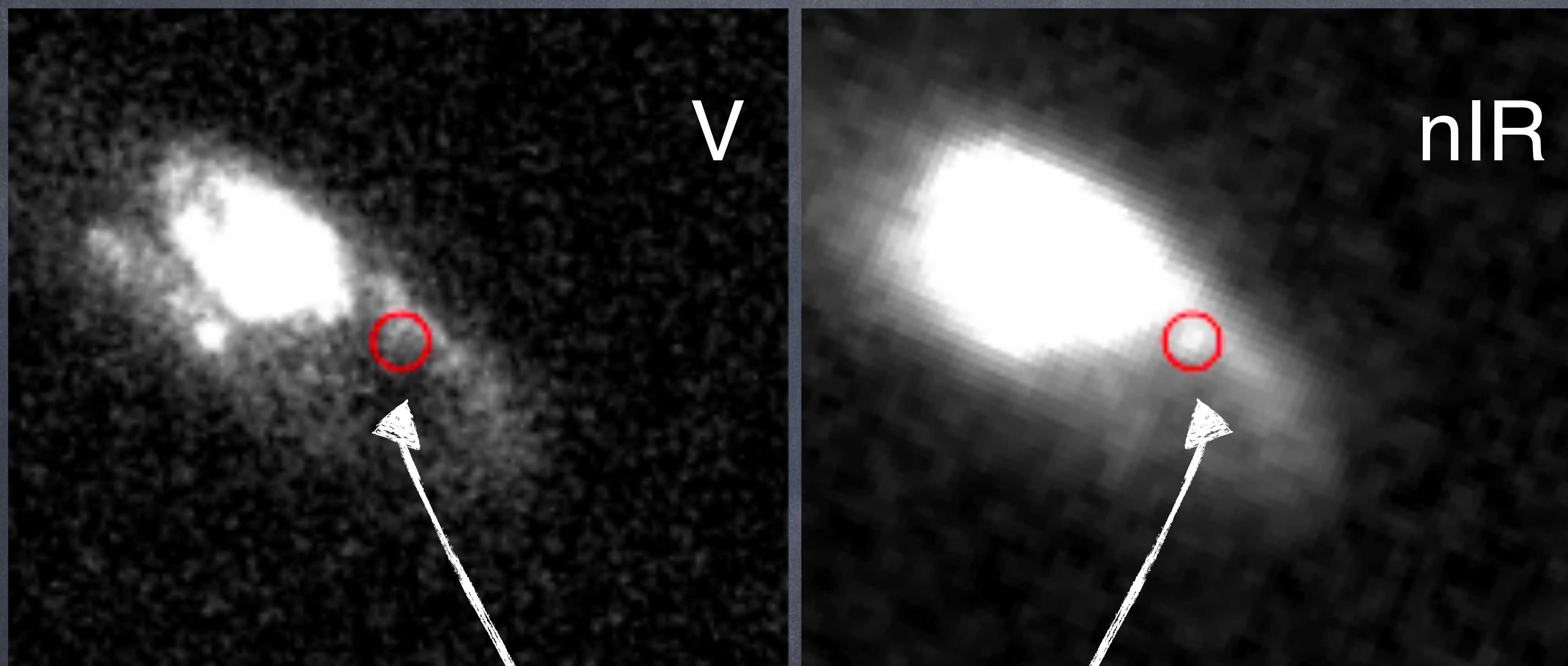


Is this the "smoking gun" proving the origin of Gold (and other heavy elemets) in the Universe?

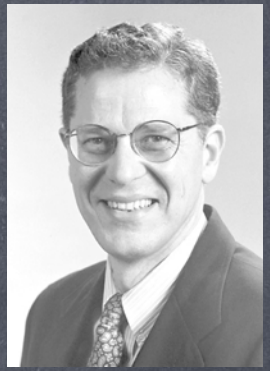
Does this assures us the identification of EM counterparts to gravitational wave sources?

Outline

1. Gravitational Waves
2. Gamma-Ray Bursts
3. The Li-Paczynski Macronova (kilonova)
4. Nucleosynthesis
5. Putting it all togather - GRB 130603B
6. The origin of Gold
7. Confirmations: GRB 060614; Radio Flares; Plutonium

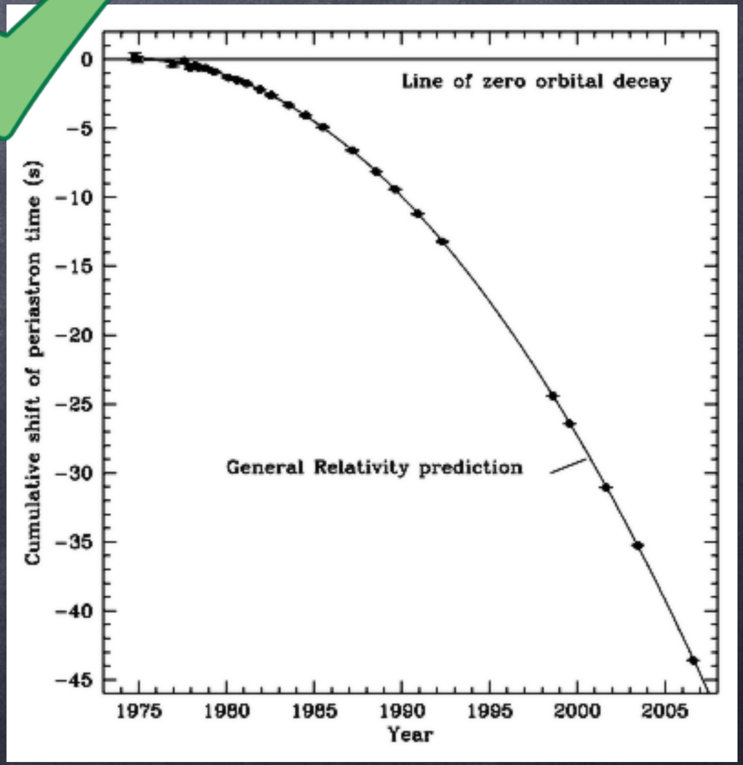
1. Gravitational Waves

R. Hulse



J. Taylor

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



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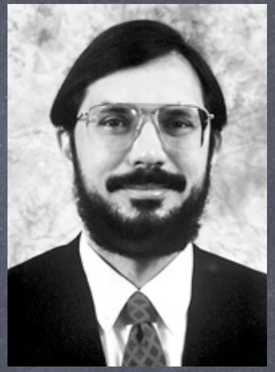

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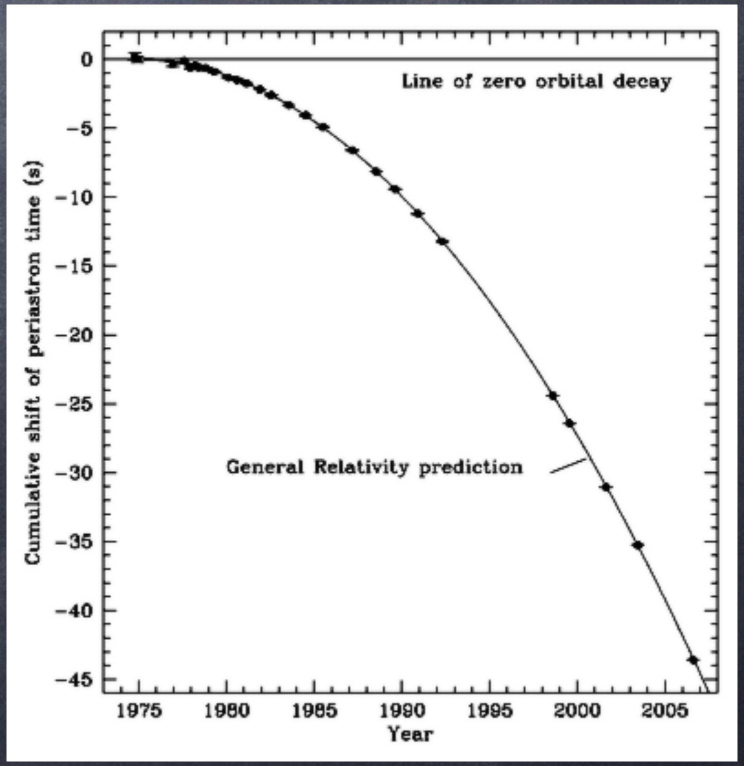

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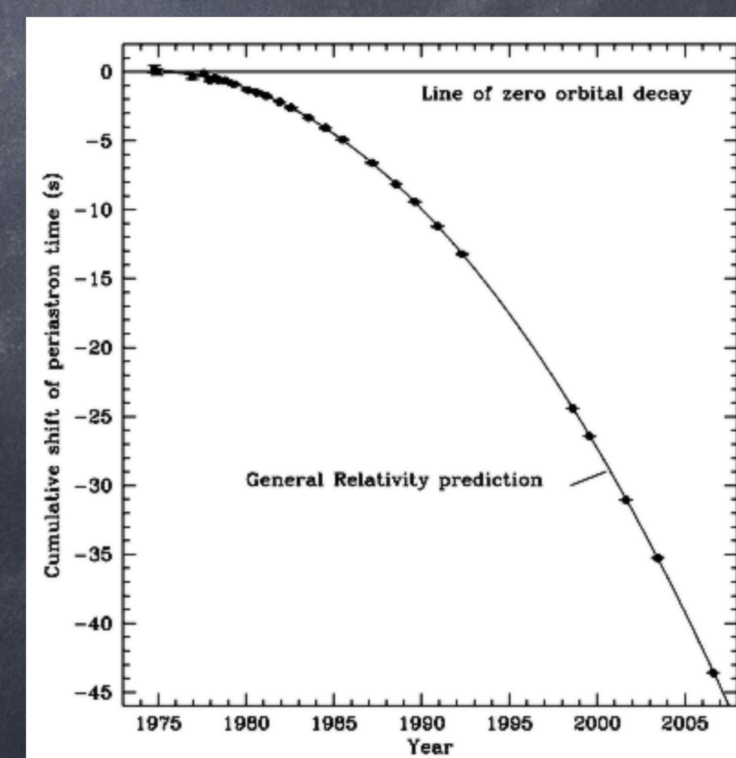

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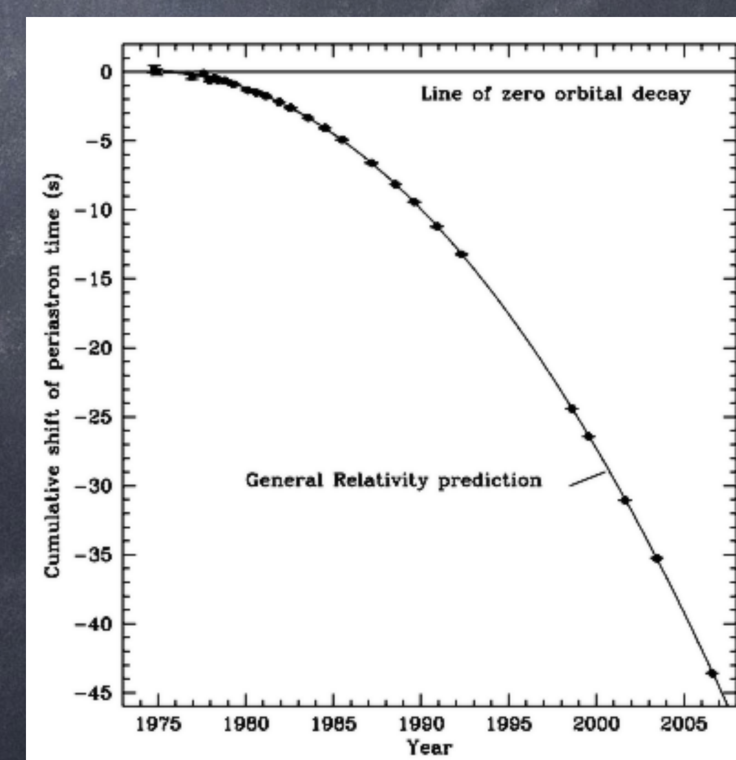
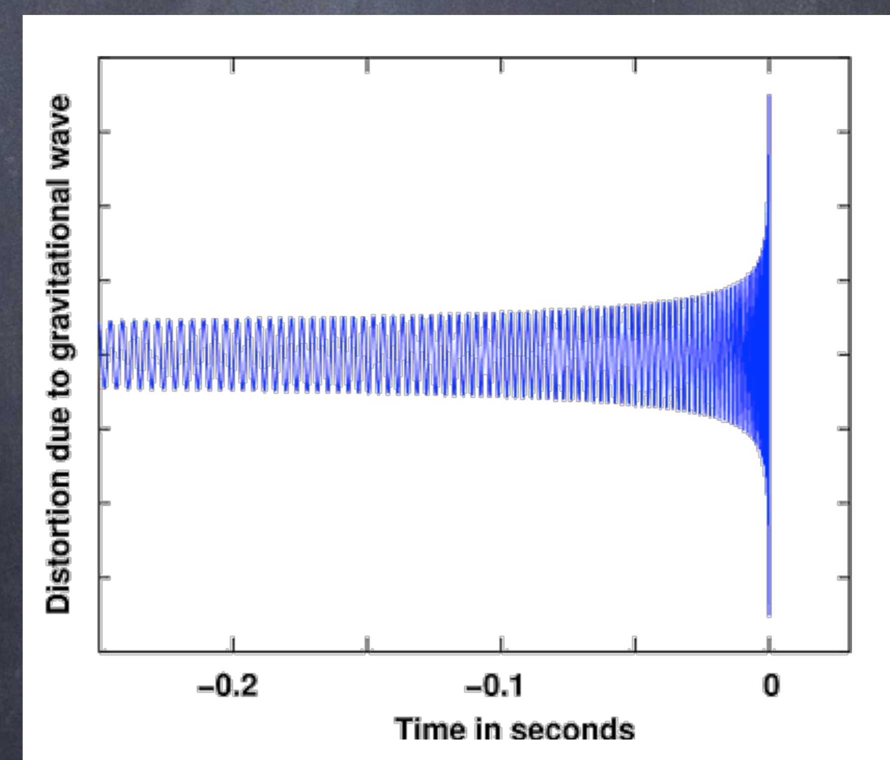


LIGO Virgo and KAGRA



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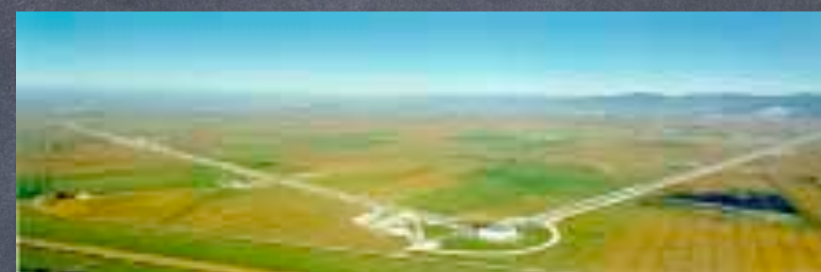
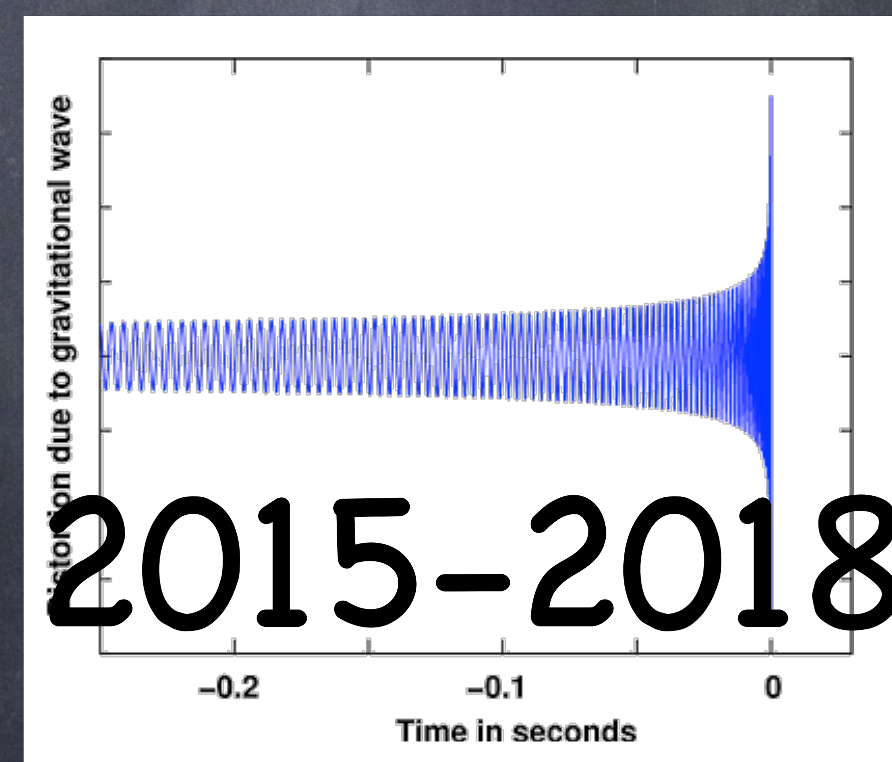
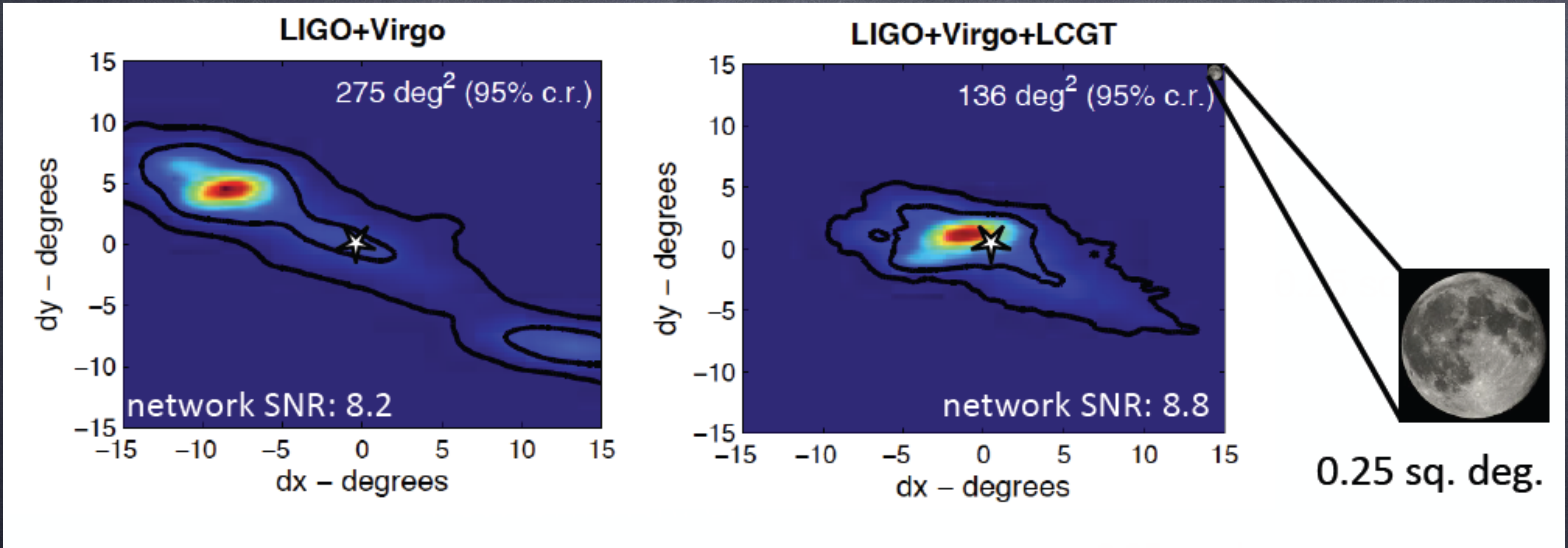




The Gravitaitional Waves Challenge



Nissanke + 13

Kochaneck +TP 93: need an EM counterpart

2. Gamma - Ray Bursts (GRBs)

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Once or twice a day we see a burst of low energy gamma-rays lasting for a few seconds.

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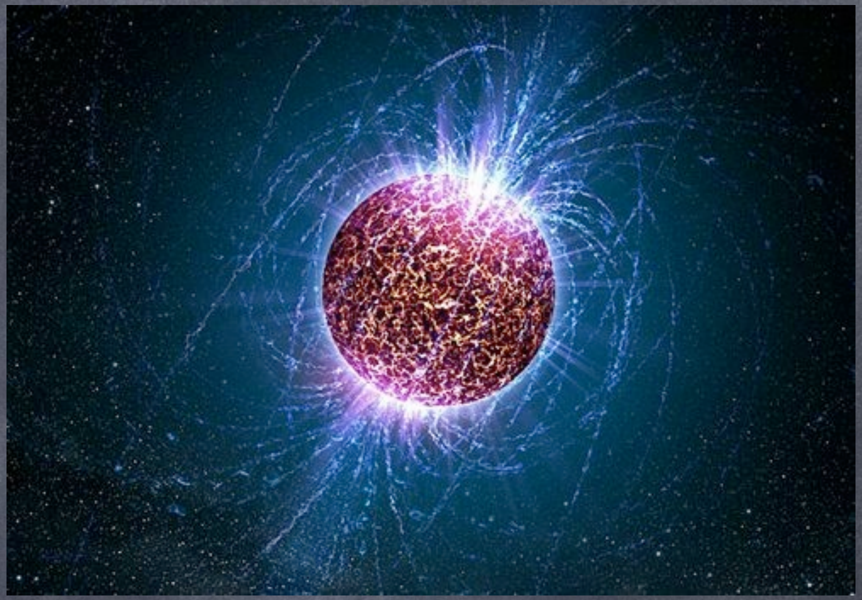
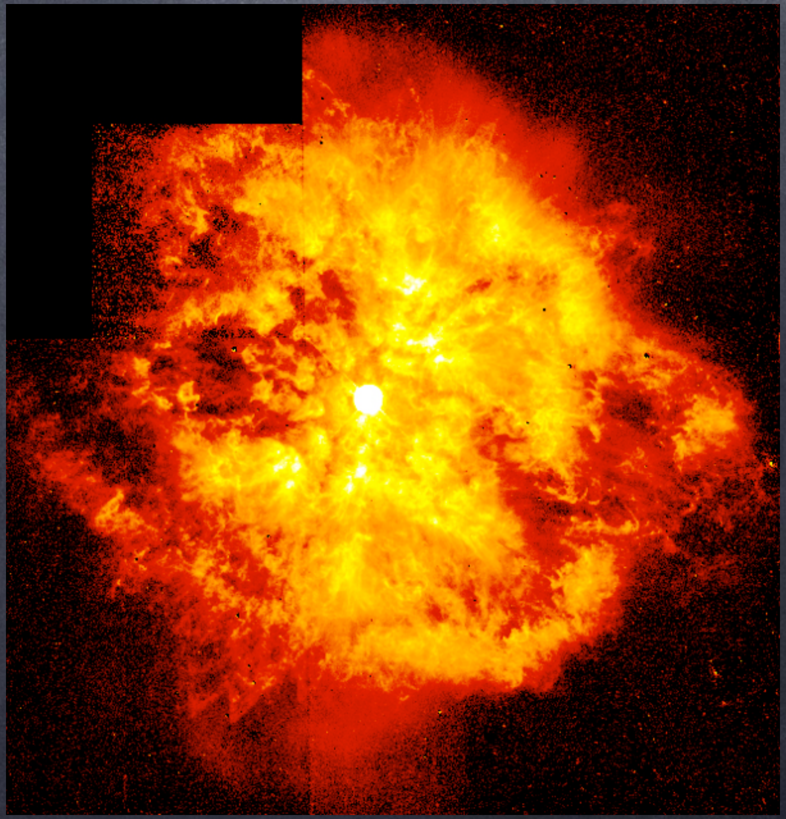
The energy released during a burst (~10^{51} erg within a few seconds) is only a few orders of magnitude below the energy released by the rest of the Universe at the same time!

The late 80ies

- GRBs from magnetic flares on <u>galactic</u> neutron stars ($E \sim 10^{40}$ ergs).
- All nucleosynthesis takes place in Supernovae





Two provocative ideas

LETTERS TO NATURE

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

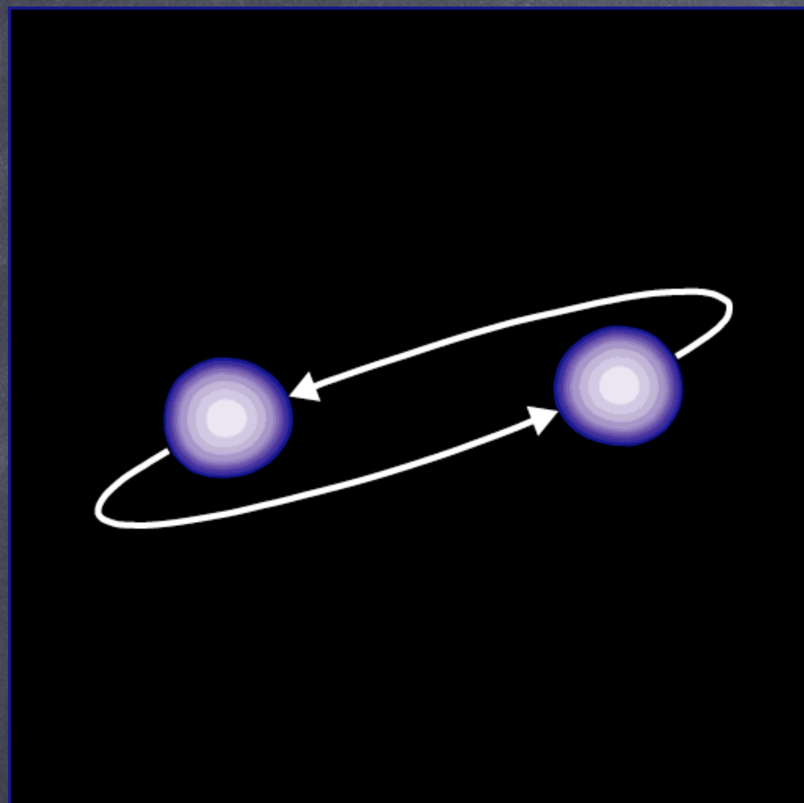
David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

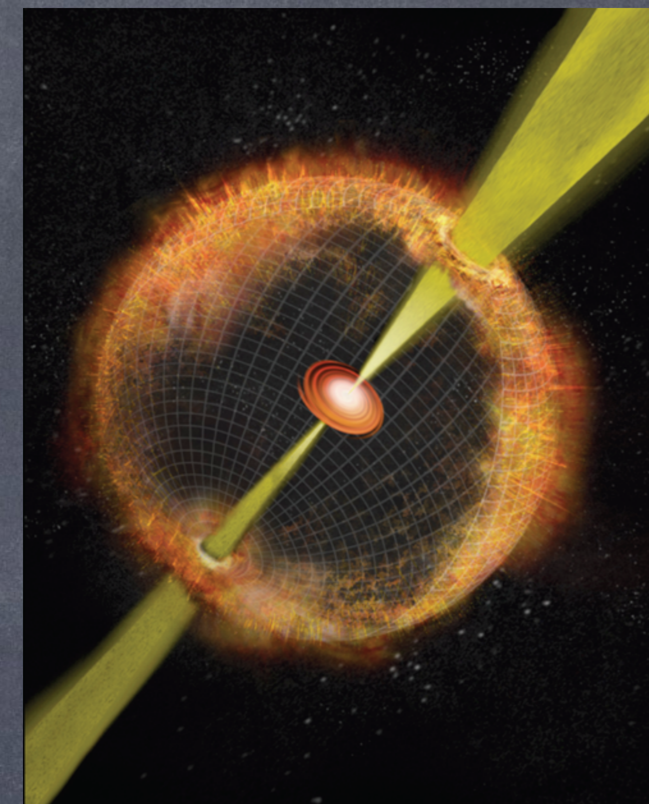
NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave 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.

1988		2015
GRBs from magnetic flares on galactic neutron stars (E~10^{40} ergs).	→	GRBs are cosmological
All nucleosynthesis takes place in Supernovae	→	Supernovae cannot produce A>130

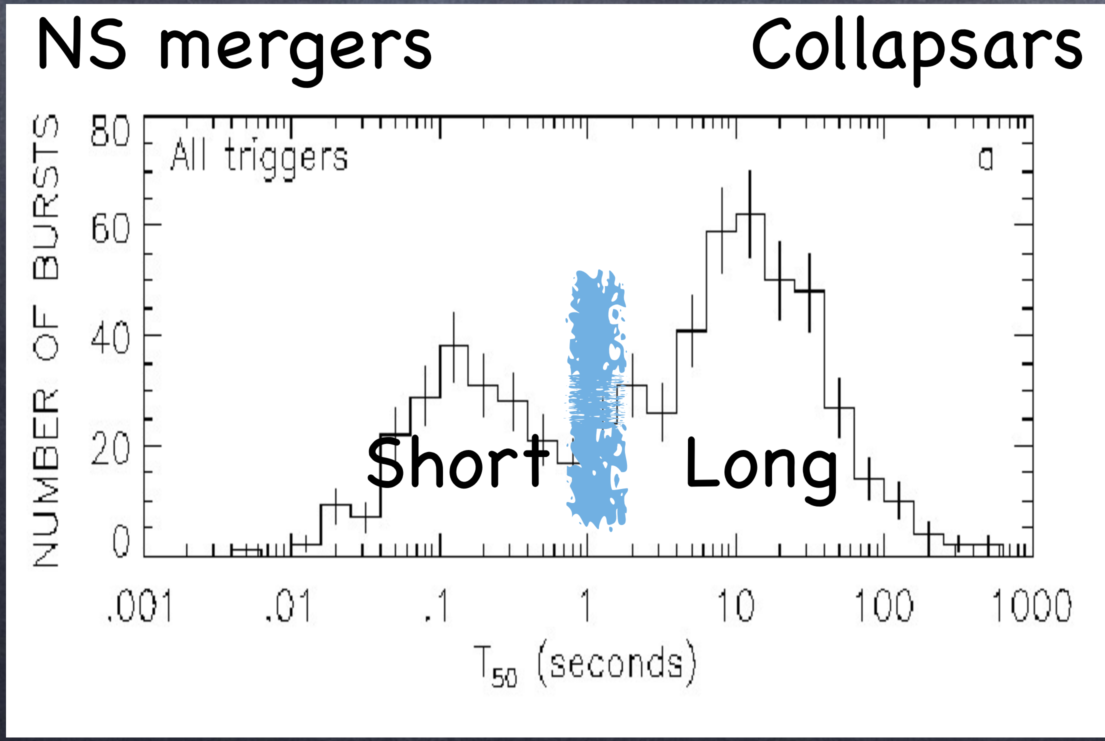
Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley, 98



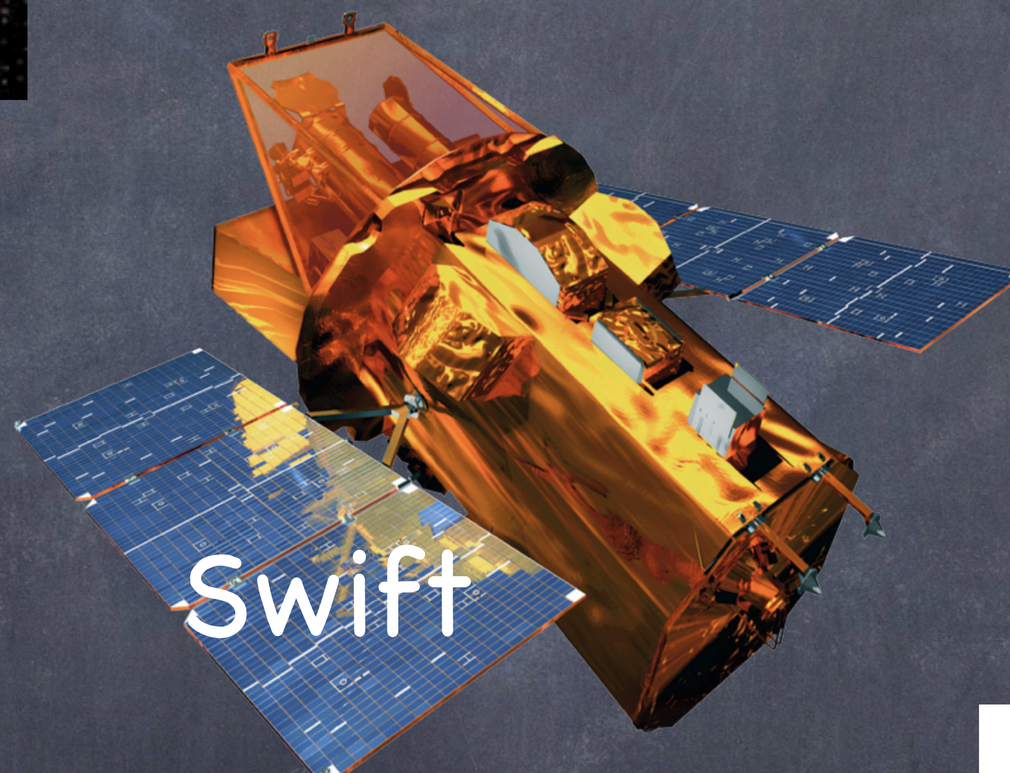


Indirect Evidence

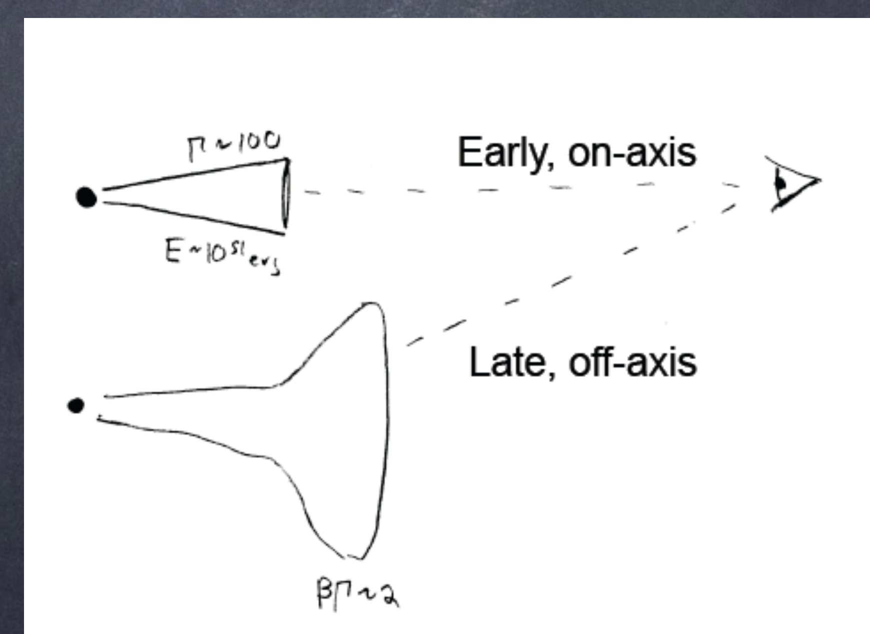


Direct Evidence

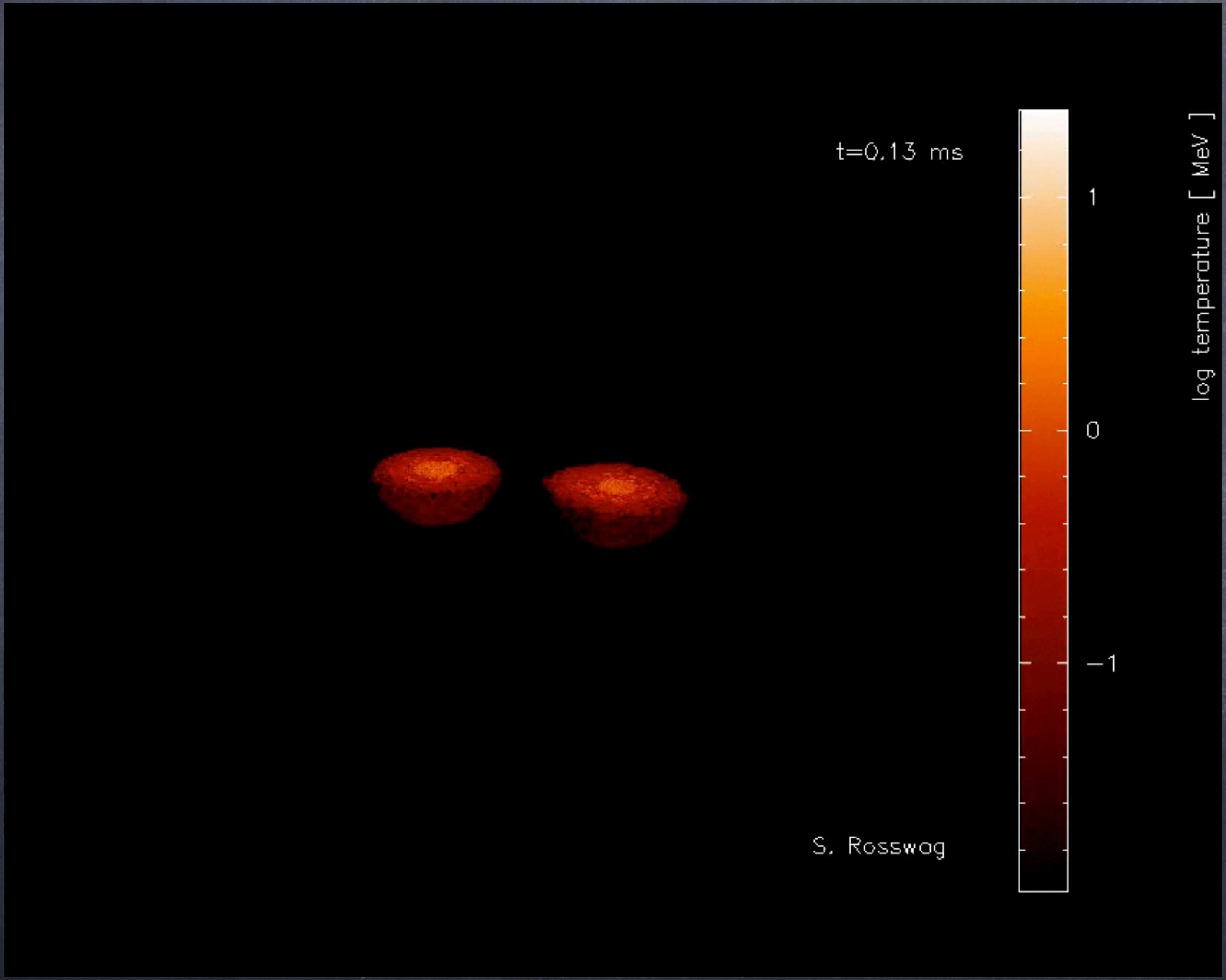
GRBs are beamed – only 1:10 chance of detection



Orphan afterglow is too weak to



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



Stephan Rosswog

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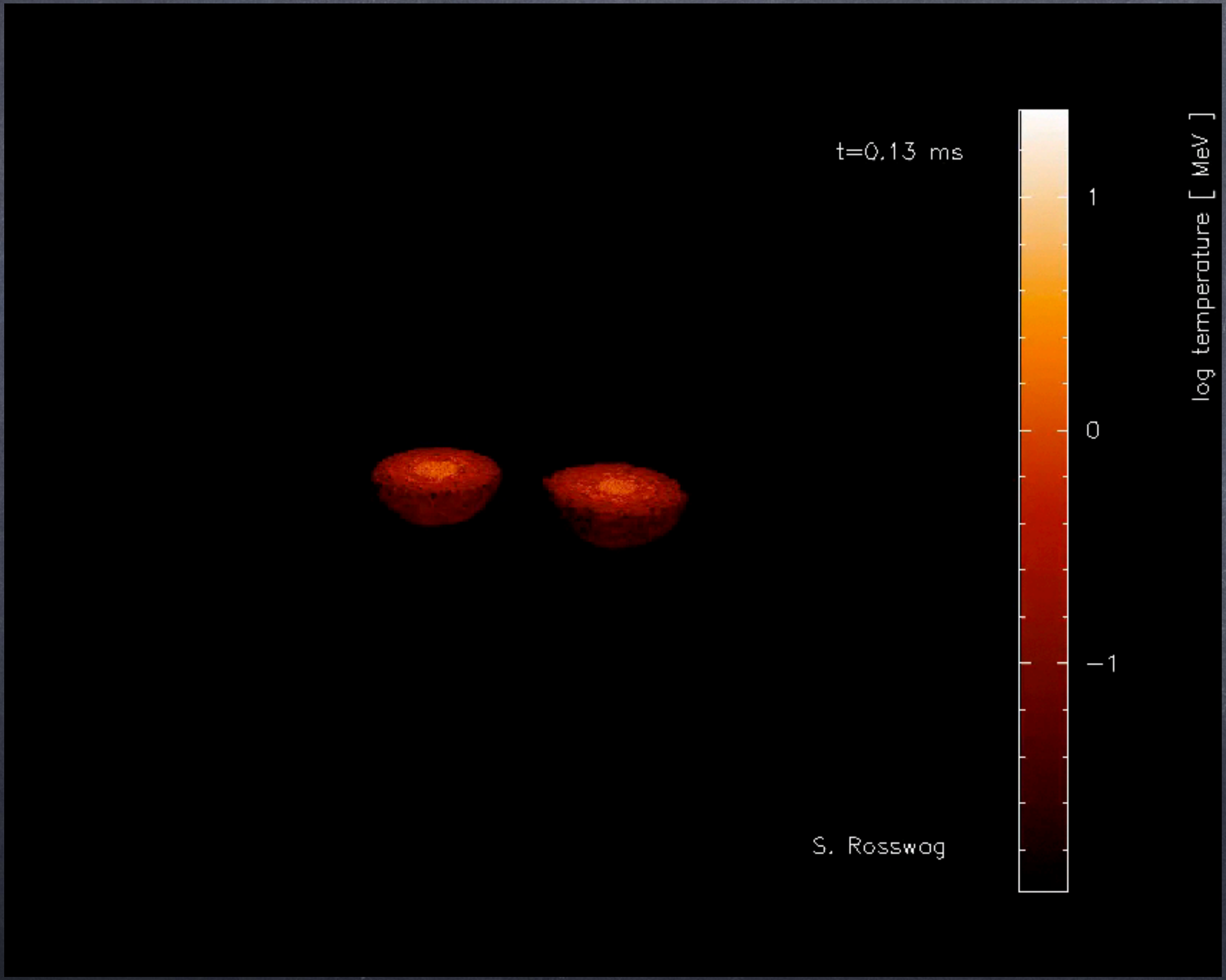

Stephan Rosswog

3. 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.

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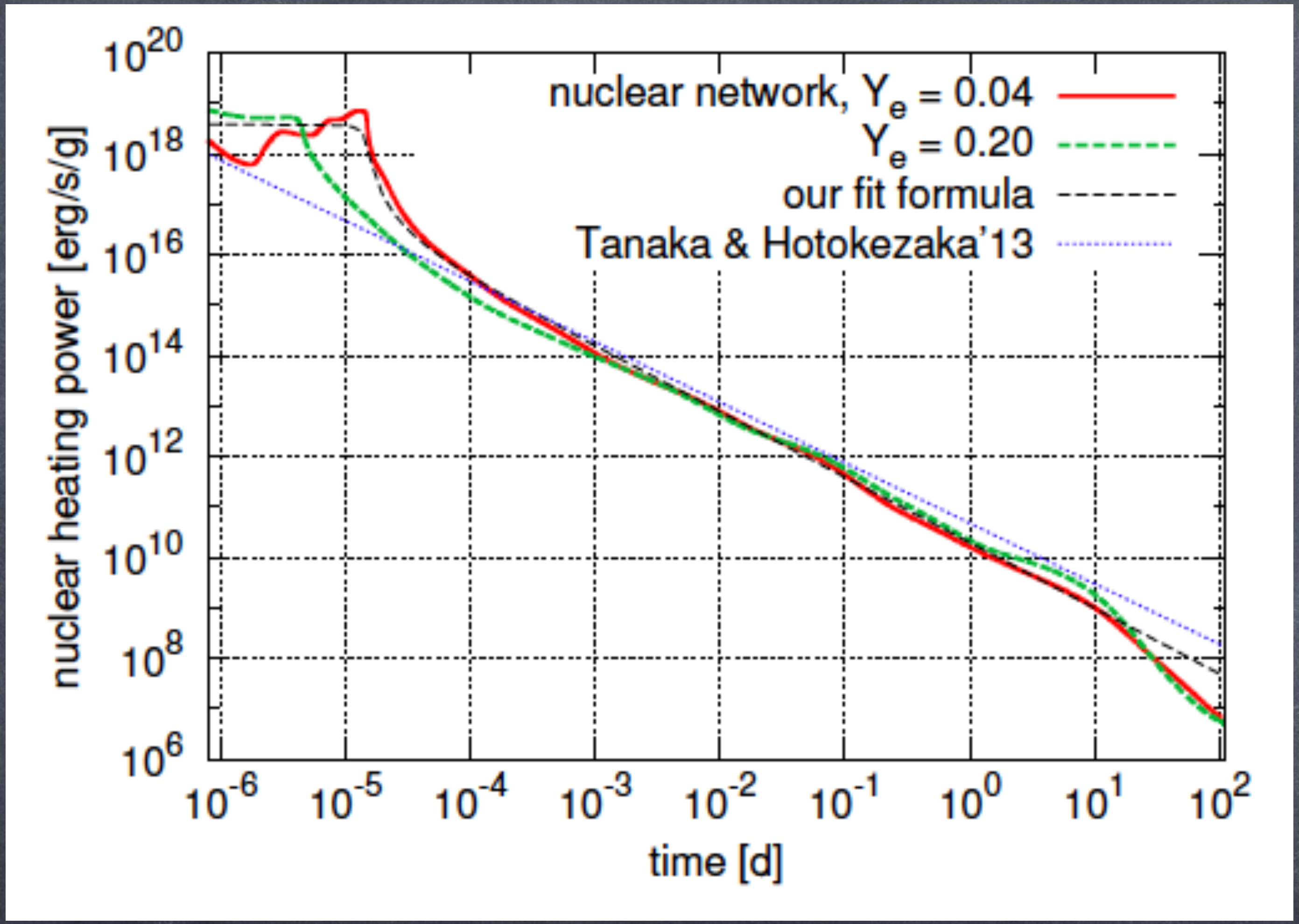
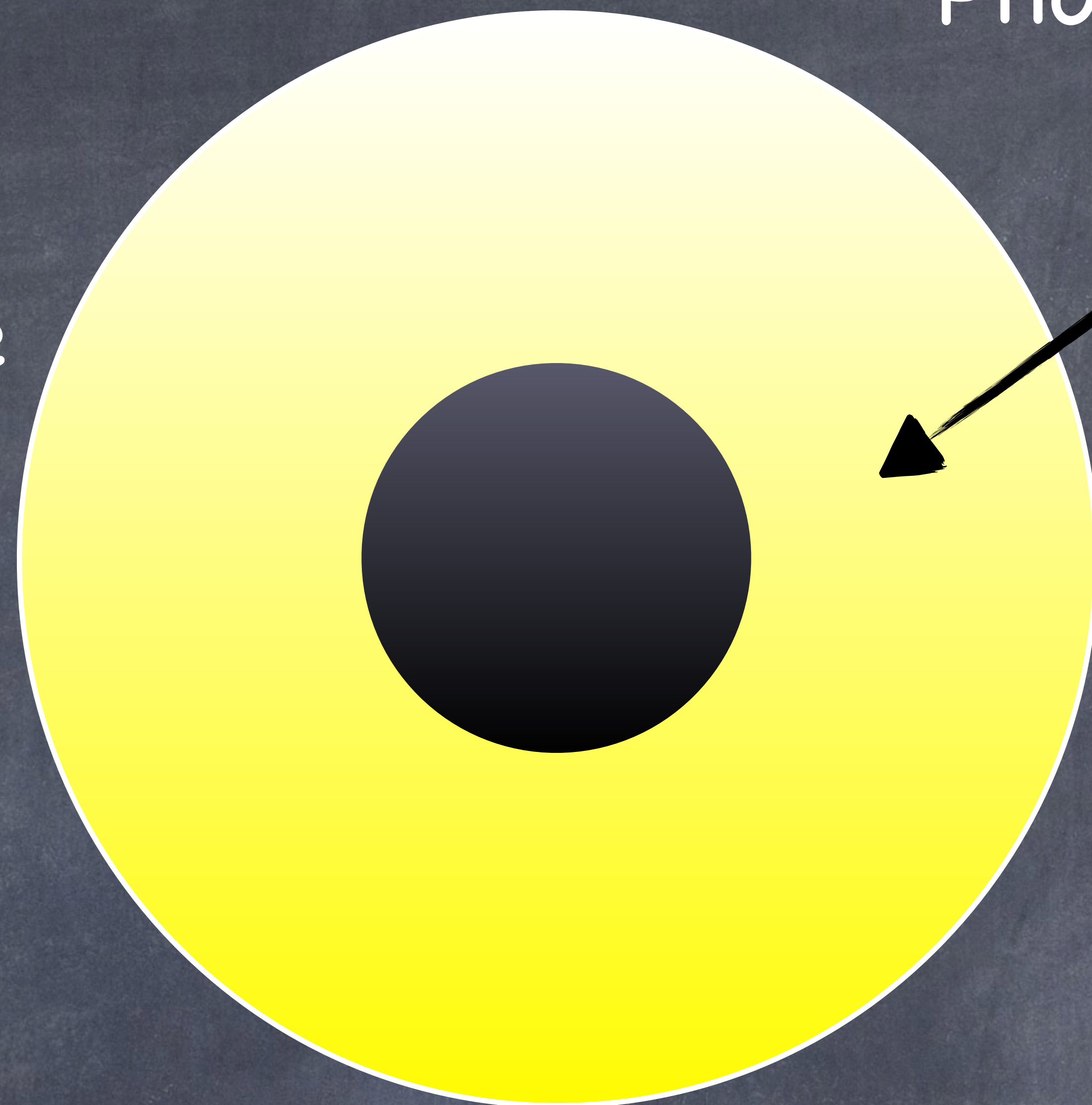
Radioactive Decay

Korobkin + 13; Rosswog, Korobkin + 13



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

Photons escape from this region



The light curve depends on

1. mass
2. velocity
3. opacity

Increase as we see a large fraction of the matter.

Decrease due to radioactive decay

Macronova

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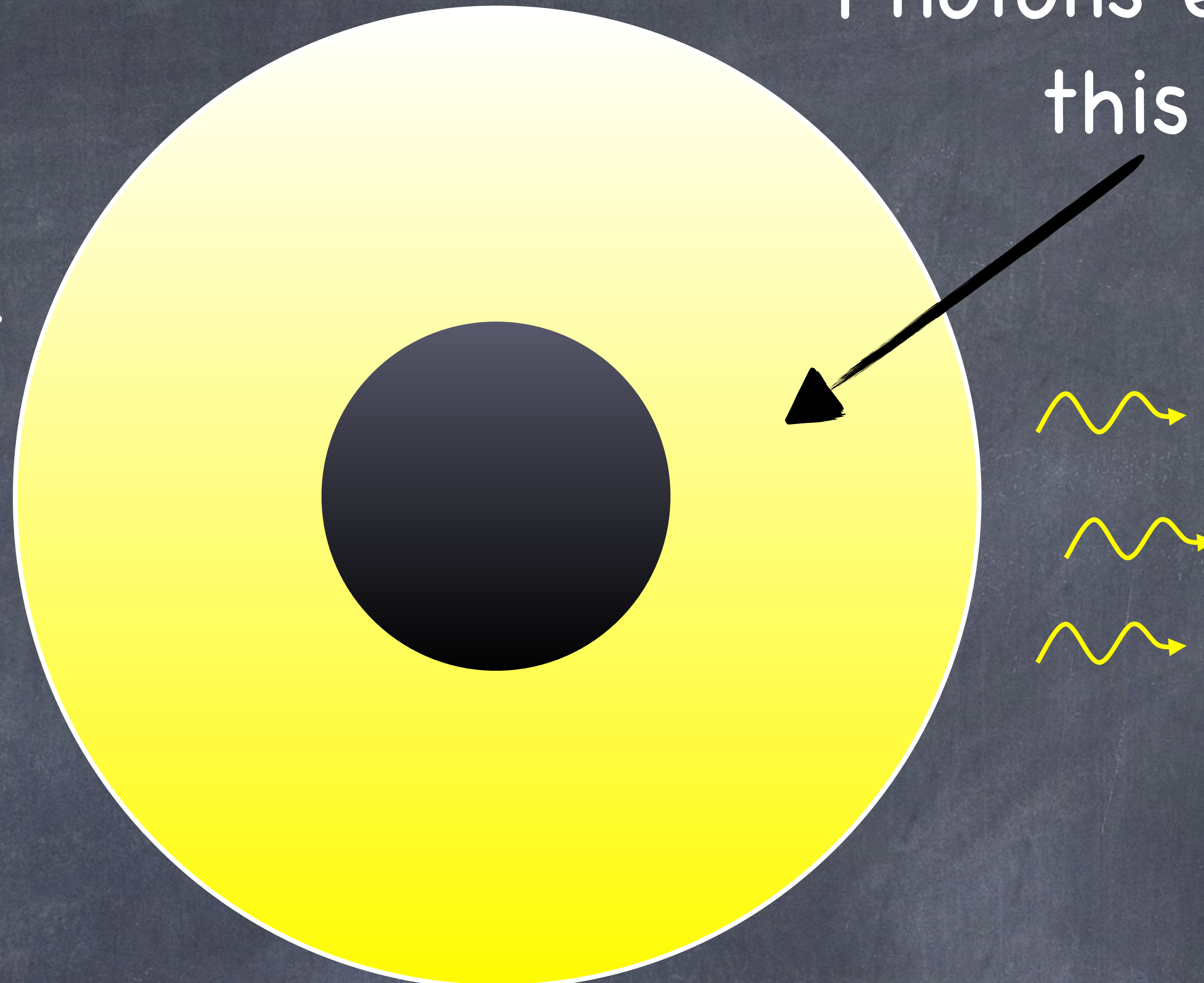

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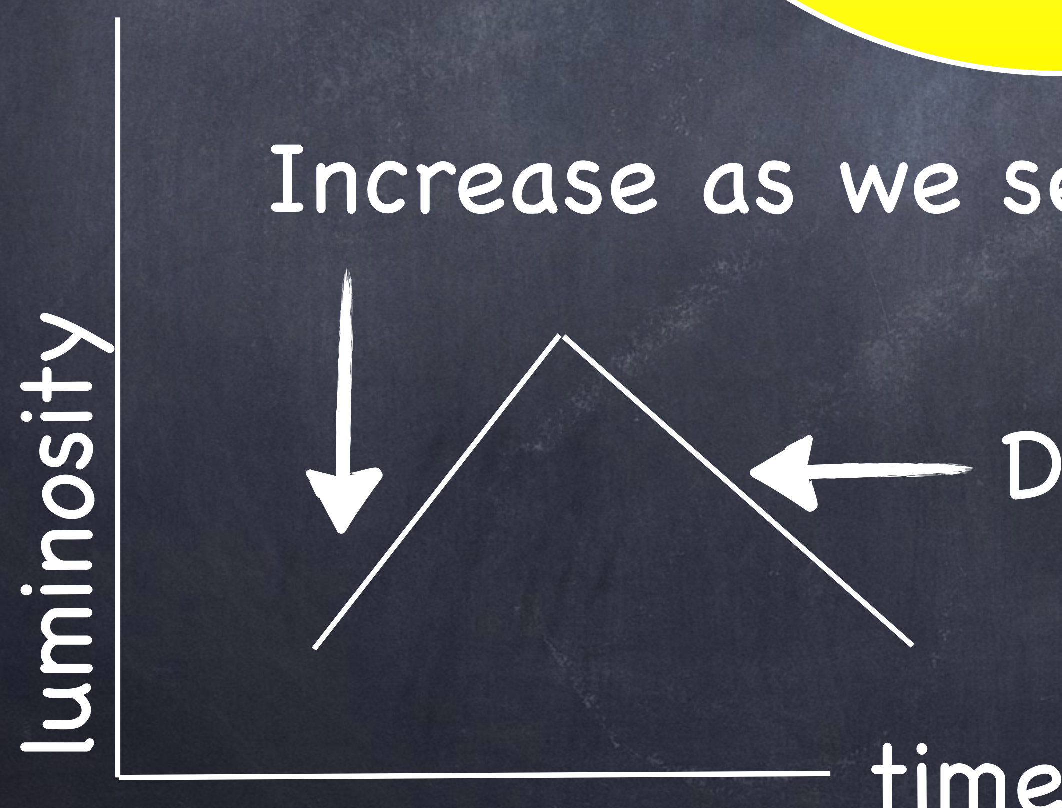
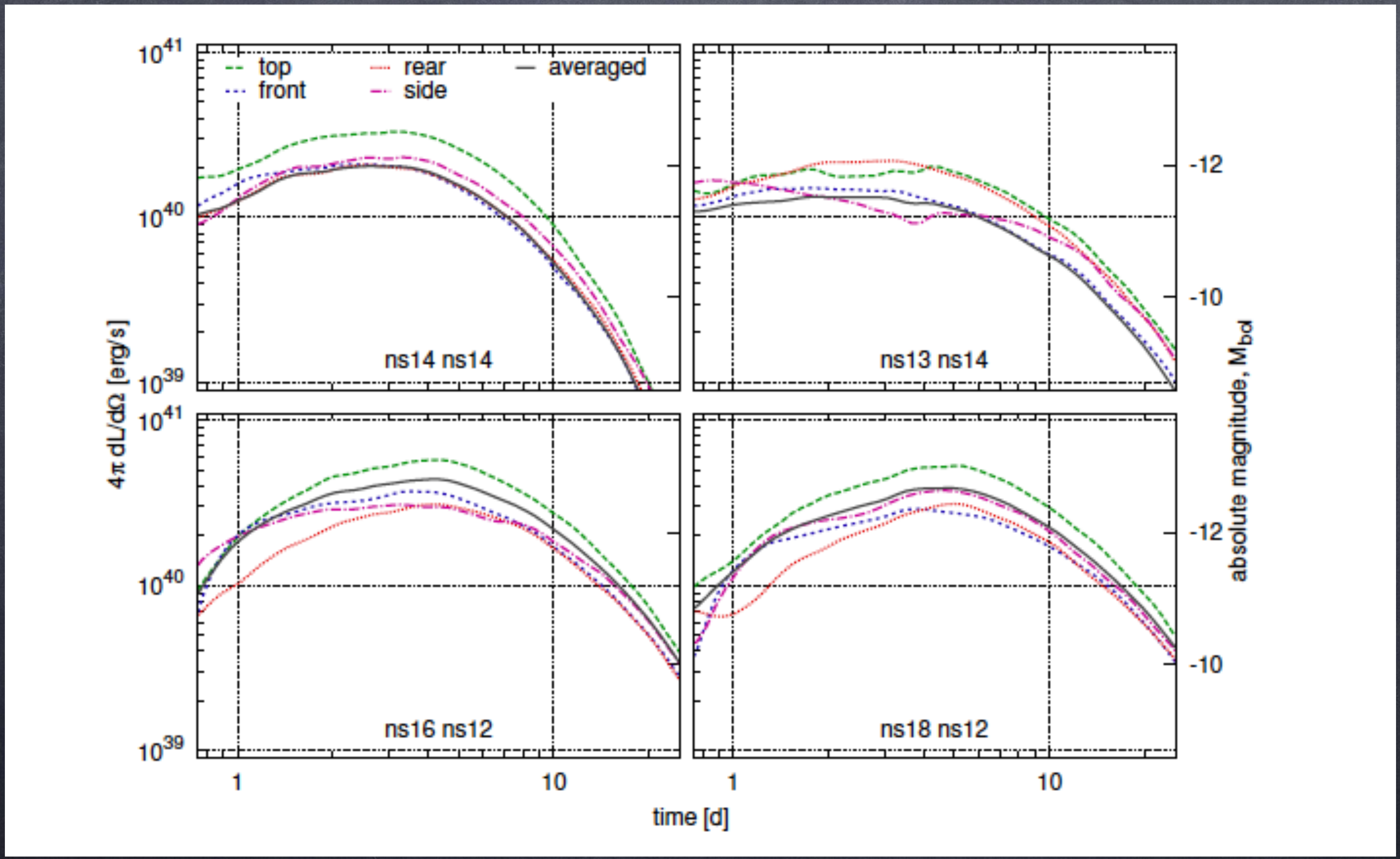
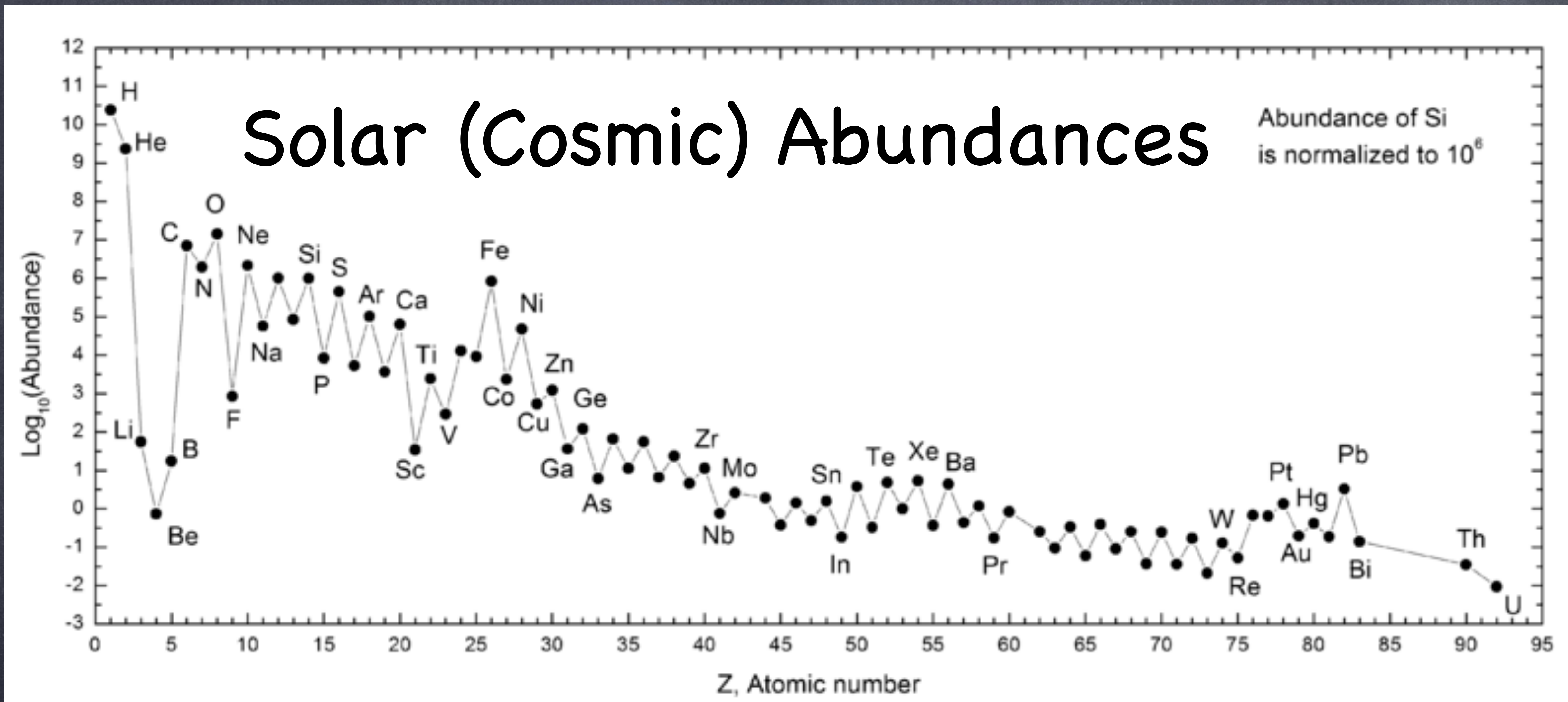


Macronova

Bolometric light curves



4. Nucleosynthesis



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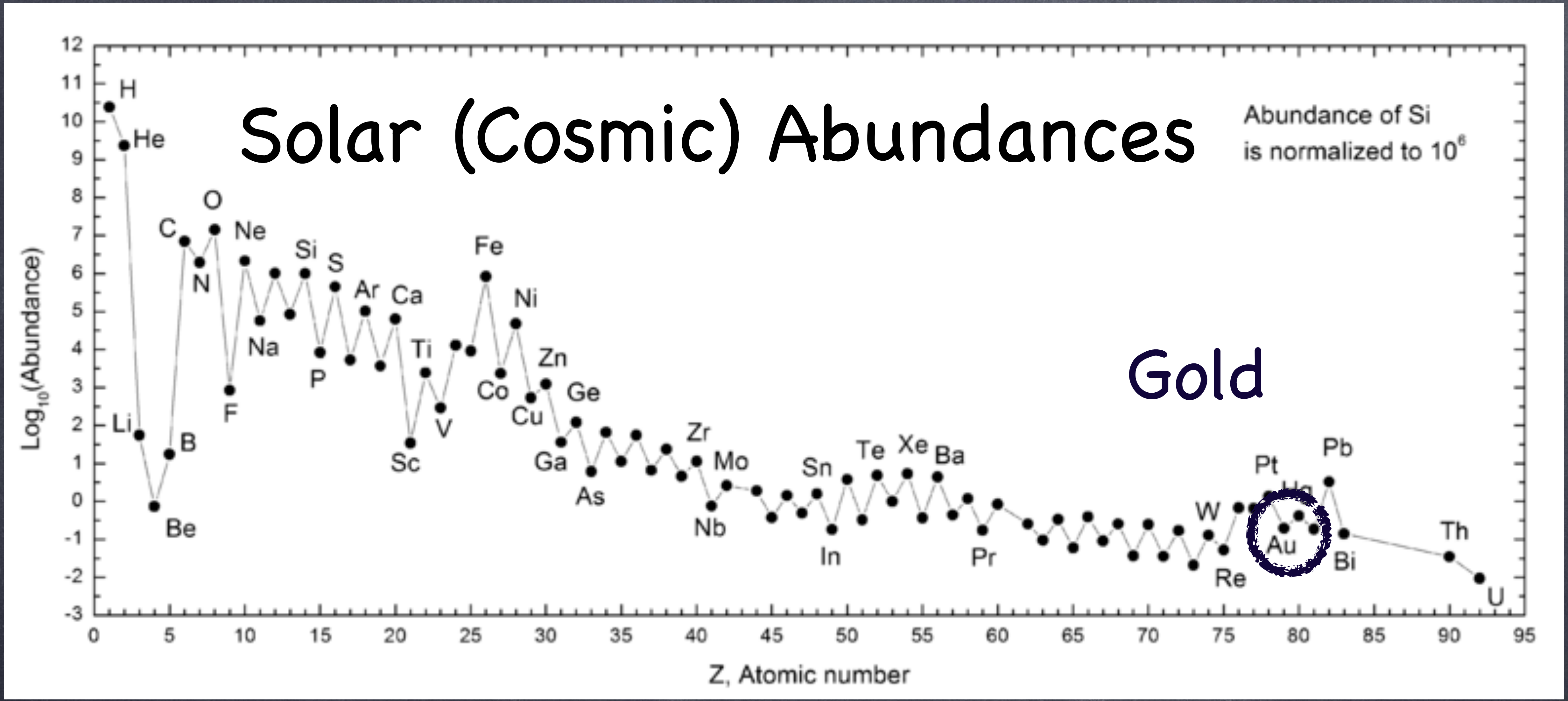

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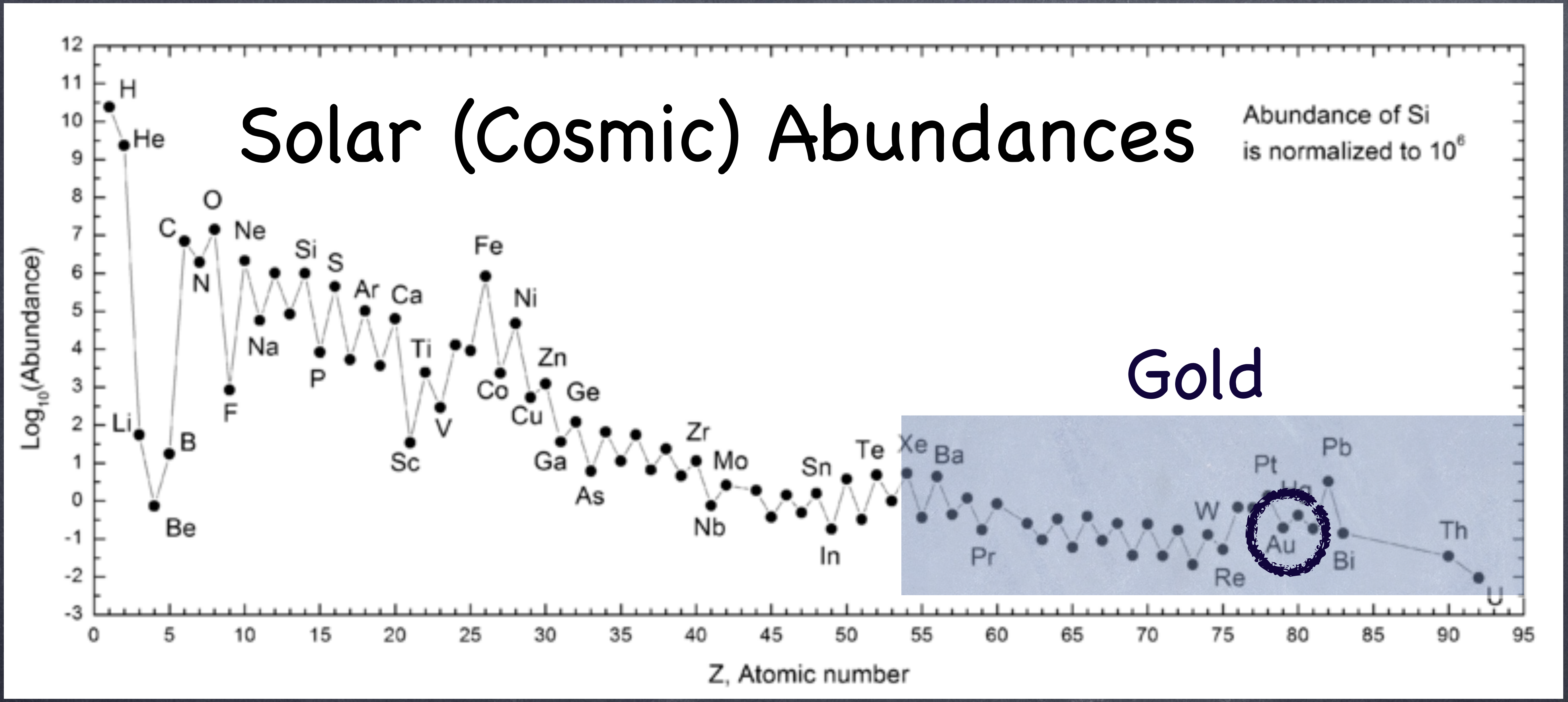

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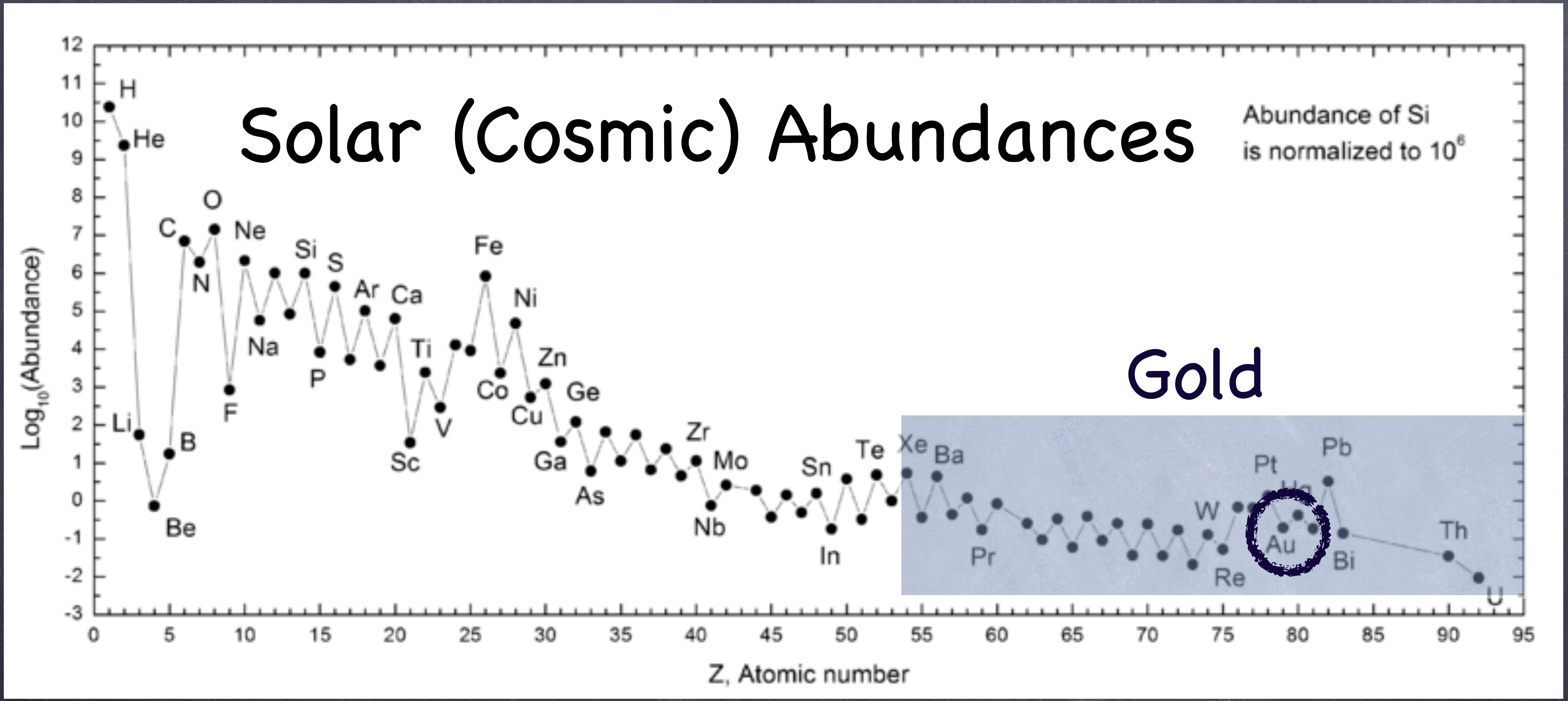
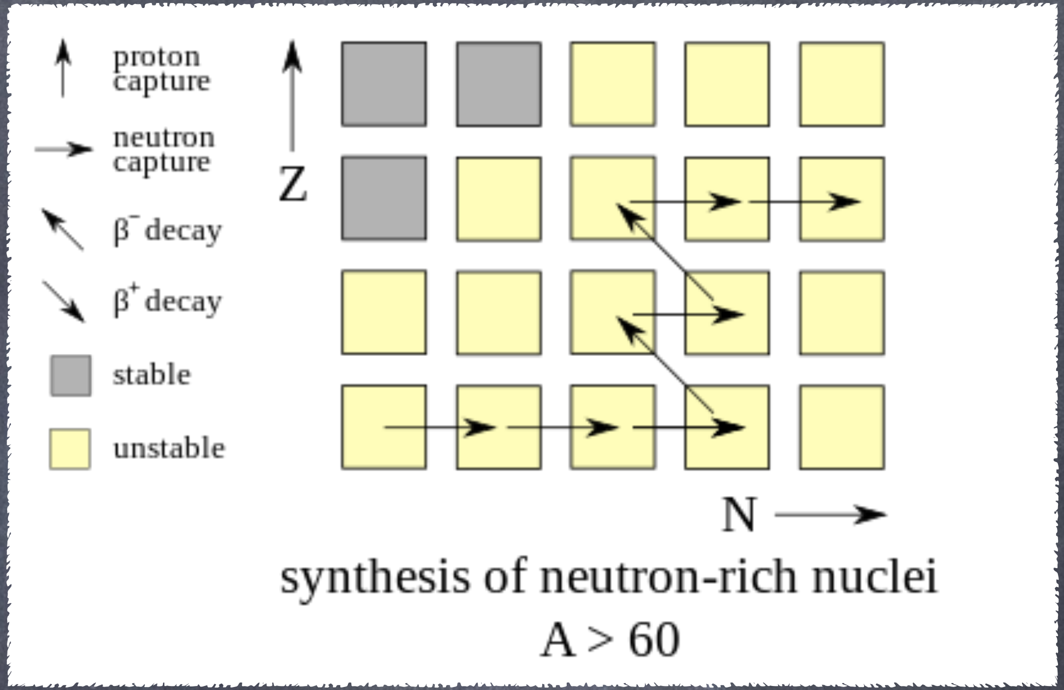
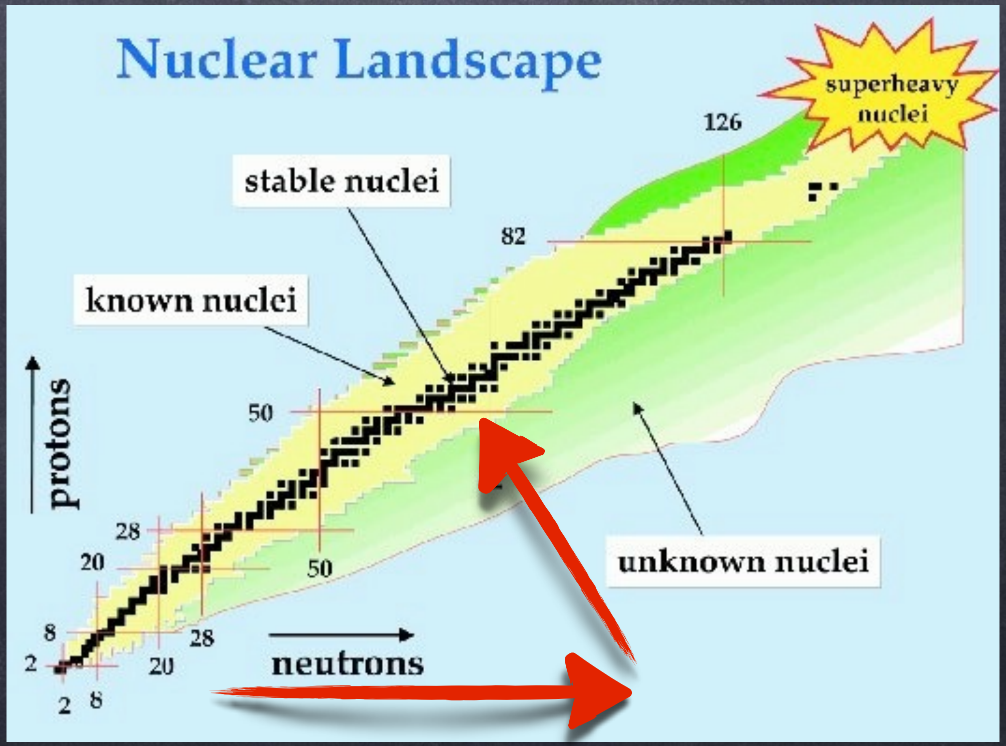


How are these elements produces?

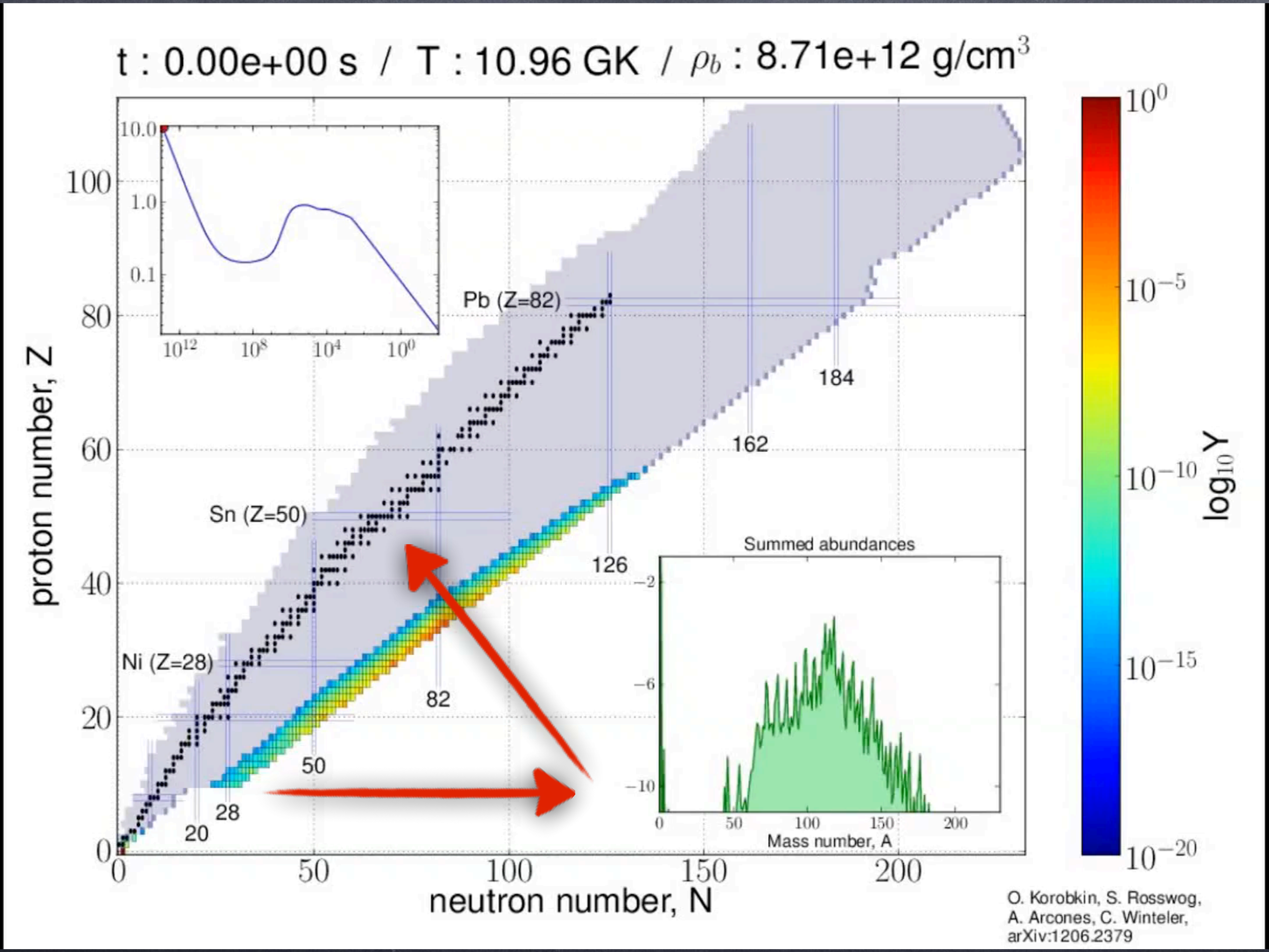
r (rapid) Process

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





Decay of neutron star matter



Neutron Star Mergers

Korobkin + 13

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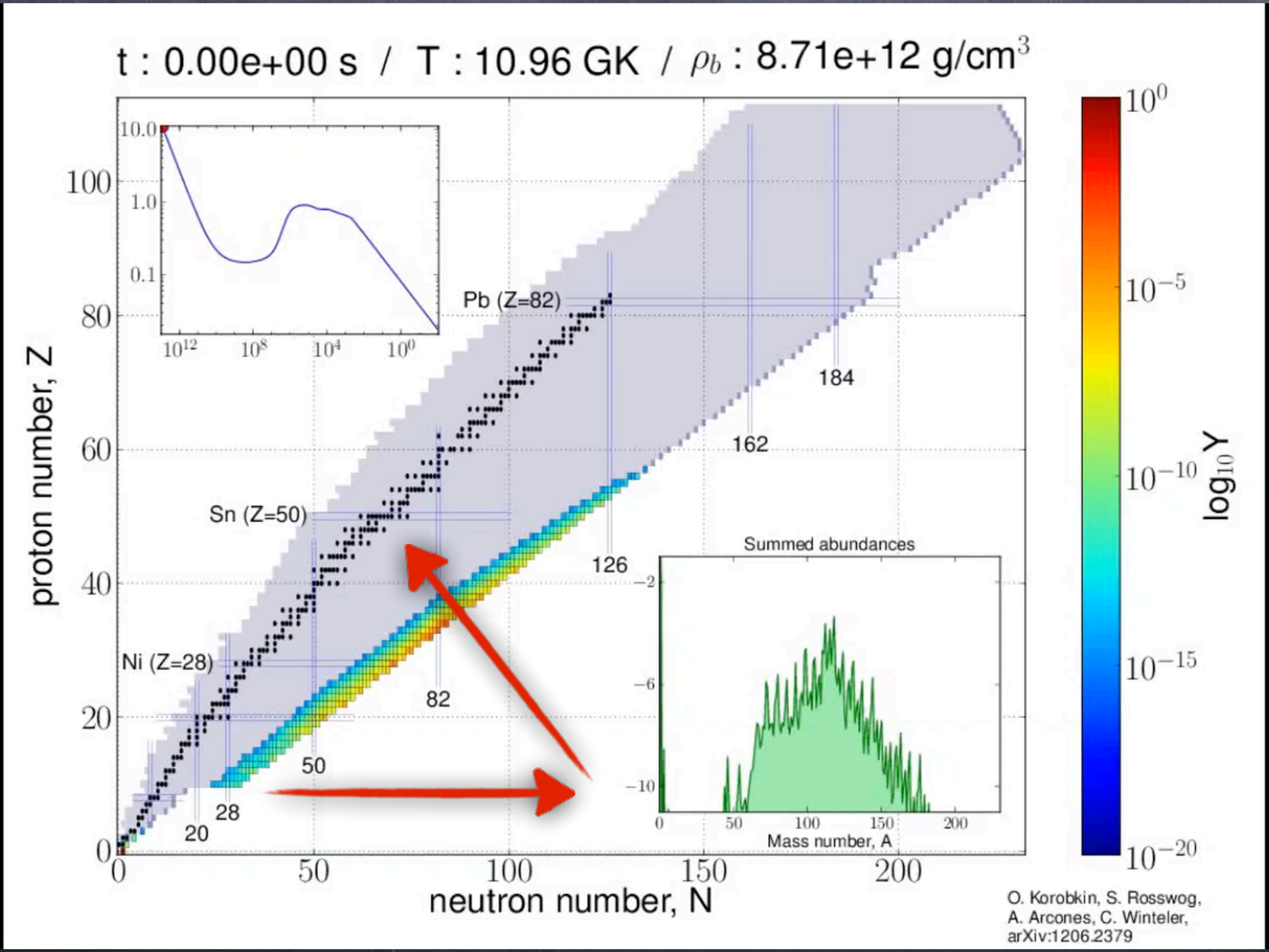
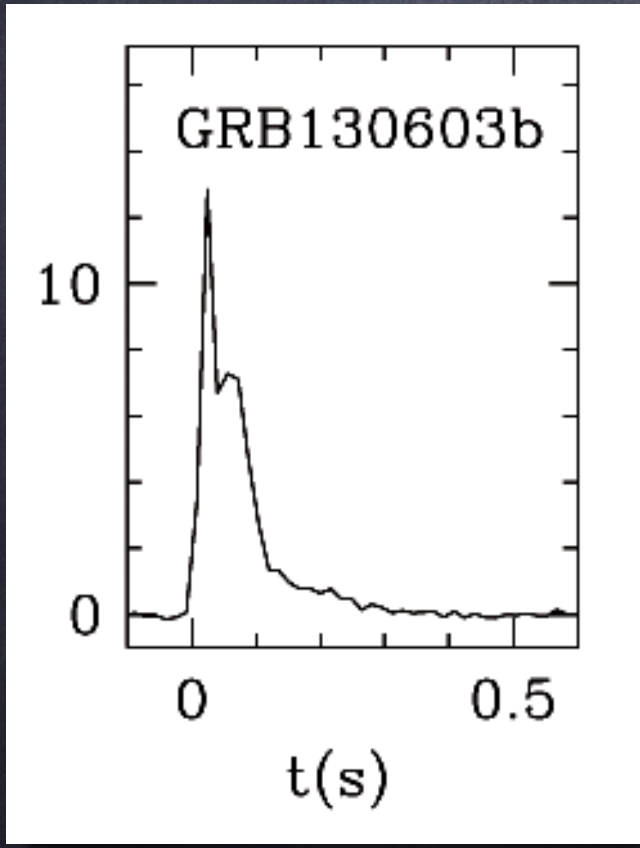
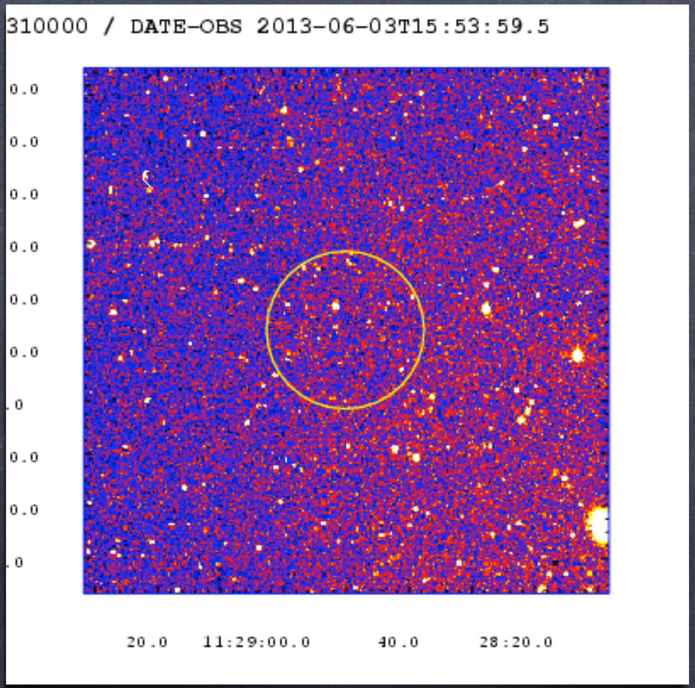


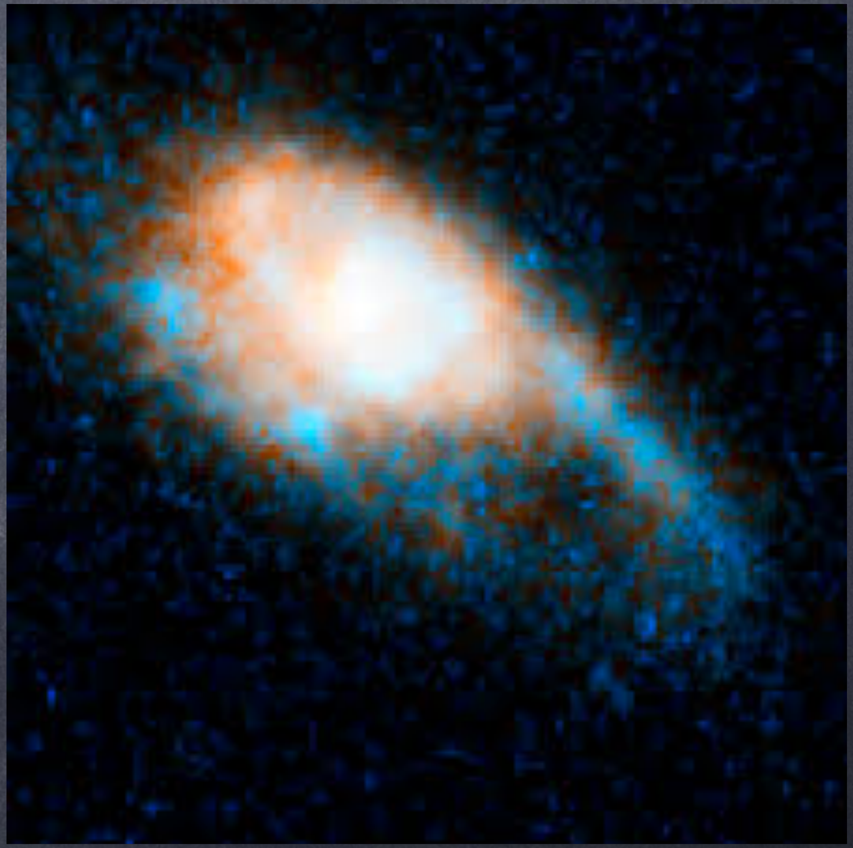
Neutron Star Mergers

Korobkin + 13

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





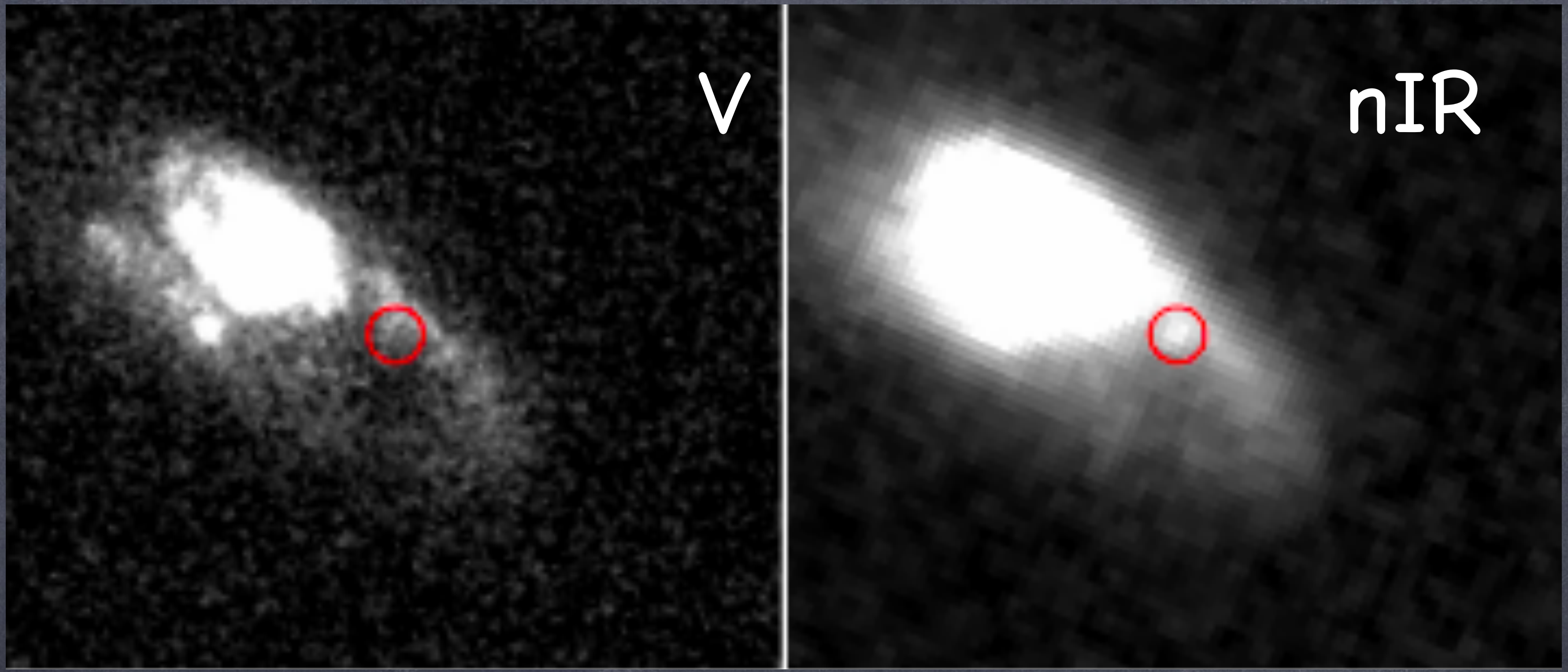


GRB 130603B

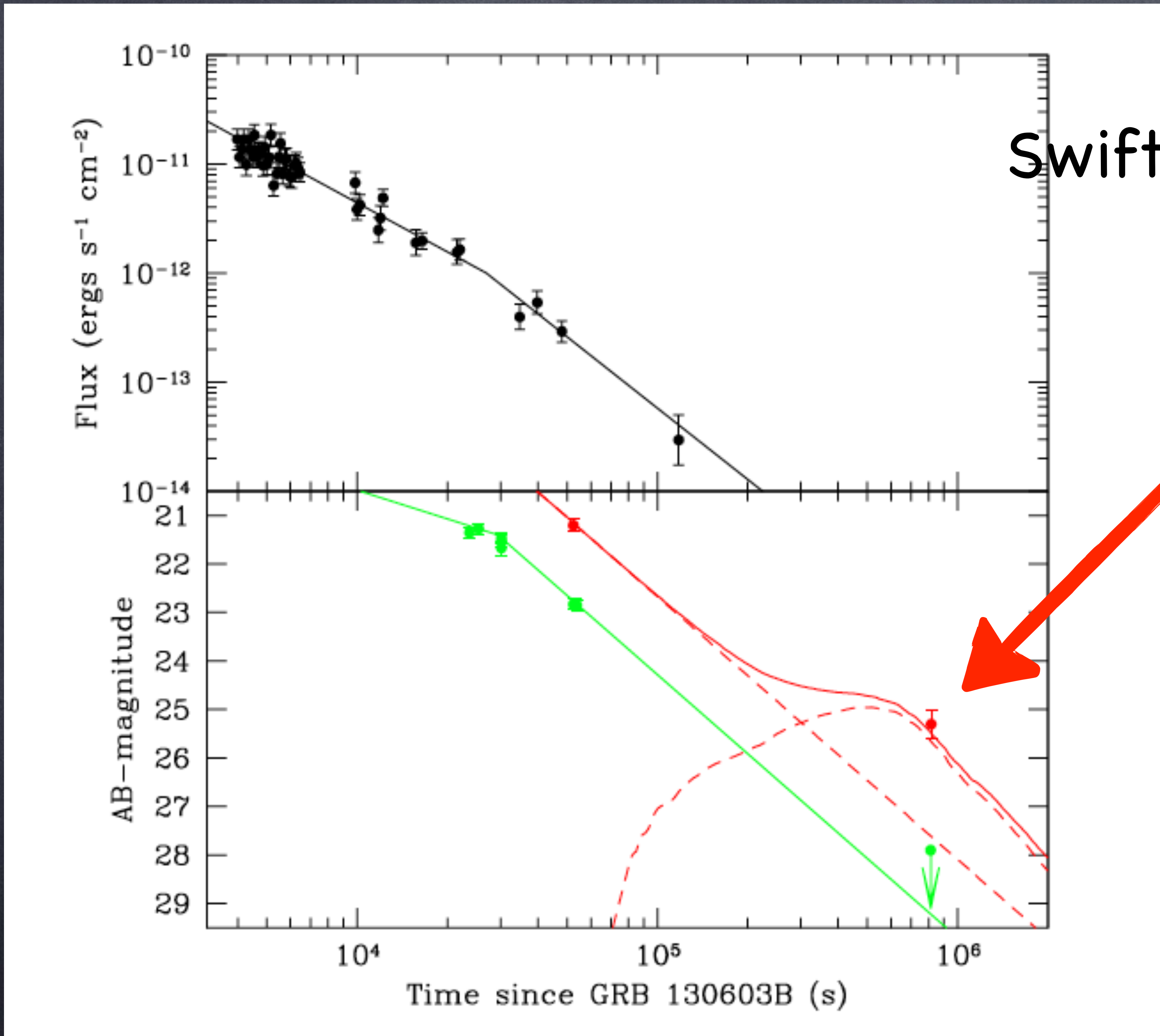
z=0.356 <=> 1 Gpc = 3 Glyr

GRB130603B @ 9 days AB

(6.6 days at the source frame)



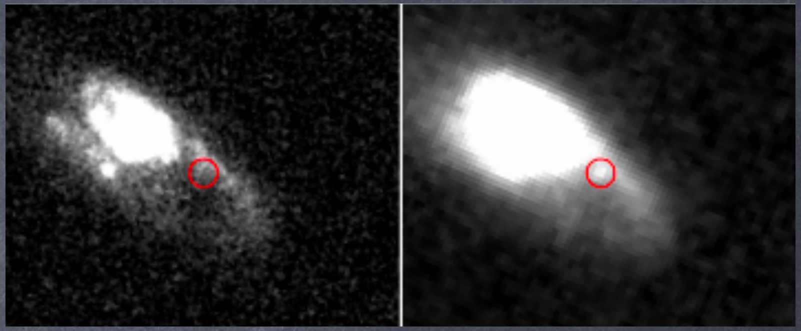
HST image (Tanvir + 13)

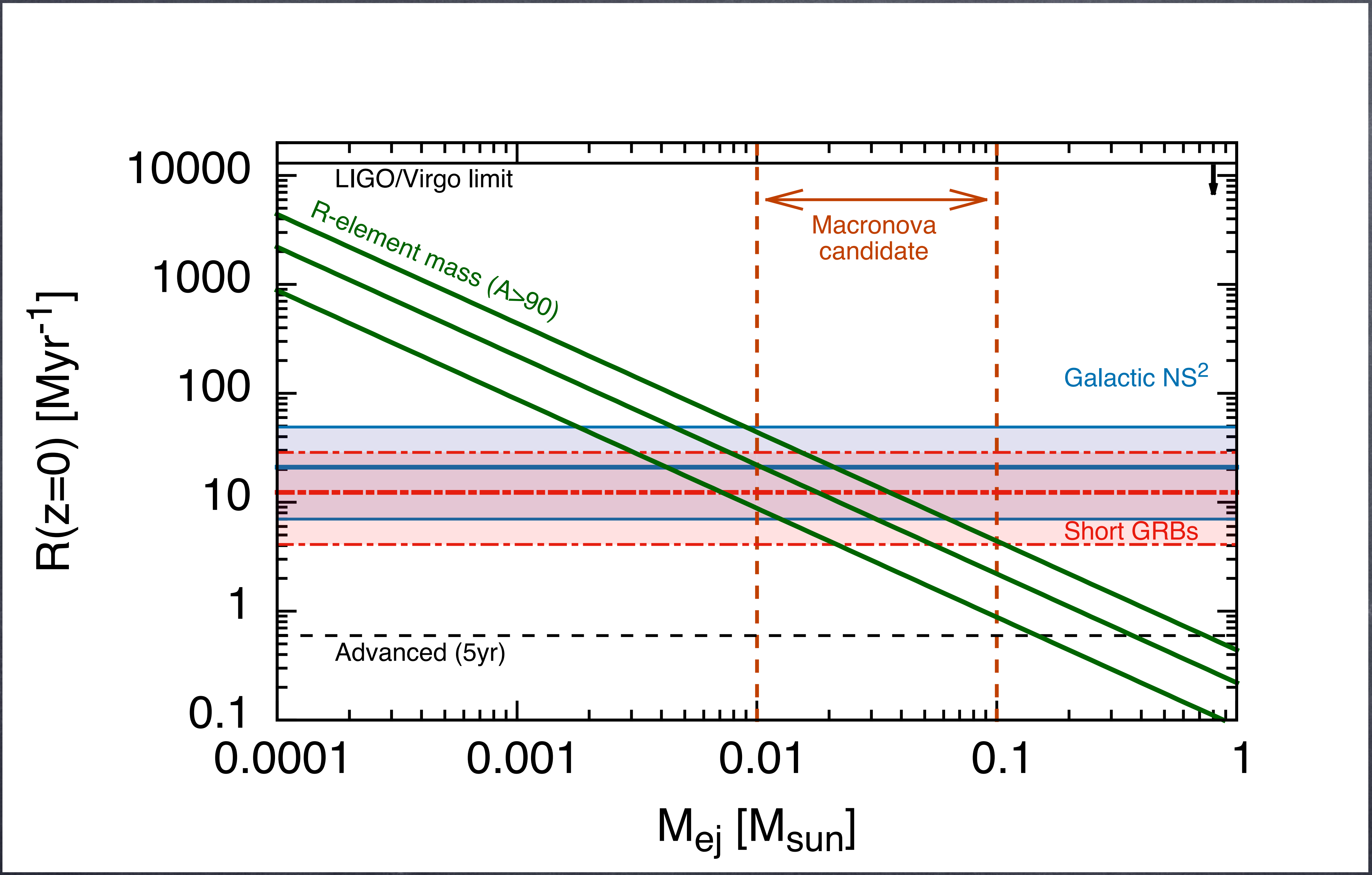


Macronova?

Tanvir + 13, Berger + 13

6. The Origin of GOLD

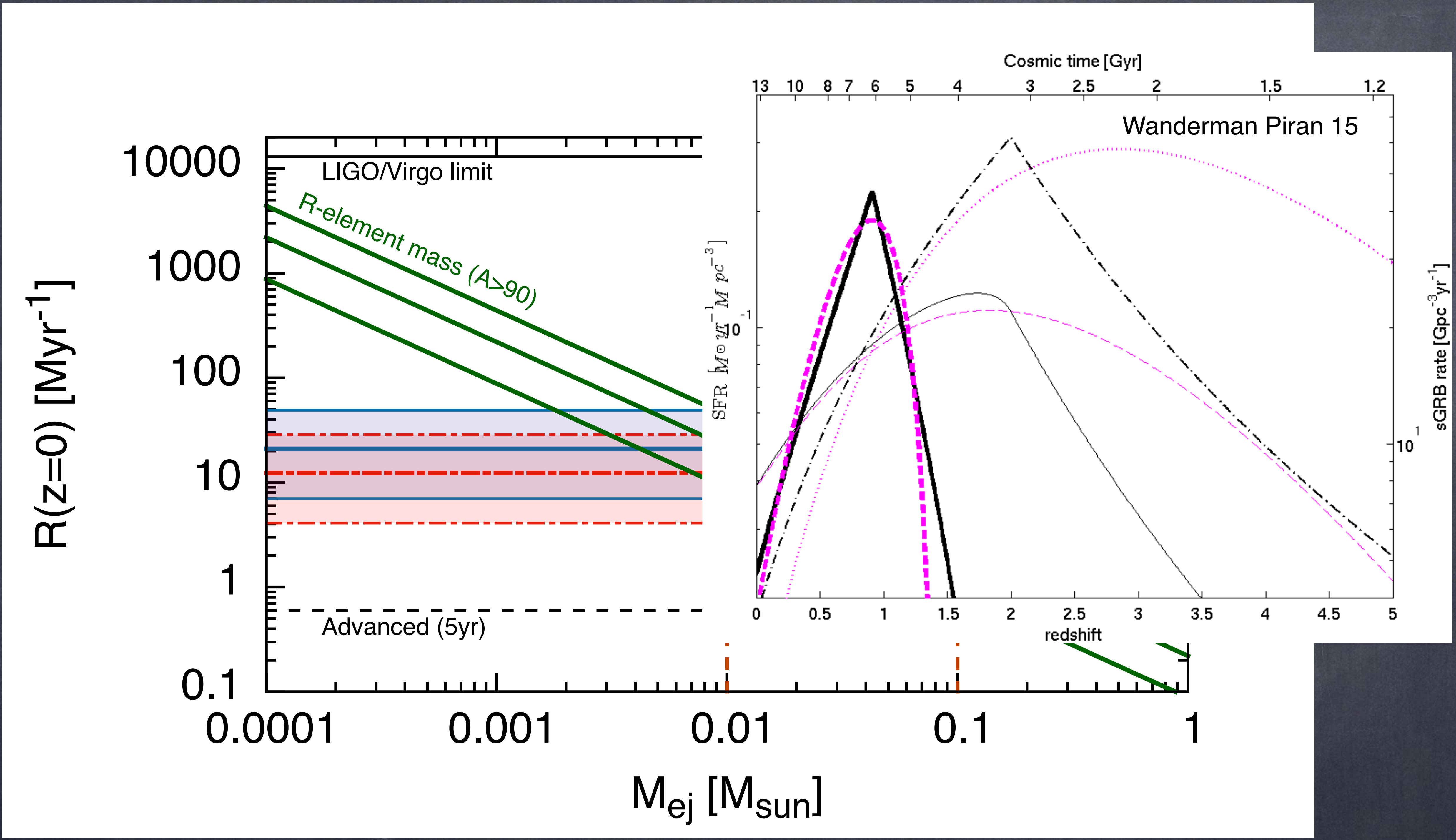




lines of R-mass: Current event rate is lower than the average one by a factor of 5 (lower line), 3 (middle line).

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

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



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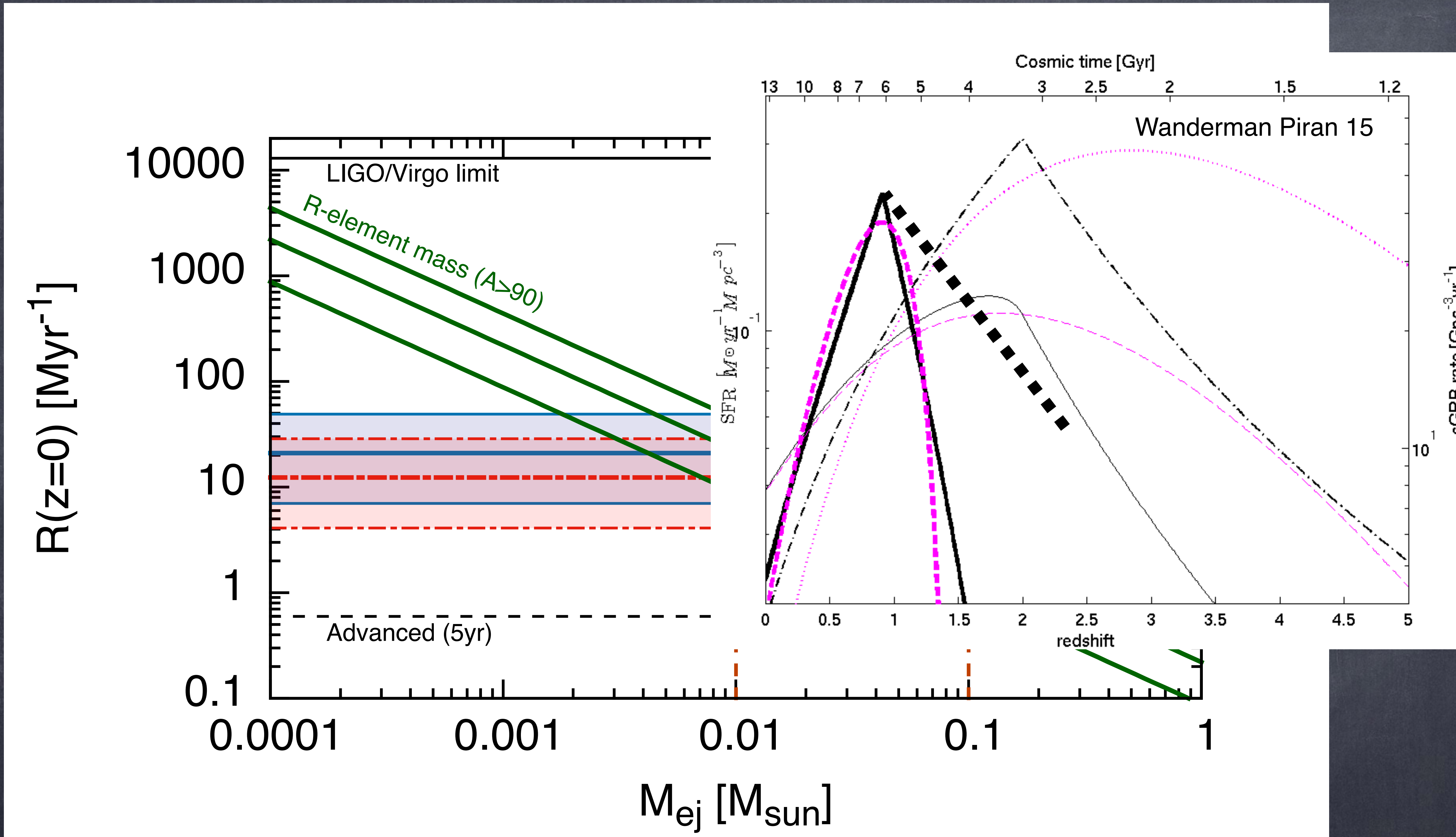

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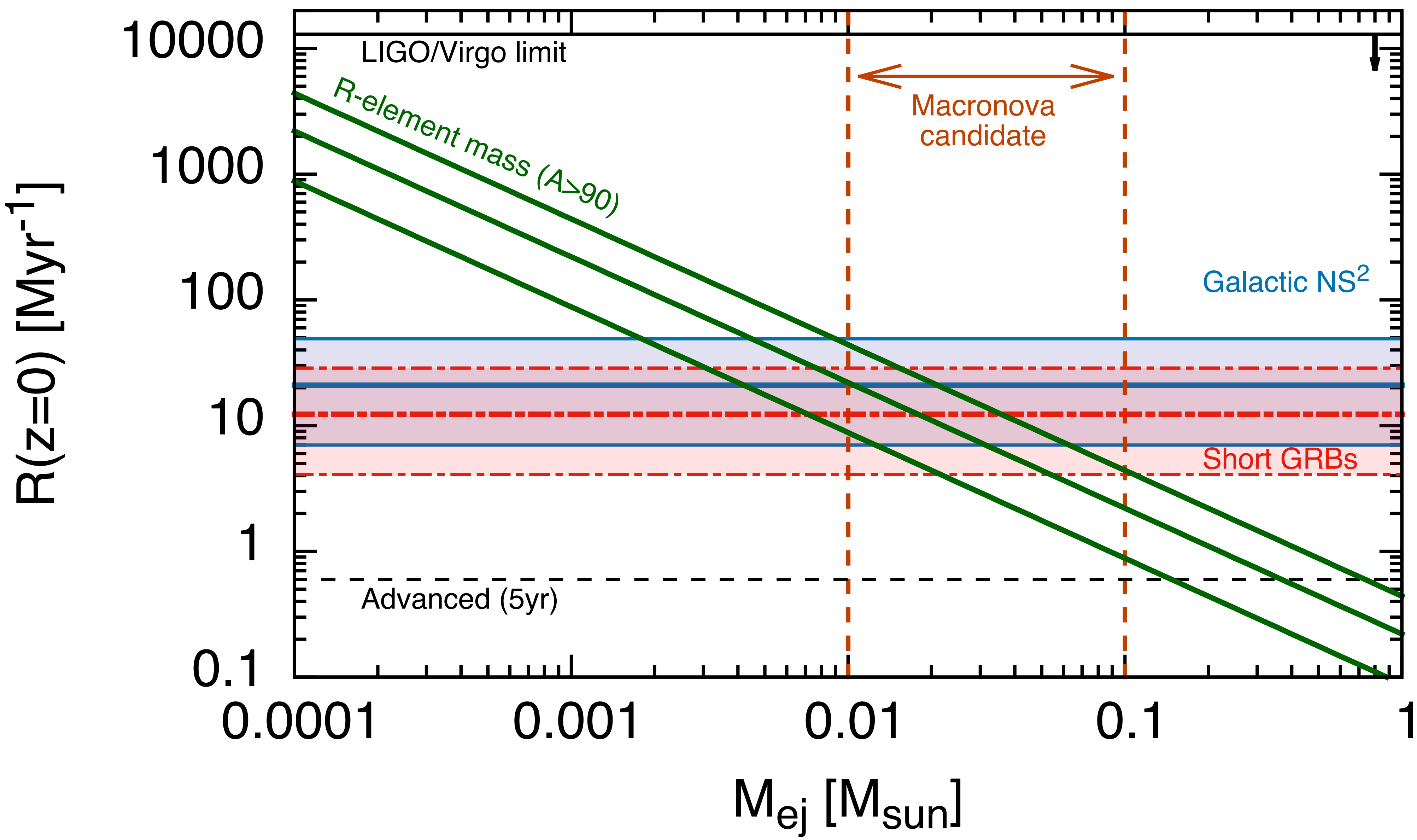

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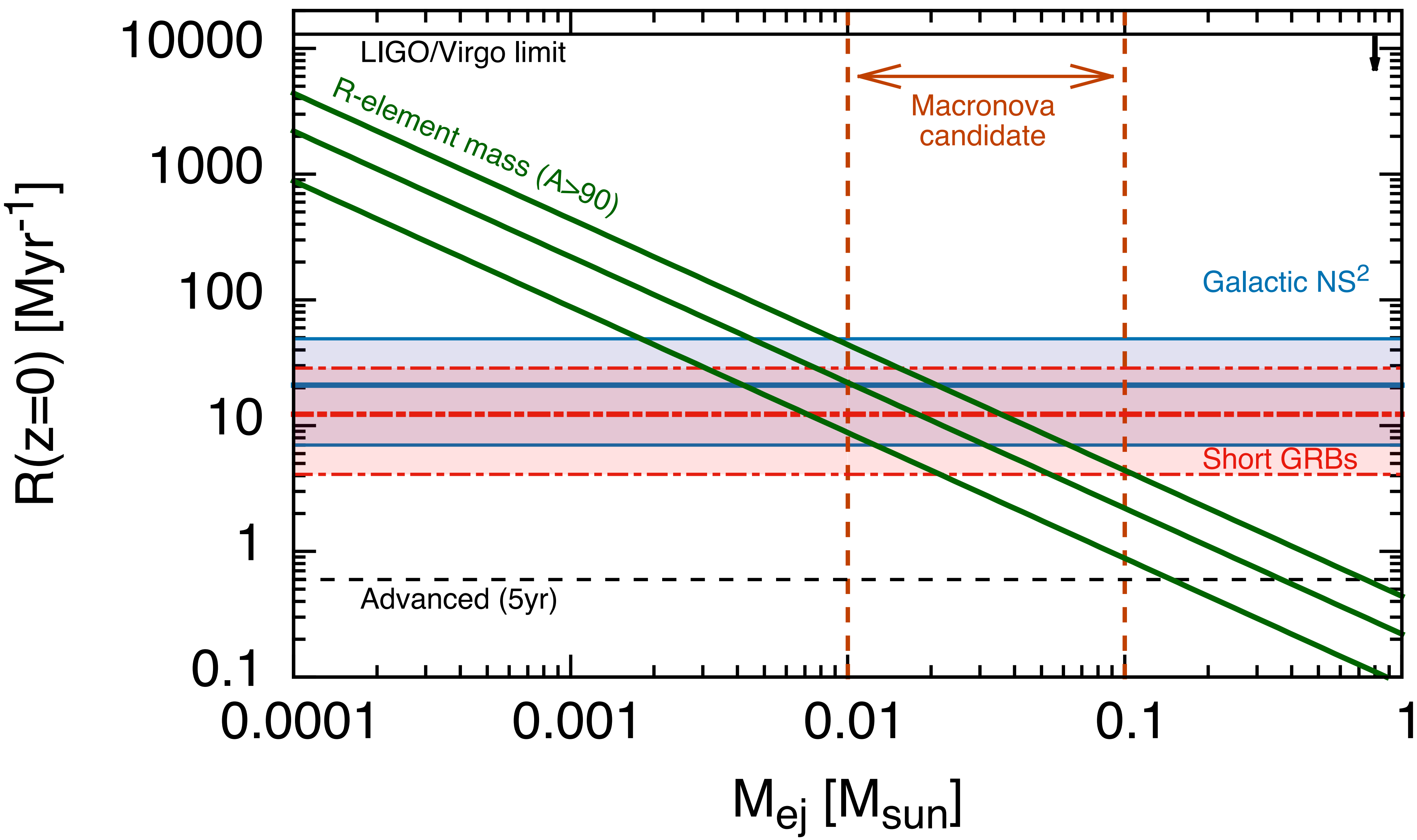

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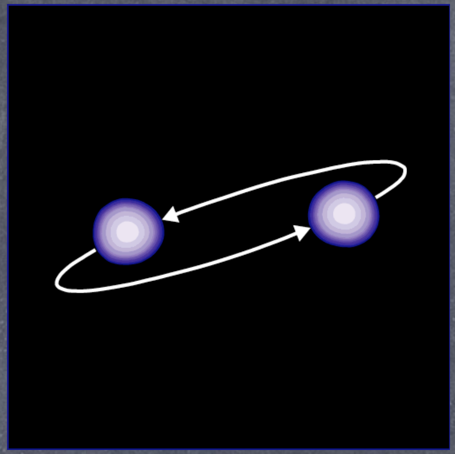
lines of NSNS: 95% confidence level (Kim et al 2015) *

If correct

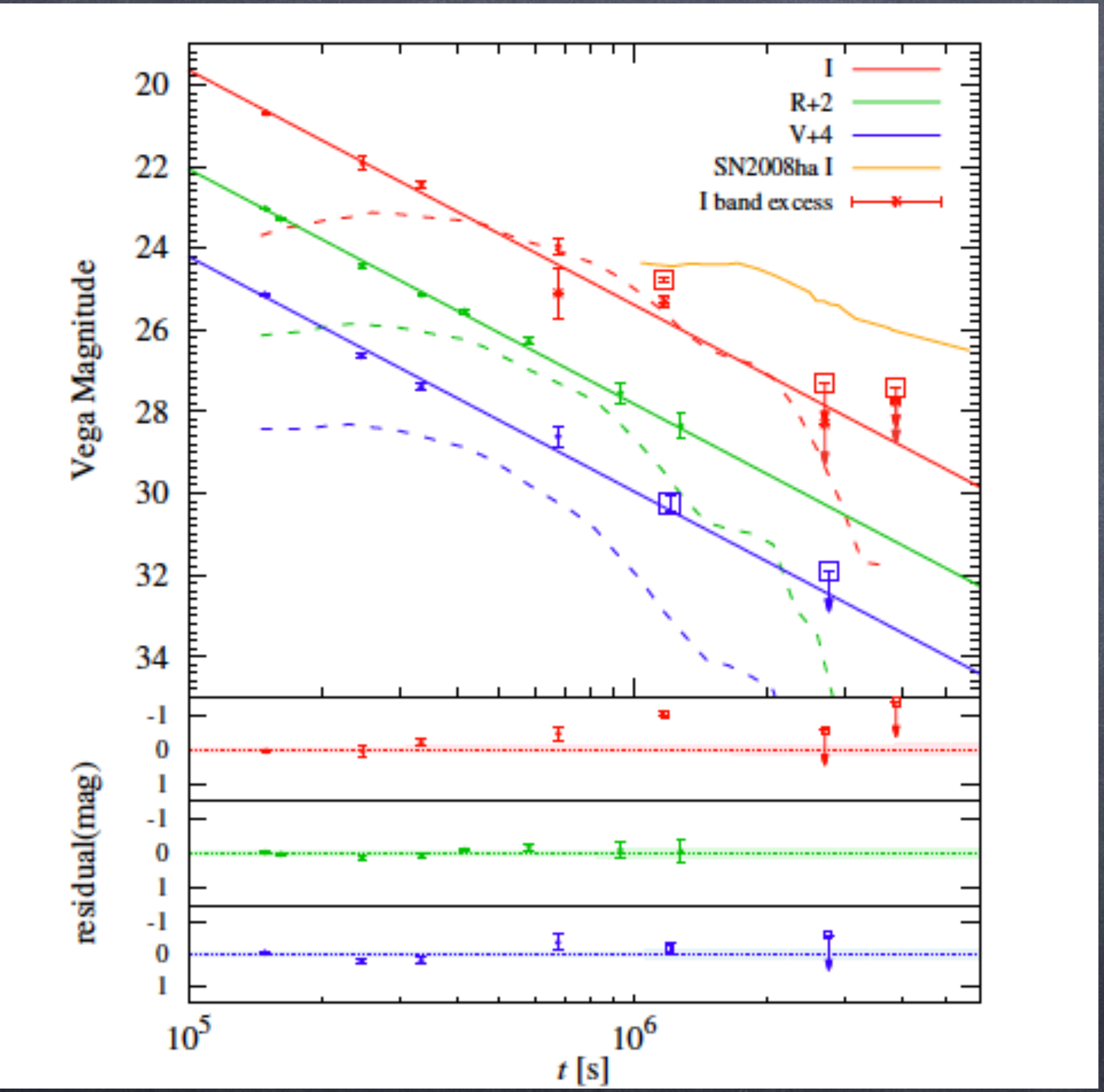
- Confirmaiton of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).
- Confirmation of the Li-Paczynski Macronova (Li-Paczynski 1997).
- Confirmation that compact binary mergers are the source of heavy (A>130) r-process material: Gold, Silver, Platinum, Plotonium, Uranium etc...(Lattimer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



Confirmations

- The GRB060614 Macronoaa - BH-NS?
- Radioactive elements - ^{244}Pu
- Radio Flares

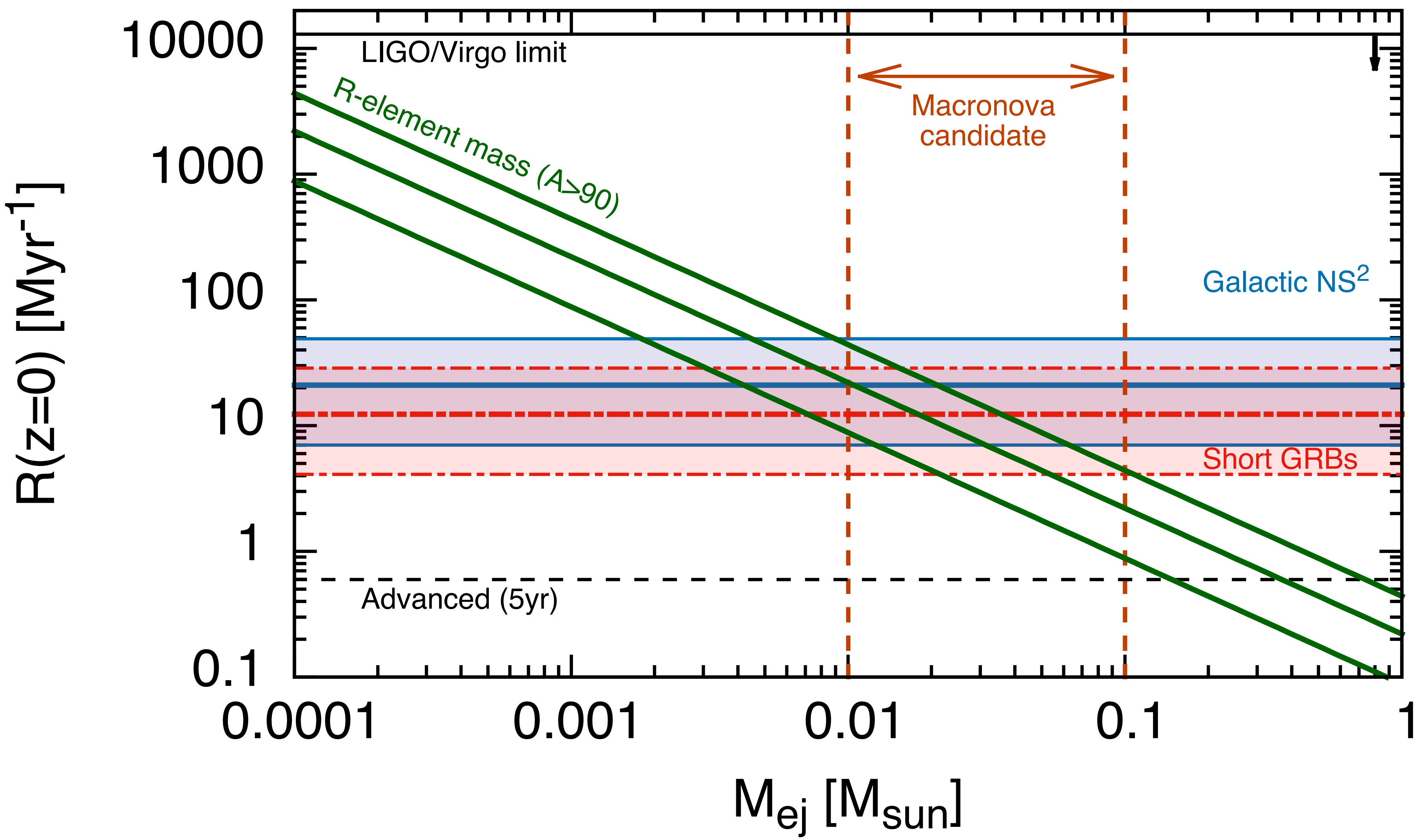
GRB 060614



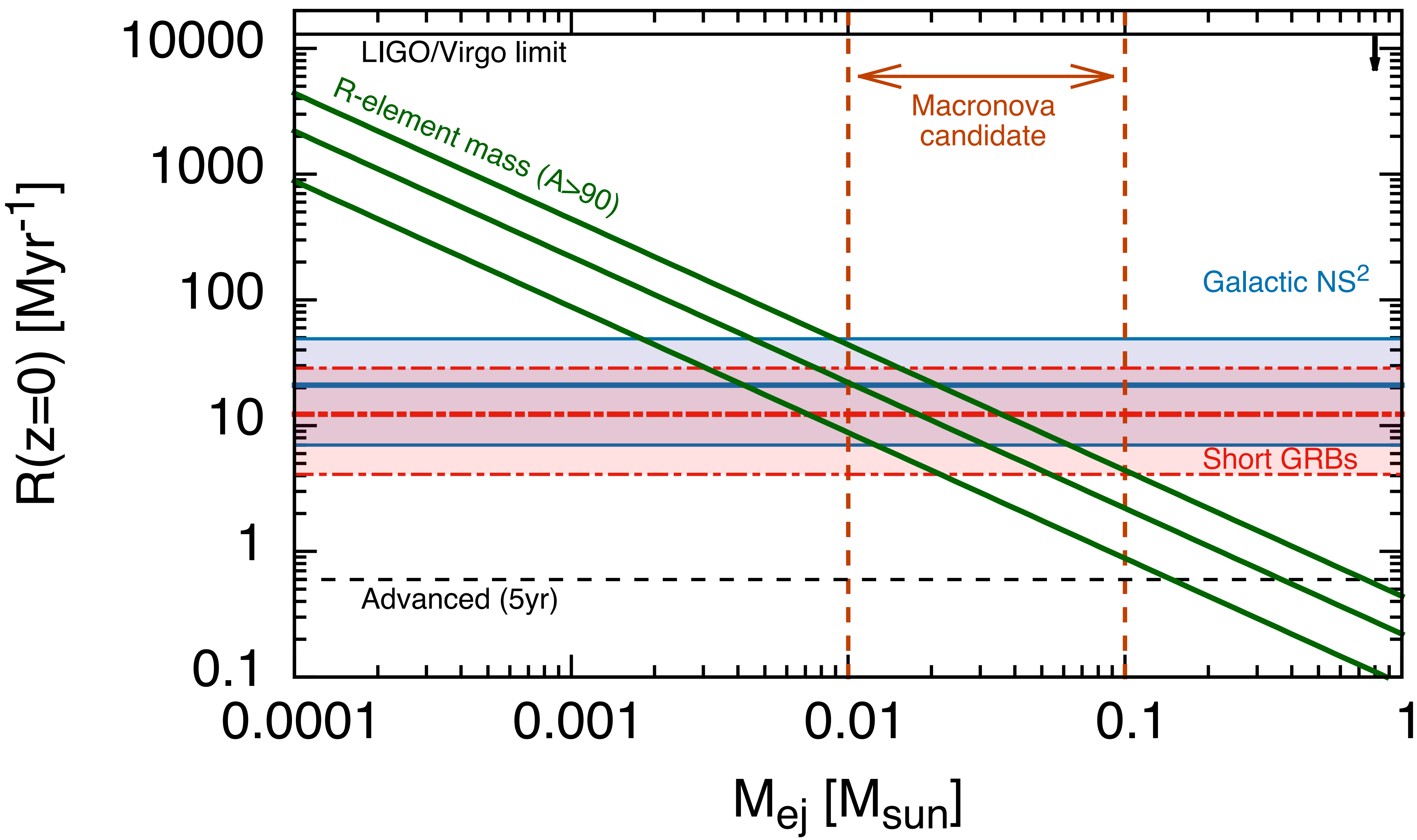
Need $M \simeq 0.1 M_\odot$

=> BH-NS ?

Yang et al., Nature Comm 2015



Can we break the yield - rate degeneracy?



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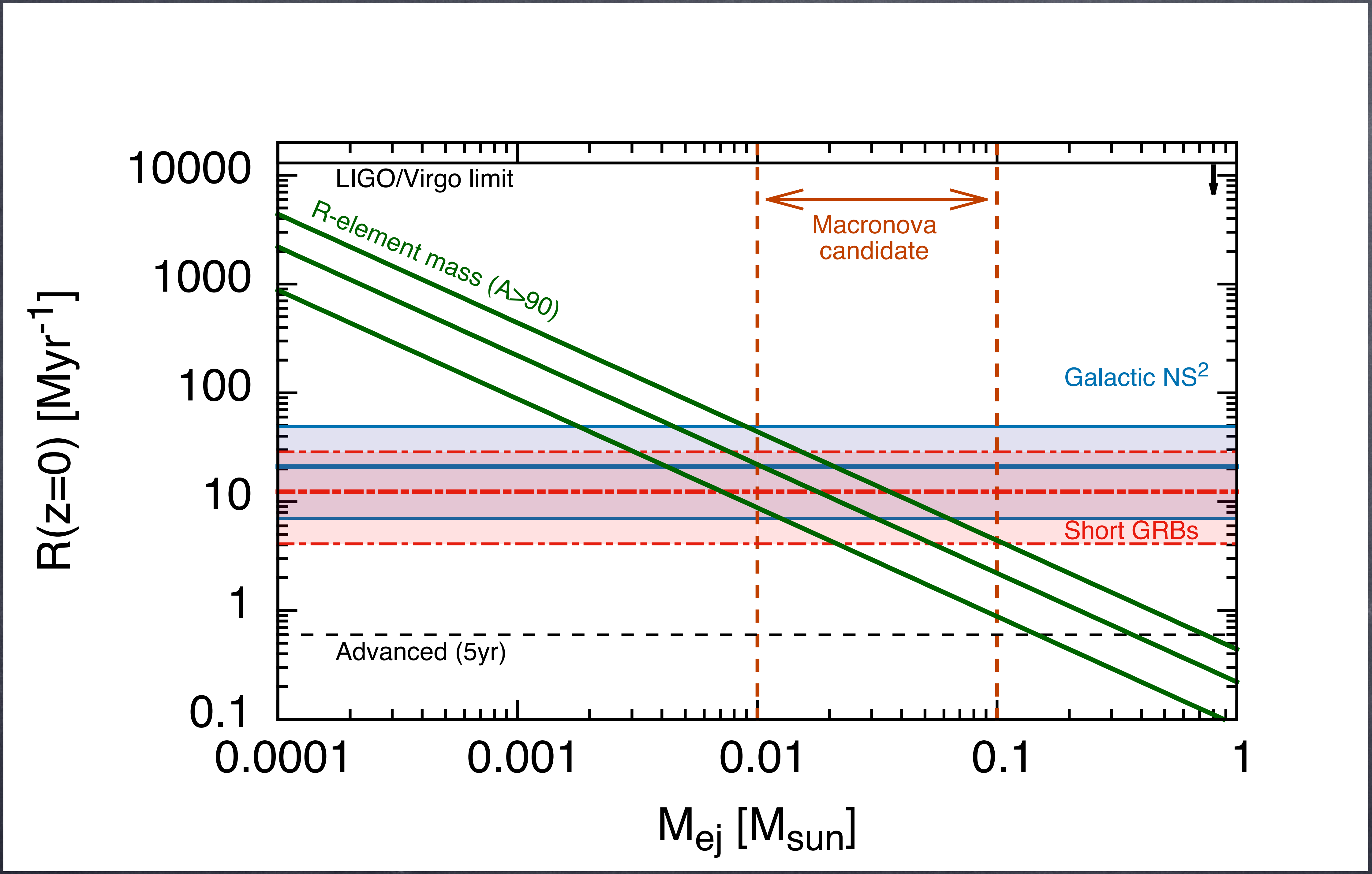

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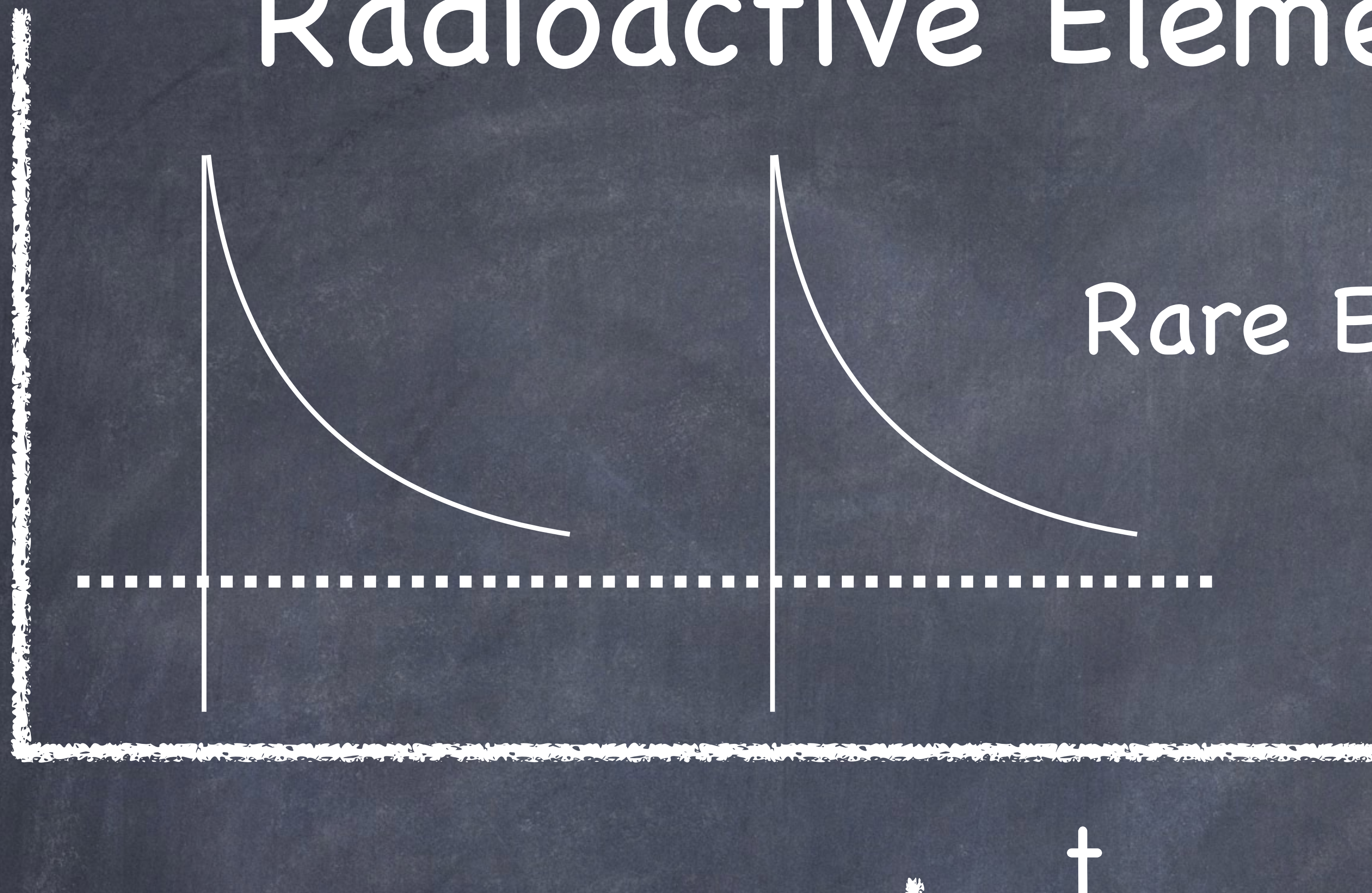
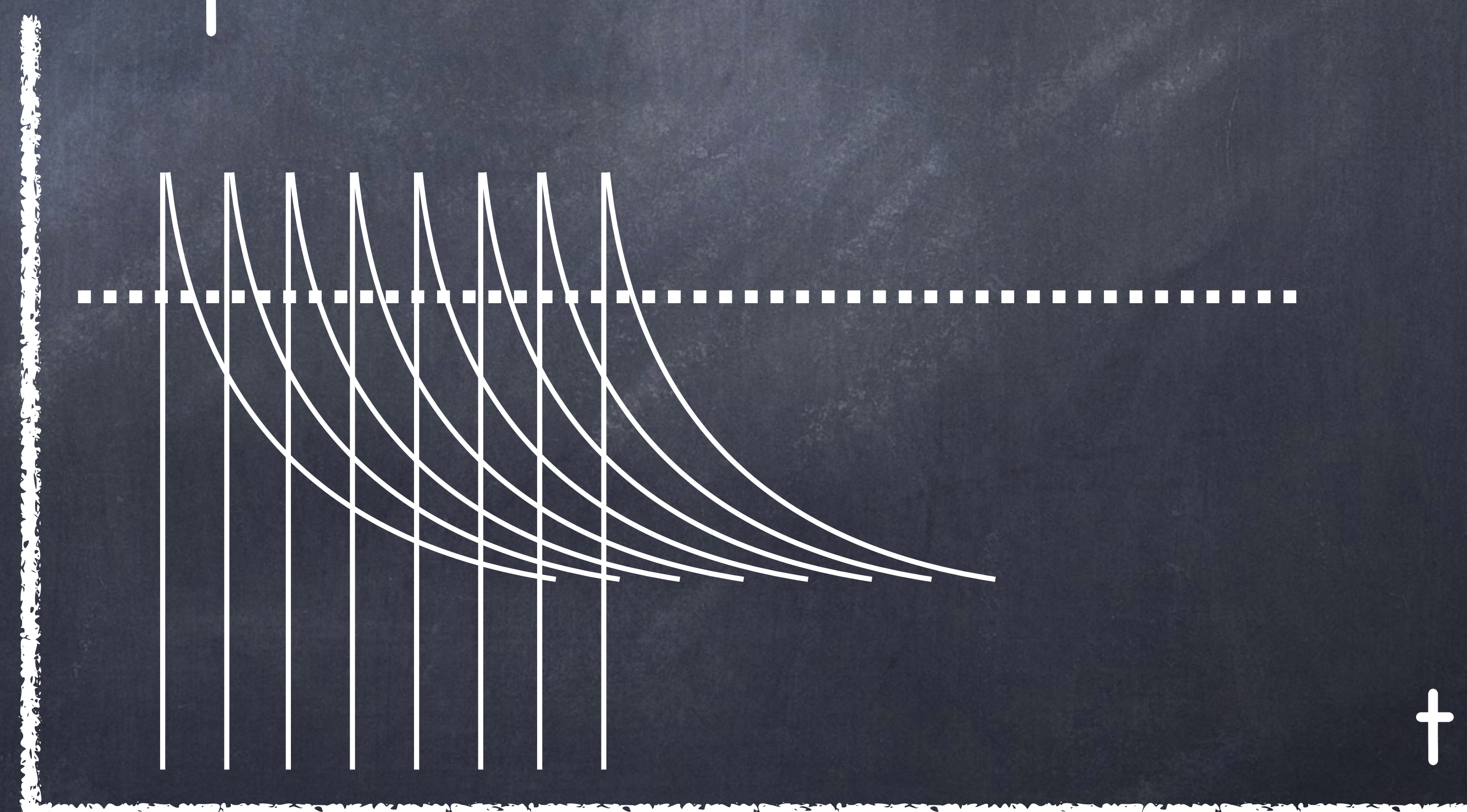
Radioactive Elements



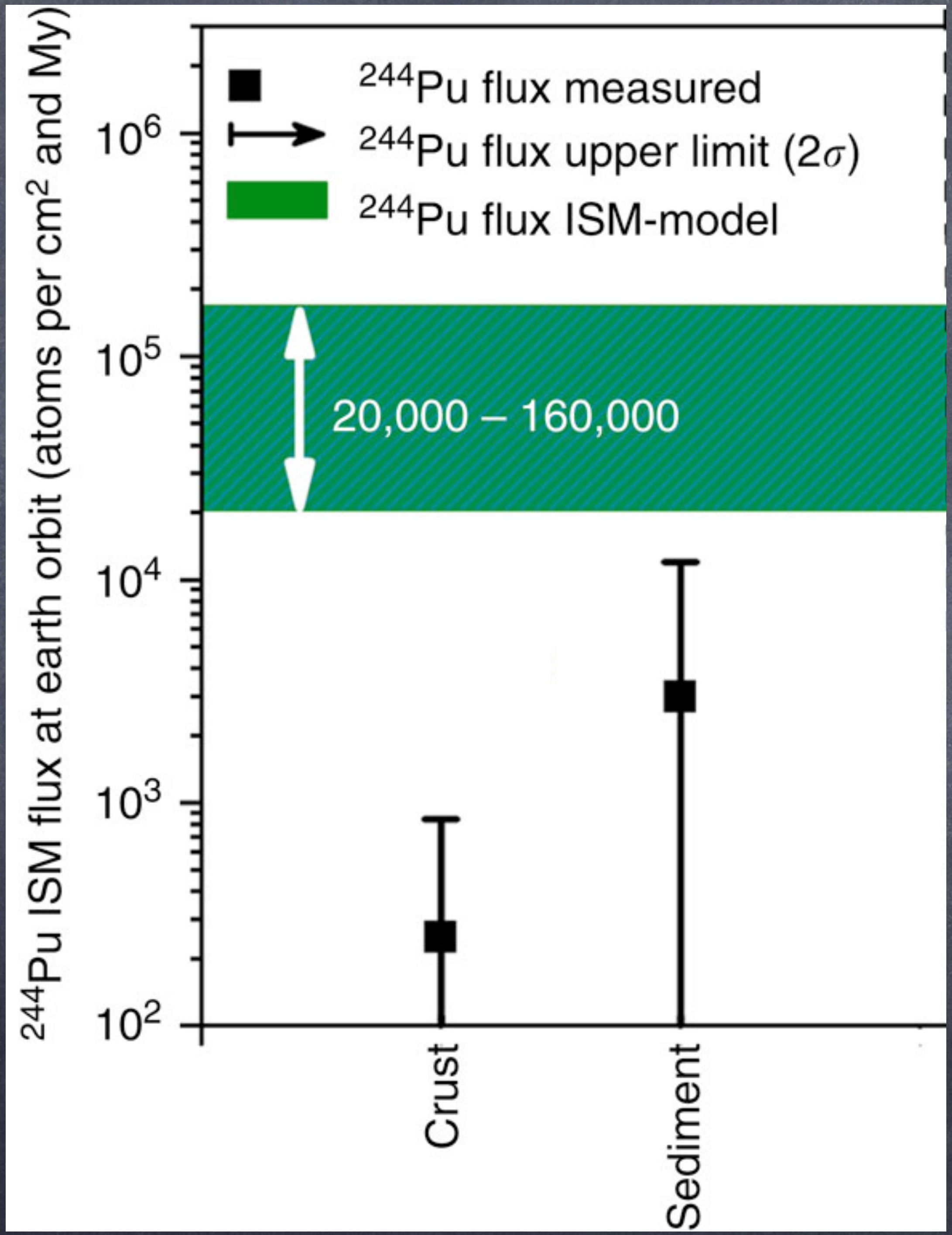
Rare Events

Frequent events



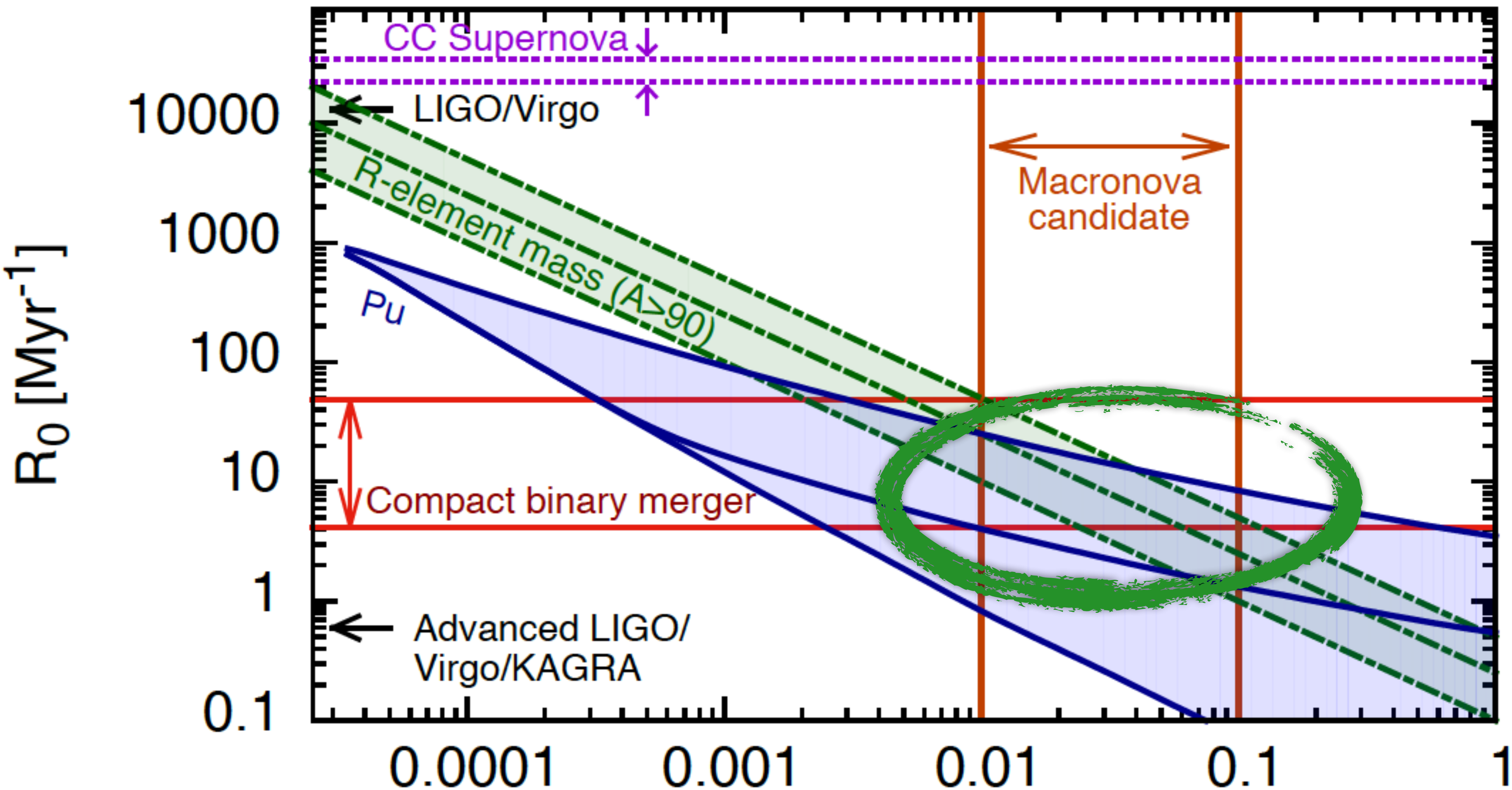
^{244}Pu (half life 81Myr)

The early solar system



Wallner + 14

Rare and "massive" events



Implication to GW detection

- Rate of GW detection with 200 Mpc horizon is < 30 yr^{-1}.
- Mass ejection is significant hence a good chance for detection of a Macronova or a Radio Flare.

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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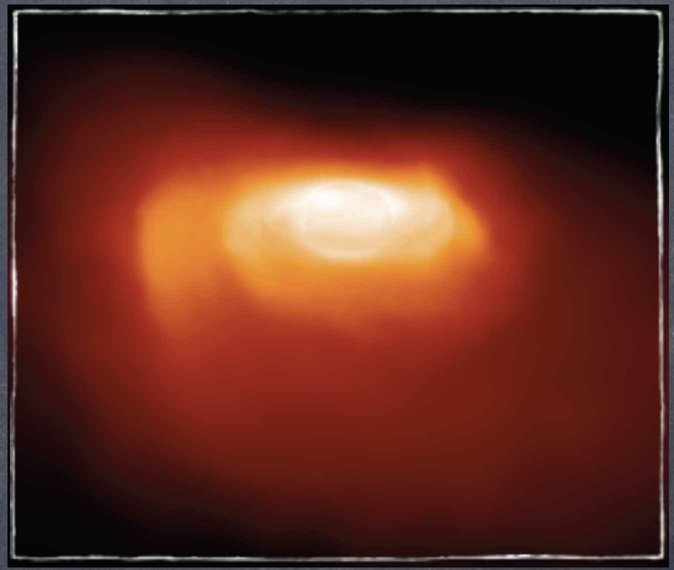

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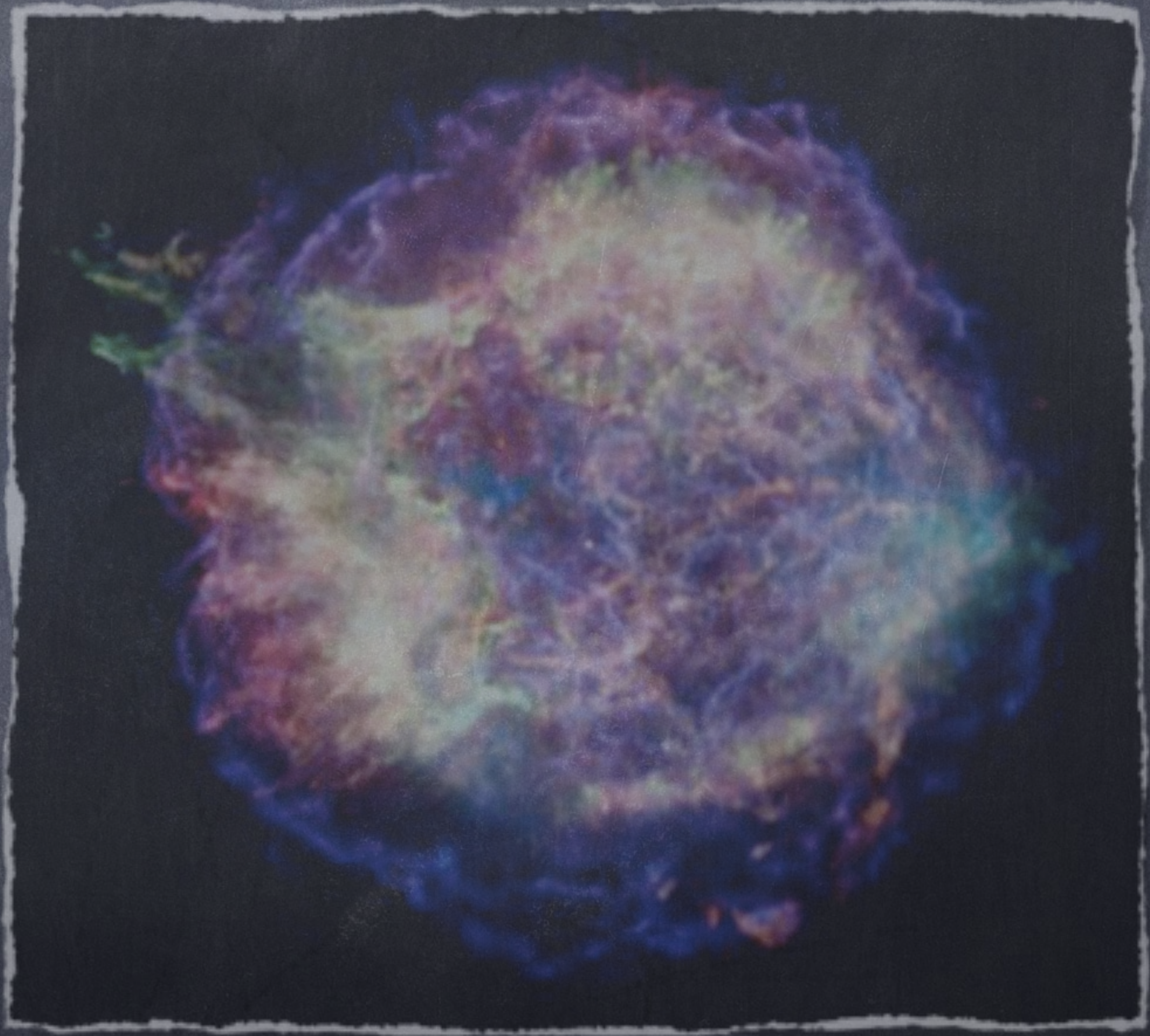

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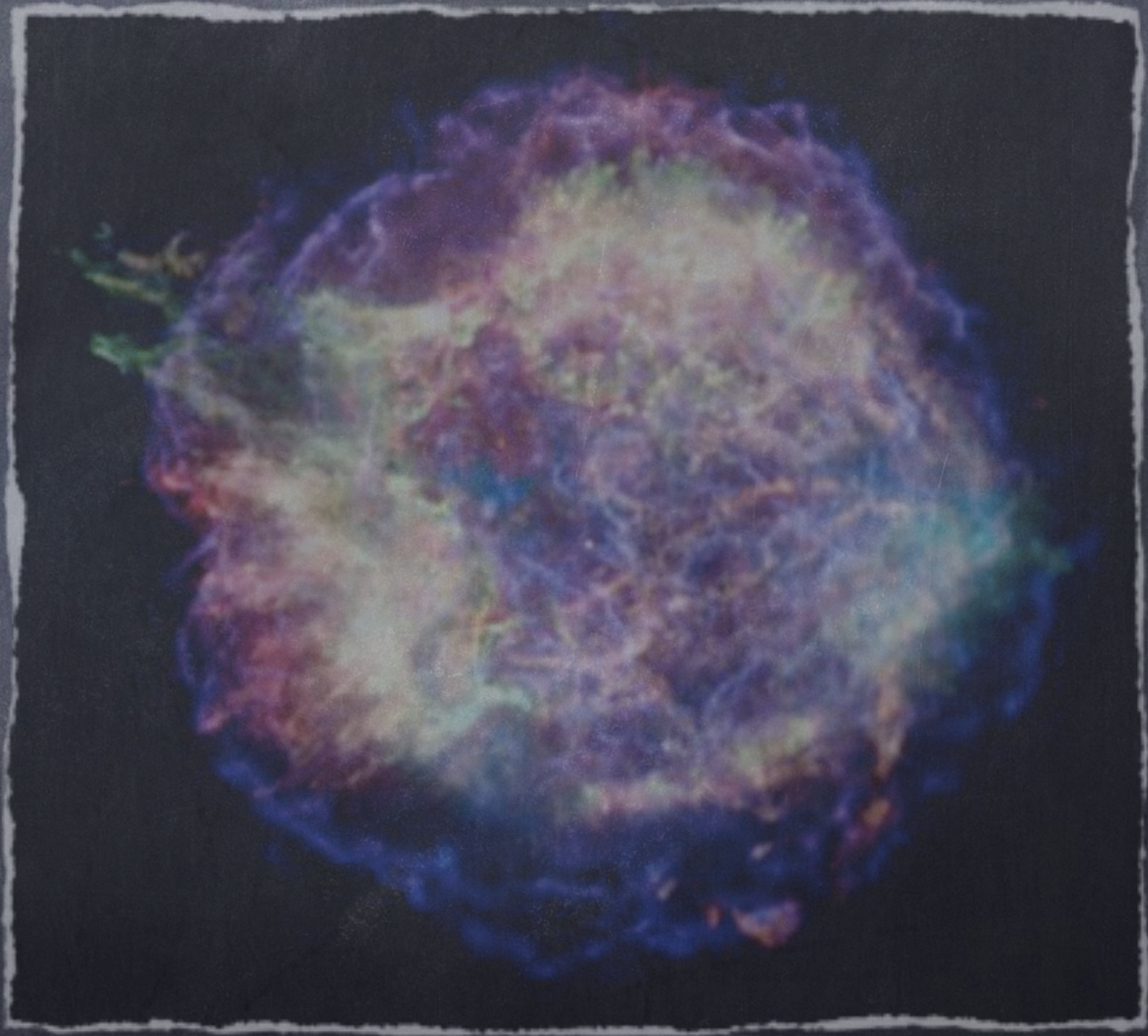
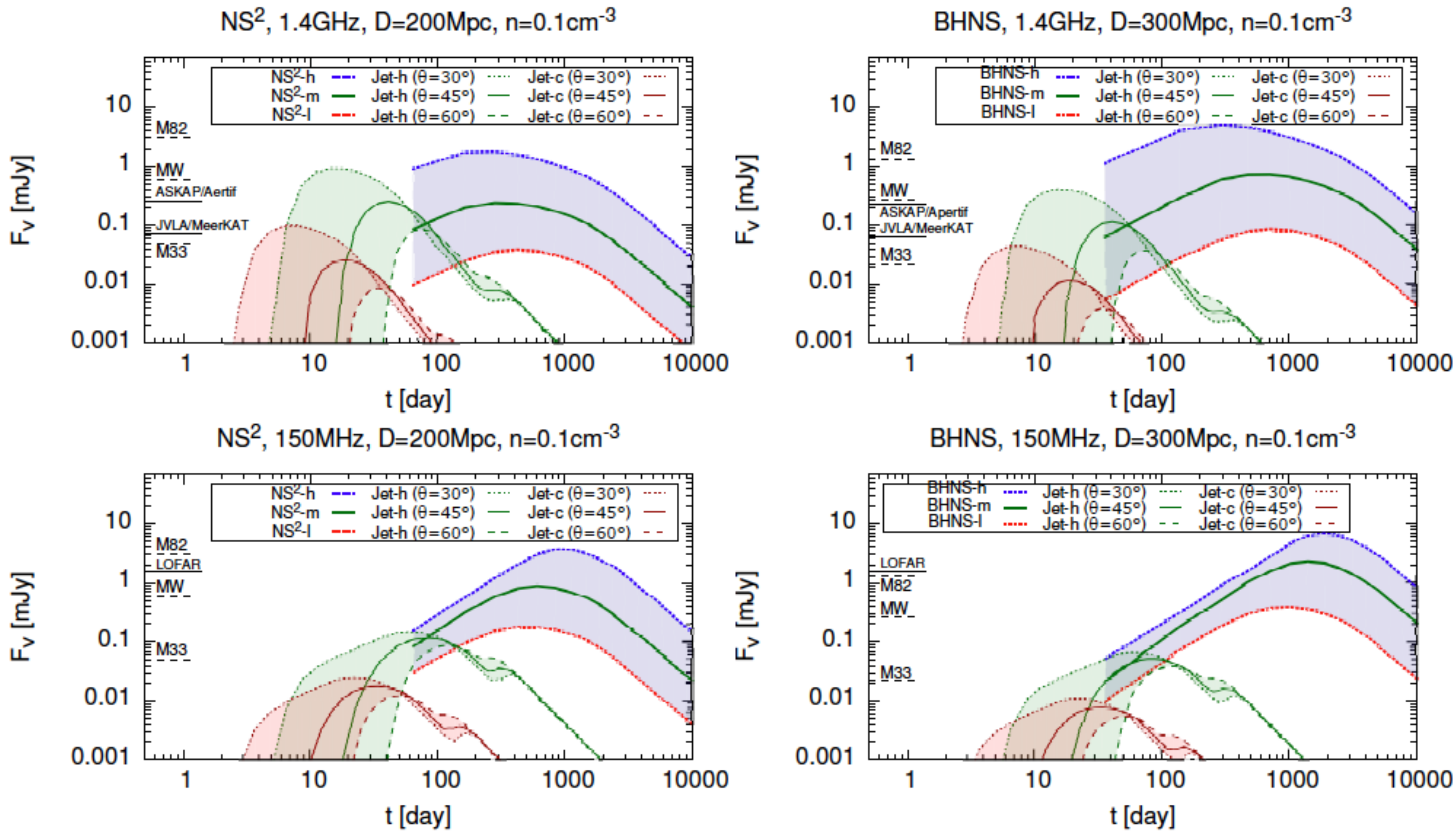


Supernova -> Supernova remnant

Macronova -> Radio Flare



Nakar, TP 2011; TP+13; Hotokezata + TP, 15

Search for the flare from GRB 130603B by the EVLA

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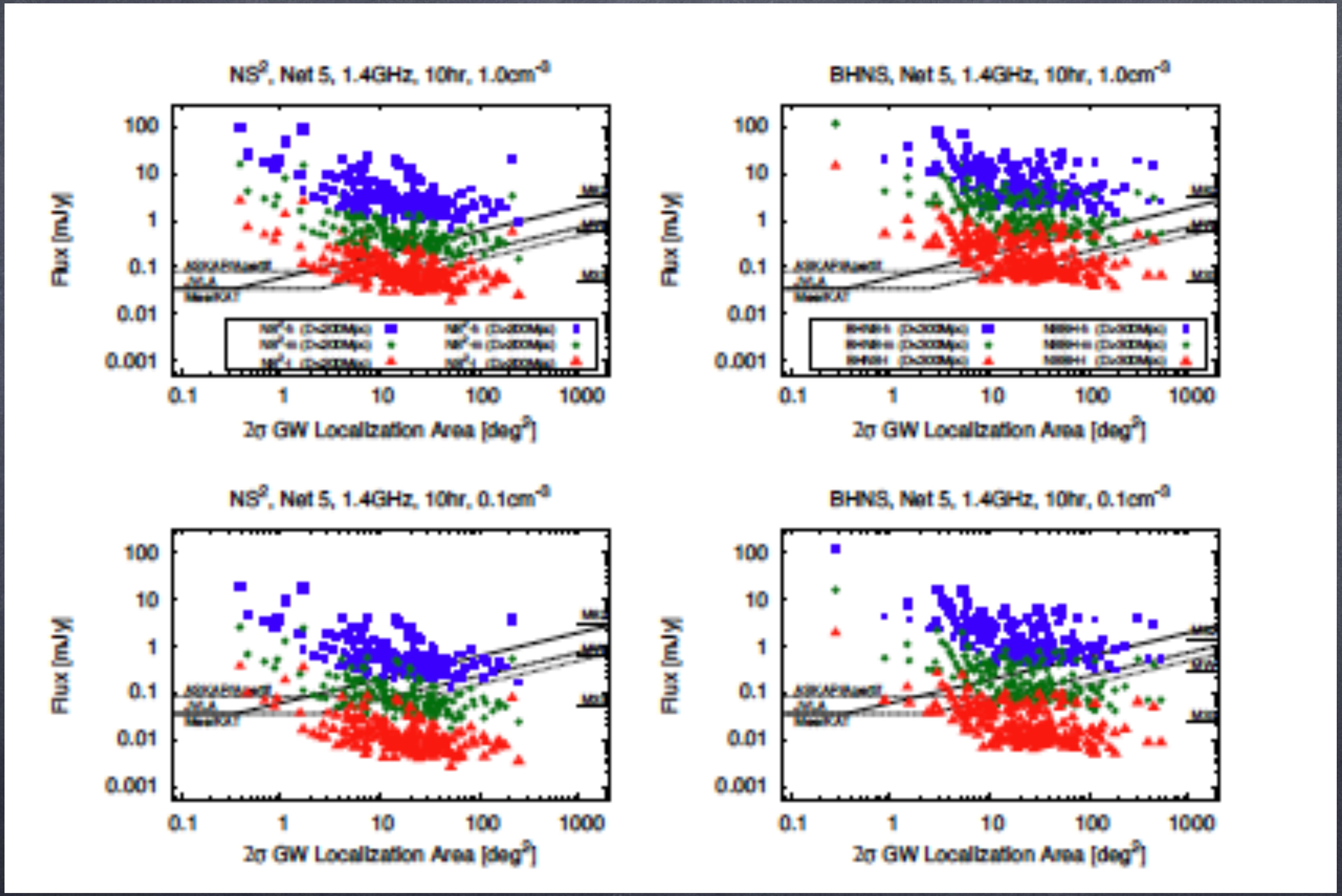
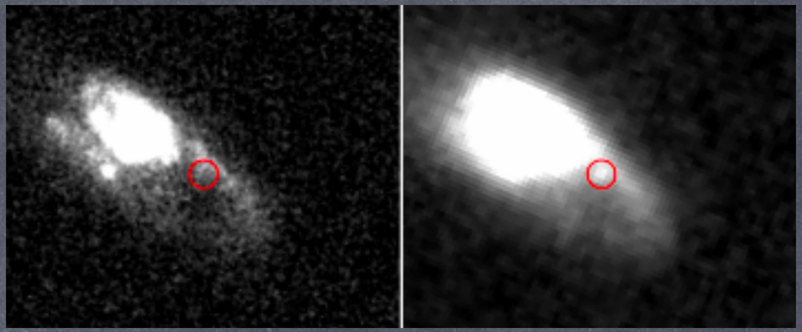
Detectability of Radio Flares



(Hotokezaka, Nissanke + 15)

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} and short time delay).

- A radio flare may confirm this!
- A second Macronova suggests a BH-NS merger

- Plutonium abundance (from deposition now and from early solar system suggests that R-process production is in rare events.

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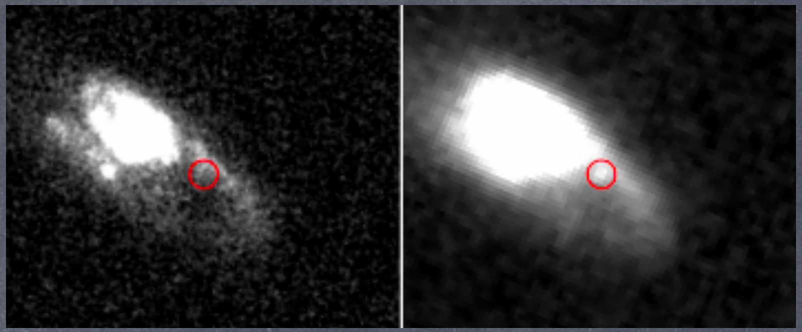

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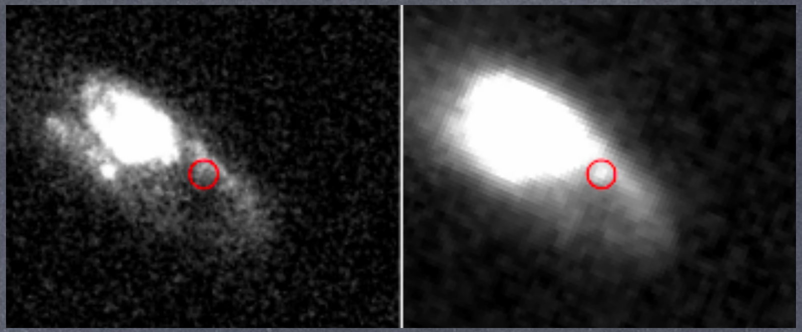

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