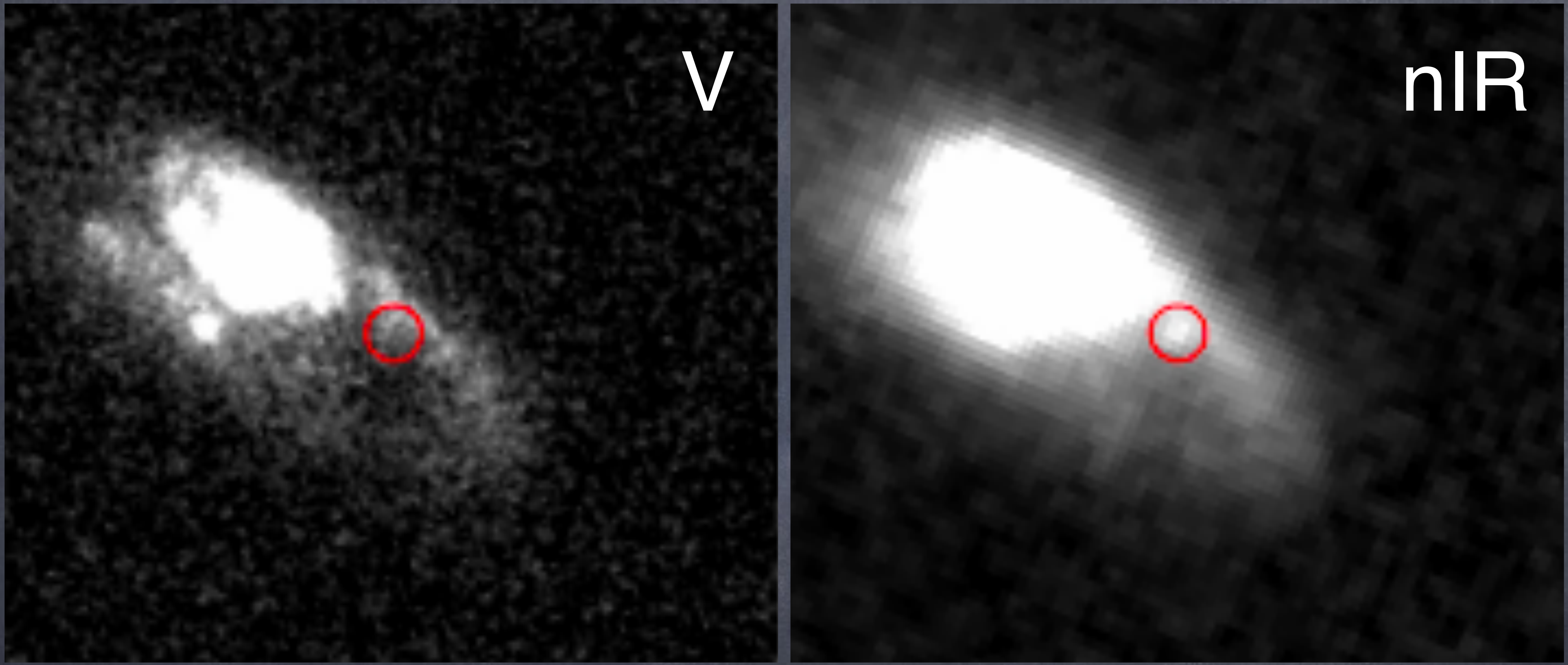
Mergers, Gamma-Ray Bursts and Gold

Tsvi Piran

The Hebrew University

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

The Hubble Space Telescope
June 13th 2013



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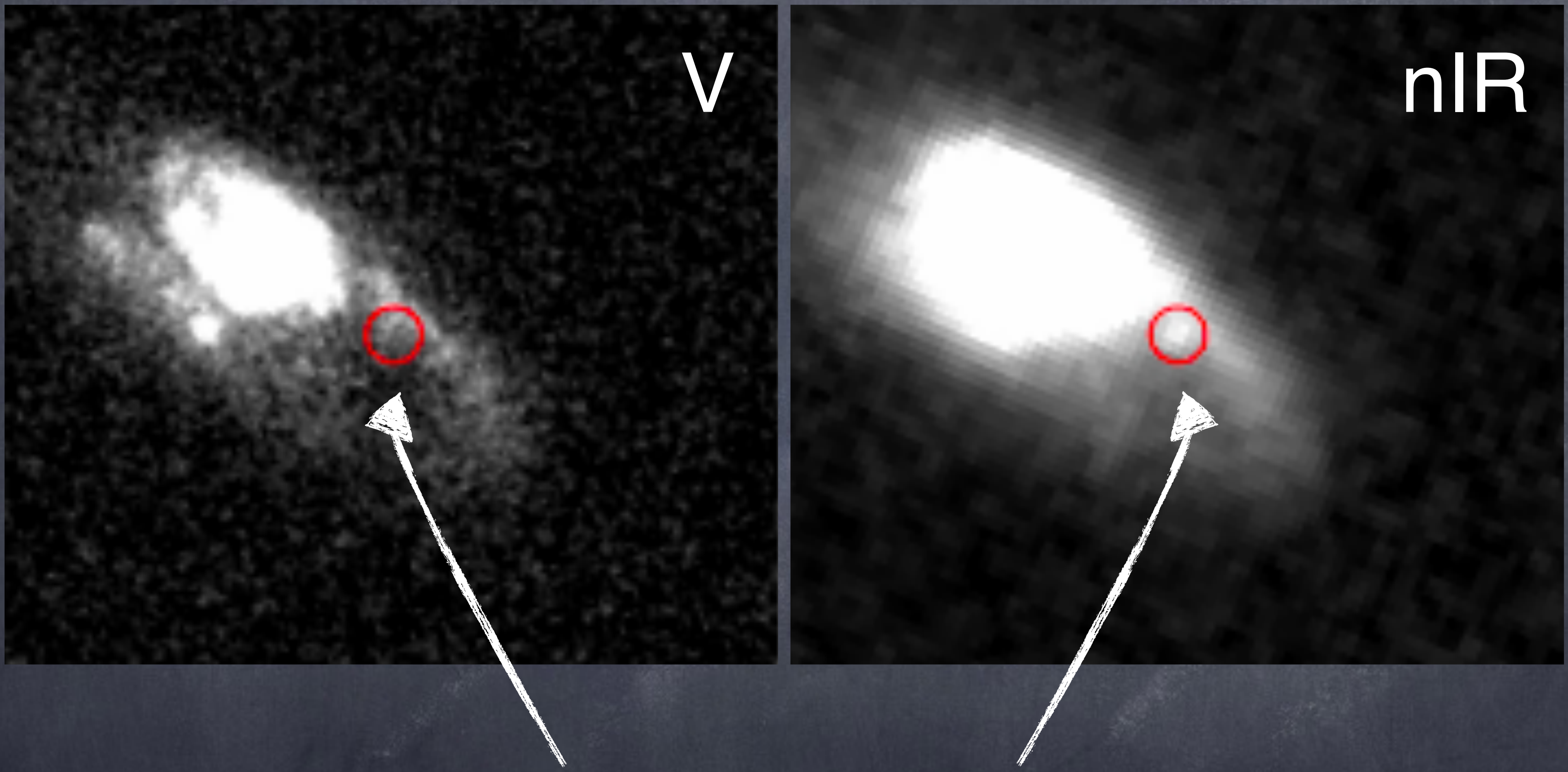
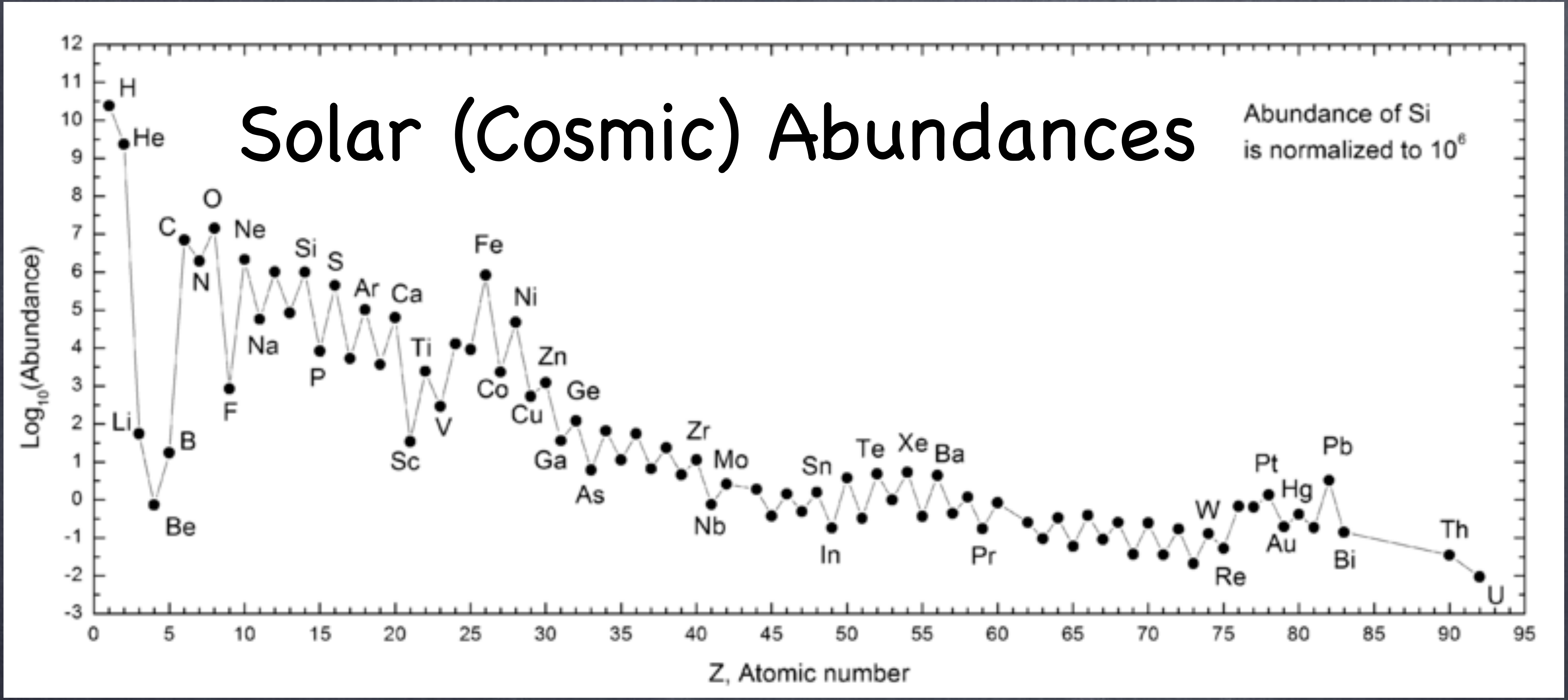


Is this the “smoking gun” proving the origin of Gold (and other heavy elemets) in the Universe?

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 - GRB 060614
7. The origin of Gold

1. Nucleosynthesis 101



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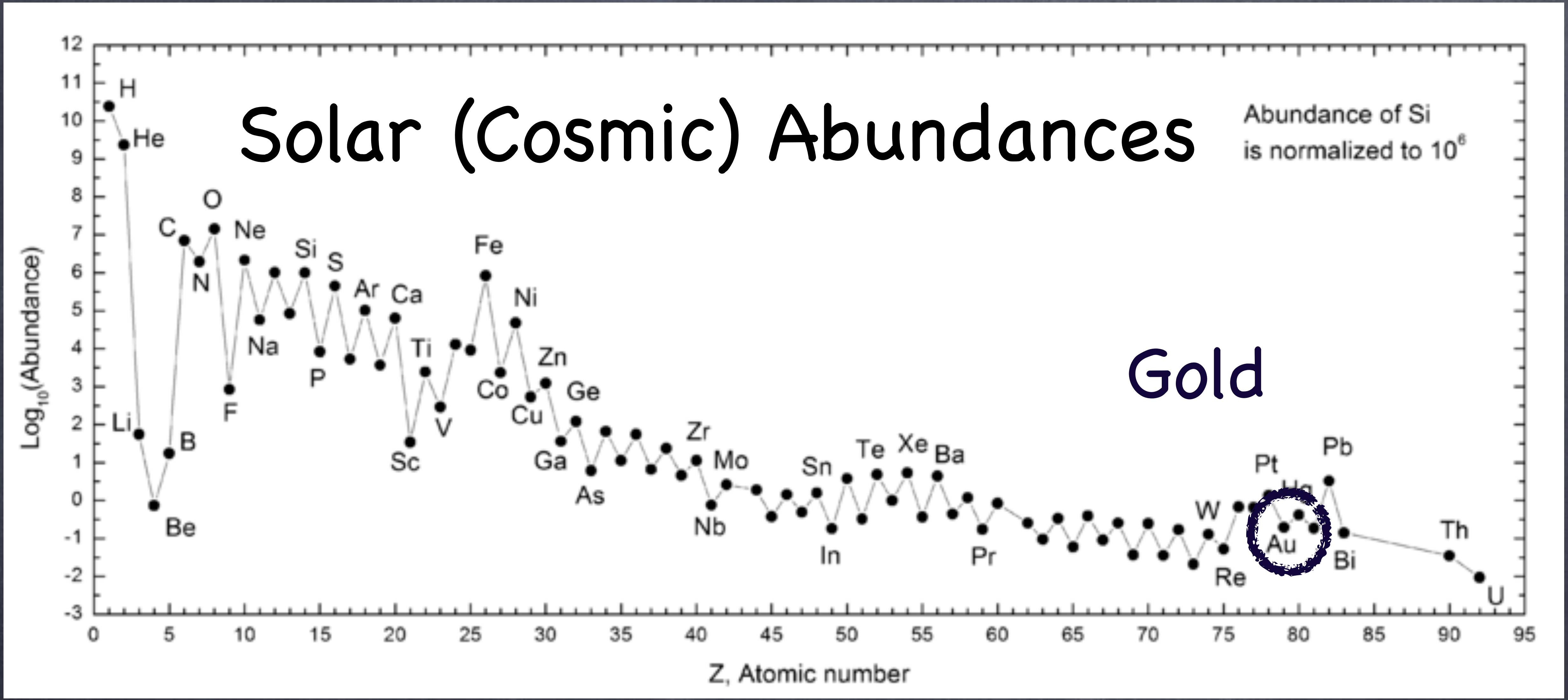
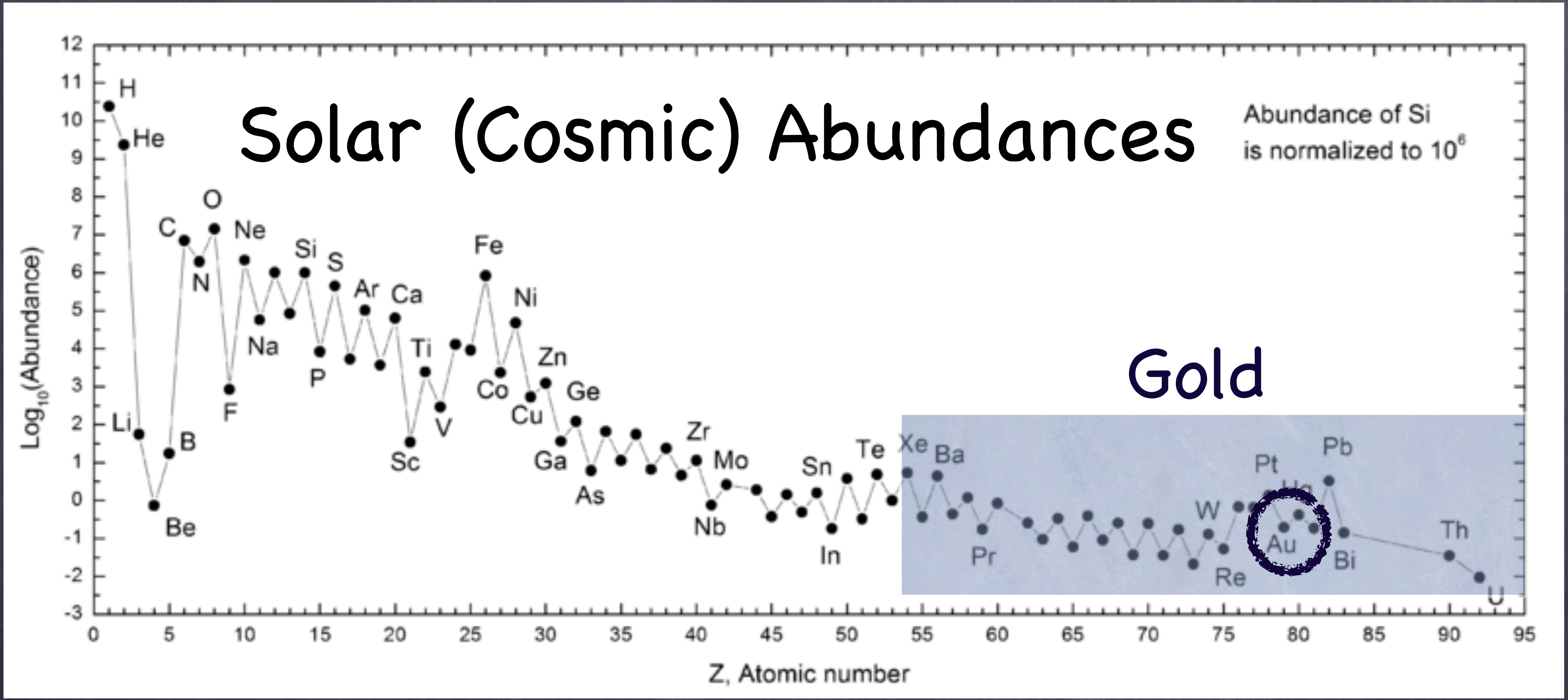


Solar (Cosmic) Abundances

Gold

1. Nucleosynthesis 101



Solar (Cosmic) Abundances

Gold

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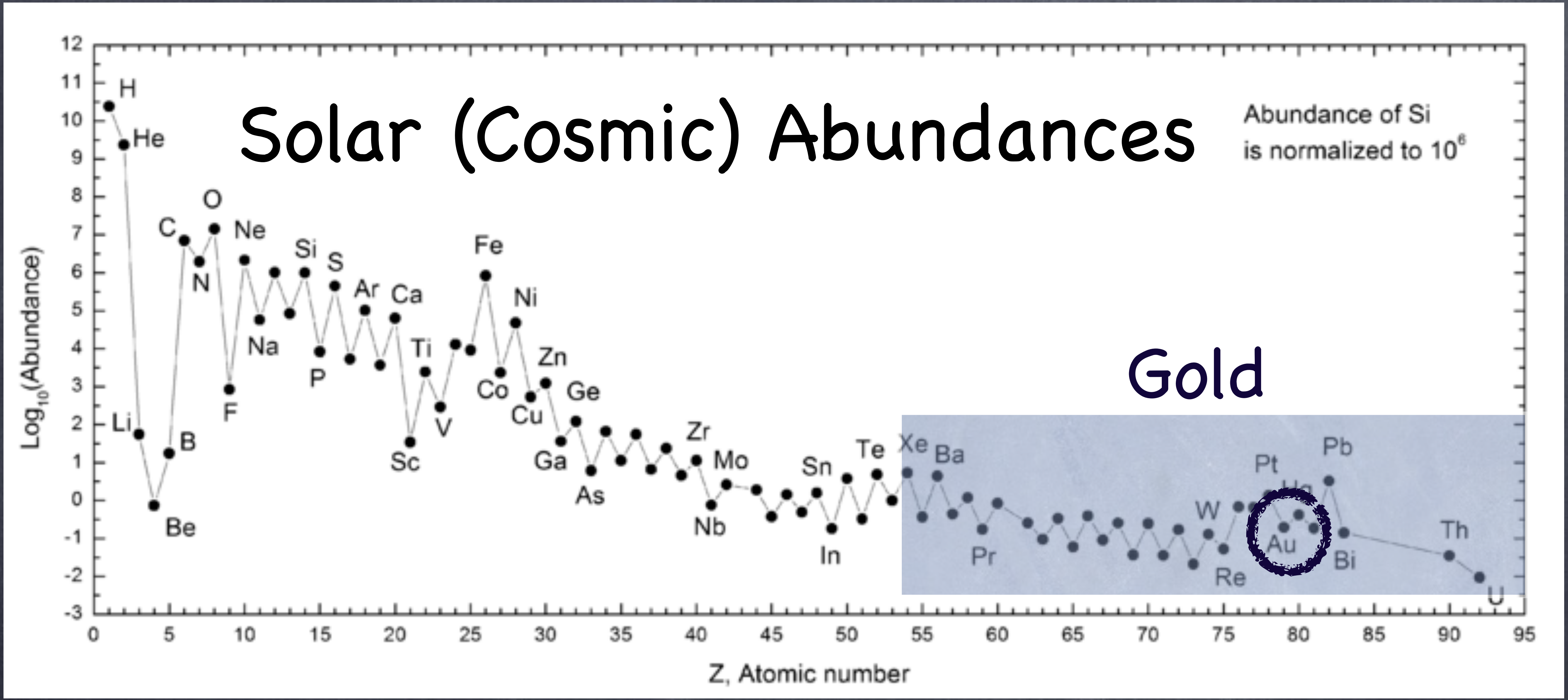

Solar (Cosmic) Abundances

Gold

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

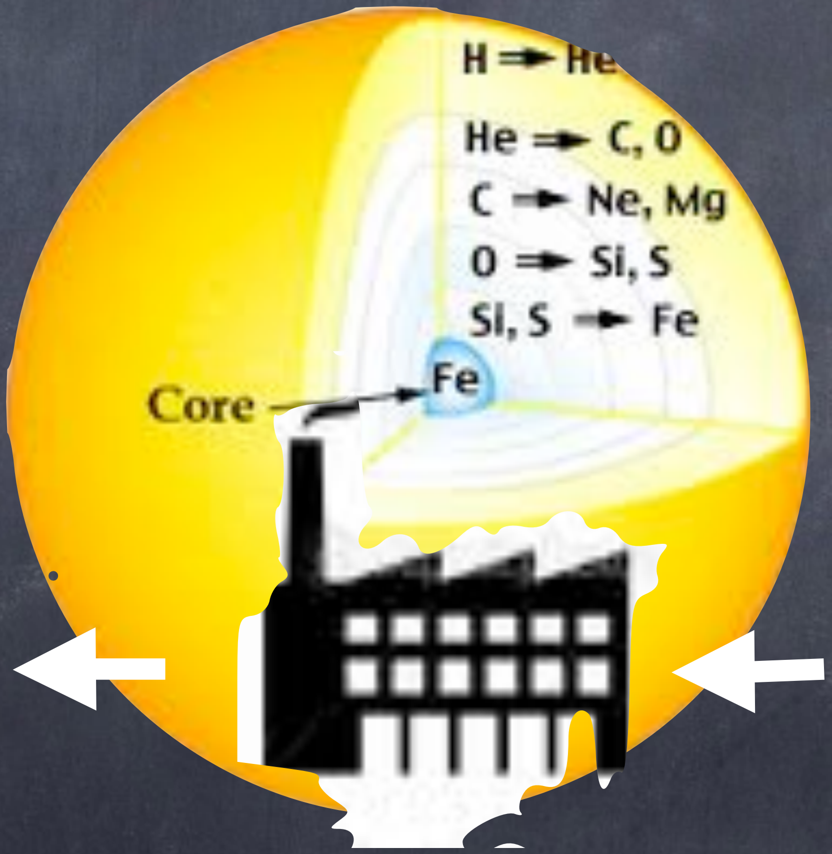
BB (Big Bang) Nucleosynthesis

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

George Gammow

Burbidge, Burbidge, Fowler and Hoyle

B^2FH 1957



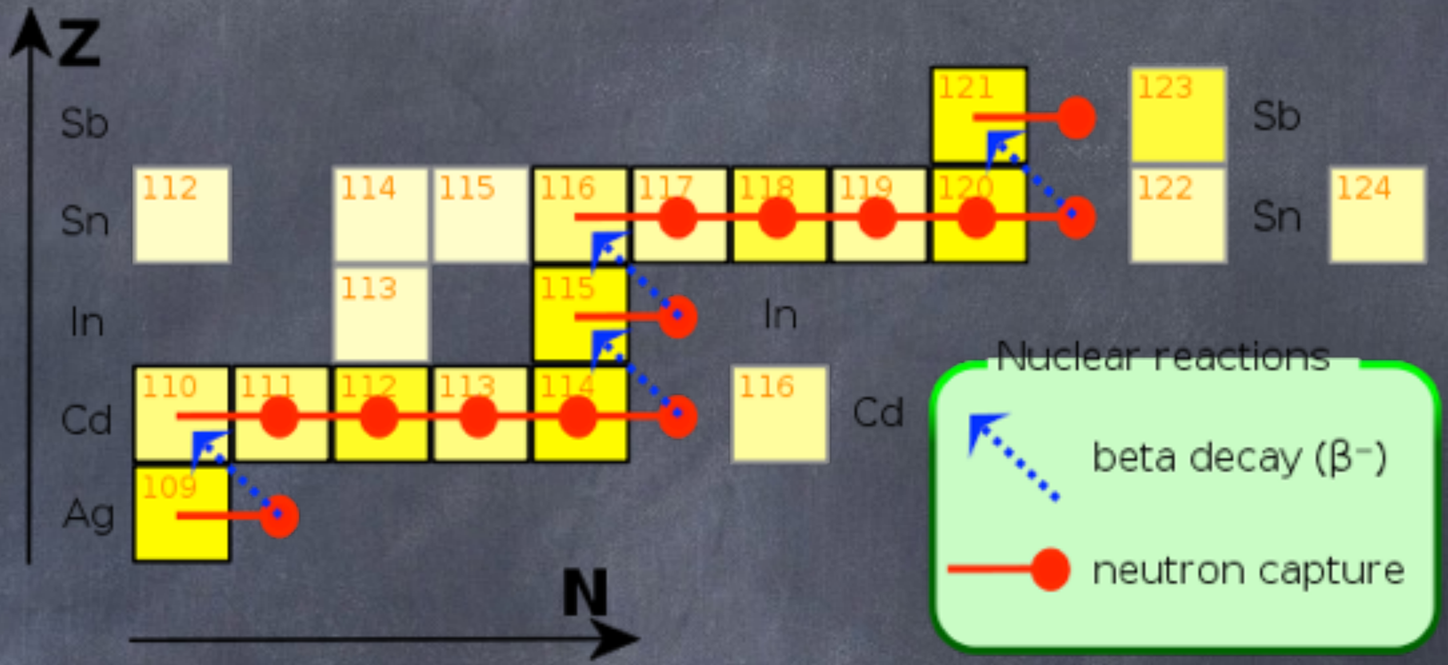
He,C,O,Ne,Mg
Si,S,Fe,Ni.....

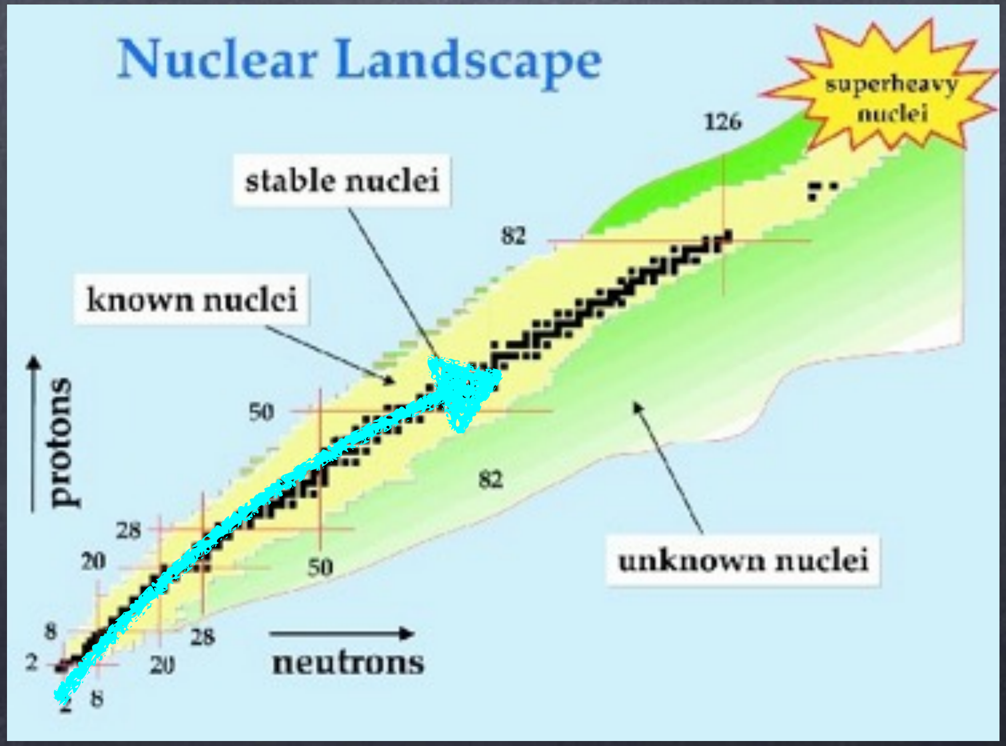
H

Elements up to Iron are produced in stars

S (slow) Process

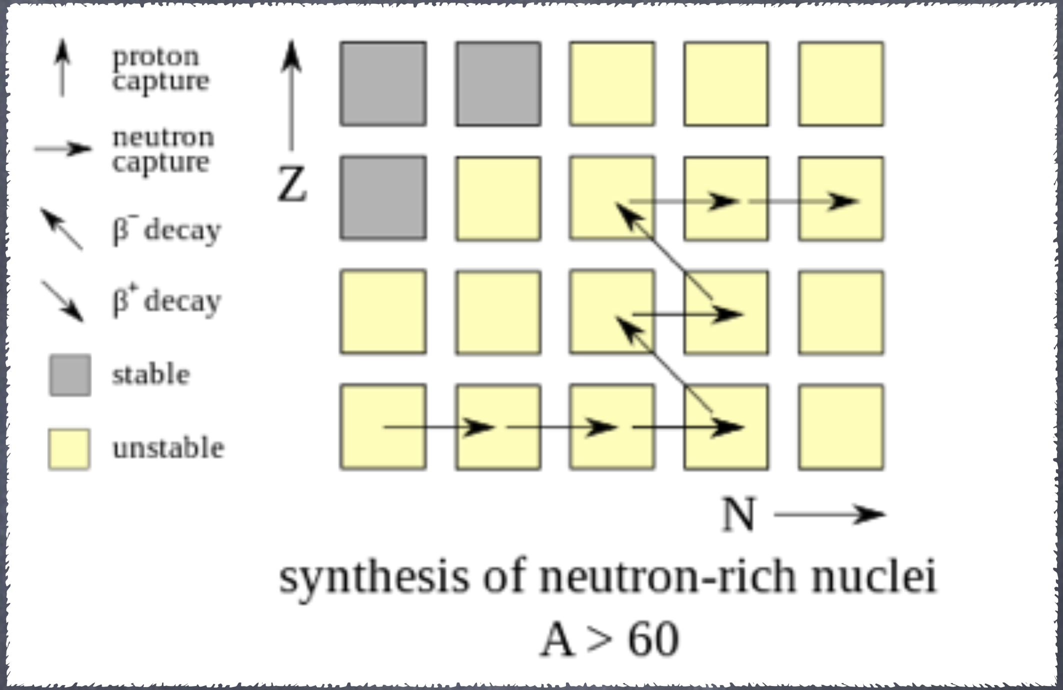
- Neutron capture slower than beta decay.
- Low neutron densities.
- time scale - years.
- Moves along the valley of nuclear stability.
- Final abundances depend on the conditions within the site.

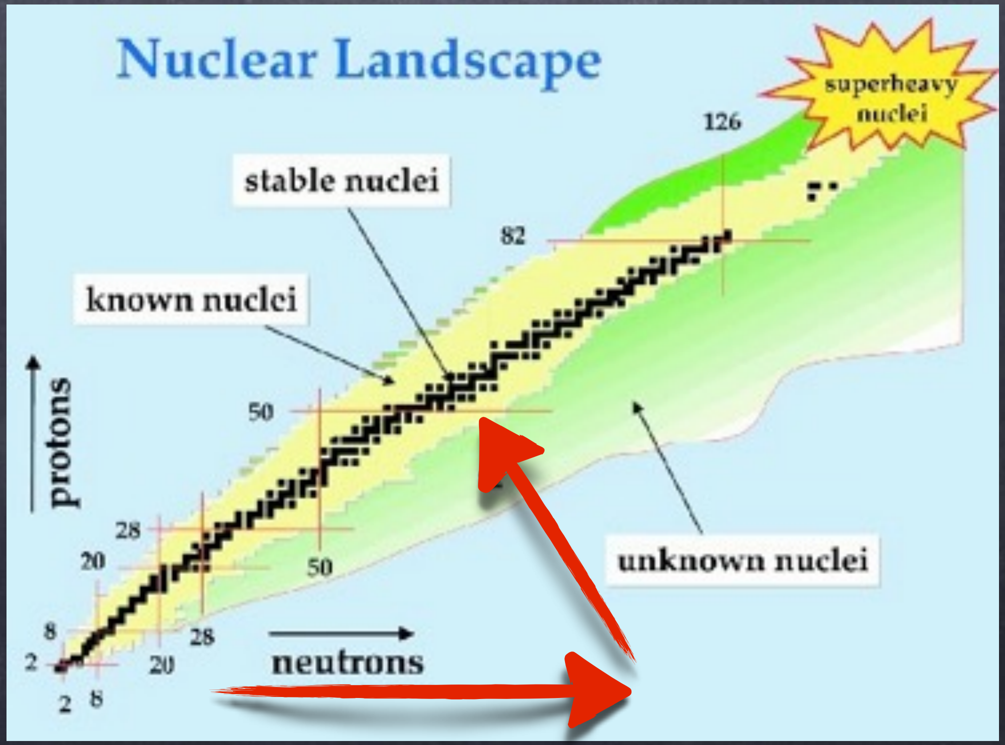




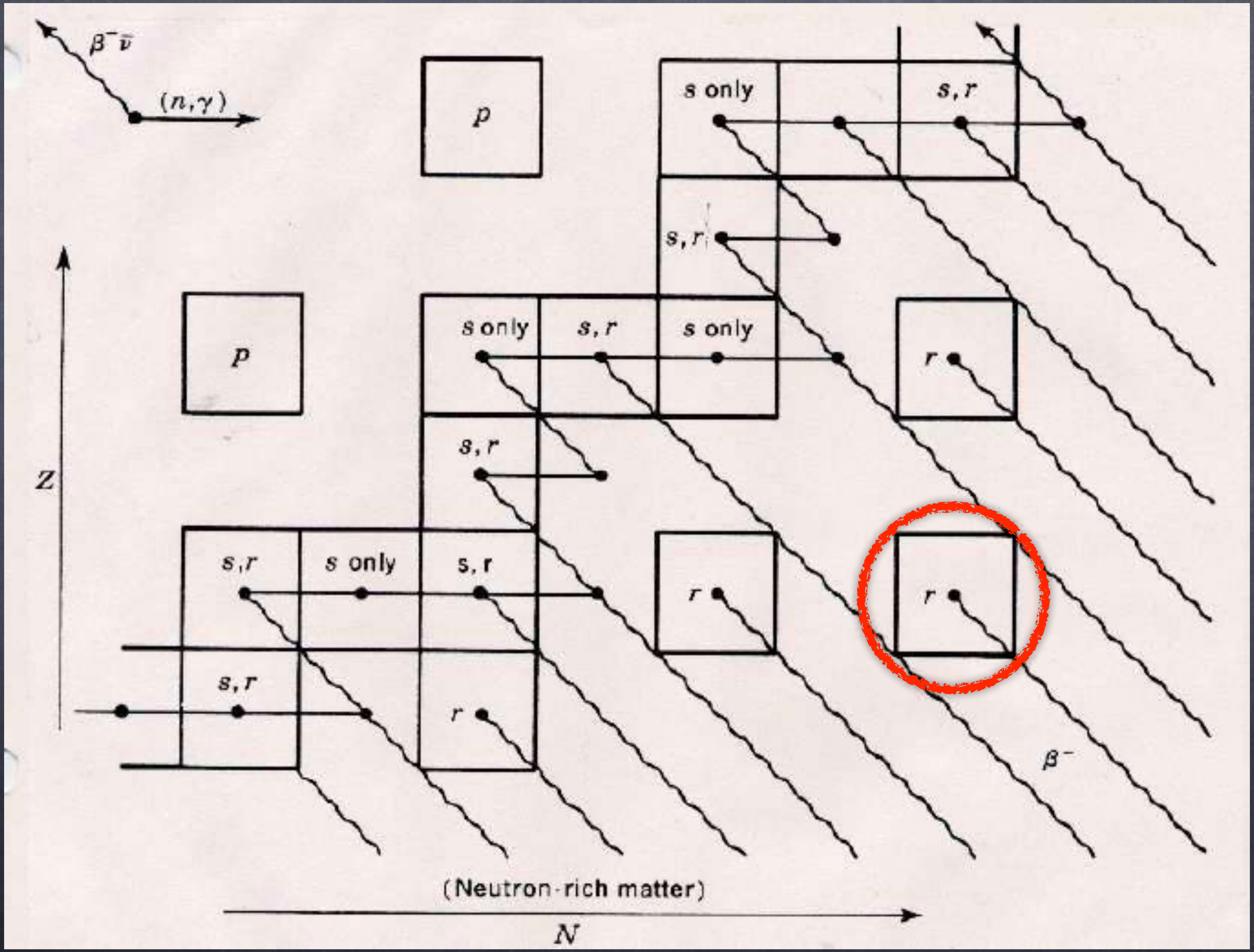
r (rapid) Process

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



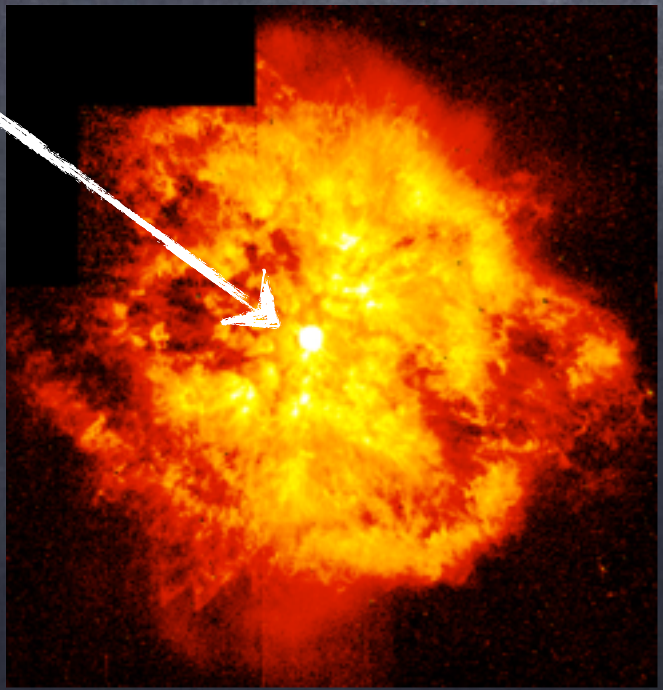


s and r processes

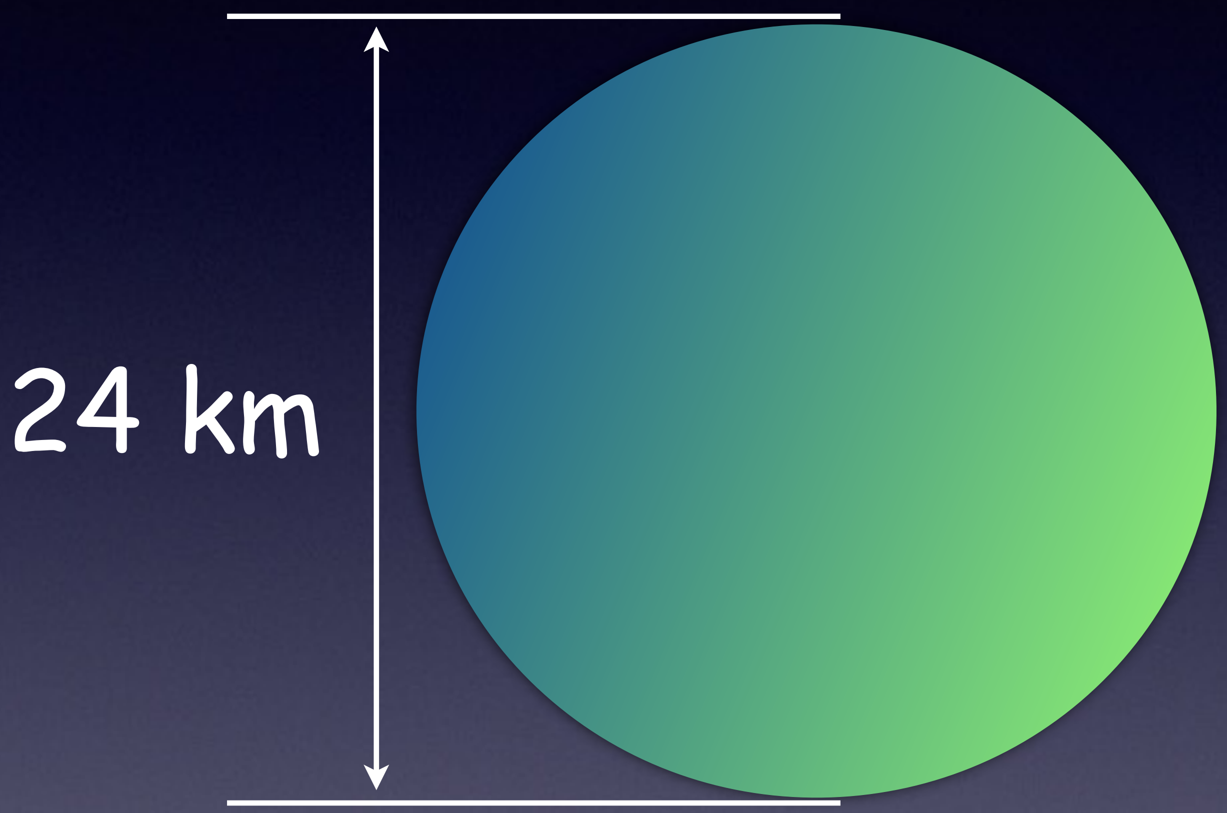


Explosive r-process

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



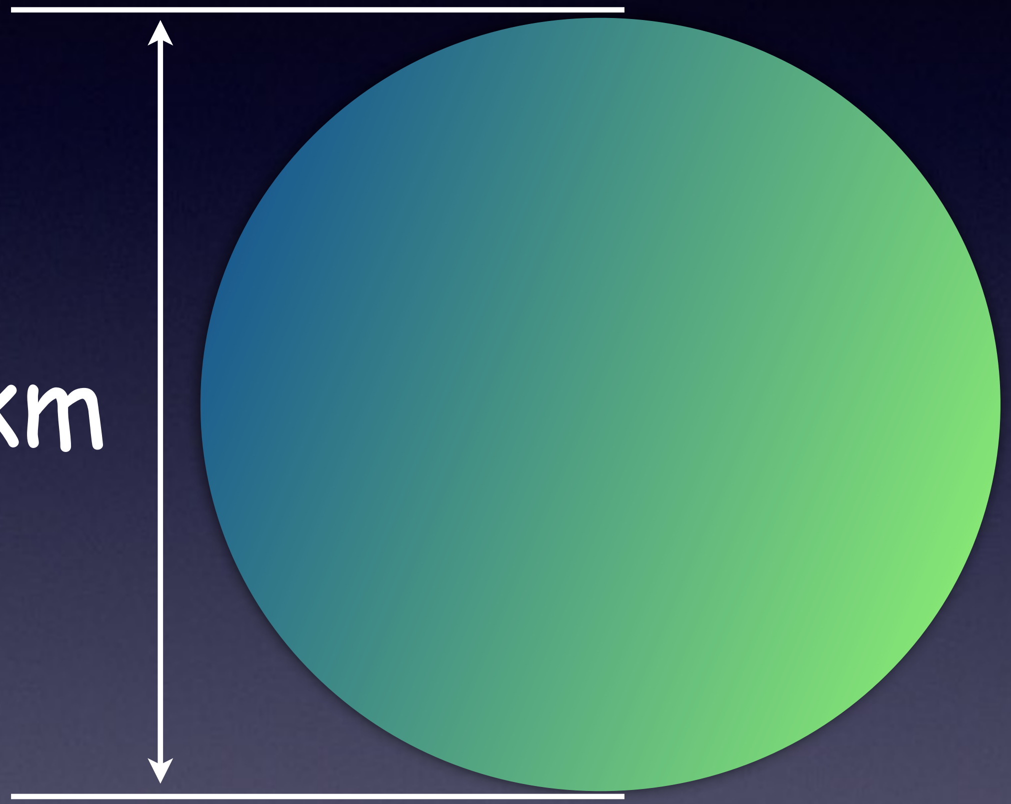
2. Neutron stars and mergers



2. Neutron stars and mergers

1 cc of neutron star material

2. Neutron stars and mergers

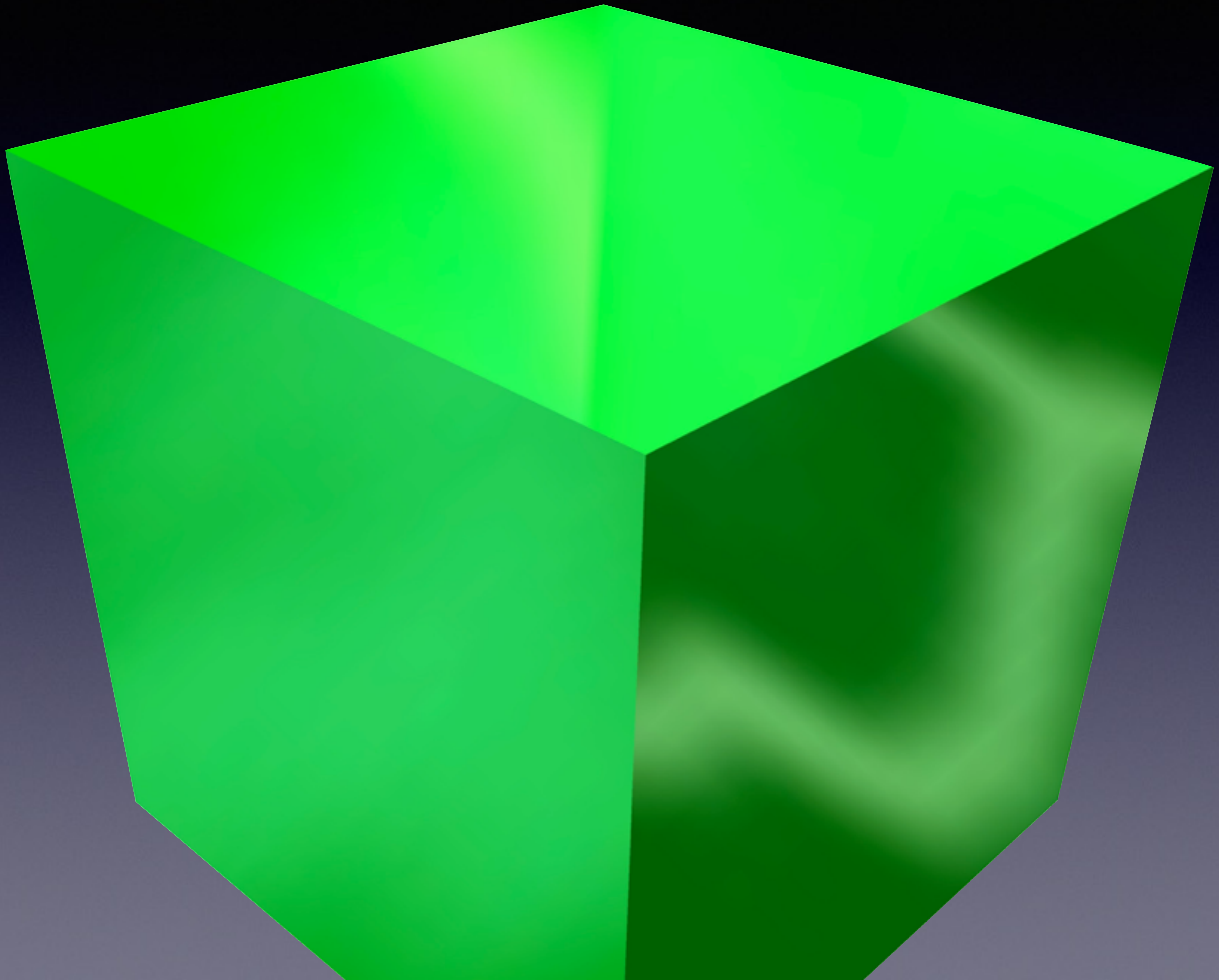


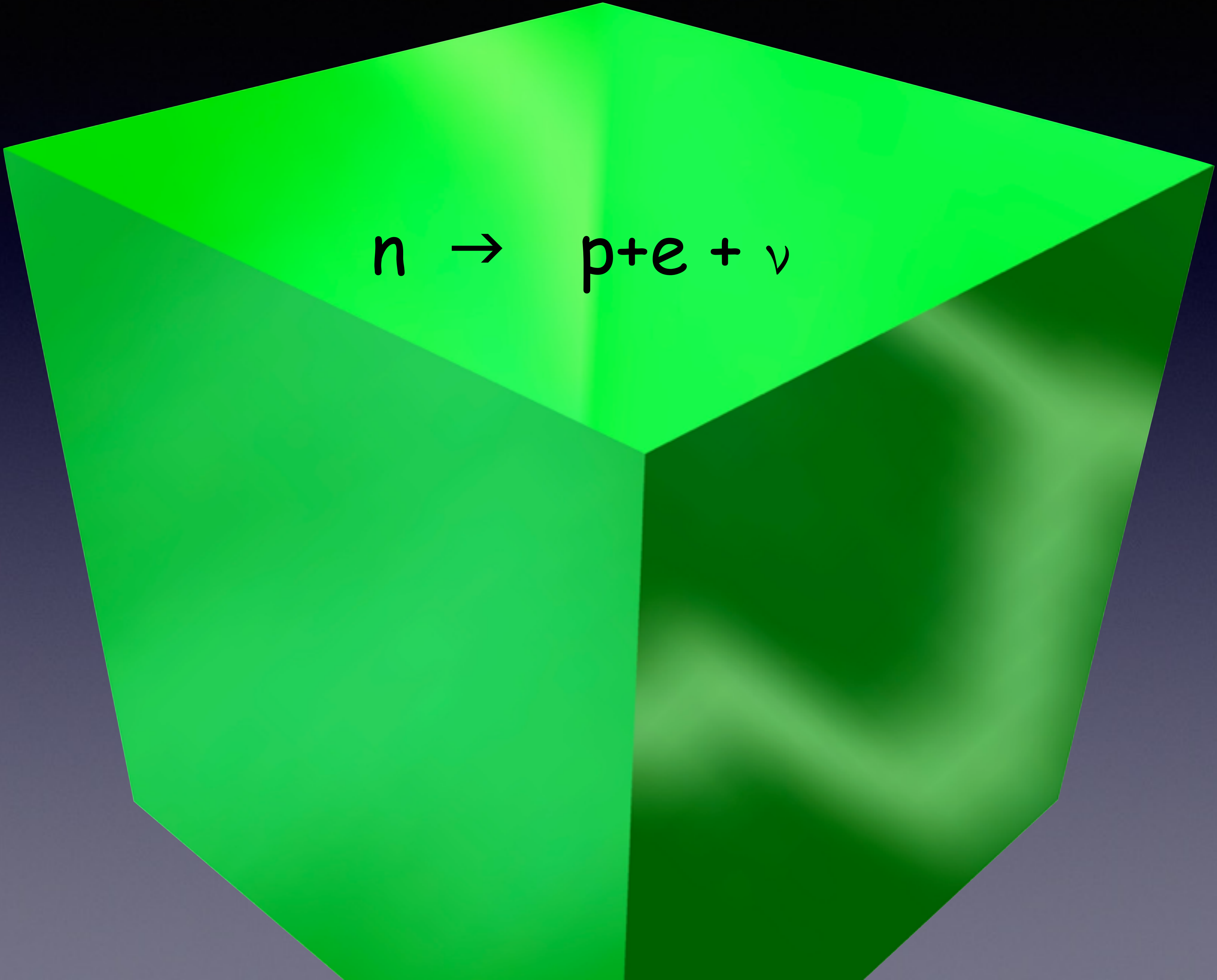
24 km

95% neutrons!

10,000,000

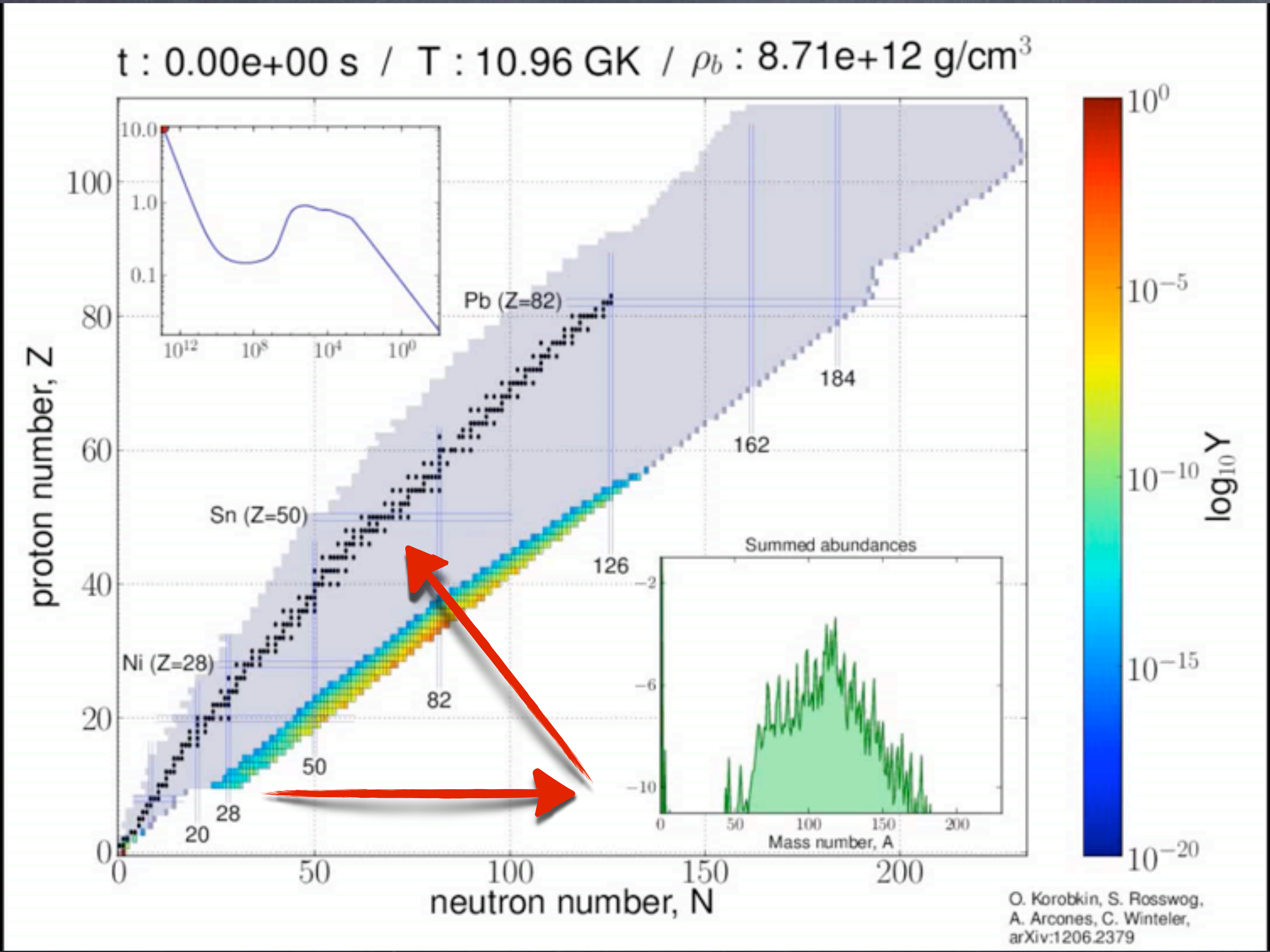
1 cc of neutron star material





$n \rightarrow p + e + \nu$

Decay of neutron star matter



O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

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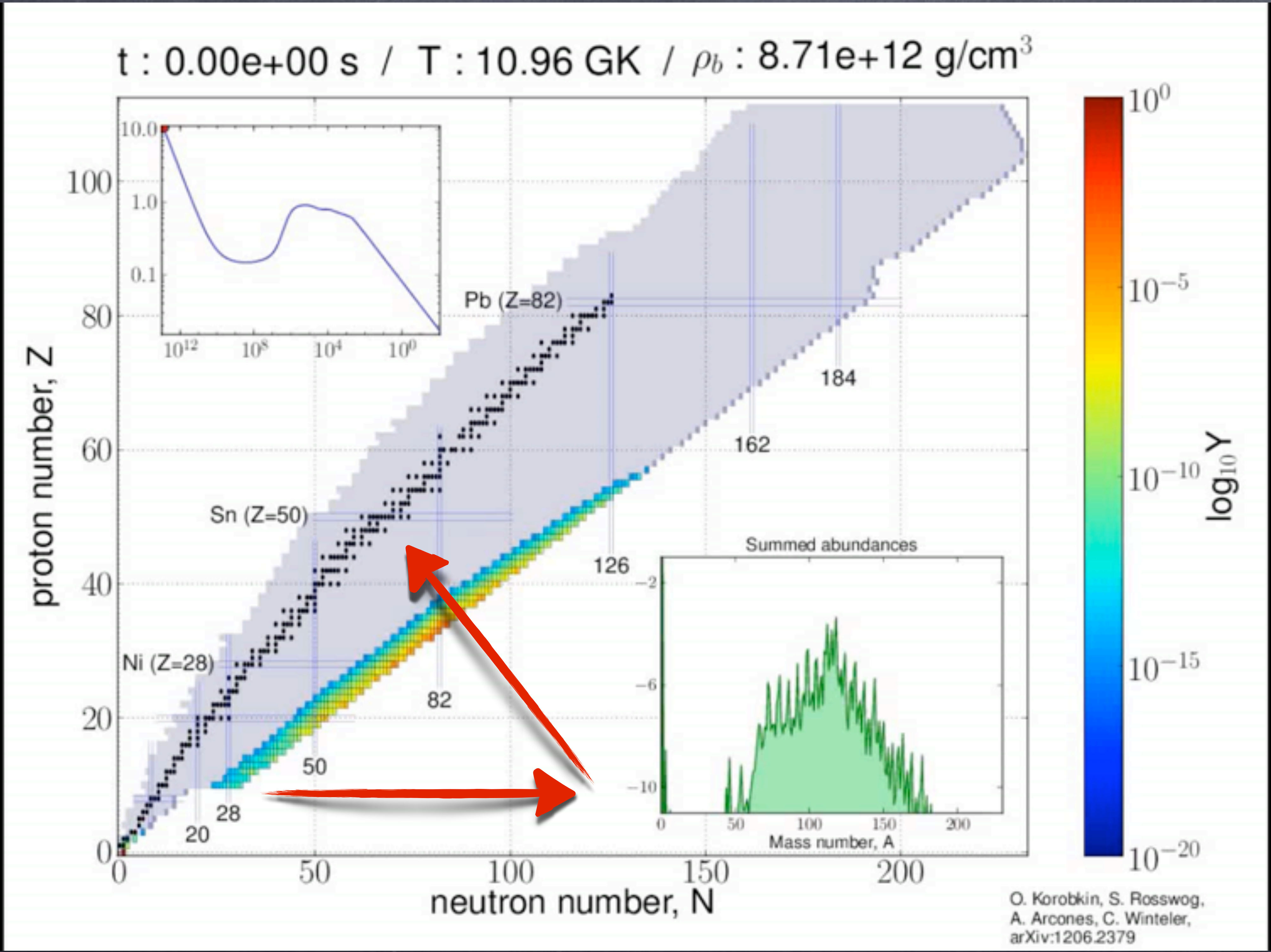

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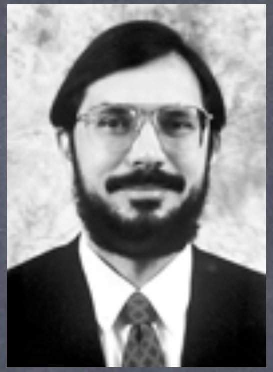
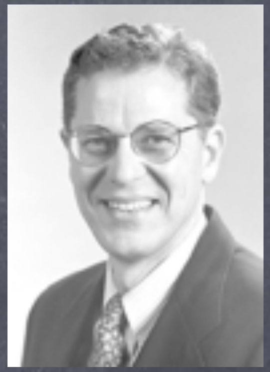
Binary Neutron Stars

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

→

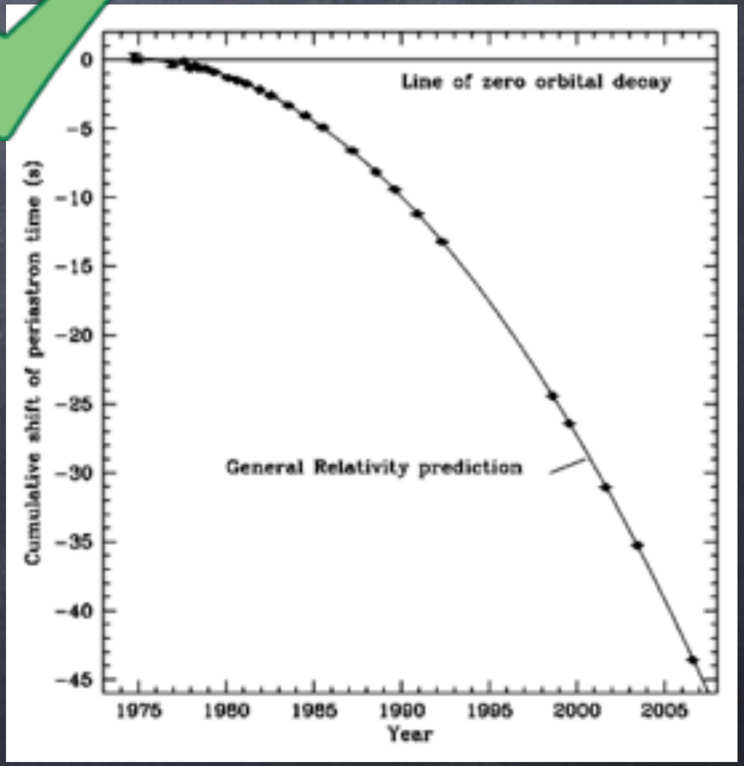


R. Hulse



J. Taylor

✓



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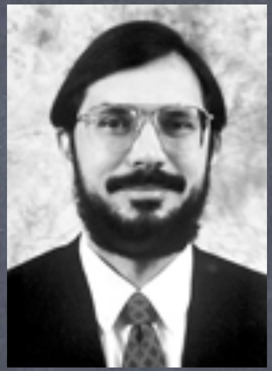

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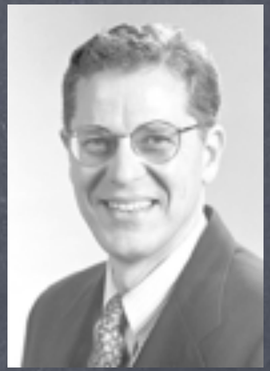

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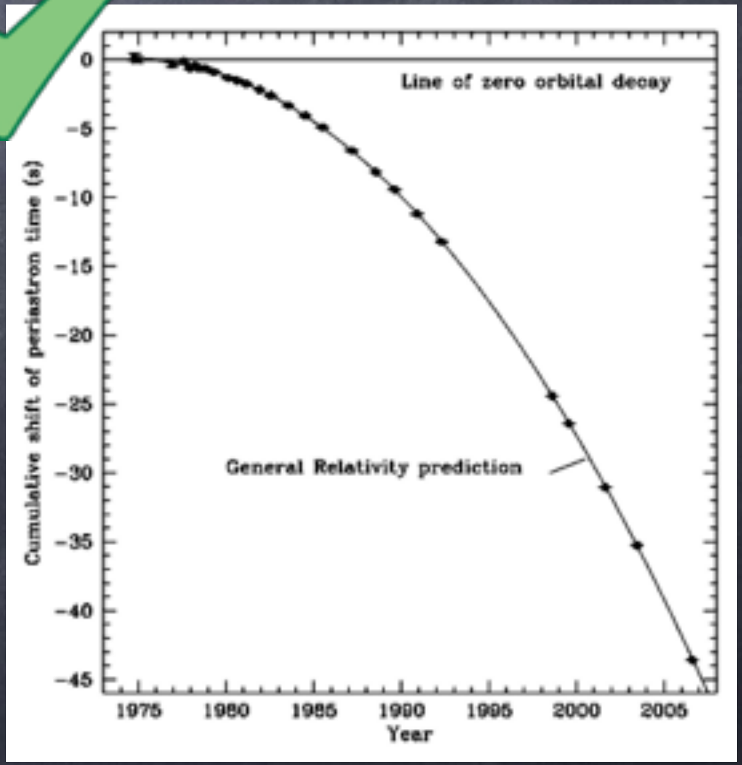

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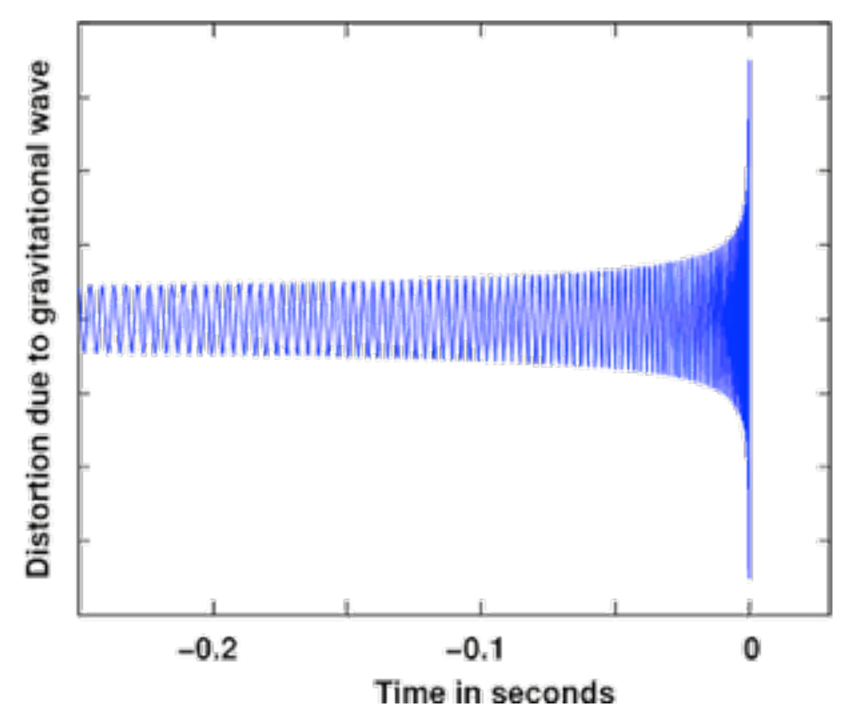
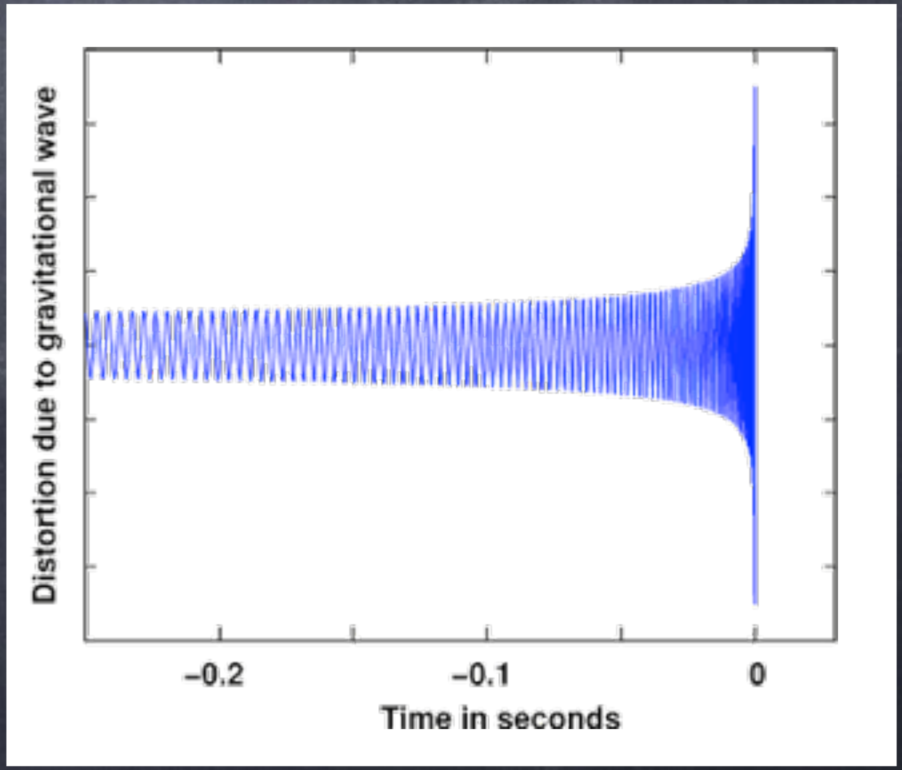


Binary Neutron Stars

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



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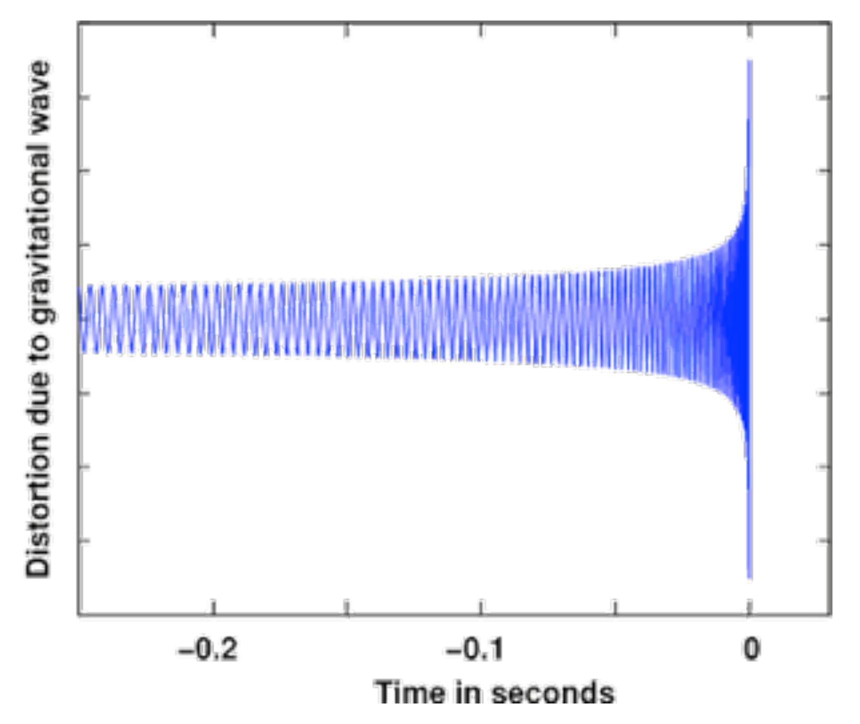
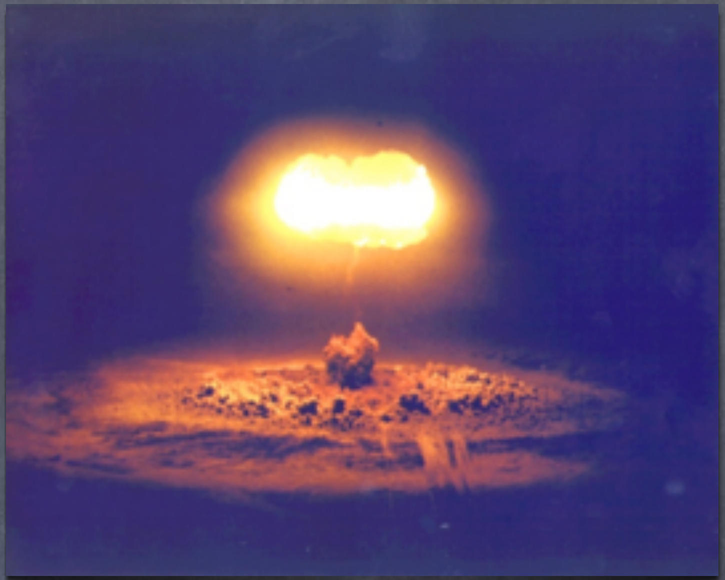


3. Gamma Ray Bursts

The Vela Satellites



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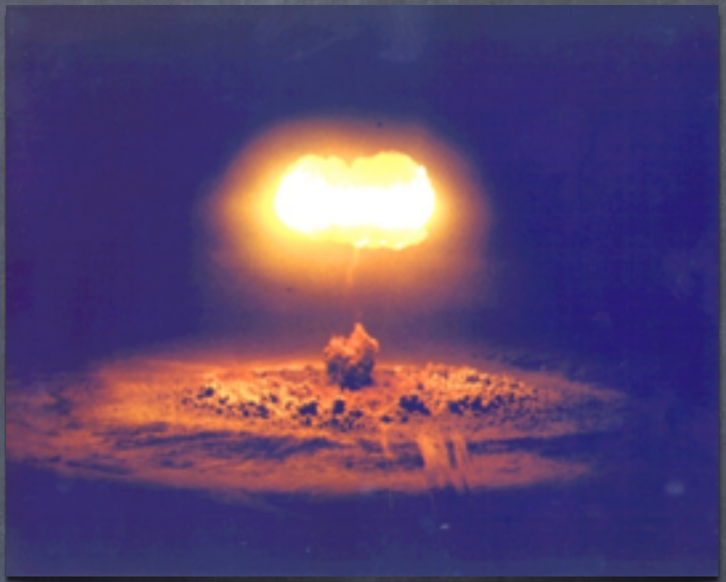
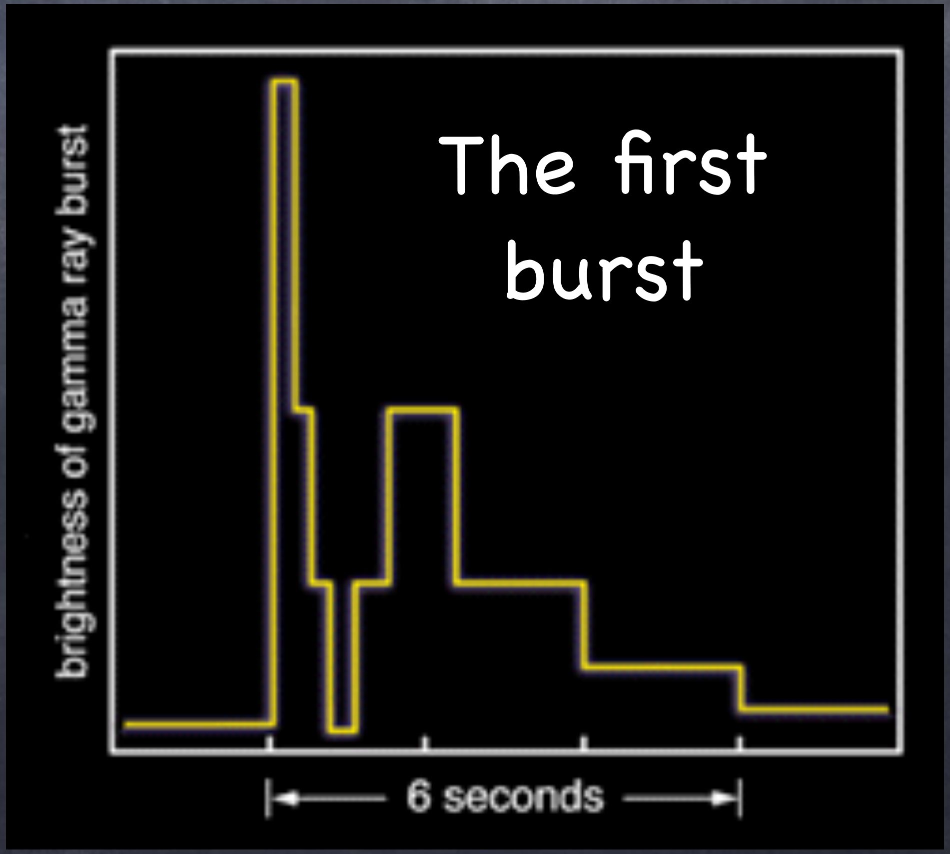
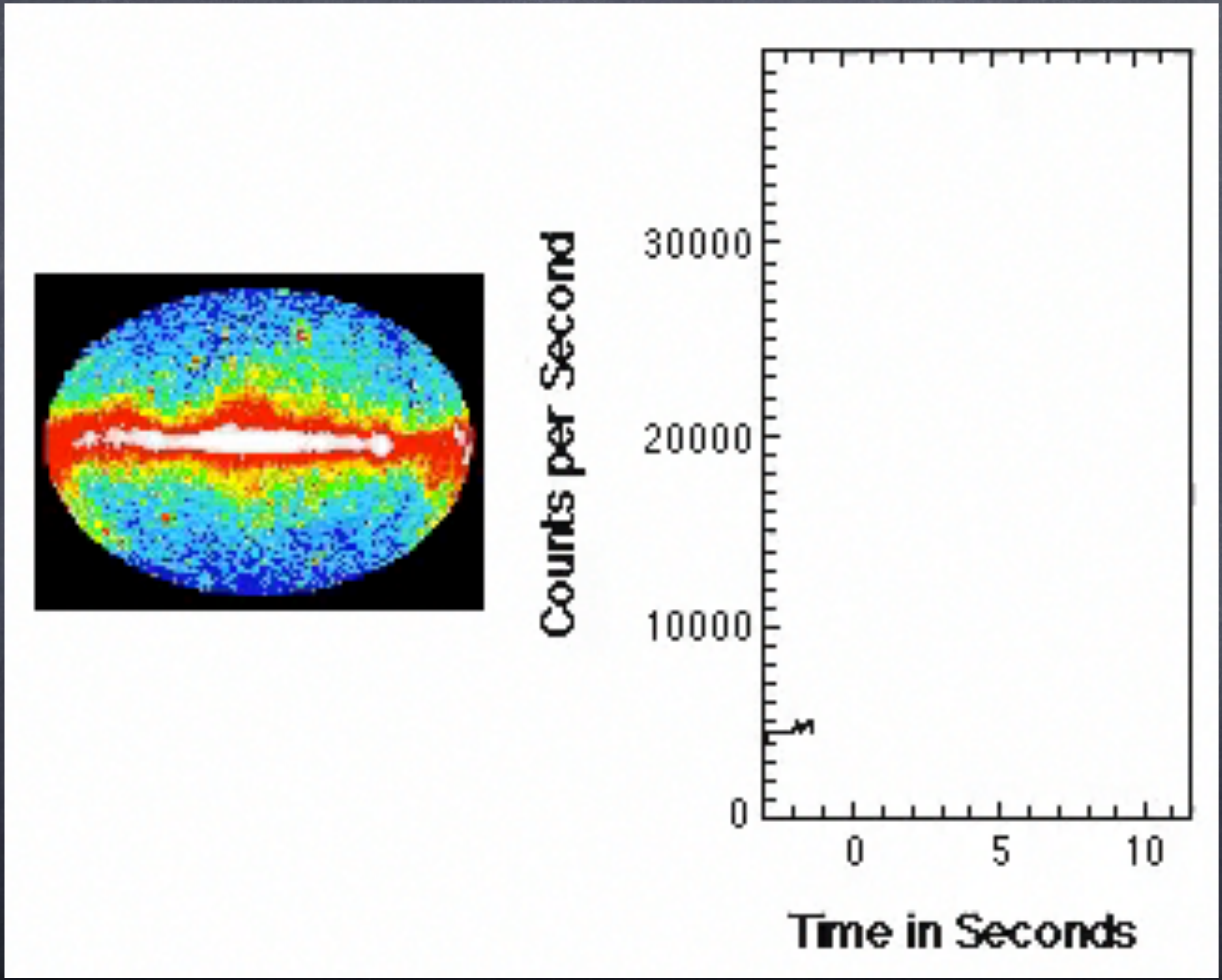




The sky in gamma-Rays



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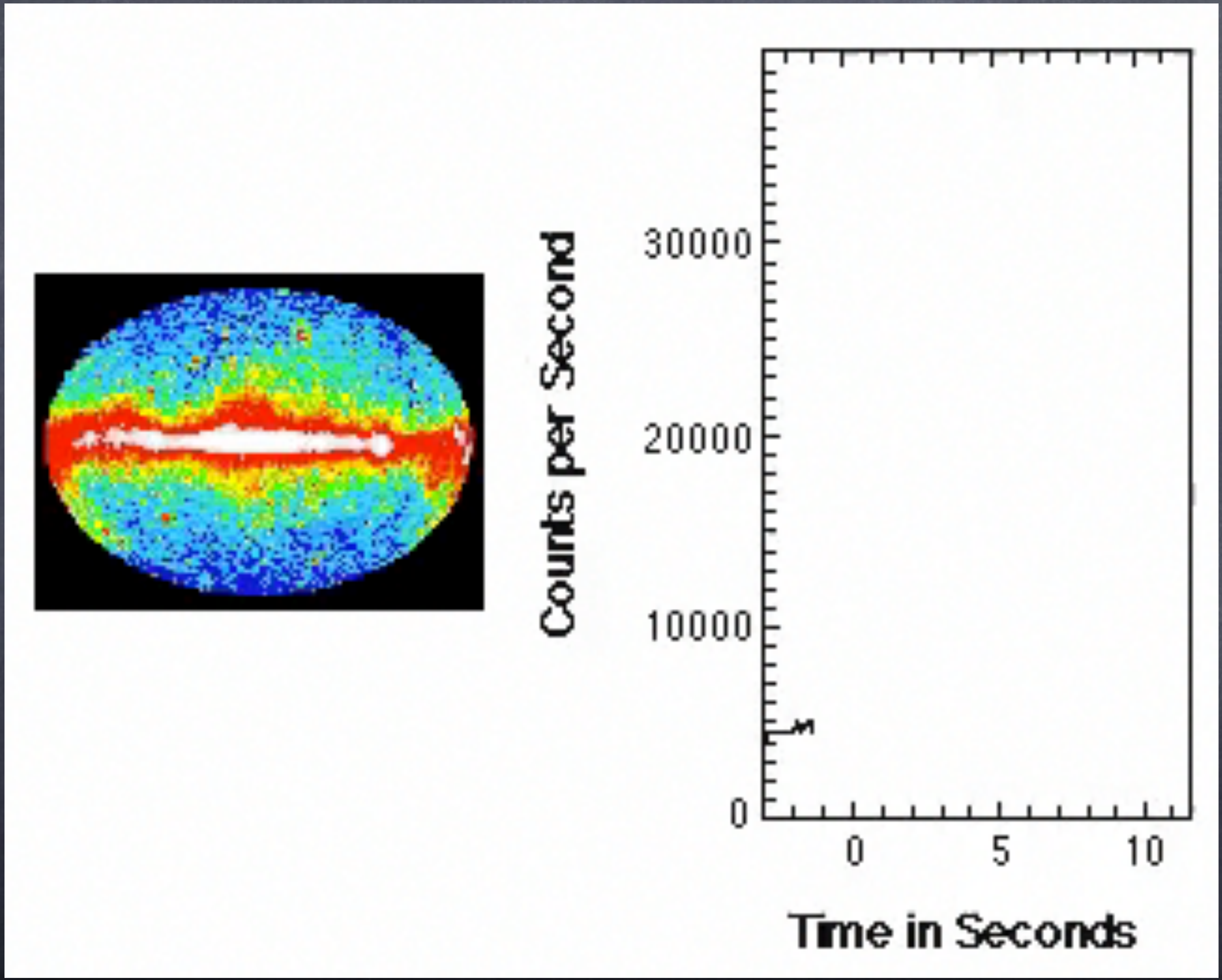
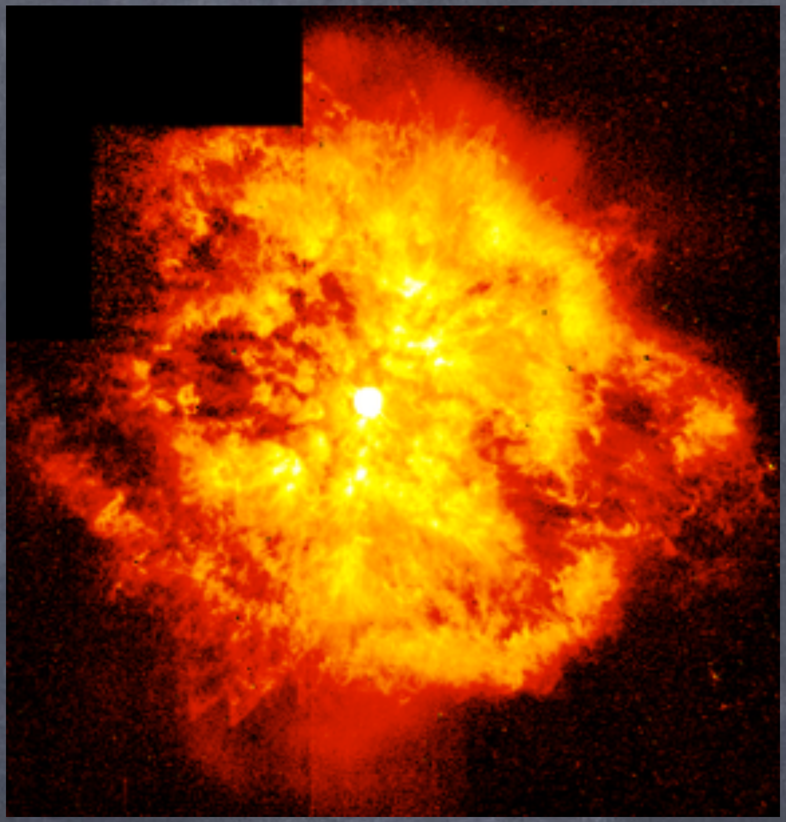
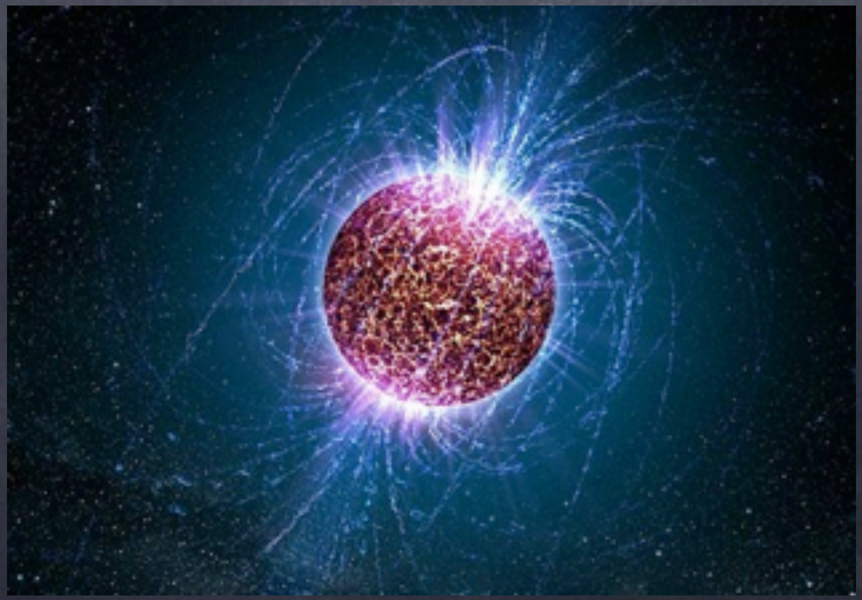


The late 80ies

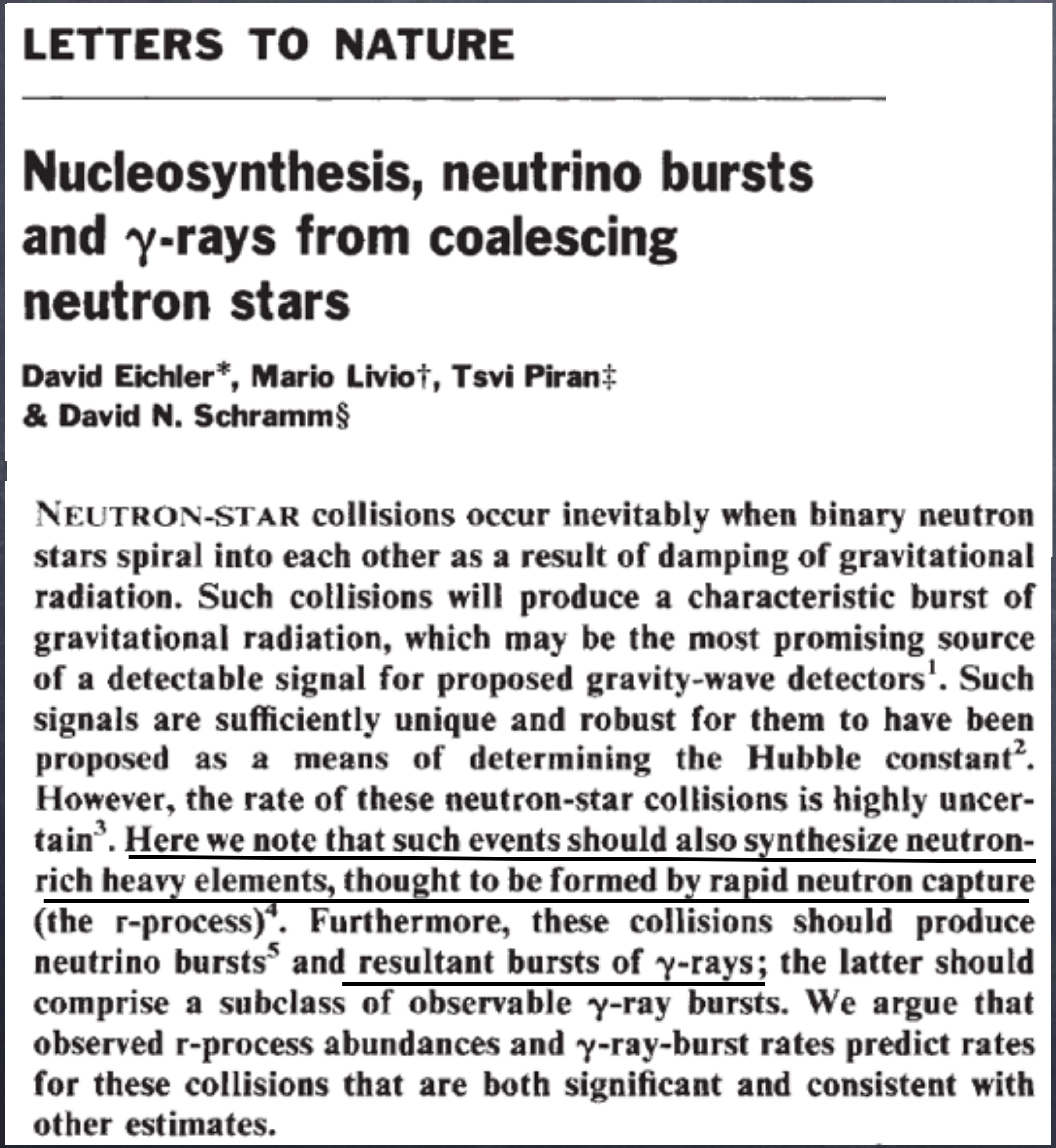
- r-process material from Supernovae



- GRBs from magnetic flares on <u>galactic</u> neutron stars (E~10^{40} ergs).



Two provocative ideas



LETTERS TO NATURE

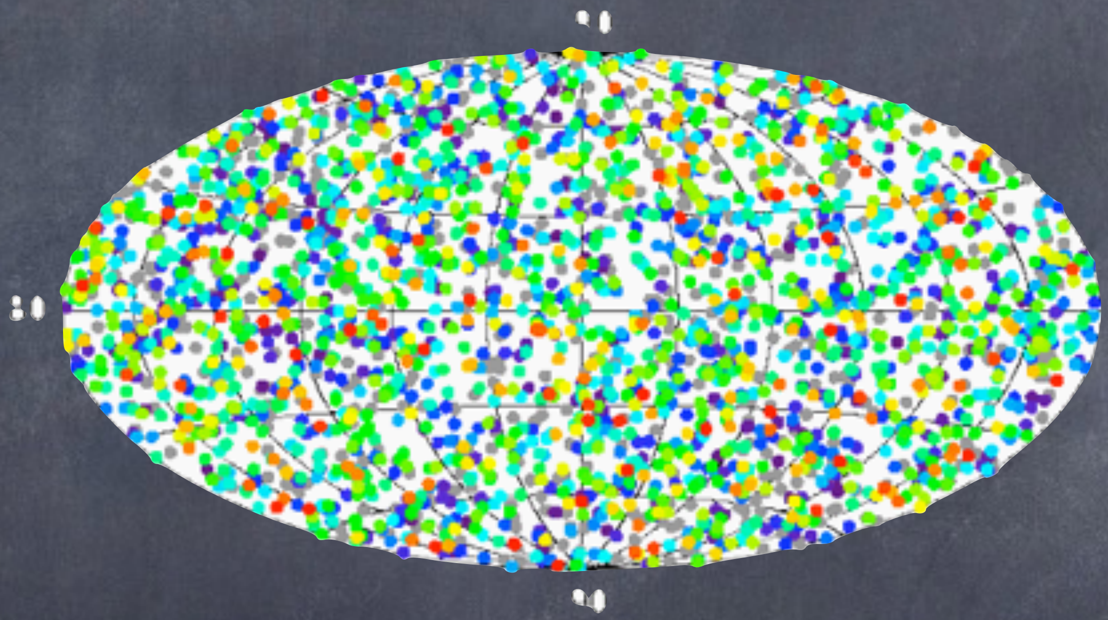
Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

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.

90ies: GRBs are cosmological

1992: BATSE - GRBs have a coslomogical distribution



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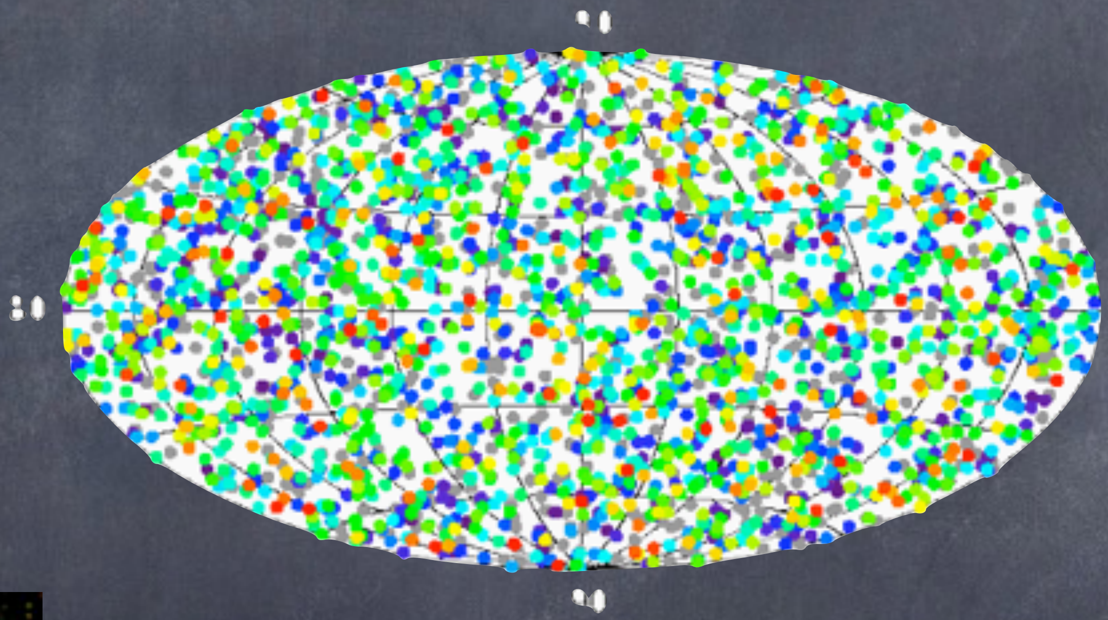


Gamma-Ray Bursts

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

1988

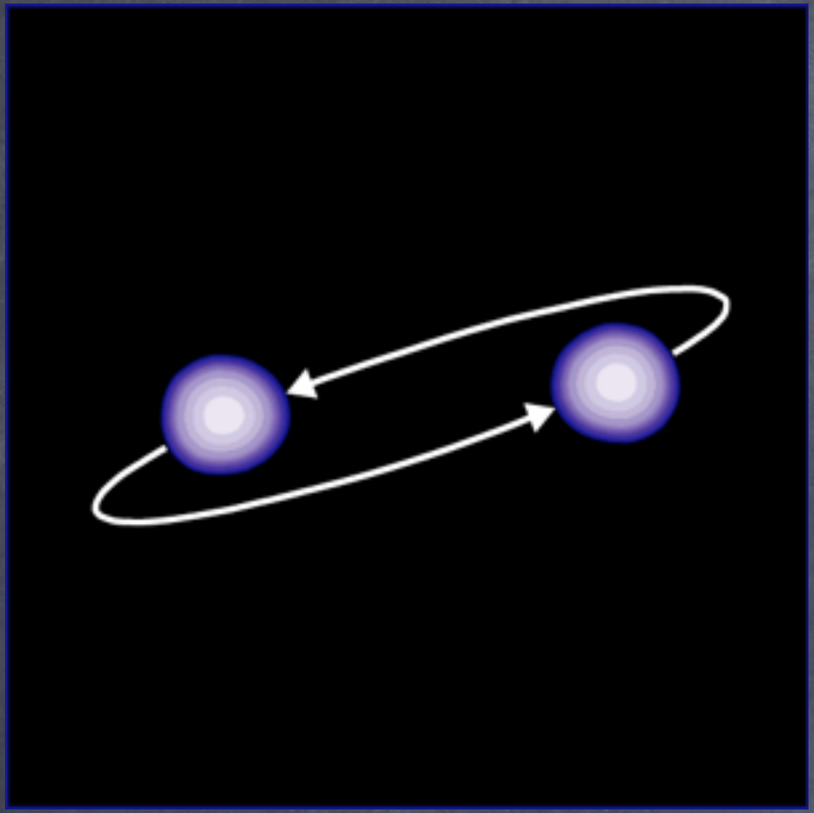
- ~~r-process from Supernovae~~
- ~~GRBs from magnetic flares on galactic neutron stars~~ (E ~10^{40} ergs).

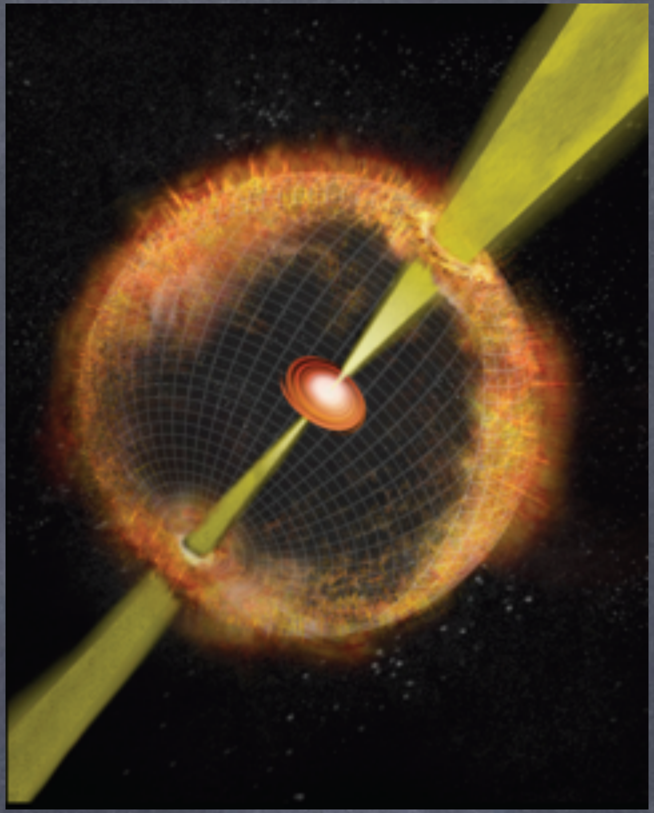
2015

- Supernovae cannot produce A>130
- GRBs are cosmological (E ~10^{51} ergs).

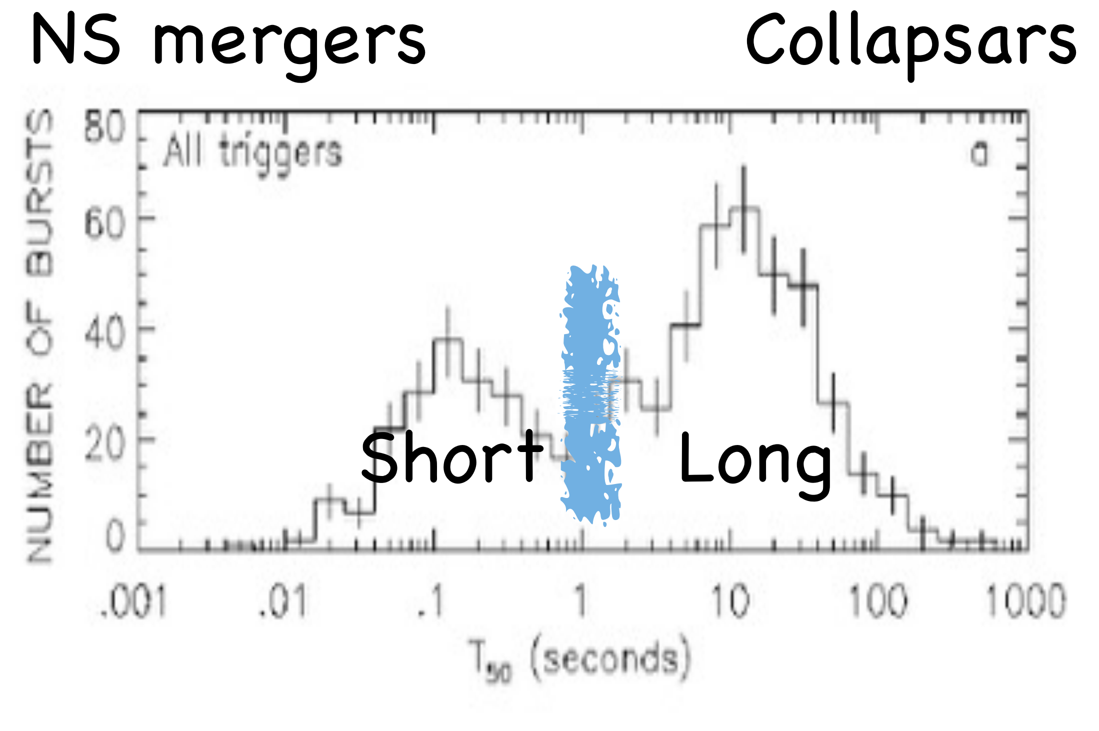
Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley, 98



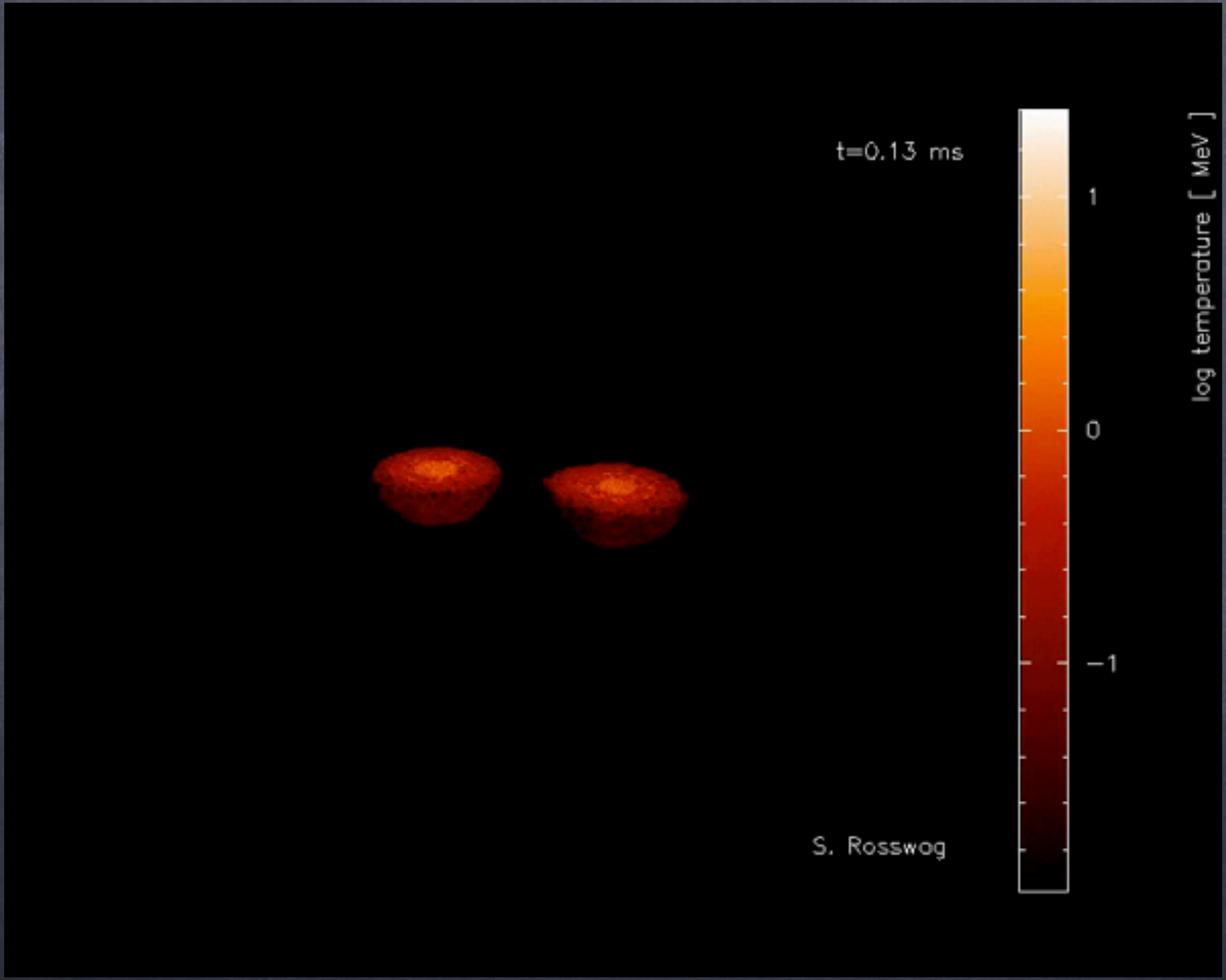


Indirect Evidence



Direct Evidence

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



Stephan Rosswog

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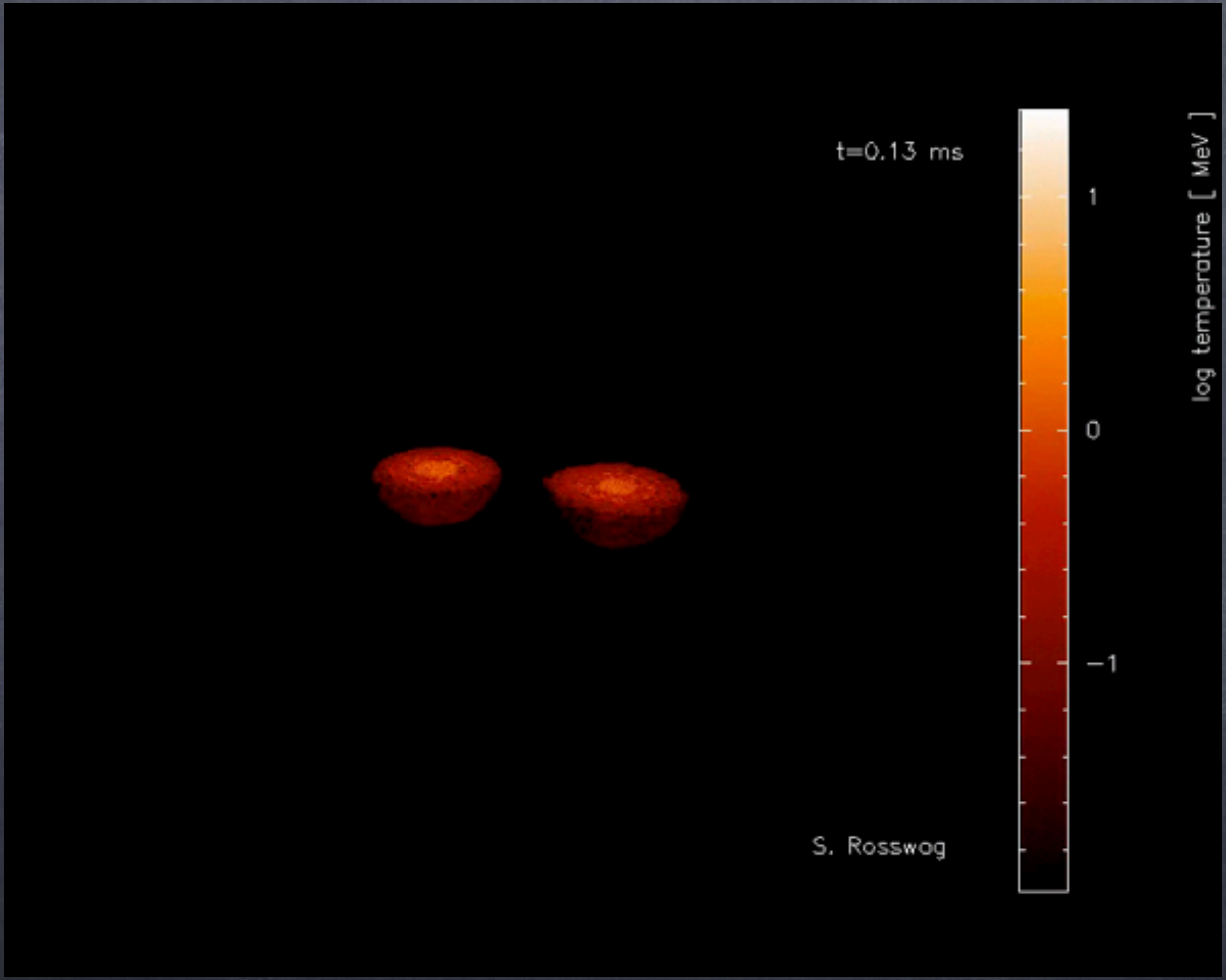


Stephan Rosswog

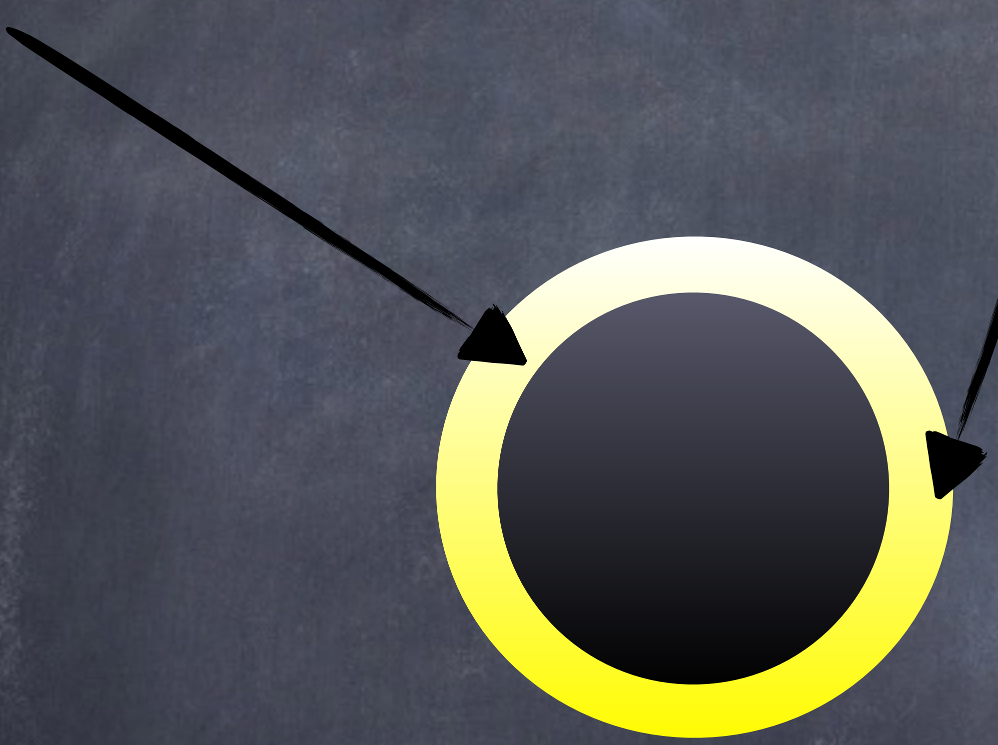
4. Macronova* (Li & Paczynski 1997)

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.

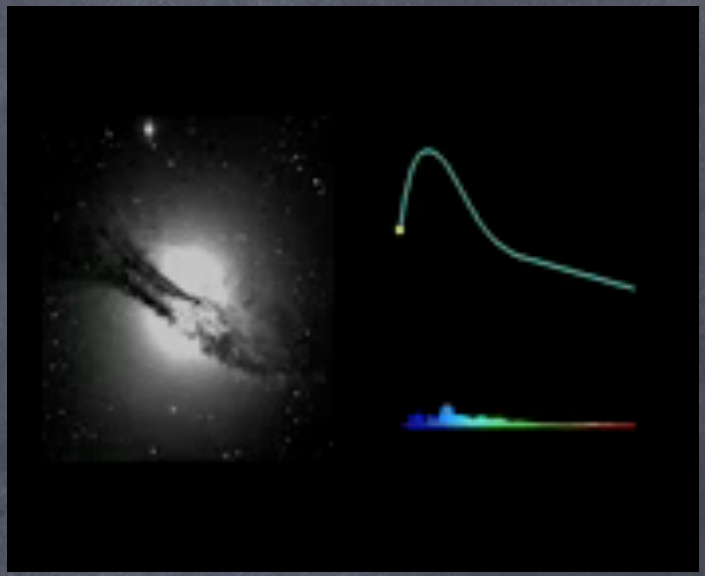
*Also called Kilonova

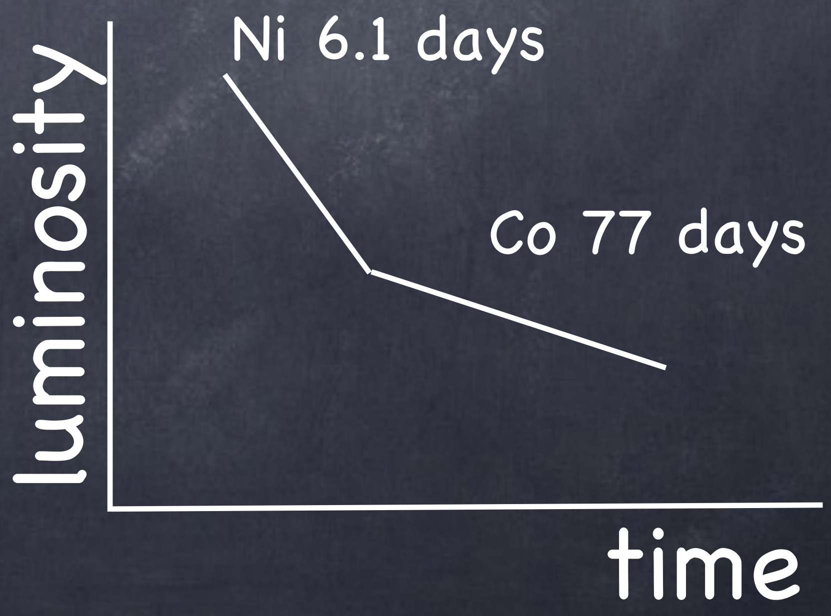
Supernova



Photosphere

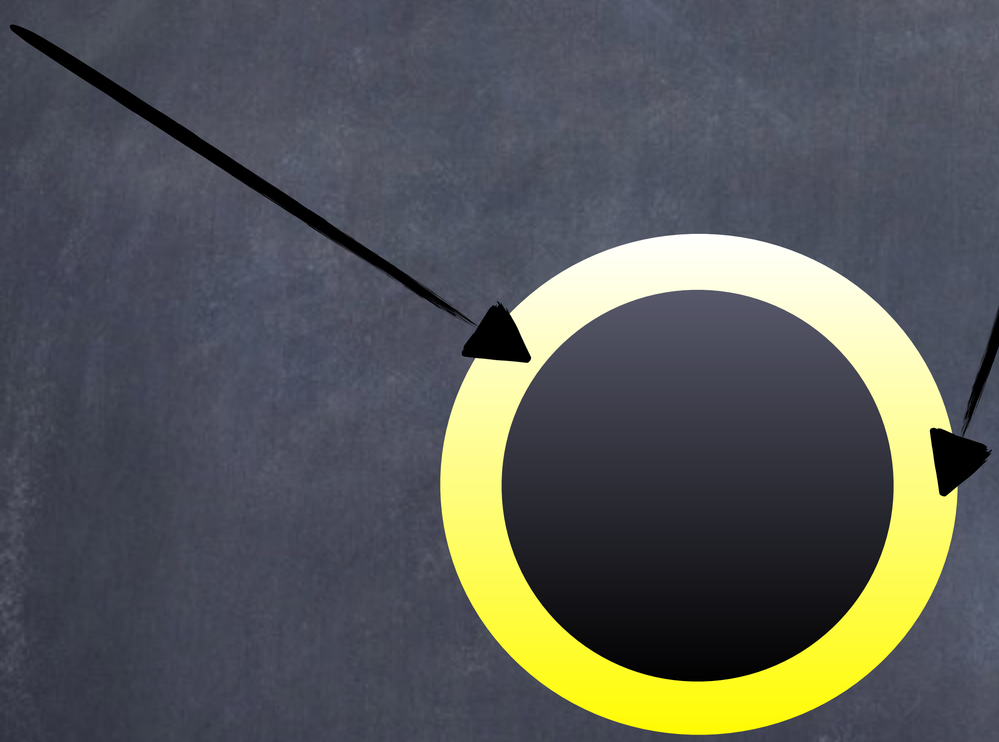
Photons escape





Powered by radioactive decay of ^{56}Ni->^{56}Co->^{56}Fe

Supernova



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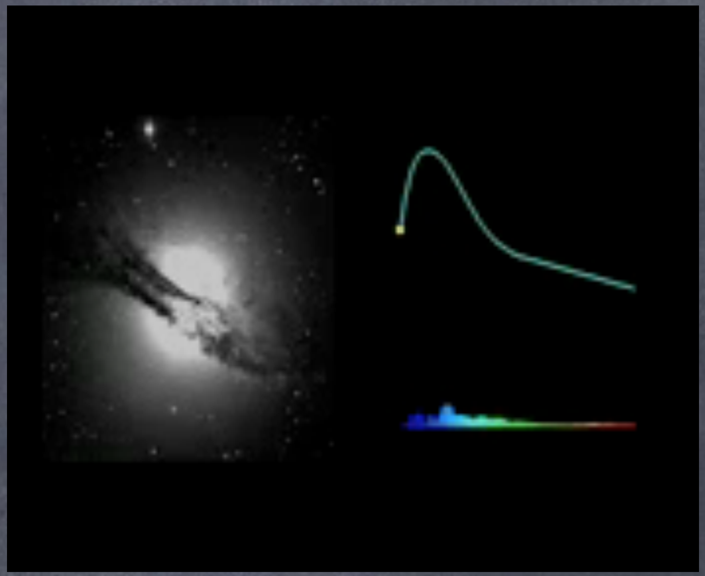

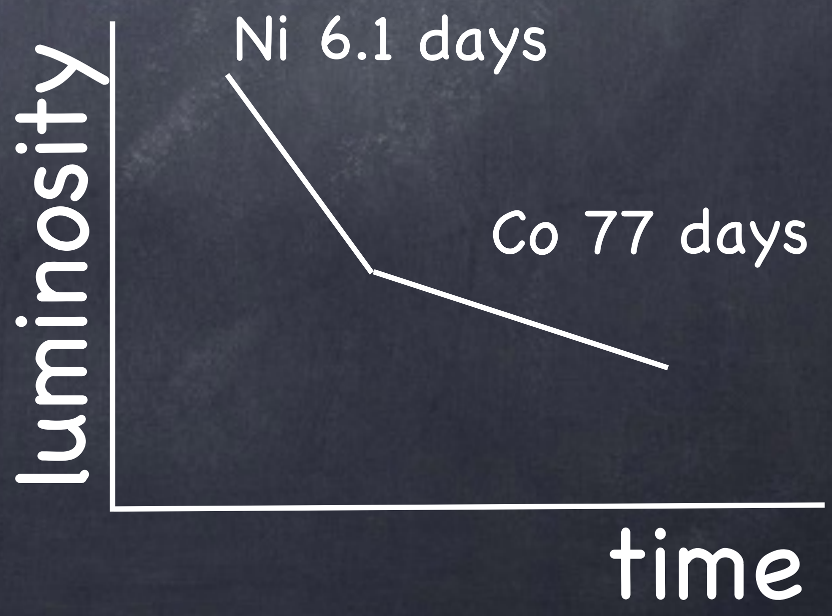

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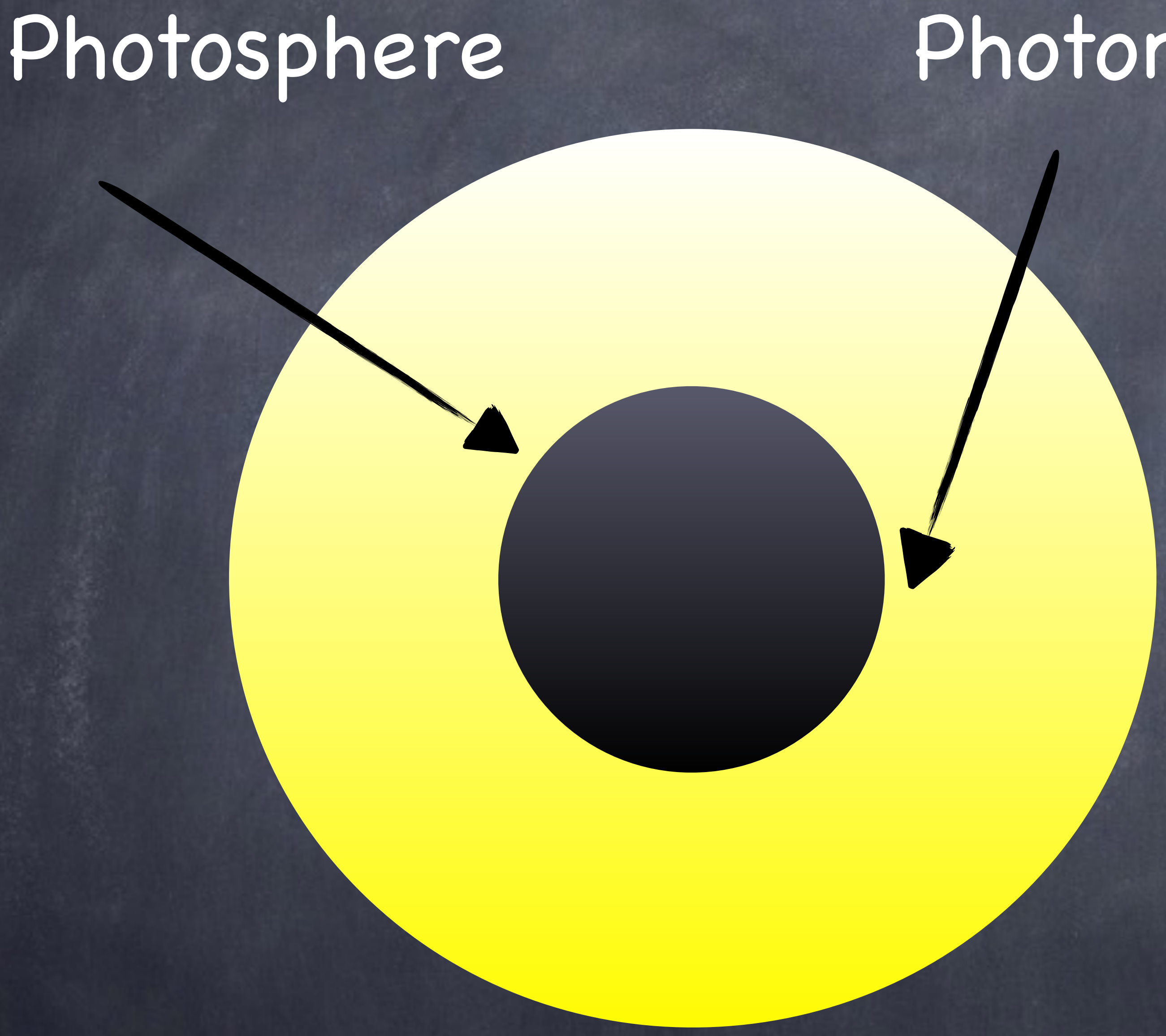

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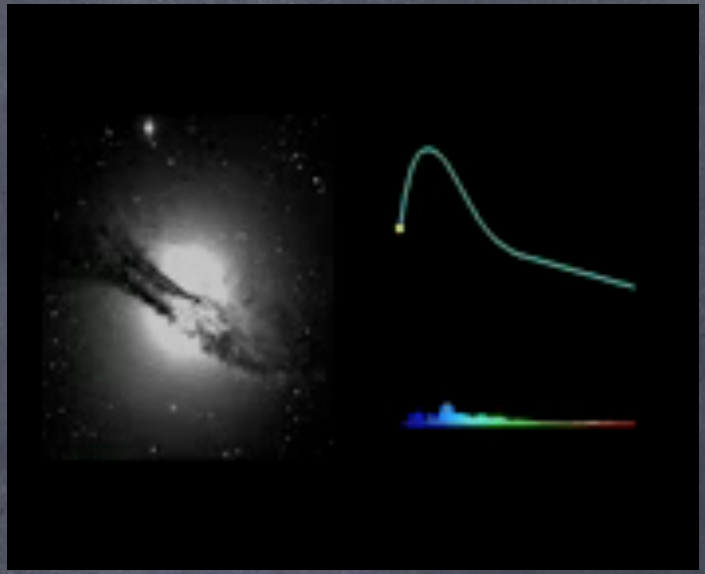
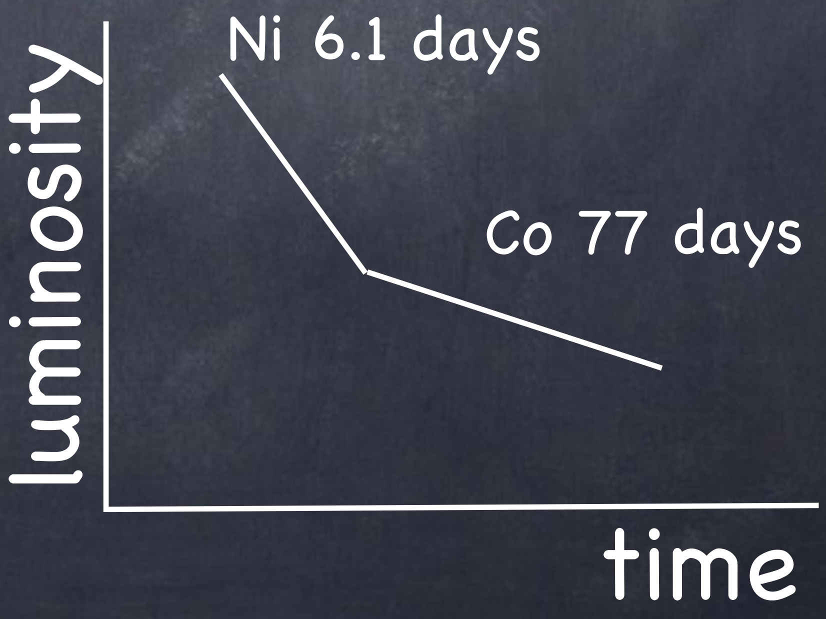
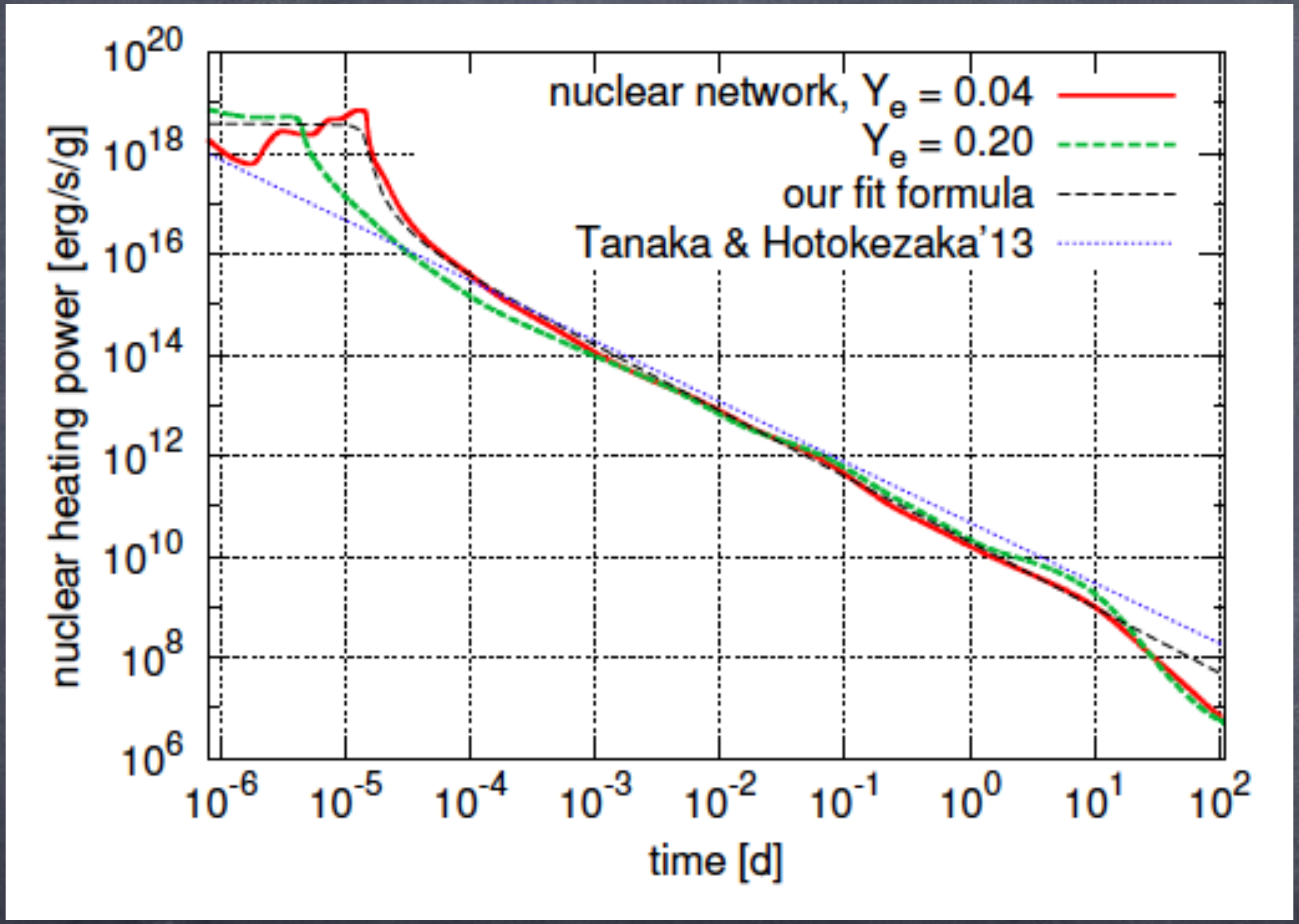




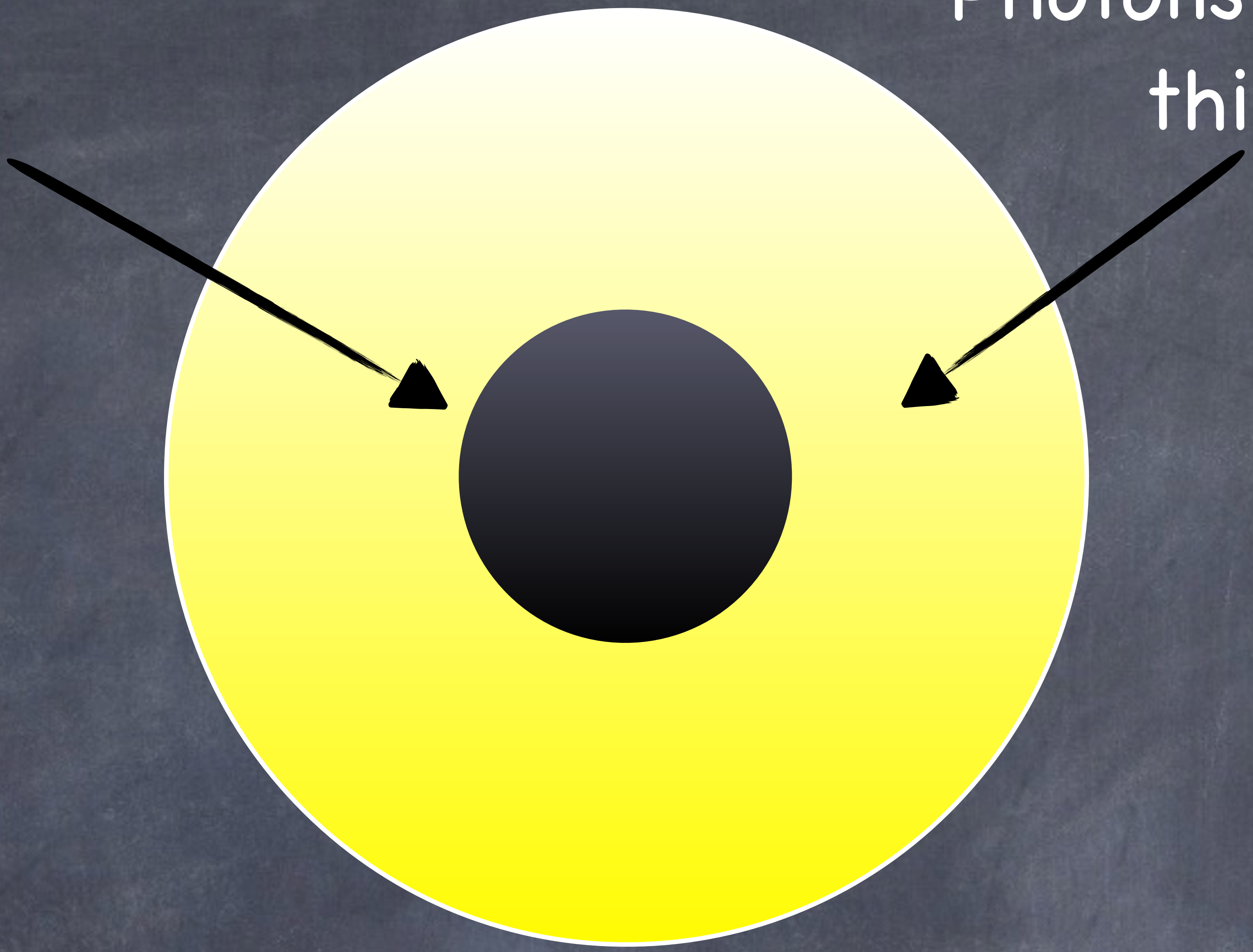
Powered by radioactive decay of ^{56}Ni->^{56}Co->^{56}Fe

Radioactive Decay

Korobkin + 13; Rosswog, Korobkin + 13



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



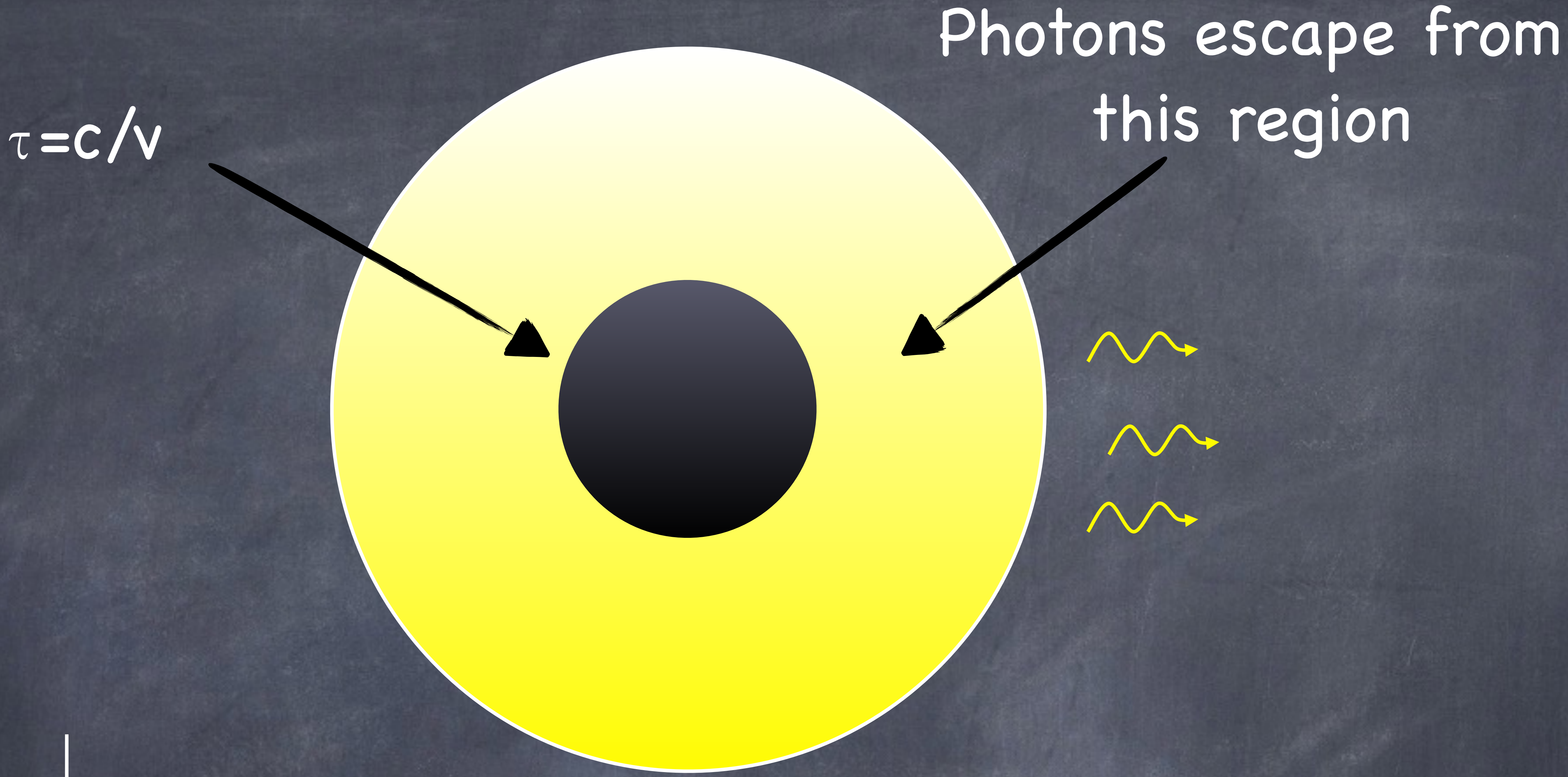
$\tau = c/v$

Photons escape from this region

Increase as we see a large fraction of the matter.

Decrease due to radioactive decay

Macronova



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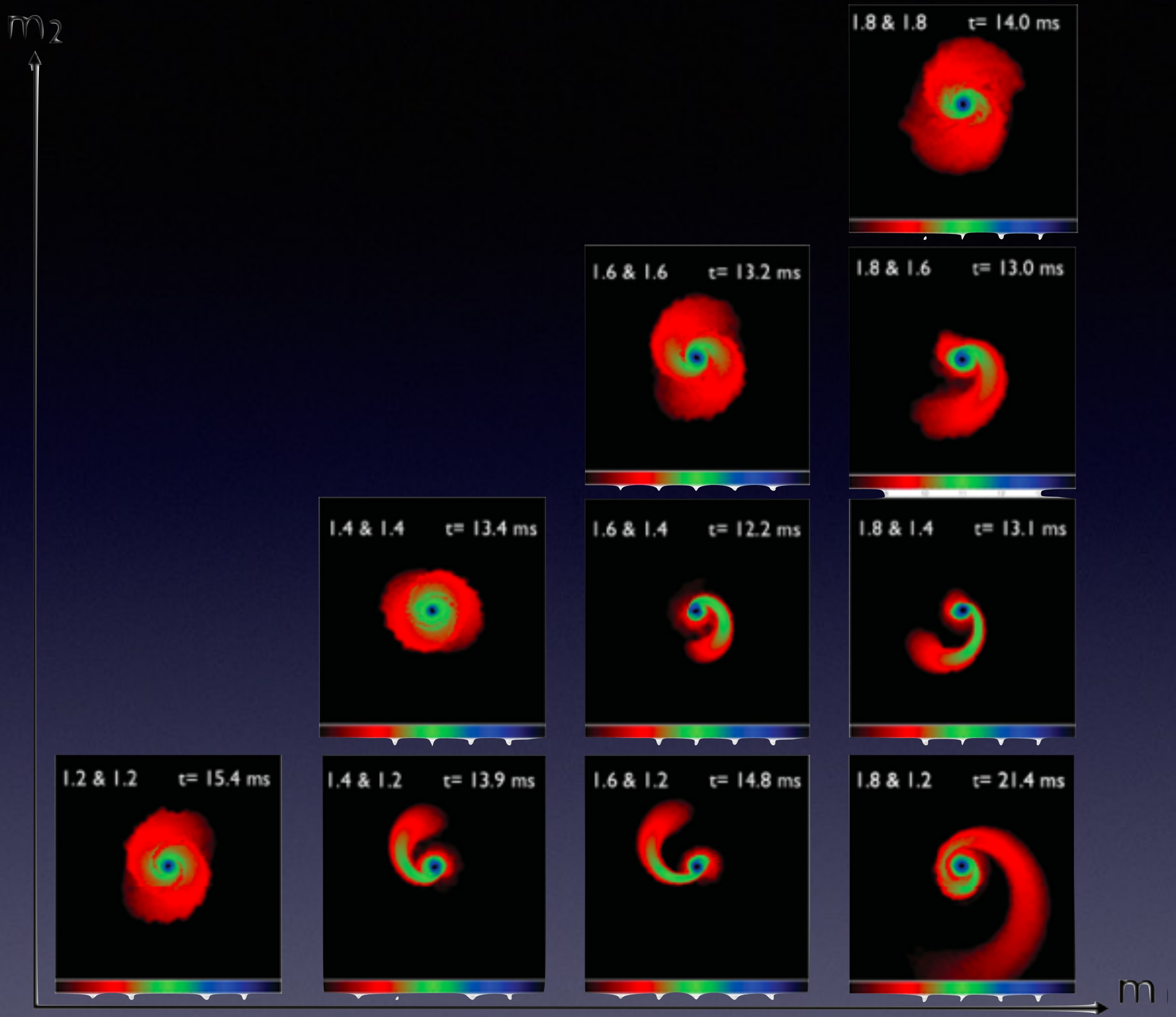
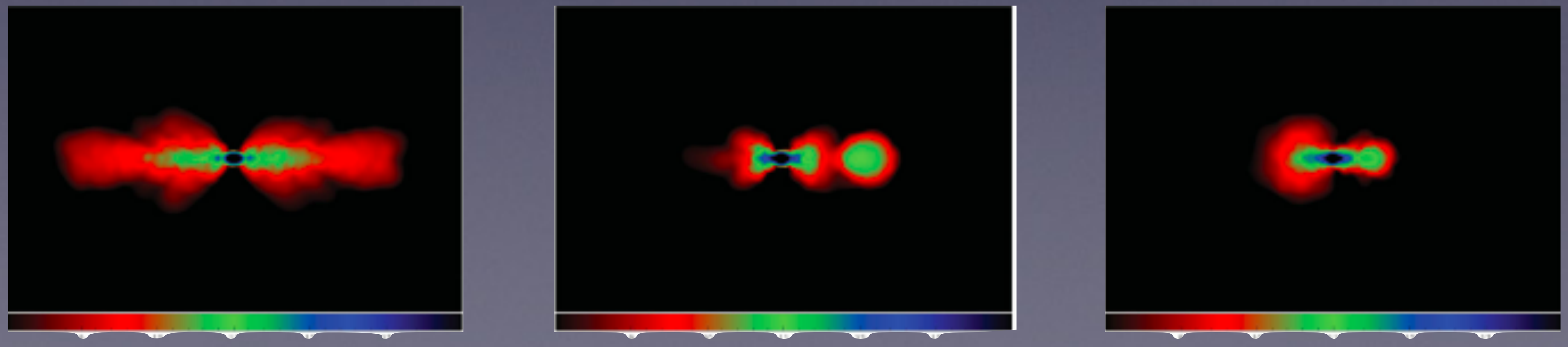

m2
1.8 & 1.8 t= 14.0 ms
1.6 & 1.6 t= 13.2 ms
1.8 & 1.6 t= 13.0 ms
1.4 & 1.4 t= 13.4 ms
1.6 & 1.4 t= 12.2 ms
1.8 & 1.4 t= 13.1 ms
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms
m1



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

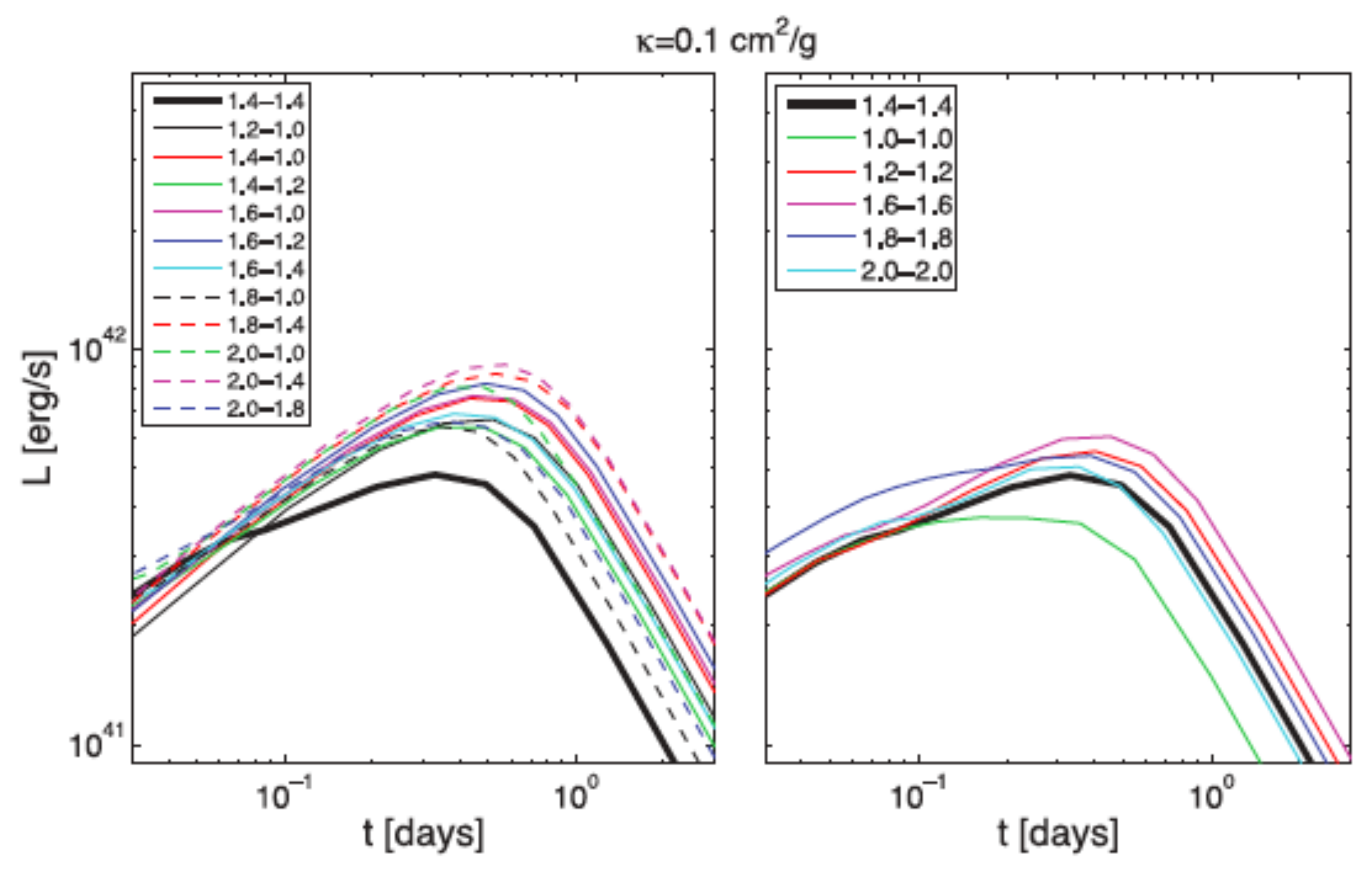
$$\tilde{t}_p \approx \sqrt{\frac{\kappa m_{\rm ej}}{4\pi c \bar{v}}} = 4.9\ {\rm days} \left(\frac{\kappa_{10} m_{{\rm ej},-2}}{\bar{v}_{-1}}\right)^{1/2}$$

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 light curves

Metzger et al., 2011; TP, Nakar, Rosswog, 13



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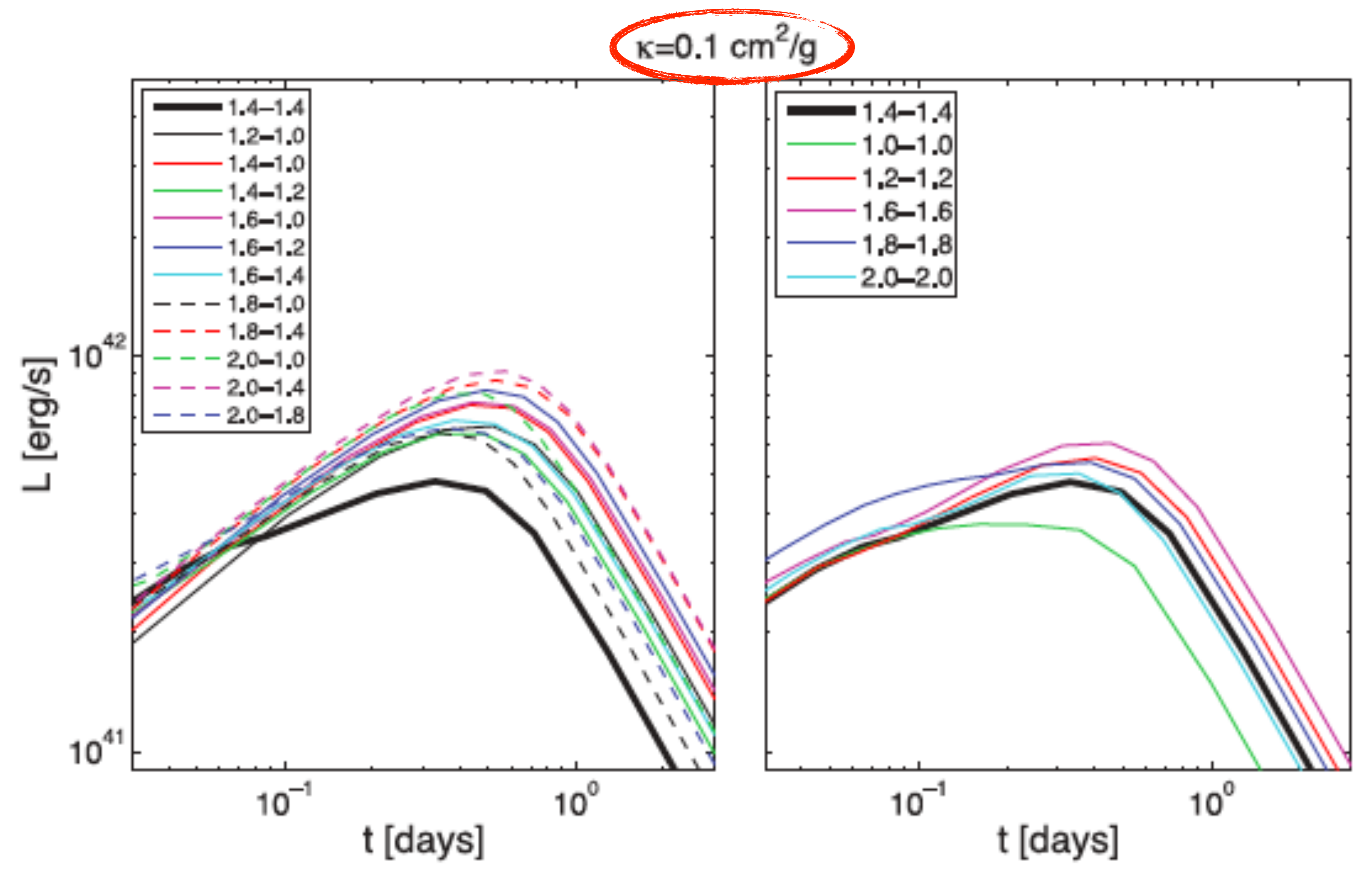
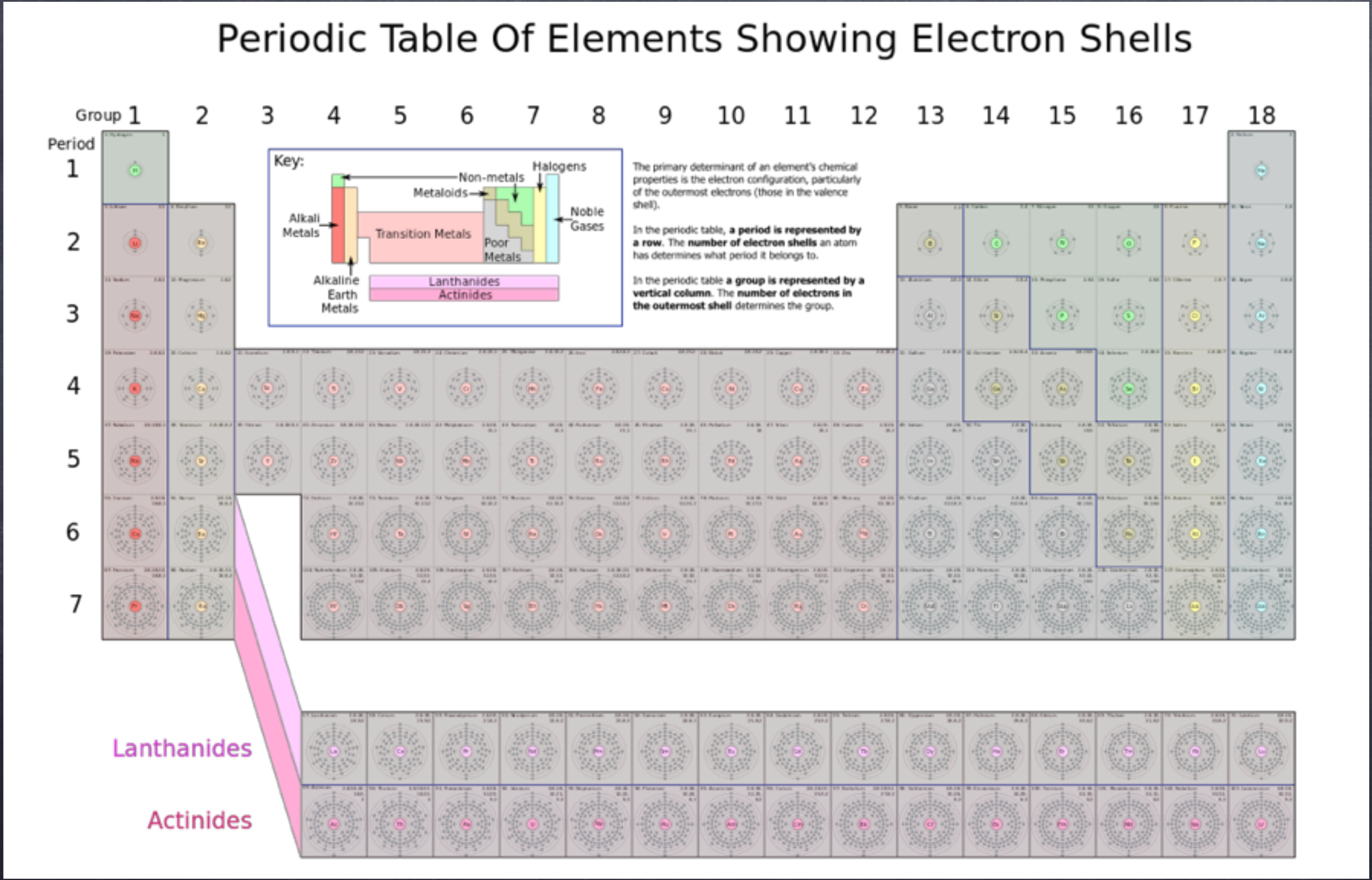


Lanthanides



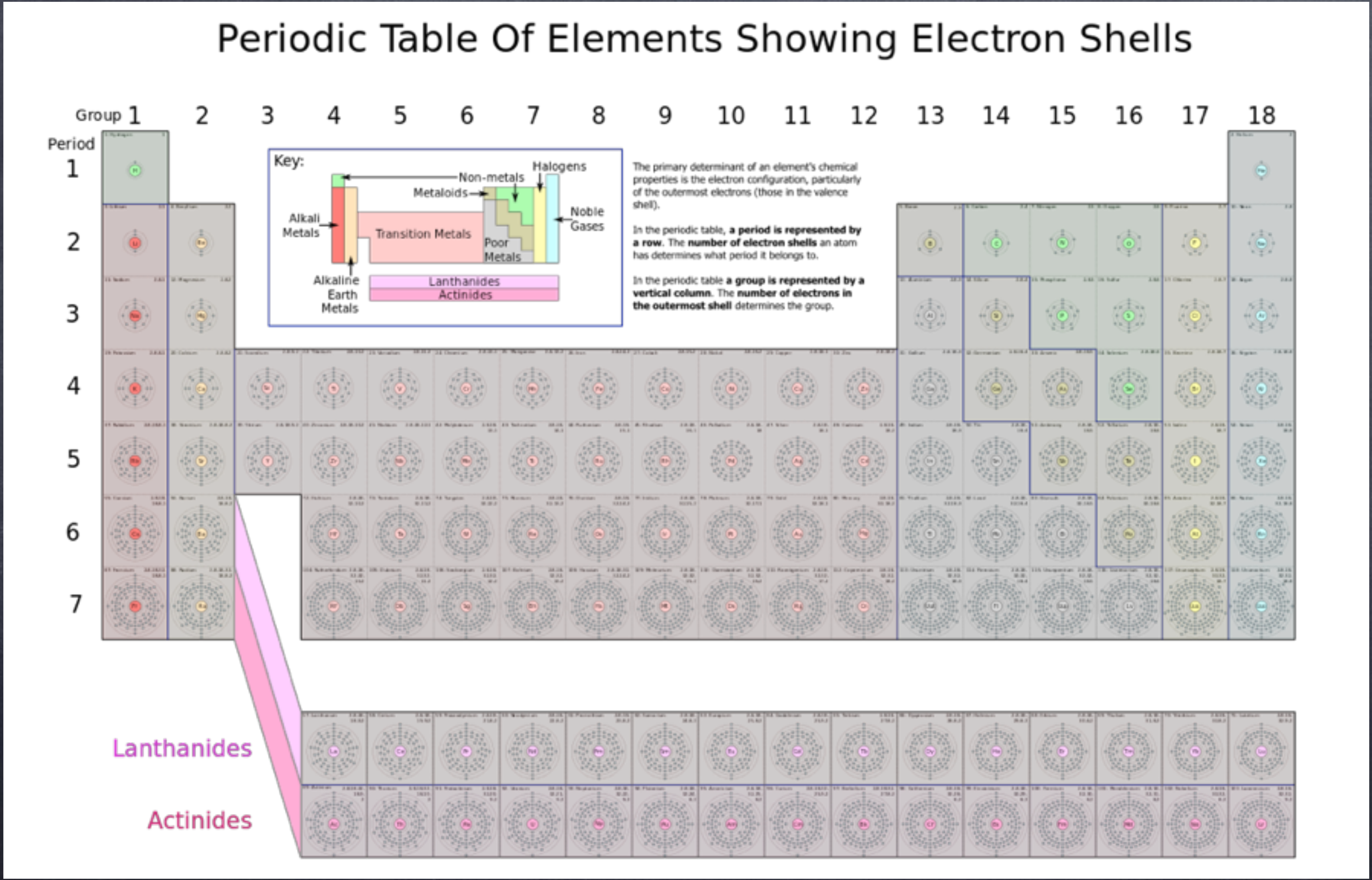
Periodic Table Of Elements Showing Electron Shells

The primary determinant of an element's chemical properties is the electron configuration, particularly of the outermost electrons (those in the valence shell).

In the periodic table, **a period is represented by a row**. The **number of electron shells** an atom has determines what period it belongs to.

In the periodic table **a group is represented by a vertical column**. The **number of electrons in the outermost shell** determines the group.

Lanthanides



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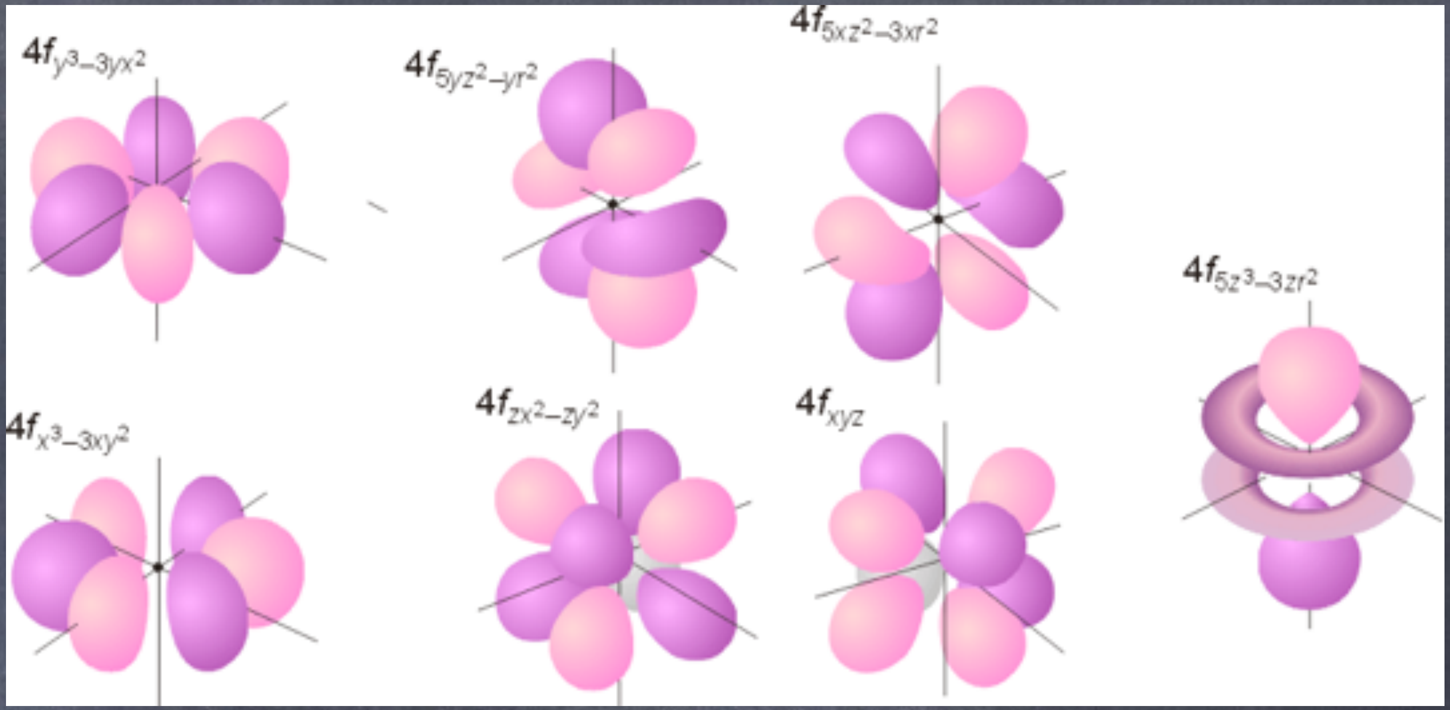
Why do are the Lanthanides “out” of the table?

The Lanthanides' Opacity

Kassen & Barnes 2013



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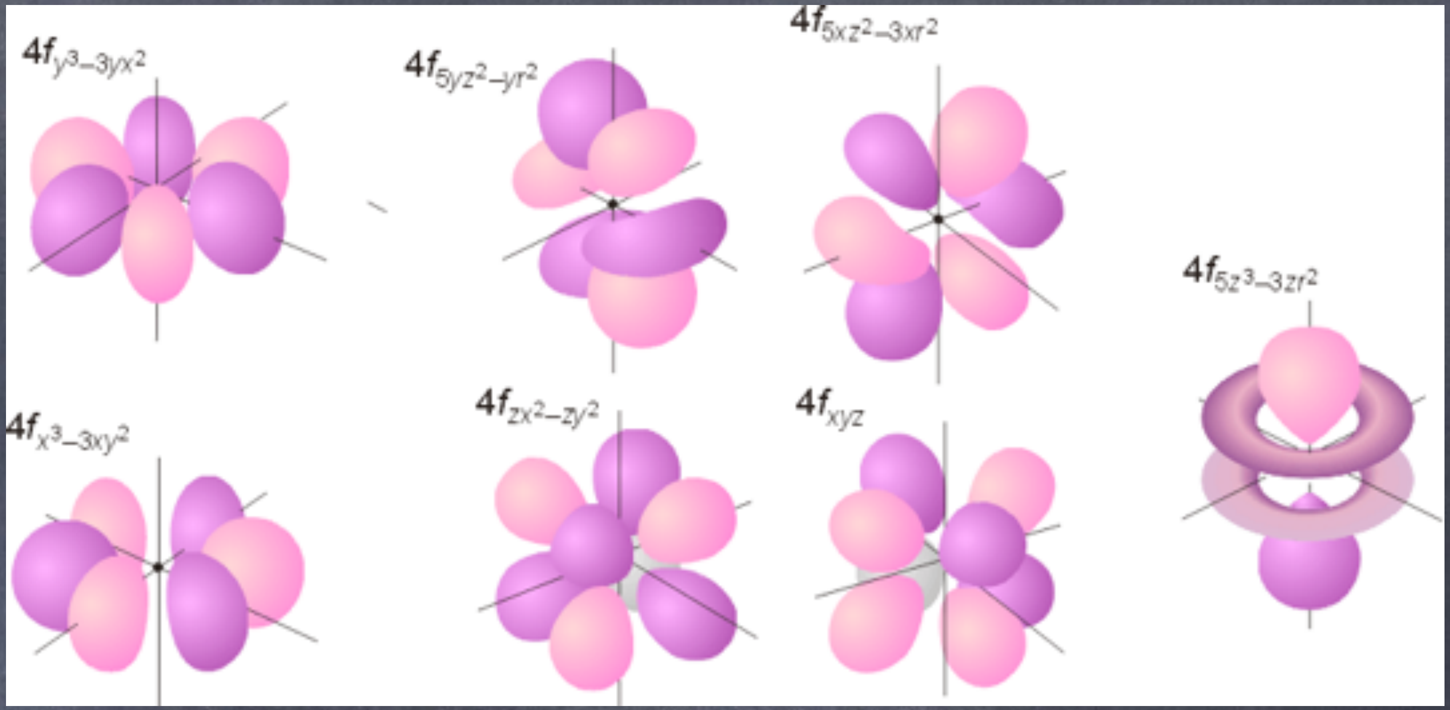

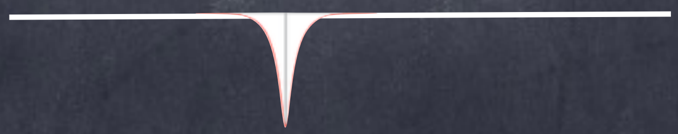

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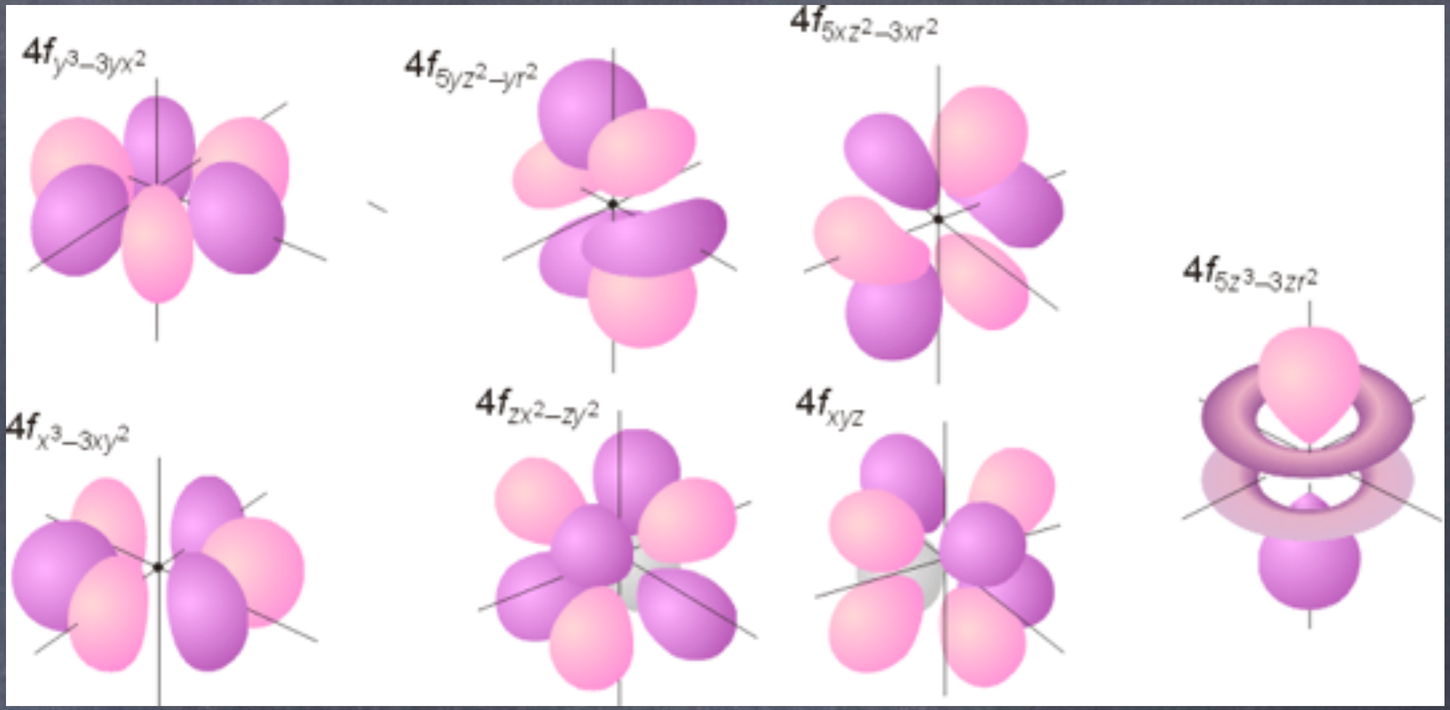

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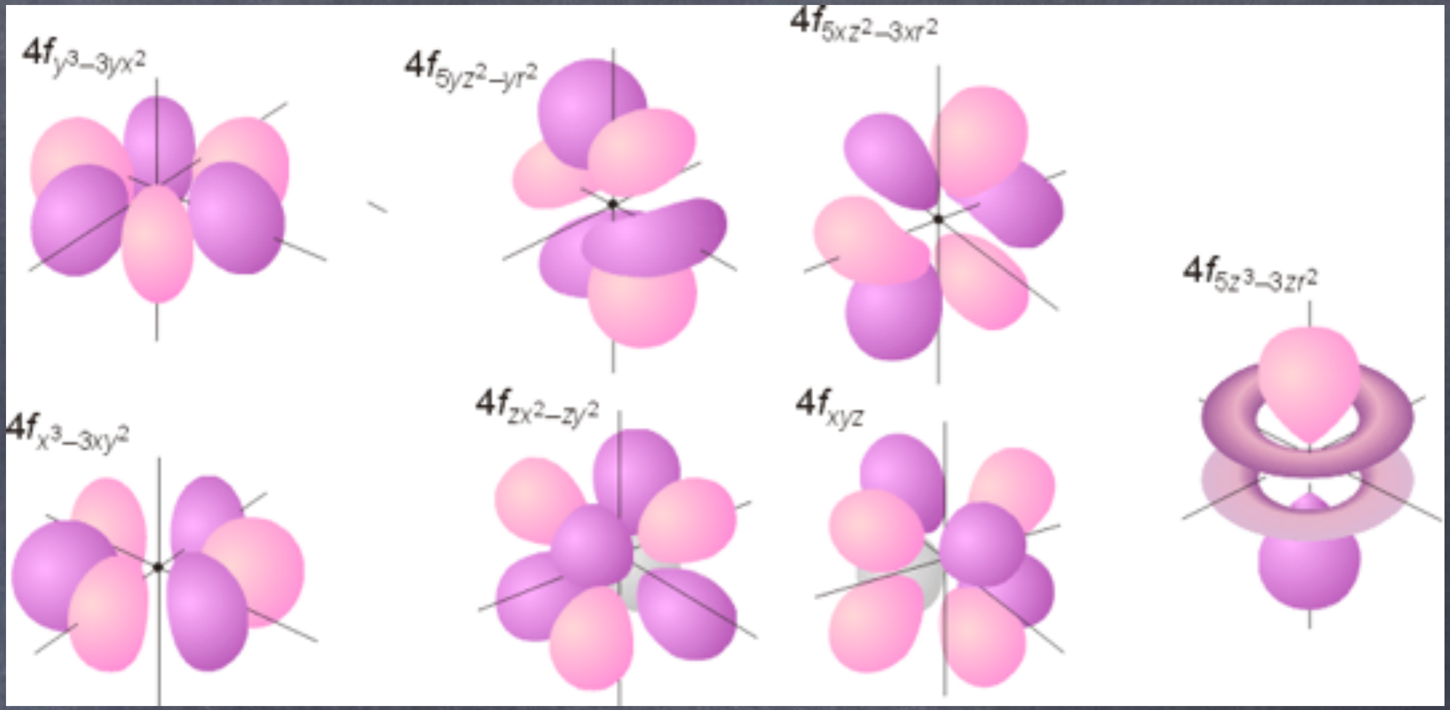

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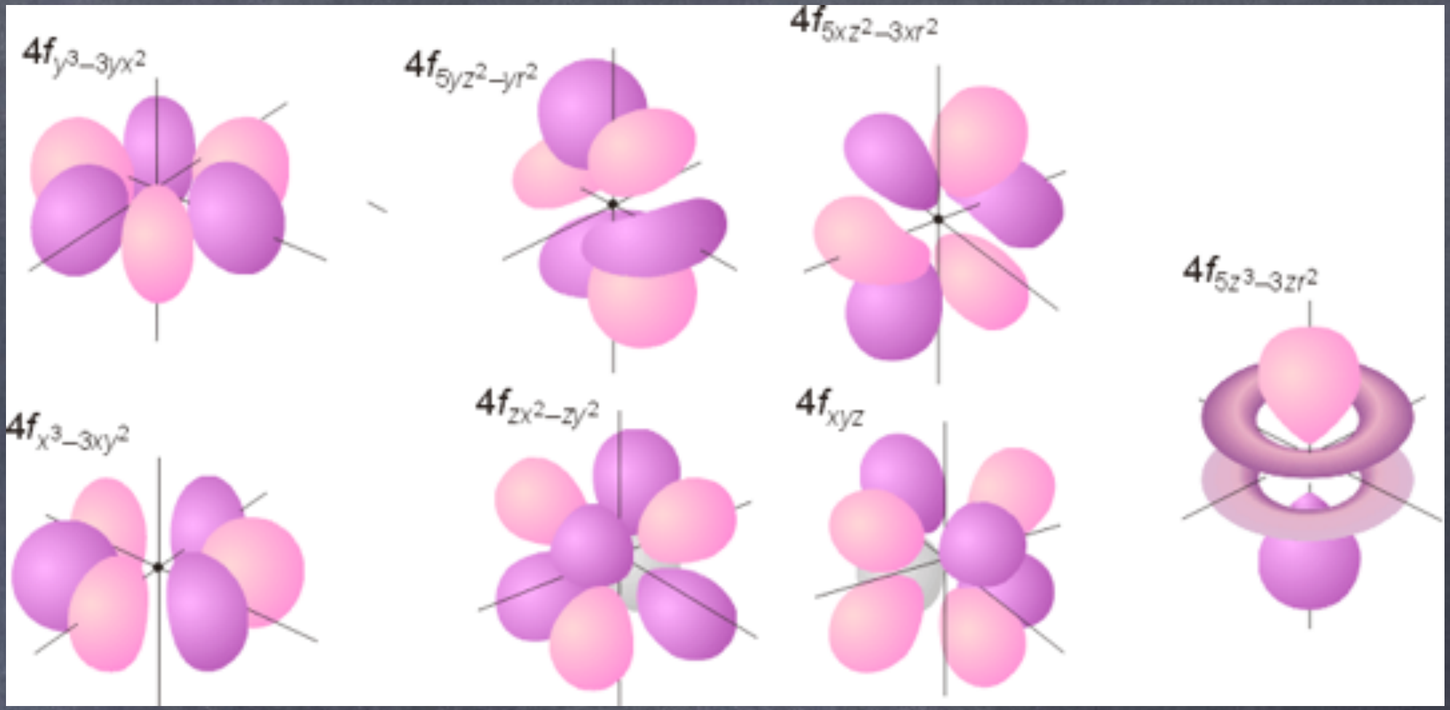

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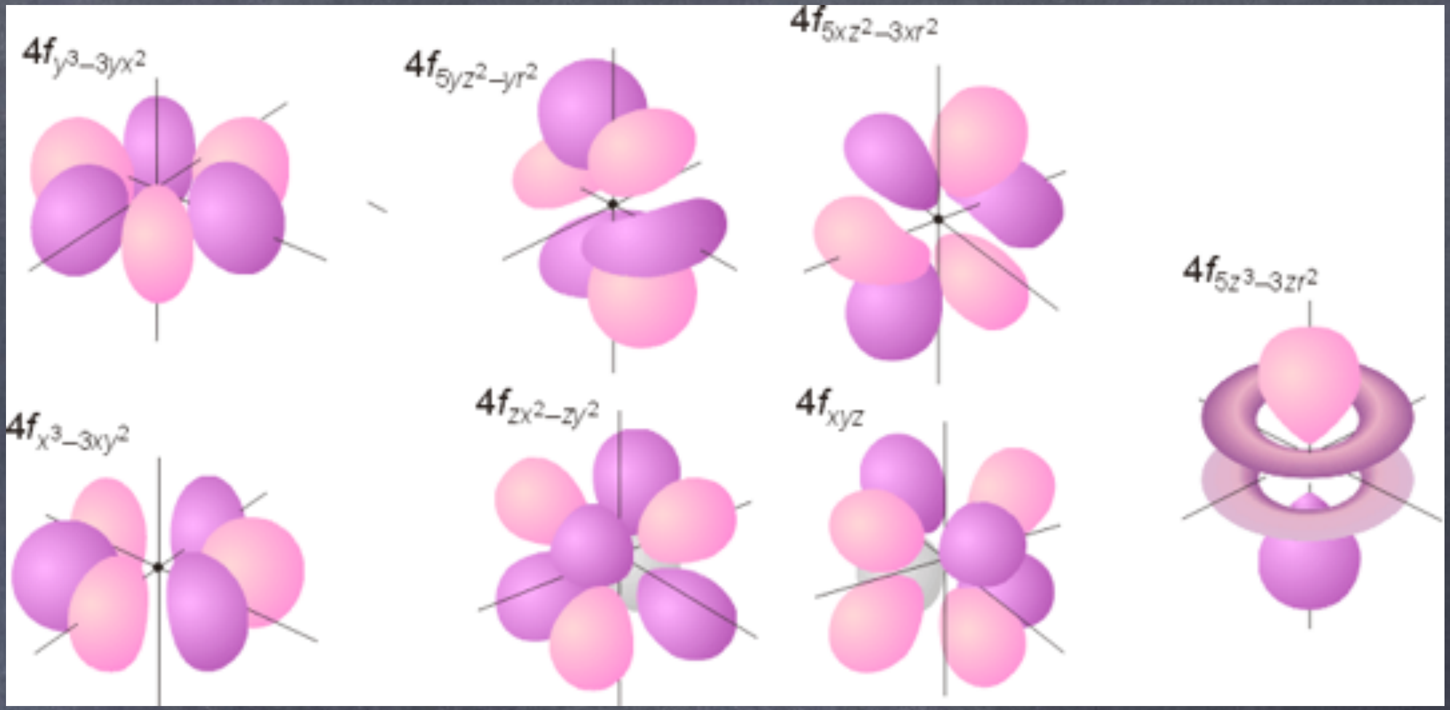

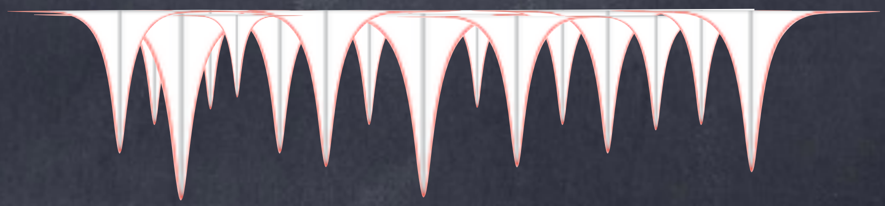

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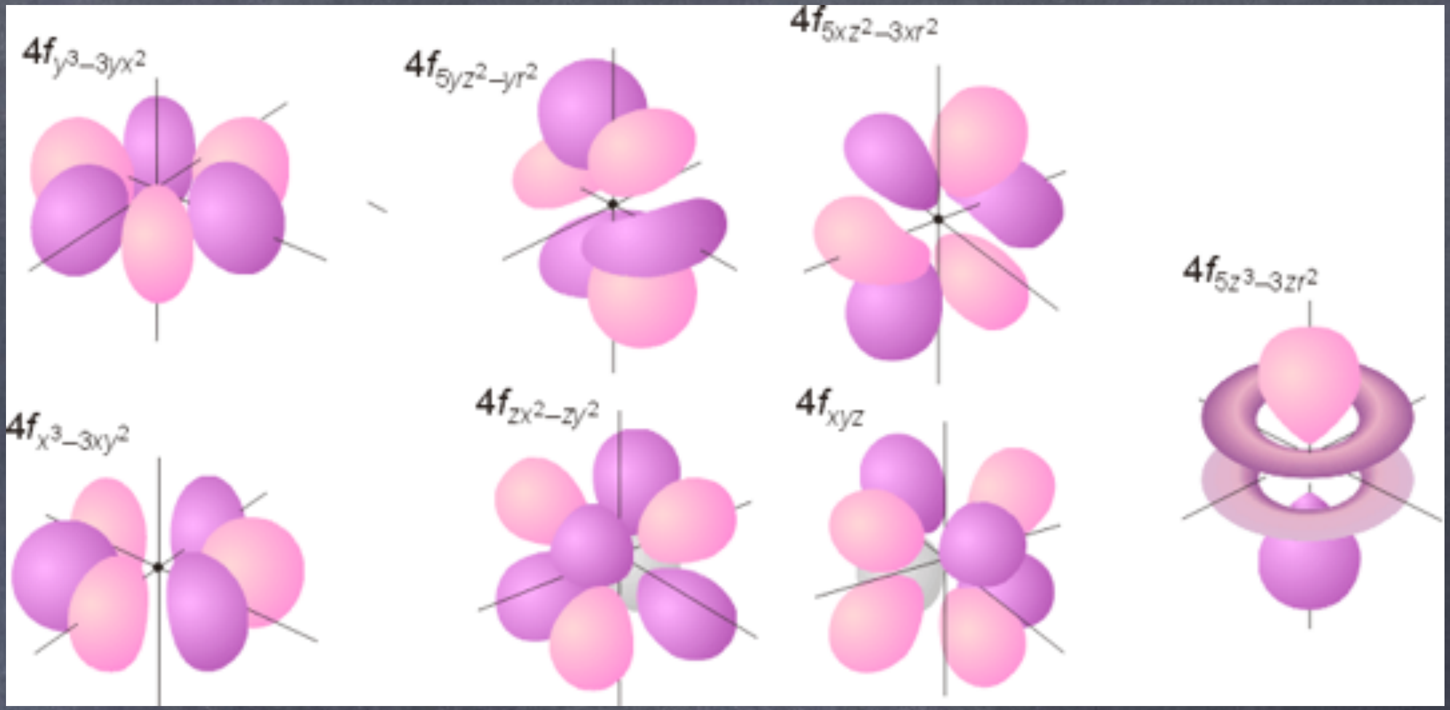
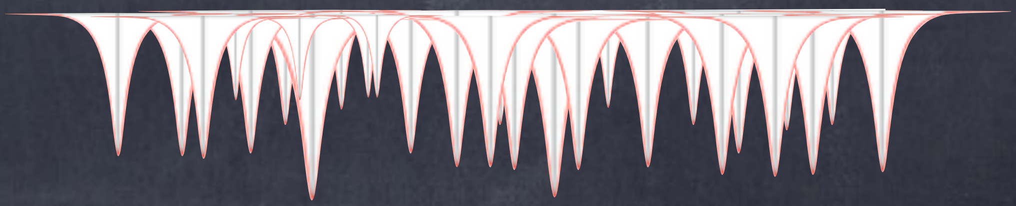




The Lanthanides' Opacity

Kassen & Barnes 2013

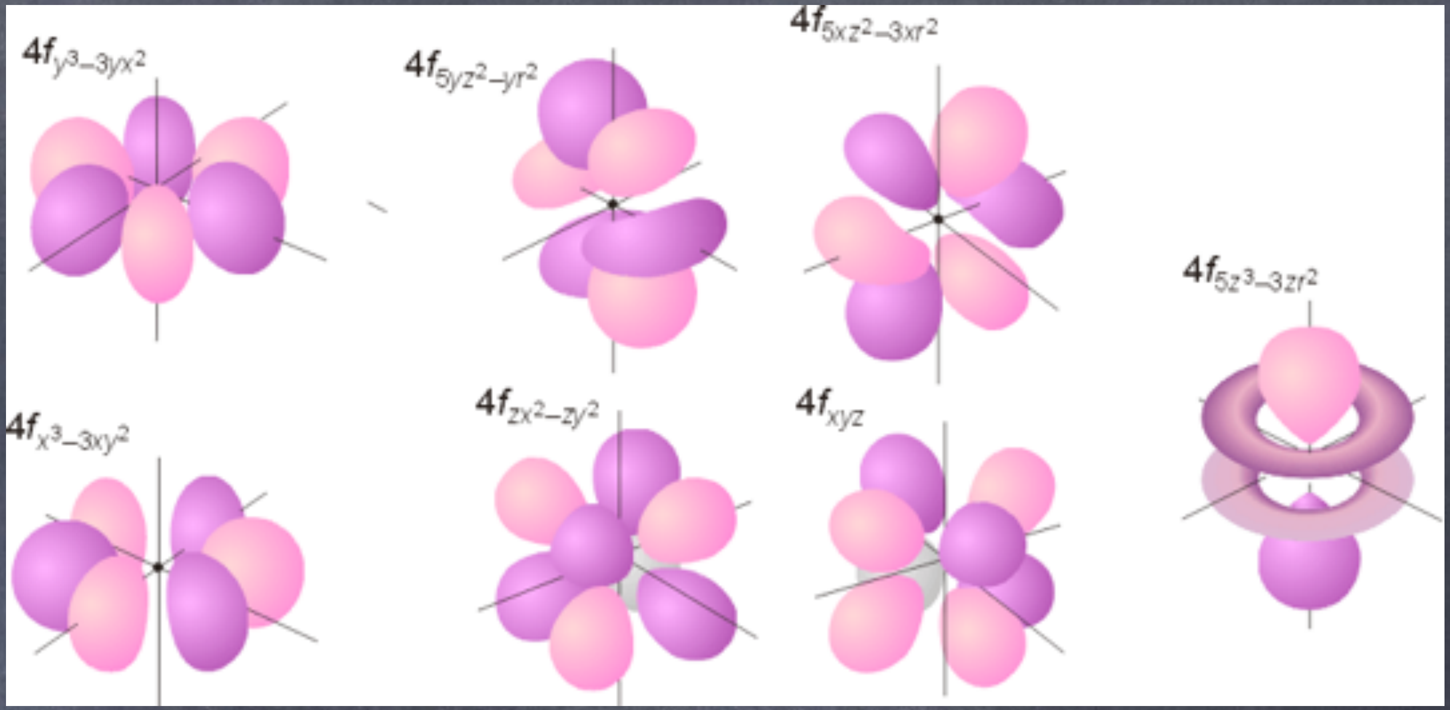
The Lanthanides have "too many" lines

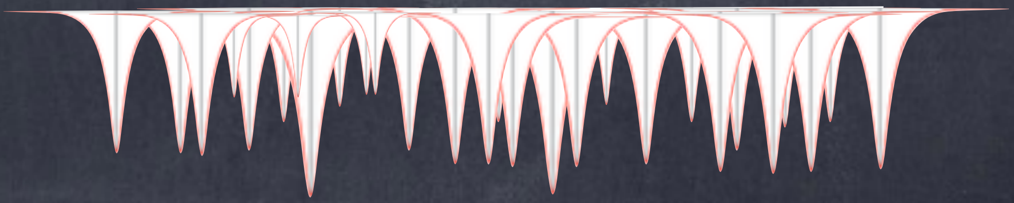
<u>κ=10 cm^2/gm</u>

compare with

κ =0.4 cm^2/gm for the iron group

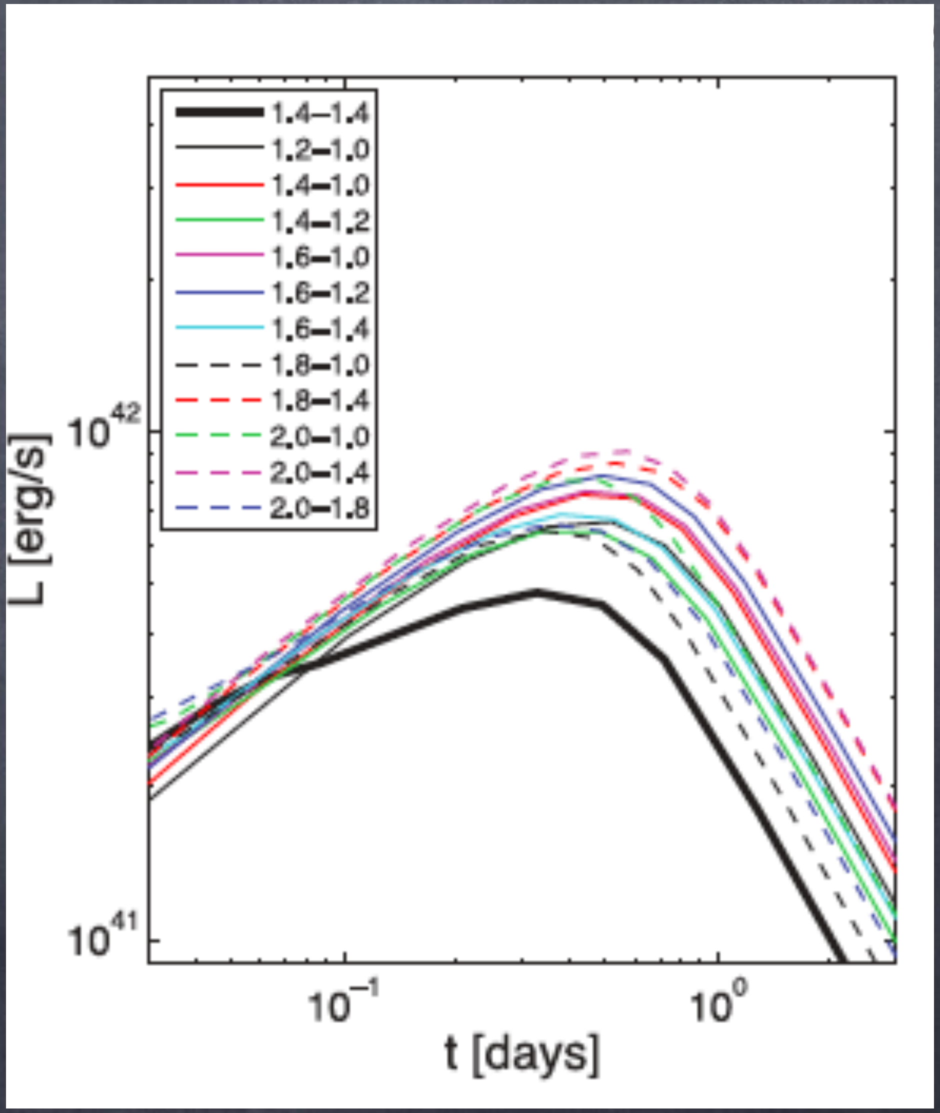
κ_T=0.1 cm^2/gm for electron scattering





Lanthanides dominate the Opacity (Kassen & Barnes 13)

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



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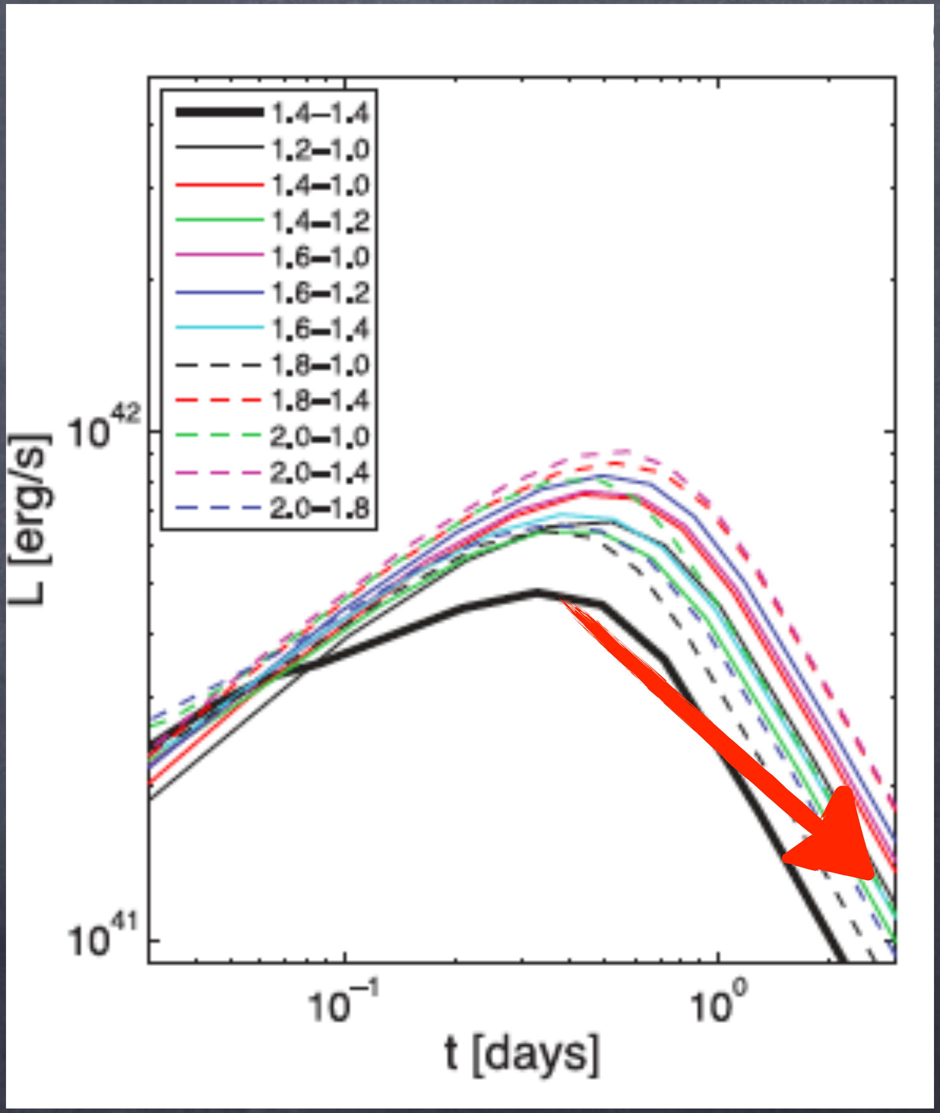

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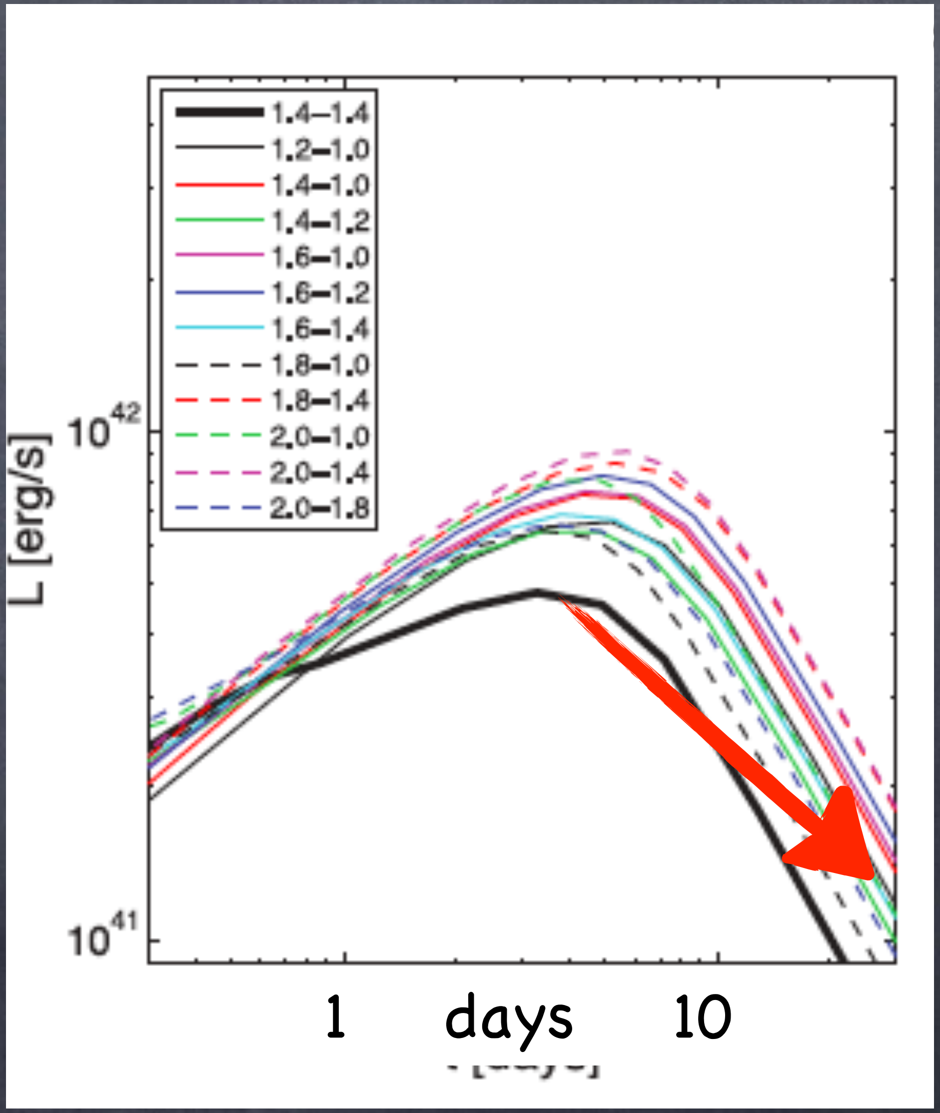

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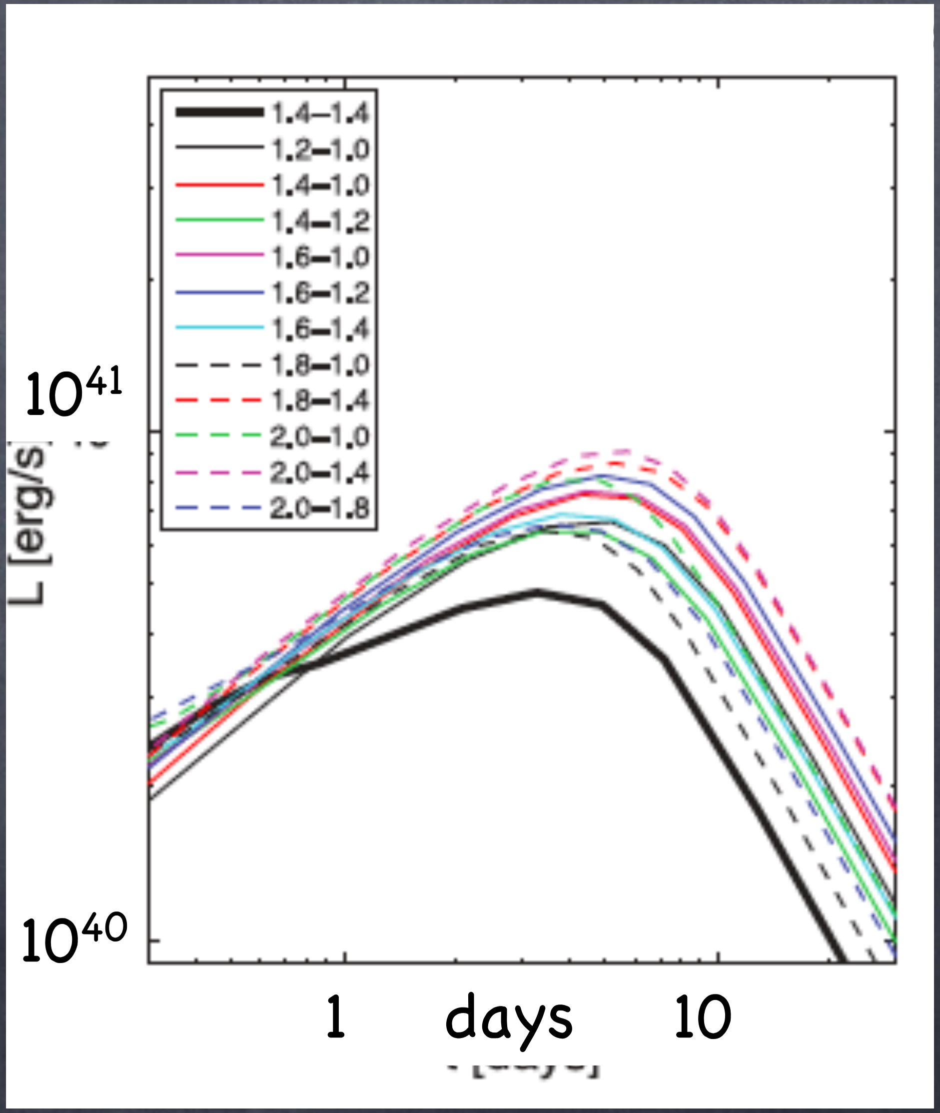

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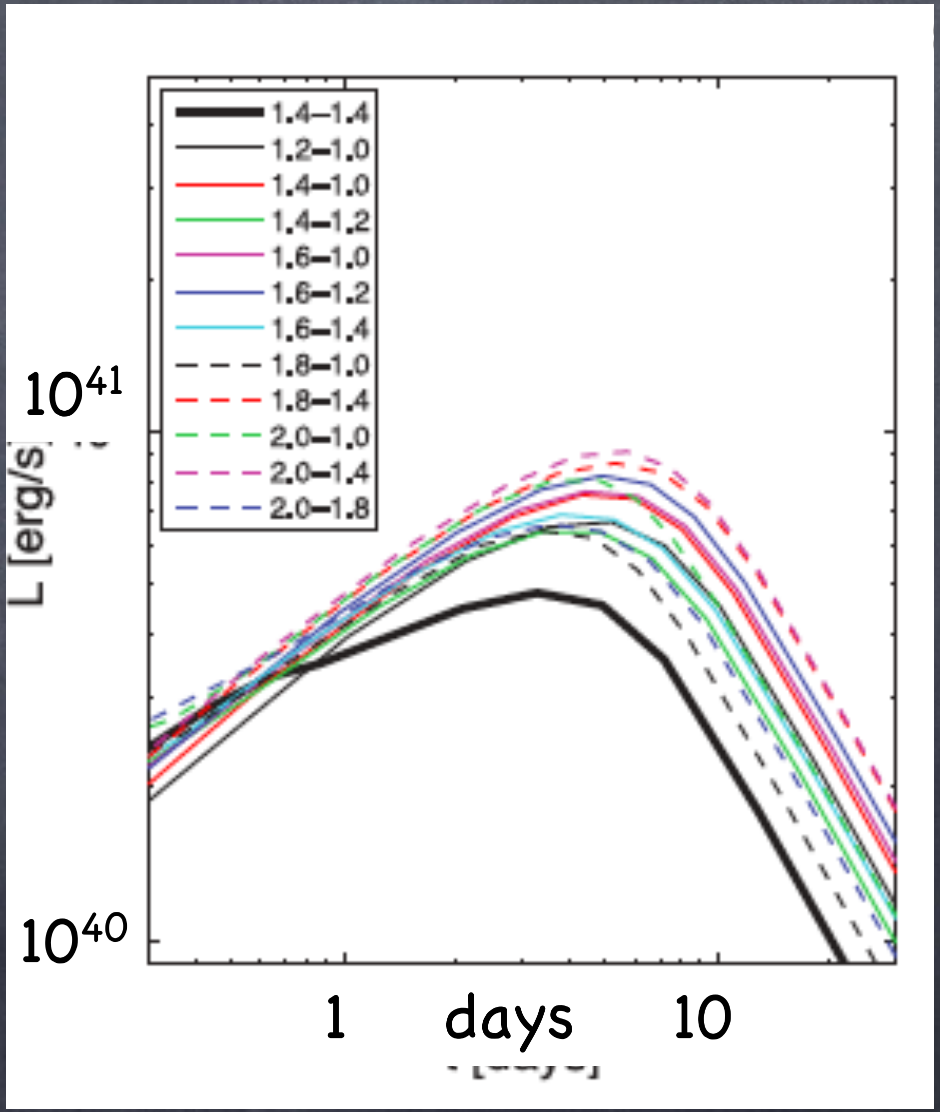
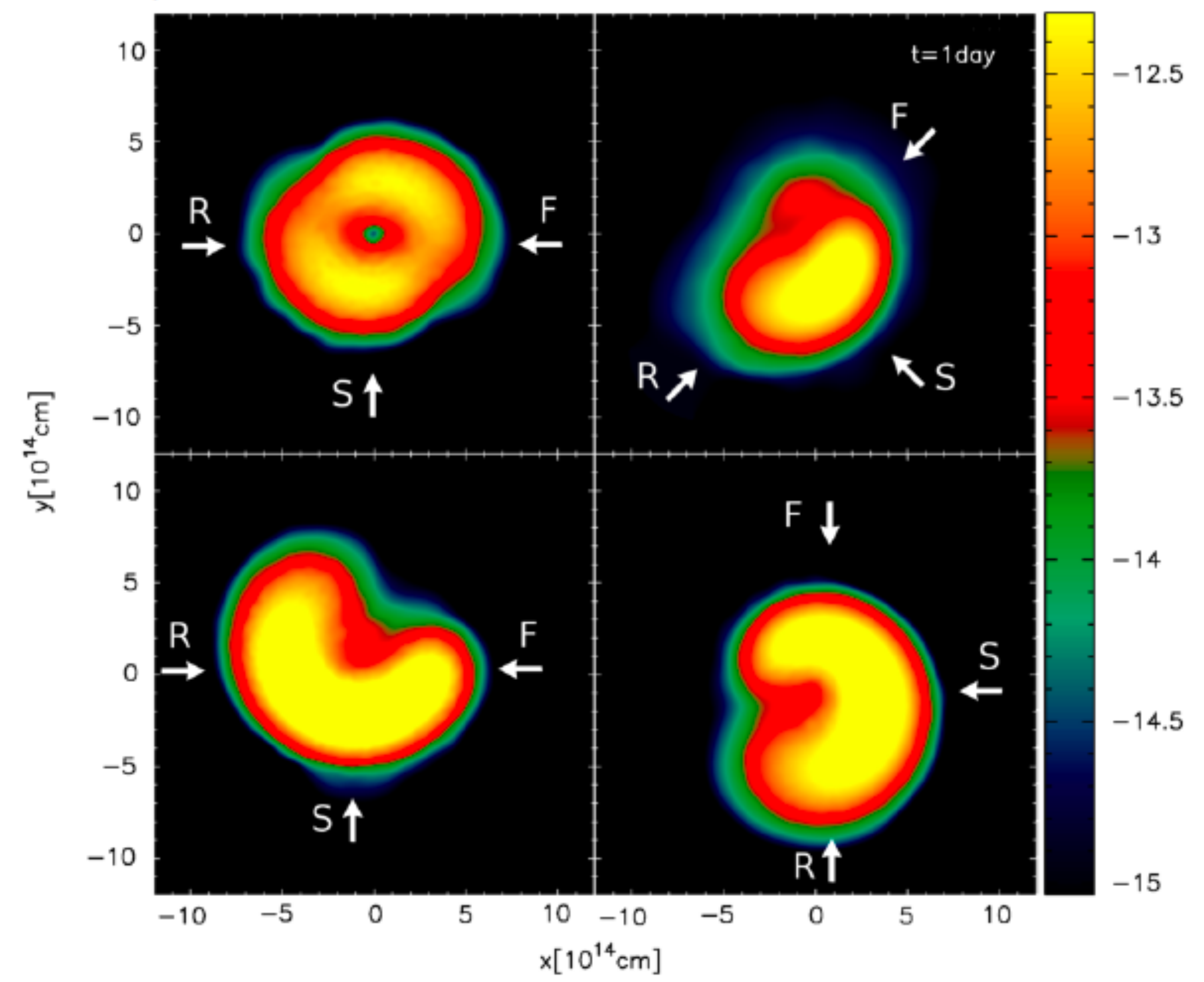


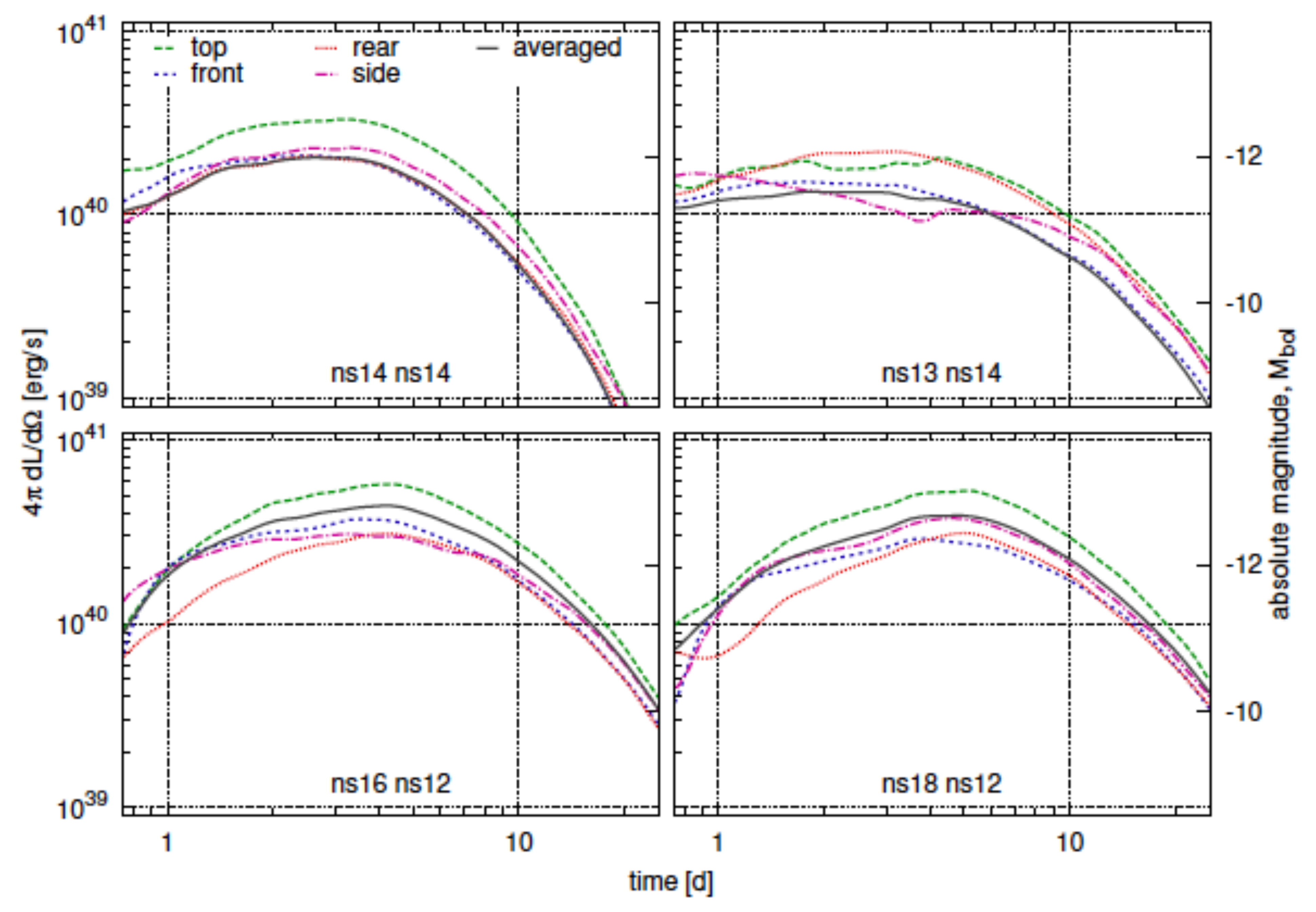
uv or optical -> IR

More detailed estimates

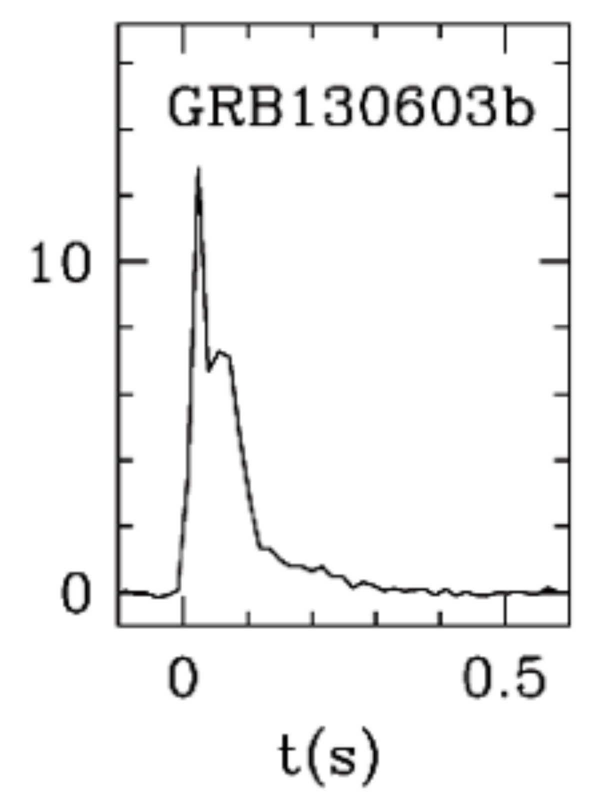
Grossman, Korobkin TP Rosswog, 13

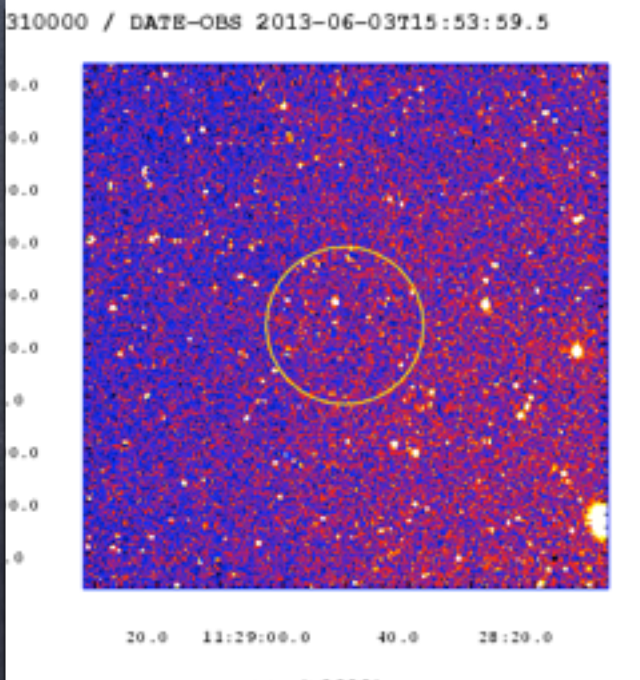


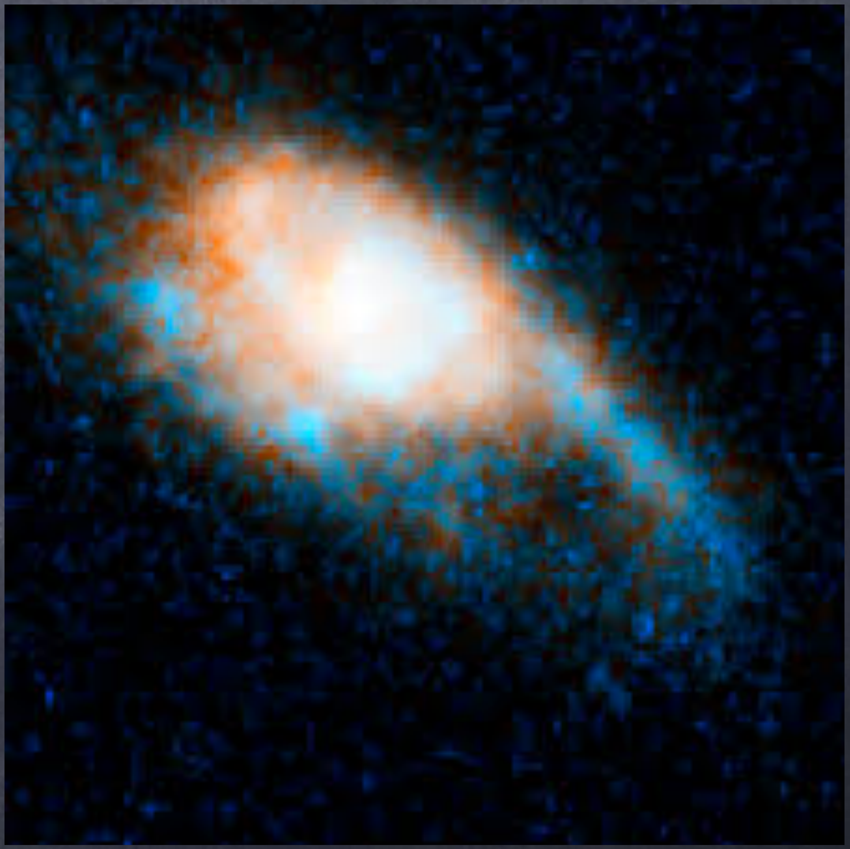
Bolometric light curves



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

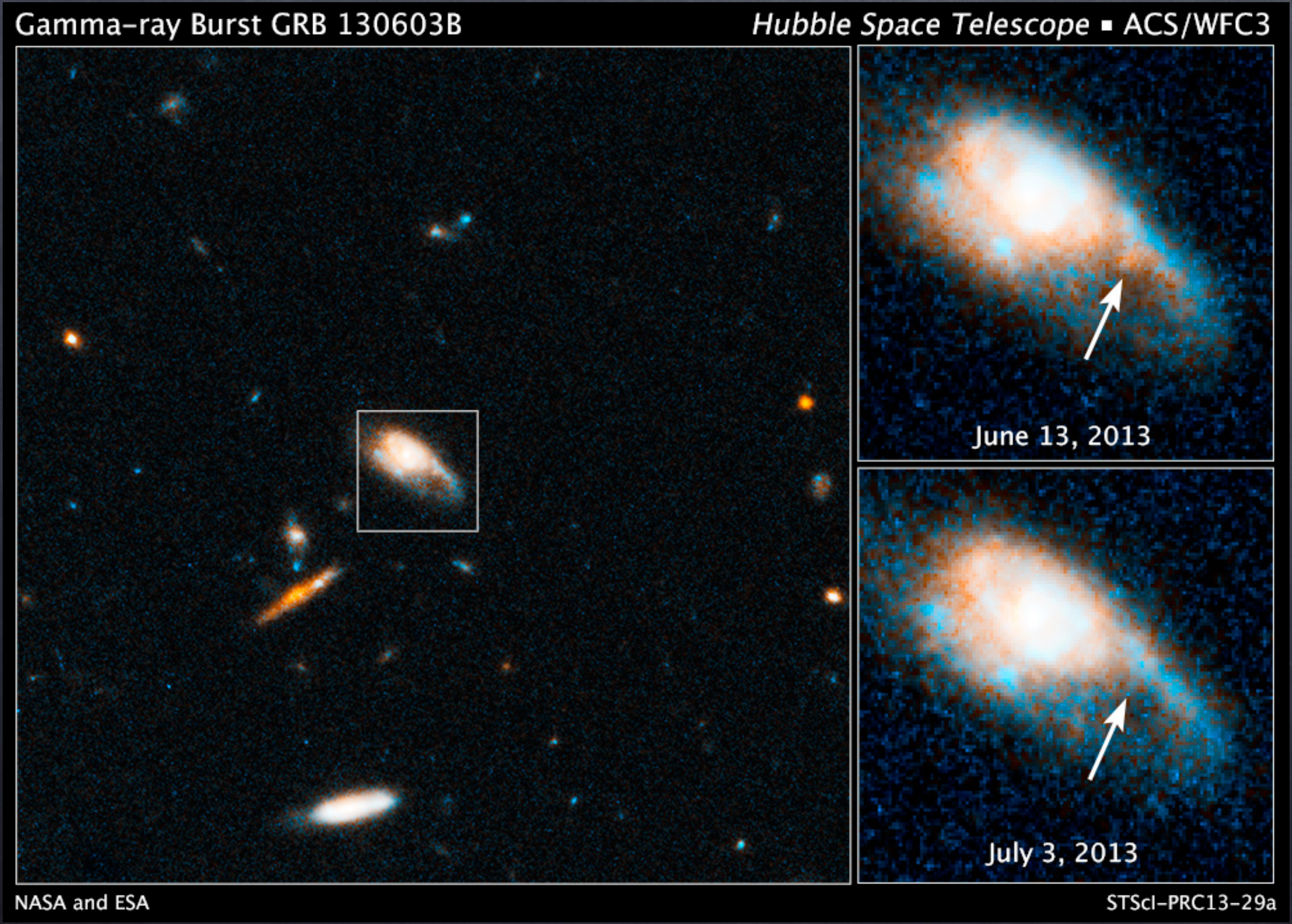






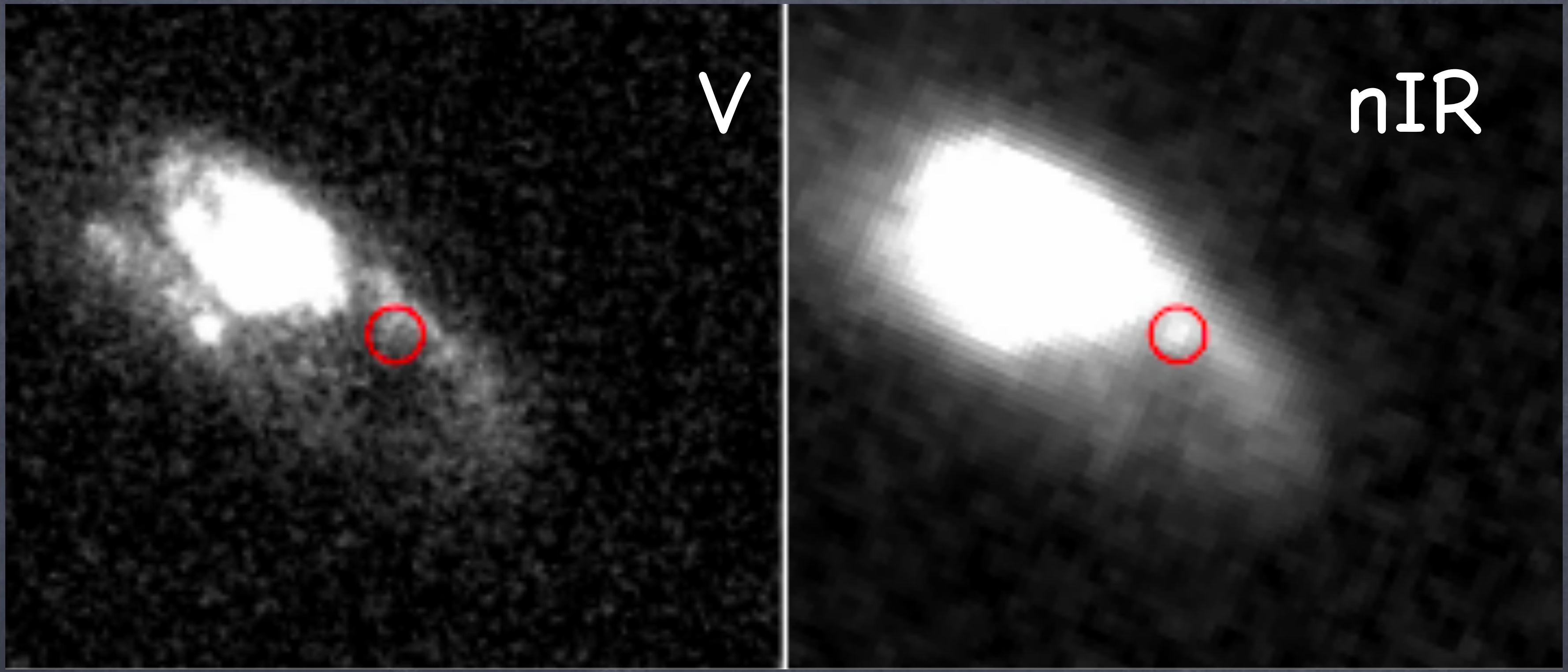
GRB 130603B

z=0.356 <=> 1 Gpc = 3 Glyr

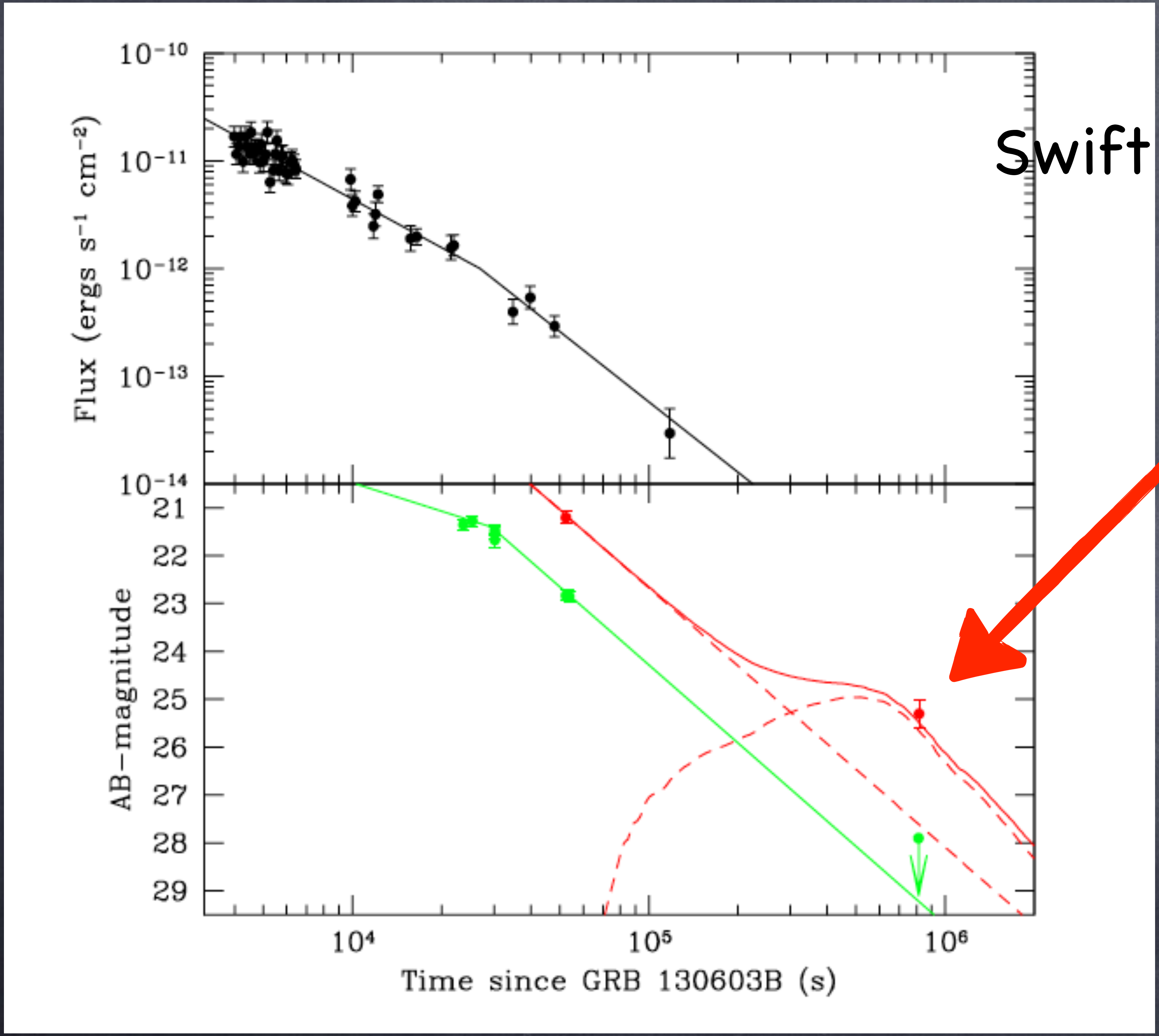

Gamma-ray Burst GRB 130603B
Hubble Space Telescope ▪ ACS/WFC3
June 13, 2013
July 3, 2013
NASA and ESA
STScI-PRC13-29a

GRB130603B @ 9 days AB

(6.6 days at the source frame)



HST image (Tanvir + 13)



Swift

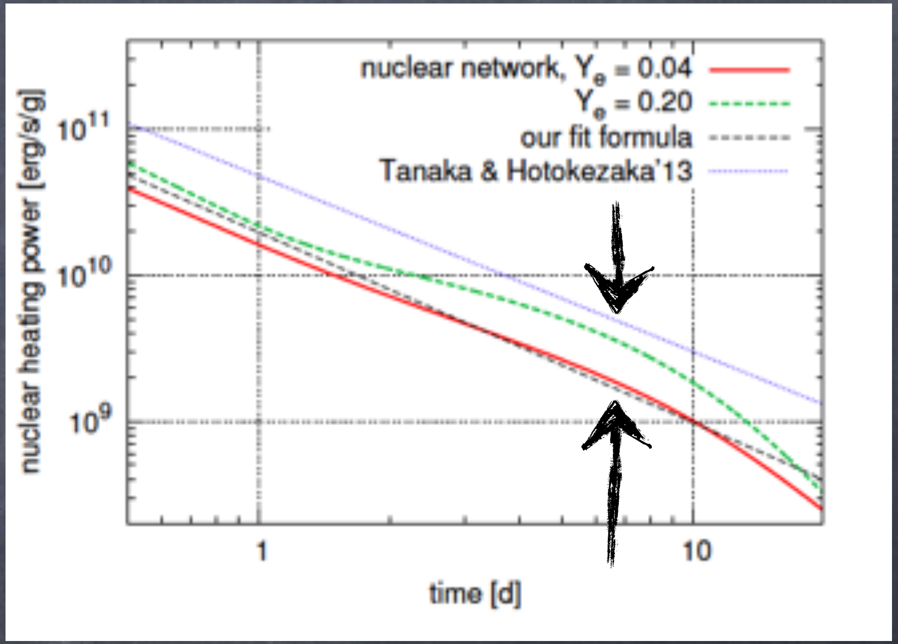
Macronova?

Tanvir + 13

GRB130603B @ z=0.356 nIR transient

- Consistent with Barnes & Kasen (13) and Tanaka & Hotozoka (13)

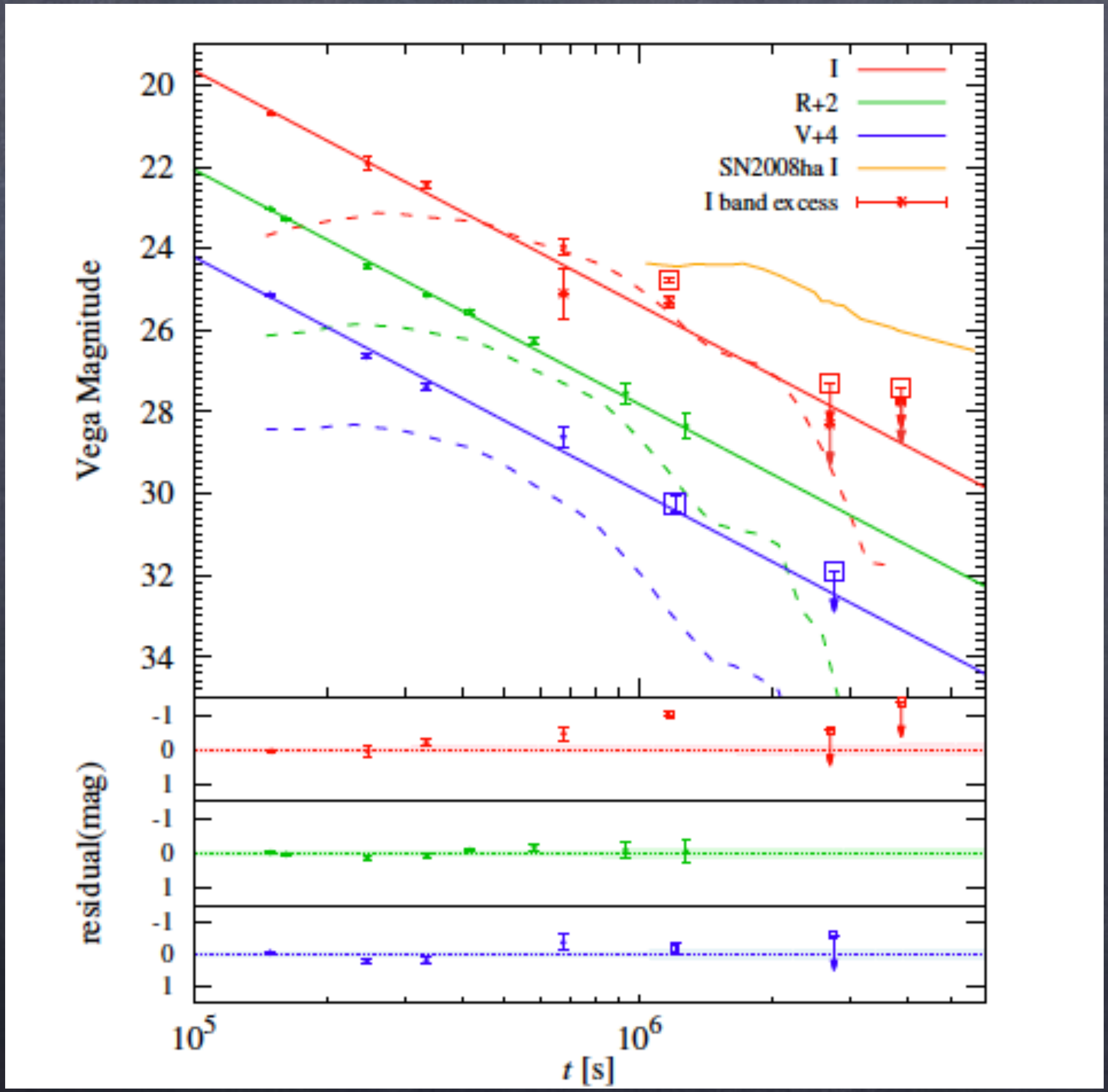
- But Both groups possibly overestimated radioactive heating rate by a factor of 2-4



- The expected signal is slightly too large

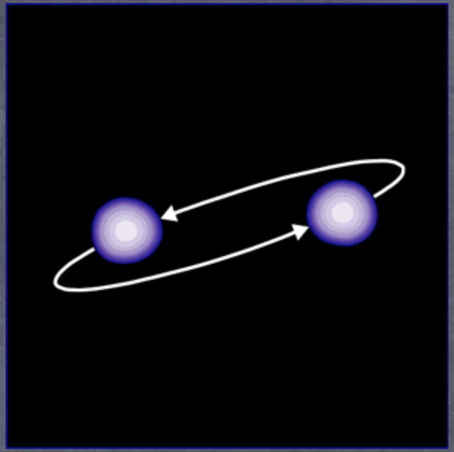
GRB 060614
the “long” - short Burst

Yang et al., Nature Comm 2015



If correct

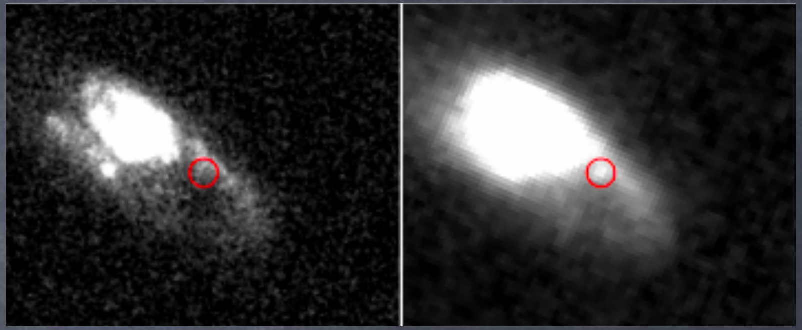
- Confirmaiton of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).



- 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...).

6. 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

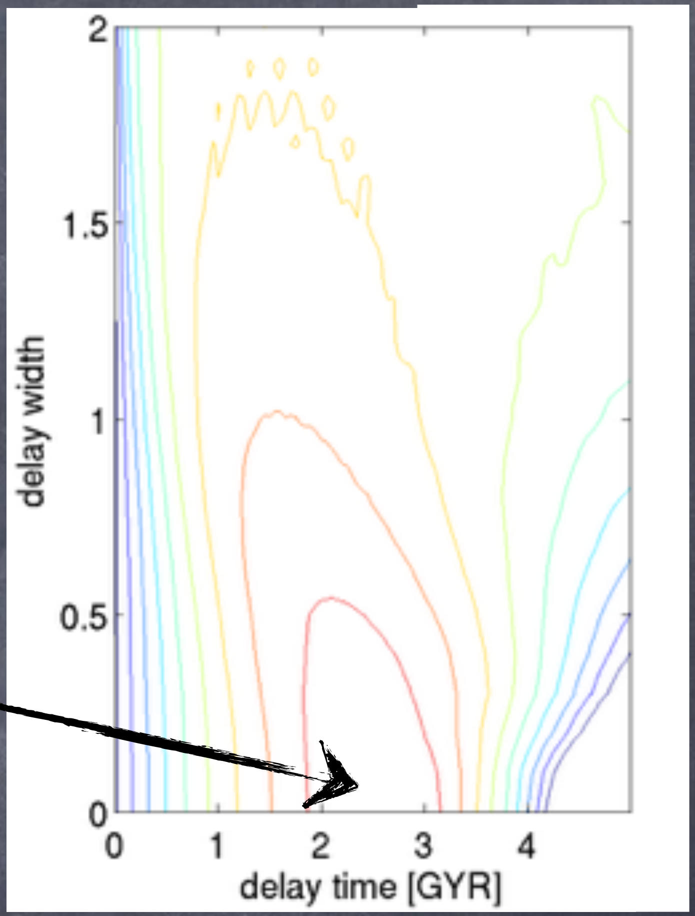
Mergers' Rate

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

The rate of short GRBs

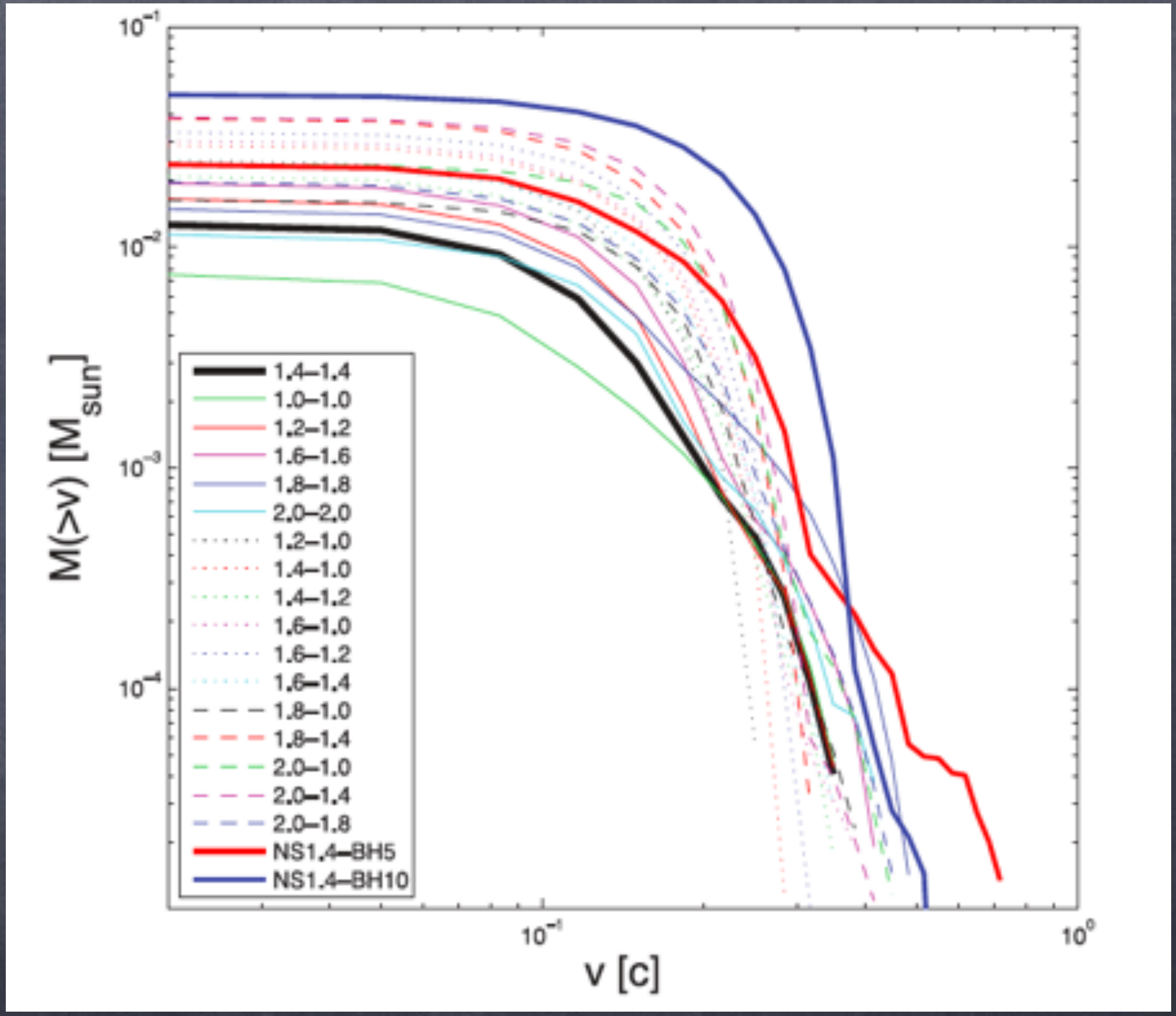
Guetta & TP 2006; Wanderman & TP 2015

- $R_{sgrb} = 4.1^{+2.3}_{-1.9}$ Gpc^{-3} yr^{-1}
- Typical spiral-in phase of 2.7 Gyr. But selection effects? May be consistent with $p(\tau) \sim 1/\tau$
- Consistent with $R_{merger} = 200$ Gpc^{-3} yr^{-1} for a reasonable beaming factor of 40.
- Consistent with rate estimates based on galactic neutron star binaries.

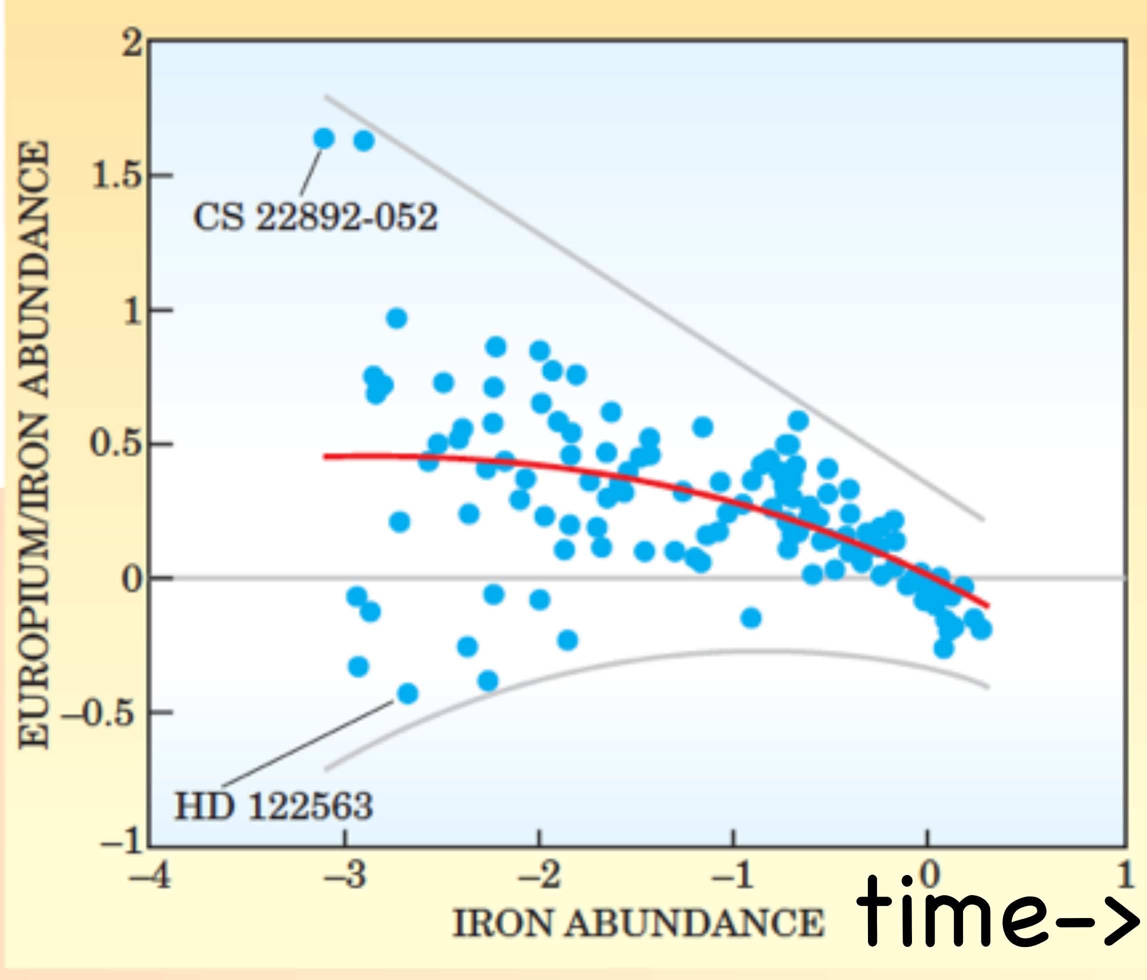


But:

- The ejected mass is about 0.04 M_{sun}. The minimal mass is 0.02 M_{sun}.
- This is rather large for neutron star binary merger.
- Is the solution black hole - neutron star merger?



Early nucleosynthesis - a challenge



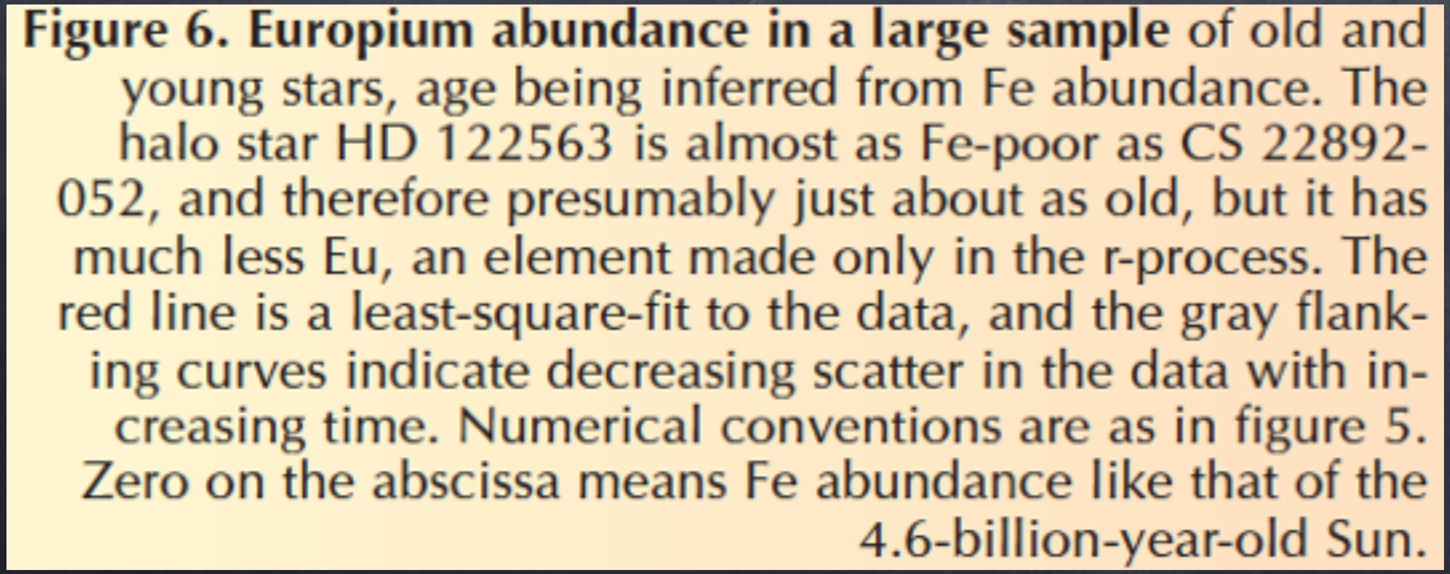


Figure 6. Europium abundance in a large sample of old and young stars, age being inferred from Fe abundance. The halo star HD 122563 is almost as Fe-poor as CS 22892-052, and therefore presumably just about as old, but it has much less Eu, an element made only in the r-process. The red line is a least-square-fit 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.

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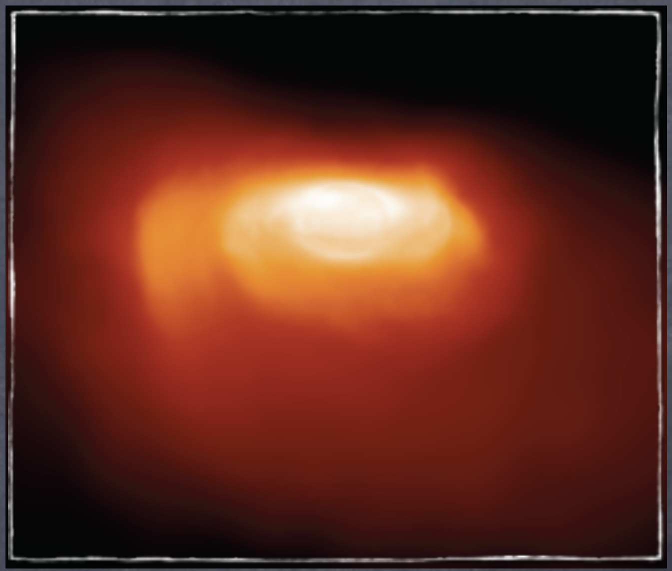

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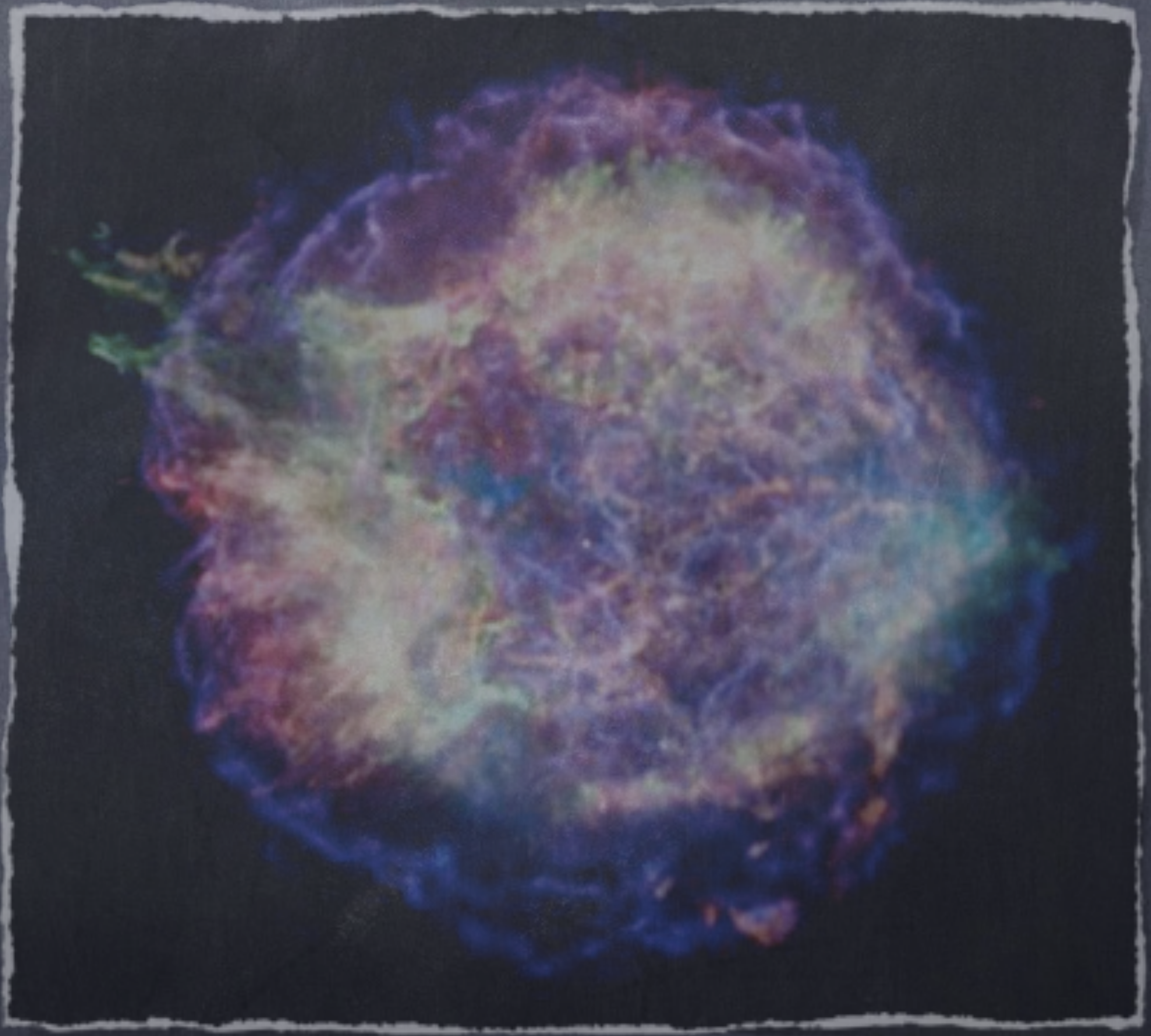

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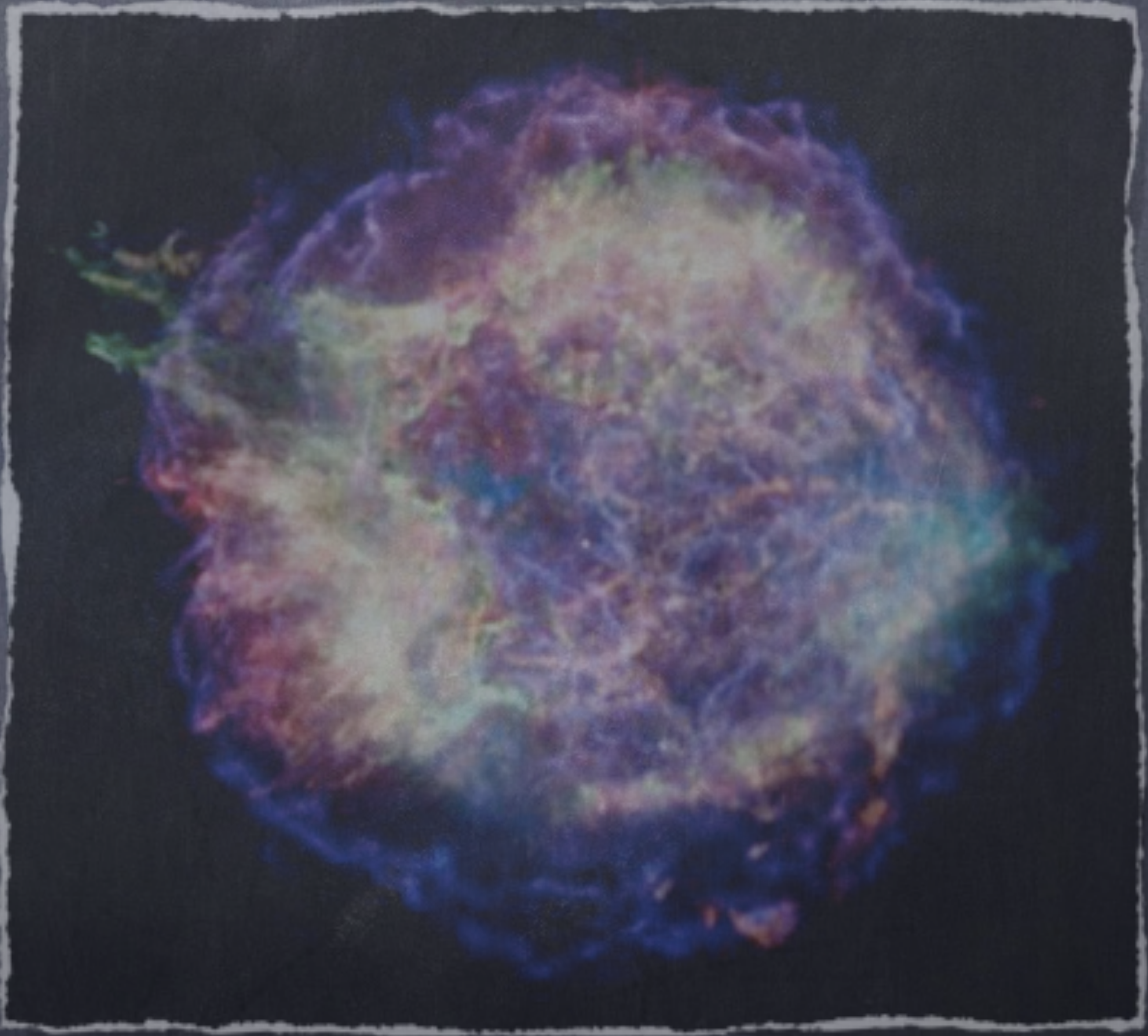
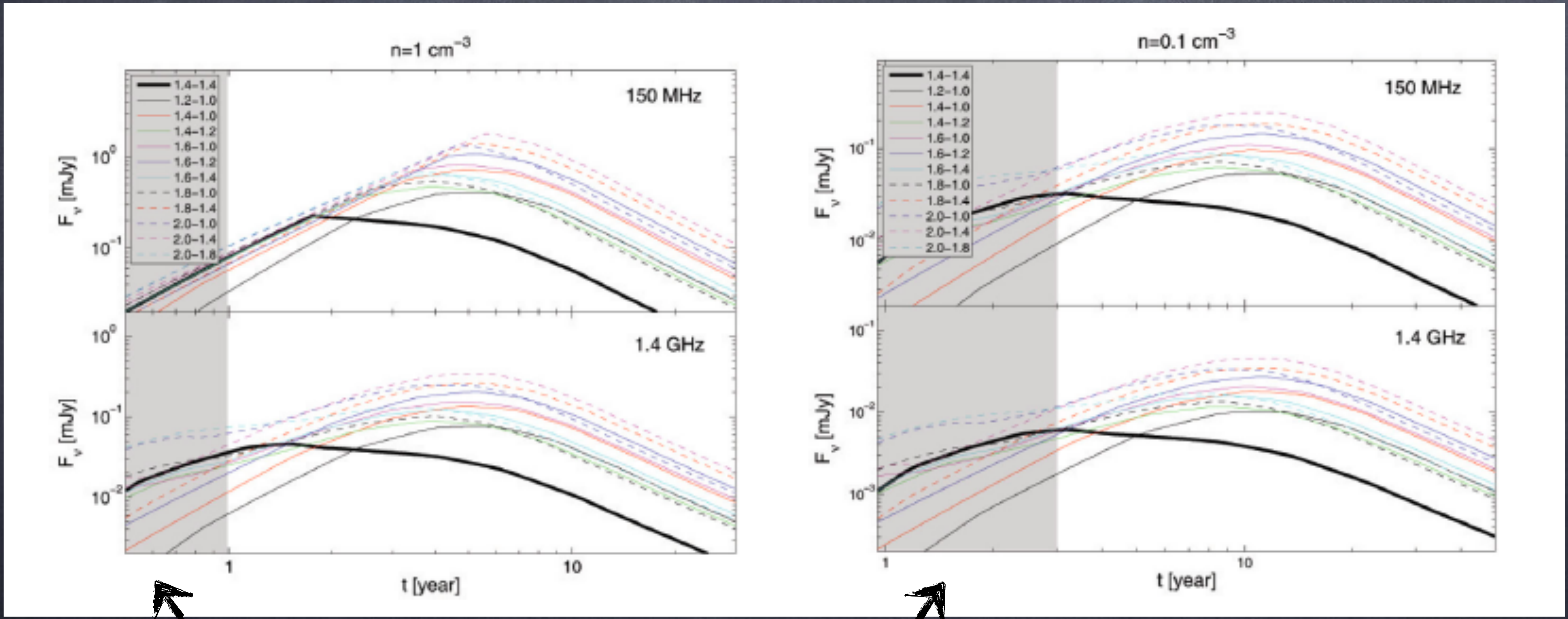


A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.

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)

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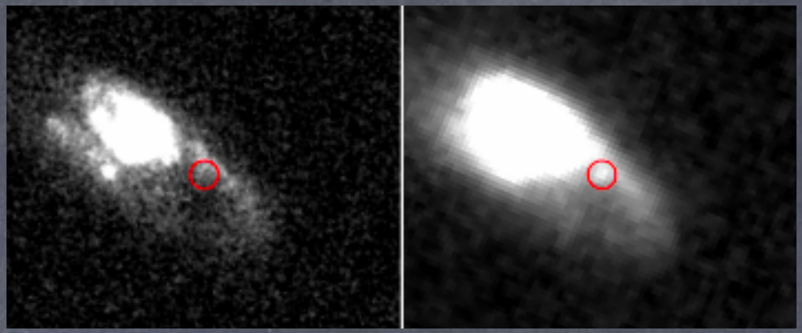
Summary



- **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.

And ->

Summary

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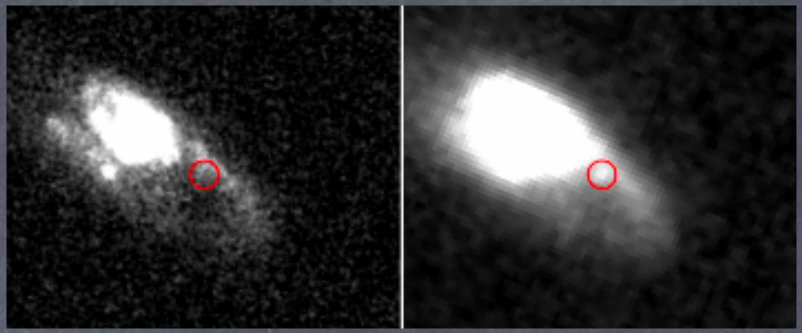

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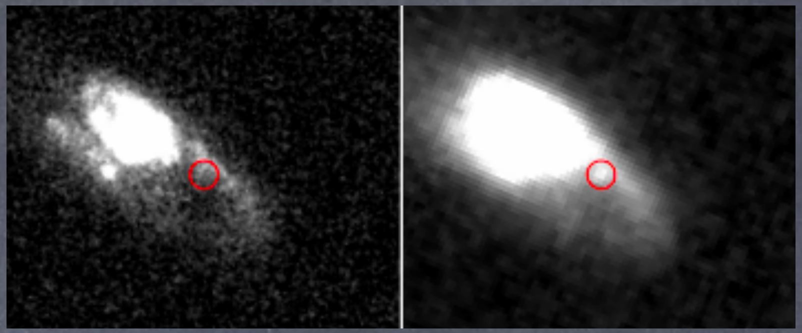

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And ->

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

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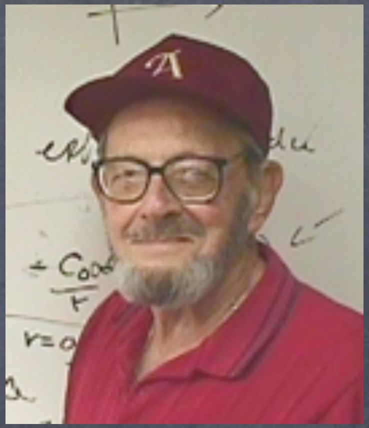
- The early Solar System had ^{244}Pu (τ = 117 Myr)

  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?

The End ?