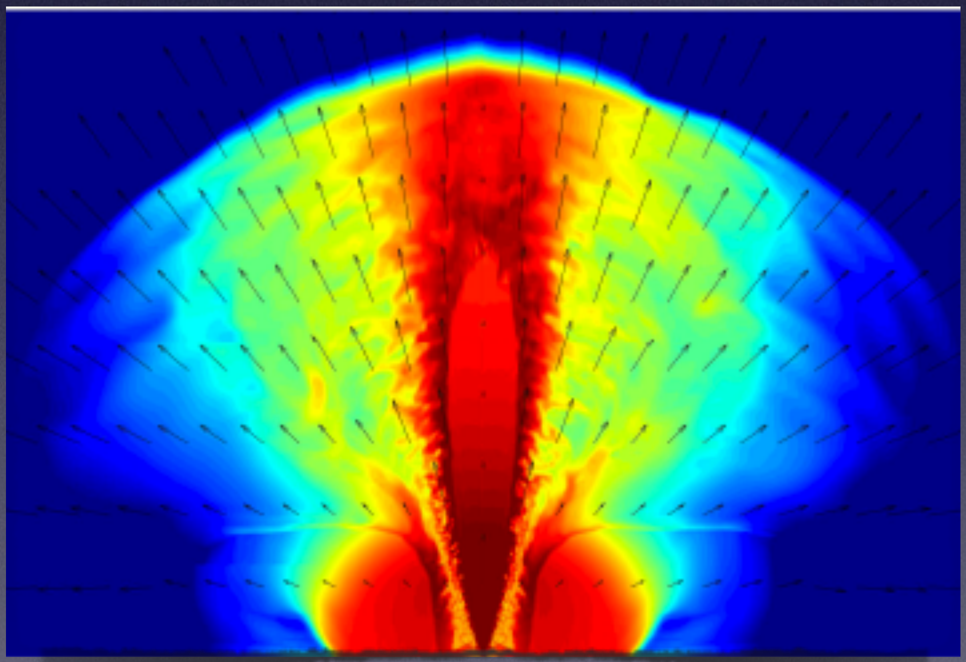
ELECTROMAGNETIC COUNTERPARTS OF NS^2 MERGERS: SGRBs, Macronova, Cocoon Emission and Radio Flares

Tsvi Piran

The Hebrew University of Jerusalem

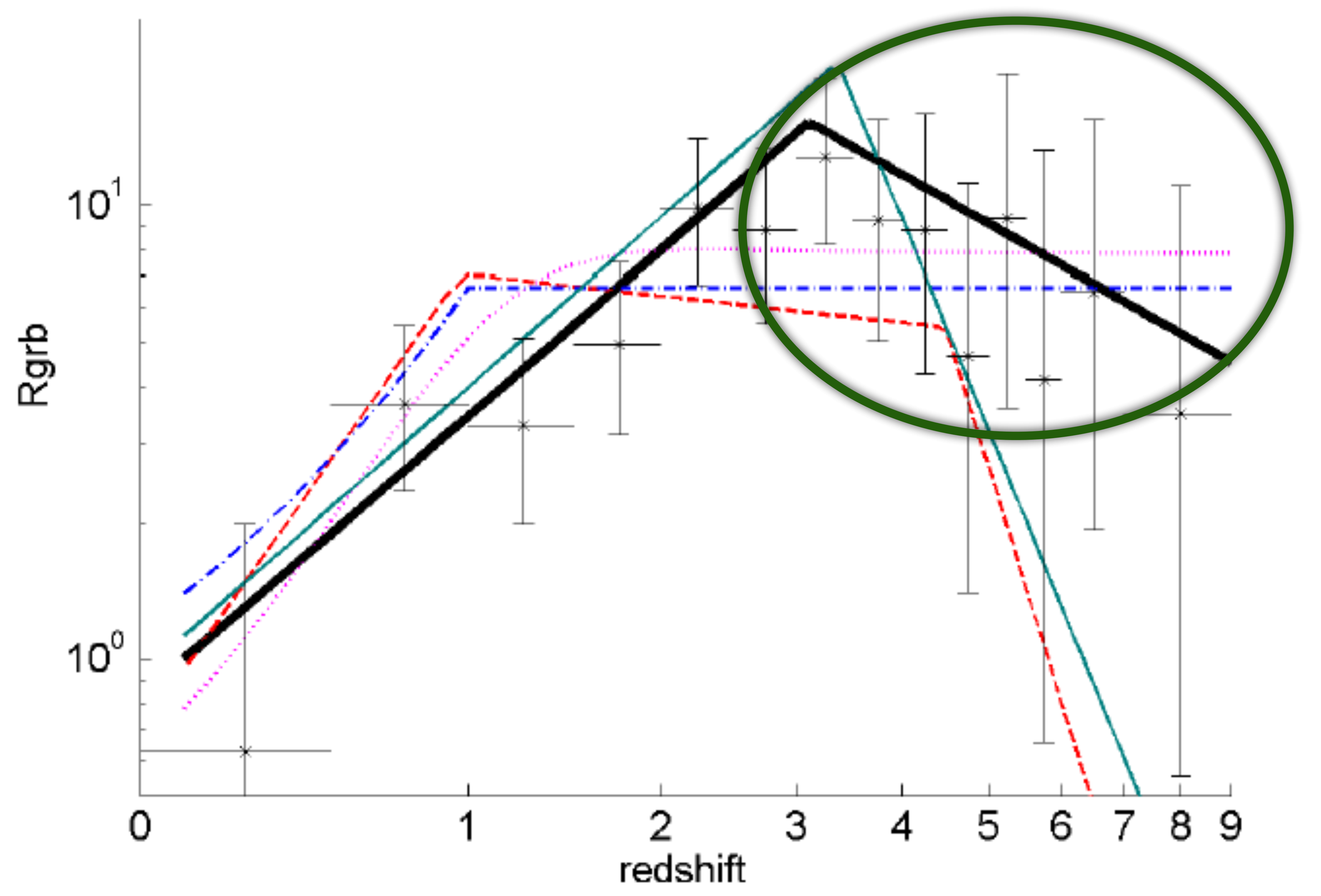


Kenta Hotokezaka, Ben Margalit, Odelia Teboul, Doron Grossman, Paz Beniamini, David Wanderman, Reetanjali Moharana, Ore Gottlieb, Ehud Nakar

Outline

- A side remarks on BBH mergers and Long GRBs
- Why EM counterparts?
- Rates
- GRBs - excellent but beamed
- Mass ejection in NS mergers
- Evidence for mass surrounding short (non-Collapsar) GRBs.
- Consistency with r-process Nucleosynthesis.
- Short GRB cocoons and their signature - the brightest quasisotropic EM counterpart.
- Jets in SNe - the observational signature.

Long GRBs



Wanderman & TP 2011

Long GRBs vs BBH merges

Hotokezaka & TP 2017

- LGRB observed rate ~ 1 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- With beaming ~ 50 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Comparable to BBH merger rate!

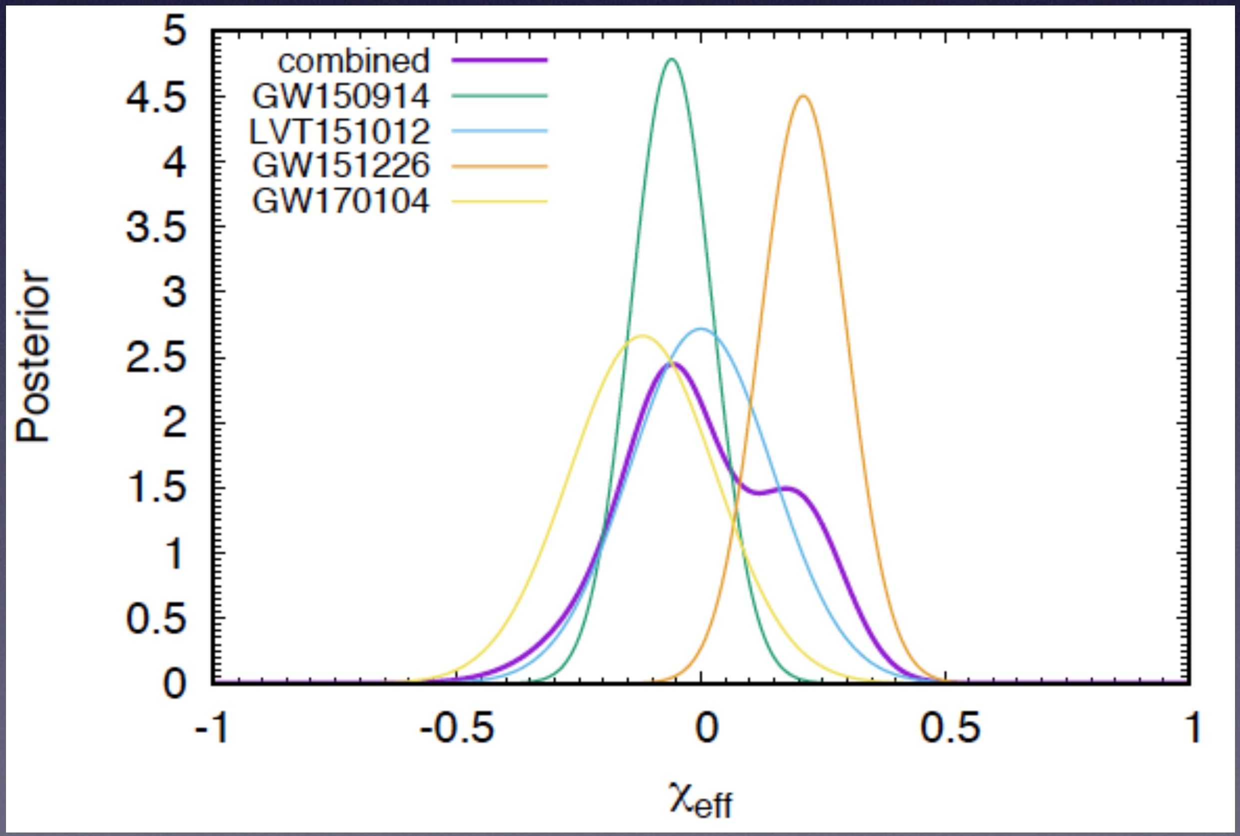
- LGRBs arise from the death of massive stars

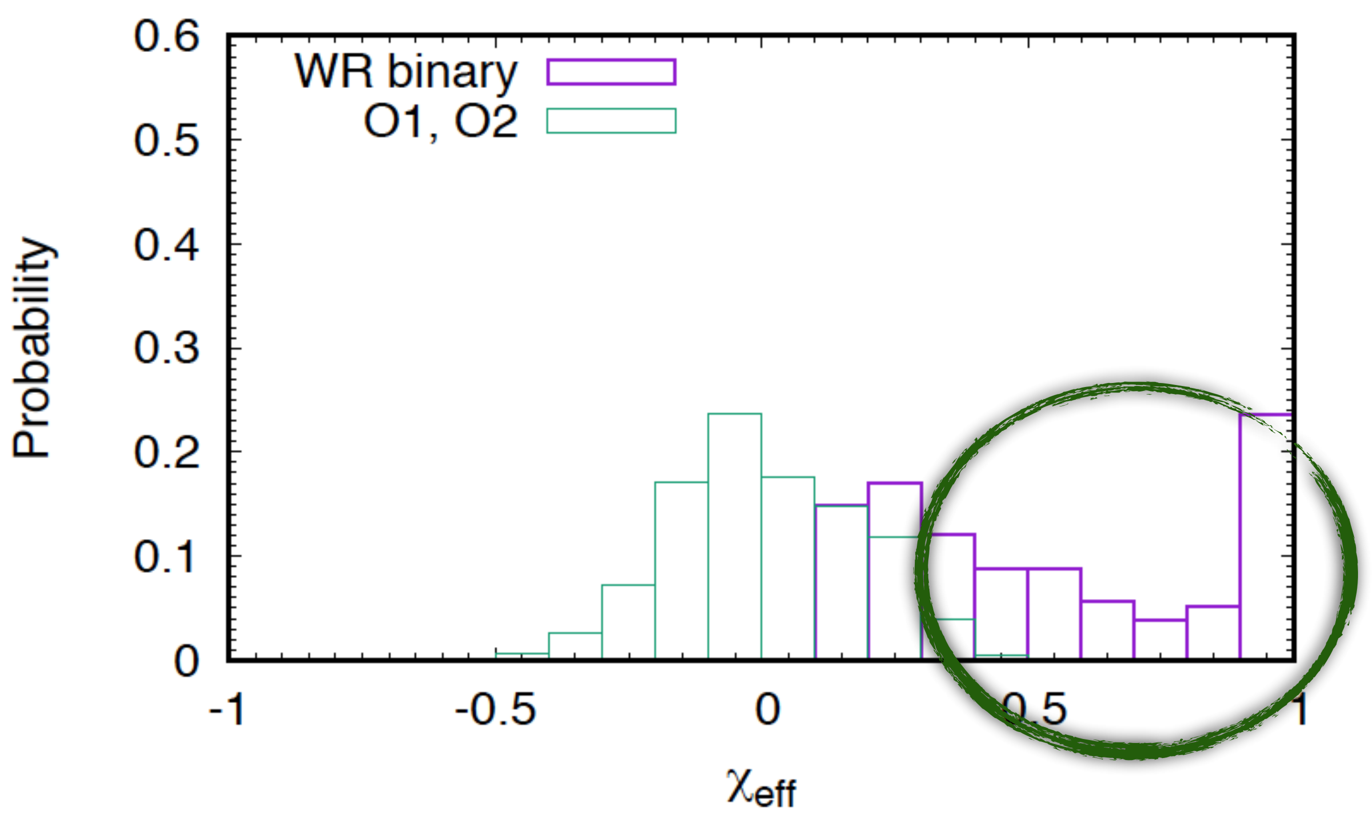
- LGRBs arise in low metallicity Galaxies
- Massive BBH require low metallicity

==> LGRBs signal the formation of the BHs of the BBH

(the merger takes place, of course Gyrs later)

The expected χ_{eff} (Hotokezaka & TP 17a,b)



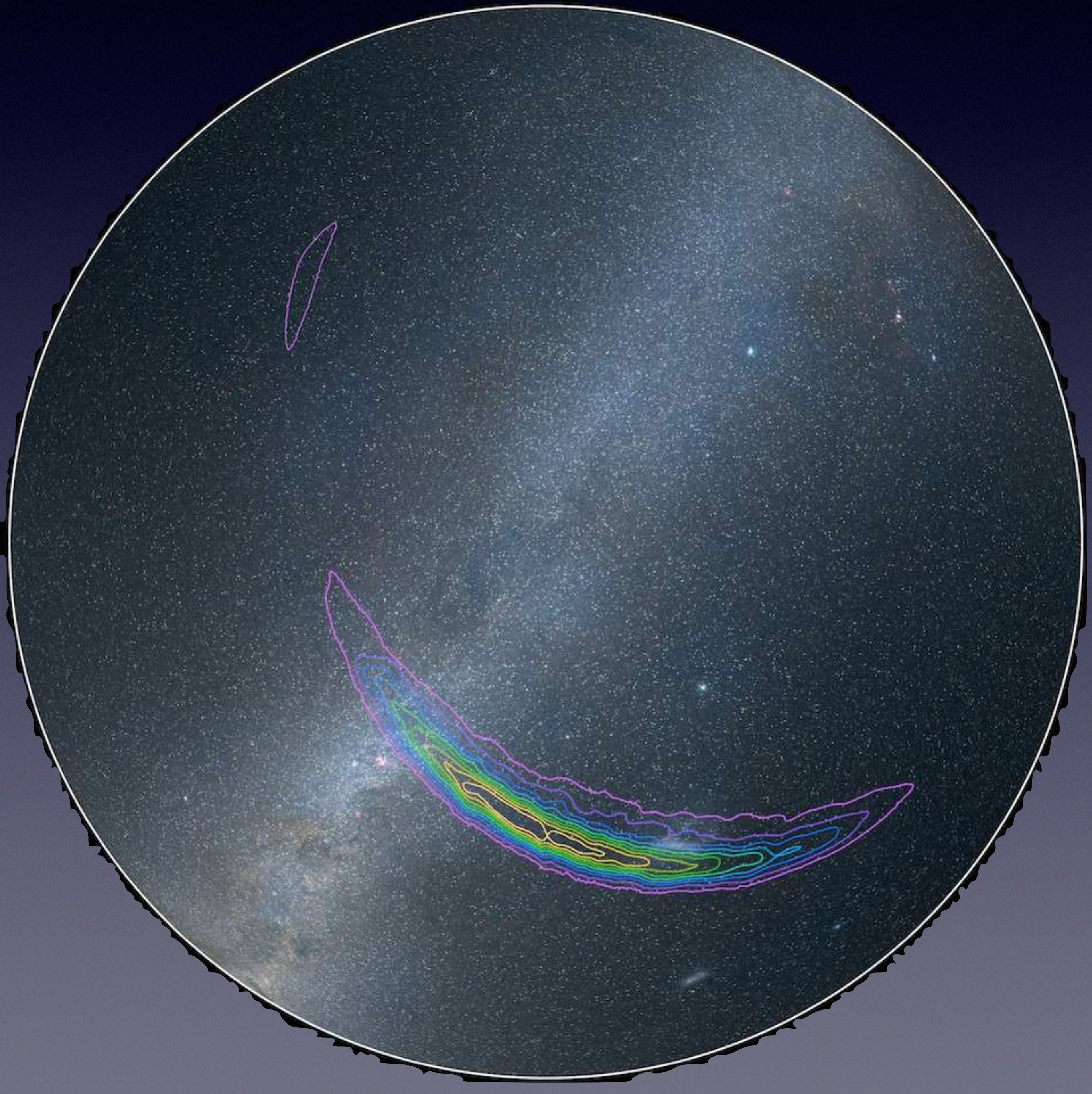


From a WR population that follows the LGRB rate

Why EM Counterparts?

(Kochanek & TP 1993)

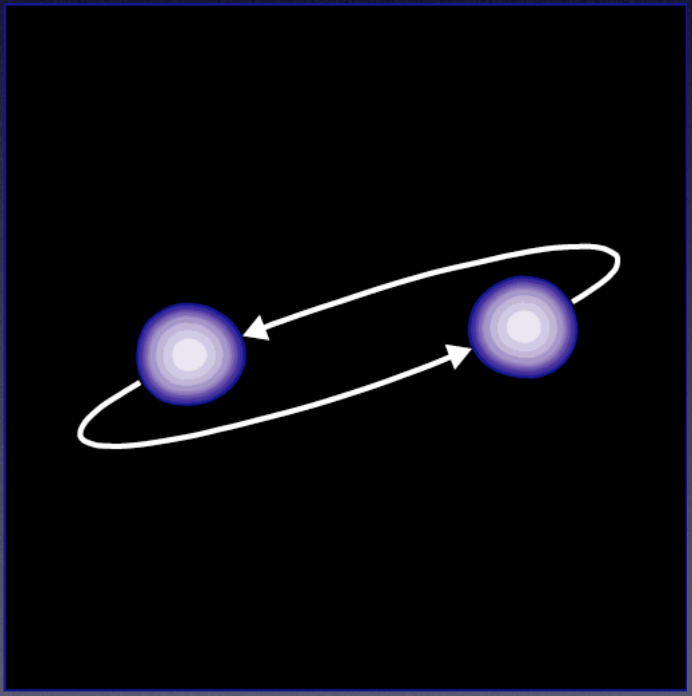
Where?
What?
How?



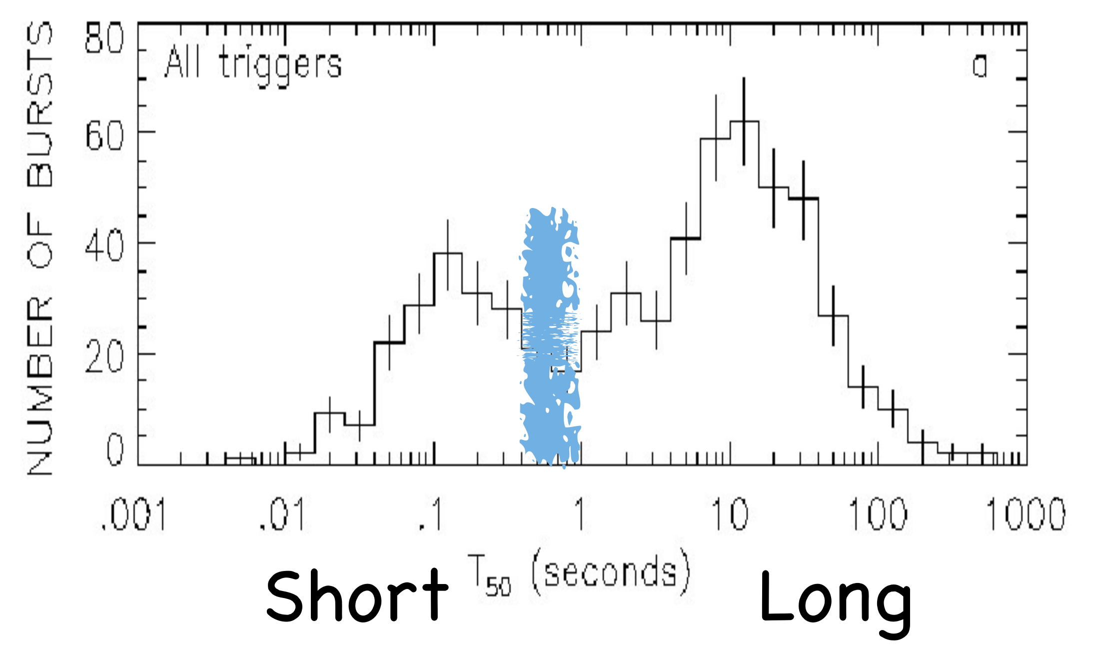
Short vs. Long and Mergers vs. Collapsars

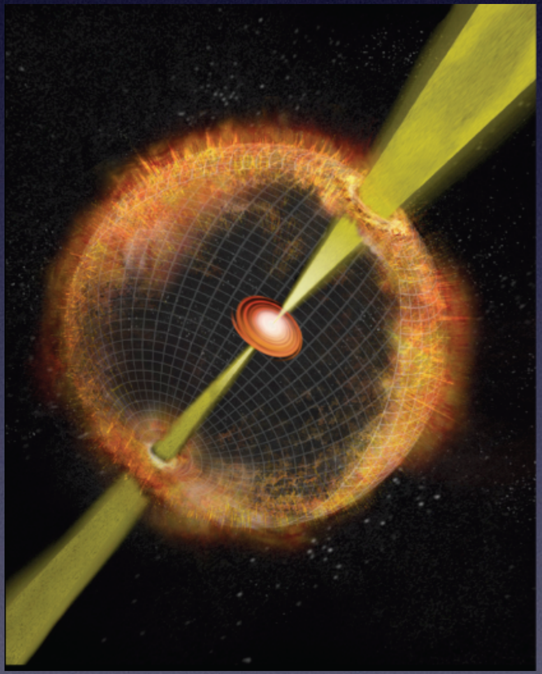
Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley 98



NS mergers





Collapsars

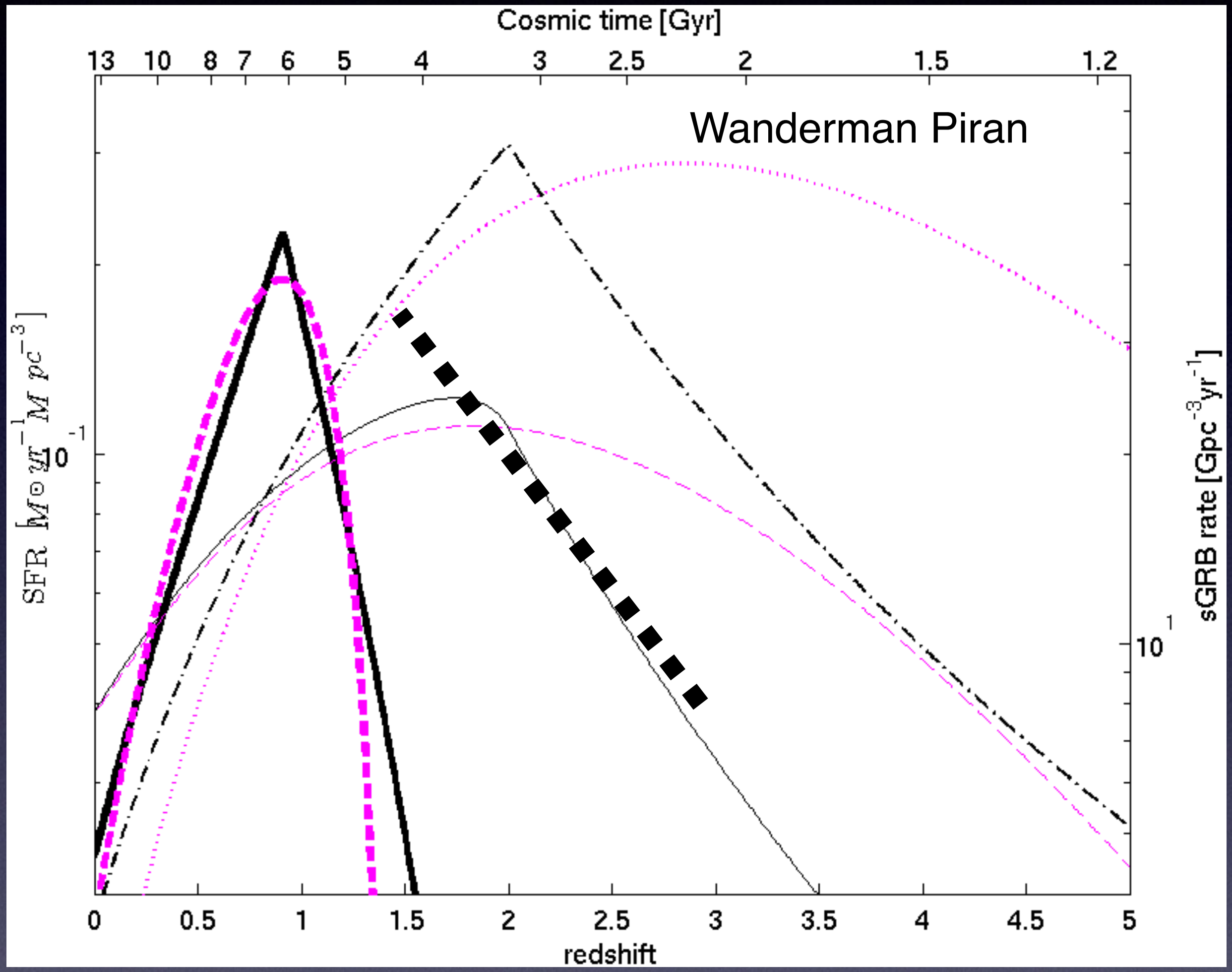
Indirect Evidence

Direct Evidence

The Rate of short GRBs

(Wanderman & TP 2015)

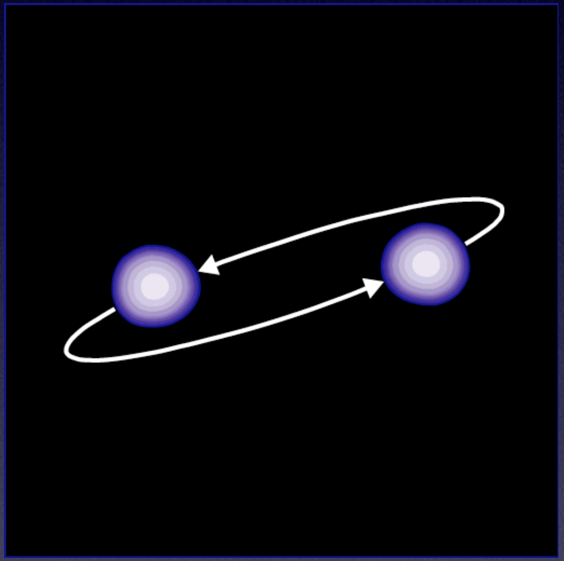
- Current observed rate $\sim 5 \text{ Gpc}^{-3} \text{ yr}^{-1} \sim 0.5 \text{ Myr}^{-1}$
- Higher z rate is larger
- Uncertainties
  - Short delay mergers (need high redshift sGRBs) can be ~20 Myr!!!
  - Lowest energy (rate can be higher)
  - Beaming factor x10-70 (Very uncertain)

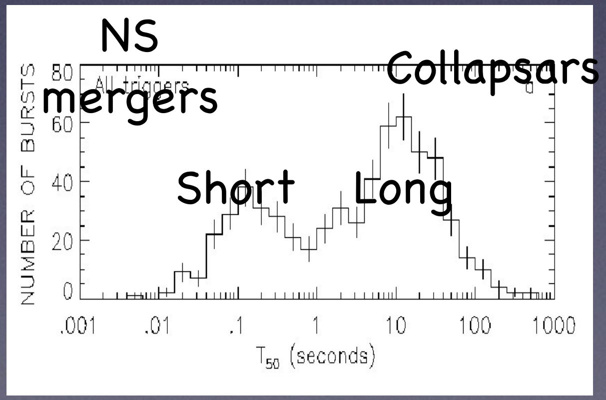


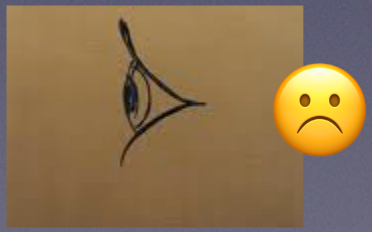
- Galactic rate from binary pulsars 21_{-14}^{+28} My^{-1} (Kim + 15)
- Most pop synthesis estimate ignore low kick channel

Short GRBs as EM counterparts

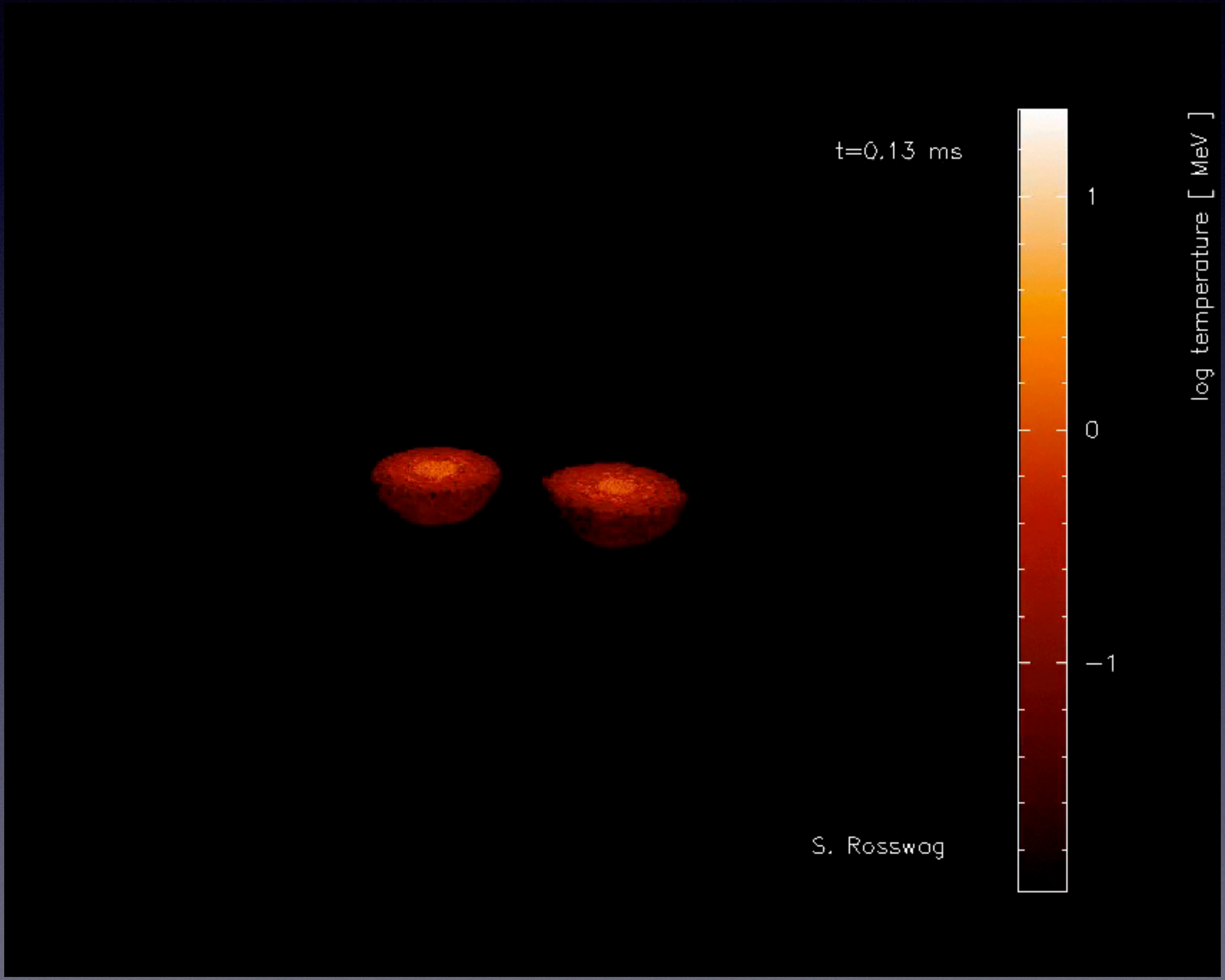
- GRBs are beamed and the probability for a joint observations is rather small (about 1 in 20)
- Joint GW + GRB detection - once in ~10 years







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



Stephan Rosswog

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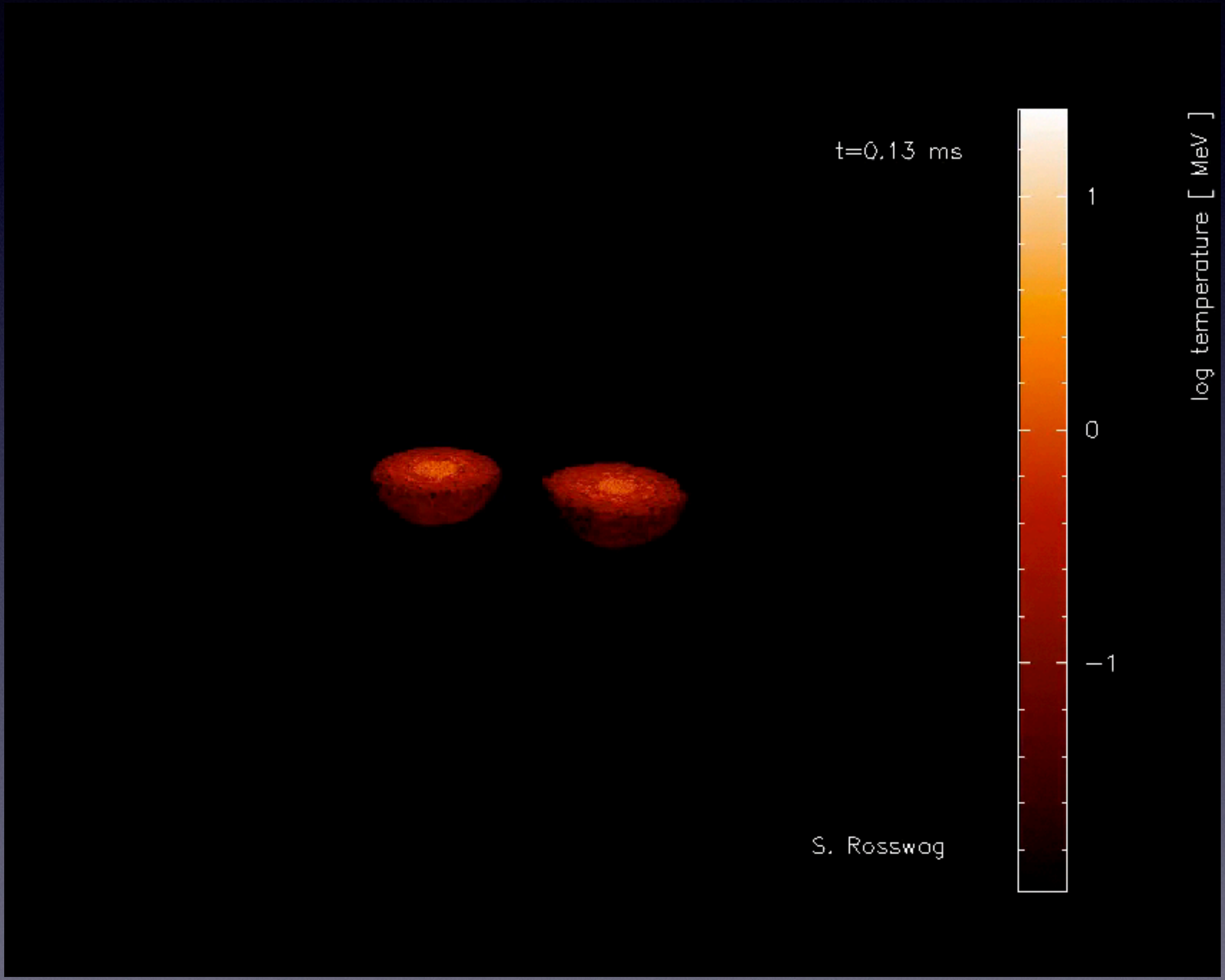
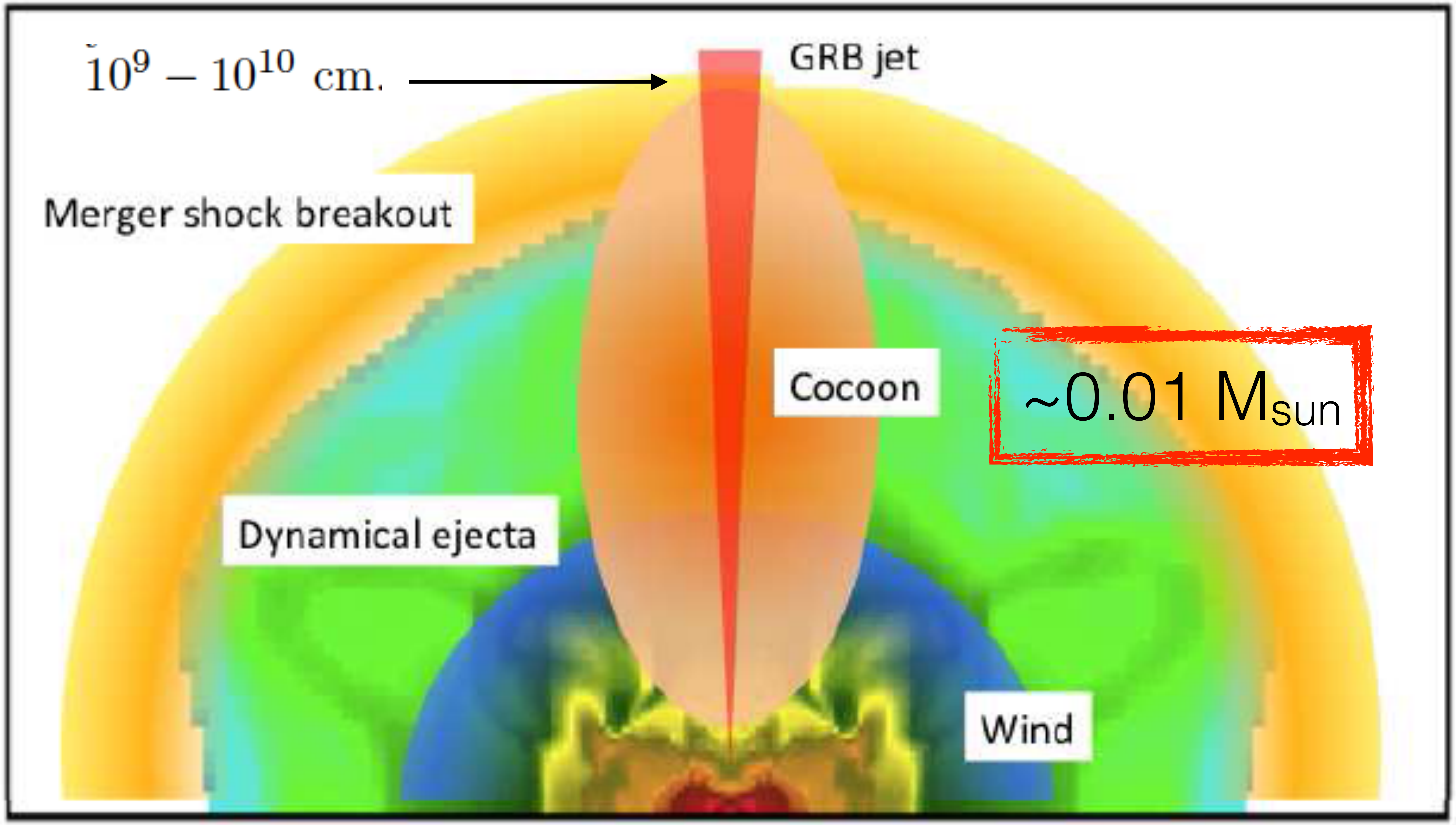


Stephan Rosswog

Different ejecta components



~0.01 M_{sun}

From Hotokezaka & TP 2015

Macronova* (Li & Paczynski 1997)

- 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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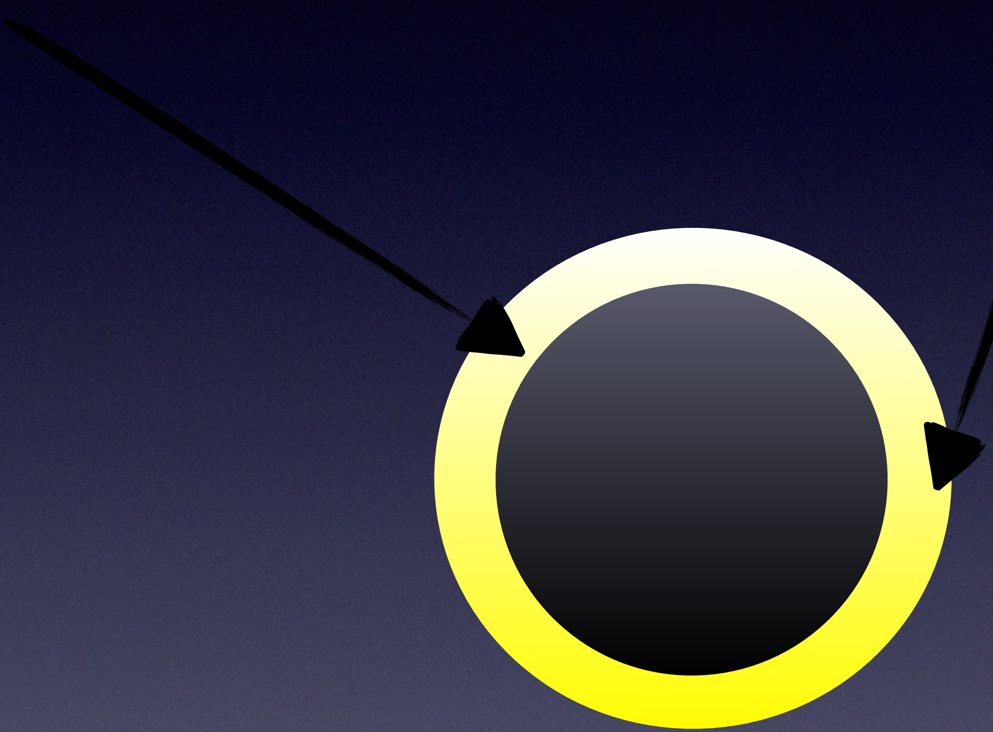
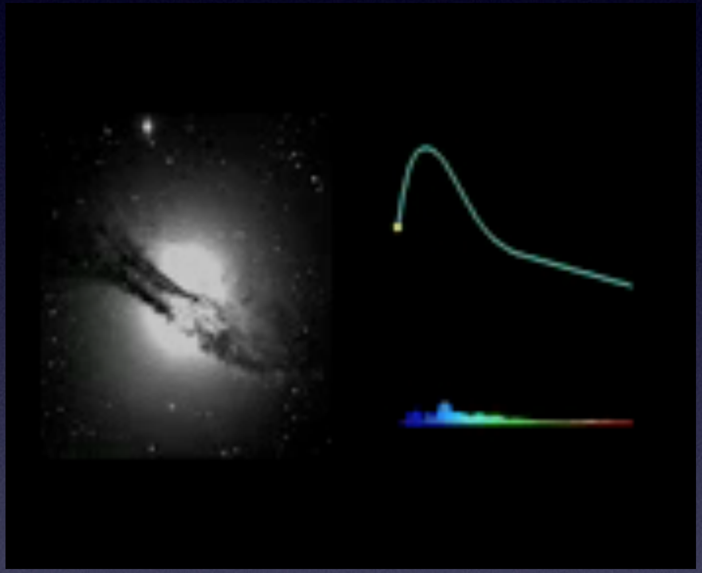
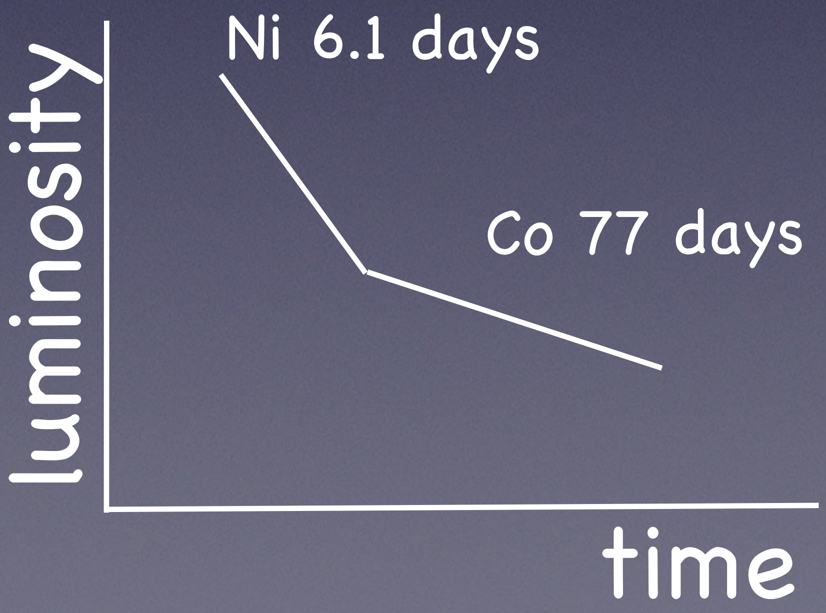
Supernova



Photosphere

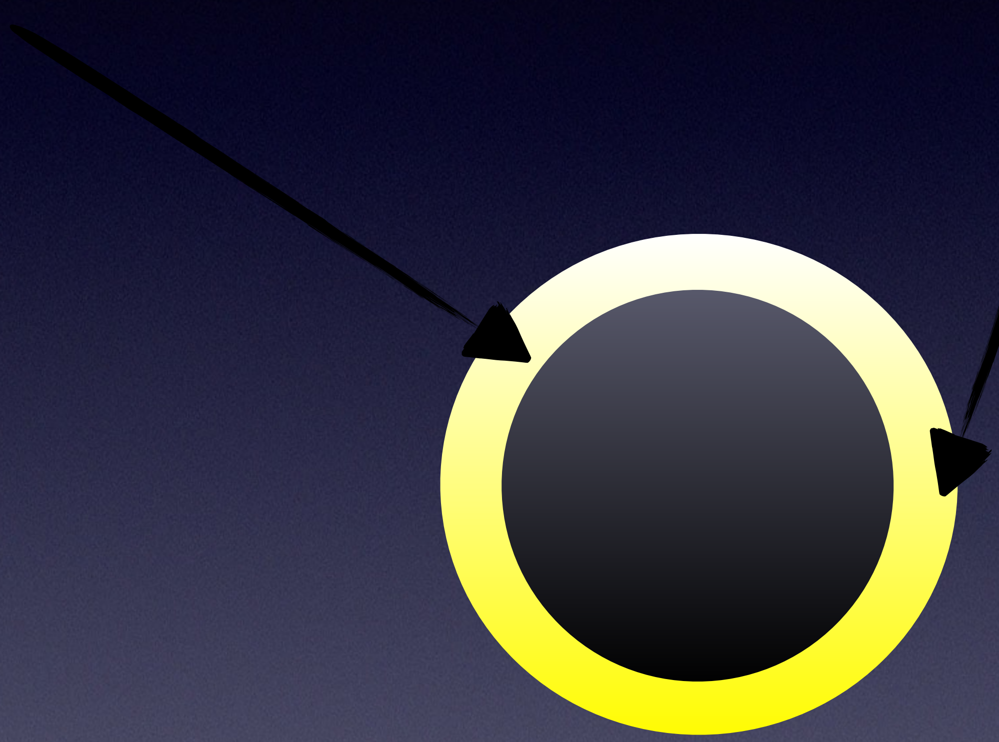
Photons escape





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

Supernova



Photosphere

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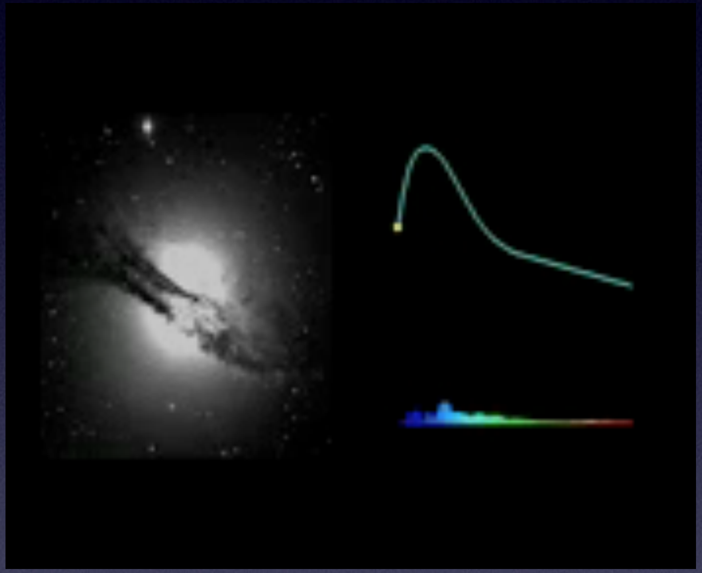
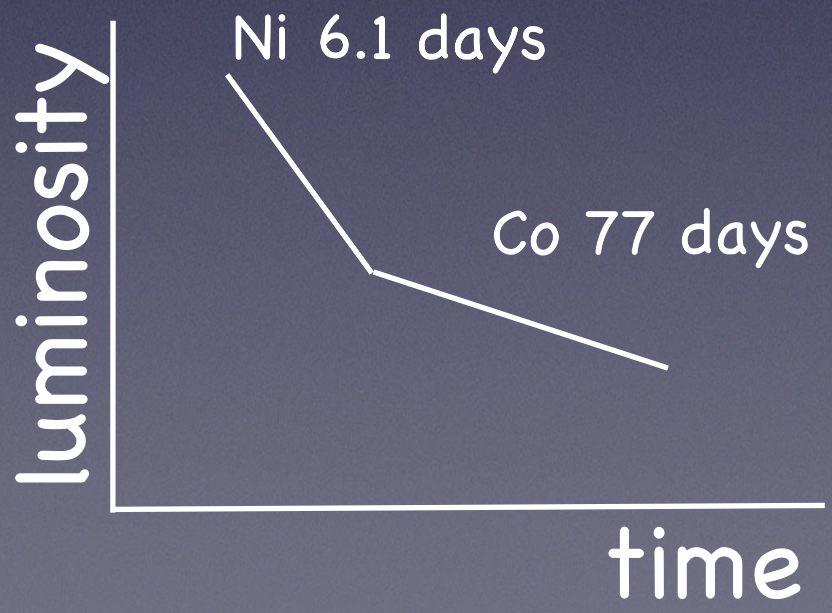
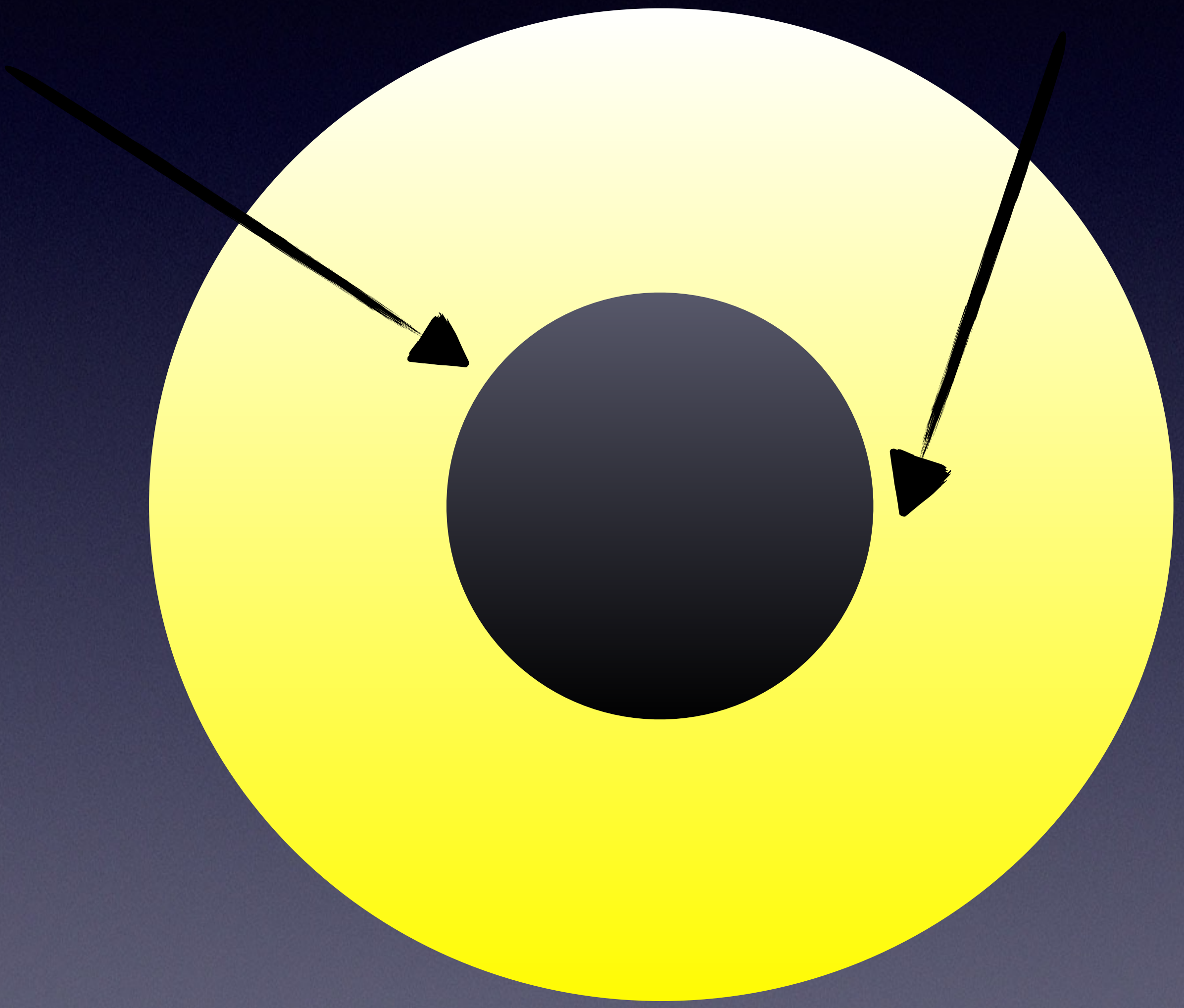


Powered by radioactive decay of $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$



Supernova



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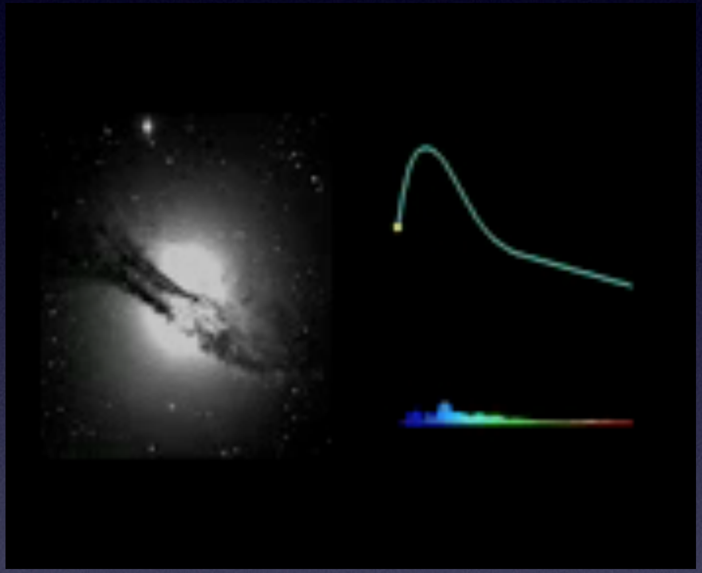
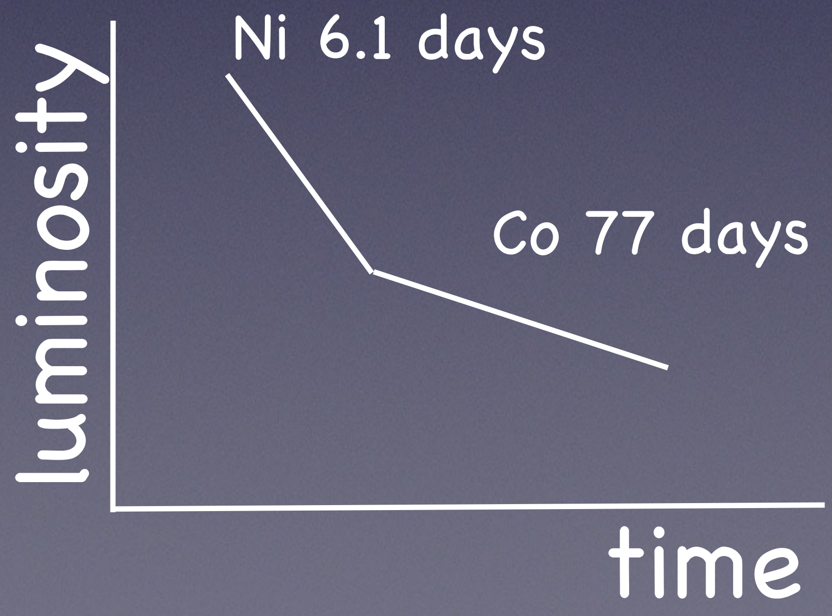
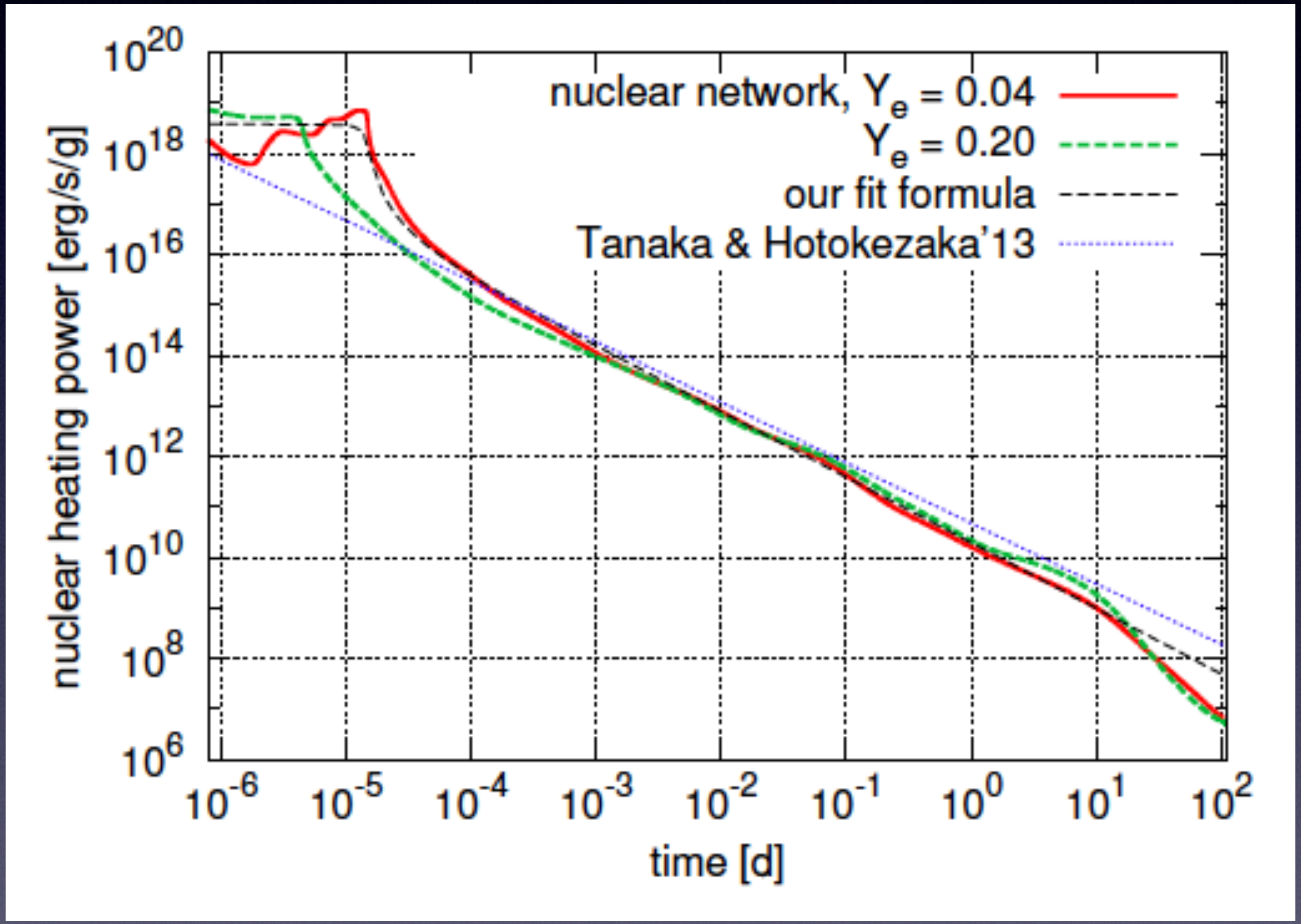




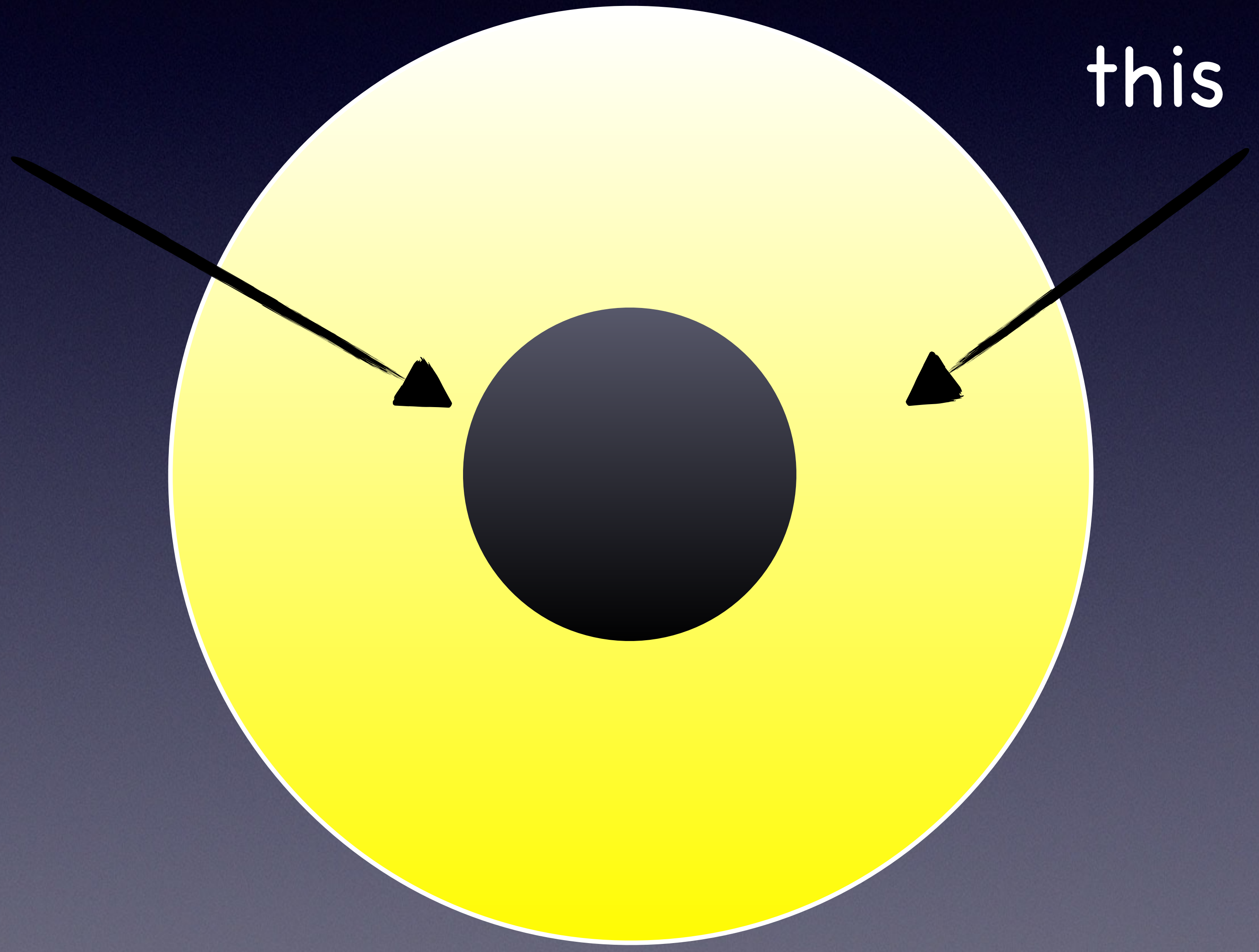
Radioactive Decay

Korobkin + 13; Rosswog, Korobkin + 13



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

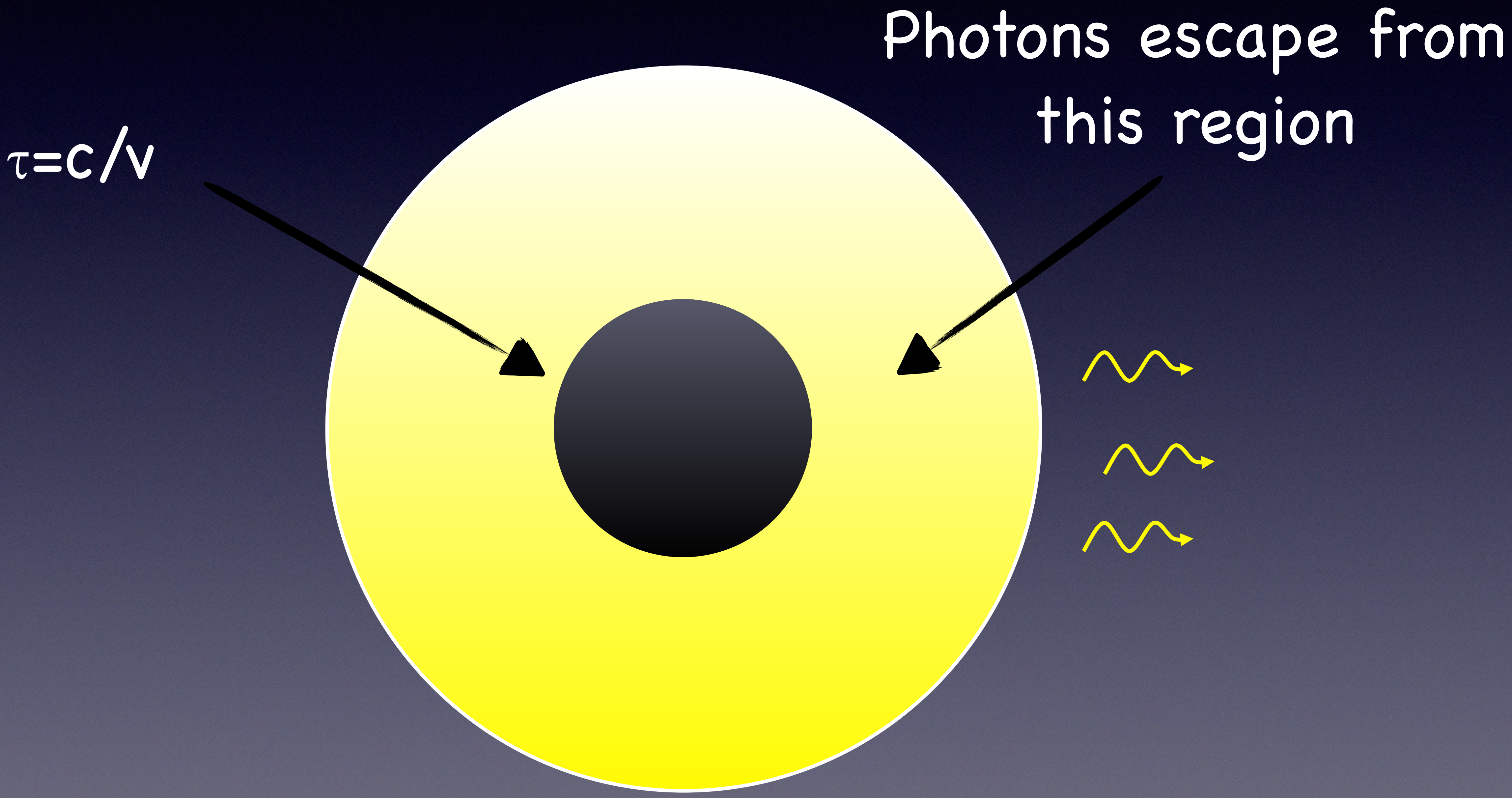
Macronova emission



τ=c/v

Photons escape from this region

Macronova emission



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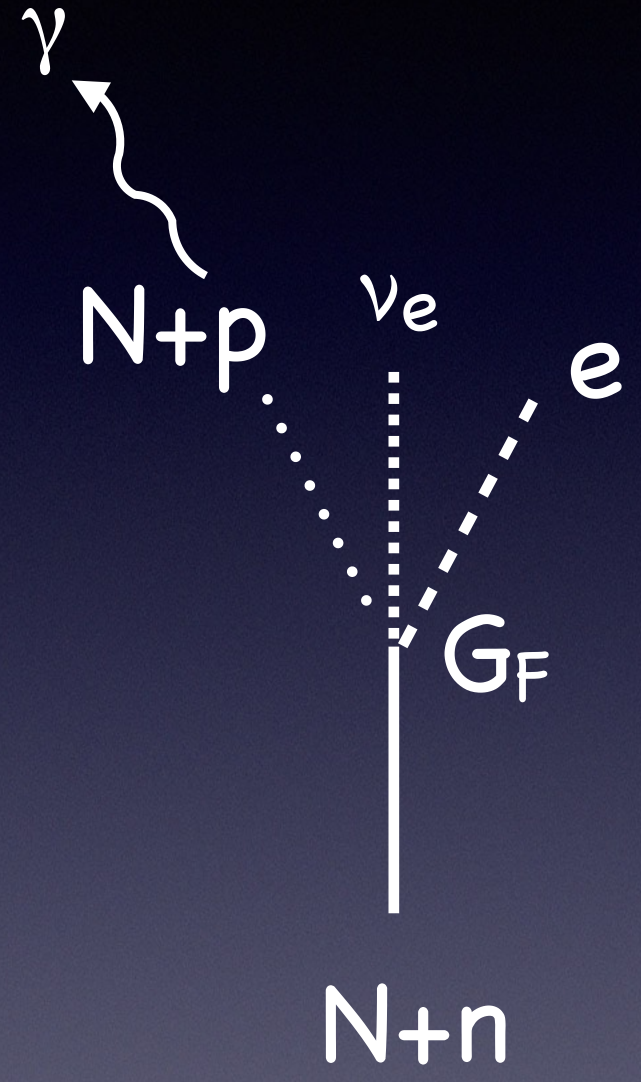
Energy Generation

Hotokezaka, Sari & TP + 16



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

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

$$\frac{1}{\tau} \propto \frac{d}{dE}\underset{\substack{\nearrow \\ E^3 \text{ or } E^{3/2}}}{\int d^3 p_e}\underset{\substack{\nwarrow \\ E^3}}{\int d^3 p_\nu}$$

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

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

Diffusion time

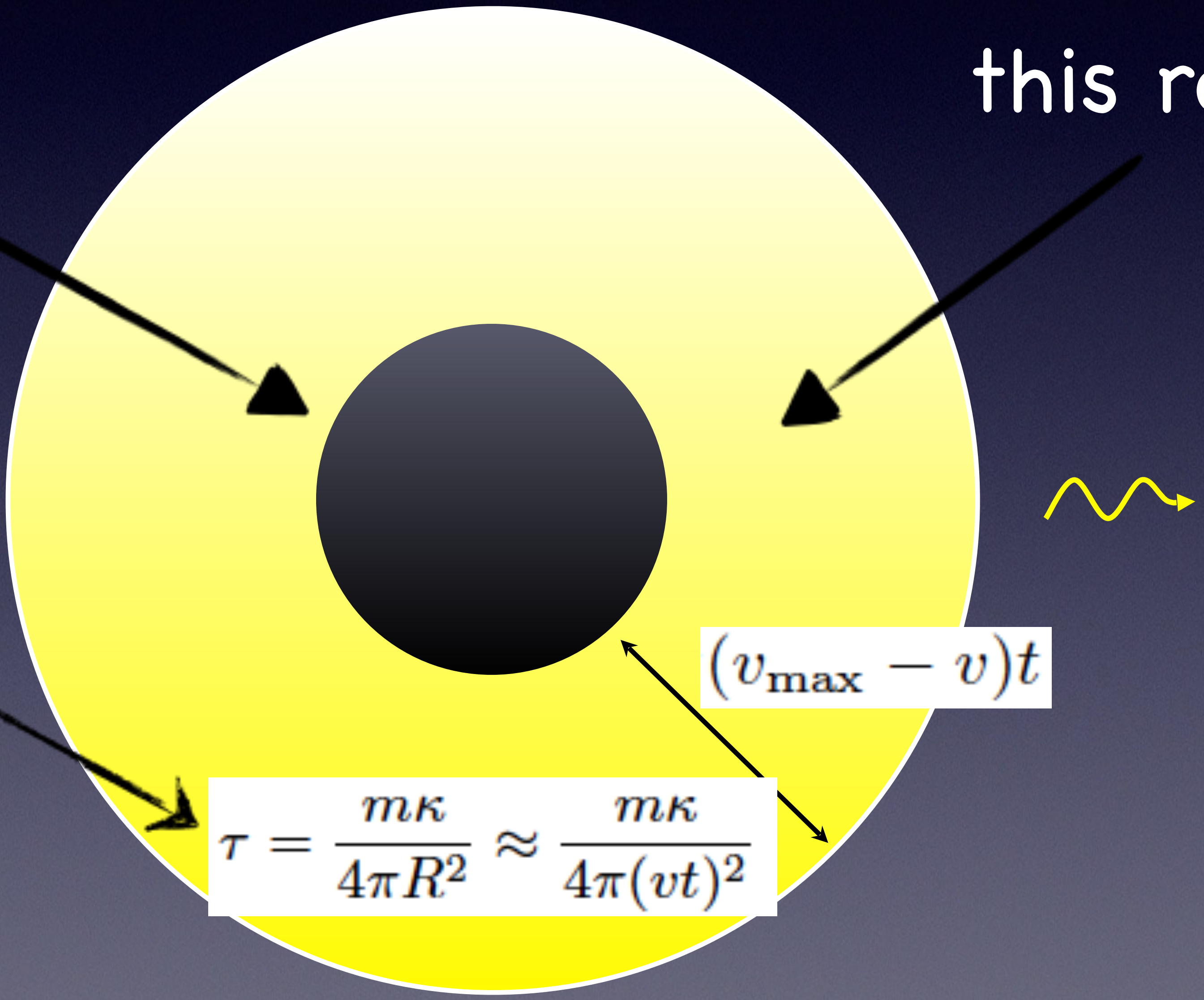
Opacity

$$t_{\rm diff} = \frac{\tau(v_{\rm max} - v)t}{c} = \frac{m\kappa}{4\pi cvt}$$

$$\tau = \frac{c}{v}$$

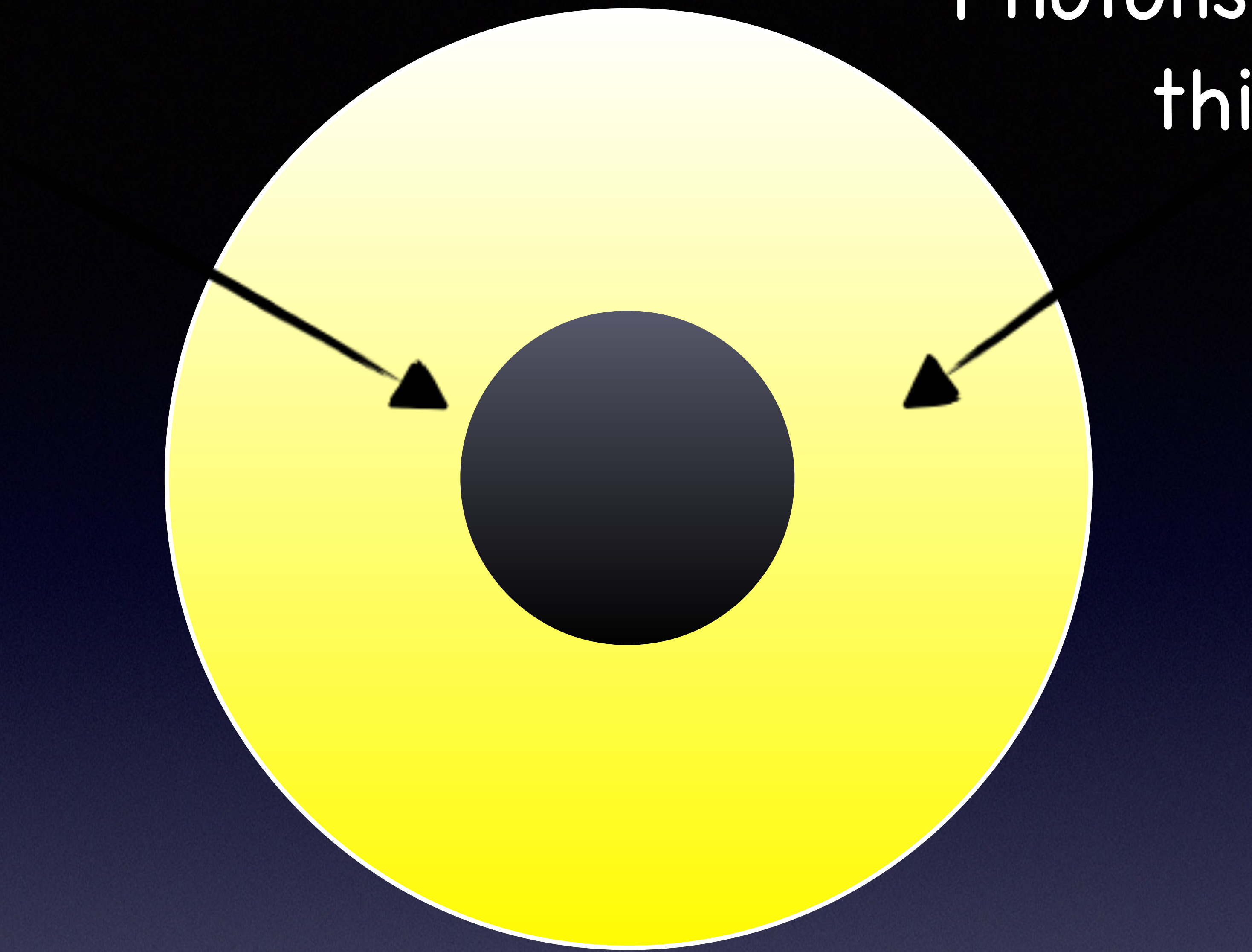
Photons escape from this region

Optical depth



$$(v_{\rm max} - v)t$$

$$\tau = \frac{m\kappa}{4\pi R^2} \approx \frac{m\kappa}{4\pi(vt)^2}$$



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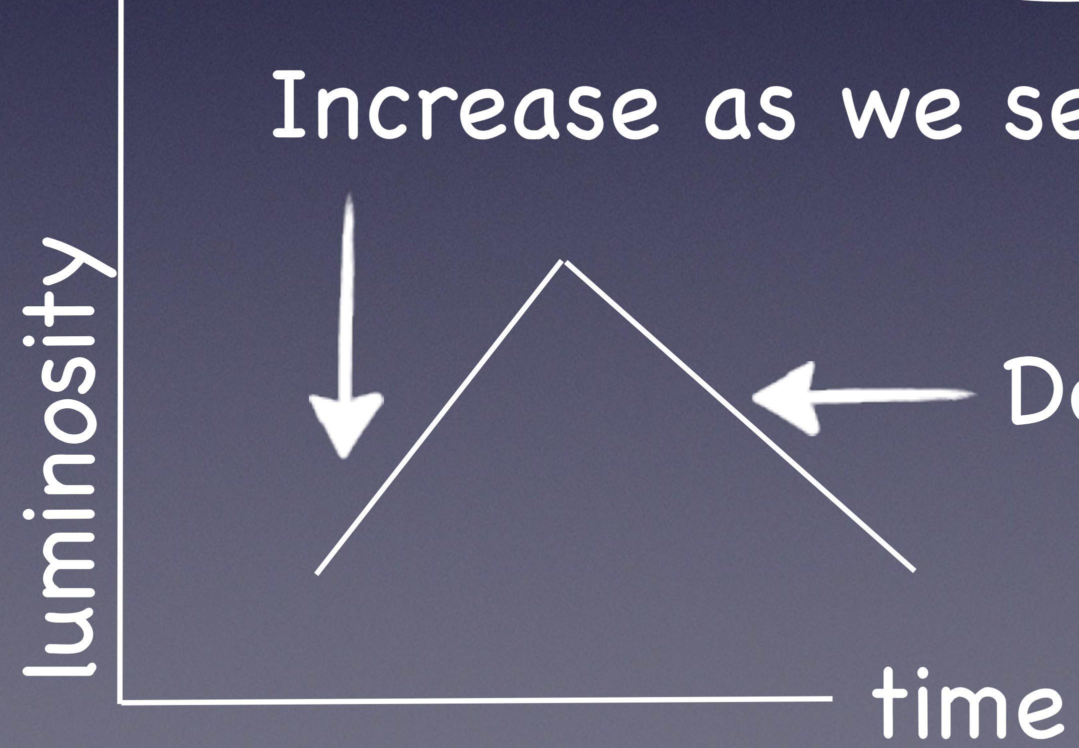
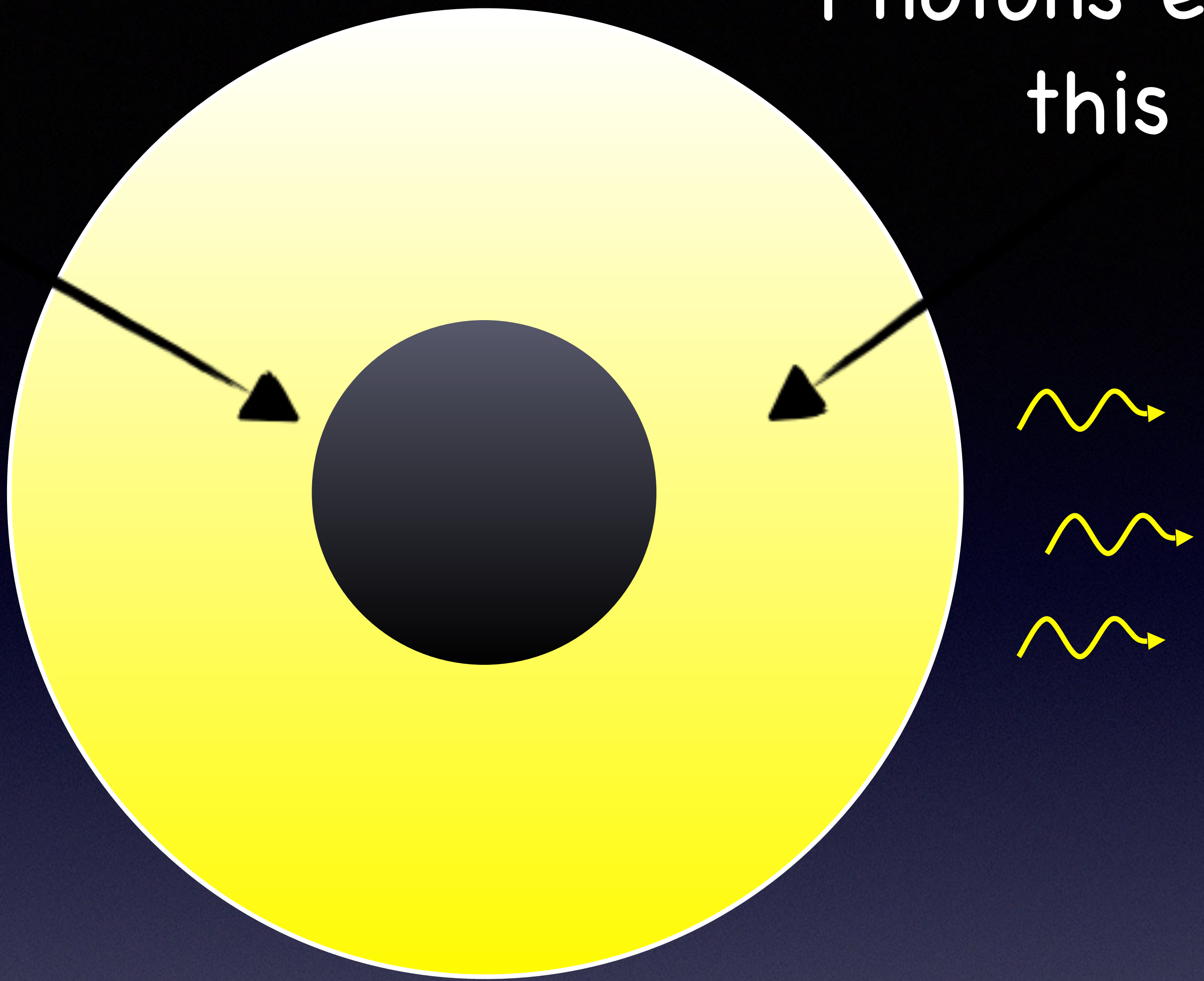


Increase as we see a large fraction of the matter.

Decrease due to radioactive decay

Macronova



τ=c/v

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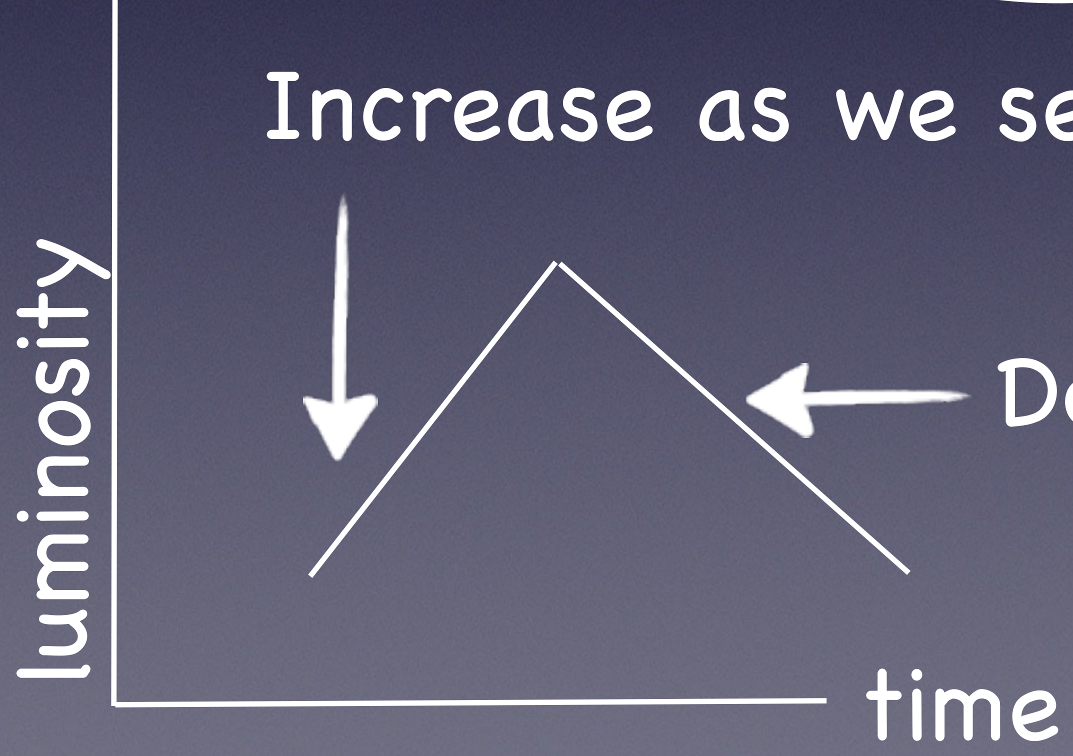

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Decrease due to radioactive decay

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

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

The peak luminosity

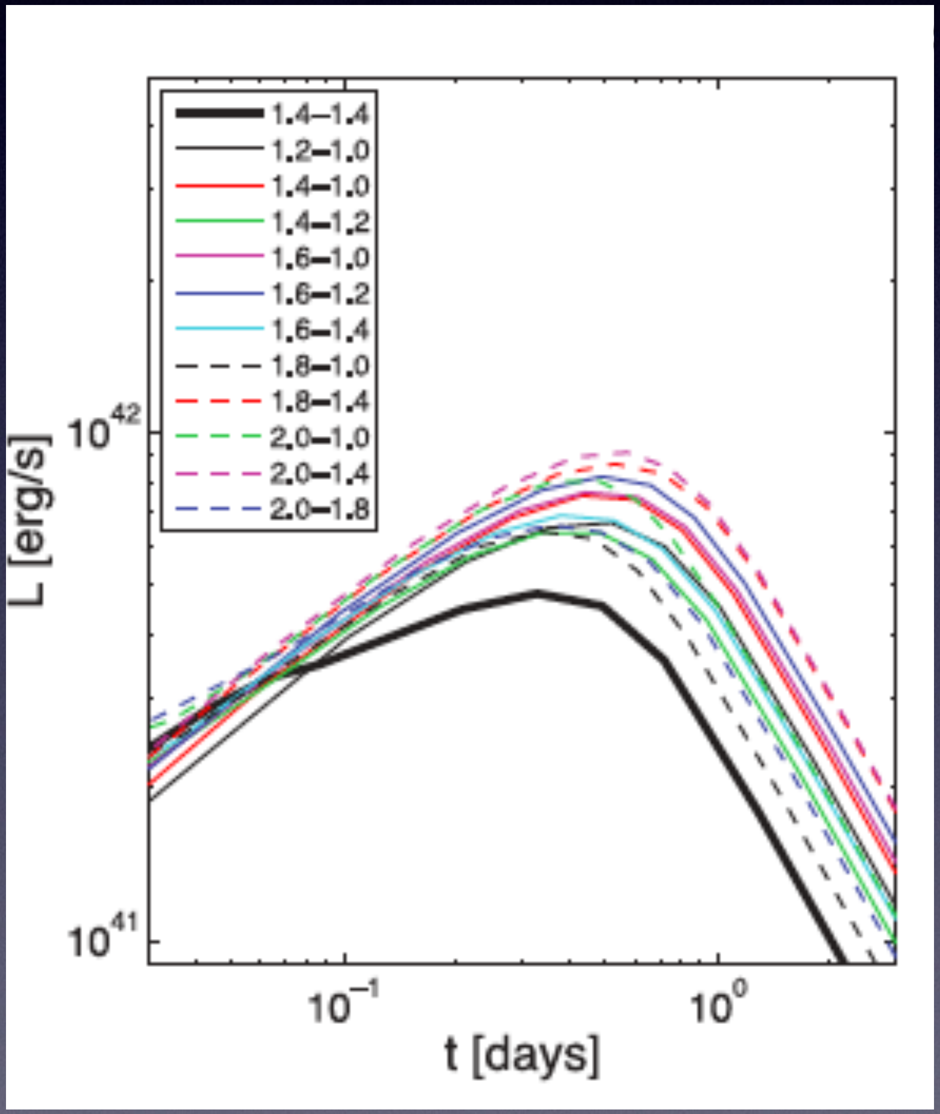
$$\tilde{L}_p \approx \dot{\epsilon}_0 m_{\mathrm{ej}} \left(\frac{\kappa m_{\mathrm{ej}}}{4\pi c \bar{v} t_0^2}\right)^{-\alpha/2} = 2.5 \times 10^{40} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{\bar{v}_{-1}}{\kappa_{10}}\right)^{\alpha/2} m_{\mathrm{ej},-2}^{1-\alpha/2}$$

Macronova

Lanthanides dominate the opacity

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

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



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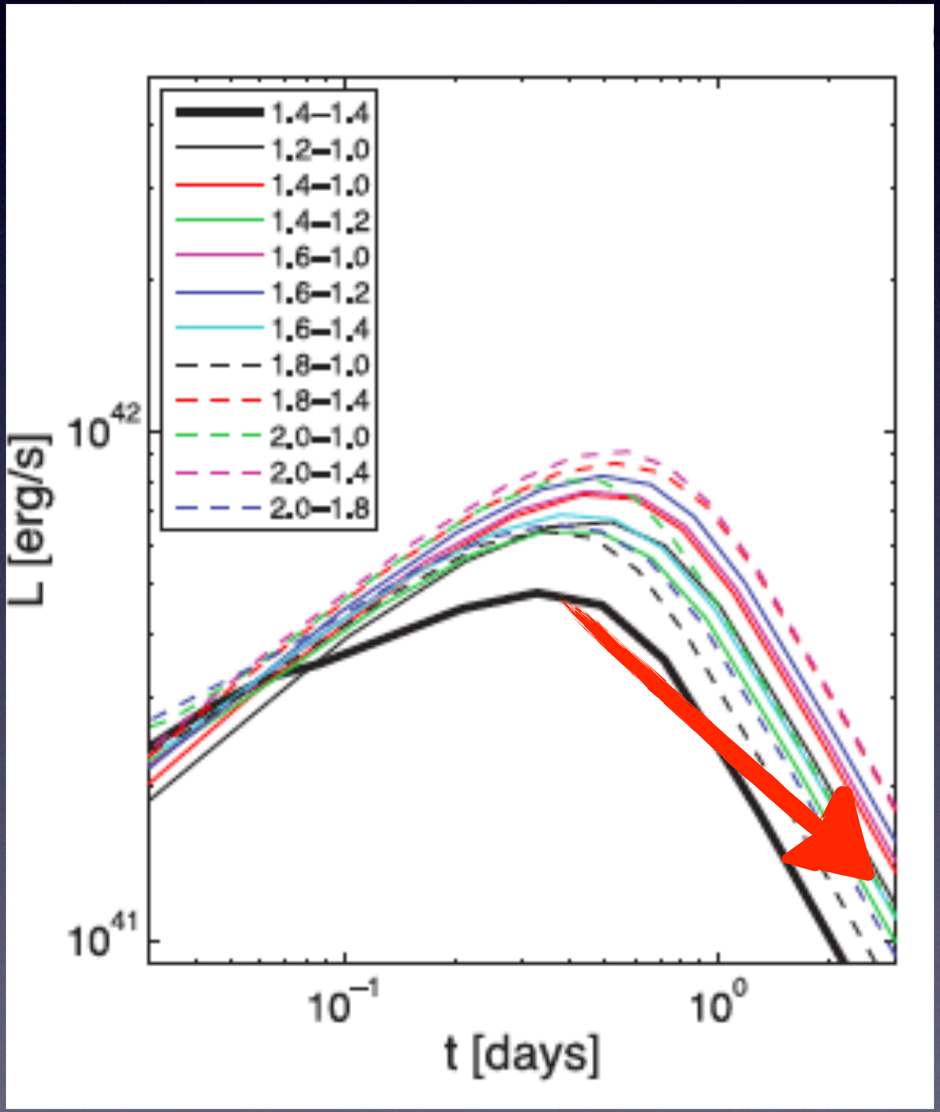

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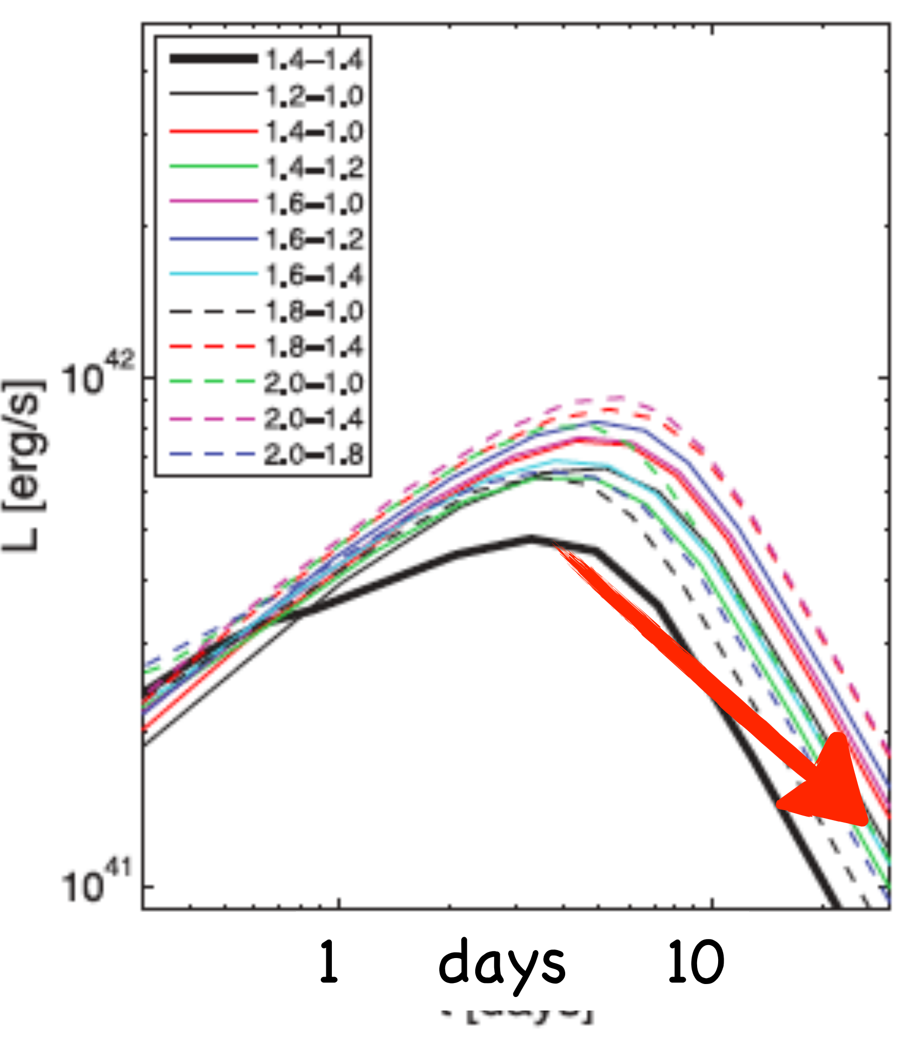

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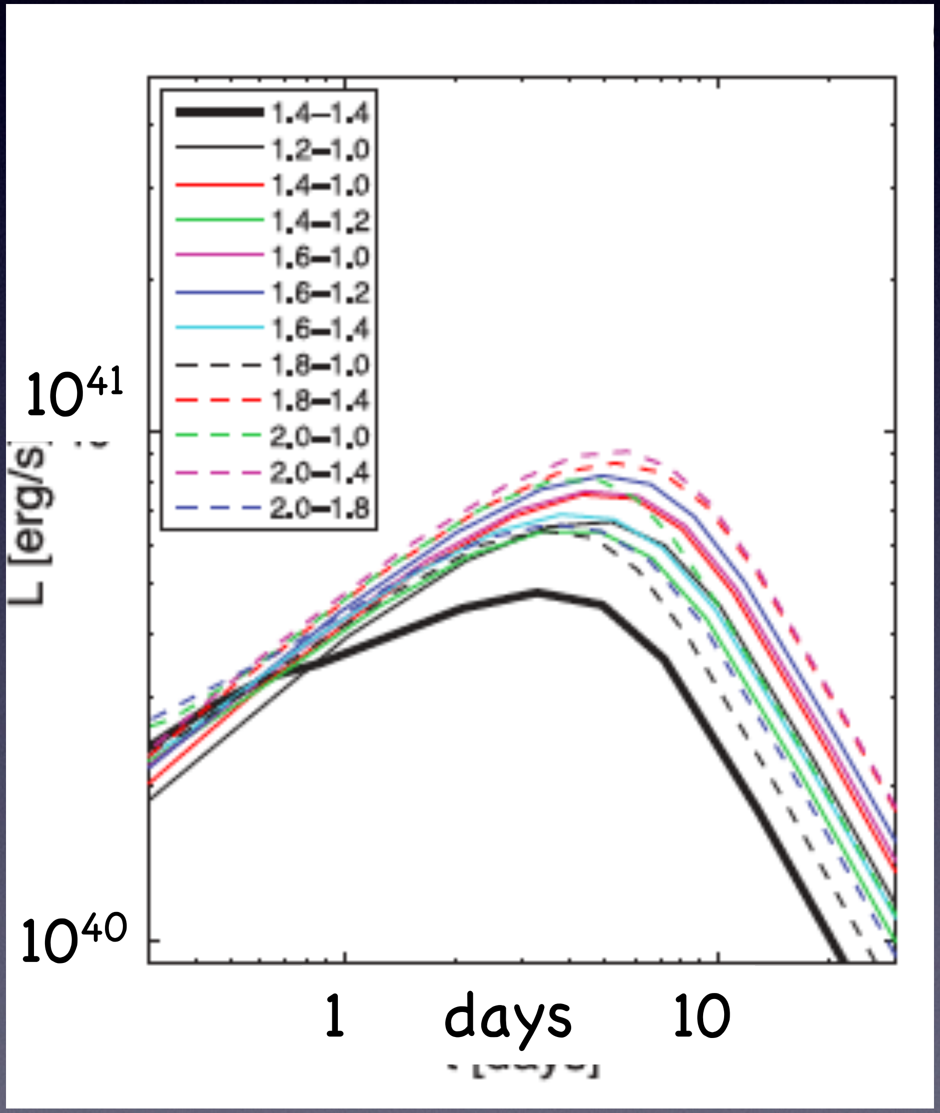

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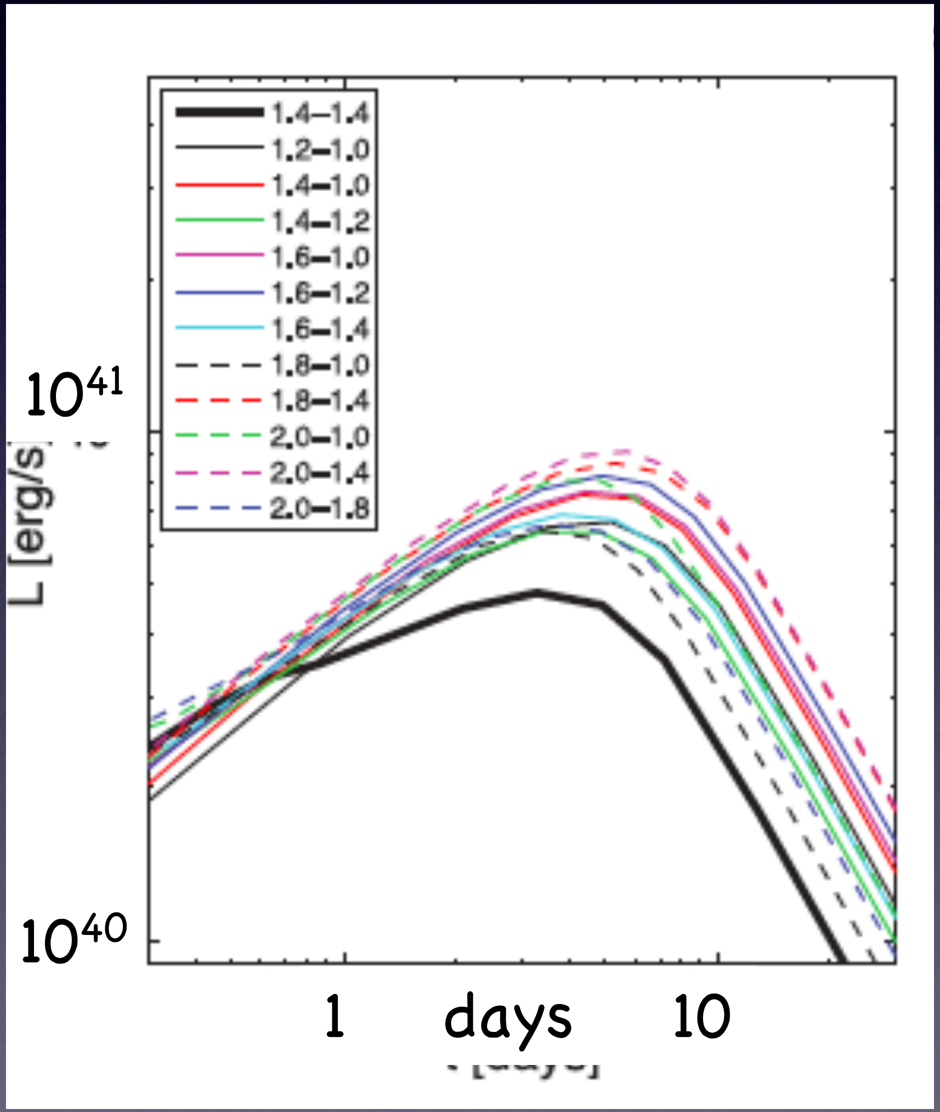
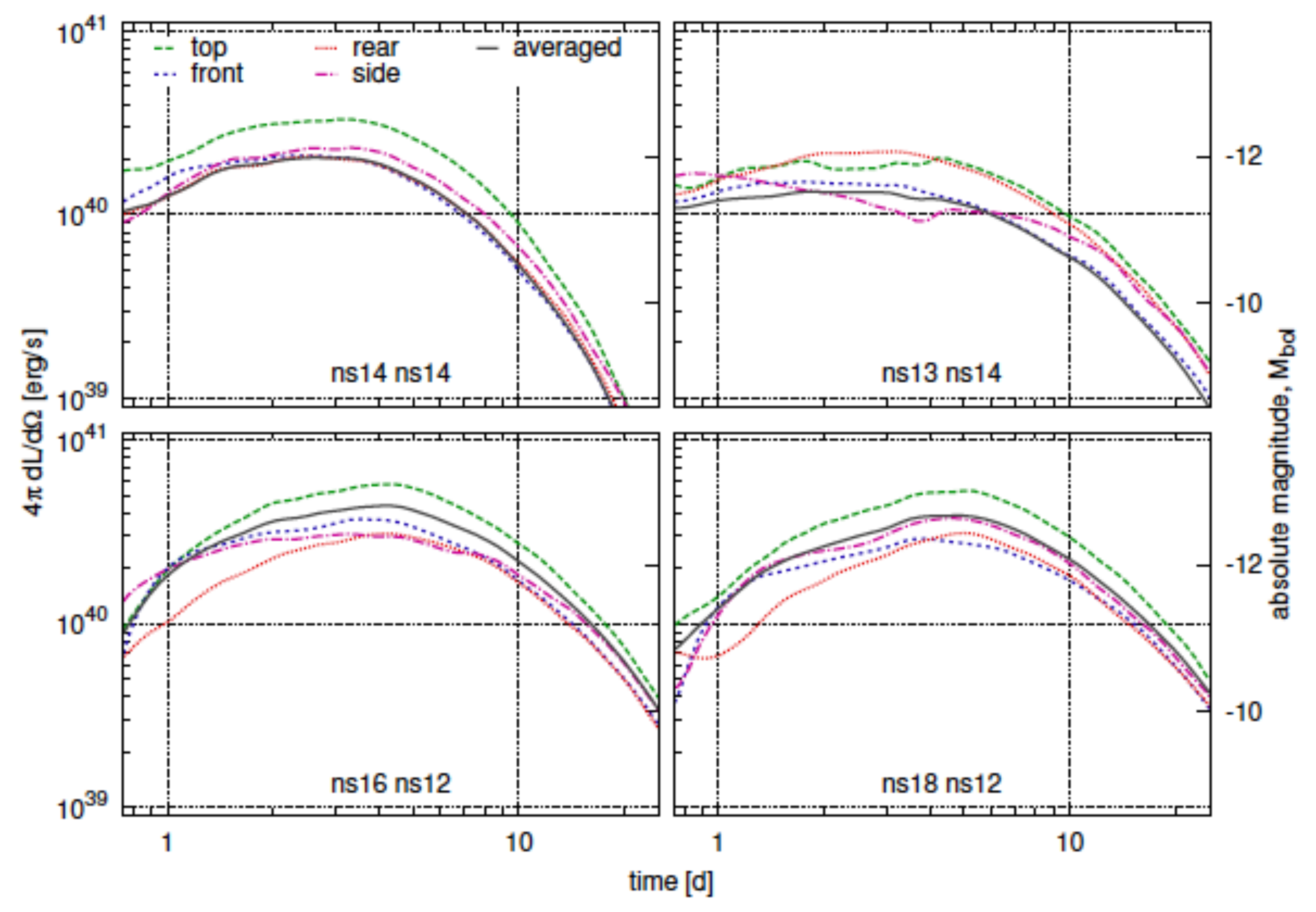


uv or optical -> IR

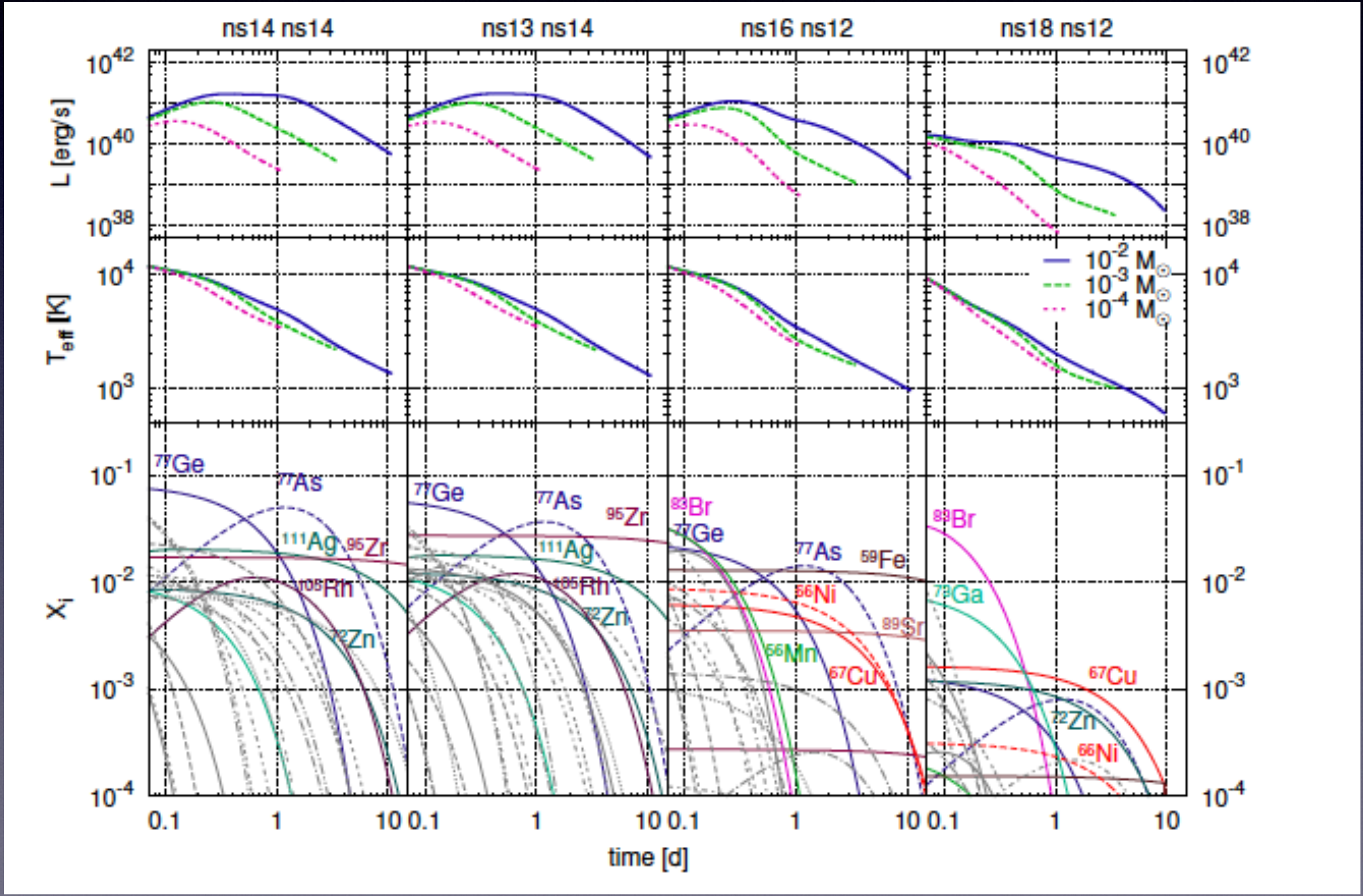
Bolometric light curves



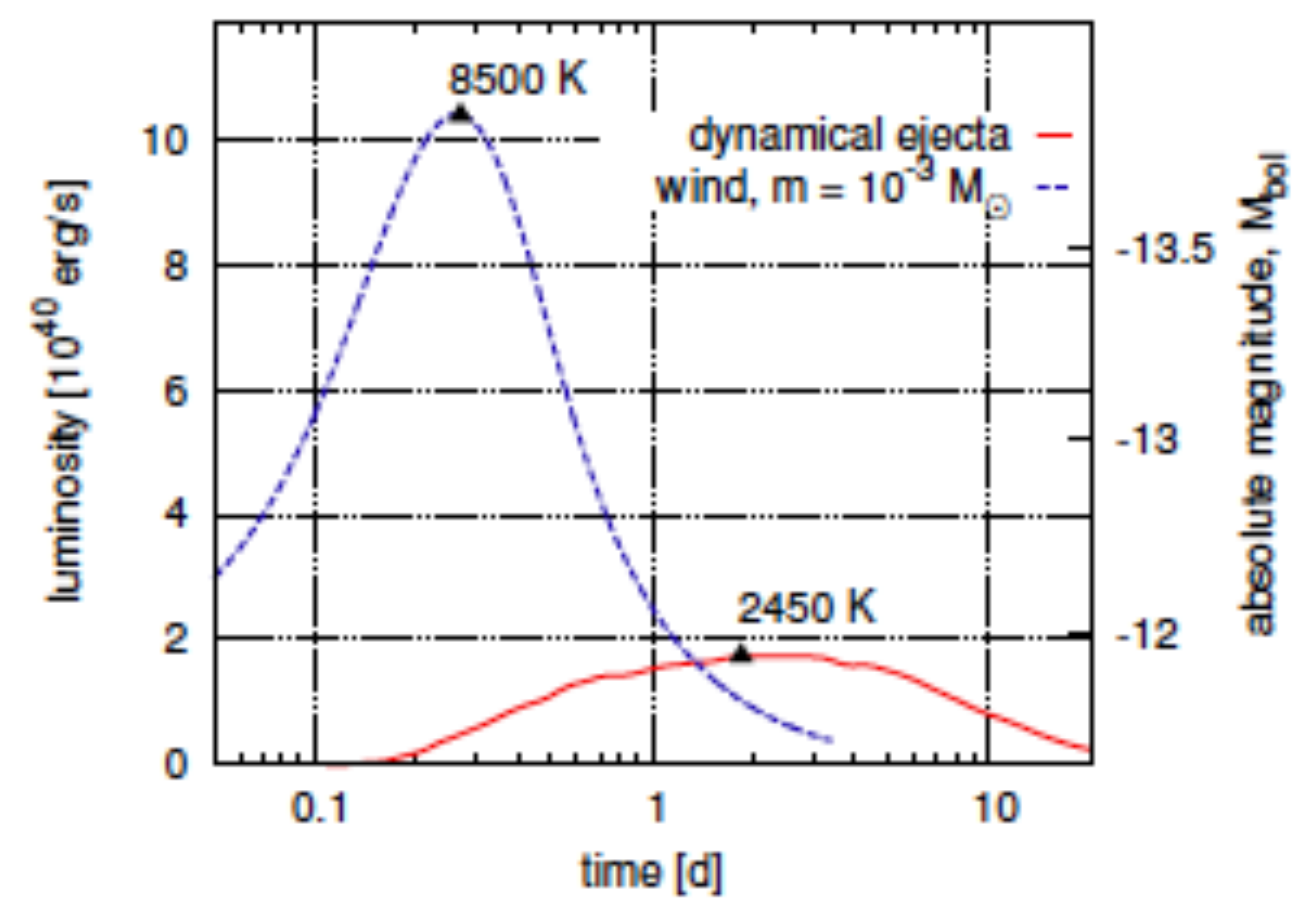
neutrino driven winds

Different Y_e, different nucleosynthsis, different opacity: $\varkappa = 1\text{cm}^2/\text{gm}$

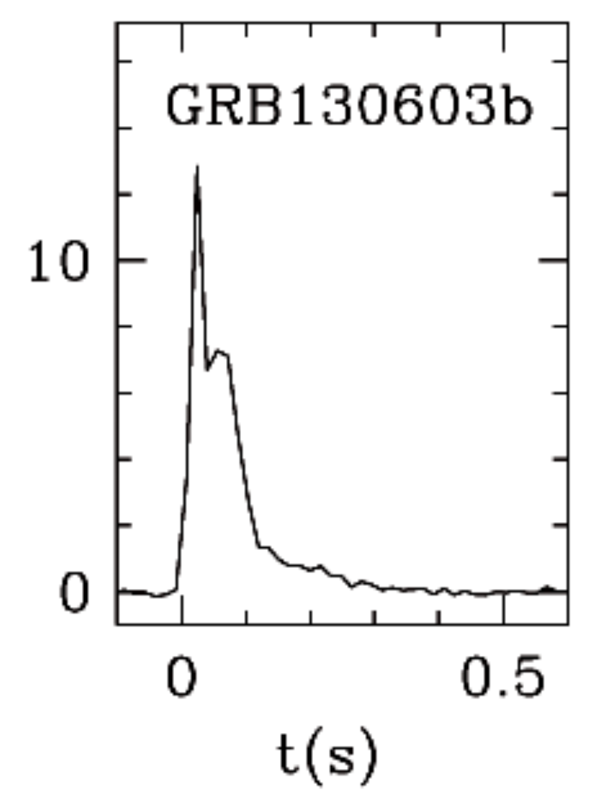
neutrino driven winds - lightcurves

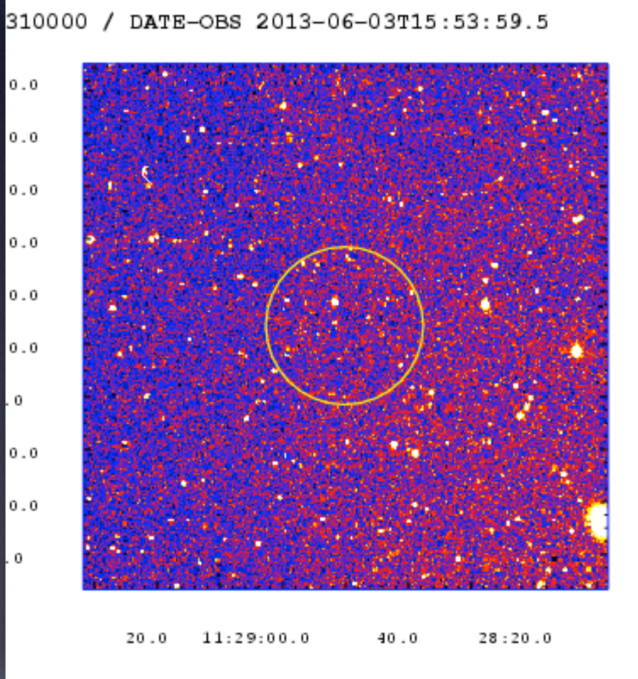


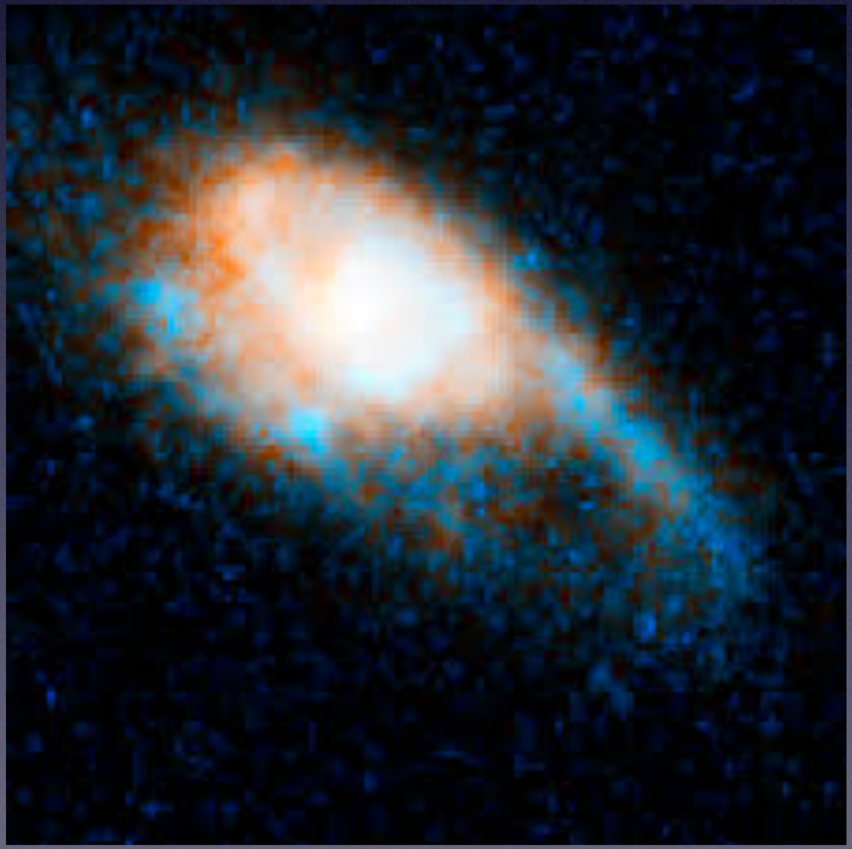
Combined macronova signal



The short Gamma-Ray Burst (GRB) 130603B



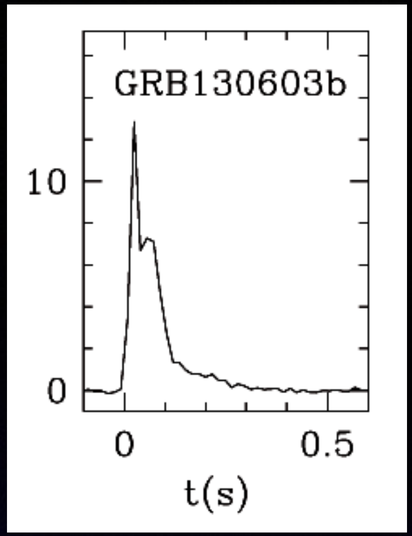


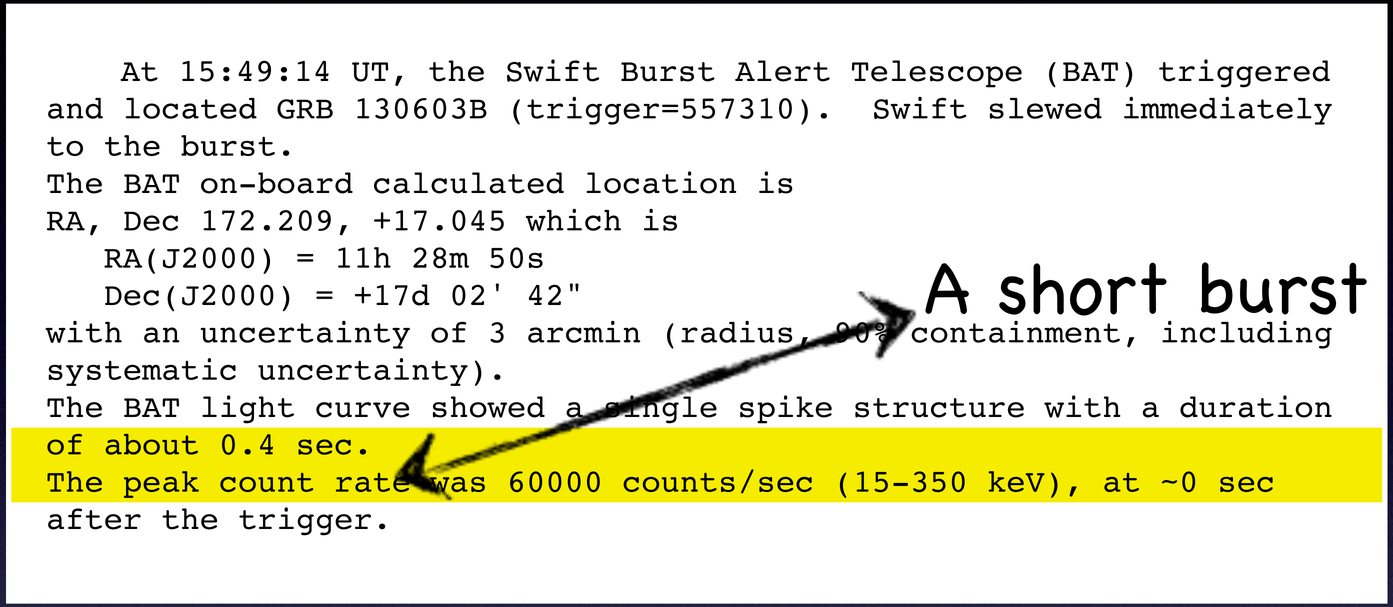


GRB 130603B

z=0.356 <=> 1 Gpc = 3 Glyr

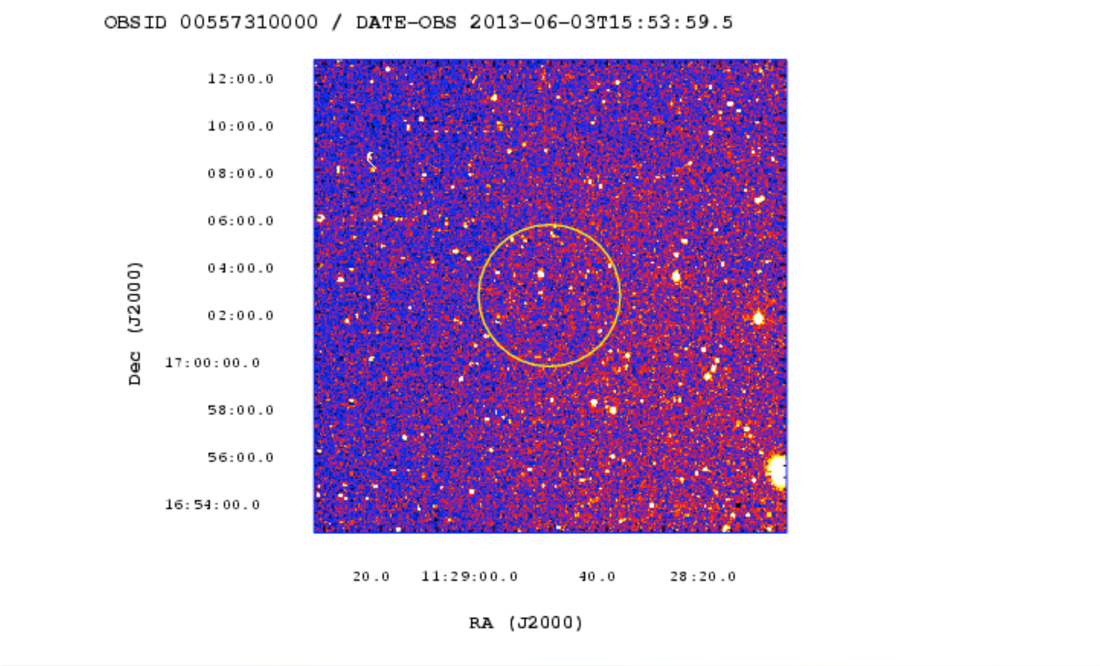
GRB 130603B

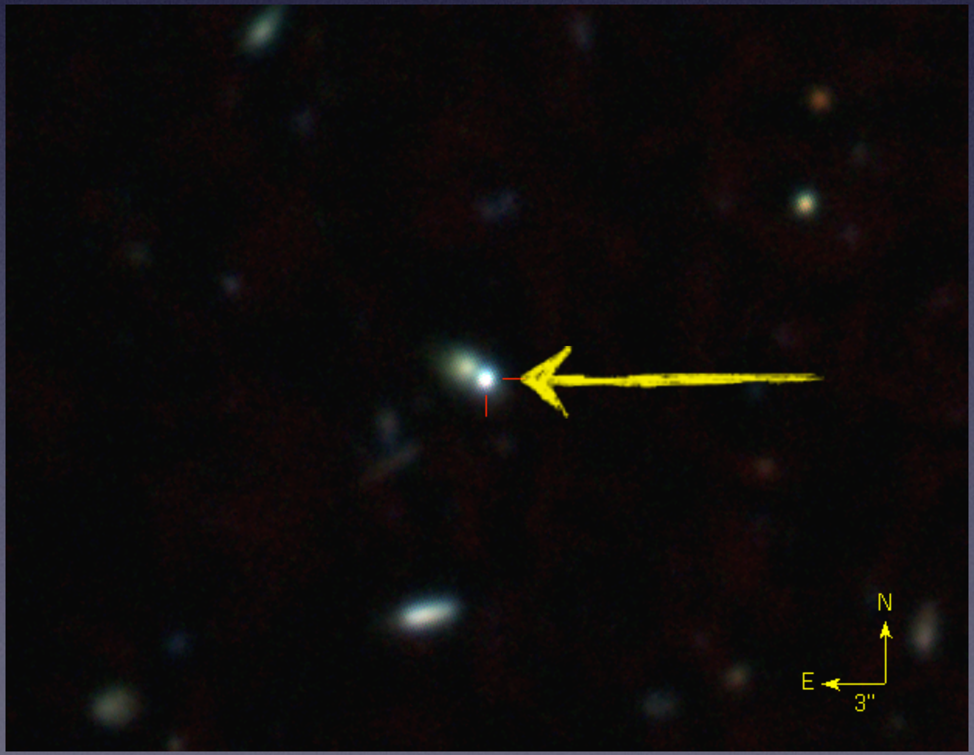




At 15:49:14 UT, the Swift Burst Alert Telescope (BAT) triggered and located GRB 130603B (trigger=557310). Swift slewed immediately to the burst.
The BAT on-board calculated location is
RA, Dec 172.209, +17.045 which is
RA(J2000) = 11h 28m 50s
Dec(J2000) = +17d 02' 42"
with an uncertainty of 3 arcmin (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

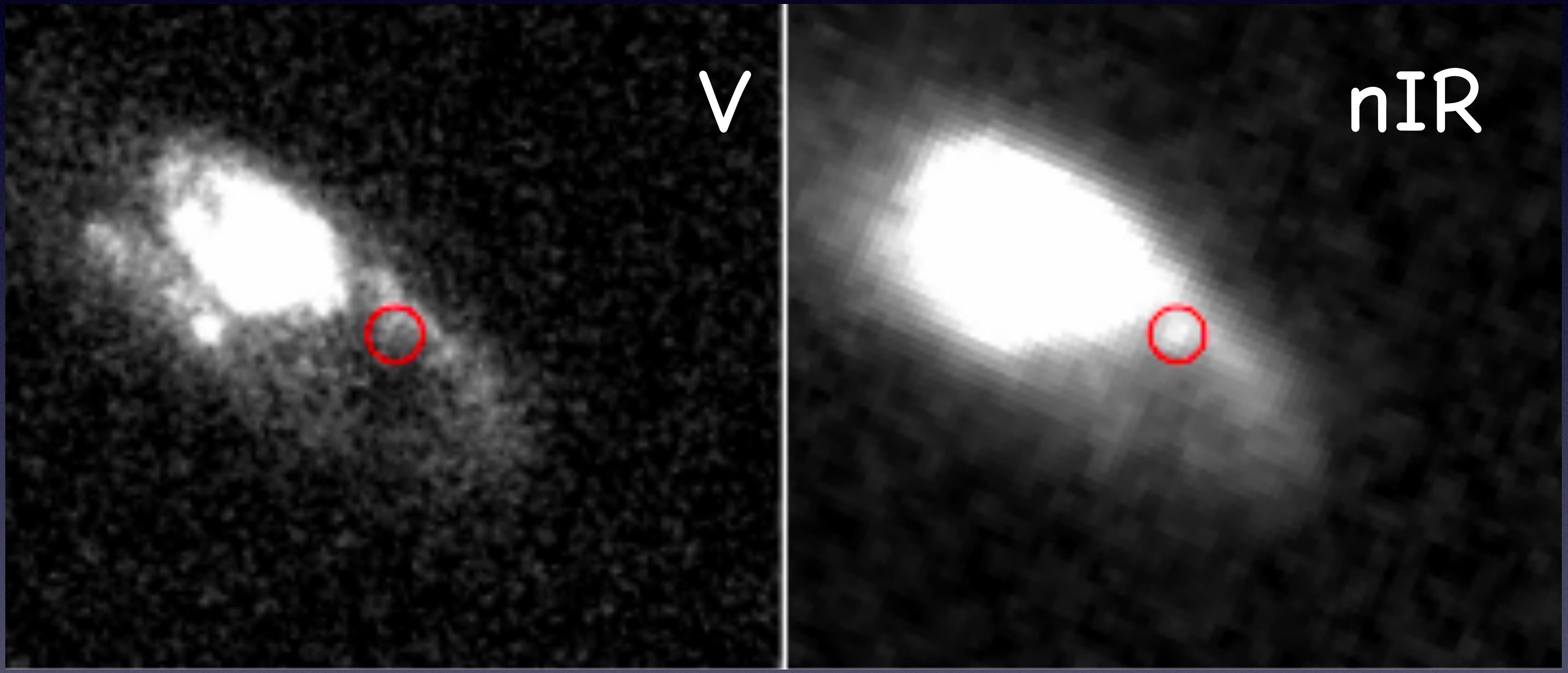




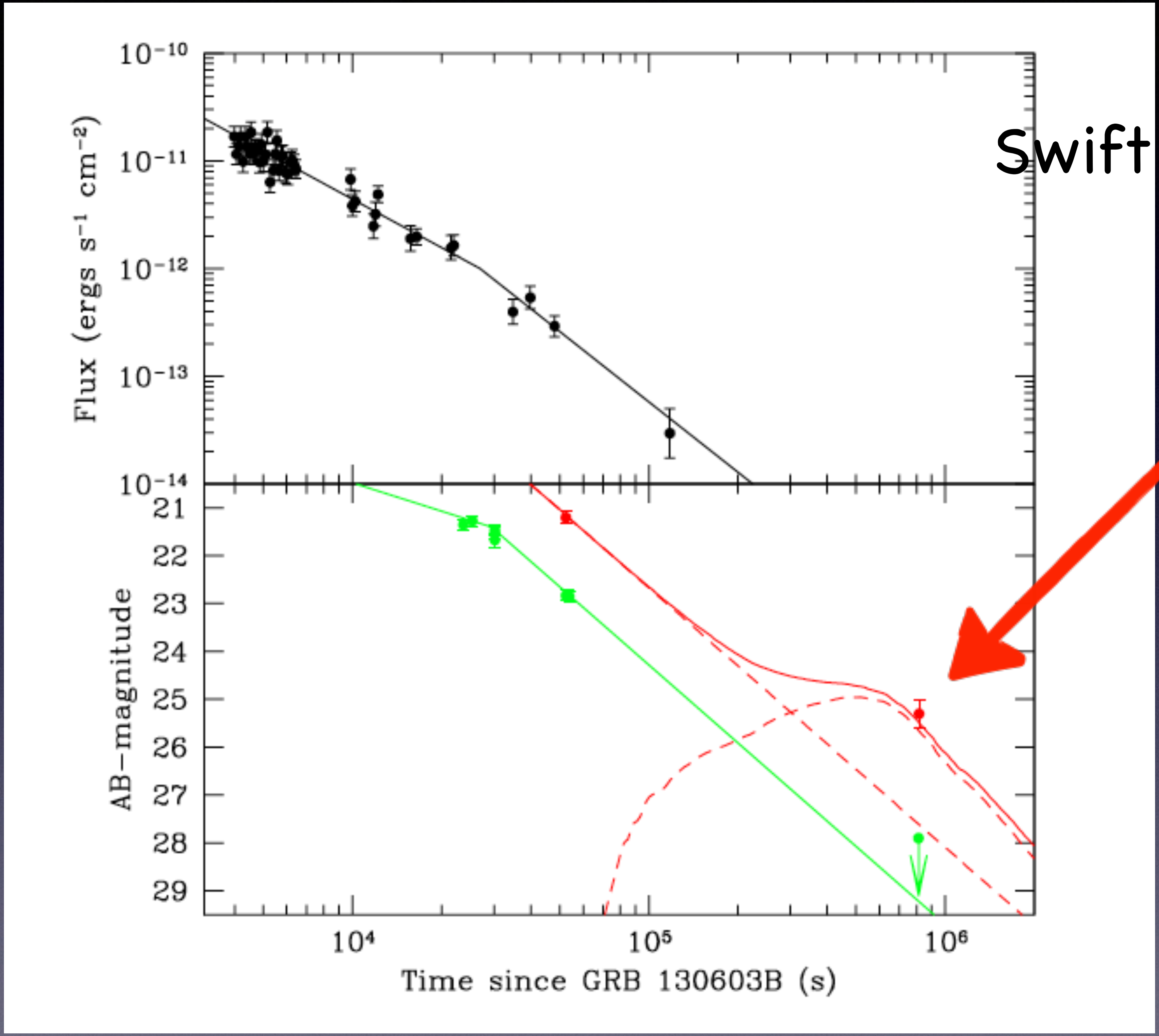
z=0.356 <=> 1 Gpc = 3 Glyr

GRB130603B @ 9 days AB

(6.6 days at the source frame)



HST image (Tanvir + 13)



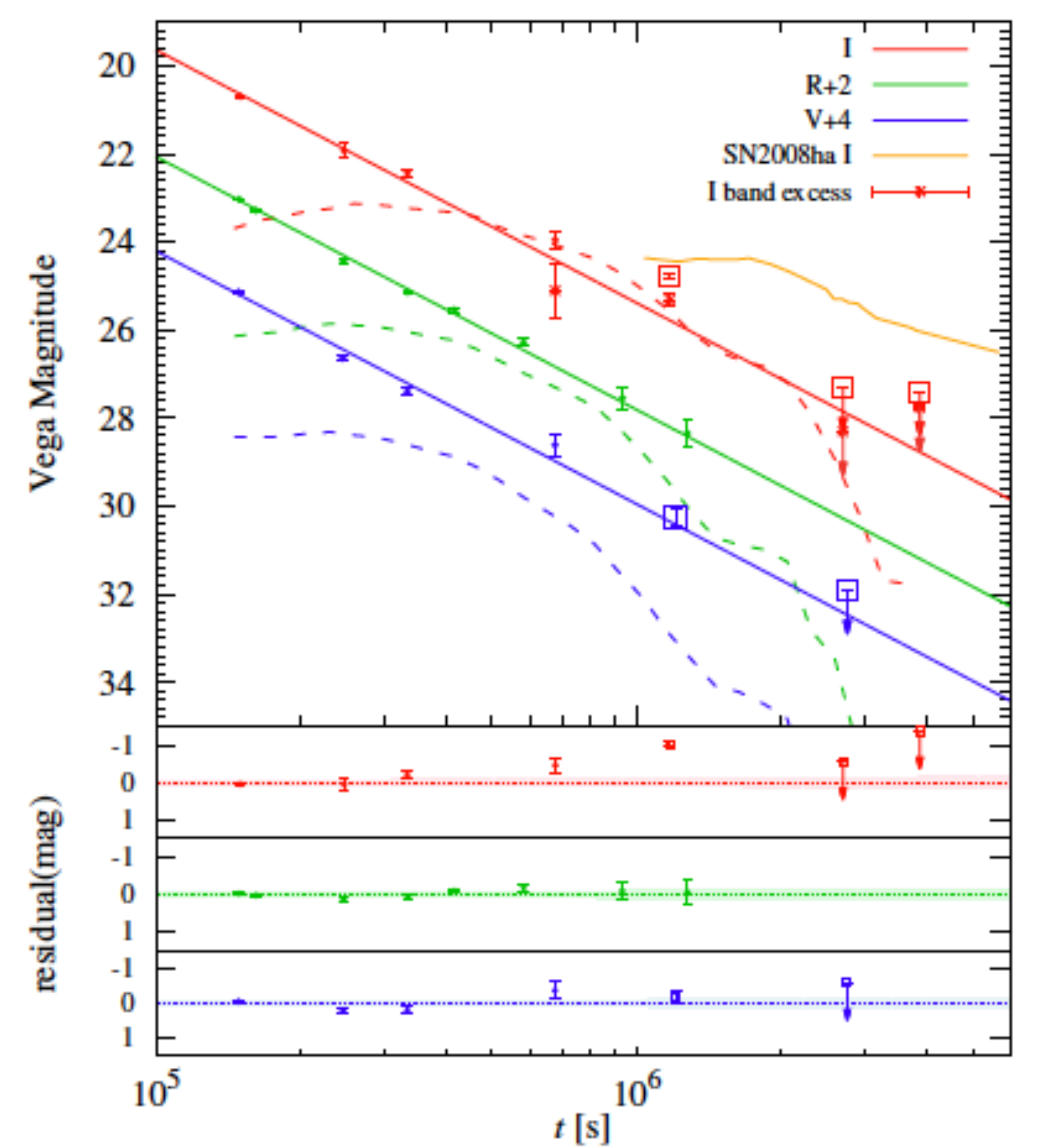
Macronova?

$0.01\text{–}0.05\ M_\odot$

Tanvir + 13 (see also Berger + 13)

GRB 130603B

GRB 060614

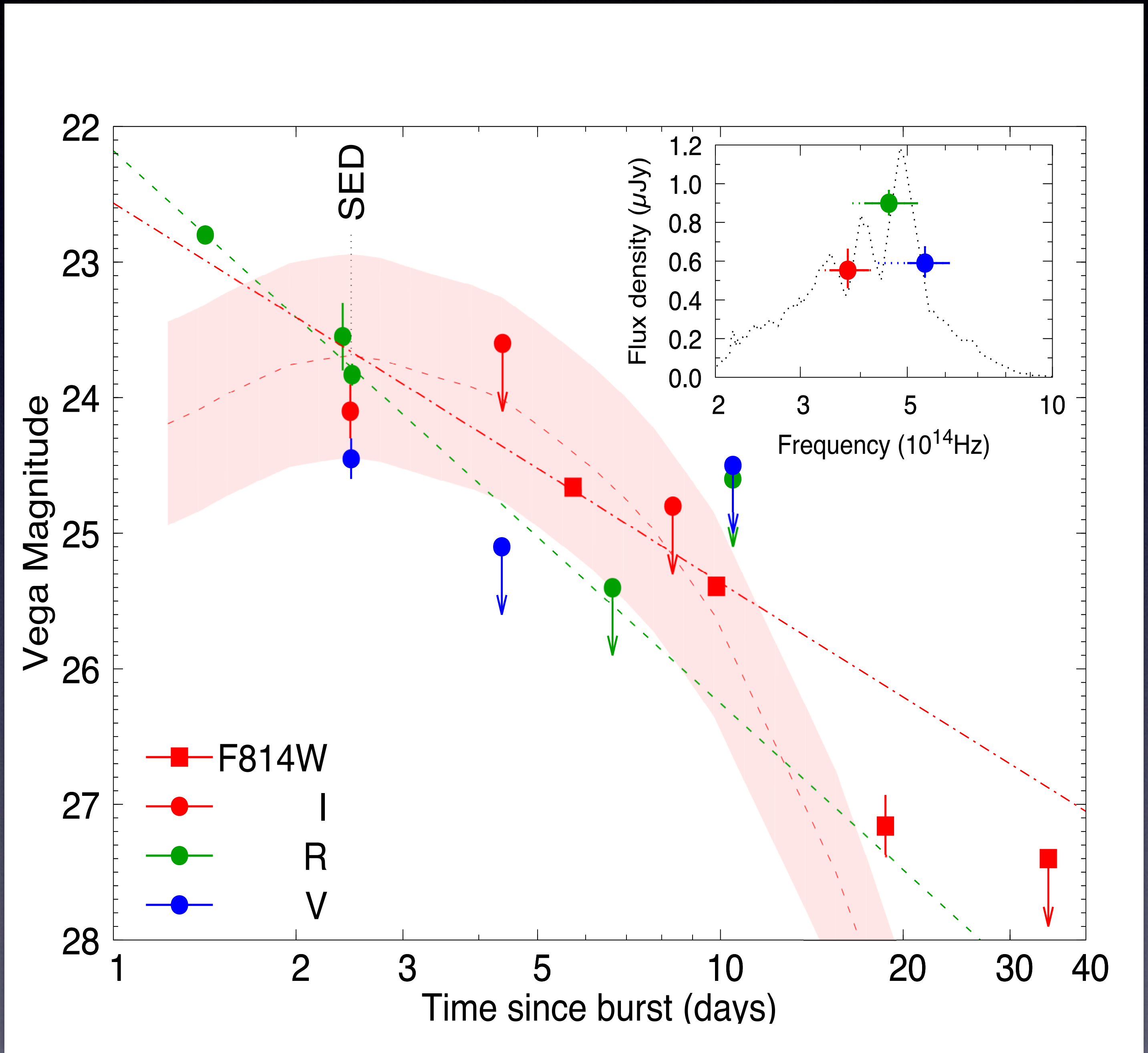


Need $M \simeq 0.1 M_\odot$

=> BH-NS ?

Yang et al., 2015

GRB 050709



Need $M \simeq 0.05 M_{\odot}$

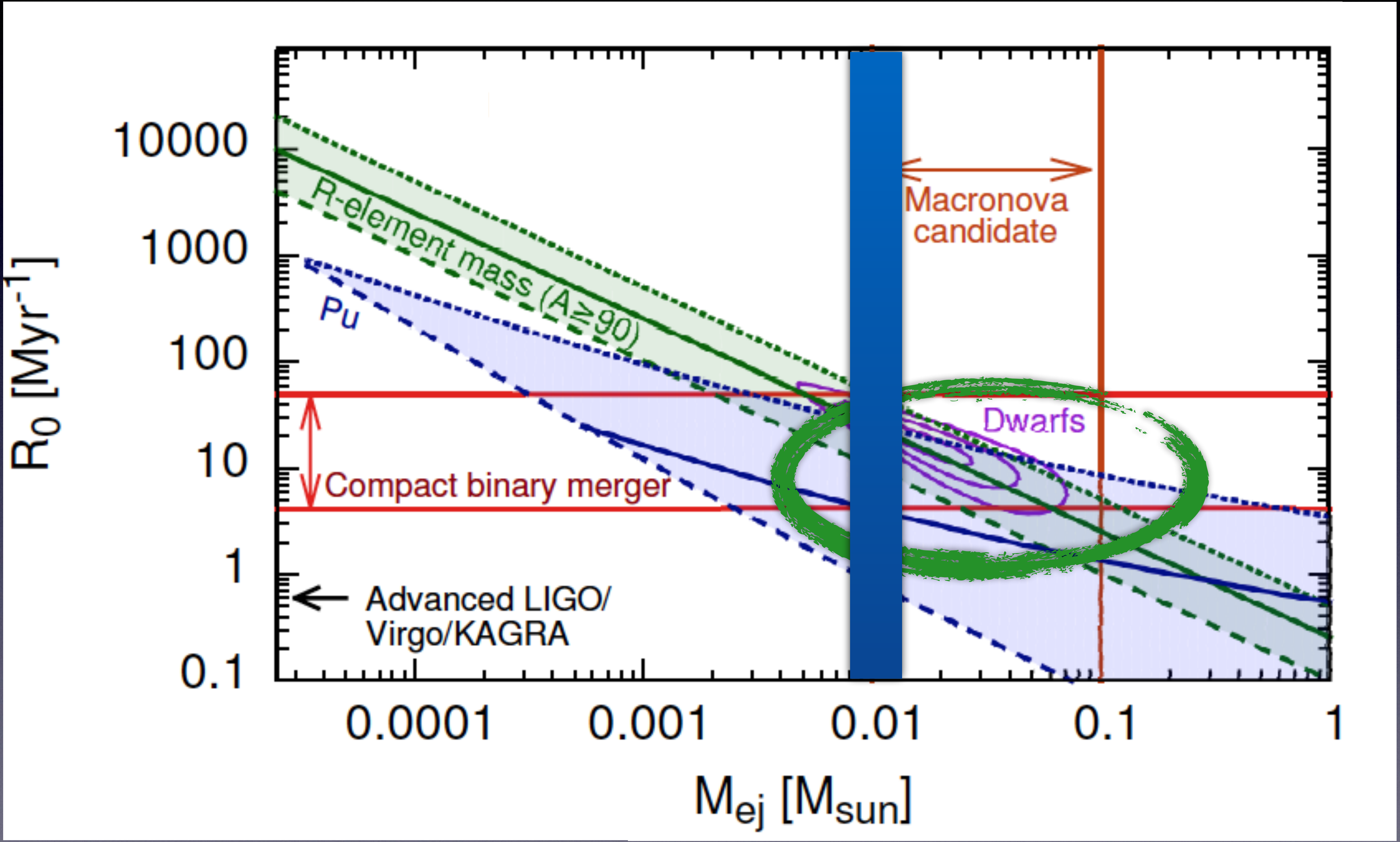
=> BH-NS ?

Jin et al., 2016

Are Macronova Frequent?

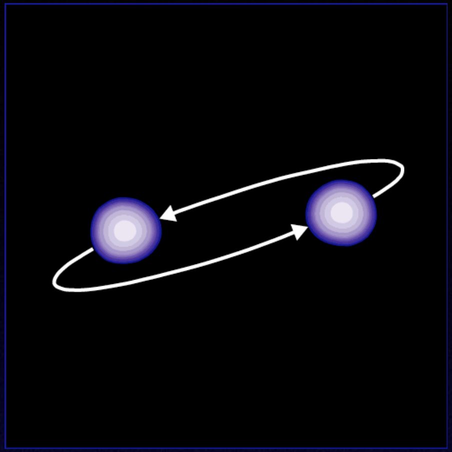
- There are 3 (6) possible (nearby) historical candidates with a good enough data
- In 3/3 (3/6) there are possible Macronovae

r-process consistency



Hotokezaka & TP 17

If correct



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

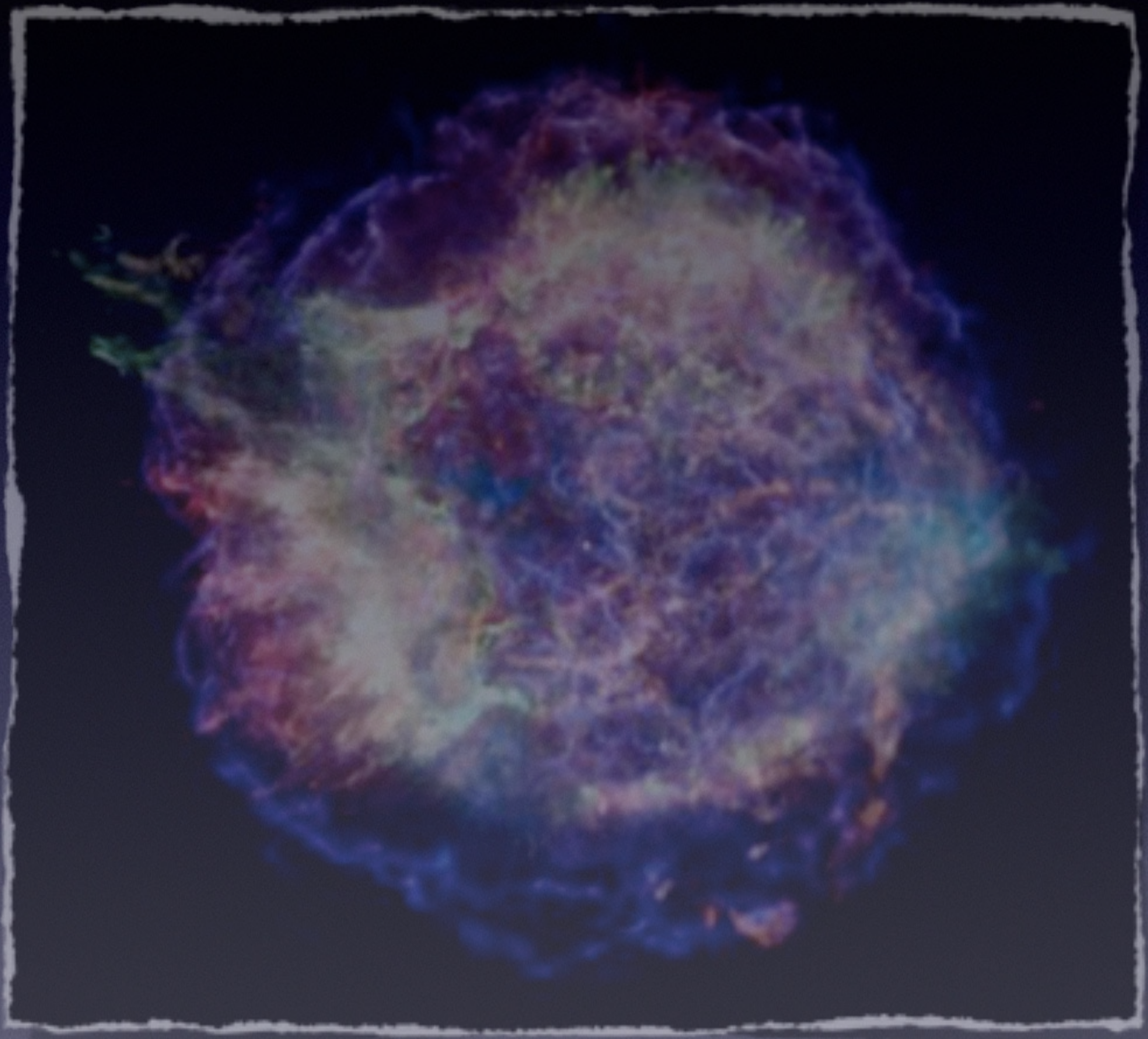
- Confirmation of the Li-Paczynski Macronova.

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

Radio Flares (Nakar & Piran 2011)

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

Radio Flares (Nakar & Piran 2011)



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

Supernova

Months

Supernova remnant

a few x 10^4 years

↓

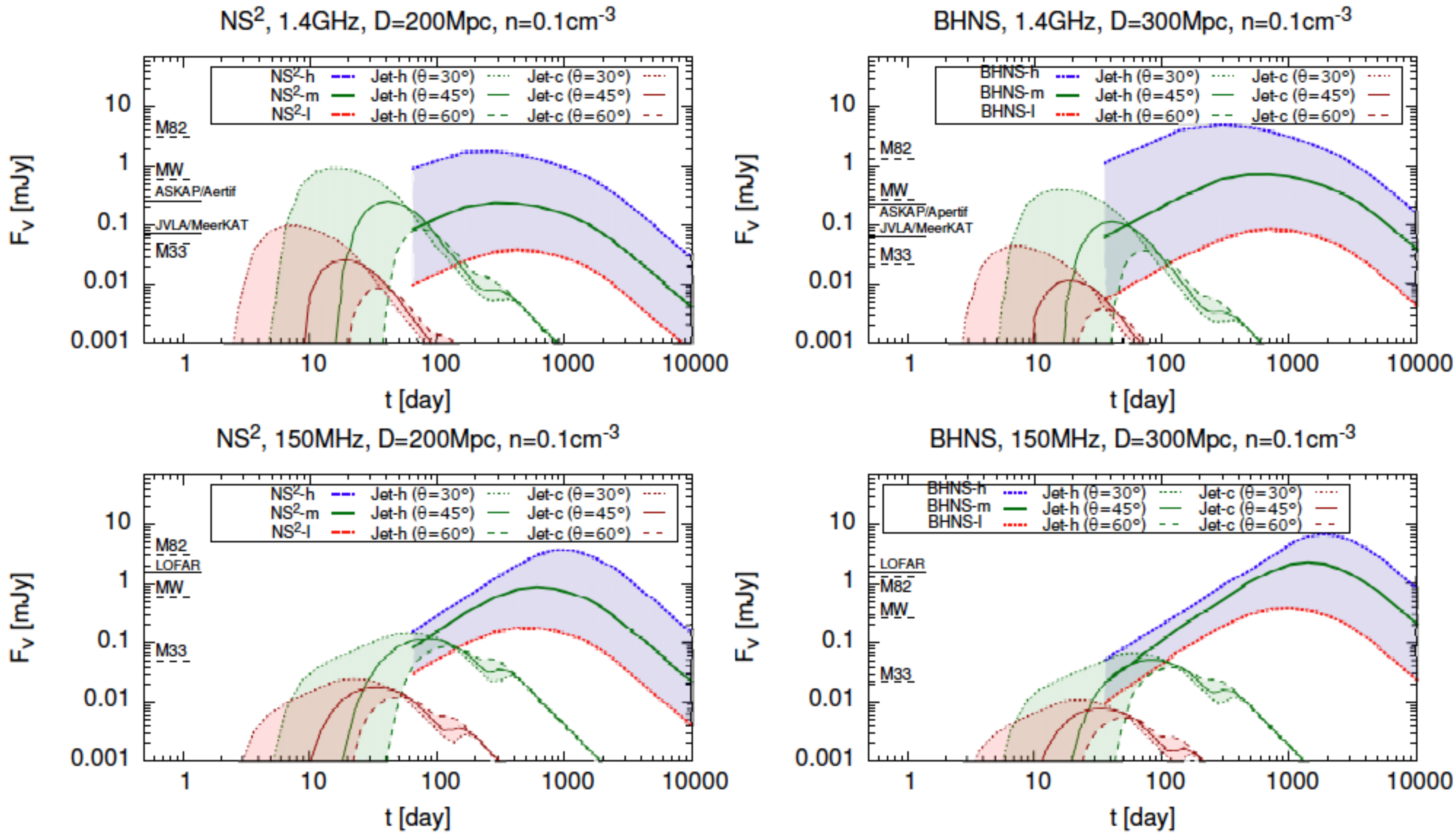
Macronova

Weeks

Radio Flare

months - years

Radio Flare light curves



Nakar, TP 2011; TP+13; Hotokezata + TP, 15; Hotokezaka et al., 16

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

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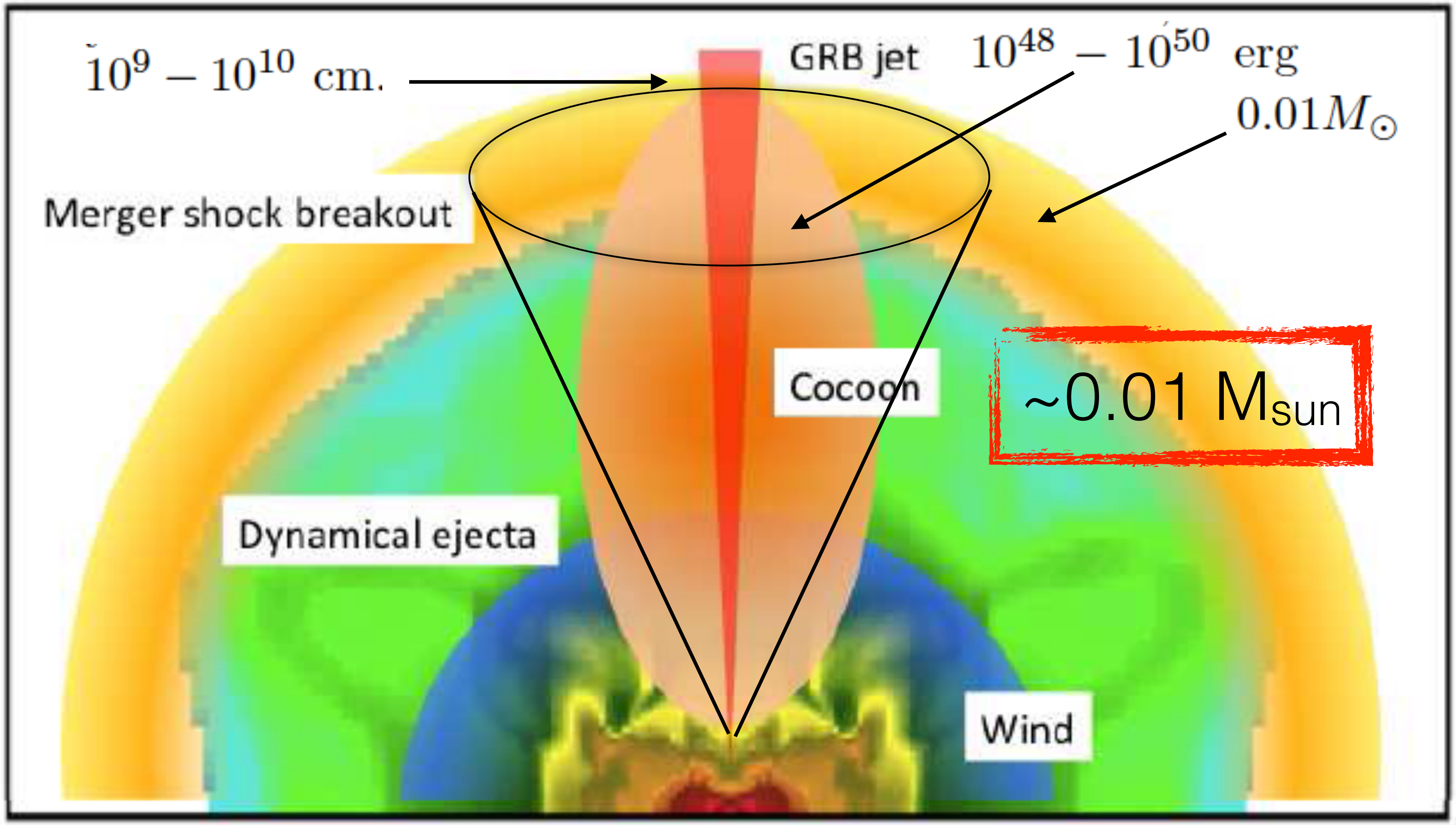
The Cocoon signature

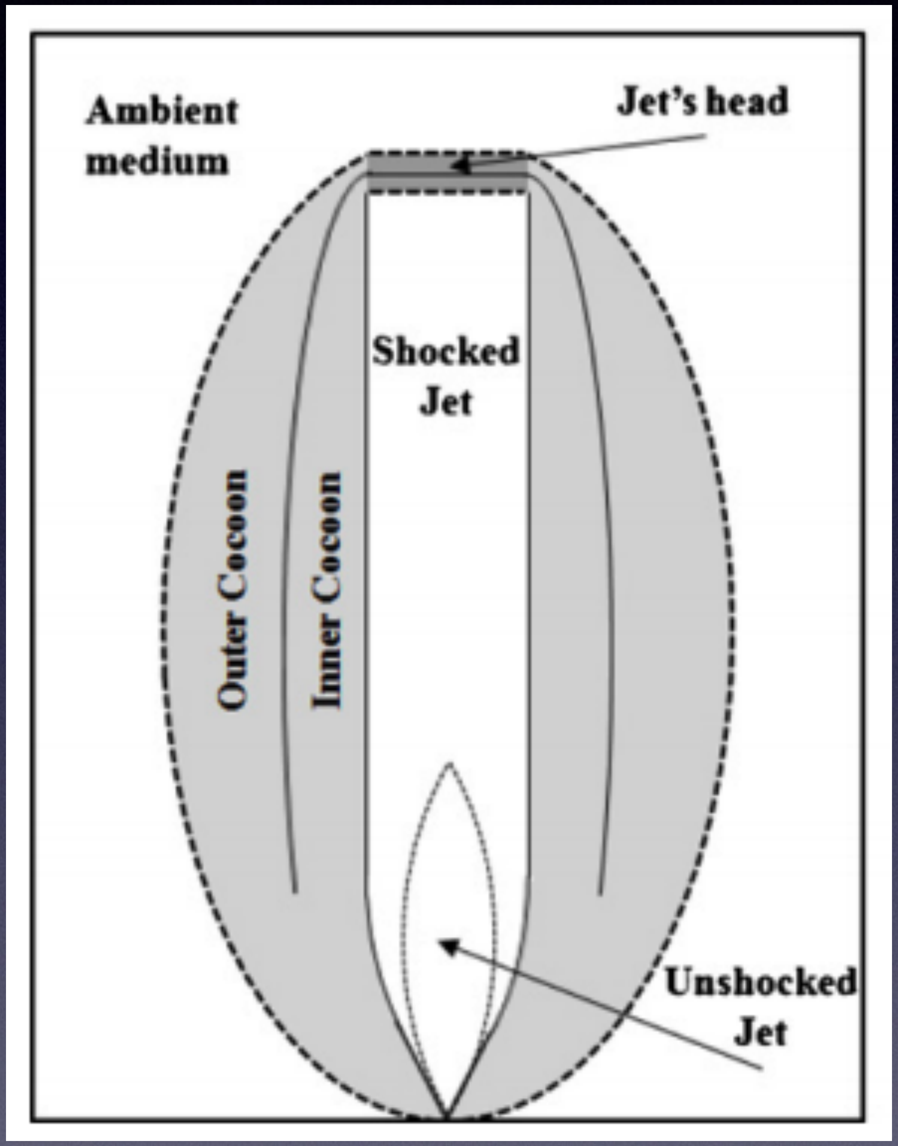


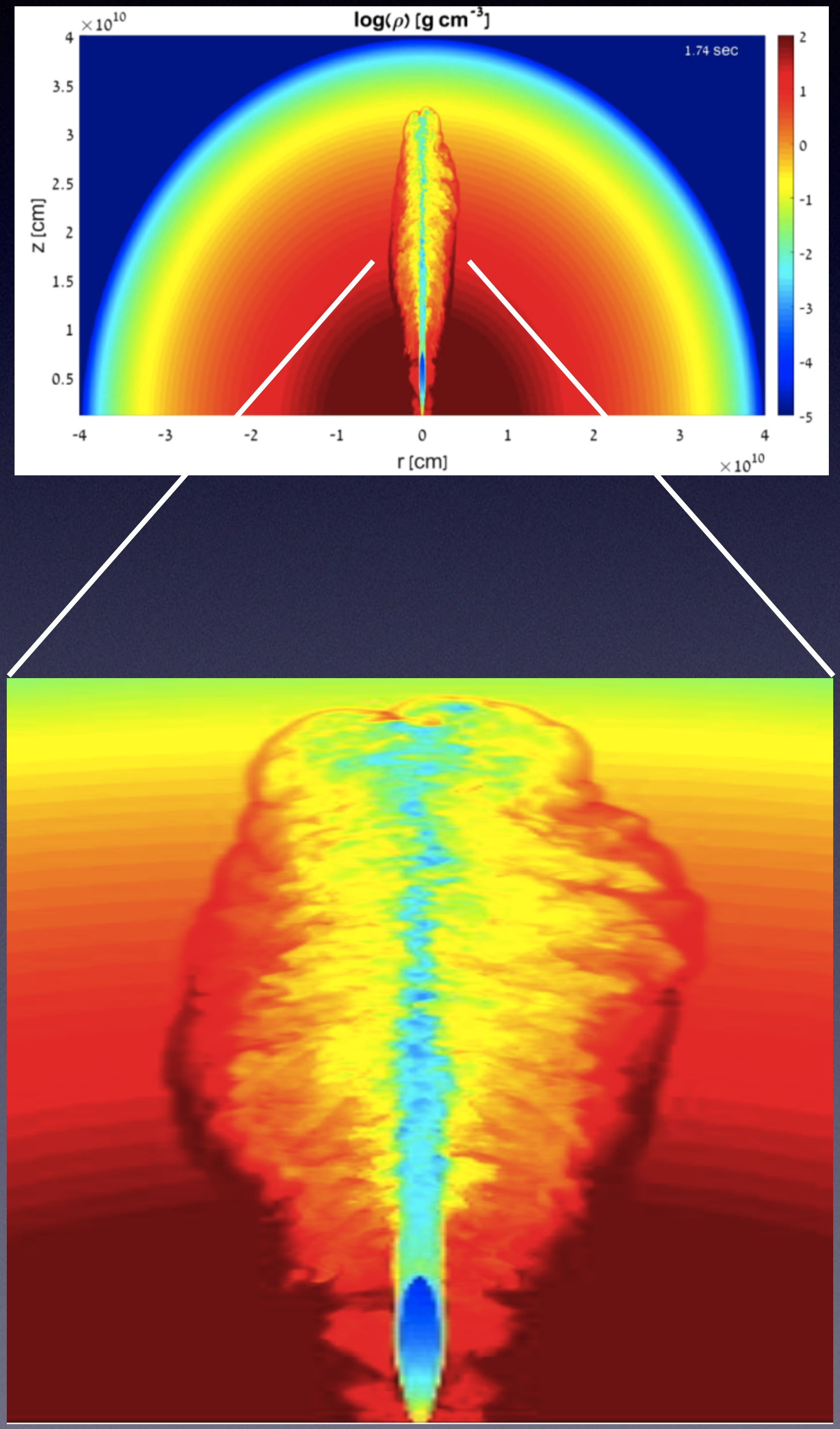
~0.01 M_{sun}

From Hotokezaka & TP 2015

Jet Propagation

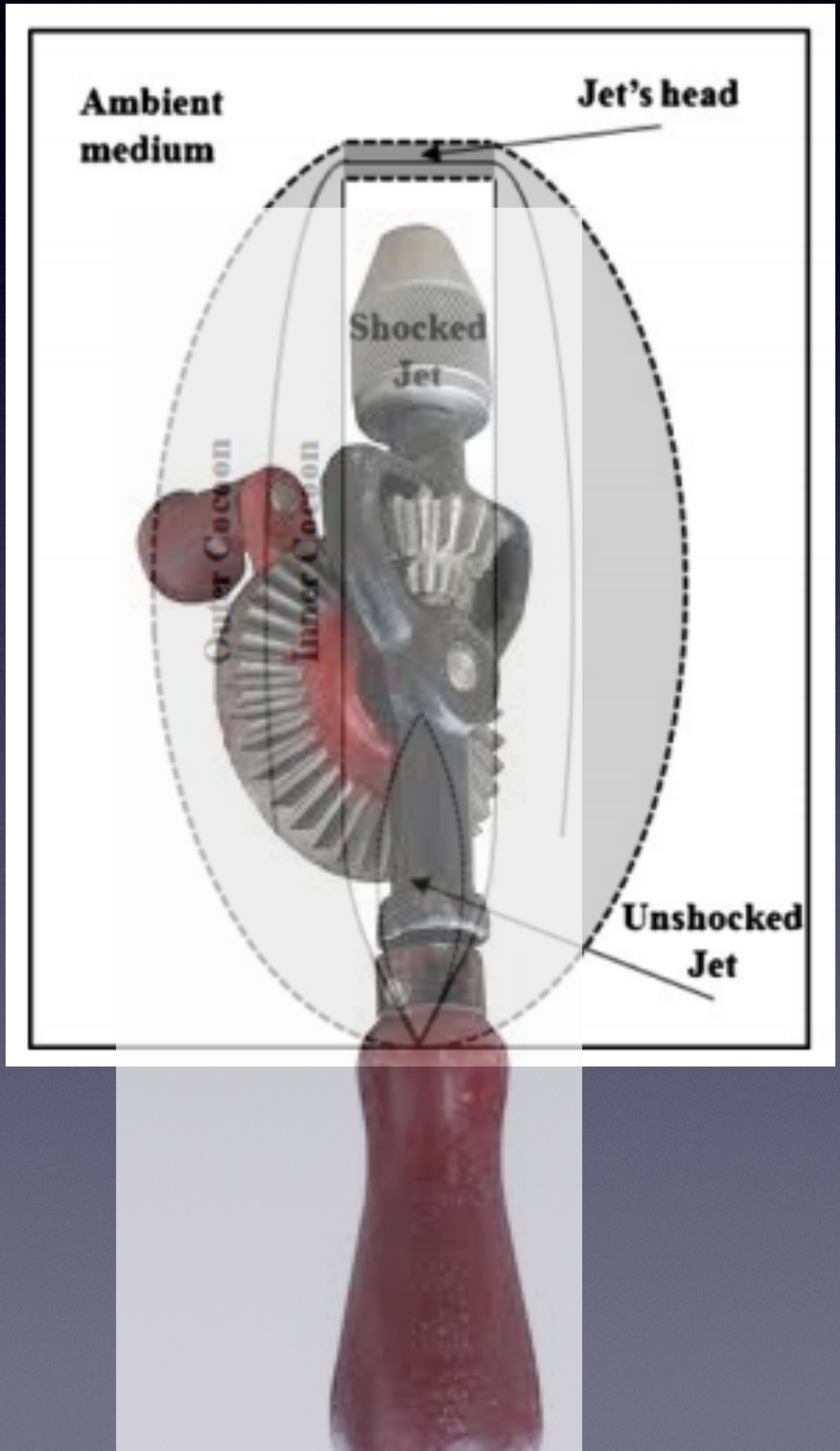
(MacFayden & Woosley 1998; Aloy+ 1999; Matzner 2003; Lazzati and Begelman,05; Bromberg + 2011….)

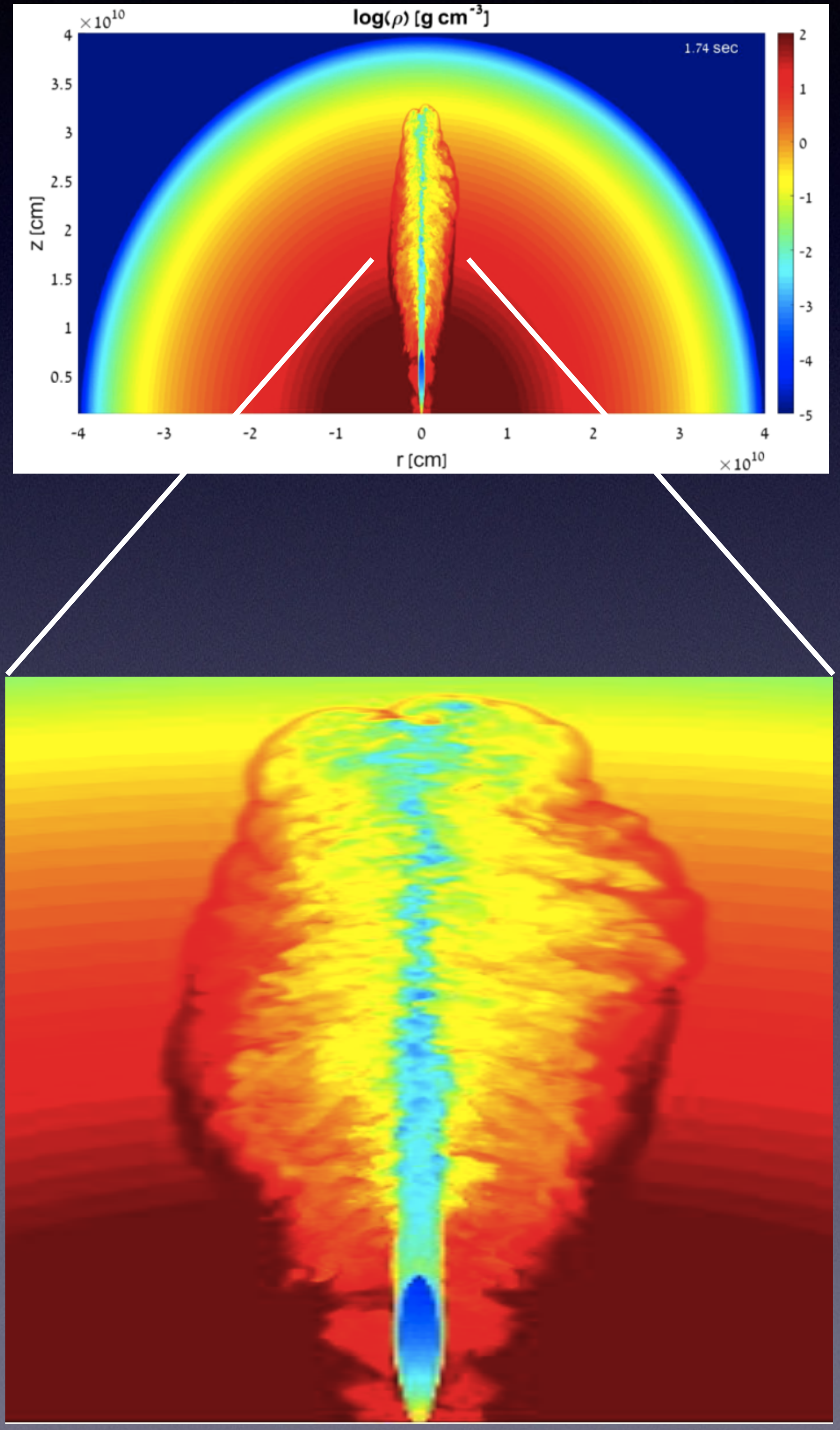


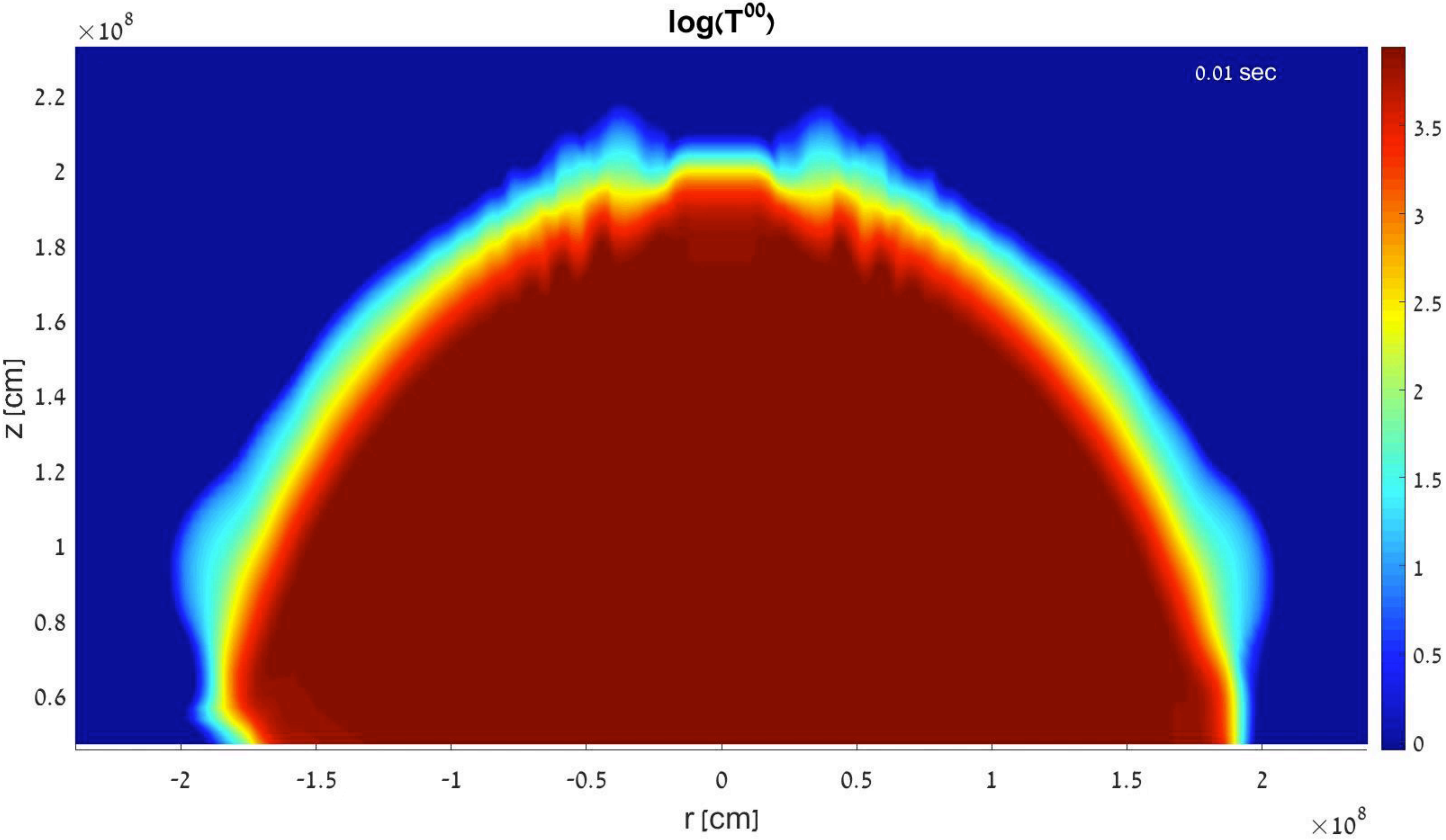


Jet Propagation

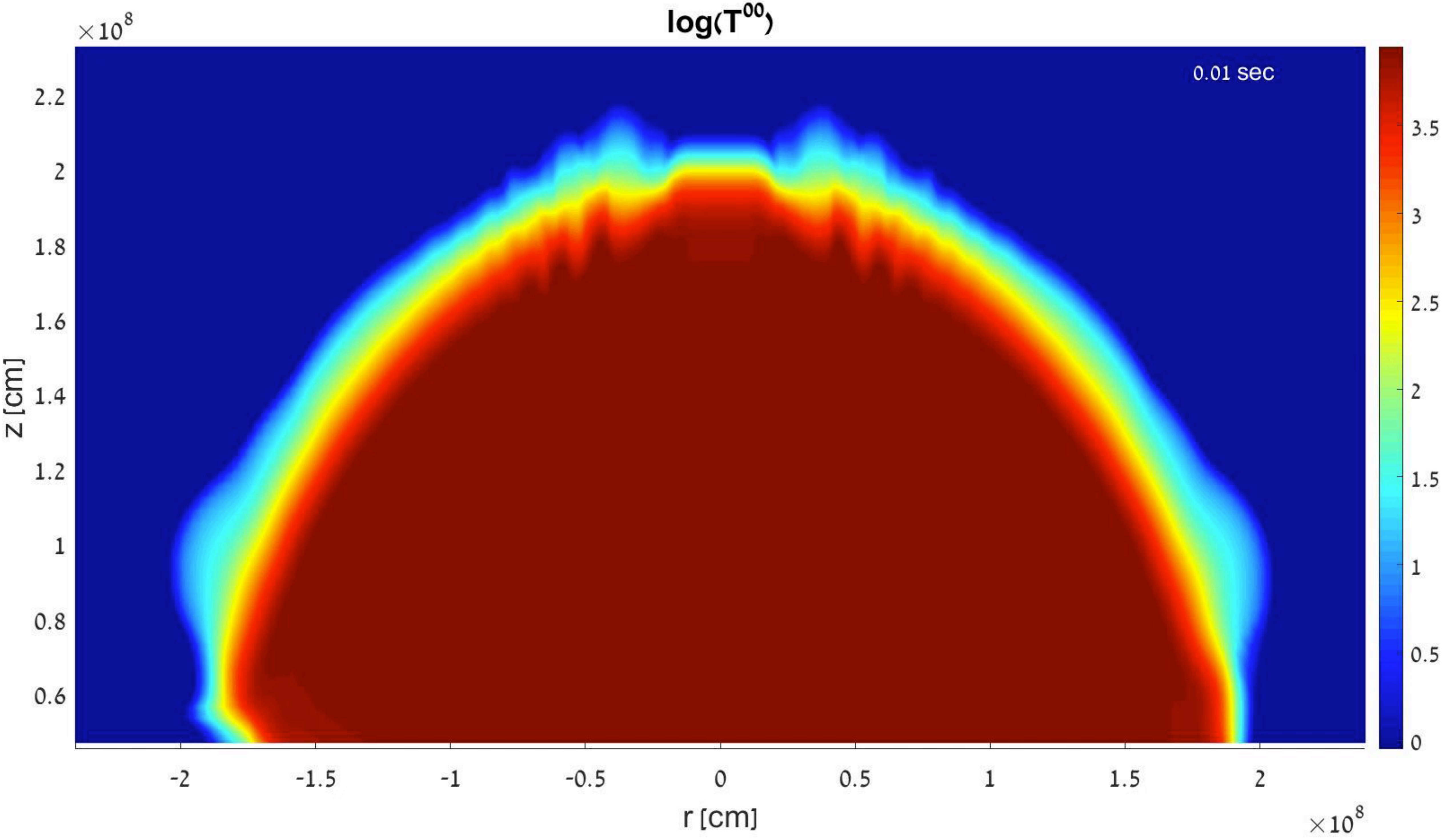
(MacFayden & Woosley 1998; Aloy+ 1999; Matzner 2003; Lazzati and Begelman,05; Bromberg + 2011….)







3D Simulations by Ore Gottlieb using Pluto.
Breakout time ~0.2 sec
Ejecta from the simulations of Nakagura et al 2014



3D Simulations by Ore Gottlieb using Pluto.
Breakout time ~0.2 sec
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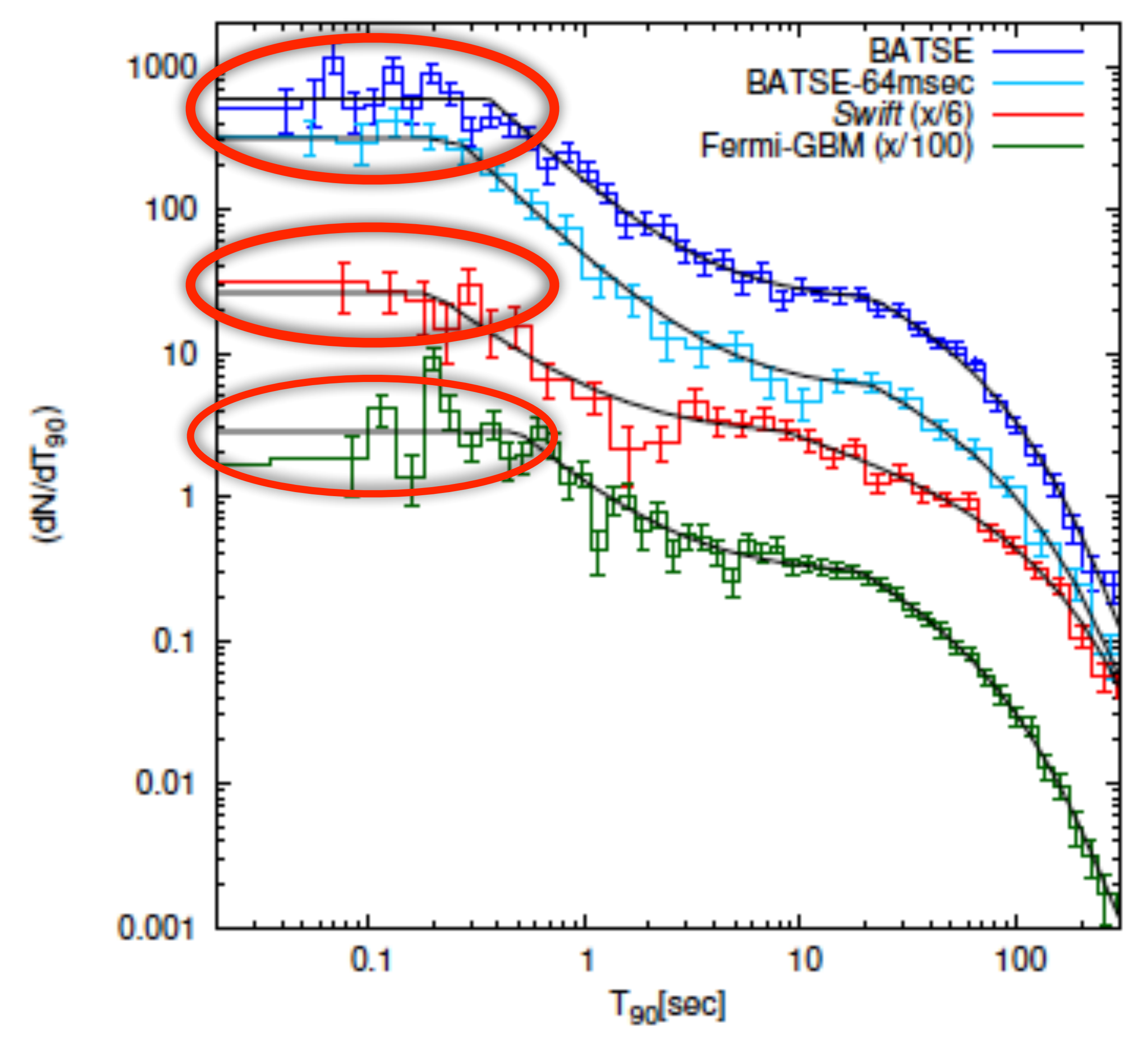
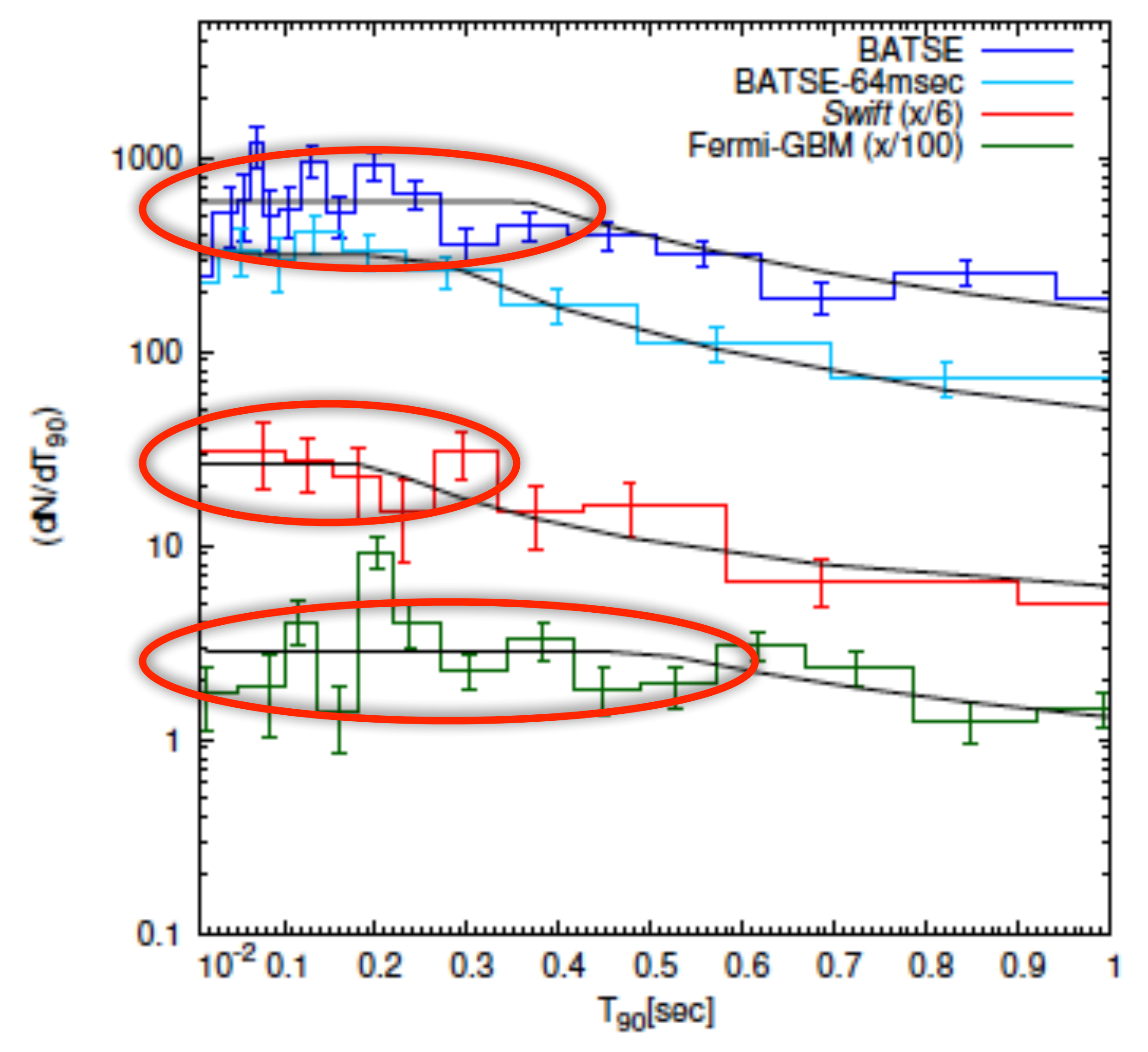
The “short” plateau

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!

While propagating in the ejecta the jet dissipates its energy ($\sim 10^{49}$ ergs) in a cocoon

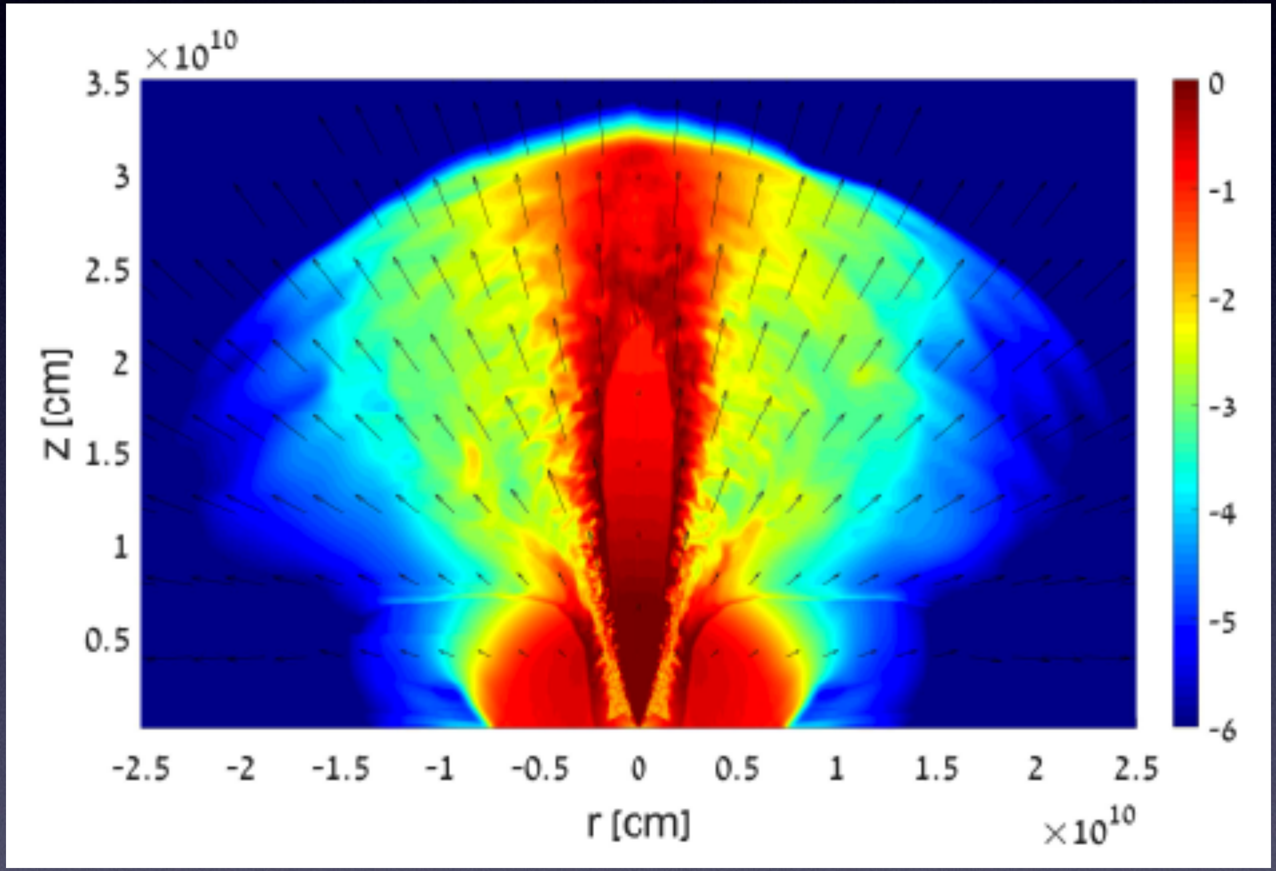
Can we see this energy ?

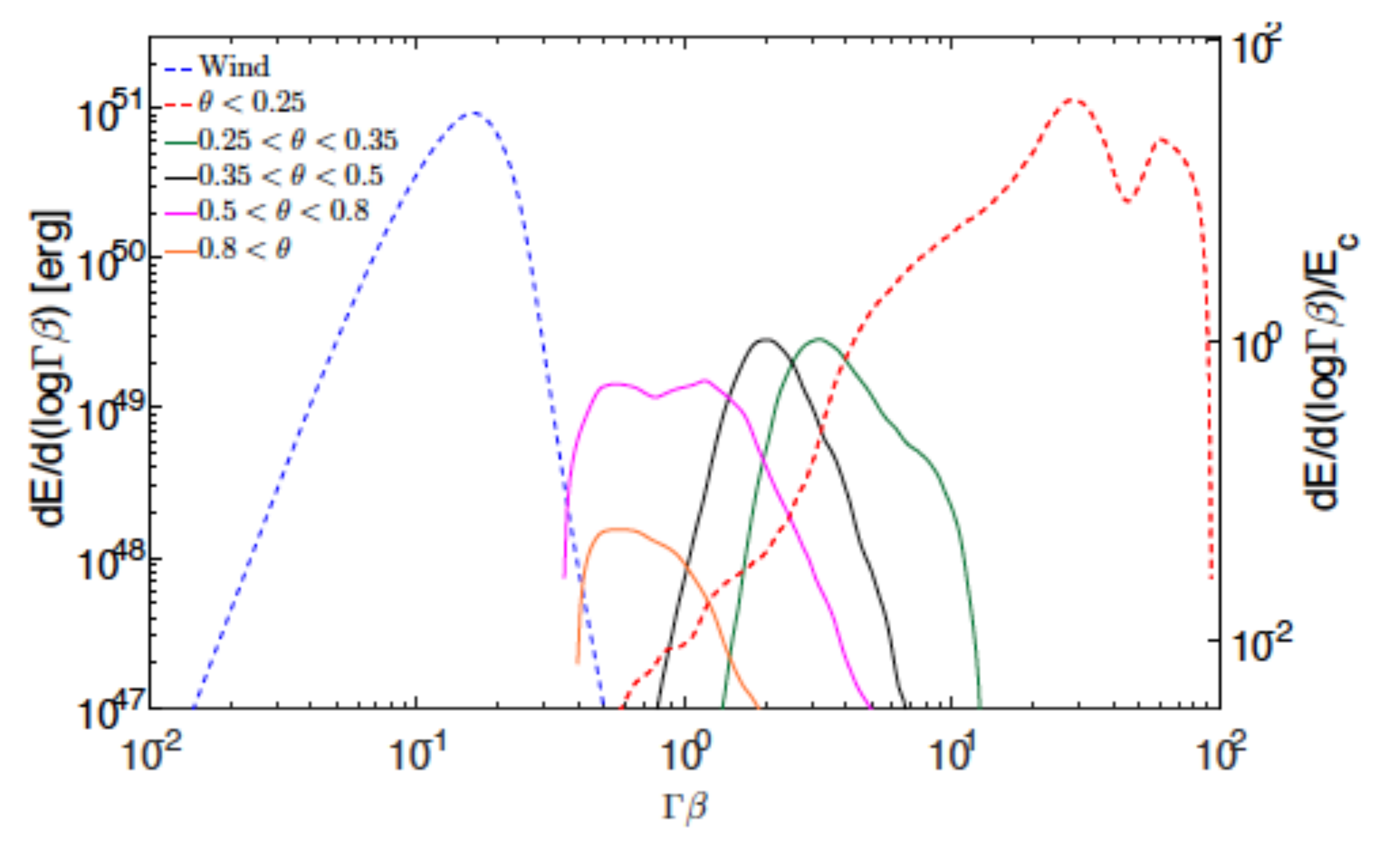
Yes

The cocoon breakout

arXiv170510797G

Ore Goettlib, Ehud Nakar & TP 17





Cooling + Radioactivity

=> short lived bright signal

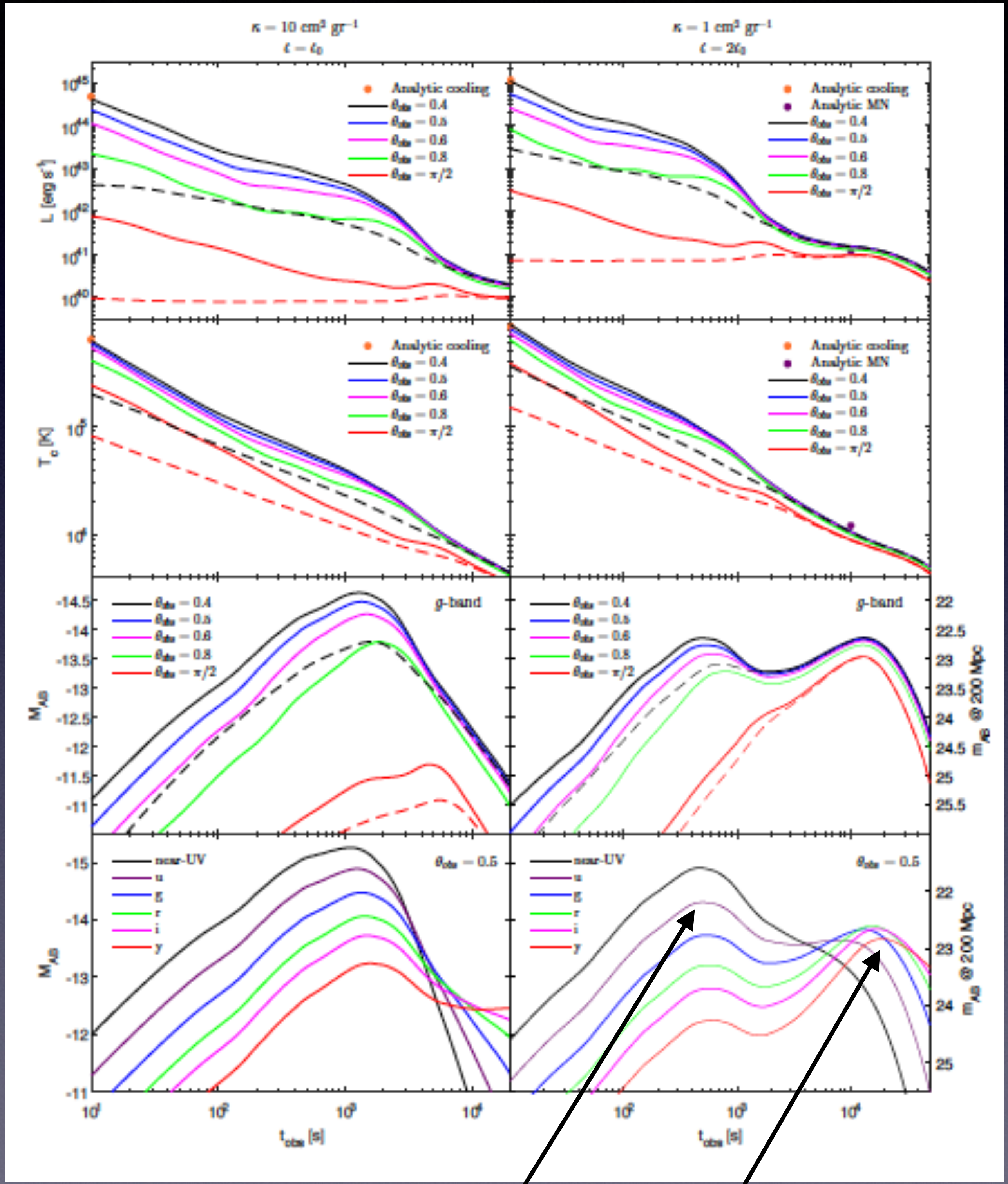
The brightest counterpart

Bolometric Luminosity

Temperature

g Magnitude

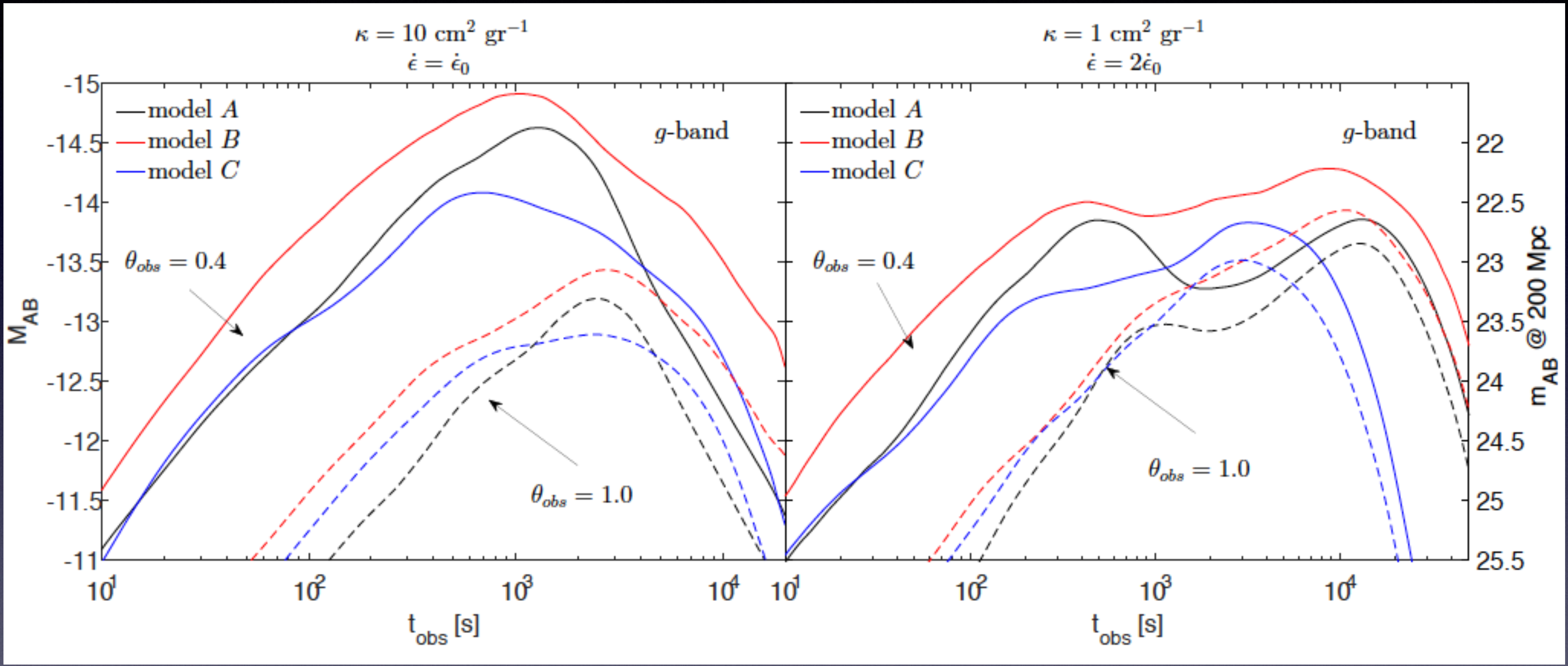
Multiwavelengths



cooling emission

cocoon macronova

g band light curve



=> Observational strategy: look for a rapid (hour) bright blue signal and followup in IR (Grossman, Korobkin, Rosswog, TP, 14)

Cocoon Afterglow
Teboul & TP 17

- The relativistic part of the cocoon’s ejecta may lead to an afterglow emission due to the interaction of the ejecta with the surrounding matter.

Detectability

aLIGO will provide a 100 deg^2 error box

- The Dynamical ejecta IR signal
  - @ 300 Mpc -> $M_H \approx 23.5\text{-}24.5$ (-1 at optimal viewing angle) on a time scale of a few days
  - Rapid follow up is impossible in the IR.
- neutrino driven wind UV/Blue signal
  - @ 300 Mpc -> $M_H \approx 23.7\text{-}24.2$ on a time scale of a < day
  - Possible with SHC on subaru or continous cover with ZTF or equivalent or LSST
- Cocoon signature
  - @ 300 Mpc -> $M_H \approx 22\text{-}23$ on a time scale of an hour
  - Possible with SHC on subaru or continous cover with ZTF or equivalent or LSST

Detection strategy

- Deep search in the optical using HSC or multiple exposures on a very wide field telescope (ZTF).
- With detection deep localized search in the near IR
- Blind searches in Optical and clearly in IR are hopeless (a few single event detections per year with the LSST).

Conclusions

- Short GRBs are the best EM counterparts - but the rate of a sGRB+GW signal is small ~ 1 in 10 years.
- NS^2 ejecta produces a weak "supernova" first a supernova like optical/IR signal (Macronova/kilonova) and then a SNR like Radio Flare.
- Consistently of numerous observations pointing out to NS^2 mergers as sources of r-process.
- The GRB jet deposits~10^{49} ergs in a cocoon.
- Cocoon cooling emission + radioactivity
  => <u>a bright (22-23 mag) blue short (hours) signal.</u>
- <u>Observational strategy: look for a rapid bright blue signal and follow up in IR.</u>

1) **Physical Processes in Astronomical Transients**
Jerusalem winter school
27/12/2017 - 4/1/2018

2) Several **Postdoc** positions under the **ERC** grant **TReX**

A remark about binary neutron stars

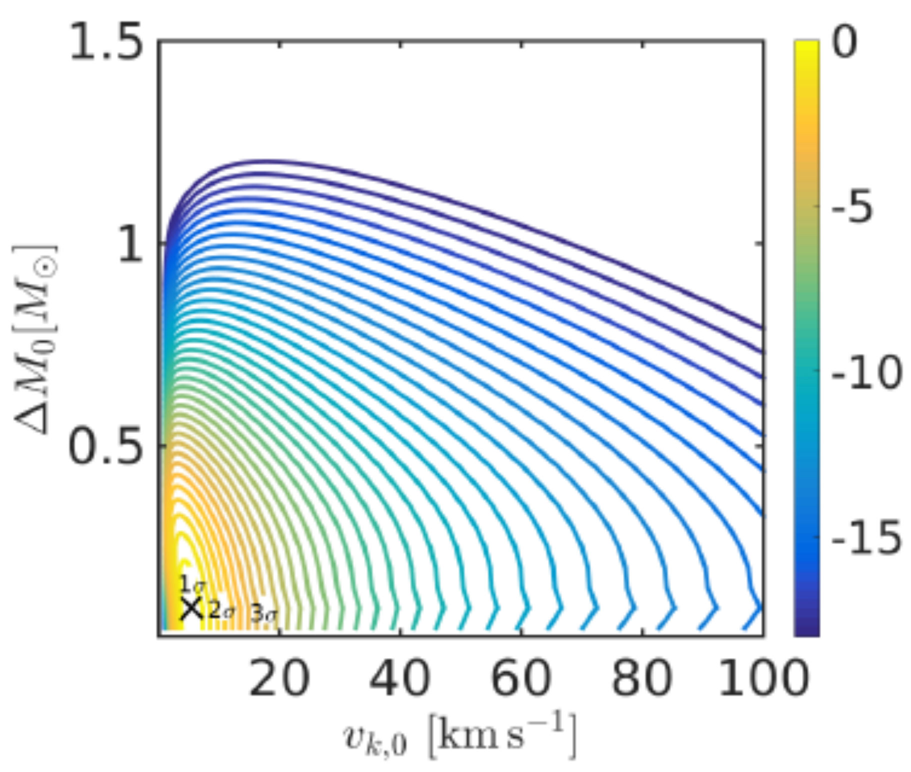
TP & Shaviv 2005; Dall'Osso, TP & Shaviv 2013,
Beniamini & TP 2015; Beniamini, Hotokezaka & TP 16

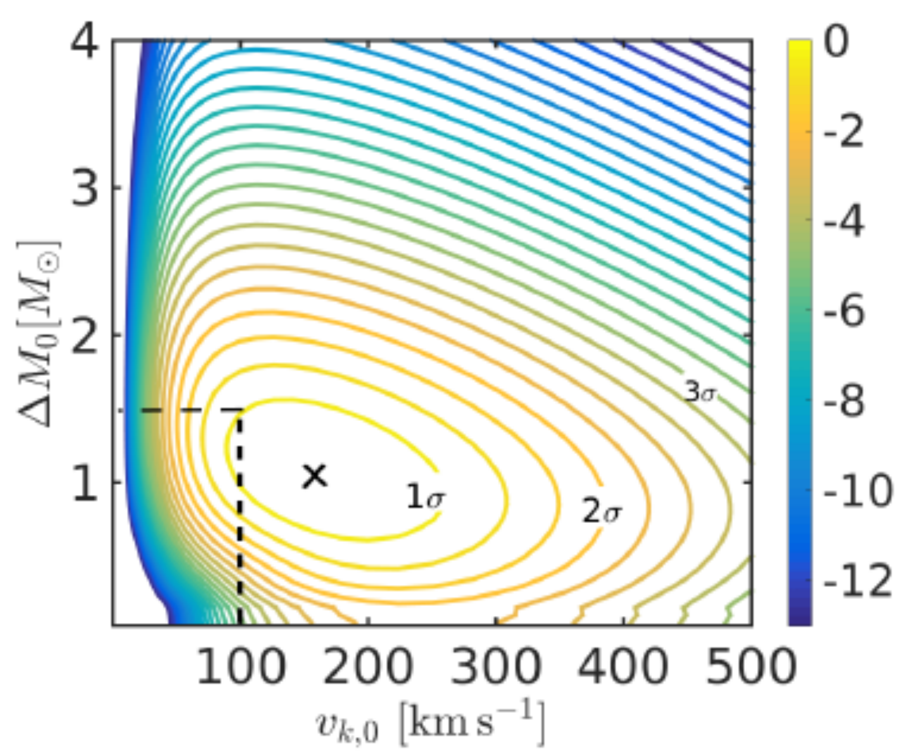
✳Most observed Galactic binary neutron stars have almost circular orbits and a low proper motion

➡Very low mass ejection (<0.1 M_{sun} for J0737-3039B)

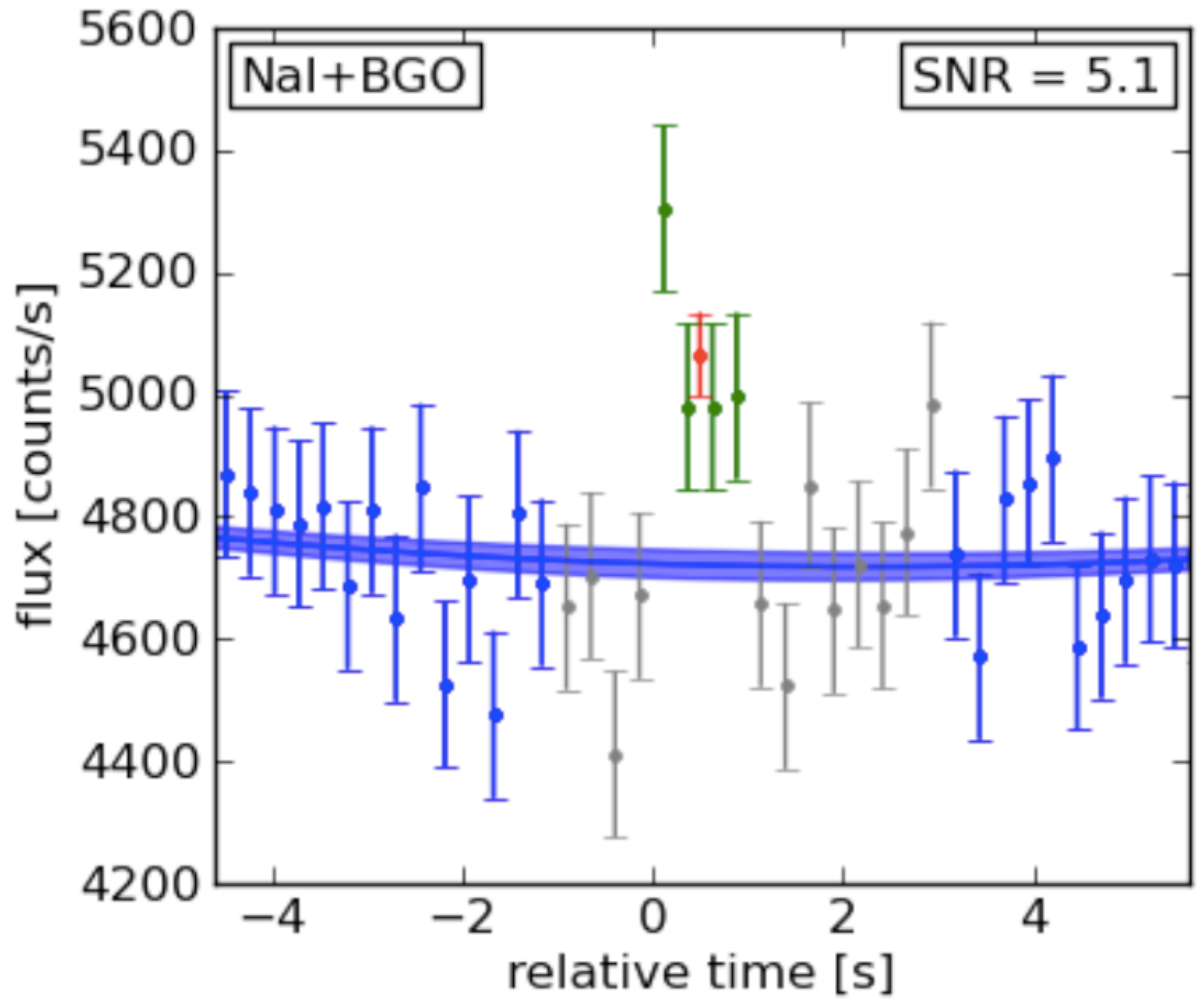
➡NOT formed in a regular SNe

This is not taken into account in most (e.g. Cote +) Pop synthesis calculations.

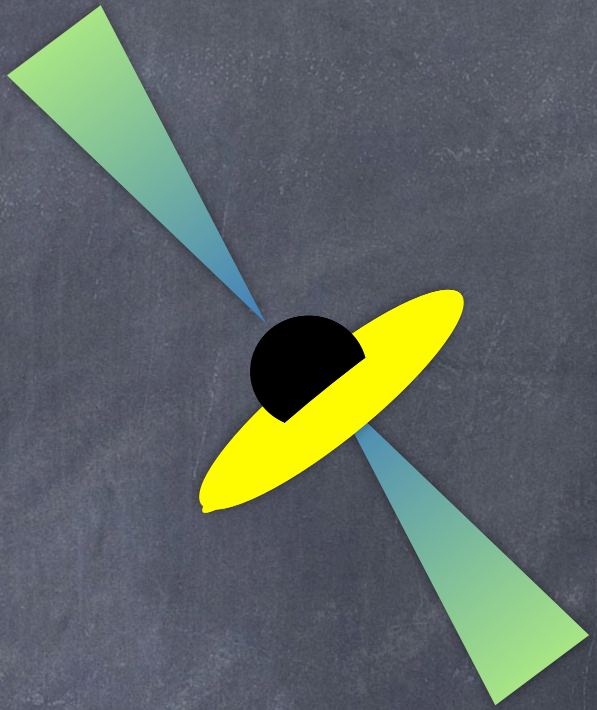




GBM counterpart (p=0.002)



The BHBH (GW150914) EM counterpart problem



- $>10^{49}$ ergs => $> 10^{-5}$ m_{sun}
- Life time of a BHBH binary ~1 Gyr (from minimal separation)
- Cannot keep so much mass from formation for 1 Gyr.
- Need to link (in time) the mass accumulated to the merger.

???

- A short distance capture + matter injection

=> A 3 body interaction in a globular cluster?

=> Maybe possible but extremely rare