Setting the stage: GW++

NS mergers as multimesenger systems - (GRBs) Macronovae, Radio Flares and neutrinos

Tsvi Piran

The Hebrew University of Jerusalem

Kenta Hotokezaka, Ehud Nakar, Ben Margalit, Doron Grossman, Stephan Rosswog

OUTLINE

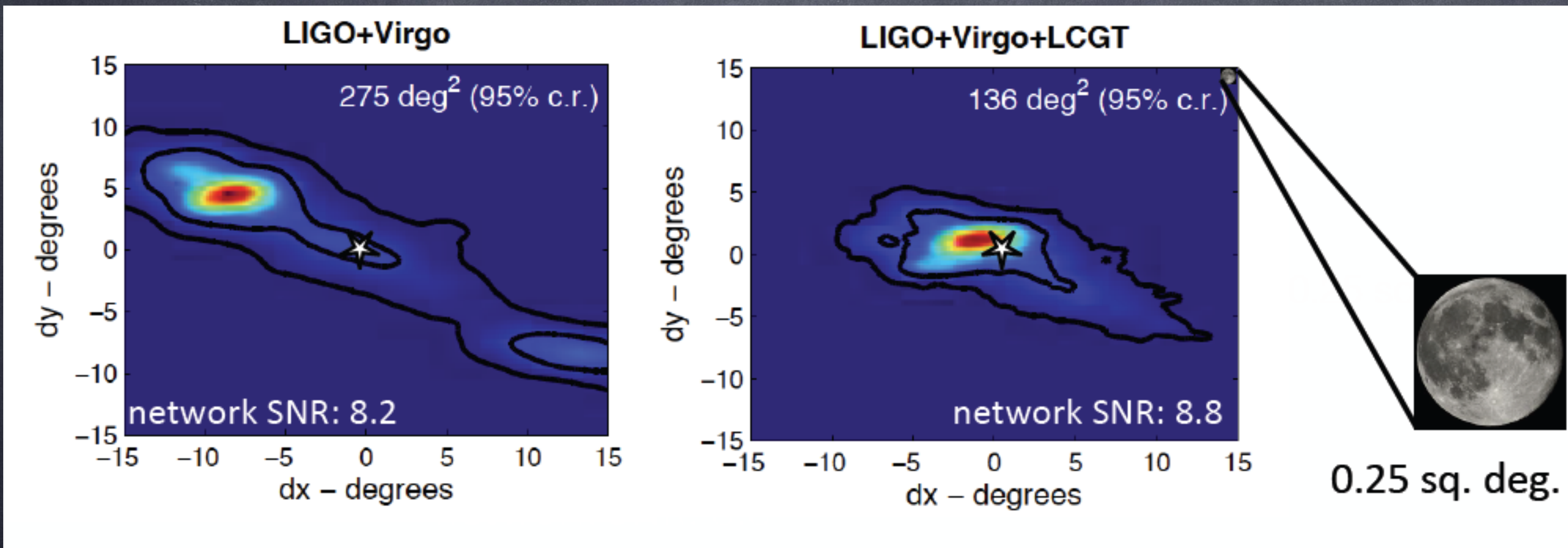
- Why ++: why do we care about EM counterparts?
- Overview of mass ejection components
- Macronova/kilonova
- Radio Flares

Why EM signal?

(Kochaneck & Piran 1993)

- Improves detectability
- Essential for localization
- Much more physics: Nucleosynthesis, neutrinos, magnetic fields

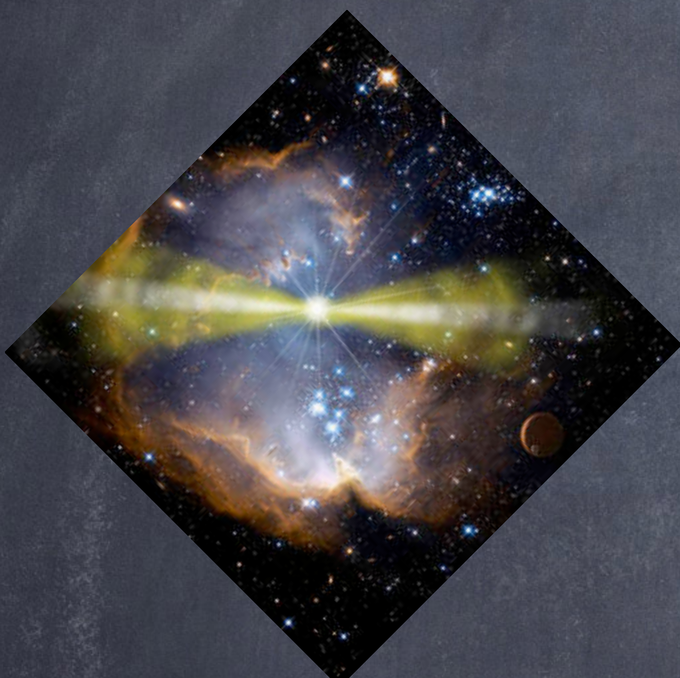
The Gravitaitional Waves Challenge

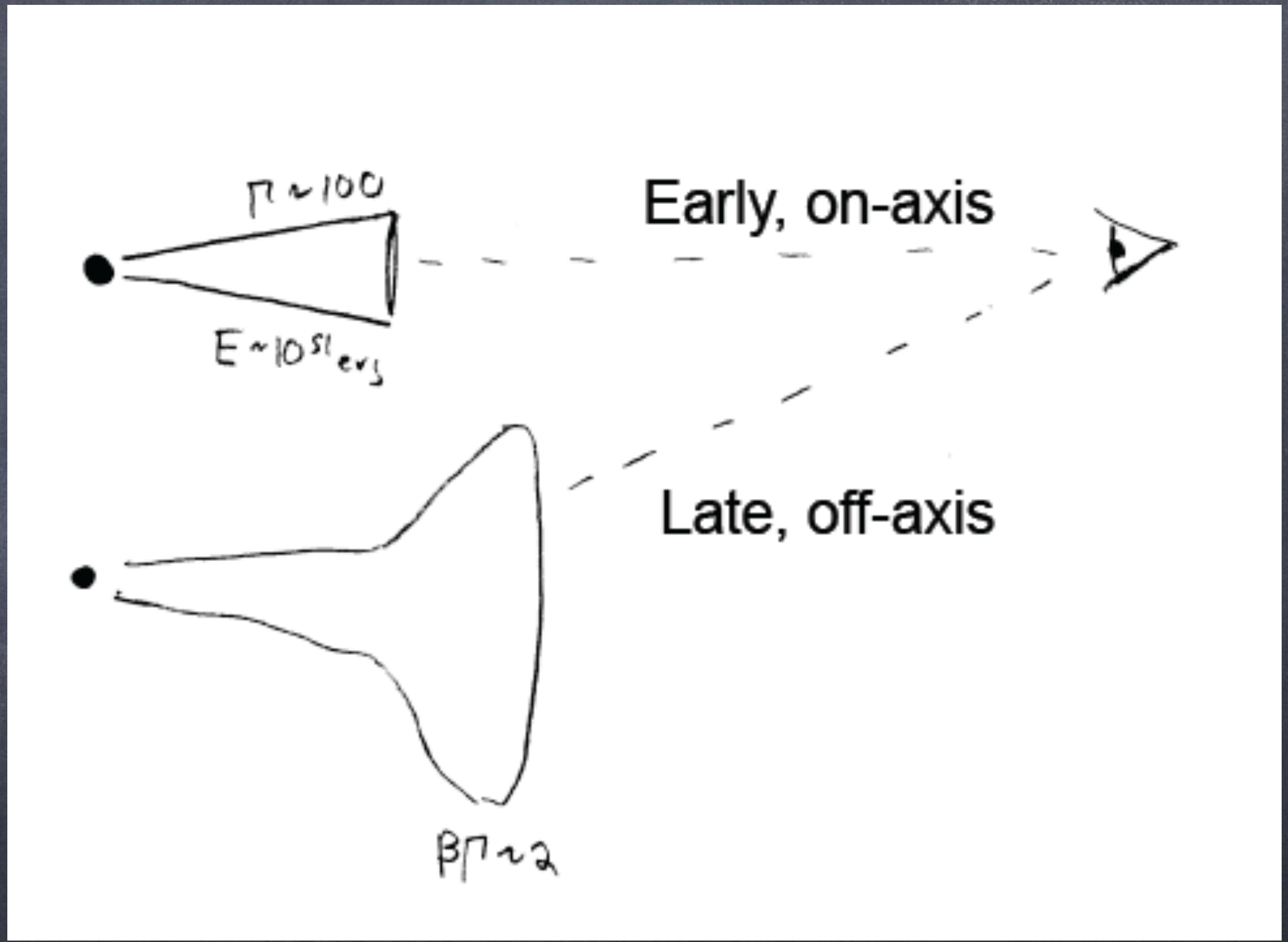


Nissanke + 13

Kochaneck +TP 93: need an EM counterpart

GRBs are beamed -> unlikely to catch the GRB

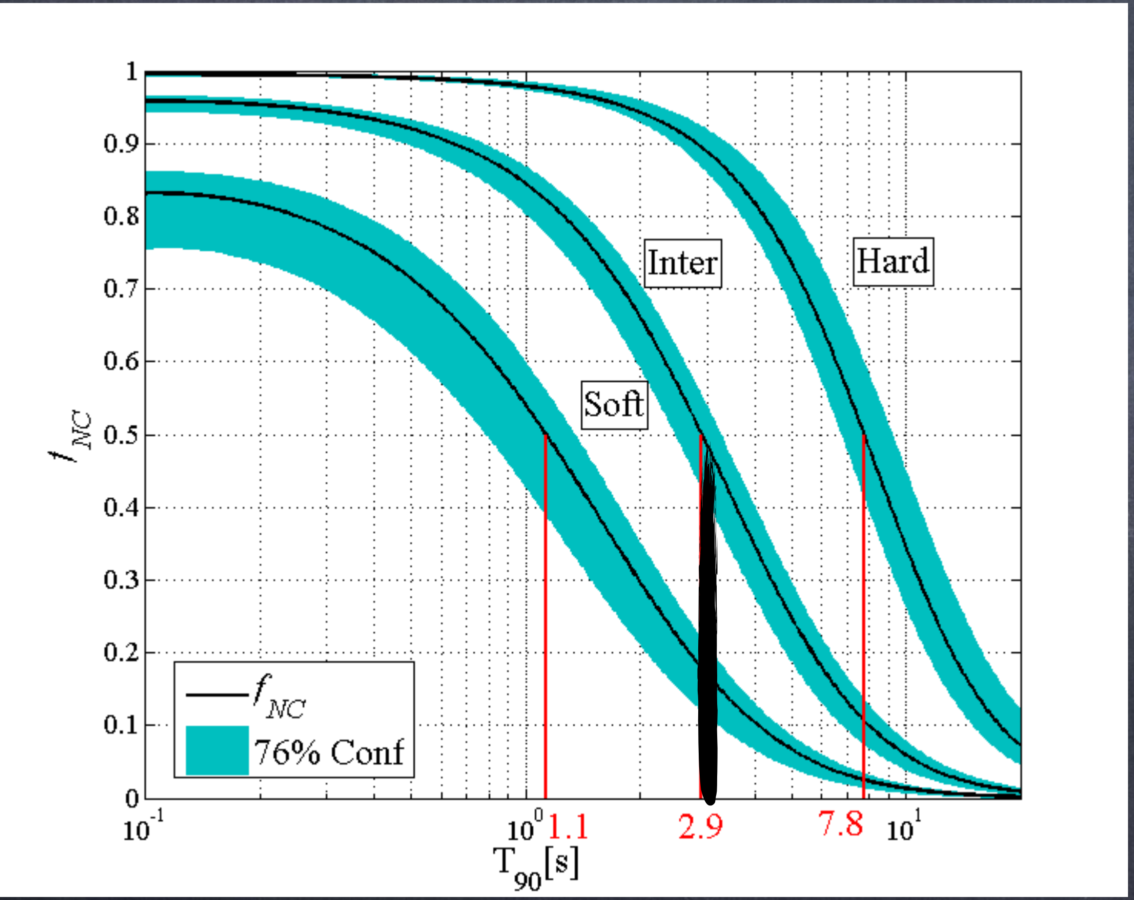




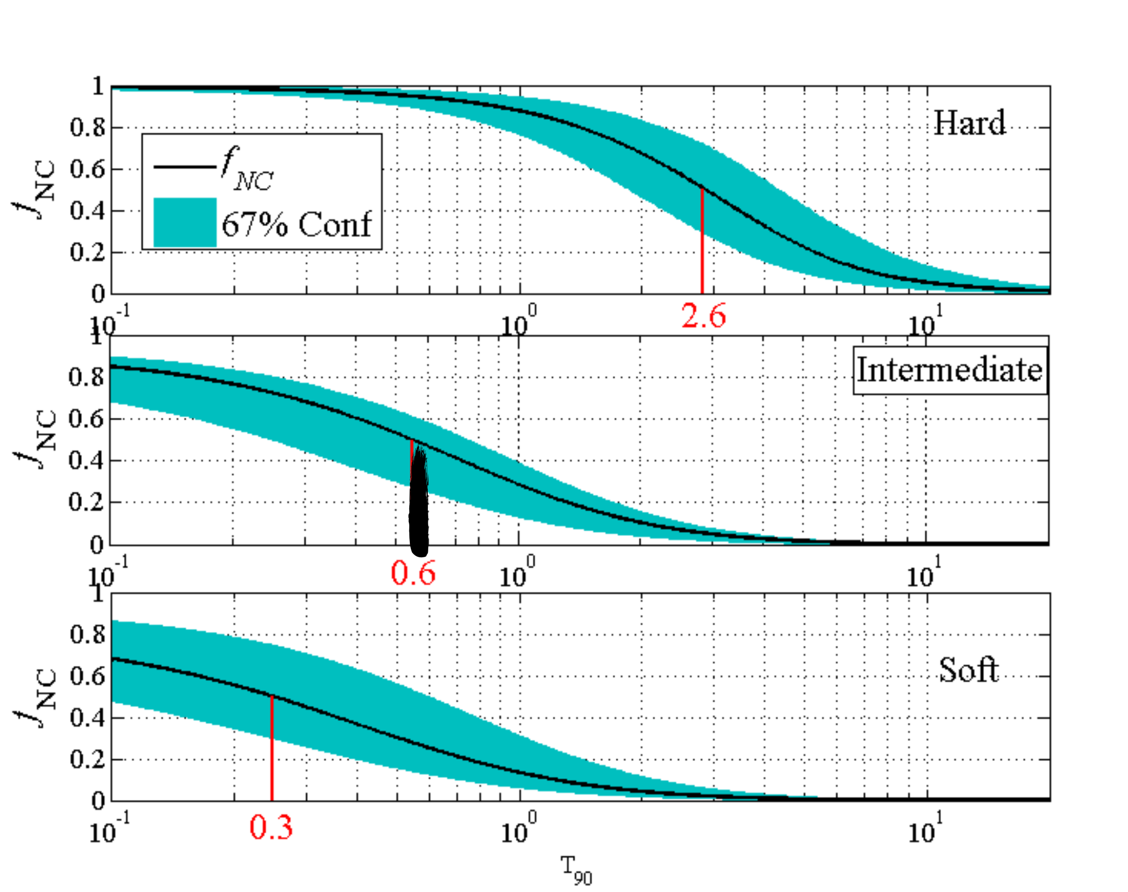
Off axis emission is too weak

What is a really short GRB? P_{nc}: Non-Collapsar Probability

BATSE

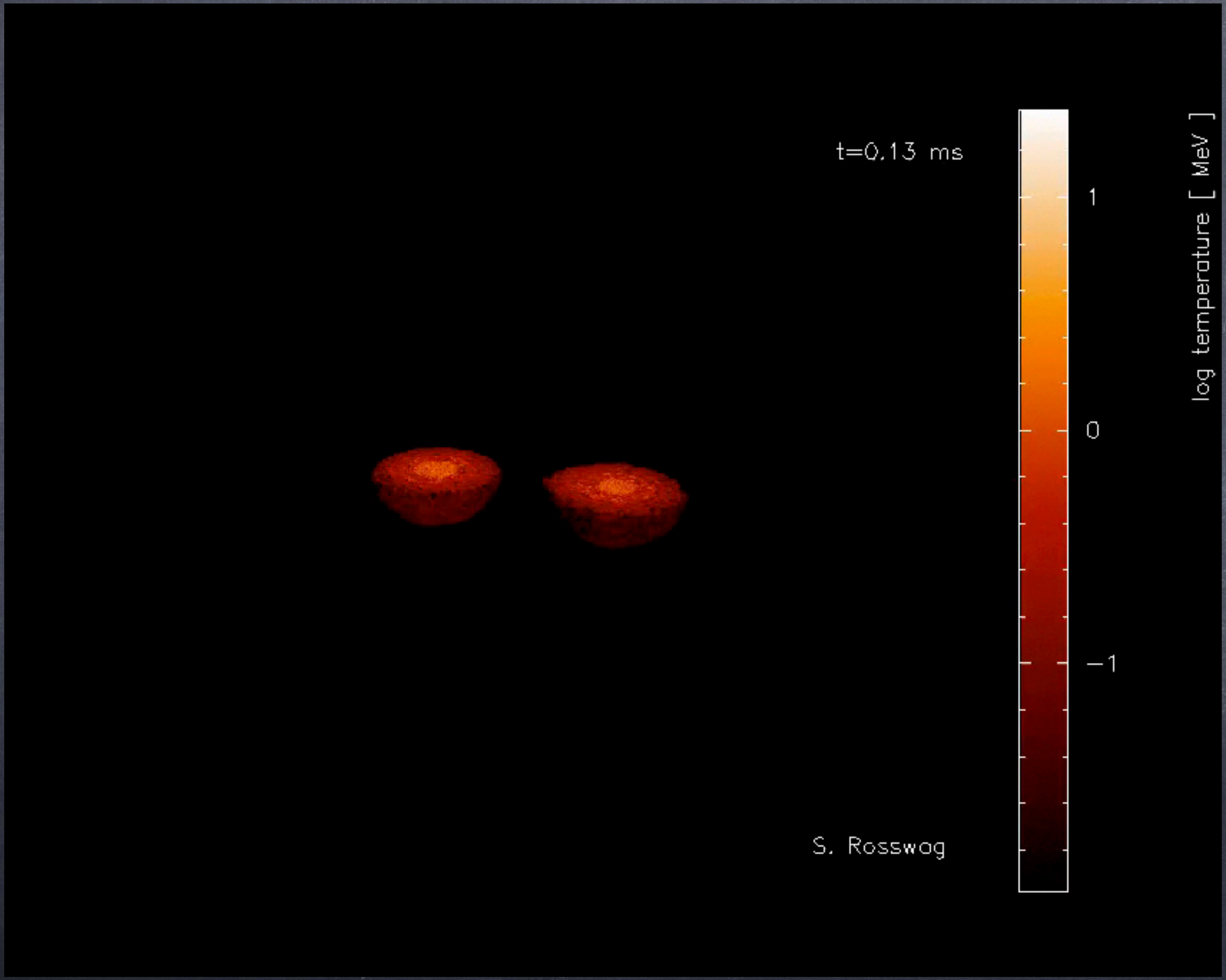


Swift



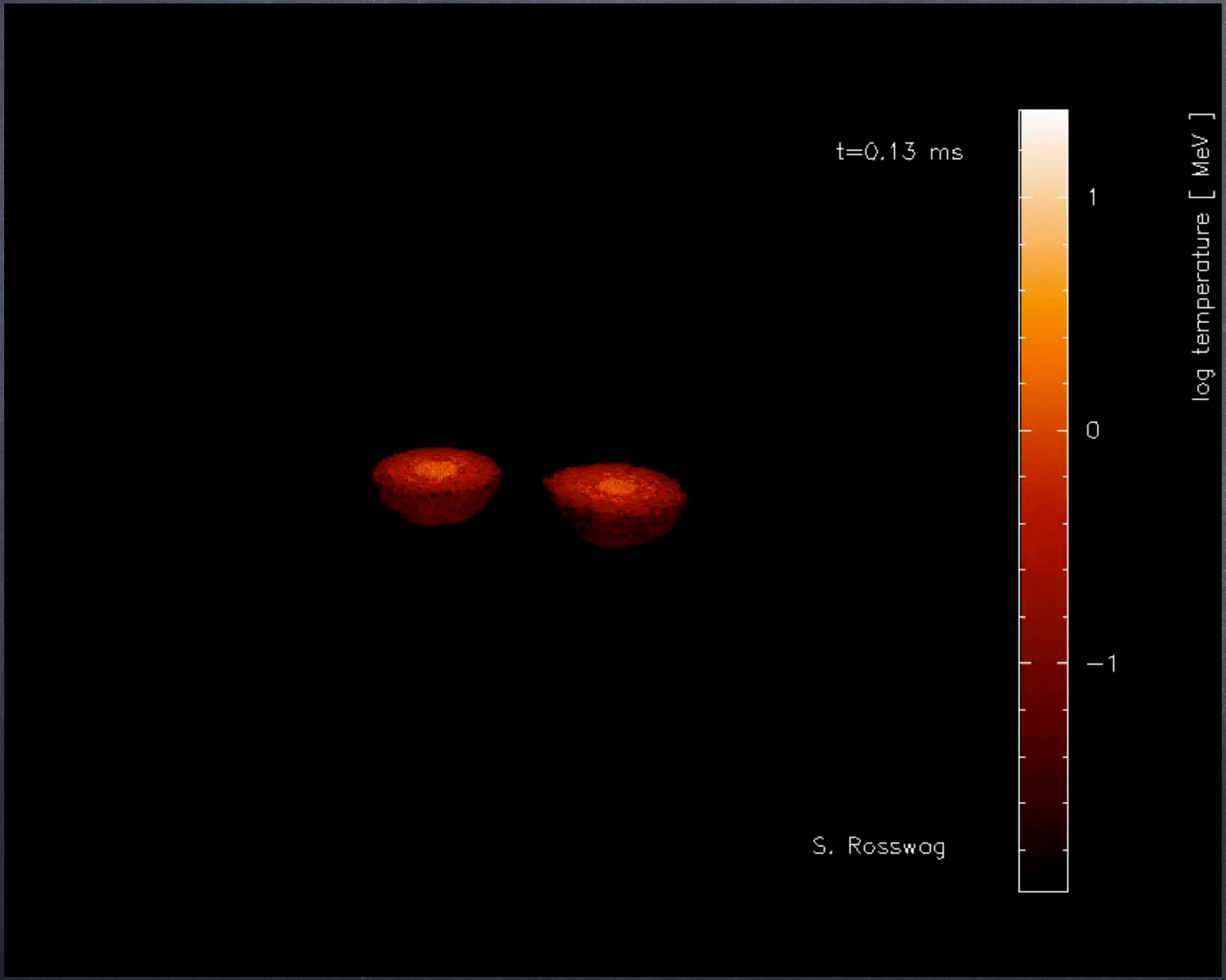
See http://www.phys.huji.ac.il/~tsvi/SGRB_Probability

Mergers ejects 0.01-0.04M_{sun} with $E_k \sim 10^{49}$-10^{51} ergs



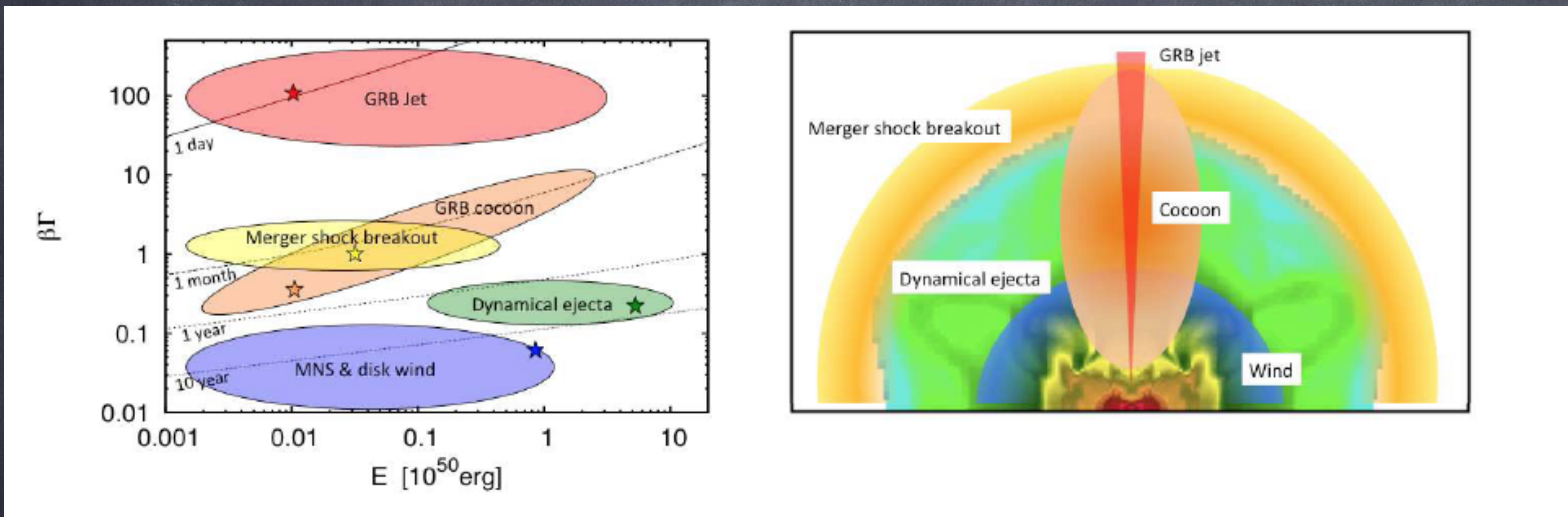
Stephan Rosswog

Mergers ejects 0.01-0.04M_{sun} with E_k ~ 10^{49}-10^{51} ergs



Stephan Rosswog

Outflows from mergers



Available Energy

- 10^{49}-10^{51} ergs of kinetic energy ====> GRB, GRB afterglow, Radio flare + ??
- 10^{49}-10^{51} ergs of Poynting flux? ====> GRB?
- ~10^{50} ergs of radioactive energy ====> Macronova/kilonova

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.

* Kilonova

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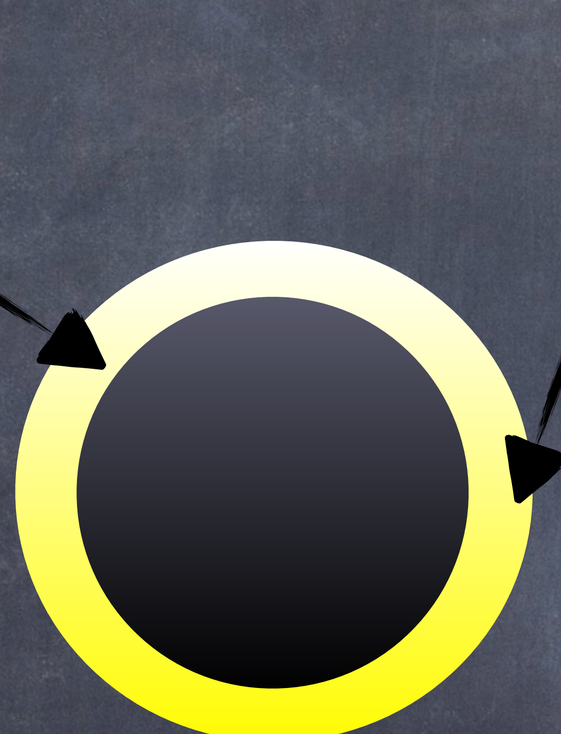
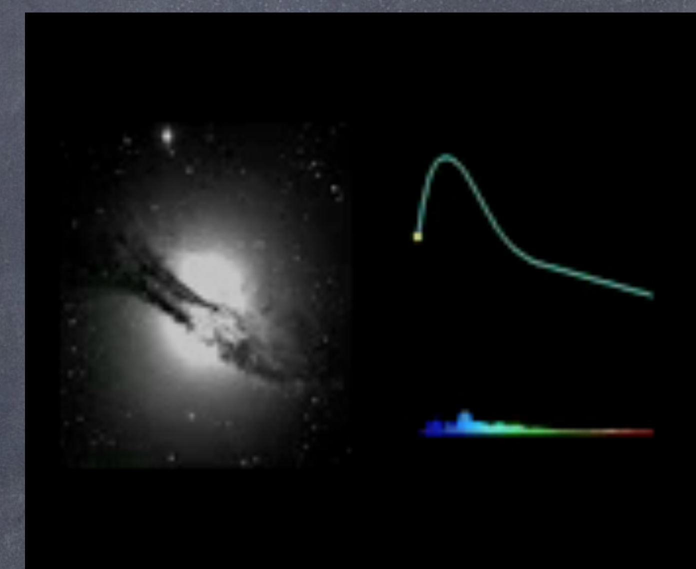
* ~~Kilonova~~ → ~~Hektanova~~ → Decanova

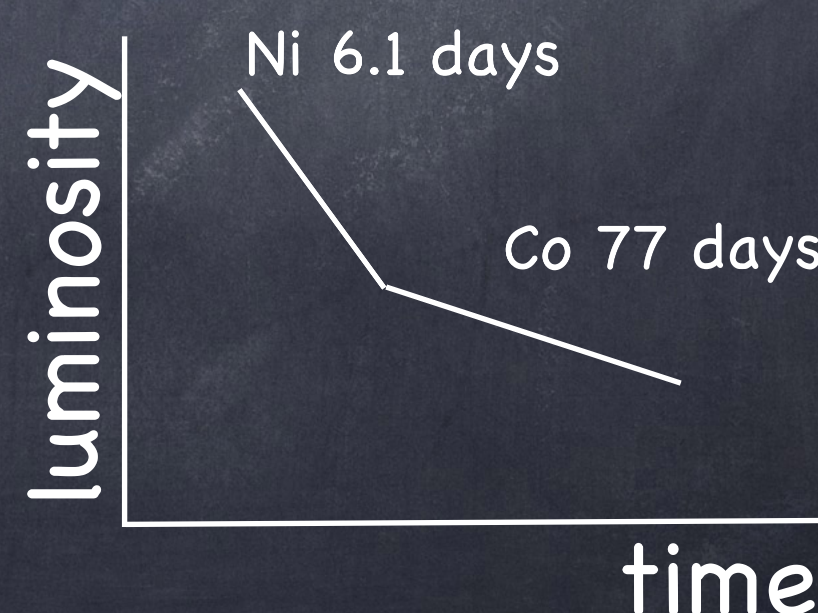
Supernova

Photosphere

Photons escape





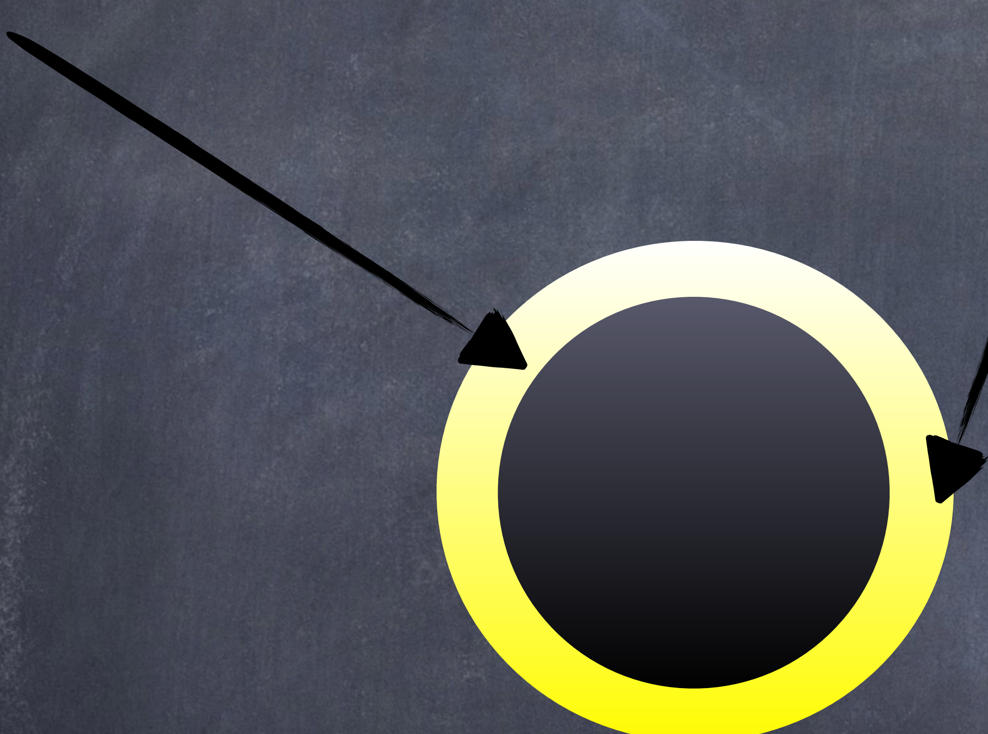


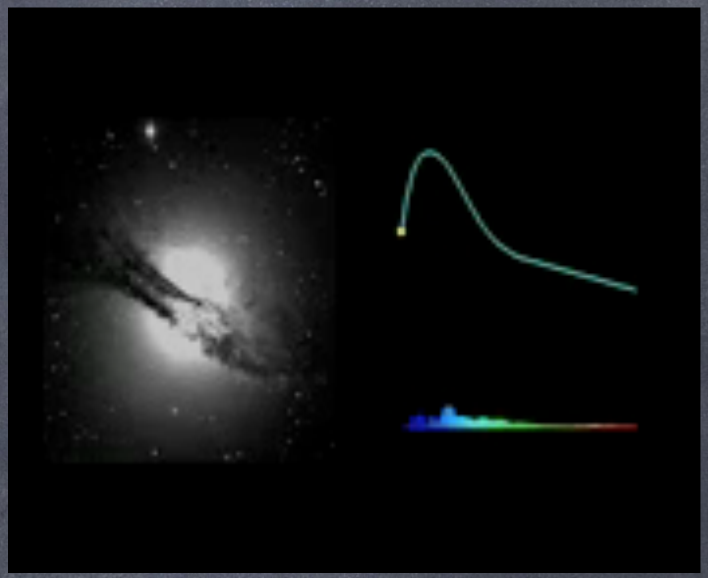
Powered by radioactive decay of $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

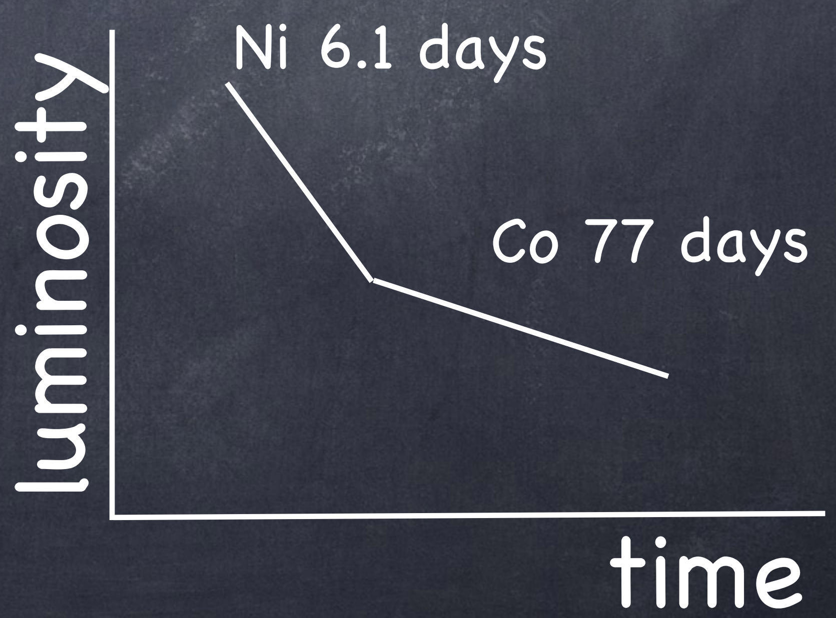
Supernova

Photosphere

Photons escape







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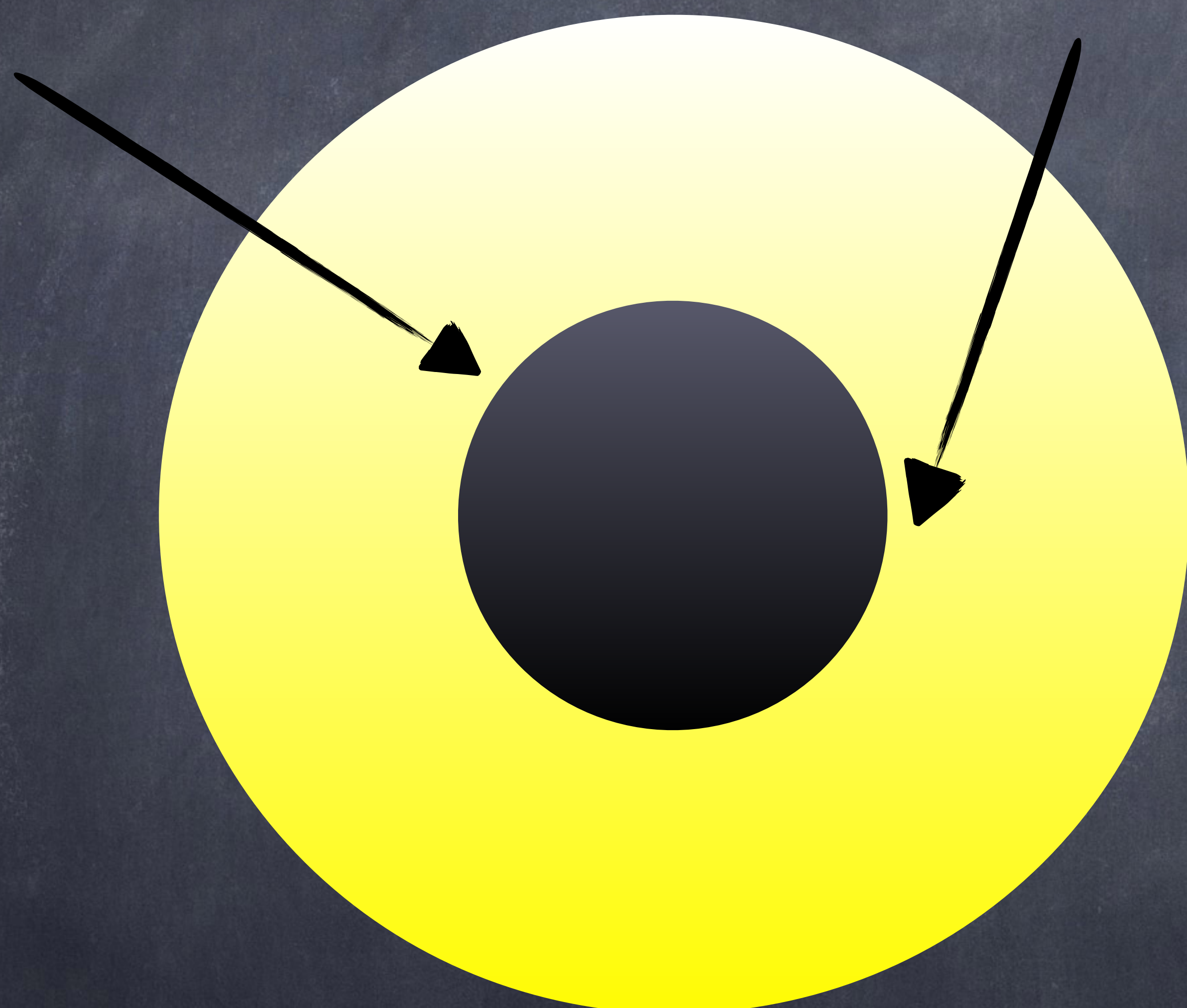
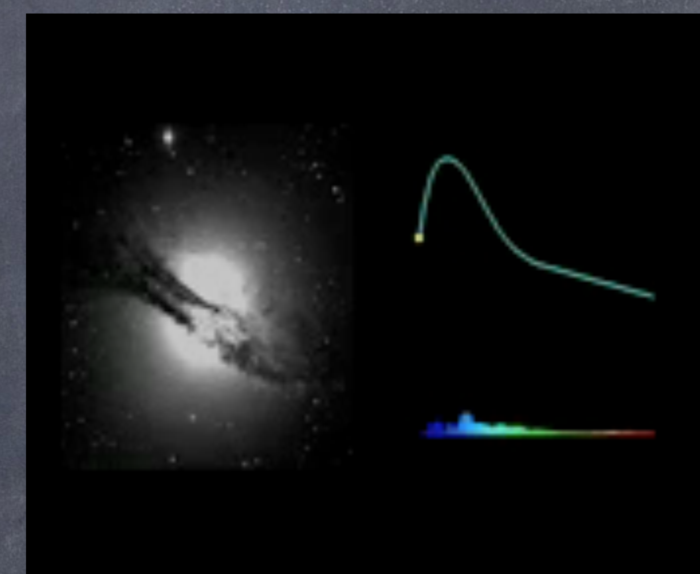
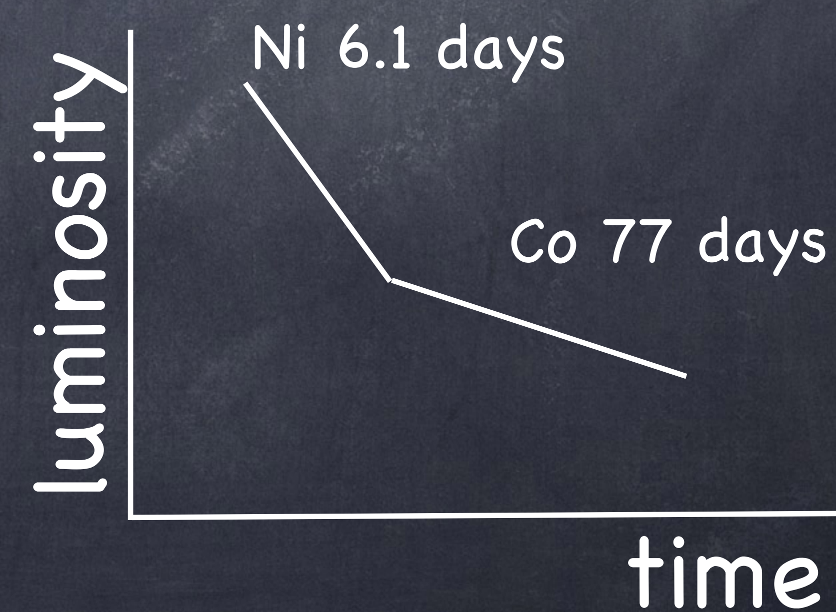
Supernova



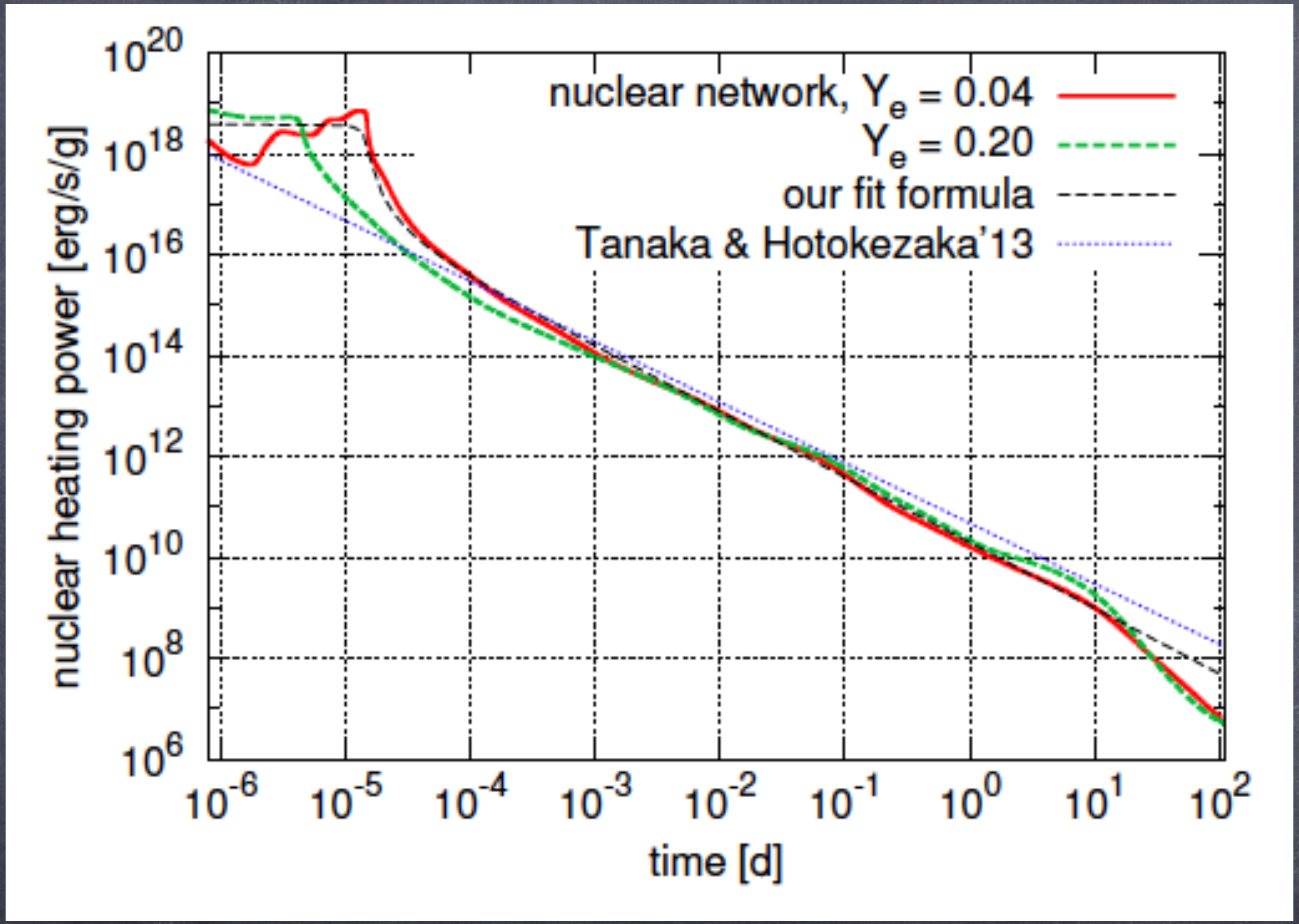




Powered by radioactive decay of $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

Radioactive Decay

Korobkin + 13; Rosswog, Korobkin + 13



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

Diffusion time

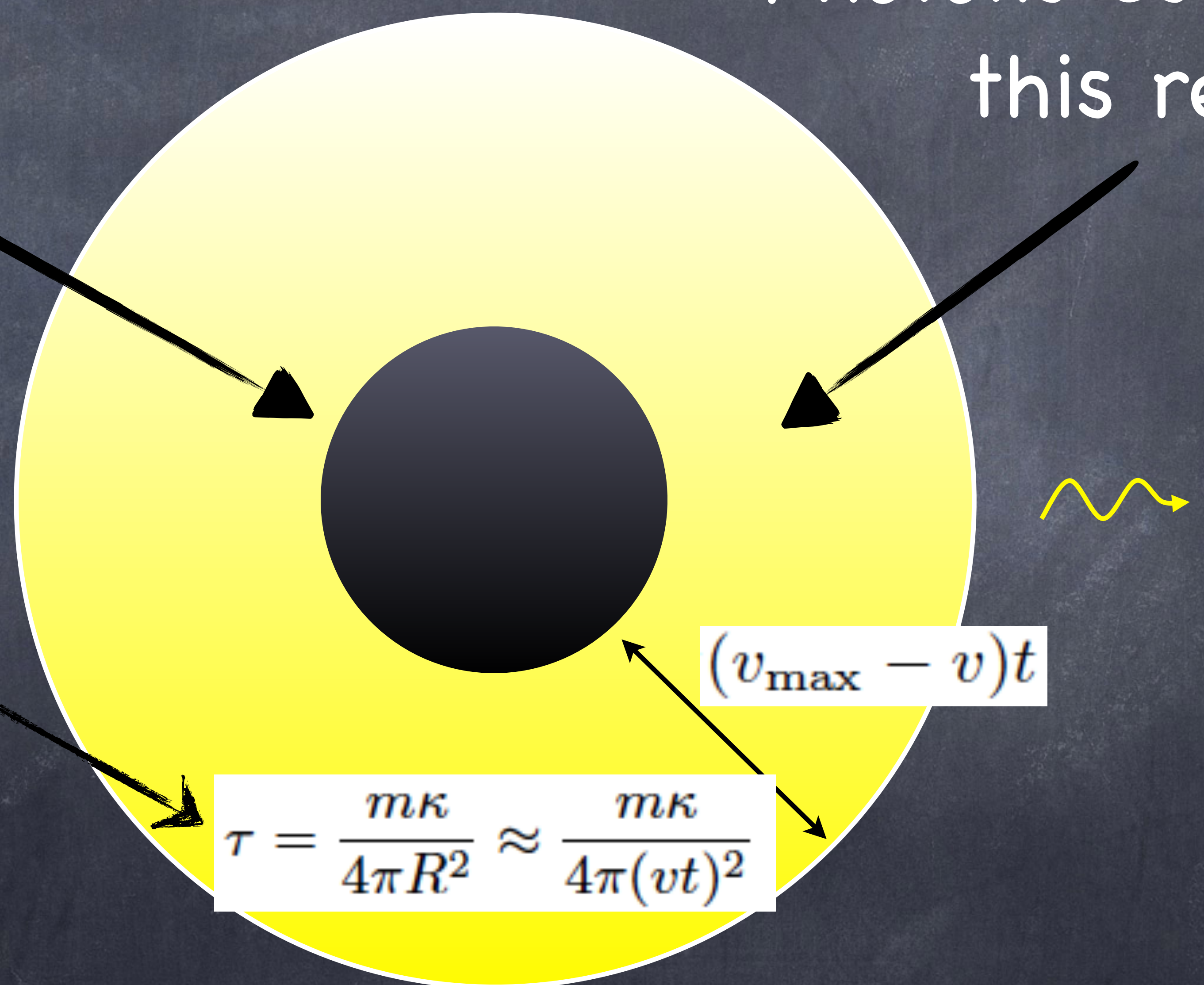
Opacity

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

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

Optical depth

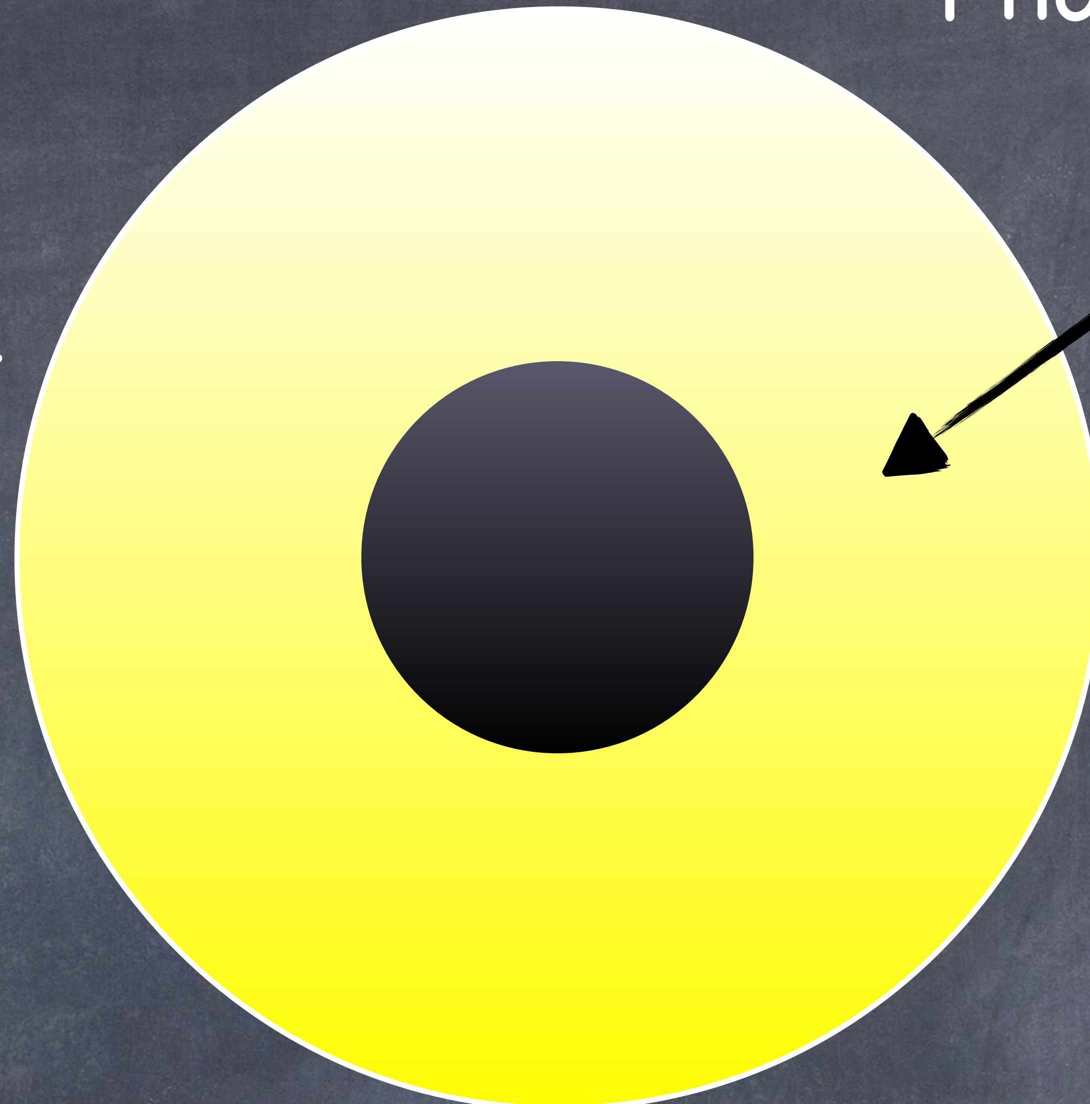
Photons escape from this region



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

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

Photons escape from this region



The light curve depends on

1. mass
2. velocity
3. opacity

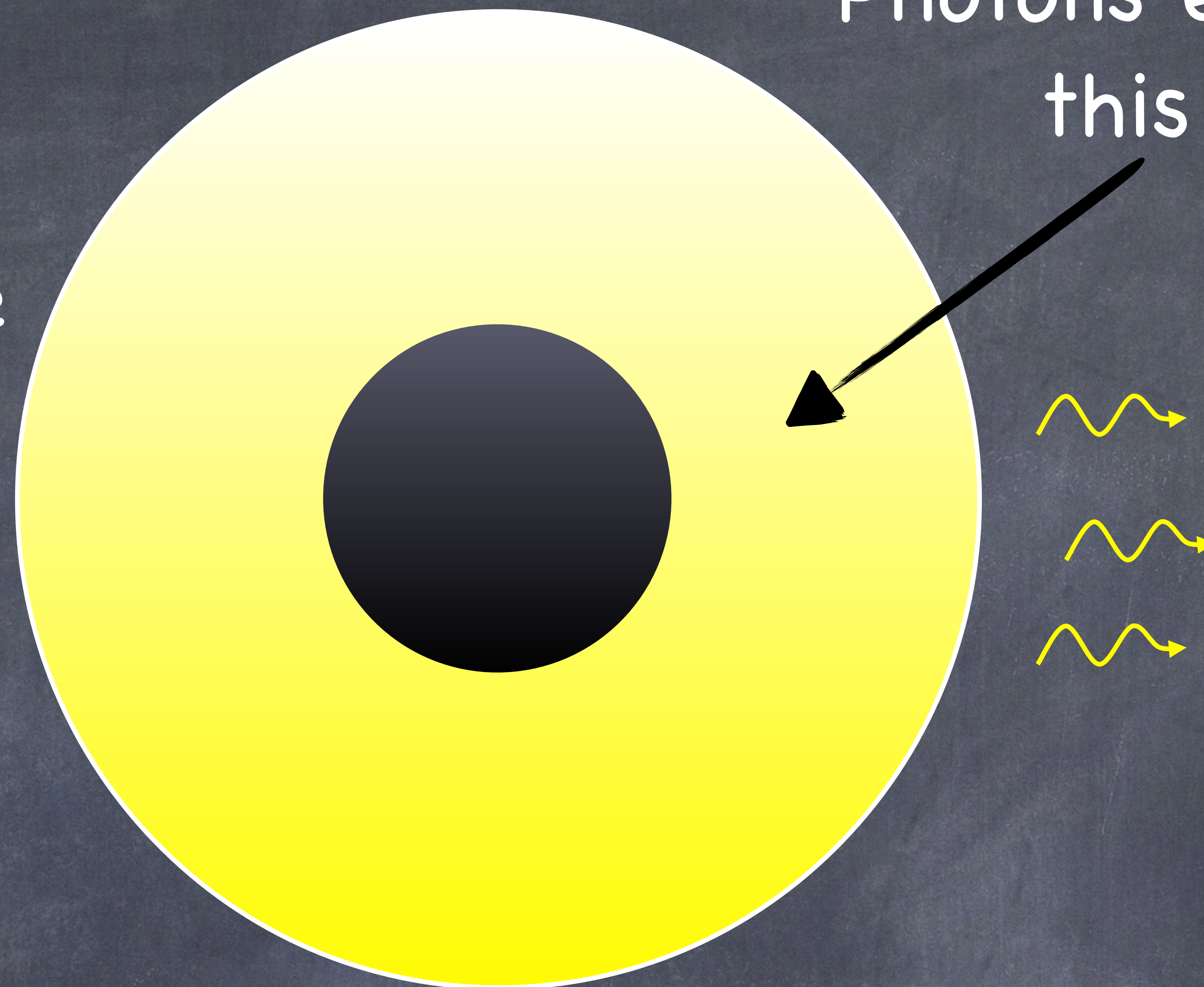
Increase as we see a large fraction of the matter.

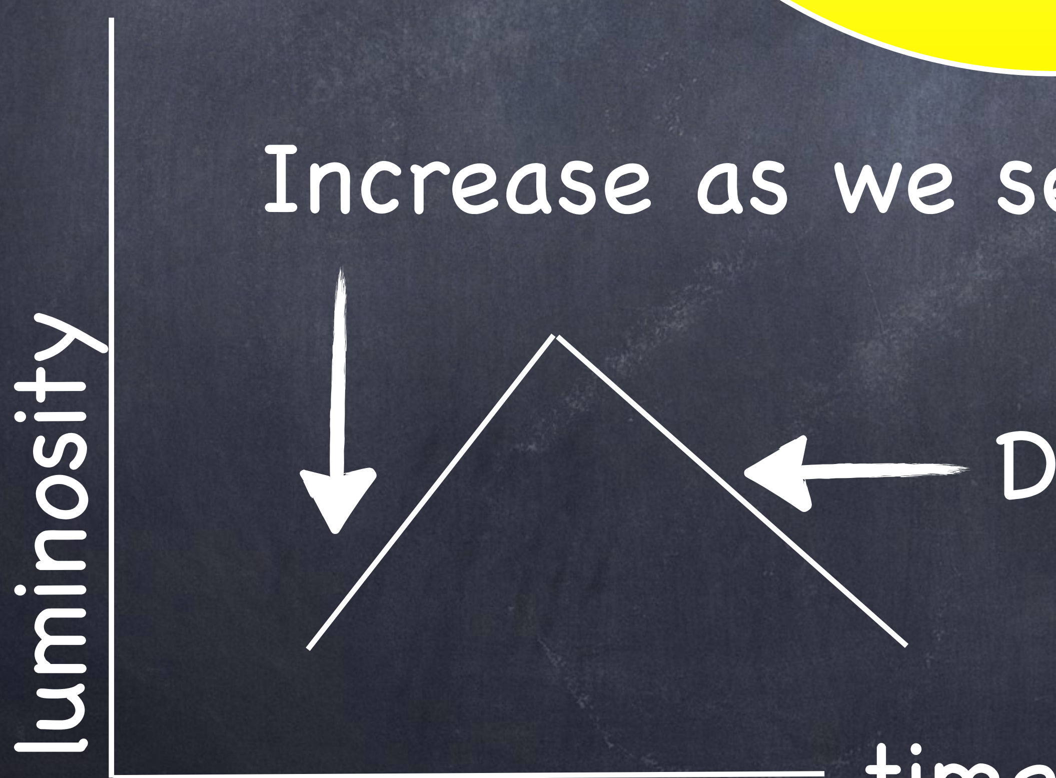
Decrease due to radioactive decay

Macronova

The light curve depends on

1. mass
2. velocity
3. opacity





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

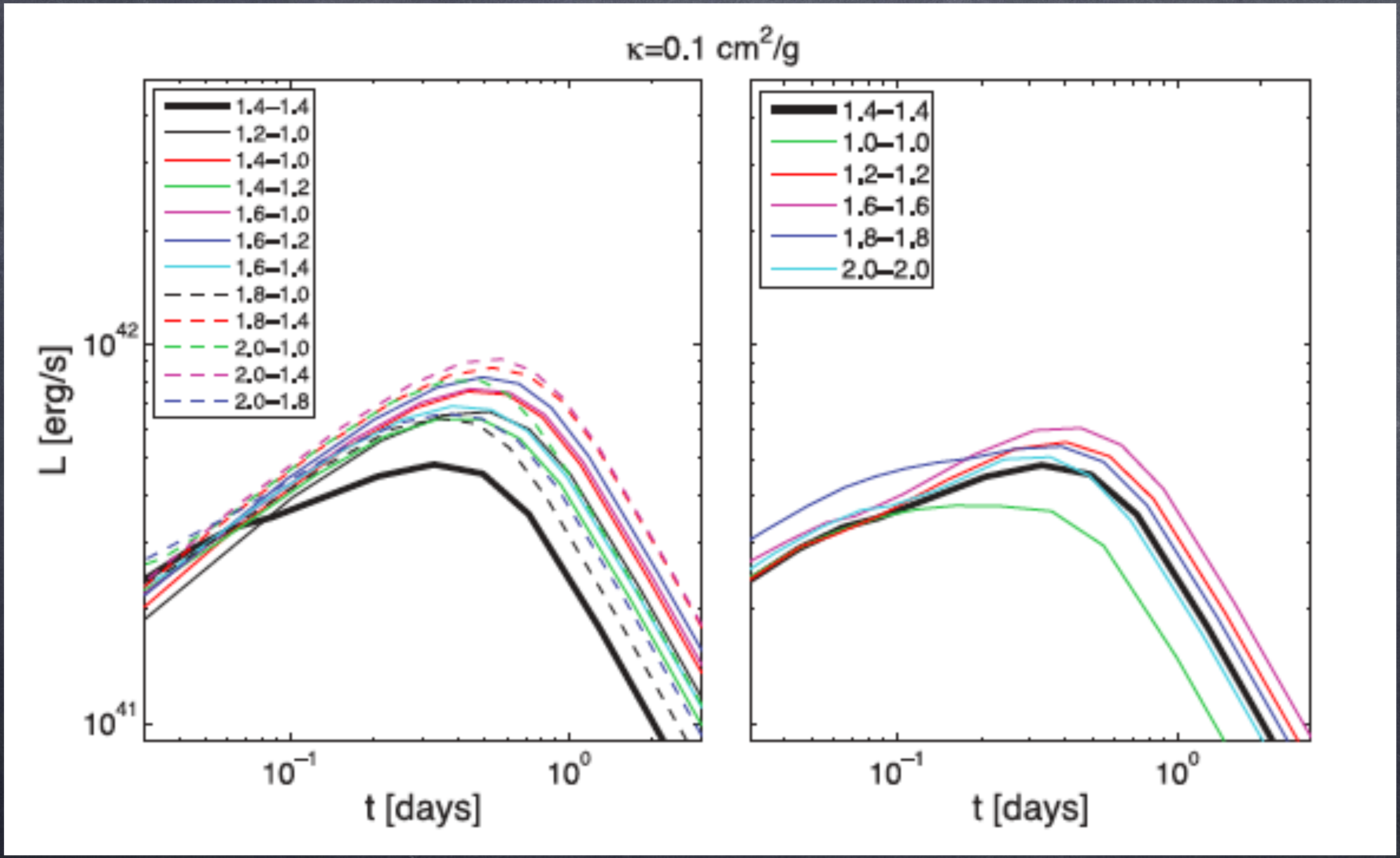
$$\tilde{t}_p \approx \sqrt{\frac{\kappa m_{\rm ej}}{4\pi c \bar{v}}} = 4.9\ \mathrm{days} \left(\frac{\kappa_{10} m_{{\rm ej},-2}}{\bar{v}_{-1}}\right)^{1/2}$$

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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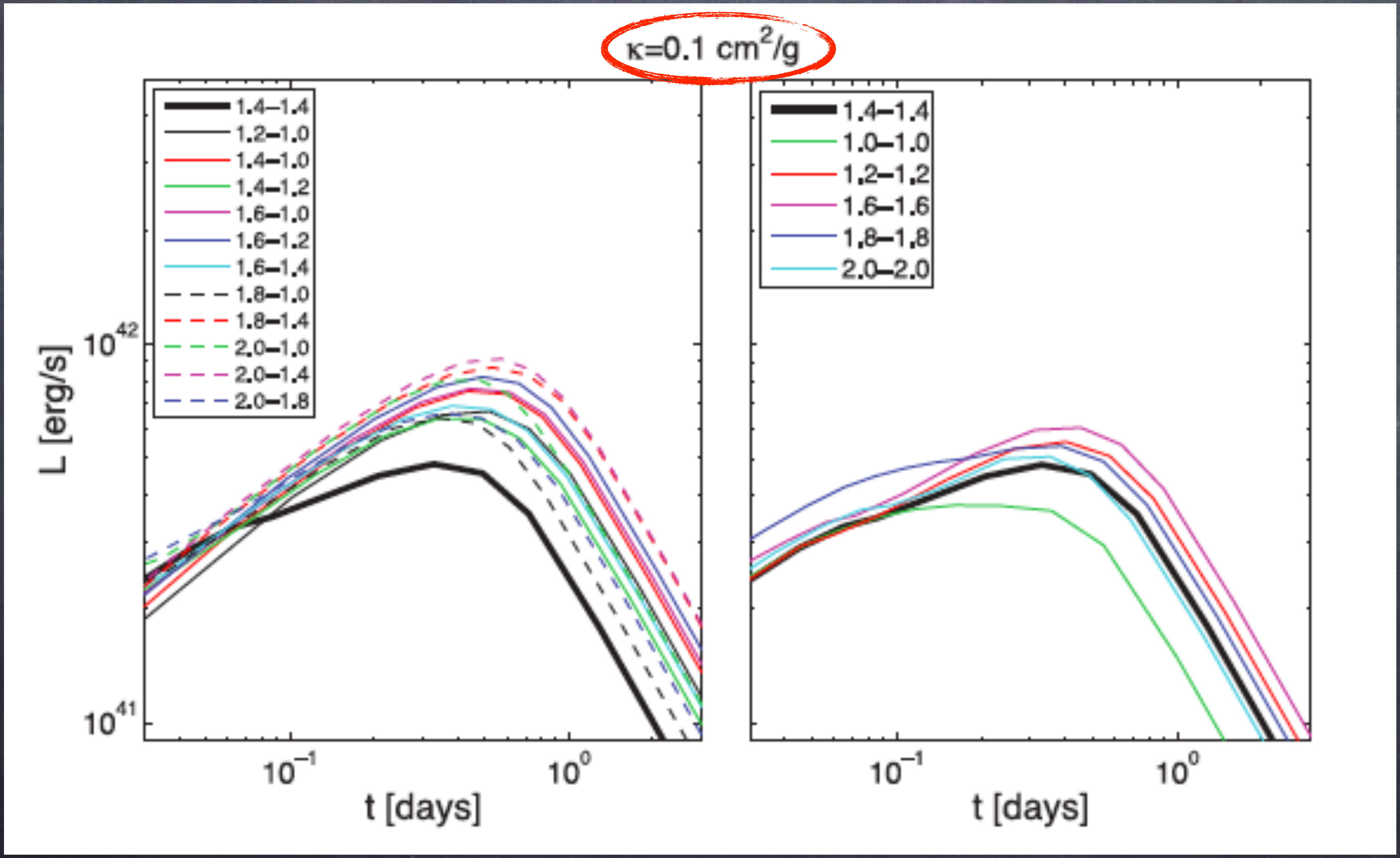
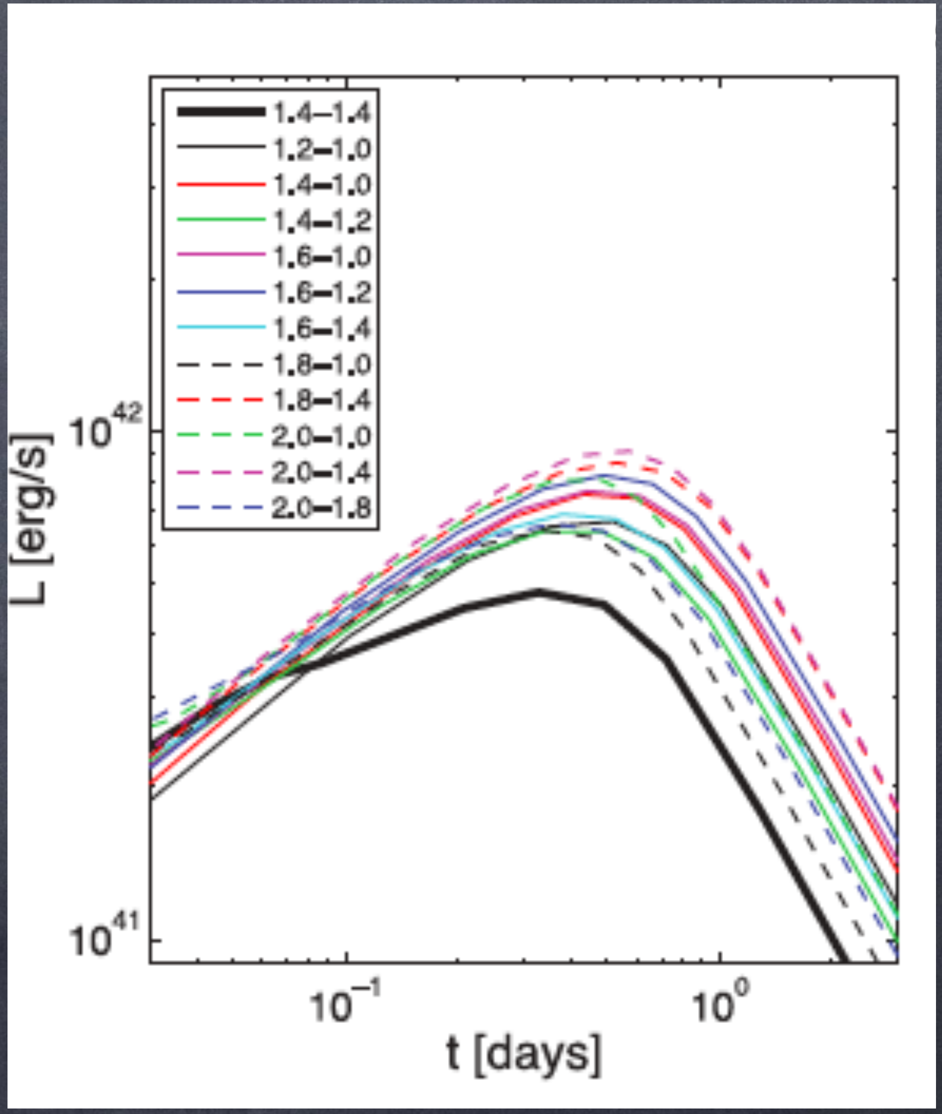


Lanthanides dominated Opacity

(Barnes & Kassen 13, Tanaka & Hotokezaka 13)

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



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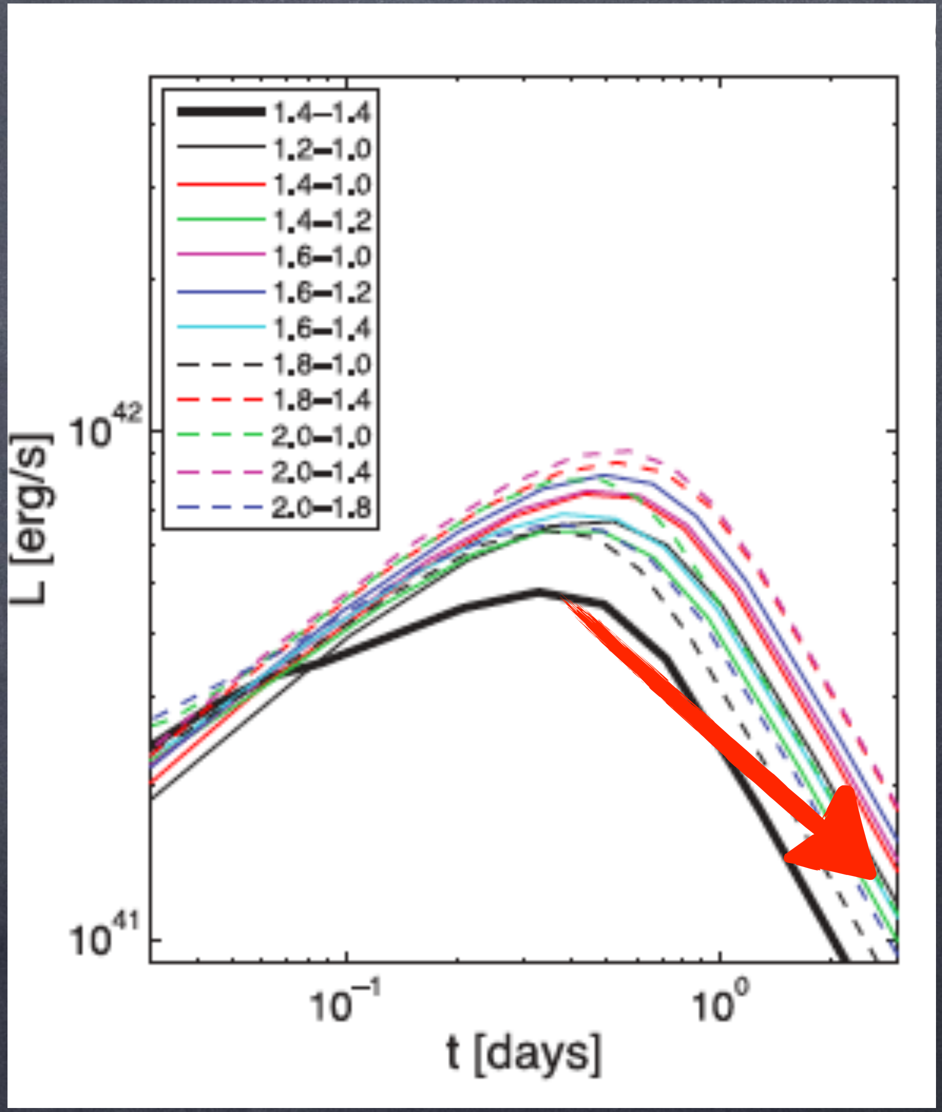

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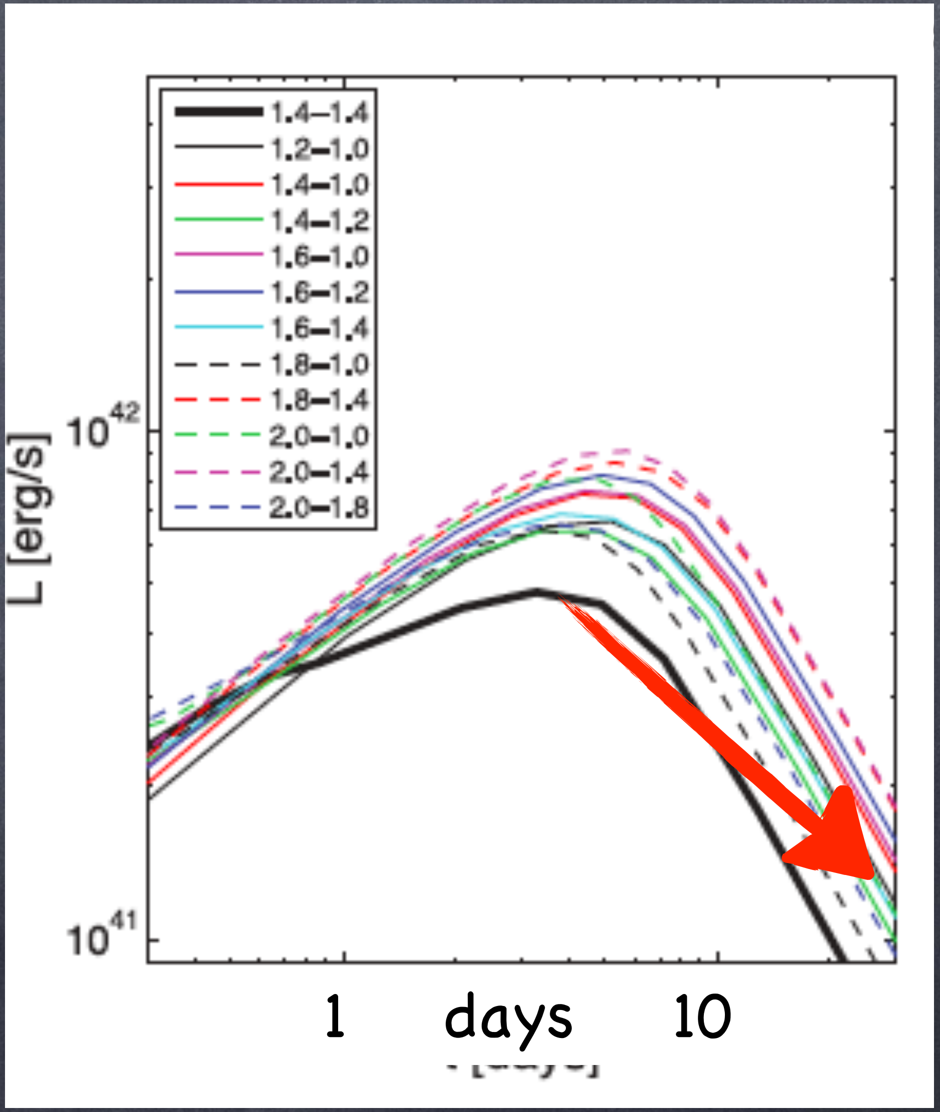

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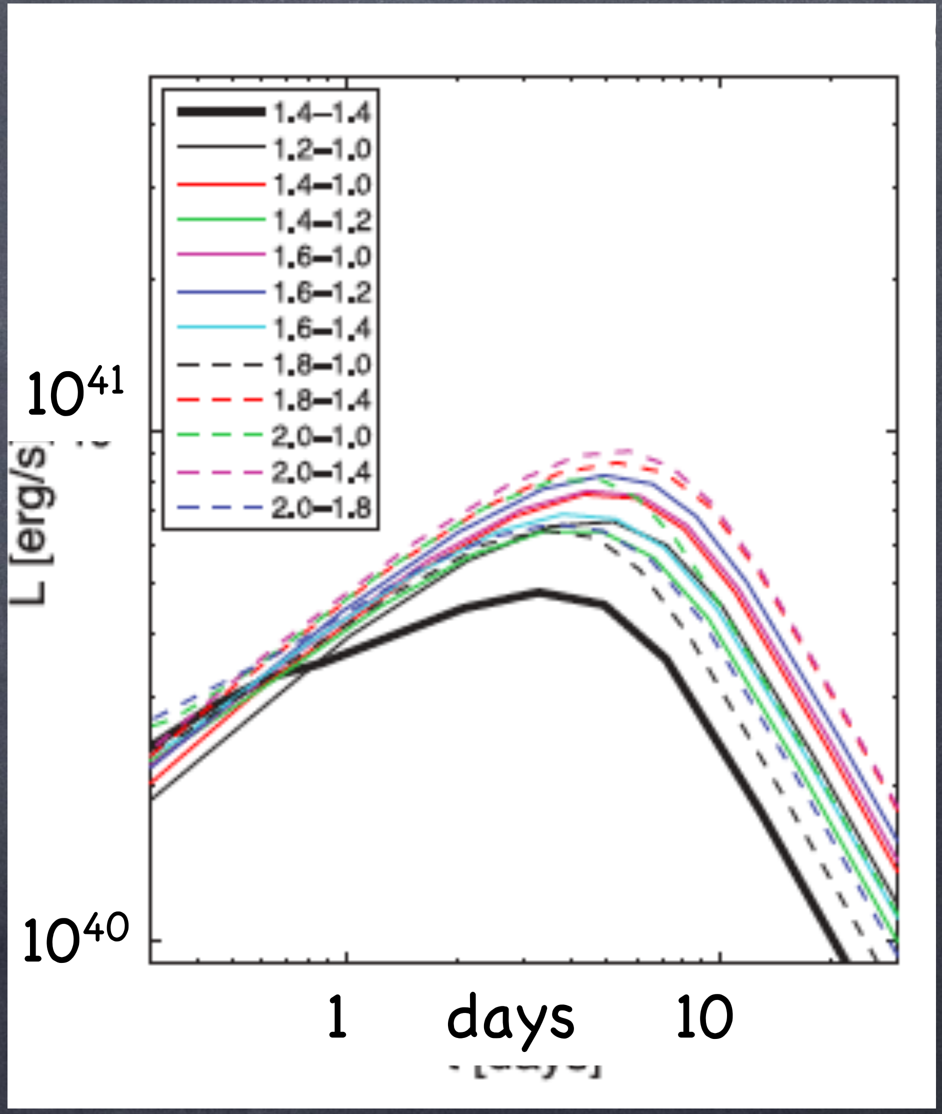

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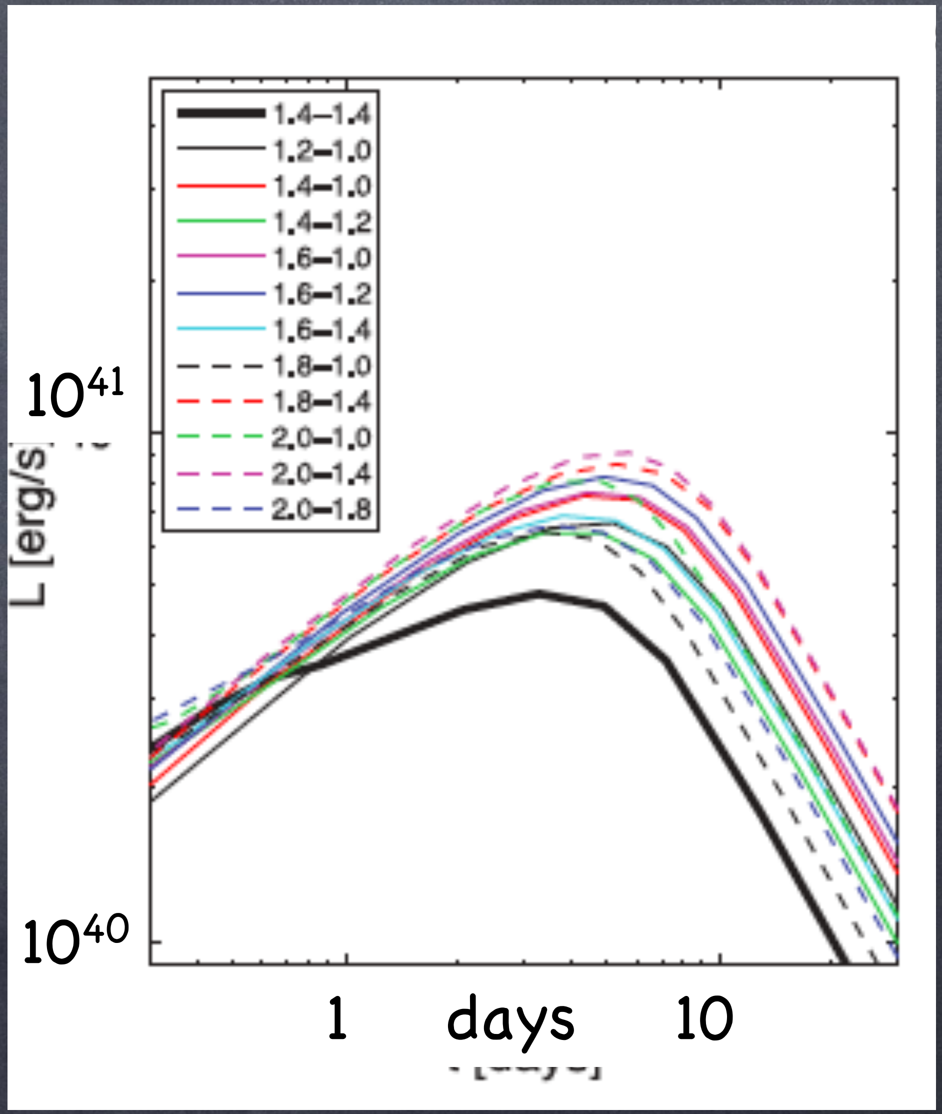
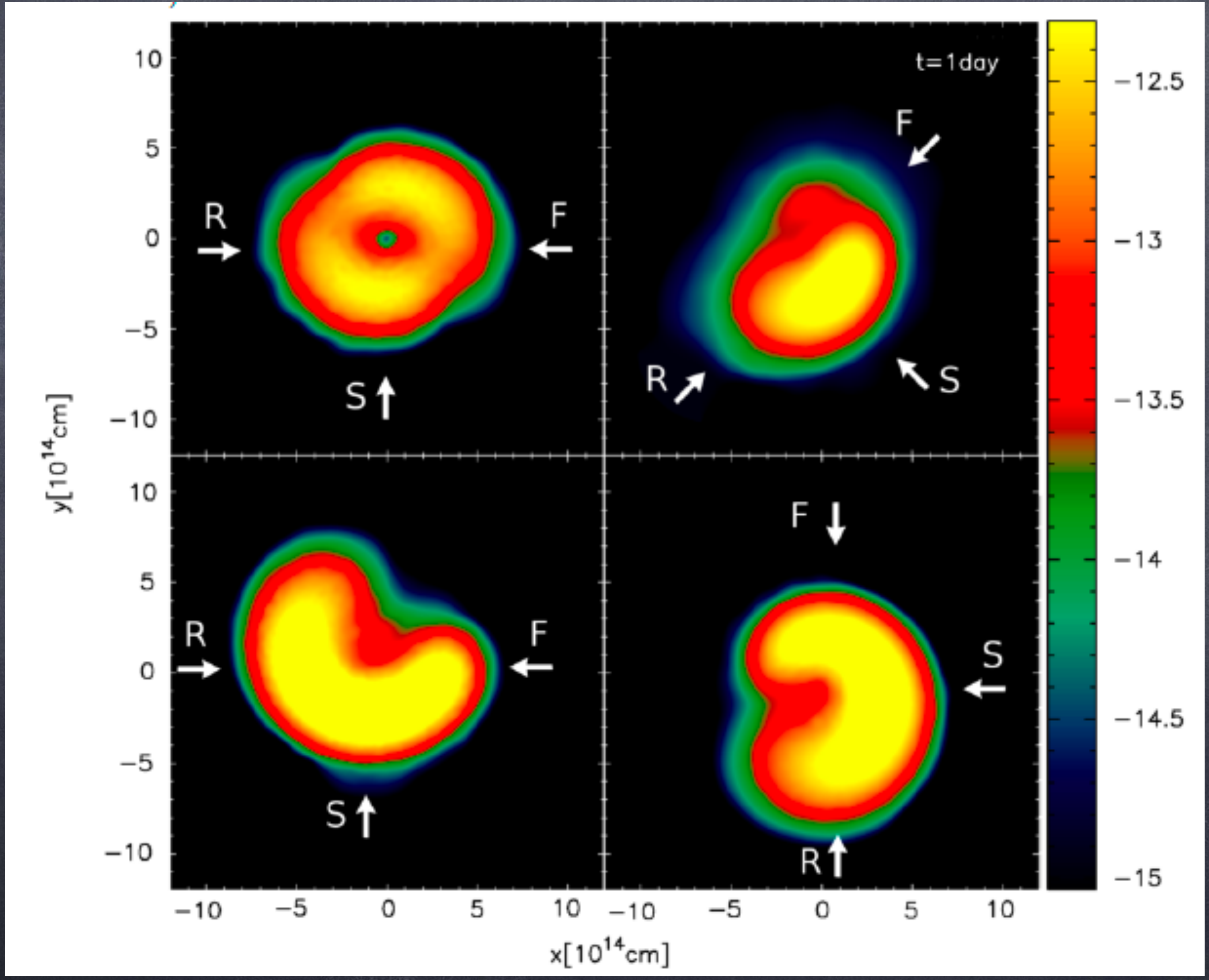


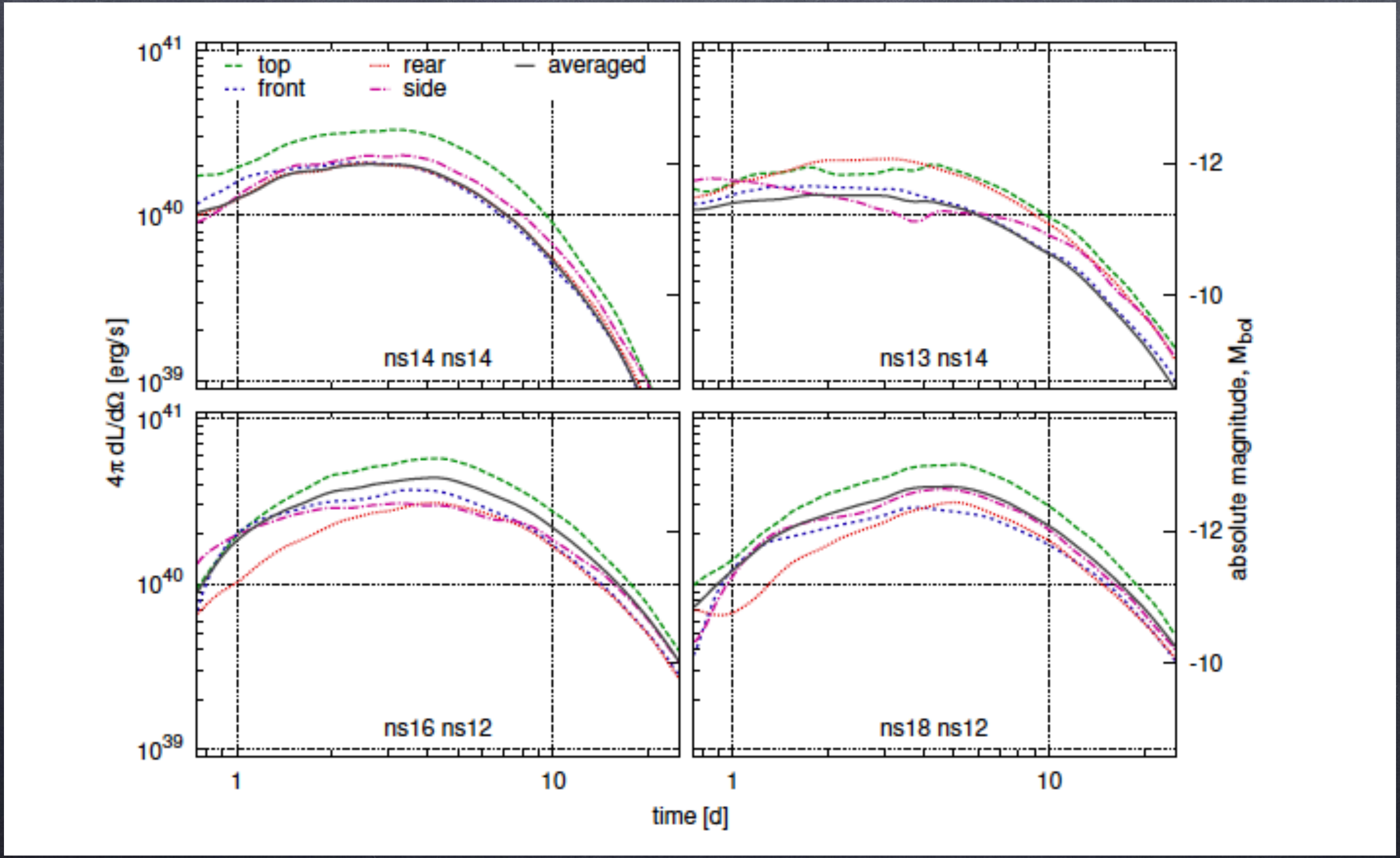
uv or optical -> IR

Non Sphericity

Grossman, Korobkin TP Rosswog, 13



Bolometric light curves



wind + dynamical ejecta

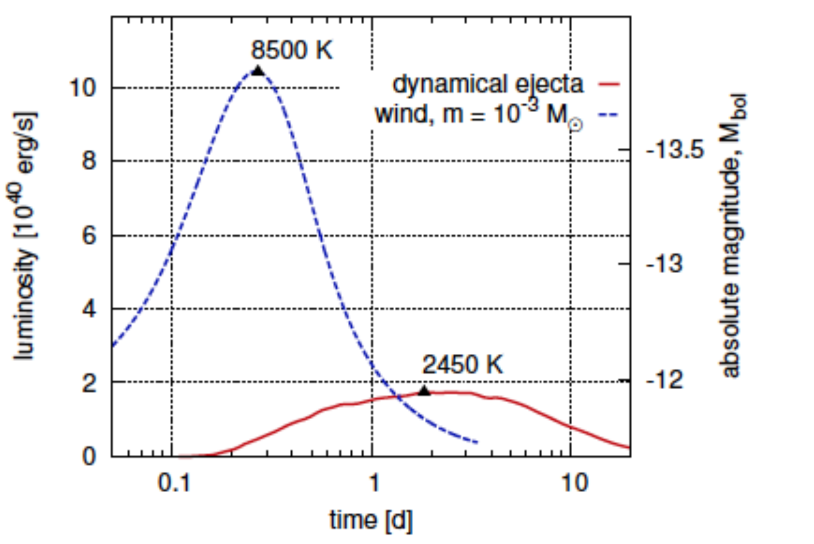
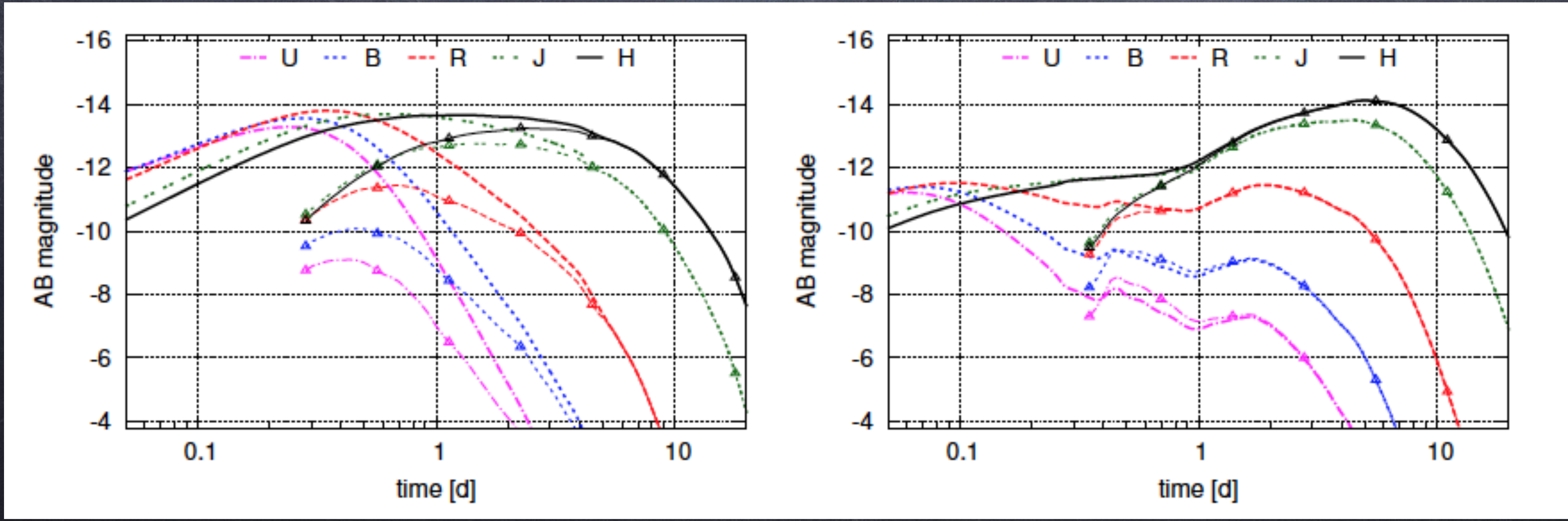
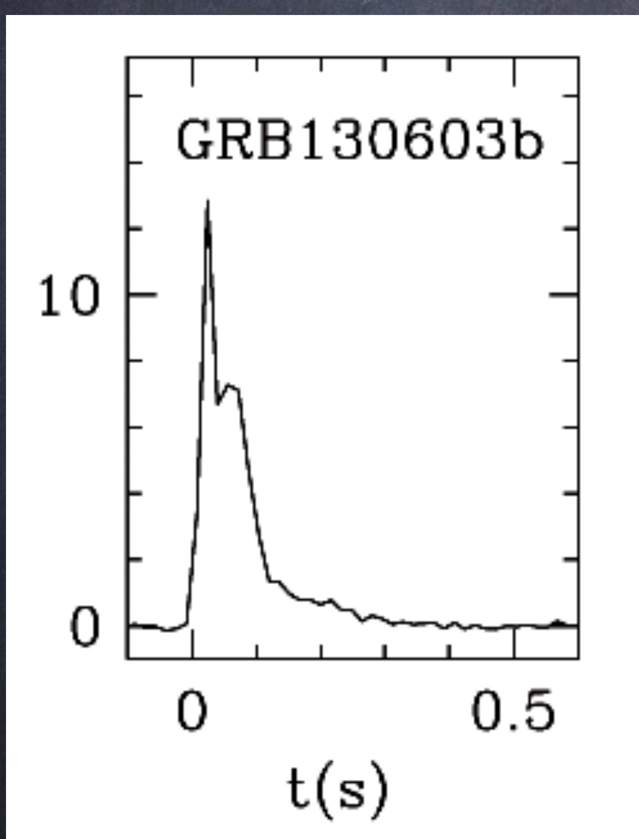
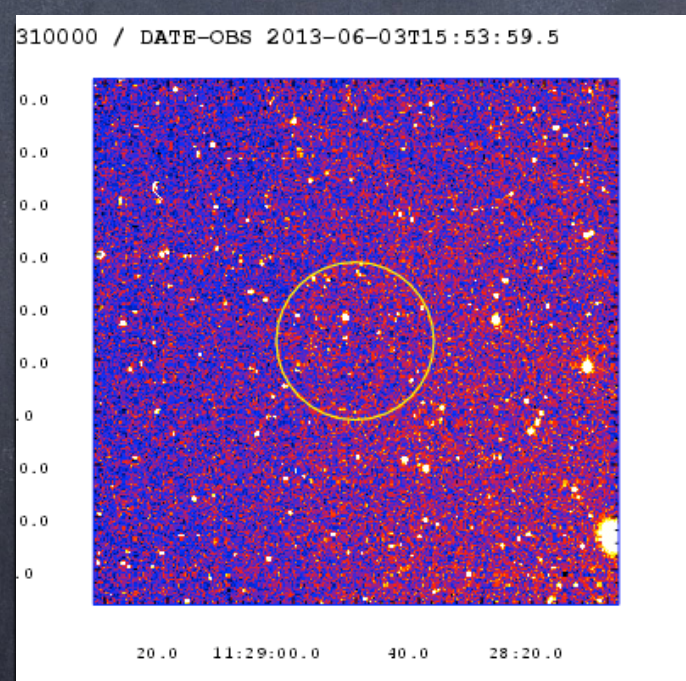


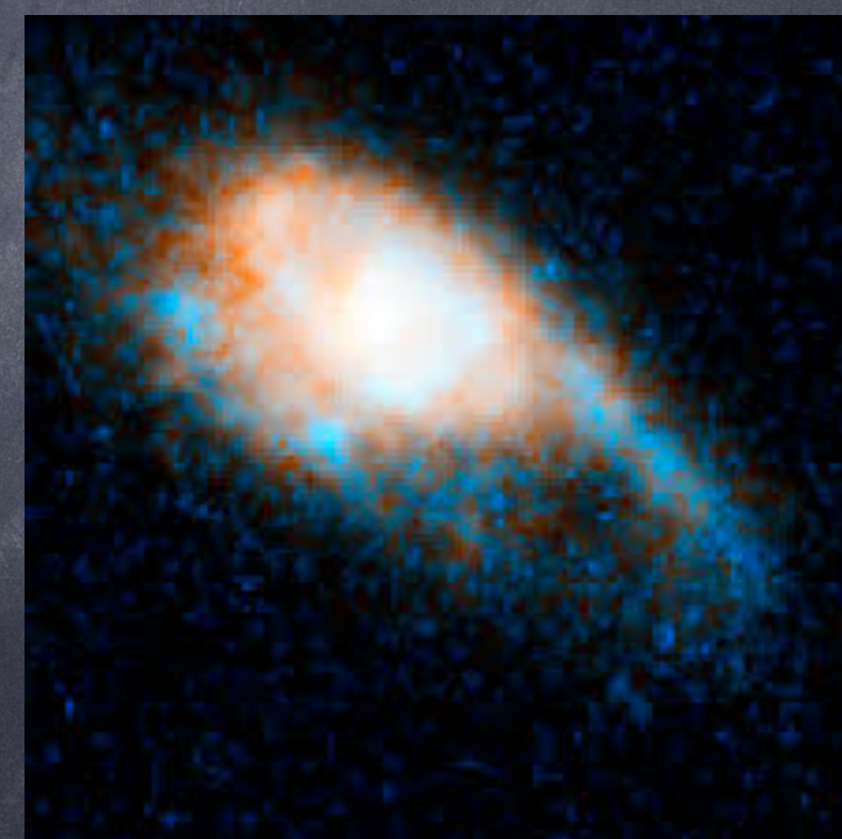
Figure 11. Combined light curves for the 1.3 - 1.4 $M_\odot$ configuration from the dynamically ejected material and the neutrino-driven wind.



Macronova following Gamma-Ray Burst (GRB) 130603B





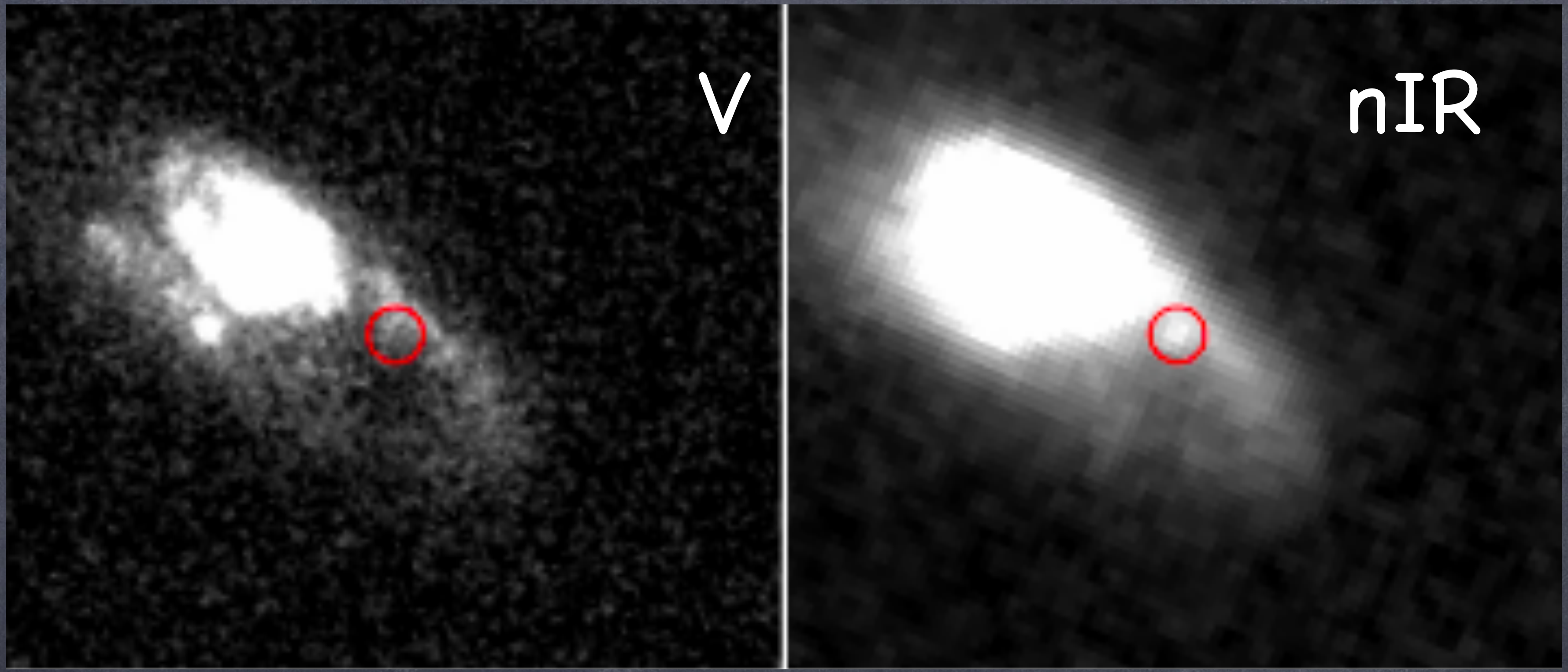


GRB 130603B

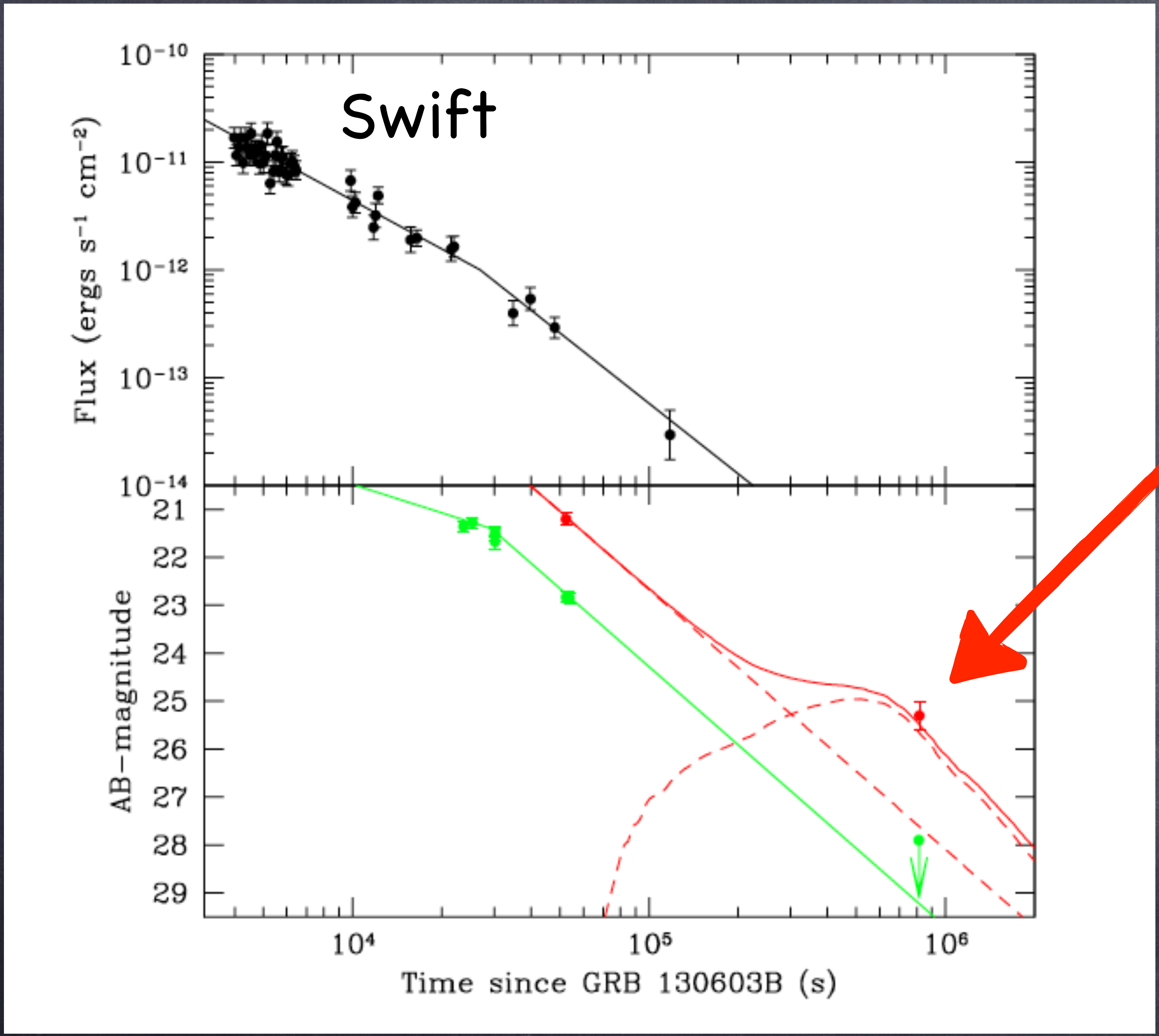
z=0.356 <=> 1 Gpc = 3 Glyr

GRB130603B @ 9 days AB

(6.6 days at the source frame)



HST image (Tanvir + 13)

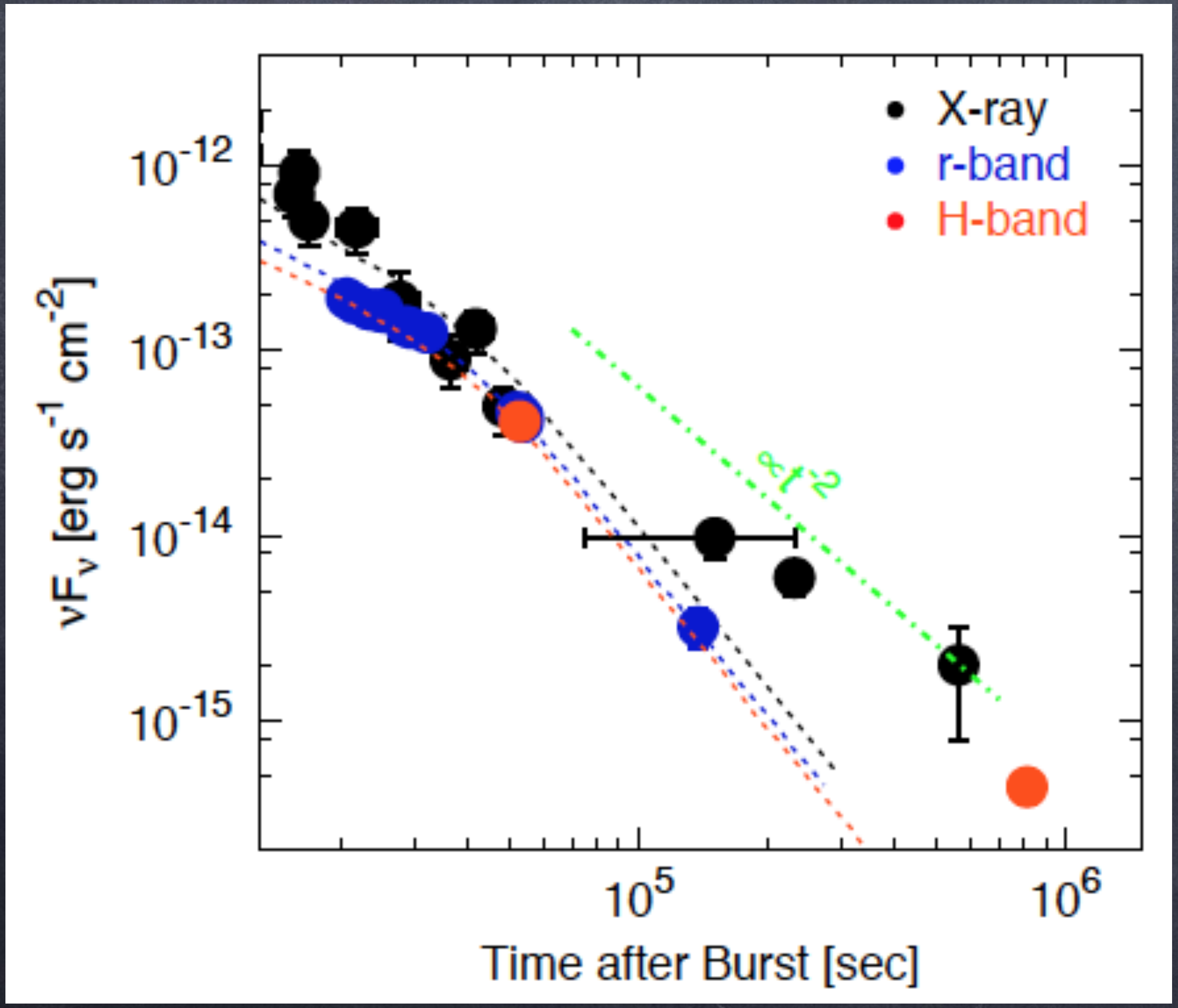


Tanvir + 13, Berger + 13

Macronova? need about 0.04 $m_\odot$

Warning X-ray powered macronova?

(Kisaka, Ioka, Nakar - in prep)



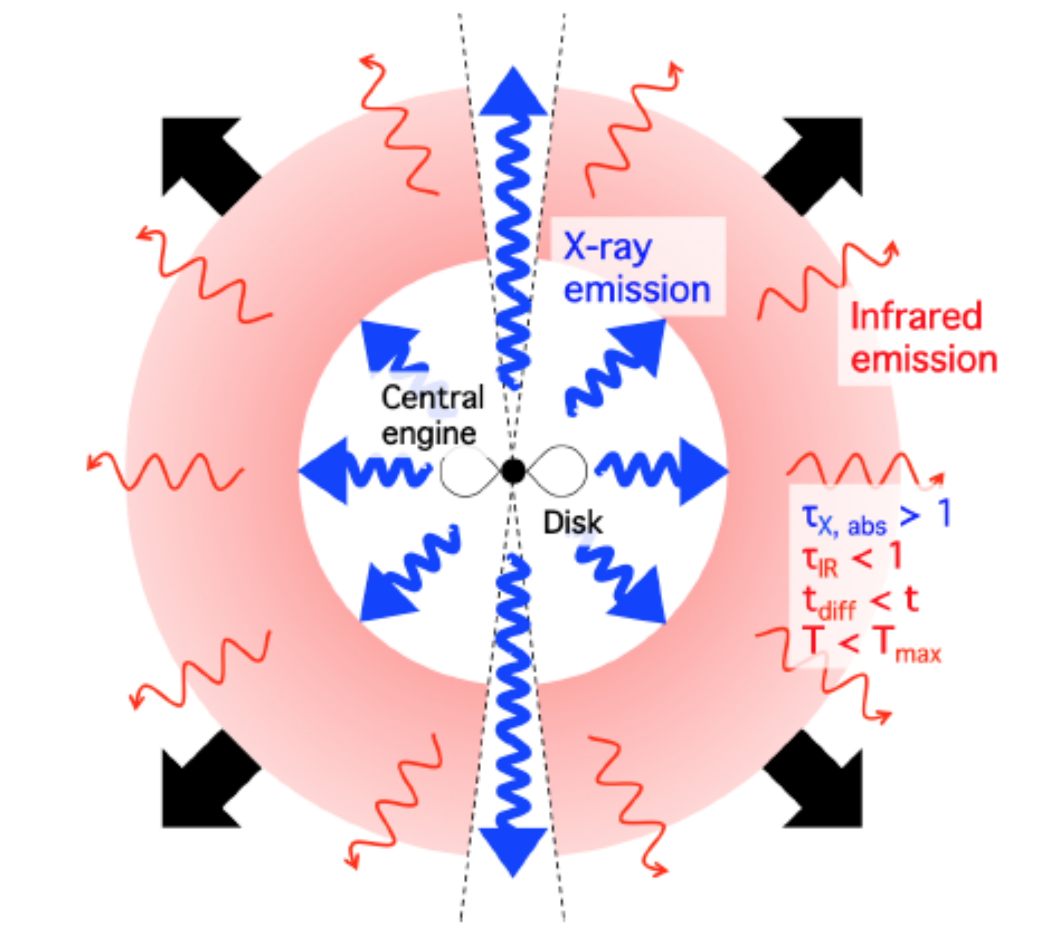


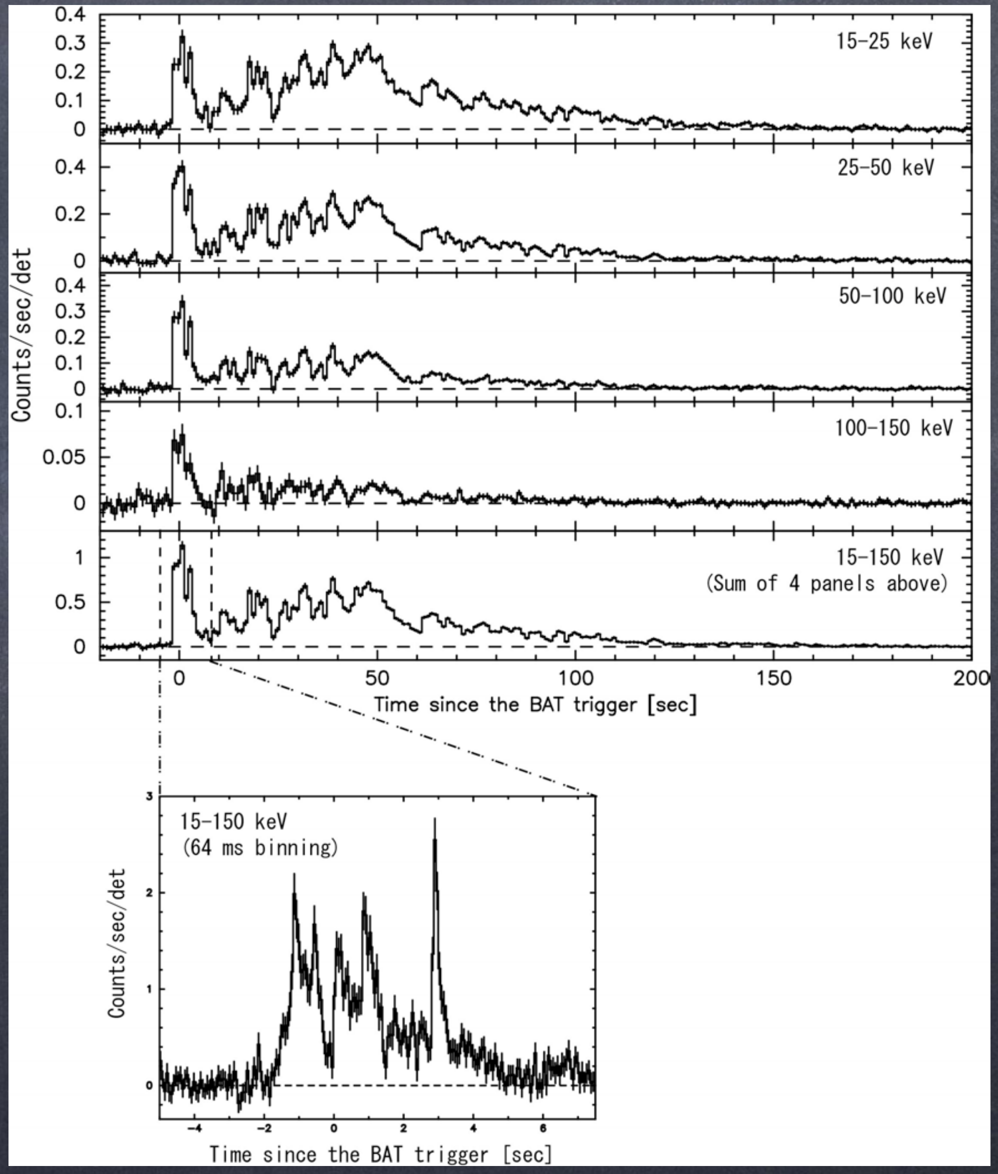
FIG. 2.— Schematic picture of the X-ray-powered model.

Also GRB 080503

The Macronova in 060614

Bin Yang et al., Nature Phys. 2015

- 060614 - a nearby "long-short" burst
- 102 sec
- No SNe
- z=0.125



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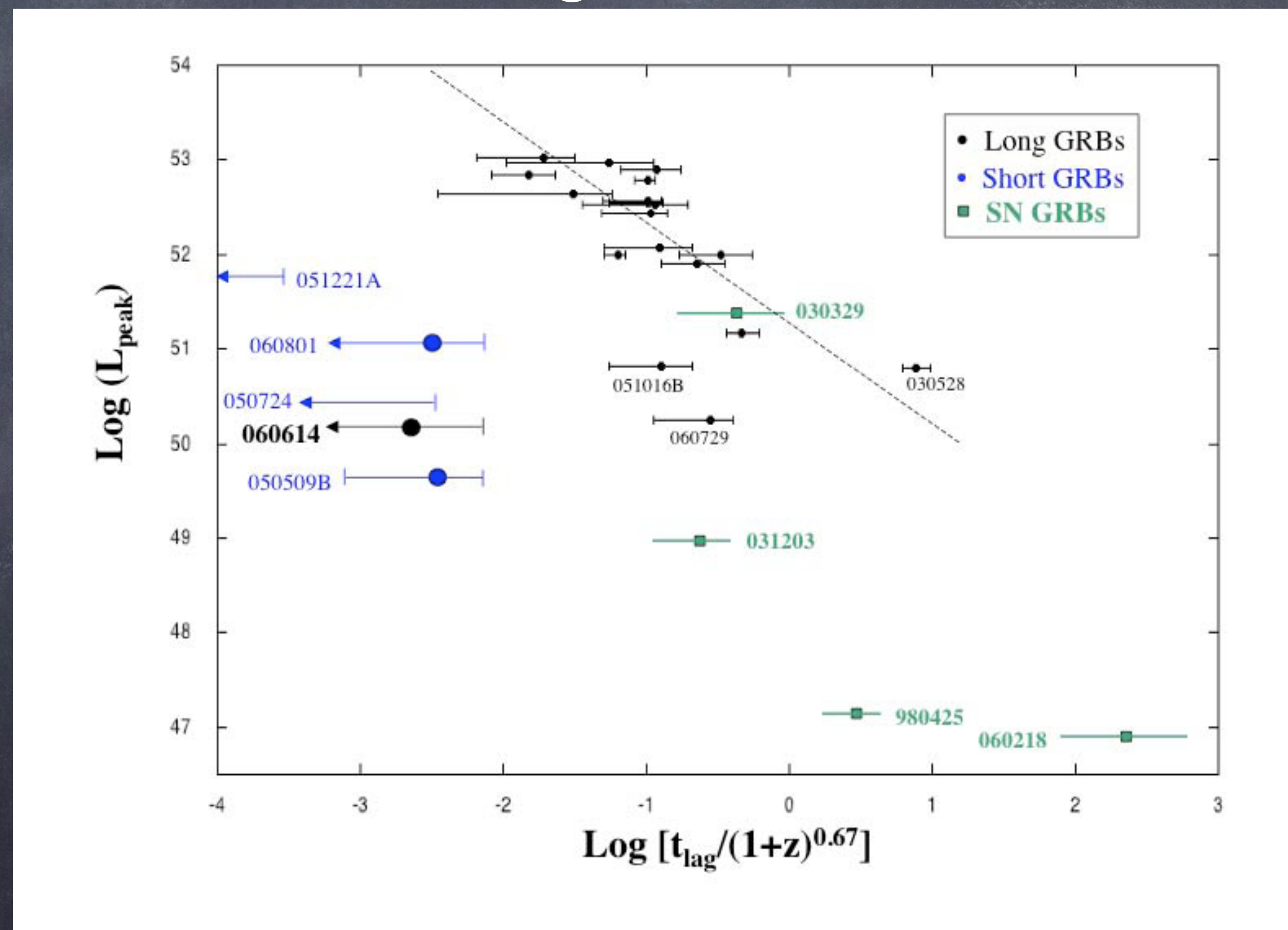


060614

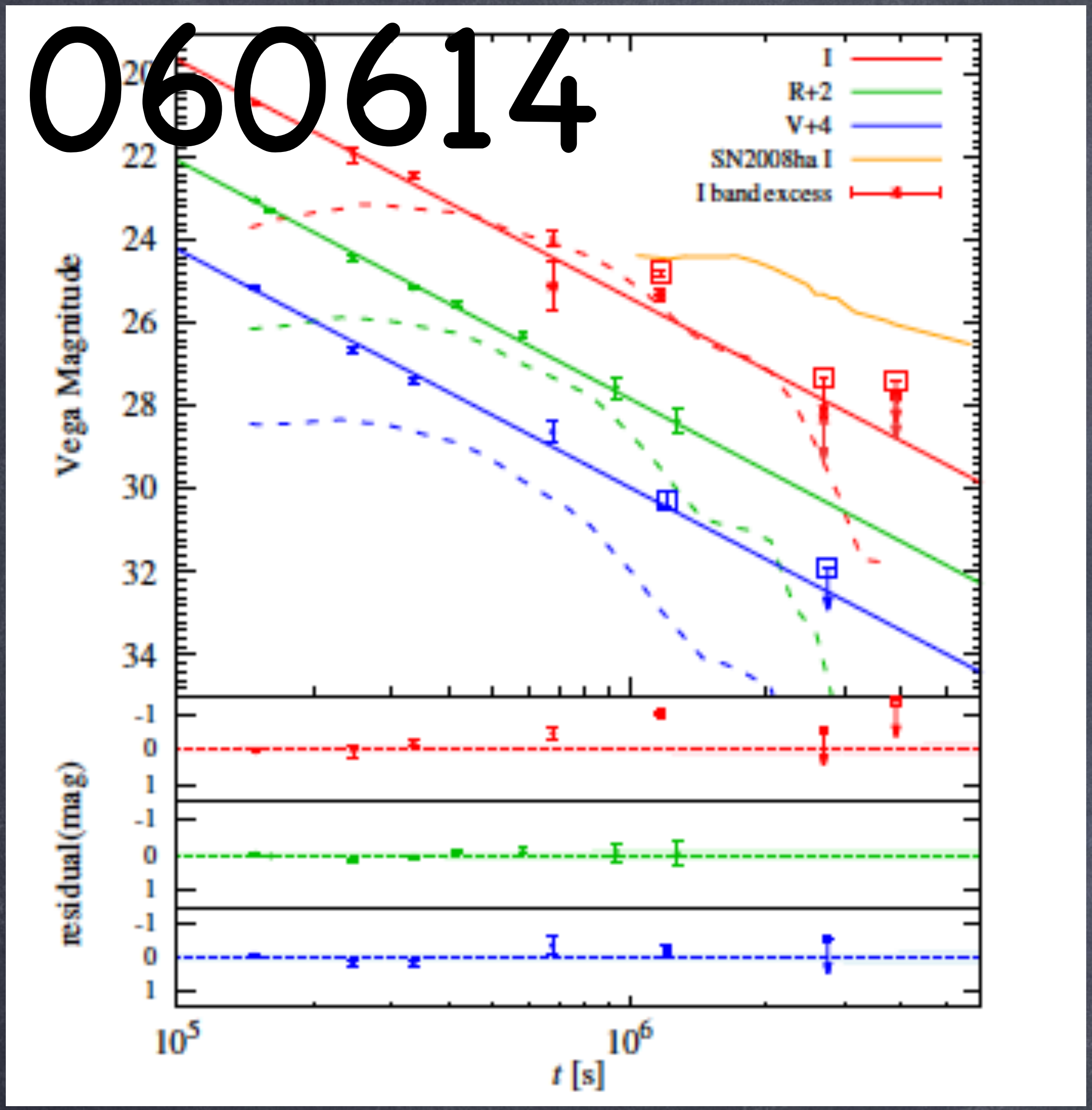
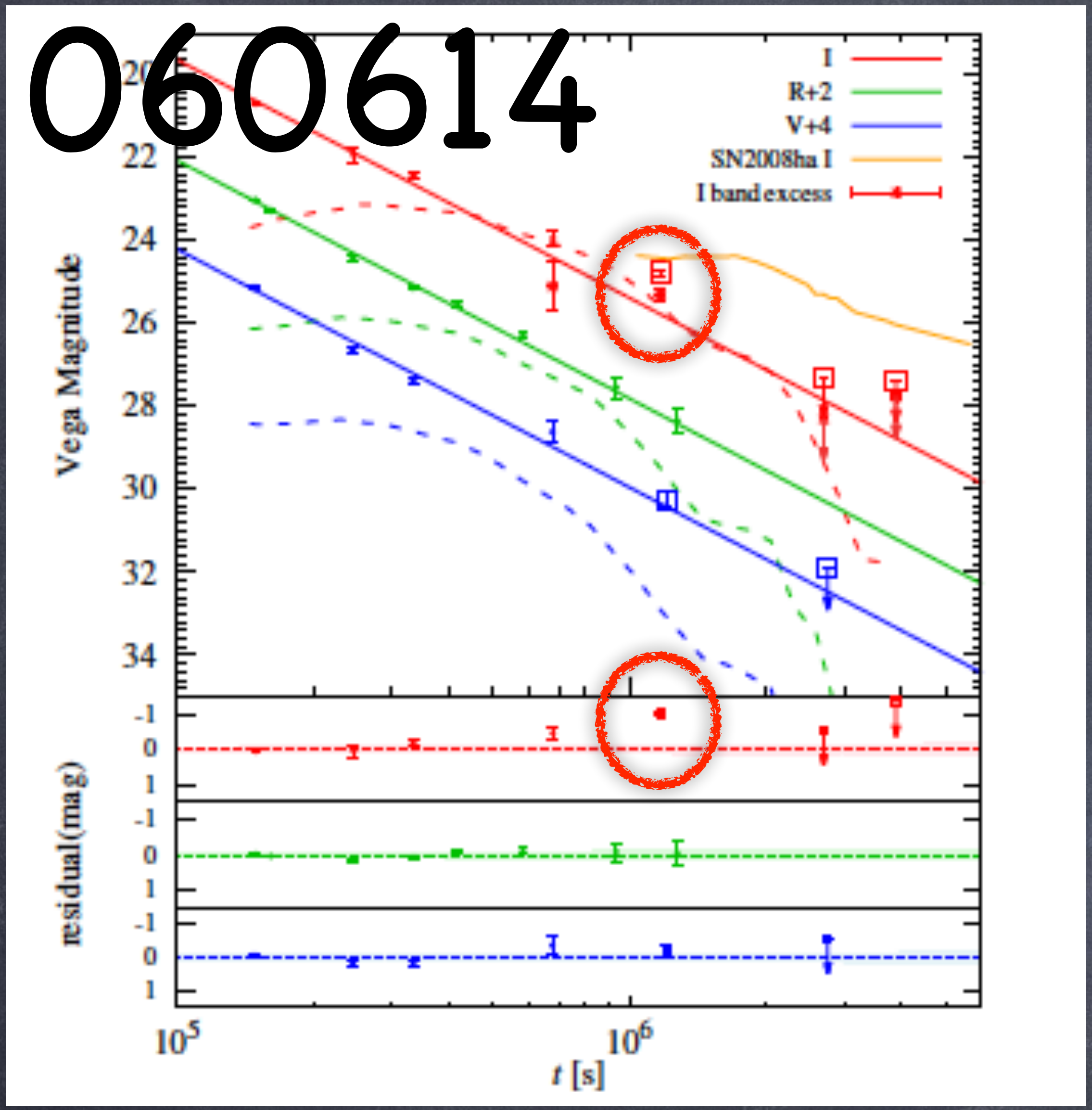


FIG. 1. **The afterglow emission of GRB 060614.** The VLT and HST observation magnitudes including their 1σ statistical errors **of the photon noise and the sky variance** and the 3σ upper limits (the downward arrows) are adopted from Supplementary Table 1. The small amounts of foreground and host extinction have not been corrected. Note that the VLT V/I band data have been calibrated to the HST F606W/F814W filters with proper $k-$corrections (see the Methods). The VLT data (the circles) are canonical fireball afterglow emission while the HST F814W detection (marked in the square) at $t \sim 13.6$ day is significantly in excess of the same extrapolated power-law decline (see the residual), which is at odds with the afterglow model. The F814W-band lightcurve of SN 2008ha[25] expected at $z = 0.125$ is also presented for comparison. The dashed lines are macronova model light curves generated from numerical simulation[28] for the ejecta from a black hole−neutron star merger. Error bars represent s.e.



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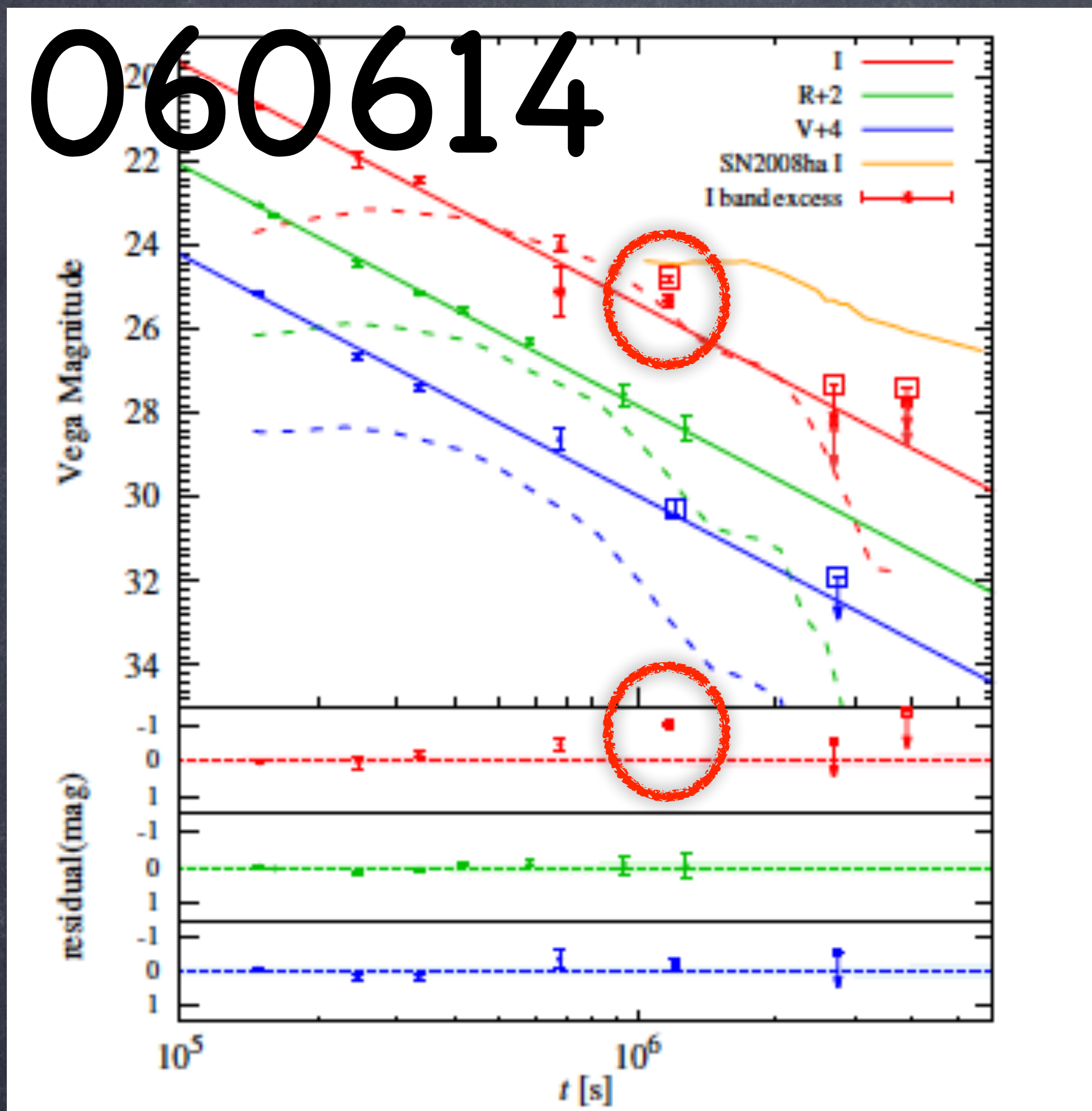

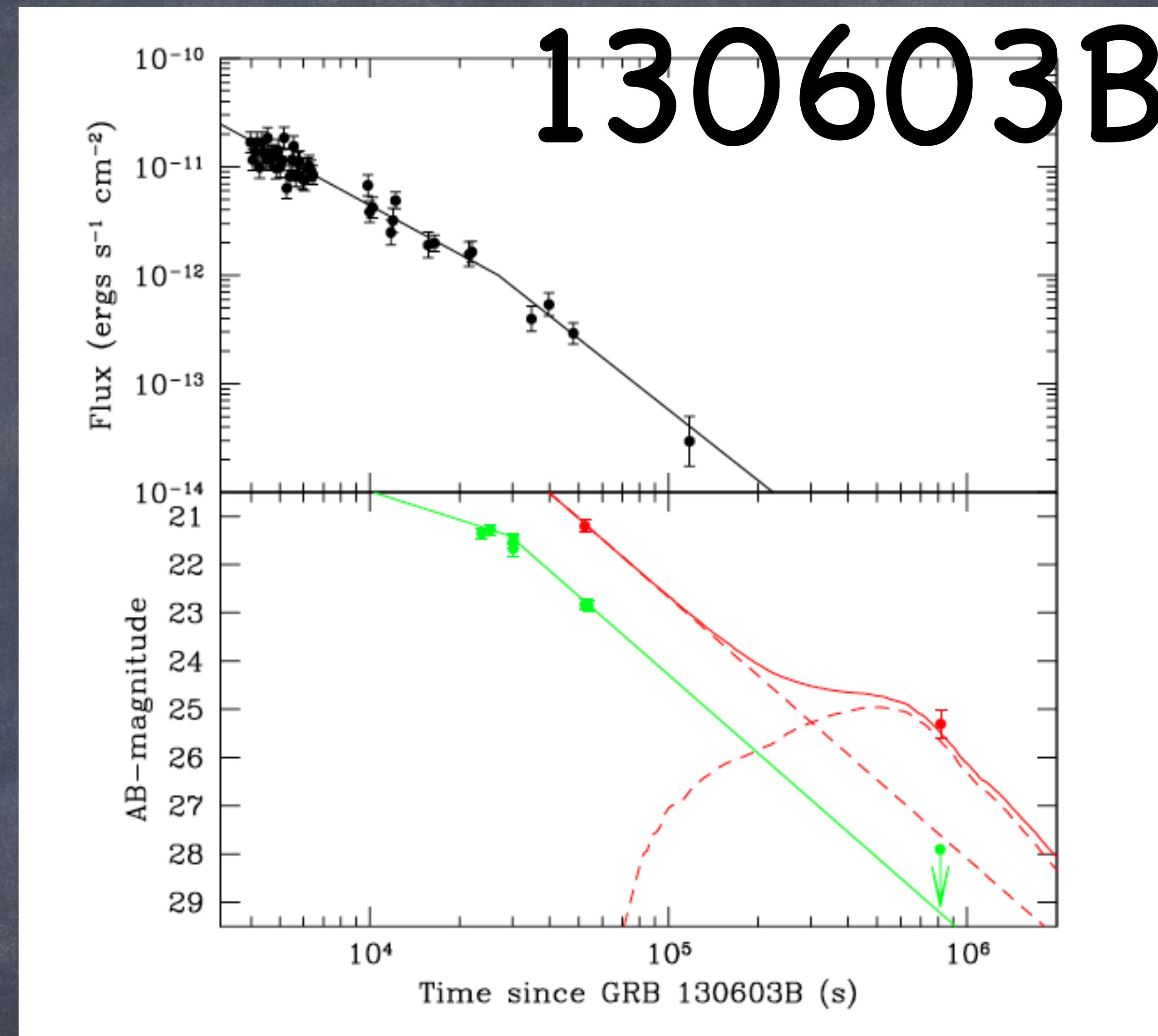

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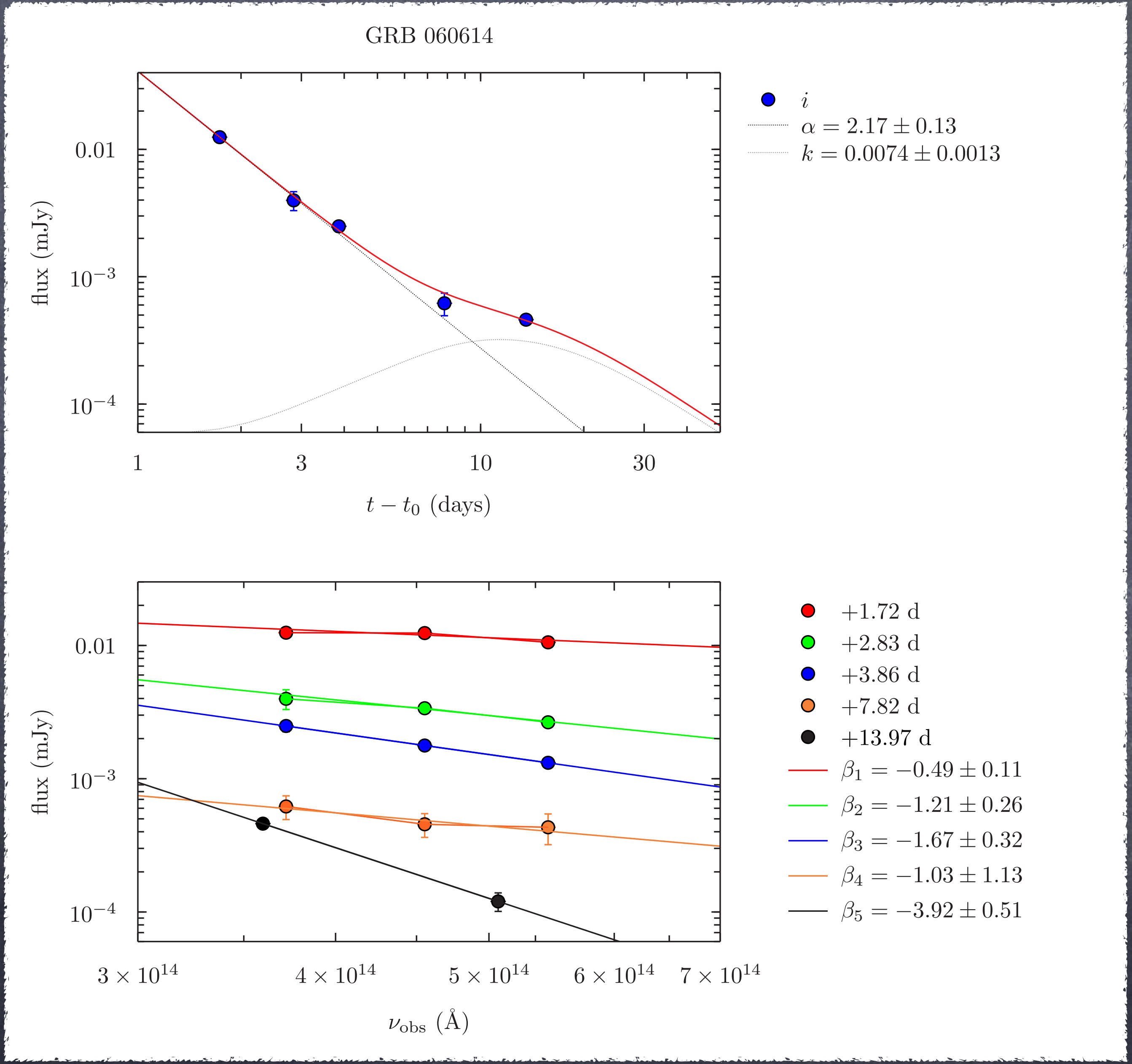
Independent Analysis



Zach Cano 2015

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

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

Not so easy

- Peak at 10-13 days -> ~ 0.1 M_{sun} -> ?
- Black Hole - NS merger?

Macronova

Macronova

Nucleosynthesis

Lattimer Schramm 76

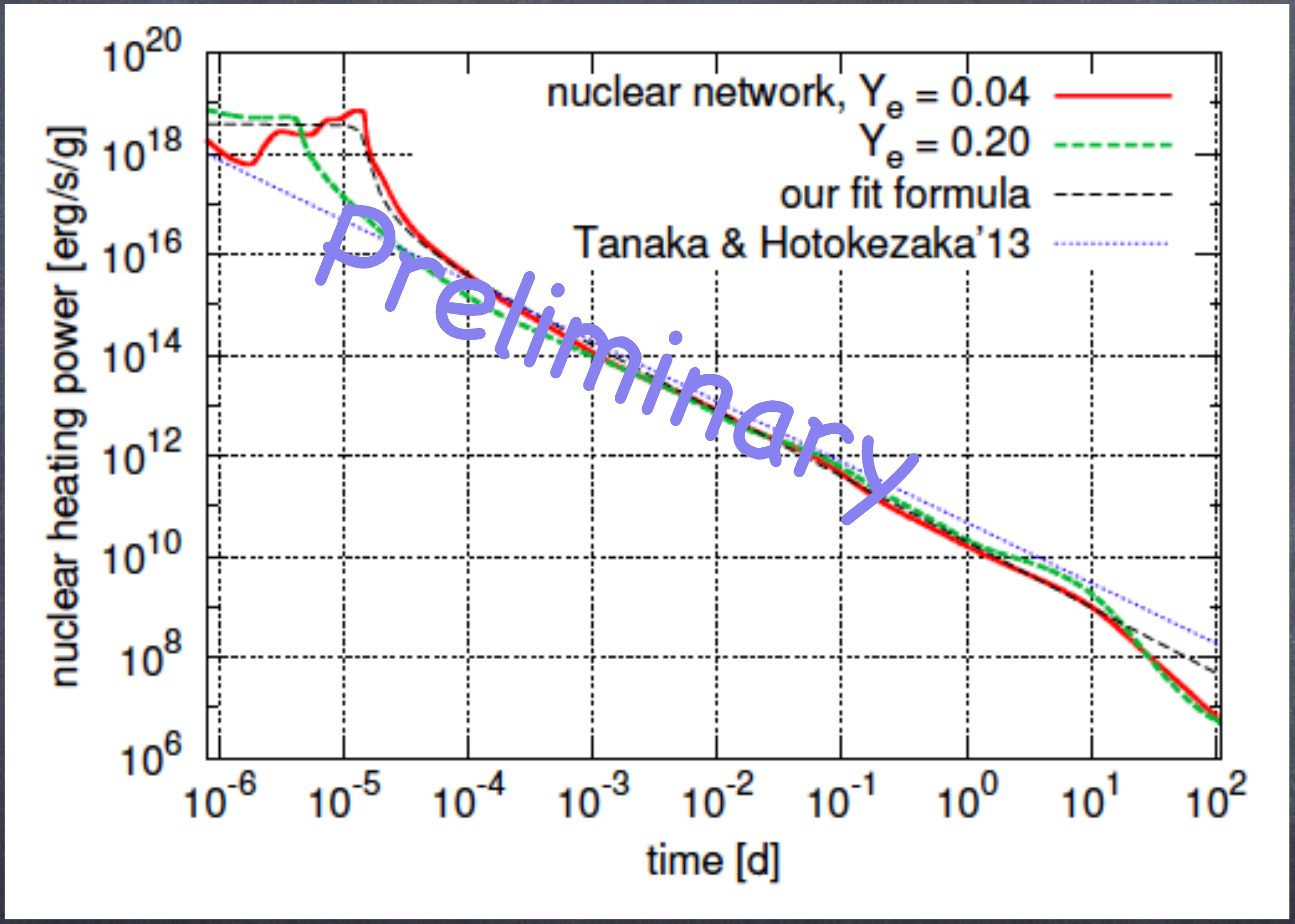
Macronova

Nucleosynthesis ↔ GRBs

Lattimer Schramm 76

Eichler, Livio
Piran, Schramm 89

Questions about energy deposition (Hotokezaka + TP, in prep)



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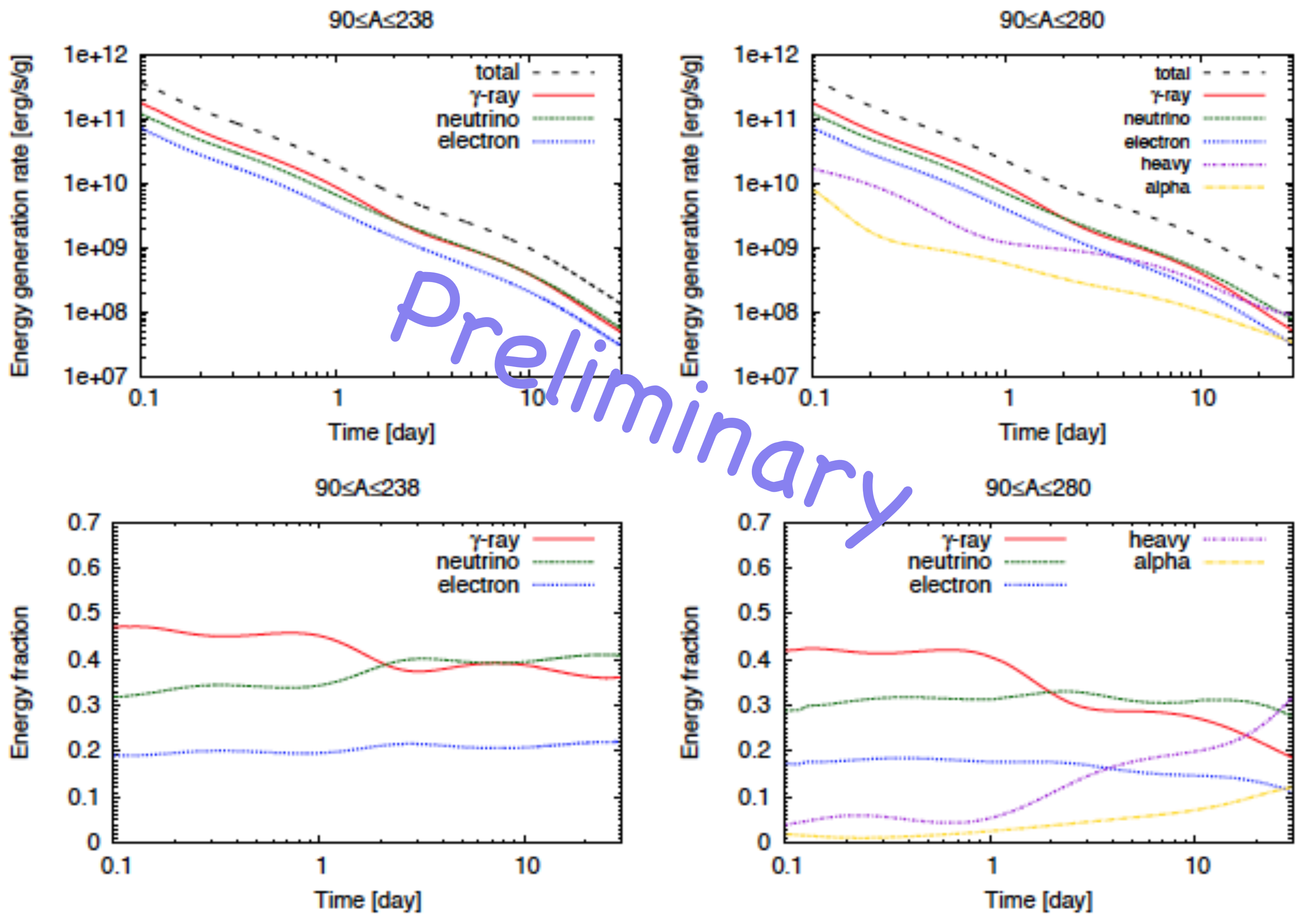


Figure 1. Energy generation rate (upper) and the energy fraction carried by each type of radiations (bottom).

Diffusion time

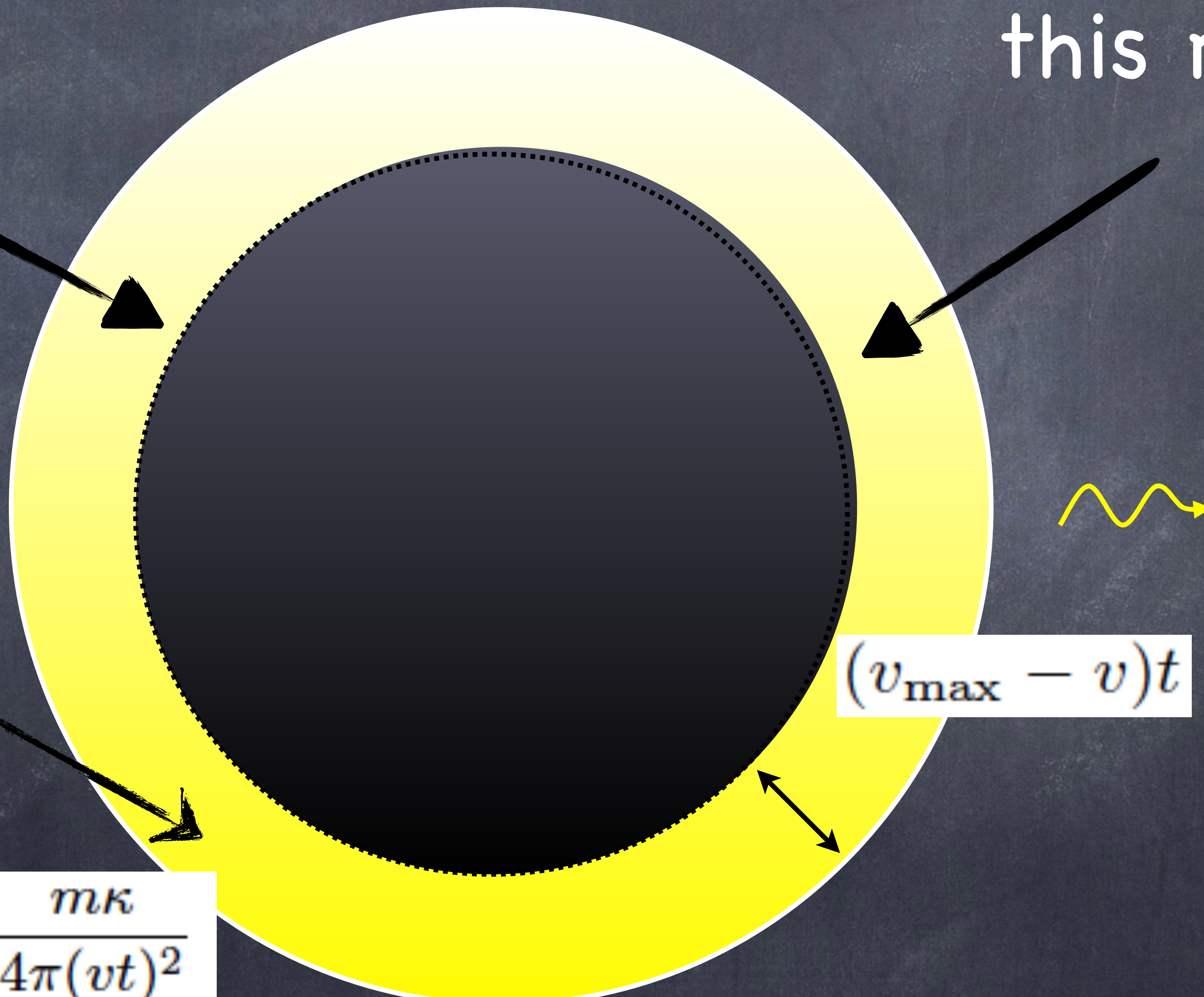
Opacity

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

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

Photons escape from this region

Optical depth



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

Diffusion time

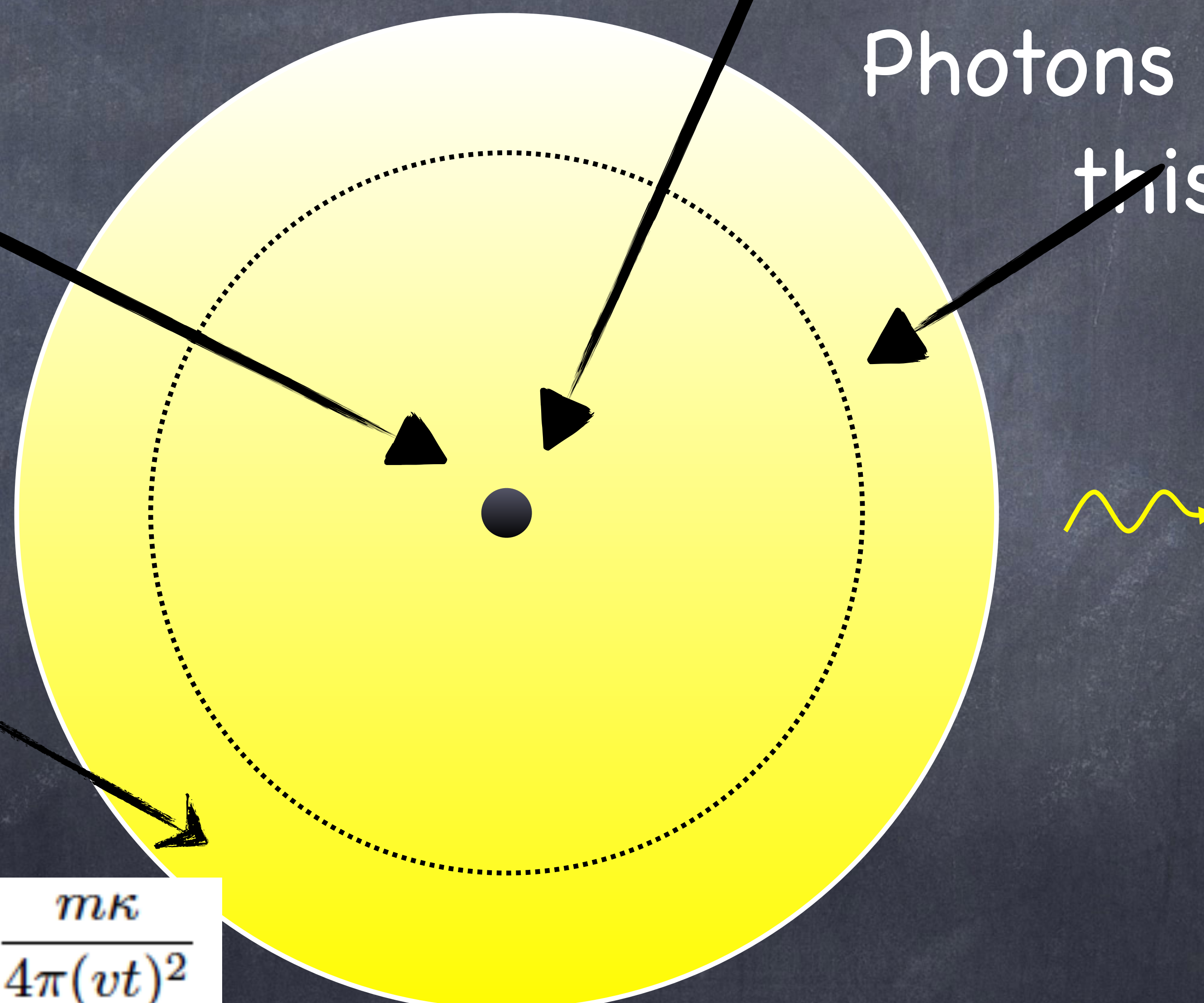
Opacity

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

γ-rays escape from this region

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

Photons escape from this region



Optical depth

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

γ-rays heating is lost very early!

Implications

- A weaker macronova signal (less heating)

Implications

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- A new (too weak) hard x-ray soft γ counterpart

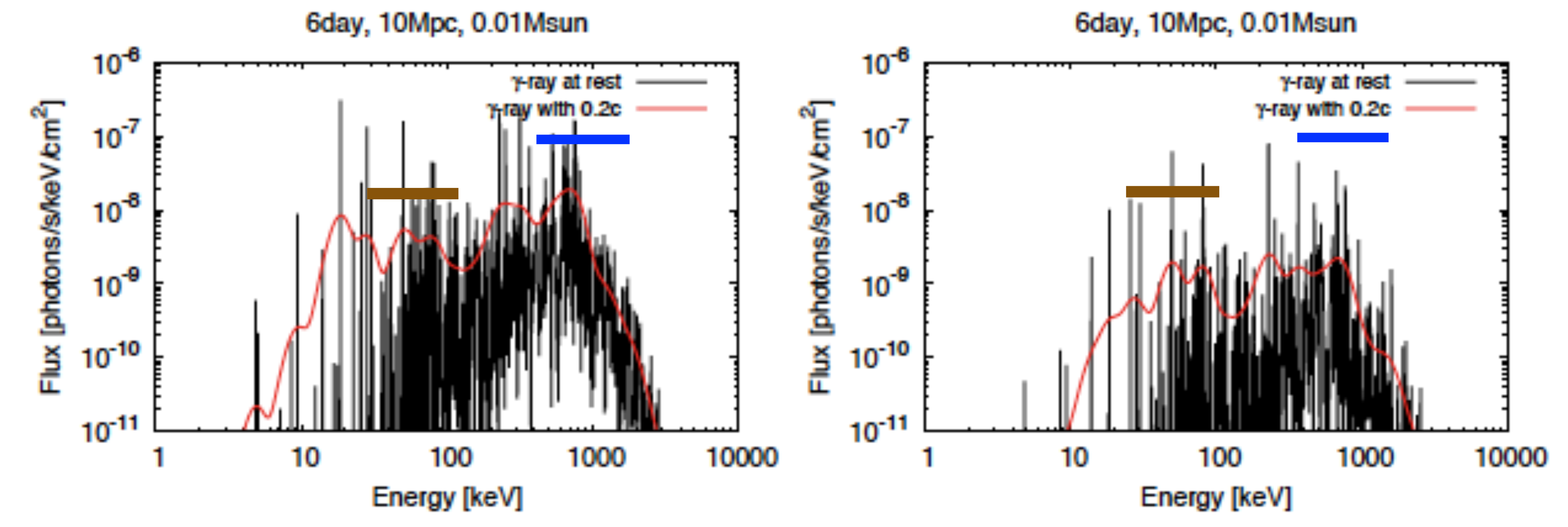

Figure 2.

Implications

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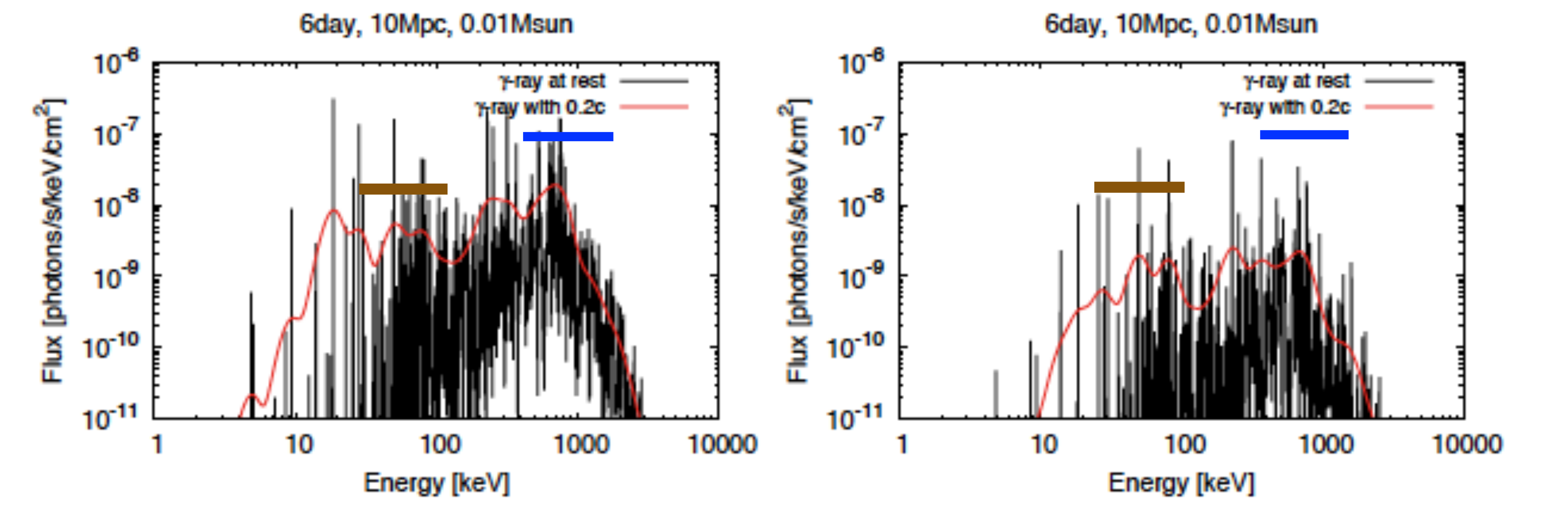
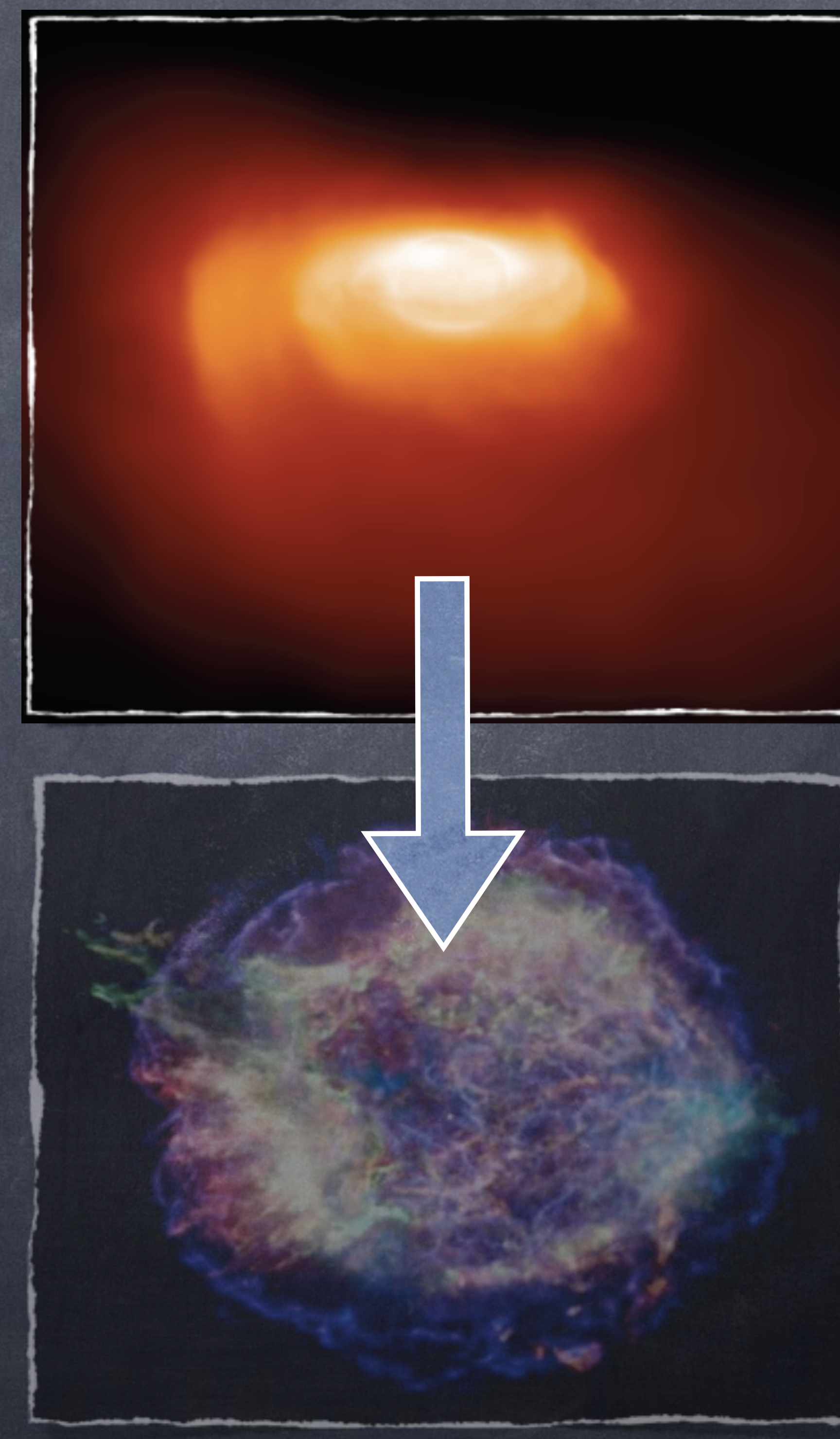


Figure 2.

- nustar and Integral @ 10^6 sec integration

The kinetic energy - Radio Flares (Nakar & Piran 2011)

Interaction of the sub or mildly relativistic outflow with the ISM produces a long lived radio flare

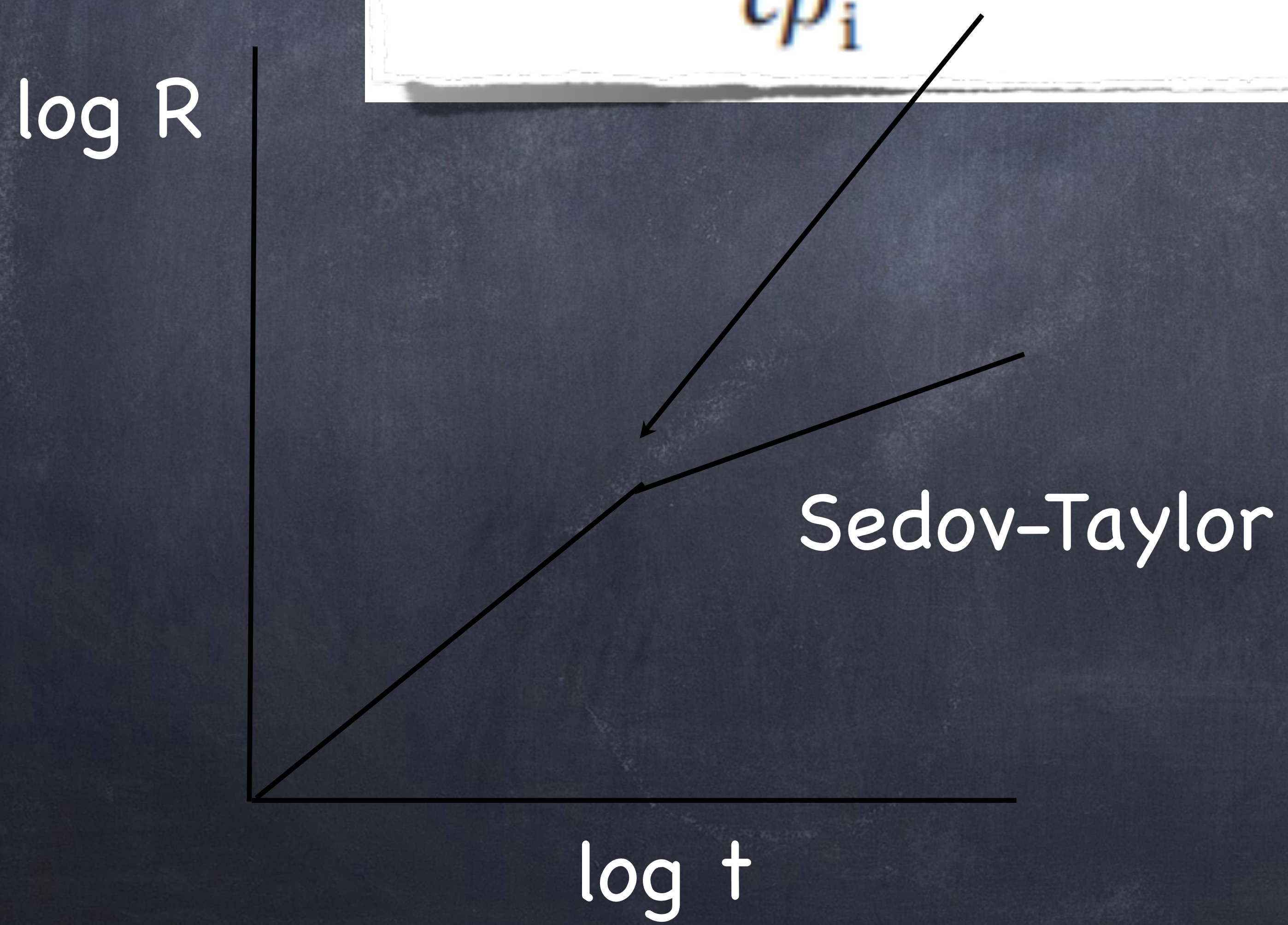


Supernova -> SNR

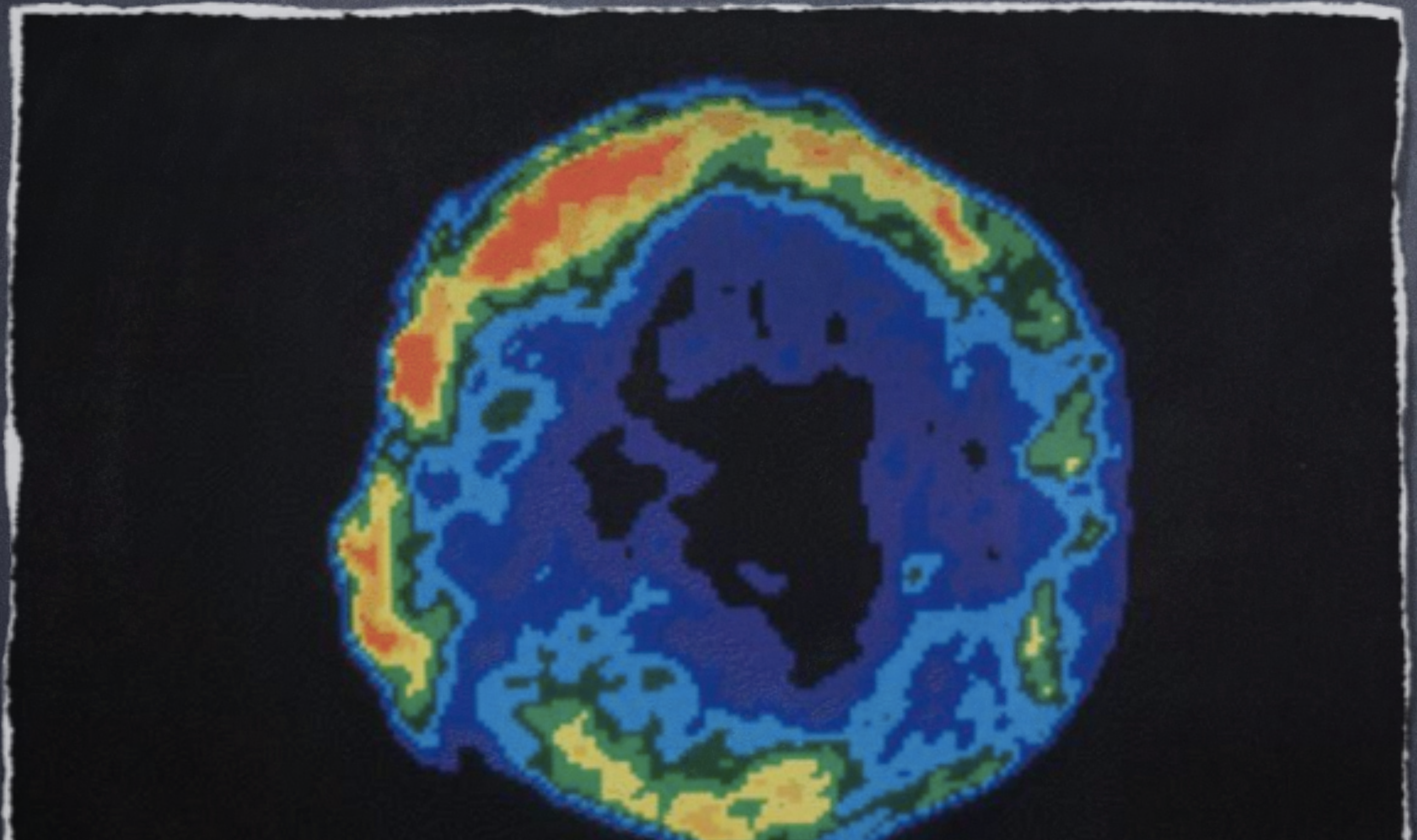
macronova -> Radio Flare

Dynamics

$$t_{\rm dec} = \frac{R_{\rm dec}}{c\beta_{\rm i}} \approx 30\ E_{49}^{1/3} n_0^{-1/3} \beta_{\rm i}^{-5/3}\ \text{days}$$



Radio Supernova
e.g. 1998bw (Chevalier 98)


Tycho's **supernova** remnant seen at **radio** wavelengths

$e_e = \varepsilon_e e$

$e_B = B^2/8\pi = \varepsilon_B e$

$N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$

$p = 2.5 - 3$

$\gamma_m = (m_p/m_e) e_e (\Gamma - 1)$

$\nu = (3/4\pi) eB\gamma^2$

$F_\nu = (\sigma_T c/e) N_e B$

Frequency and Intensity

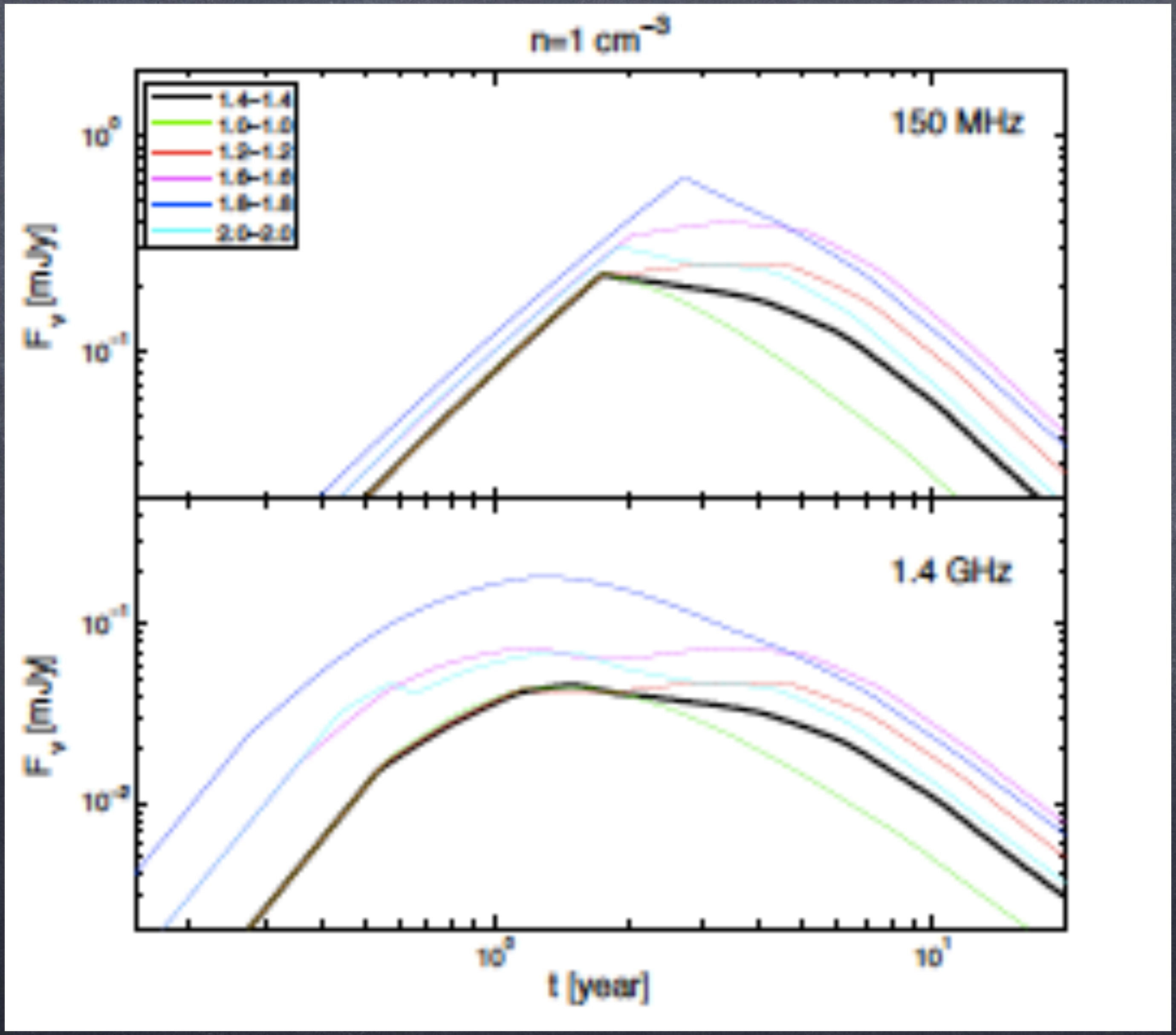
(Nakar & TP Nature, 2011)

$$\nu_{m,dec} \equiv \nu_m(t_{dec}) \approx 1 \text{ GHz } n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} (\Gamma_0 - 1)^{5/2},$$

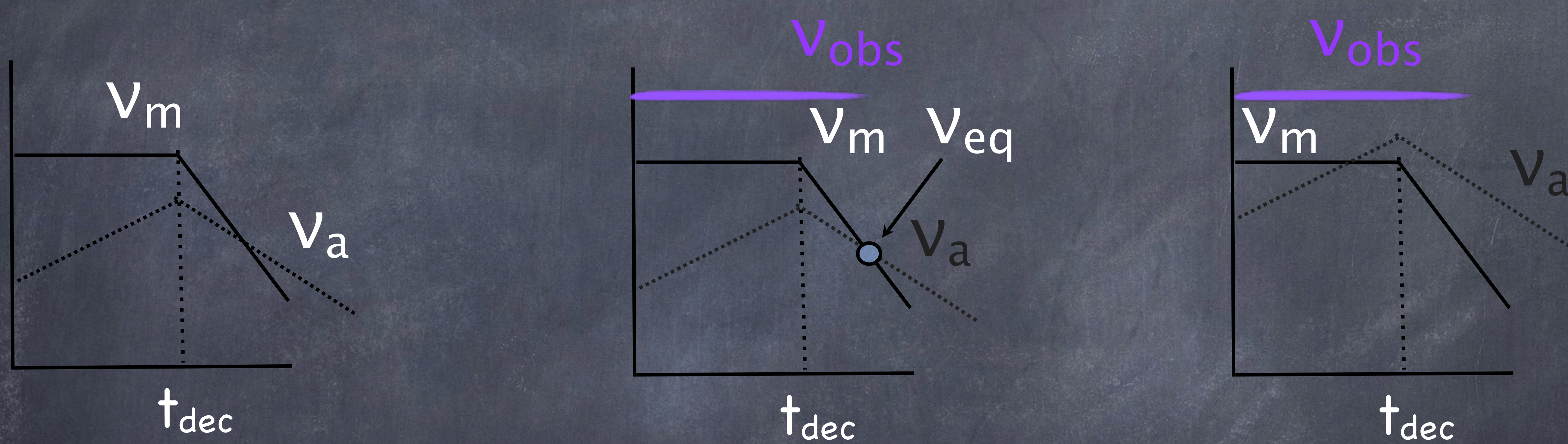
$$F_{\nu_{obs},\mathrm{peak}}[\nu_{obs} > \nu_{m,dec},\ \nu_{a,dec}] \approx$$

$$0.3 E_{49} n_0^{\frac{p+1}{4}} \varepsilon_{B,-1}^{\frac{p+1}{4}} \varepsilon_{e,-1}^{p-1} \beta_i^{\frac{5p-7}{2}} d_{27}^{-2} \left(\frac{\nu_{obs}}{1.4}\right)^{-\frac{p-1}{2}}$$

Radio Flares



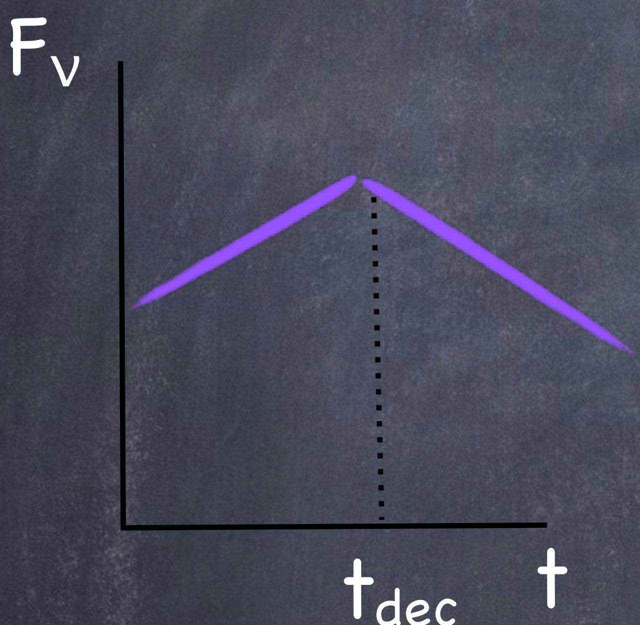
The light curve

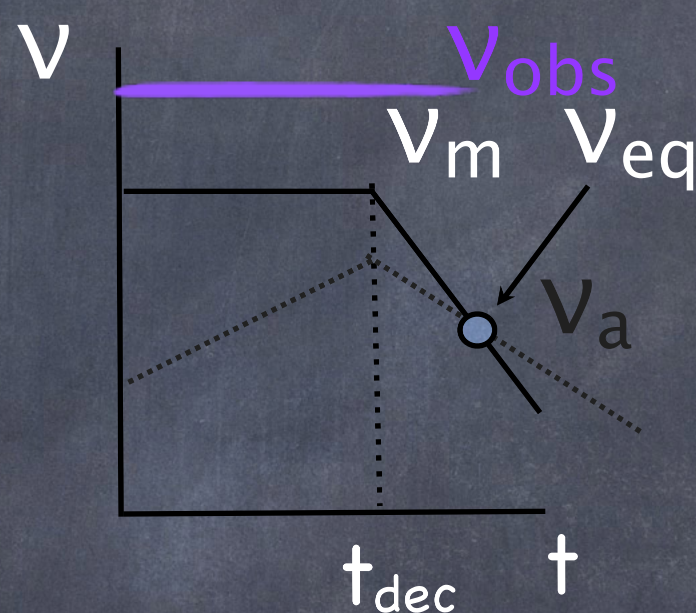


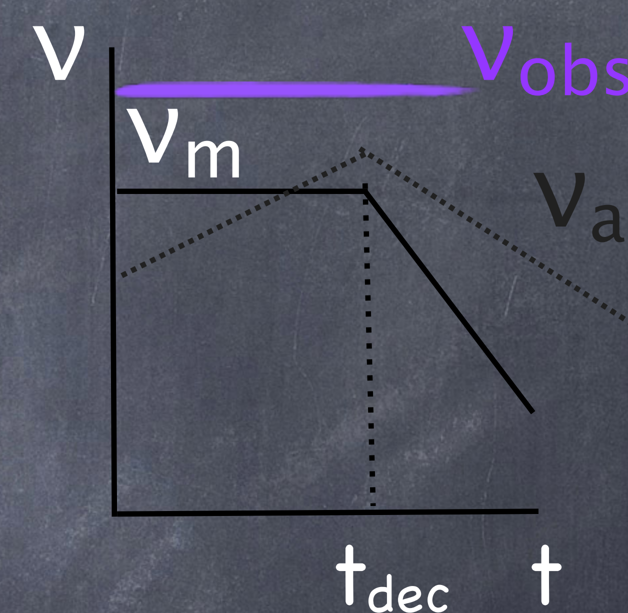
Text

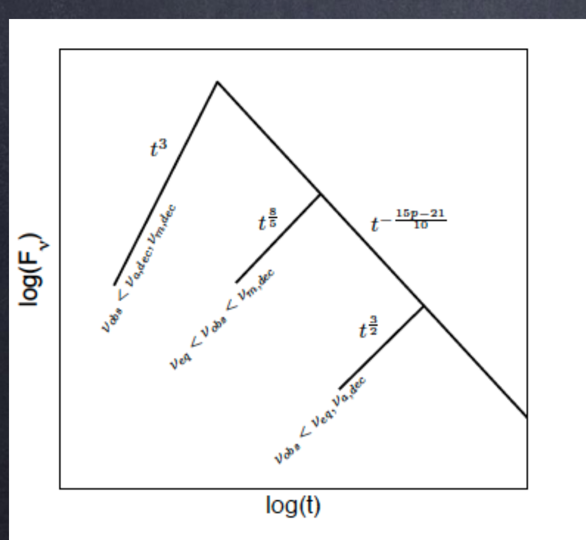
$$\nu_{eq} = 1\ \mathrm{GHz}\ E_{49}^{1/7} n^{4/7} \epsilon_{B,-1}^{2/7} \epsilon_{e,-1}^{-1/7}$$

The light curve









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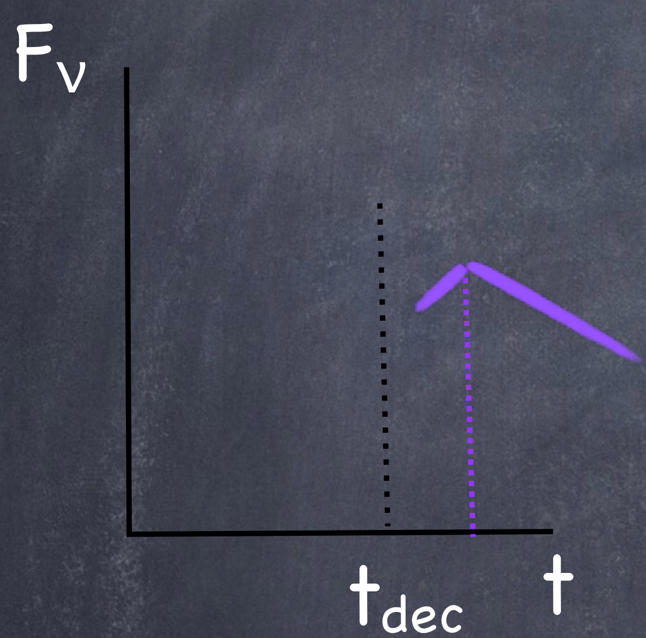

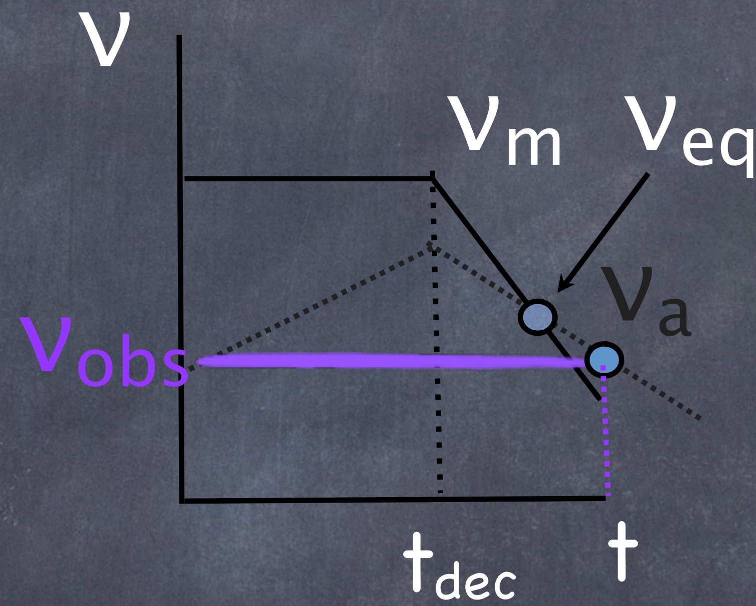

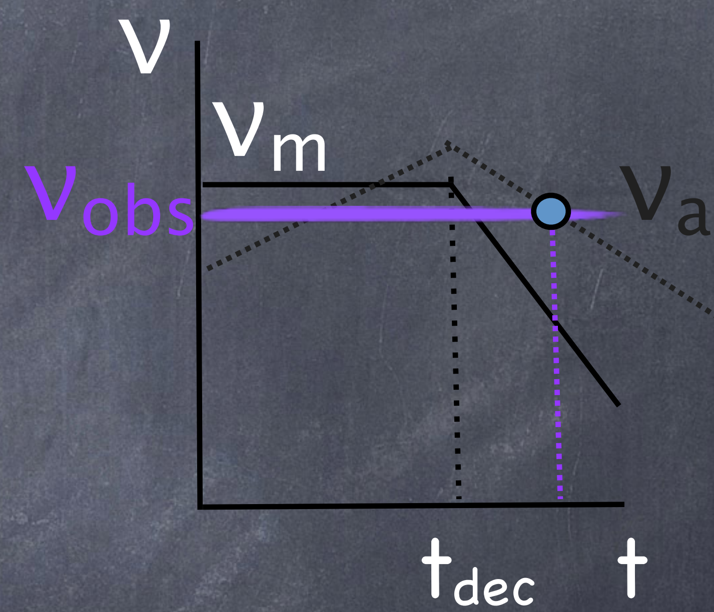

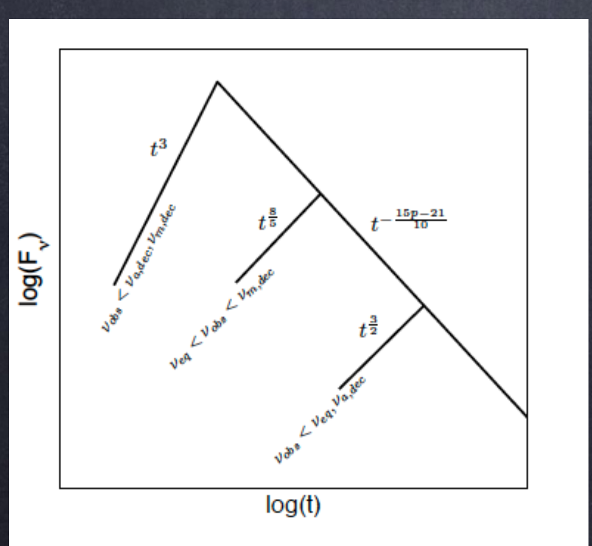

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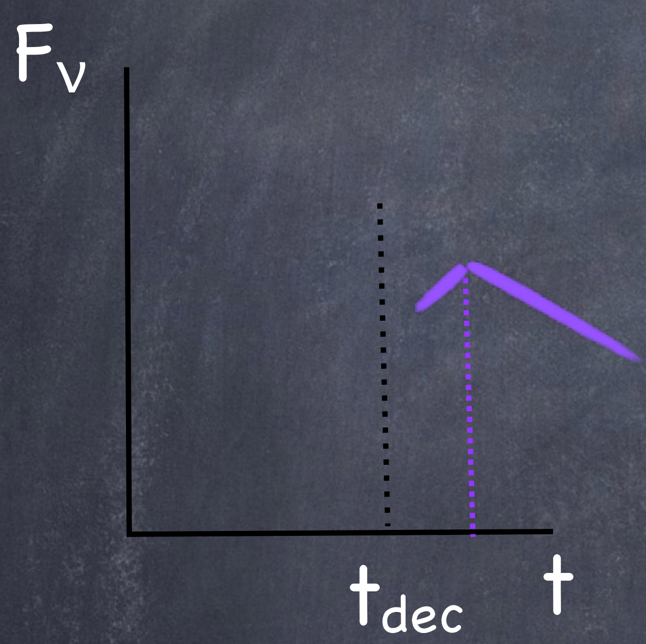

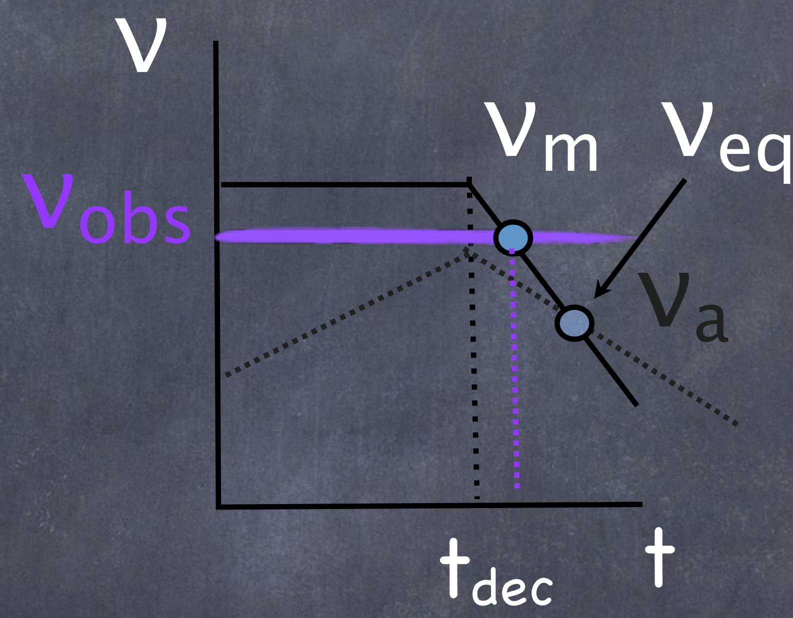

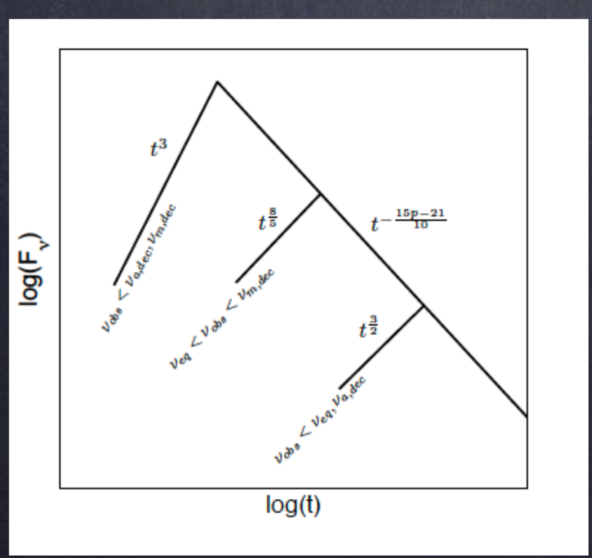

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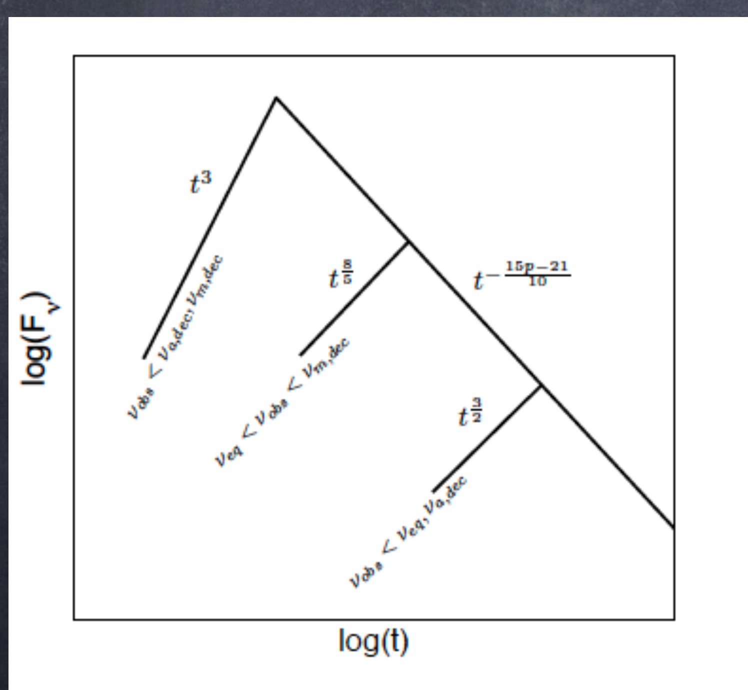
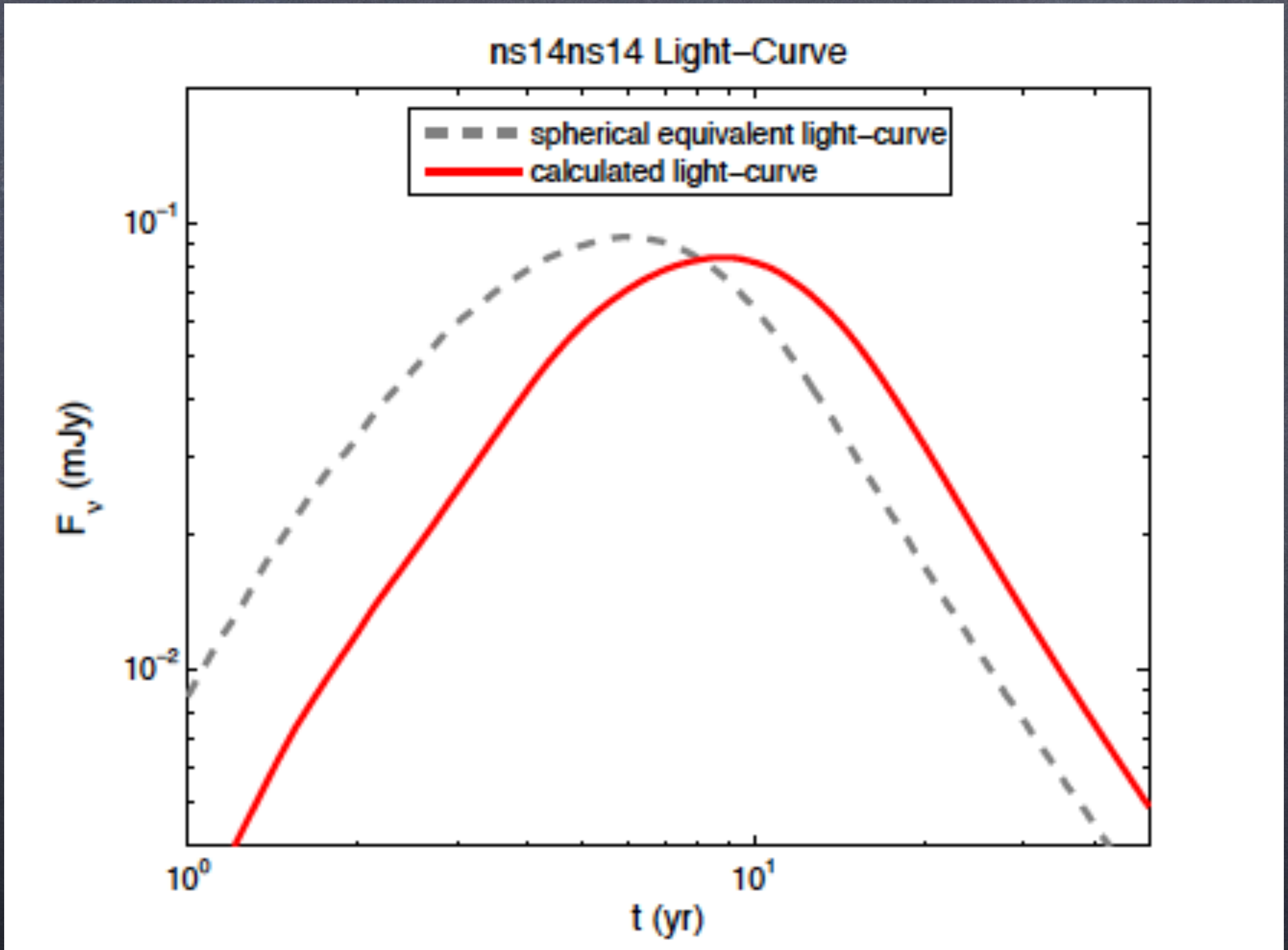
Regime	$F_{\nu_{obs},peak}/F_{m,dec}$	t_{peak}/t_{dec}	$F_{\nu_{obs}}$ $t > t_{peak}$	$F^{\dagger}_{\nu_{obs}}$ $t < t_{peak}$
$\nu_{m,dec}, \nu_{a,dec} < \nu_{obs}$	$(\nu_{obs}/\nu_{m,dec})^{-\frac{p-1}{2}}$	1	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^3$
$\nu_{eq} < \nu_{obs} < \nu_{m,dec}$	$(\nu_{obs}/\nu_{m,dec})^{-1/5}$	$(\nu_{obs}/\nu_{m,dec})^{-1/3}$	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^{\frac{8}{5}}$
$\nu_{obs} < \nu_{eq}, \nu_{a,dec}$	$\nu_{m,dec}^{\frac{p-1}{2}} \nu_{a,dec}^{-\frac{3(p+4)(5p-7)}{10(3p-2)}} \nu_{obs}^{\frac{(32p-47)}{5(3p-2)}}$	$(\nu_{obs}/\nu_{a,dec})^{-\frac{4+p}{3p-2}}$	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^{\frac{3}{2}}$

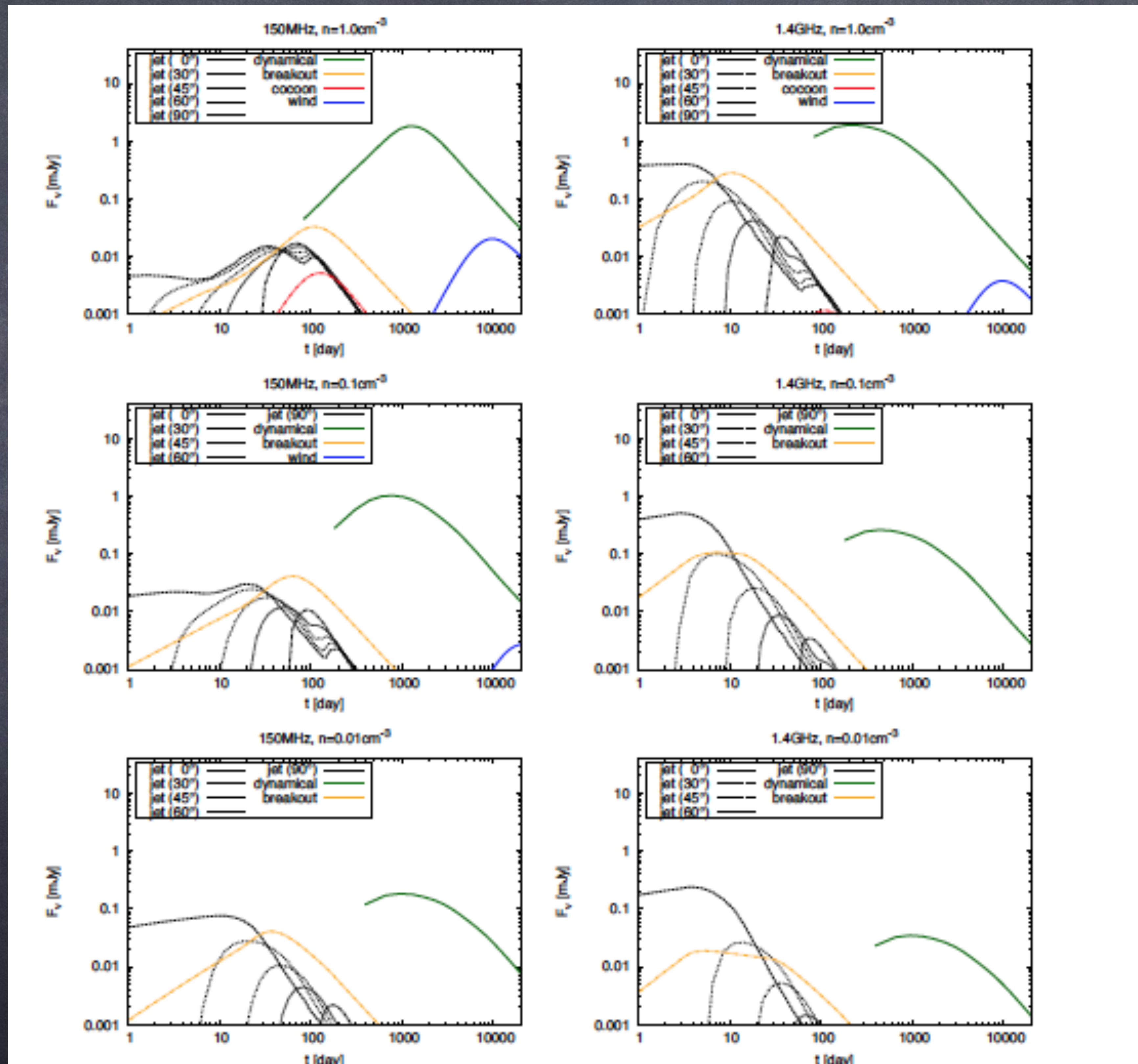


Effect of sphericity

Margalit & Piran 15



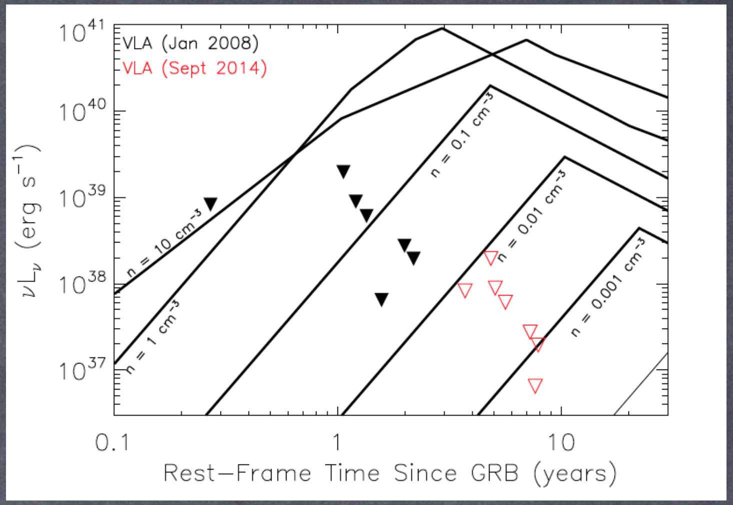
Additional Components



Hotokezaka & TP 15

Limits on GRB 130603B and 060614

Horesh, TP Nakar in prep



Metzger & Bower 14

- 060614 < 300 μjy @ 8 years
- The limits f… …B060614 ==> rule out a Magne… …ernal densities down to n…
- For GRB130603B, <20 μJy … ==> rule out a Magnetar down to n~0.1

Preliminary

Radio facilities for GW-EM Counterpart Searches: EVLA

- The 500-lb gorilla of radio astronomy
- 27 25-m antennas
- Upgrade project almost finished. Will deliver order of magnitude increase in continuum sensitivity
- 1-50 GHz + 74 and 327 MHz
- 1-hrs, rms~7 uJy at 1.4 GHz
- Responds to external triggers
- Sub-arrays can be used to image a large (irregular) error box

NRAO

Dale Frail

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NRAO

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Radio facilities for GW-EM Counterpart Searches

Radio Facility	Observing Freq.	Field of View	1 hr rms	Beam	Start Date
ASKAP	1.4 GHz	30 deg^2	30 uJy	20”	2013
Apertif	1.4 GHz	8 deg^2	50 uJy	15”	2013
MeerKAT	1.4 GHz	1.5 deg^2	35 uJy	15”	2013
EVLA	1.4 GHz	0.25 deg^2	7 uJy	1.3-45”	2010
EVLA	327 MHz	5 deg^2	2 mJy	5-18”	2011
LOFAR	110-240 MHz	50 deg^2	1 mJy	5”	2011
EVLA	74 MHz	100 deg^2	50 mJy	25-80”	2011
MWA	80-300 MHz	1000 deg^2	8 mJy	300”	2011+
LOFAR	15-80 MHz	500 deg^2	8 mJy	120”	2011

(Only Apertif, EVLA, LOFAR has demonstrated noise perfprmance)

Dale Frail

$$N_{all-sky}(1.4\mathrm{GHz}) \approx 20 E_{49}^{11/6} n^{\frac{9p-1}{24}} \epsilon_{B,-1}^{\frac{3(p+1)}{8}} \epsilon_{e,-1}^{\frac{3(p-1)}{2}} (\Gamma_0 - 1)^{\frac{45p-83}{24}} \mathcal{R}_{300} F_{lim,-1}^{-3/2} .$$

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Summary

- A detection of a macronova like signal in 060614
- But need 0.1 M_{sun} ?
- Lower efficiency because of leakage of γ
- IF Macronova ==> R process nucleosynthesis + sGRBs from Mergers
- Radio flares are a second type of EM counterparts that can follow Mergers (long term - advantage)
- Detectablity prospects of radio flares is reasonable as a follow up for GW detection (Hotokezaka et al. in preparation)
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