# Electromagnetic Counterparts of GW sources Past, Present and Future

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erc

Origins: From the Big Bang to Planets I-CORE

NSFC National Natural Science Foundation of China

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Est. 1925

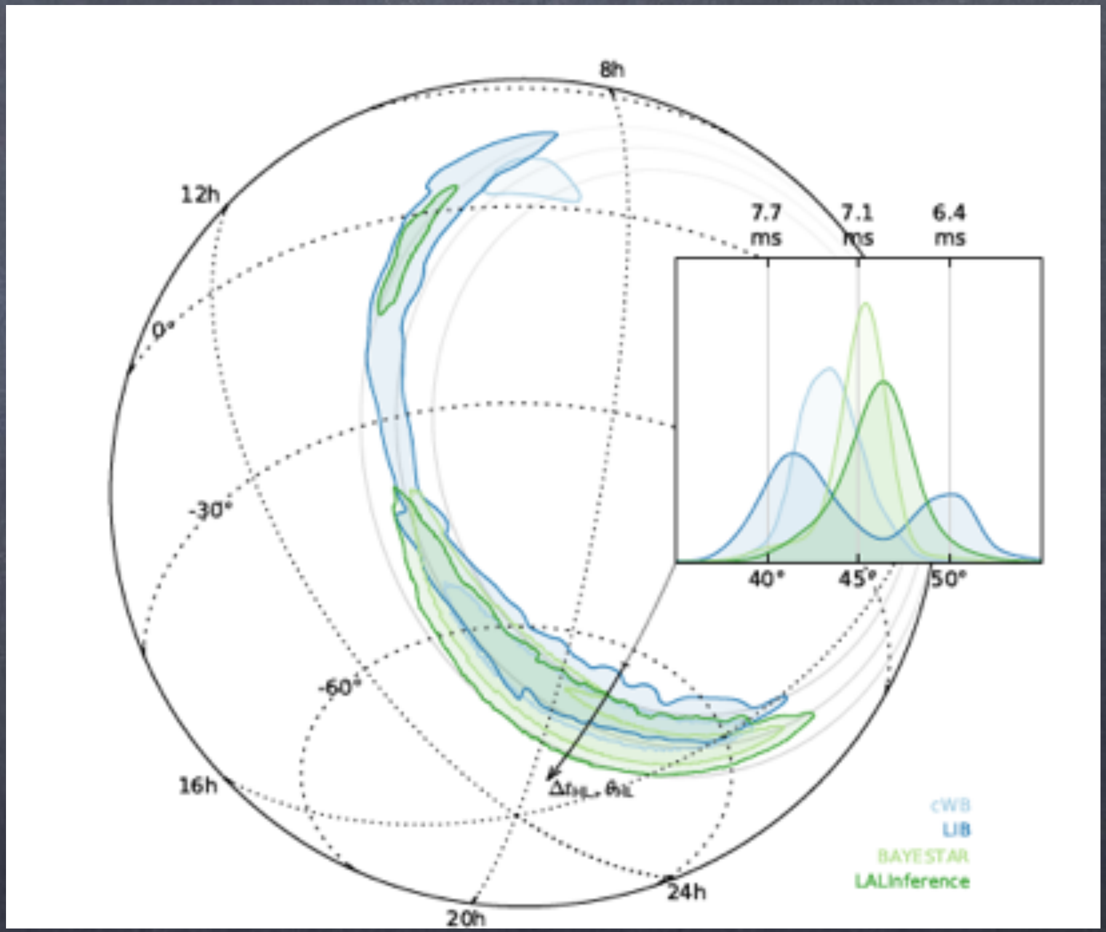
# Joseph Katz
# 1930-2016

# Outline

- Why?
- What and How?
    - Short GRBs
    - Macronova (kilonova)
    - Radio Flares
- BHBH mergers and GW150914-GBM ?
- Conclusions

# Why?
## (Kochaneck & TP 1993)

- Where (host, redshift, distance ....)
- Much more physics
- Increase sensitivity (and confidence)




GW 150914 Ligo + 16, Localization

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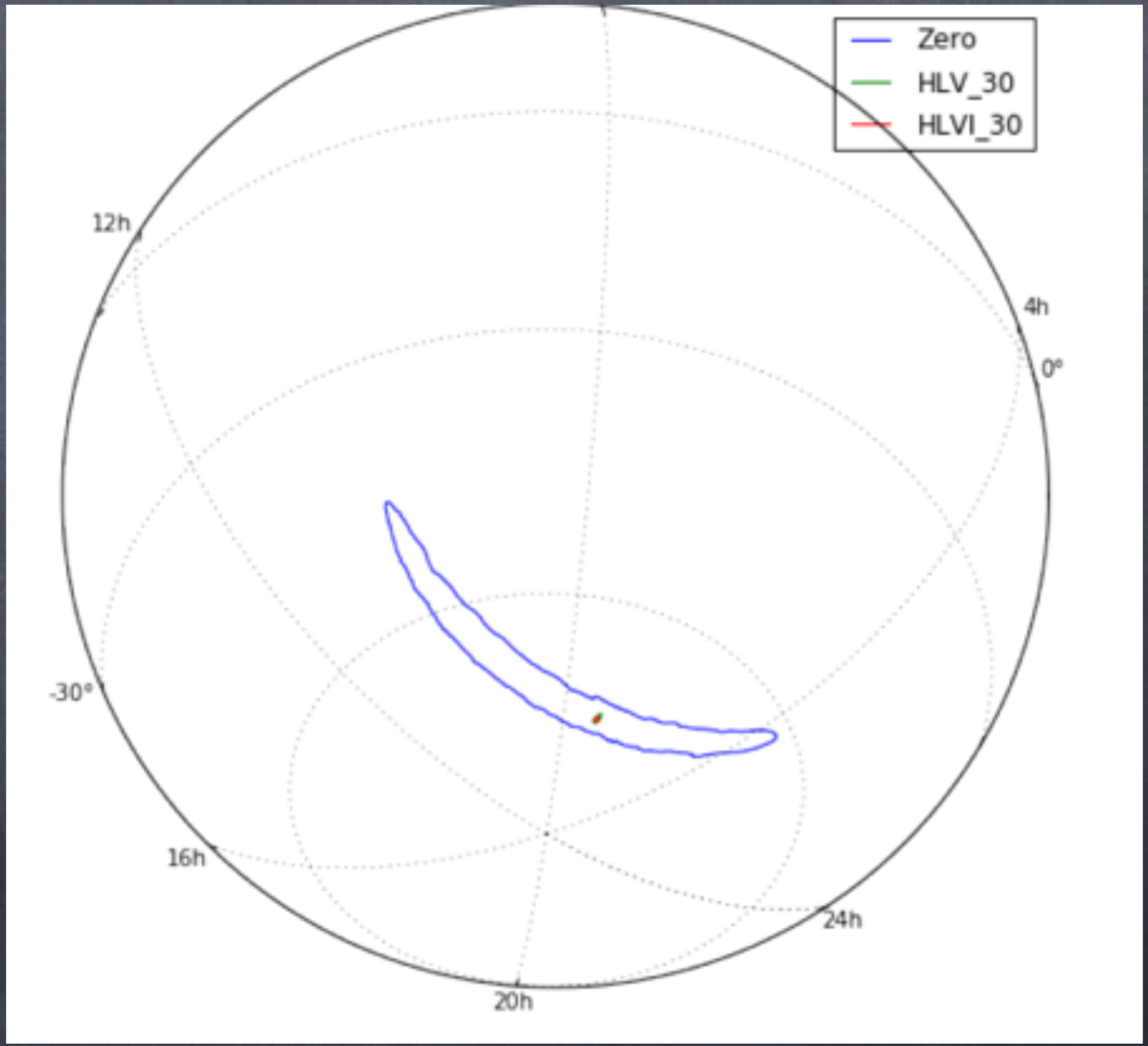


GW 150914 Ligo + Virgo +Indigo, Localization

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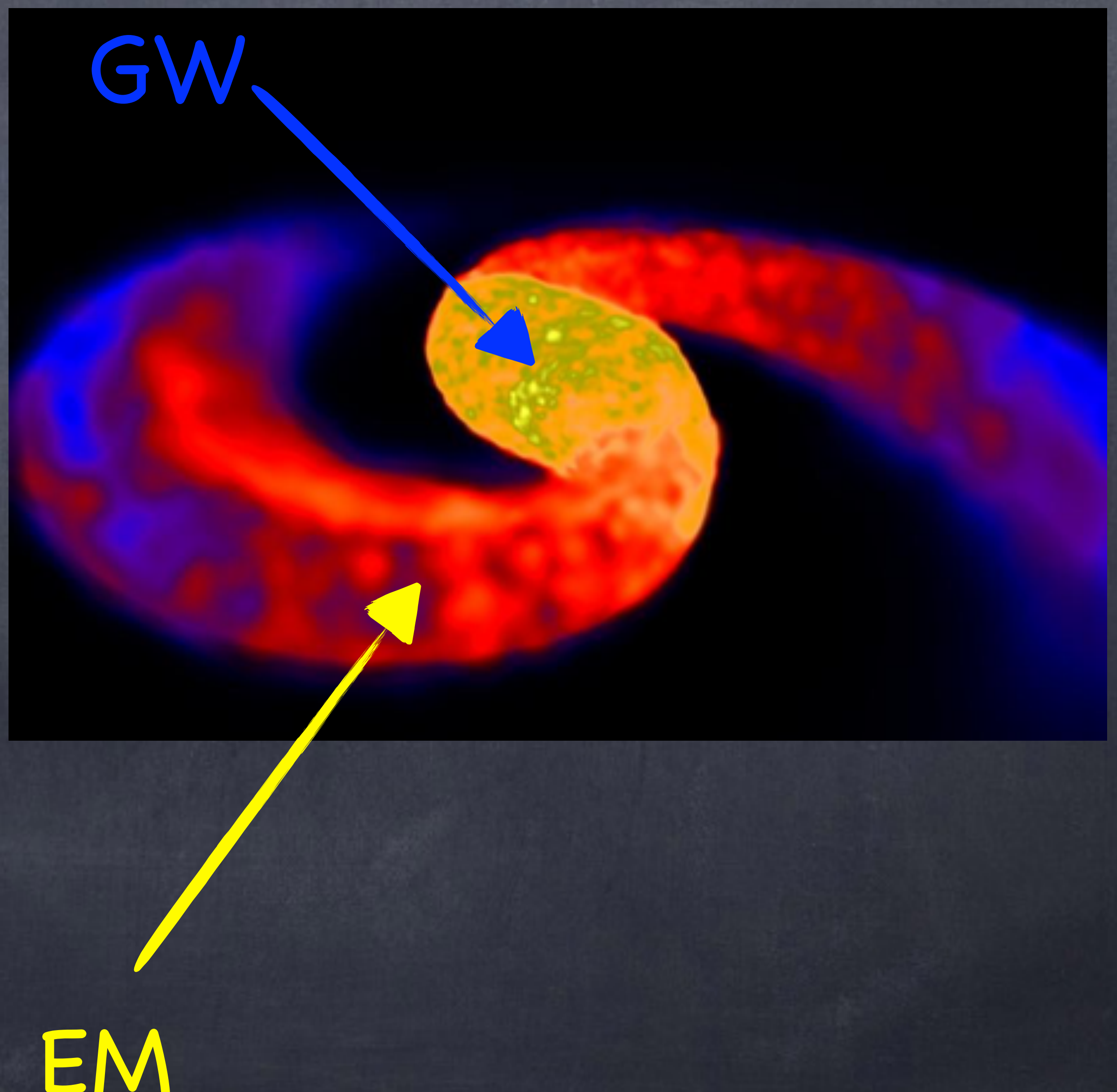

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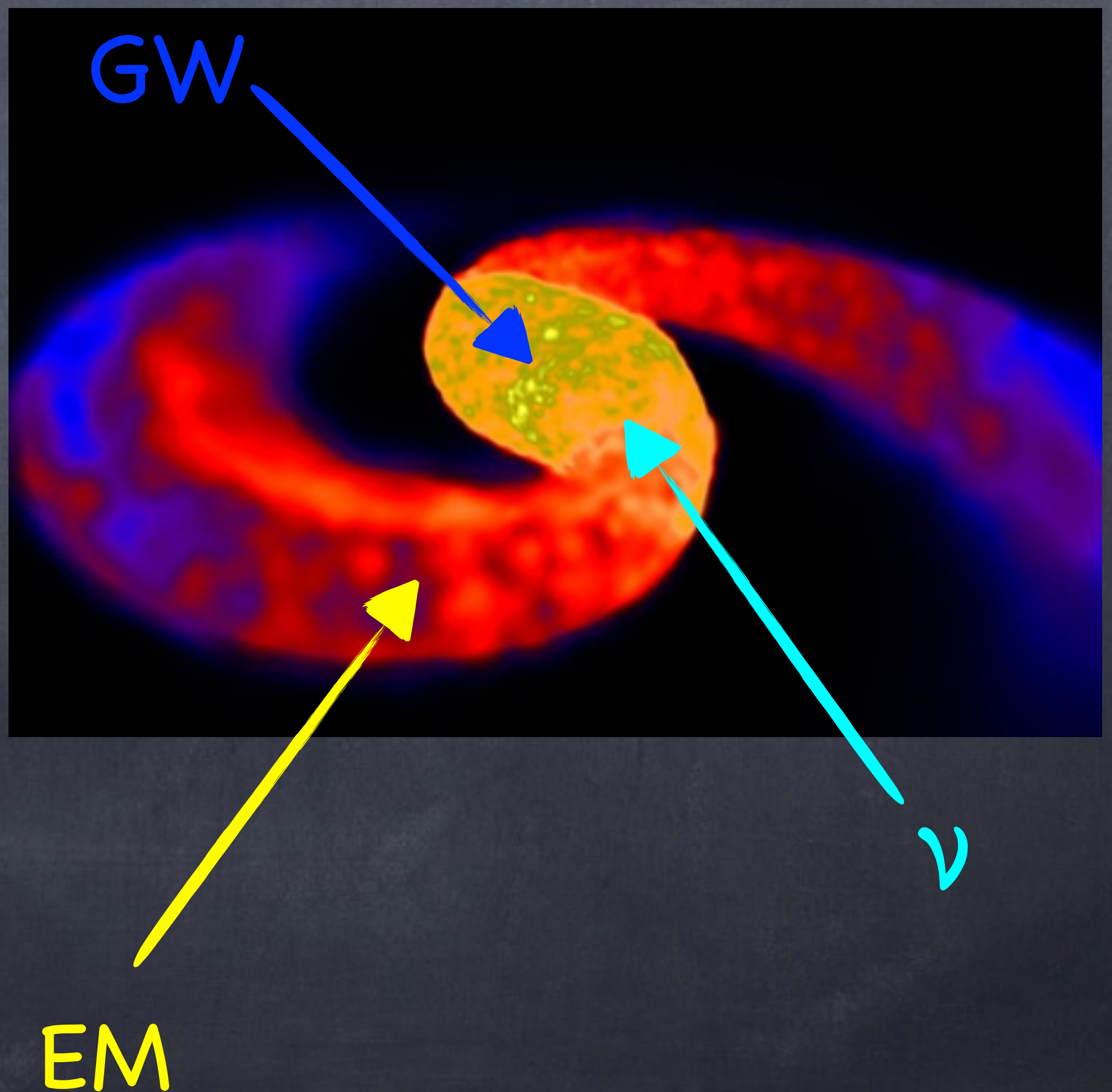

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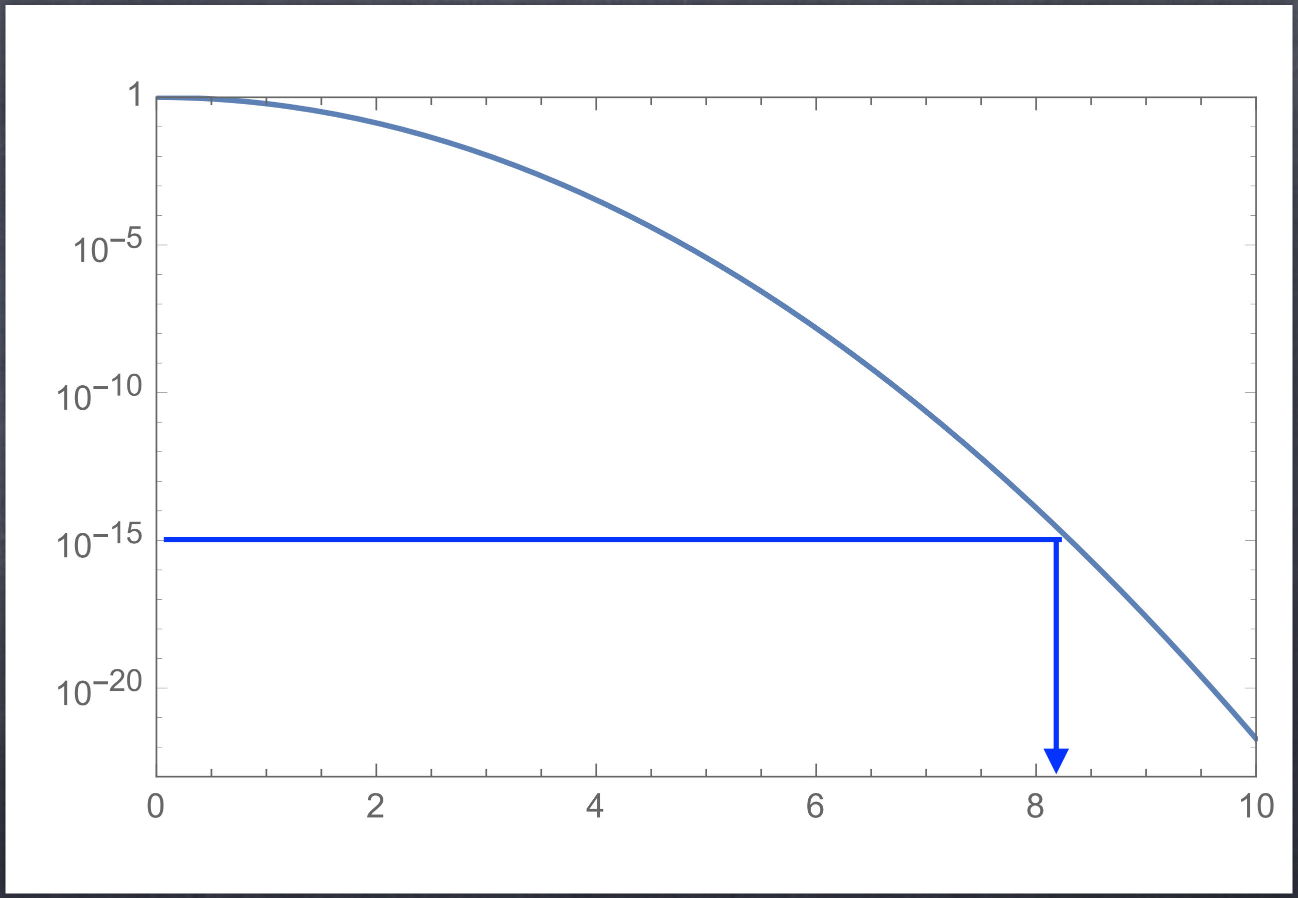

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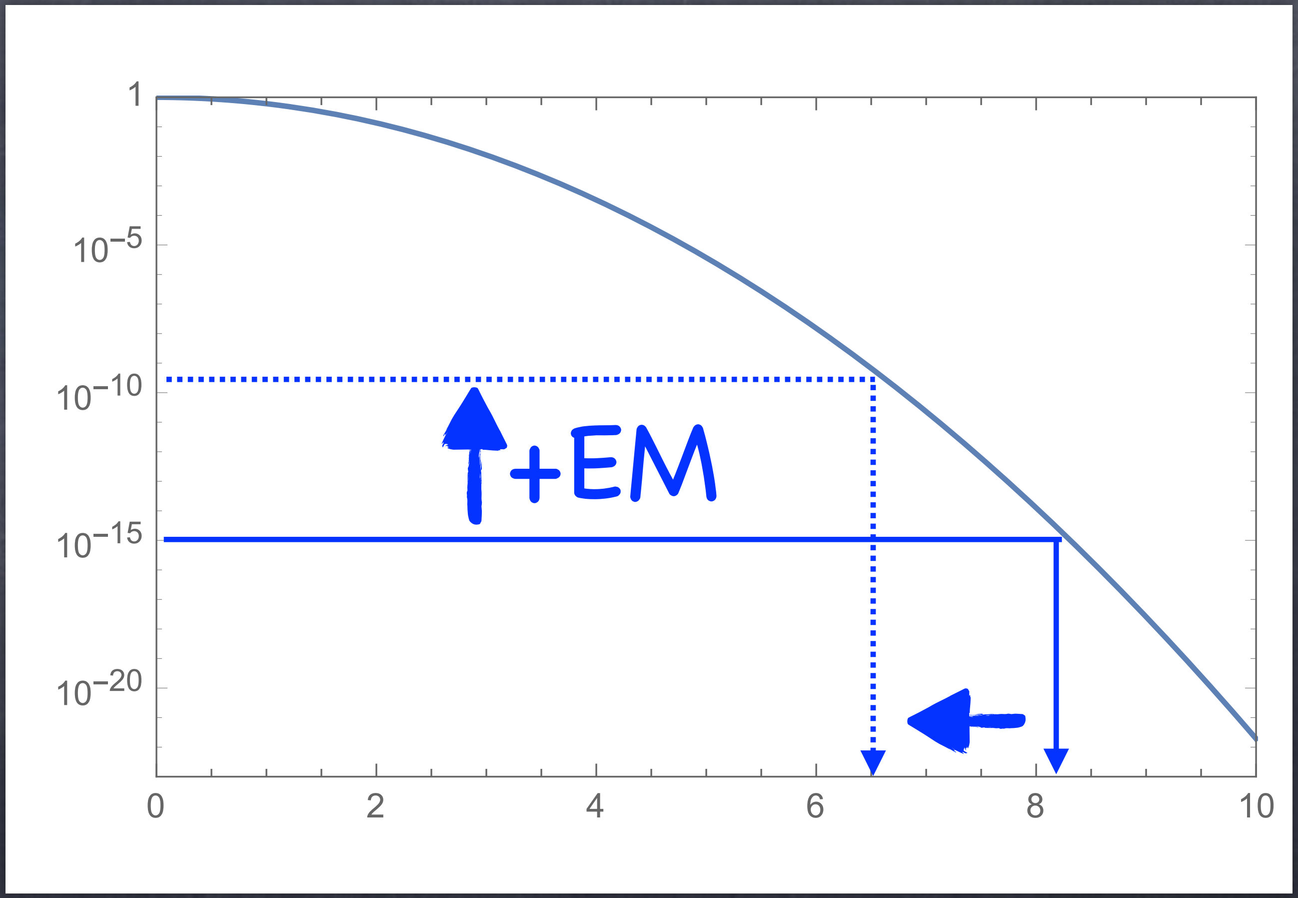

# What and how?

* For $ns^2$ and ns-BH
Nothing is really expected for BHBH

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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 energy available is $10^{53-54}$erg. Can a small fraction of this energy produce an EM signal?

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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.

# GRBs - Observations

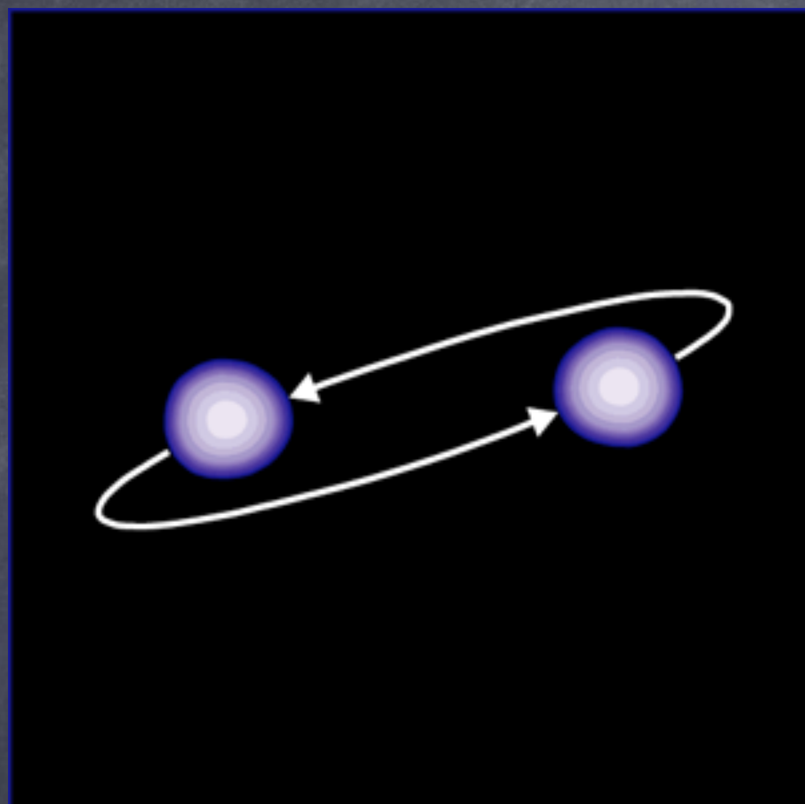
- Prompt gamma rays (0.1-100 sec)
- Energy $10^{49}$-$10^{52}$ ergs
- Spectrum ~300 keV but up to a few GeV
- Afterglow:  X-ray (~ days), optical (~ weeks) and radio (~ year)

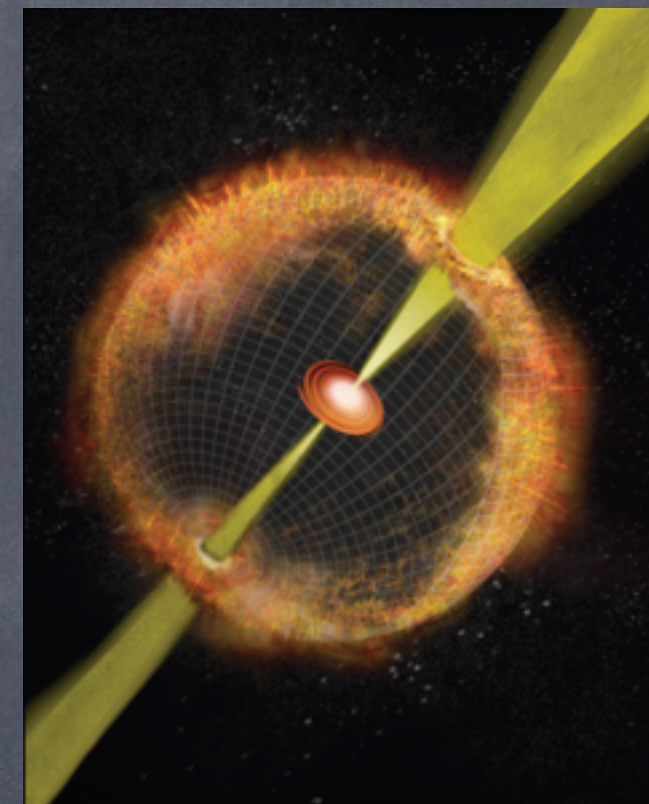
# GRBs - Theory

- Relativistic jets ($\Gamma$>100)
- Afterglow - slowing down of the jet by interaction with surrounding.

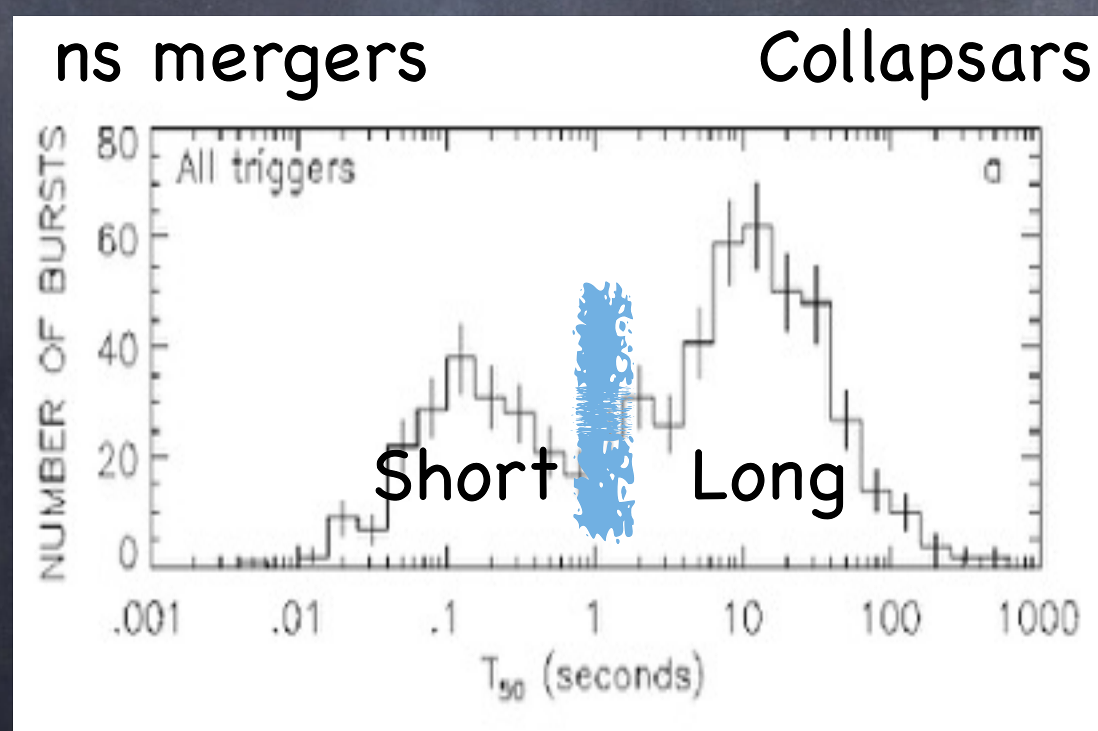
Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley, 98





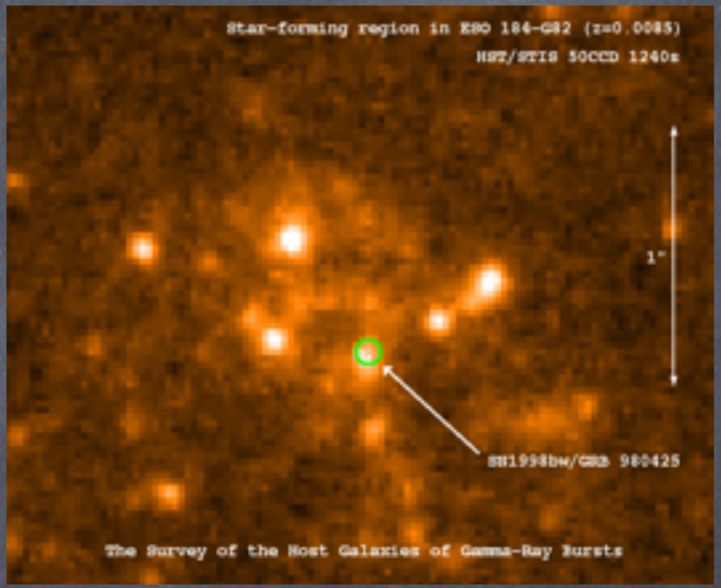
Indirect Evidence rate hosts macronova

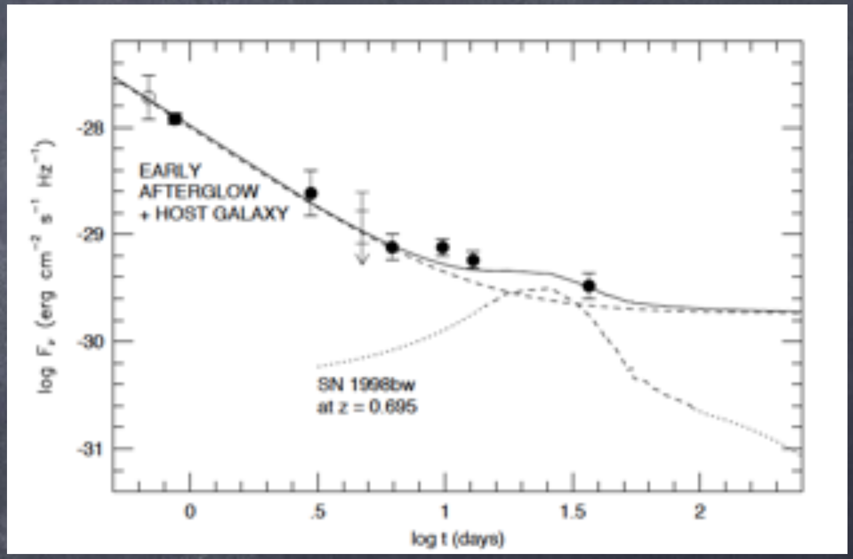


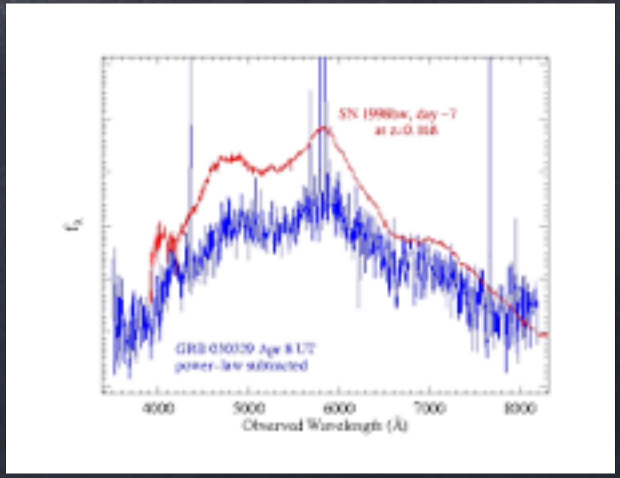

Direct Evidence (low metallicity)

# History of Long GRB-SN association

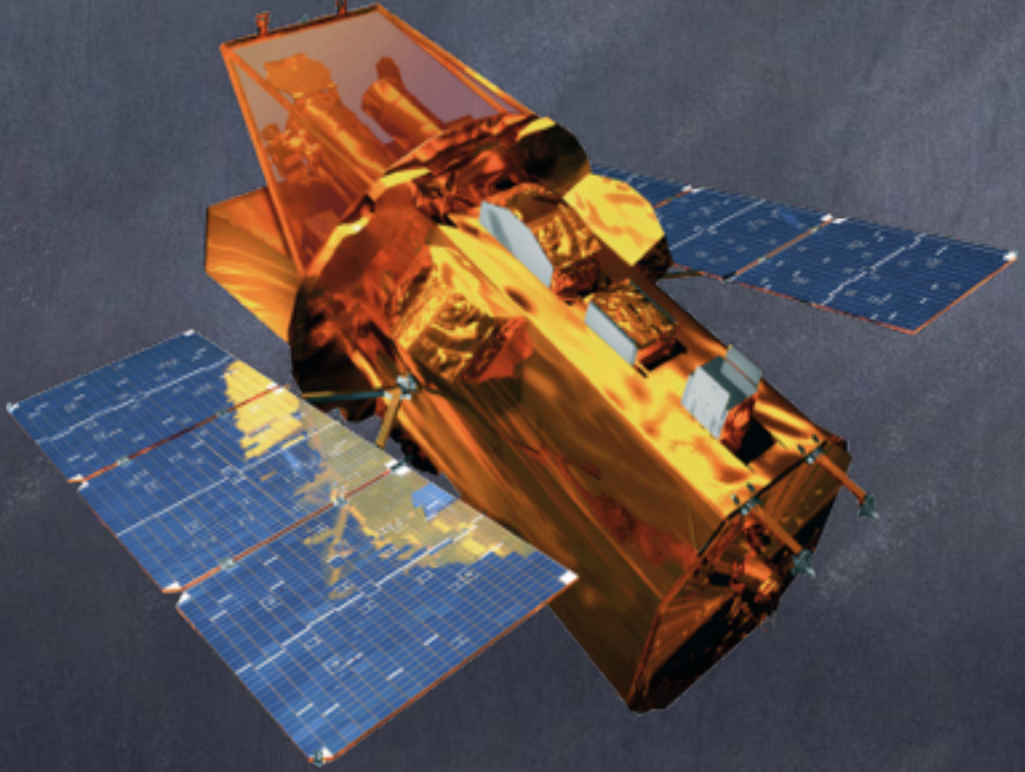
- 1997/8: Indirect evidence long GRBs in star forming regions.
- 1998: Tentative association of the peculiar GRB 980425 with the very luminous SN 1998bw
- 1999-2003 Red bumps in long GRB light curves
- 29 March 2003 Clear association of SN 2003dh with GRB 030329



# GRBs are beamed - chance of coincidence <1:10 (?)



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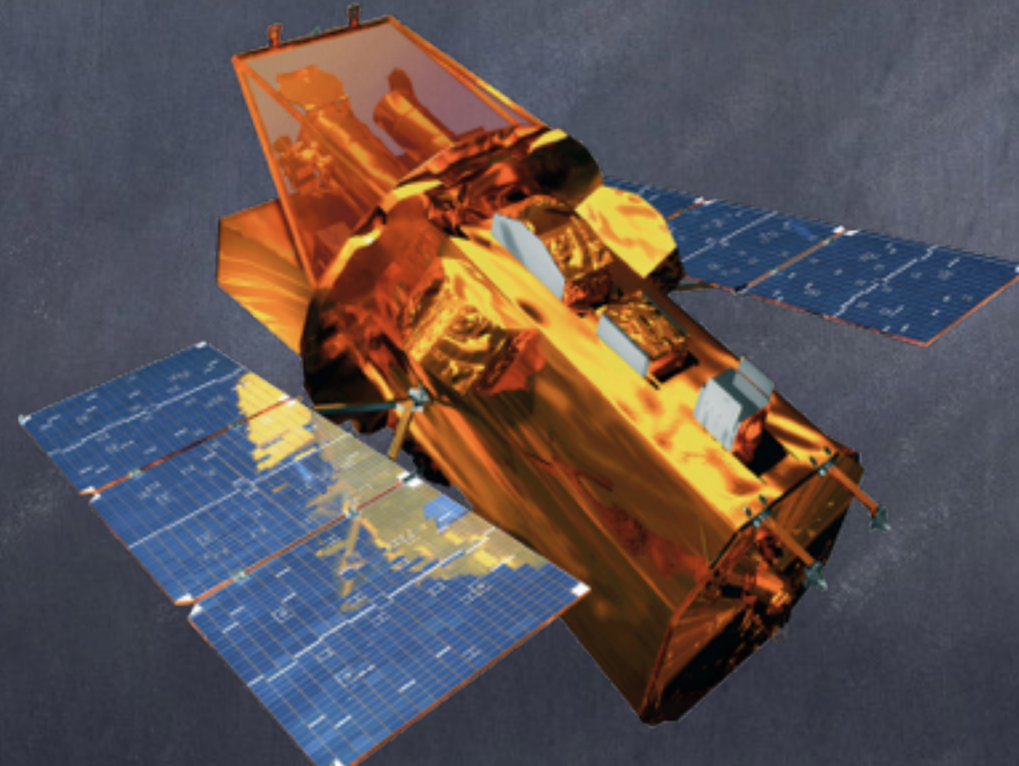
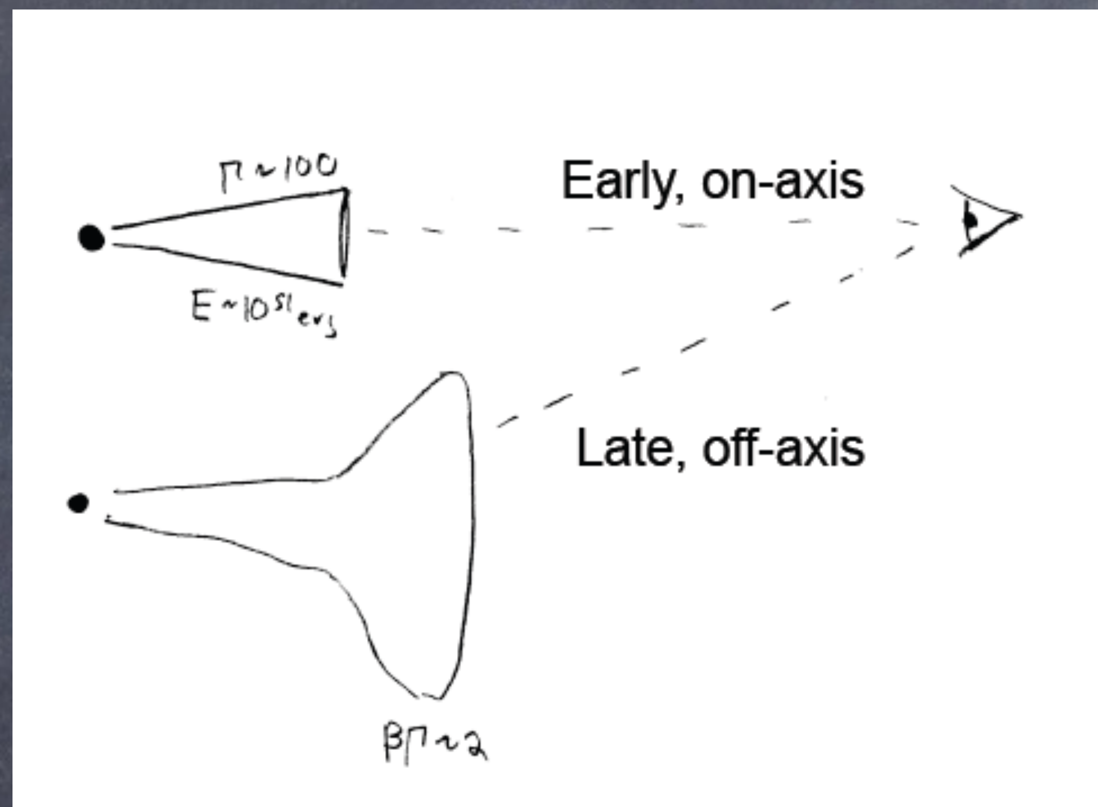
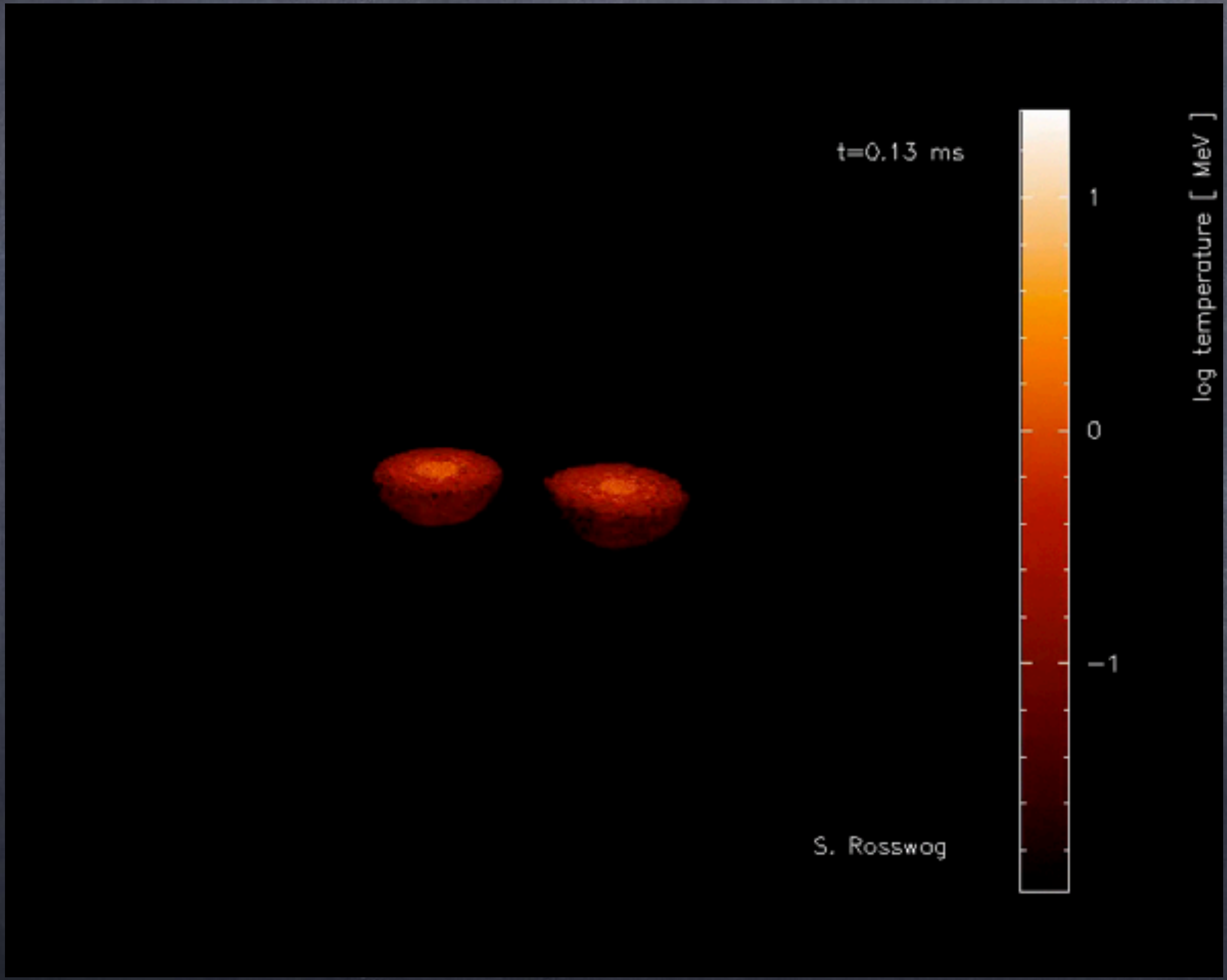


# Orphan Afterglow




SGRBs are weak =>
Orphan afterglow is too weak ☹️
(>24 mag) - not observed yet even from long GRBs

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




Stephan Rosswog

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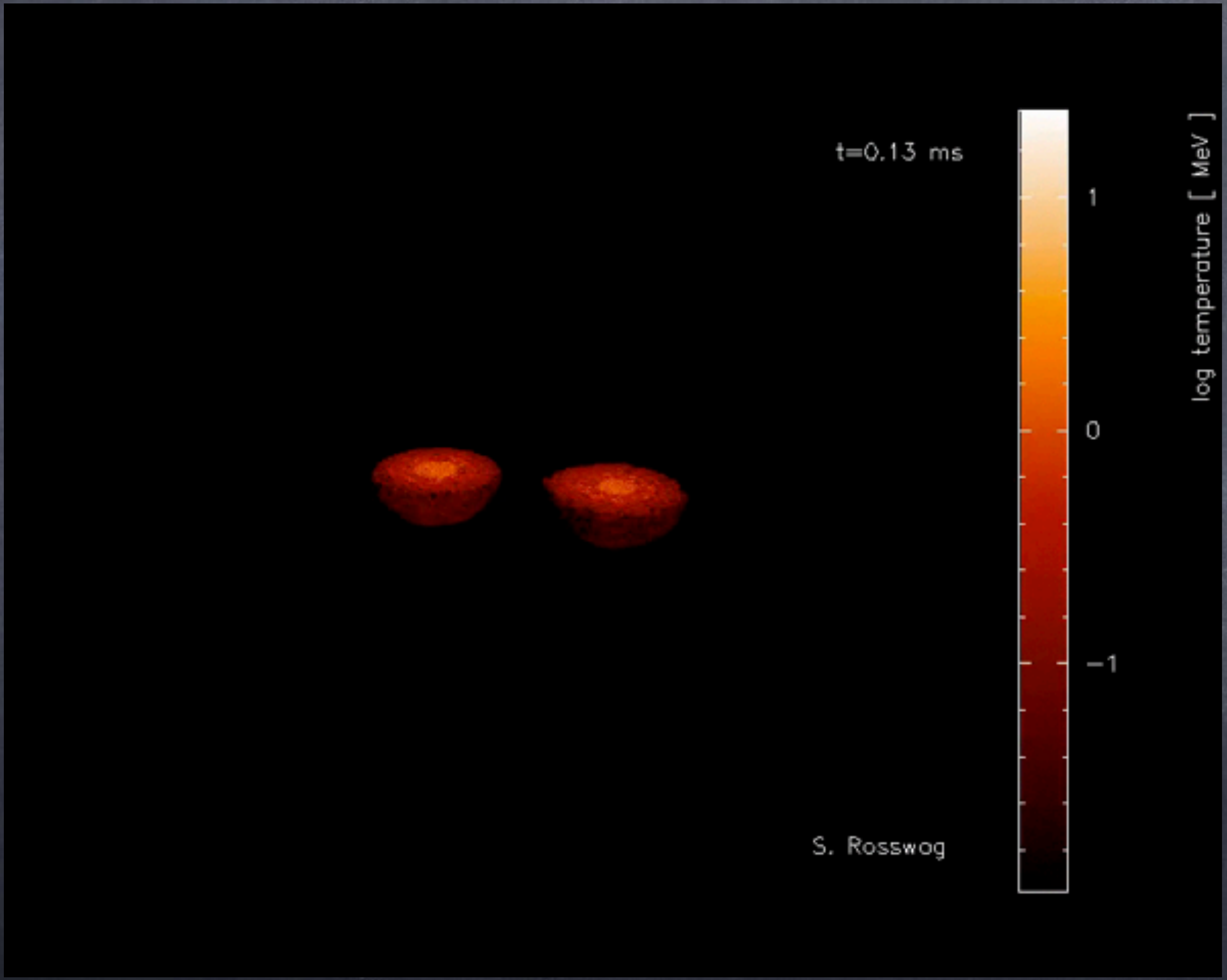


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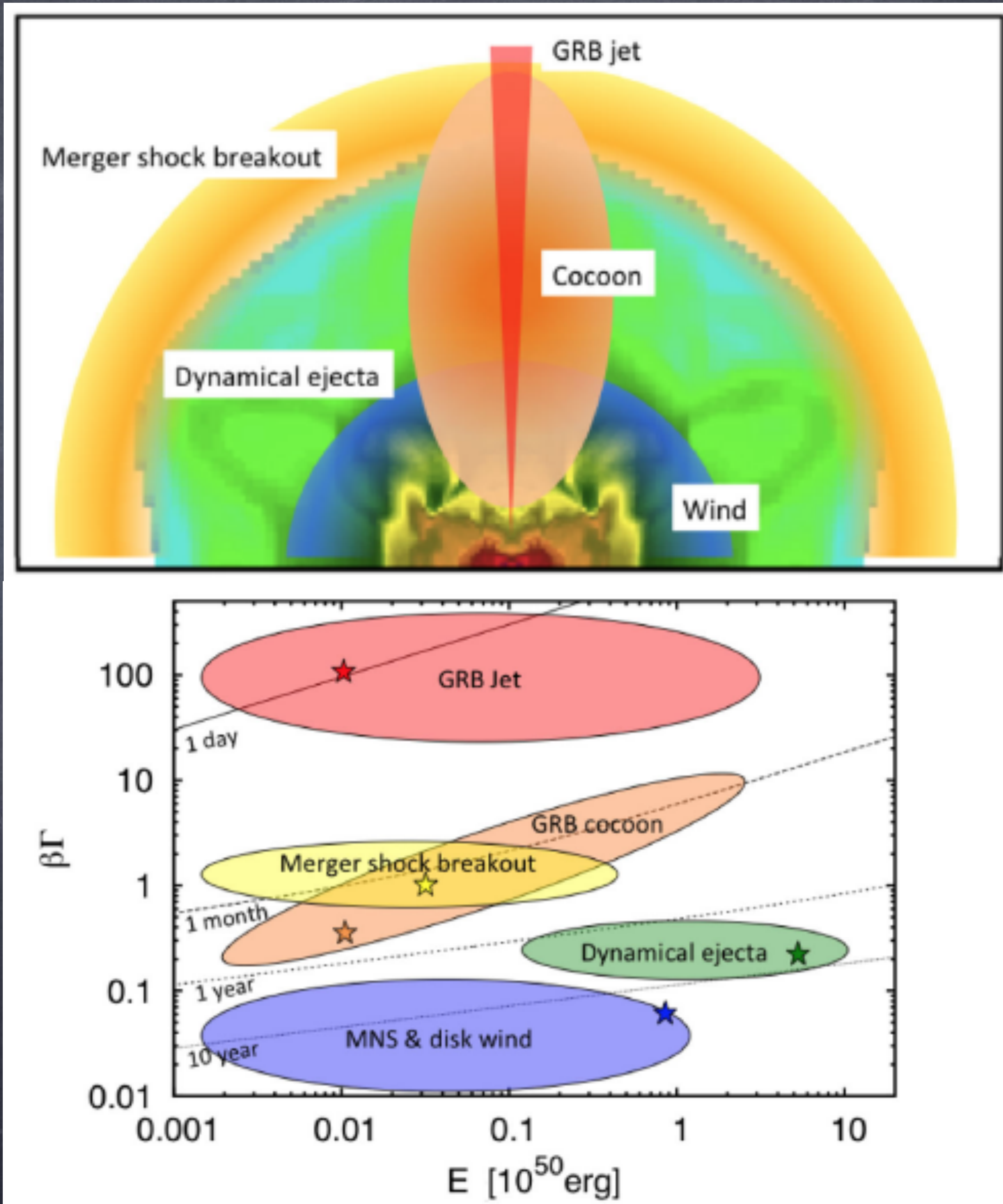
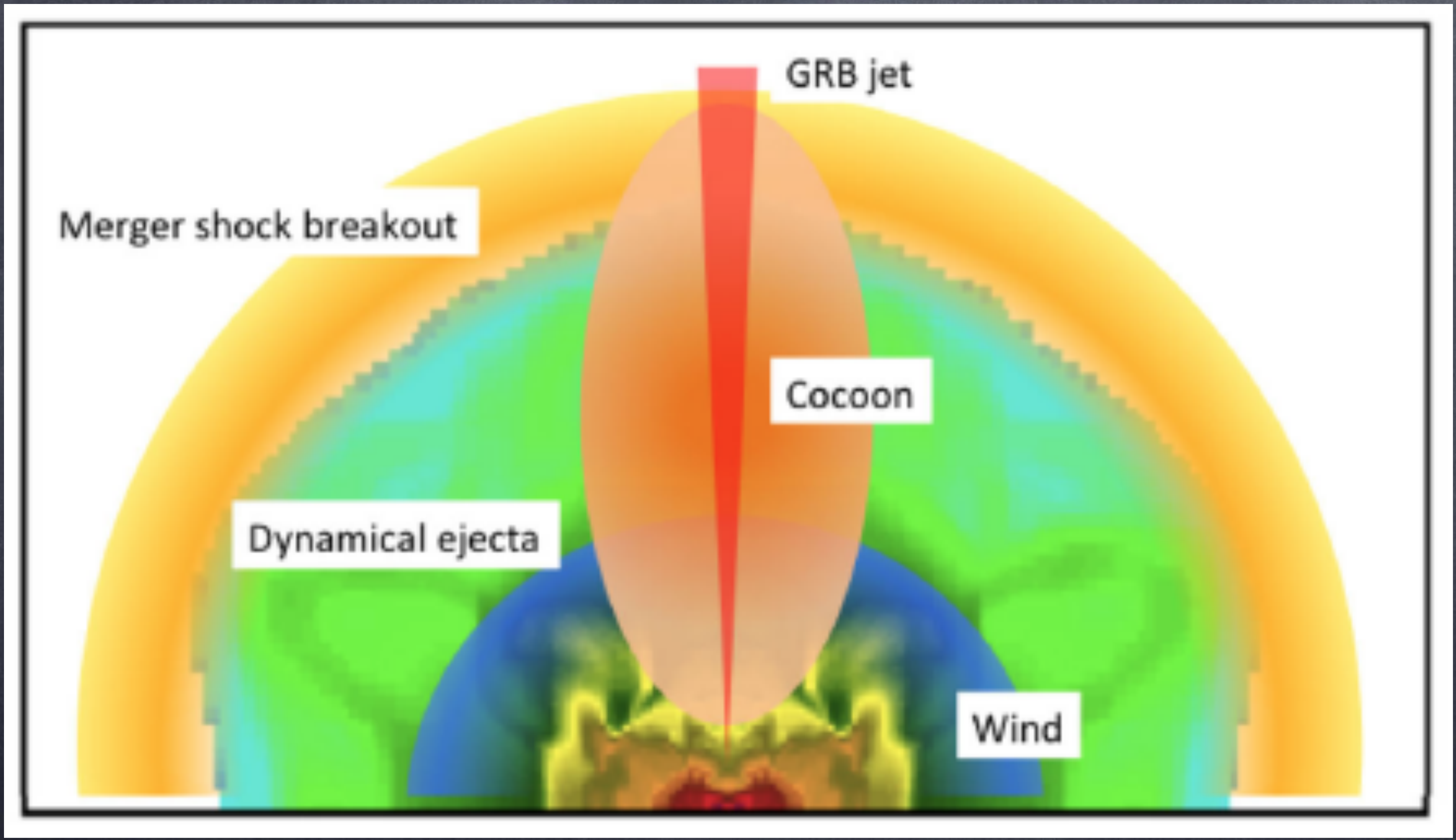
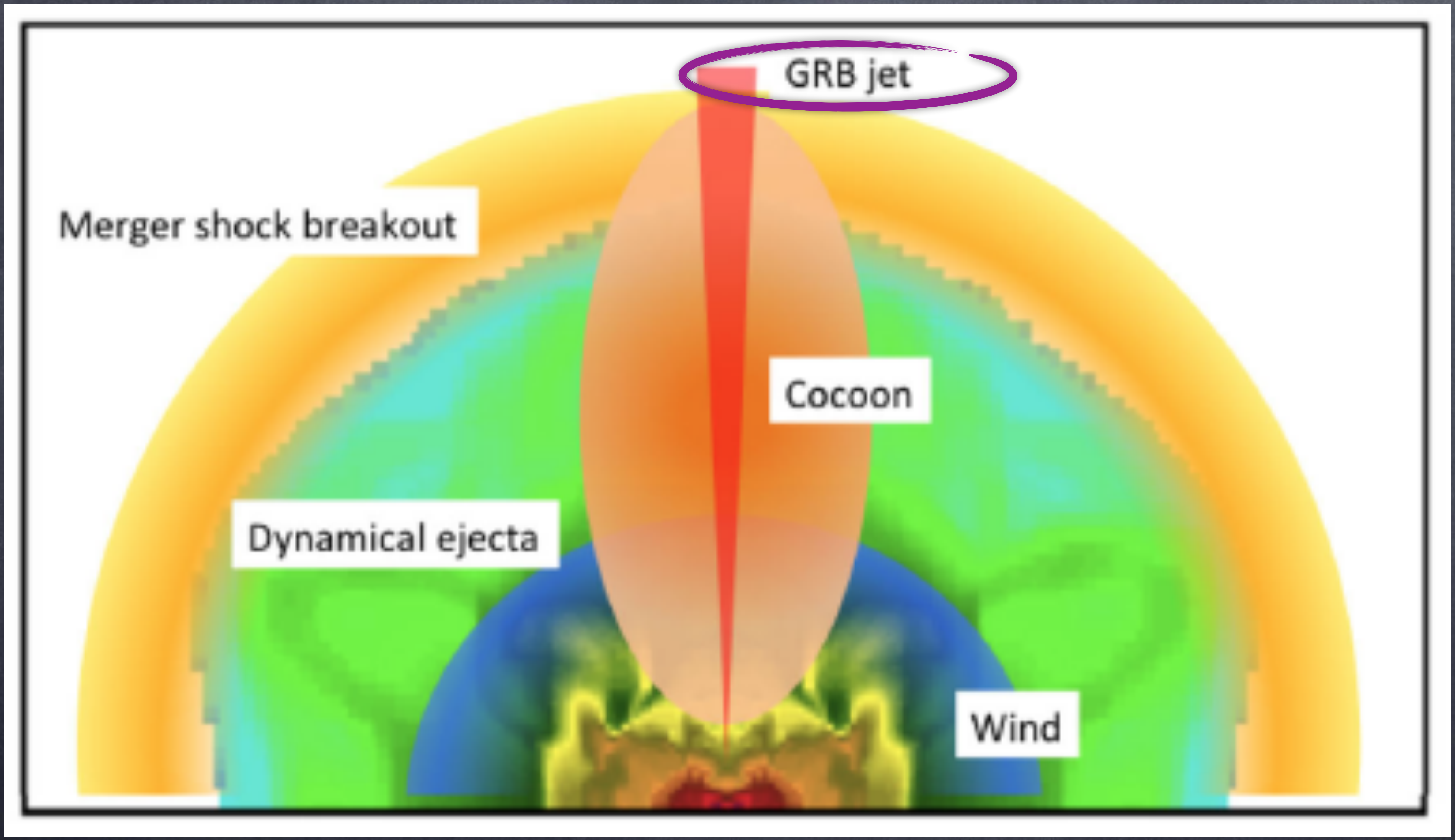
# Different components of mass outflows from mass mergers (Hotokezata & TP 15)




GRB jet
Merger shock breakout
Cocoon
Dynamical ejecta
Wind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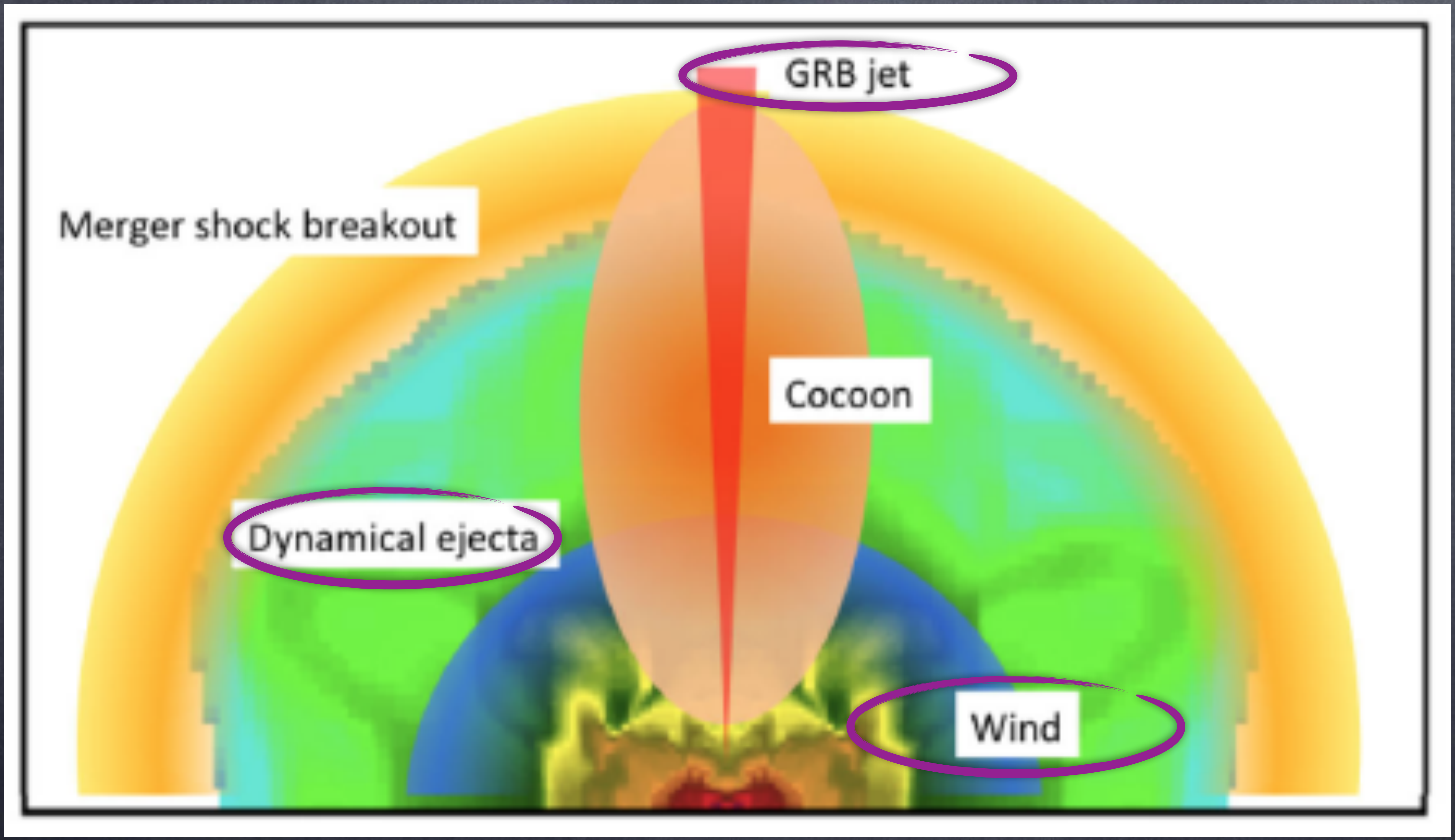
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*Also called Kilonova

- Expanding cloud of ejected matter.
- Radioactive decay of the neutron rich matter. $E_{radioactive} \approx 0.001\ Mc^2 \approx 10^{50}\ (M/0.1\ M_{sun})$ erg

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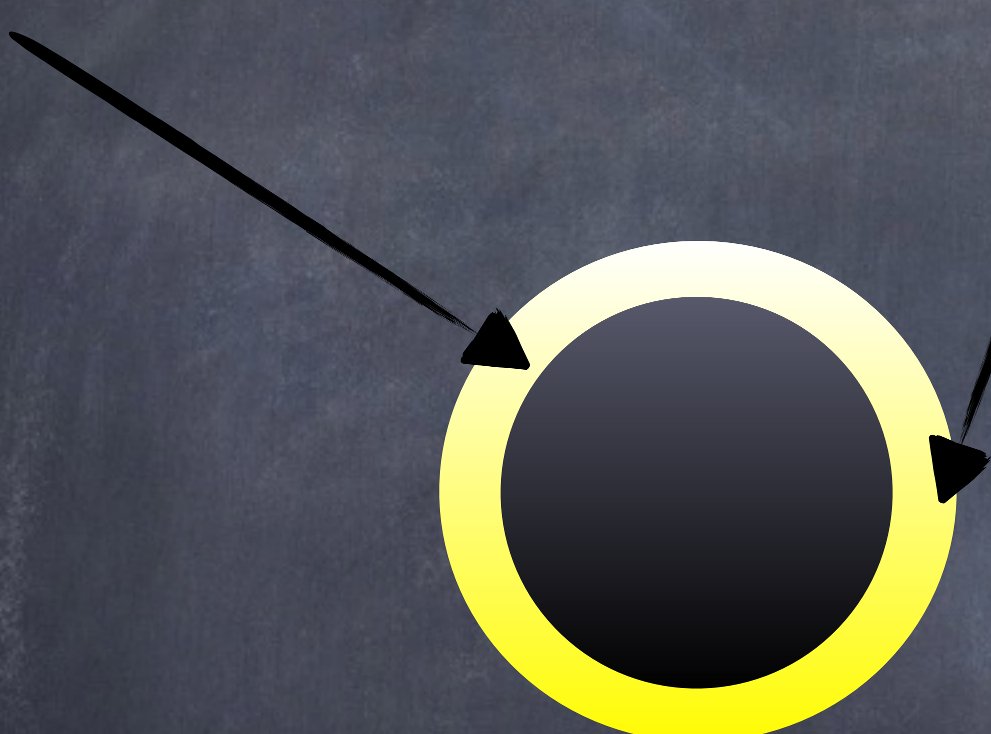
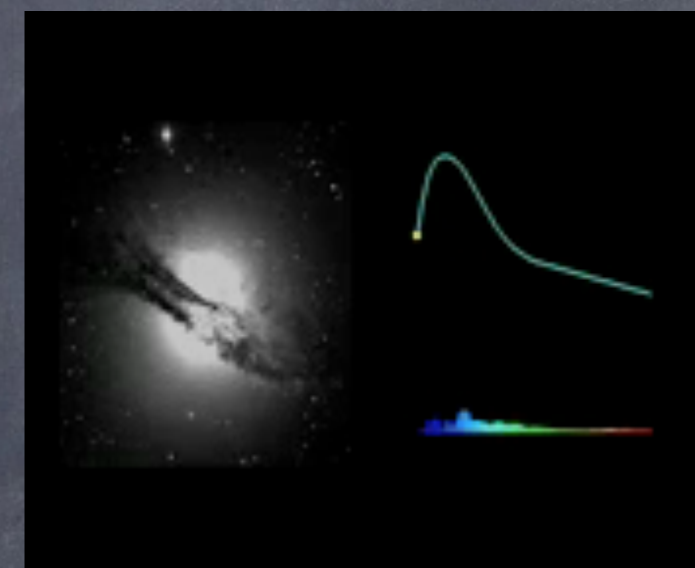
=> A weak short Supernova

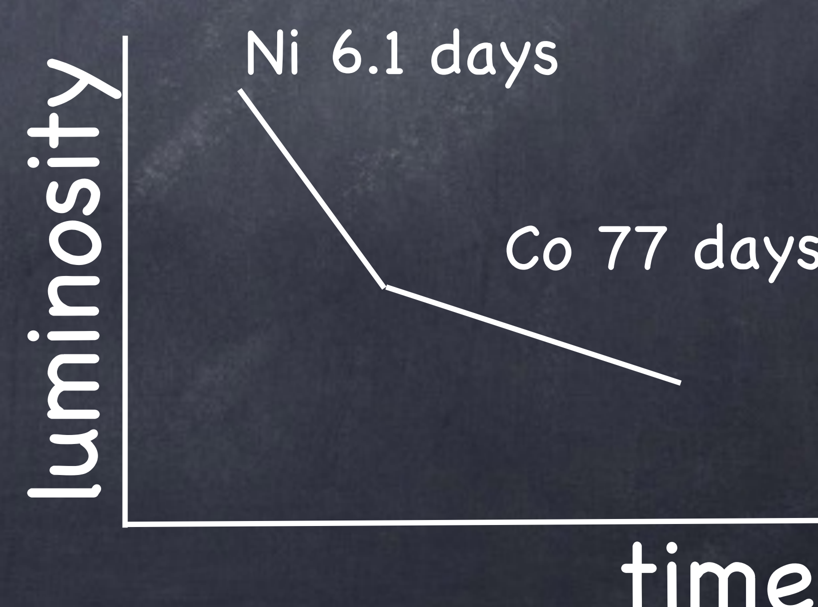
# Supernova

Photosphere

Photons escape








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

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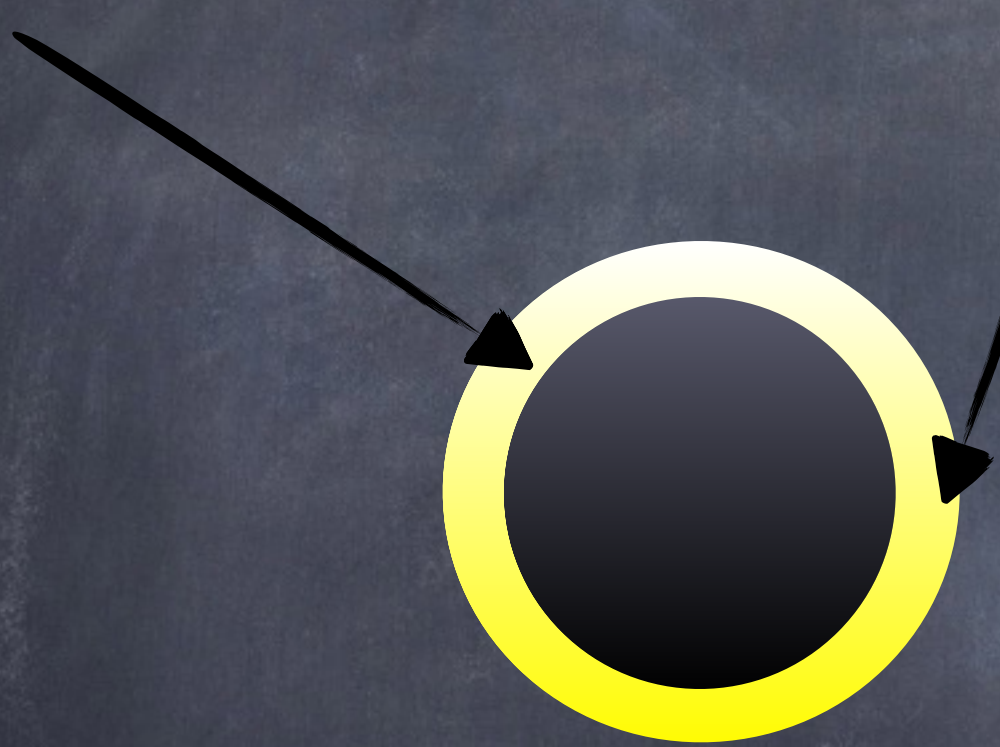

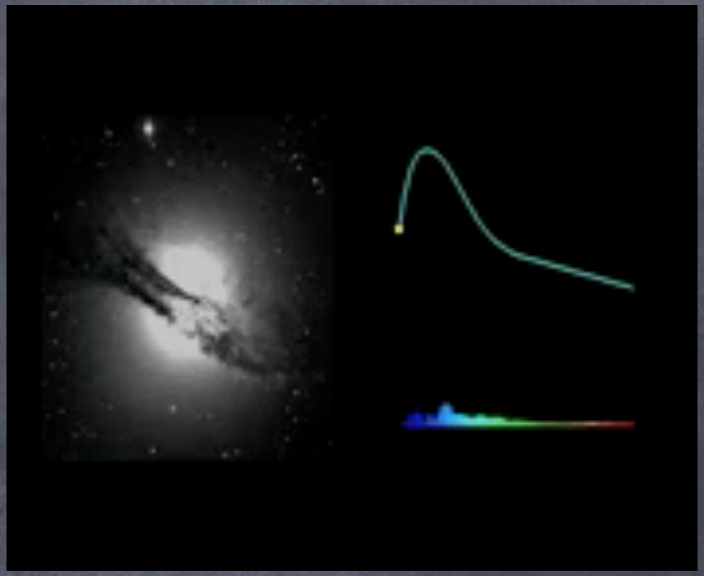

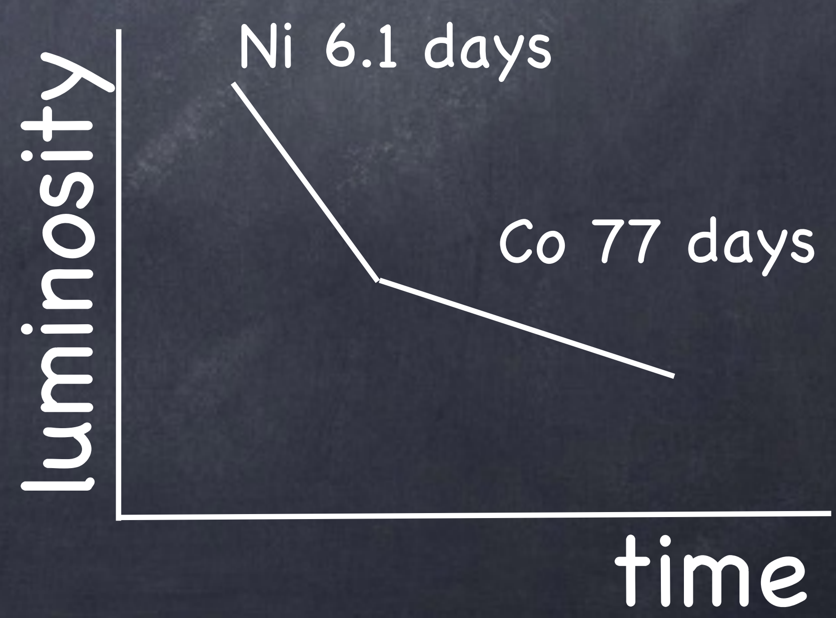


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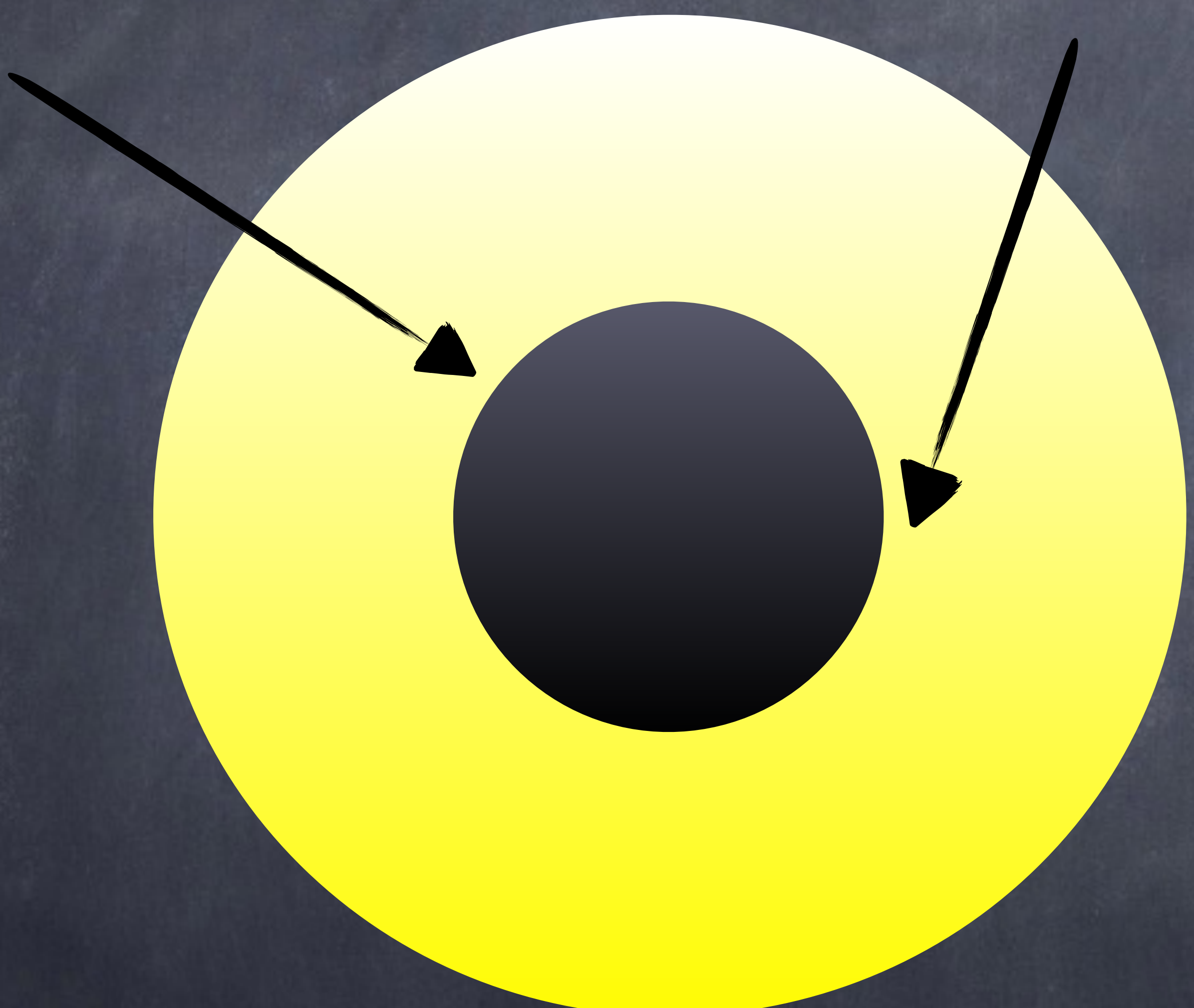

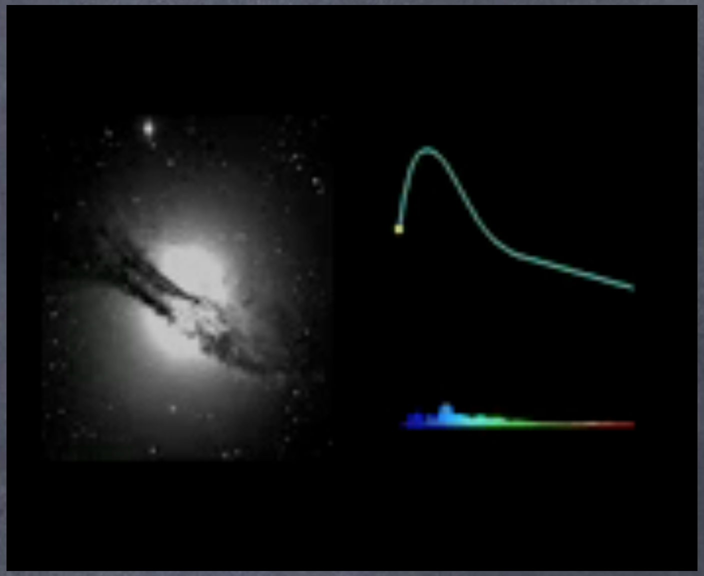

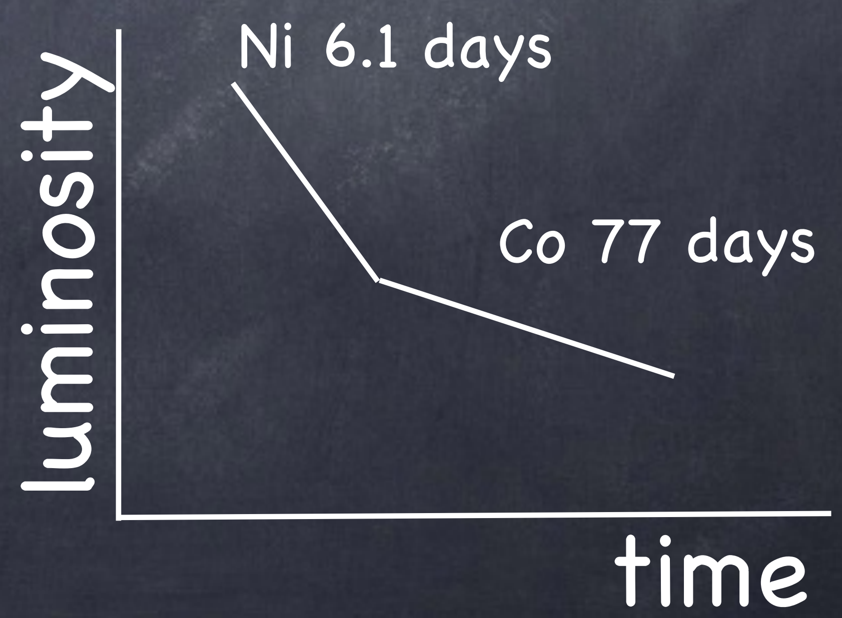


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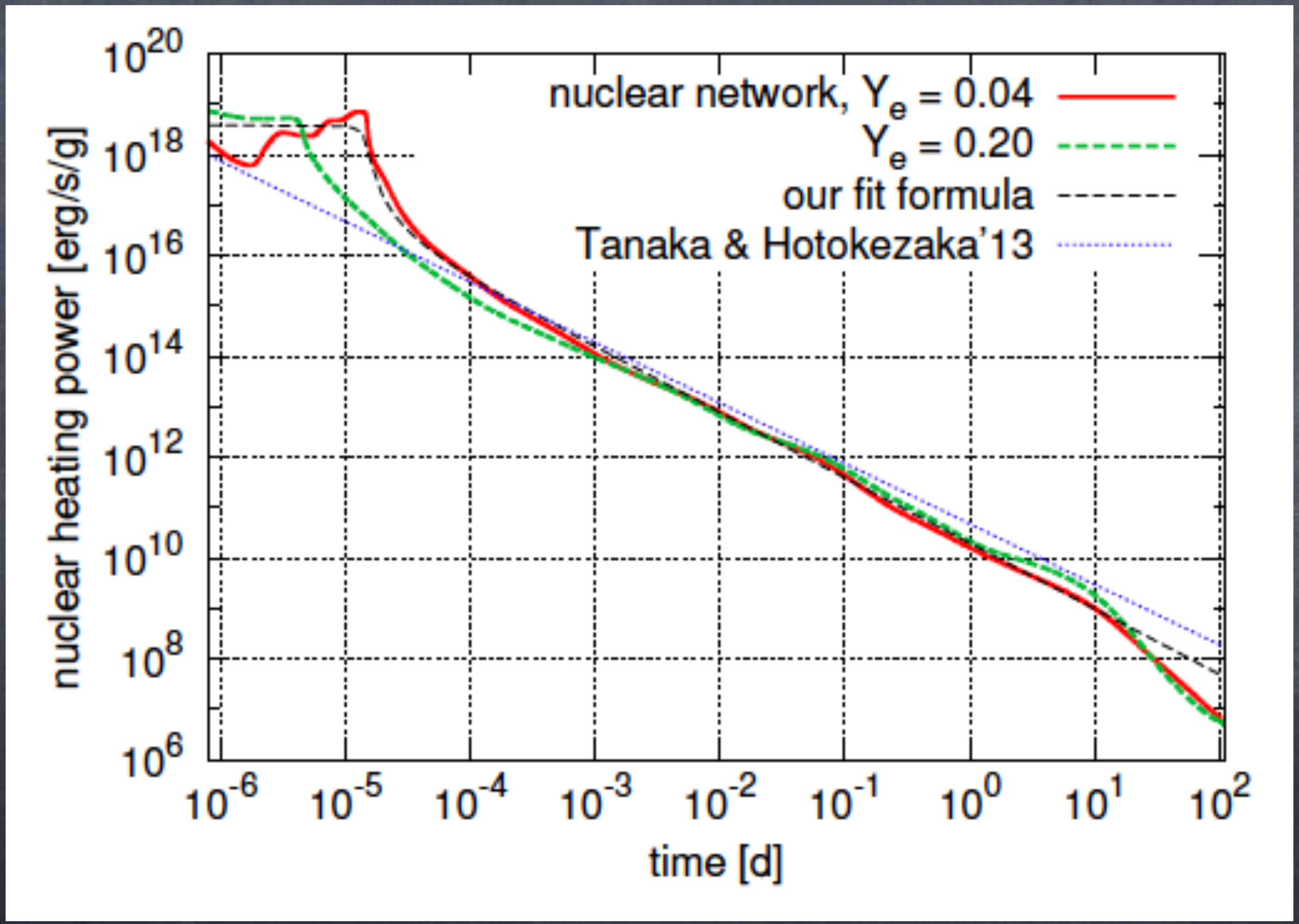
# Radioactive Decay

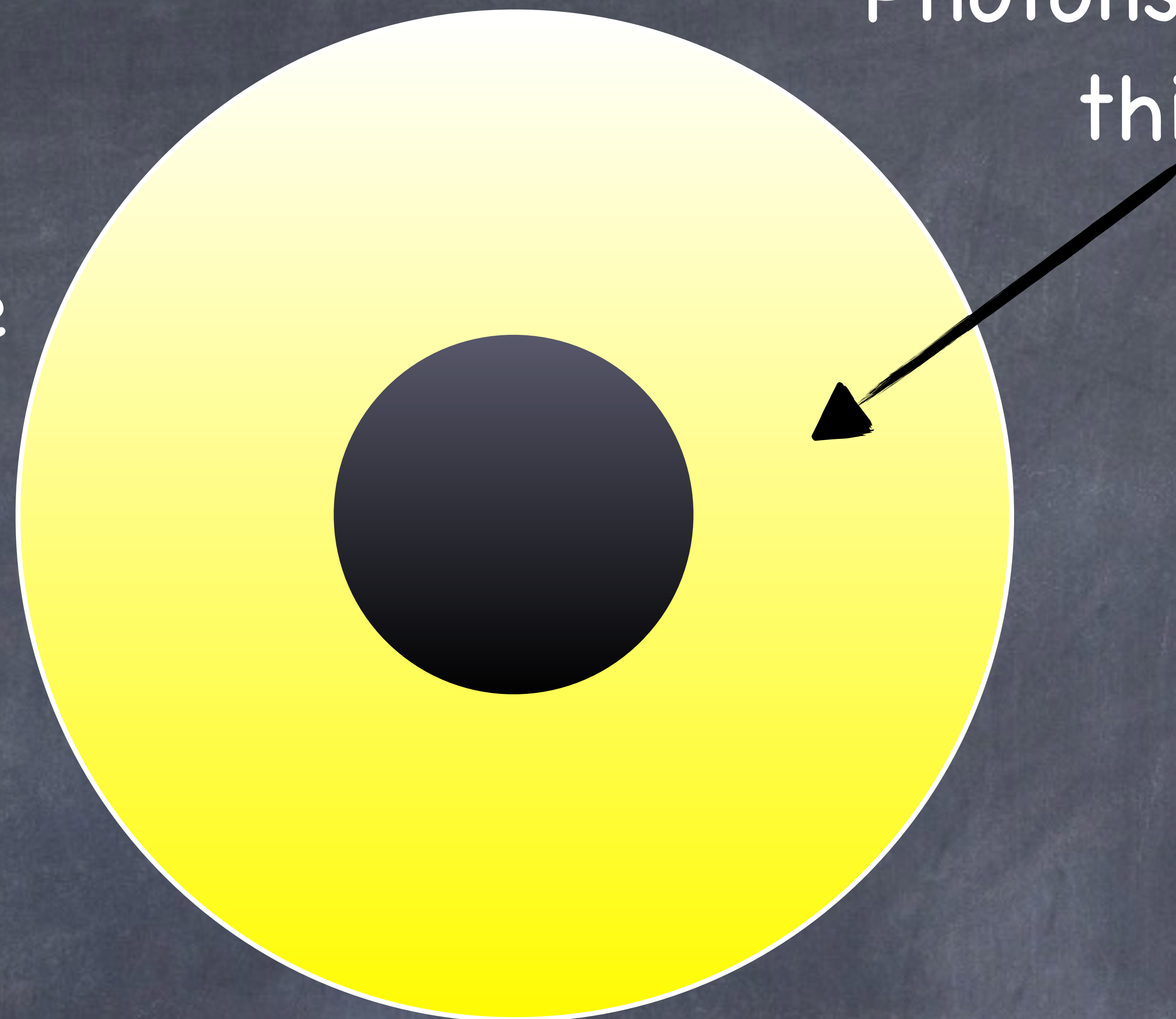
(Freiburghaus+ 99; Metzger + 11; Goriely + 11; Korobkin + 13; Wanajo + 14)

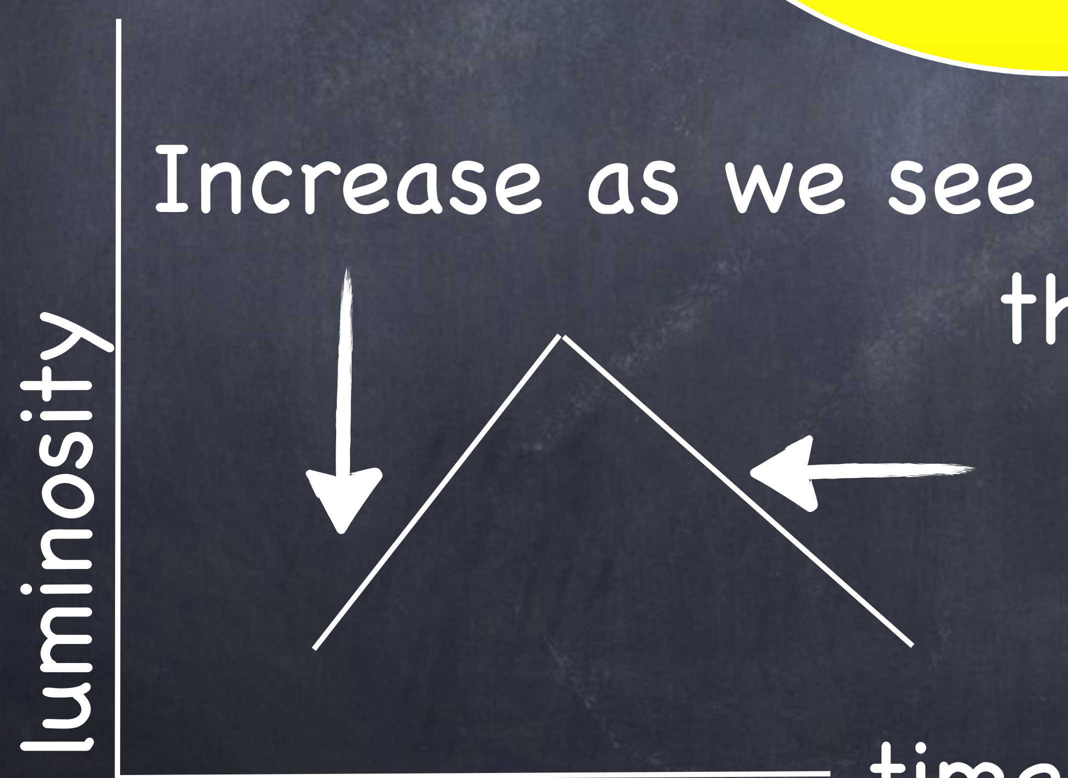



After a second $dE/dt \propto t^{-1.3}$ (Hotokezaka 16)

The light curve depends on

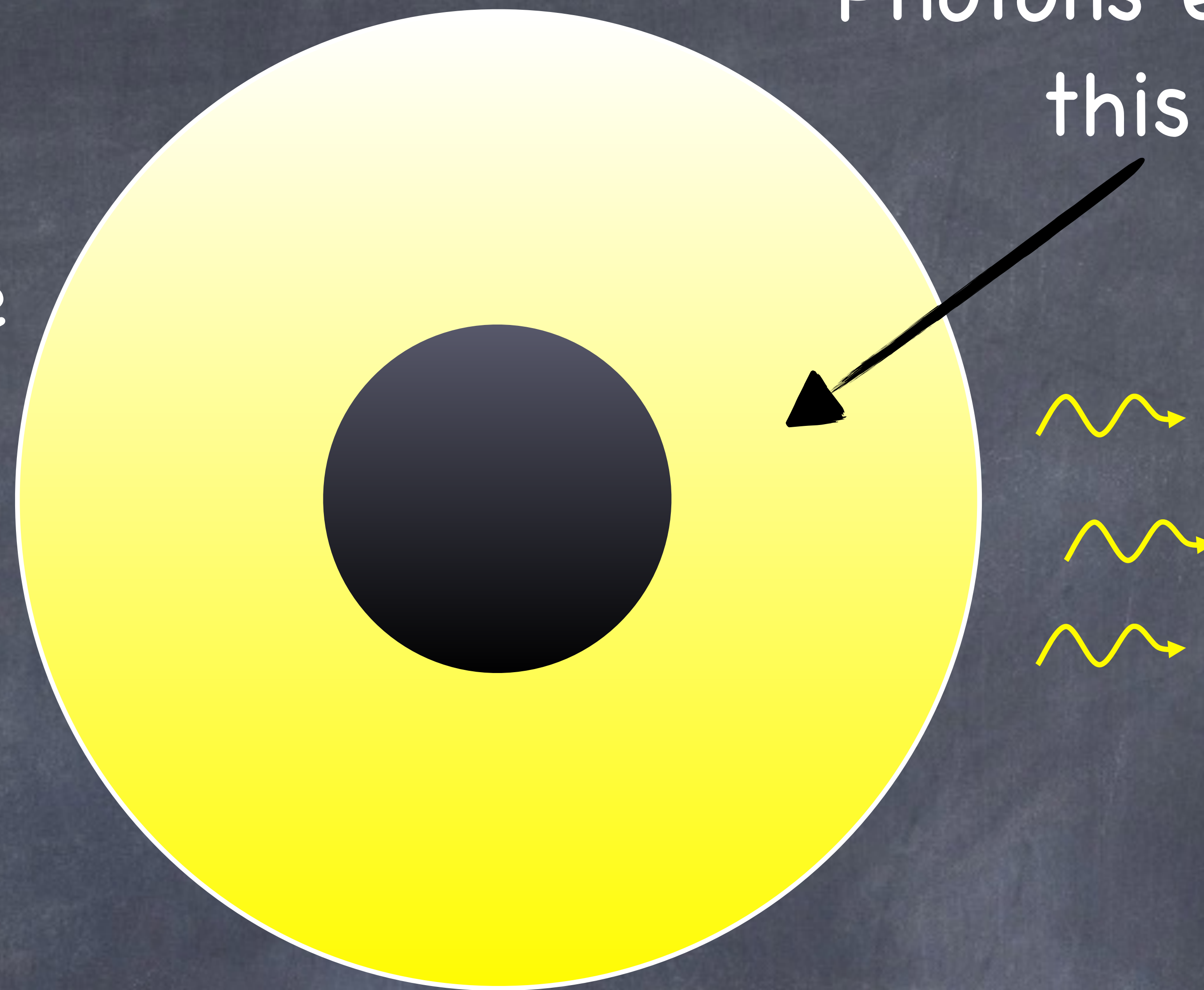
1. mass
2. velocity
3. opacity




Macronova

Photons escape from this region



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1. mass
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Increase as we see large and larger fraction of the matter.


Decrease due to radioactive decay

Macronova

# Light Curve

mass with velocity >v

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

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

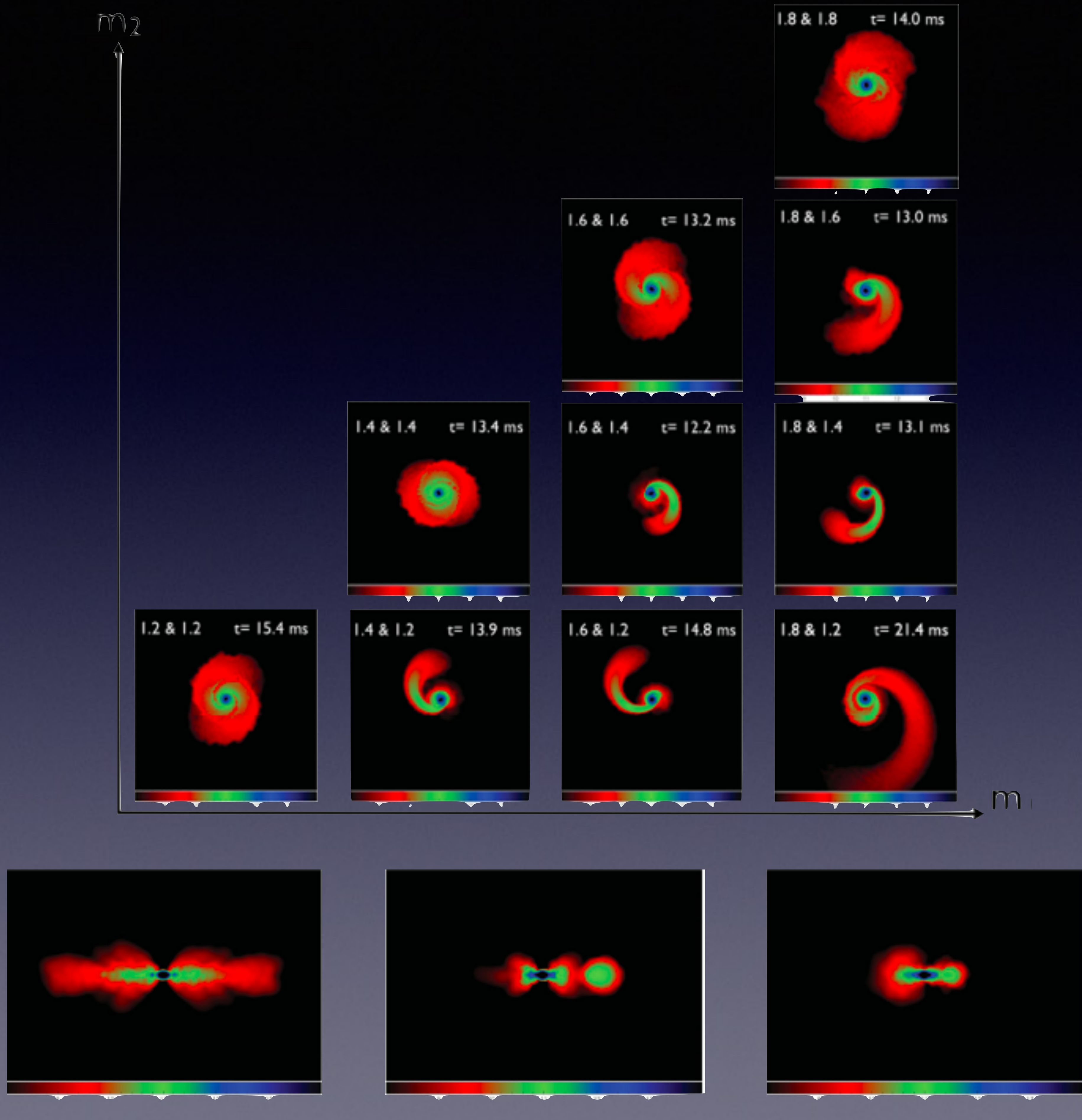
velocity

Opacity

=> Luminosity

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

Radioactive heating rate


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
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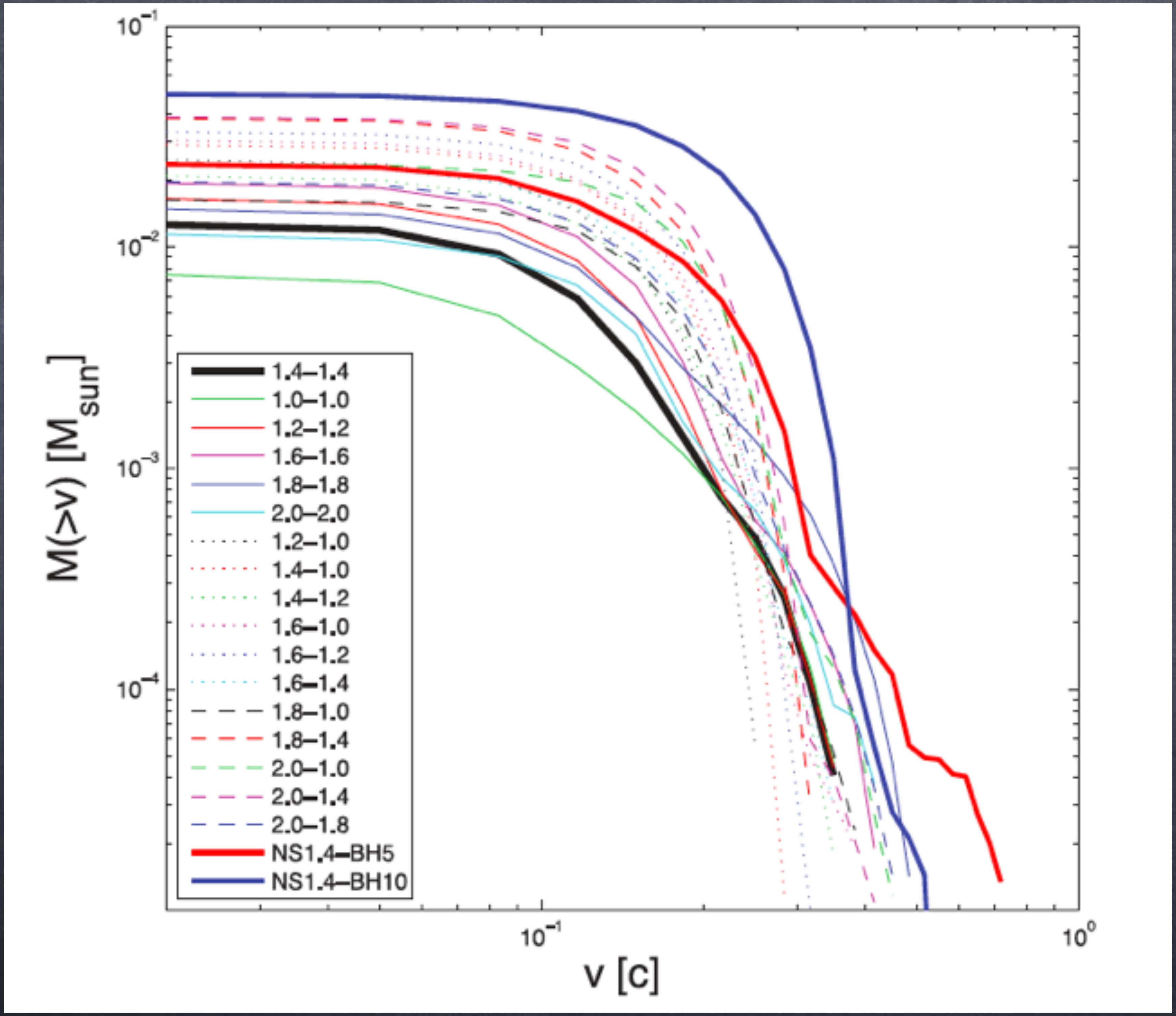
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms
m1

# $m_{ej}(v)$ for different configurations

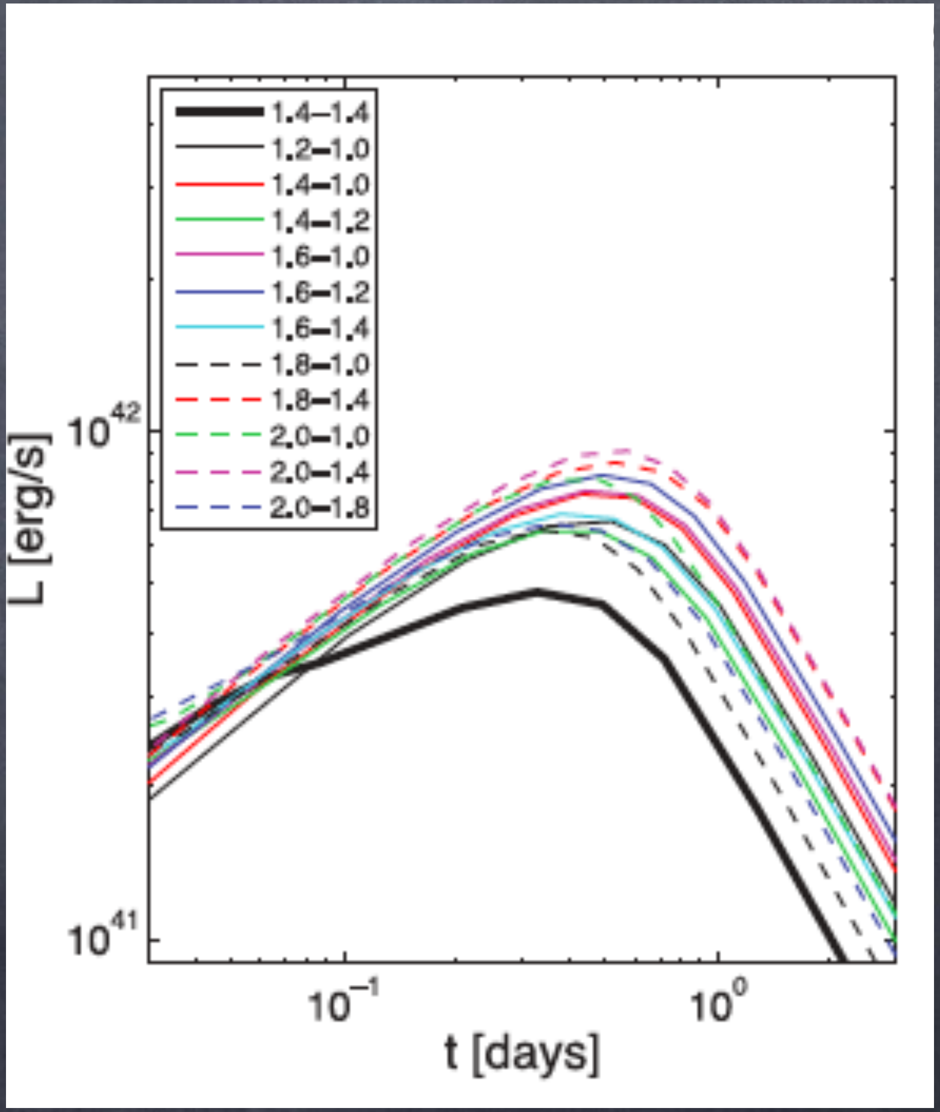
TP, Nakar & Rosswog, 13



# Lanthanides dominate the Opacity

(Kasen & Barnes 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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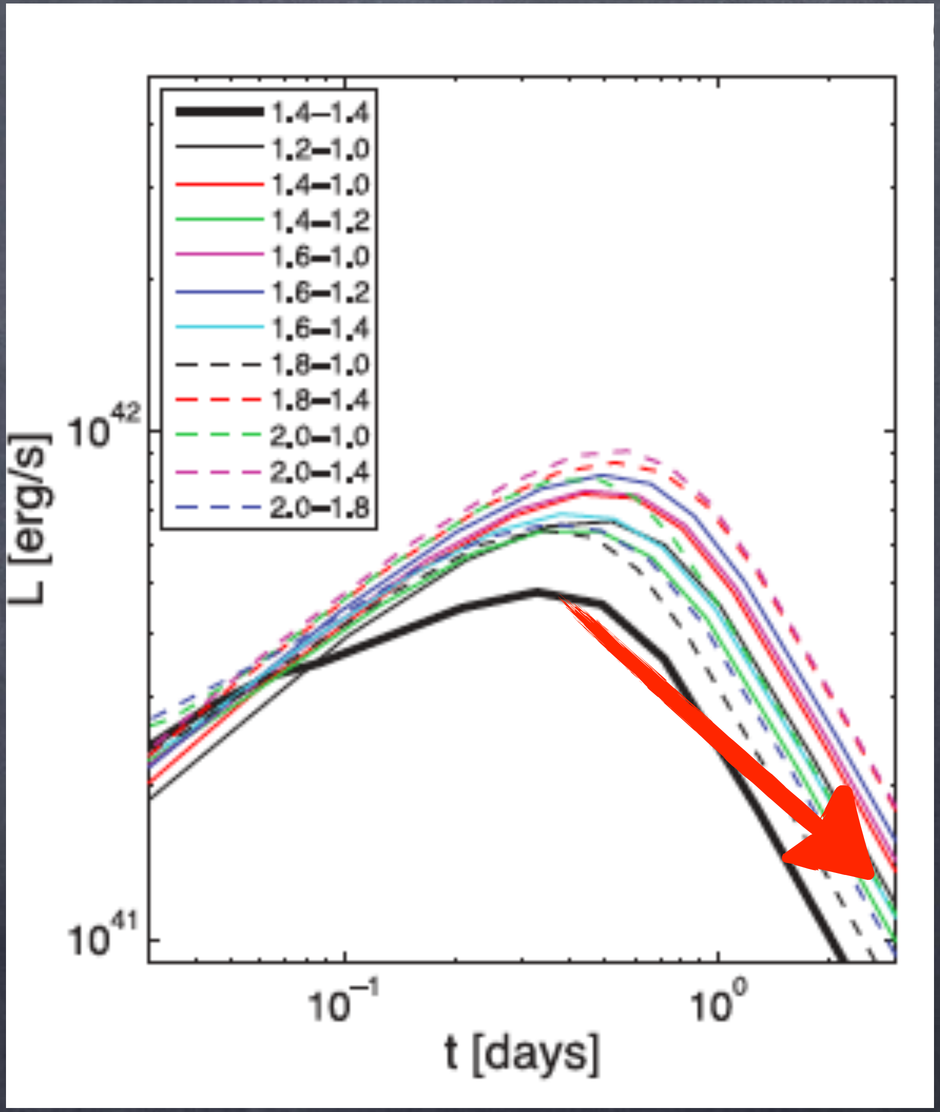


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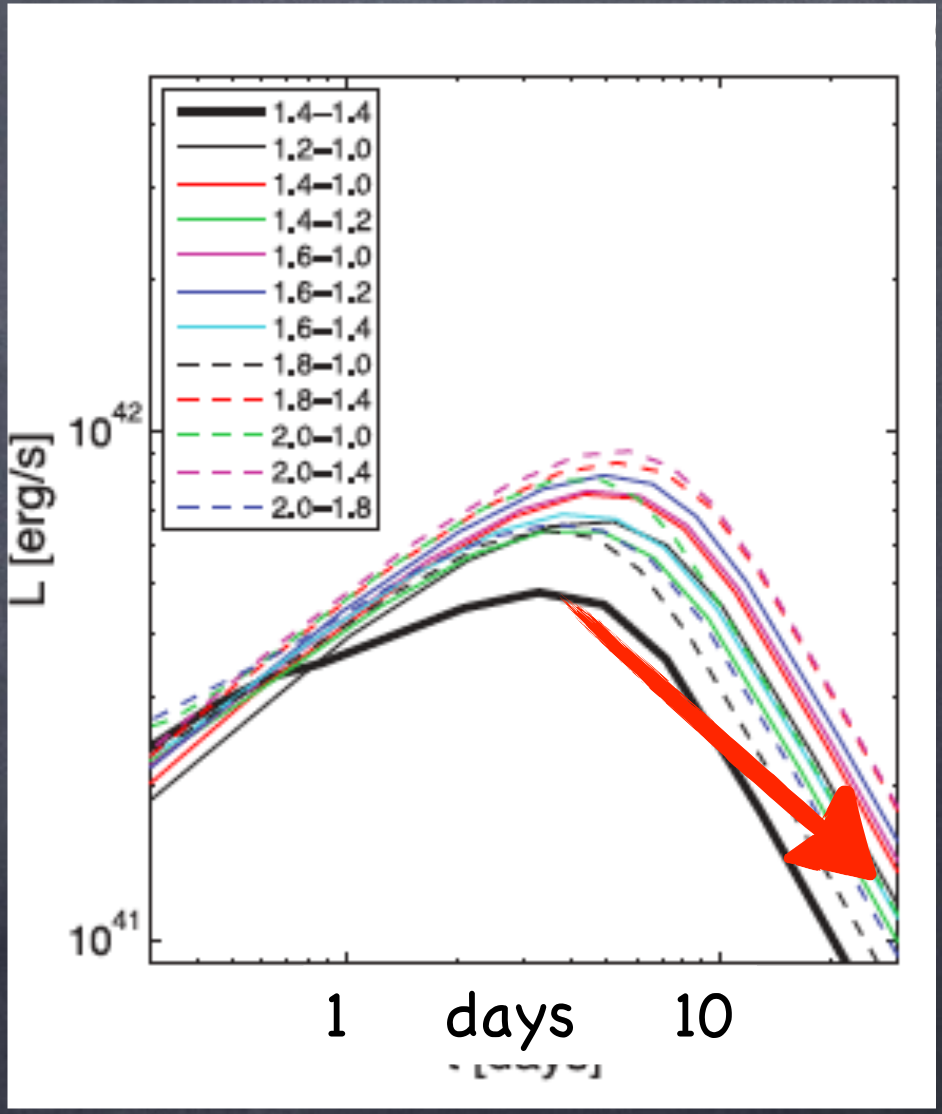


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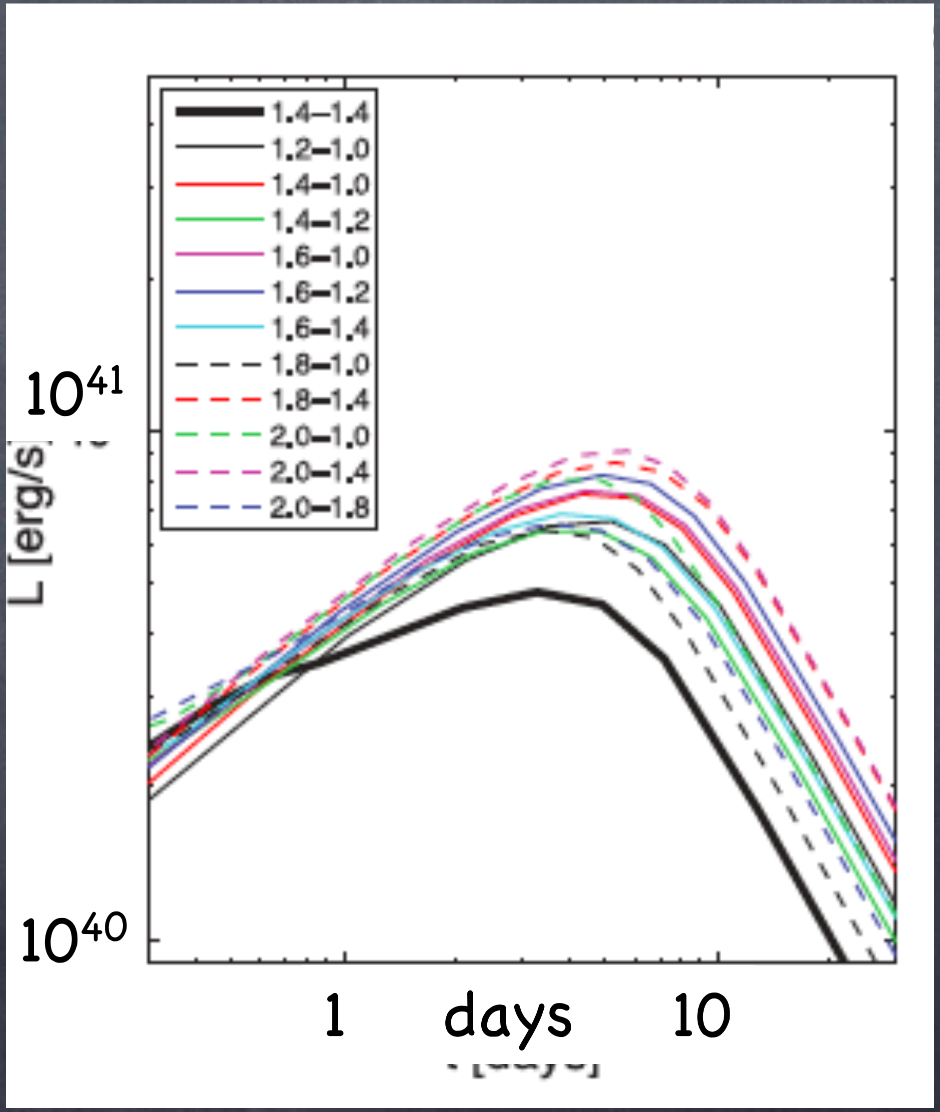


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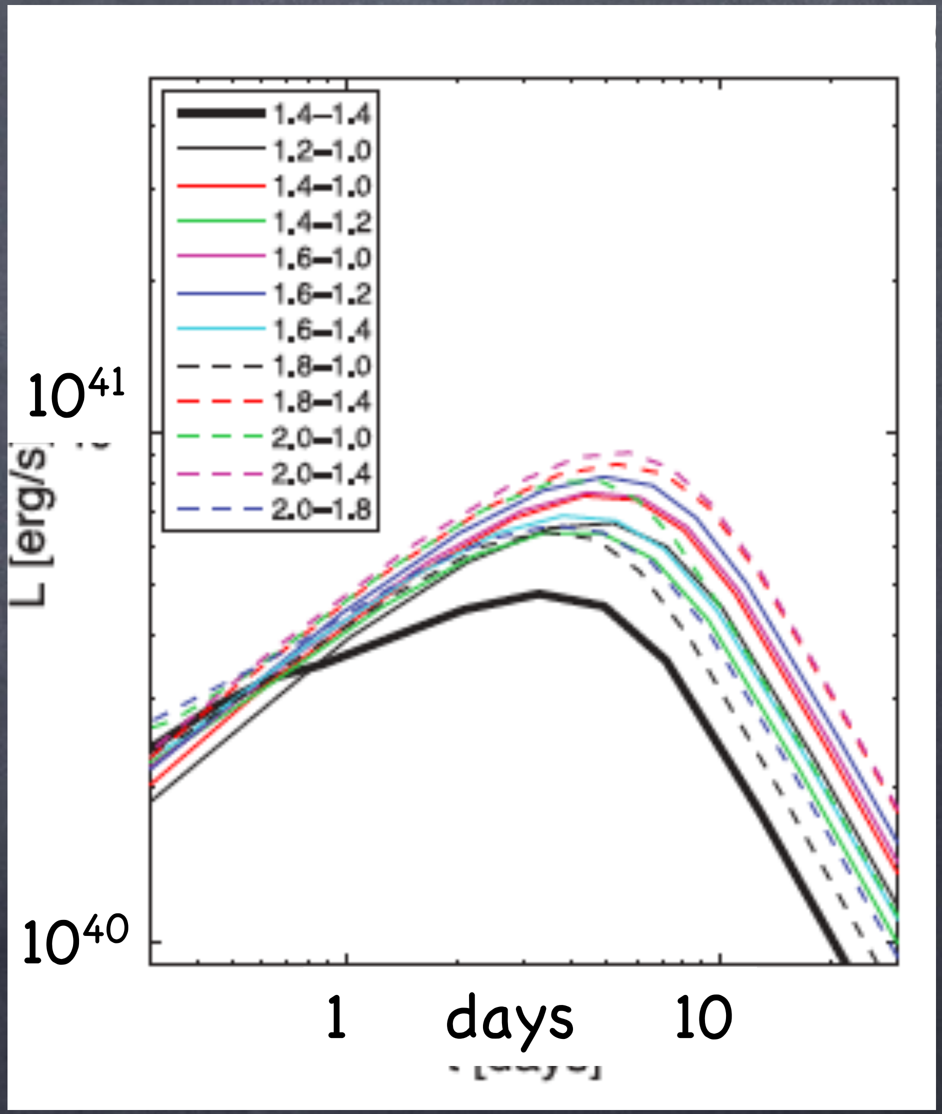



uv or optical -> IR

TP, Nakar, Rosswog, 13

# Peak time and peak luminosity

Opacity

ejected mass

The peak time

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

velocity

The peak luminosity

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

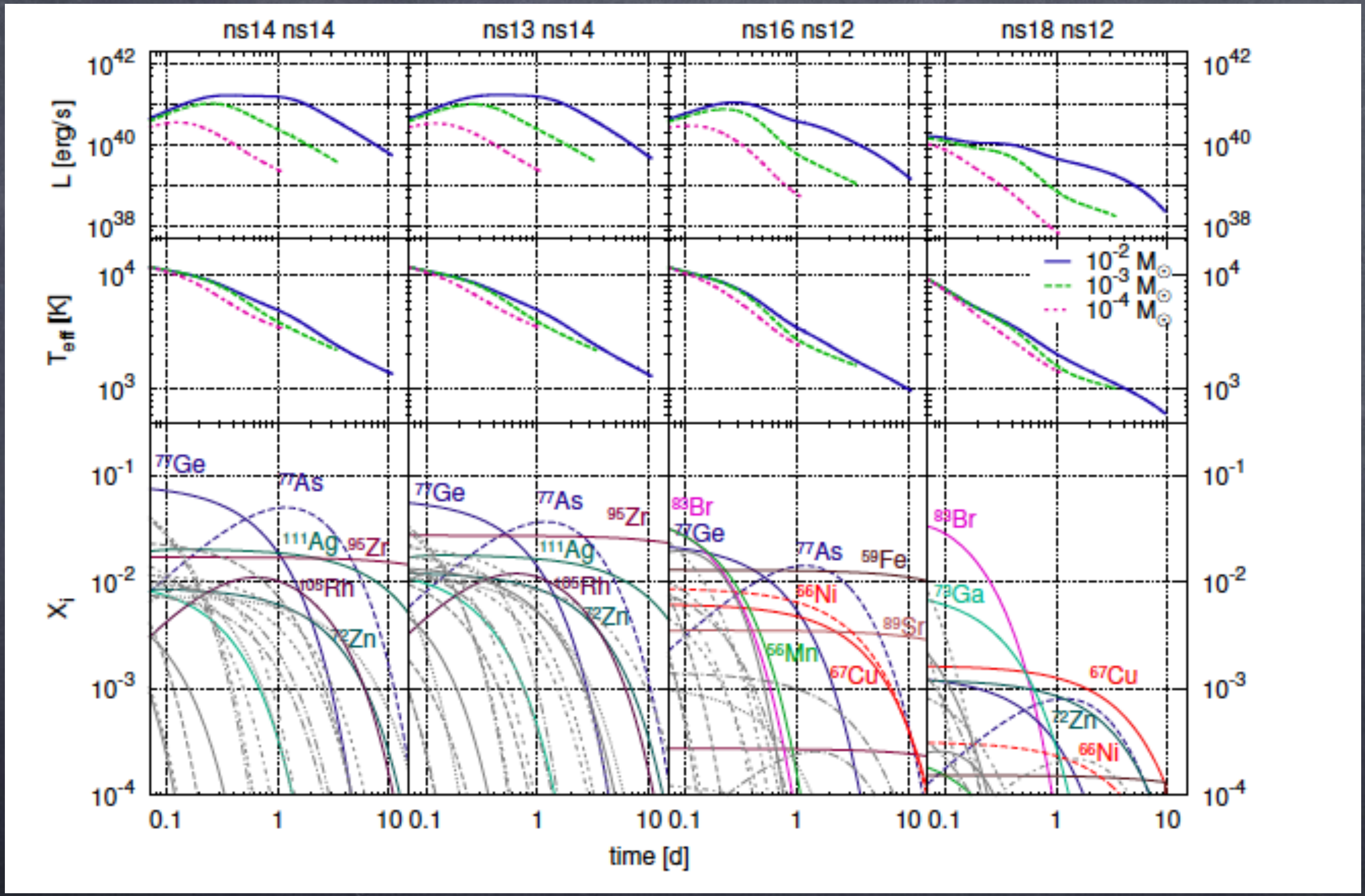
# $\nu$ driven winds

Different $Y_e$, different nucleosynthsis,

different opacity:  $\kappa$= 1cm$^2$/gm

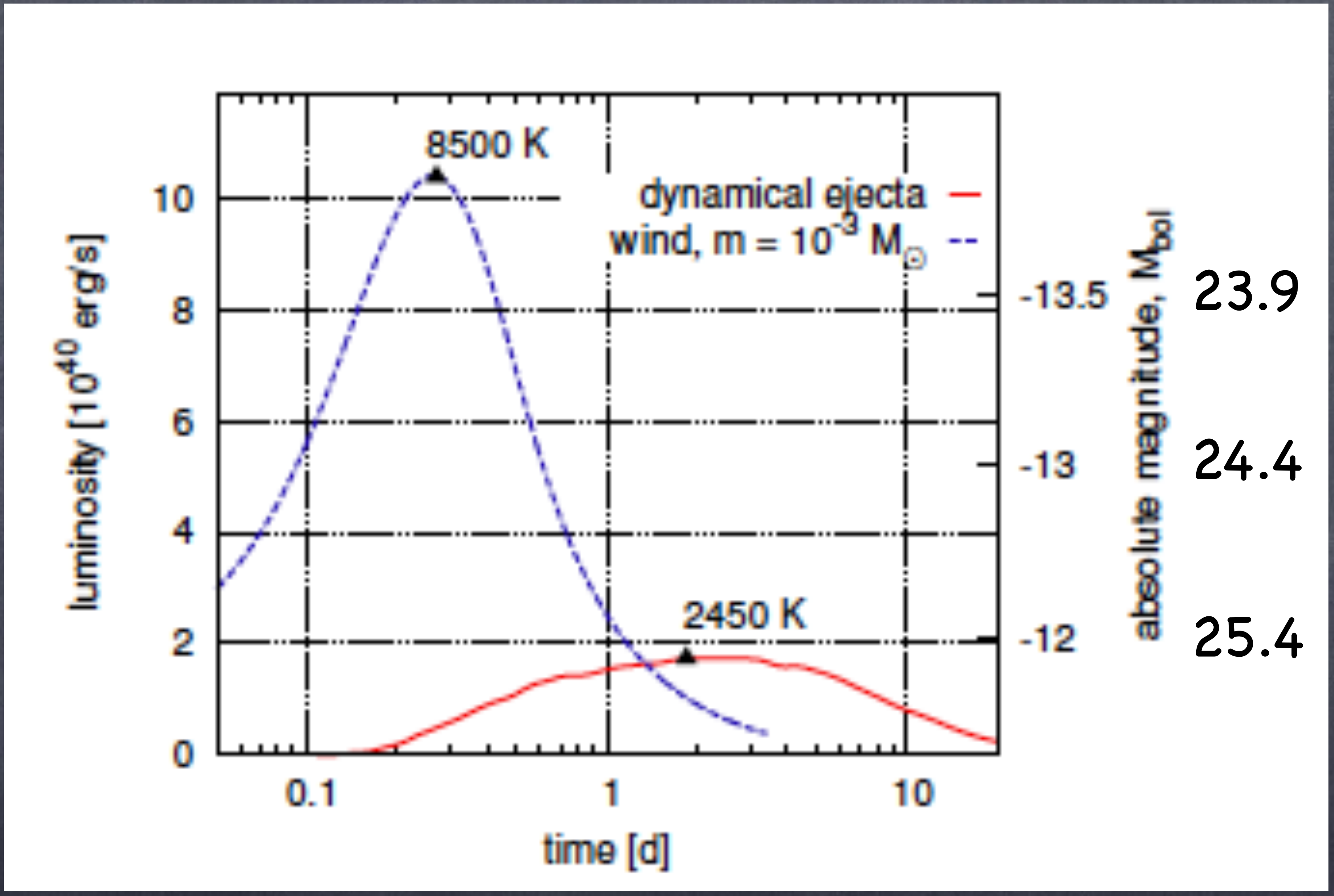
# ν driven winds - lightcurves

(Metzger & Fernandez 14; Just + 14; Perego + 14)




Grossman, Korobkin, Rosswog, TP 14

# Combined macronova signal

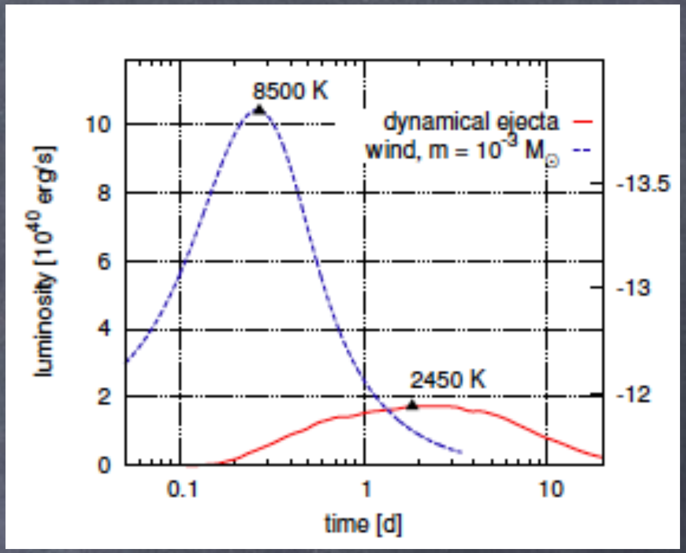



(Grossman, Korobkin, Rosswog, TP 14)

# Detectability @ 300 Mpc

- Dynamical ejecta (IR signal)
  - ≈23.5-24.5 mag on a time scale of a few days

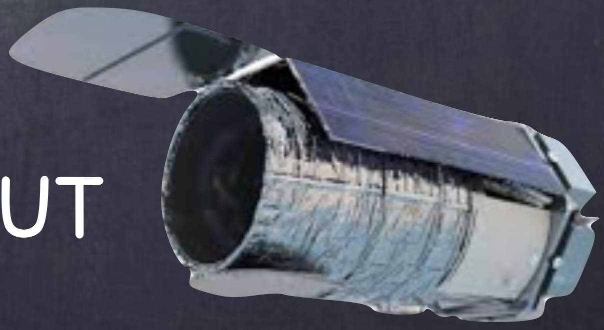
  => Rapid follow up is impossible in the IR.




- Neutrino driven wind (UV/Blue signal)
  - ≈23.7-24.2 mag on a time scale of a < day

  => Follow up is possible with HyperSupremeCamera on subaru or continous cover with ZTF or equivalent.

"Easily" detectable with LSST in 2021 (no IR) - BUT

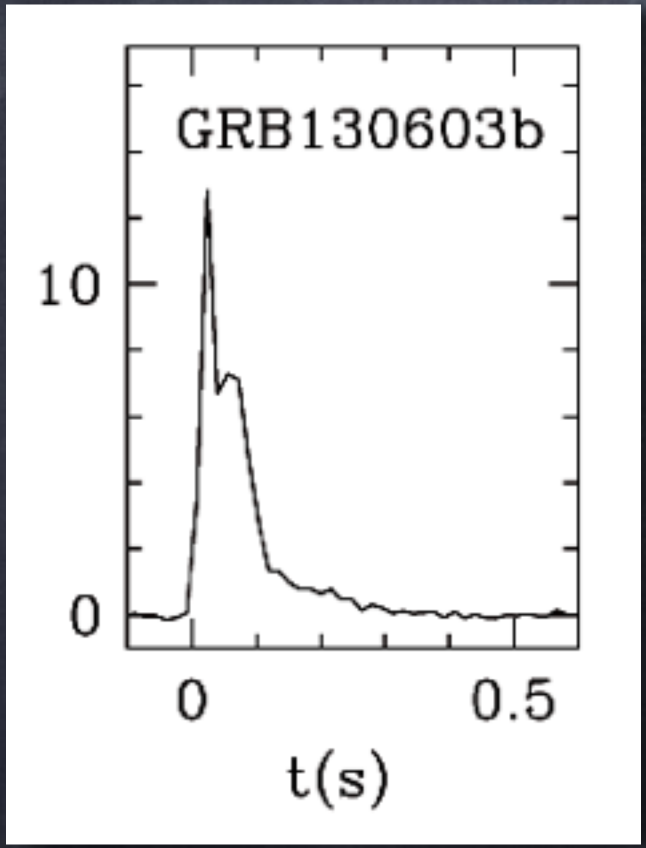


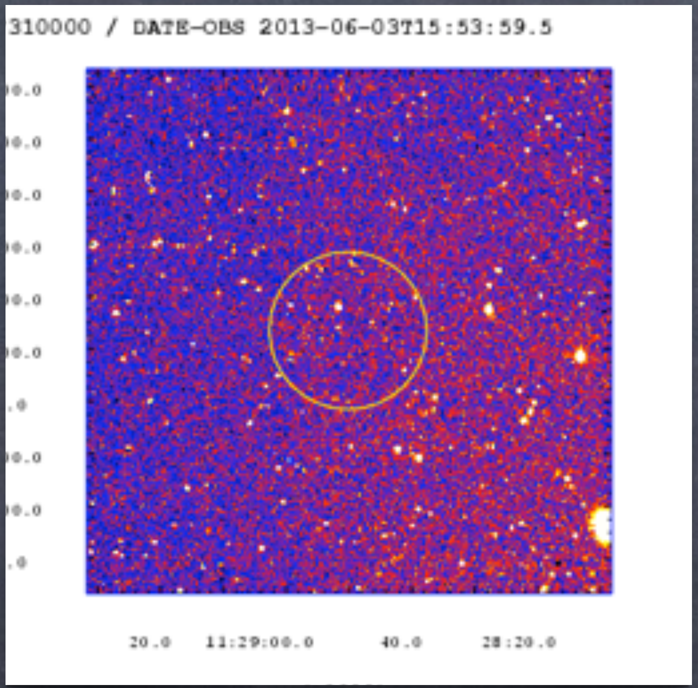
- False alarm: 60/(sq deg) at 24 (Nissanke + 13)

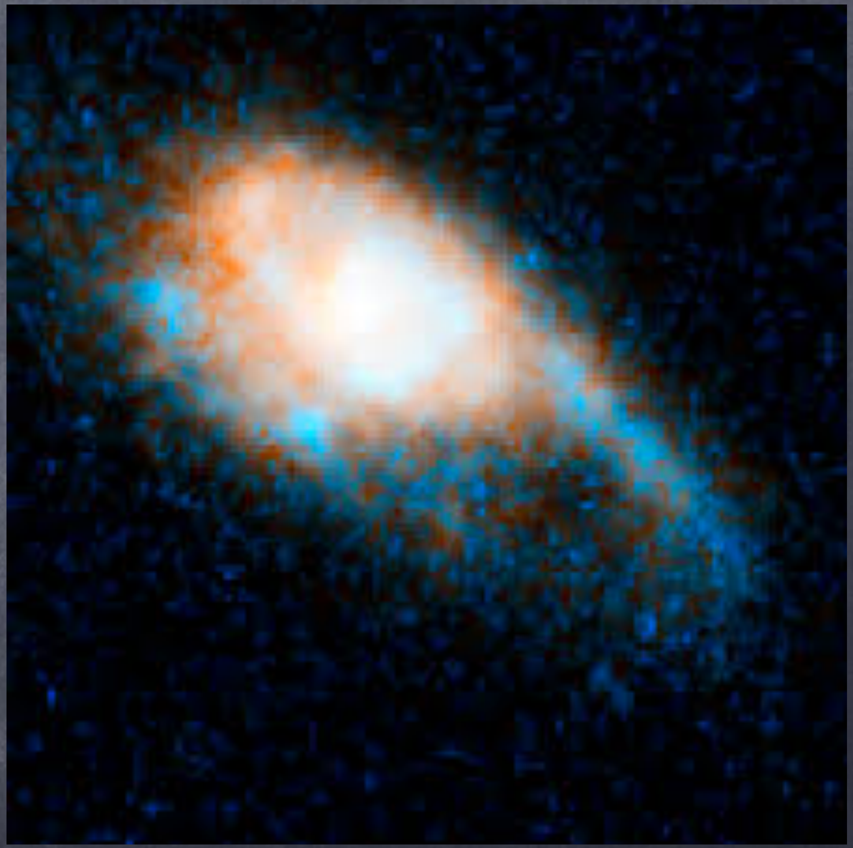
WFIRST

# Macronova Observations

# GRB 130603B



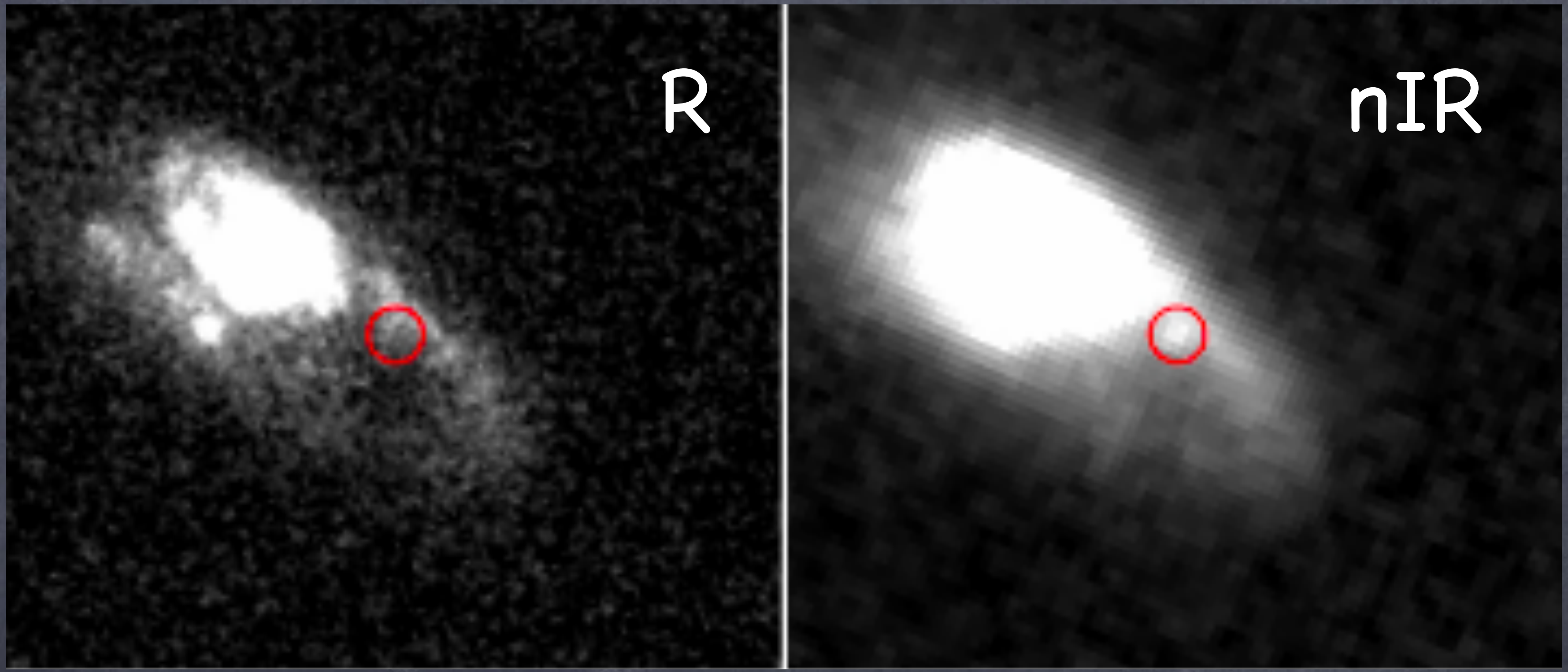



GRB 130603B

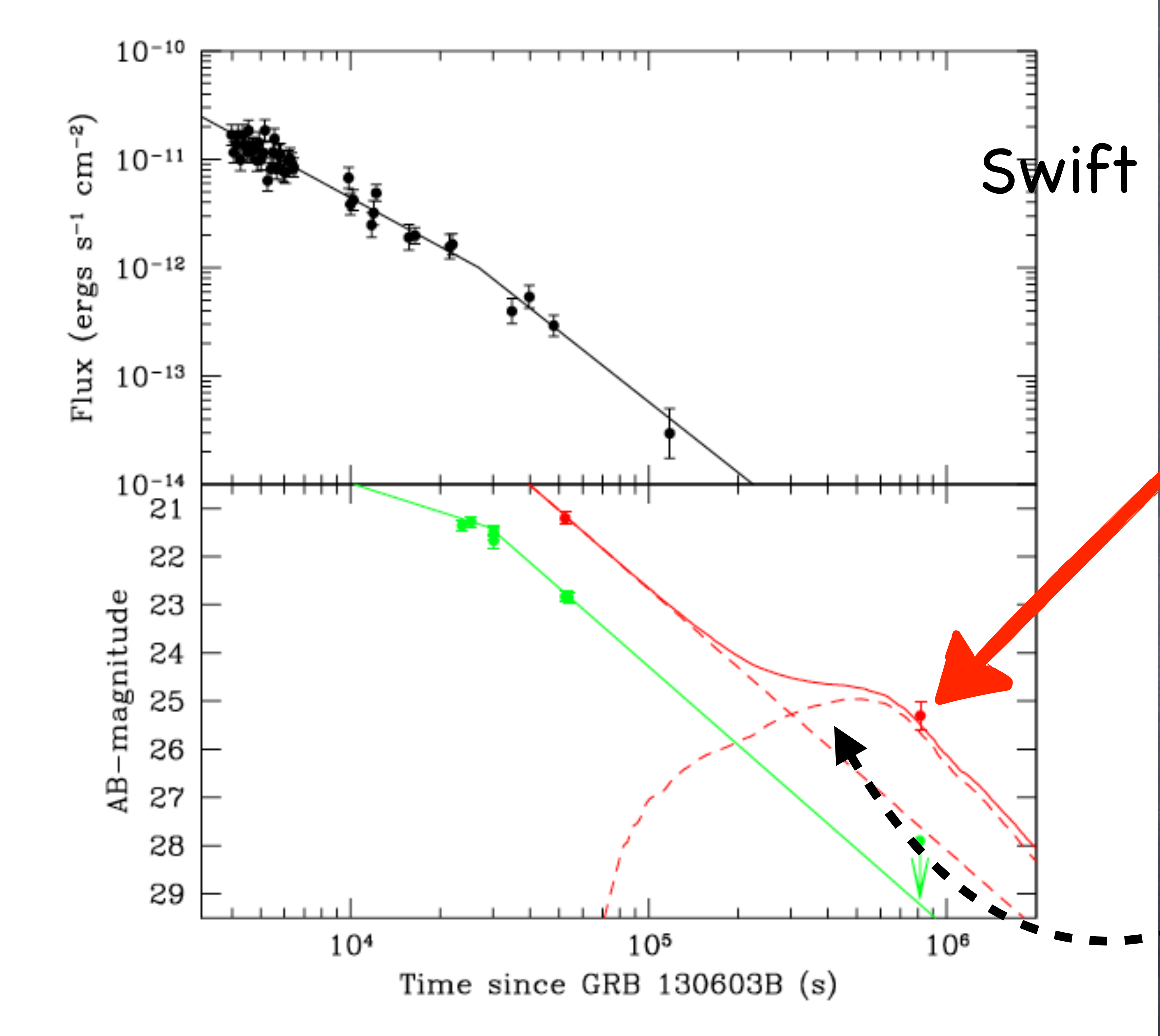
z=0.356 <=> 1 Gpc = 3 Glyr

# GRB130603B @ 9 days AB

## (6.6 days at the source frame)




HST image (Tanvir + 13)

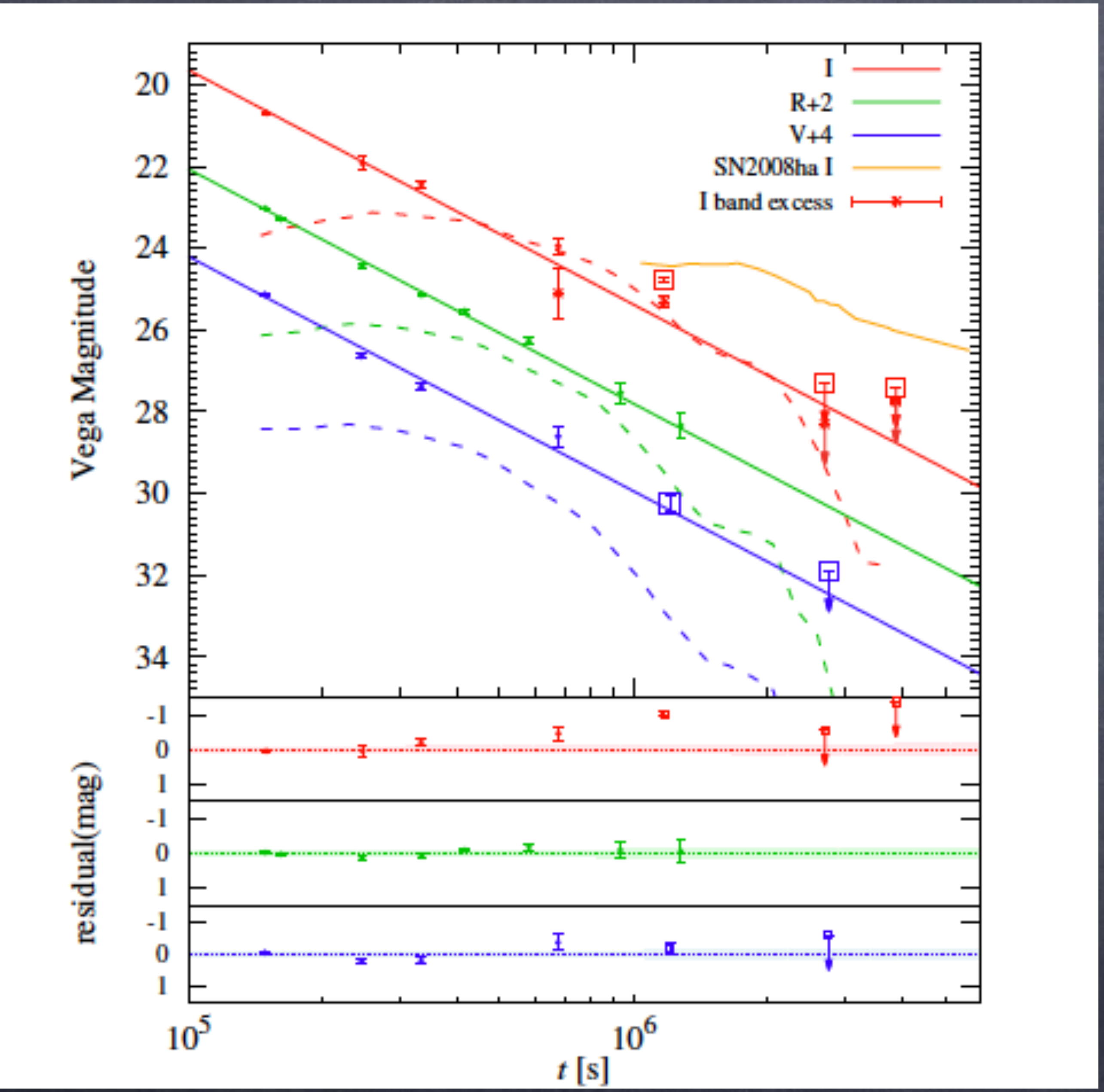



Macronova?

Kasen & Barnes 13

Tanvir + 13, Berger + 13

# GRB 060614

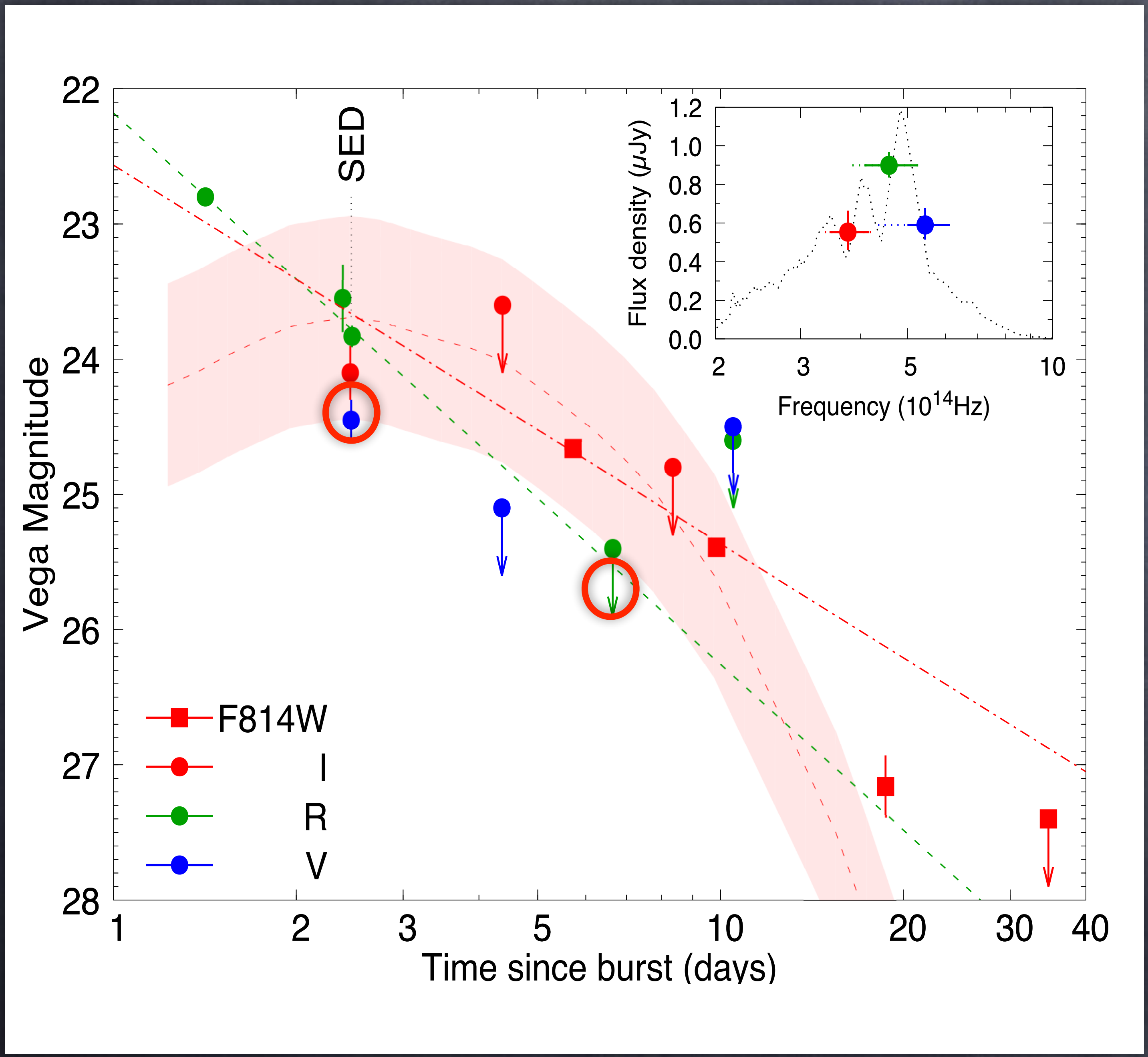



Need $M \simeq 0.1 M_\odot$

=> BH-NS ?

Yang et al., Nature Comm 15

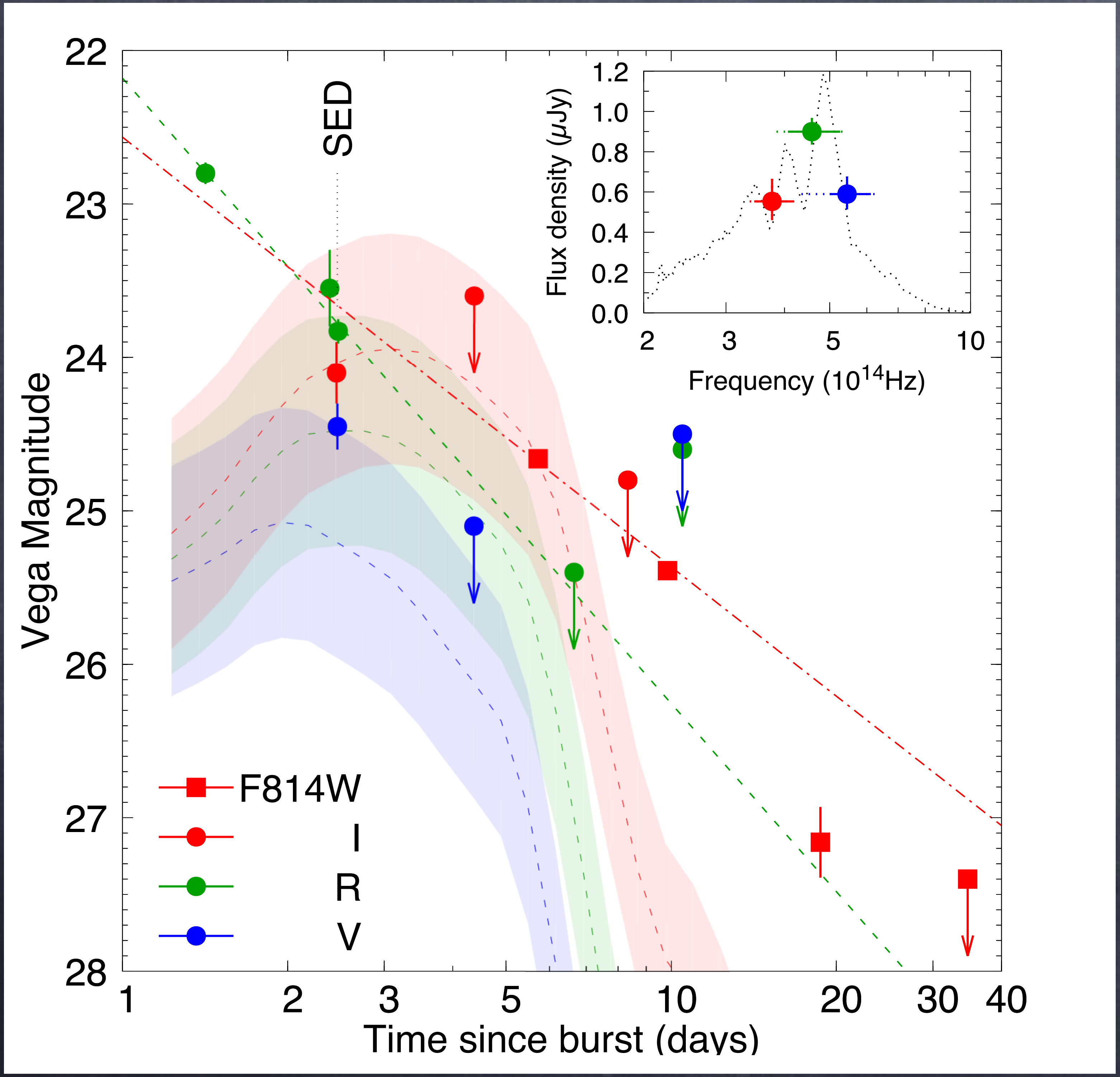
# GRB 050709




- Fox et al., 2005; Watson et a., 2006 - not a power law.
- Re-analysis of the VLT and a new unreported HST point.
- Need $M \simeq 0.05 M_\odot$

Jin et al., 16 submitted

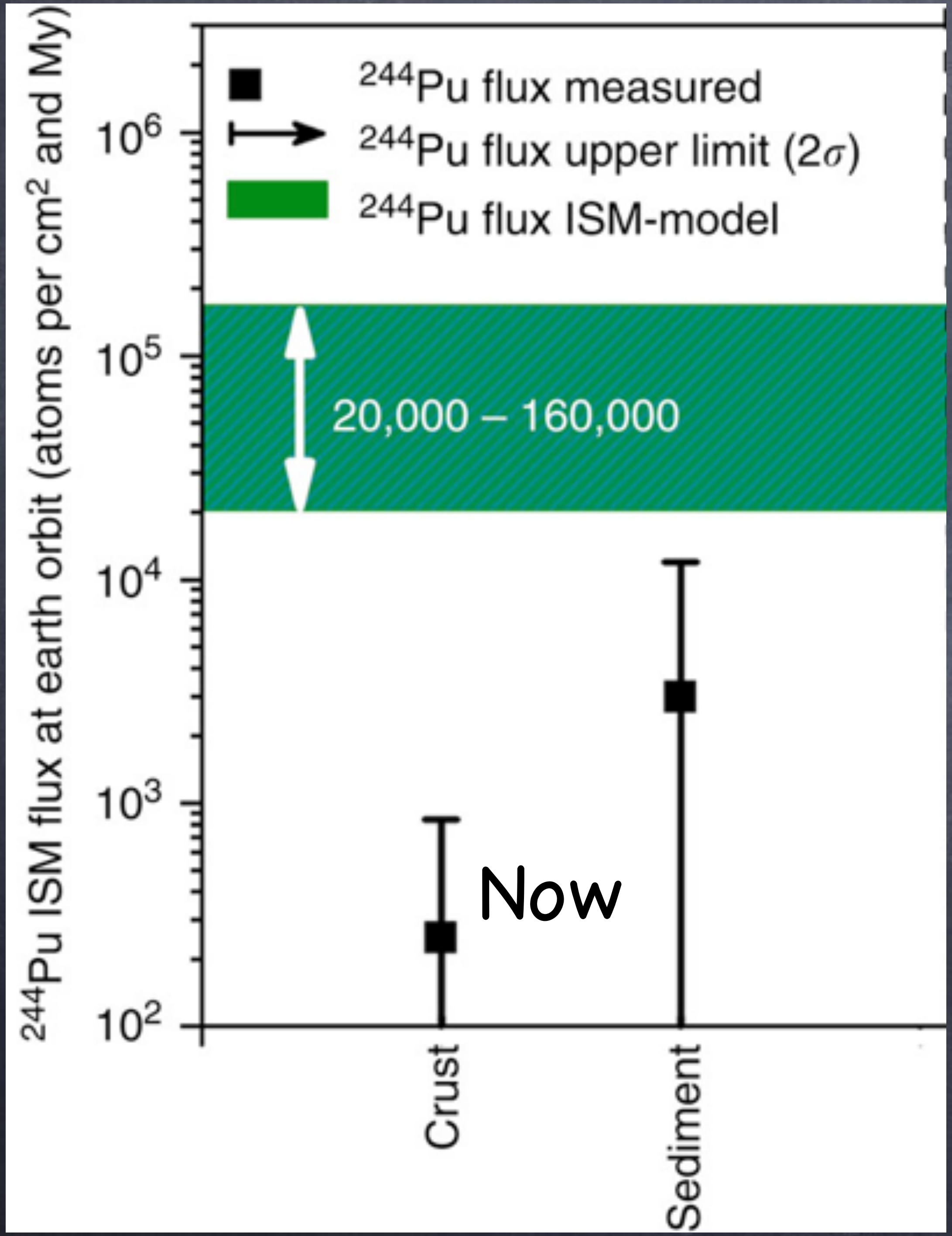
# GRB 050709




Spectrum at 2 days

=> ν Wind?

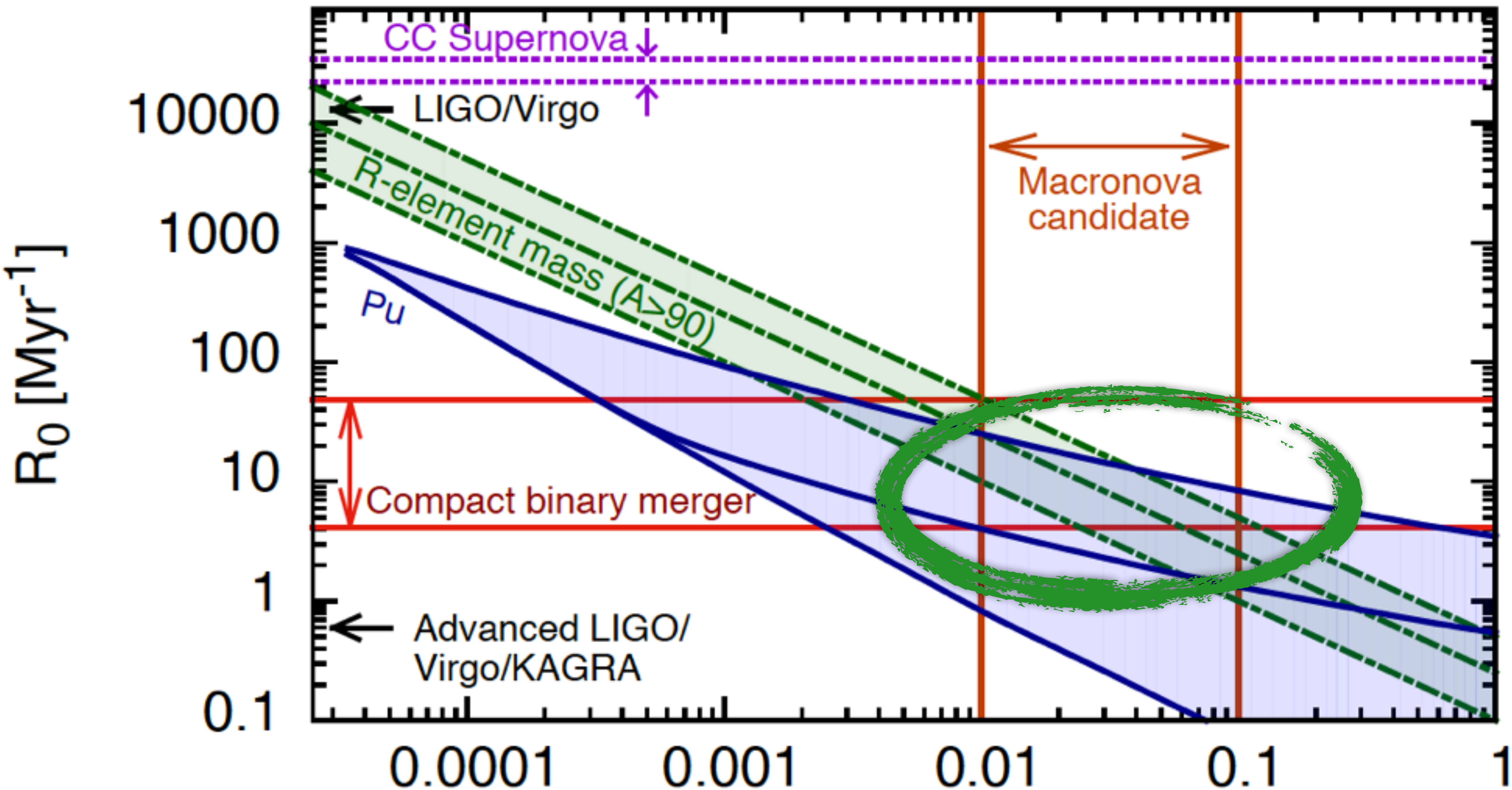
# Astroarcheology Radioactive data provides indirect evidence




Wallner + 14

$^{244}$Pu (half life 81 Myr)

# Rare and "massive" events




Hotokezaka et al., Nature Phys 2015

# Implication

- Jin et al, 16 explored all nearby short GRB light curves for which there is suitable data
- In 3 out of 3 (5) a Macronova Candidate signal was detected.
- Some of the signals are in optical rather than IR => much easier to detect!
- Early spectrum in 050709 suggest a possible wind signature.

=> Promising detection prospects.

# The Radio Flare
## (Nakar & TP 2011)

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

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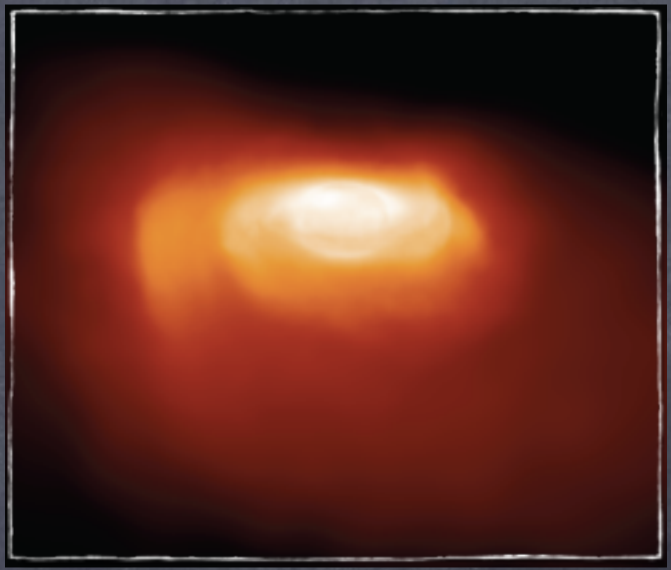

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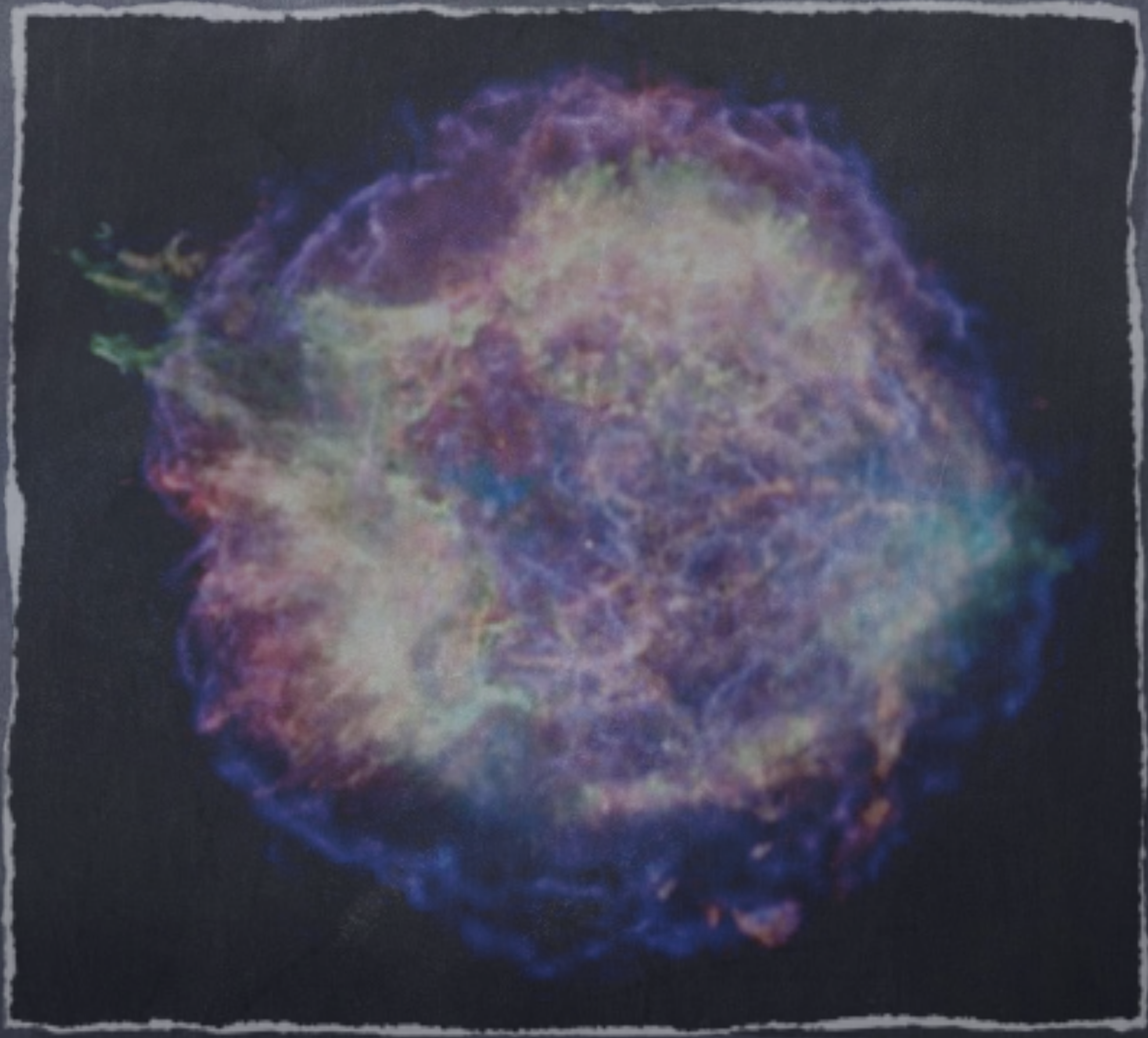

Supernova

Months

Supernova remnant

a few x $10^4$ years

Macronova

Weeks

Radio Flare

months - years

# Search for the flare from GRB 130603B by the EVLA

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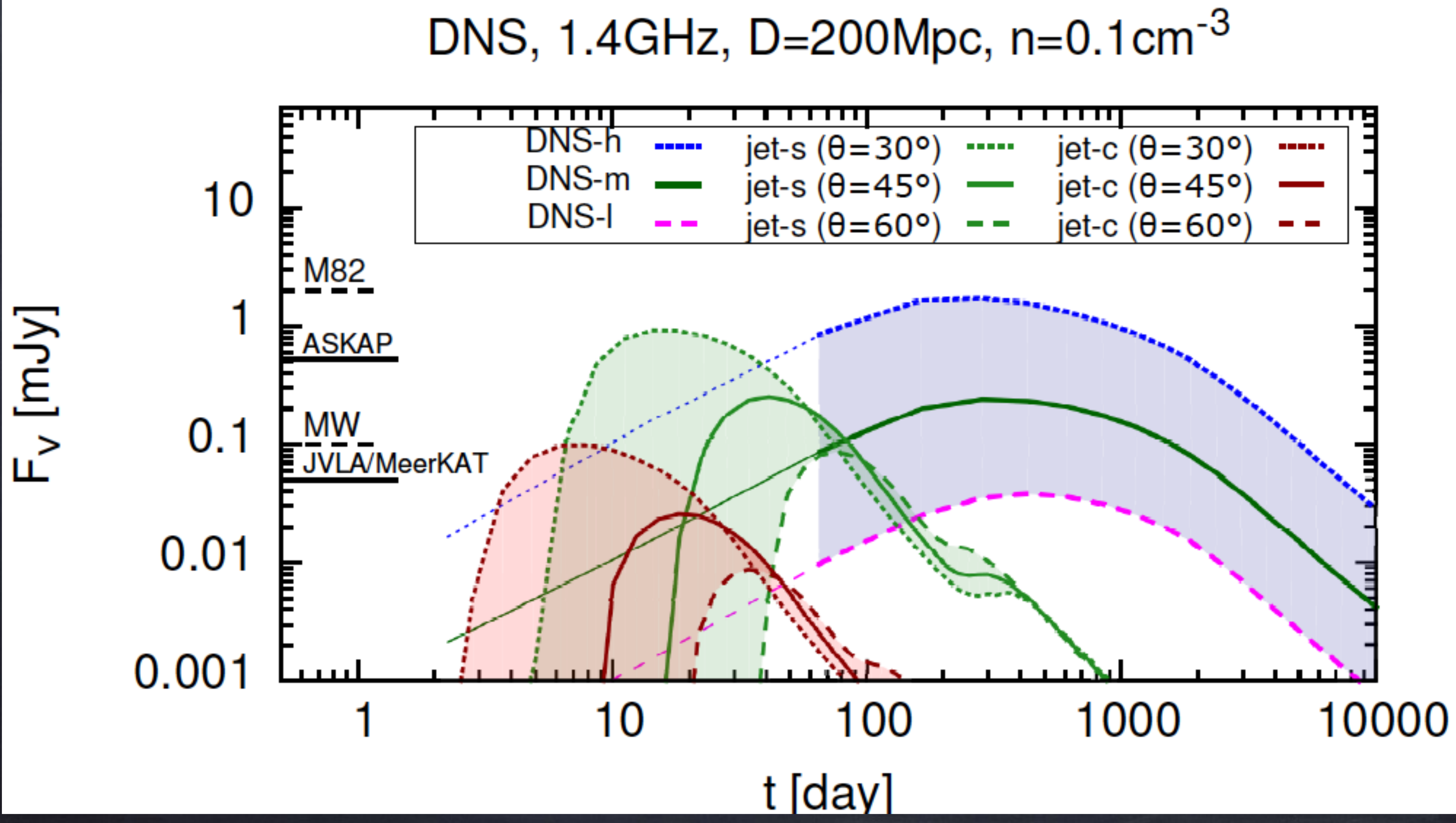
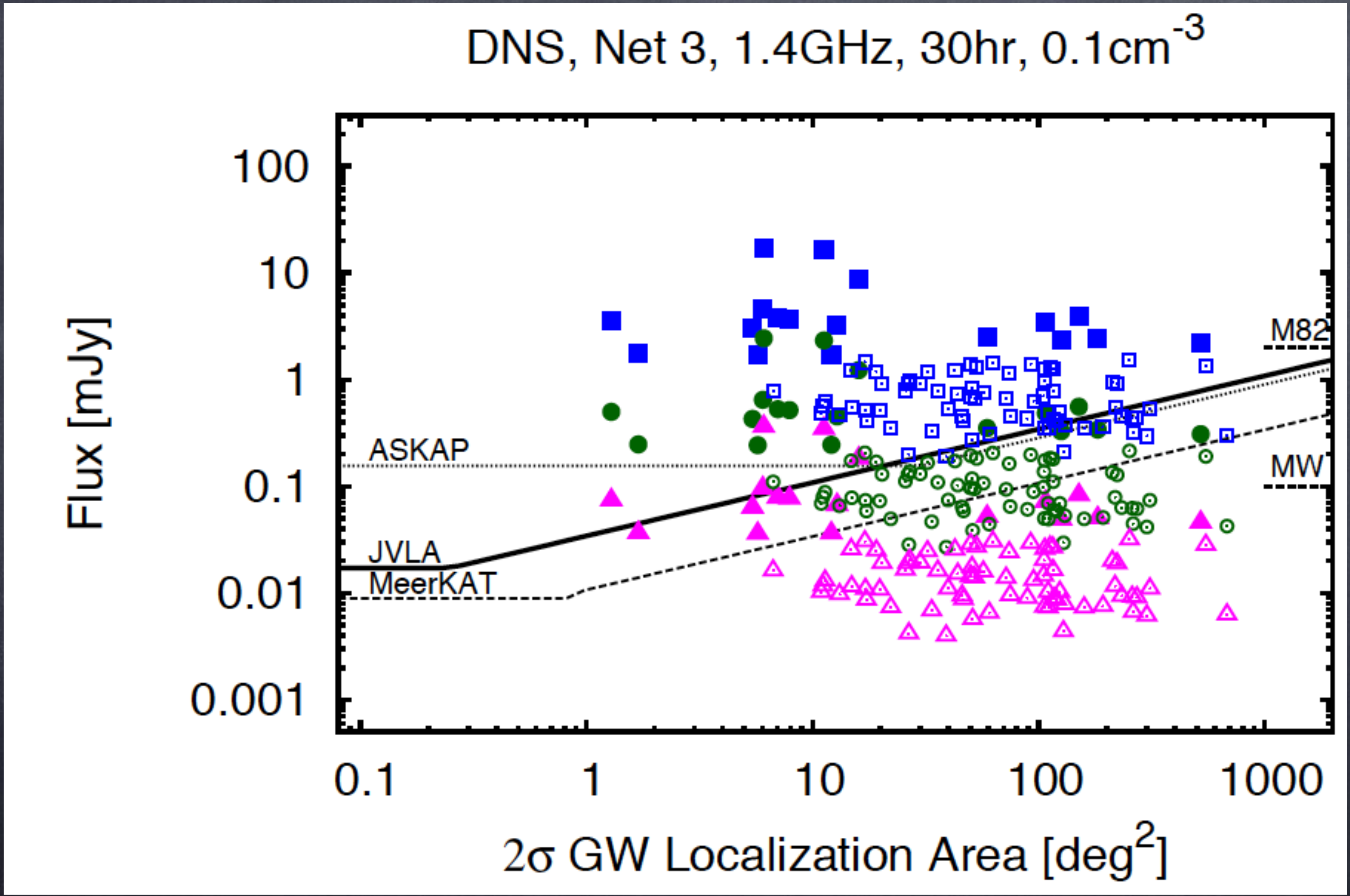
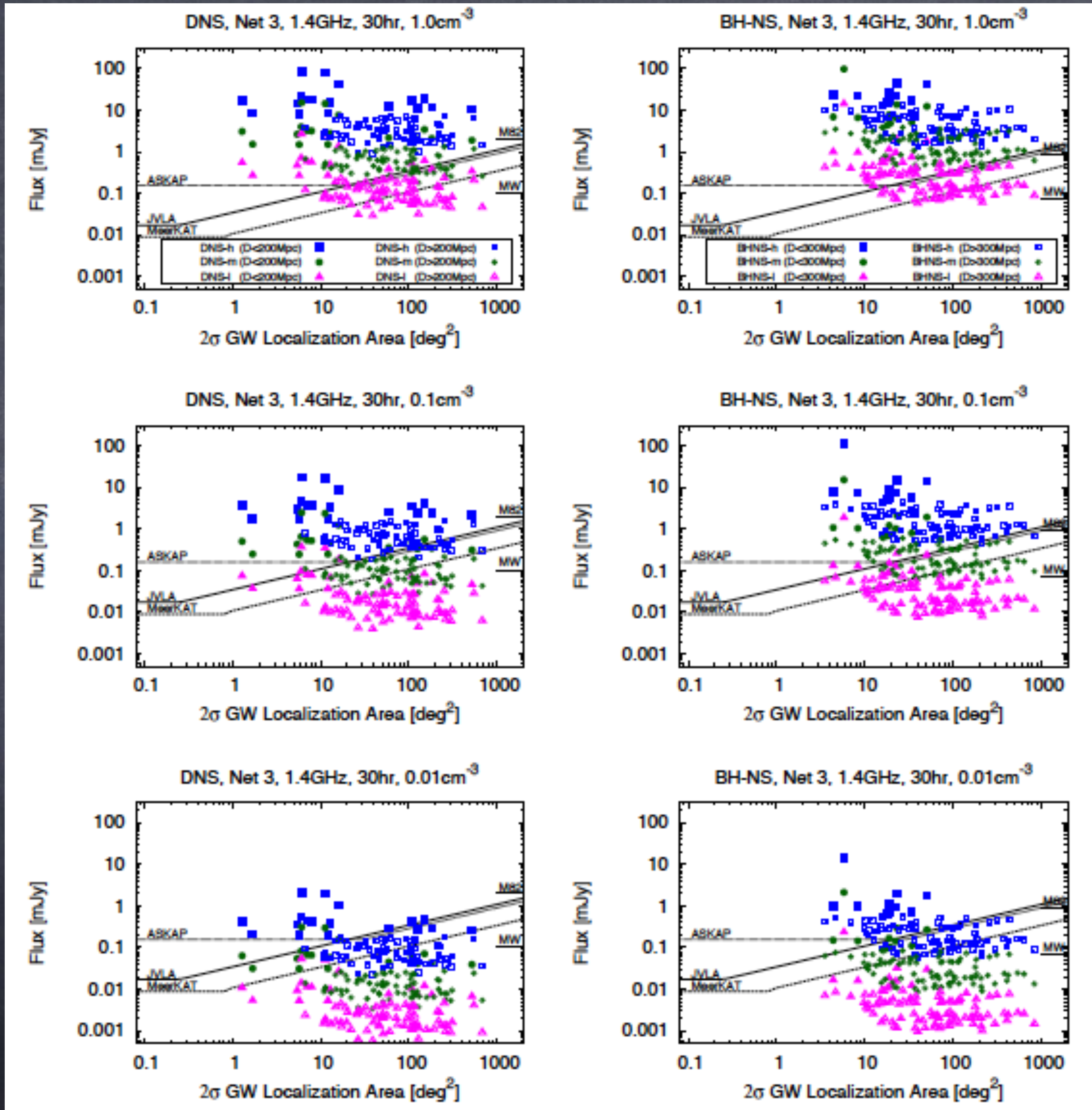
# Estimates of radio signals from mergers (Hotokezaka + 16)

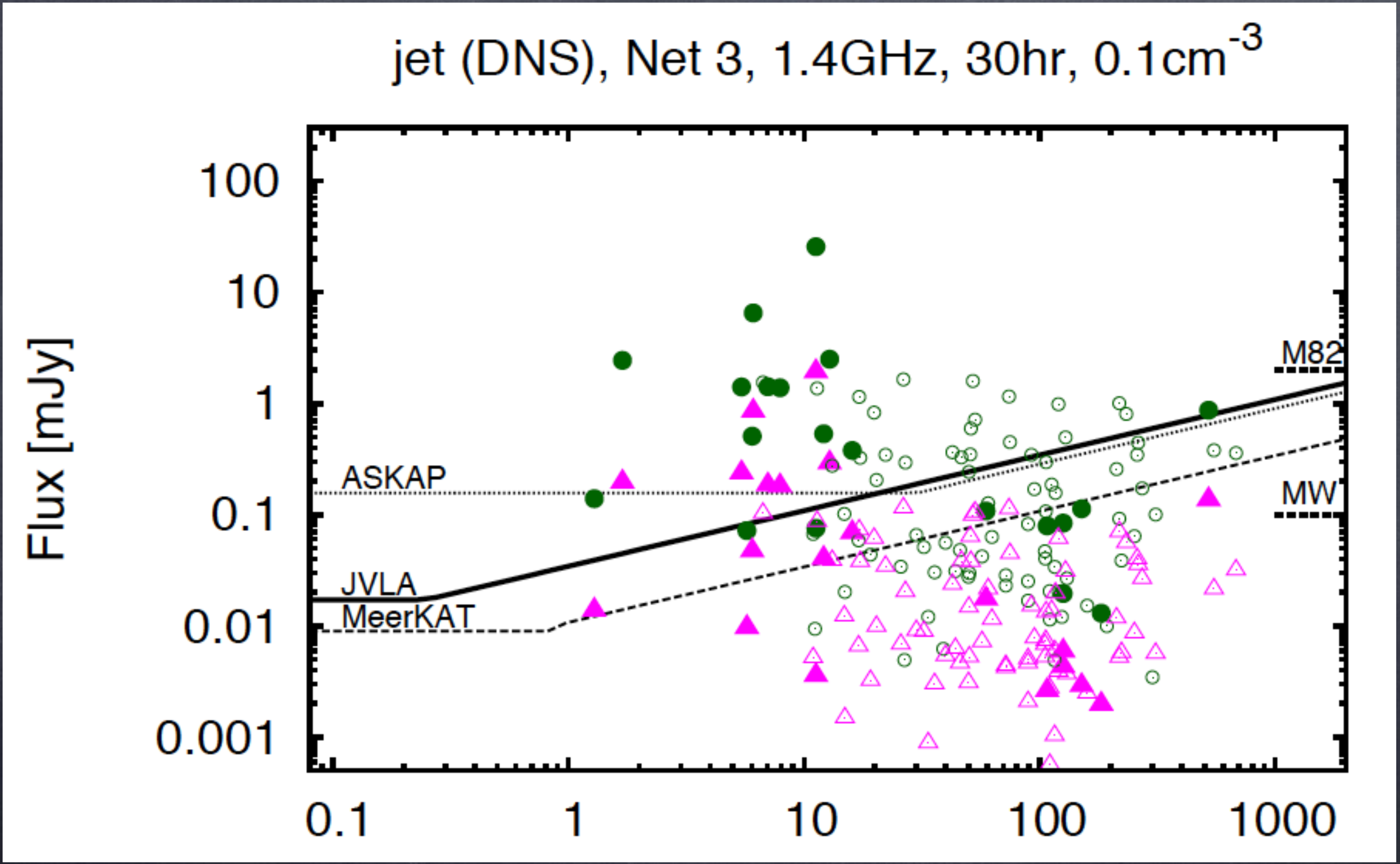
| Model | $E_K$ [erg] | $\langle\beta_0\rangle$ [c] | $L^{n=1}_{1.4\mathrm{GHz}}$ [erg s$^{-1}$Hz$^{-1}$] | $L^{n=0.1}_{1.4\mathrm{GHz}}$ | $L^{n=0.01}_{1.4\mathrm{GHz}}$ |
|---|---|---|---|---|---|
| $\mathrm{DNS}_h$ | $10^{51}$ | 0.3 | $4\cdot10^{29}$ | $8\cdot10^{28}$ | $10^{28}$ |
| $\mathrm{DNS}_m$ | $3\cdot10^{50}$ | 0.25 | $8\cdot10^{28}$ | $10^{28}$ | $2\cdot10^{27}$ |
| $\mathrm{DNS}_l$ | $10^{50}$ | 0.2 | $10^{28}$ | $2\cdot10^{27}$ | $3\cdot10^{26}$ |
| $\mathrm{BH\text{-}NS}_h$ | $5\cdot10^{51}$ | 0.3 | $2\cdot10^{30}$ | $5\cdot10^{29}$ | $7\cdot10^{28}$ |
| $\mathrm{BH\text{-}NS}_m$ | $2\cdot10^{51}$ | 0.25 | $5\cdot10^{29}$ | $8\cdot10^{28}$ | $10^{28}$ |
| $\mathrm{BH\text{-}NS}_l$ | $5\cdot10^{50}$ | 0.2 | $7\cdot10^{28}$ | $9\cdot10^{27}$ | $10^{27}$ |
| *strong-jet* | $10^{49}$ | $\sim1$ | $3\cdot10^{28}$ | $10^{28}$ | $2\cdot10^{27}$ |
| *canonical-jet* | $10^{48}$ | $\sim1$ | $4\cdot10^{27}$ | $10^{27}$ | $2\cdot10^{26}$ |

# Radio Light Curves
## (Hotokezaka et al., 16)




DNS, Net 3, 1.4GHz, 30hr, 0.1cm^-3
Flux [mJy]
100
10
1
0.1
0.01
0.001
ASKAP
JVLA
MeerKAT
M82
MW
0.1
1
10
100
1000
2σ GW Localization Area [deg^2]


DNS, Net 3, 1.4GHz, 30hr, 1.0cm-3
BH-NS, Net 3, 1.4GHz, 30hr, 1.0cm-3
DNS, Net 3, 1.4GHz, 30hr, 0.1cm-3
BH-NS, Net 3, 1.4GHz, 30hr, 0.1cm-3
DNS, Net 3, 1.4GHz, 30hr, 0.01cm-3
BH-NS, Net 3, 1.4GHz, 30hr, 0.01cm-3
Flux [mJy]
2σ GW Localization Area [deg2]
ASKAP
JVLA
MeerKAT
MW
DNS-h (D<200Mpc)
DNS-m (D<200Mpc)
DNS-l (D<200Mpc)
DNS-h (D>200Mpc)
DNS-m (D>200Mpc)
DNS-l (D>200Mpc)
BHNS-h (D<300Mpc)
BHNS-m (D<300Mpc)
BHNS-l (D<300Mpc)
BHNS-h (D>300Mpc)
BHNS-m (D>300Mpc)
BHNS-l (D>300Mpc)


jet (DNS), Net 3, 1.4GHz, 30hr, 0.1cm-3
Flux [mJy]
100
10
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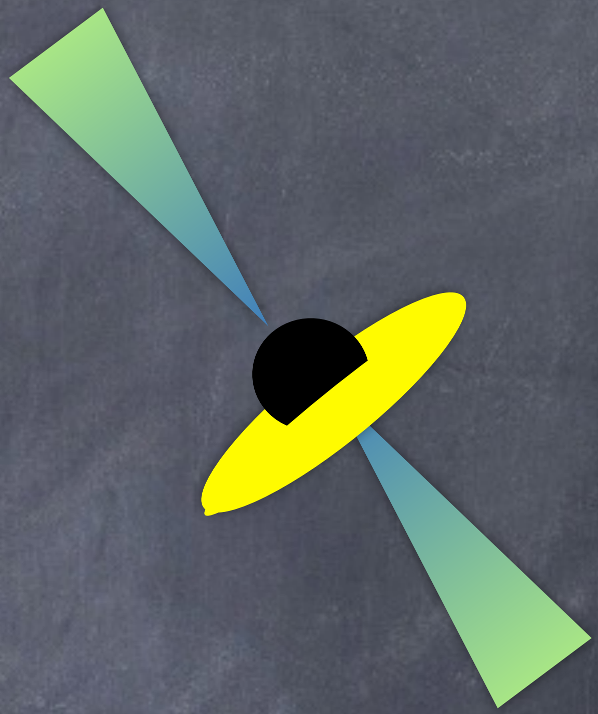
0.1
0.01
0.001
0.1
1
10
100
1000
ASKAP
JVLA
MeerKAT
M82
MW

# Radio Flare Detectability @ 300 Mpc

- Detectable for high $E_k$ and density and a quite host (can be resolved on the VLA)
- False positives: 0.1/sq deg.
- Long observing time - no rush

# 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.

# ???

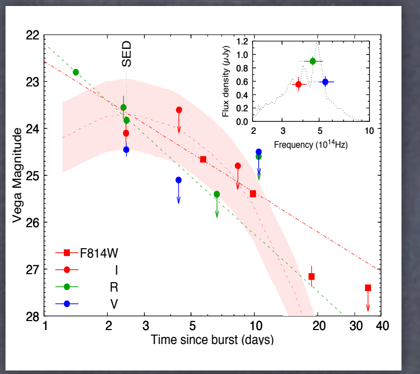
- A short distance capture + matter injection

=> A 3 body interaction in a globular cluster?

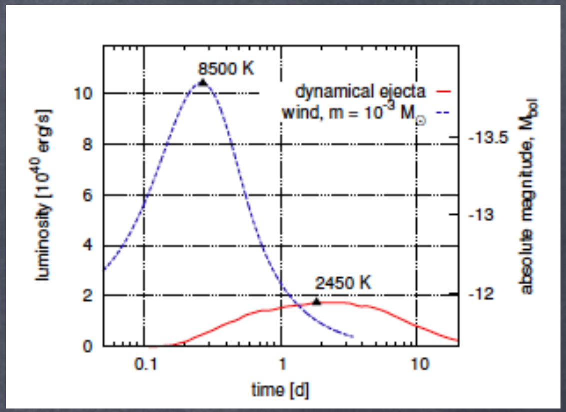
=> Maybe possible but extremely rare

- Short GRBs are (most likely) the best EM counterparts - but they are beamed :(

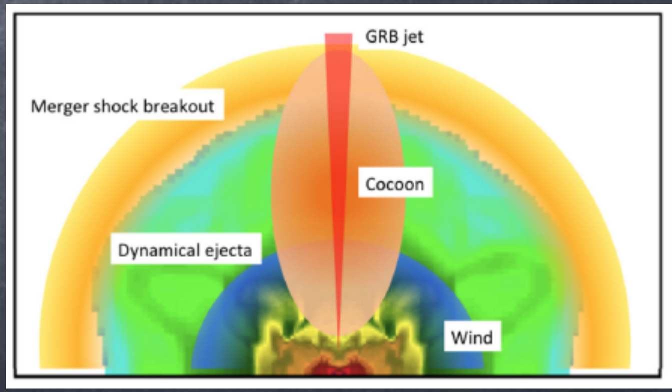
- 3 out of 3 (5) short GRB candidates show a macronova signal :)




- Macronova (kilonova) are extremely dim and in IR. Furthermore the sky is dominated by optical/IR transients at this level.




- Optical/uv neutrino wind signal is easier to detect - but it is short lived.




- Room for other signatures

- Radio signal is robust (but depends on external density). Detection may take month - no rush.

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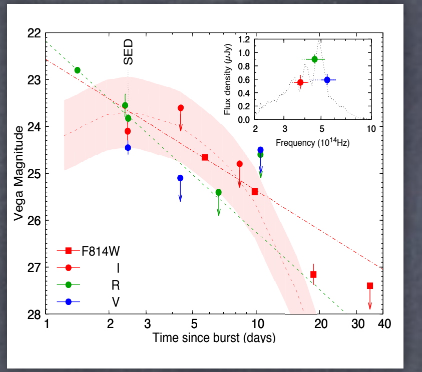


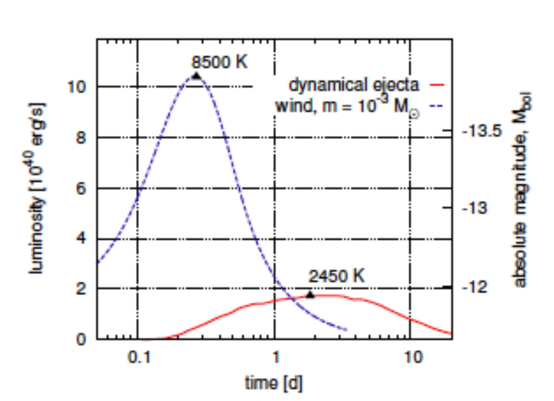


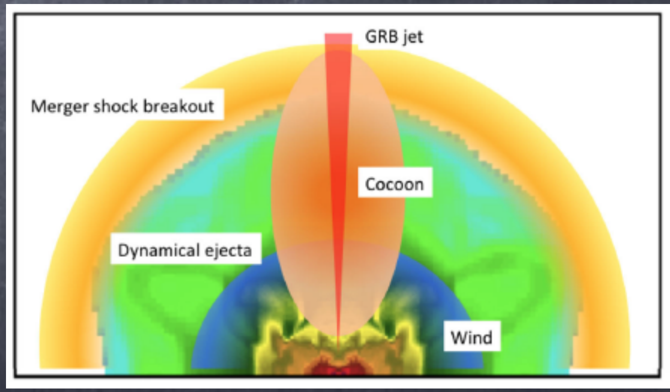


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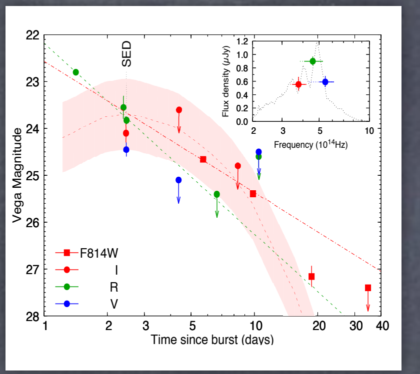


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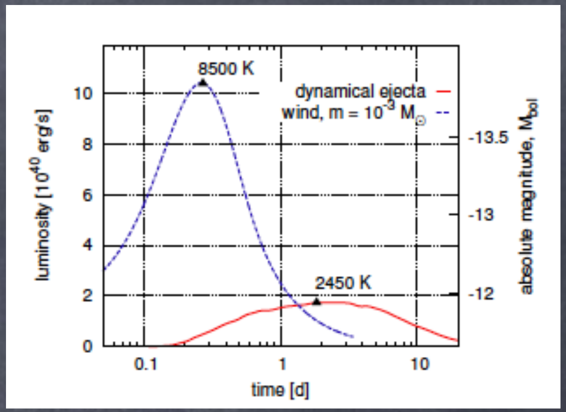


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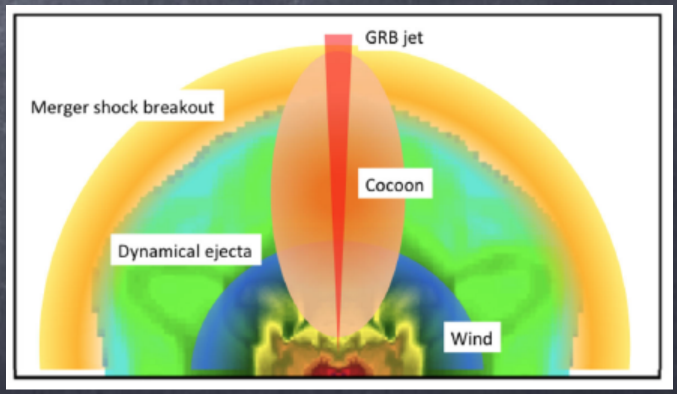


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