Electromagnetic counterparts and r-process

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Outline

1. The Li-Paczynski Macronova (kilonova)
2. GRBs 060614/050709 and their Macronove
3. Plutonium
4. Dwarf Galaxies
5. The cocoon's macronova - the strongest EM counterpart?
6. Limits on magnetars from radio flares
7. * The energy deposition rate
8. Conclusions

1. 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.

Bohdan Paczynski

*Also called Kilonova

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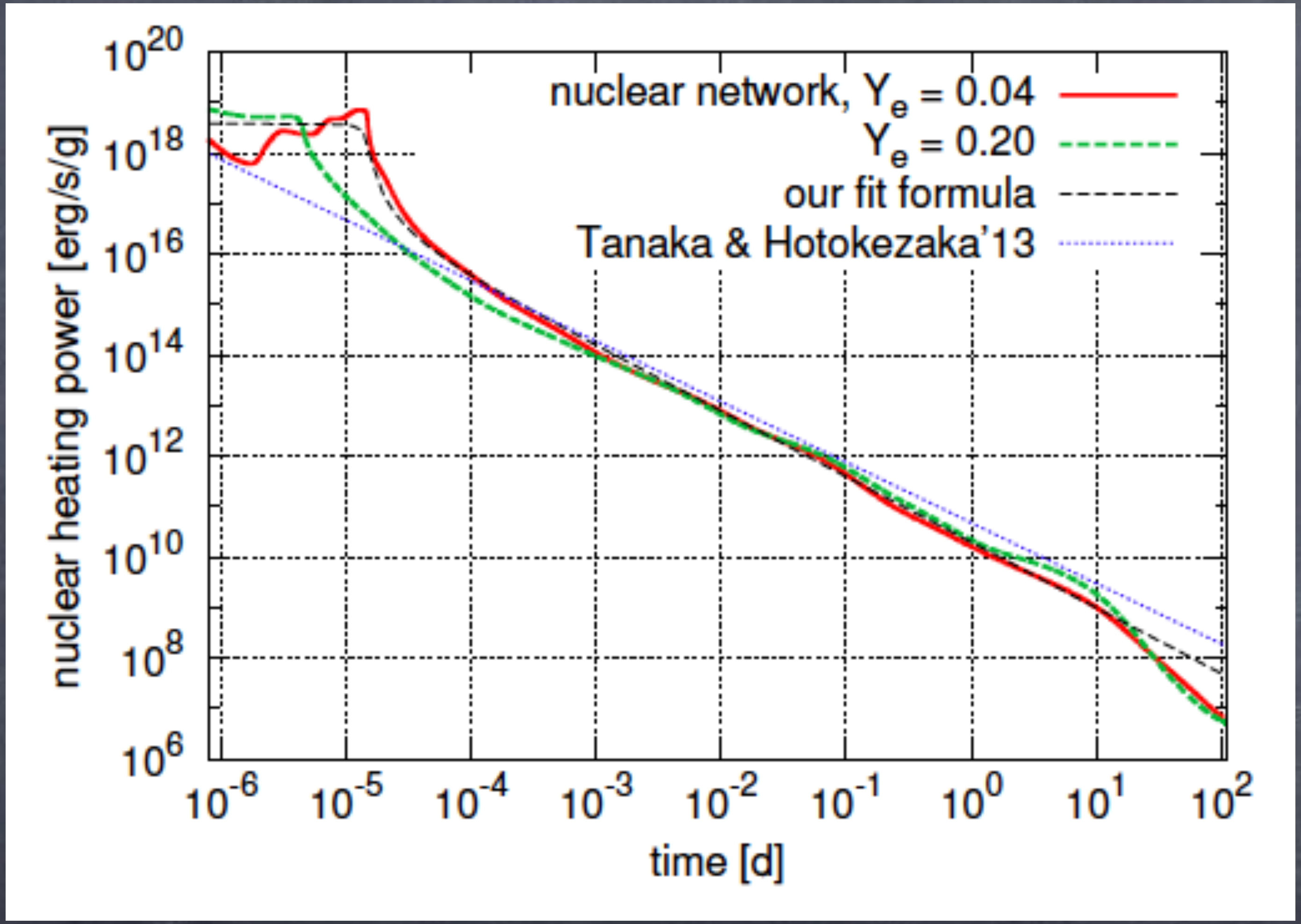
*Also called ~~Kilonova~~ ▶ ~~Hektanova~~ ▶ Decanova

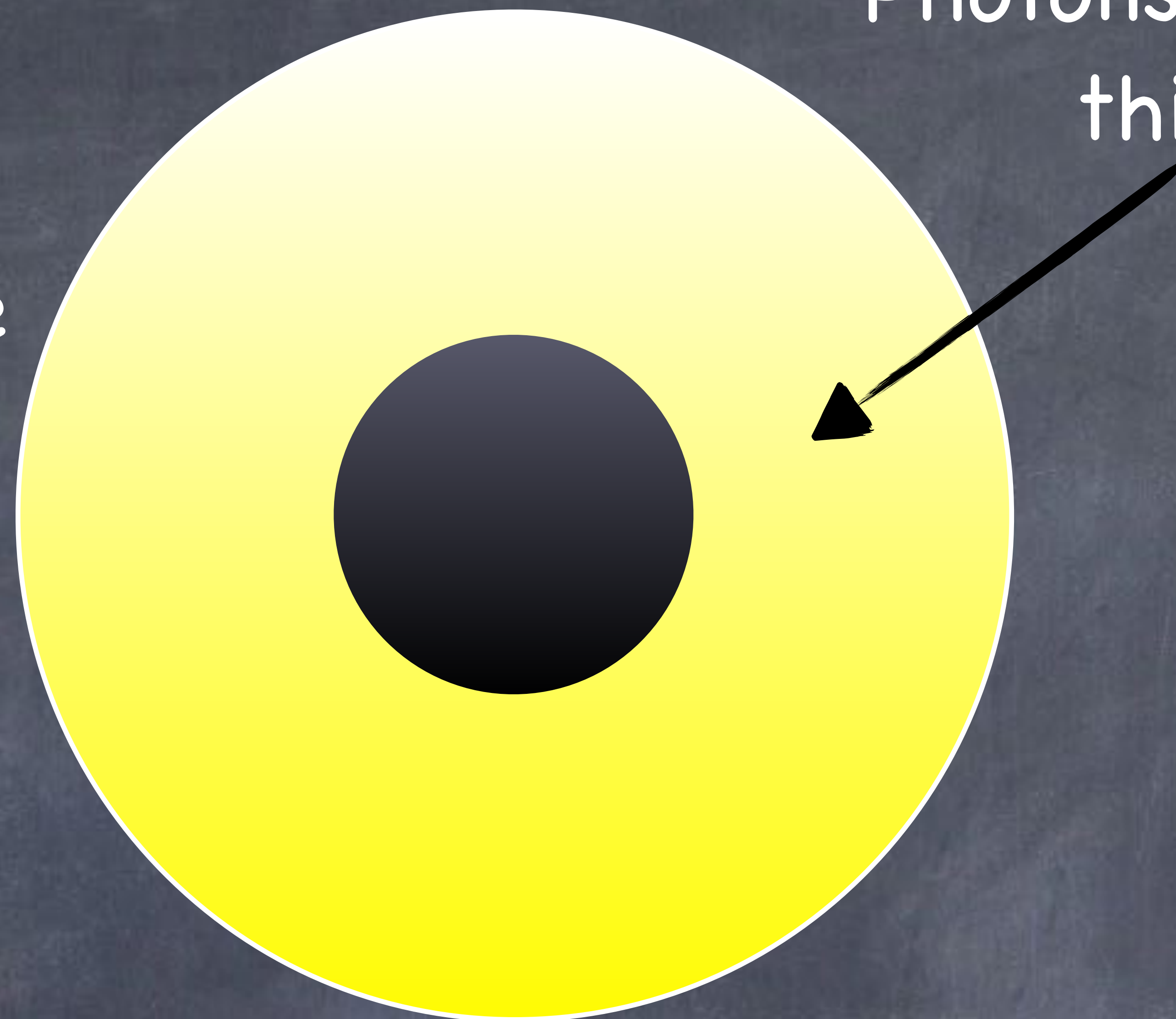
Radioactive Decay*

Korobkin + 13; Rosswog, Korobkin + 13



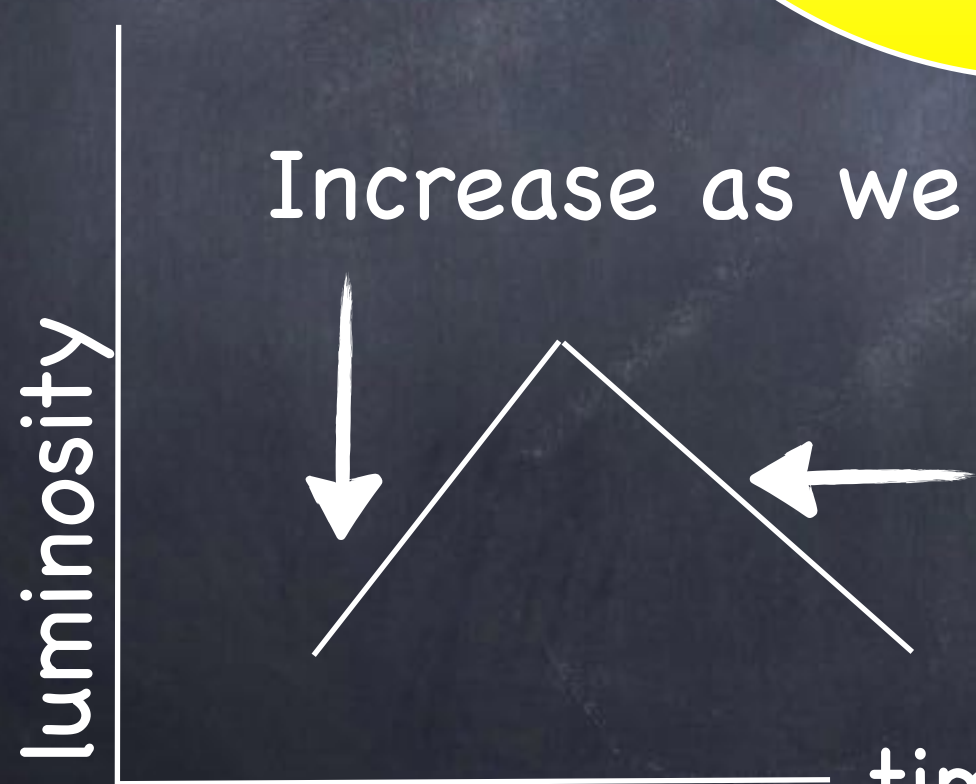
- After a second $dE/dt \propto t^{-1.3}$ (Freiburghaus+ 1999; Korobkin + 2013)

Photons escape from this region



The light curve depends on

1. mass
2. velocity
3. opacity



Increase as we see a large fraction of the matter.

Decrease due to radioactive decay

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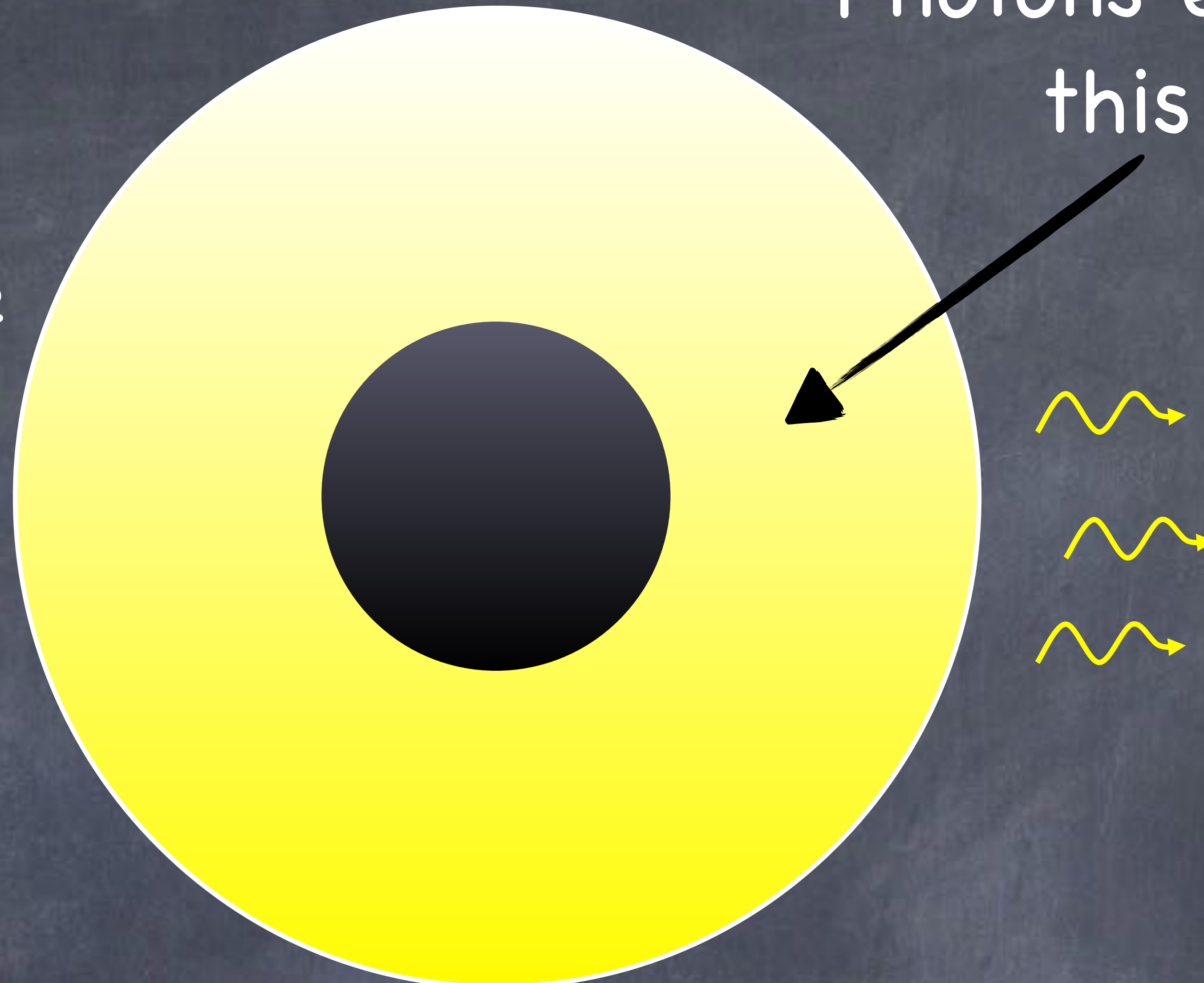

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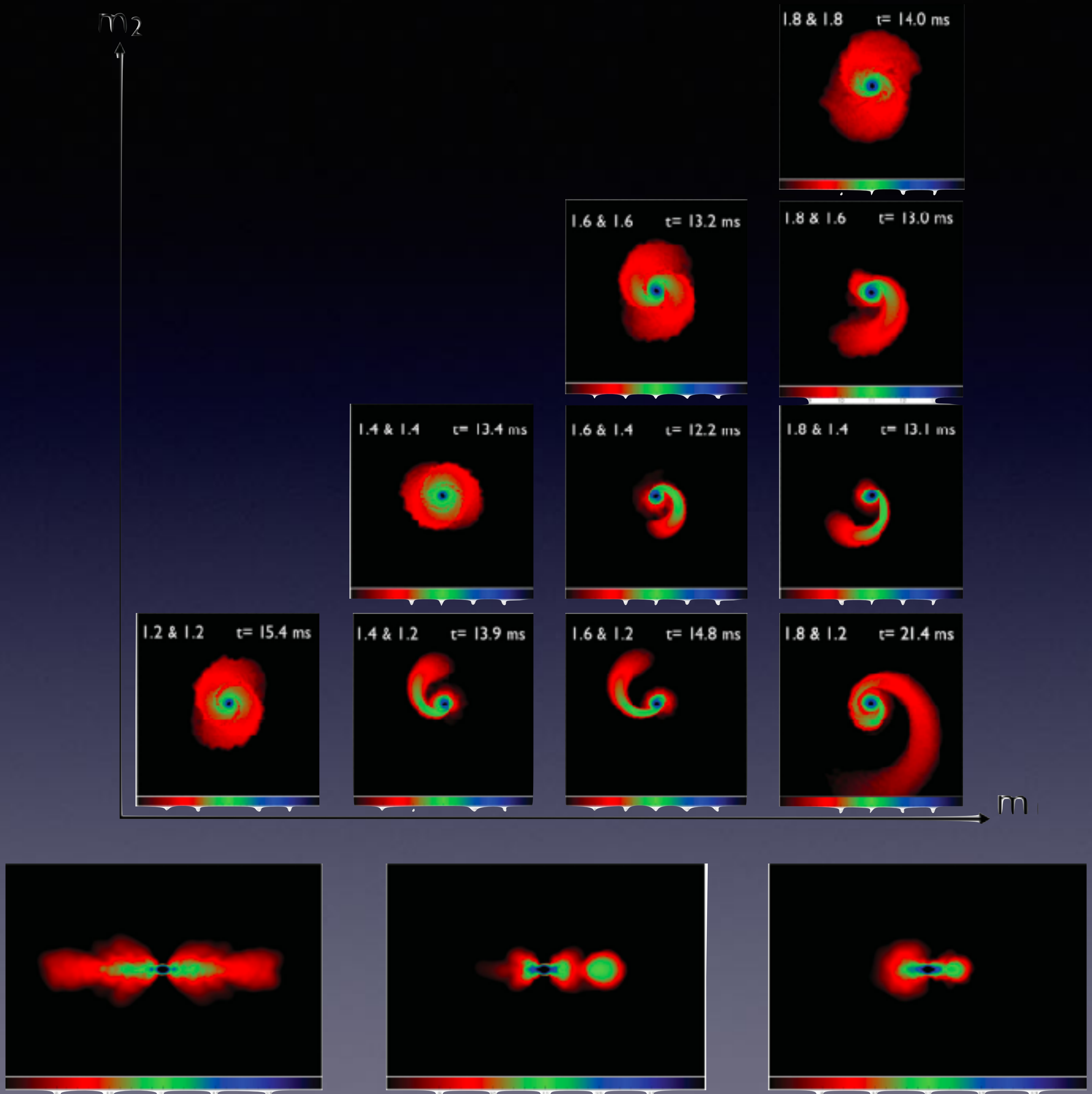
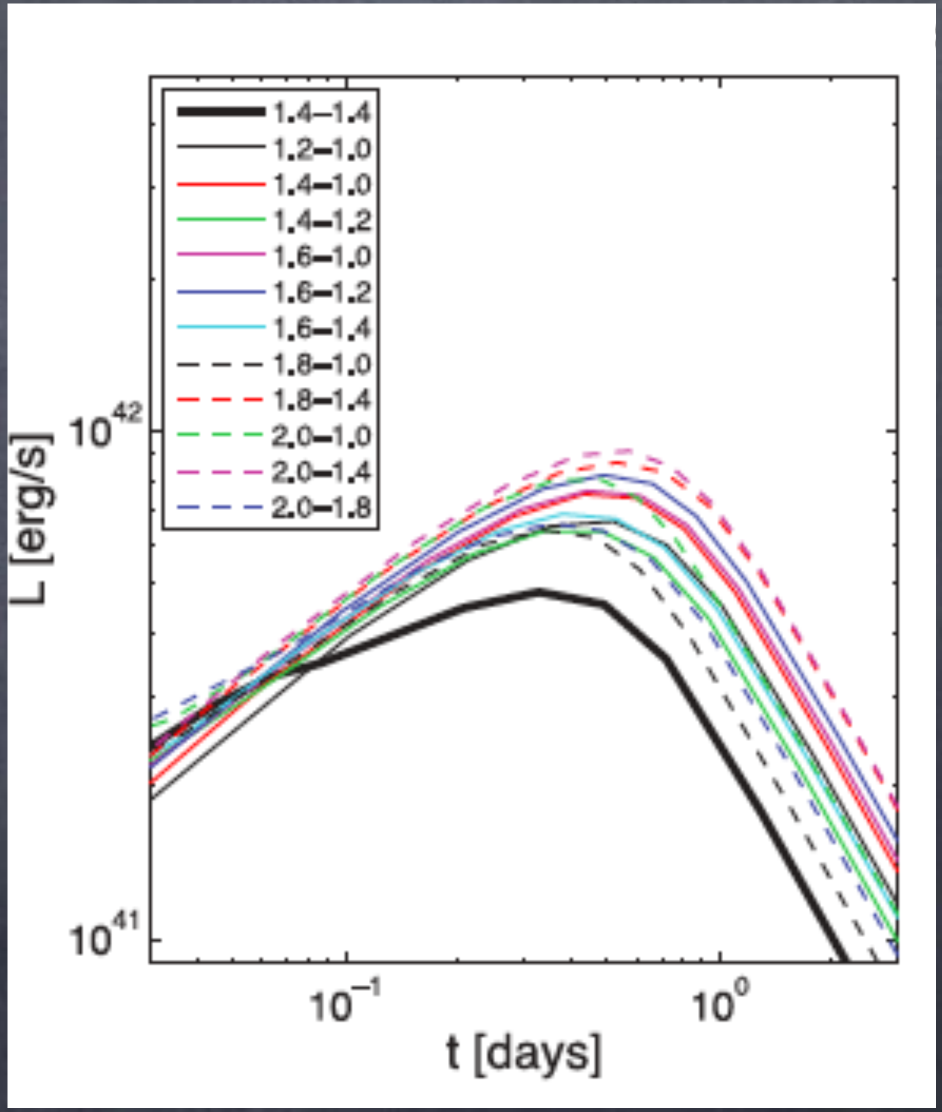


S. Rosswog, ... Following Davies + 1994

Lanthanides dominate the opacity

(Kassen & 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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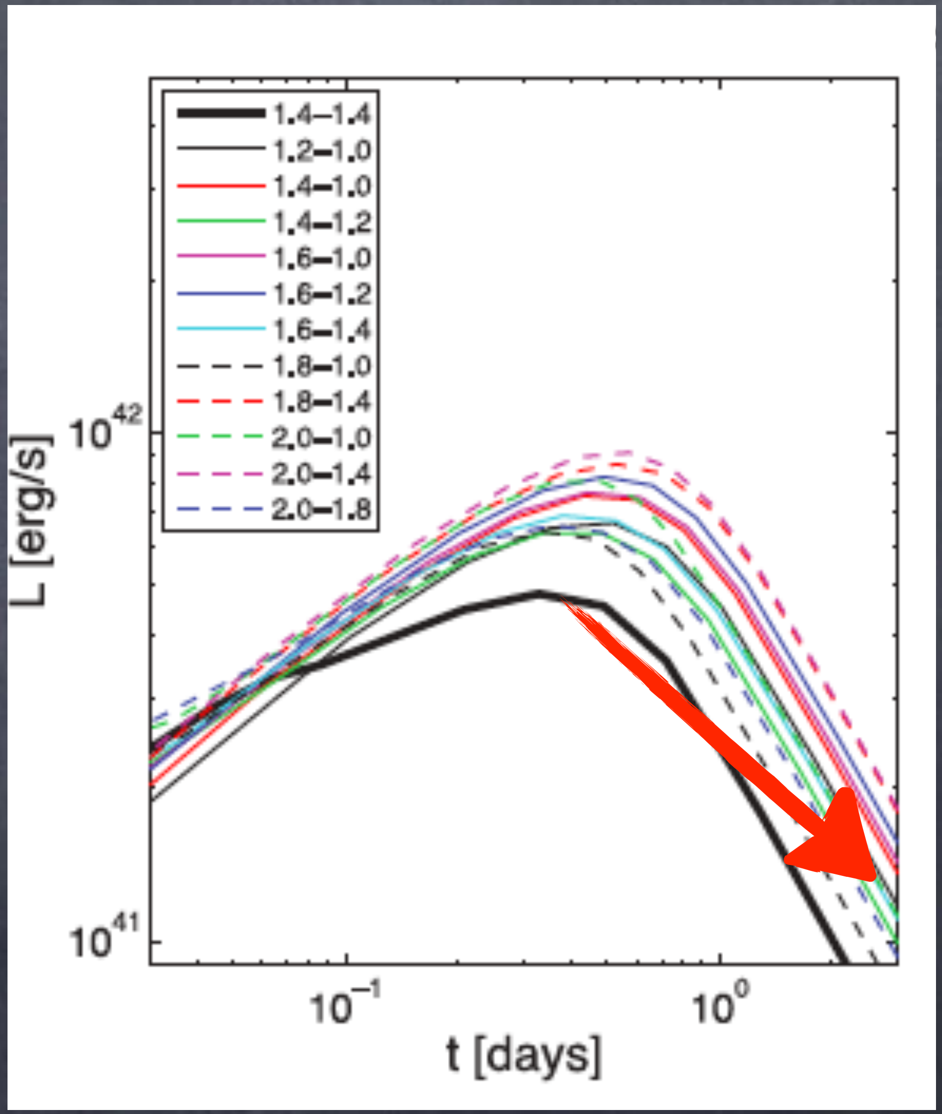

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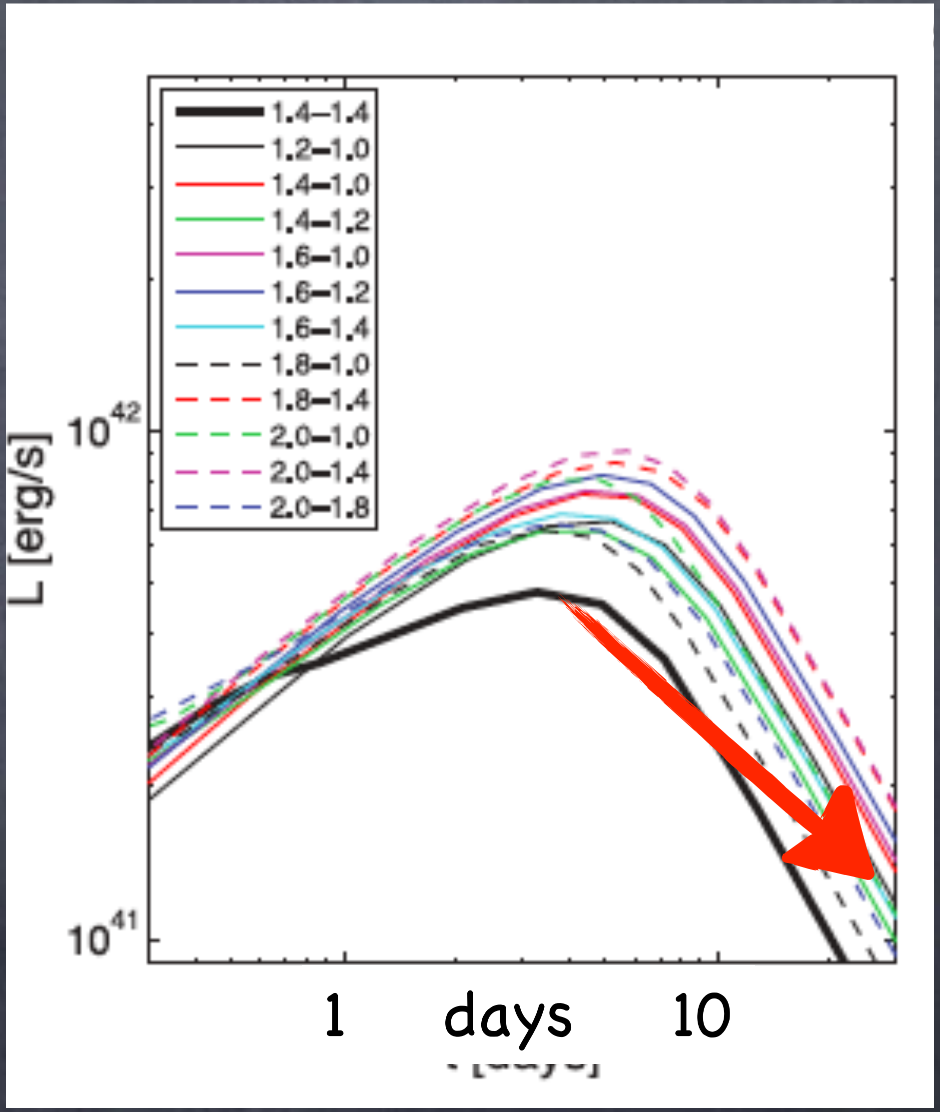

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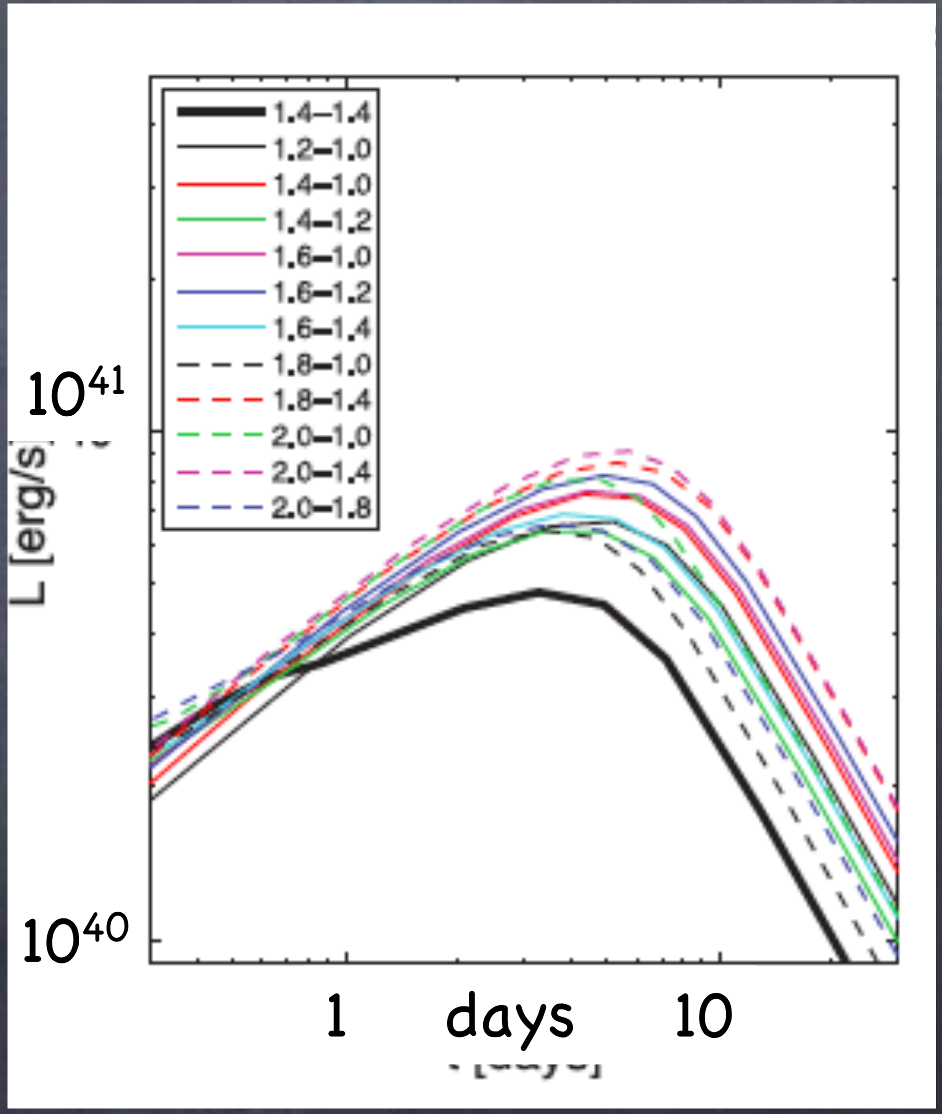

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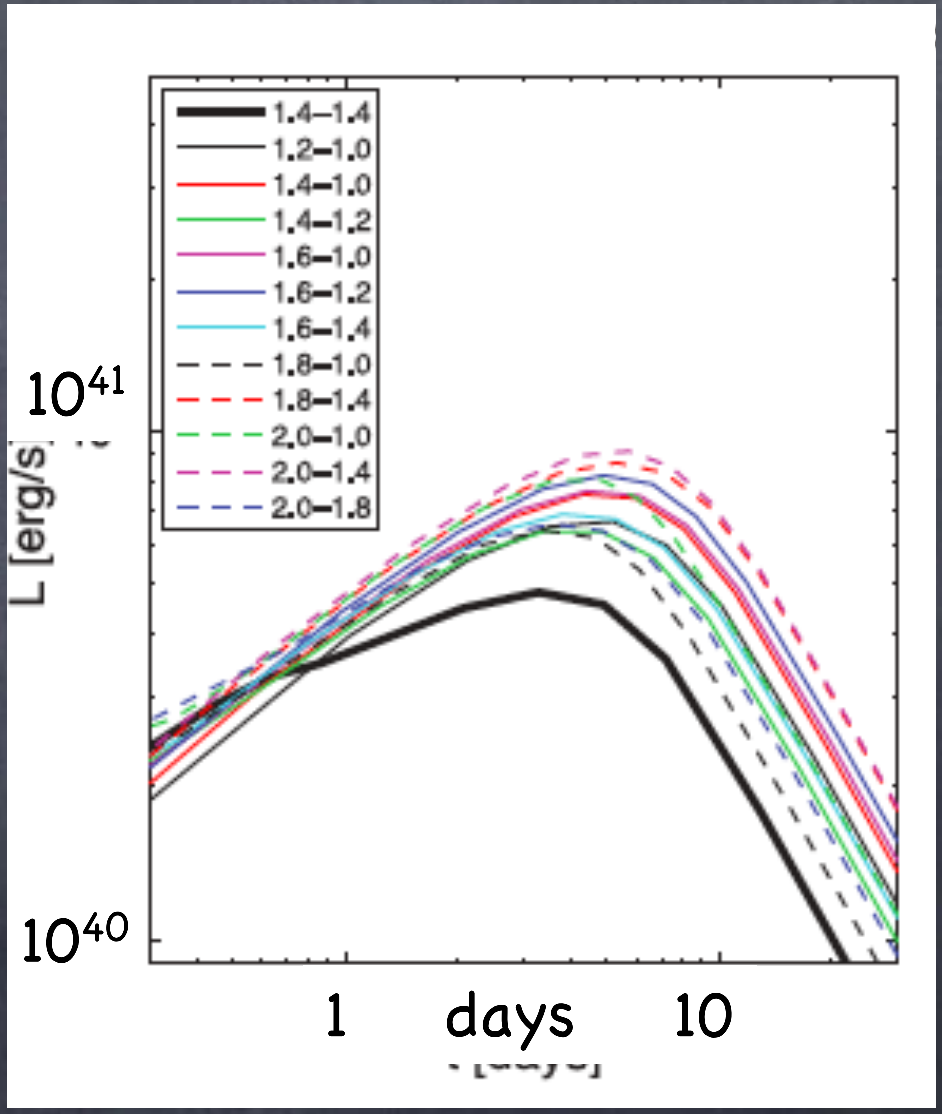
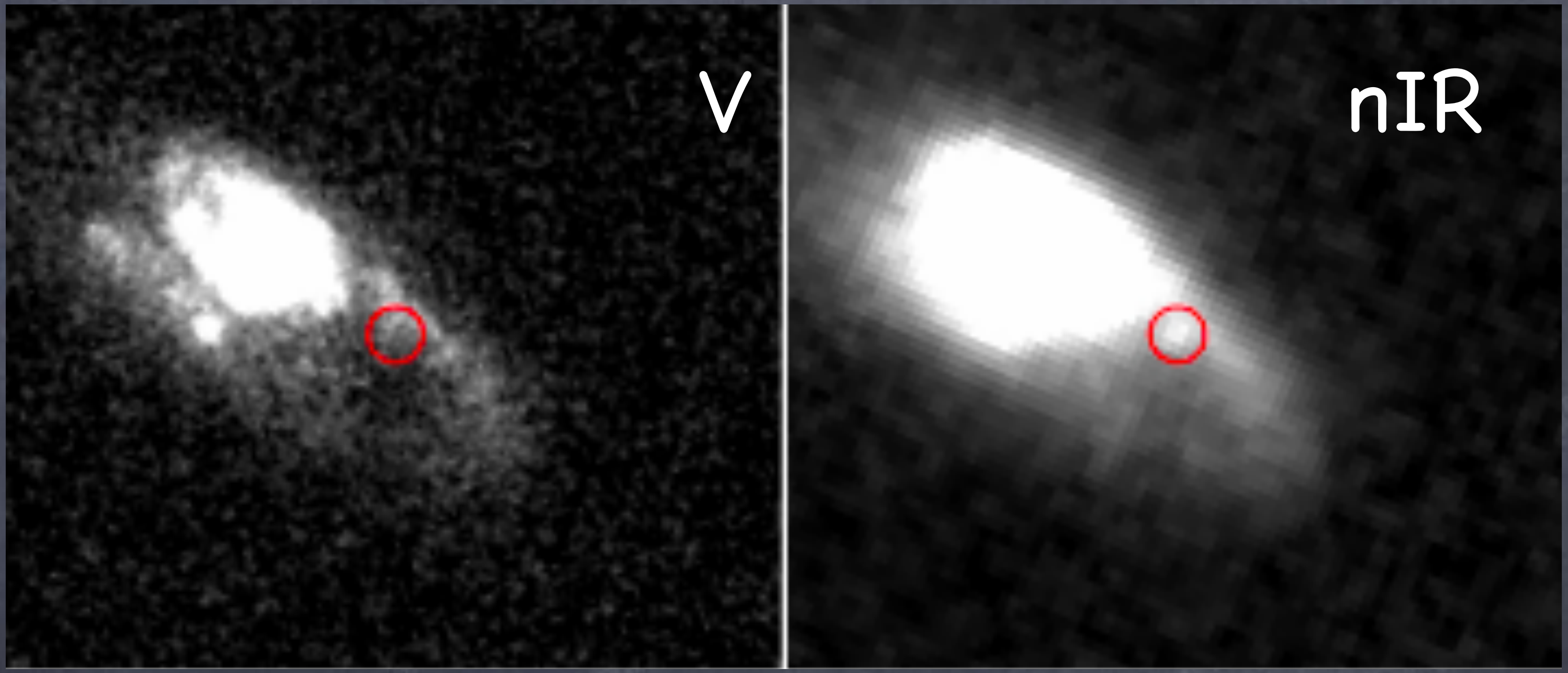


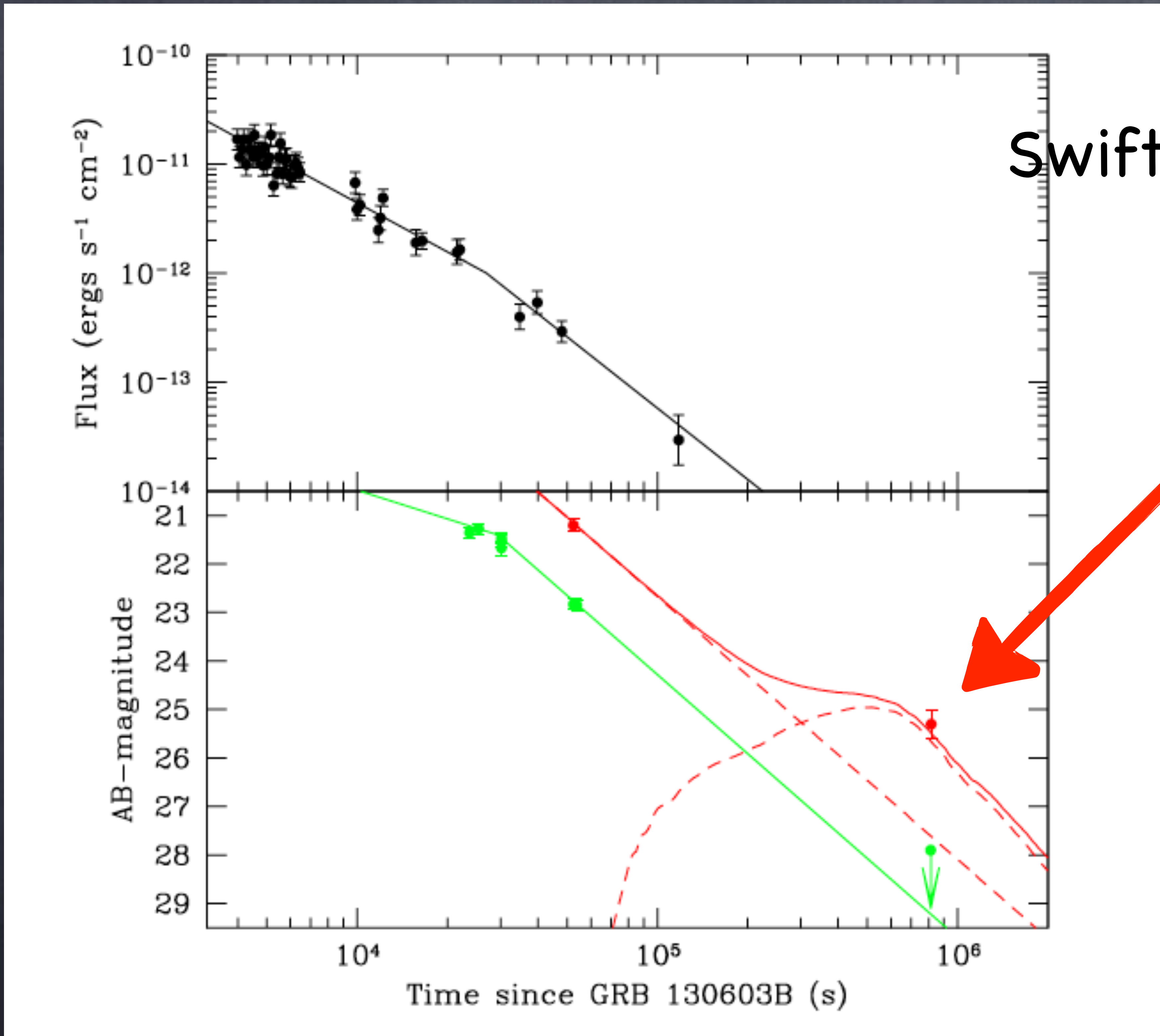
uv or optical -> IR

GRB130603B @ 9 days AB

(6.6 days at the source frame)



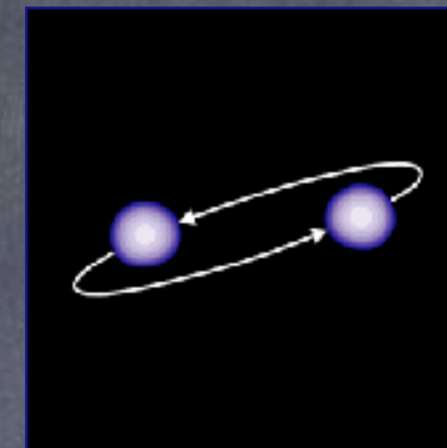
HST image (Tanvir + 13)



Macronova?

Tanvir + 13, Berger + 13

If correct

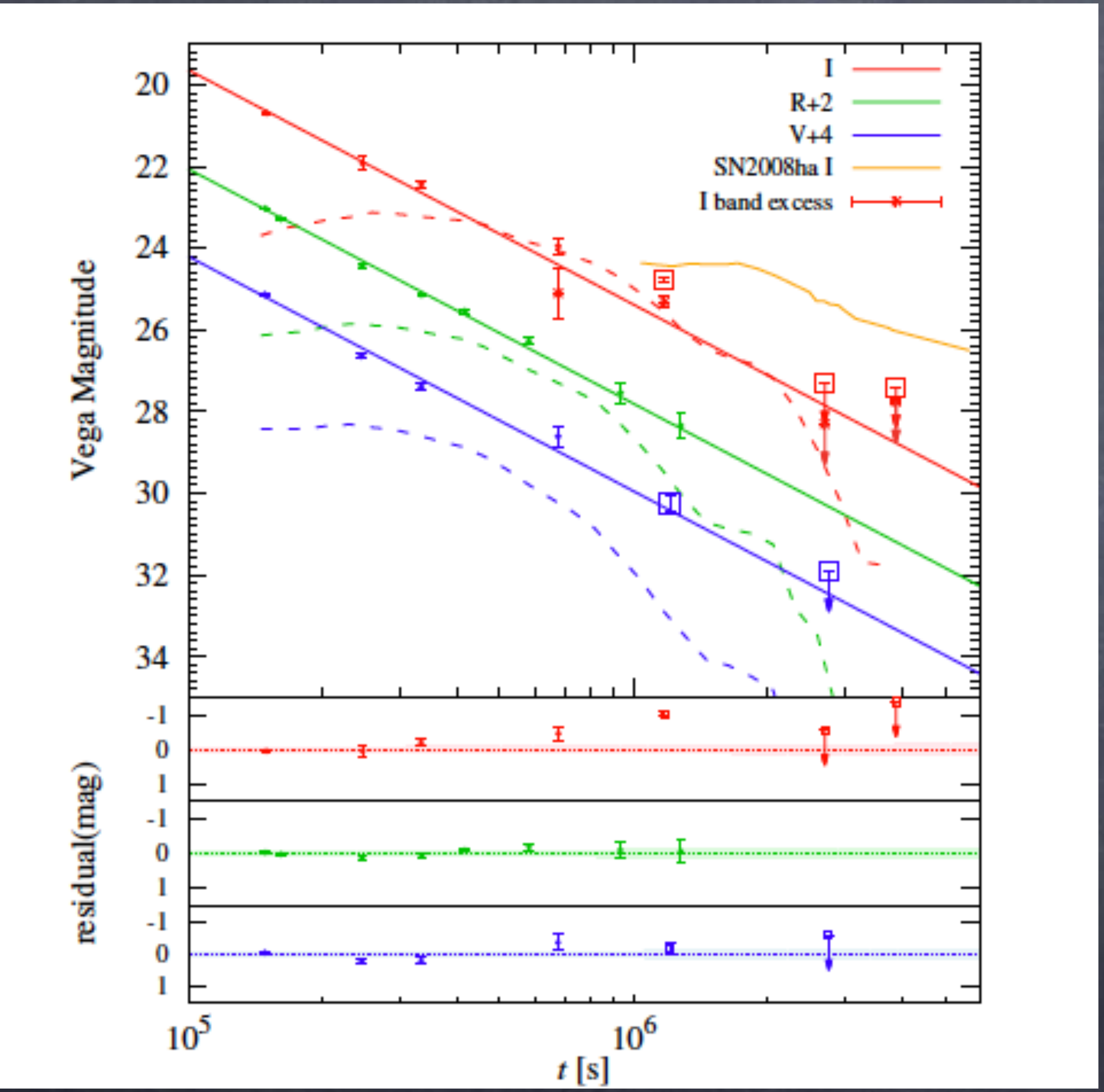


- Confirmaiton of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).
- Confirmation of the Li-Paczynski Macronova (Li-Paczynski 1997).
- Confirmation that compact binary mergers are the source of heavy (A>130) r-process material: Gold, Silver, Platinum, Plotonium, Uranium etc...(Lattimer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

The rate of Short GRBs Macronova and r- process

- About 1/3 of Swift short (<2sec) GRBs are Collapsars
- The rate of non-Collapsar short GRBs (sGRbs) is $4.1^{+2.3}_{-1.9}$ Gpc^{-3} yr^{-1} (depending on the assumed minimal luminosity).
- A LIGO detection rate of 3-100 per year (0.1-3 coinciding with a sGRB)*
- A typical time delay of ~3 Gyr after SFR=> an initial separation of ~2 x 10^{11} cm
- But selection effects? Maybe consistent with $p(\tau)\sim 1/\tau$
- With beaming of ~30 and mass ejection of 0.02 M_{sun} - compatible with R-process nucleosynthesis for A>110 elements.

GRB 060614

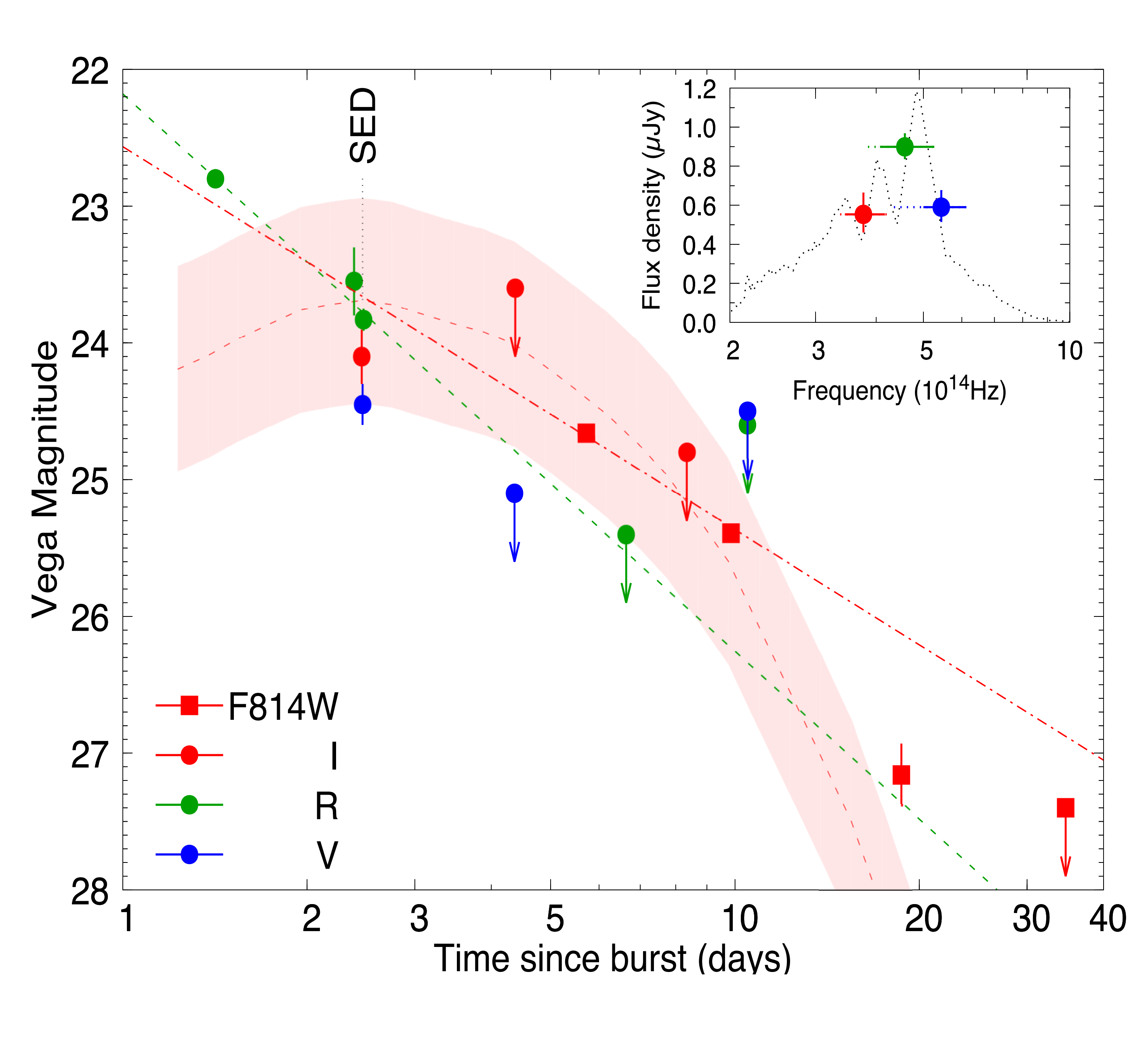


Need $M \simeq 0.1 M_\odot$

=> BH-NS ?

Yang et al., 2015

GRB 050709



Need $M \simeq 0.05 M_\odot$

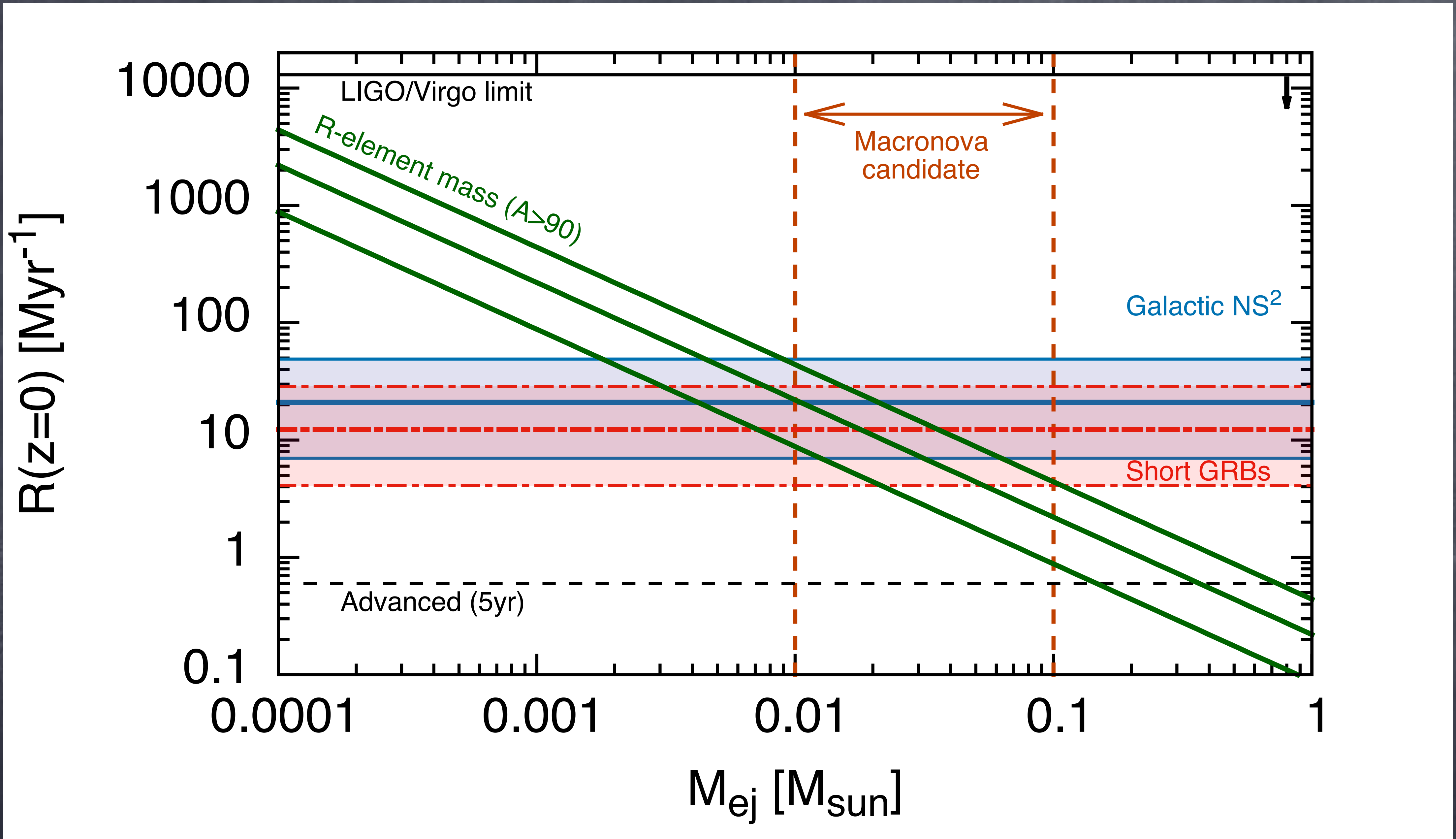
=> BH-NS ?

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

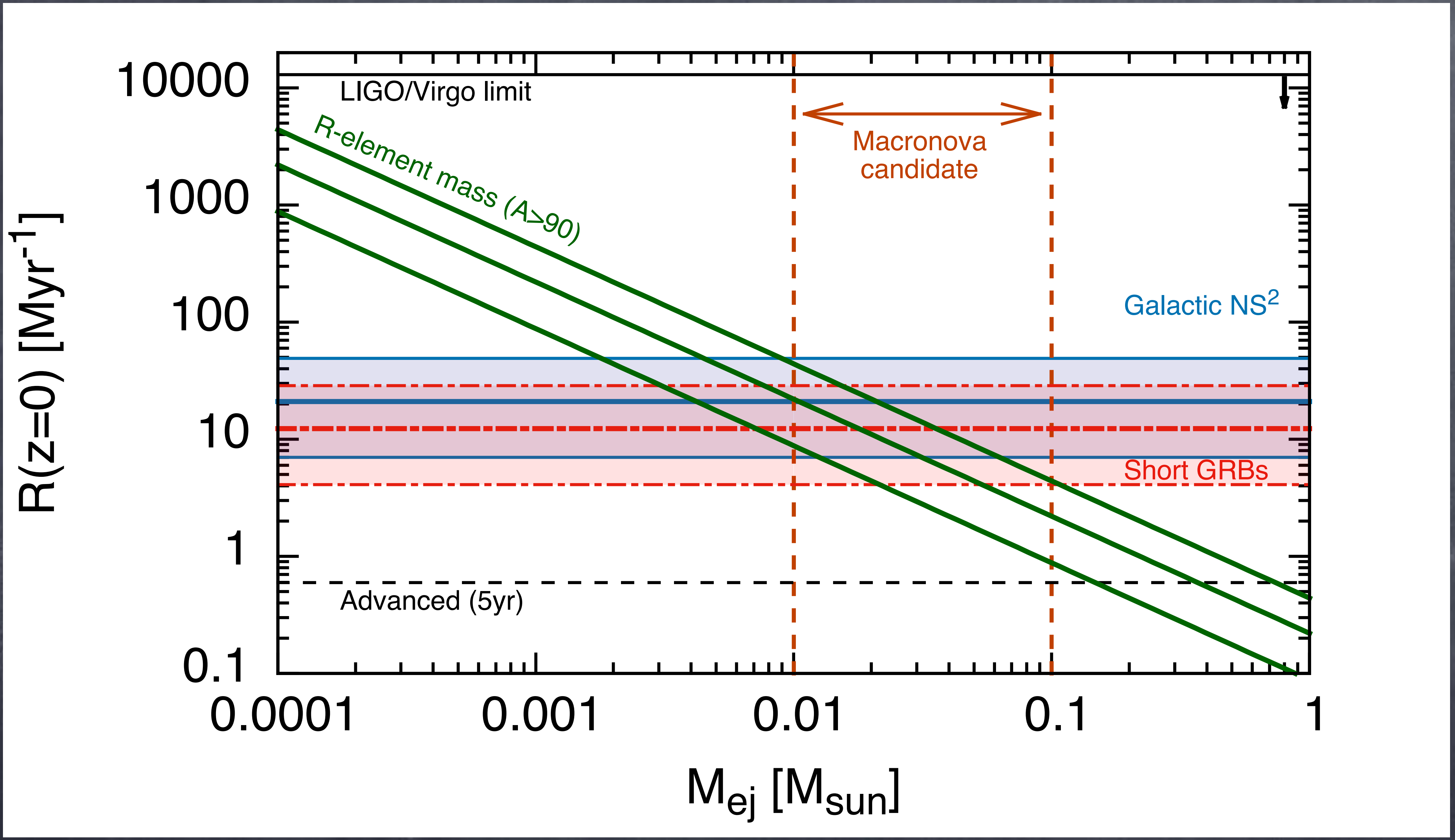


lines of R-mass: Current event rate is lower than the average one
by a factor of 5 (lower line), 3 (middle line).

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

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

R-Process



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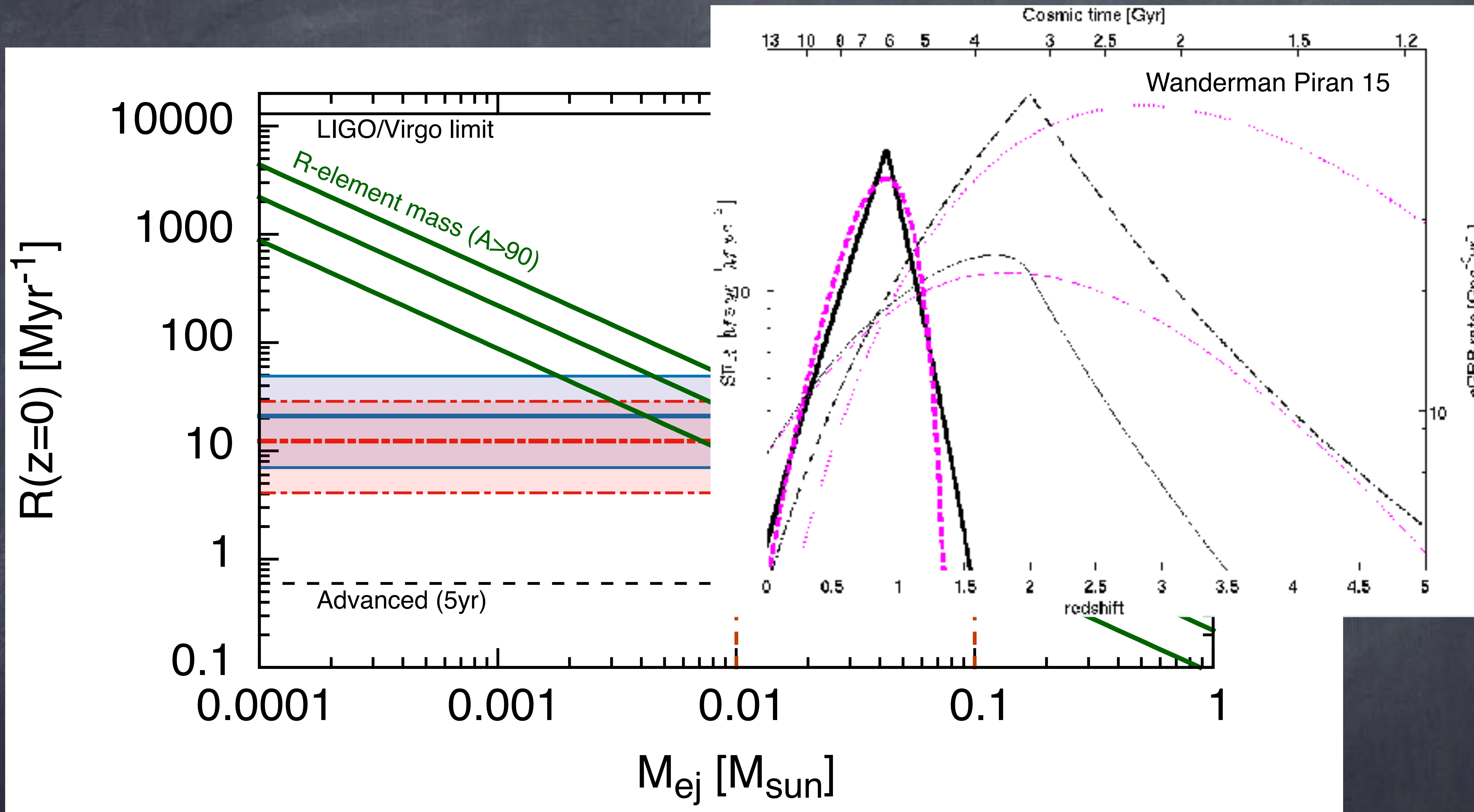

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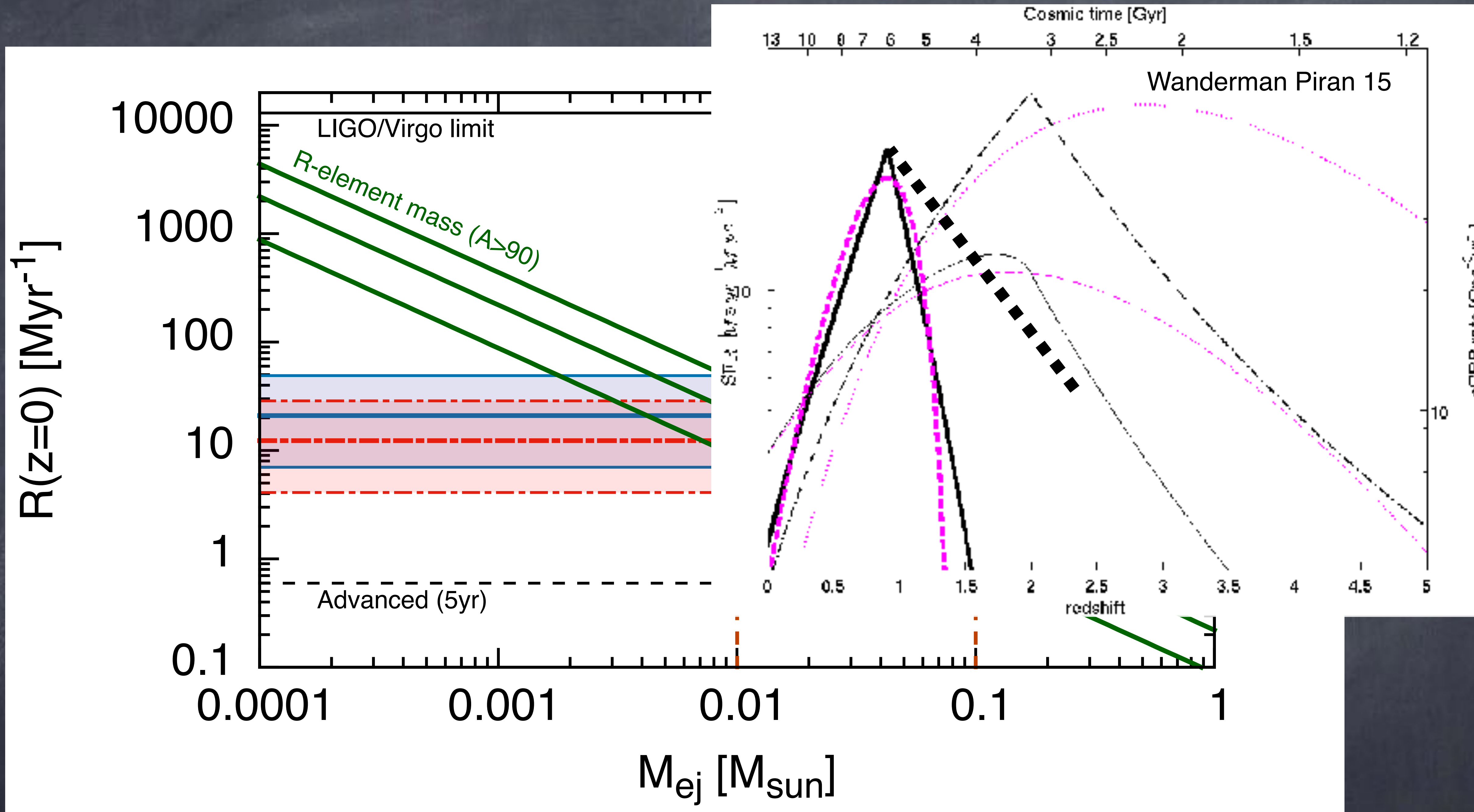

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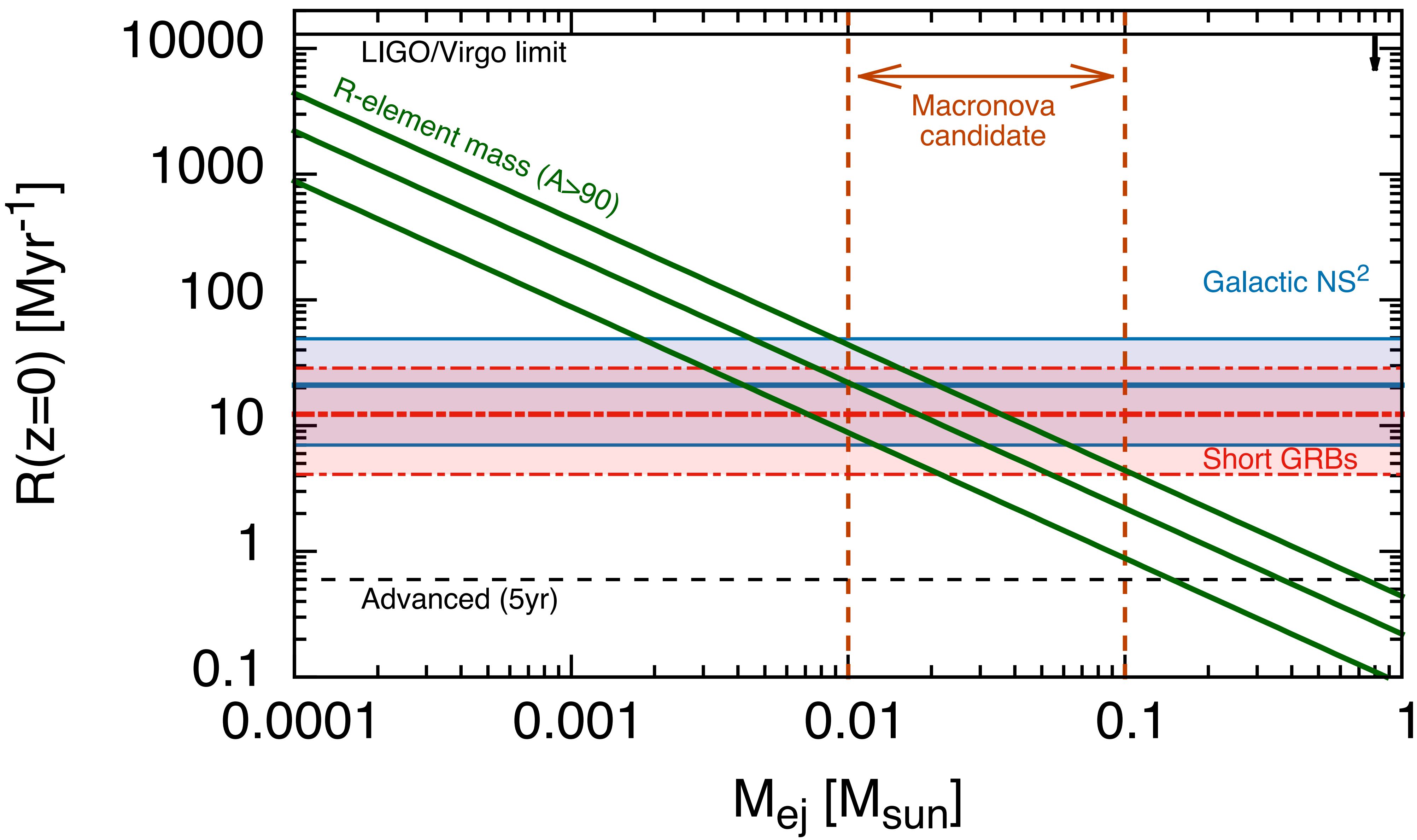
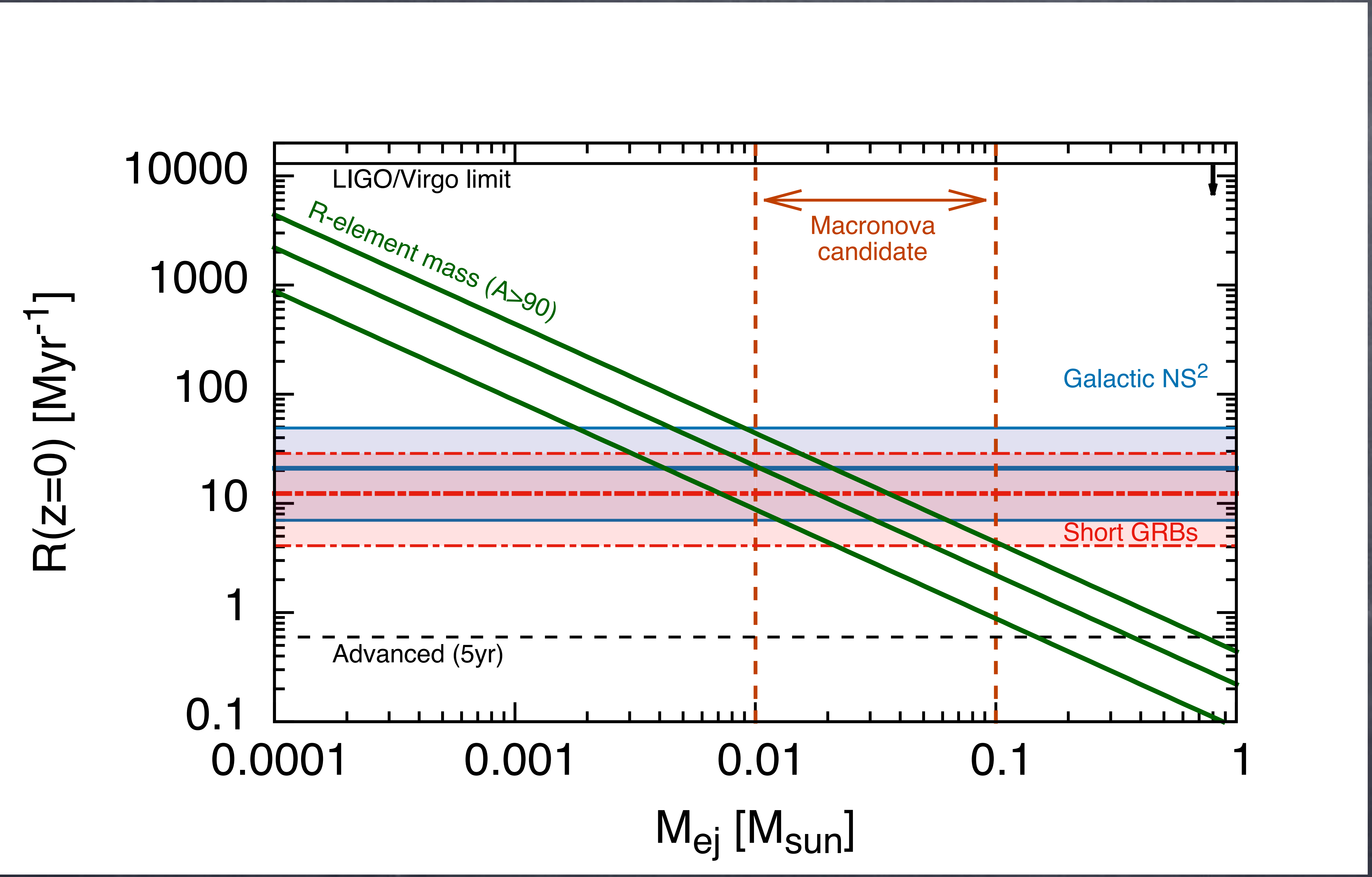


Can we break the yield - rate degeneracy?



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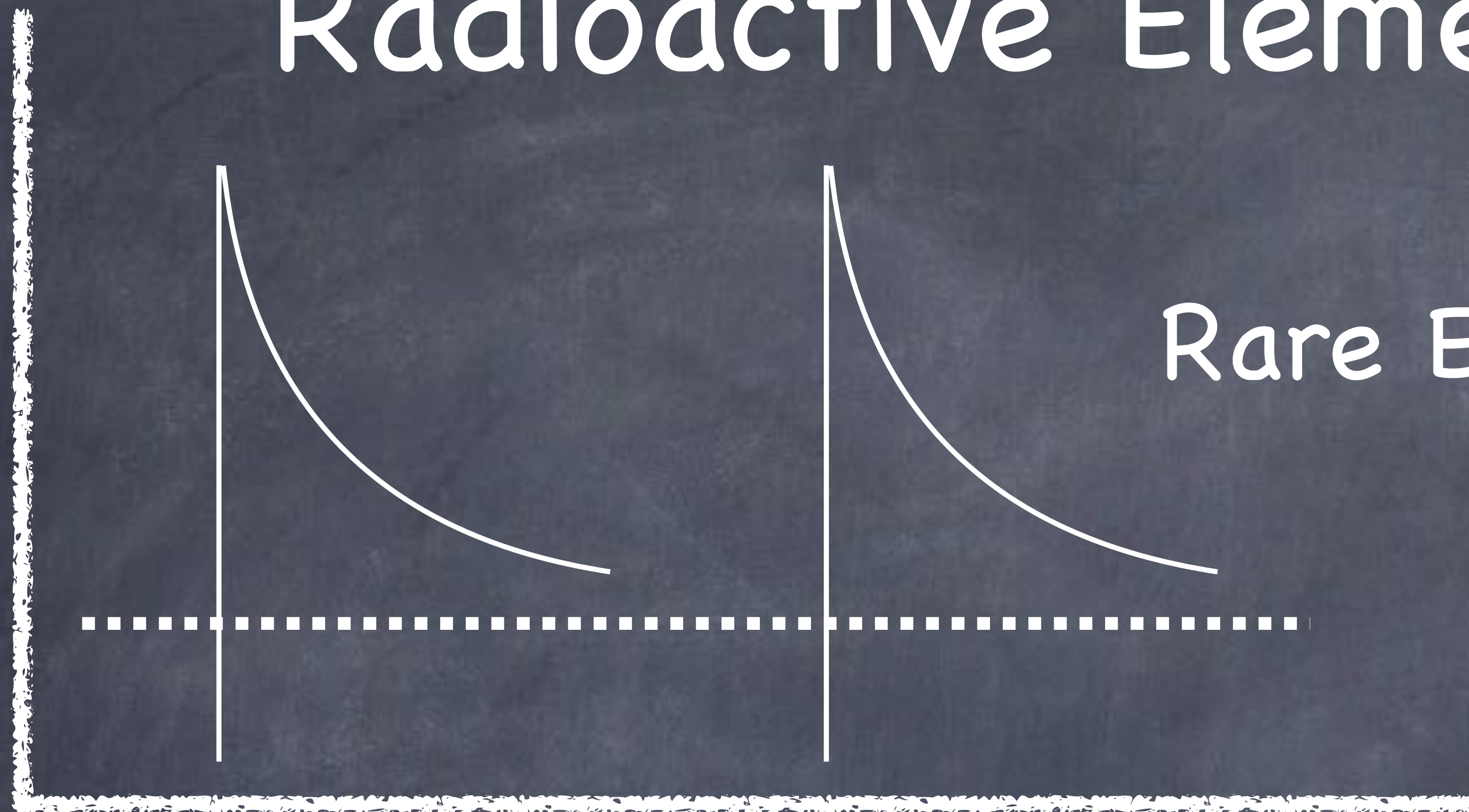
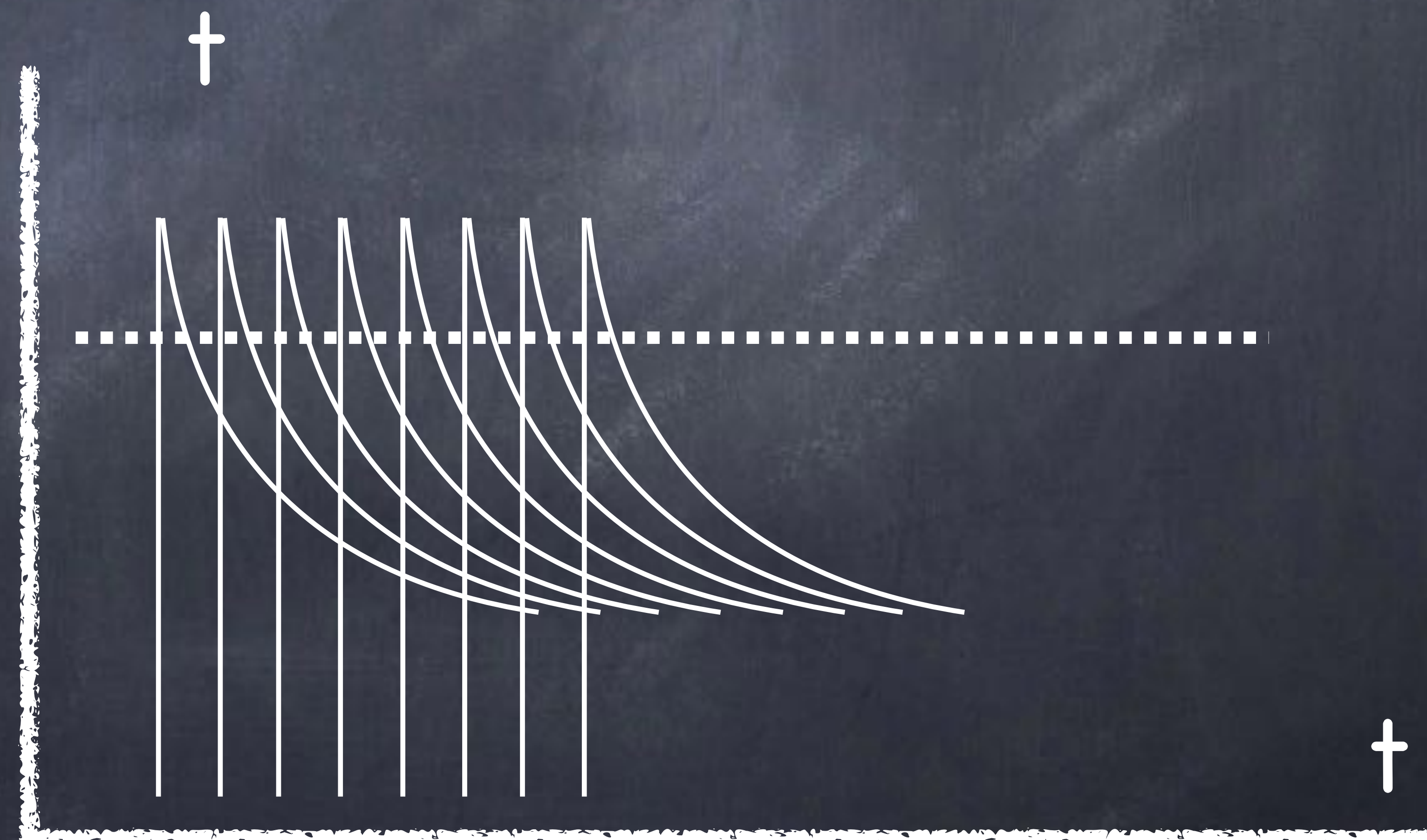
Radioactive Elements



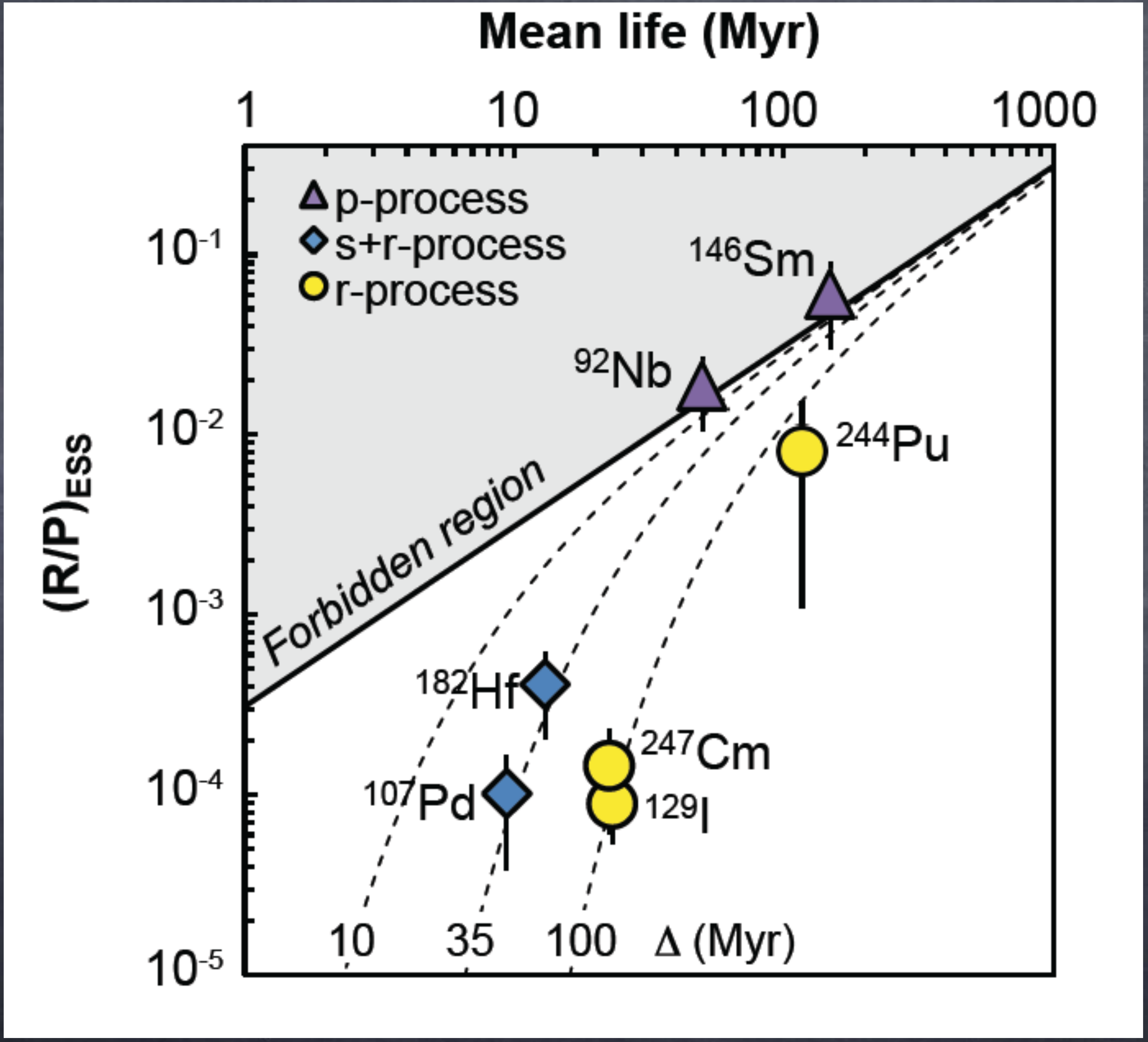
Rare Events



Frequent events

High ^{244}Pu at the early solar system =>

- ^{244}Pu Radioactive decay time ~ 100 Myear
- A nearby event near solar system
- Mixing time < 150 Myr
- Large fluctuations possible => Event rate is low
- Lack of Cu => 10 Myr < Mixing length

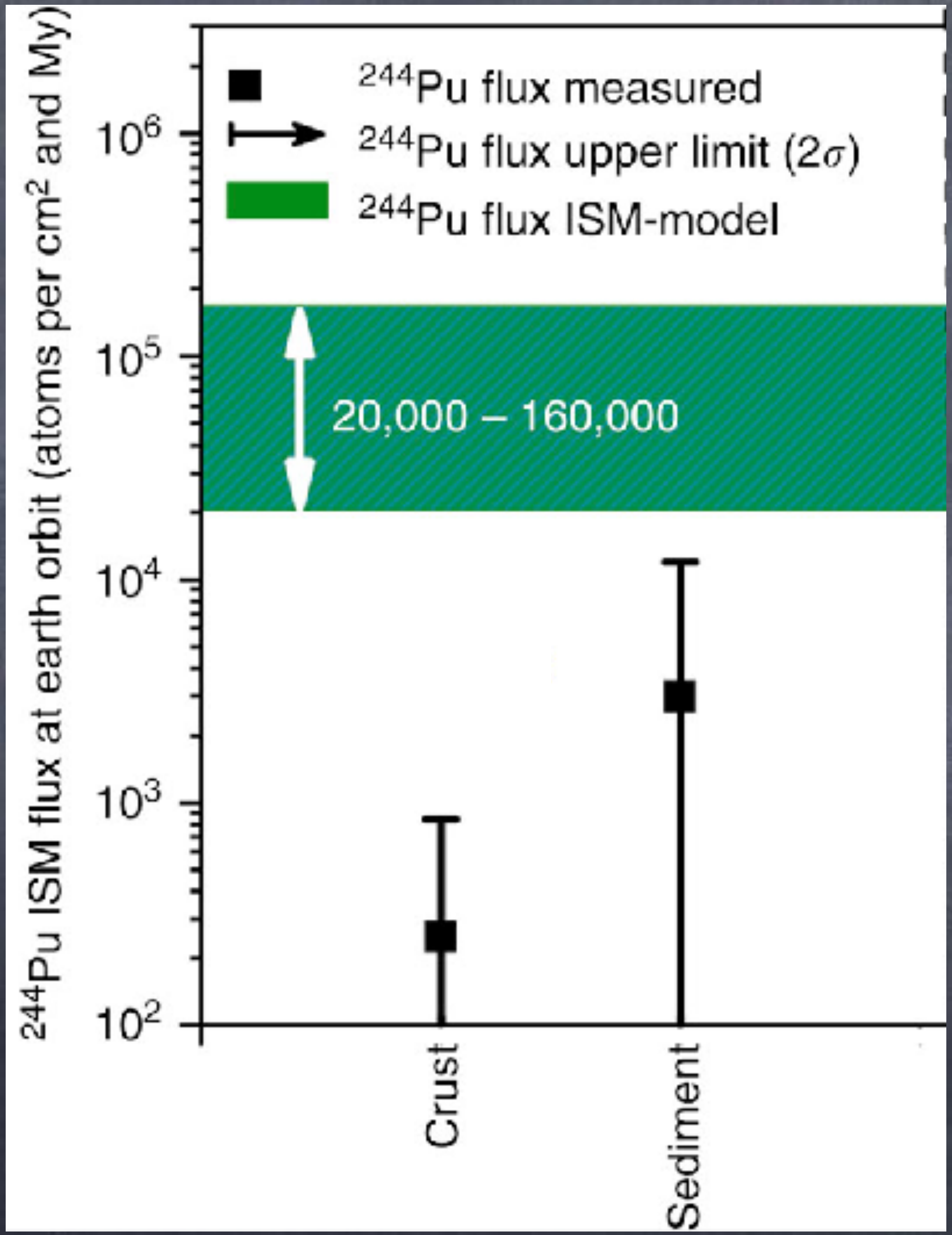


Mean life (Myr)
1
10
100
1000
(R/P)ESS
10-1
10-2
10-3
10-4
10-5
p-process
s+r-process
r-process
146Sm
92Nb
244Pu
Forbidden region
182Hf
247Cm
107Pd
129I
10
35
100
Δ (Myr)

Tissot + 16

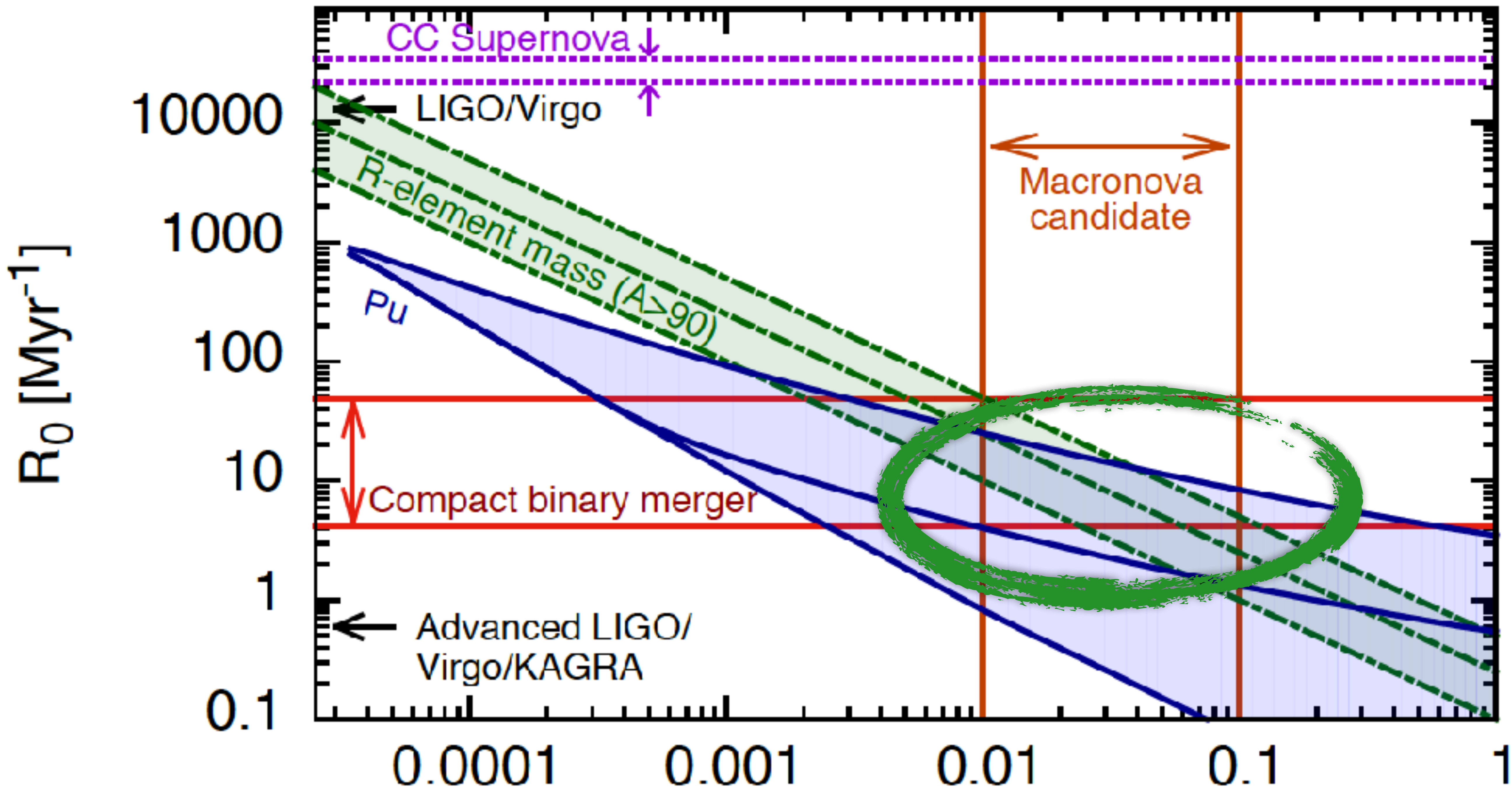
^{244}Pu (half life 81Myr)

The early solar system

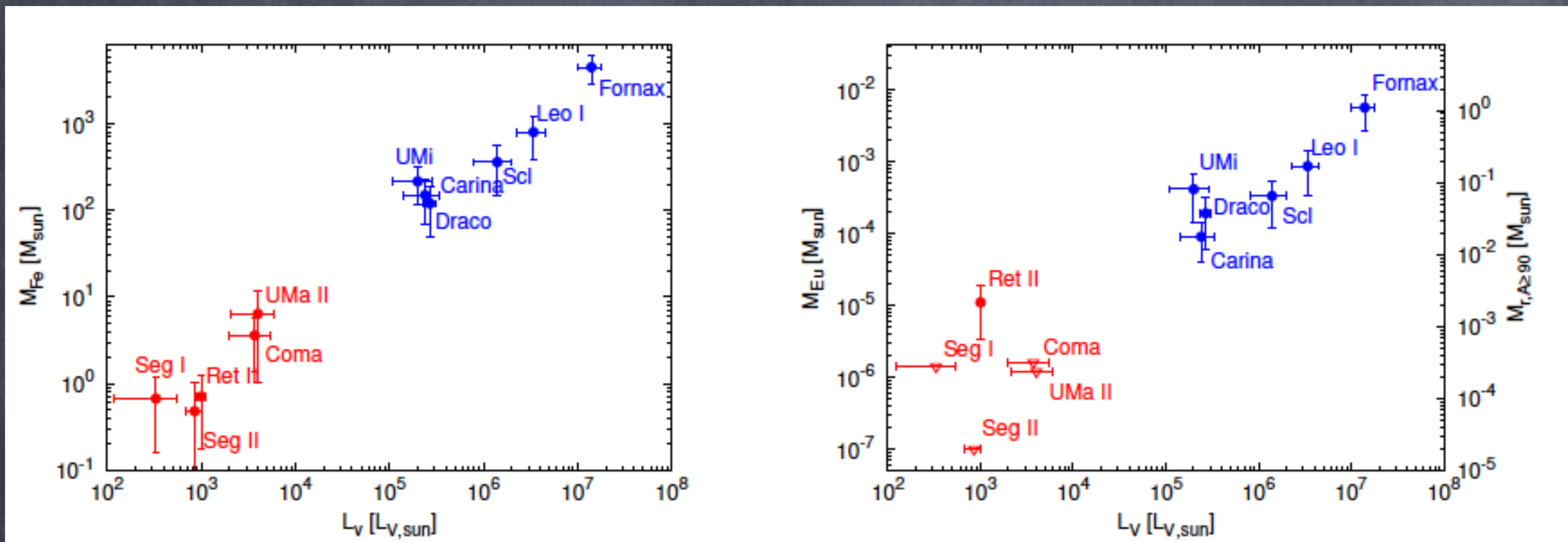


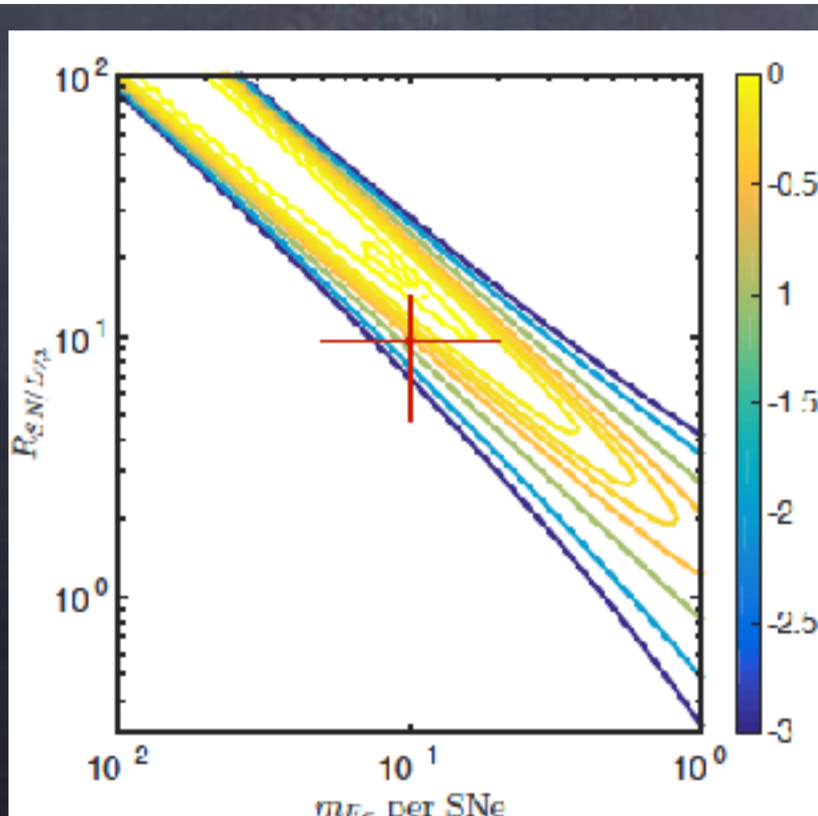
Wallner + 14

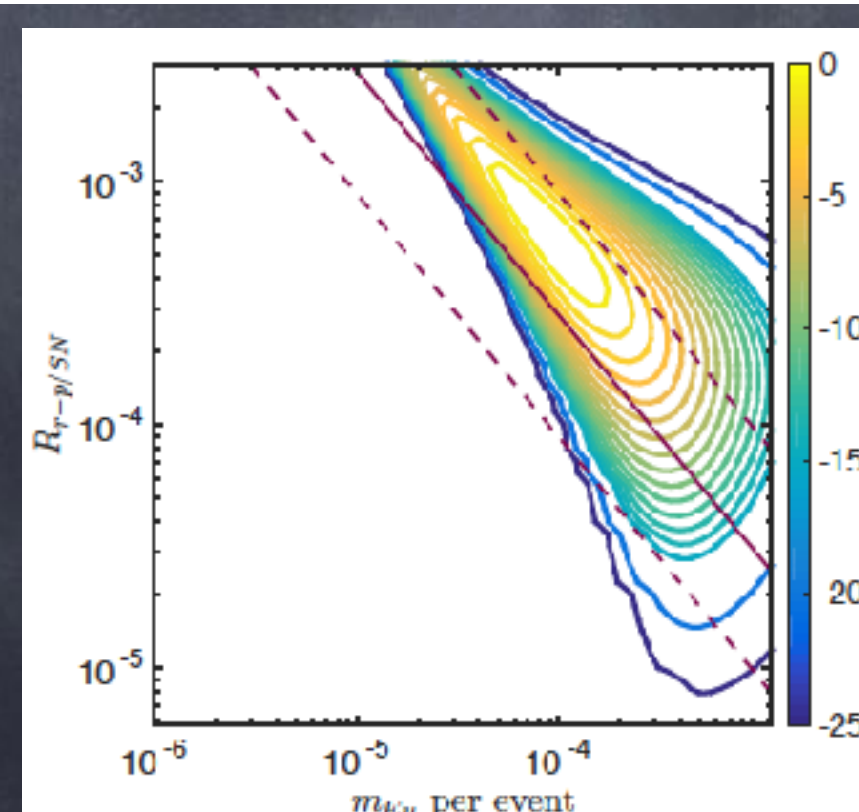
Rare and “massive” events

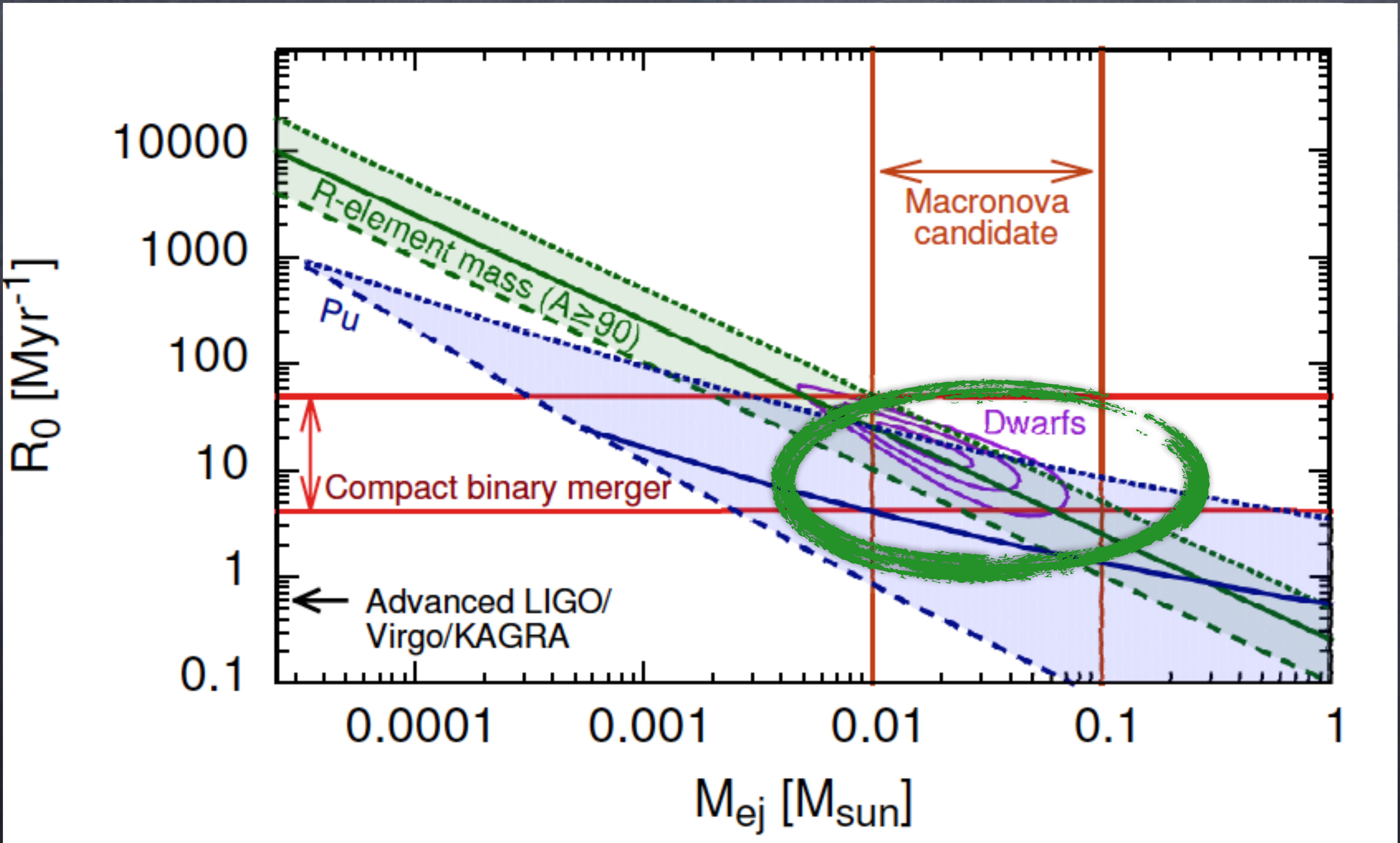


r-process material in Dwarf Galaxies (Beniamini+ 16a,b)

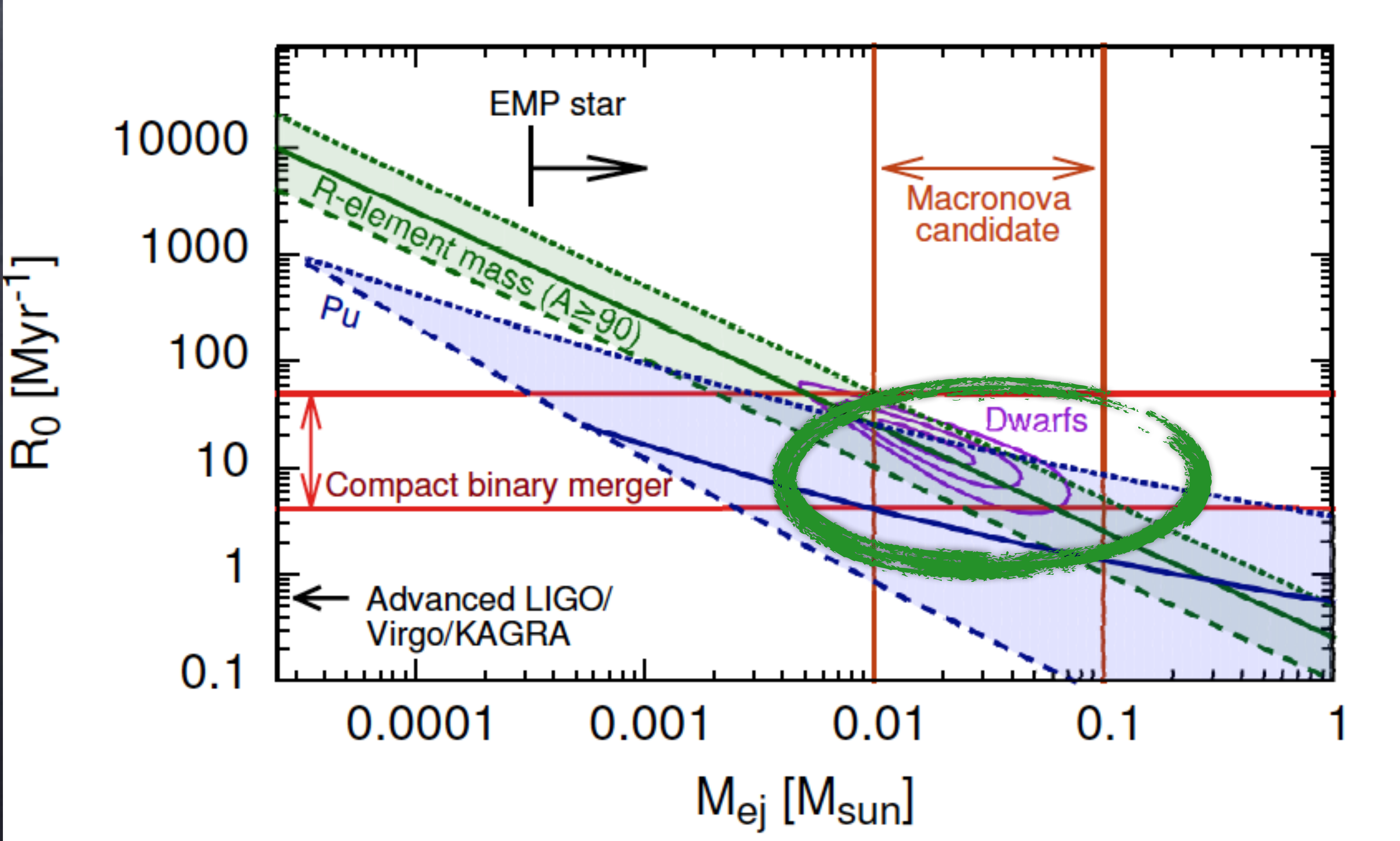




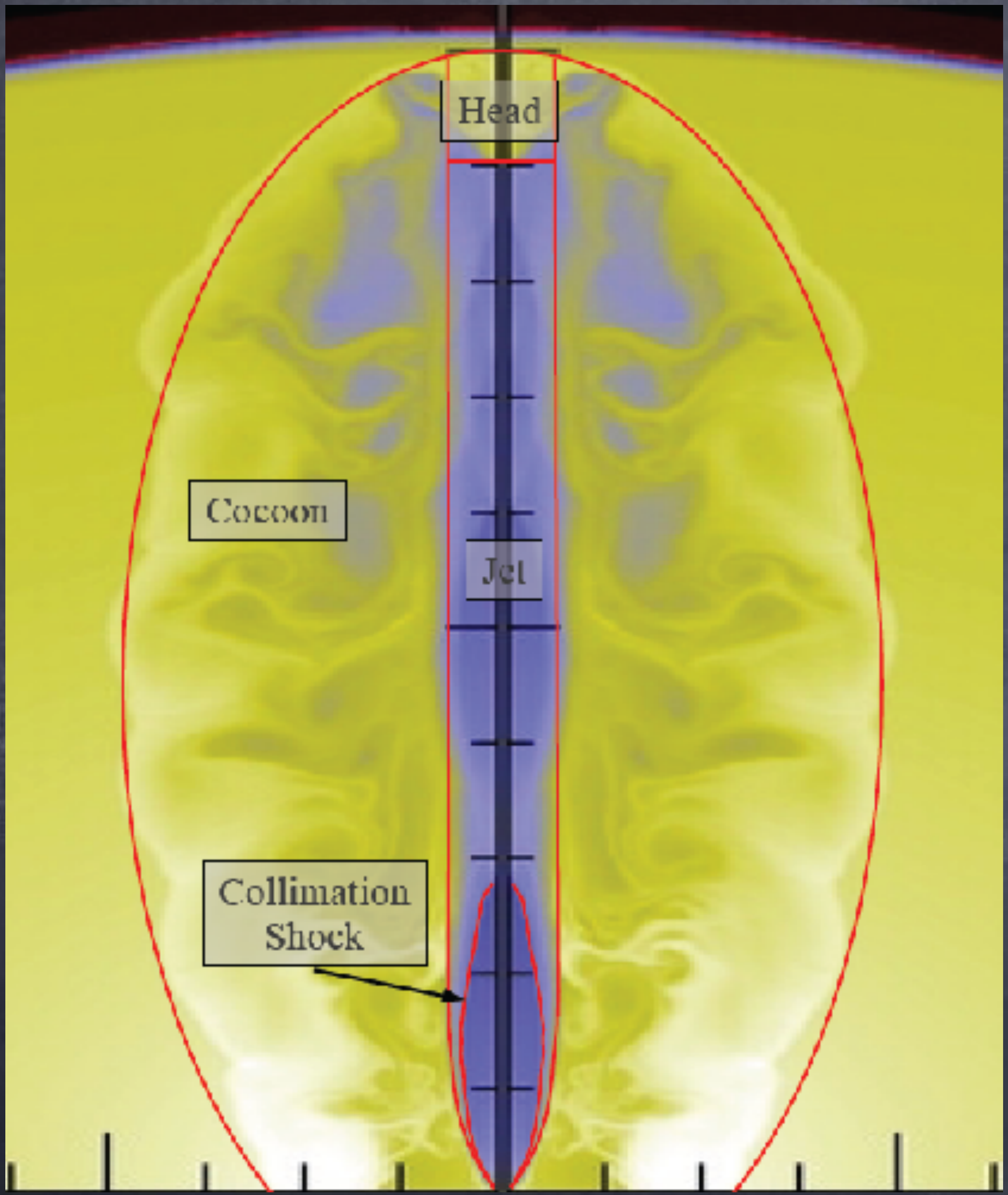




10000
1000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
R0 [Myr-1]
Mej [Msun]
R-element mass (A≥90)
Pu
Macronova
candidate
Dwarfs
Compact binary merger
Advanced LIGO/
Virgo/KAGRA


EMP star
Macronova candidate
R-element mass (A≥90)
Pu
Dwarfs
Compact binary merger
Advanced LIGO/ Virgo/KAGRA
10000
1000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
R_0 [Myr^{-1}]
M_{ej} [M_{sun}]

The Secret Signatures of GRB cocoons

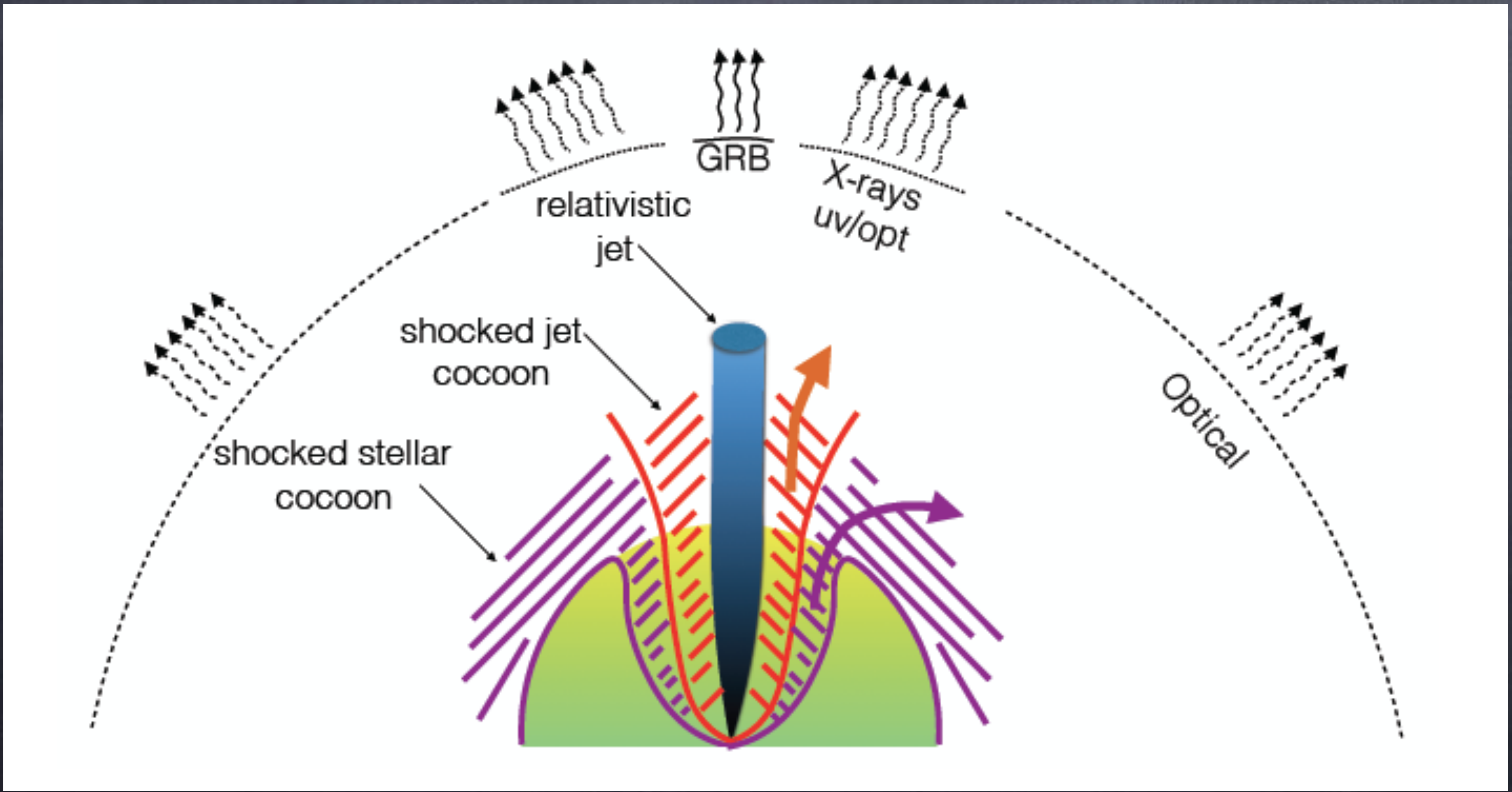


From Mizuta

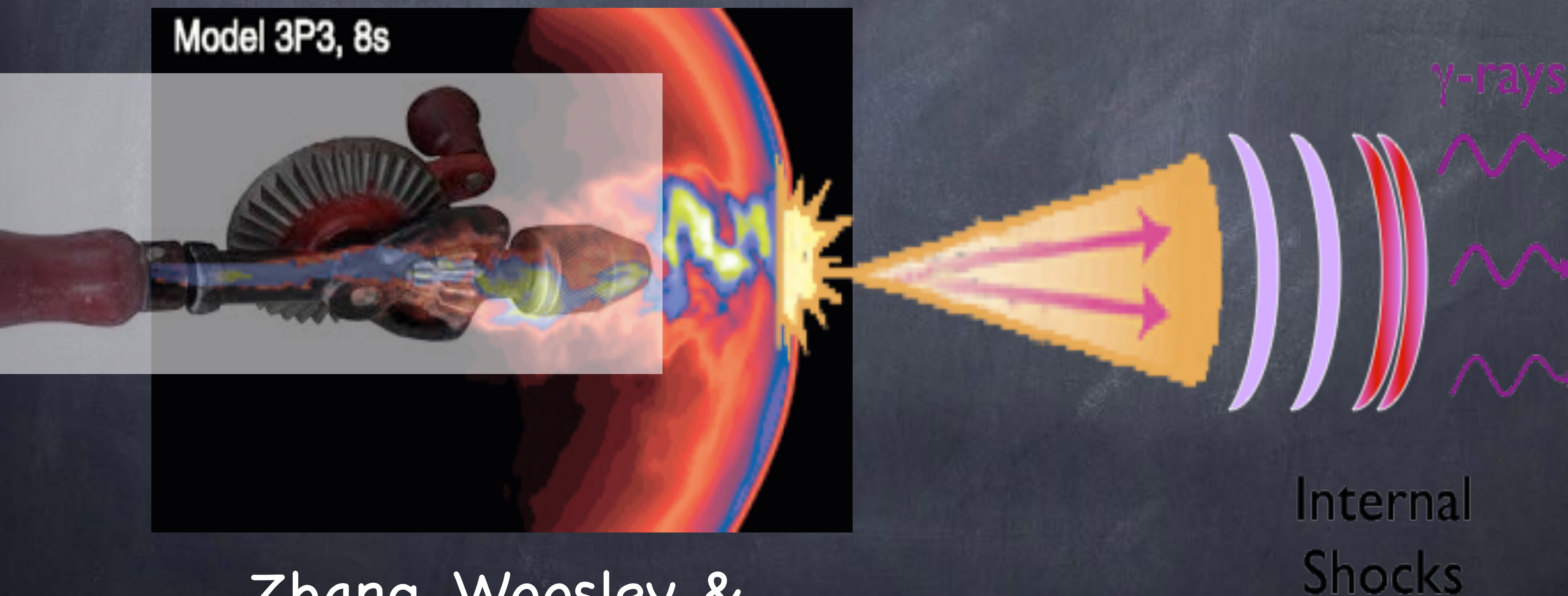
Nakar & TP

ApJ 16 in press

The idea in a single picture



The Jet drills a hole in the star



Zhang, Woosley &
MacFadyen 2004

Jet breakout

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

$$t_b \approx 8\ L_{51}^{-1/3} \theta_{10^o}^{4/3} R_{11}^{2/3} M_{10}^{1/3} \quad \mathrm{s}.$$

The engine must be active until the jet's head breaks out!*

A prediction of the Collapsar model

Observed duration

$$T_{90} = T_e - T_B$$

Engine time

Break out time

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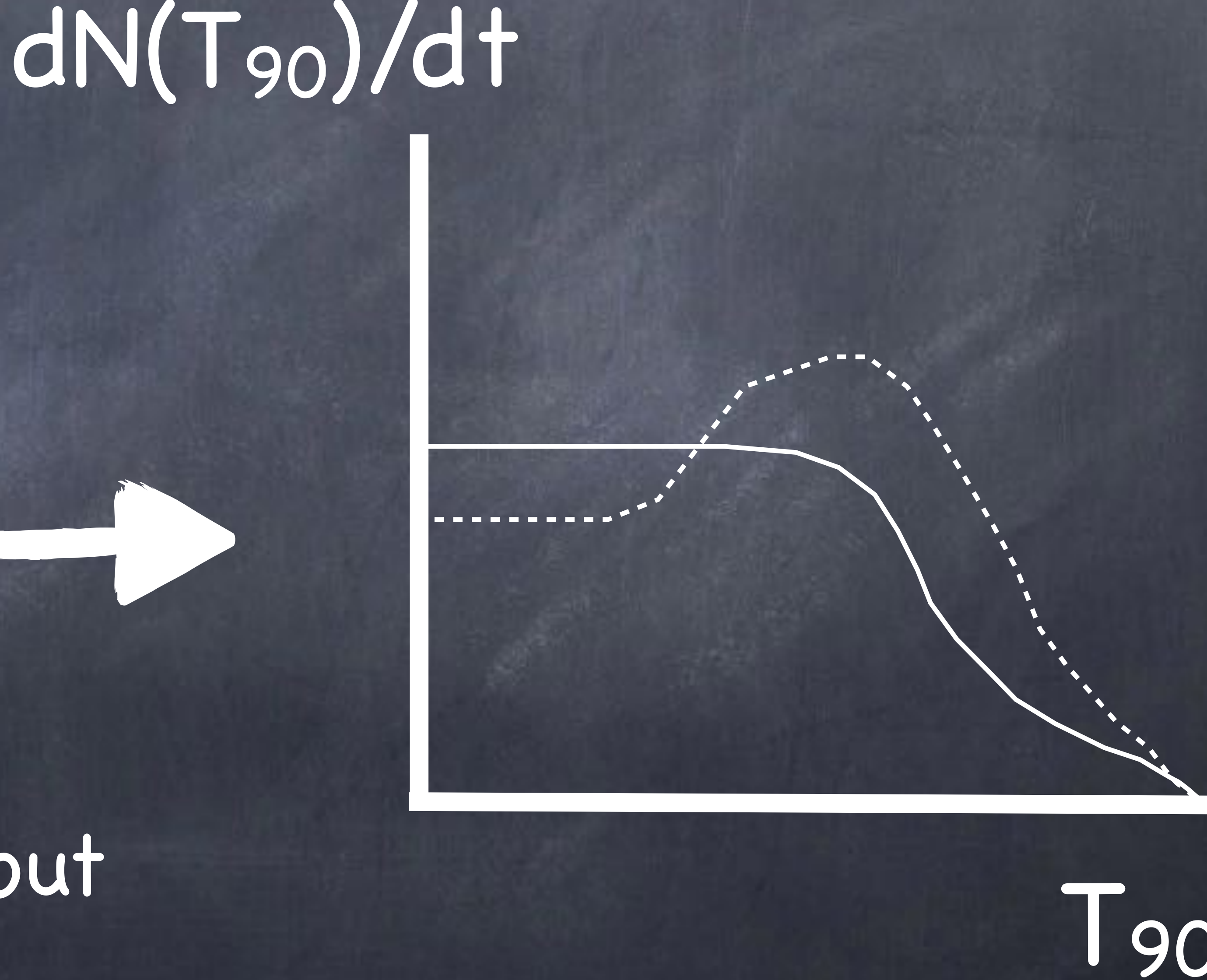

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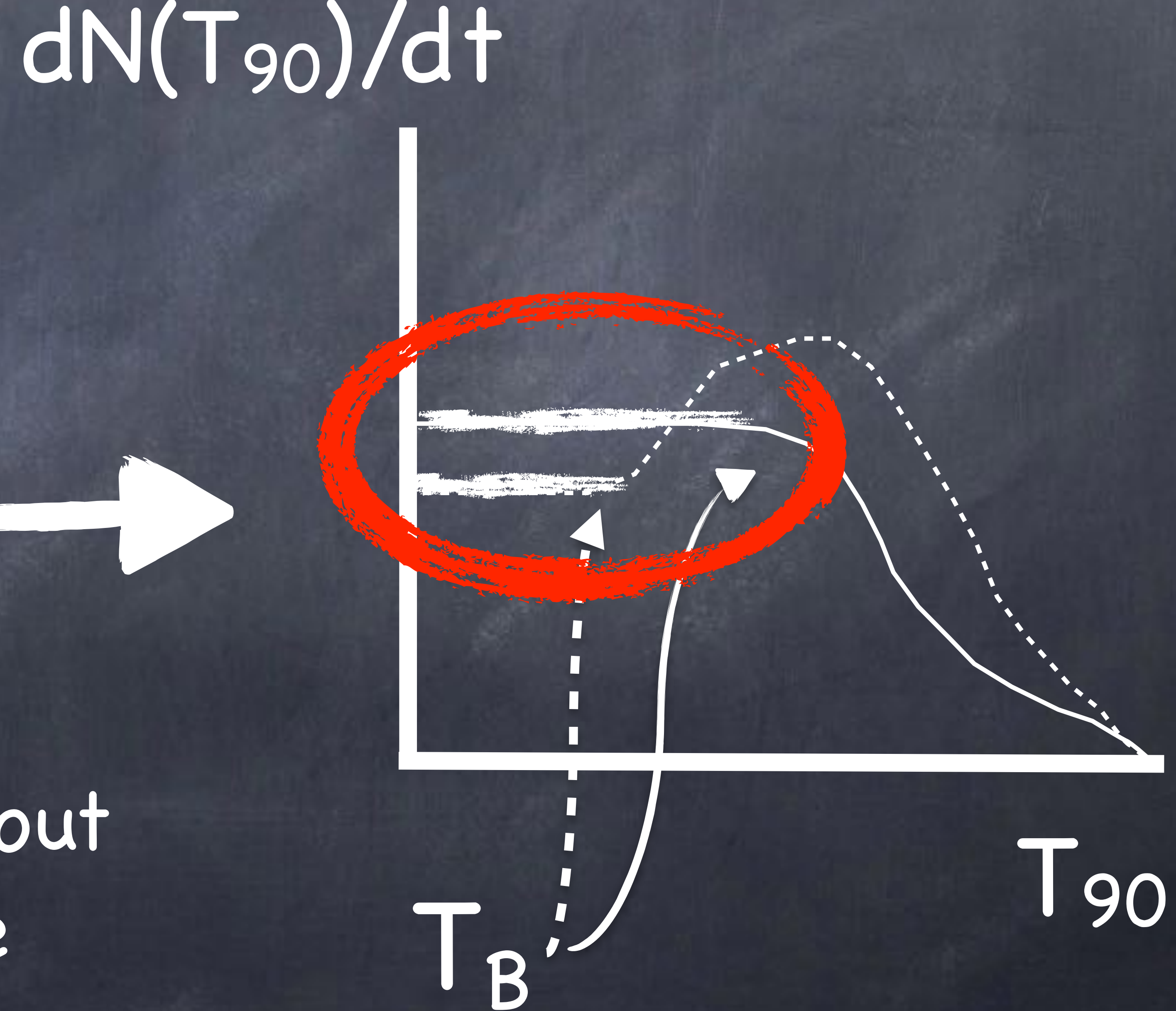
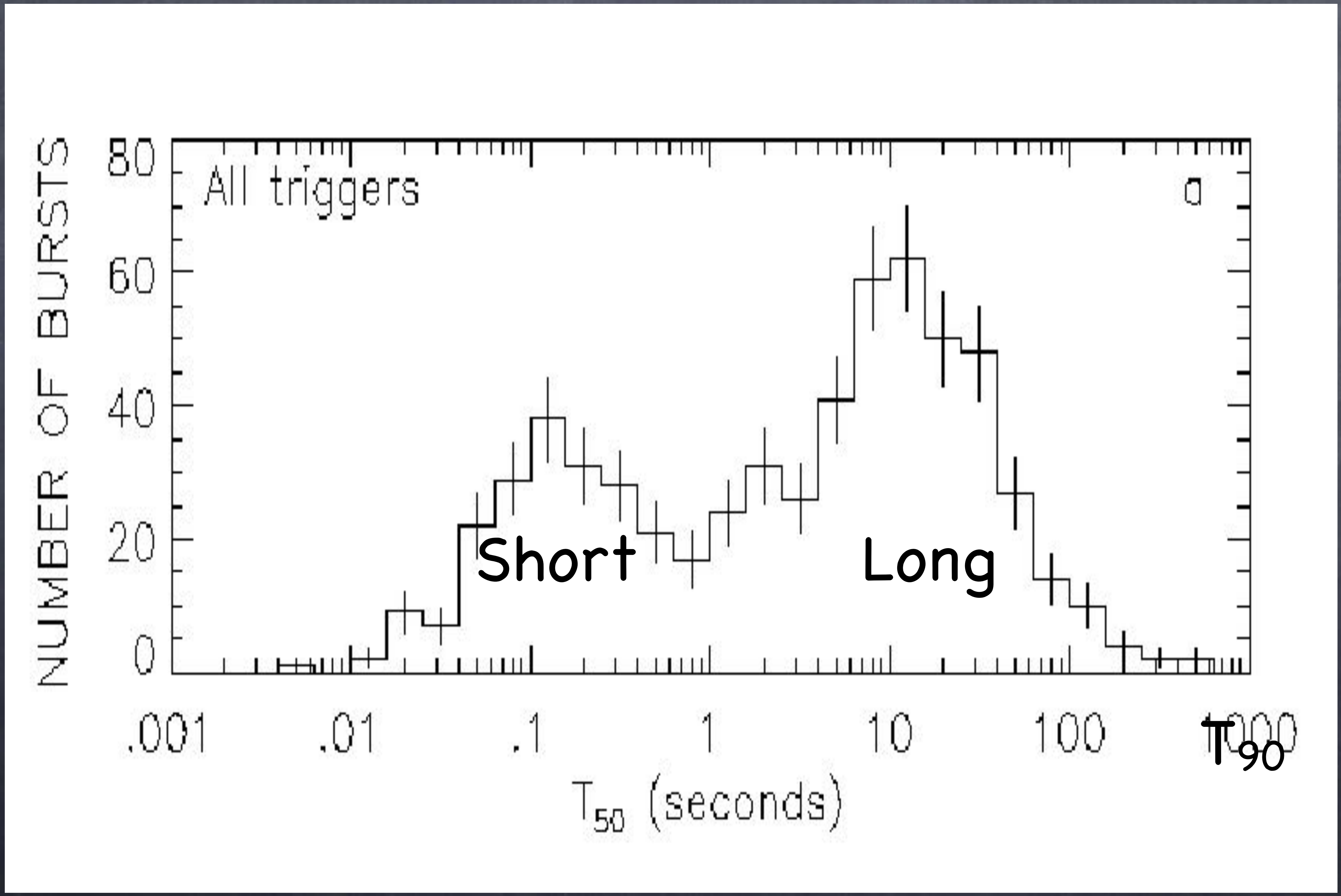
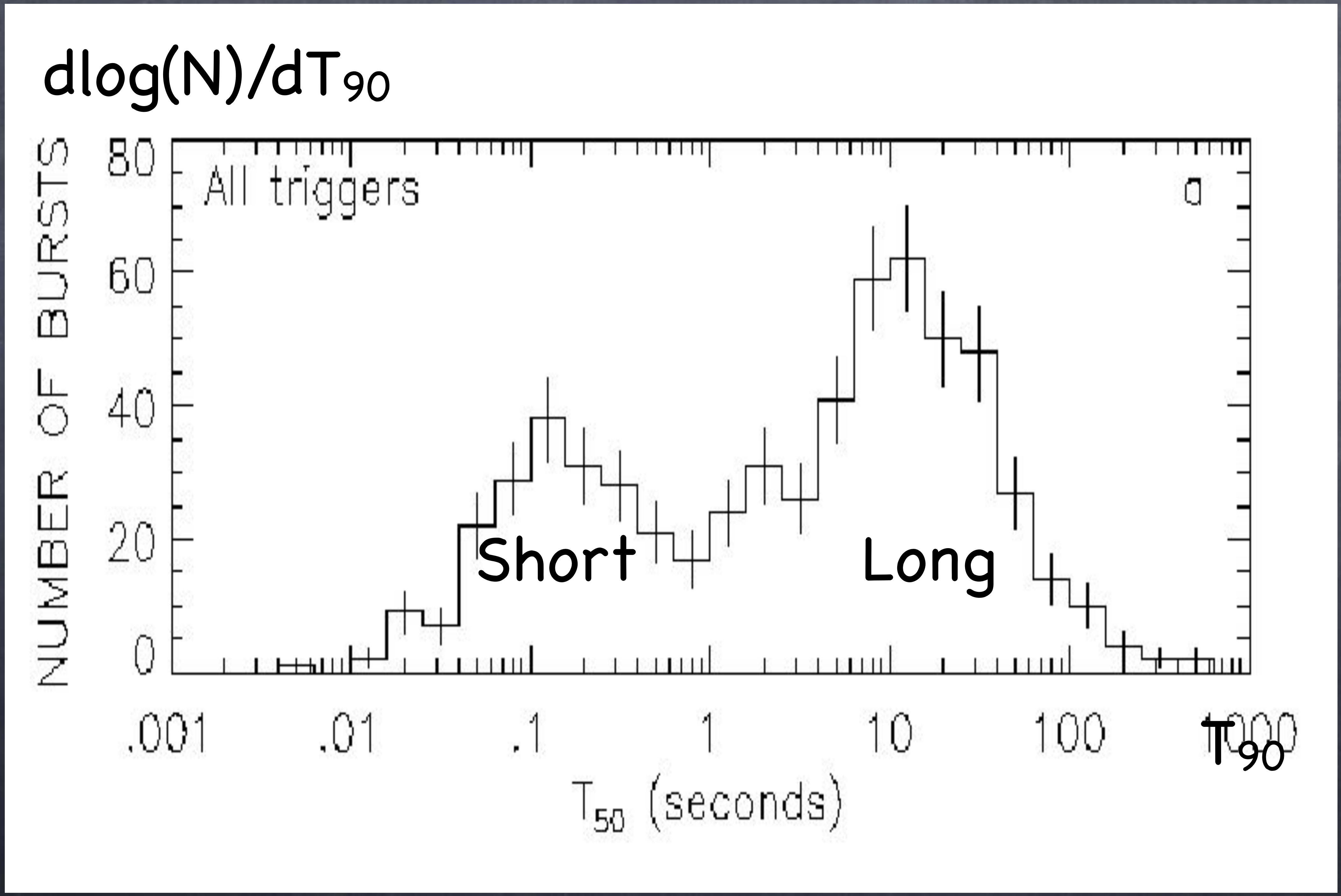


?


All triggers
a
NUMBER OF BURSTS
80
60
40
20
0
.001
.01
.1
1
10
100
1000
T
90
T_{50} (seconds)
Short
Long

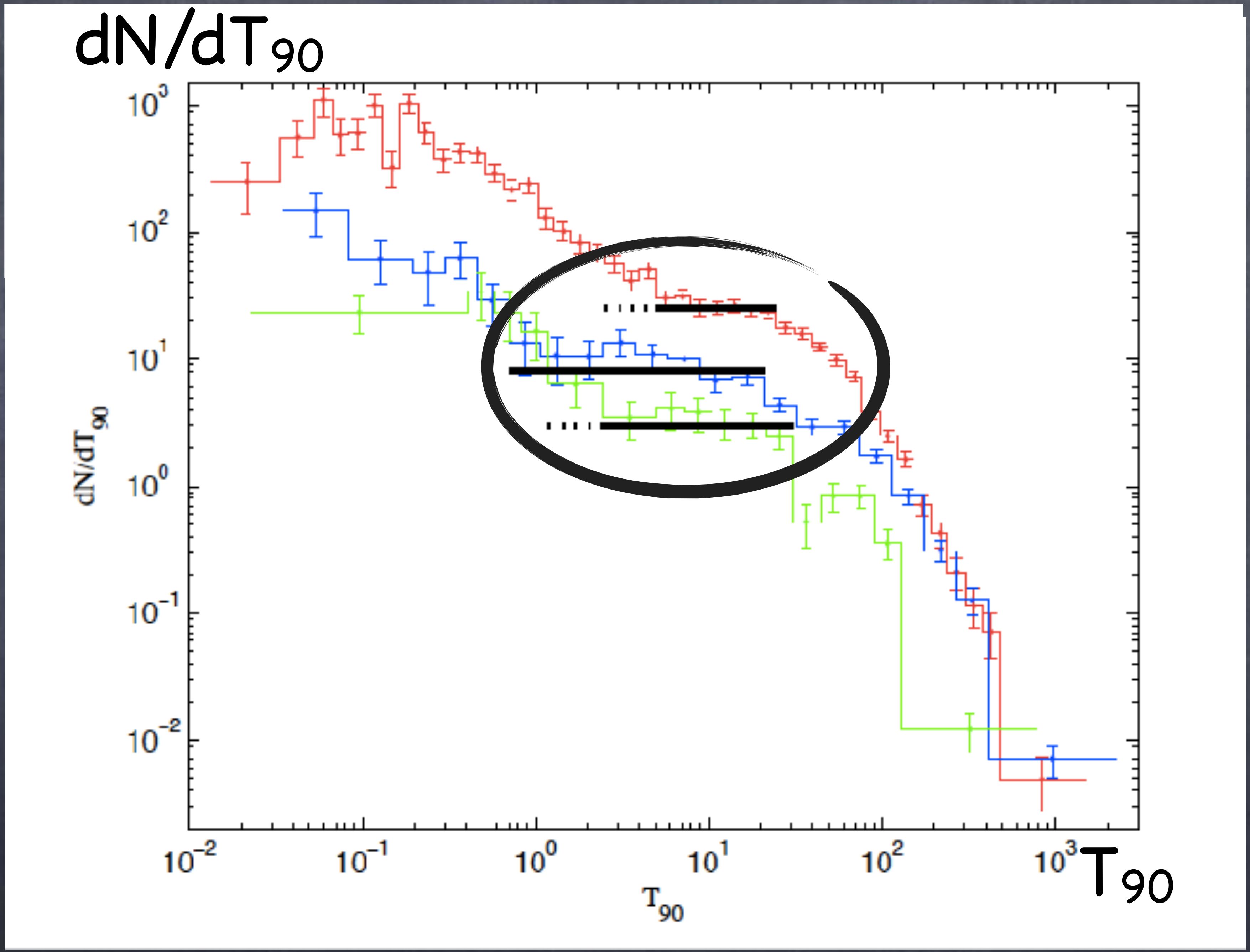
?



dlog(N)/dT90
NUMBER OF BURSTS
80
60
40
20
0
All triggers
a
Short
Long
.001
.01
.1
1
10
100
1000
T90
T50 (seconds)

A second look

(Bromberg Nakar, TP & Sari, 2011)



A second look

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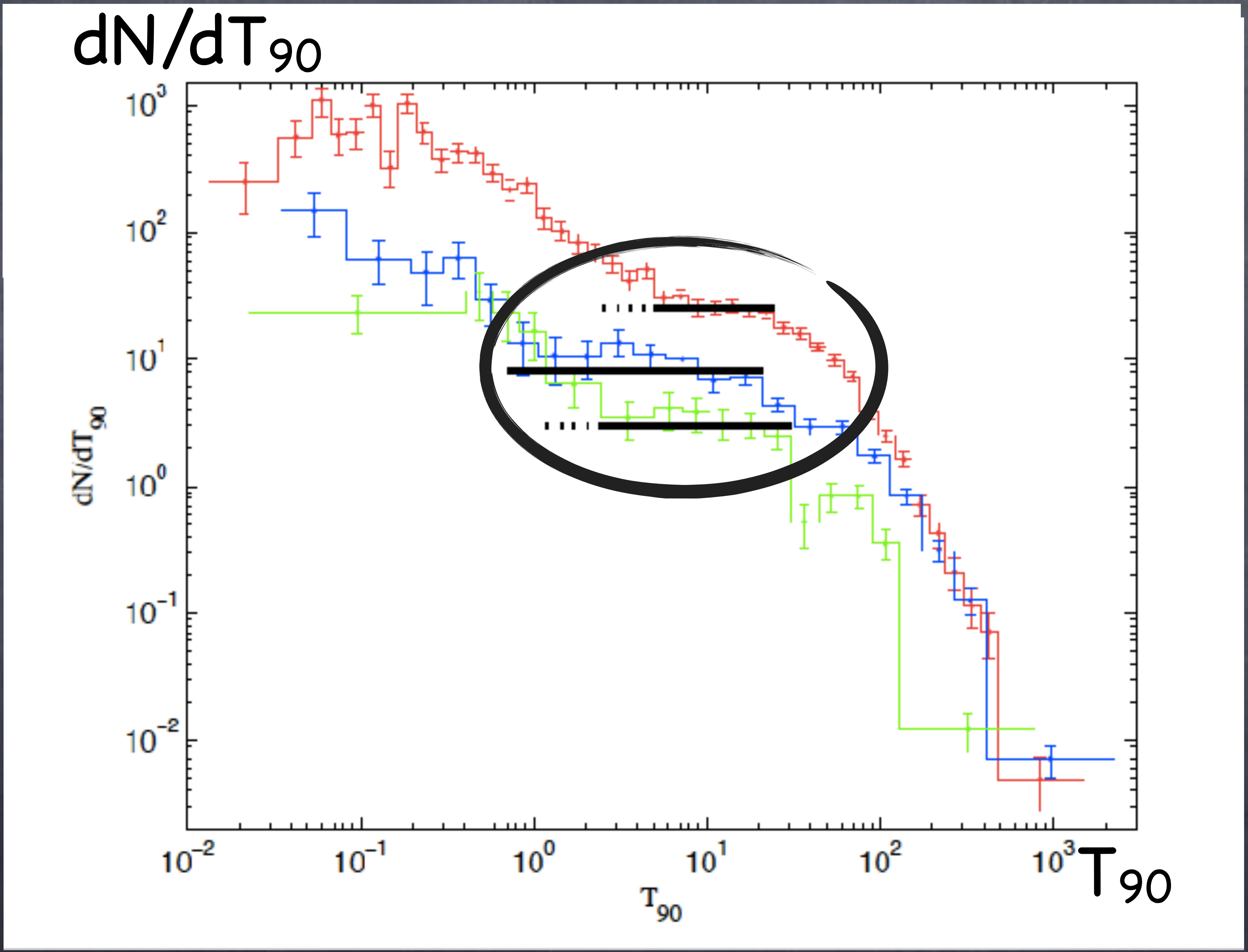
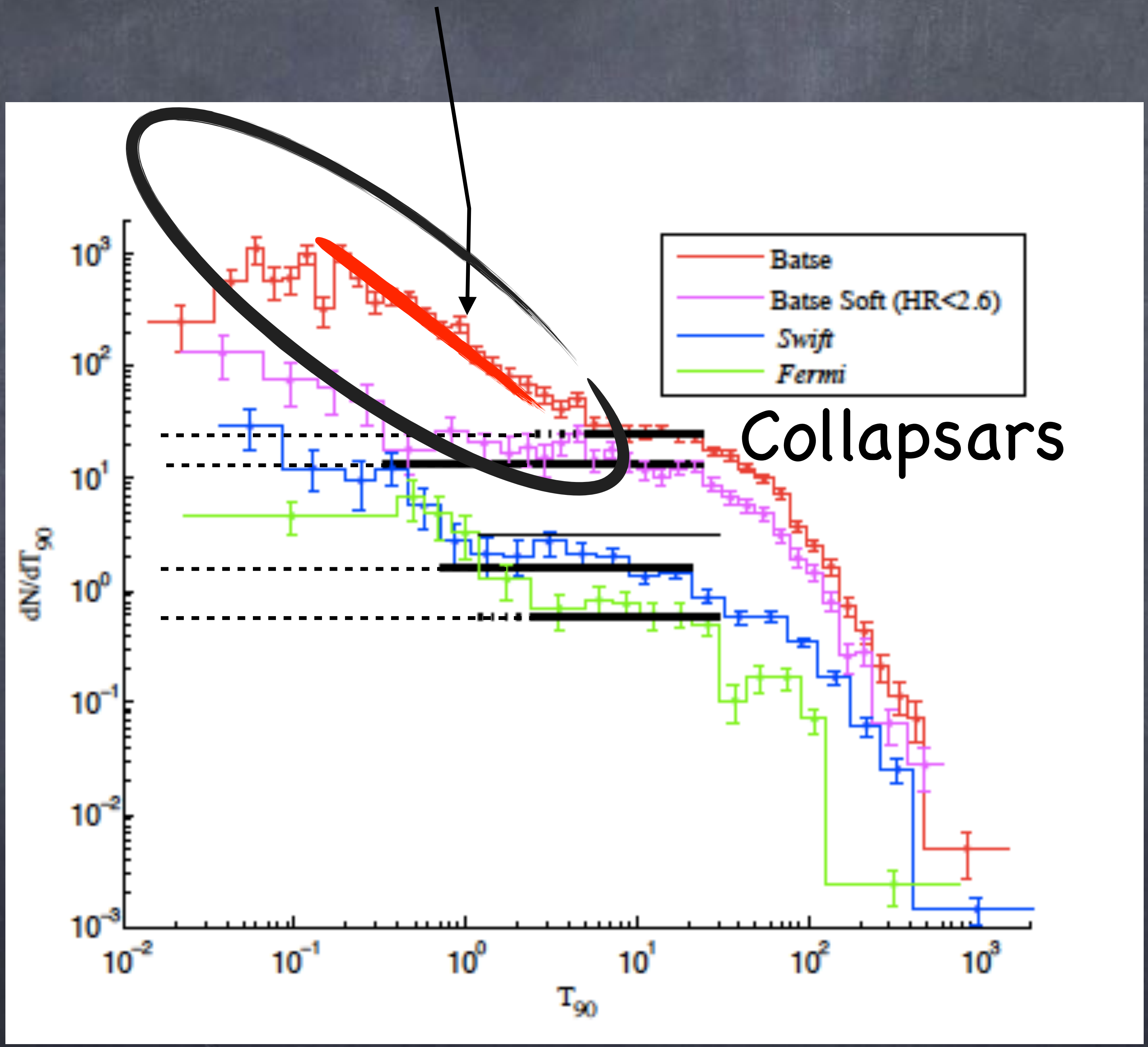


A direct observational proof of the Collapsar model.

Short (Non-Collapsars)



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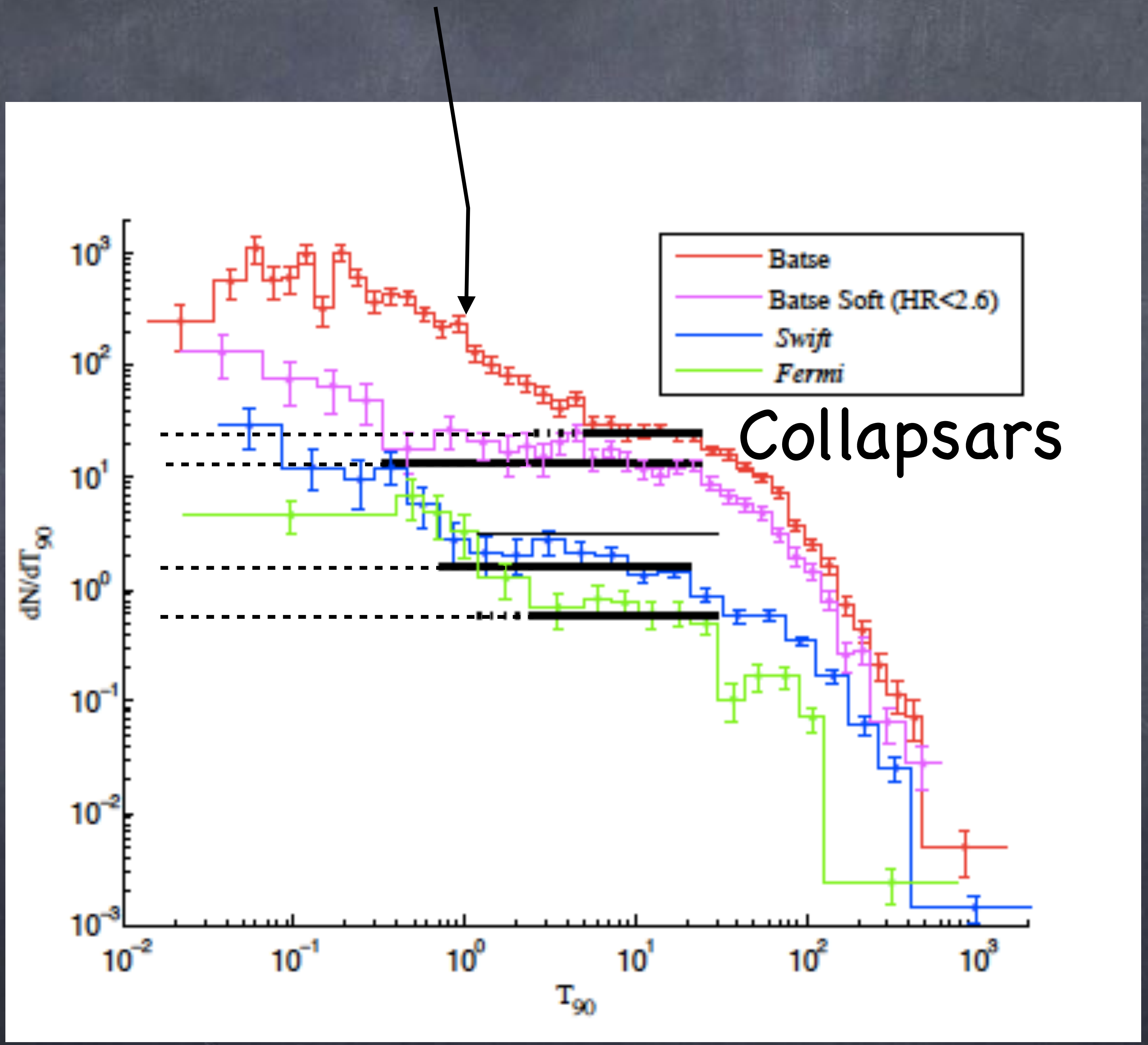
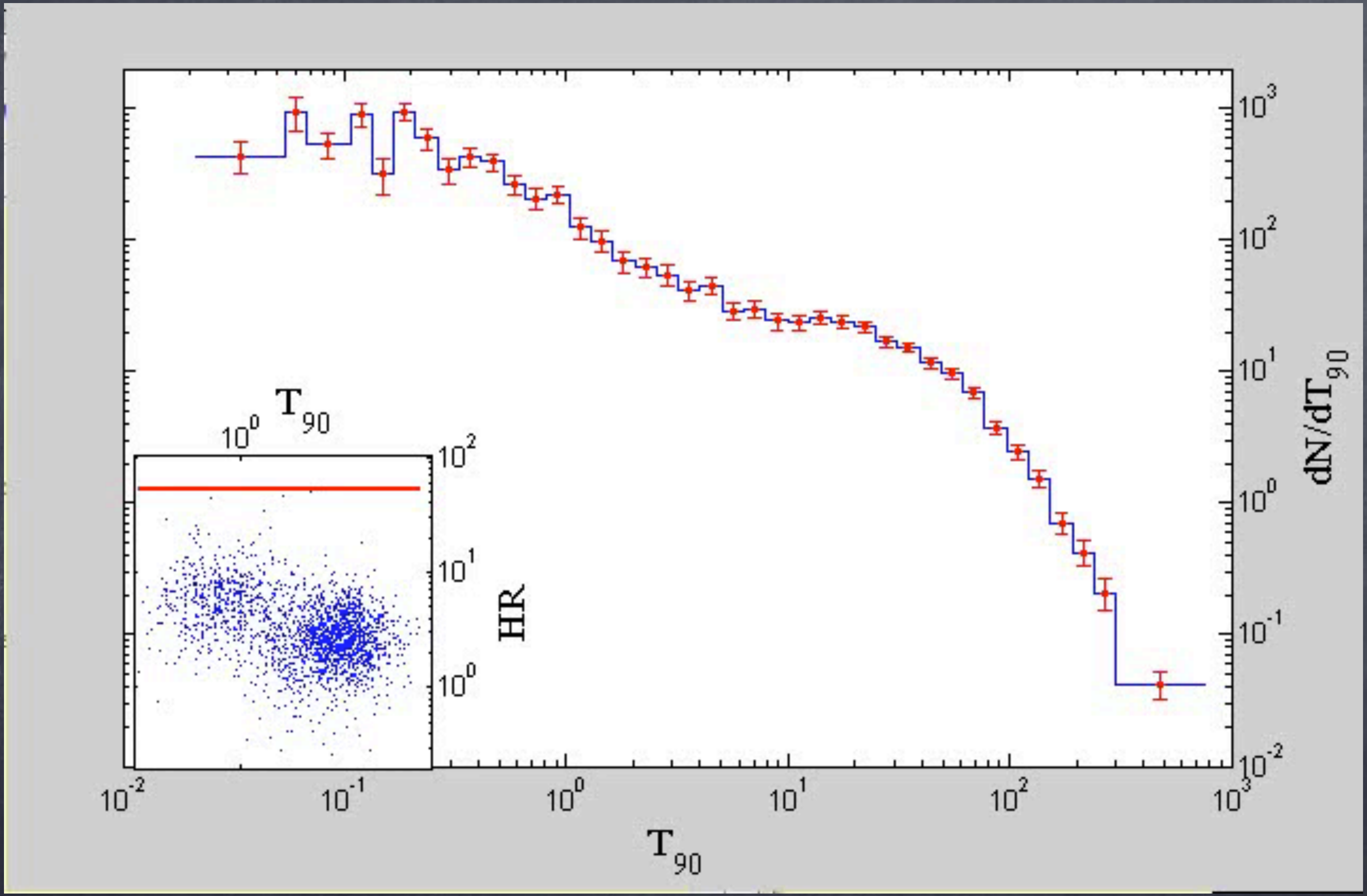
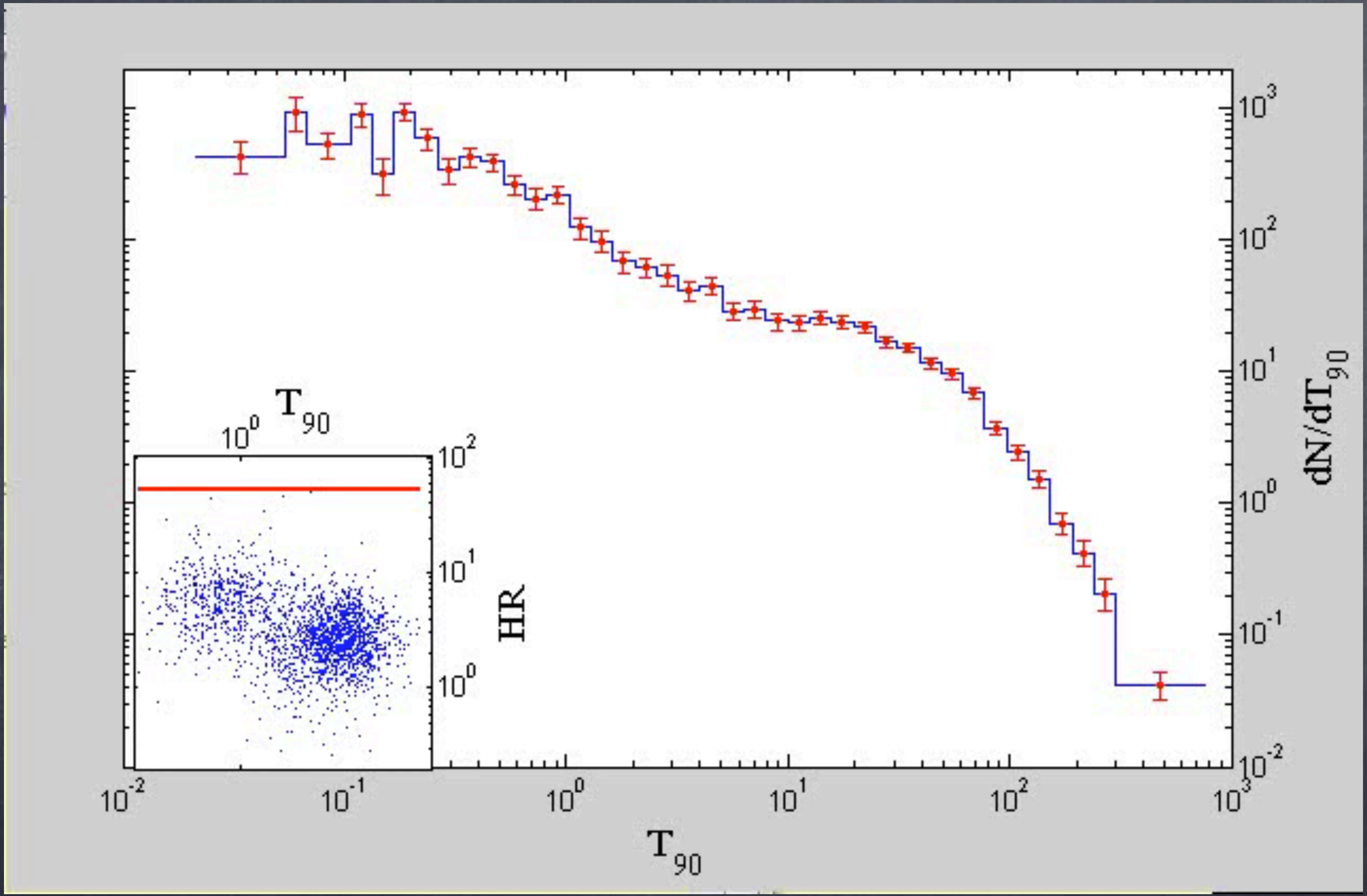


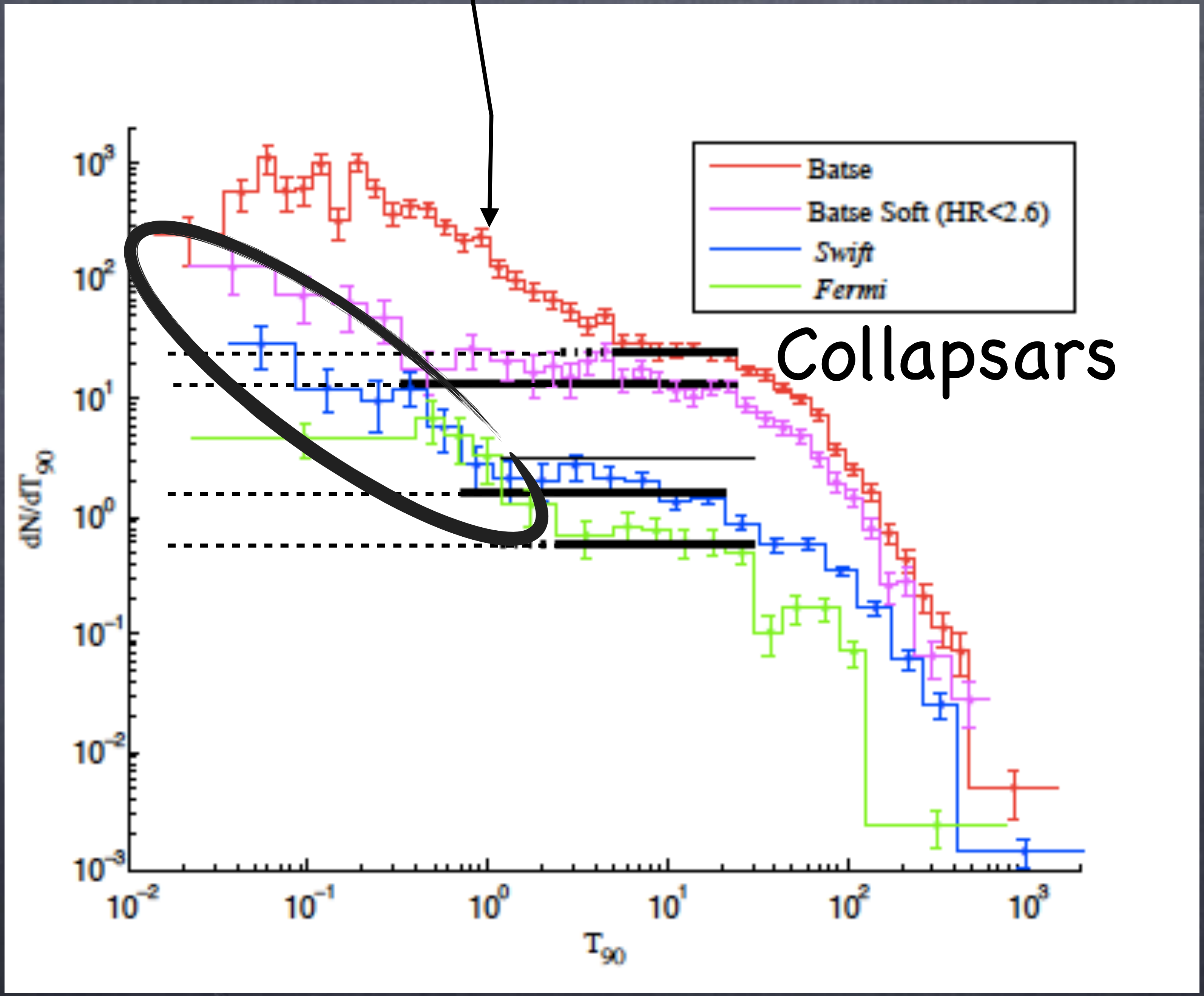


T_{90}
10^0
10^2
10^1
10^0
HR
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
dN/dT_{90}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
T_{90}

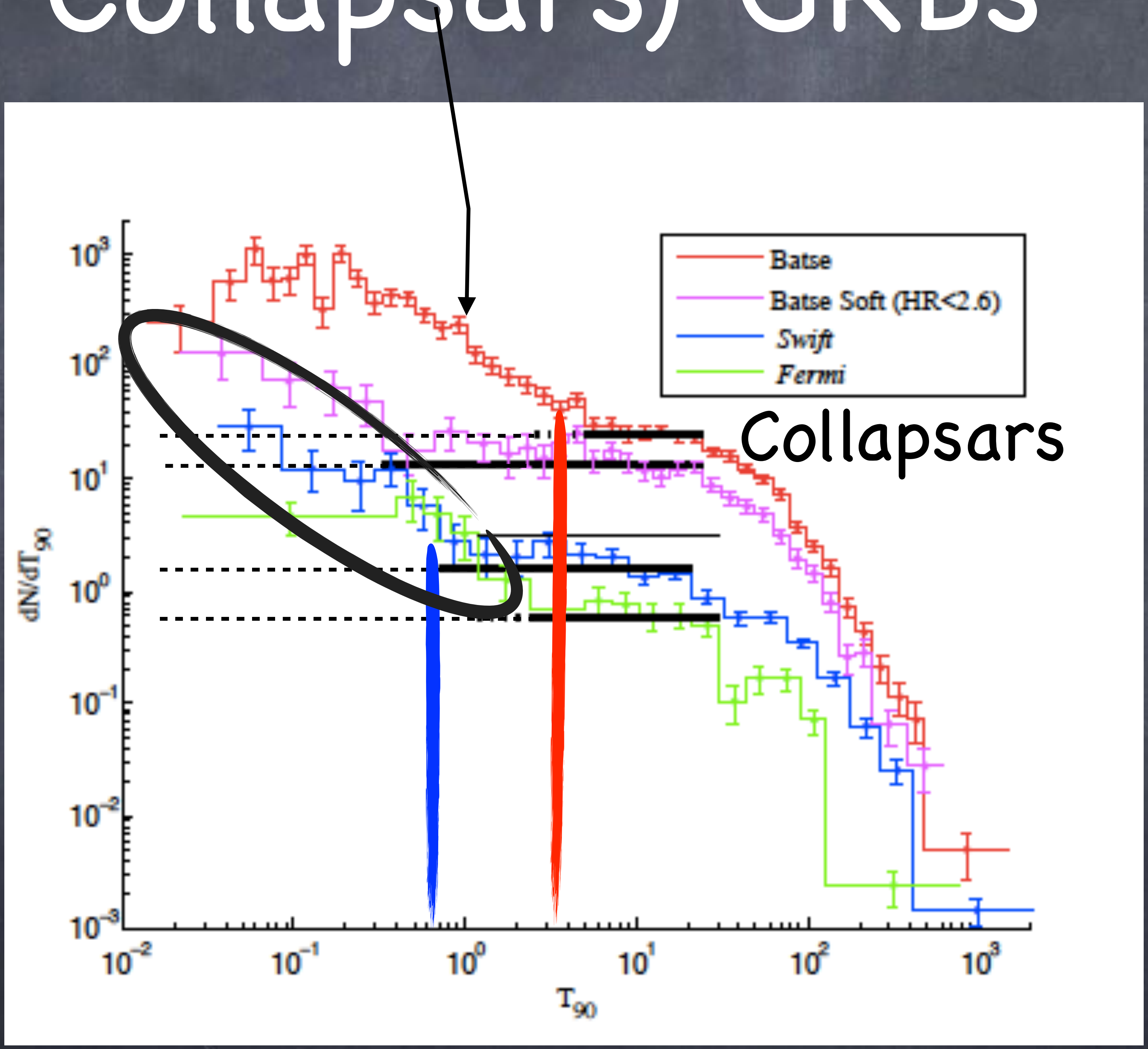


10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
T_{90}
dN/dT_{90}
10^{0}
T_{90}
HR

Swift Short (Non-Collapsars) GRBs



Swift Short (Non-Collapsars) GRBs



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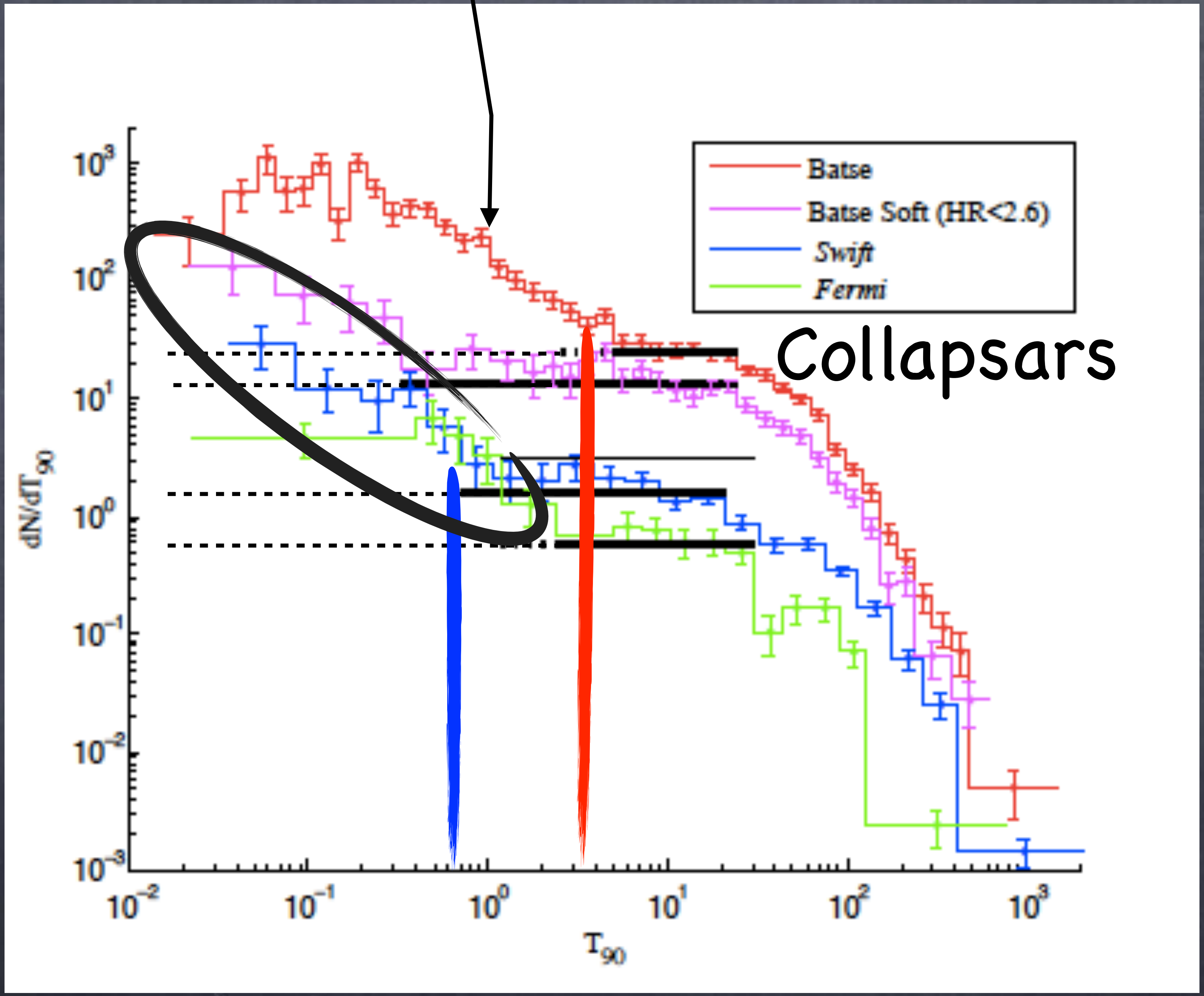
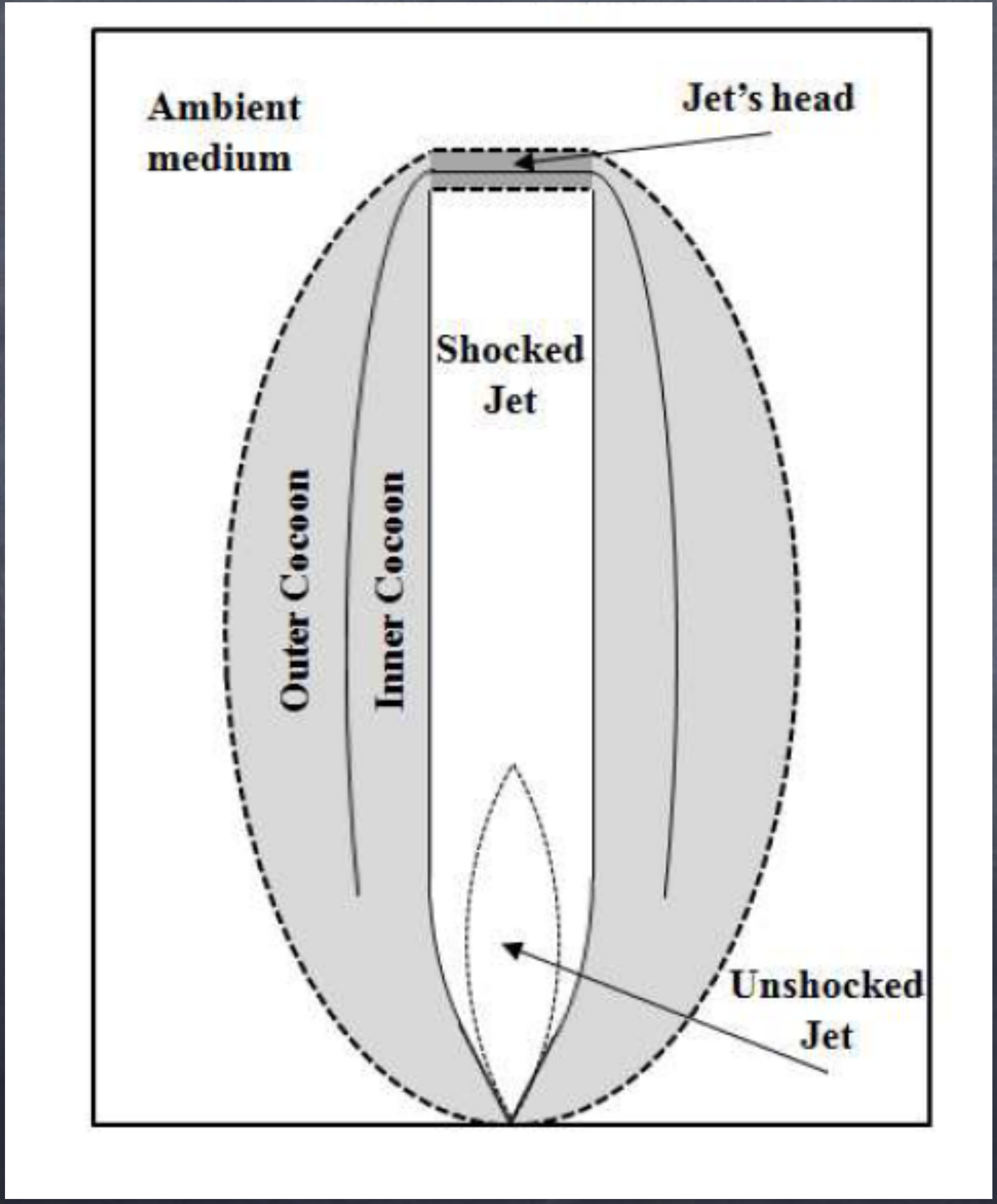


Short Swift GRBs with T_{90}>0.7sec are not “short”!

$$E_{GRB} \approx E_{ejecta} \approx E_c$$

Macronova
+ Radio flare

Cocoon's structure



3D simulation

4Msun, $R^{*}=4\times10^{10}$cm. $L_j=10^{51}$erg/s, $\theta=8^{o}$ Using Pluto with high resolution $\Delta R=10^{7}$cm. Credit: Ore Gottlieb

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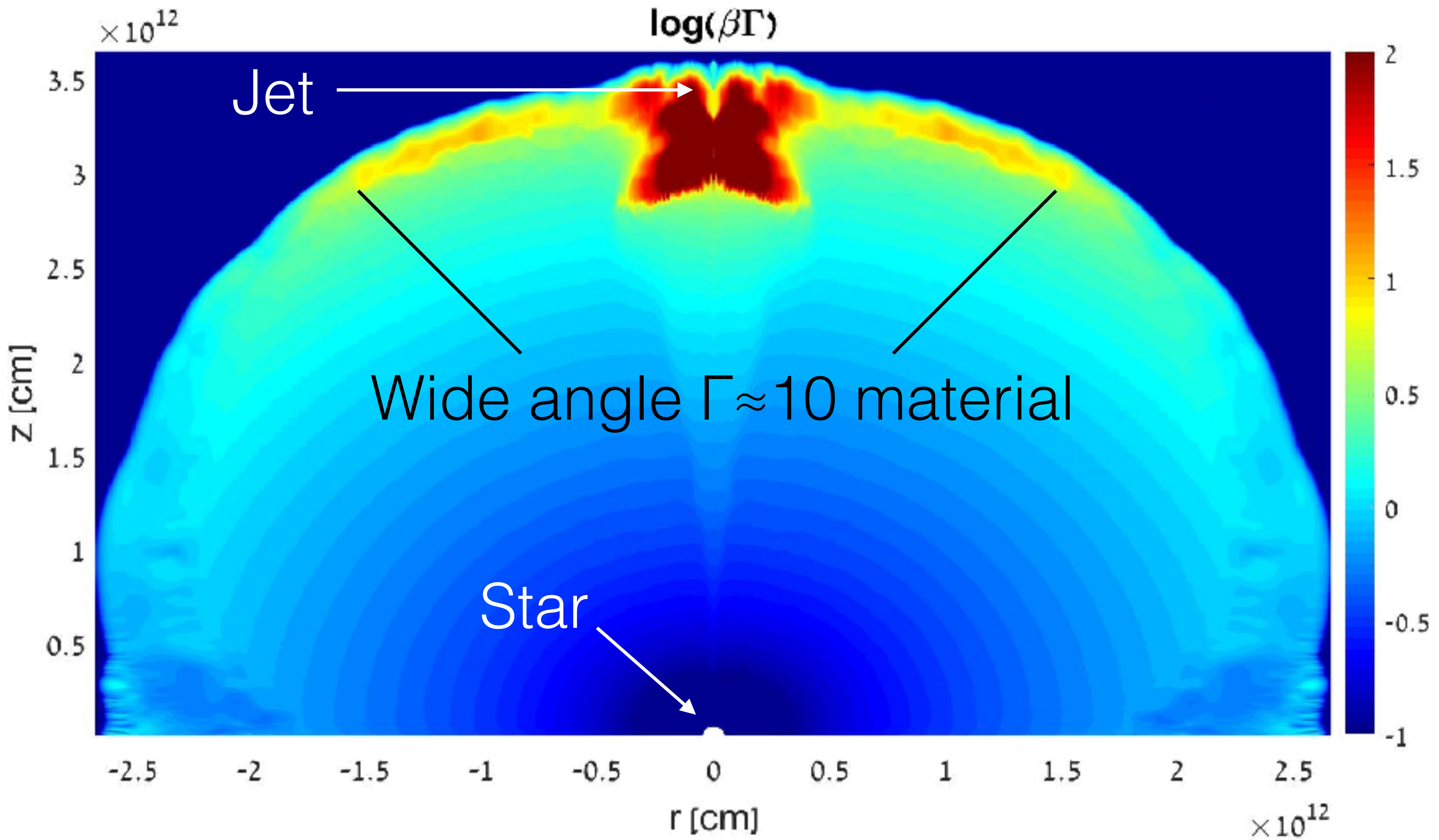
2D simulation 110sec after breakout



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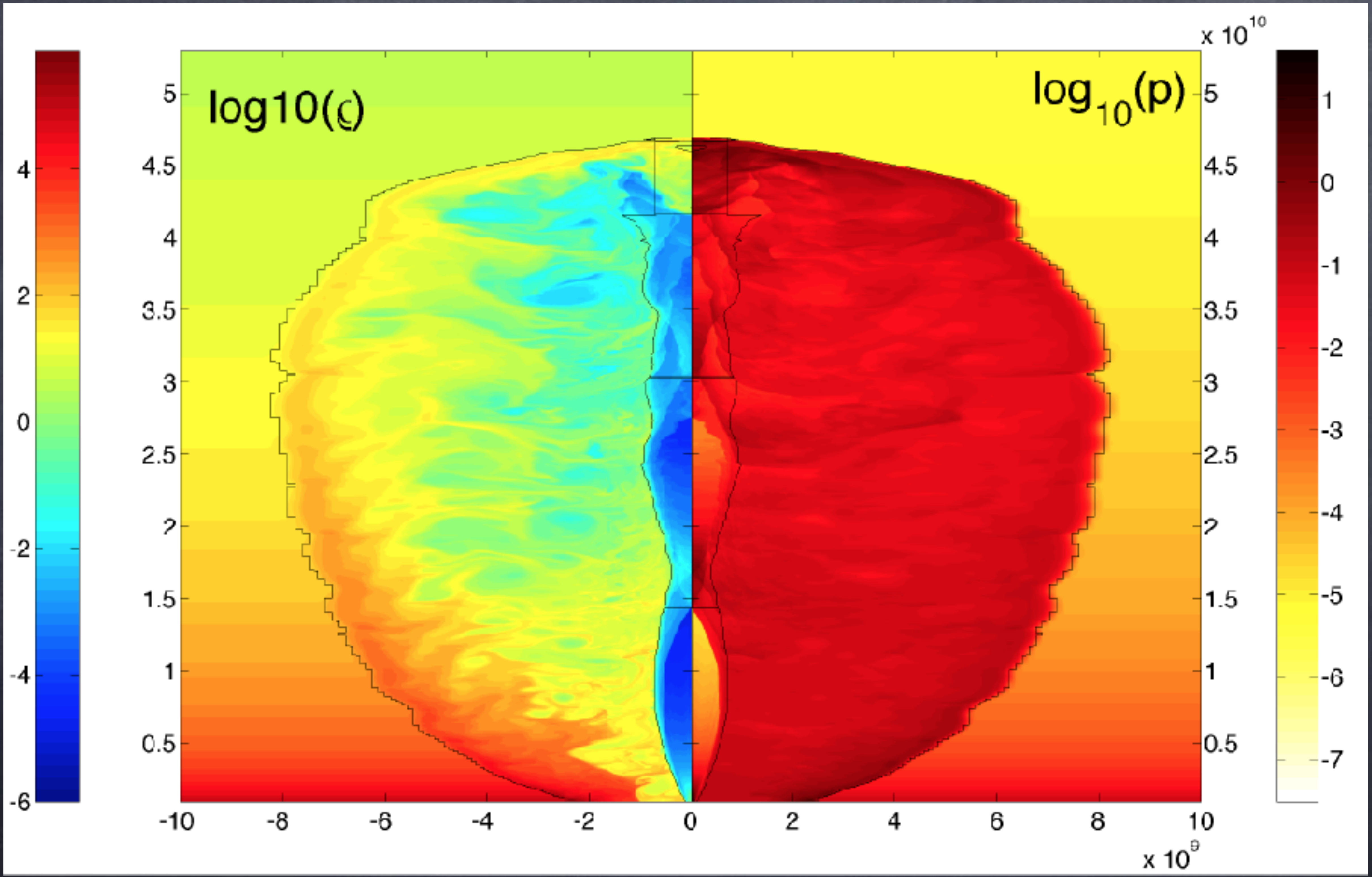
The cocoons



Harrison, Goetlieb and Nakar in prep, 2016

Emission component

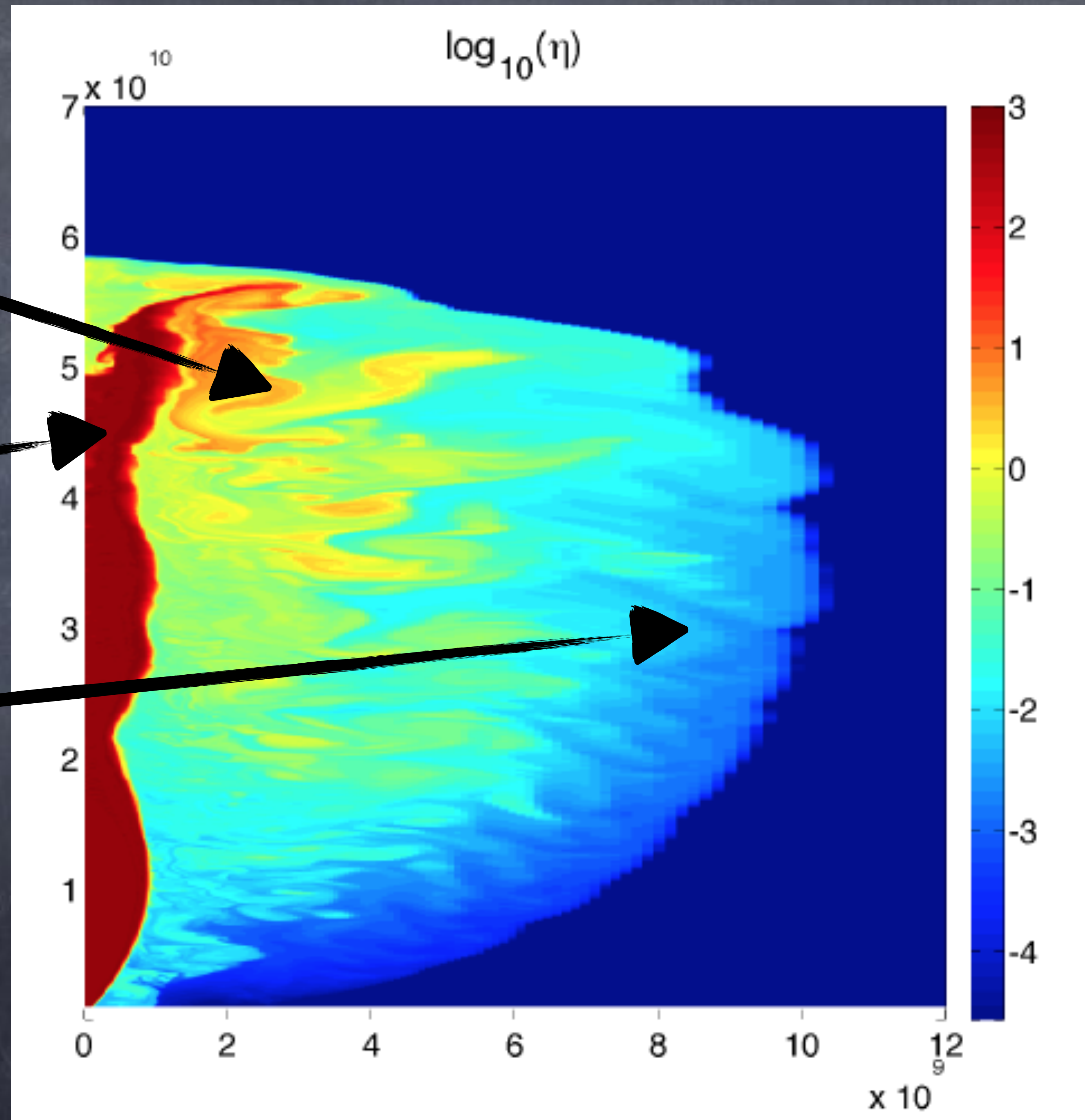
- Newtonian Cocoon - cooling (photospheric) emission
- Newtonian cocoon - macronova
- Relativistic Jet cocoon - cooling (photospheric) emission
- Relativistic Jet cocoon - afterglow

The cocoons

Light "relativistic" Jet cocoon

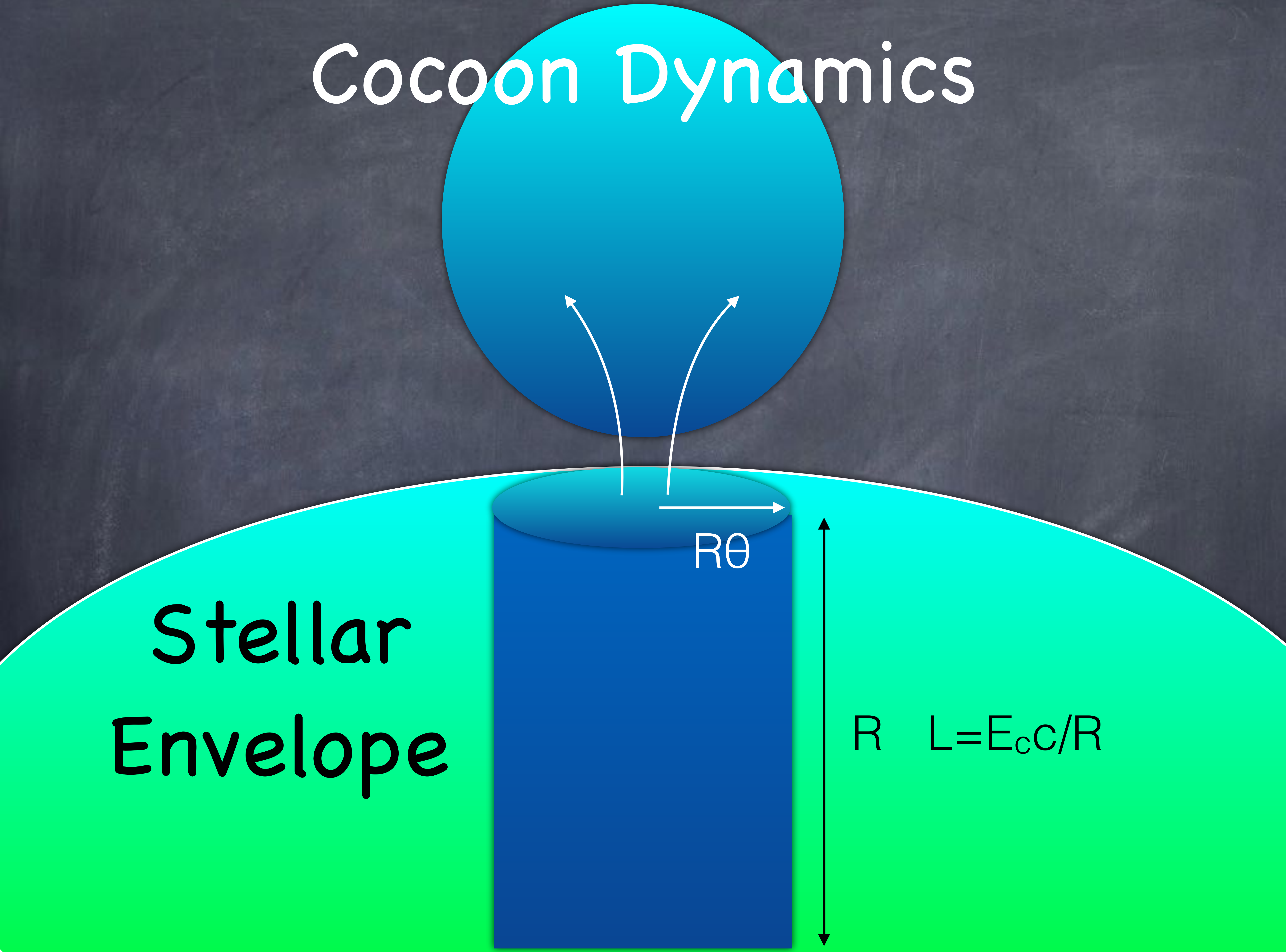
Jet

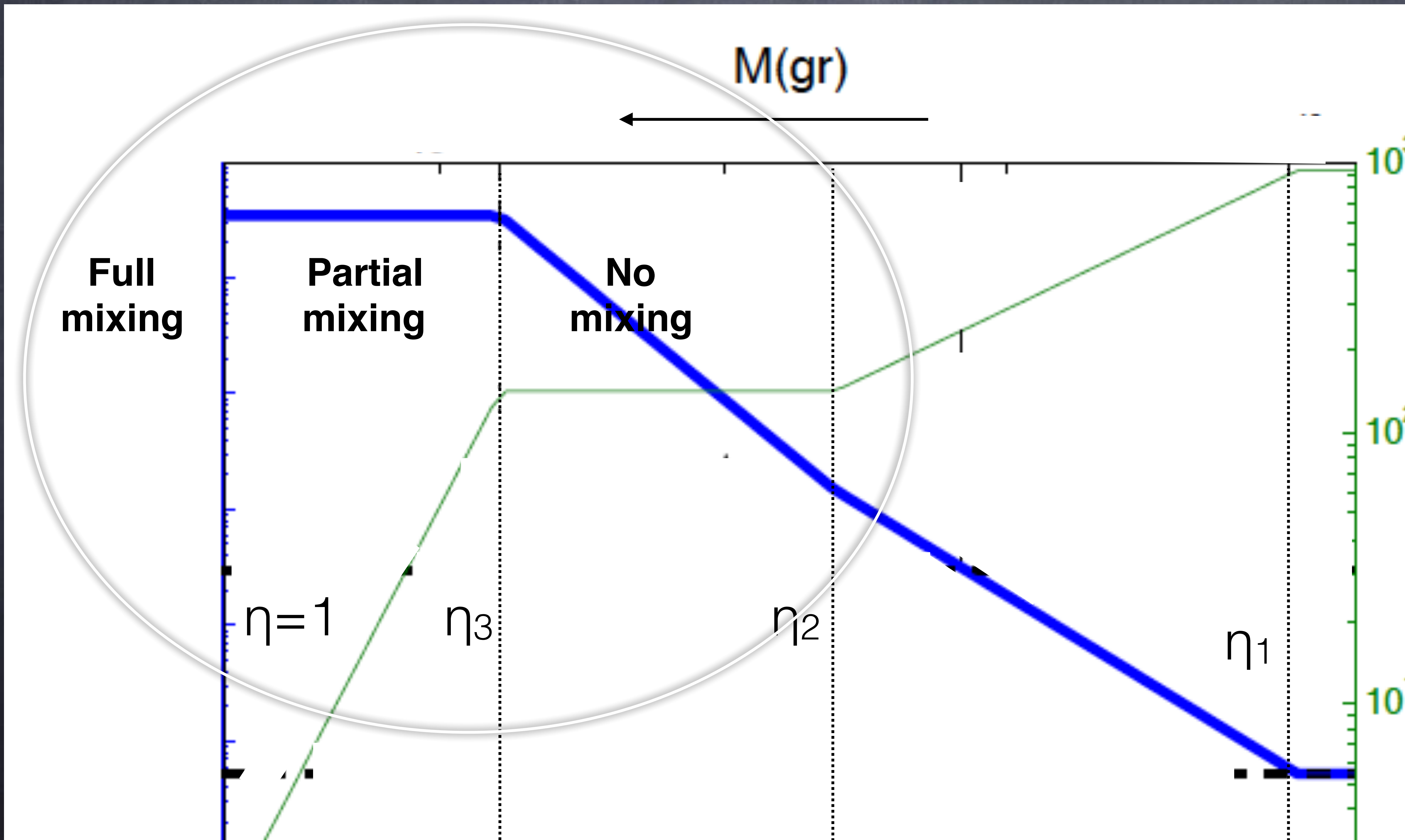
Heavy "Newtonian" stellar cocoon



Harrison, Goetlieb & Nakar in prep, 2016

Cocoon Dynamics

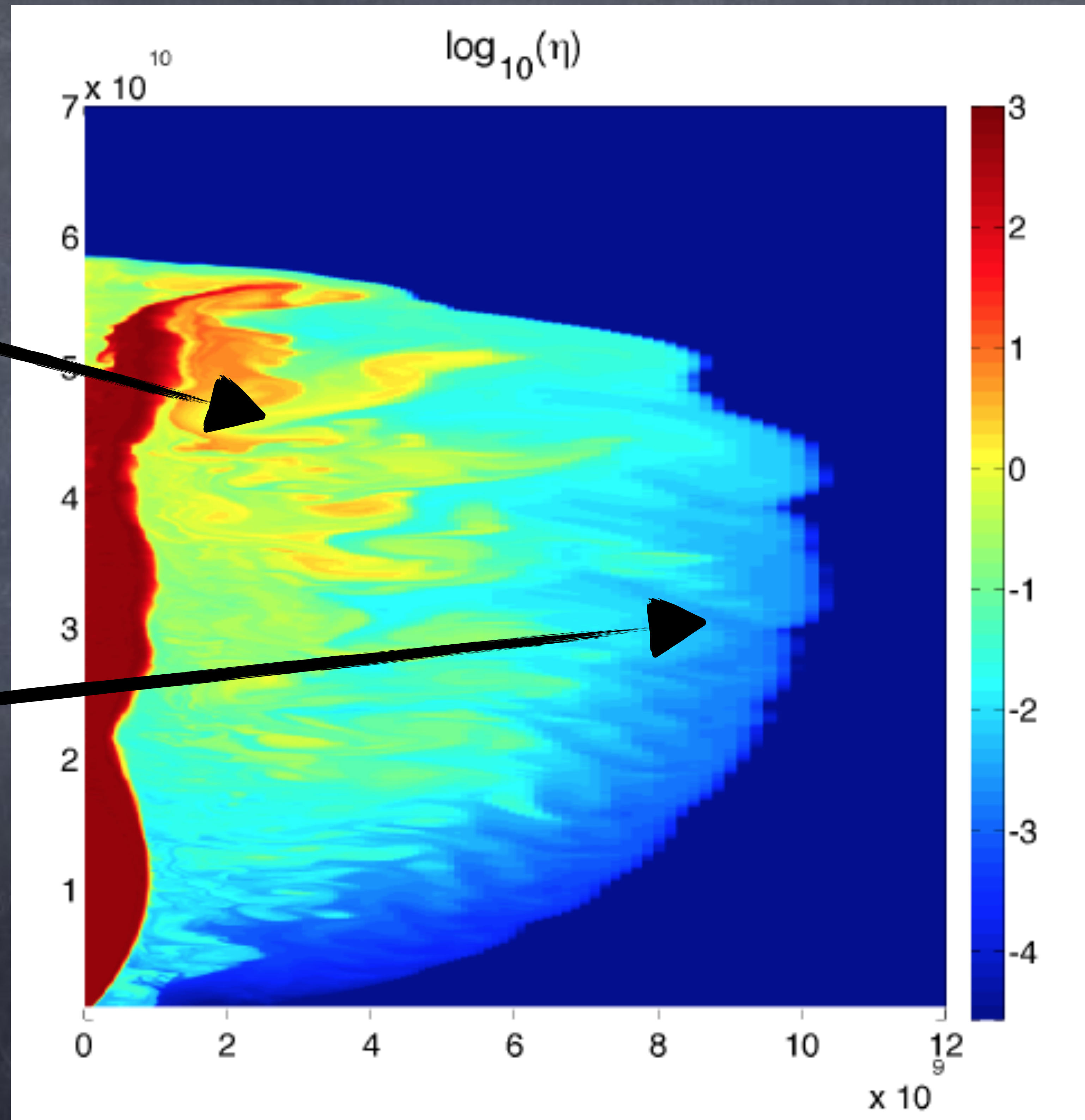




M(gr)
Full mixing
Partial mixing
No mixing
η=1
η3
η2
η1

Partial Mixing

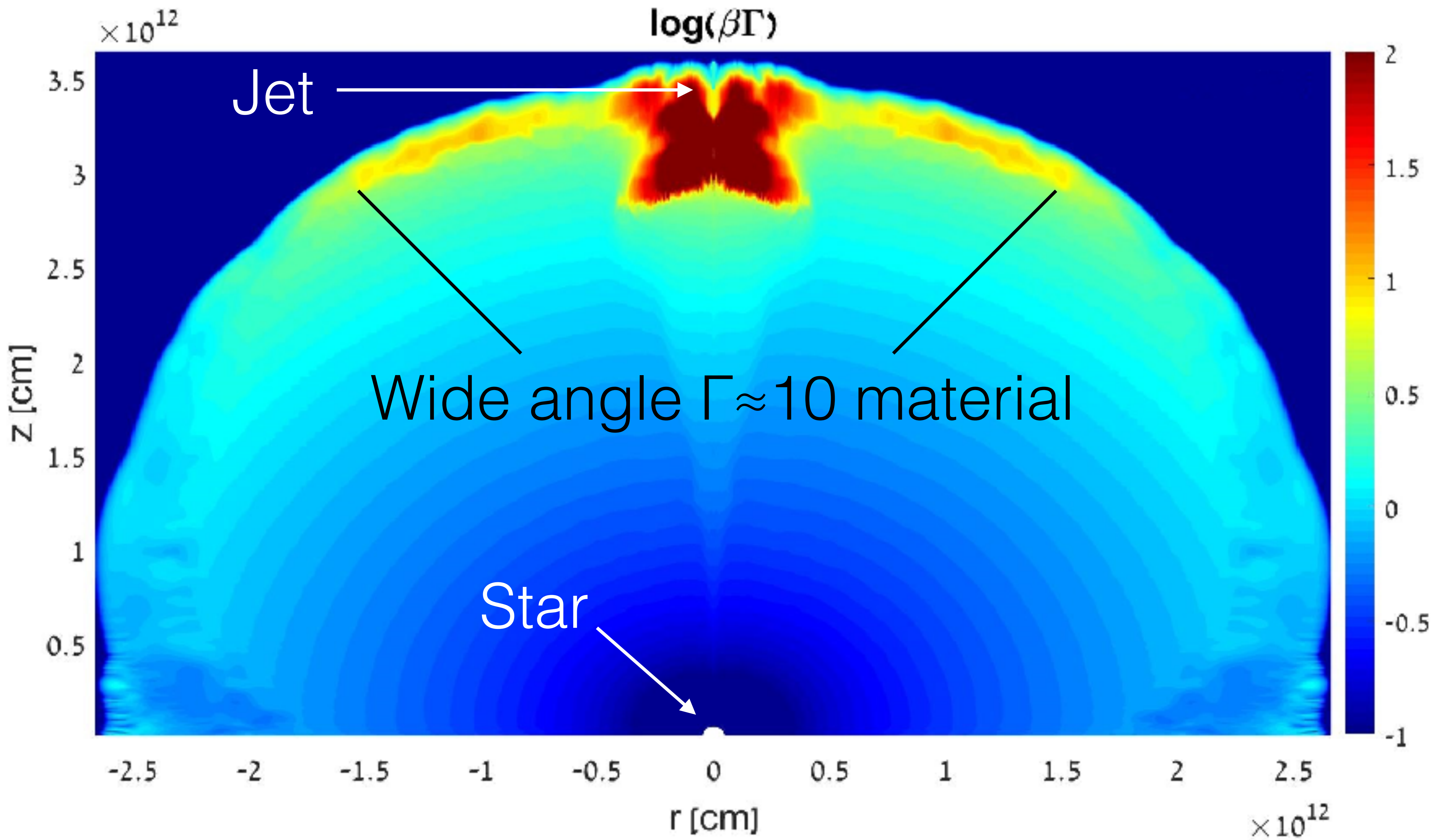
Light
“relativistic”
Jet cocoon



Heavy
“Newtonian”
Stellar cocoon

Harrison, Goetlieb and Nakar in prep, 2016

2D simulation 110sec after breakout



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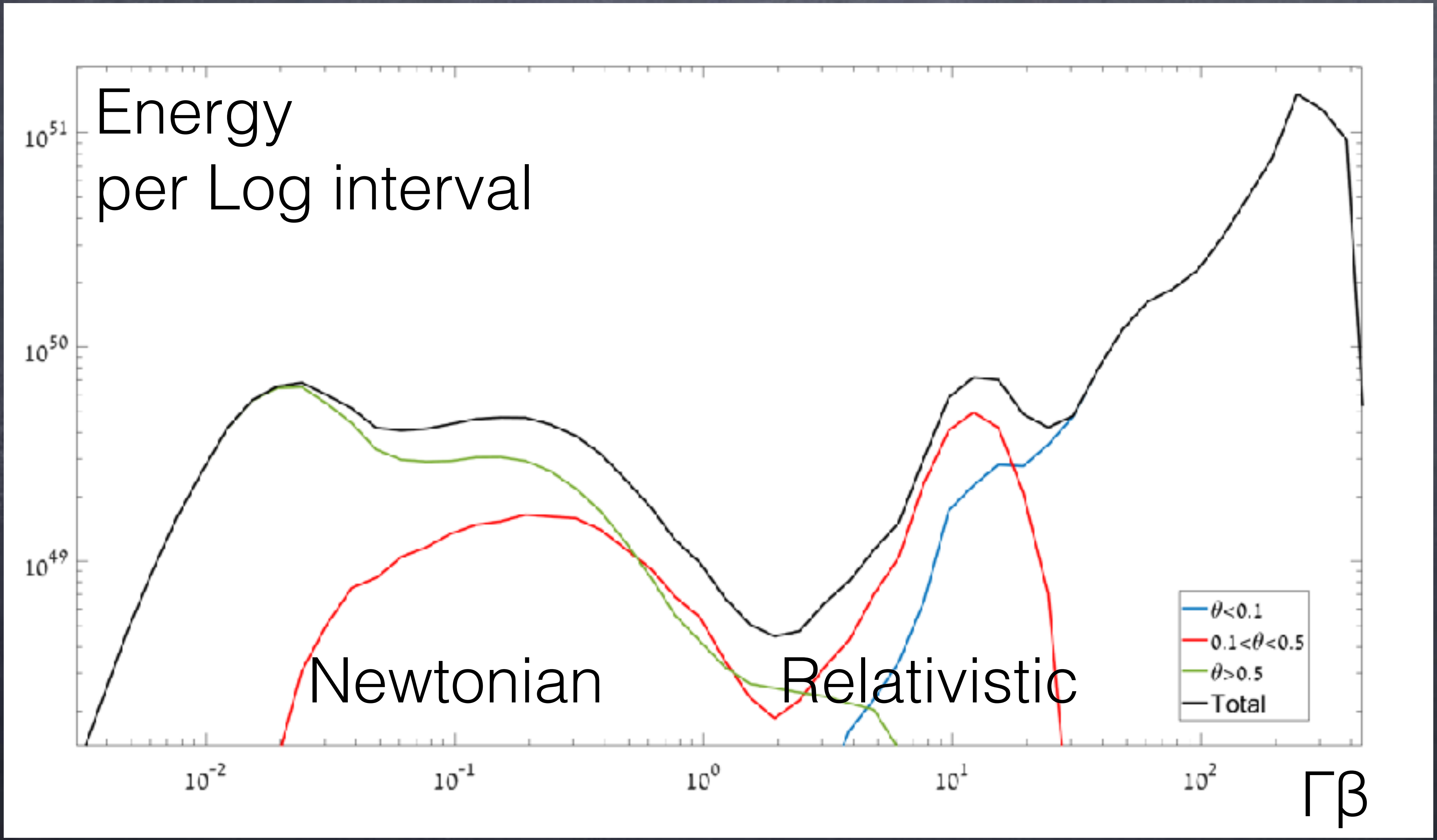
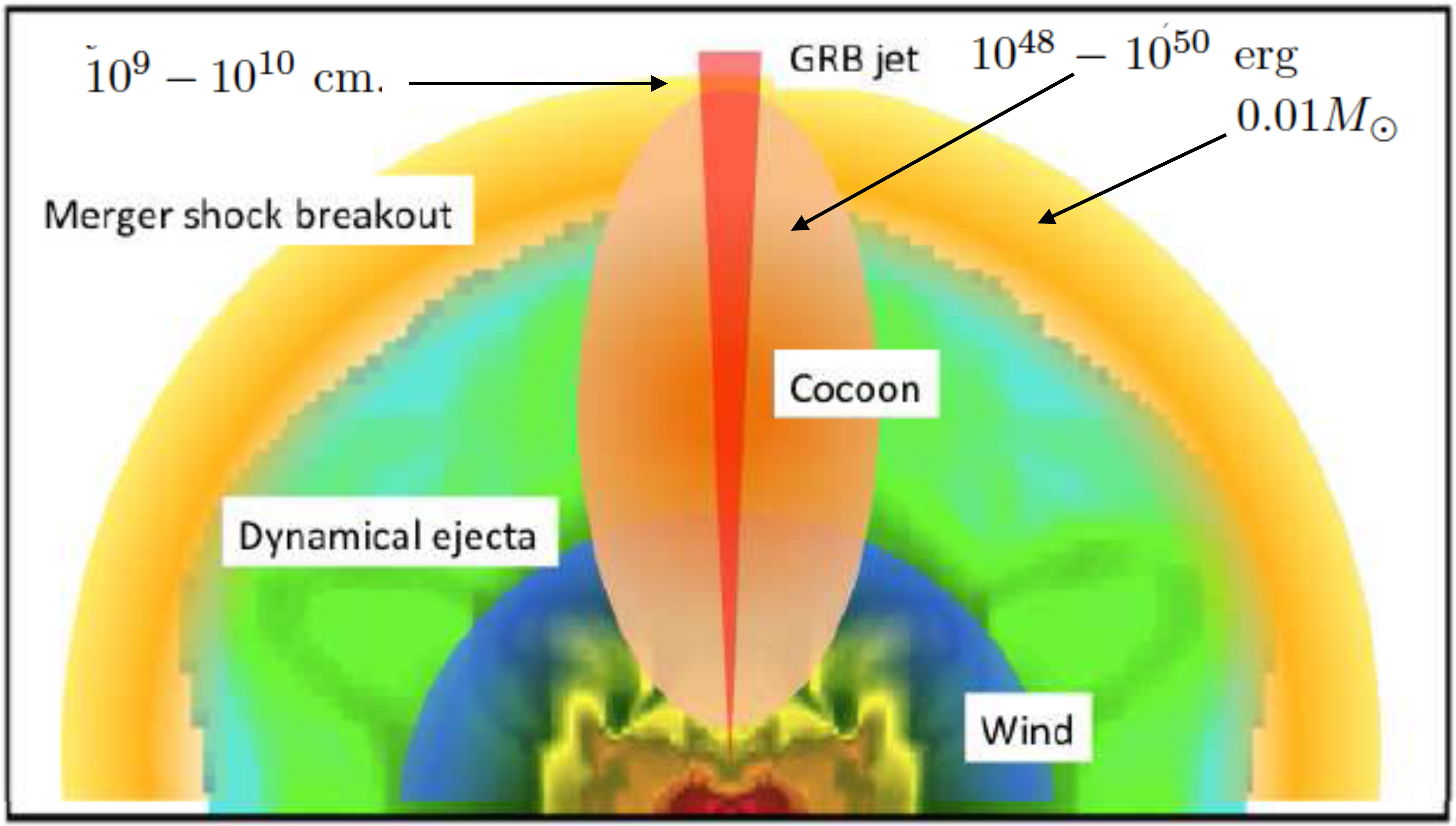


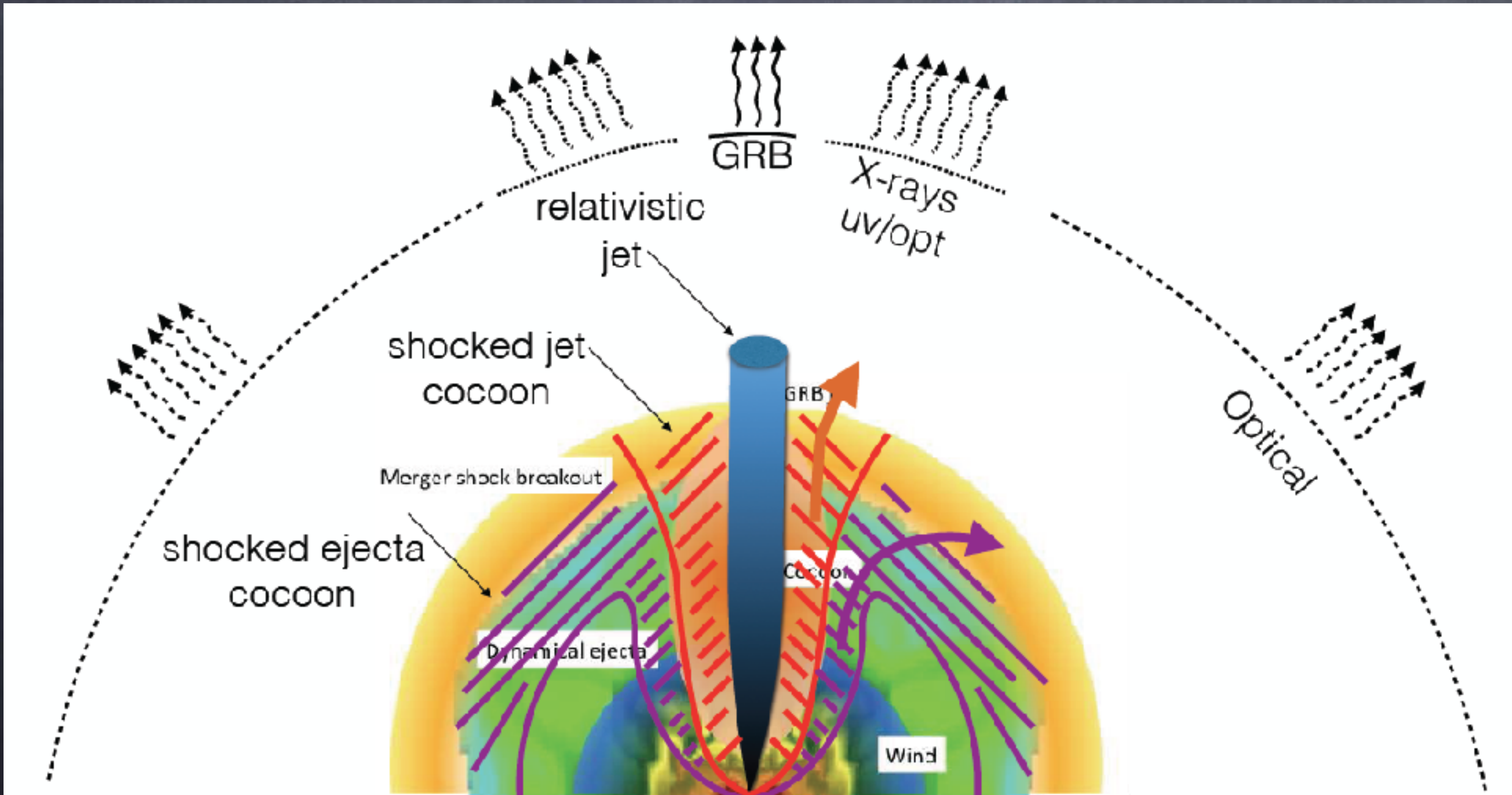
Energy
per Log interval
10^51
10^50
10^49
Newtonian
Relativistic
θ<0.1
0.1<θ<0.5
θ>0.5
Total
10^-2
10^-1
10^0
10^1
10^2
Γβ

Short GRBs



From Hotokezaka & TP 2015

Nagakura et al. 2014; Murguia-Berthier et al. 2014, 2016


GRB
relativistic
jet
X-rays
uv/opt
shocked jet
cocoon
Merger shock breakout
shocked ejecta
cocoon
Optical
GRB
Dynamical ejecta
Wind

SGRB cocoon signatures

Rel. Cocoon cooling

$E_c = 10^{50}$ + breakout radius of 10^{10} =>

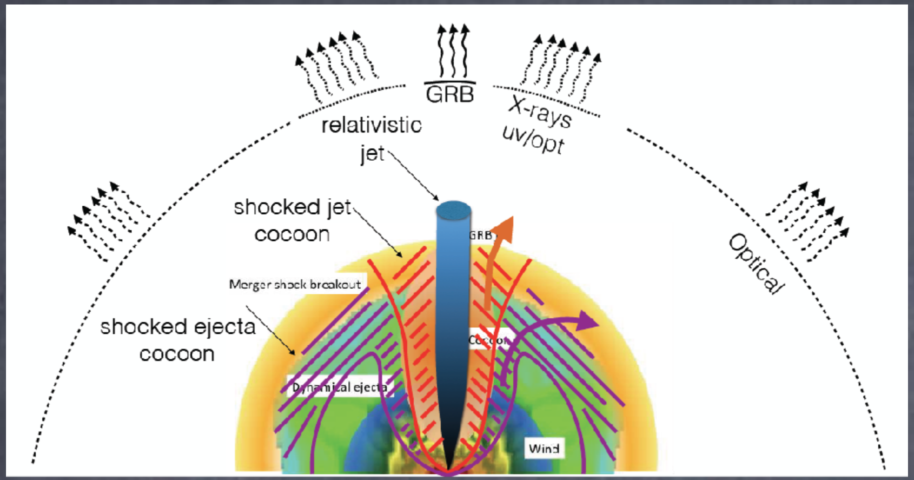
$\sim 10^{41}$ erg/s $\sim 10,000$ K. optical magnitude of about -14.

Rel. Cocoon Afterglow,
scaling from the regular SGRB afterglow

$\sim 10^{41}$ erg/s optical magnitude of about -14.

This is a wide angle signal 0.5 rad is stronger than typical SGRB orphan afterglow

Macronova cocoon signature



Heating due to radioactive decay

$$L_{MN} \sim 4 \times 10^{40}\ E_{49}^{0.325} \theta_{10}^{0.05} M_{ej,-2}^{0.025} \kappa_1^{-0.65} \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \frac{\mathrm{erg}}{\mathrm{s}},$$

$$\dot{\epsilon}_0 = 10^{10} (t/day)^{-1.3}\ \mathrm{erg/gr/s}.$$

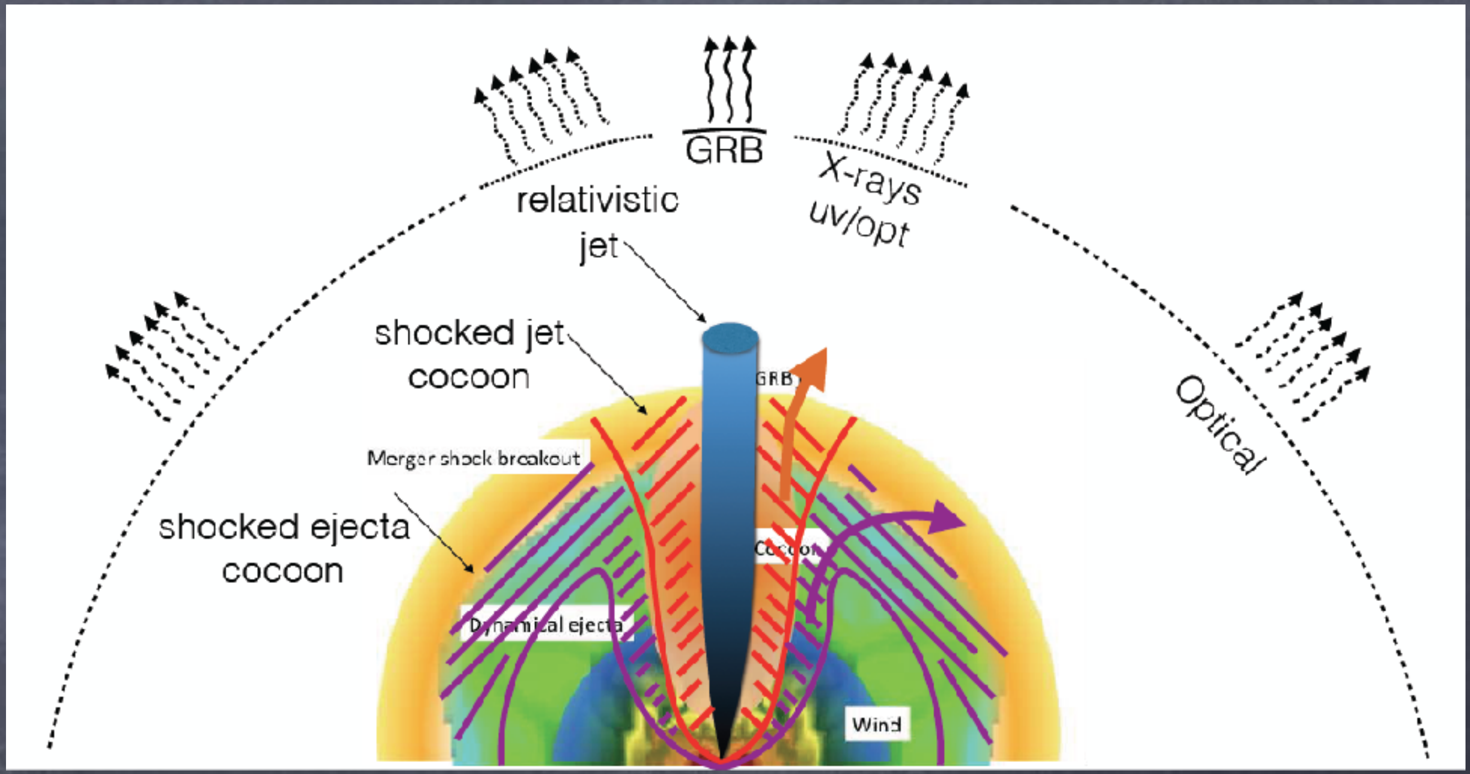
$$T_{MN} \sim 11{,}000\ E_{49}^{-0.04} \theta_{10}^{-0.24} M_{ej,-2}^{-0.12} \kappa_1^{-0.41} \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^{1/4}\ \mathrm{K}$$

Blue signal at around 0.5-1 day! Brighter or comparable to the classical Macronova

Summary

- Cocoons are the forgotten cousins in the GRB story. They carry a comparable amount of energy to the GRB and are wider than the GRBs.

- Short GRBs have their own cocoons whose signatures might be the best EM counterpart to



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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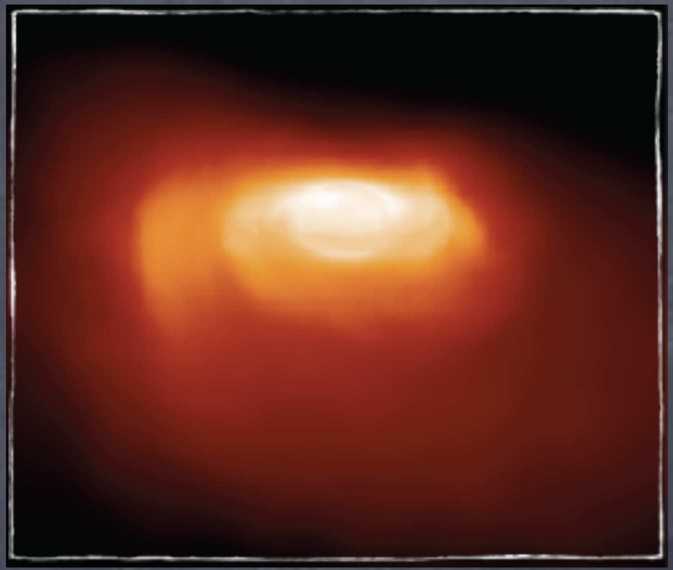

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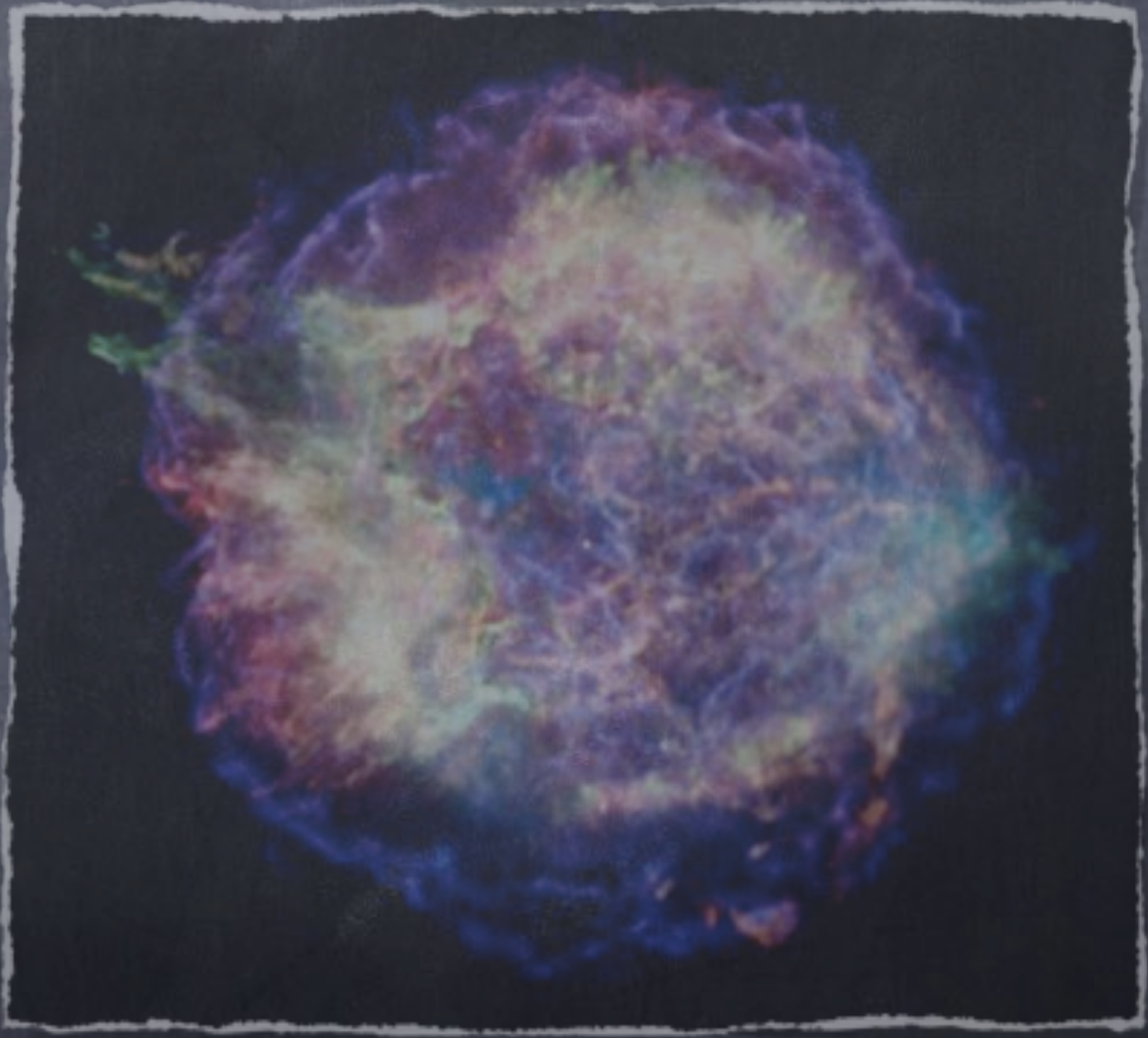

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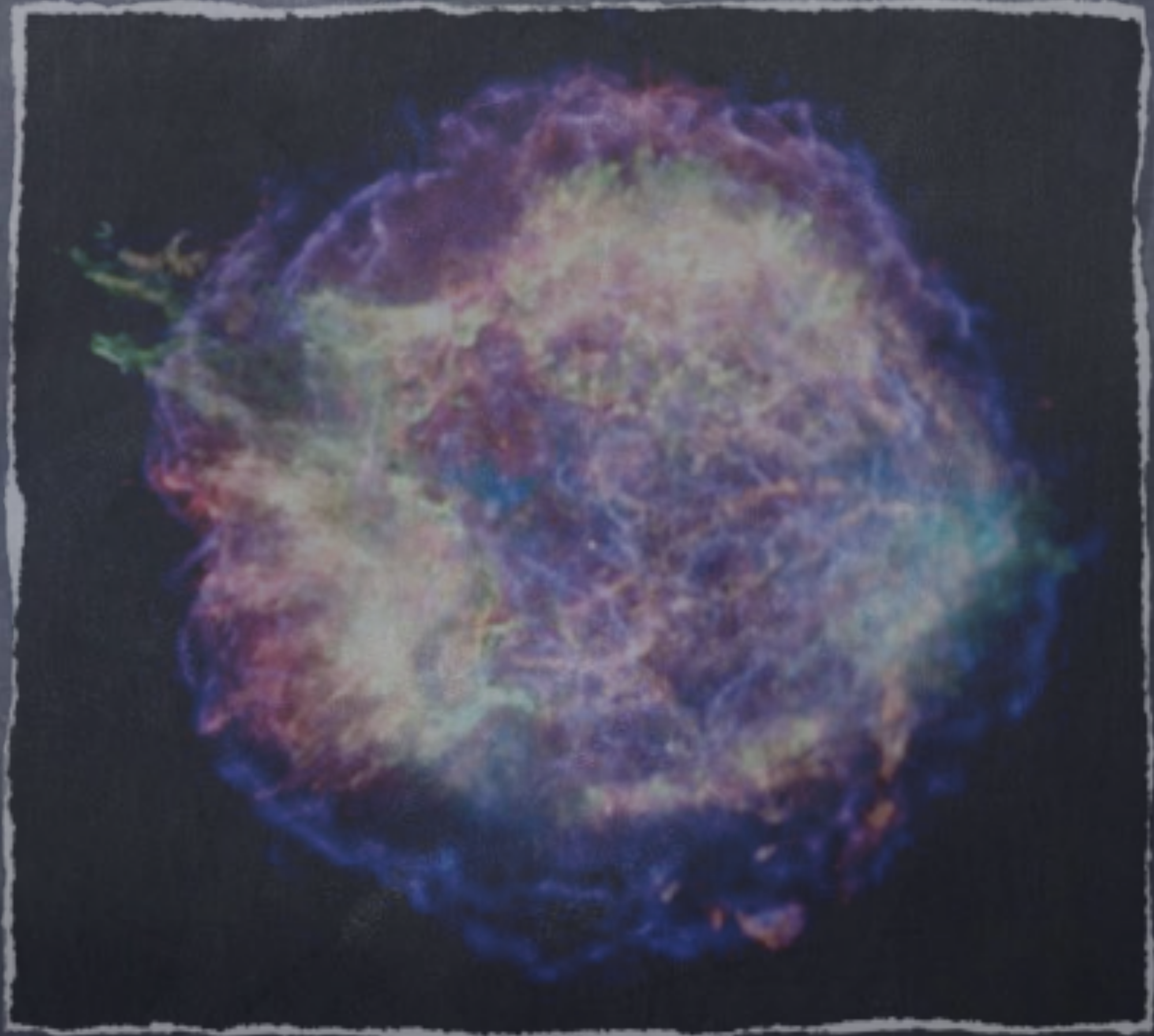

A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.

Supernova -> Supernova remnant

GRB -> Afterglow

Macronova -> Radio Flare

Search for the flare from GRB 130603B by the EVLA

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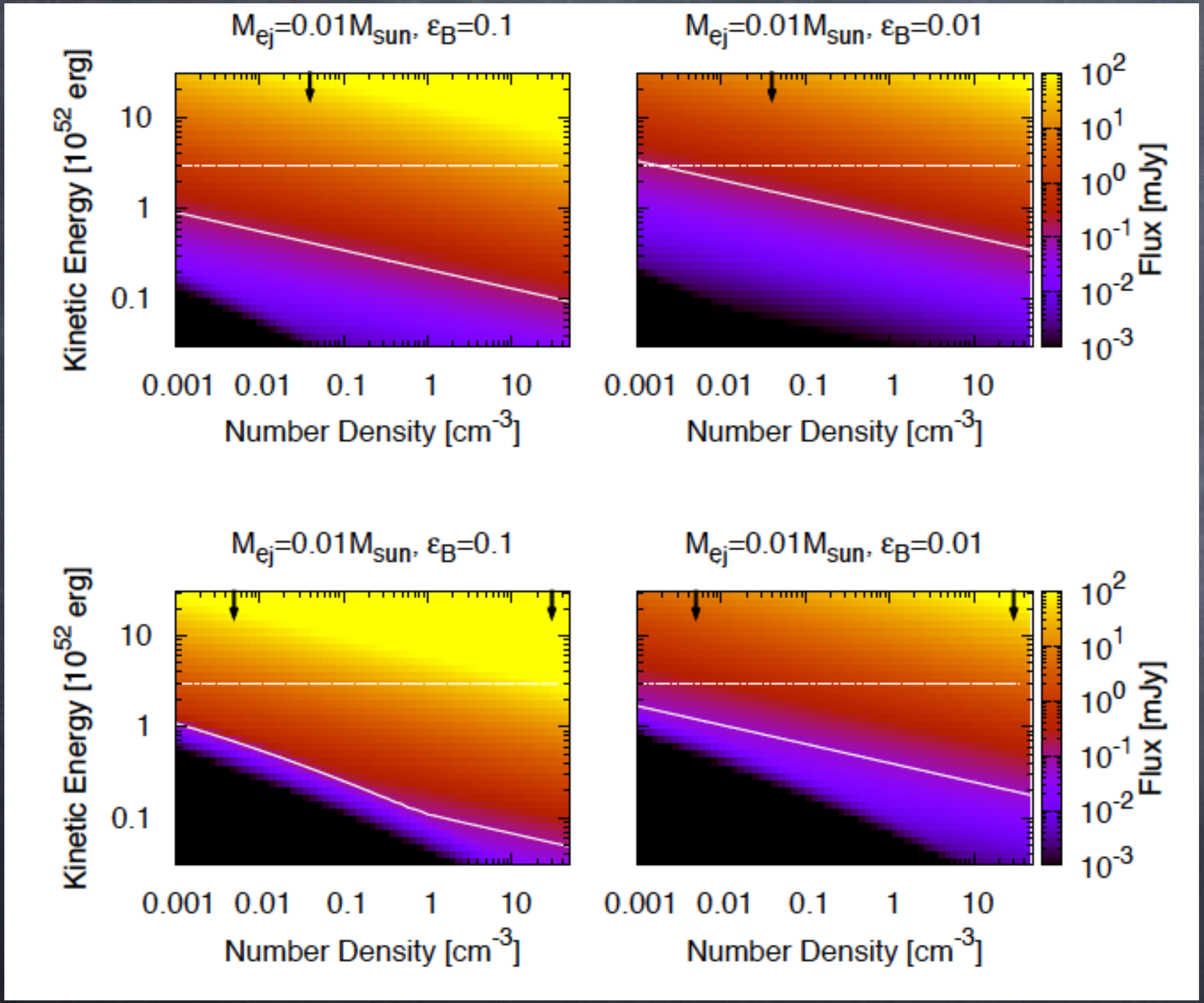
Radio limits on Magnetars



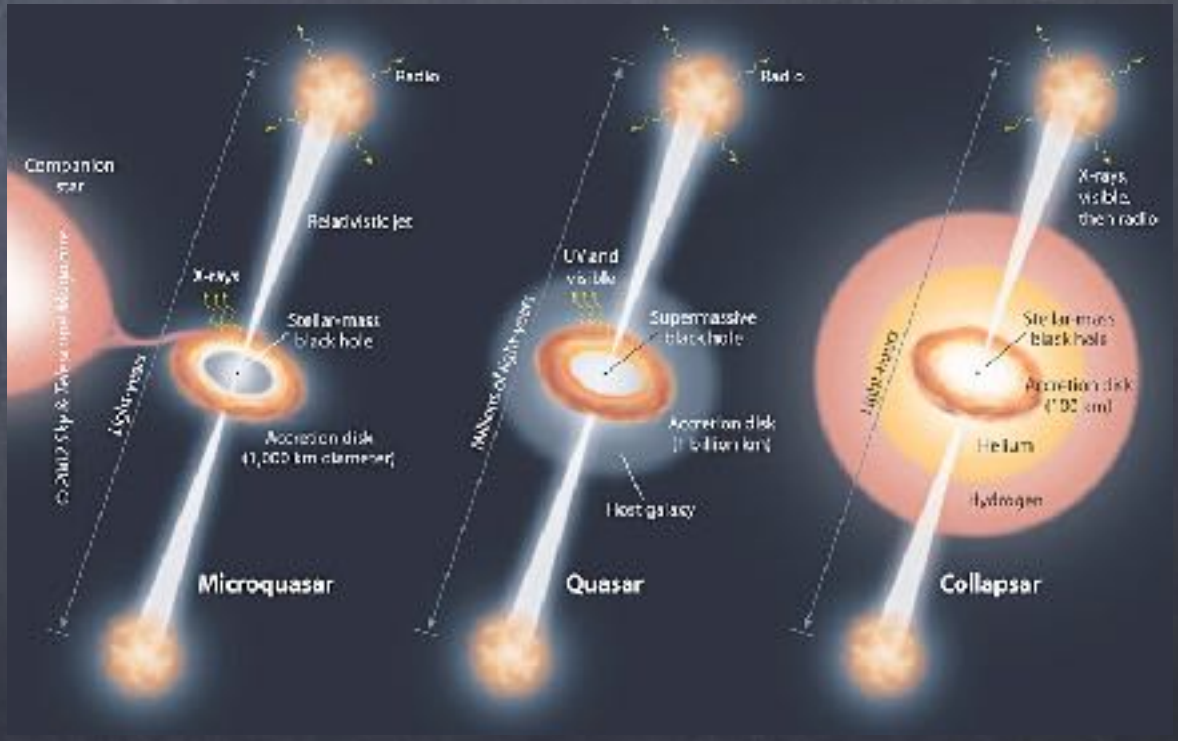
060614

130603B

Horesh + 16

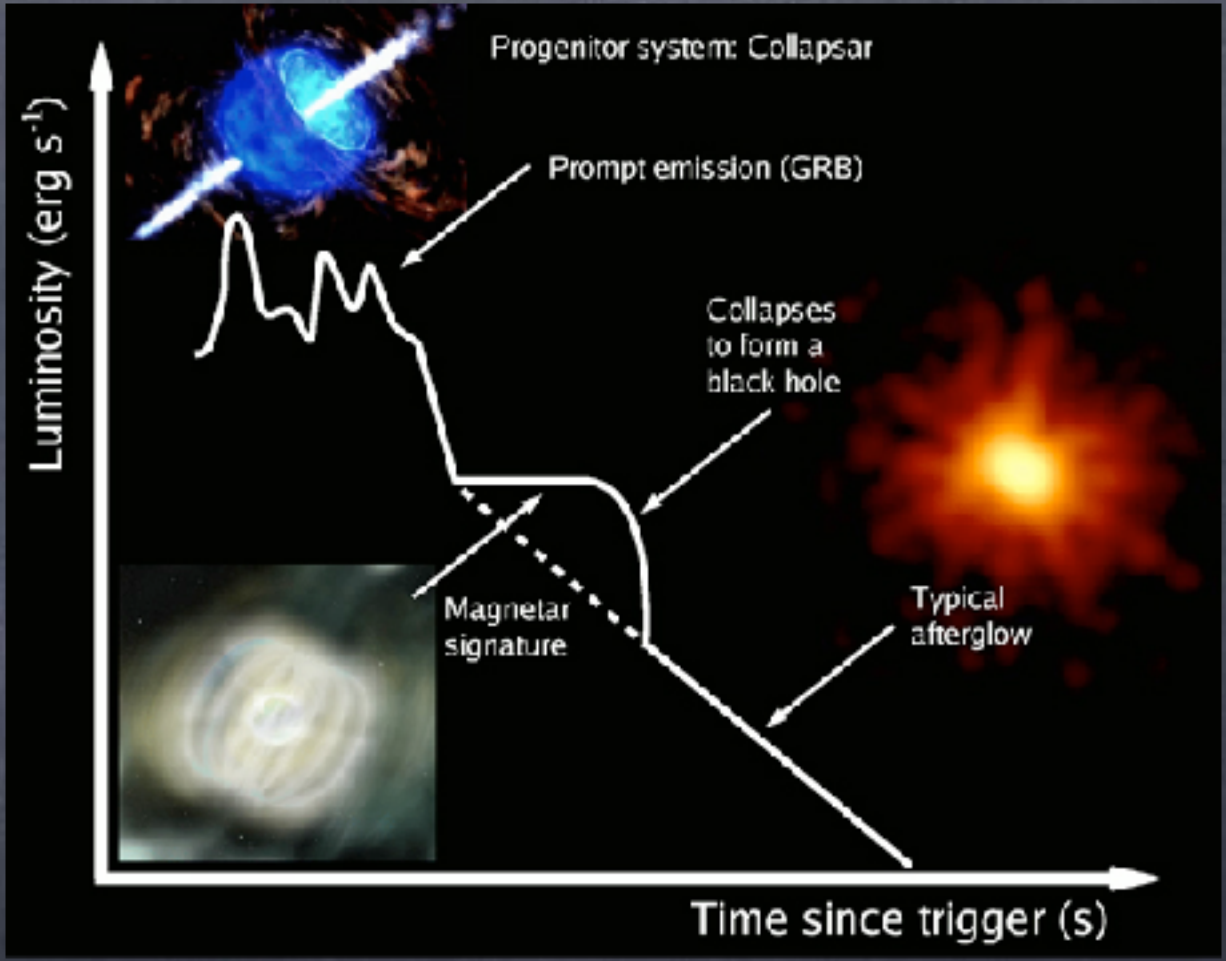
Do GRBs need magnetars?

- Quasars eject magnetic jets.
- => GRBs also have magnetic jets => Mangetars
- But quasars produce magnetic jets without magnetars



Where?

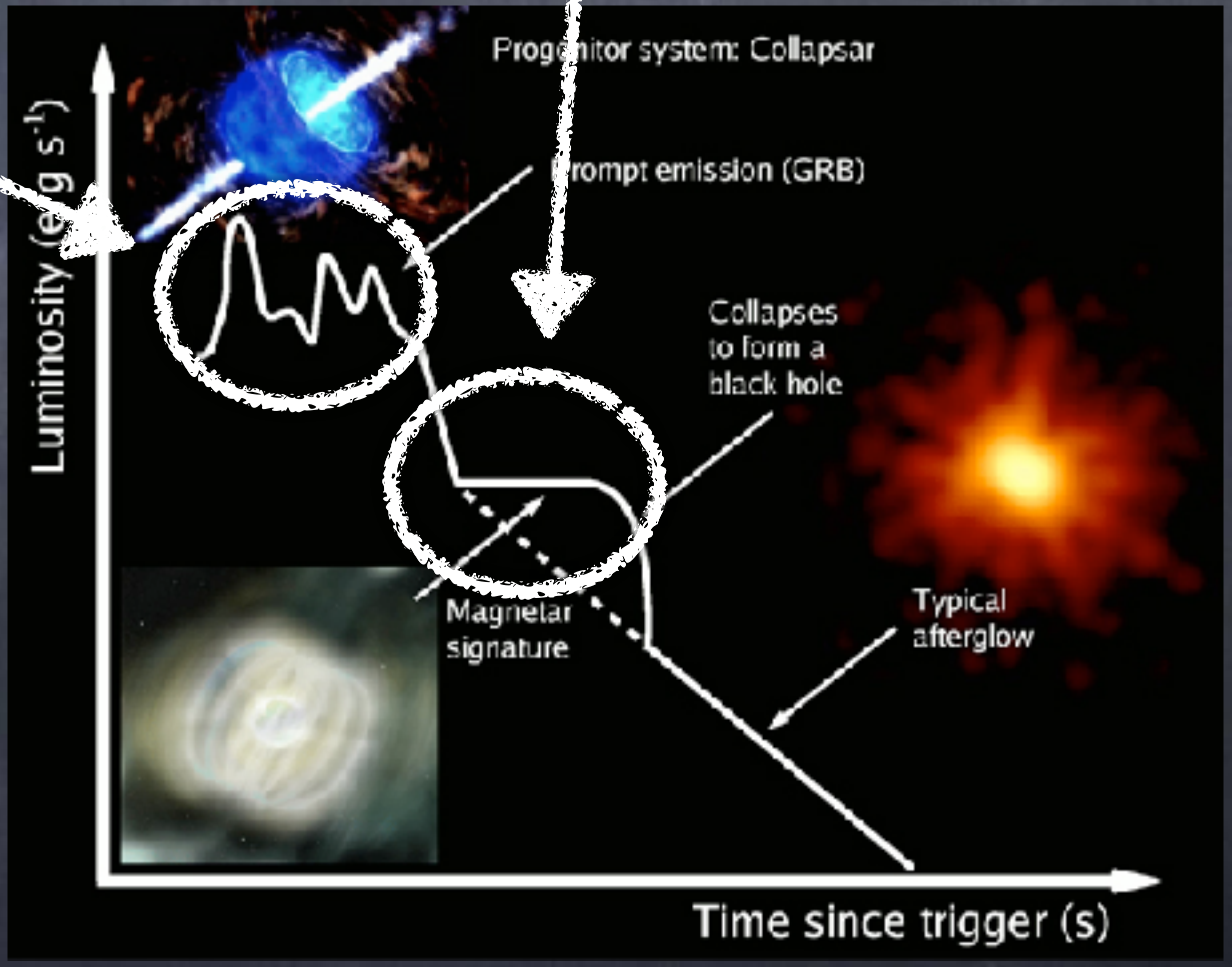
- Prompt?
- Afterglow?



Is impossible to have both from the same magnetar?

If a magnetar did this

What did that?



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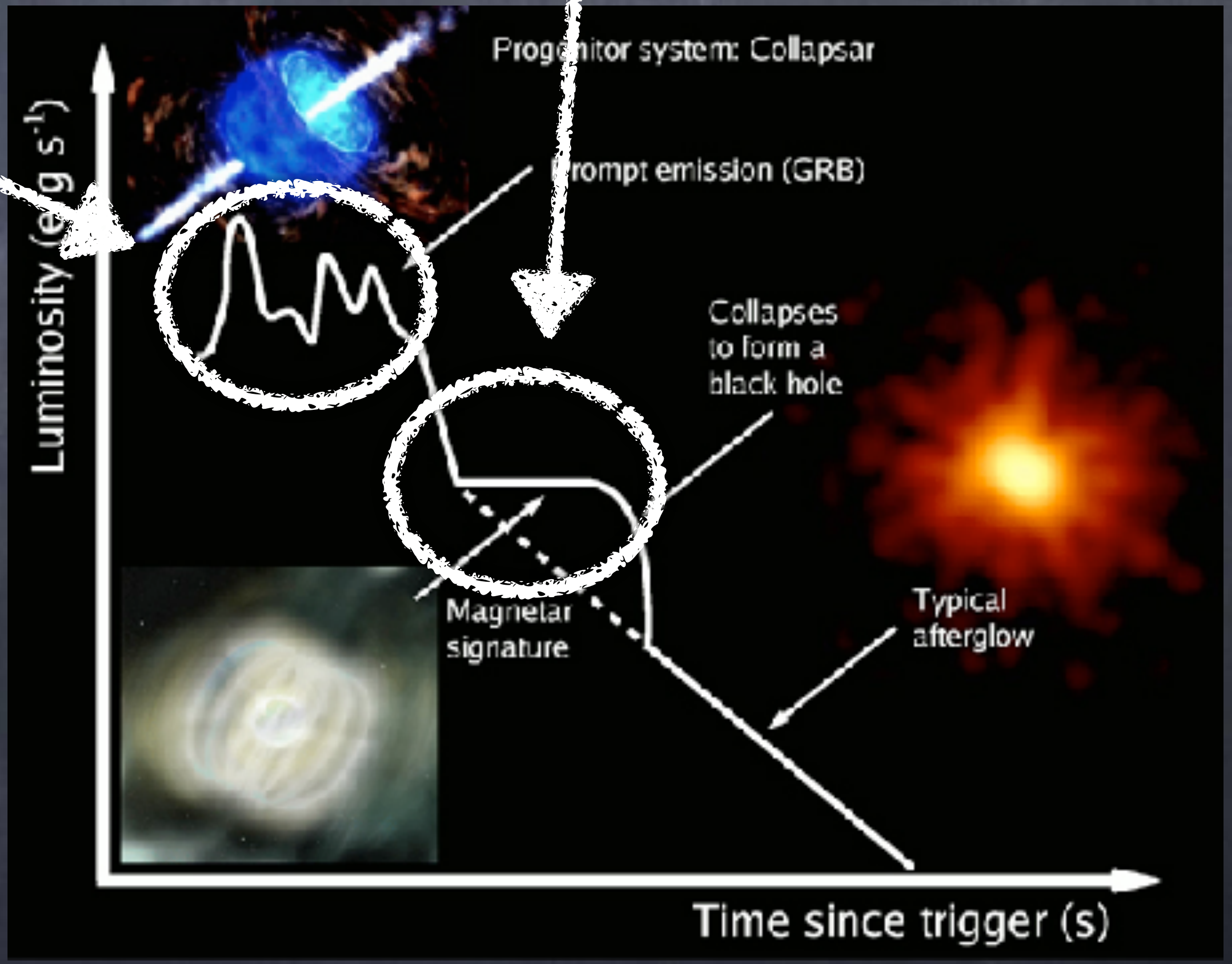
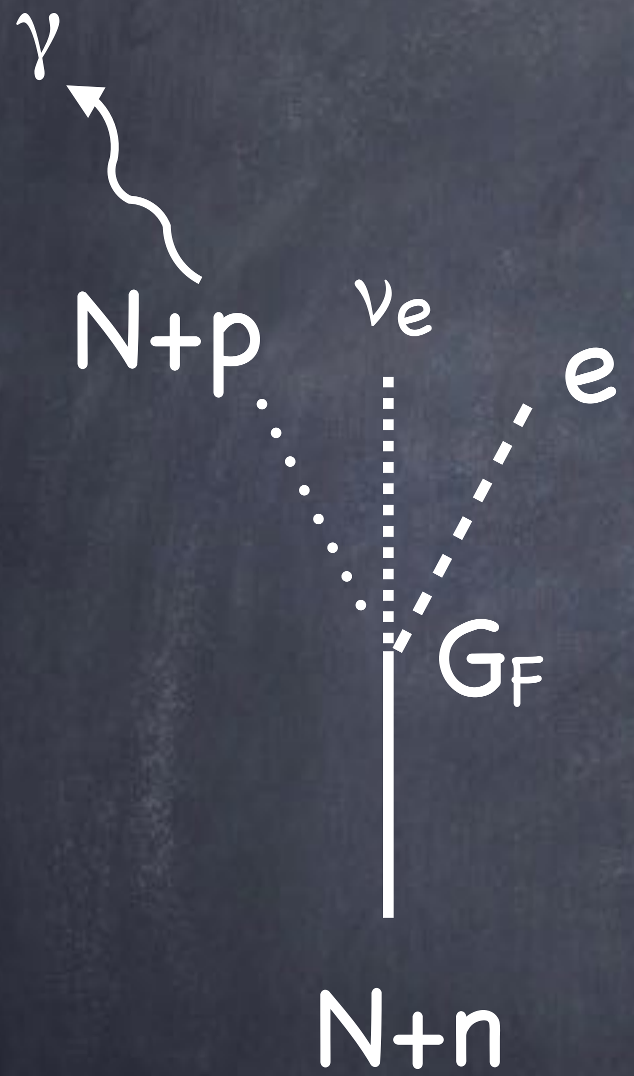


Energy Generation

Hotokezaka, Sari & TP + 16



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

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

$$\frac{1}{\tau} \propto \frac{d}{dE}\int d^3p_e \int d^3p_\nu$$

E^3 or $E^{3/2}$ $\qquad$ E^3

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

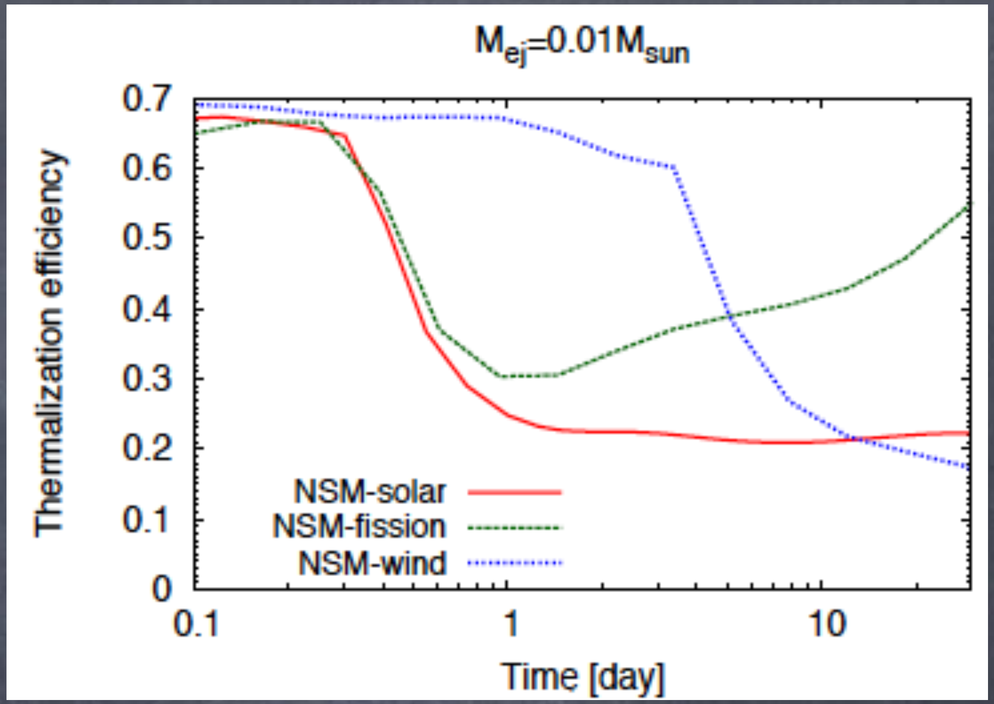
Newtonian $\quad \frac{1}{\tau} \propto E^{7/2} \quad \rightarrow \alpha = 9/7$

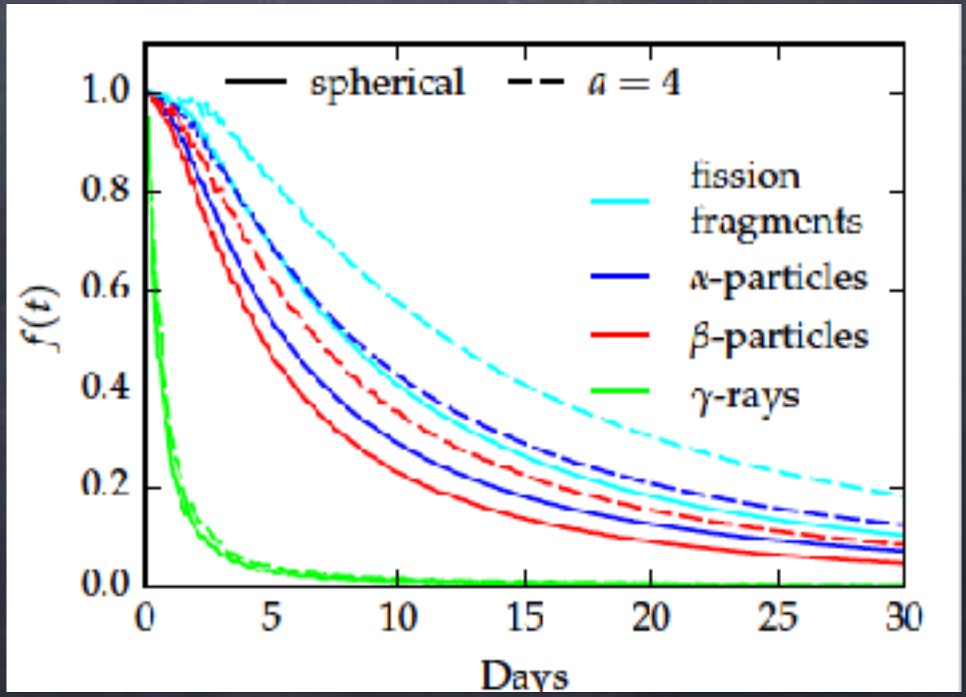
Efficiency

Hotokezaka, Wajano +…TP 16; Barnes +

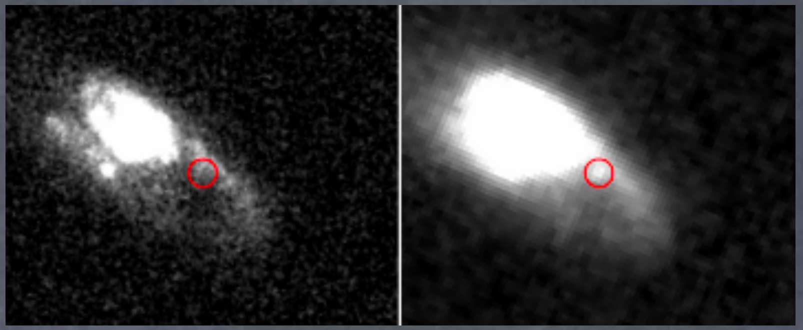
- Photon losses: The ejecta becomes optically thin to gamma-rays long before it becomes optically thin to optical/IR photons => photon leakage during the macronova peak (Hotokezaka + 16)

- Electron losses: Unlike previous believes not all the electrons energy is deposited (Barnes + 16)





Summary



- The nIR flare that followed the short GRB 130603B could have been a Macronova. If so than:
  - ✓ Short GRBs arise from mergers.
  - ✓ Gold and other A>130 elemets are produced in mergers. (But large m_{ej}).

- A radio flare may confirm this!
- A second & third Macronovae suggest a BH-NS merger

- ^{244}Pu suggests that R-process production is in rare events.
- Cocoon produces a short bright macronova
- We wait for the sGRB-GW coincidence

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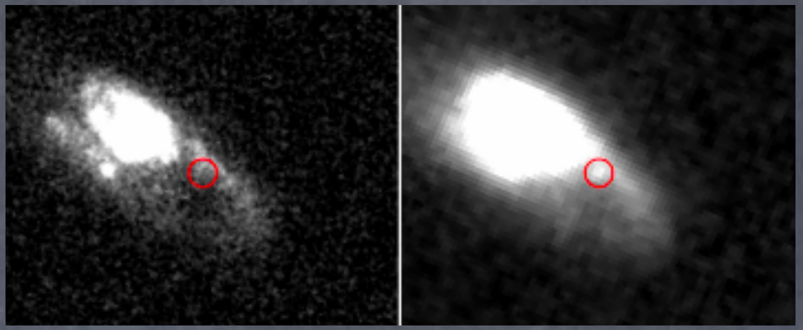

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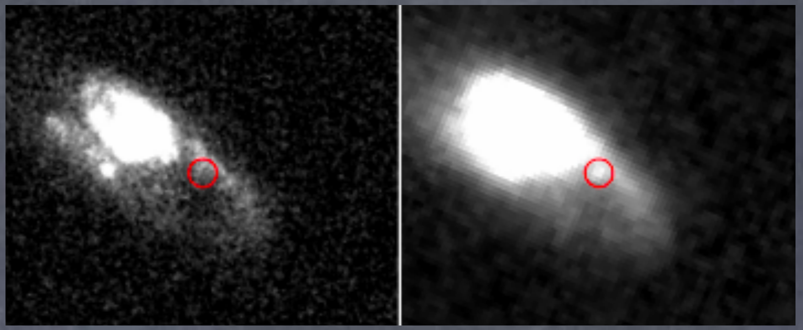

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