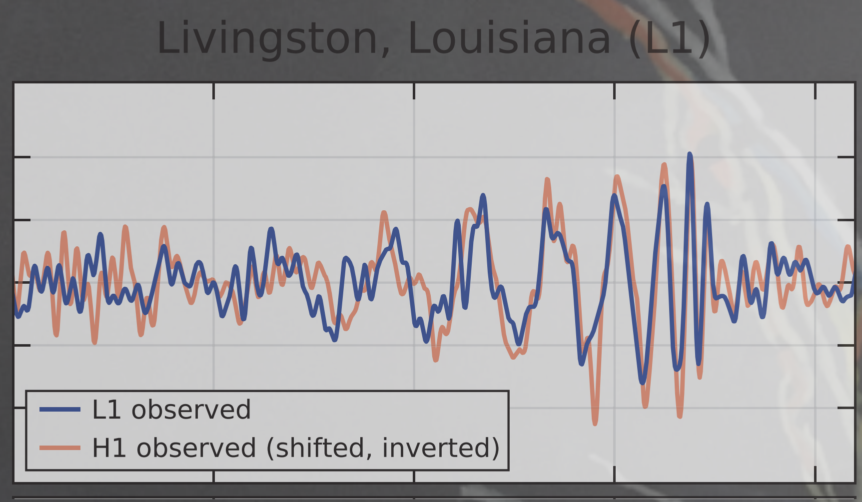
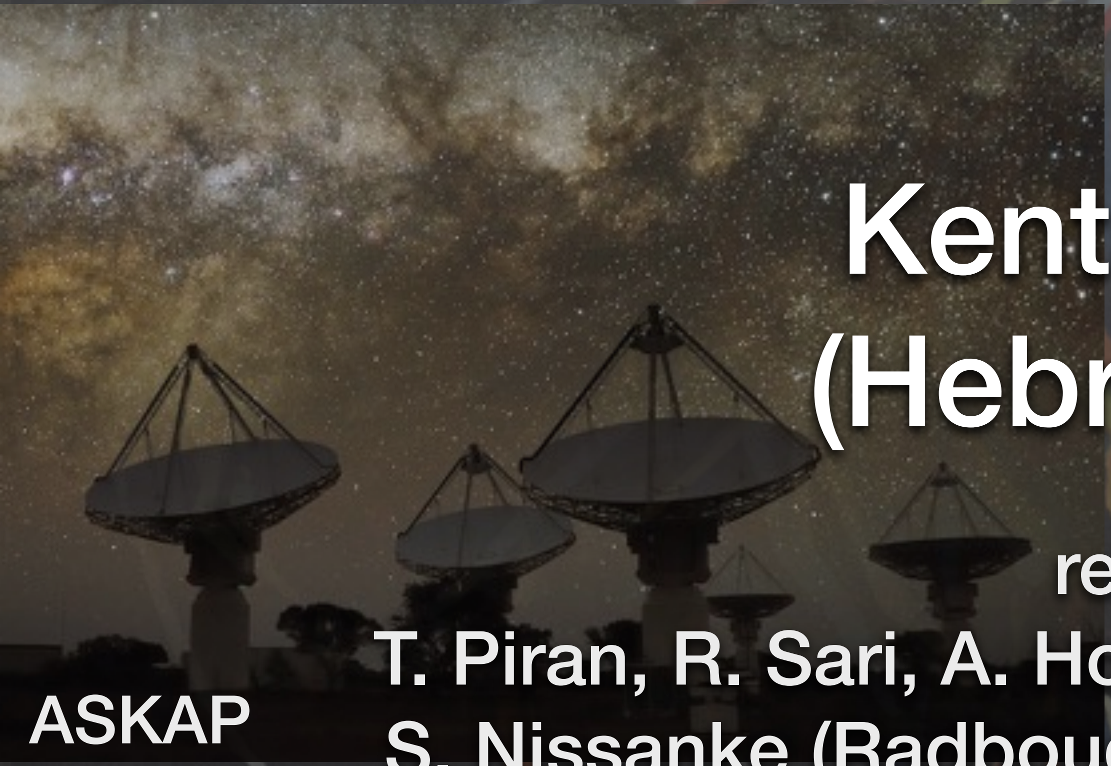


Macronova and its Radio-Remnant



Kenta Hotokezaka
(Hebrew University)

recent collaborators
T. Piran, R. Sari, A. Horesh (Hebrew), E. Nakar (Tel Aviv)
S. Nissanke (Radboud), G. Hallinan (Caltech), J. Lazio (JPL)
P. Beniamini (IPA), M. Tanaka (NAOJ), S. Wanajo (Sophia)
Y. Fan, Z.-P. Jin (PMO), S. Covino, P. D'Avanzo (INAF)

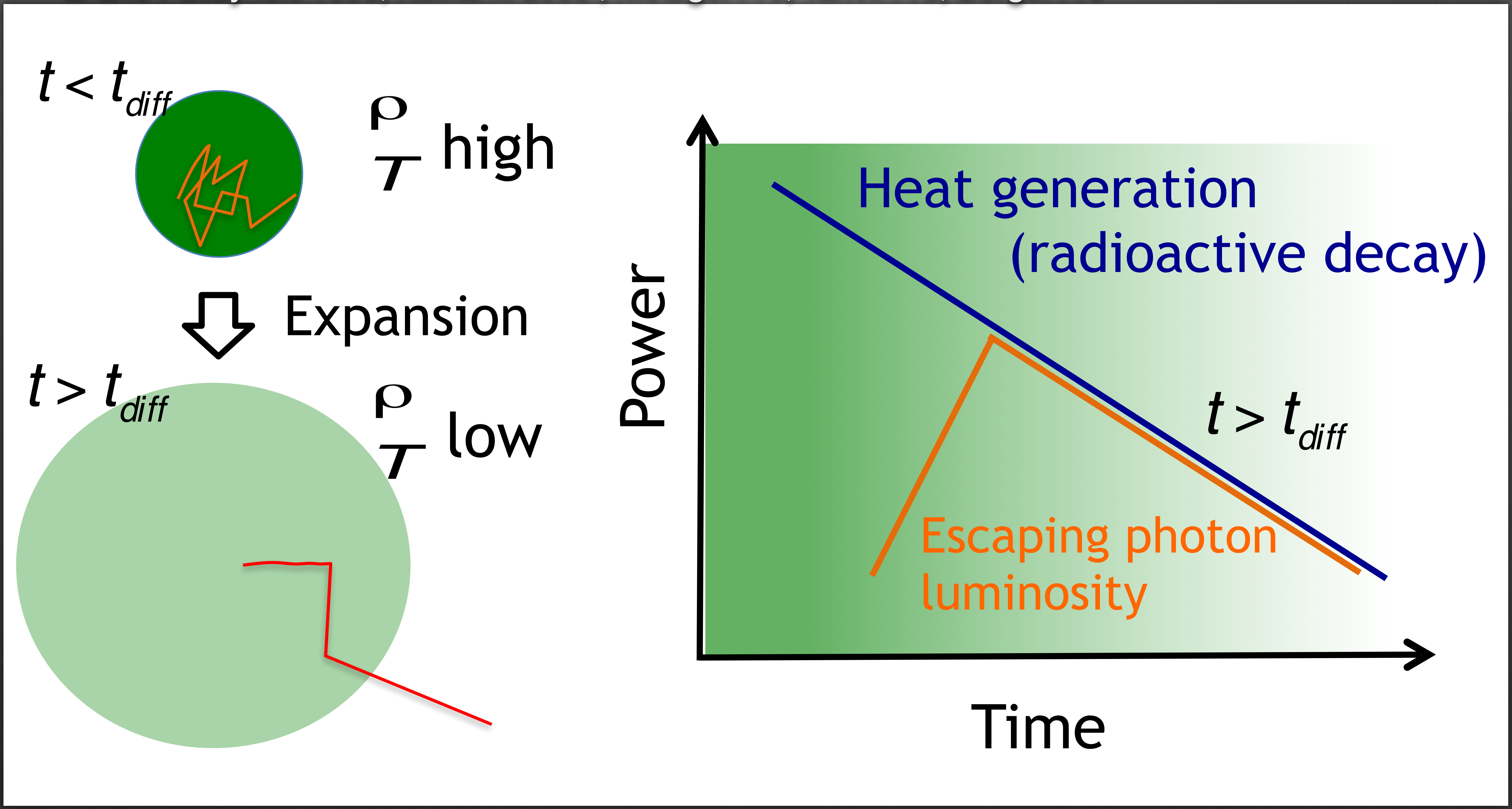
Outline

- Back of envelope calculation of beta decay heating
- “Historical” Kilonova/Macronova candidates
- Radio remnant

  (1) After short GRB afterglows
  (2) Radio GW counterparts
- Discussion

Macronova: Thermal emission from the merger ejecta

Li and Paczynski 1998, Kulkarni 2005 , Metzger+10, Tanvir+13, Berger+13



The first candidate: GRB 130603B Tanvir+13, Berger+13

Key ingredients of Macronova studies

(1) Mass Ejection: mass and velocity

Talks by Kyutoku, Kiuchi, Fujibayashi, Fernandez

(2) Radioactive heating rate

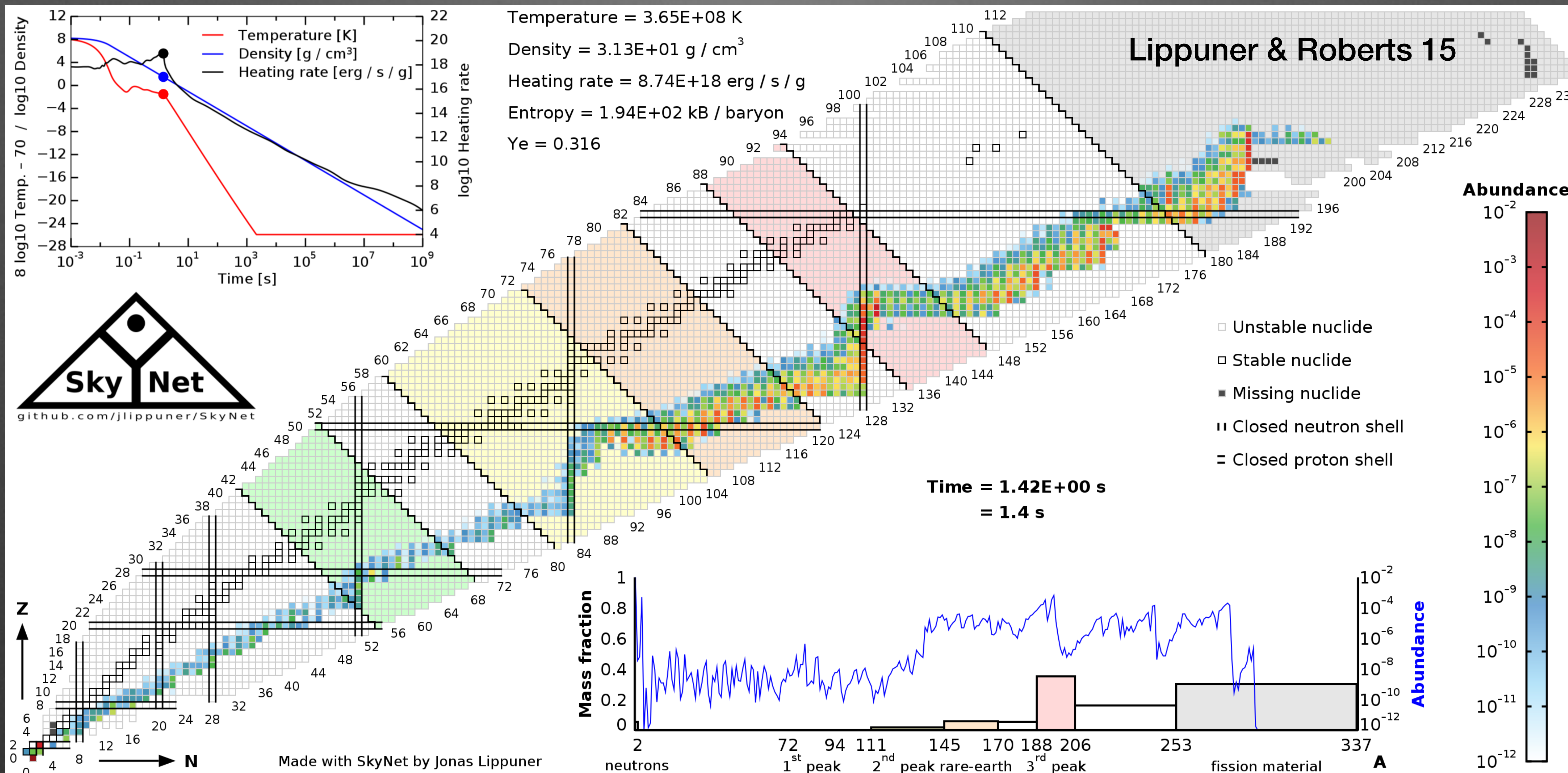
Talks by Wanajo, Martinez-Pinedo, Lippuner, Barnes

(3) Opacity

Talk by Barnes

R-process in Neutron Star Merger Ejecta

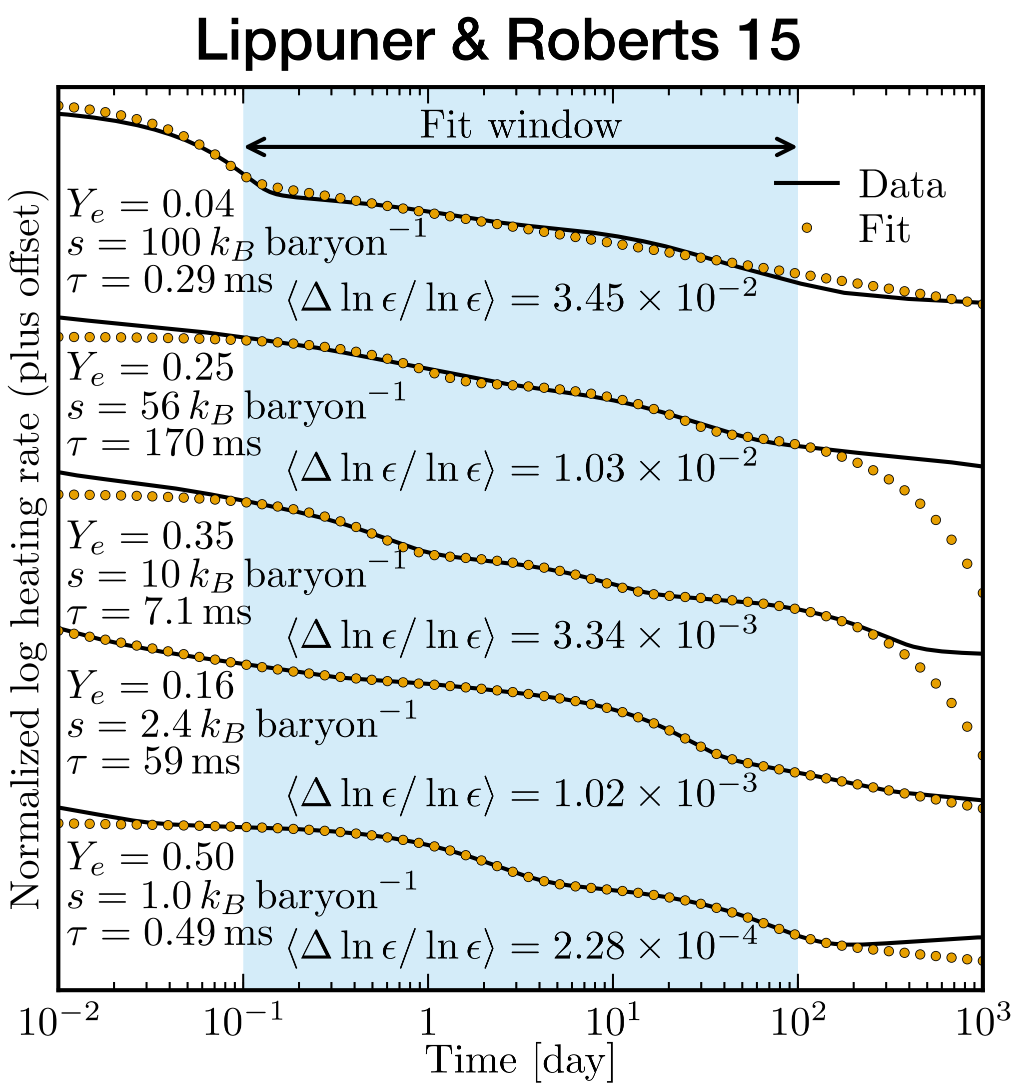
Latter & Schramm 74, Metzger+10, Goriely+11, Korobkin+12, Wanajo+14, Lippuner & Roberts 15, Wu+16

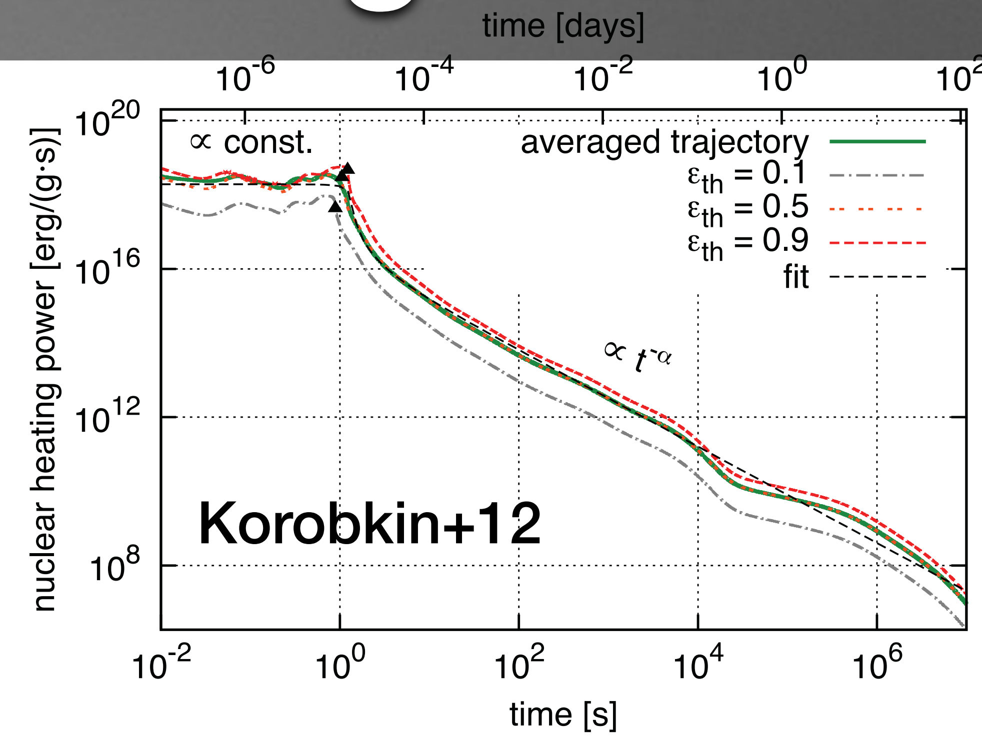


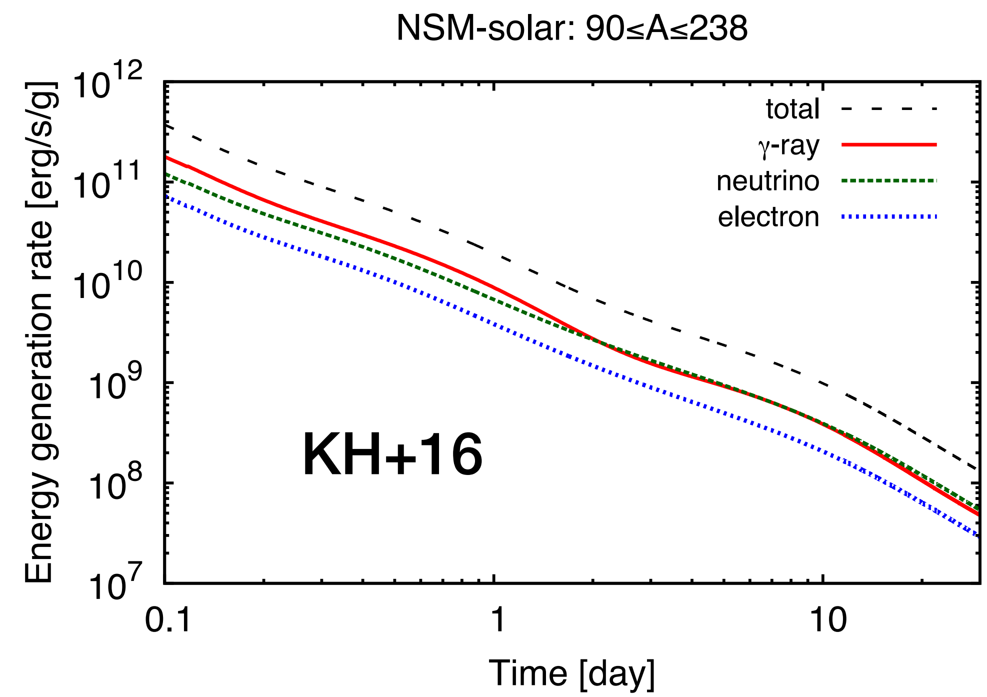
✓ Almost all material is synthesized in heavy r-process elements.

✓ Nuclei are initially far from the stability line.

Macronova Heating rate







see also Metzger+10, Goriely+11, Roberts+11, Grosmann+14,Wanajo+14,Barnes+16

A simple power low of the heating rate: $\dot{Q}(t) \approx 10^{10}\ \mathrm{erg/s/g}\ \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$

There must be a simple way to describe this.

Quick review of macronova heating

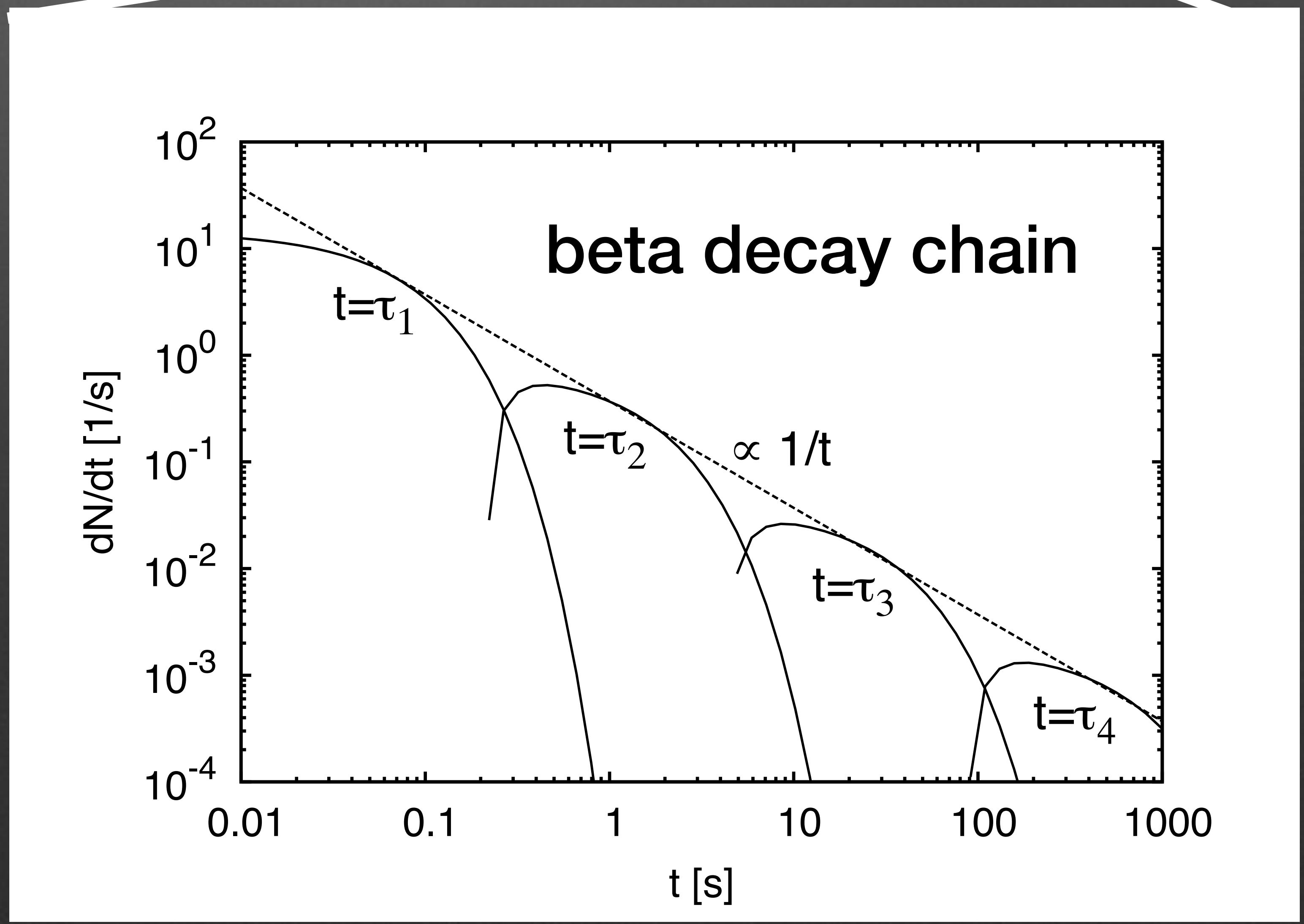
KH, Sari, Piran in prep.

Nuclides with $\tau \sim t$ contribute to the energy generation.

Heating rate/nucleus

Beta decay energy

$$\dot{Q}(t) \sim -E(t)\frac{dN}{dt} \sim \frac{E(t)}{t}$$



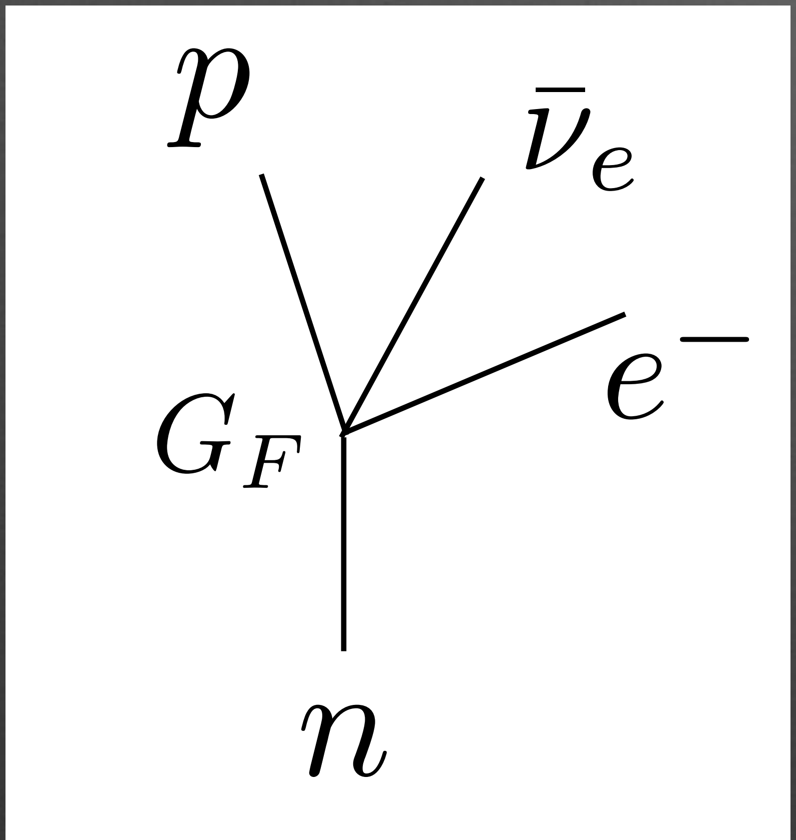
Two conditions:
(2) The total number of nuclei conserves.

(2) t > tau_1.

Quick review of macronova heating

KH, Sari, Piran in prep.

$(m_e,\ c,\ \hbar,\ G_F)$ in Fermi's theory of beta decay



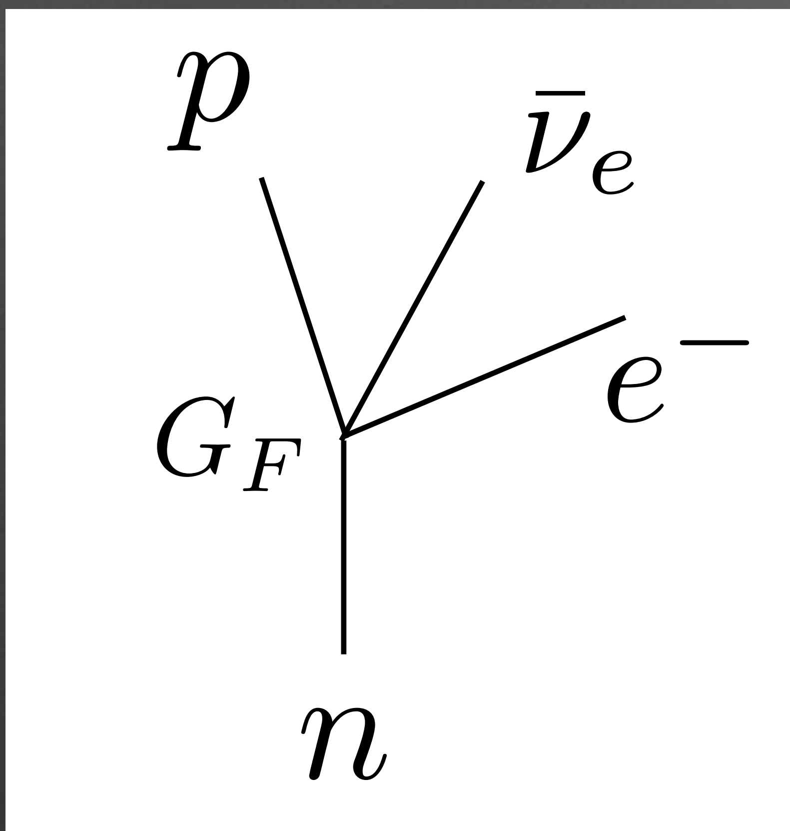
1) A fundamental timescale of beta decay:
Fermi time

$$t_F \equiv \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 9000\ \mathrm{s}$$

Quick review of macronova heating

KH, Sari, Piran in prep.

$(m_e,\ c,\ \hbar,\ G_F)$ **in Fermi's theory of beta decay**



1) A fundamental timescale of beta decay:
Fermi time

$$t_F \equiv \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 9000\ \mathrm{s}$$

2) Fermi's golden rule:

$$\frac{1}{\tau} \propto \frac{d}{dE}\int\int dp_e p_e^2 dp_\nu p_\nu^2$$

$$\propto E^5$$ (for $E \gg m_e c^2$)

$$E(t) \sim m_e c^2 \left(\frac{t}{t_F}\right)^{-0.2}$$

Quick review of macronova heating

KH, Sari, Piran in prep.

The heating rate per nucleus:

$$\dot{Q}(t) \sim \frac{E(t)}{t} \sim \frac{m_e c^2}{t_F} \left(\frac{t}{t_F} \right)^{-1.2}$$

The heating rate per unit mass:

$$\dot{Q}(t) \sim \frac{1}{\langle A \rangle} \frac{m_e}{m_p} \frac{c^2}{t_F} \left(\frac{t}{t_F} \right)^{-1.2} \sim 10^{10} \ \mathrm{erg/s/g} \ \left(\frac{t}{\mathrm{day}} \right)^{-1.2}$$

$\langle A \rangle \sim 200$

For the ejecta with 0.01Msun = 2x10^31 g:

Luminosity ~ 2x10^41 erg/s at 1 day

~ 2x10^40 erg/s at 1 week

A bit more detail

KH, Sari, Piran in prep.

$$\frac{1}{\tau} \quad = \quad \frac{|\mathcal{M}_N|^2}{t_F} \int_0^{p(E_0)} dp F(Z,E) p^2 (E - E_0)^2, \qquad (5)$$

where the variables in the integral are in units of m_e and c.

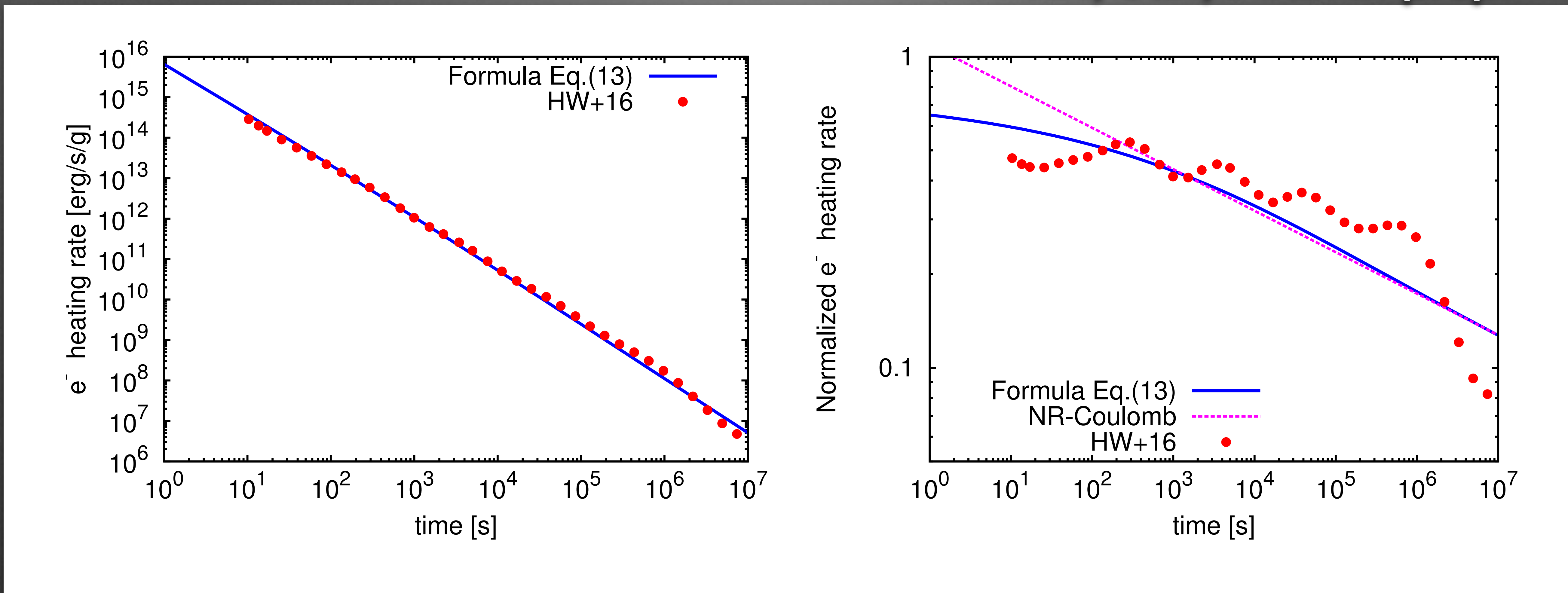
$$\begin{aligned} F(Z,E) \quad &\cong \quad \frac{|\psi_e(r_n)|^2_Z}{|\psi_e(r_n)|^2_{Z=0}}, \qquad (7) \\ &= \quad \frac{2(1+s)}{[(2s!)^2]} (2p\rho)^{2s-2} e^{\pi\eta} \left|(s-1+i\eta)!\right|^2, \end{aligned}$$

where $\eta = Zq_e^2/\hbar v$, $\rho = r_n/(\hbar/m_e c)$, $s = (1-(Z\alpha)^2)^{1/2}$, q_e is the electron charge, and $\alpha \approx 1/137$ is the fine-structure

$$\dot{Q}(t) \approx \begin{cases} 1.2 \cdot 10^{10}\ t_{\rm day}^{-\frac{6}{5}} \langle A \rangle_{200}^{-1} \left(\frac{|\mathcal{M}_N|^2}{0.05}\right)^{-\frac{1}{5}} \frac{\rm erg}{\rm s \cdot g} \ (t \lesssim t_{\rm R}), \\ 0.3 \cdot 10^{10}\ t_{\rm day}^{-\frac{4}{3}} \langle Z \rangle_{70}^{-\frac{1}{3}} \langle A \rangle_{200}^{-1} \left(\frac{|\mathcal{M}_N|^2}{0.05}\right)^{-\frac{1}{3}} \frac{\rm erg}{\rm s \cdot g} \ (t \gtrsim t_{\rm NC}), \end{cases} \qquad (14)$$

Analytic vs database approaches

KH, Sari, Piran in prep.



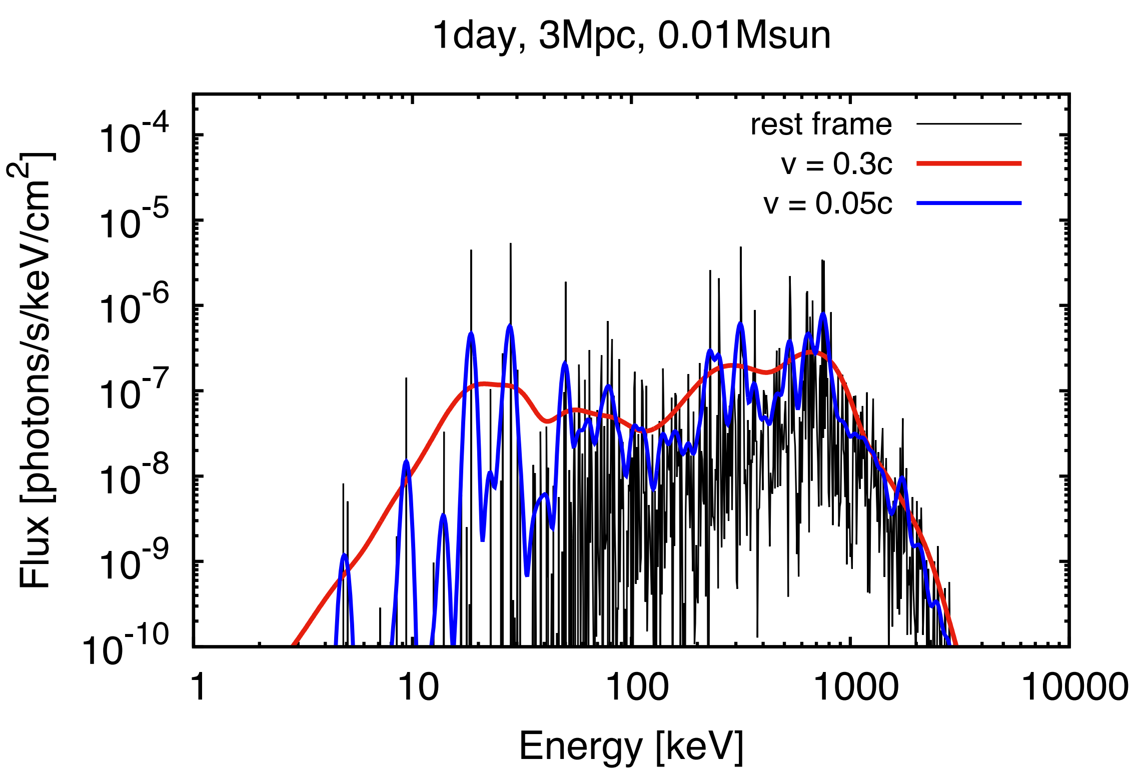
The analytic formula nicely describe the heating rate from the nuclear database.

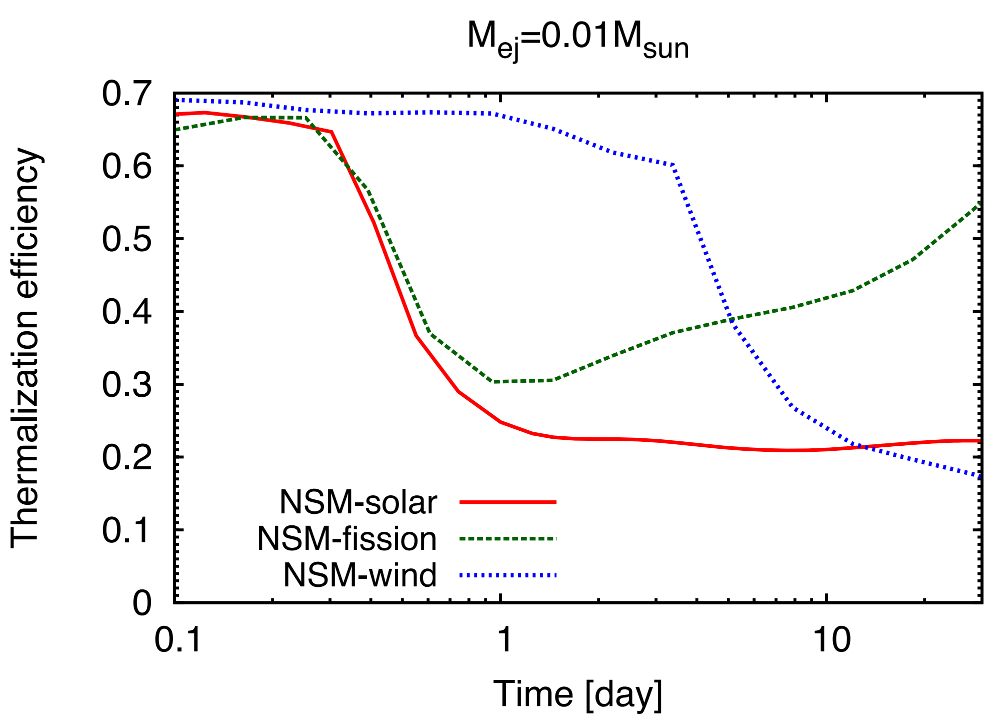
Note that forbidden transitions and the decrease of the total number of radioactive nuclei slightly change our formula.

Metzger et al 2010 show the slope of the heating with a different assumption from ours, disappearing chains. In reality, it is between the two assumptions.

Gamma-ray escape

KH+16





The optical depth of gamma rays:

$$\tau_\gamma(t) \approx \frac{\kappa_\gamma}{\kappa_o}\frac{c}{v}\left(\frac{t_{\rm diff,o}}{t}\right)^2, \approx 0.02\left(\frac{t_{\rm diff,o}}{t}\right)^2\left(\frac{\kappa_\gamma}{0.05\ {\rm cm^2/g}}\right) \times\left(\frac{\kappa_o}{10\ {\rm cm^2/g}}\right)^{-1}\left(\frac{v}{0.3c}\right)^{-1},$$

The diffuse-out time of thermal photons, i.e. the peak timescale of macronovae.

Spontaneous fission and alpha decay may contribute to the heating rate at late time. (KH+16, Barnes+16)

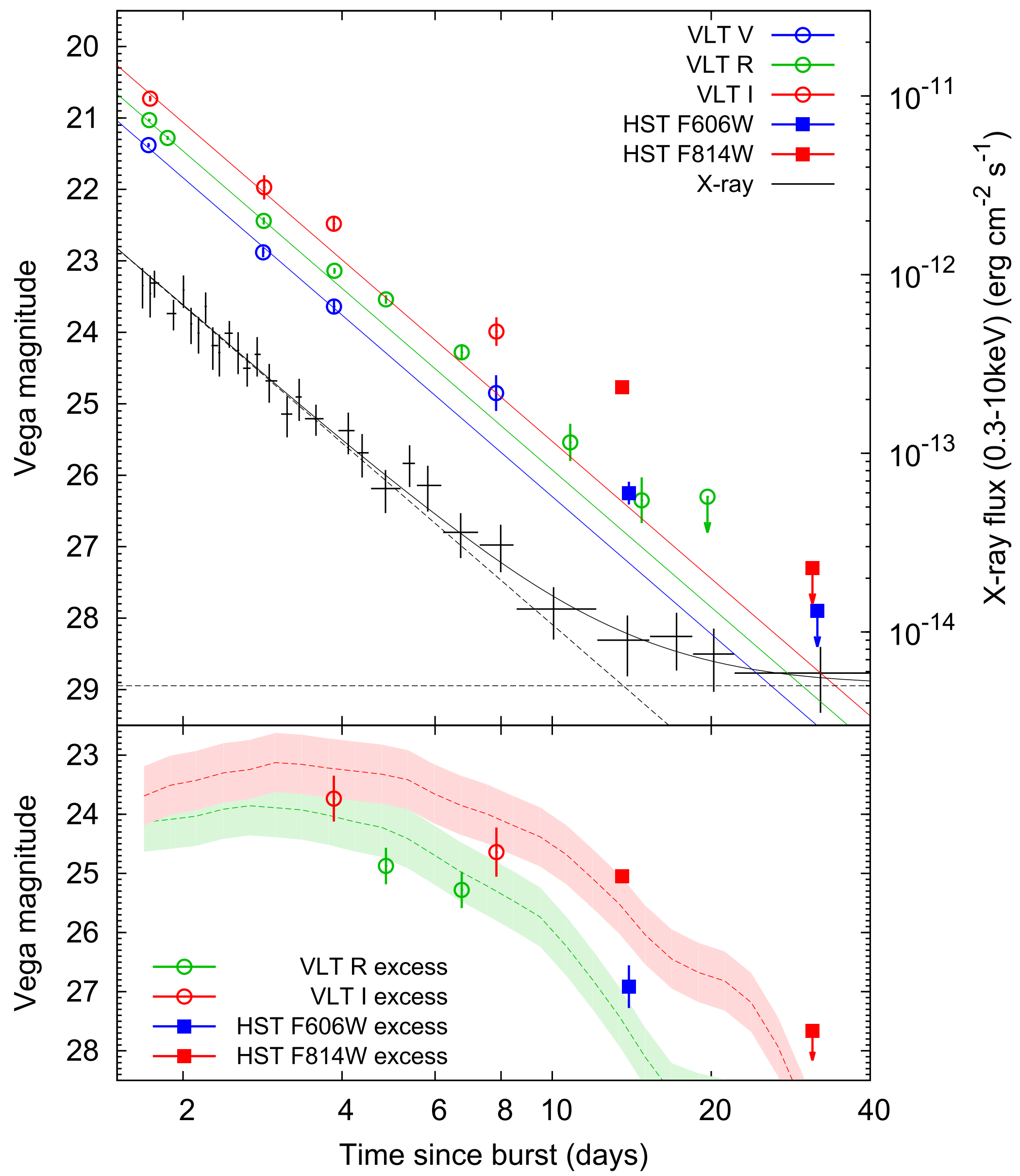
Outline

- Back of envelope calculation of beta decay heating
- “Historical” Kilonova/Macronova candidates
- Radio remnant

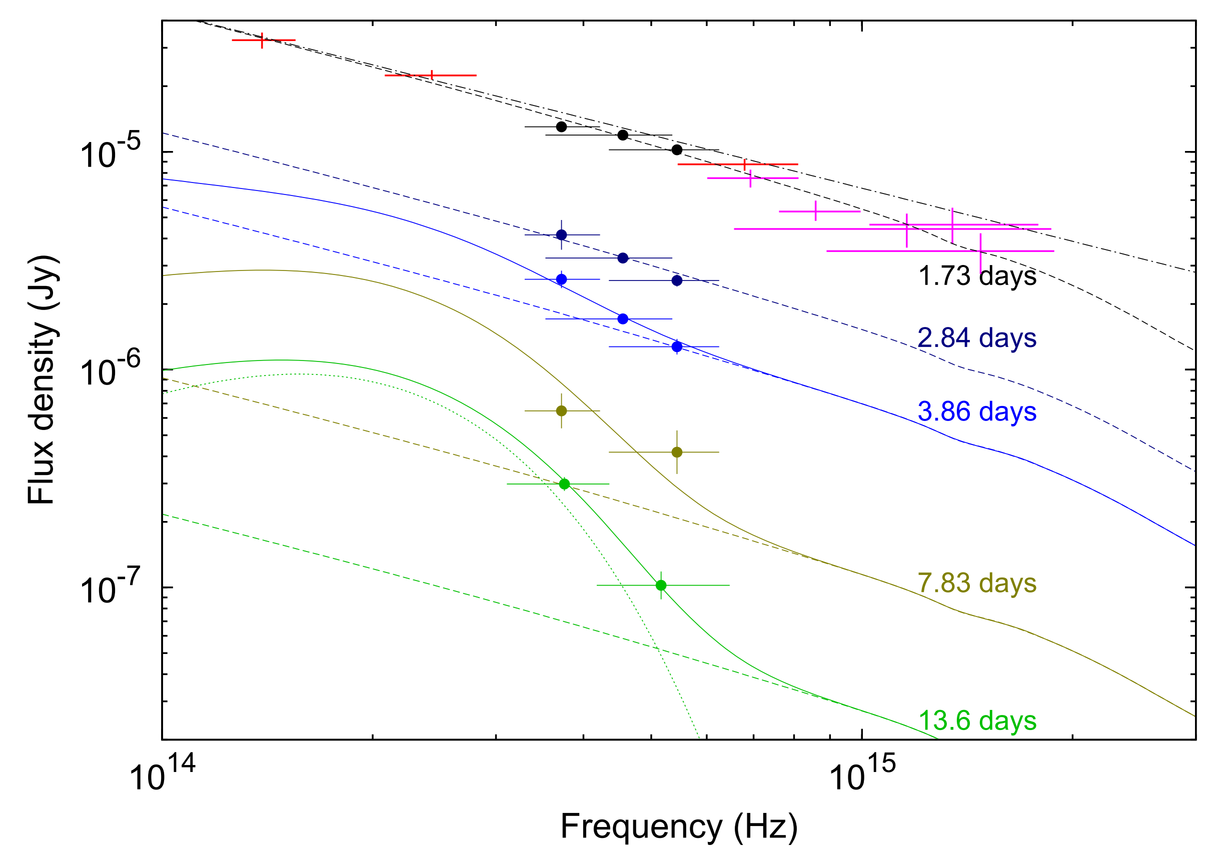
  (1) After short GRB afterglows
  (2) Radio GW counterparts
- Discussion

GRB 060614

Yang+15, Jin+15



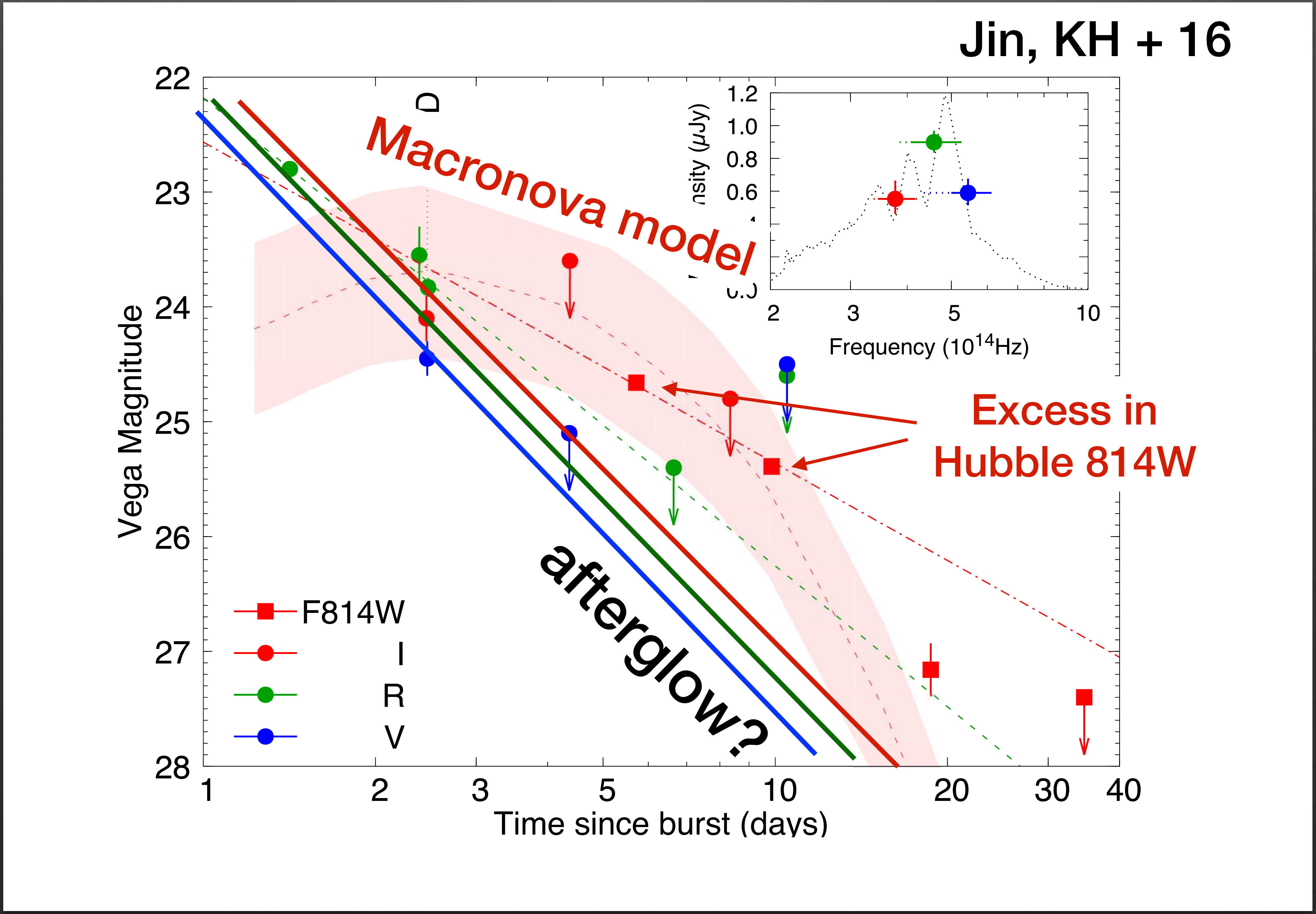
Spectrum evolution



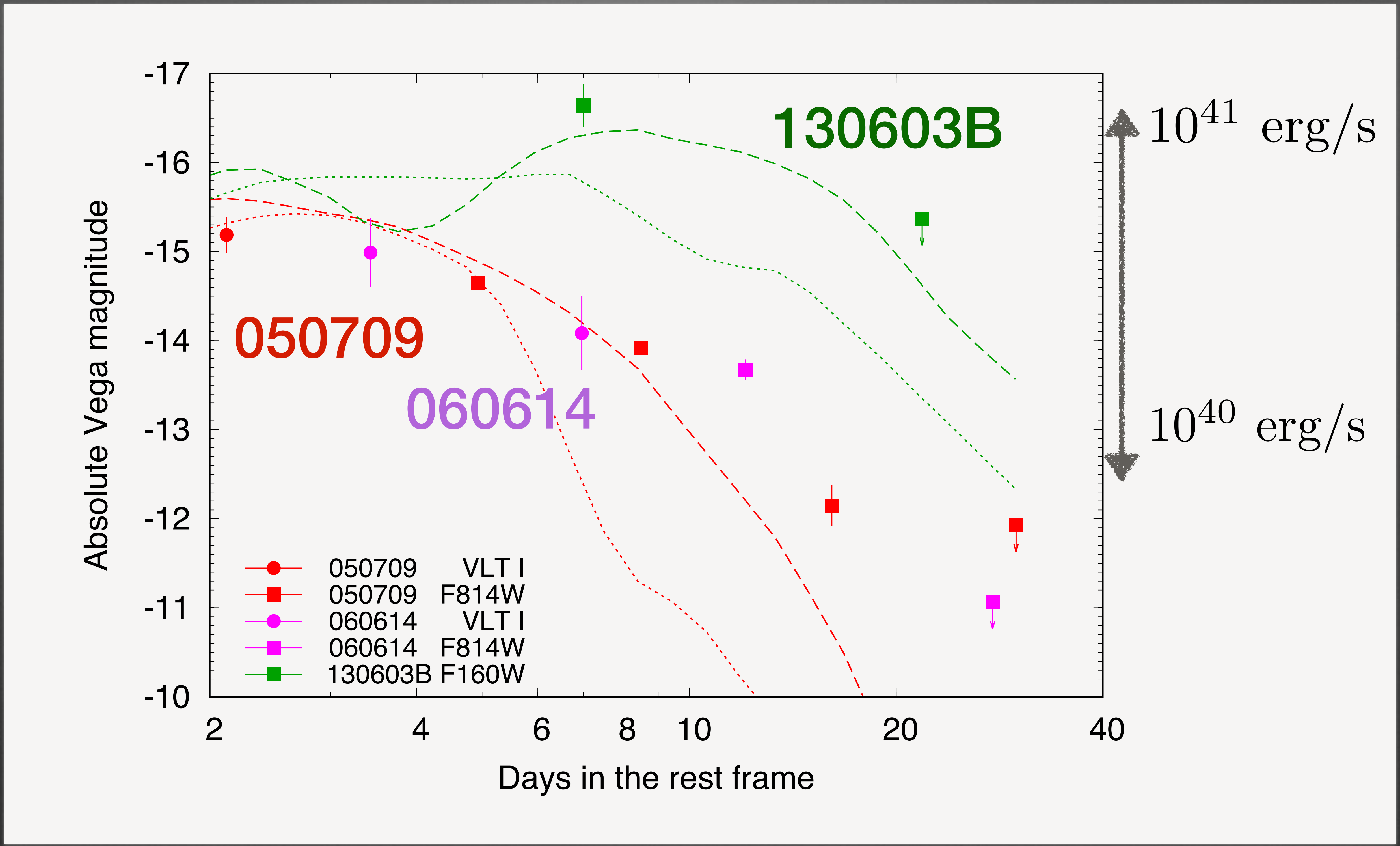
Redding with time is not expected in afterglows. It is consistent with a macronova.

Macronova interpretation of a red bump of GRB 050709

It can be a macronova.



Three macronova candidates



- Peak luminosity ~ 10^41 erg/s.
- The I-band light curves of 050709 and 060614 are quite similar.

Macronova Summary

	Redshift	T90 (s)	Eiso (10^51 erg)	Macronova (erg/s)	Note
GRB 050709	0.16	0.1 (+130)	0.07	10^41 (I-band)	very small host
GRB 060614	0.125	5 (+97)	2.5	10^41 (I-band)	not really a short burst
GRB 130603B	0.356	0.18	2.1	10^41 (H-band)	the first candidate
GRB 150101B no detection	0.134	0.012	0.013	<10^42 (H-band)	Early type host

Note that the detections rely on a few data points.

Outline

- Back of envelope calculation of beta decay heating
- “Historical” Kilonova/Macronova candidates
- Radio remnant

  (1) After short GRB afterglows
  (2) Radio GW counterparts
- Discussion

Relativistic Explosions & Radio emission

	Time Scale	log10(E)	v/c	Detected
SNe II	>10 year	51	0.01	yes
SNe Ibc	1 month	48	0.3	yes
SNe Ia	>10 year	51	0.01	yes (galactic)
GRBs	1 month	51	1	yes
TDEs (jet)	a few year	52	1	yes
optical TDEs	1 year	48	0.1	yes
Magnetar GF	1 month	45	0.3	yes (galactic)
NS mergers	a few year	50.5	0.3	no

Synchrotron Radio Flare from Blast Wave

(Newtonian)

Blast Wave in the ISM

=> particle acceleration=> Synchrotron Radiation

B amplification

$$t_{peak} \approx 80\ day\ E_{50}^{1/3} n^{1/3} \beta_i^{-5/3}$$

p=2.5

$$F_{peak} \approx 3\ mJy\ E_{50} \beta_i^{11/4} n^{7/8} \epsilon_{B,-1}^{7/8} \epsilon_{e,-1}^{3/2} D_{27}^{-2} \nu_9^{-3/4}$$

$$\nu_m \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} \beta^{5}$$

Nakar & Piran 11, KH+16

Synchrotron Radio Flare from Blast Wave

(Newtonian)

Blast Wave in the ISM
=> particle acceleration=> Synchrotron Radiation
B amplification

$$t_{peak} \approx 80\ day\ E_{50}^{1/3} n^{1/3} \beta_i^{-5/3}$$

p=2.5

$$F_{peak} \approx 3\ mJy\ E_{50} \beta_i^{11/4} n^{7/8} \epsilon_{B,-1}^{7/8} \epsilon_{e,-1}^{3/2} D_{27}^{-2} \nu_9^{-3/4}$$

$$\nu_m \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} \beta^5$$

The flux and the peak frequency are sensitive to E and velocity.

Nakar & Piran 11, KH+16

Synchrotron Radio Flare from Blast Wave
(Newtonian)

Blast Wave in the ISM
=> particle acceleration=> Synchrotron Radiation
B amplification

$$t_{peak} \approx 80\ day\ E_{50}^{1/3} n^{1/3} \beta_i^{-5/3}$$

p=2.5

$$F_{peak} \approx 3\ mJy\ E_{50} \beta_i^{11/4} n^{7/8} \epsilon_{B,-1}^{7/8} \epsilon_{e,-1}^{3/2} D_{27}^{-2} \nu_9^{-3/4}$$

$$\nu_m \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} \beta^5$$

The peak flux and frequency depend on (n x e_b).

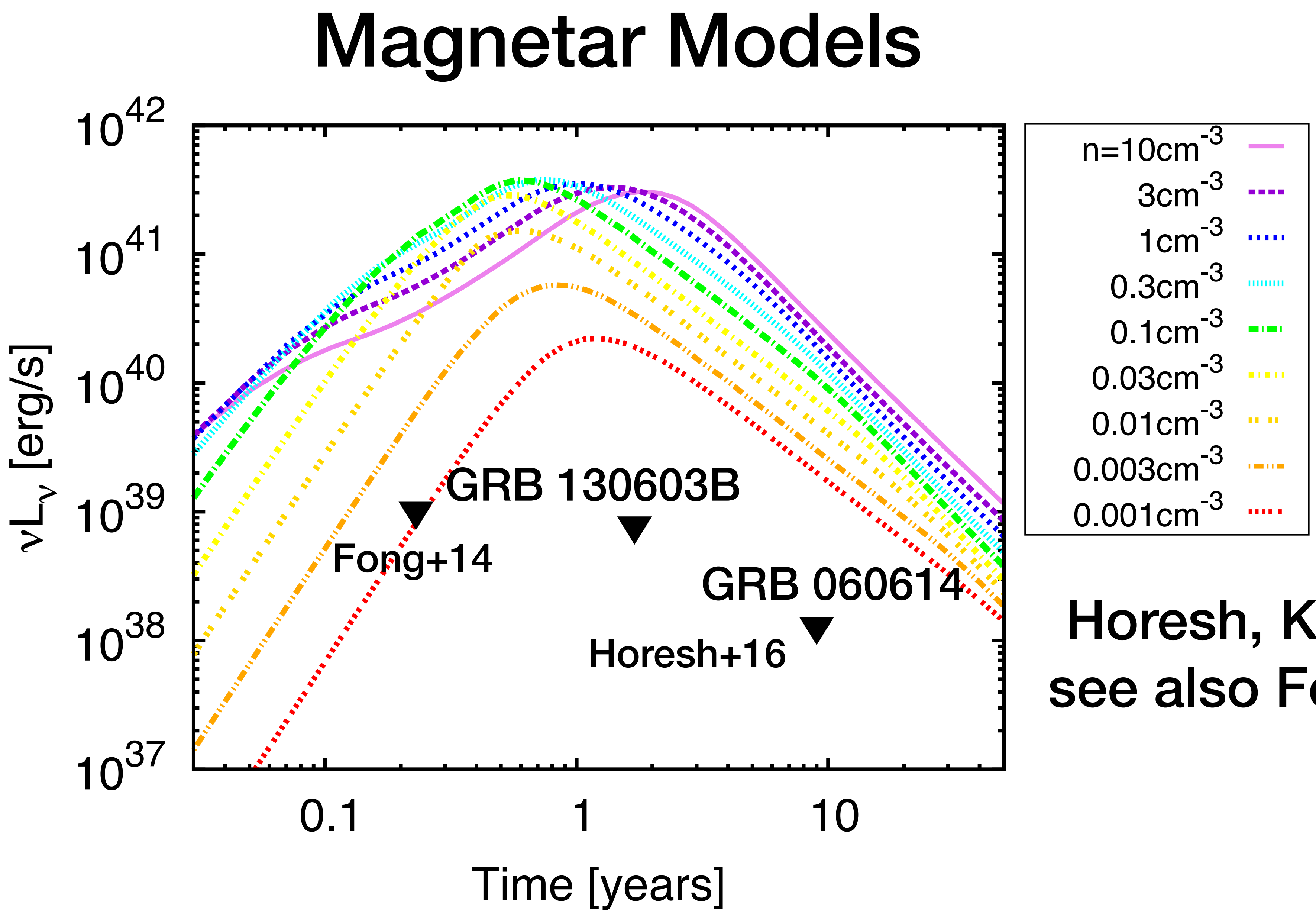
Nakar & Piran 11, KH+16

Radio Macronovae & Supernovae

	Macronova (Neutron star merger)	Radio-Supernova (Core collpase)	Ibc Supernova (Core collapse)
Kinetic energy	a few $10^{50}\,erg$	a few $10^{51}\,erg$	a few $10^{47}\,erg$
velocity	0.2 – 0.3c	0.01c	0.1 – 0.2c
ISM density	$0.1\,cm^{-3}$	Dense wind	$1\,cm^{-3}$
Peak luminosity at 1.4GHz	$10^{27}\,erg/s/Hz$	$10^{26}\,erg/s/Hz$	$10^{26}\,erg/s/Hz$
Peak time scale	a few years	year ~ 10 years	10 days - month
Peak frequency	< 1 GHz	1 – 5 GHz	1 – 5 GHz

Ref: Nakar & Piran 11, KH & Piran 15, KH+16

No radio remnant is found



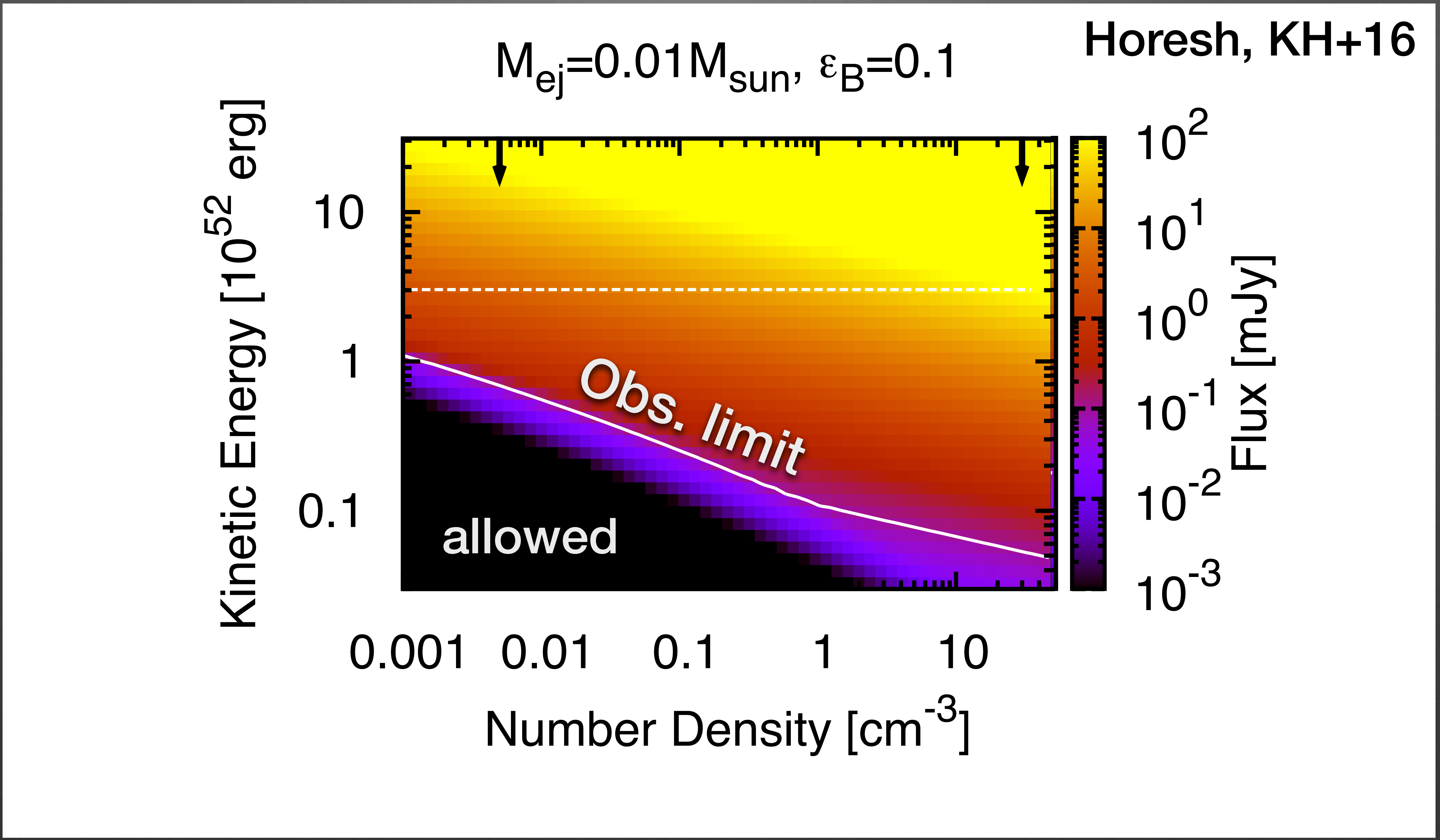
Horesh, KH + 16
see also Fong+16

Upper limits are still consistent with the merger radio remnant.

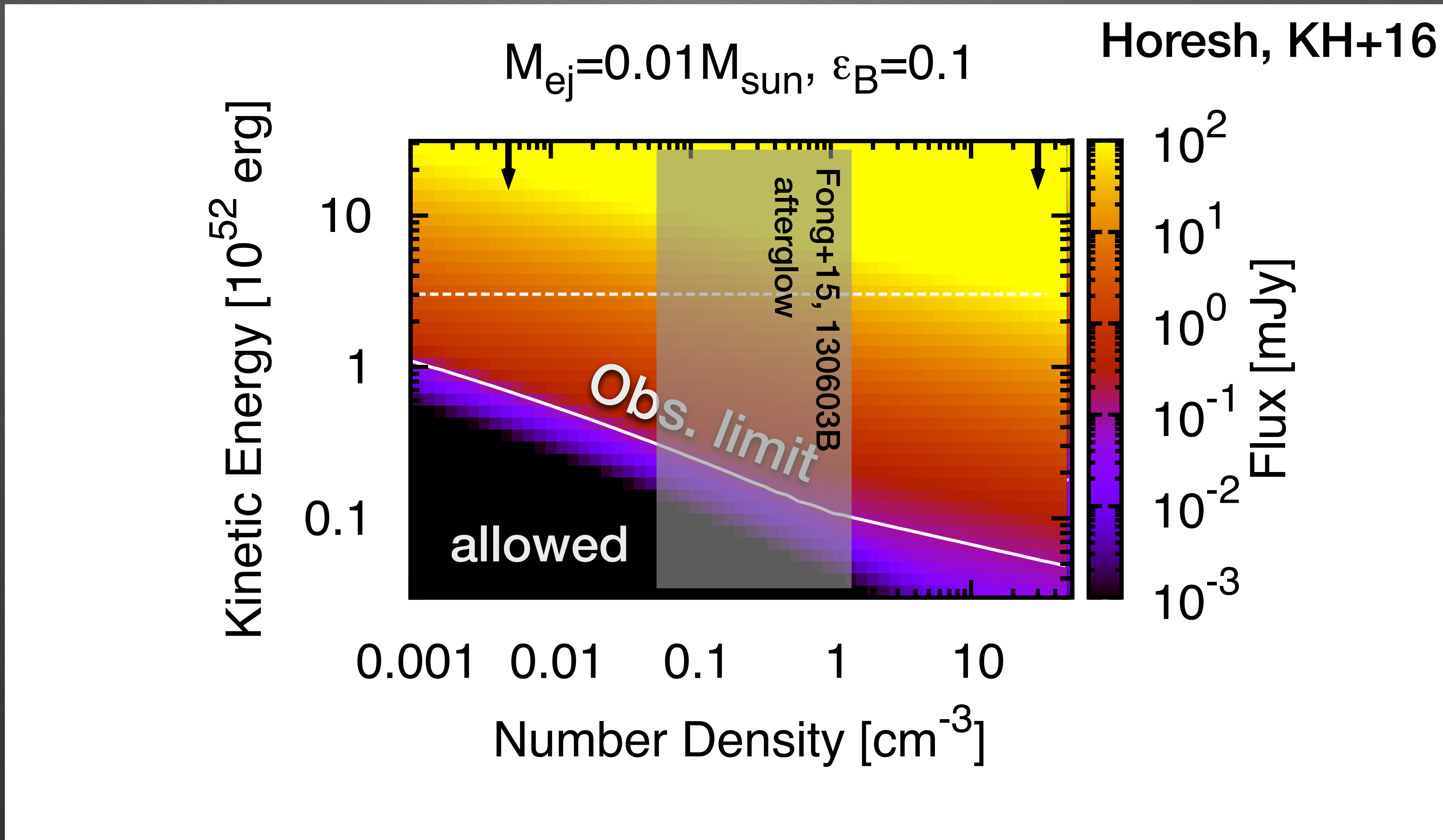
Exclude the existence of a powerful magnetar after these short GRBs.

Please do not neglect relativistic effects for magnetars (not use Nakar & Piran 11).

Limit on the ejecta kinetic energy



Limit on the ejecta kinetic energy



$E_K \lesssim 4 \cdot 10^{51}$ erg

this is still consistent with the dynamical ejecta.

Outline

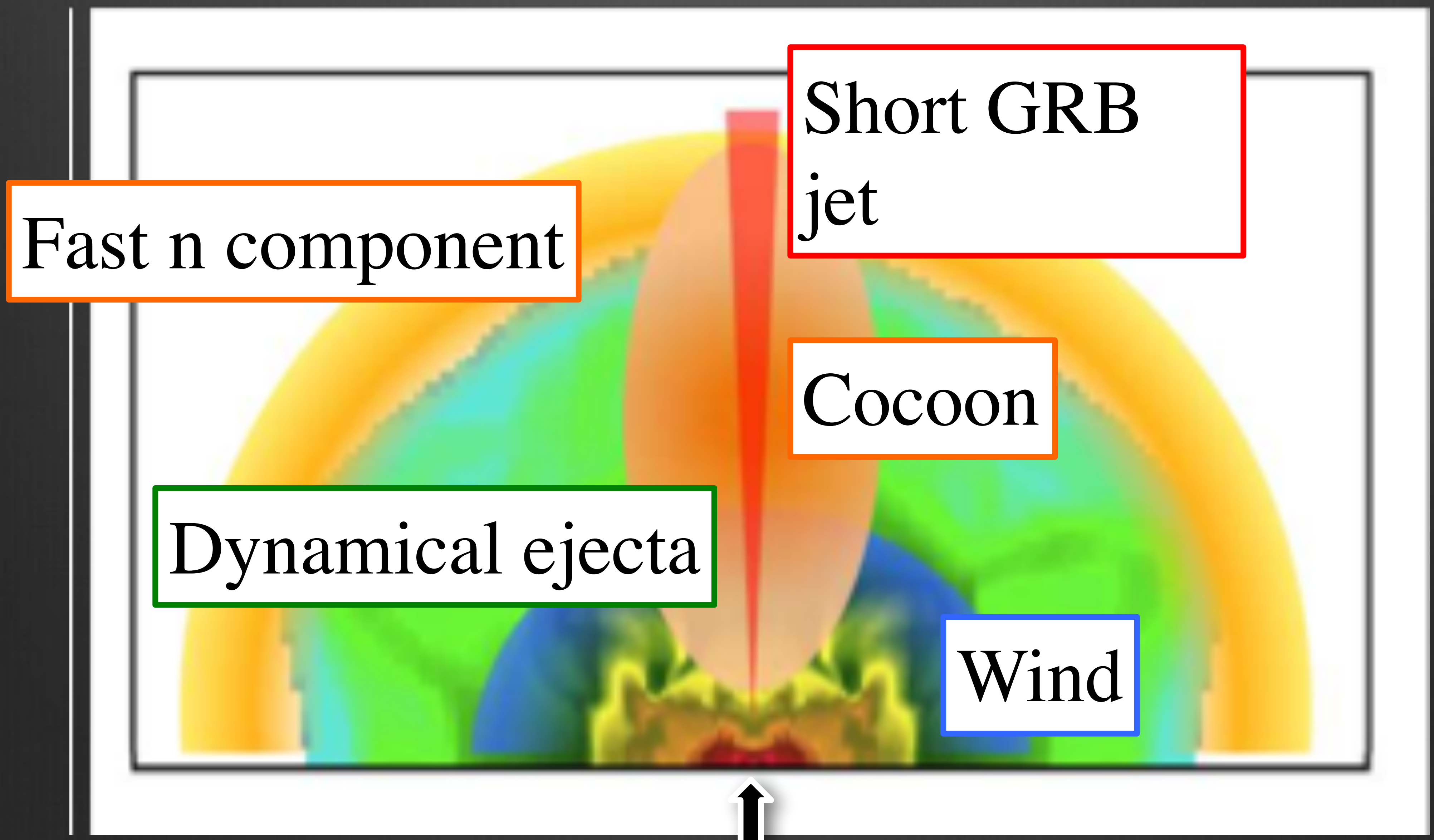
- Back of envelope calculation of beta decay heating
- “Historical” Kilonova/Macronova candidates
- Radio remnant

    (1) After short GRB afterglows
    (2) Radio GW counterparts

- Discussion

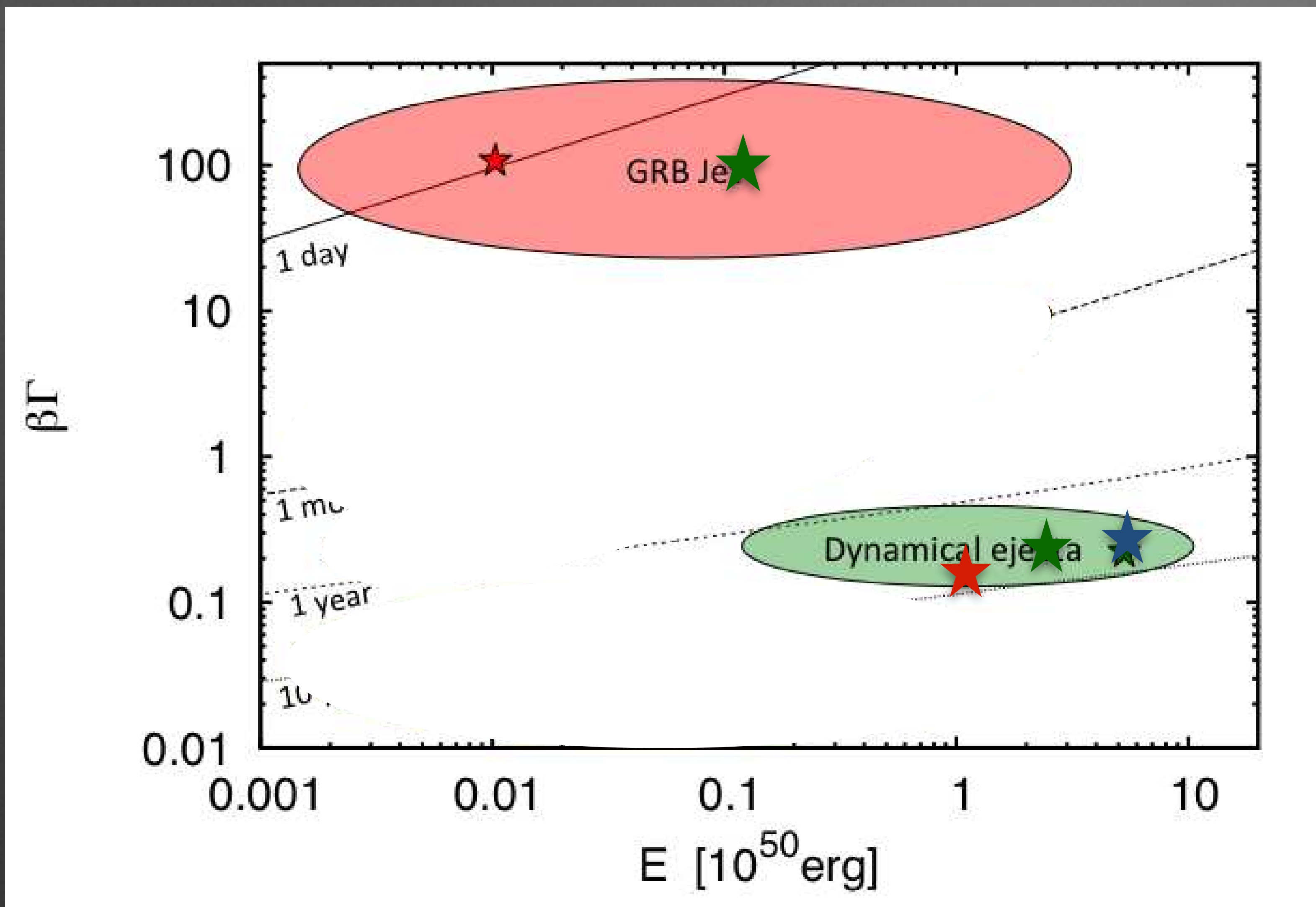
Dynamical ejecta, Wind, GRB jet…

KH & Piran 2015



Central remnant: BH or NS + accretion disk

Model: Energy, velocity, ISM density



Hotokezaka & Piran 2015

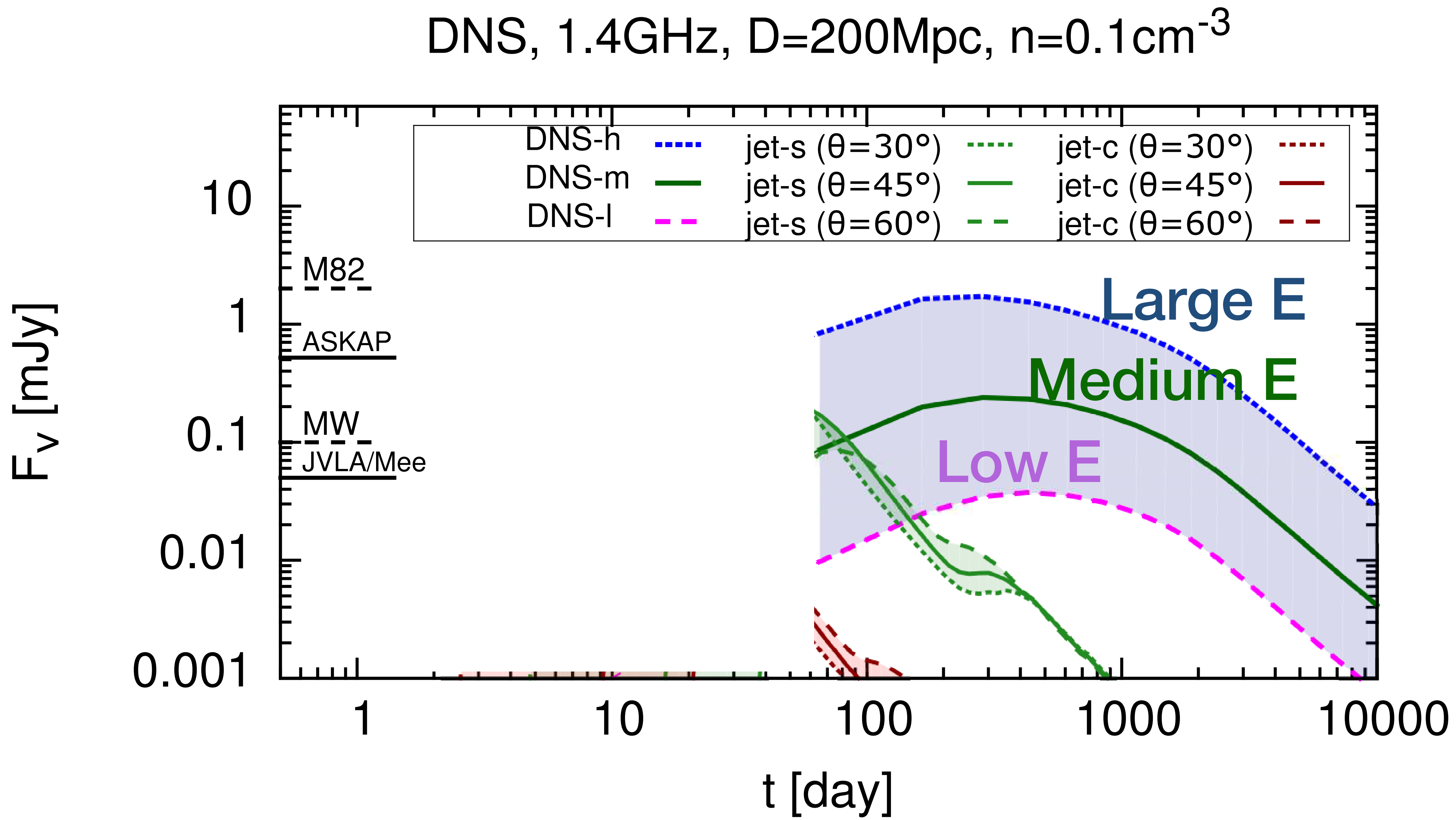
Energy
GRB jet: 10^48, 10^49 erg
(e.g., Nakar 2007, Fong et al 2015)

Ejecta: 0.2c, 10^50 erg
0.25c, 3*10^50 erg
0.3c, 10^51 erg

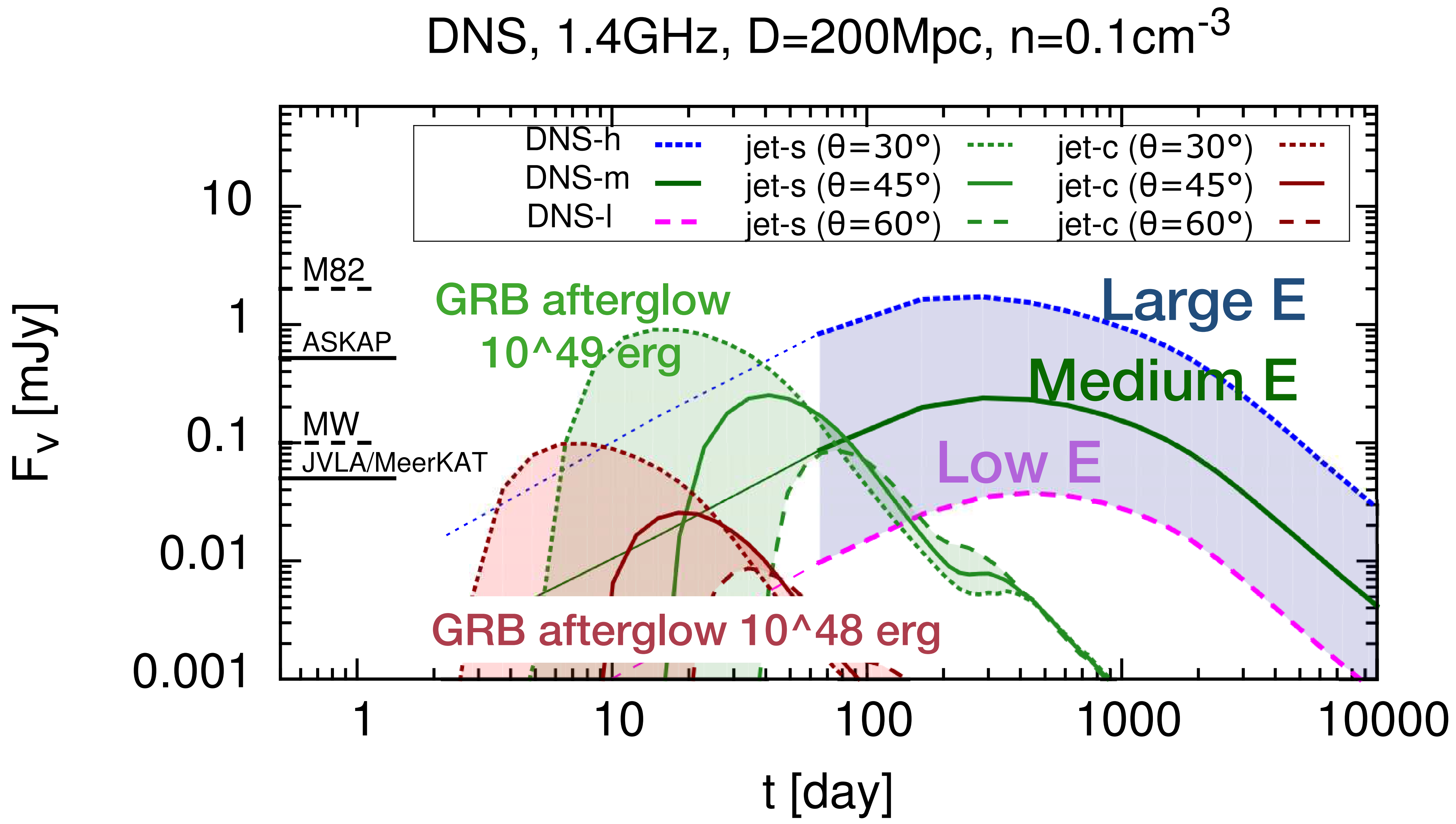
ISM density: 0.01~1 cm^-3

Miscrophys parameters:
p=2.5, e_b = e_e = 0.1 (fixed)

Expected Radio Light Curves after a GW event



Expected Radio Light Curves after a GW event



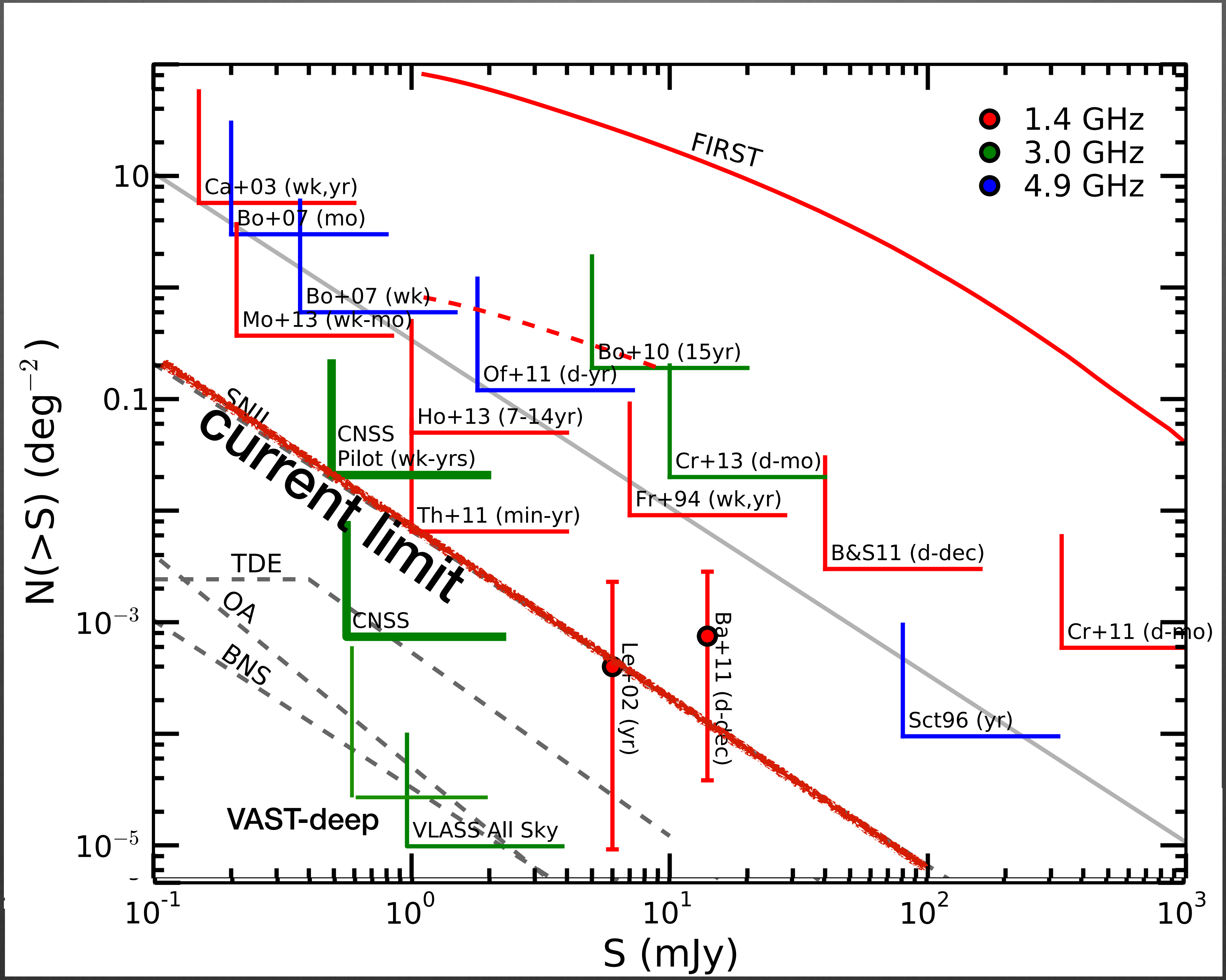
Radio Survey Facilities (in this 5 yrs)

	Frequency (GHz)	SEFD (Jy)	FoV (deg^2)	Survey Speed (deg^2/hr)	Angular resolution (arcsec)
LOFAR	0.15	31	11.35	8.2 (240)	10
JVLA	1.4	13	0.25	14	4.3
ASKAP	1.4	87	30	20	7
MeerKAT	1.4	7.7	0.86	140	5.25

Survey Speed at a noise rms of 100 micro Jy.

Radio Transient Sky & Upcoming Surveys

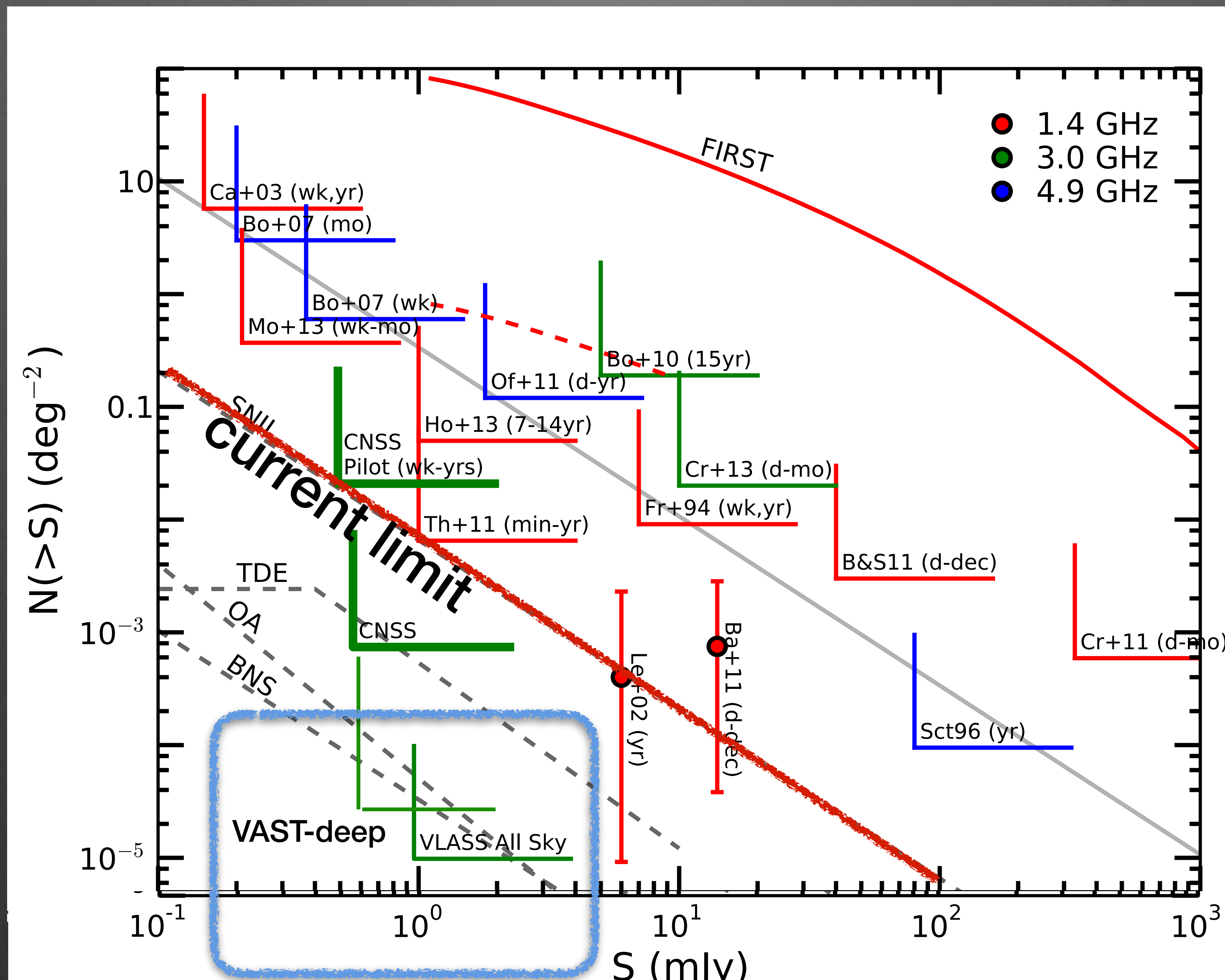
Snapshot of radio transient sky



Mooley et al 2016

Radio Transient Sky & Upcoming Surveys

Snapshot of radio transient sky

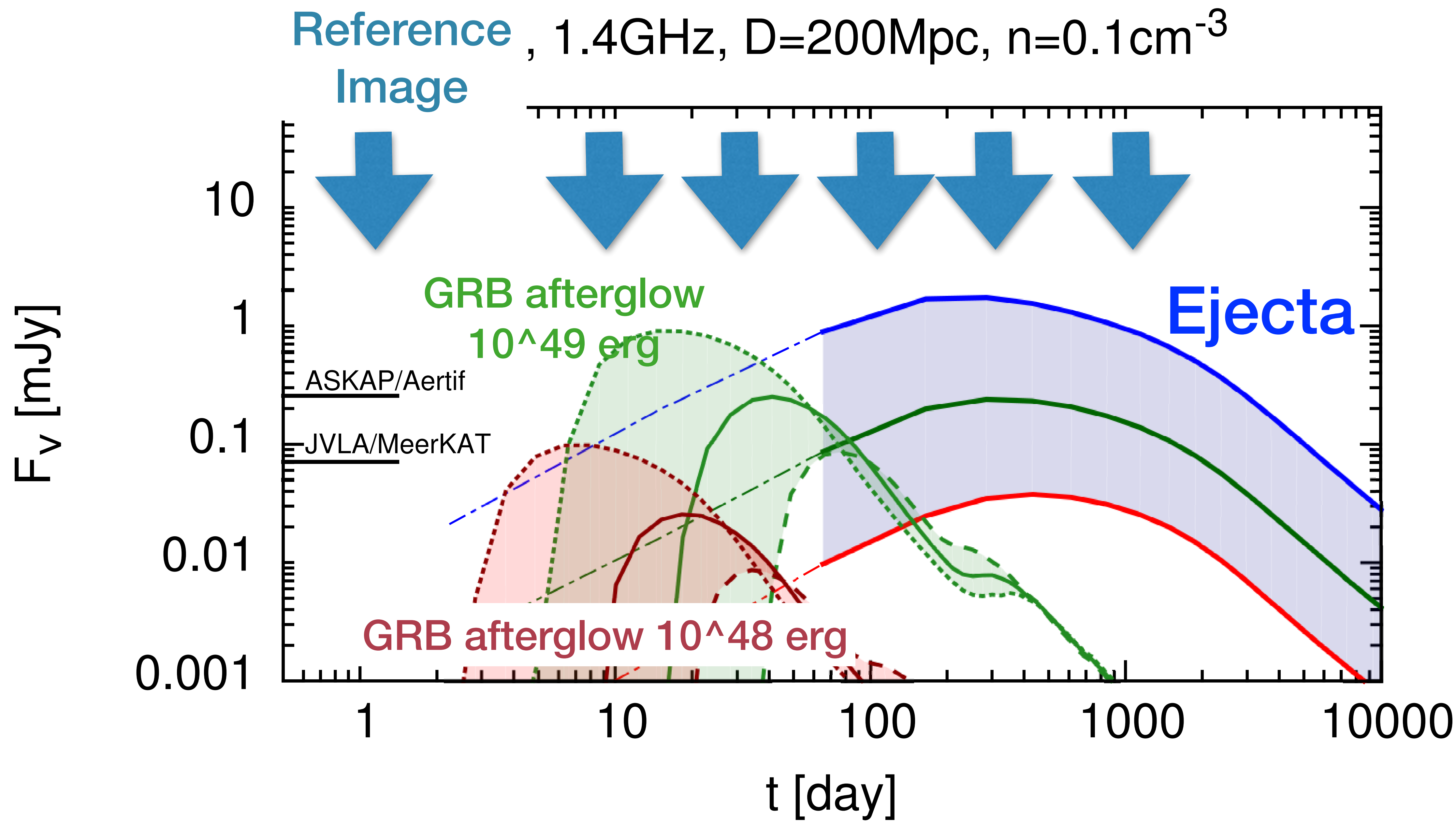


VLA & ASKAP

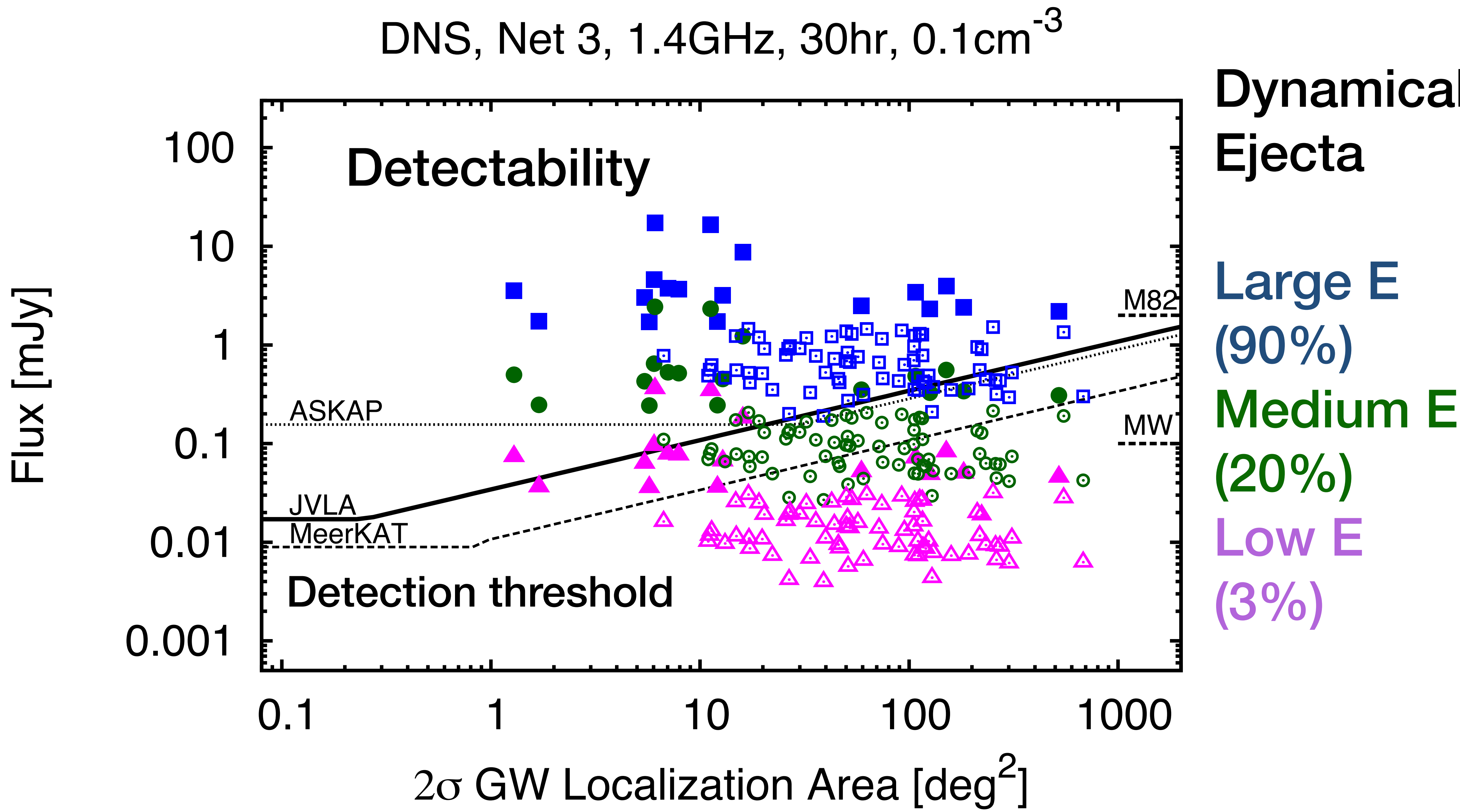
Mooley et al 2016

Significant improvement !! (3 orders of magnitude)

Survey with a logarithmic time interval



Radio Macronovae as GW counterparts

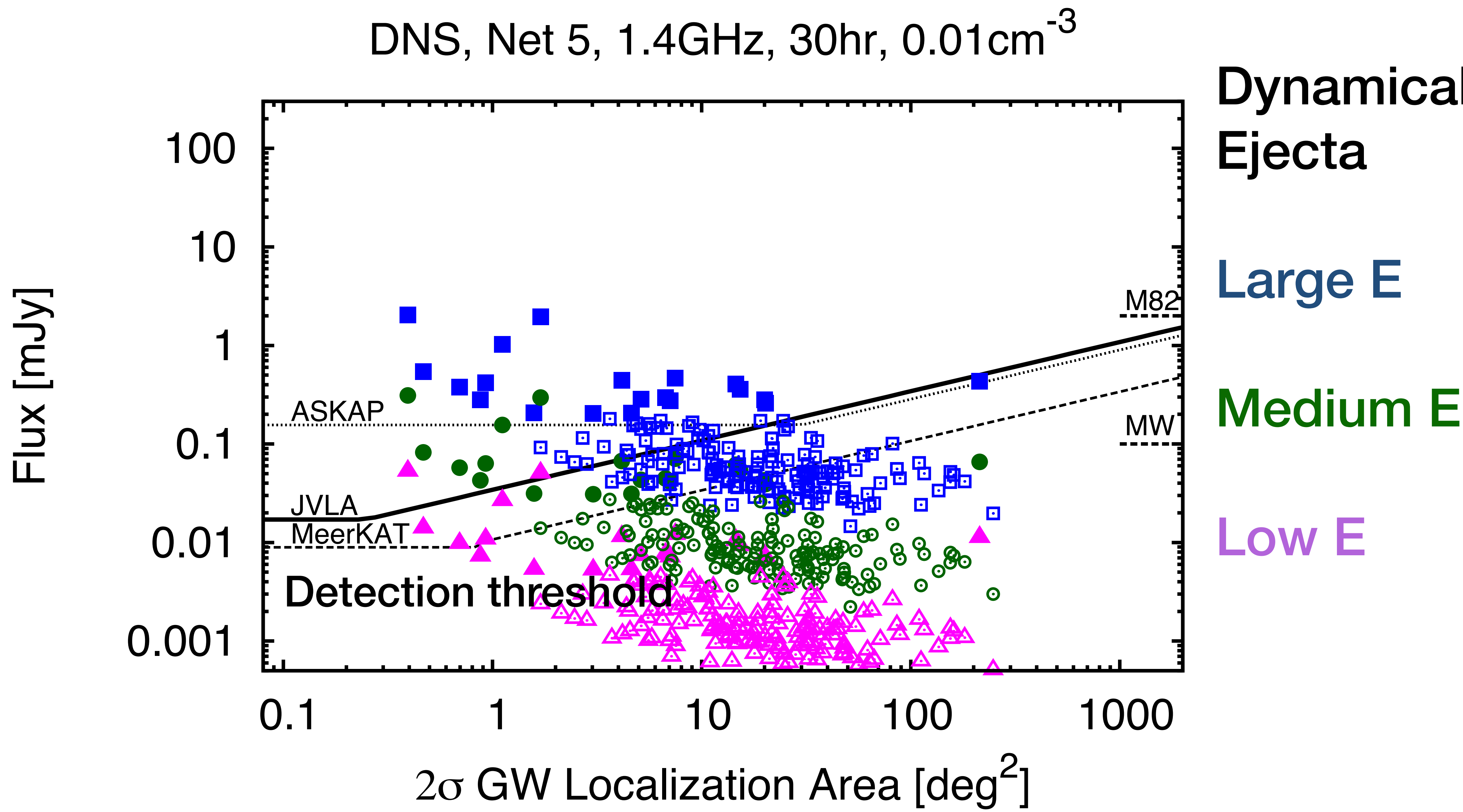


KH+16

Filled points: nearby events D<200Mpc

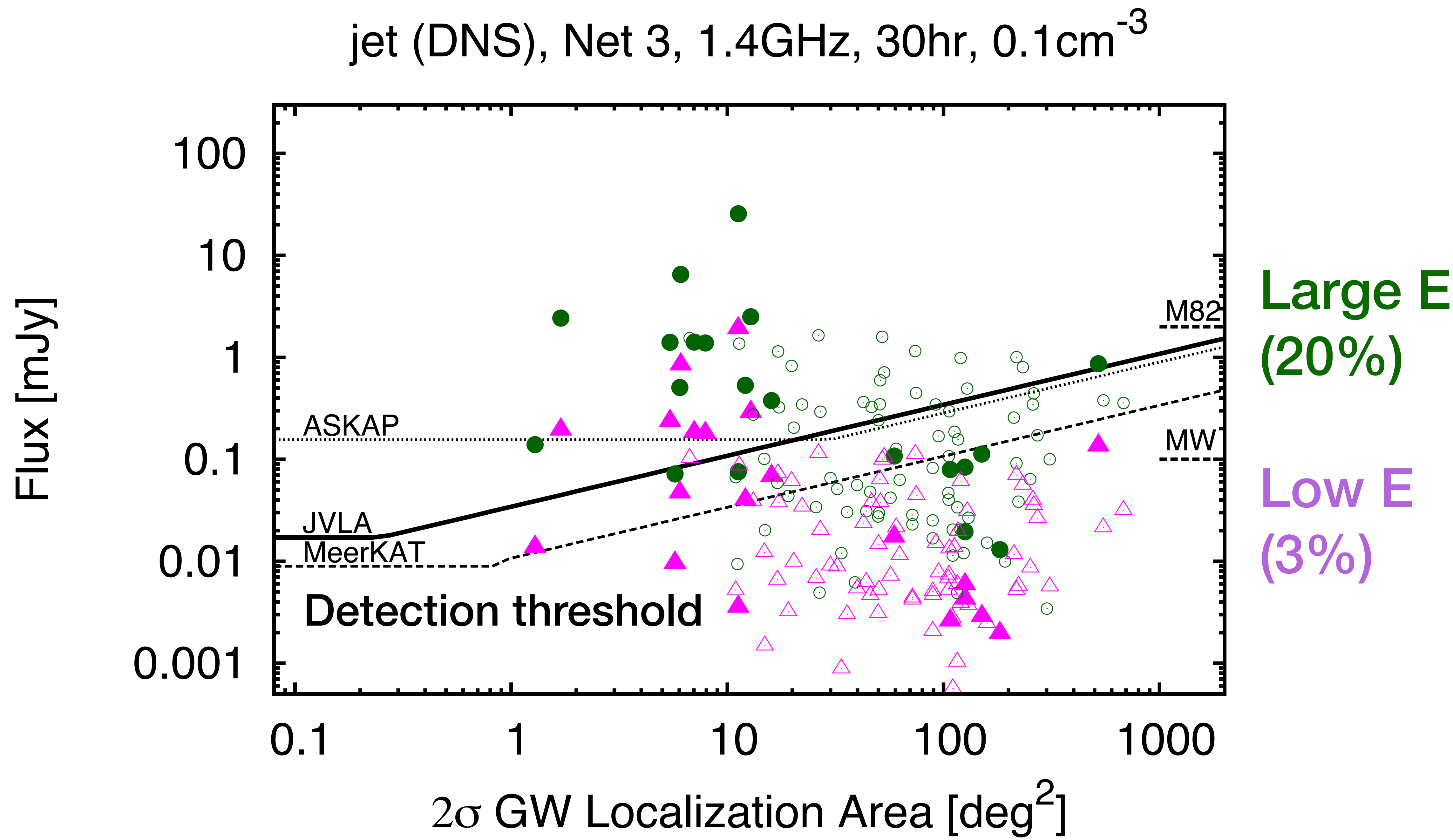
Point: radio false positives are quite rare, e.g., a few % of optical

Detection Likelihood:
Dynamical ejecta, ISM density=0.01cm^-3



Filled points: nearby events D<200Mpc

Detection Likelihood
GRB afterglow, ISM density =0.1cm^-3



Filled points: nearby events D<200Mpc

Identifying GW-Radio counterparts: Astrophysical False Positives

"Radio transient sky is very quiet compared to the optical sky"

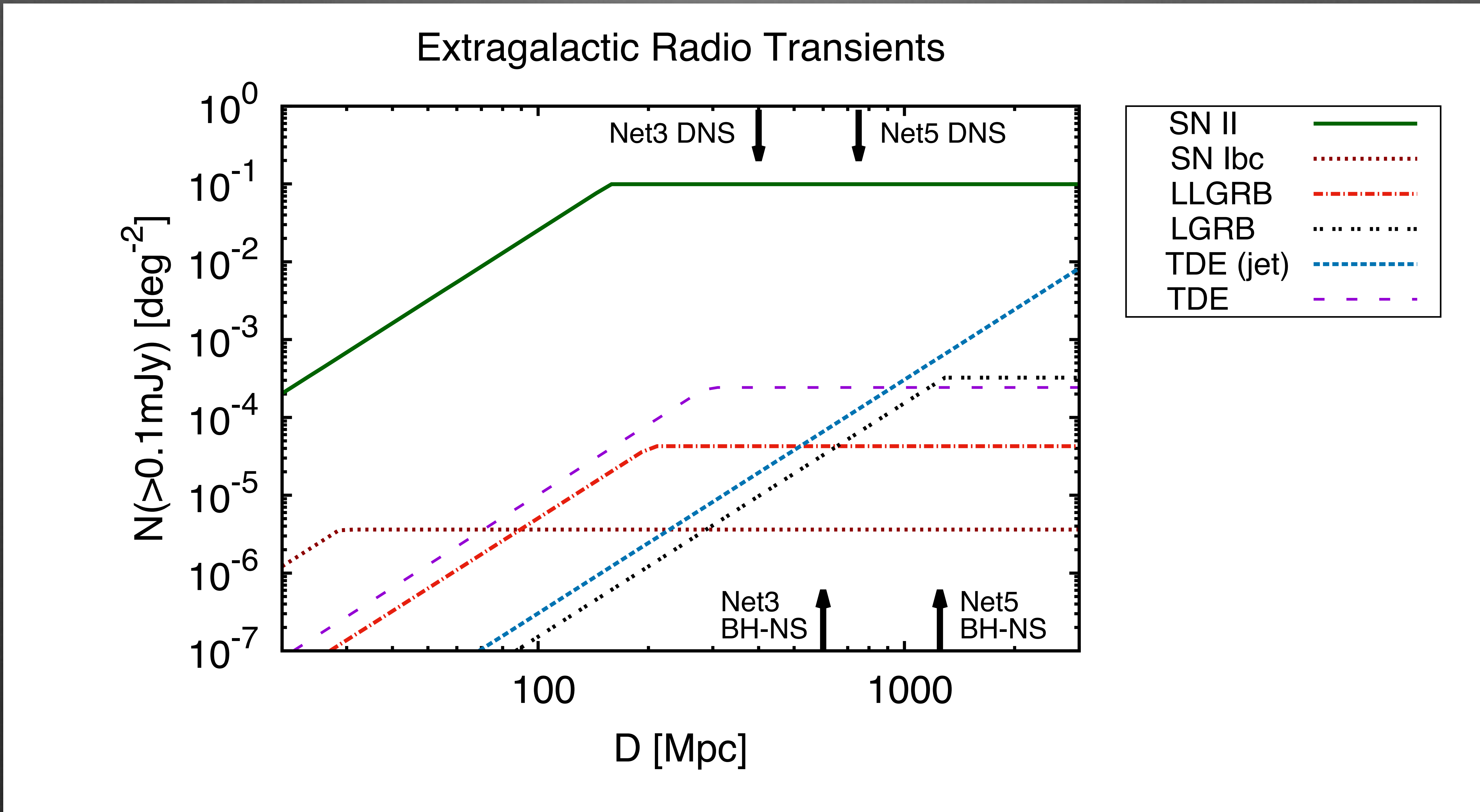
Optical-IR false positives: ~ 60 deg^-2 at 24th mag.

Nissanke et al 2013

Radio False Positives:

1. Extragalactic radio transients (supernovae, GRB etc)
2. radio variables (Active Galactic Nuclei)

False Positives: Number of radio transients at 0.1mJy

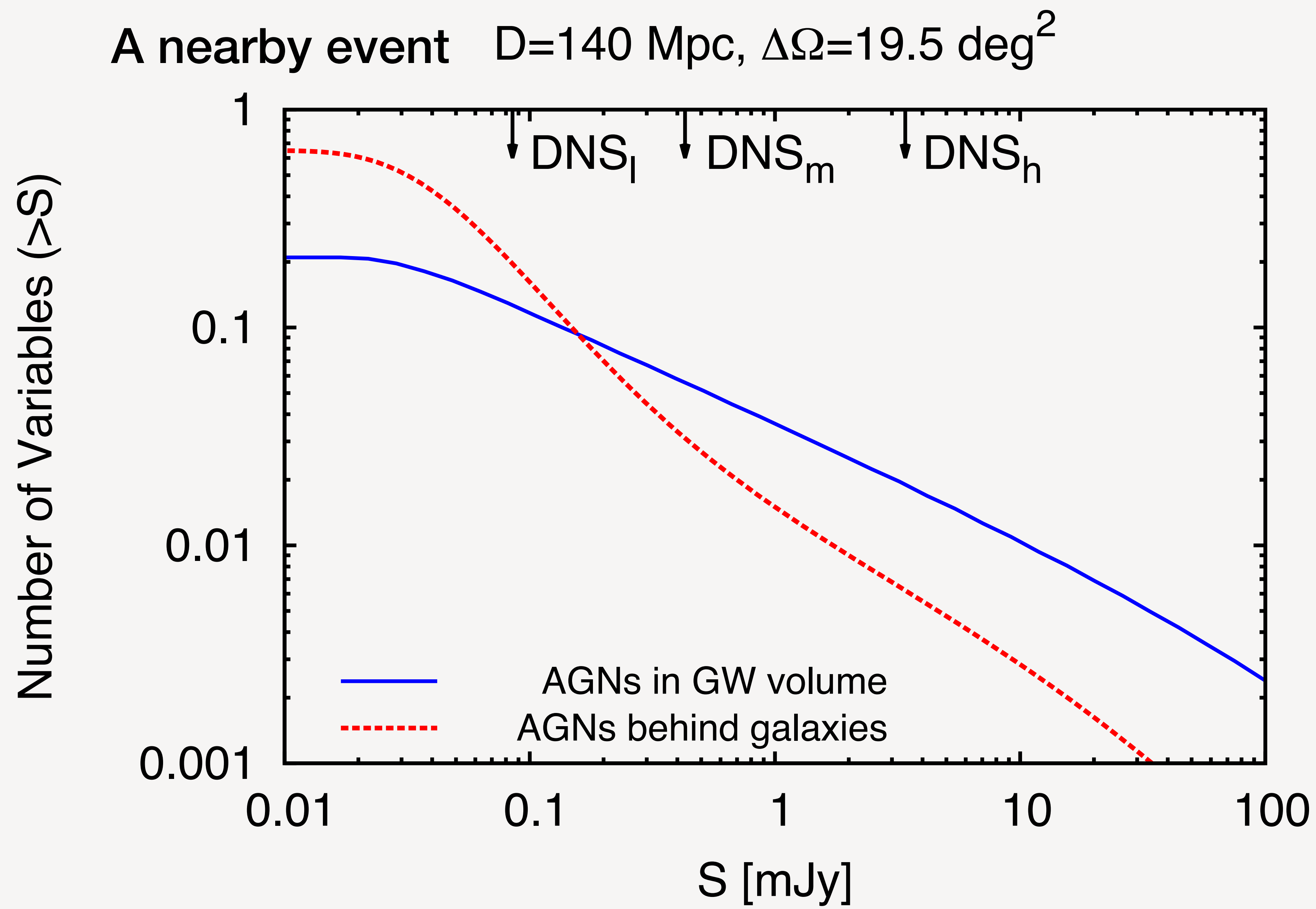


For GW events, the localization say ~100 sq. deg.

=> ~10 type II supernovae may be found.

False Positives: Radio Variables

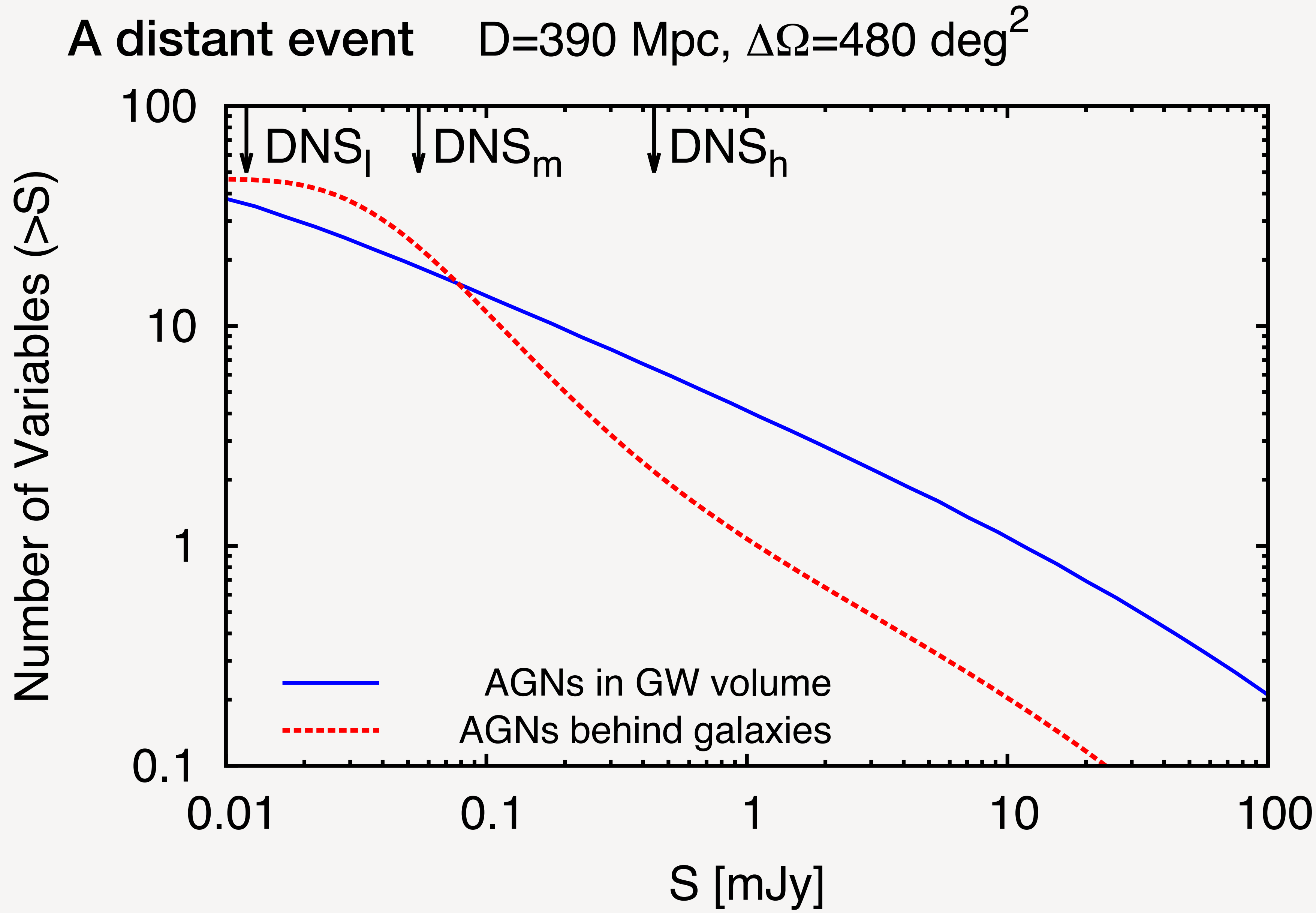
(1) AGNs inside the GW localization volume.
(2) AGNs behind the host galaxy candidates.



Assuming 1% of AGNs are variables.

False Positives: Radio Variables

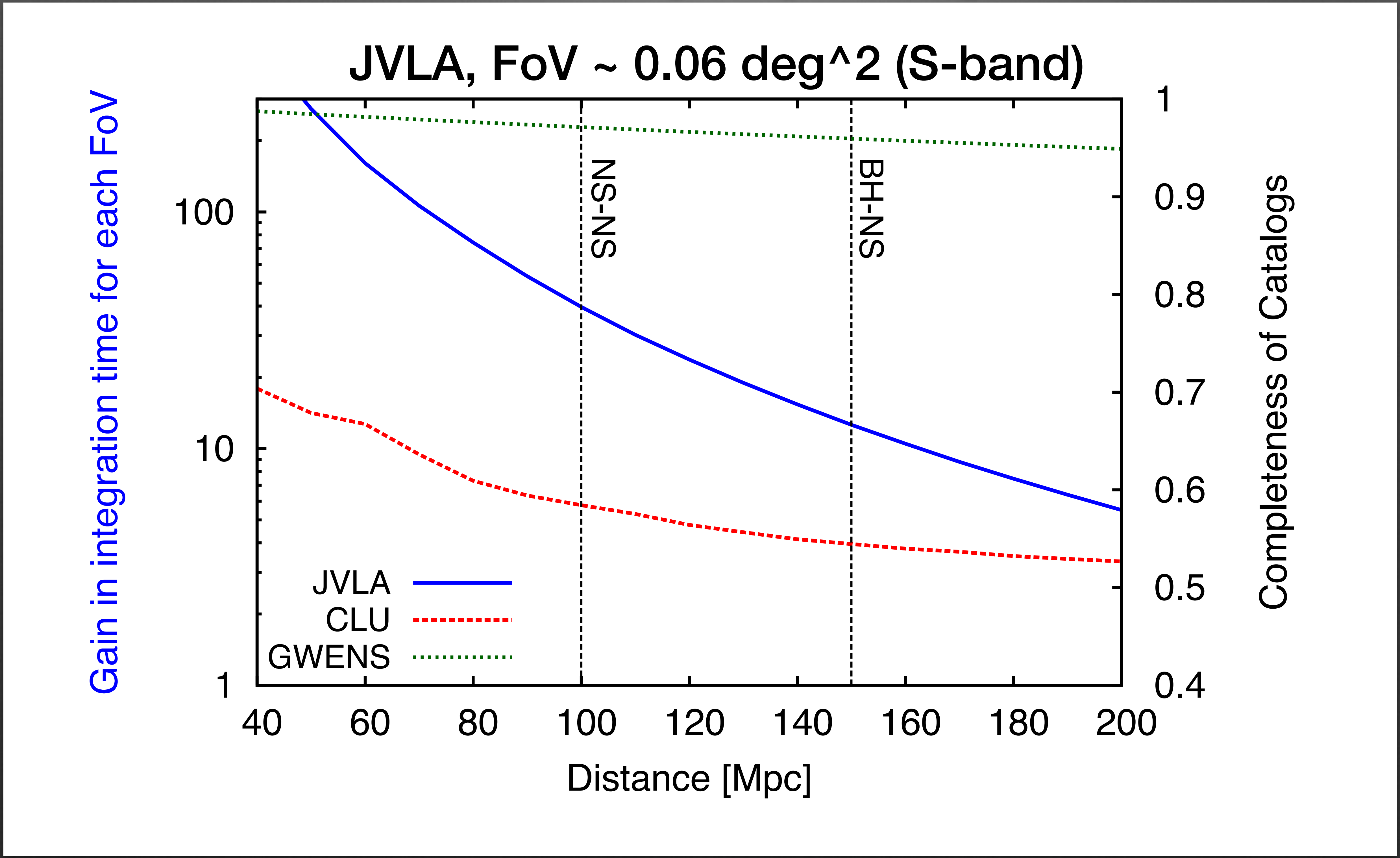
(1) AGNs inside the GW localization volume.
(2) AGNs behind the host galaxy candidates.



Assuming 1% of AGNs are variables.

Galaxy targeted search in O2 run

Small FoV => Use local galaxy catalogs



For DNSs, the sensitivity increases by a factor of ~7 when using the catalogs.

Summary

- Macronova/Kilonova powered by r-process nuclei: 22-25th mag at the I-band with a few days to 1 week.

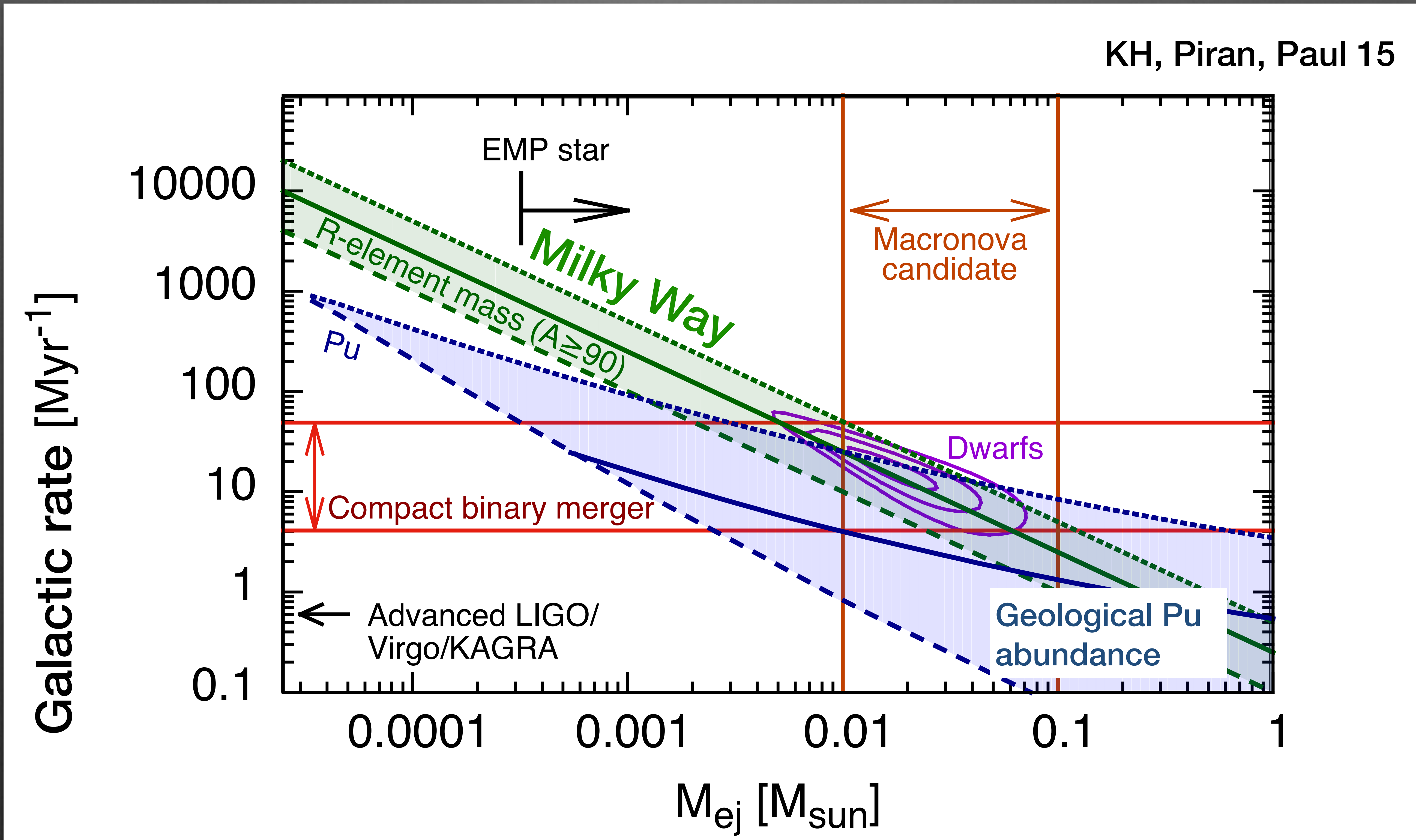
- Three macronova candidates.

- Radio counterparts: 0.01 - 1 mJy at 100 - 1000 days after merger.

- There will be a number of false positives due to radio transients (mainly supernovae) and variables (AGNs).

=> It will be quite important to qualify radio variable statistics at 0.1 mJy level.

Rate vs Mass/event of r-process



Ref: Battistini&Bensby 16 for the Milky Way, Macias & Ramirez-Ruiz 16 for Extremely Metal Poor Stars, Tuner+07, Wallner +15, KH+15 for geological Pu-244, Ji+16, Roederer+16, Bemiamini, KH, Piran 16 for Dwarf galaxies Tanvir+13, Berger+13, KH+13, Yang+15, Jin+16 for macronovae, Kim+15, Wanderman & Piran 15, Ghirlanda+16 for compact binary mergers

problem? Galactic DNS, SGRB, r-process, Theory

(1) Macronova/kilonova mass estimate <=> theory

Too much material?

(2) Late-time activity in SGRB <=> theory

What does produce the late X-ray emission?

(3) The galactic DNSs <=> SGRB offsets

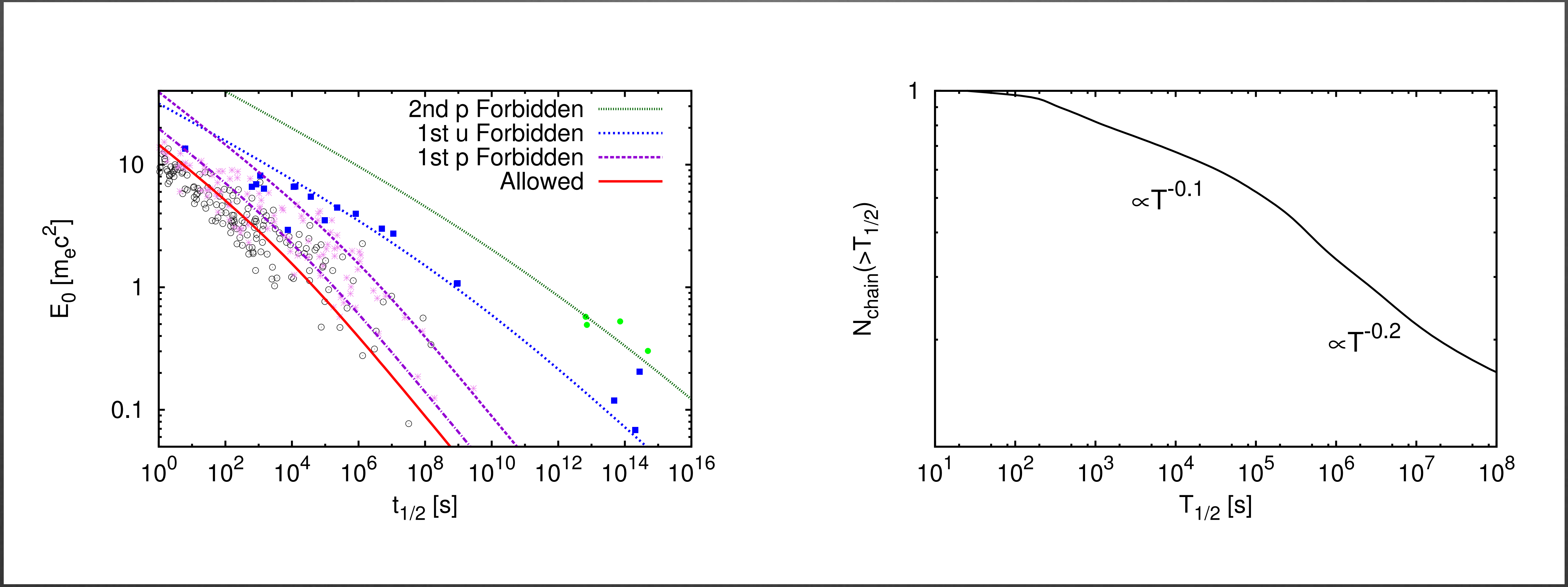
Why we see DNSs only in the galactic disk?

(4) The galactic DNSs & SGRB <=> r-process

Is there delay time?

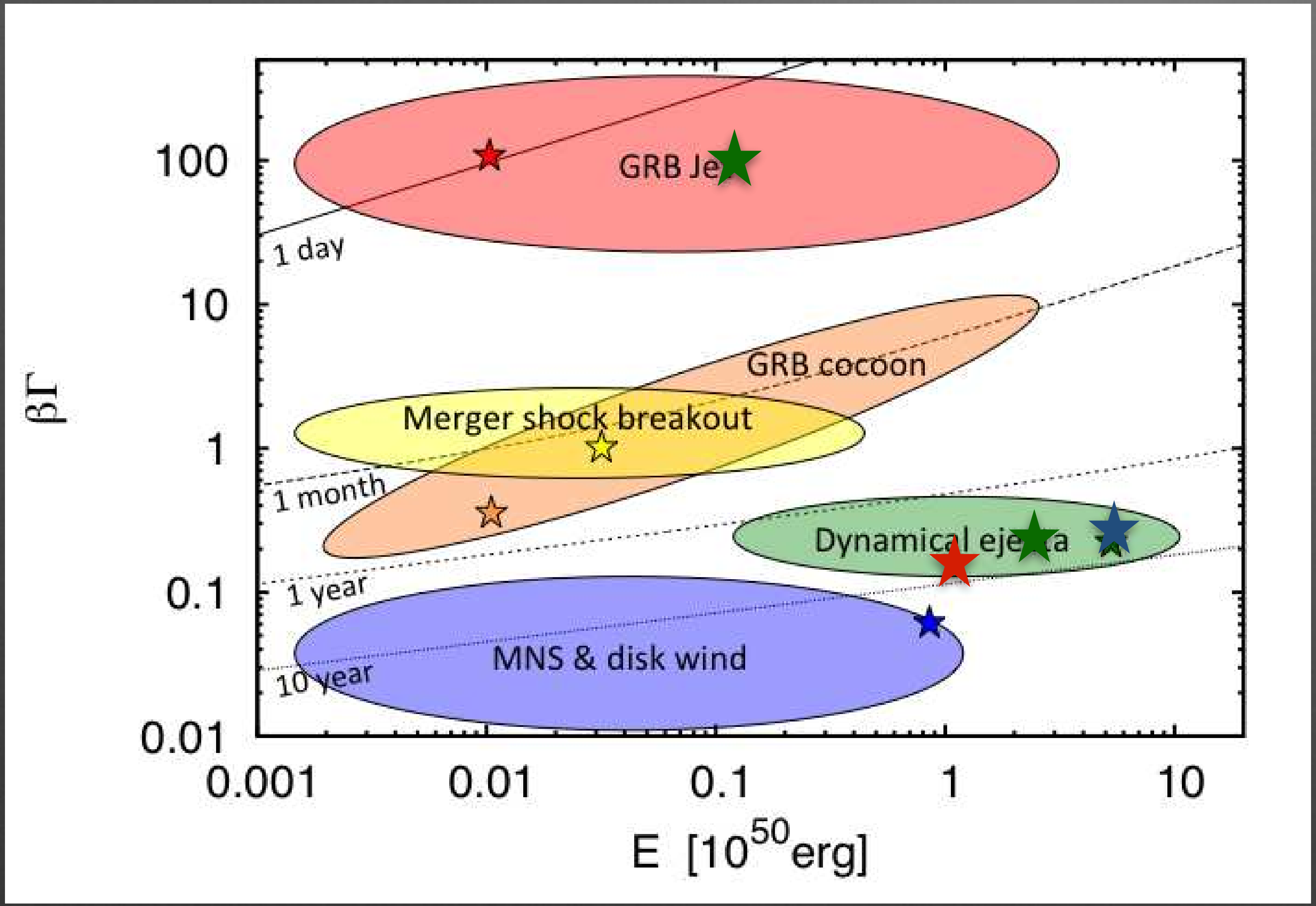
Some deviations from our approximations

Note that forbidden transitions and the decrease of the total number of radioactive nuclei slightly change our formula.



Metzger et al 2010 show the slope of the heating with a different assumption from ours, disappearing chains. In reality, it is between the two assumptions.

Model: Energy, velocity, ISM density



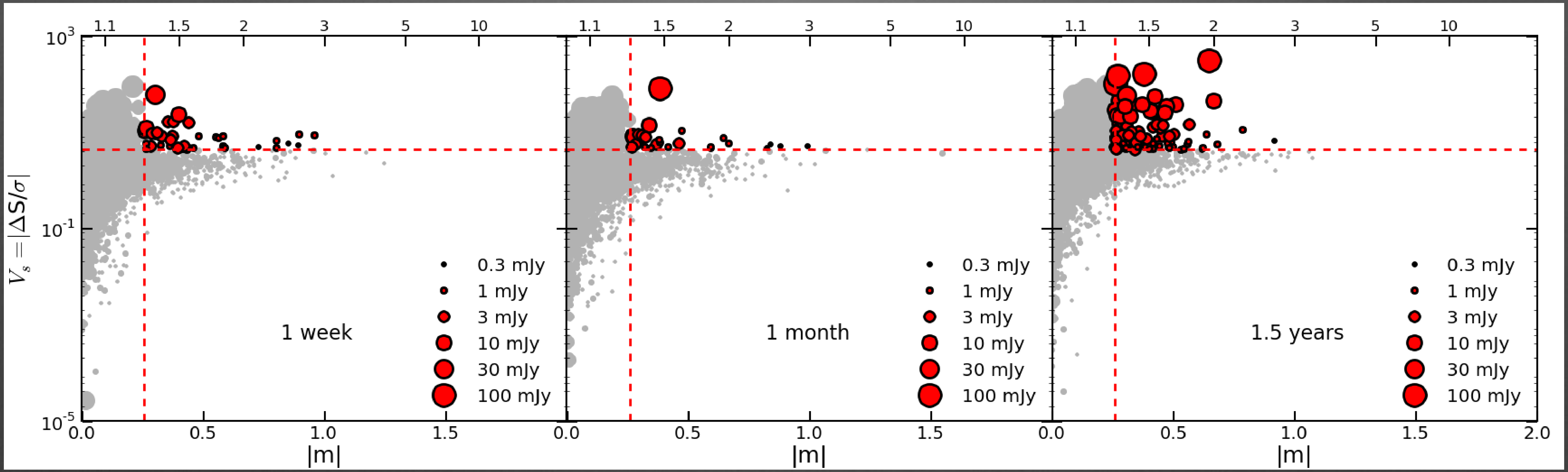
Hotokezaka & Piran 2015

Energy
GRB jet: 10^48, 10^49 erg
(e.g., Nakar 2007, Fong et al 2015)

Ejecta: 0.2c, 10^50 erg
0.25c, 3*10^50 erg
0.3c, 10^51 erg

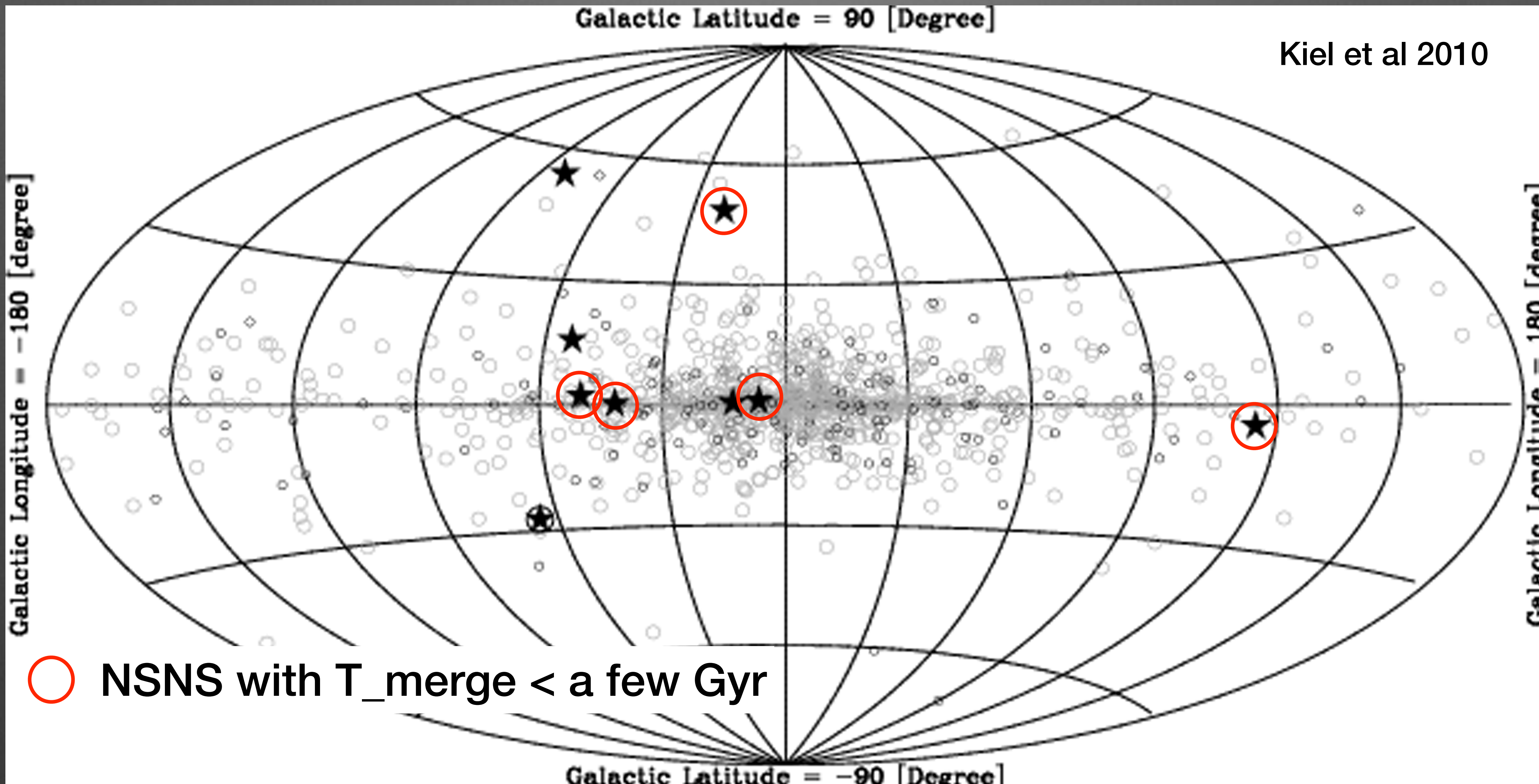
ISM density: 0.01~1 cm^-3

Miscrophys parameters:
p=2.5, e_b = e_e = 0.1 (fixed)



1.1
1.5
2
3
5
10
10^3
10^{-1}
10^{-5}
$V_s = |\Delta S/\sigma|$
0.0
0.5
1.0
1.5
2.0
|m|
1 week
1 month
1.5 years
0.3 mJy
1 mJy
3 mJy
10 mJy
30 mJy
100 mJy

Discussion: Circum-Merger density

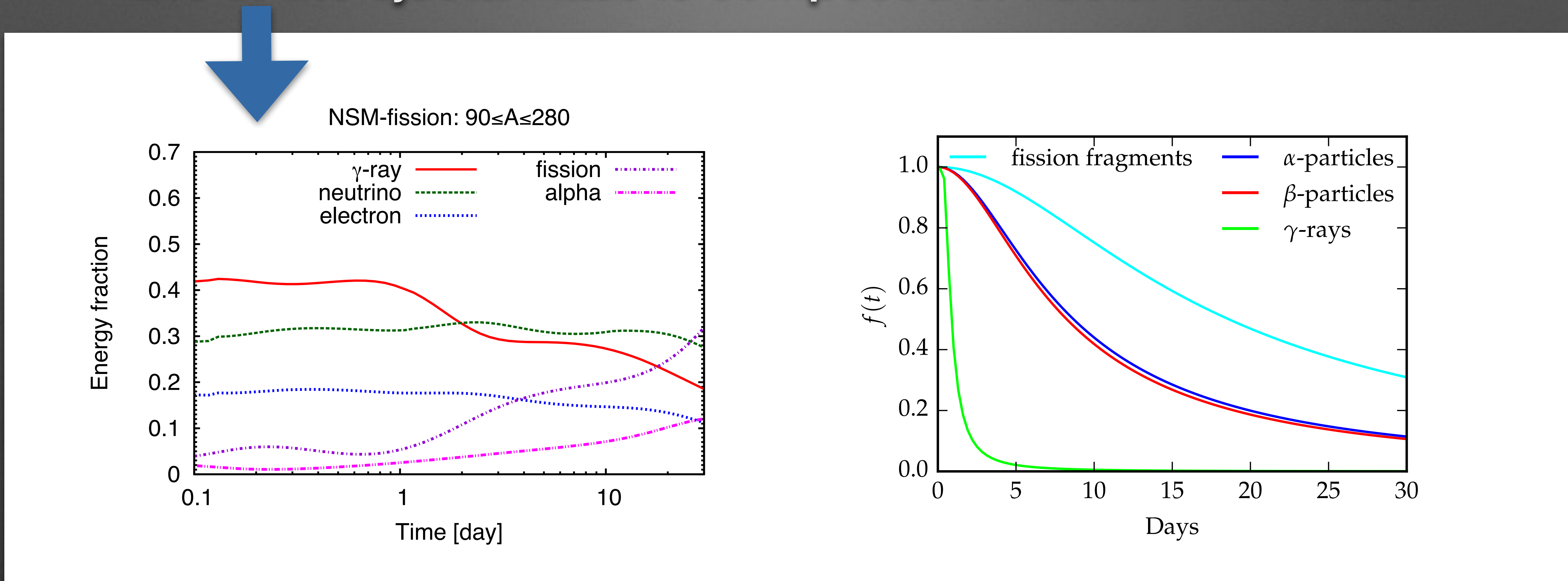


In the galactic disk (Draine 2010):

1) warm neutral gas, ~0.5 cm^-3, volume filling 40 %
2) warm ionized gas, ~0.3-10^4 cm^-3, 10 %
3) hot ionized gas, ~0.004 cm^-4, 50 %

Spontaneous Fission and Alpha-decay?

Hypothetical assumption:
2% of the ejecta mass is composed of nuclei with A>250.



The thermalization efficiency of fission fragments is high.
Fission may dominate the late time heating???