Radio Flares from Neutron Star merges + More

Tsvi Piran

Kenta Hotokezaka, Ehud Nakar, Ben Margalit

Paz Beniamini, Stephan Rosswog

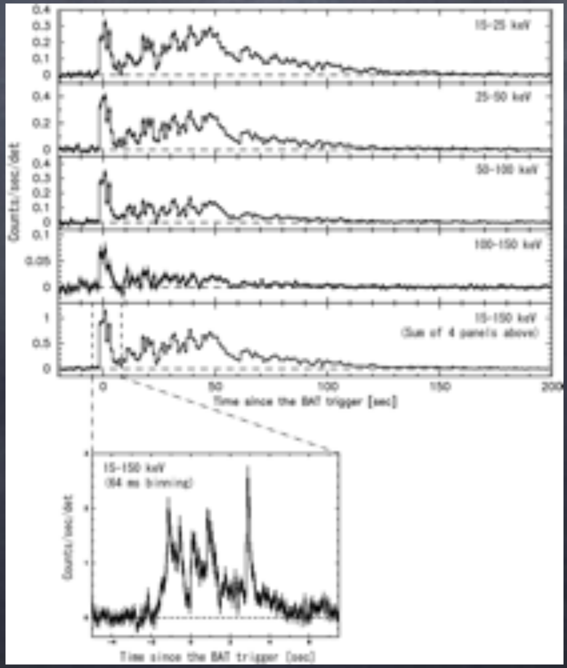
Outline

- A 2nd Macronova (Yang + 15, Nature comm in press.)
- Remarks about nucleosynthesis (Hotokezaka + Piran 15 in prep)
- Radio Flares (Nakar Piran, 11 Nature, ……)

The Macronova in 060614

Bin Yang Zhi-Ping Jin, Xiang Li, Stefano Covino, Xian-Zhong Zheng, Kenta Hotokezaka, Yi-Zhong Fan Tsvi Piran, Da-Ming; Wei Nature Phys. 2015

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



Kilonova
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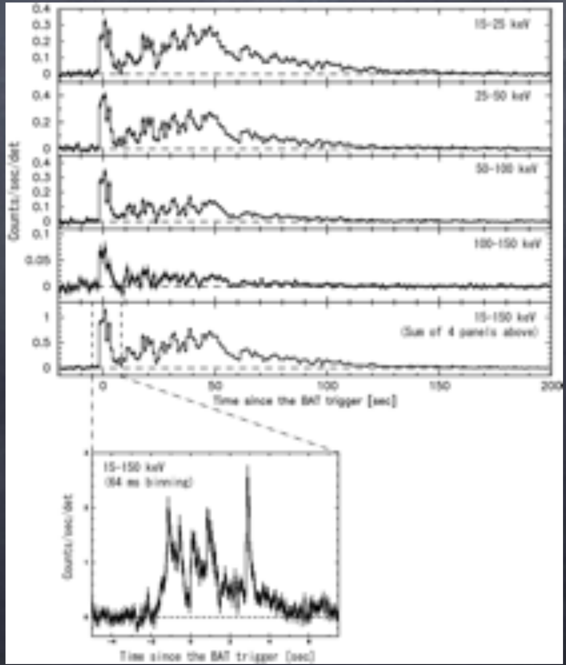

~~Kilonova~~ -> Hectonova

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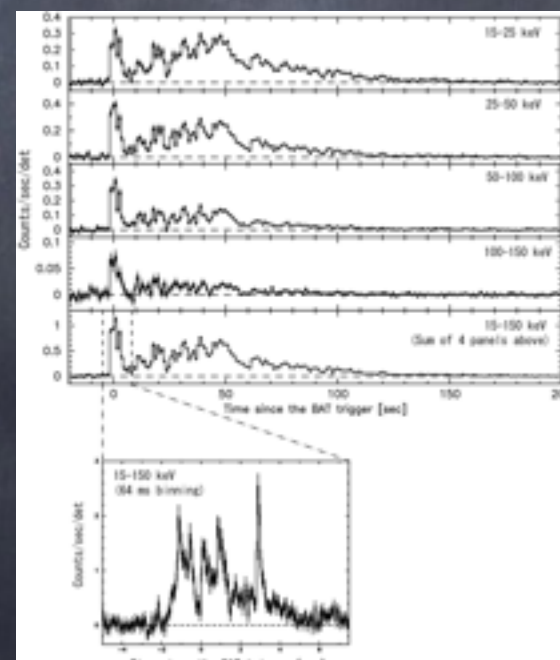

~~Kilonova~~ -> ~~Hectonova~~->Decanova?

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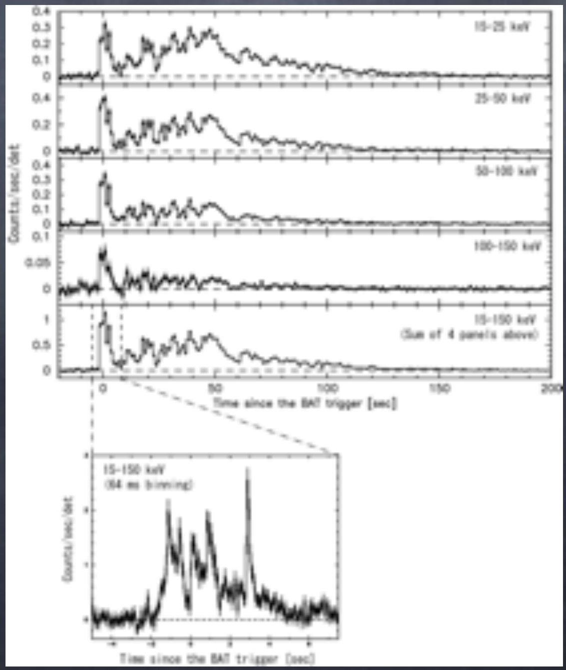

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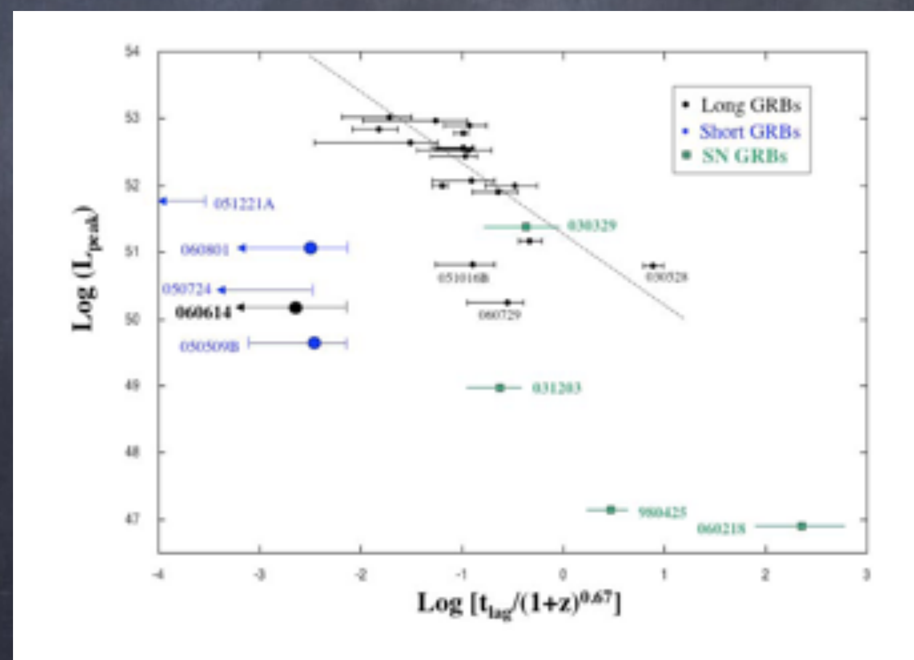


The Macronova

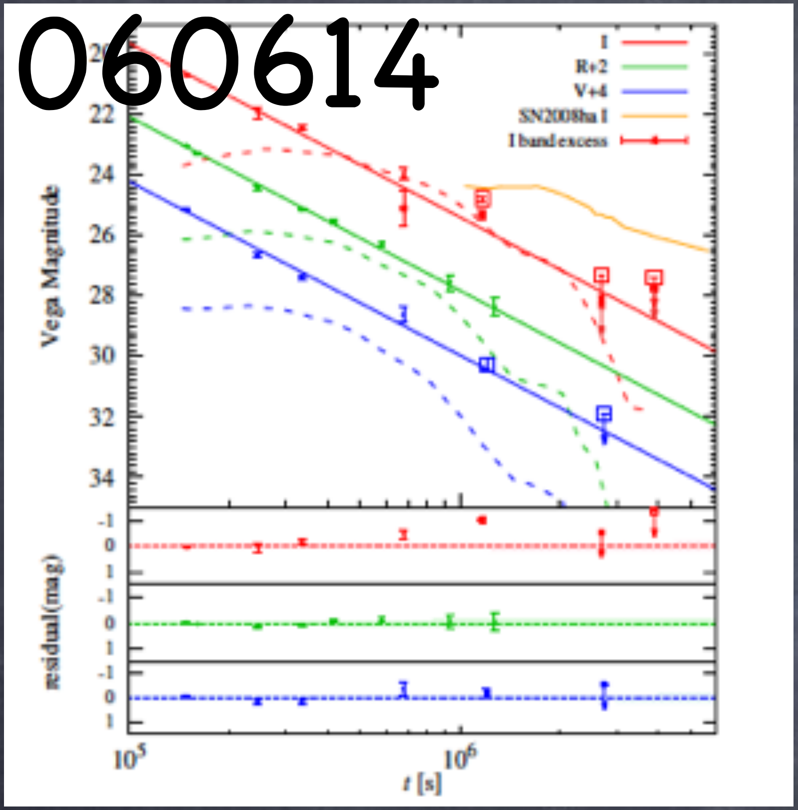
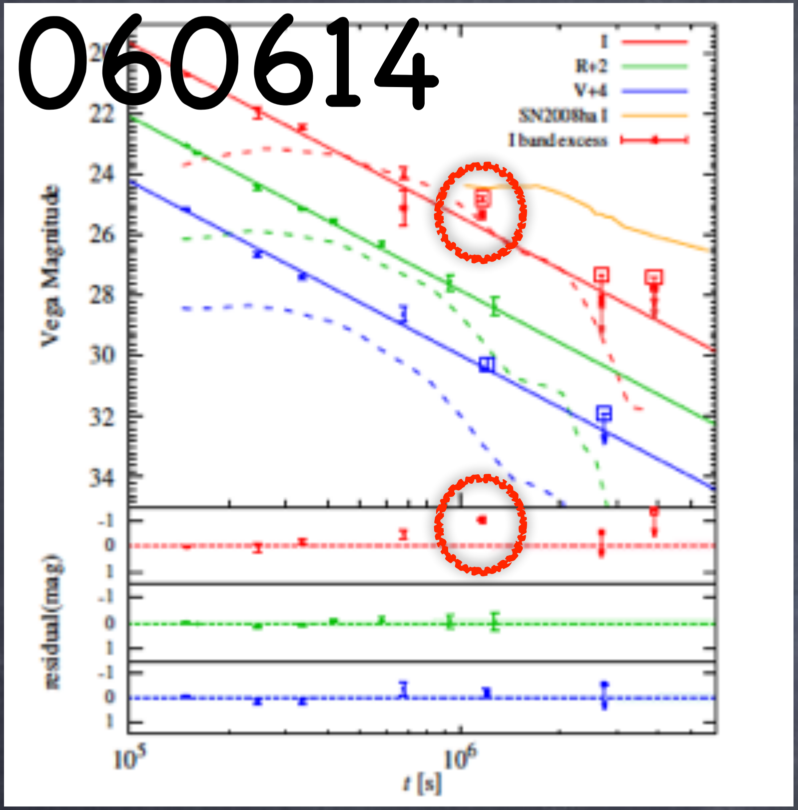


FIG. 1. **The afterglow emission of GRB 060614.** The VLT and HST observation magnitudes including their 1σ statistical errors of the photon noise and the sky variance and the 3σ upper limits (the downward arrows) are adopted from Supplementary Table 1. The small amounts of foreground and host extinction 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.

The Macronova



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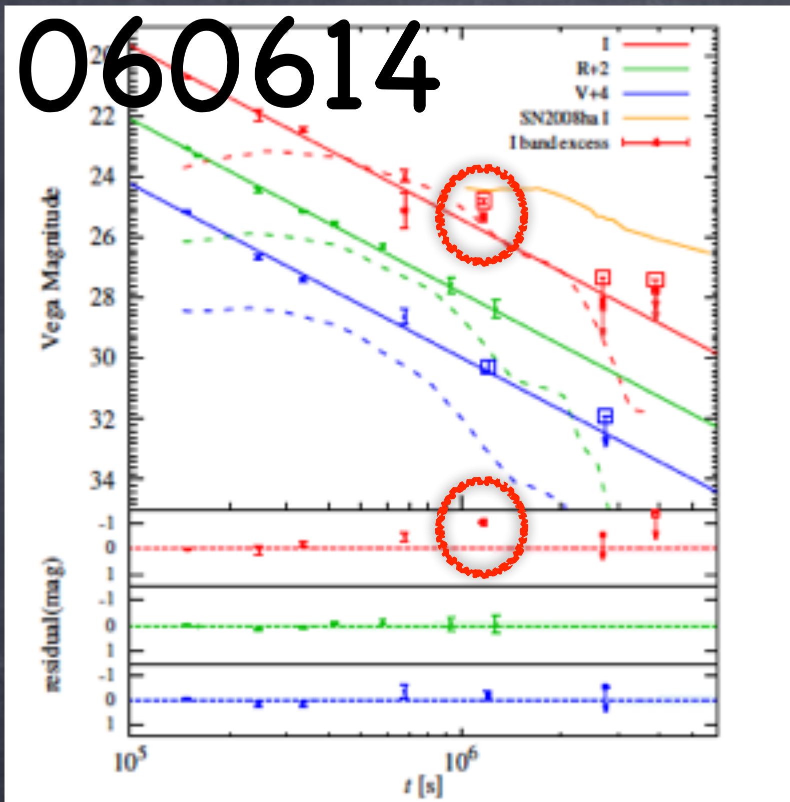

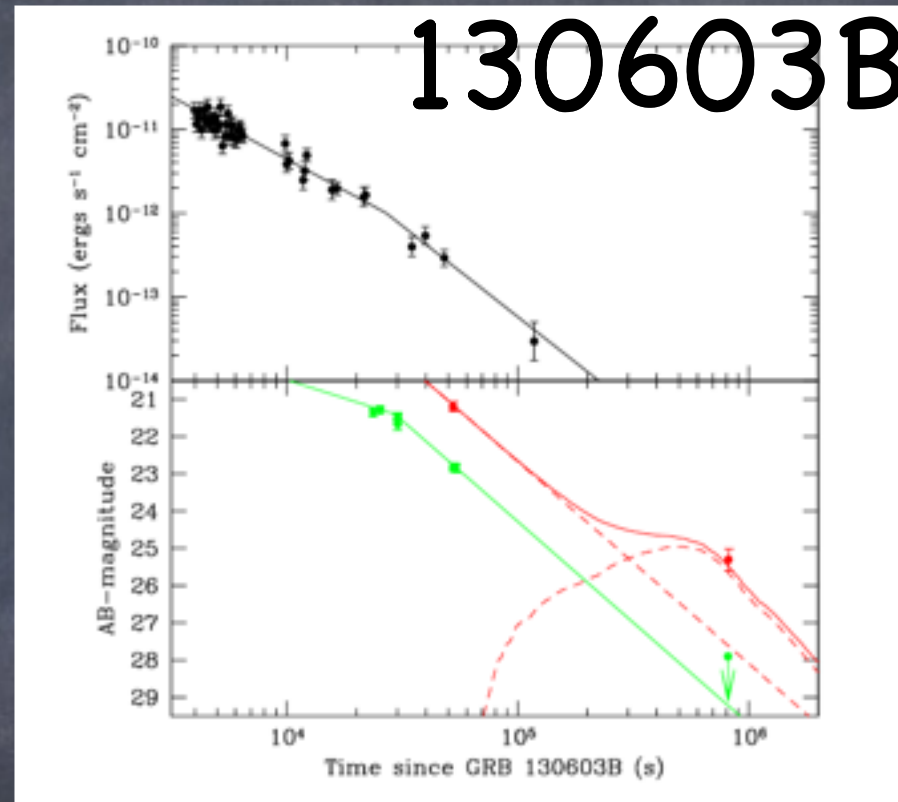

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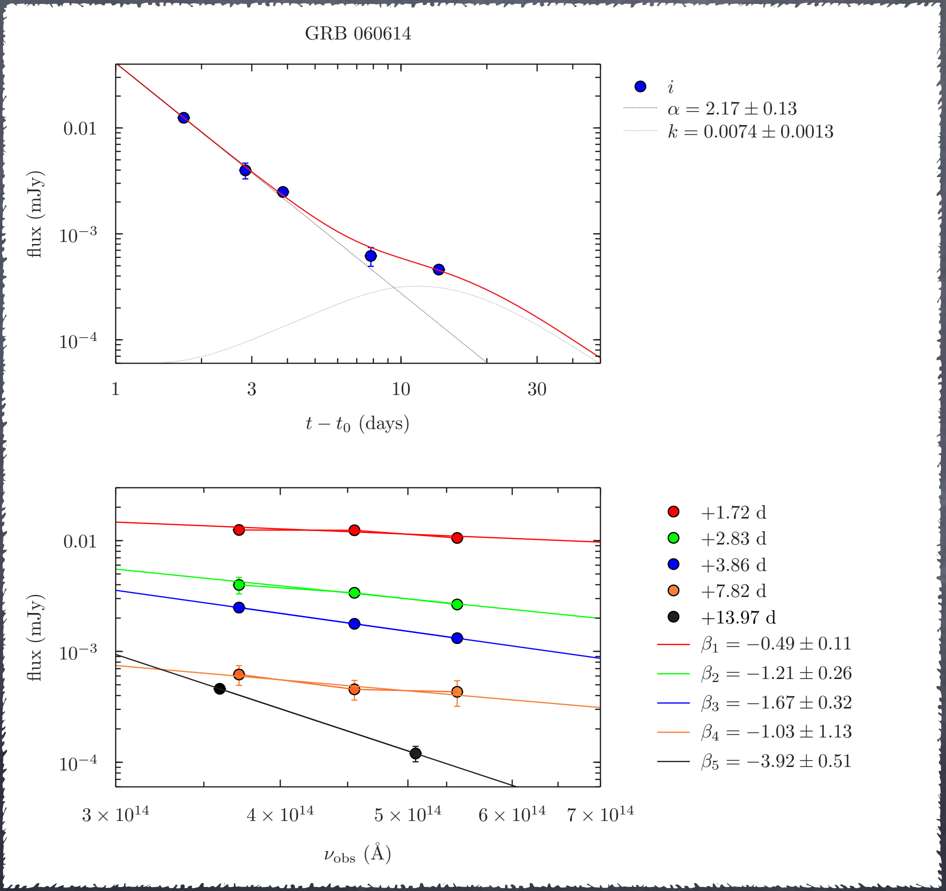
Independent Analysis



Zach Cano 2015 in prep.

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

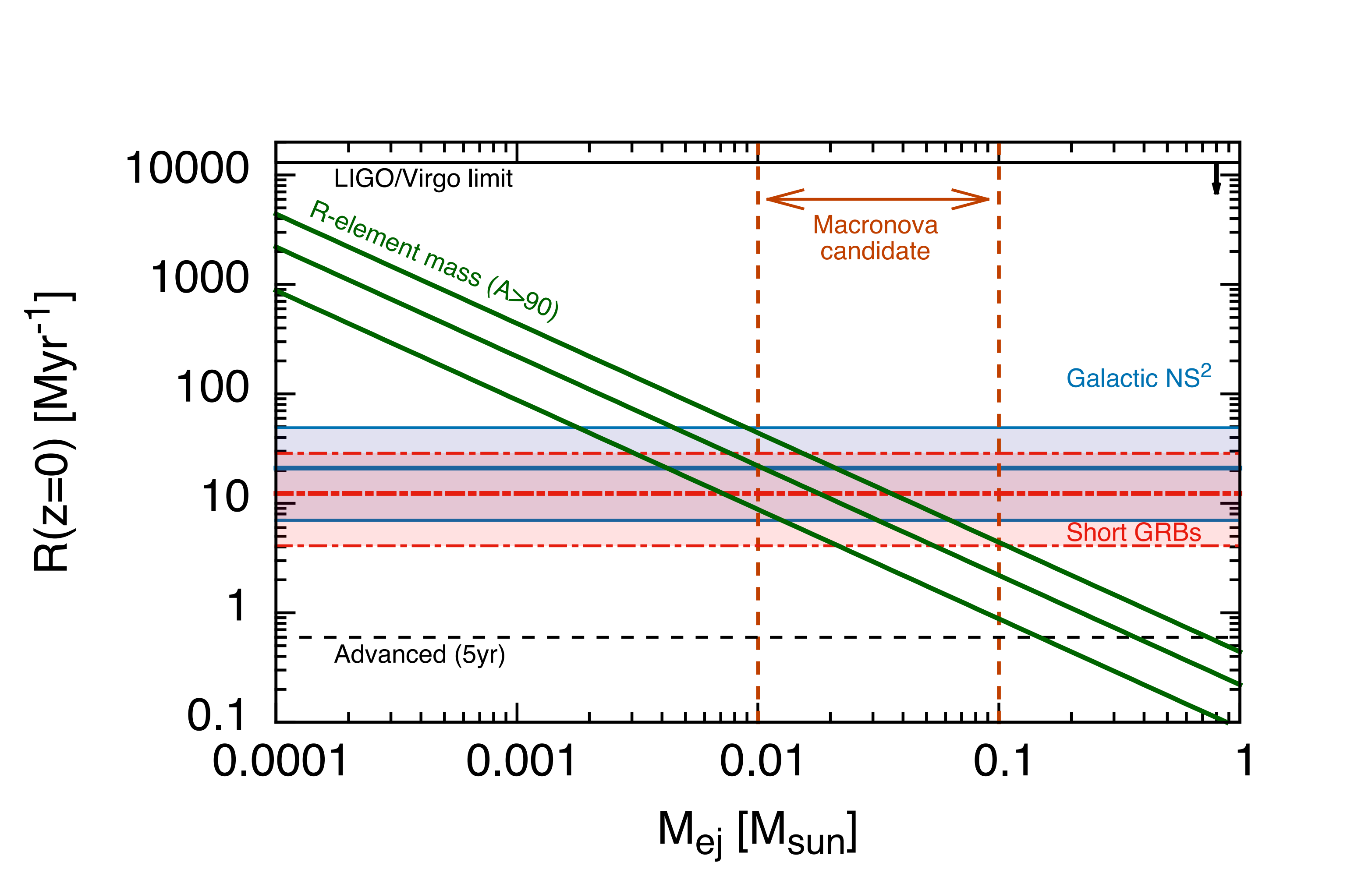
Lattimer Schramm 76

Macronova

Nucleosynthesis ⟷ GRBs

Lattimer Schramm 76

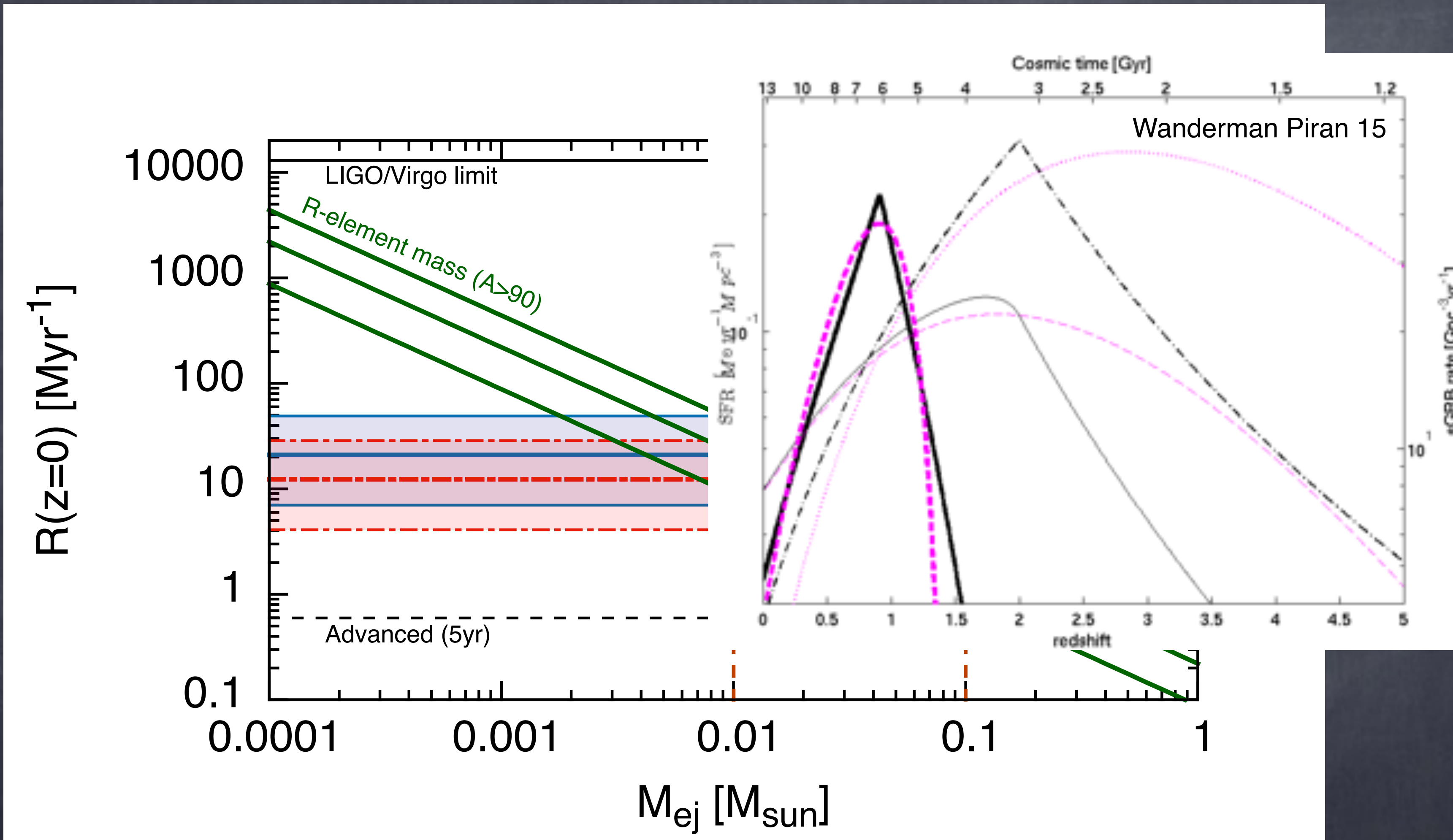
Eichler, Livio
Piran, Schramm 89



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)



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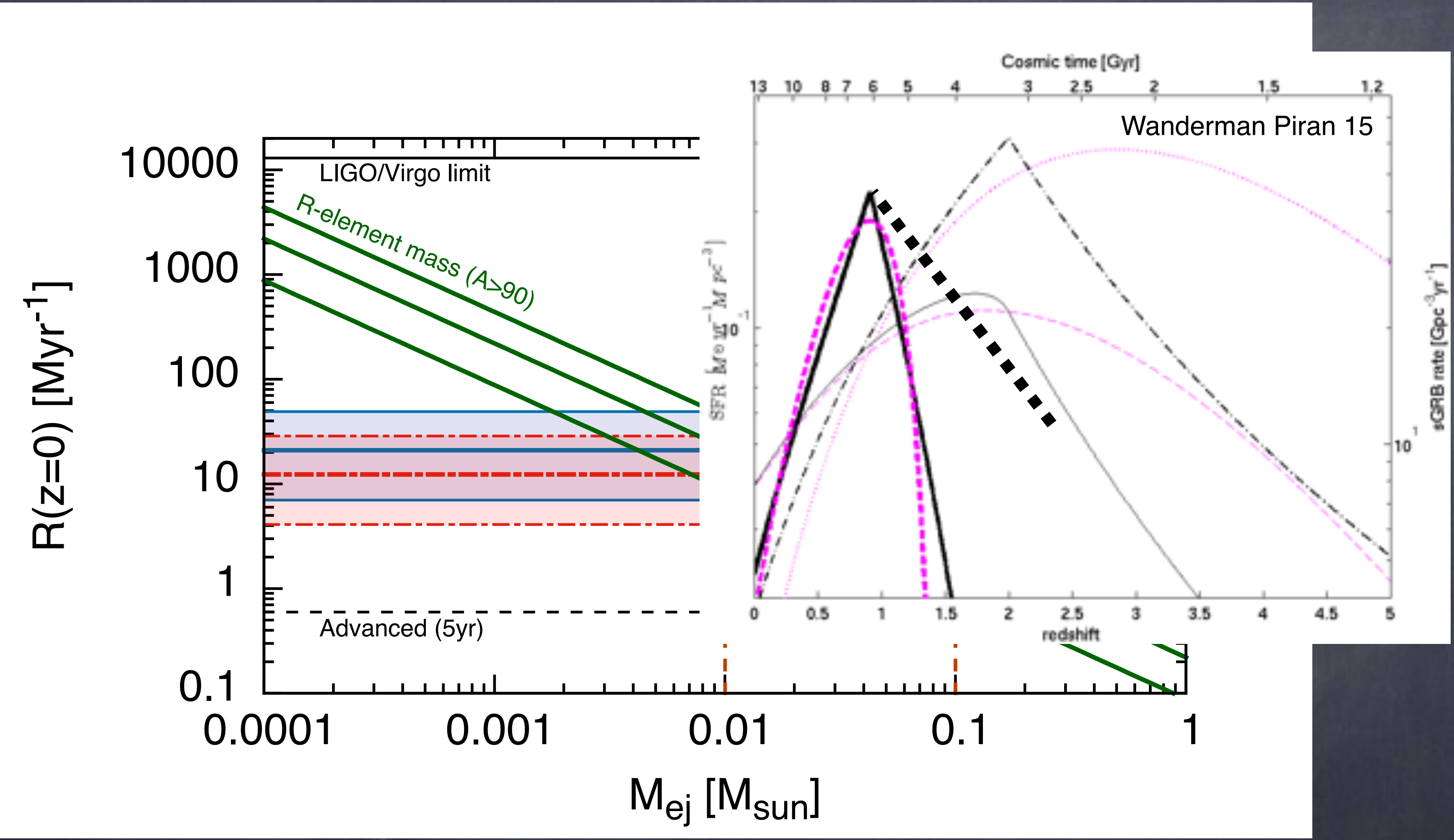

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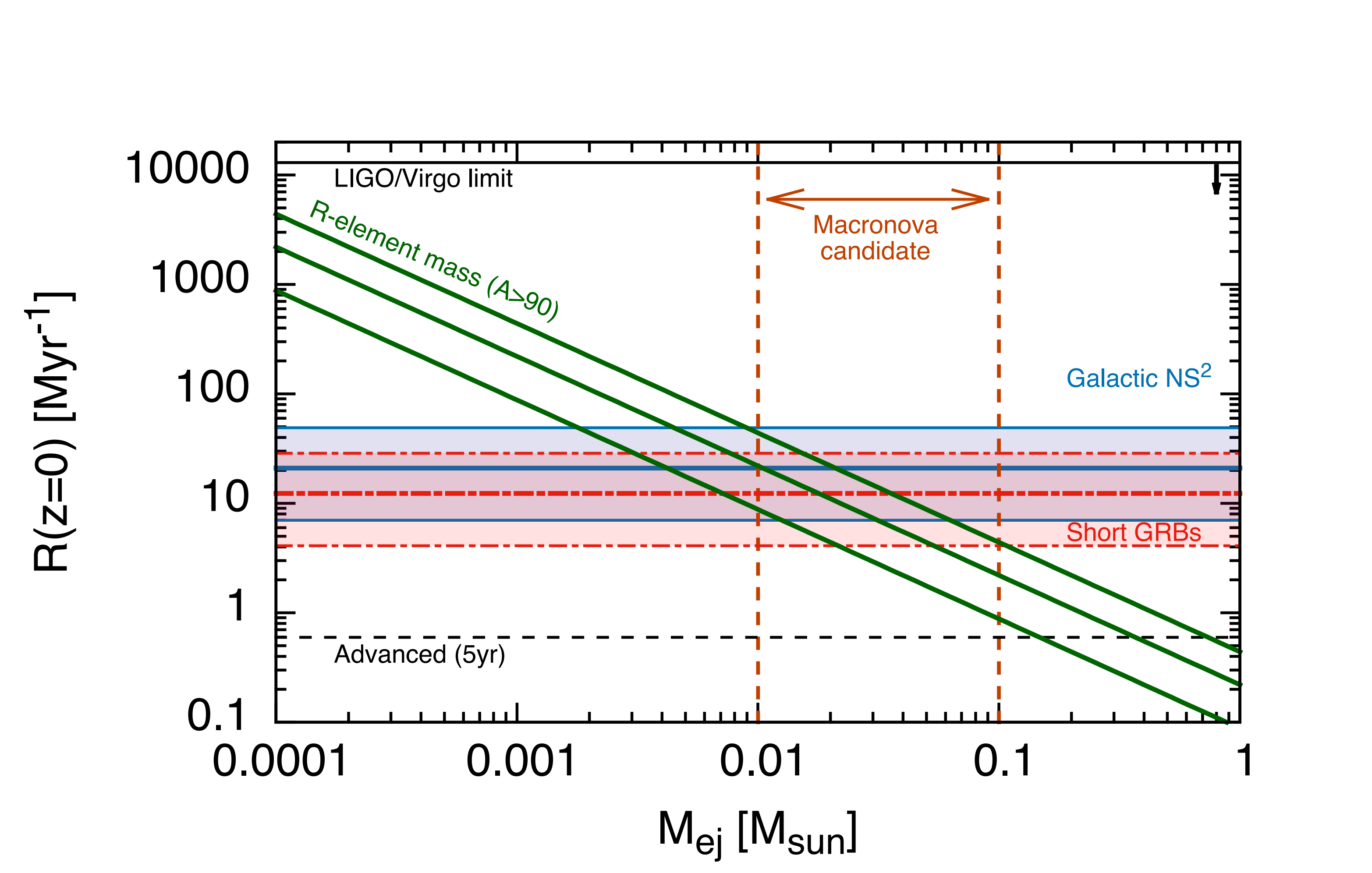

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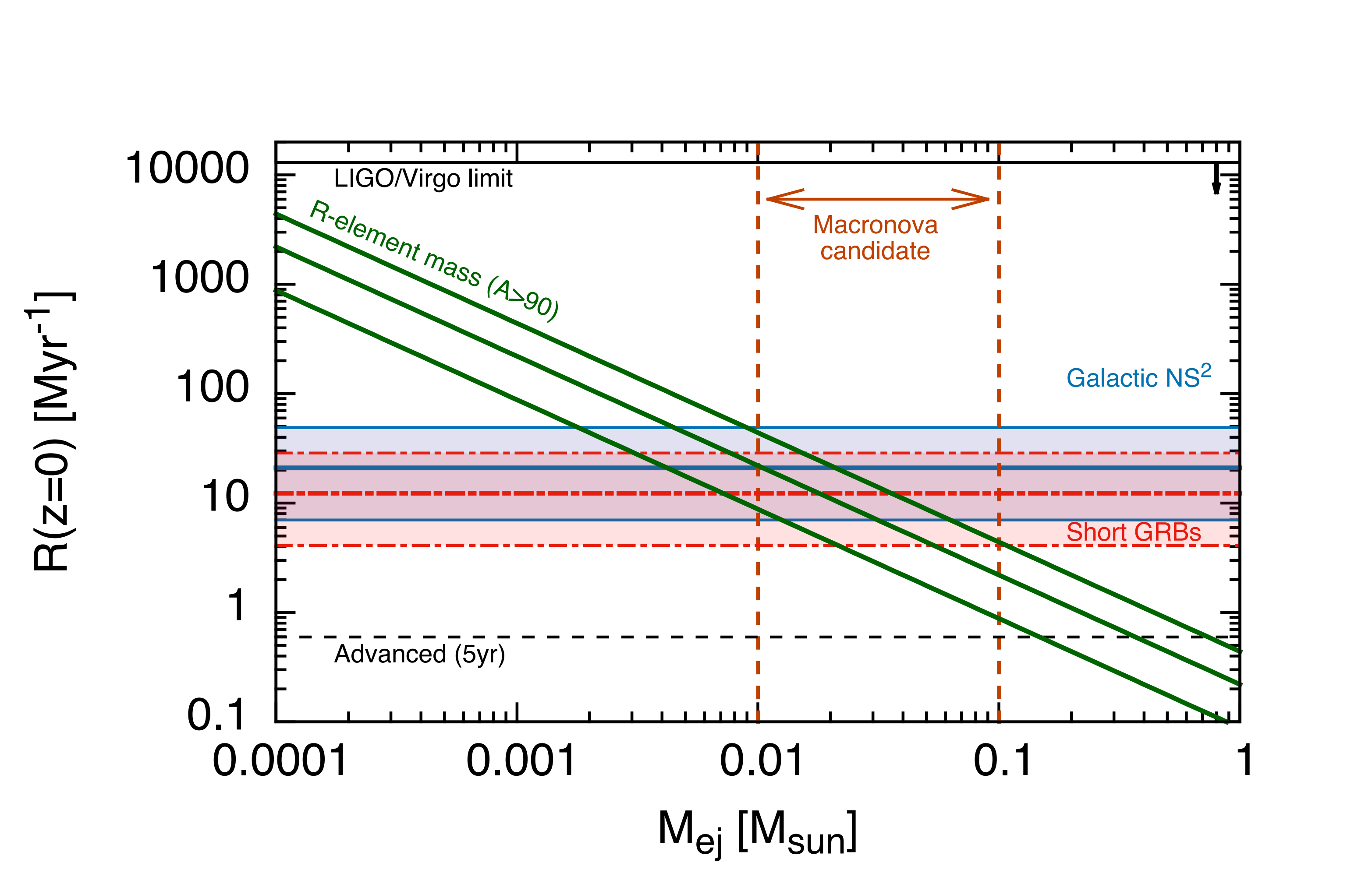

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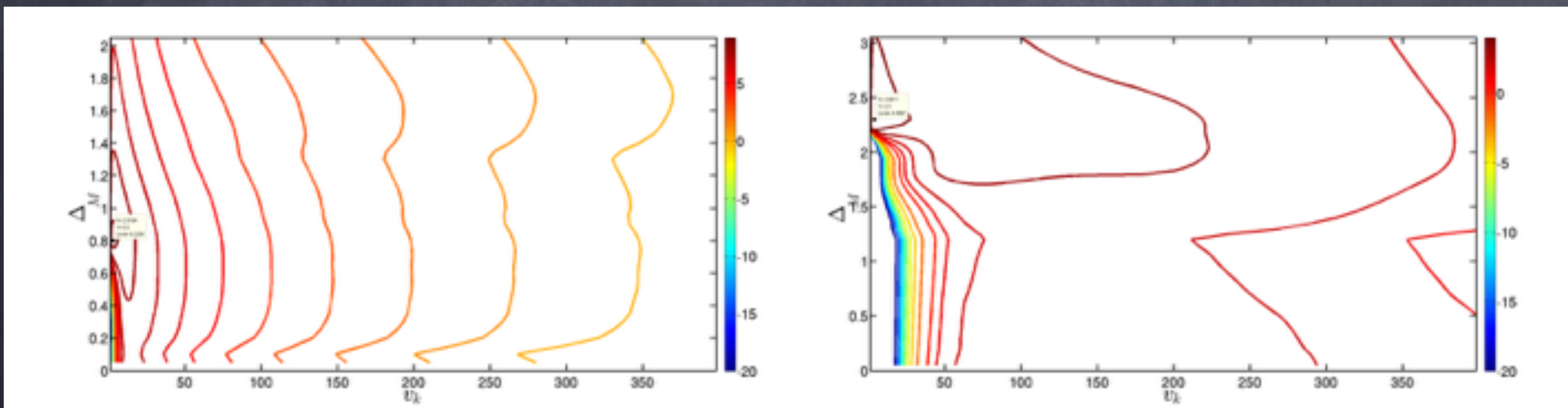
A comment on Galactic NS binary population

Biniamin and Piran 15 in prep



MS pulsars
No kick
Almost No mass ejection

Regular pulsars
Large kick
Significant mass ejection

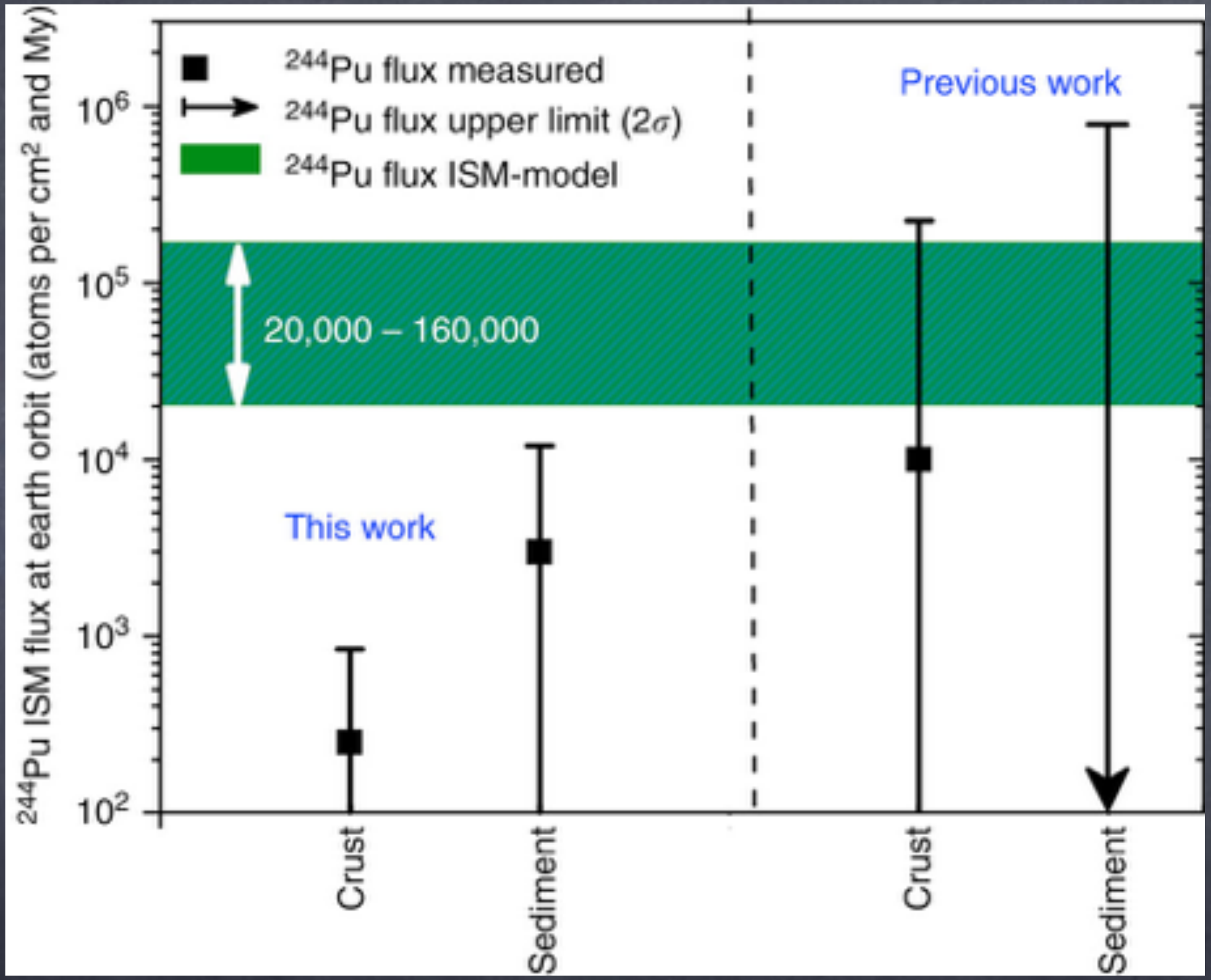
R-Process Nucleosynthesis - limits from the solar system

Kenta Hotokezaka and Tsvi Piran

Abundance of live 244Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis

A. Wallner, T. Faestermann, J. Feige, C. Feldstein, K. Knie, G. Korschinek, W. Kutschera, A. Ofan, M. Paul, F. Quinto, G. Rugel & P. Steier

Nature Comm. 2014



^{244}Pu ISM flux at earth orbit (atoms per cm^2 and My)
^{244}Pu flux measured
^{244}Pu flux upper limit (2σ)
^{244}Pu flux ISM-model
Previous work
20,000 – 160,000
This work
10^6
10^5
10^4
10^3
10^2
Crust
Sediment
Crust
Sediment

Mixing time

$D(t_{mix}) = A^{1/2} / (R\ t_{mix})$

$D(t_{mix})$ - mixing distance

A - Area of the Galaxy

R - Rate of events in the Galaxy

We should compare t_{mix} with the age of the Galaxy.

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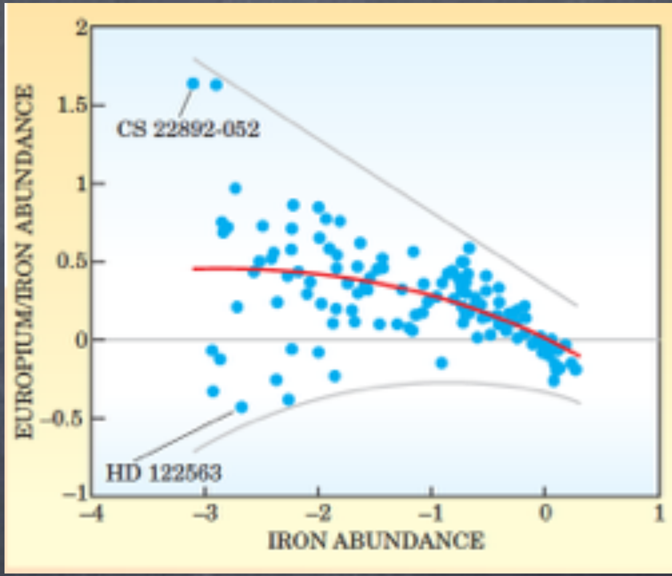

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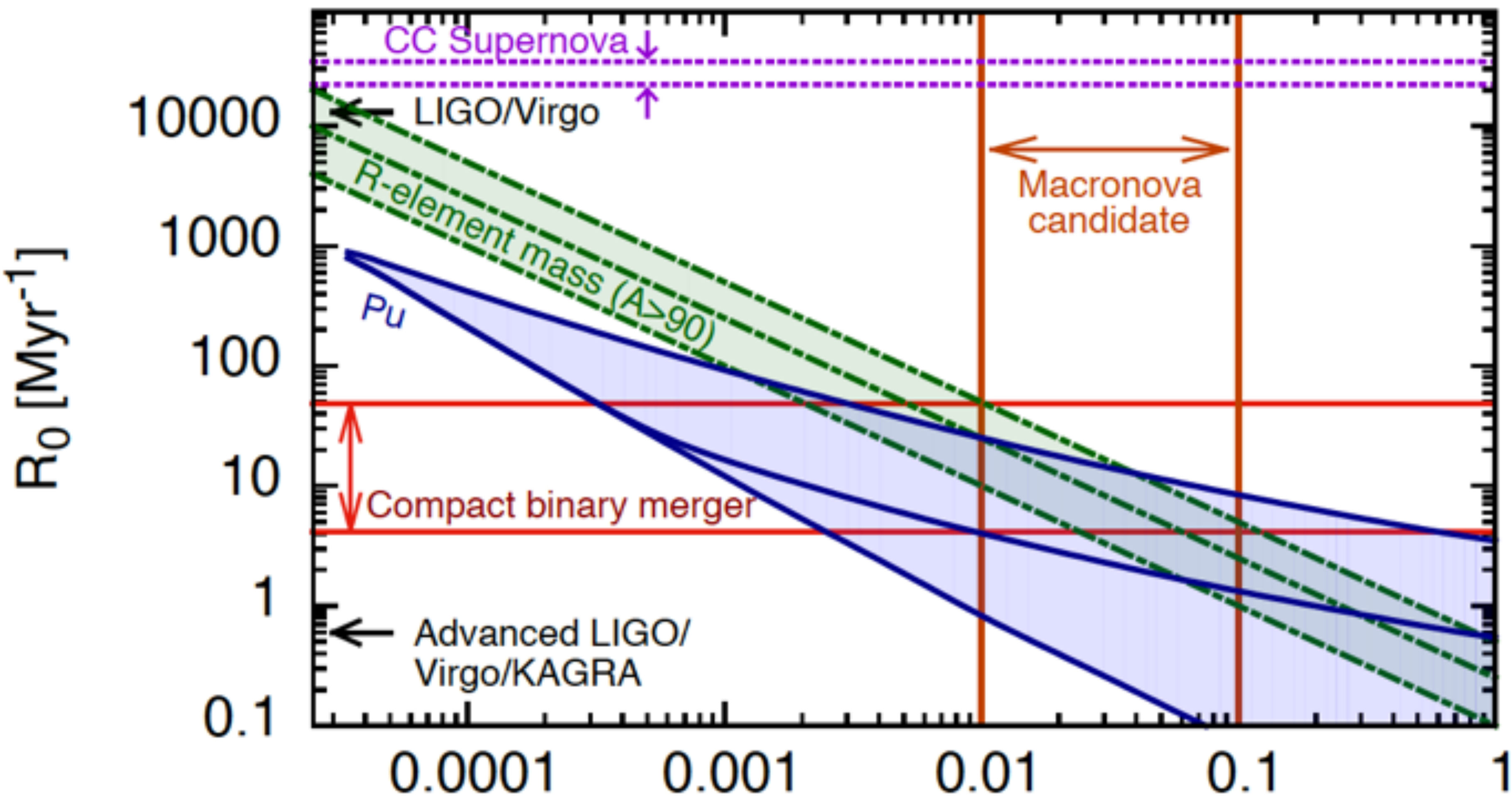


CC Supernova
LIGO/Virgo
R-element mass (A>90)
Macronova
candidate
Pu
Compact binary merger
Advanced LIGO/
Virgo/KAGRA
R0 [Myr-1]
10000
1000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1

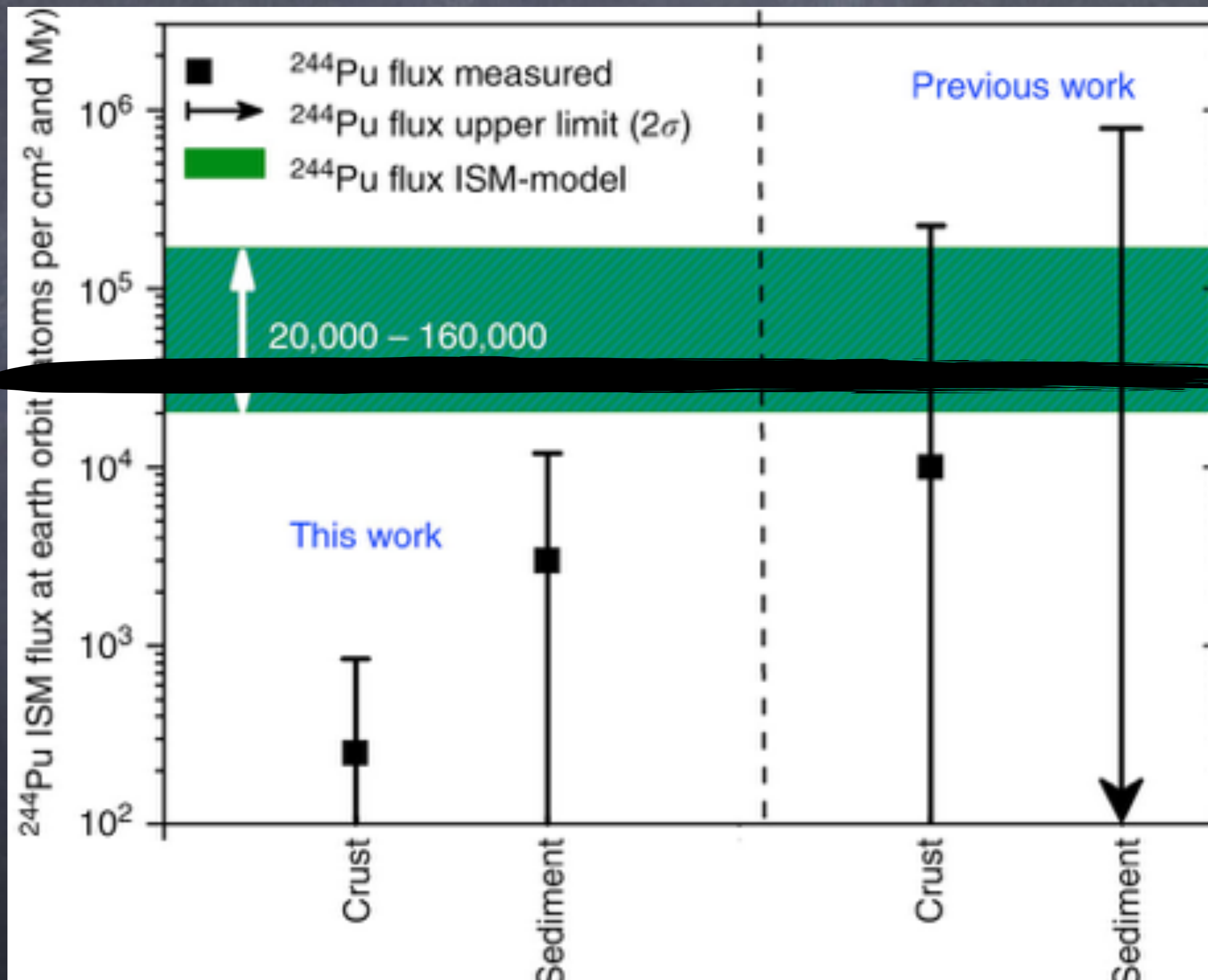
Turbulent mixing

$$D = \frac{1}{3} v_t l_{mix} = \alpha v_t H$$

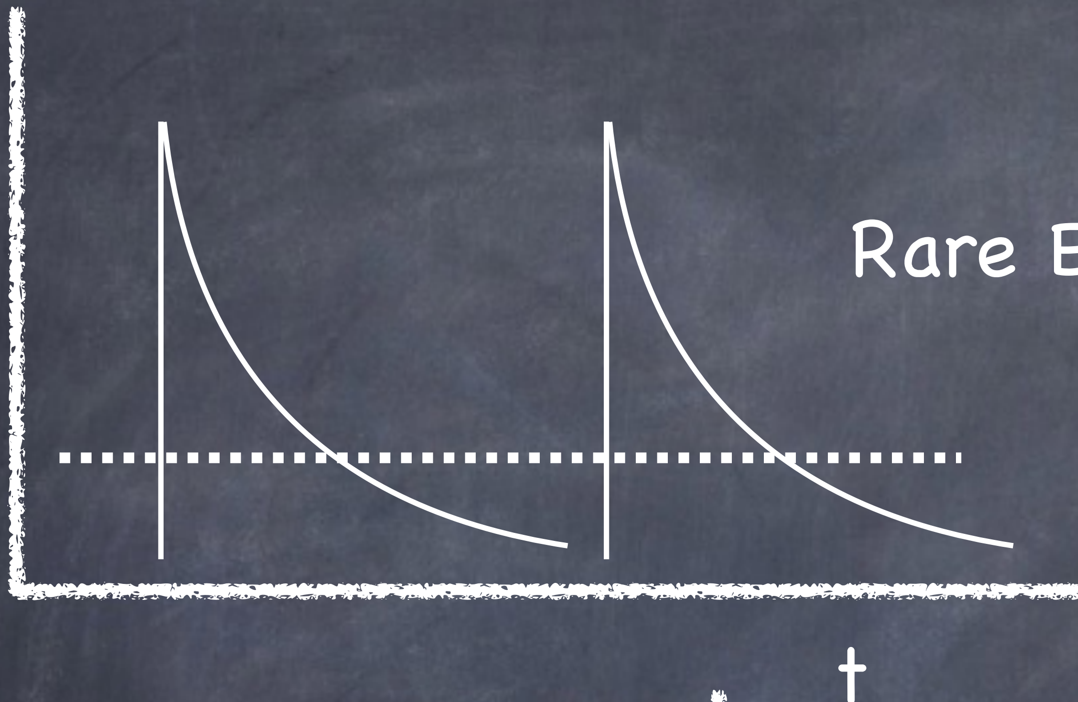
$$\approx 10^{-4}\, kpc^2 / Myr \left(\frac{\alpha}{0.1}\right)\left(\frac{v_t}{7km/s}\right)\left(\frac{H}{200\,pc}\right)$$

This means the ISM mixed over 1kpc with a timescale of 10Gyr, which is consistent with the ~1kpc chemical homogenity of stars in the galactic disk.

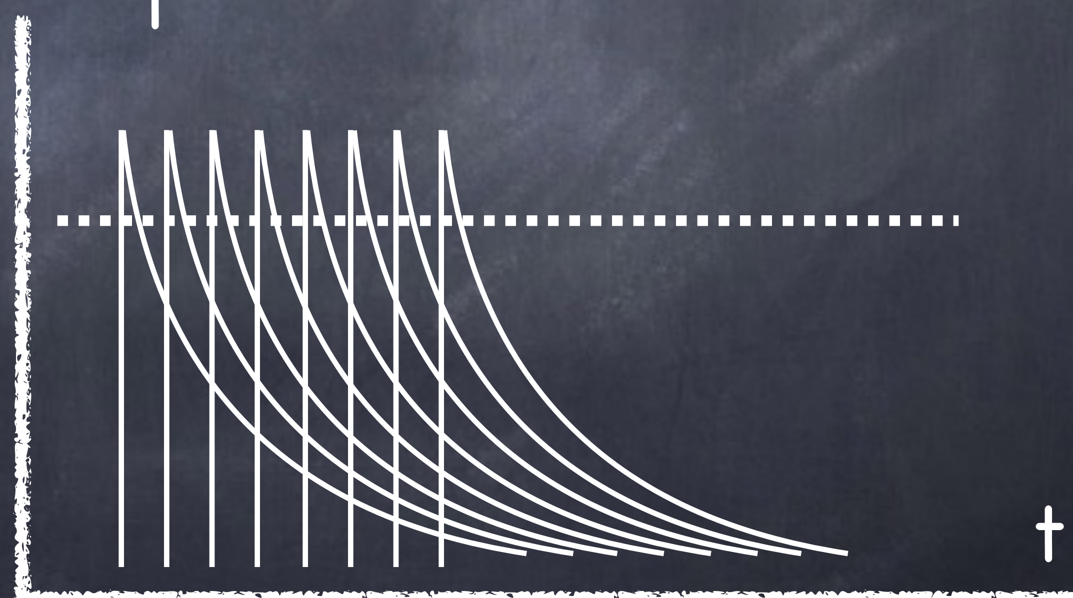
The early solar system



Rare Events



Frequent events



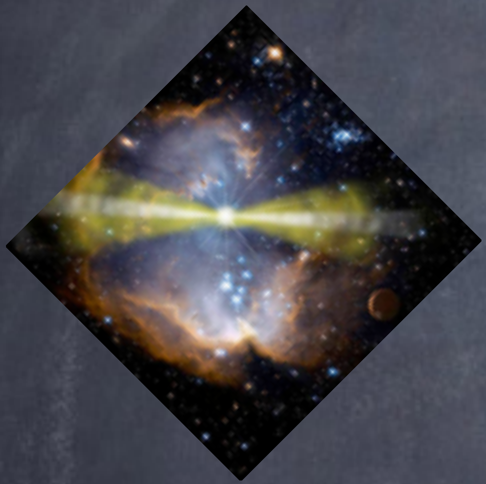
High ^{244}Pu at the early solar system =>

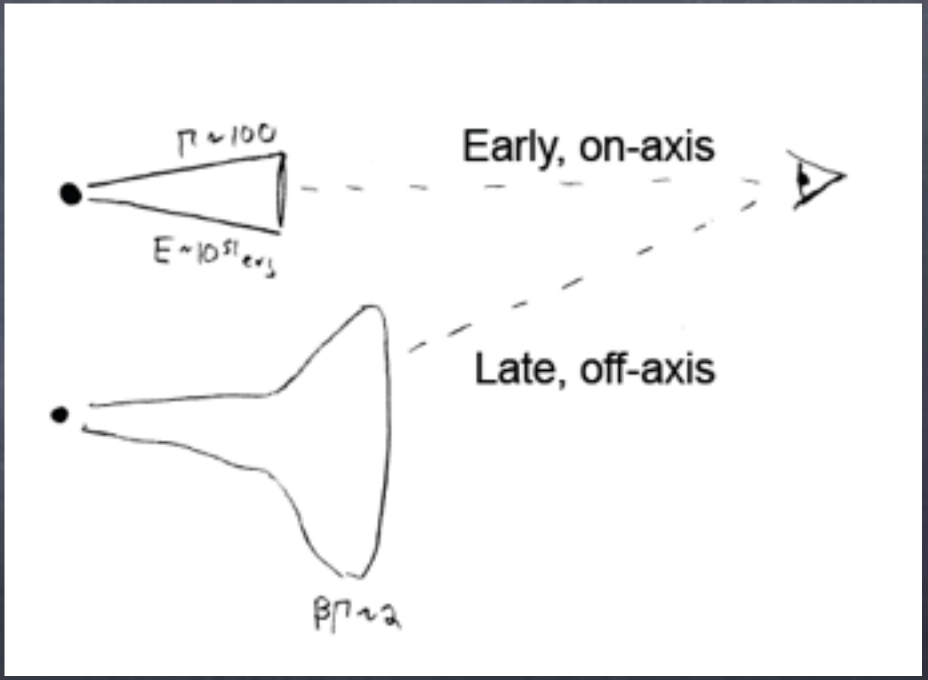
- ^{244}Pu Radioactive decay time ~ 100 Myear
- A nearby event near solar system
- Mixing time < 150 Myr
- Large fluctuations possible => Event rate is low
- Lack of Cu => 10 Myr < Mixing length

Why EM signal?
(Kochaneck & Piran 1993)

- Improves detectability
- Essential for localization
- Much more physics

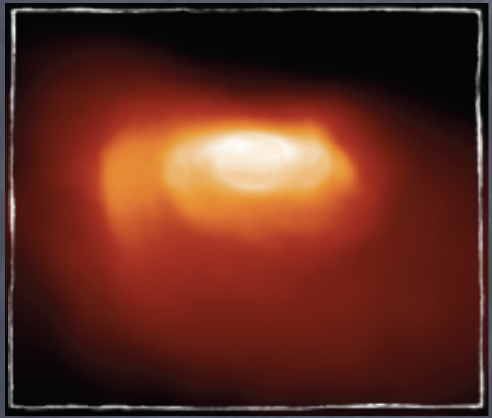
GRBs are beamed -> dificult to catch the GRB





Orpha afterglow will be too weak

Macronova
Li & Paczynski 1997



Numerical simulations => NS merger eject >0.1 $M_{\odot}$

Davies, Benz, Piran & Thielemann 1994;

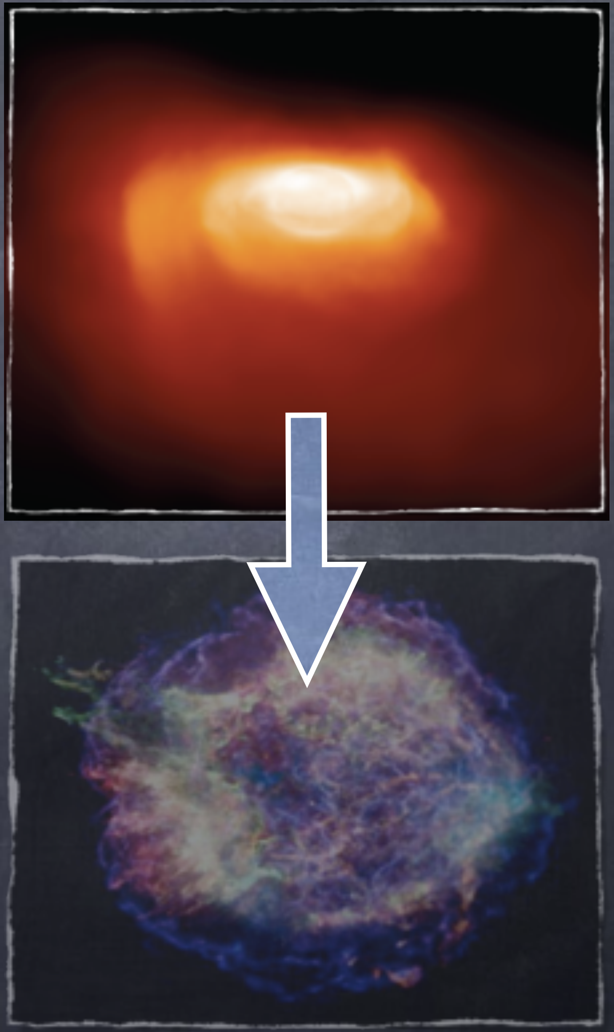
Rosswog et al., 1999

Freiburghaus, Rosswog, & Thielemann, 1999

Radio Flares

Nakar & Piran 2011

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

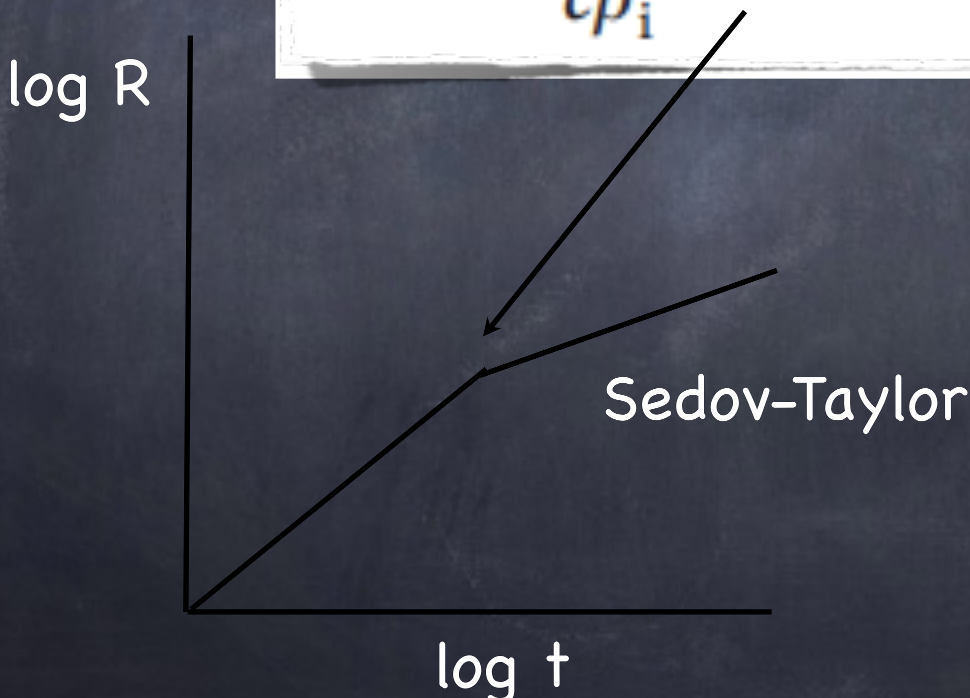


Supernova -> SNR

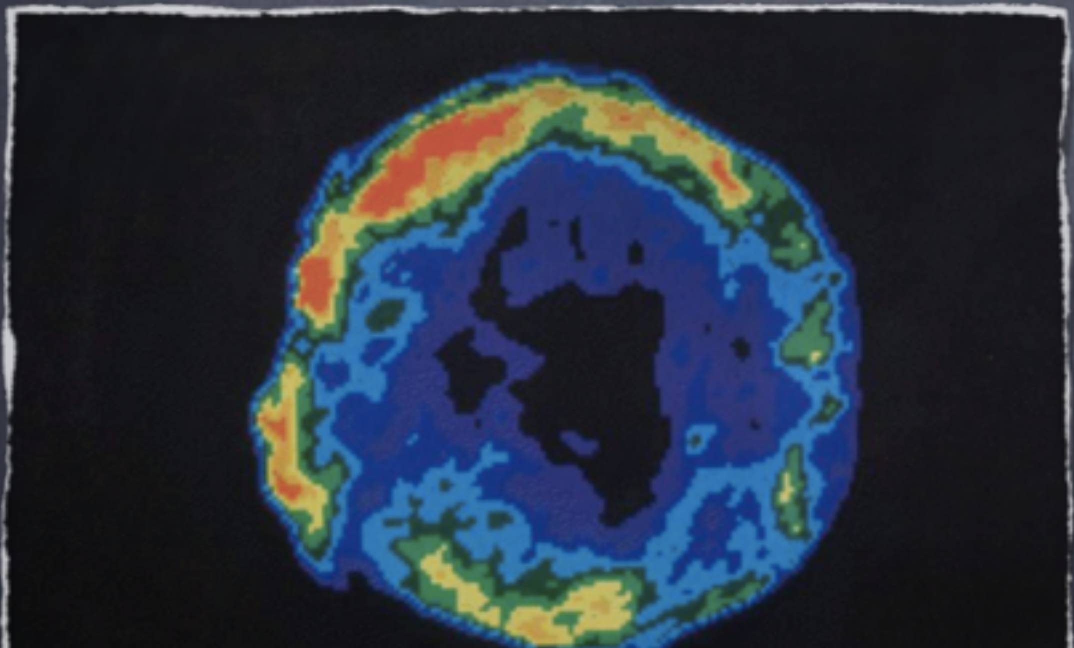
macronova -> Radio Flare

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 $\gamma > \gamma_m$

$p = 2.5 - 3$

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

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

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

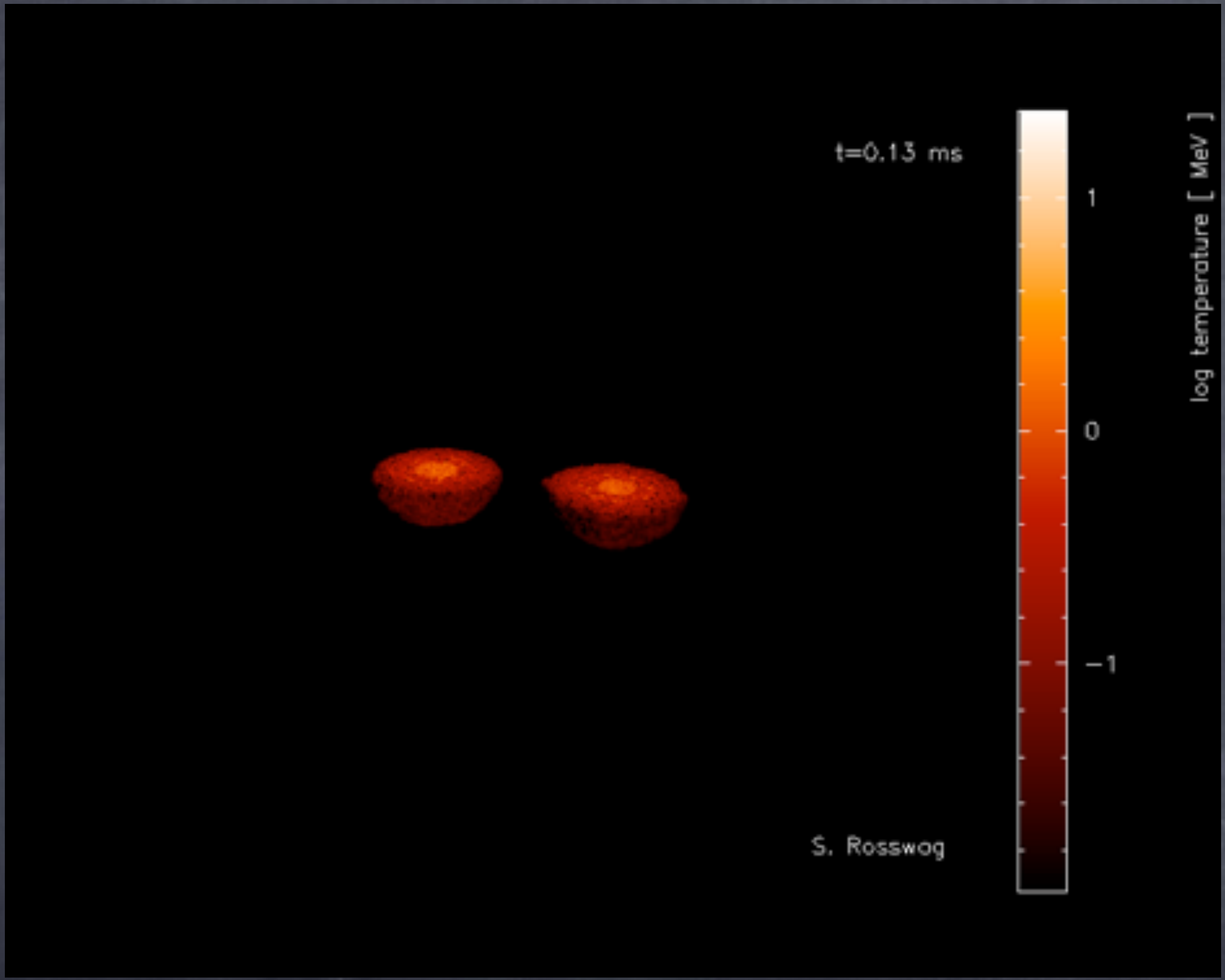
Frequency and Intensity

(Nakar & TP Nature, 2011)

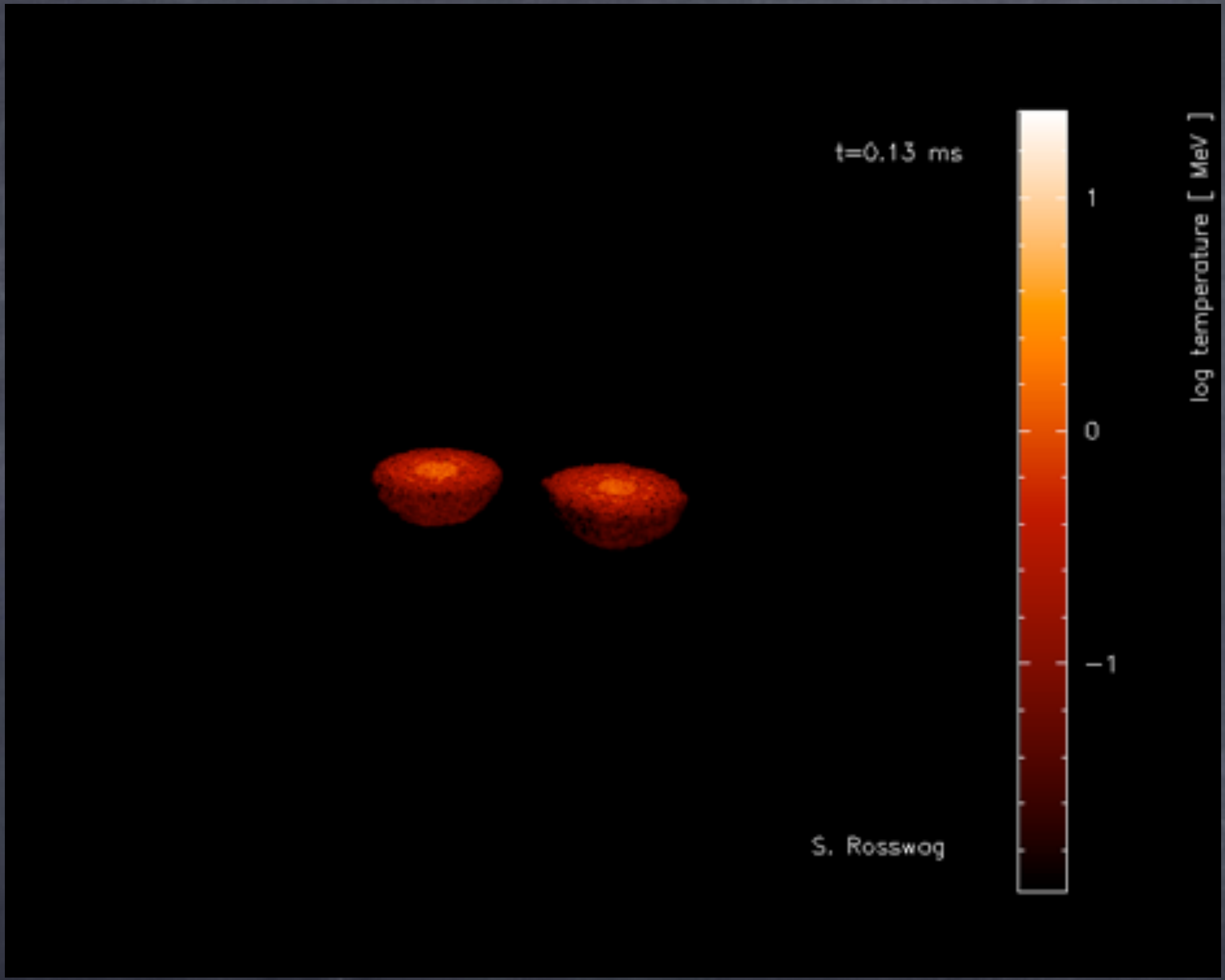
$$\nu_{m,dec} \equiv \nu_m(t_{dec}) \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} (\Gamma_0 - 1)^{5/2},$$

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

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



Rosswog, TP, Nakar 13, TP, Nakar, Rosswog 13



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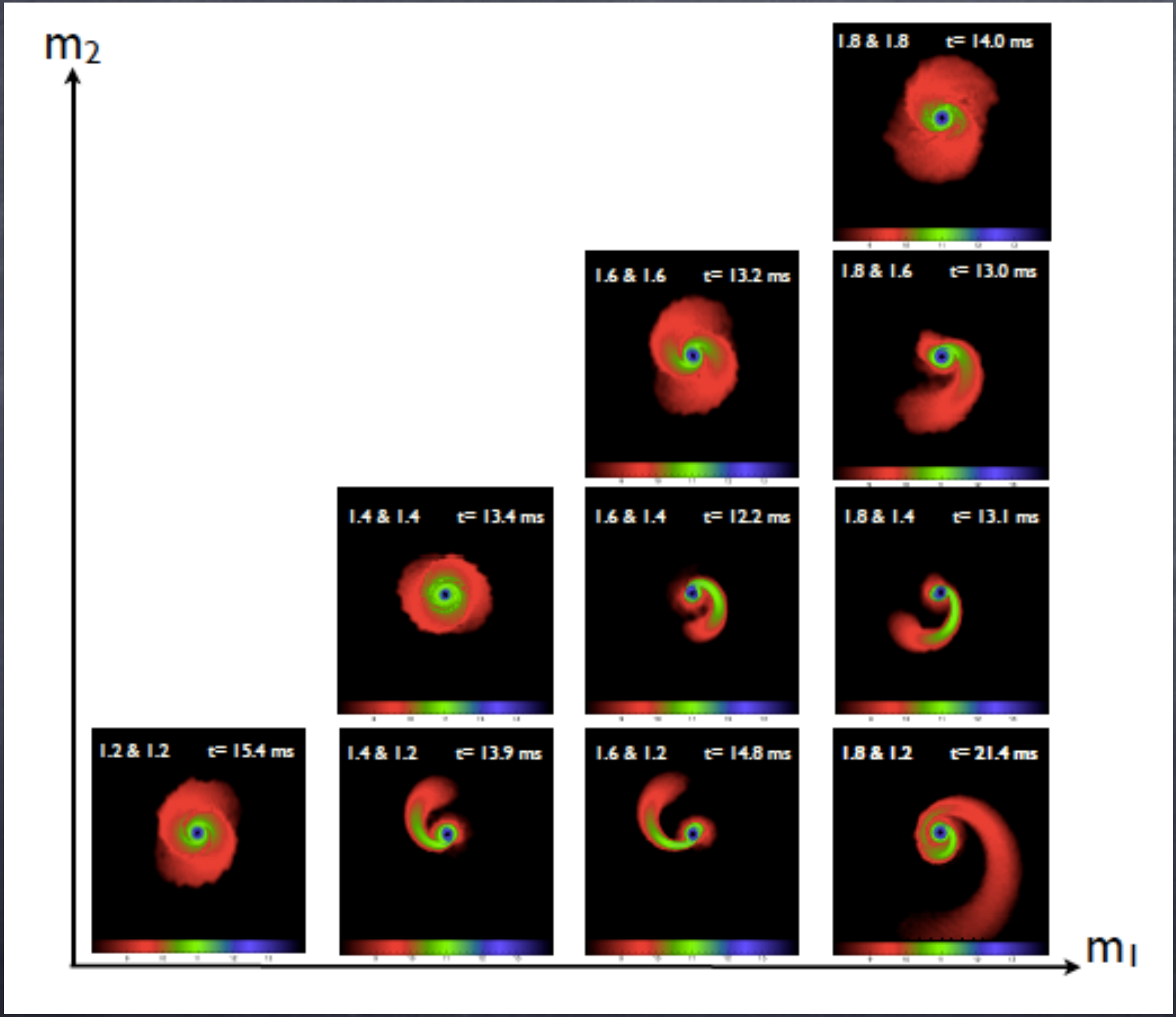
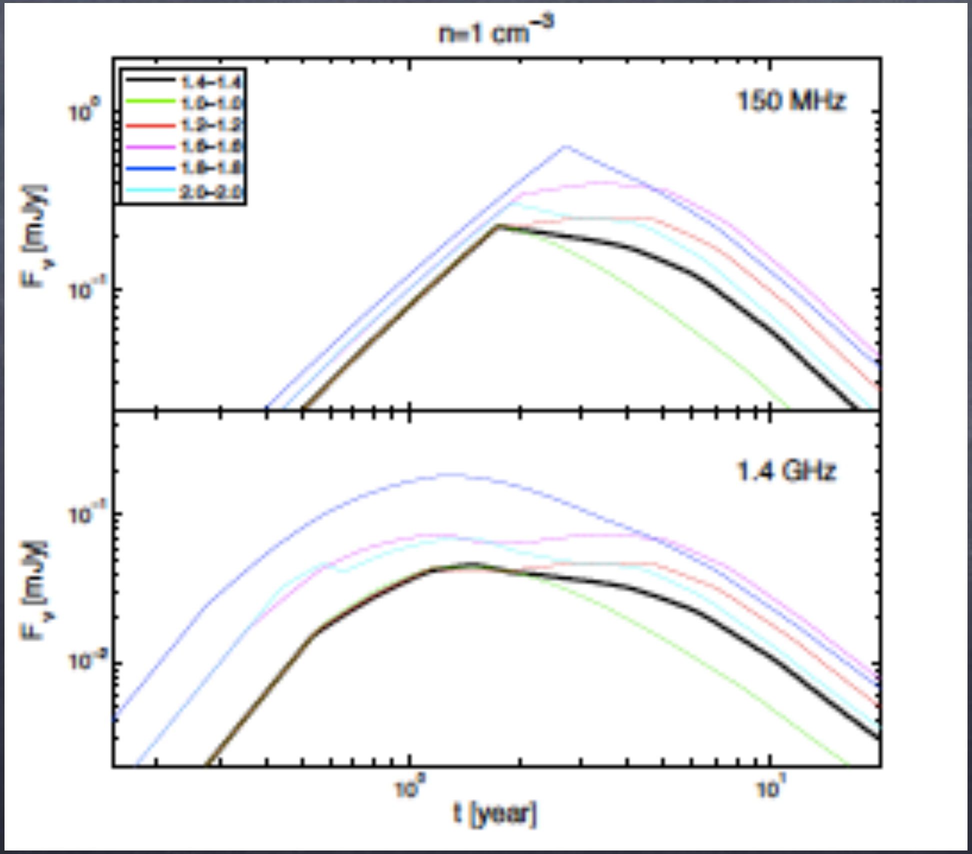
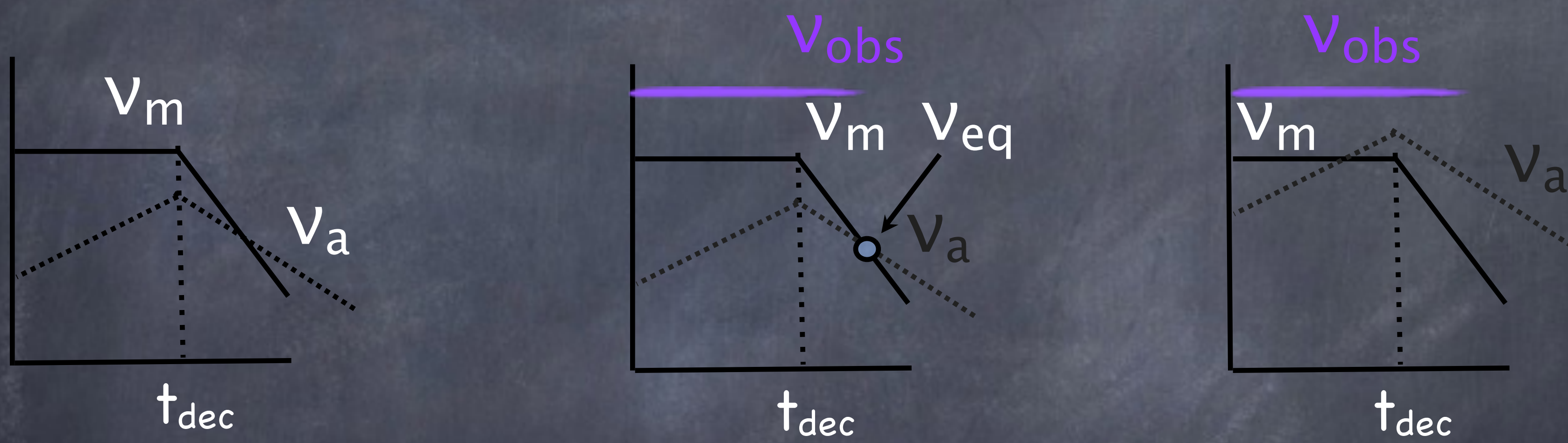

m2
1.8 & 1.8 t= 14.0 ms
1.6 & 1.6 t= 13.2 ms
1.8 & 1.6 t= 13.0 ms
1.4 & 1.4 t= 13.4 ms
1.6 & 1.4 t= 12.2 ms
1.8 & 1.4 t= 13.1 ms
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms
m1

Radio Flares



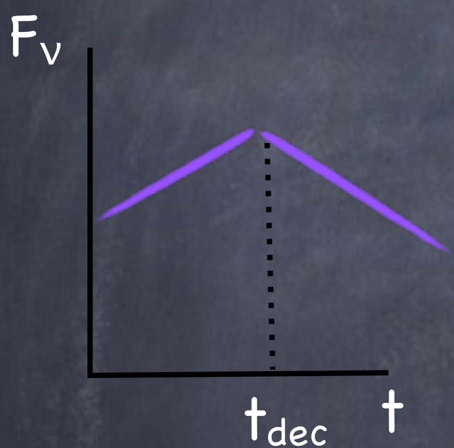
The light curve

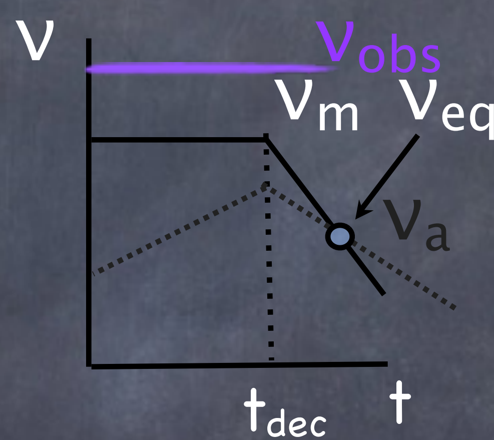


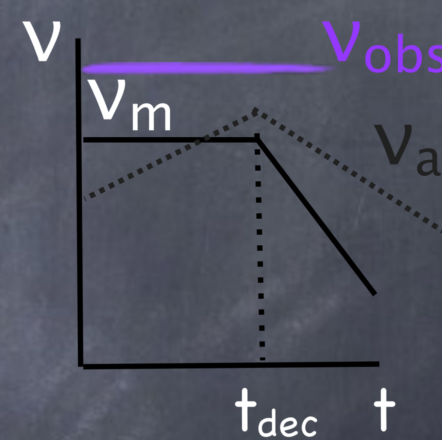
Text

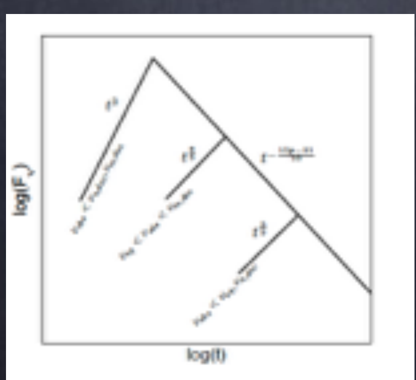
$$\nu_{eq} = 1 \text{ GHz } E_{49}^{1/7} n^{4/7} \epsilon_{B,-1}^{2/7} \epsilon_{e,-1}^{-1/7}$$

The light curve









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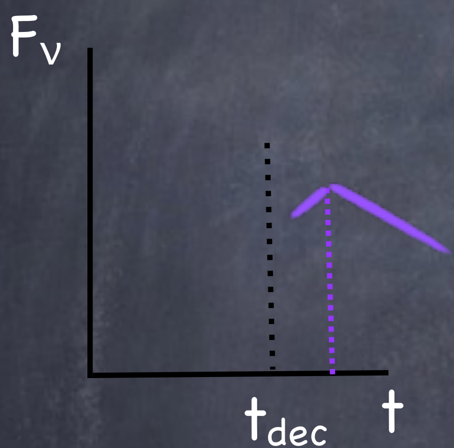
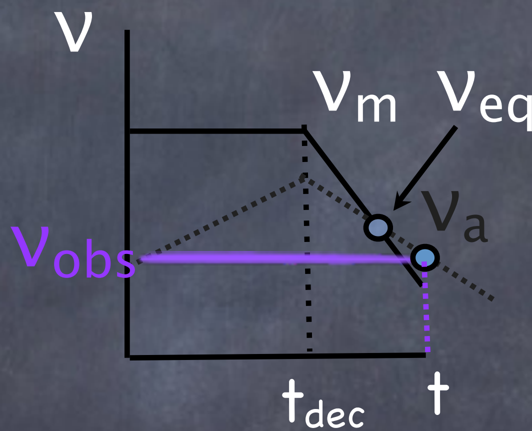
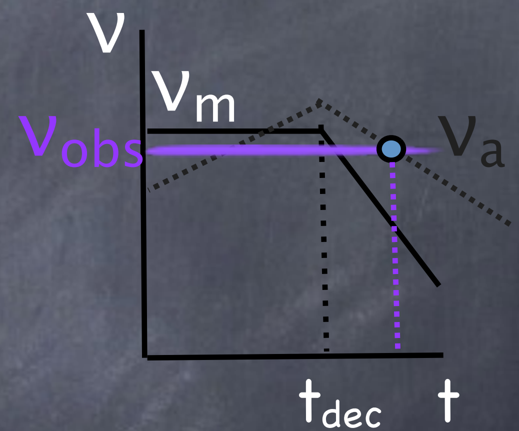
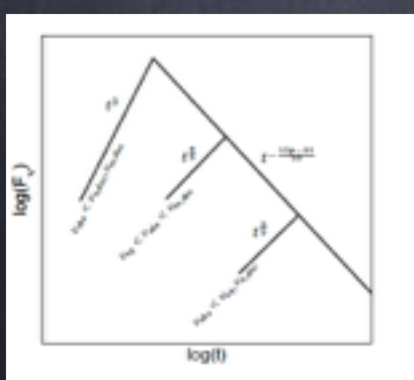




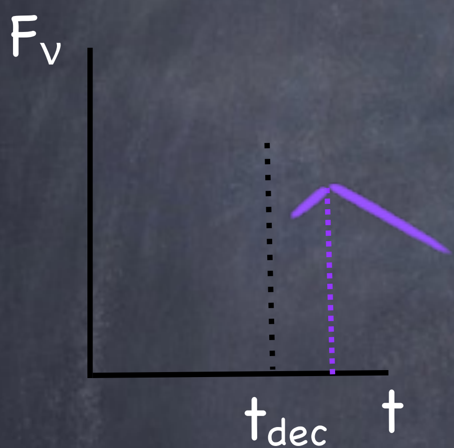


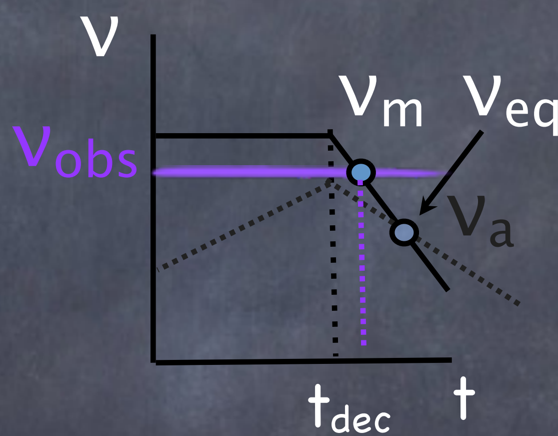


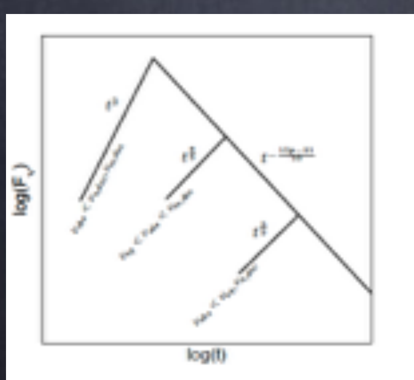
Text

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

The light curve







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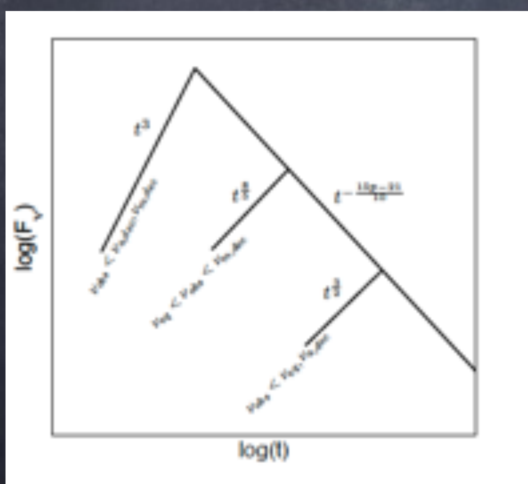
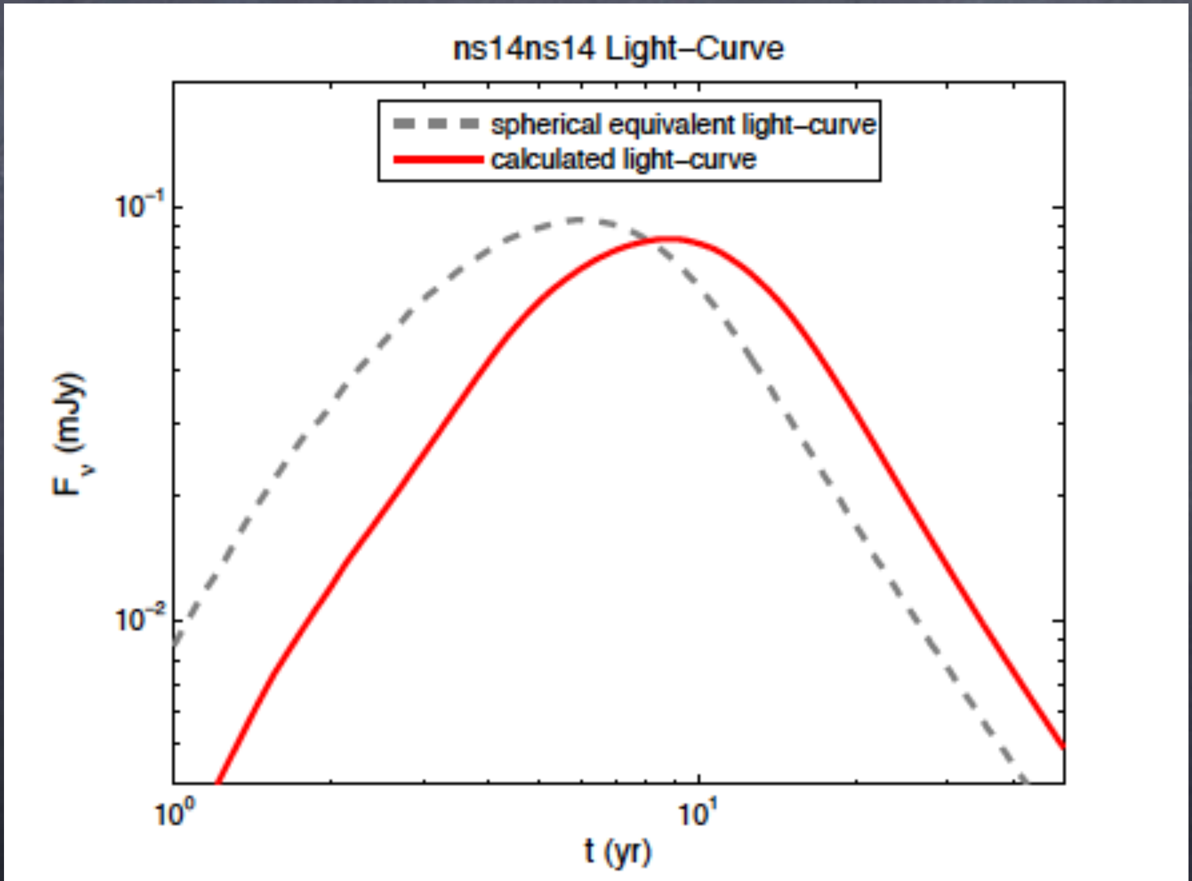
Regime	$F_{\nu_{obs},peak}/F_{m,dec}$	t_{peak}/t_{dec}	$F_{\nu_{obs}}$ $t > t_{peak}$	$F^{\dagger}_{\nu_{obs}}$ $t < t_{peak}$
$\nu_{m,dec}, \nu_{a,dec} < \nu_{obs}$	$(\nu_{obs}/\nu_{m,dec})^{-\frac{p-1}{2}}$	1	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^3$
$\nu_{eq} < \nu_{obs} < \nu_{m,dec}$	$(\nu_{obs}/\nu_{m,dec})^{-1/5}$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



Effect of sphericity

Margalit & Piran 15



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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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

NRAO

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

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Summary

- A detection of a macronova like signal in 060614
- But need 0.1 M_{sun} ?
- Macronova ==>
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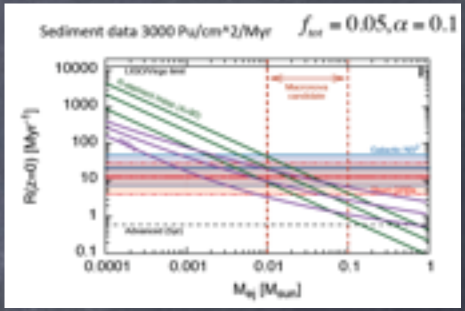
- ^{244}Pu gives strong support for R process nucleosynthesis consistent with Mergers



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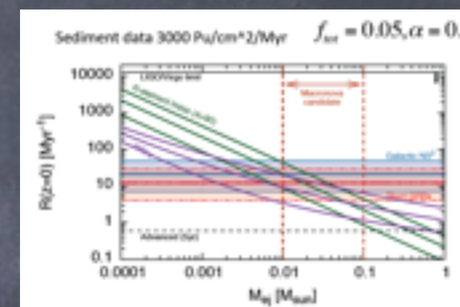

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