The Electromagnetic signals that follow the Gravitational Waves

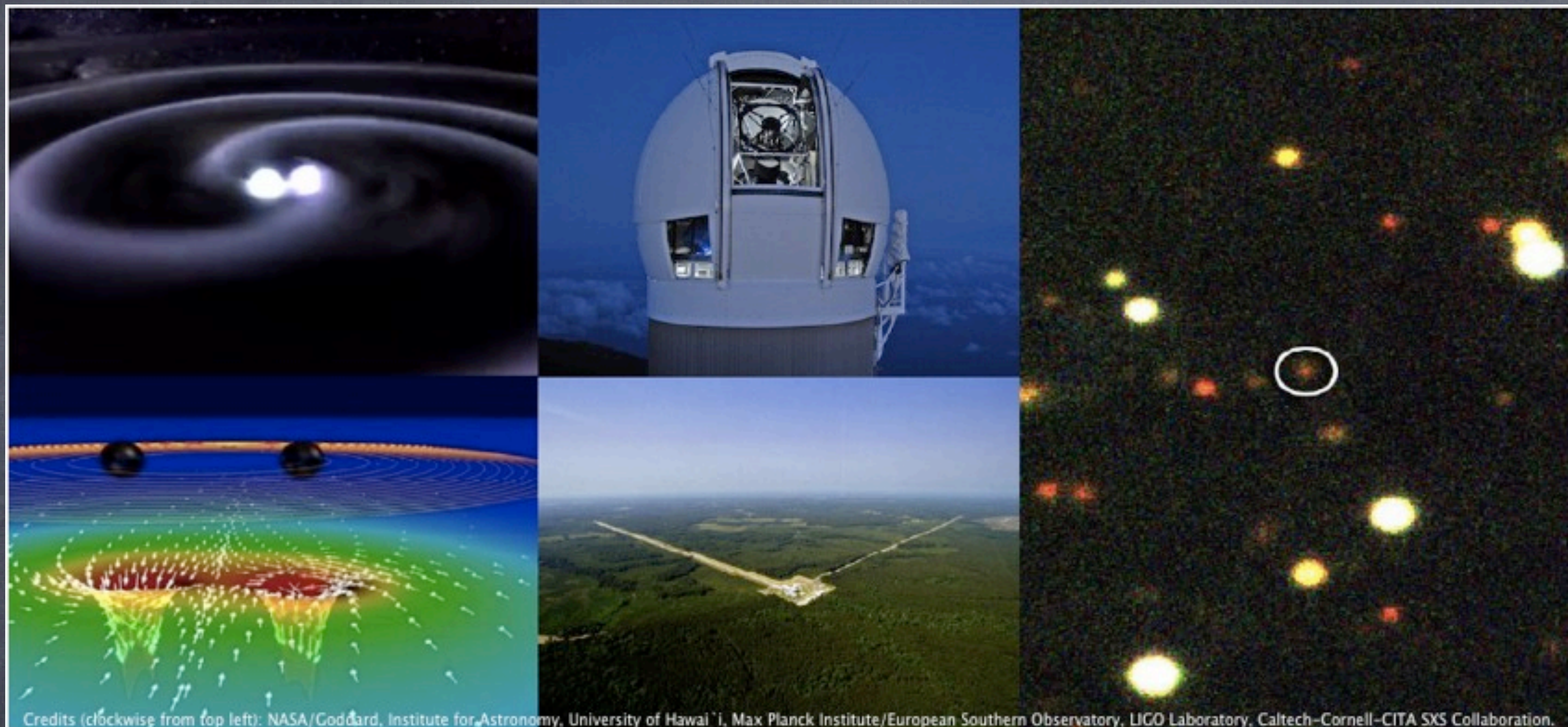
Tsvi Piran

The Hebrew University of Jerusalem, Israel

Ehud Nakar + Stephan Rosswog

Rattle and Shine - KITP July 30 2012

Rattle and Shine KITP 2012



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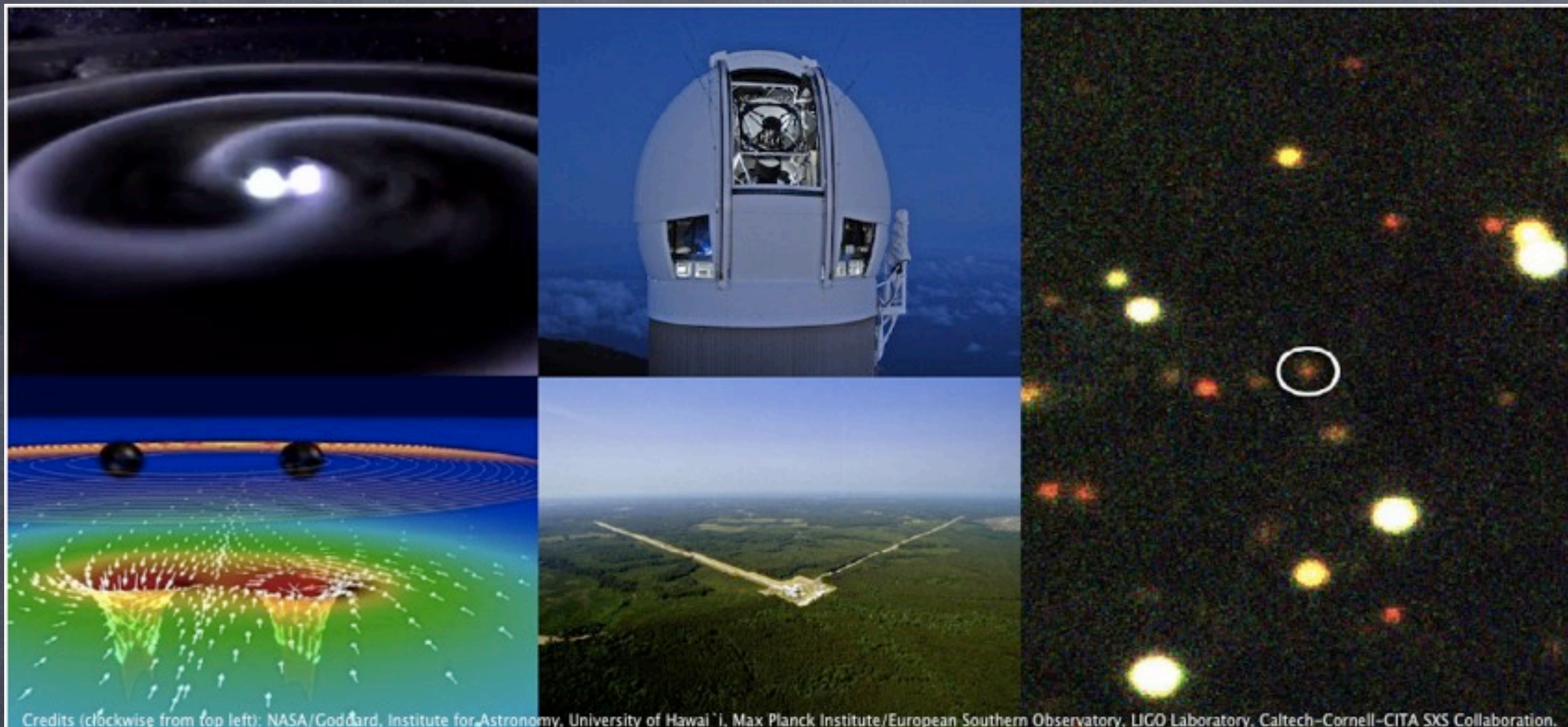

GRAVITATIONAL WAVES AND γ-RAY BURSTS

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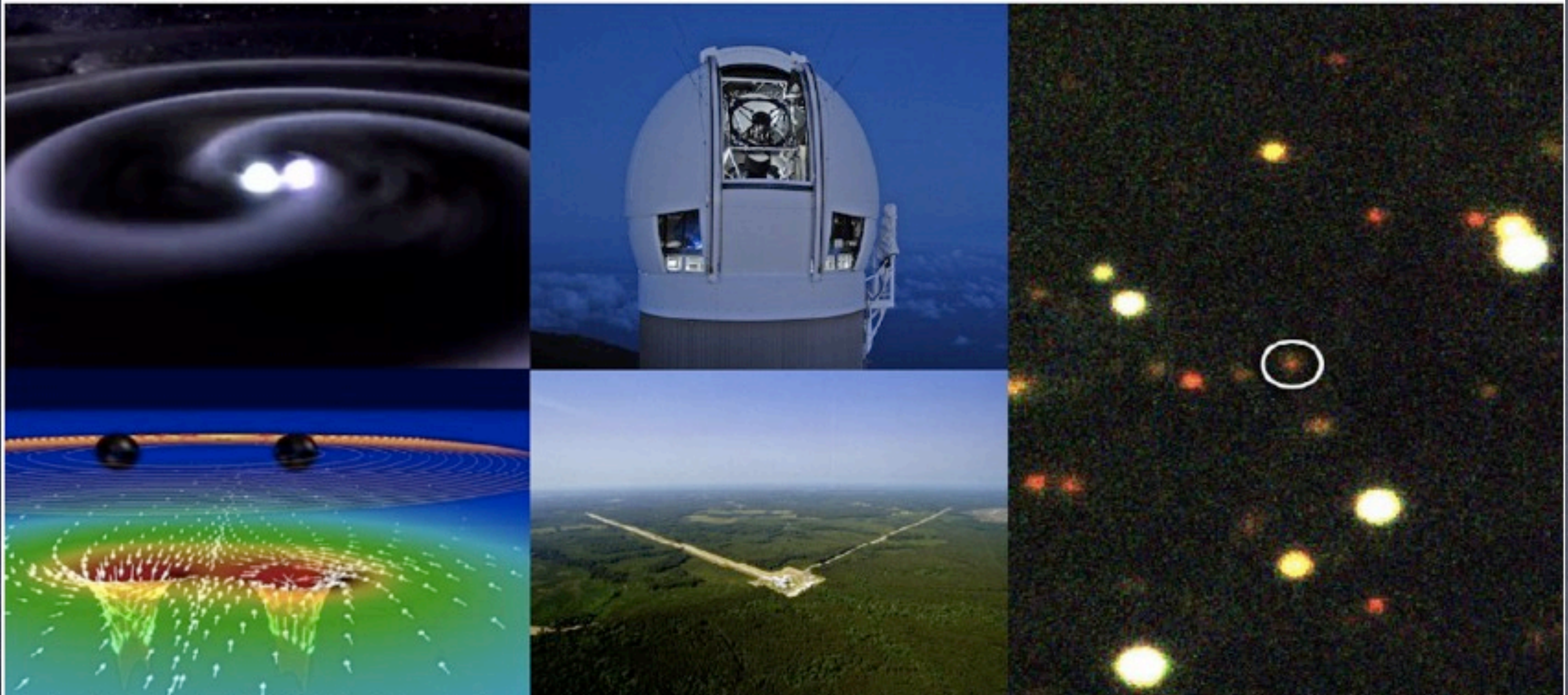
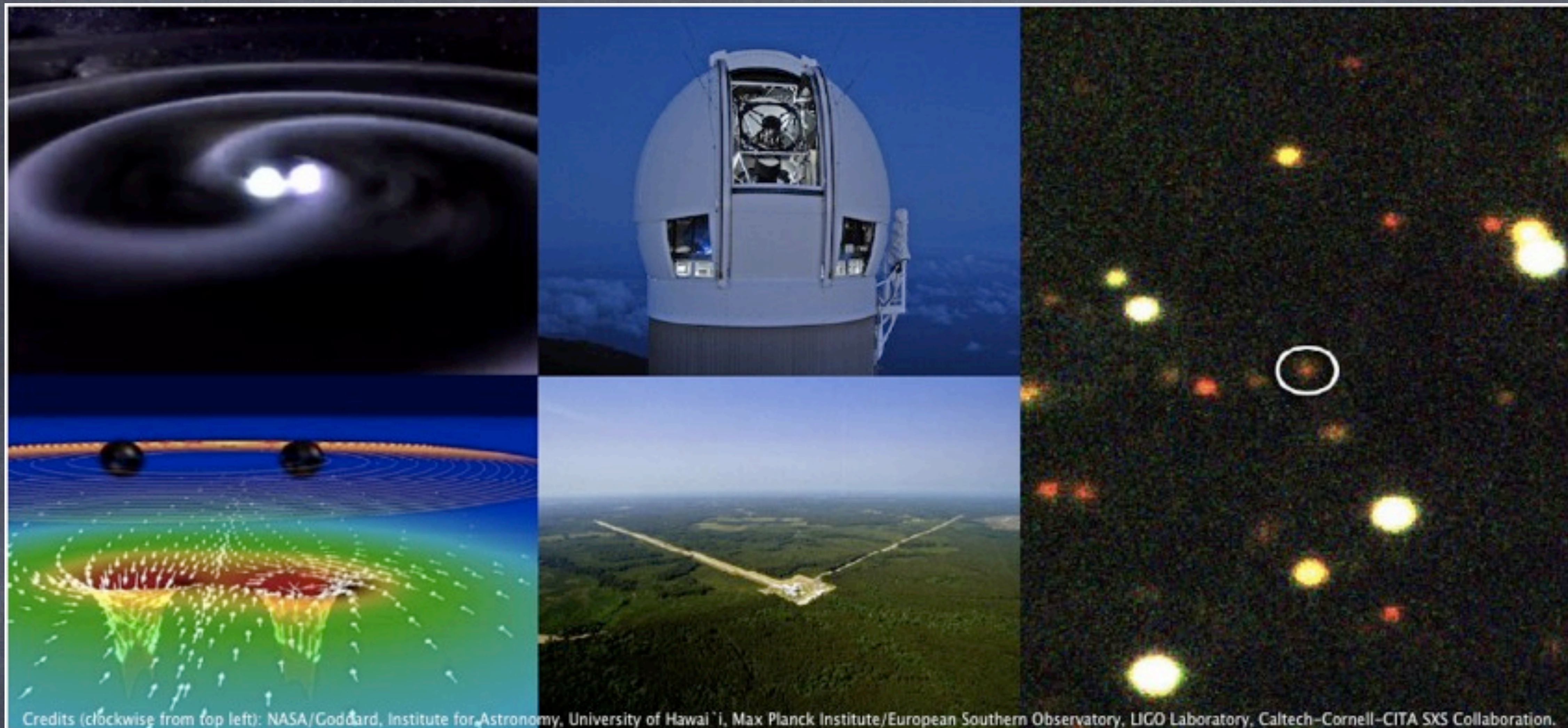
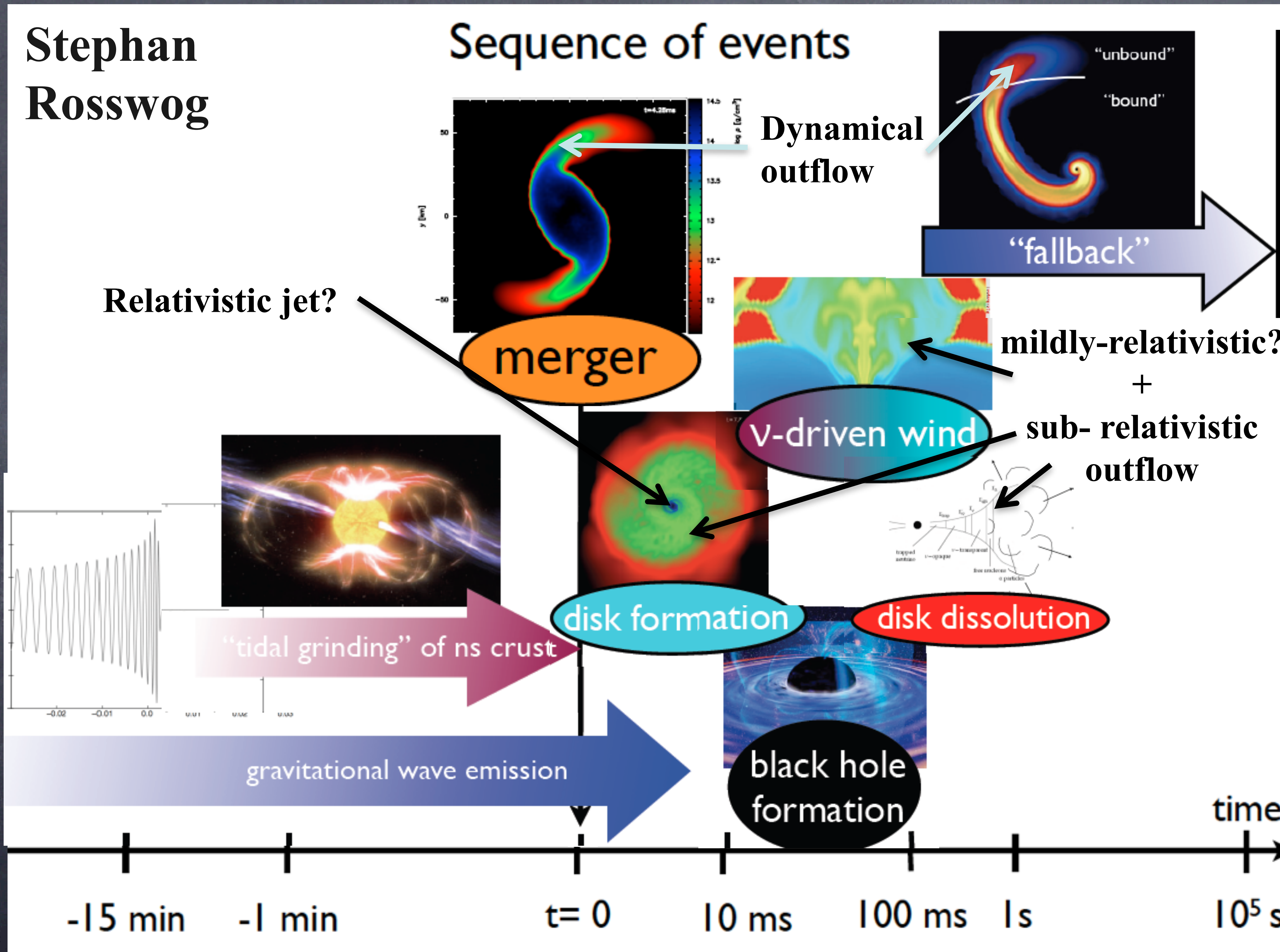
Received 1993 June 1; accepted 1993 August 18


Credits (clockwise from top left): NASA/Goddard, Institute for Astronomy, University of Hawai`i, Max Planck Institute/European Southern Observatory, LIGO Laboratory, Caltech-Cornell-CITA SXS Collaboration.

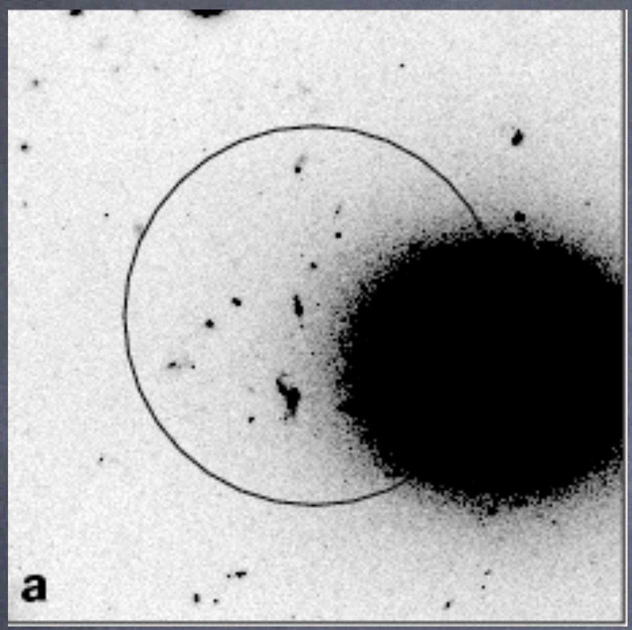


A long lived radio flare:
A relatively strong remnant lasting a few years with comfortable follow up options.
Nakar & TP, Nature 2011


Stephan Rosswog
Sequence of events
"unbound"
"bound"
Dynamical outflow
"fallback"
Relativistic jet?
merger
mildly-relativistic?
+
sub- relativistic outflow
ν-driven wind
disk formation
disk dissolution
"tidal grinding" of ns crust
gravitational wave emission
black hole formation
time
-15 min
-1 min
t= 0
10 ms
100 ms
1s
10^5 s

Short γ-ray Bursts

(Eichler, Livio, TP & Schramm, 1989)

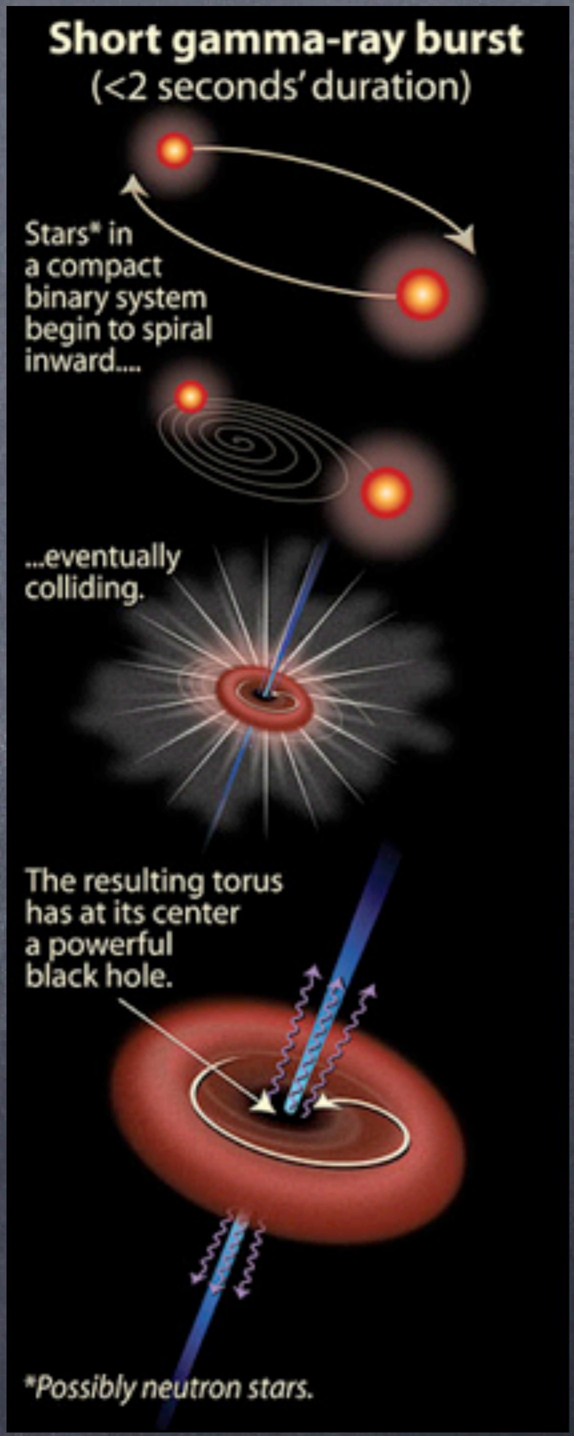


GRB 050709

Elliptical host

⇓

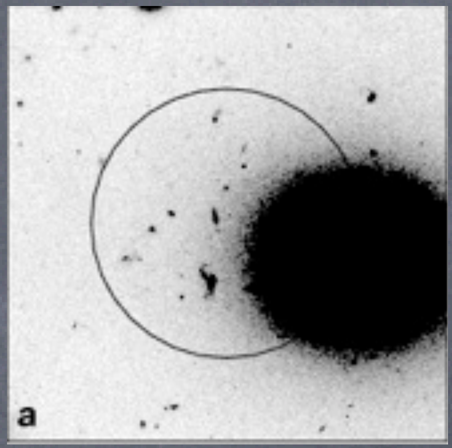
Old stellar population



A coincident detection of a short GRB and GW
(Kochaneck & TP 1993)

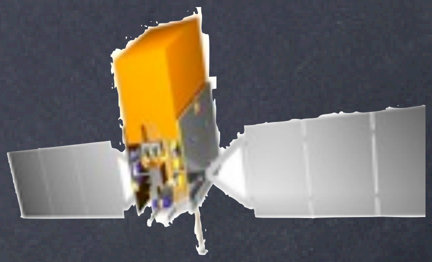
(Short) GRB

- In spite of significant circumstantial evidence - **the origin of short GRBs is still uncertain.**



- Short GRBs are beamed - **A generic observer won't detect a burst.**

- **Will a GRB sattelite be available when Advanced LIGO/Virgo are operational ?**

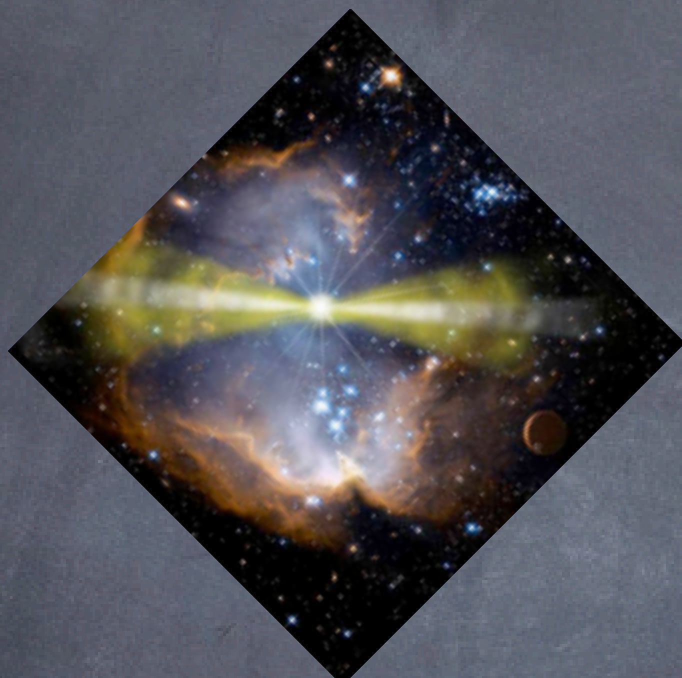


?

(Short) GRB Afterglow

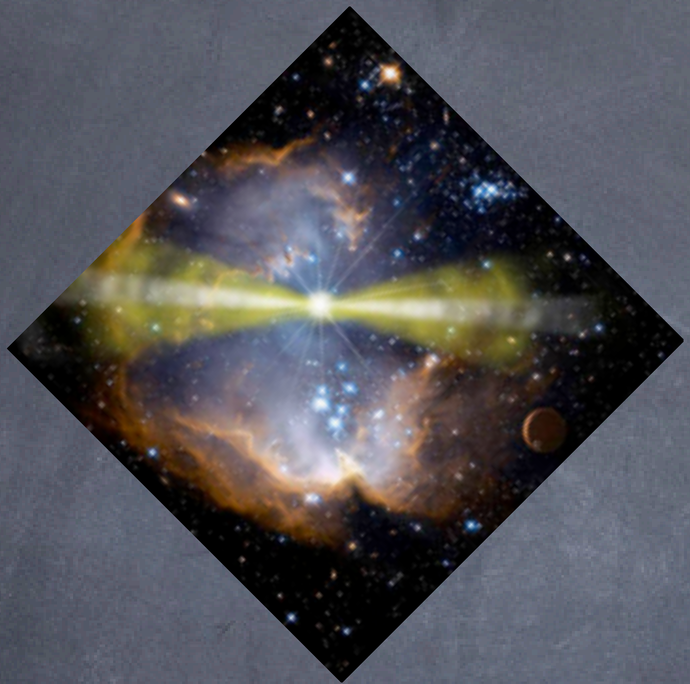
- Afterglow on a day time scale (at 300 Mpc & 1 day):
  - X-ray ~ 10^{-10} erg/s/cm^2
  - optical m_R~21
- A promising candidate on a scale of 1 day if the GRB points towarsd us.

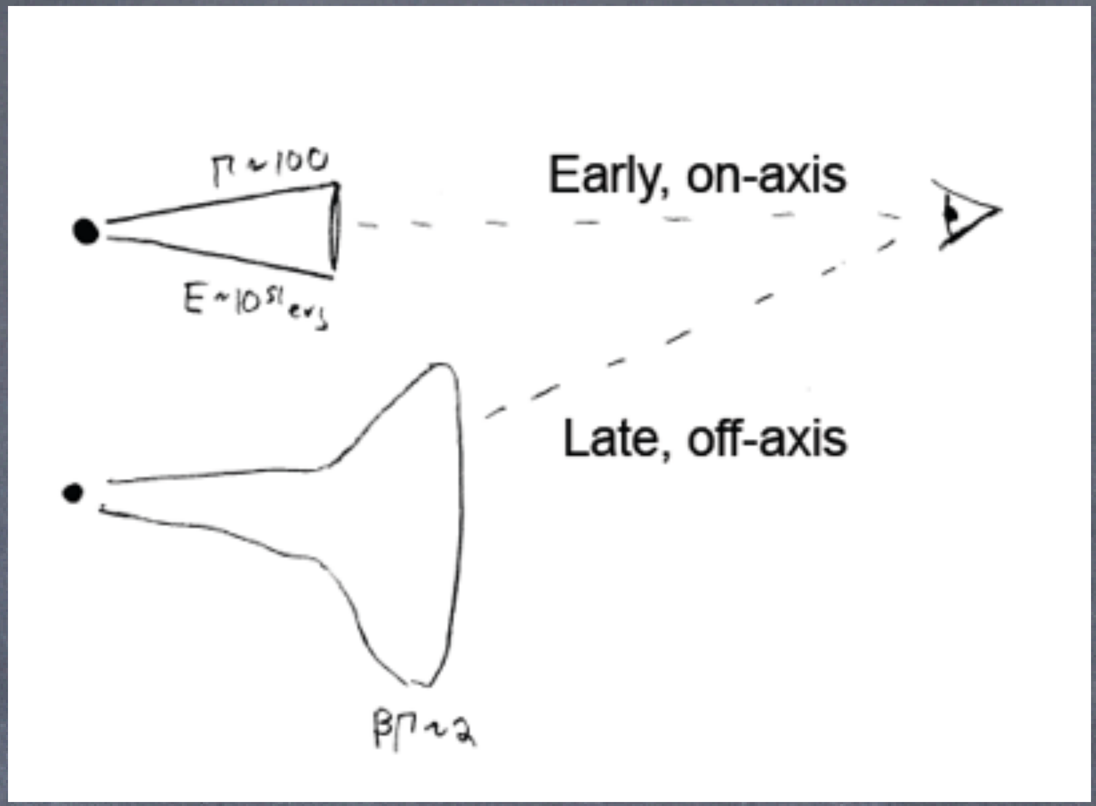
Orphan Afterglow



- X-ray and optical are too weak (Nakar, Granot, TP, 2003).
- Radio orphan afterglow is subdominant compared to the "radio remenant".

Orphan Afterglow





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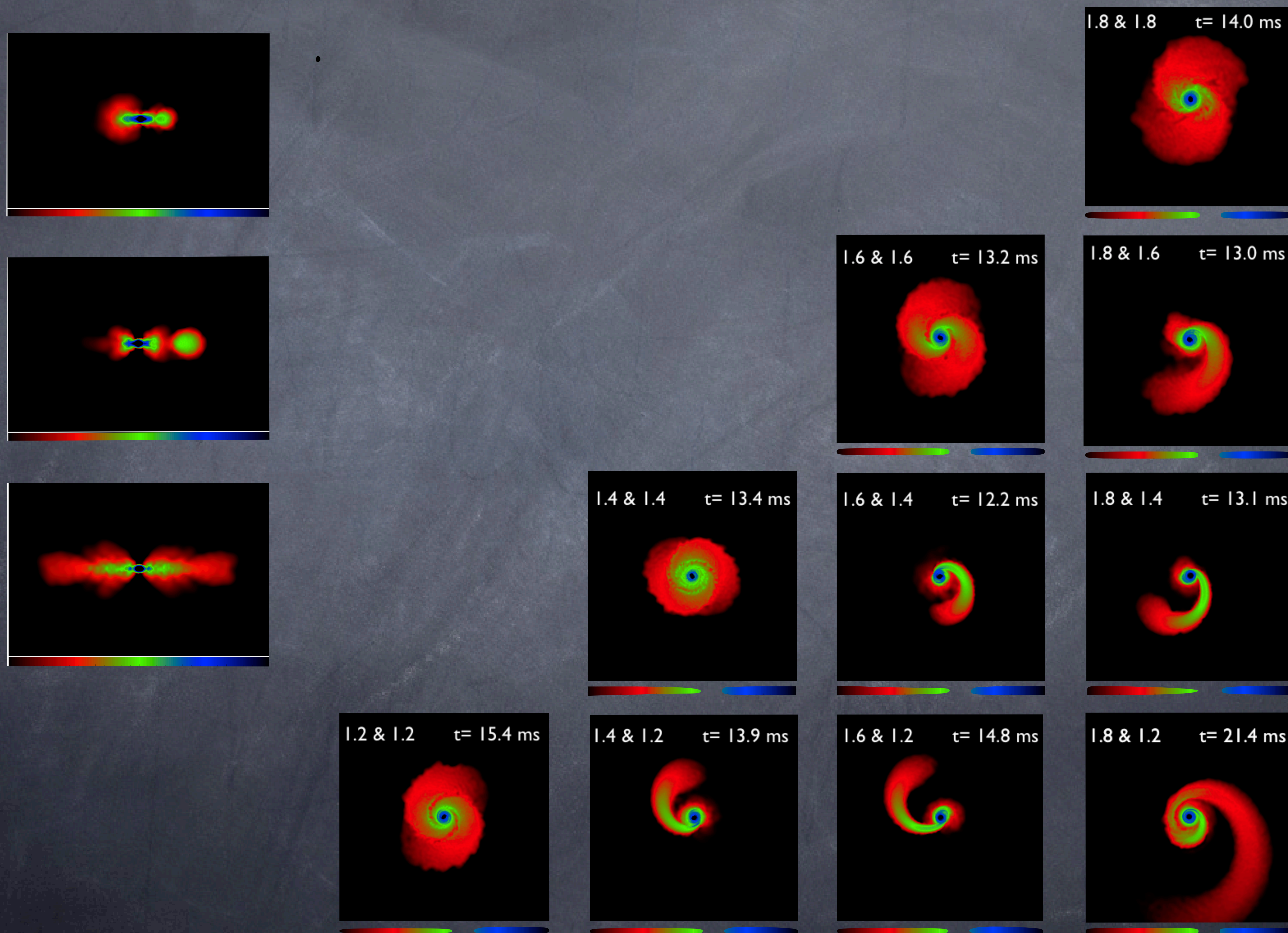
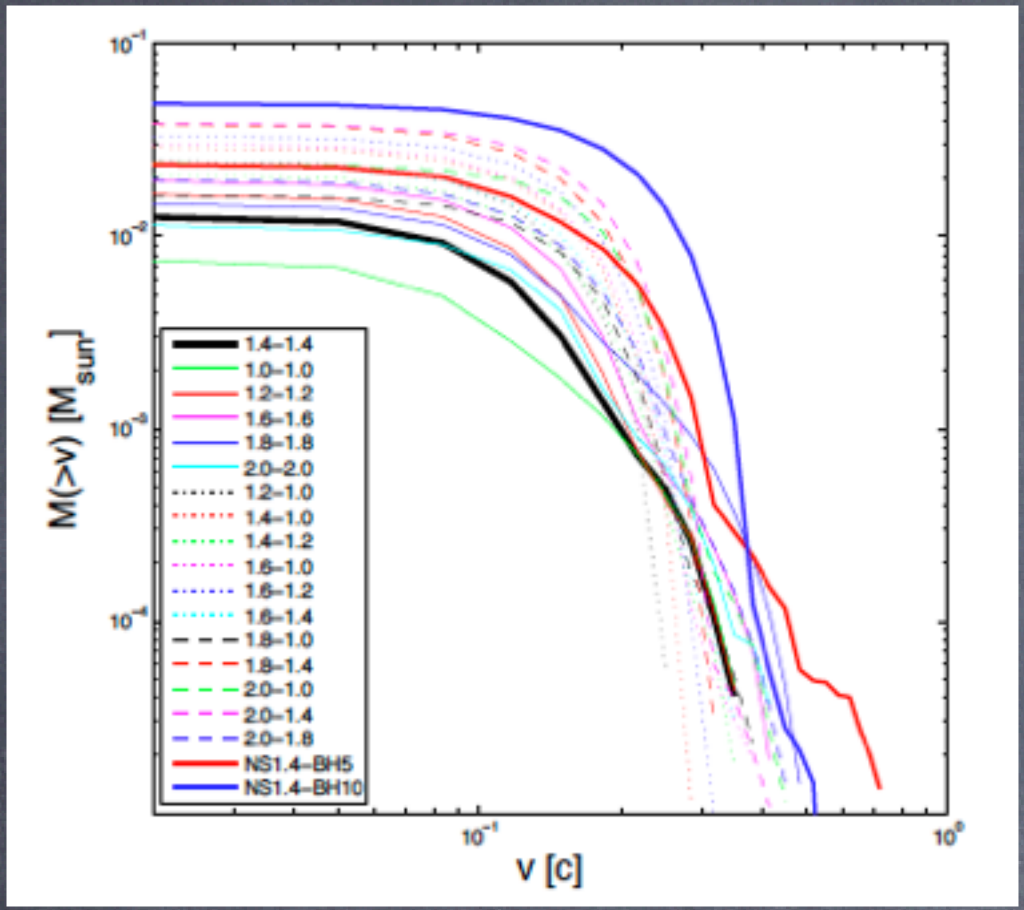
S. Rosswog

A significant Mass is ejected during a NS^2 merger. This will produce EM signature (analogue to SN and SNR)

NS^2 Merger outflow (Rosswog +, 2012)



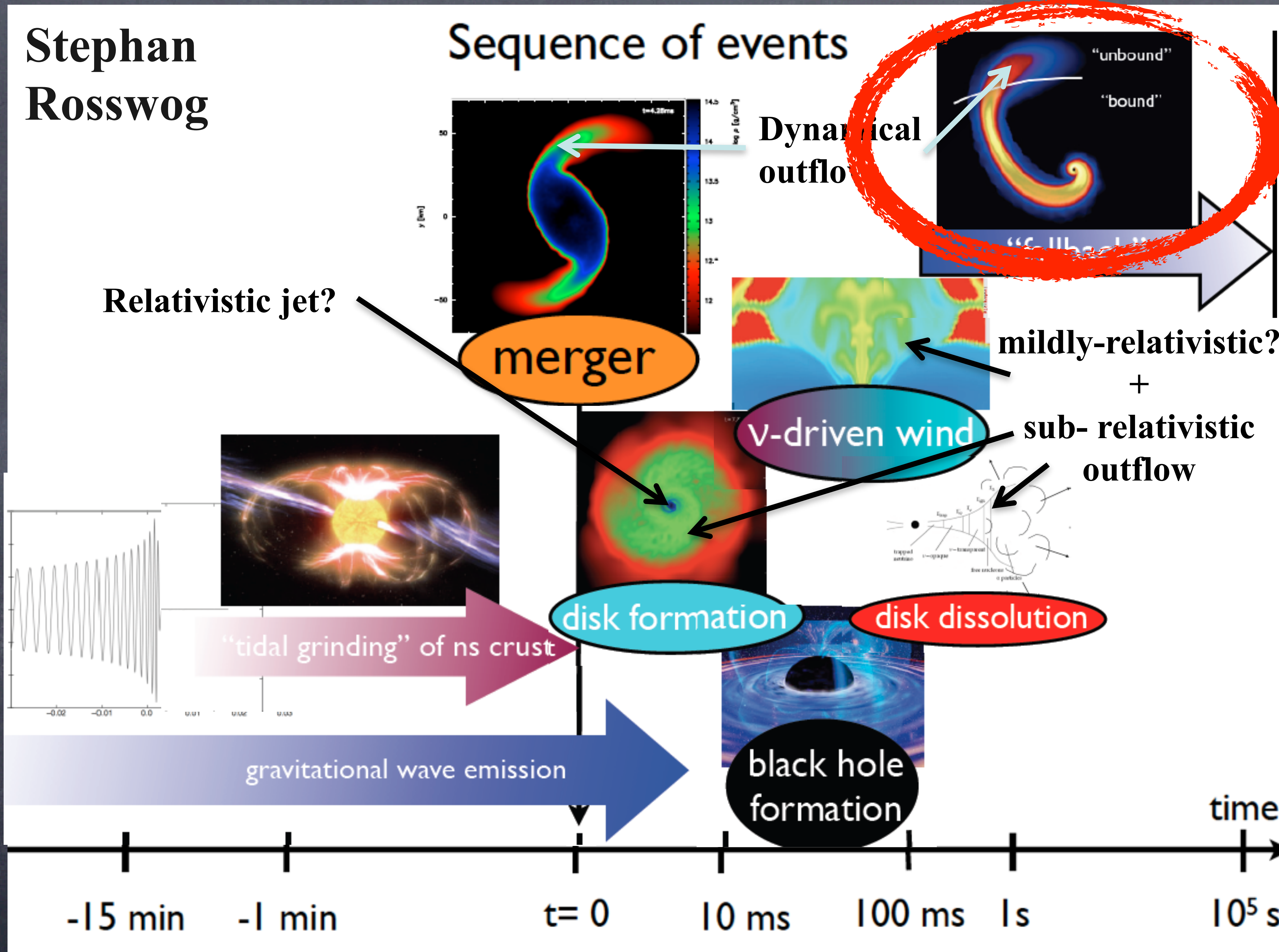
Typical Parameters



- Mass and Energy ejection increases significantly with mass asymmetry.

Mass	Velocity	Energy
0.01-0.1 m_o	0.1-0.2 c	0.1-1 x 10^{51} erg

This total enegy is comparable to a supernova with a lower mass but much faster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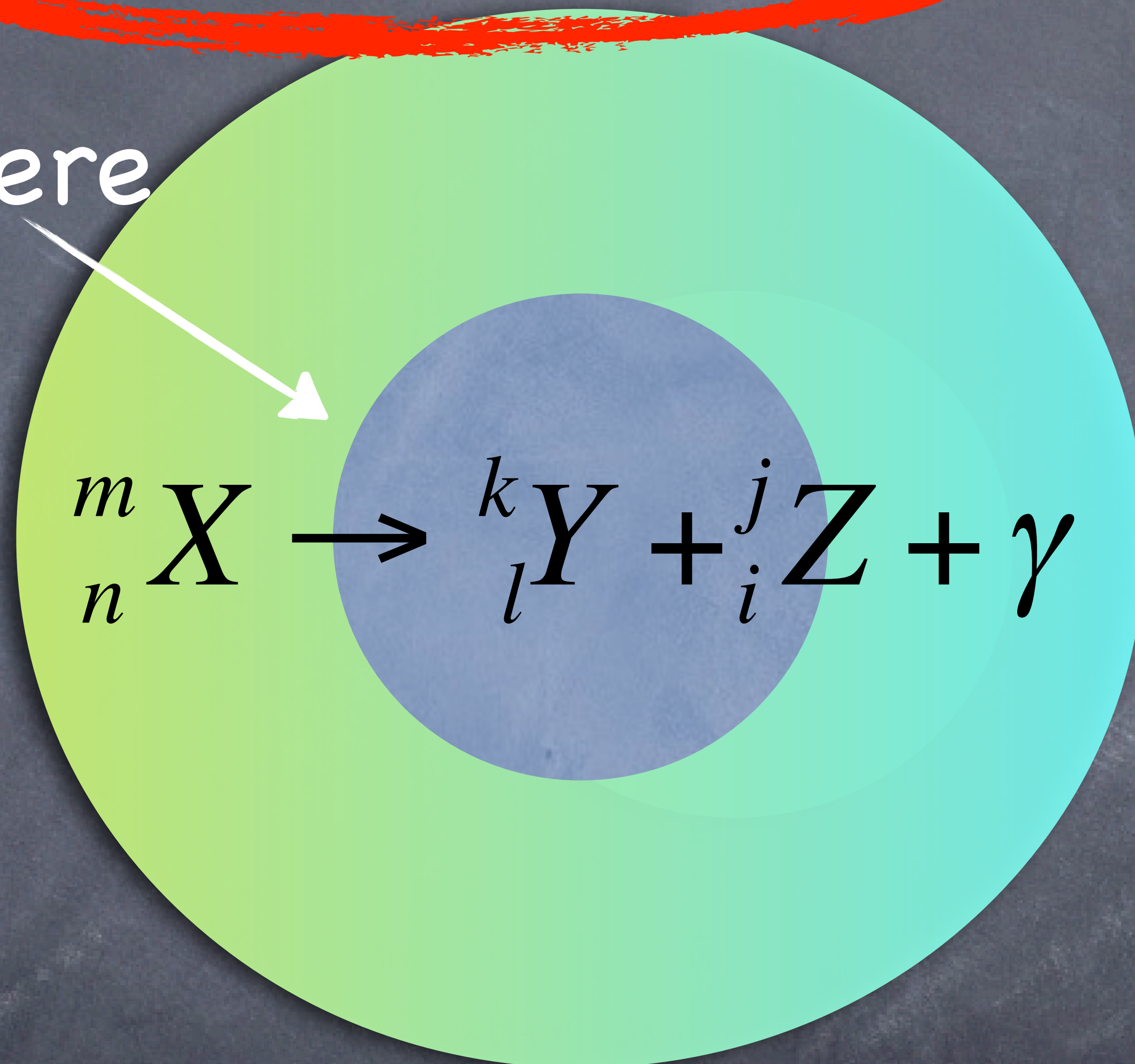
Radioactive material within the ejected outflow powers a weak short lived supernova

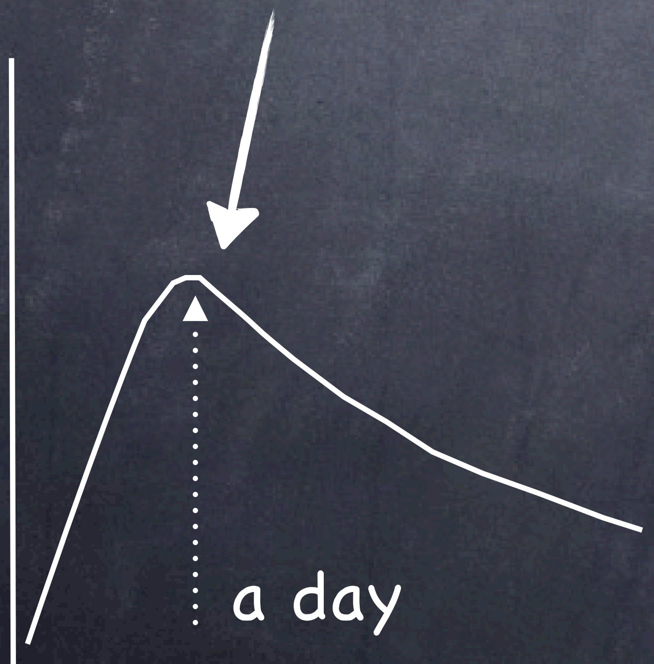
- Macronova

photosphere



$$ {}^{m}_{n}X \rightarrow {}^{k}_{l}Y + {}^{j}_{i}Z + \gamma $$

Maximum when the system becomes transparent



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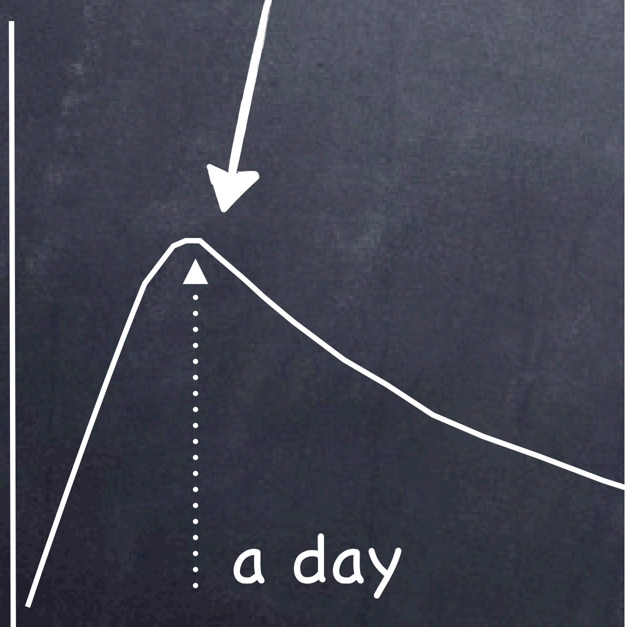
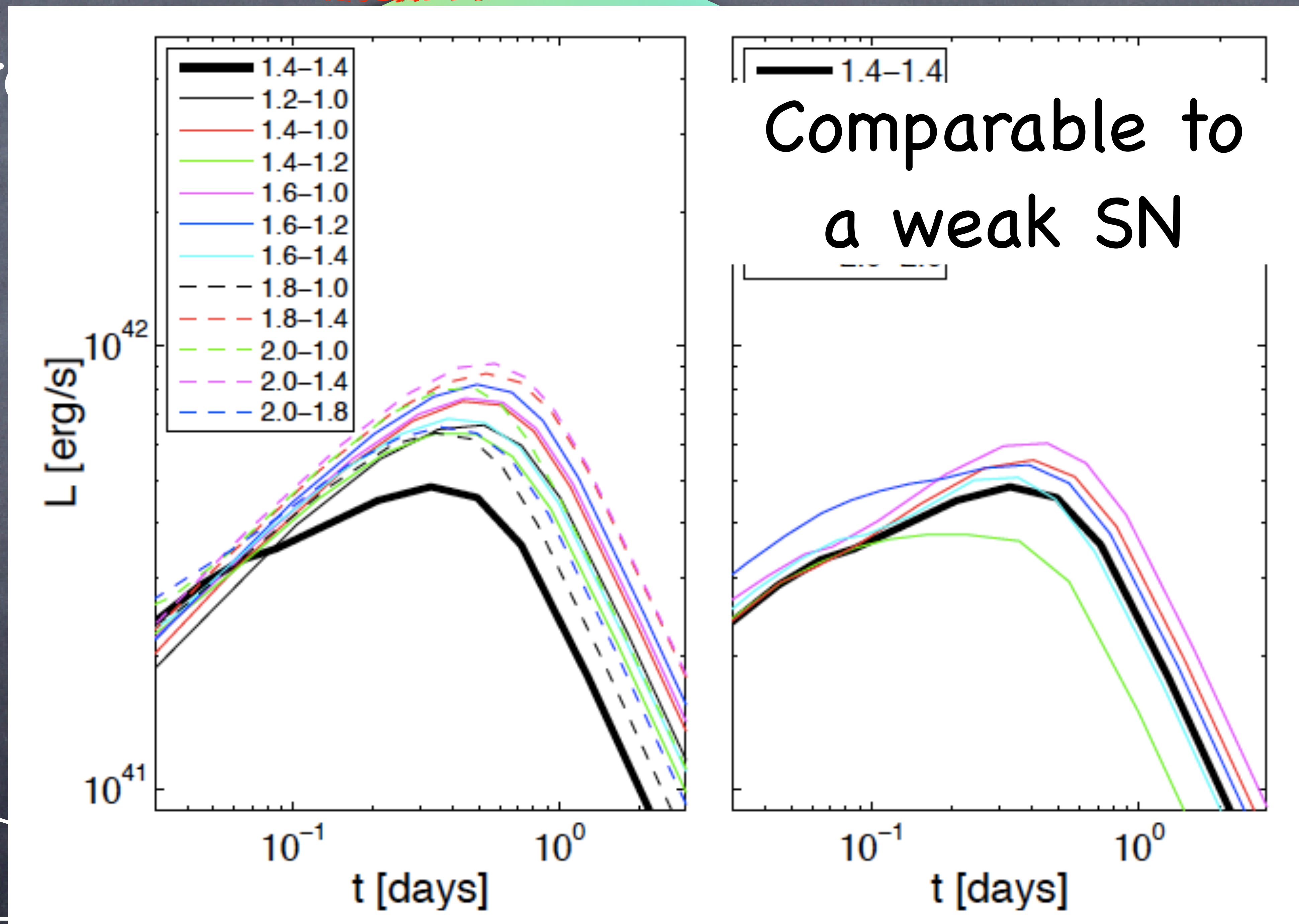


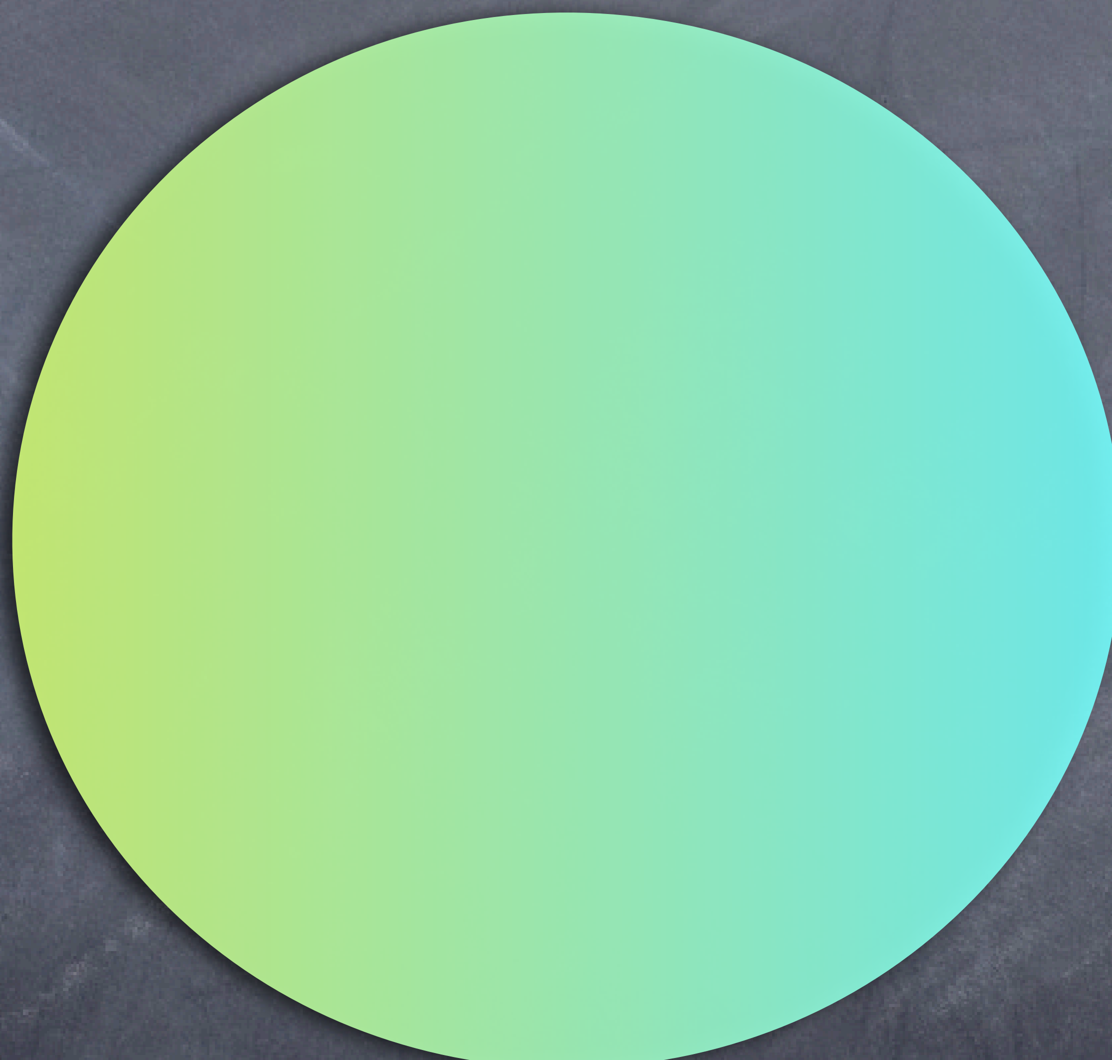


Comparable to a weak SN

Merger

Radio Flare

Expanding
ejecta



Macronova

Radio Flare


Expanding
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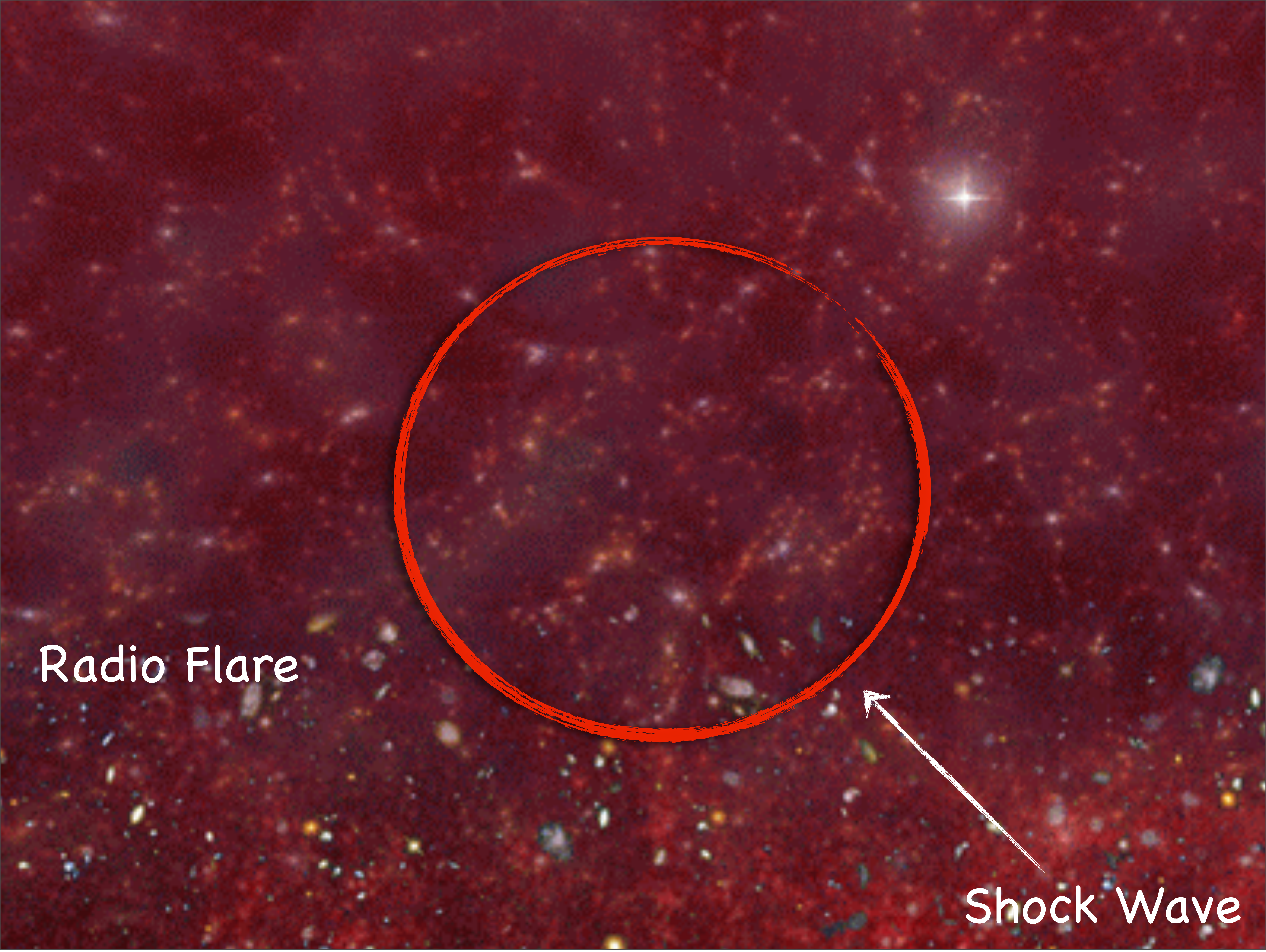
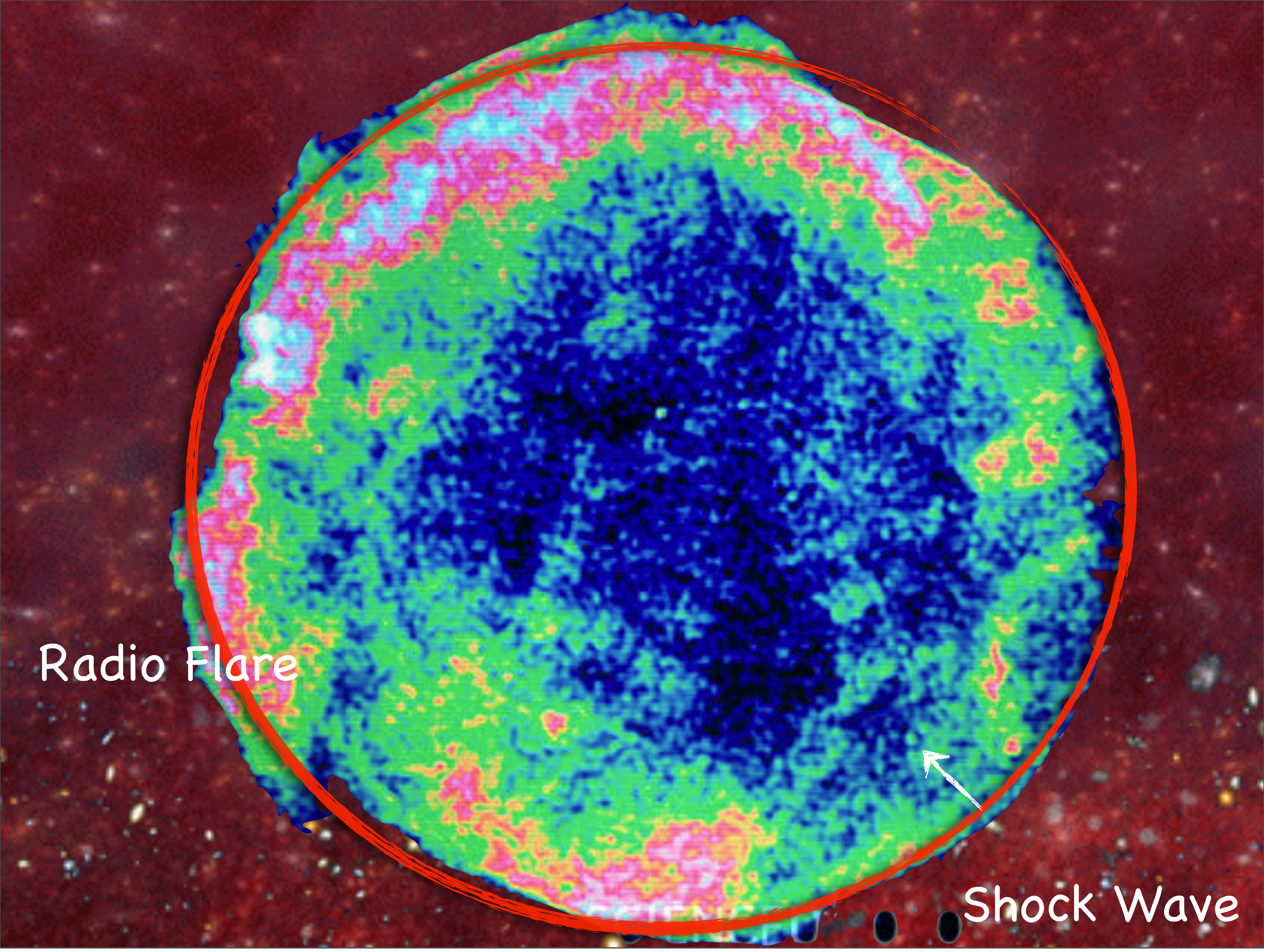
Radio Flare

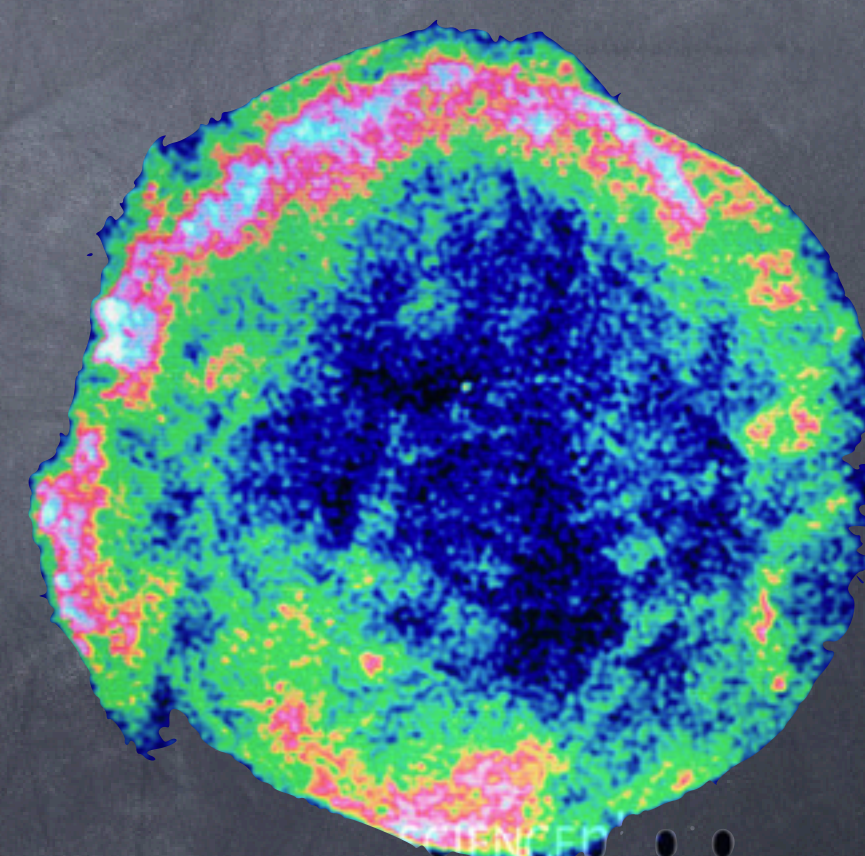

Radio Flare
Shock Wave


Radio Flare
Shock Wave

Radio Flares

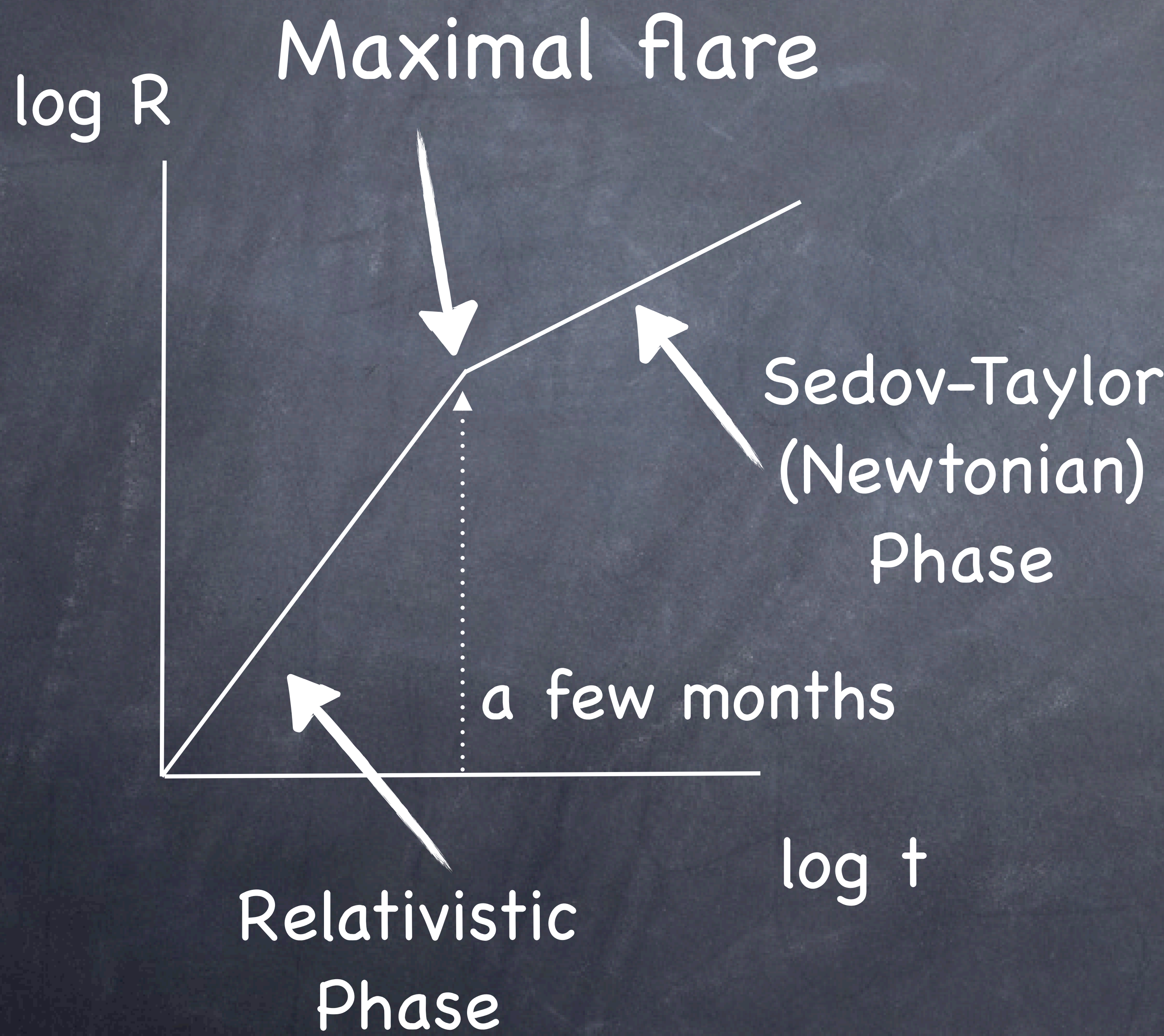
(Nakar & TP, Nature 2011; TP Nakar & Rossowg,

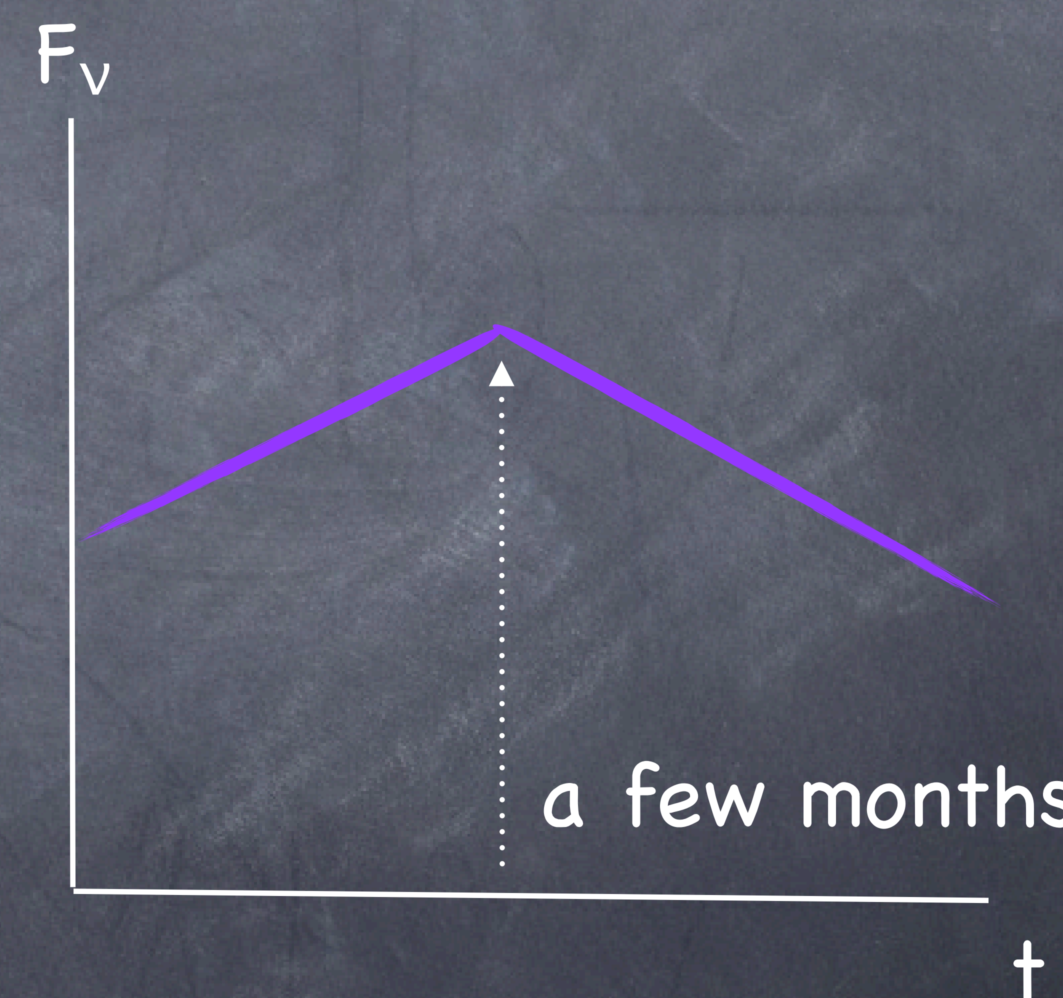
- Mildly relativistic outflow with $E \geq 10^{49}$ ergs
- Interaction of the outflow with the surrounding matter
- -> **A radio flare**



Supernova	⟺	Macronova
A few months		One day
Supernova Remnant	⟺	NS2 (Radio) Remnant
10^4 years		A few years

Dynamics and light Curve



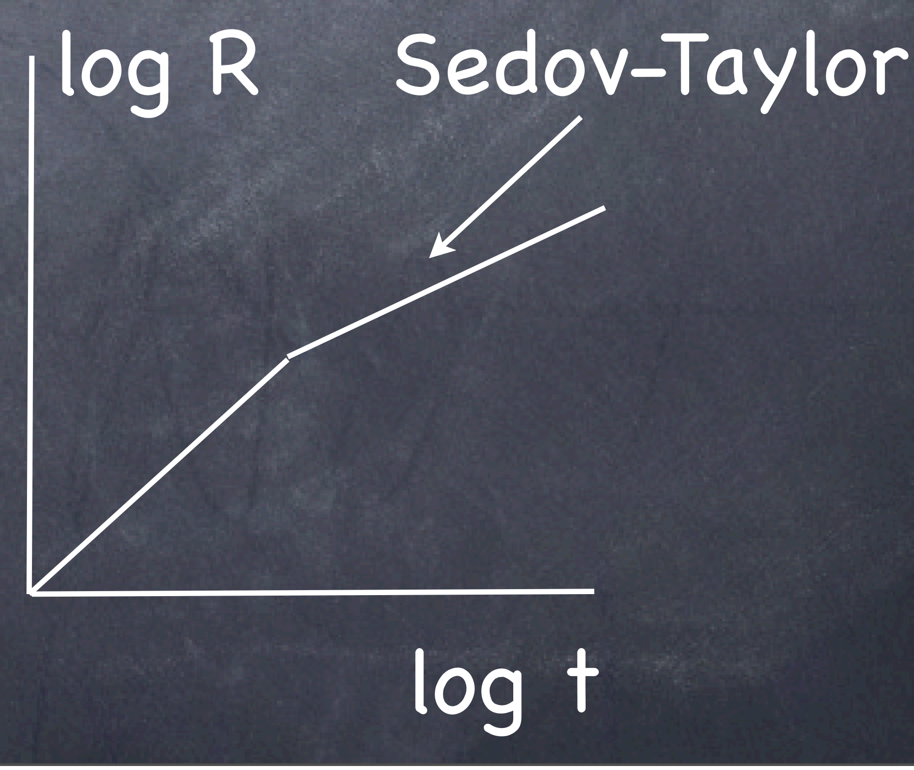


Dynamics

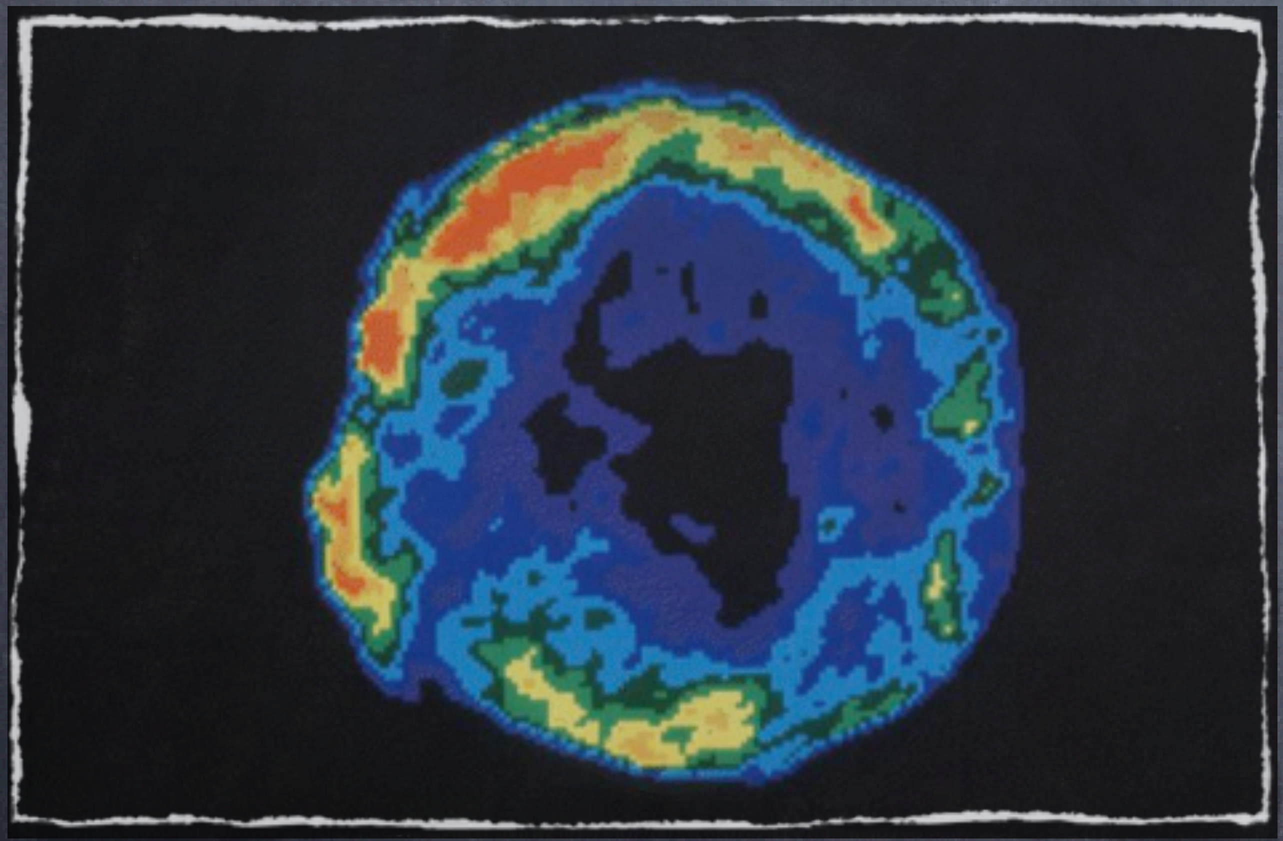
$$R_{dec} = \left(\frac{3E}{8\pi n m_p c^2(\Gamma_0 - 1)}\right)^{1/3} = 0.9 \times 10^{17}\ \mathrm{cm}\ E_{49}^{1/3} n^{-1/3} (\Gamma_0 - 1)^{-1/3},$$

$$t_{dec} = \frac{R_{dec}}{c\beta_0} \approx 30\ \mathrm{day}\ E_{49}^{1/3} n^{-1/3} (\Gamma_0 - 1)^{-5/6}.$$

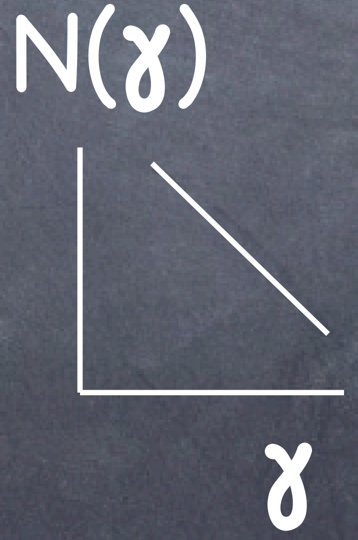
$$\Gamma - 1 \approx (\Gamma_0 - 1) \begin{cases} 1 & R \leq R_{dec}\ , \\ (R/R_{dec})^{-1/3} & R \geq R_{dec}\ . \end{cases}$$



GRB afterglow and Radio Supernova e.g. 1998bw (Chevalier 98)



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



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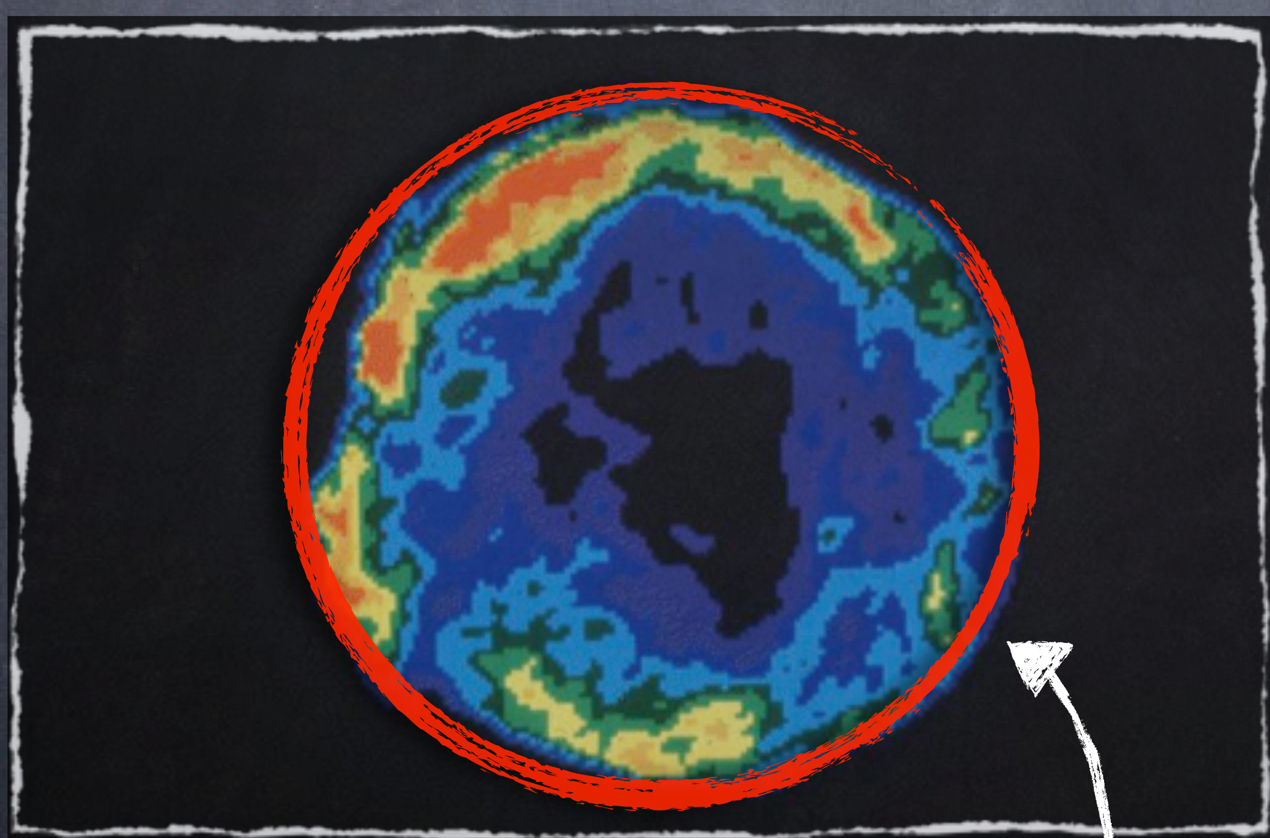
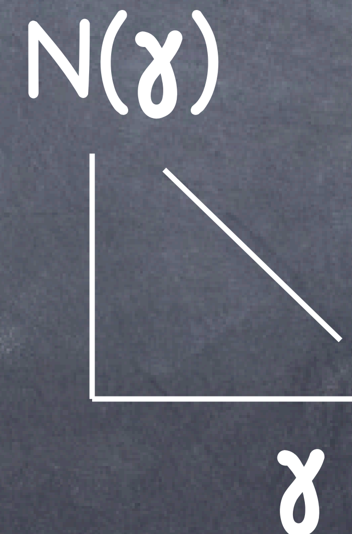


Tycho's **supernova** remnant seen at **radio** wavelengths

The shock wave accelerates the electrons and amplifies the Magnetic field.



$e_e=\epsilon_e e$

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

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

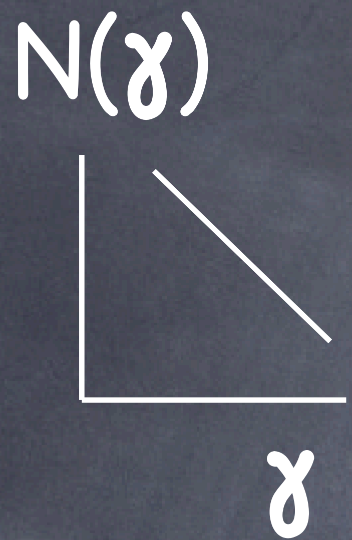
$p=2.5 - 3$

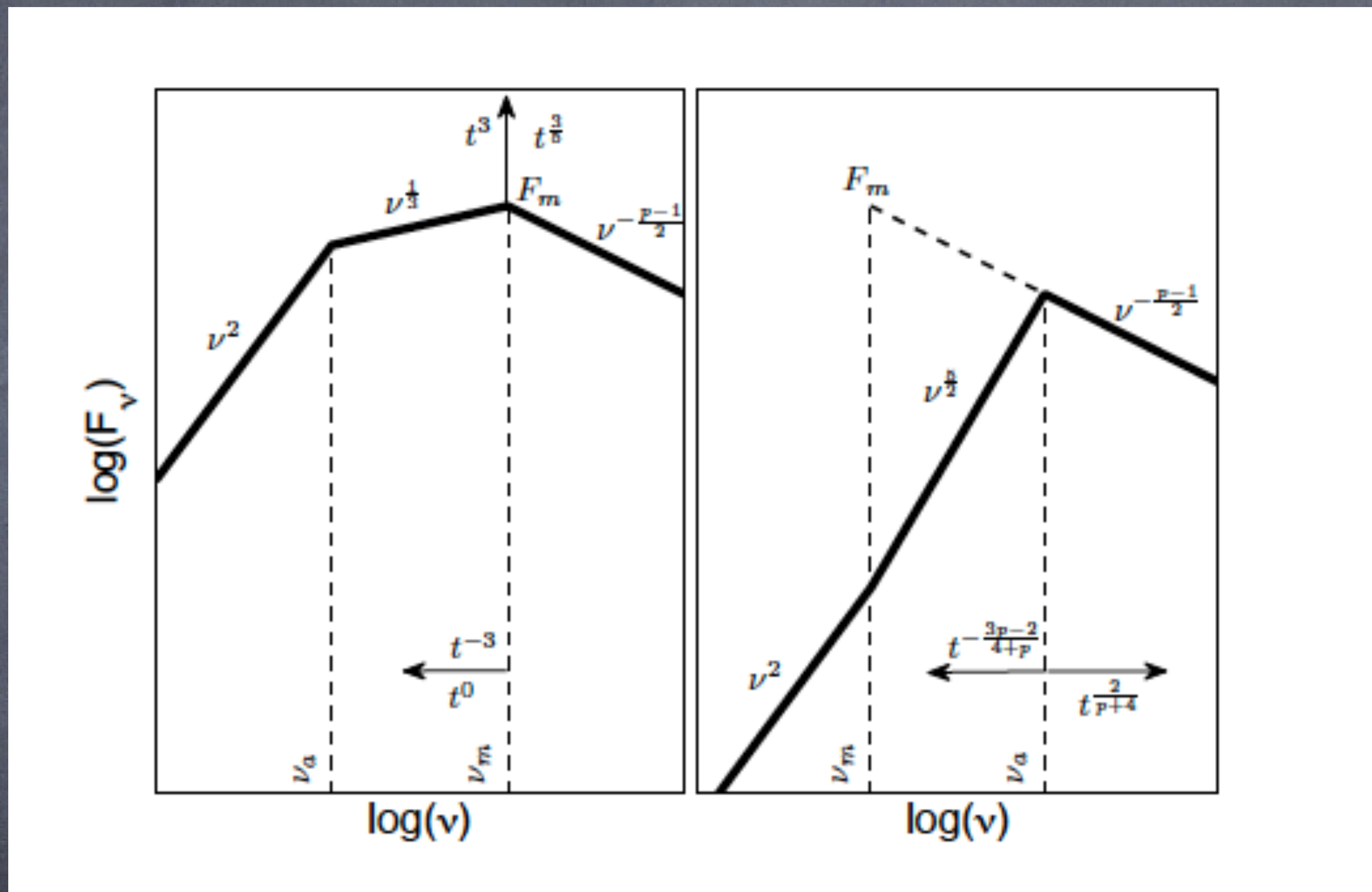
$\gamma_m= (m_p/m_e)e_e\ (\Gamma-1)$

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

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

The Spectrum





$\nu_m \approx$ 1Ghz

Radio Fluxes

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

$$F_{m,dec} \approx 0.5\ \mathrm{mJy}\ E_{49} n^{1/2} \epsilon_{B,-1}^{1/2} (\Gamma_0 - 1)^{-1/2} d_{27}^{-2}.$$

$$\nu_{a,dec} \equiv \nu_a(t_{dec}) \approx 1\ \mathrm{GHz}\ E_{49}^{\frac{2}{3(4+p)}} n^{\frac{14+3p}{6(4+p)}} \epsilon_{B,-1}^{\frac{2+p}{2(4+p)}} \epsilon_{e,-1}^{\frac{2(p-1)}{4+p}} (\Gamma_0 - 1)^{\frac{15p-10}{6(4+p)}}.$$

Radio Fluxes

External density

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Radio Fluxes

External density

Outflow velocity

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- All known ns^2 are in the galactic disk
- Typical density in the disk is n~ $1cm^{-3}$ (40% $n=0.6cm^{-3}$, 10% n>> $1cm^{-3}$, 50% n~ $10^{-3}cm^{-3}$)
- Some will have only a weak radio but many will have a strong radio remnant.
- To these we should add an unknown fraction that escape the host galaxies.

The external density

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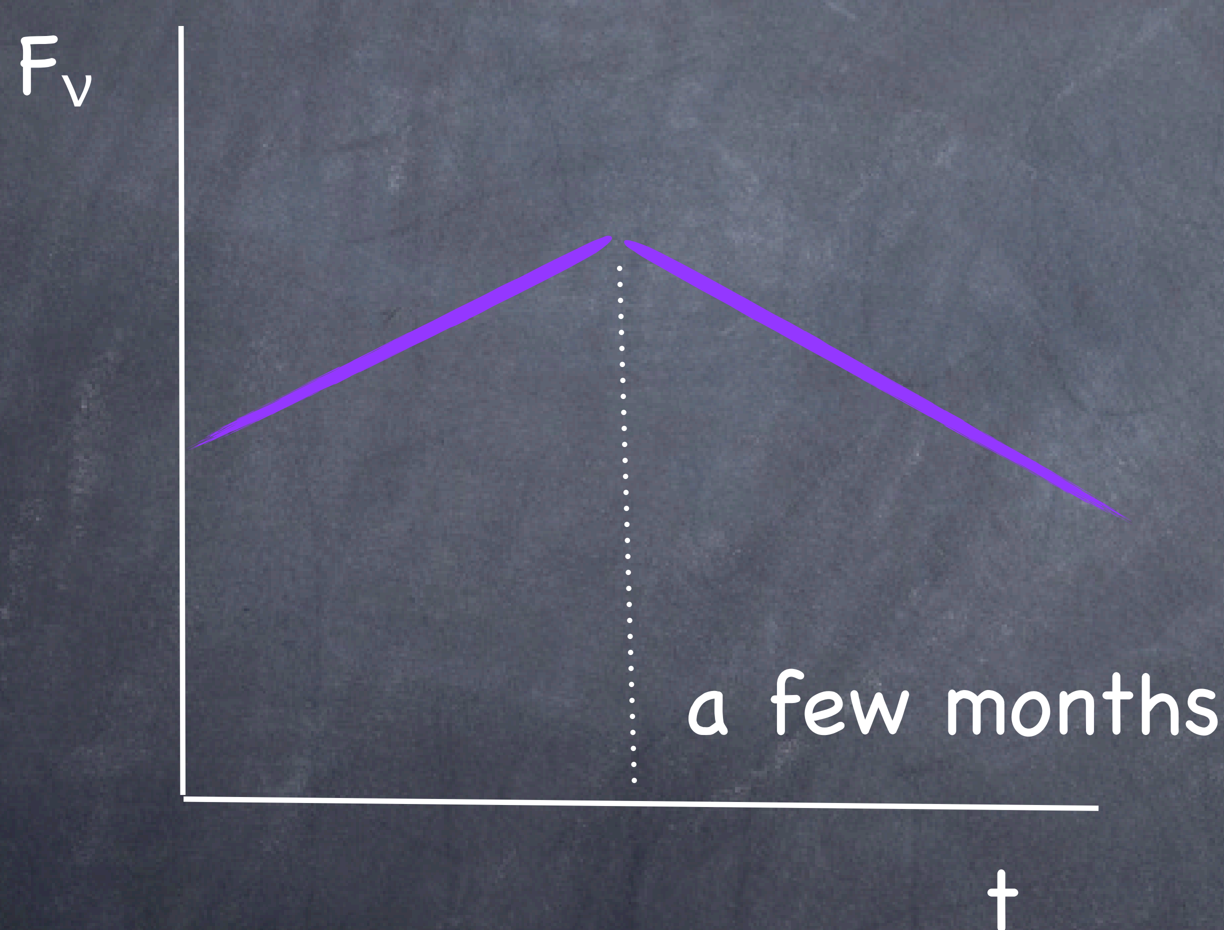
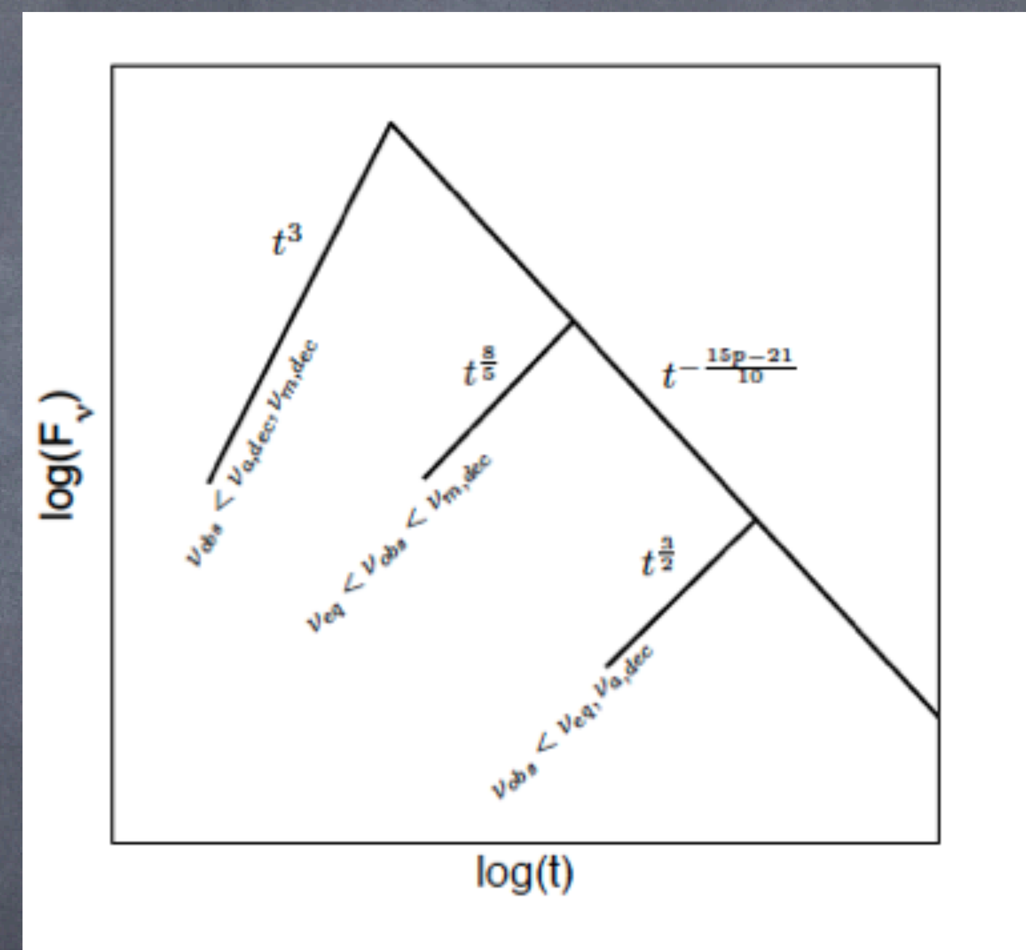
Schematic light curve

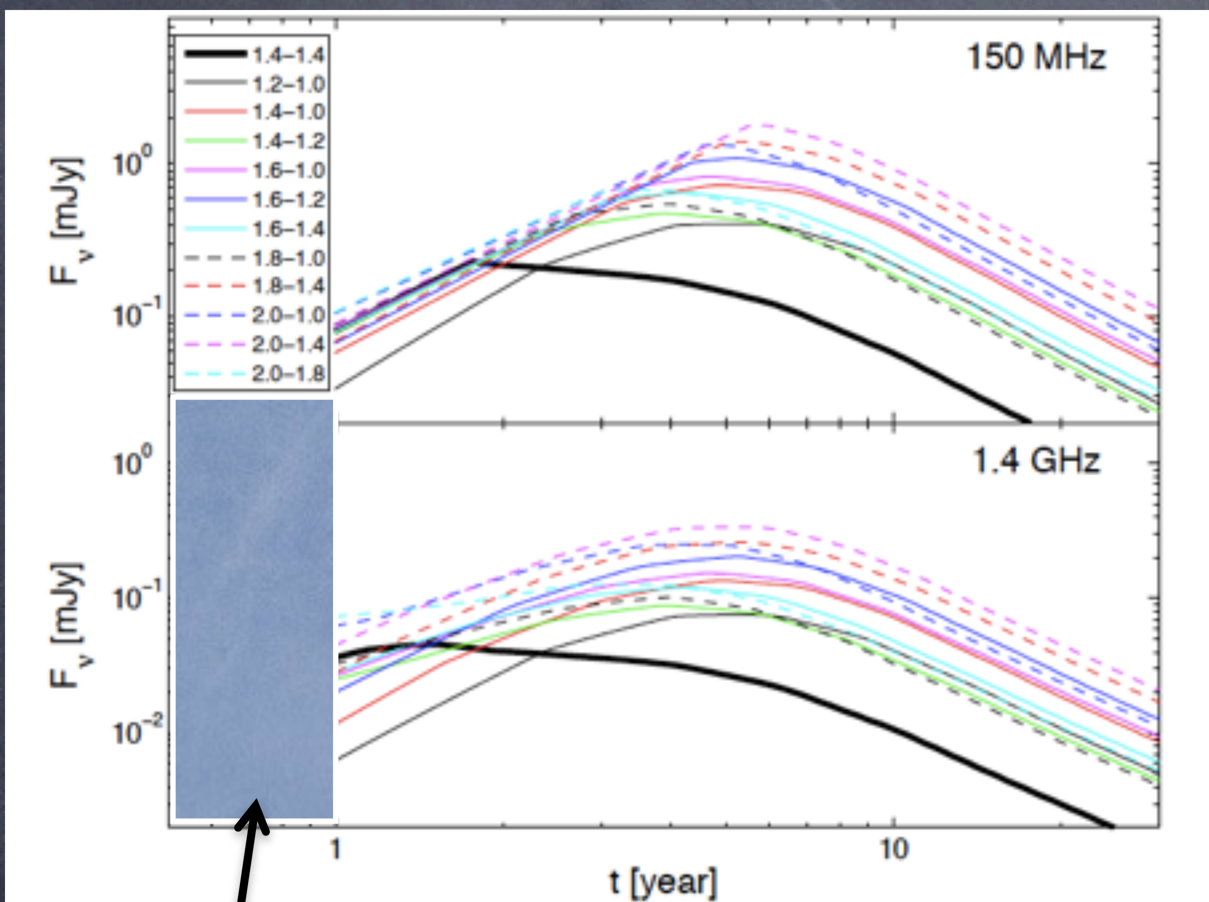




Numerical Lightcurves

(TP, Nakar & Rosswog, 2012)

At 300 Mpc



(Piran, Nakar & Rosswog, 2012)

Dominated by v>0.3c not included in the hydro simulation

150 MHz

$F_{\nu\ \mathrm{peak}} \approx$ 0.3=1 mJy

$t_{\mathrm{peak}} \approx$ 2-5 years

1.4 GHz

$F_{\nu\ \mathrm{peak}} \approx$ 0.05 mJy

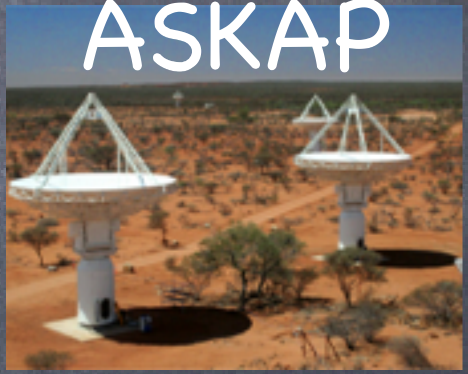
$t_{\mathrm{peak}} \approx$ 1.5-5 years

Detectability

Radio Facility	Obs Freq. (GHz)	Field of view (deg^2)	1 hr rms μJy	ns^2 1 hr horizon† $n = 1\text{cm}^{-3}$	ns^2 10 hr horizon†† $n = 0.1\text{cm}^{-3}$	nsbh 1 hr horizon† $n = 1\text{cm}^{-3}$	nsbh 10 hr horizon†† $n = 0.1\text{cm}^{-3}$
EVLA[a]	1.4	0.25	7	360 Mpc	200Mpc	1.8 Gpc	1.4 Gpc
ASKAP[b]	1.4	30	30	170 Mpc	100 Mpc	850Mpc	700 Mpc
MeerKAT[c]	1.4	1.5	35	160 Mpc	90 Mpc	800 Mpc	650 Mpc
Apertif[d]	1.4	8	50	135 Mpc	75 Mpc	670 Mpc	550 Mpc
LOFAR[e]	0.15	20	1000	70 Mpc	40 Mpc	300Mpc	250 Mpc


EVLA


MeerKAT


ASKAP


Apertif

LOFAR

Blind Radio Search

$$N^{{ns}^2}_{all-sky} \sim 20\mathcal{R}^{{ns}^2}_{300}\mathcal{F}^{-3/2}_{-1}$$

A mildly-relativstic component may increase the rate

Rate and density based on Galactic ns^2

Survey limit 0.1mJy

A blind search may determine the event rate even before ALIGO/Virgo become operational

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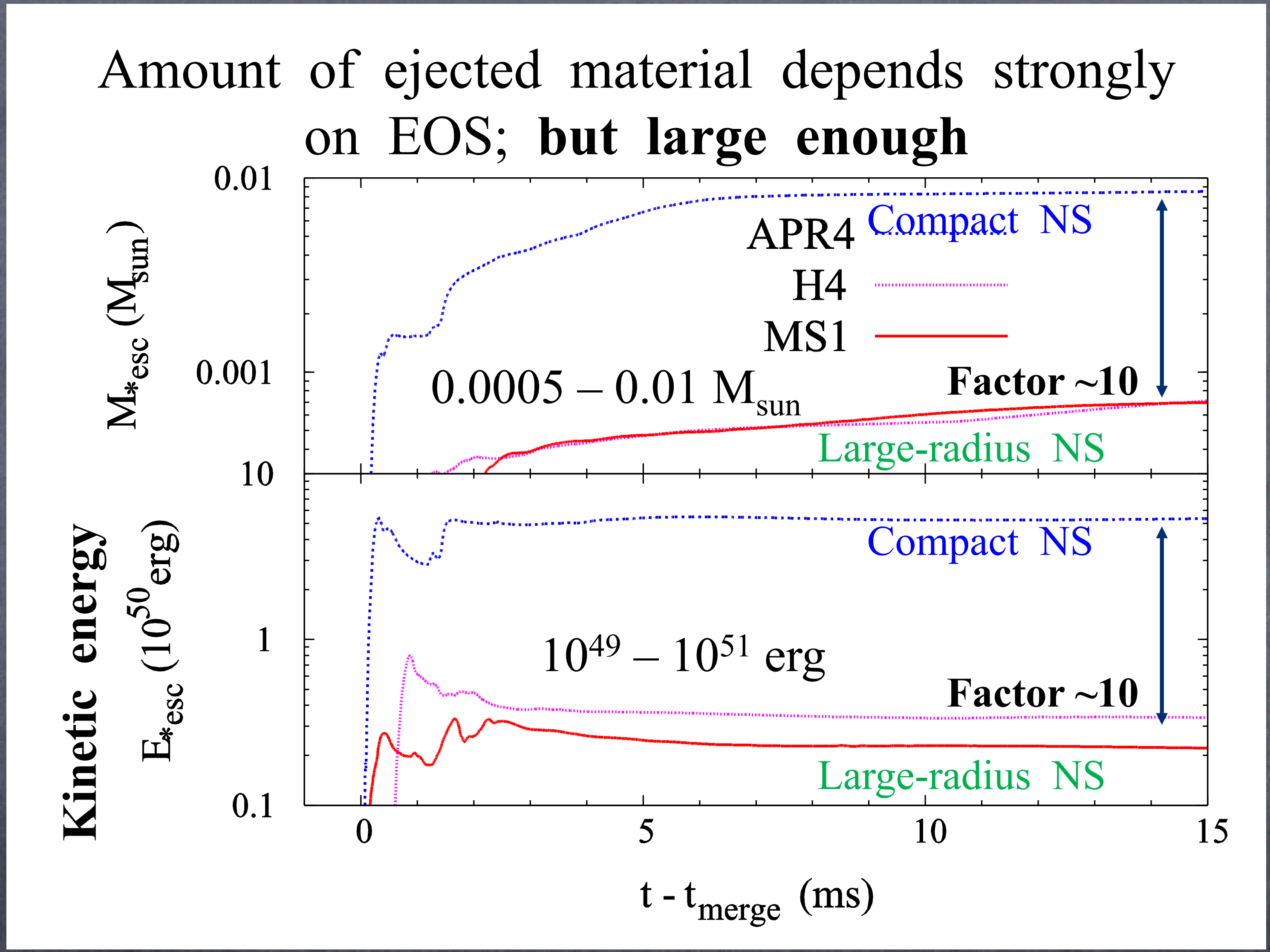
Relativistic merger Simulations

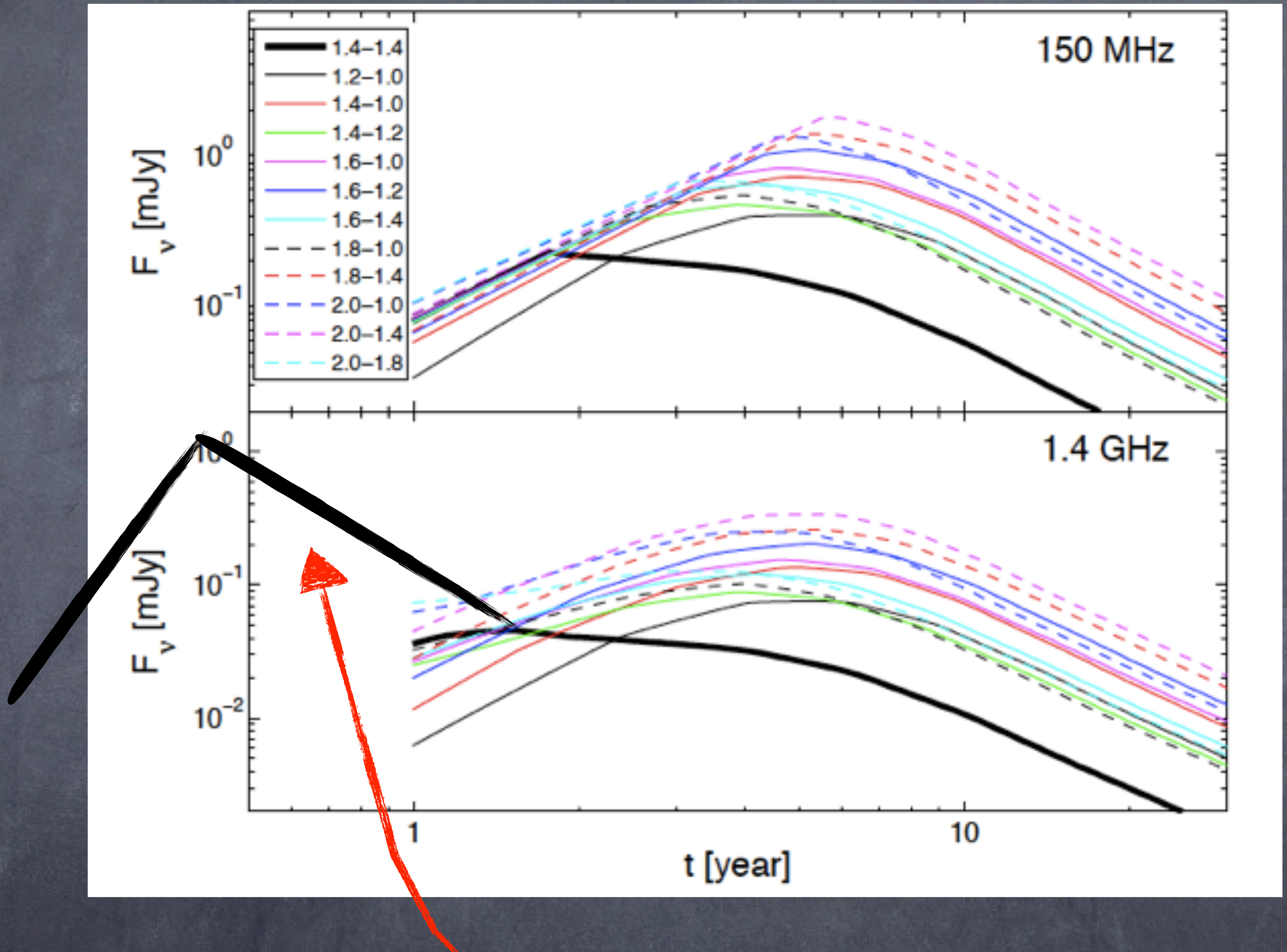
Hotokezaka and Shibata (Kyoto U) 2012



Average velocity 0.2–0.3c

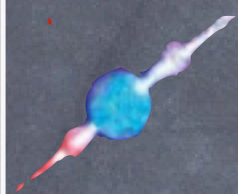
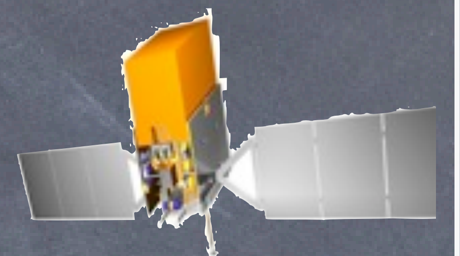
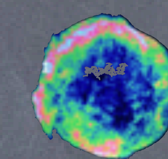
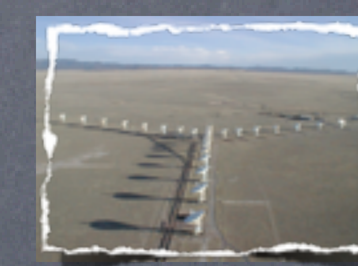
Max velocity 0.7–0.8c

Even stronger signal!



Mildly Relativistic outflow:
Stronger and peaks at one month

Summary

	Short GRB	Macronova	Radio Flare
	 	 	 
Band	γ - rays	Optical UV	Radio (1.4GHz)
Duration	<2 sec	< day	~months-years
Horizon	a few Gpc	500 Mpc	0.3-1 Gpc
Drawbacks	•Association ? •Beaming •Available Satellite	•Micro-physics ? •Identification among many optical transients	• External density ? • Some may have a weak radio remnant.
Advantages	•A very strong signal	•Numerous optical transient searches exist •Needs a quick response	•Strong signal •Quiet radio sky (?) •Long duration