Electromagnetic Transients as Triggers for Gravitational Waves from Compact Binary Mergers

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LSC - ExtTrig

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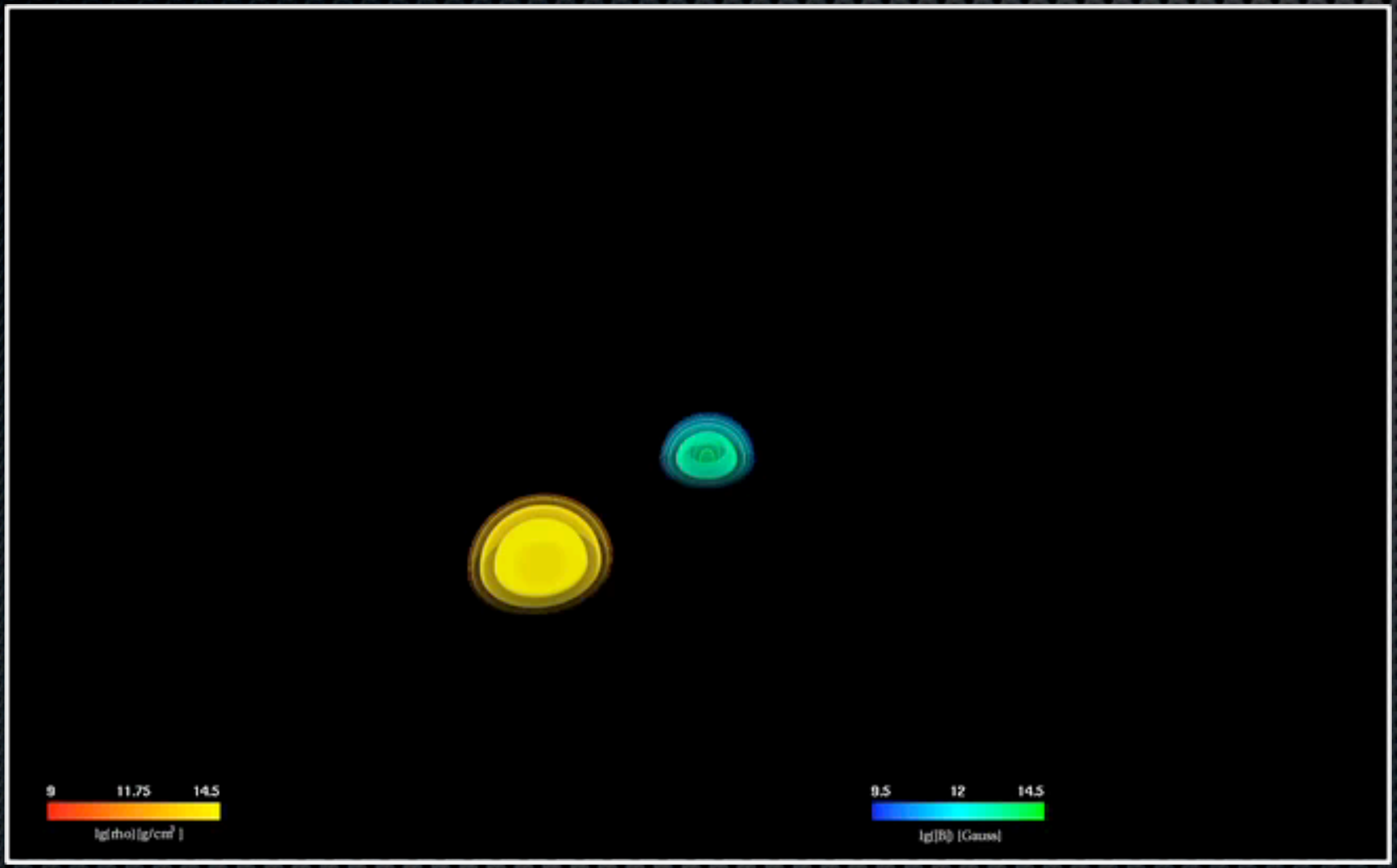
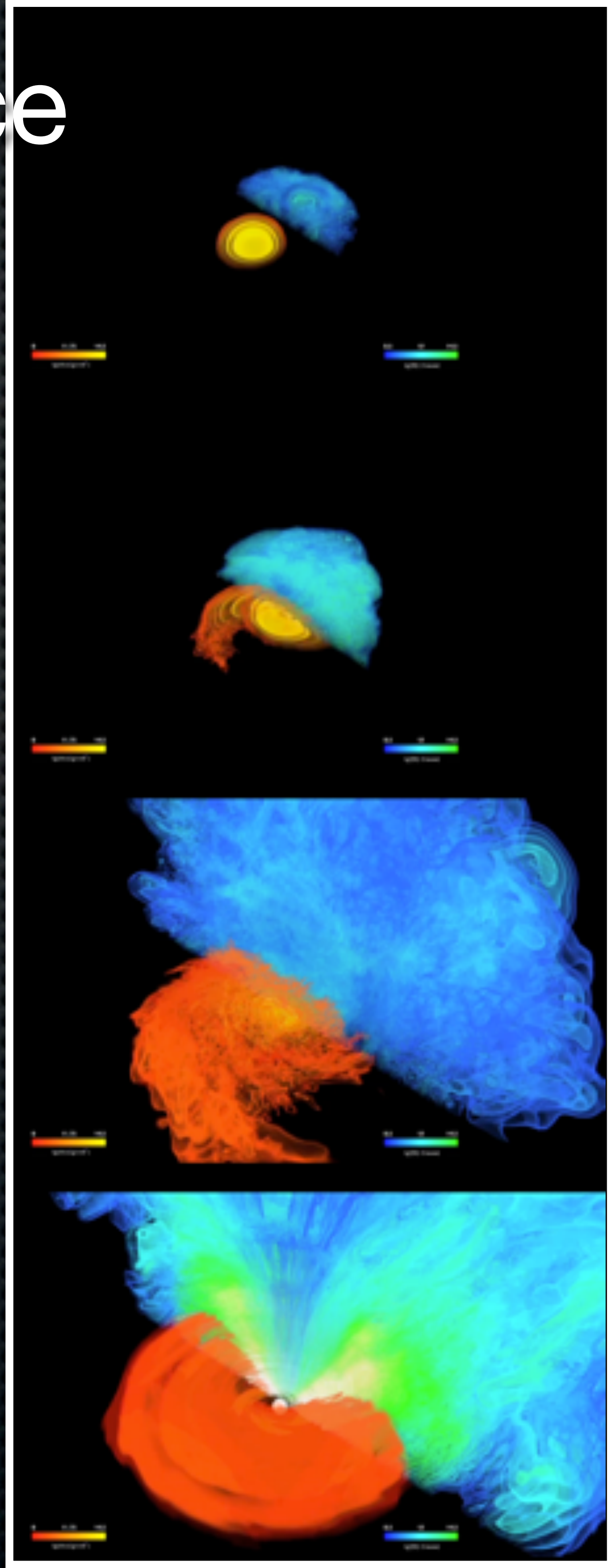
EM Transients from Binary Coalescence





B. Giacomazzo+2010 (1009.2468)
L. Rezzolla+2011 (1101.4298)

Numerical Relativity Group @ Albert Einstein Institute

EM Observations

γ/x-Ray
Optical
Radio

Compact Binary

Localization:
Time
Distance
Angular Position

Enhanced Priors

GW Detections
Adv. LIGO+Virgo

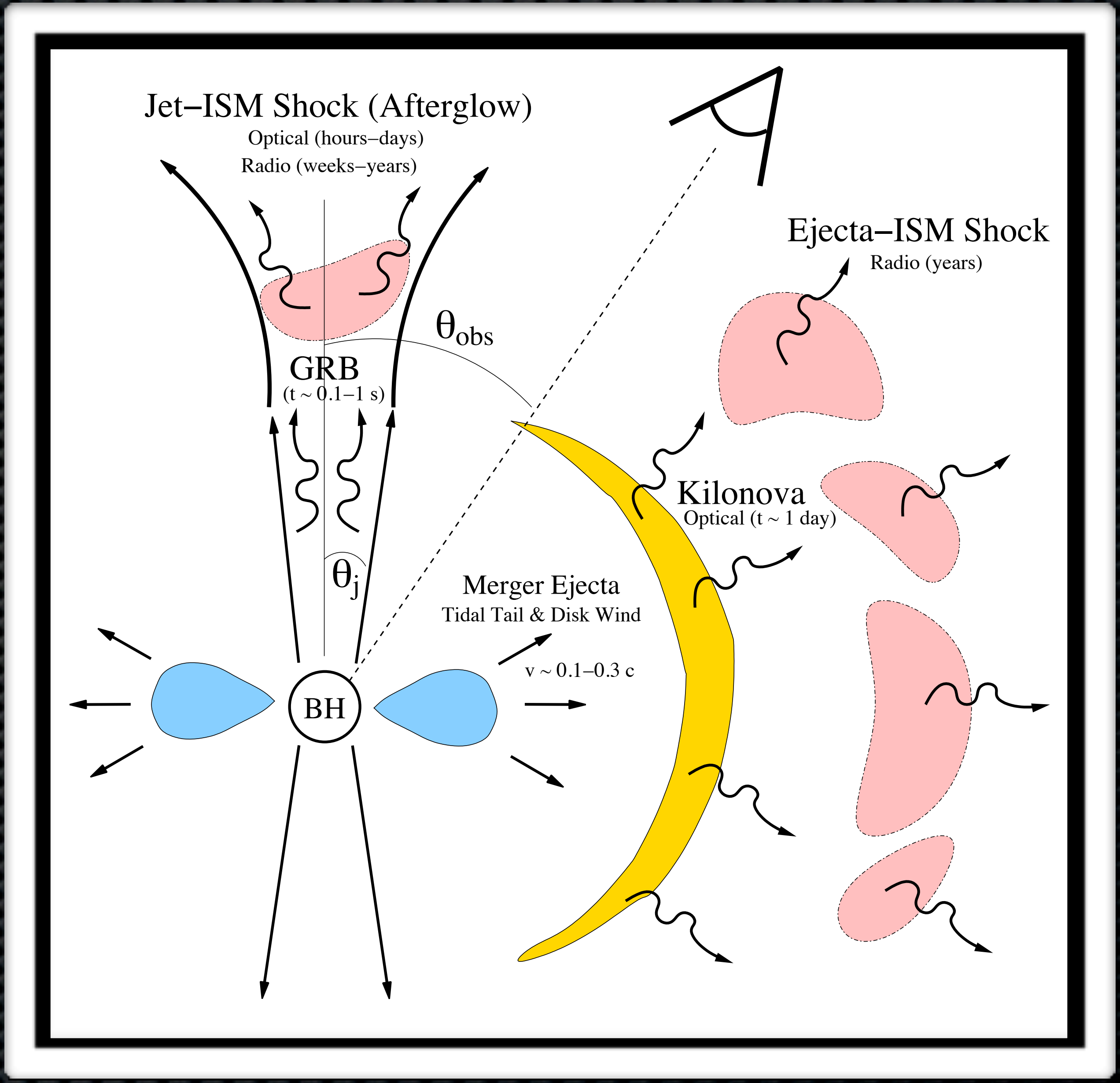
Synthetic Lightcurves
Parametrized EM Surveys
Bayesian Formalism

GW+EM Coincident Observations

- Cosmology
- Merger Parameters
- Nature of SGRBs & R-Process Elements

EM Transients from Binary Coalescence

- **SGRBs**
  - High Energy, Beamed
- Orphan Afterglows
  - Radio-Optical, Broad
- R-Process 'Kilonovae'
  - Optical (IR), Isotropic



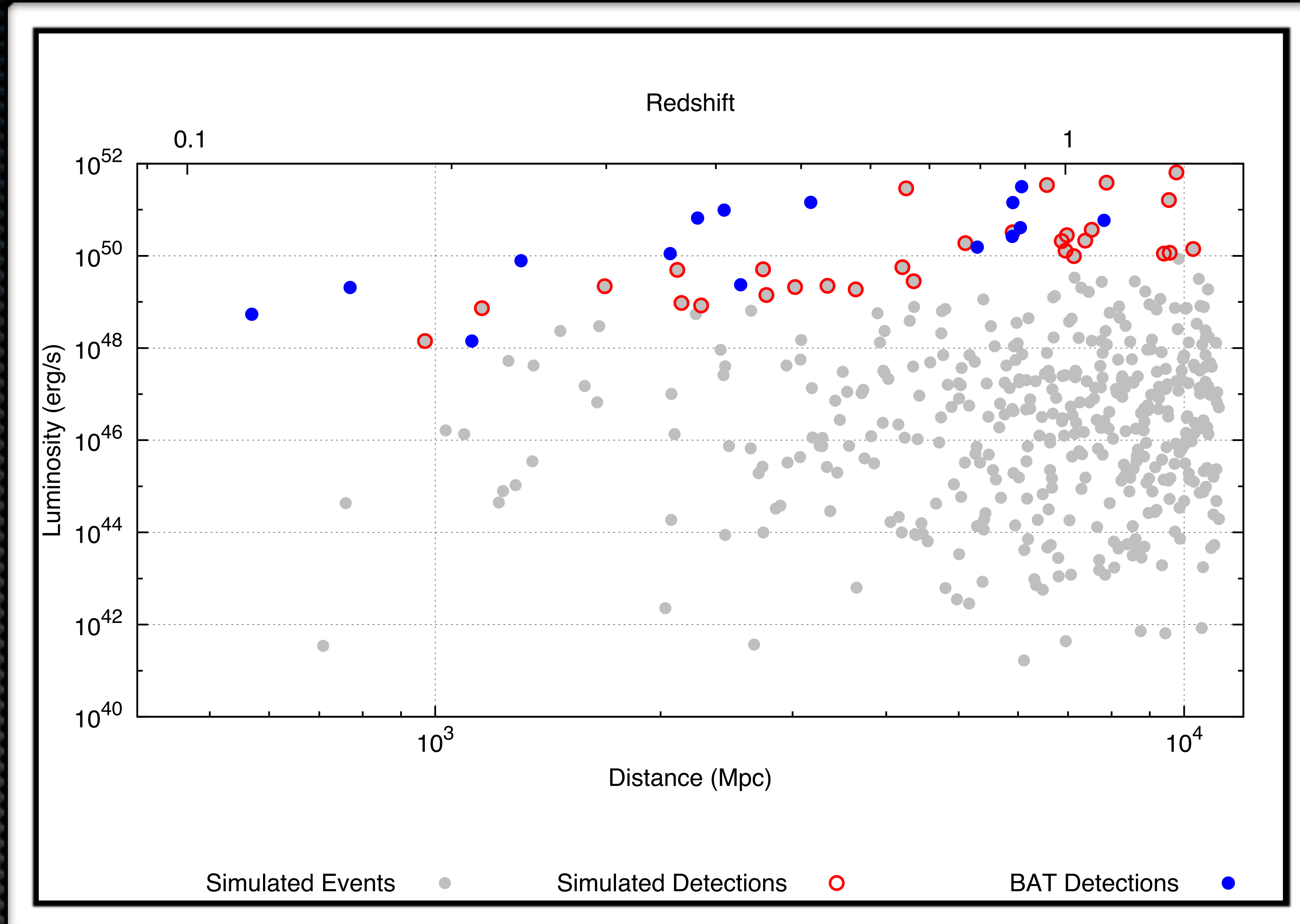
Metzger & Berger, 2011 (1108.6056)

Short GRBs

GRB	z	Distance (Mpc)	T_{90}(s)	L_x (erg/s)	T_{opt} (hr)	L_{opt} (erg/s/Hz)
050709	0.161	770	0.07	2.9×10^{50}	34.0	1.6×10^{27}
050724	0.257	1,302	3.00	2.6×10^{49}	12.0	1.7×10^{28}
051221A	0.546	3,172	1.40	1.0×10^{51}	3.1	7.0×10^{28}
061006	0.438	2,431	0.42	2.4×10^{51}	14.9	2.1×10^{28}
070714B	0.923	6,068	3.00	1.1×10^{51}	23.6	3.1×10^{28}
070724	0.457	2,558	0.40	5.9×10^{49}	2.3	3.9×10^{28}
071227	0.381	2,059	1.80	6.2×10^{49}	7.0	8.1×10^{27}
080905	0.122	568	1.00	5.4×10^{48}	8.5	3.1×10^{26}
090426	2.609	22,077	1.28	1.1×10^{52}	2.6	1.2×10^{31}
090510	0.903	5,905	0.30	4.7×10^{51}	9.0	9.6×10^{28}
100117	0.920	6044	0.30	1.4×10^{51}	8.4	$< 1.3\times10^{28}$
050509B	0.225	1,119	0.04	3.6×10^{49}	2.1	$< 1.0\times10^{27}$
060801	1.130	7,815	0.50	1.2×10^{51}	12.4	$< 5.8\times10^{28}$
061210	0.409	2,240	0.19	3.5×10^{51}	2.1	$< 8.4\times10^{27}$
061217	0.827	5,292	0.21	2.7×10^{51}	2.8	$< 6.7\times10^{28}$
070429B	0.902	5,896	0.50	5.2×10^{50}	4.8	$< 2.5\times10^{28}$
Average	0.70	4,707	0.90	5.9×10^{49}	11.7	2.6×10^{28}

E. Berger, 2010 (1007.0003)

Short GRBs



$$p\left(\log \frac{L}{\mathrm{erg\ s^{-1}}}\right) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{[\log(L/(\mathrm{erg\ s^{-1}})) - \mu]^2}{2\sigma^2}\right)$$

$$\mu = 106.7,\ \sigma = 4.6$$

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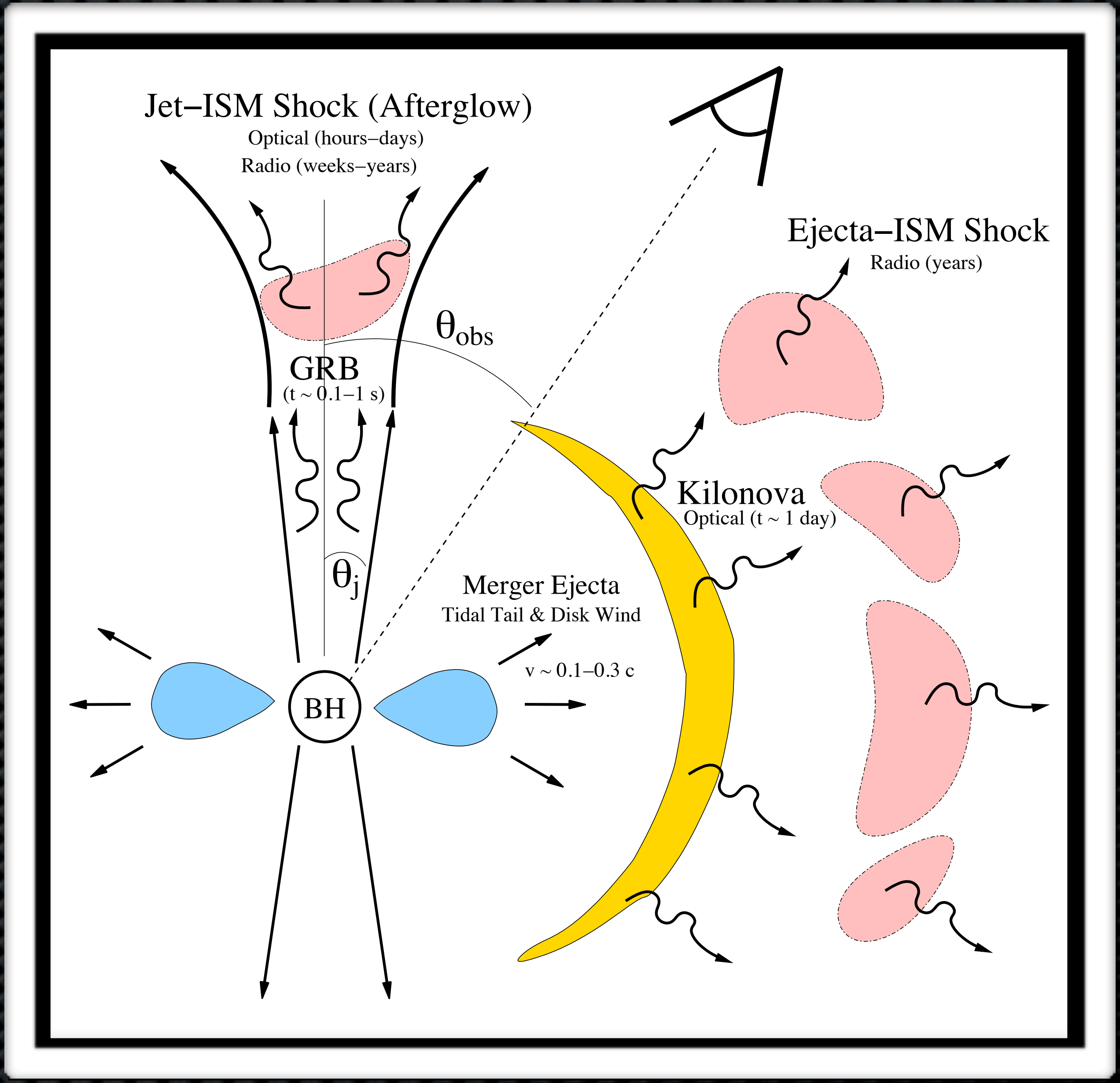

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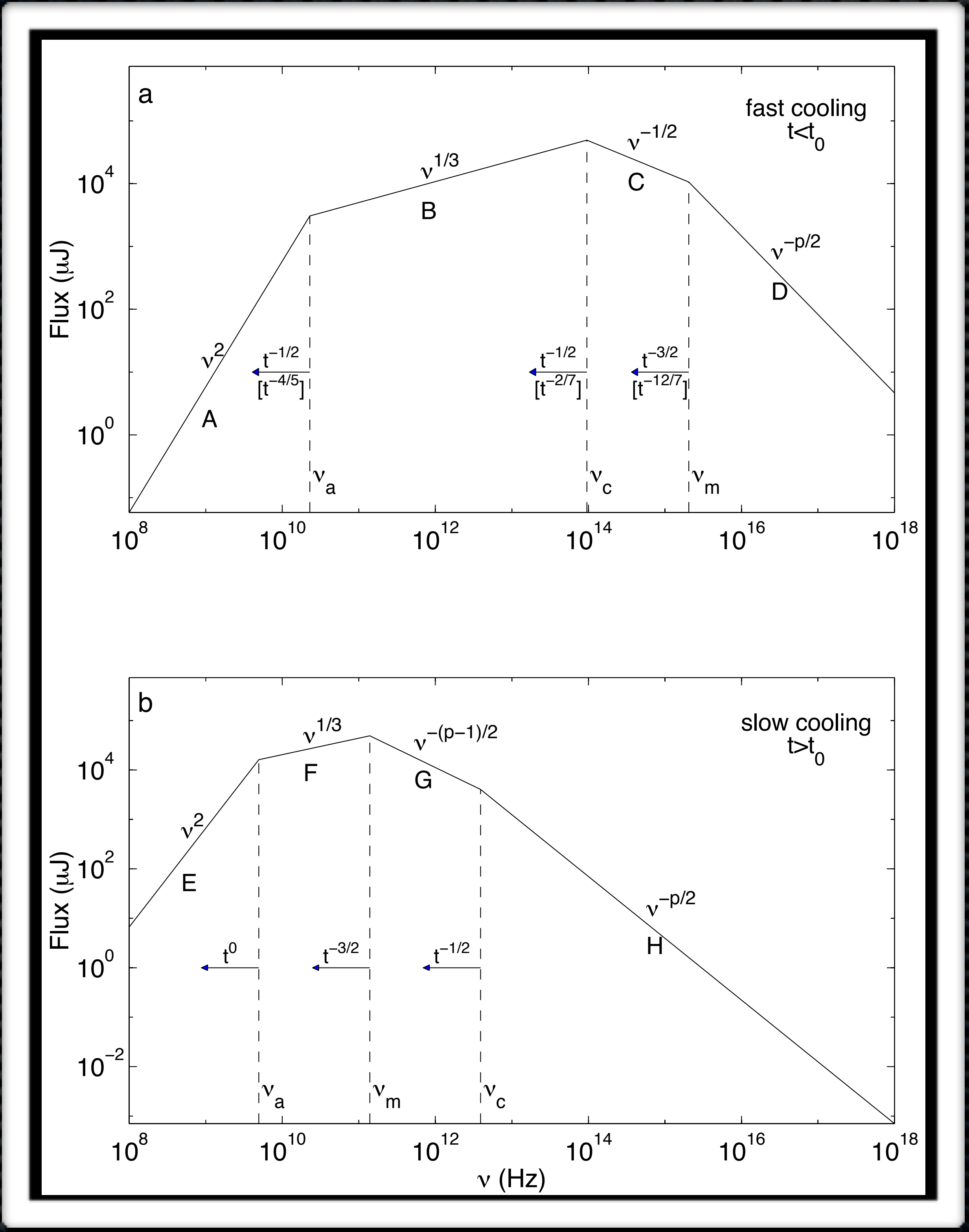
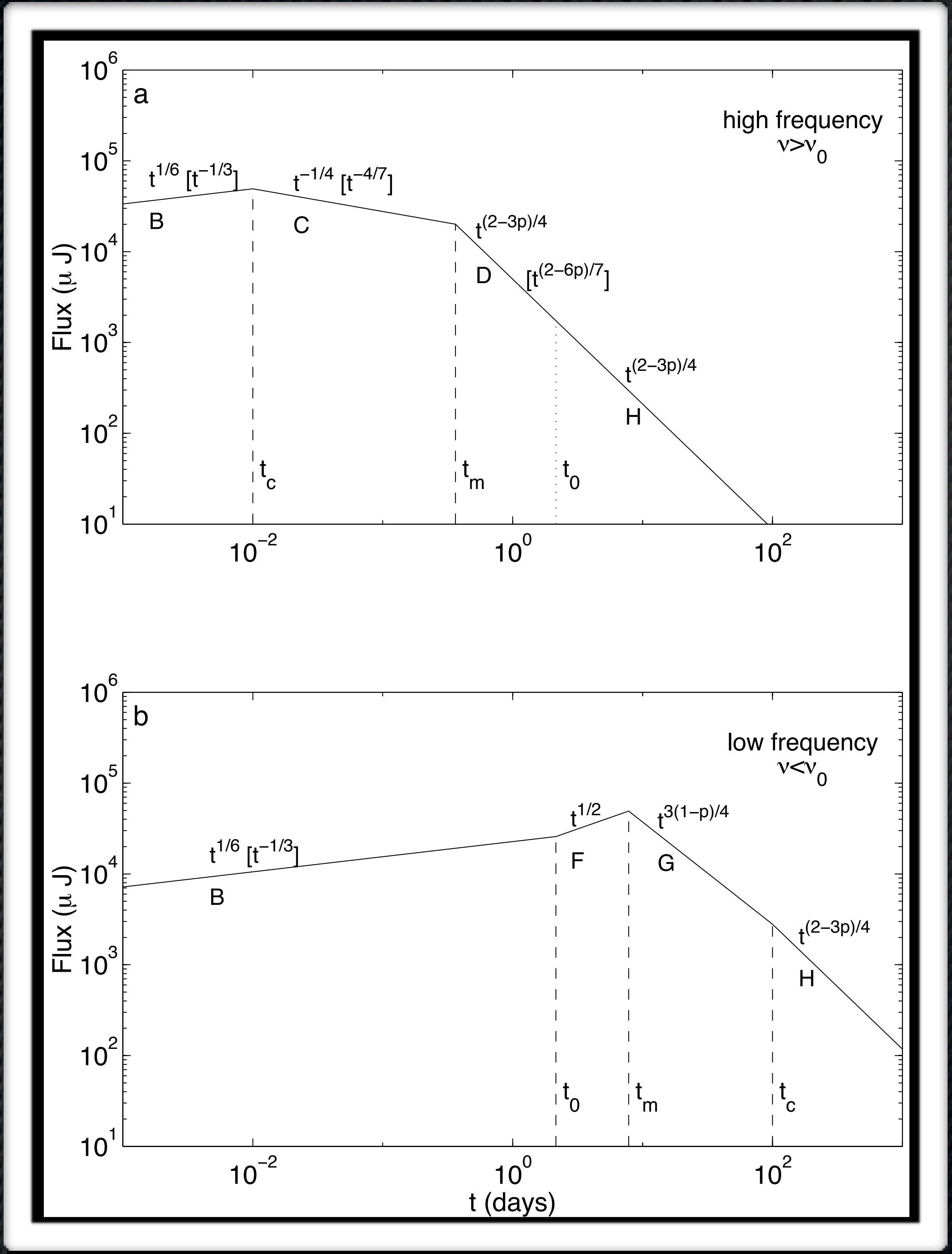
Afterglows



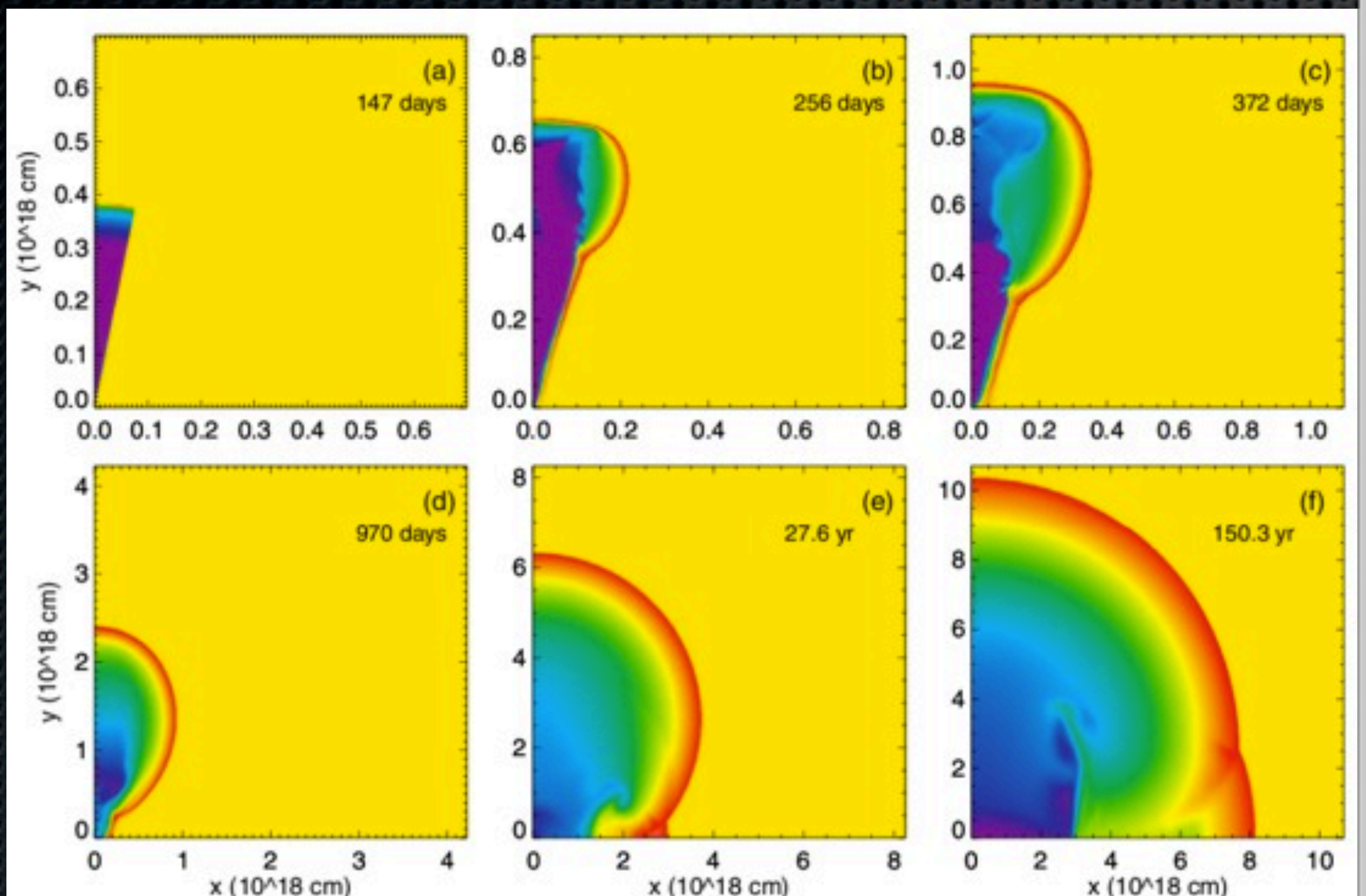
Sari+1997

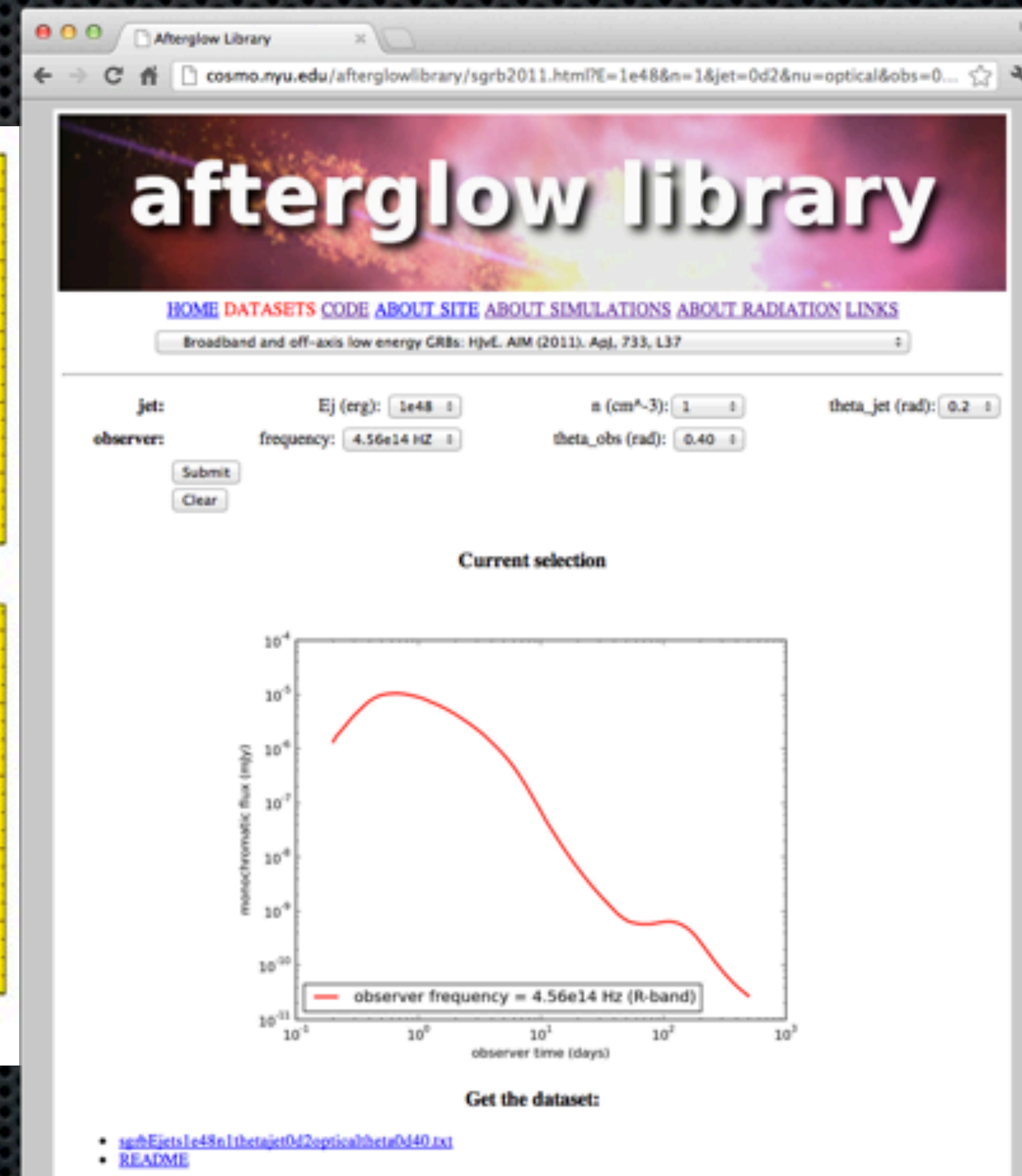
Afterglows



Sari+1997

Afterglows





Zhang & MacFadyen 2006,2009
H. van Eerten+2010 (1006.5125)

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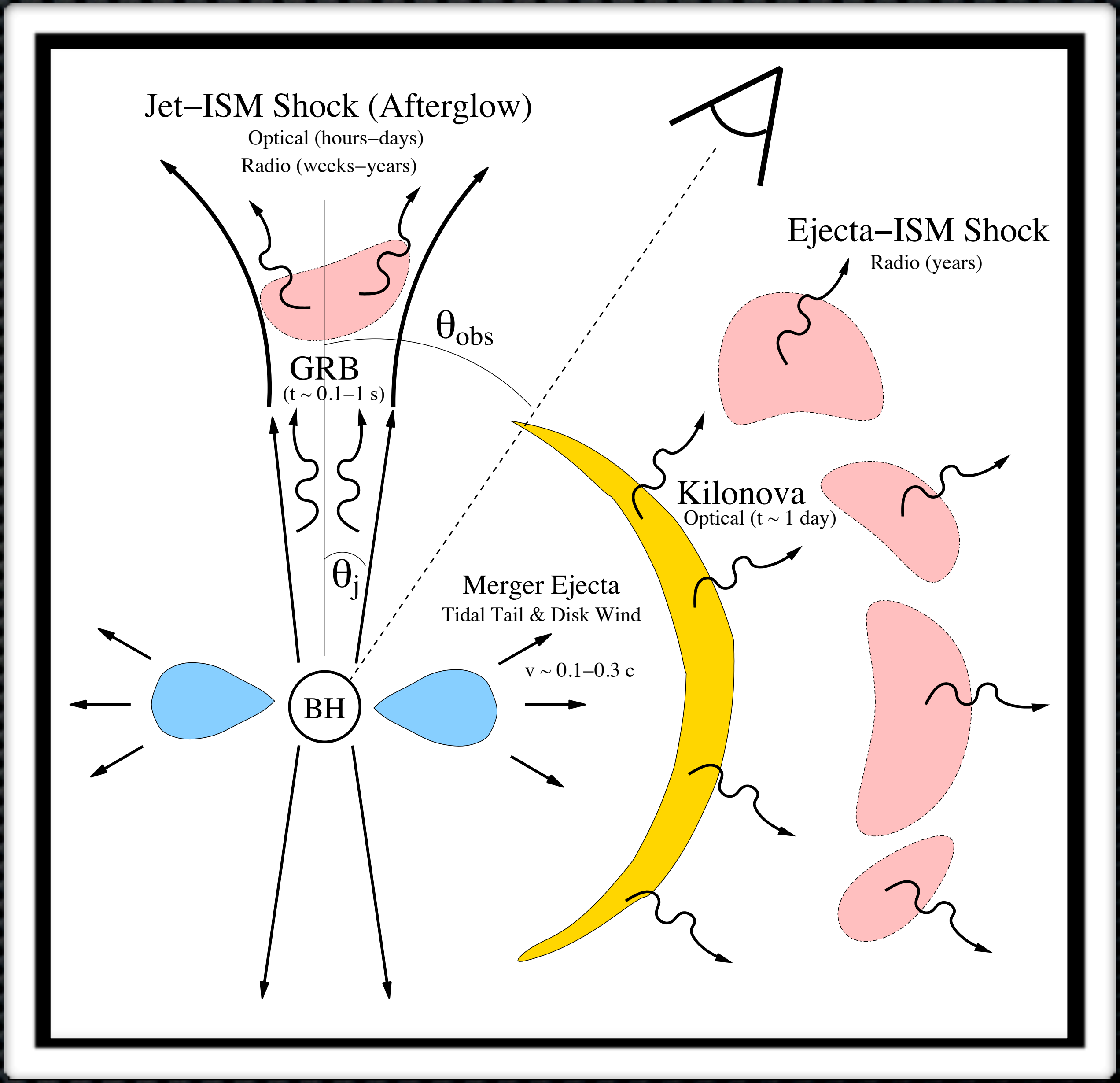
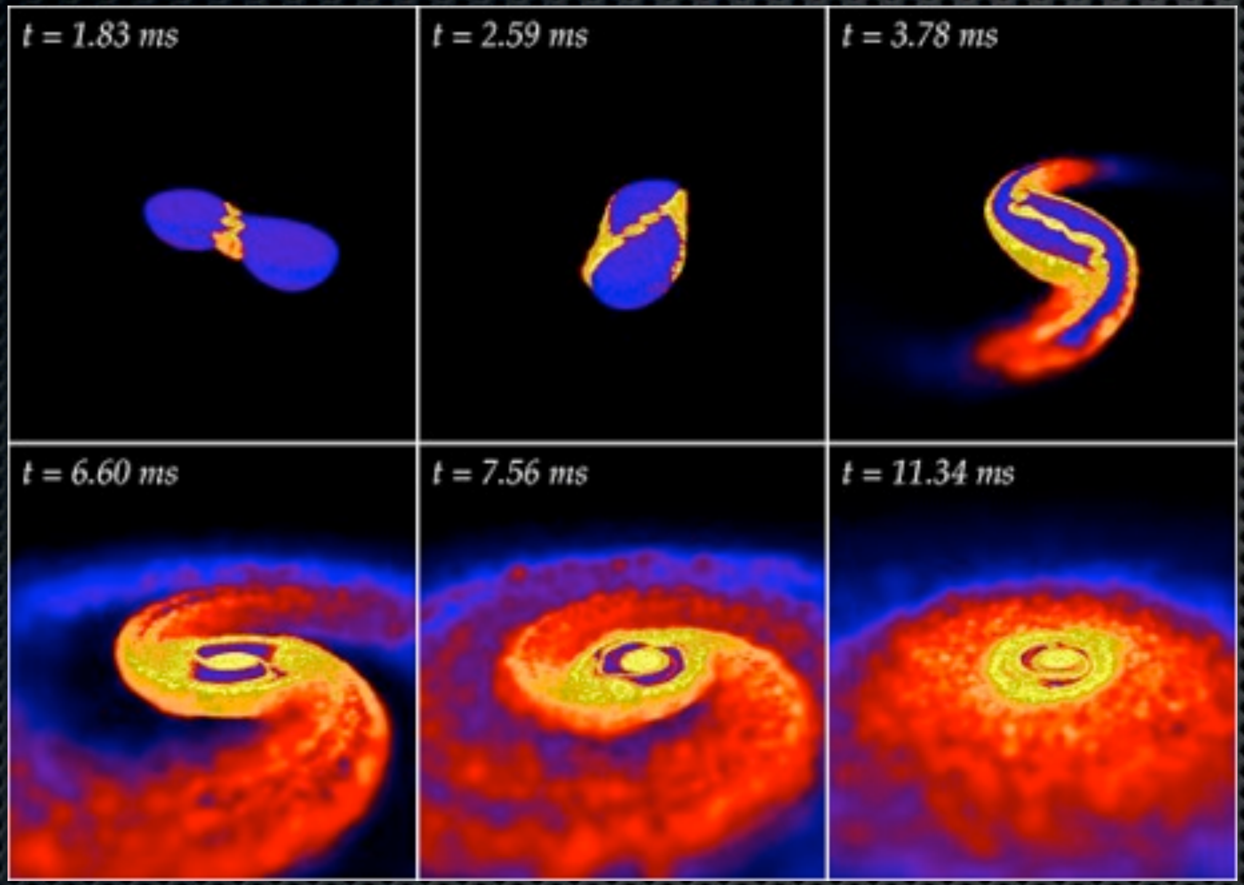
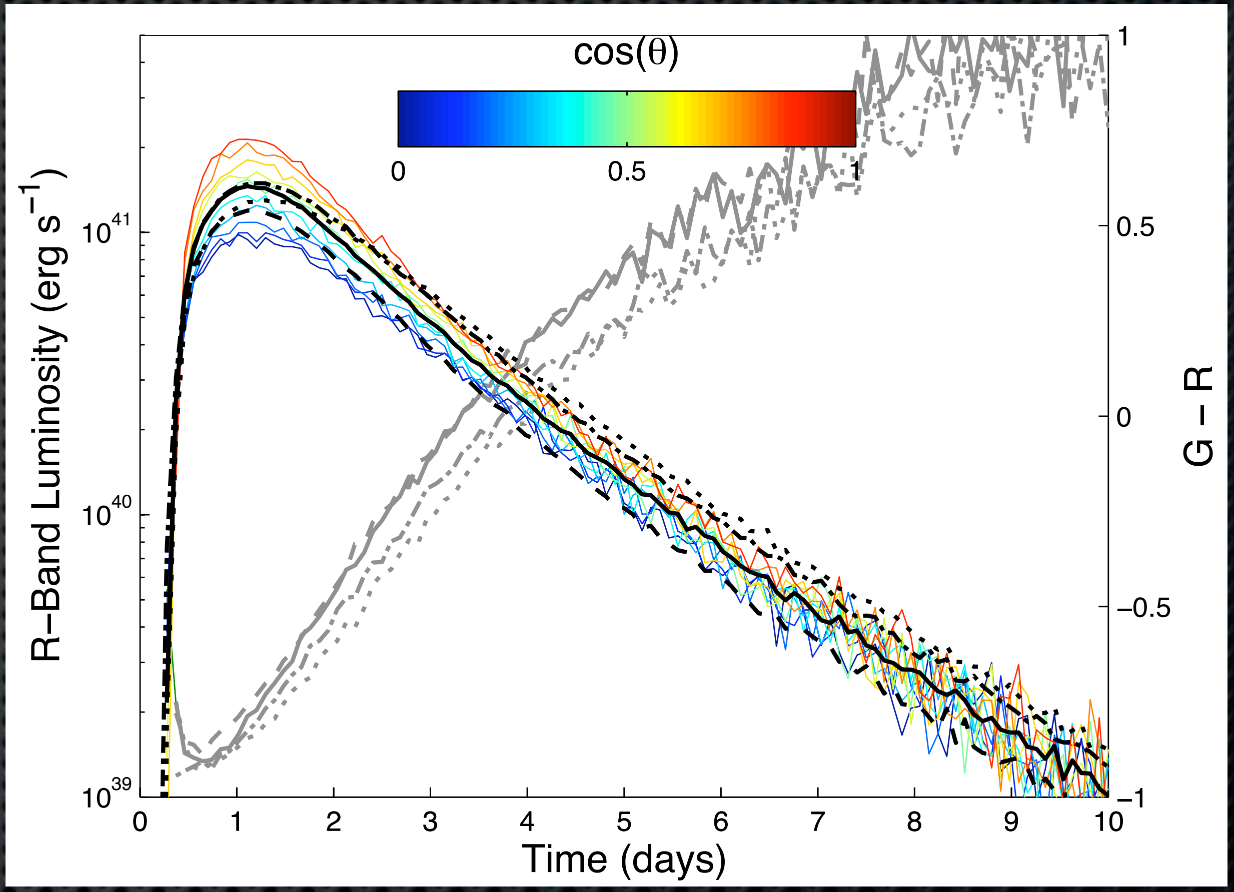


Metzger & Berger, 2011 (1108.6056)

Kilonovae

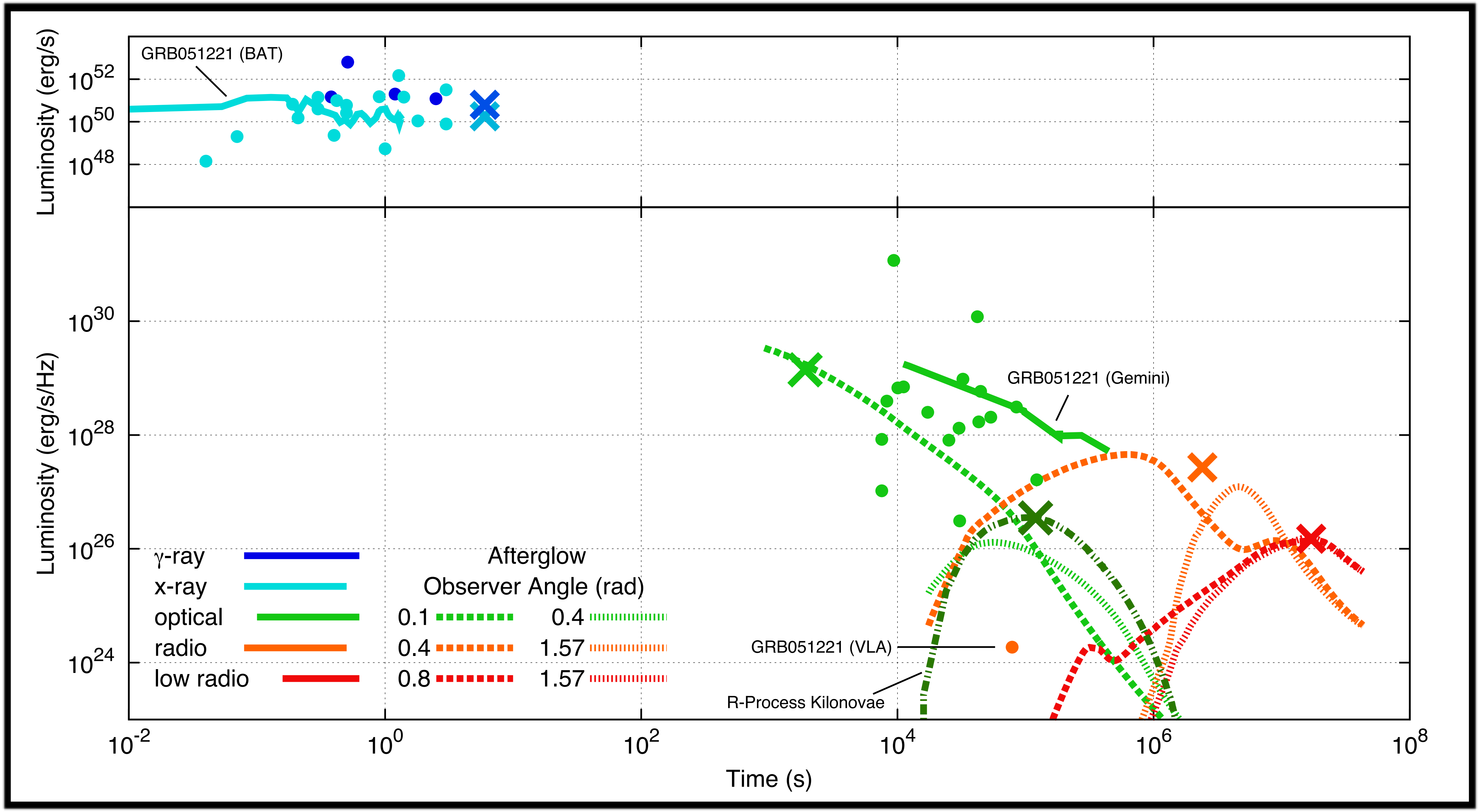




Rosswog 2005
Rosswog+Price 2006 (astro-ph/0603845)

Roberts+2011 (arXiv:1104.5504)

EM Transients from Binary Coalescence



Telescopes and Surveys

Project	Band	Sensitivity	FoV (Survey)	Cad.(d)
Swift (BAT)	X-ray (15 - 150 KeV)	10^{-8} (erg cm^{-2} s^{-1})	4,600 (40,000)	2
Fermi (GBM)	γ-Ray (8 KeV - 40 MeV)	10^{-6} (erg cm^{-2} s^{-1}) [1]	31,200 (40,000)	1
LSST	Optical (r: 550 - 700 nm)	24.5 5.8×10^{-30} (erg cm^{-2} s^{-1} Hz^{-1})	9.6 (10,000)	3
PTF	Optical (r)	21.0 1.4×10^{-28} (erg cm^{-2} s^{-1} Hz^{-1})	7.9 (8000)	5
Apertif	Radio (1000 - 1750 MHz)	0.1 μJy 1.0×10^{-30} (erg cm^{-2} s^{-1} Hz^{-1})	8.0	1
ASKAP	Radio (700 - 1800 MHz)	0.1 mJy 1.0×10^{-27} (erg cm^{-2} s^{-1} Hz^{-1})	30.0 (20,000)	1
LOFAR	Low Radio (10 - 200 MHz)	1.0 mJy 1.0×10^{-26} (erg cm^{-2} s^{-1} Hz^{-1})	3,000 (20,000)	1

EM Transient Monte Carlo

- Distribute Mergers
  - 1 Mpc^{-1} Myr^{-1}
- Generate Light Curve
  - EM Detection?
- Generate GW Signal (SNR)
  - Blind GW Detection?
  - Triggered GW Detection?

Monte Carlo EM Detections

Transient	Telescope	Mean EM Properties				
		d_L (Mpc)	Lum (erg s^{-1} Hz^{-1})	Angle (rad)	ToT (s)	TaM (s)
SGRB Prompt	BAT	5200	1.8×10^{50} (erg s^{-1})	0.13	-	-
	GBM	4800	6.3×10^{50} (erg s^{-1})	0.13	-	-
Afterglow	LSST	4100	1.4×10^{29}	0.16	4.0×10^{4}	1.9×10^{3}
	PTF	1600	2.4×10^{29}	0.13	9.1×10^{3}	1.3×10^{3}
	Apertif	3200	2.7×10^{27}	0.82	3.6×10^{6}	2.4×10^{6}
	ASKAP	130	3.3×10^{27}	0.69	1.7×10^{6}	1.4×10^{6}
	LOFAR	8.26	1.5×10^{26}	1.0	2.7×10^{7}	1.7×10^{7}
R-Process	LSST	460	3.5×10^{26}	1.0	2.4×10^{5}	1.2×10^{5}
	PTF	92	3.5×10^{26}	1.0	2.4×10^{5}	1.1×10^{5}

Monte Carlo EM Detections

Transient Type	Emission	Telescope	EM Rate (yr^{-1})
SGRB Prompt	X-ray	Swift (BAT)	29.1 ± 0.4
	Gamma/X-ray	Fermi (GBM)	71.2 ± 0.3
Afterglow	Optical	LSST	69 ± 2
		PTF	1.1 ± 0.2
	Radio	Apertif	8 ± 1
		ASKAP	5.80 ± 0.01
	Low Radio	LOFAR	$2.678 \times 10^{-3} \pm 3 \times 10^{-6}$
R-Process Tails	Optical	LSST	146.0 ± 0.1
		PTF	0.880 ± 0.002

Formalism

$$p(\vec{\theta}_i|d, M_i) = \frac{L(d|\vec{\theta}_i, M_i)\, p(\vec{\theta}_i|M_i)}{p(d|M_i)} \quad 1$$

$$p(M_i|d) = \frac{p(d|M_i)\, p(M_i)}{p(d)} \quad 2$$

$$\mathcal{O} \equiv \frac{p(M_1|d)}{p(M_2|d)} = \frac{p(M_1)}{p(M_2)}\, \frac{p(d|M_1)}{p(d|M_2)} \quad 3$$

$$\mathcal{O} \equiv \frac{p(\mathrm{GW}|\mathrm{d})}{p(\mathrm{N}|\mathrm{d})} = \frac{p(\mathrm{GW})}{p(\mathrm{N})}\, \frac{p(\mathrm{d}|\mathrm{GW})}{p(\mathrm{d}|\mathrm{N})} \quad 4$$

Formalism

$$\mathcal{O} \equiv \frac{p(\mathrm{GW}|\mathrm{d})}{p(\mathrm{N}|\mathrm{d})} = \frac{p(\mathrm{GW})}{p(\mathrm{N})} \frac{p(\mathrm{d}|\mathrm{GW})}{p(\mathrm{d}|\mathrm{N})} \tag{5}$$

$$\mathcal{B} \equiv \frac{p(d|GW)}{p(d|N)} \propto \eta e^{\frac{1}{2}(\mathrm{SNR})^2} \tag{6}$$

$$\boxed{\mathcal{O} \propto \frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta \cdot e^{\frac{1}{2}(\mathrm{SNR})^2}} \tag{7}$$

Formalism

$$\mathcal{O} \propto \frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta \cdot e^{\frac{1}{2}(\mathrm{SNR})^2} \qquad 8$$

$$\zeta \equiv \frac{\mathrm{SNR}}{\mathrm{SNR}_{|\mathrm{EM}}} = \left[\frac{\ln\left(\mathcal{O}_{\mathrm{GW}} \cdot \left[\frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta_{\mathrm{GW}}\right]^{-1}\right)}{\ln\left(\mathcal{O}_{\mathrm{EM}} \cdot \left[\frac{p(\mathrm{GW|EM})}{p(\mathrm{N|EM})} \cdot \eta_{\mathrm{EM}}\right]^{-1}\right)} \right]^{\frac{1}{2}} \qquad 9$$

GW Signal

$$\mathrm{SNR} = 2.0\,(1+z)^{5/6}\left(\frac{d}{d_H}\right)^{-1}\Theta(\mathrm{angles}) \qquad 10$$

$$\Theta \equiv 2\left[F_+^2\left(1+\cos^2\iota\right)^2 + 4F_\times^2\cos^2\iota\right]^{1/2} \qquad 11$$

$$F_+ \equiv \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi,$$

$$F_\times \equiv \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi\sin 2\psi + \cos\theta\sin 2\phi\cos 2\psi$$

Finn & Chernoff, 1993 (gr-qc/9301003)

Parameters - Priors

$$\zeta \equiv \frac{\mathrm{SNR}}{\mathrm{SNR}_{|\mathrm{EM}}} = \left[\frac{\ln\left(\mathcal{O}_{\mathrm{GW}} \cdot \left[\frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta_{\mathrm{GW}}\right]^{-1}\right)}{\ln\left(\mathcal{O}_{\mathrm{EM}} \cdot \left[\frac{p(\mathrm{GW|EM})}{p(\mathrm{N|EM})} \cdot \eta_{\mathrm{EM}}\right]^{-1}\right)} \right]^{\frac{1}{2}}$$

$$p(\mathrm{GW}) = \mathcal{R} \cdot \frac{4\pi}{3}\delta^3 \cdot \tau_{\mathrm{GW}} \quad (12)$$

$$p(\mathrm{GW|EM}) = \mathcal{F} \cdot \frac{\tau_{\mathrm{GW}}}{\Delta t} \cdot \frac{(4/3)\pi\delta^3}{V_{\mathrm{EM}}} \quad (13)$$

Parameters - Priors

Δt ↓

Transient	Telescope	d_L (Mpc)	Lum (erg s^{-1} Hz^{-1})	Angle (rad)	ToT (s)	TaM (s)
		Mean EM Properties				
SGRB Prompt	BAT	5200	1.8×10^{50} (erg s^{-1})	0.13	-	-
	GBM	4800	6.3×10^{50} (erg s^{-1})	0.13	-	-
Afterglow	LSST	4100	1.4×10^{29}	0.16	4.0×10^4	1.9×10^3
	PTF	1600	2.4×10^{29}	0.13	9.1×10^3	1.3×10^3
	Apertif	3200	2.7×10^{27}	0.82	3.6×10^6	2.4×10^6
	ASKAP	130	3.3×10^{27}	0.69	1.7×10^6	1.4×10^6
	LOFAR	8.26	1.5×10^{26}	1.0	2.7×10^7	1.7×10^7
R-Process	LSST	460	3.5×10^{26}	1.0	2.4×10^5	1.2×10^5
	PTF	92	3.5×10^{26}	1.0	2.4×10^5	1.1×10^5

Parameters - Space

$$\zeta \equiv \frac{\mathrm{SNR}}{\mathrm{SNR}_{|\mathrm{EM}}} = \left[\frac{\ln\left(\mathcal{O}_{\mathrm{GW}} \cdot \left[\frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta_{\mathrm{GW}}\right]^{-1}\right)}{\ln\left(\mathcal{O}_{\mathrm{EM}} \cdot \left[\frac{p(\mathrm{GW|EM})}{p(\mathrm{N|EM})} \cdot \eta_{\mathrm{EM}}\right]^{-1}\right)} \right]^{\frac{1}{2}}$$

$$\eta = \eta_d \cdot \eta_\phi$$

Distance(-inclination)

$\eta_d(\mathrm{GW})$		10^{-2}
$\eta_d(\mathrm{GW\|EM})$	with redshift:	1
	without:	10^{-2}

Sky-position (angle)

$$\eta_\phi(\mathrm{GW}) \equiv \Omega_{\mathrm{GW}}/\Omega_{\mathrm{sky}} \approx 10^{-3}$$

$$\eta_\phi(\mathrm{GW|EM}) = 1$$

	η_ϕ		η_d	η
GW	10^{-3}		10^{-2}	10^{-5}
GW|EM	1	with redshift:	1	1.0
		without:	10^{-2}	10^{-2}

Parameters - Space

redshift? ↓

Transient	Telescope	Mean EM Properties d_L (Mpc)	Lum (erg s^{-1} Hz^{-1})	Angle (rad)	ToT (s)	TaM (s)
SGRB Prompt	BAT	5200	1.8×10^{50} (erg s^{-1})	0.13	-	-
	GBM	4800	6.3×10^{50} (erg s^{-1})	0.13	-	-
Afterglow	LSST	4100	1.4×10^{29}	0.16	4.0×10^{4}	1.9×10^{3}
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	Apertif	3200	2.7×10^{27}	0.82	3.6×10^{6}	2.4×10^{6}
	ASKAP	130	3.3×10^{27}	0.69	1.7×10^{6}	1.4×10^{6}
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	PTF	92	3.5×10^{26}	1.0	2.4×10^{5}	1.1×10^{5}

Benefits

$$\zeta \equiv \frac{\mathrm{SNR}}{\mathrm{SNR}_{|\mathrm{EM}}} = \left[\frac{\ln\left(\mathcal{O}_{\mathrm{GW}} \cdot \left[\frac{p(\mathrm{GW})}{p(\mathrm{N})} \cdot \eta_{\mathrm{GW}}\right]^{-1}\right)}{\ln\left(\mathcal{O}_{\mathrm{EM}} \cdot \left[\frac{p(\mathrm{GW}|\mathrm{EM})}{p(\mathrm{N}|\mathrm{EM})} \cdot \eta_{\mathrm{EM}}\right]^{-1}\right)} \right]^{\frac{1}{2}}$$

		ζ		
Transient Type	Telescope	With Redshift	Without Redshift	Mean
SGRB Prompt	Swift (BAT)	-	1.063	1.063
	Fermi (GBM)	-	1.063	1.063
Afterglow	LSST	1.131	1.000	1.014
	PTF	1.135	1.035	1.035
	Apertif	1.053	1.000	1.015
	ASKAP	1.058	1.015	1.025
	LOFAR	1.034	1.000	1.007
R-Process Tails	LSST	1.084	1.038	1.056
	PTF	1.085	1.038	1.058

Detection Rates

Transient Type	Telescope	GW Detections (yr^{-1}) Triggered	Gain vs. blind
SGRB Prompt	Swift (BAT)	0.01 ± 0.003	1.000 ± 0.001
	Fermi (GBM)	0.06 ± 0.02	$1.002 \pm 1 \times 10^{-3}$
Afterglow	LSST	0.51 ± 0.09	1.017 ± 0.004
	PTF	0.00 ± 0.01	1.000 ± 0.006
	Apertif	0.00 ± 0.04	1.000 ± 0.002
	ASKAP	0.13 ± 0.07	1.004 ± 0.003
	LOFAR	0.00 ± 0.07	1.000 ± 0.003
R-Process Tails	LSST	2.74 ± 0.02	$1.089 \pm 1 \times 10^{-3}$
	PTF	0.03 ± 0.02	1.001 ± 0.001

Detection Rates

Transient Type	Telescope	GW+EM Coincident Rate: Blind	GW+EM Coincident Rate: Blind + Triggered	GW+EM Coincident Rate: Gain
SGRB Prompt	Swift (BAT)	$0.0908 \pm 9\times10^{-4}$	$0.1046 \pm 9\times10^{-4}$	1.15 ± 0.02
	Fermi (GBM)	0.368 ± 0.002	0.422 ± 0.002	1.147 ± 0.008
Afterglow	LSST	1.80 ± 0.02	2.31 ± 0.02	1.28 ± 0.02
	PTF	0.096 ± 0.005	1.008 ± 0.005	1.05 ± 0.07
	Apertif	$0.0051 \pm 6\times10^{-4}$	0.007 ± 0.001	1.3 ± 0.2
	ASKAP	4.64 ± 0.05	4.77 ± 0.05	1.03 ± 0.02
	LOFAR	$0.0028 \pm 8\times10^{-4}$	$0.0028 \pm 8\times10^{-4}$	1.0 ± 0.4
R-Process Tails	LSST	7.14 ± 0.02	9.88 ± 0.03	1.384 ± 0.005
	PTF	0.661 ± 0.001	0.69 ± 0.001	1.044 ± 0.002

Conclusions

- Full formalism for Triggered searches
  - Accurate to noise and observations
  - General to any coincident detections
- No benefit for GW; Good for GW+EM
  - Cosmology
  - Merger Parameters
  - Nature of SGRBs & R-Process Elements