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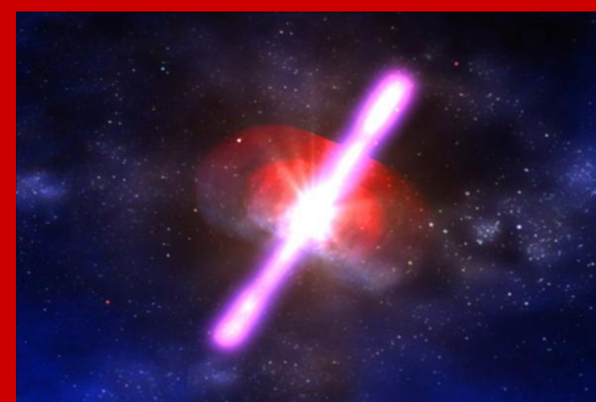
LSC

Astrophysics of GW transients

Alessandra Corsi



What comes next for LIGO?
May 7-8, 2015 – Silver Spring, MD

LIGO-G1500602

GW transients in the aLIGO era

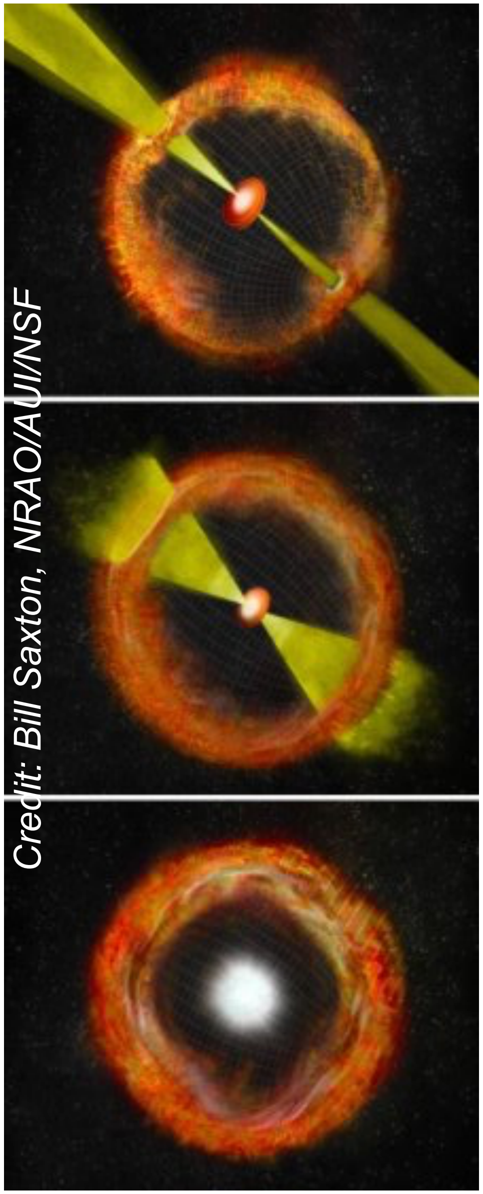
- GW transients: *significant uncertainty in predicted waveforms* → matched filtering with bank of templates unfeasible.
- Un-modeled GW transients typically identified in detector data as excess power in the time-frequency domain.
- In the absence of detailed GW waveforms, some astrophysical guidance (including EM follow-up) is valuable (may help confirm astrophysical nature of a detection).
- Given their potential to impact the field, events like the next galactic supernova (SN), the next 980425 gamma-ray bursts (GRB; 40 Mpc), or the next SGR giant flare, should remain high priorities even after the first few in-spiral detections, but ...
- What science can we expect aLIGO to be doing between first few (in-spiral) detections and the next galactic SN?
- Are aLIGO plans covering it all? Could minimal improvements and/or changes help us increase the scientific return (or perhaps make a tremendous difference if by 2020 there is no detection…)?

Burst range implies small event rates…

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

- Distance range for "standard candles": E_{GW}=0.01$M_\odot$ at 150 Hz.
- Distance range scale as $(E_{GW})^{1/2}$.
- Basic stellar collapse ($E_{GW} \leq 10^{-7} M_\odot$; e.g. Ott 2008 for a review) → GW range likely galactic or near-galactic.
- Extreme (optimistic) core-collapse (possibly, rotational instabilities or core/disk fragmentation, e.g. Kobayashi & Meszaros 2003) up to E_{GW}=0.01$M_\odot$. With optimal orientation could reach ~150 Mpc.

Extreme and "ordinary" core-collapse...



$R_{GRB} \approx R_{GRB,obs}(1-\cos\theta_j)^{-1}$

R_{LGRB}(obs) $\approx$ 0.3-1 $(Gpc)^{-3}$ yr^{-1}
$(1-\cos\theta_j)^{-1} \approx 50$ (i.e. $\theta_j \approx 0.2$)
≈0.02-0.05/yr at ≤ 100Mpc (only ≈2% would have γ-rays, optical / radio counterpart could be accessible).

$R_{LLGRB} \approx$ 250-500 $(Gpc)^{-3}$ yr^{-1}
≈0.25-0.5/yr at ≤100 Mpc (≥20% with 980425-like emission assuming $\theta_j \geq 0.6$).
aLIGO might exclude extreme GW emission in a 3yr-run.
30% increase in aLIGO sensitivity → ≈(0.5-1)/yr
(Note: from 1998 to 2015, ≈ 5 LLGRBs discovered via EM emission → 0.3/yr).

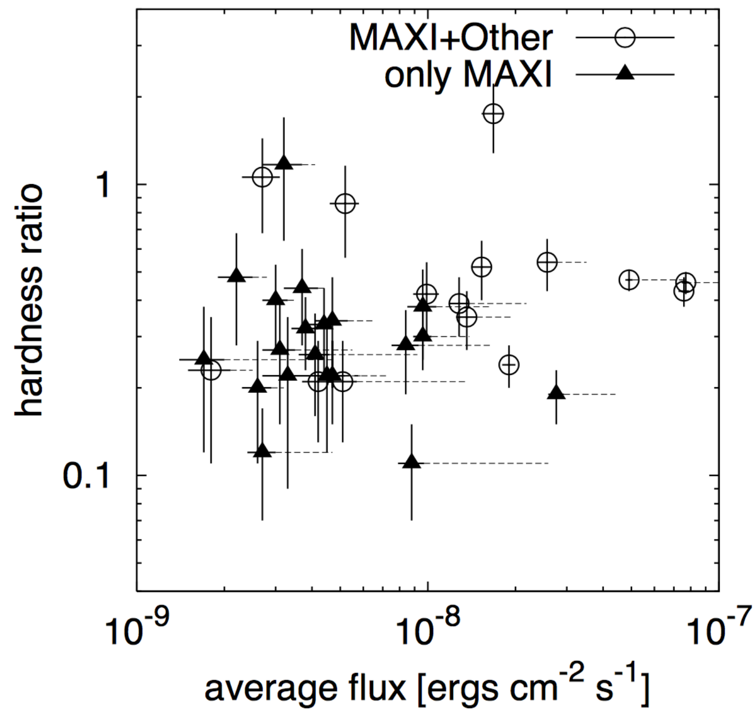
Galactic core-collapse SNe: $R_{SN,MW}$ = 0.028+/-0.006 yr^{-1}.
≈2x higher rate within local group of galaxies (≈1 Mpc).

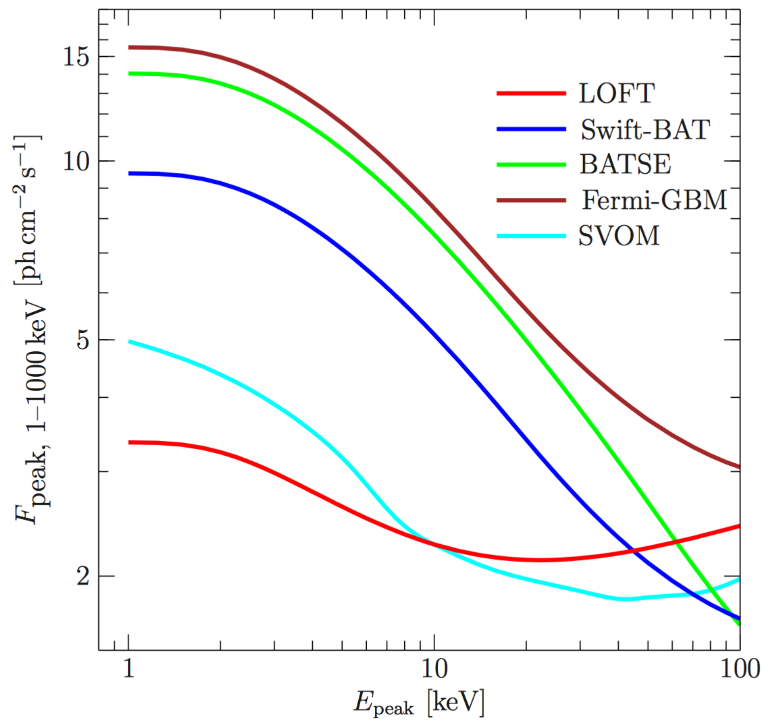
Do X-ray flashes help us?

- XRFs (prompt emission at 2–20 keV) may be the missing link between hard/luminous GRBs and LLGRBs. Perhaps dirty fireballs / lower Lorentz factor events?

- 2009-2013 MAXI (Japanese ISS Experiment) XRF sample suggests ≈3x rate of hard/luminous GRBs → ≈3x0.05/yr + 30% increase in aLIGO sensitivity → 0.3/yr (1 detection in 3yrs might be possible). EM counterpart may be accessible with future NASA missions.

Serino et al. arXiv:1406.3912



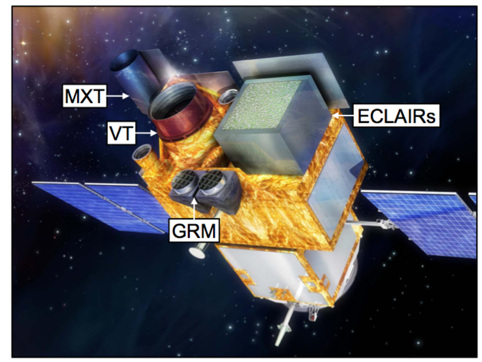


Amati et al. arXiv:1501.02772v

XTIDE advertisement…

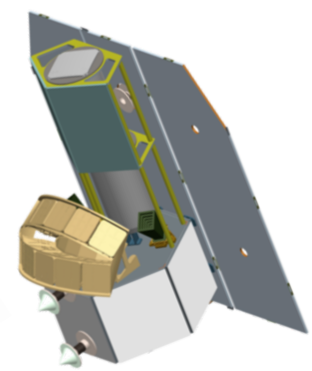
PI: Dave Burrows PS: Derek Fox

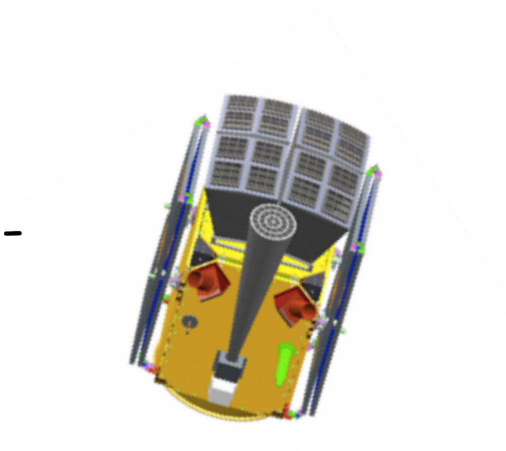
- Large and medium mission science highly competitive
- Multi-messenger focus can be successful for small missions
- Key science requirement: Good positions for bright bursts
  - Wide field of view
  - Real time sub-arcmin positions
- Follow-up science requirement: Multi-messenger transient TOOs
  - Sensitivity over >10 deg^2 field
  - Rapid TOO upload capability



SVOM

XTiDE





Einstein Probe

Energy injection and longer duration transients

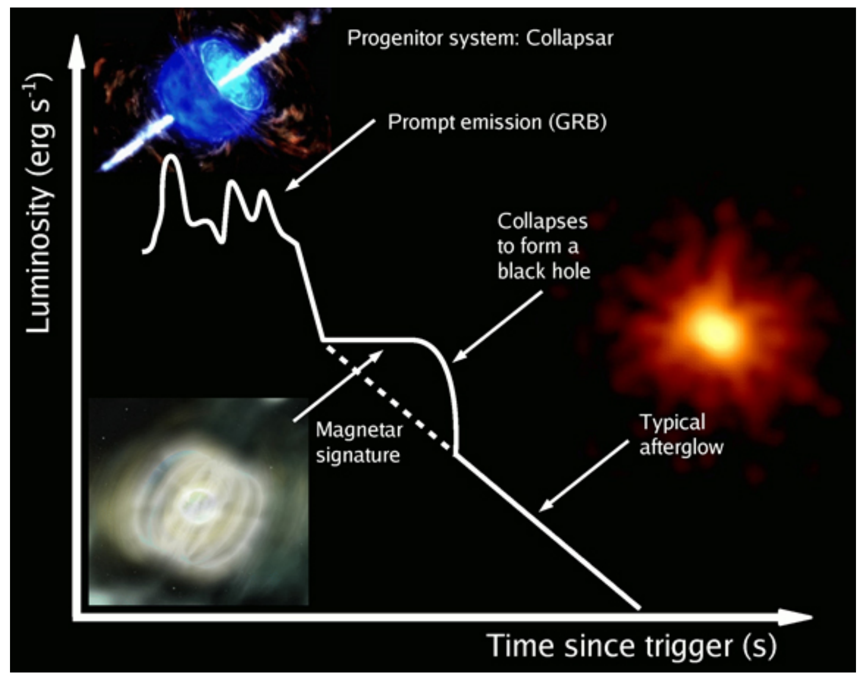
- Magnetar rather than BH may form in explosion (e.g. GRB060218/SN2006aj, Mazzali et al. 2006). Magnetar can pump energy into the fireball (e.g. Dai & Lu 1998; Zhang & Meszaros, 2001; … , Rowlinson et al. 2013, …).

- Associated bar-like GW signal (e.g. Lai & Shapiro 1995, Corsi & Meszaros 2009) or magnetic deformation (e.g., … Cutler 2002, Dall'Osso et al. 2015, Mastrano et al. 2015)?

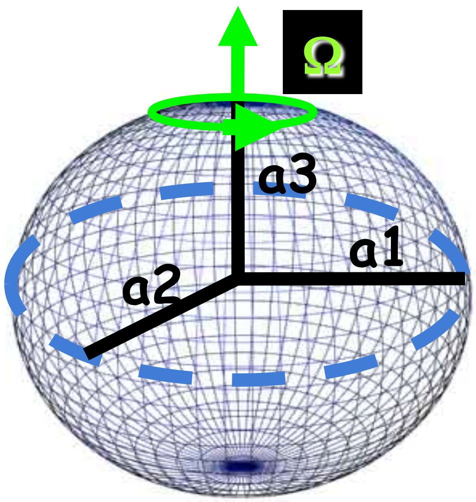
- Plateaus: ≈60% of LGRBs, ≈3% of SGRBs.

- If fraction of EM representative of fraction of GRBs that form unstable magnetars, then LLGRB are the best bet in terms of event rates.

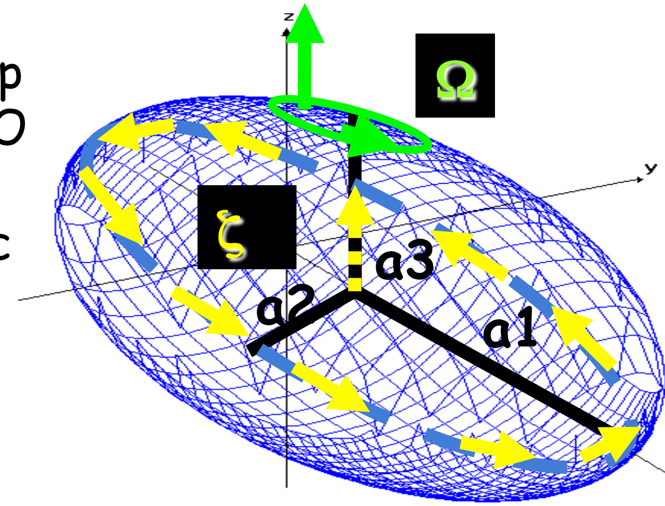
- Might first use robust techniques (few pipelines currently available) then follow-up candidates with more sensitive but more model dependent approaches (currently under study).



Secular bar-mode instability (most optimistic scenario)



GW signal detectable up to ≈100 Mpc with aLIGO (studies underway to estimate more realistic detectability range).



Initial configuration:
Maclaurin spheroid a1=a2≠a3

Riemann-S ellipsoid a1≠a2≠a3

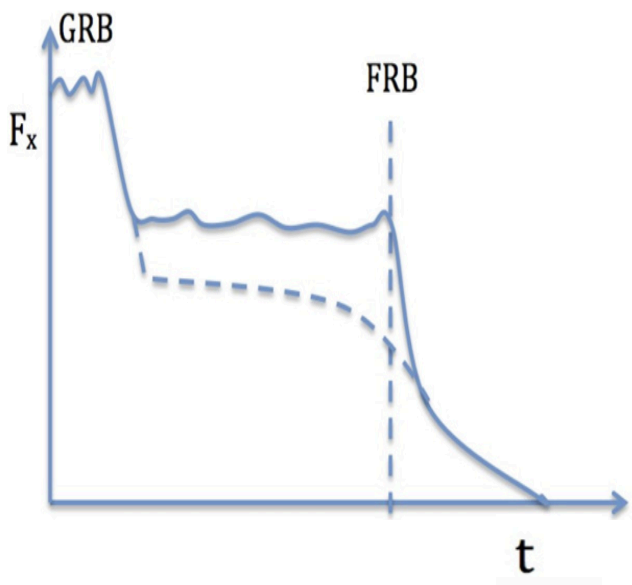
Non-axisymmetric instabilities in rapidly rotating fluid bodies

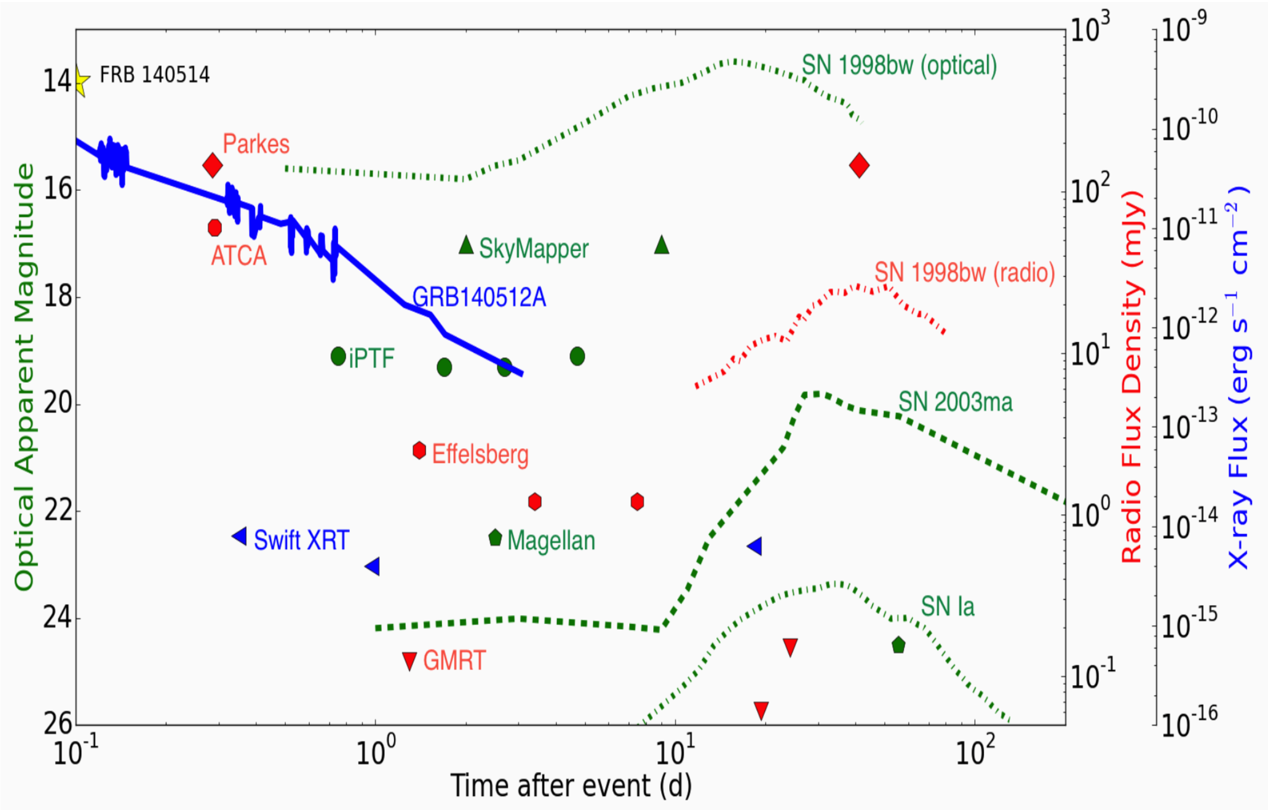
- kinetic-to-gravitational potential energy ratio, $\beta = T/|W|$
- $\beta > 0.27$: dynamical instability (possibly a burst-type signal)
- $\beta > 0.14$: l=m=2 "bar"-mode oscillations secularly unstable due to e.g. gravitational radiation (e.g. Lai & Shapiro 1995) →sequence of compressible Riemann-S ellipsoids.

Supra-massive NSs and fast radio bursts

- Falcke & Rezzolla (2013): supra-massive NS collapsing to BH could be source of FRBs. Zhang 2014 linked FRBs to short-lived supra-massive NS formed in short / long GRBs with plateaus (and possible GW counterparts).

- Real-time follow-up by Petroff et al. 2015 seems to disfavor link with LGRBs.

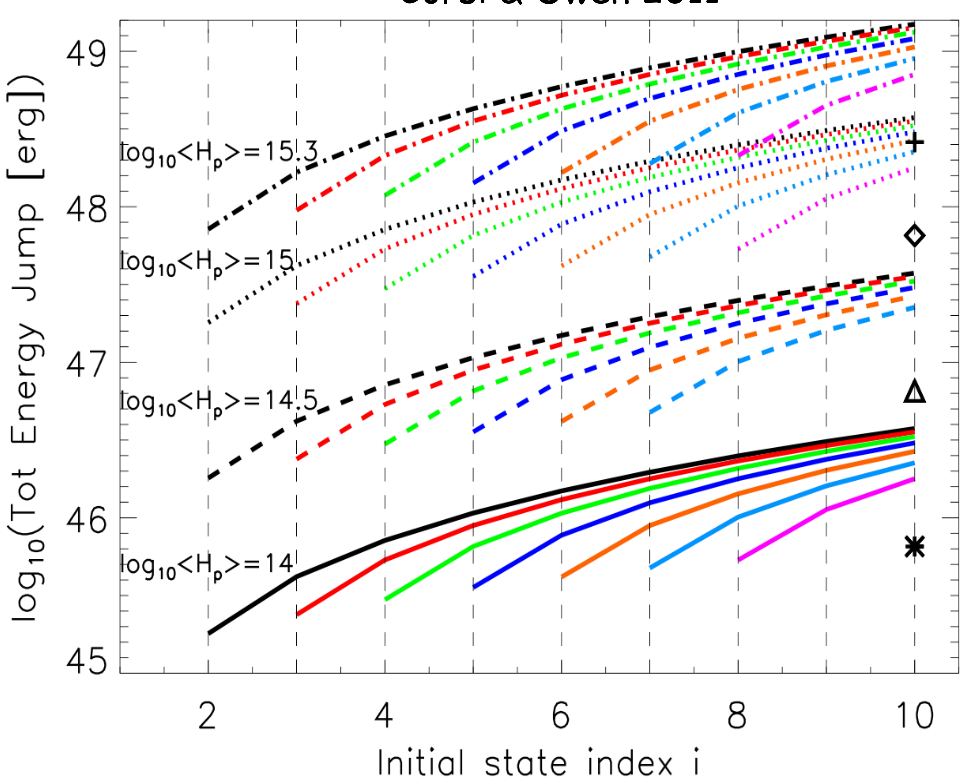




SGR giant flares

- Observed galactic rate of GFs ($\gtrsim 10^{46}$erg): $(0.005-1)\times10^{-2}$yr^{-1}SGR^{-1} (Svinkin et al. 2014) → $\lesssim$0.15/yr considering known SGRs/AXP population.
- Observed galactic rate of less energetic flares: $(0.05-1.4)\times10^{-2}$ yr^{-1} SGR^{-1} x 15 SGRs (Svinkin et al. 2014) → $\lesssim$0.21/yr considering known SGRs/AXP population.
- E_{GW}/E_{EM} unknown. LIGO ULs: $E_{GW} \lesssim 3\times10^{45}$-$3\times10^{51}$ erg depending on frequency (Abadie et al. 2011).
- aLIGO will go 100x deeper in energy: 3×10^{43}-3×10^{49} erg.
- *2x better sensitivity (as from LIGO to eLIGO) → UL range below the max theoretical limit of $\approx 10^{49}$erg.*

Corsi & Owen 2011



In summary…

- **INSTRUMENT:** aLIGO sensitivity improvement: 30% up to 2x → would bring LLGRB / XRF much closer to the "horizon" of the typical astronomer… (>=1 detection in 3 yrs → interesting; less than 1 detection in 3 yrs: hard to get a grant for it, hard to graduate a student… not interesting). NB: duty cycle IMPORTANT!

- **DA/COMPUTATIONAL RESOURCES:** The searchers for longer duration bursts may be promising, but may require additional computing resources, especially for untargeted (all-sky) approach.

- **HOW THE LSC OPERATES:** New ideas and EM counterparts are important (especially when GW waveforms are not well known). Perhaps small "Guest Investigator" program (say 3-yr program starting after first few in-spiral detections when LIGO data are public) may help? Could it make collaboration with EM facilities more practical, maximizing scientific return?

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	local rate (ρ_0) [$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$]	L_{min} [erg/s]	This work for a similar L_{min}
Ando (2004) (1)	$0.51^{+0.36}_{-0.19}$	10^{50}	$2.1^{+1.0}_{-0.9}$
Guetta & Piran (2006) (1)	$0.6^{+8.4}_{-0.3}$	2×10^{50}	$1.1^{+0.4}_{-0.4}$
Guetta & Piran (2006) (2)	8^{+40}_{-4}	7×10^{49}	$3.0^{+1.6}_{-1.4}$
Guetta & Piran (2006) (1)	30^{+50}_{-20}	2×10^{49}	$9.4^{+6.6}_{-4.9}$
Nakar et al. (2006)	40^{+12}_{-12}	10^{49}	$18.9^{+15.5}_{-10.5}$
Guetta & Stella (2009) (1)	1.3	2×10^{49}	$9.8^{+6.9}_{-5.1}$
Guetta & Stella (2009) (3)	4	0.8×10^{49}	$23.4^{+20.0}_{-13.2}$
Dietz (2011)	$1.05^{+0.5}_{-0.9}$	$4 \times 10^{50}(*)$	$0.5^{+0.2}_{-0.2}$
Coward et al. (2012)	8^{+5}_{-3}	$2 \times 10^{50}(*)$	$1.0^{+0.4}_{-0.4}$
Siellez et al. (2013)	$2.7^{+0.9}_{-0.9}$	$2 \times 10^{50}(*)$	$1.0^{+0.4}_{-0.4}$
This work	$4.1^{+2.3}_{-1.9}$	5×10^{49}	$4.1^{+2.3}_{-1.9}$

Table 4. A comparison of different estimates of the local short bursts rate, without a beaming correction.

Notes: (*) When no luminosity low-end cutoff (erg/s) is specified we take the cutoff to be just below the least luminous burst in the given sample. (1) For a model with time delay $1/t$ for $t > 20Myr$ with respect to Porciani & Madau (2001) SF2. (2) For a model with a constant rate at all redshifts. (3) For a constant time delay of 6 Gyr with respect to Porciani & Madau (2001) SF2.

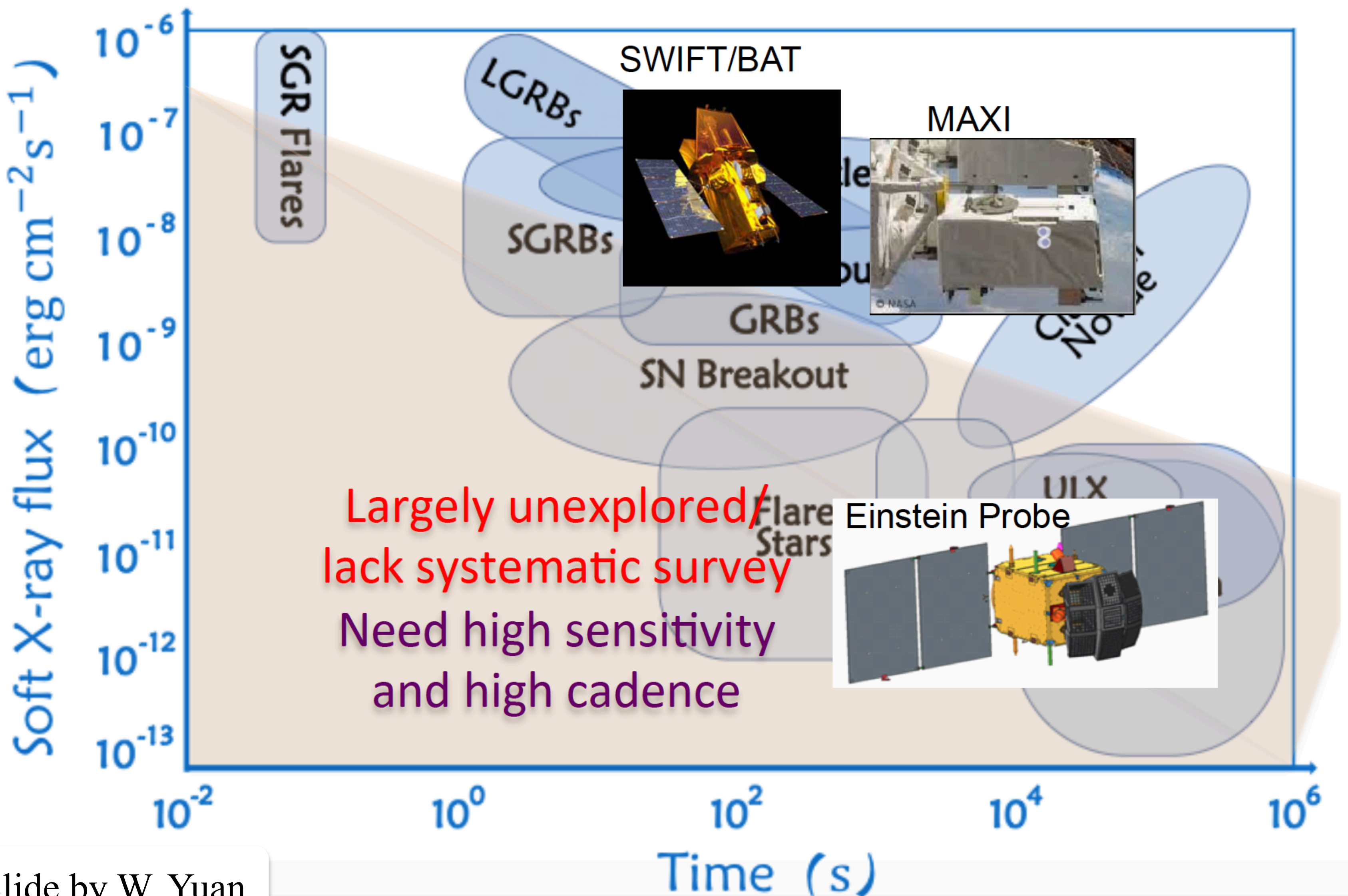
Wanderman & Piran 2015

TABLE 1
EXTRAGALACTIC TRANSIENT CLASSES

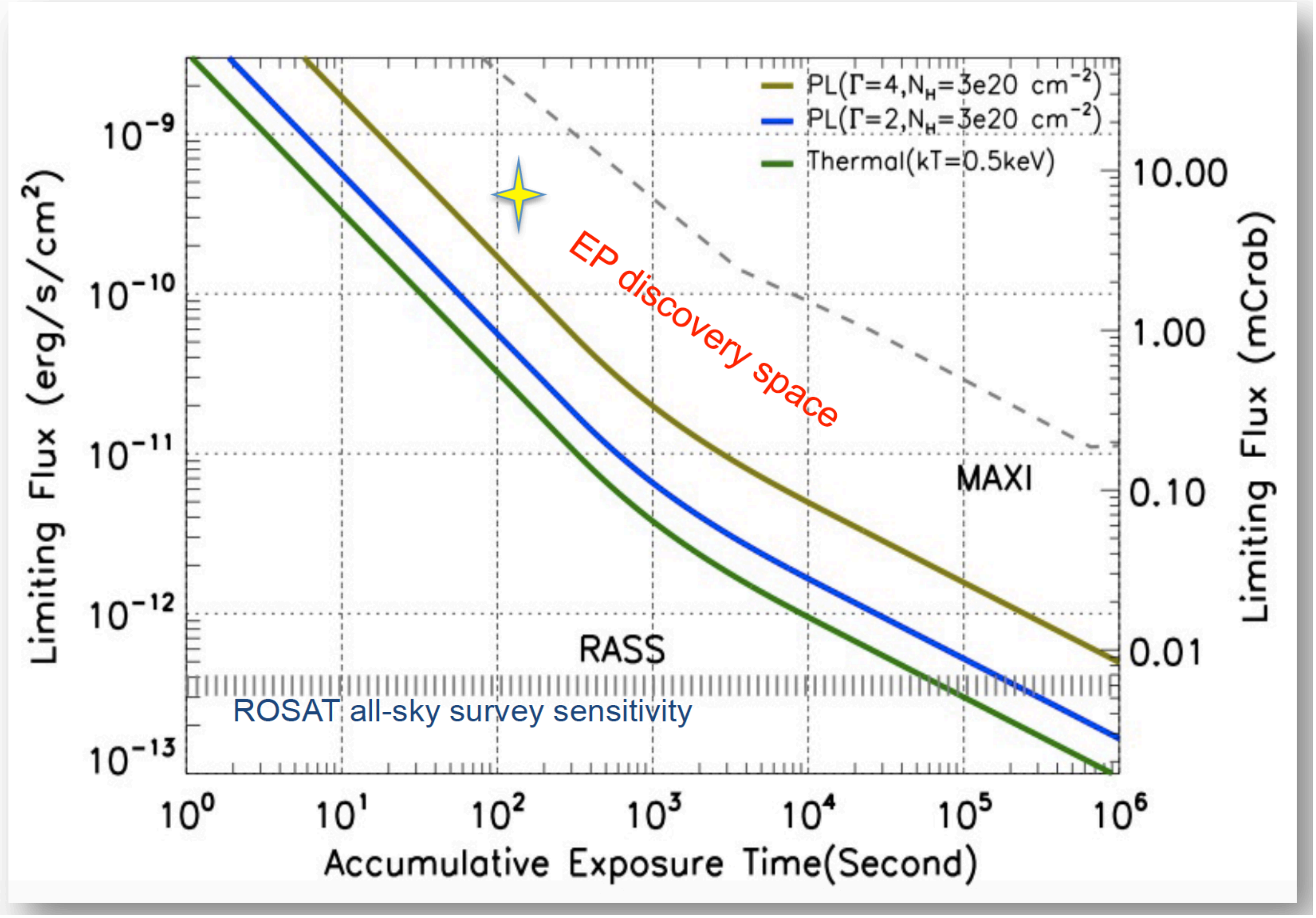
Transient	$\mathcal{R}(z=0)$ ($\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$)	E_K (erg)	n (cm^{-3})	β_i	$\tau_{0.15}$ $^{(a)}$ (d)	$\tau_{1.3}$ $^{(b)}$ (d)	τ_3 $^{(c)}$ (d)	τ_{150} $^{(d)}$ (d)	Ref.
LGRB, $\theta_{\rm obs}=0.2$	$0.3^\dagger$	10^{51}	1	1	320	62	31	4	1
LGRB, $\theta_{\rm obs}=0.4$	$1^\dagger$	10^{51}	1	1	450	90	55	12	1
LGRB, $\theta_{\rm obs}=0.8$	$4^\dagger$	10^{51}	1	1	1900	230	150	150	1
LGRB, $\theta_{\rm obs}=1.57$	$12^\dagger$	10^{51}	1	1	1300	620	550	590	1
Low Luminosity LGRB ("LLGRB")	$500^\dagger$	10^{49}	1	0.8	200	43	90	110	9
SGRB, $\theta_{\rm obs}=0.2$	$5^\dagger$	10^{50}	10^{-3}	1	220	110	90	110	6
SGRB, $\theta_{\rm obs}=0.4$	$15^\dagger$	10^{50}	10^{-3}	1	360	180	160	180	6
SGRB, $\theta_{\rm obs}=0.8$	$60^\dagger$	10^{50}	10^{-3}	1	730	480	410	480	6
SGRB, $\theta_{\rm obs}=1.57$	$185^\dagger$	10^{50}	10^{-3}	1	1900	2200	2000	650	6
On-Axis TDE ("Sw J1644+57")	$0.01^\ddagger$	10^{52}	0.1	1	3700	920	1040	180	2–4
Off-Axis TDE, spherical	$1^\ddagger$	10^{52}	0.1	0.8	3700	900	900	900	5
NSM: prompt BH	$500^\dagger$	3×10^{50}	0.1	0.2	4000	4000	4000	4000	7
NSM: stable remnant ("NSM-magnetar")	$5^\dagger$	3×10^{52}	0.1	1	2800	1300	1300	1300	8
Type Ib/c SNe ("RSN")	$5000^\dagger$	10^{47}	1	0.2	870	120	55	1.1	10

NOTE. — †Scaled with redshift according to star formation rate (Cucciati et al. 2012). ‡ Scaled with redshift according to volumetric density of supermassive black holes (Sijacki et al. 2014). $^{(a)}$ Light curve duration at observer frequency $\nu = 0.15$ GHz. $^{(b)}$ Light curve duration at observer frequency $\nu = 1.3$ GHz. $^{(c)}$ Light curve duration at observer frequency $\nu = 3$ GHz. $^{(d)}$ Light curve duration at observer frequency $\nu = 150$ GHz. References: (1) van Eerten et al. 2010; (2) Zauderer et al. 2011; (3) Berger et al. 2012; (4) Zauderer et al. 2013; (5) Giannios & Metzger 2011; (6) van Eerten & MacFadyen 2011; (7) Nakar & Piran 2011; (8) Metzger & Bower 2014; (9) Barniol Duran et al. 2014; (10) Soderberg et al. 2008

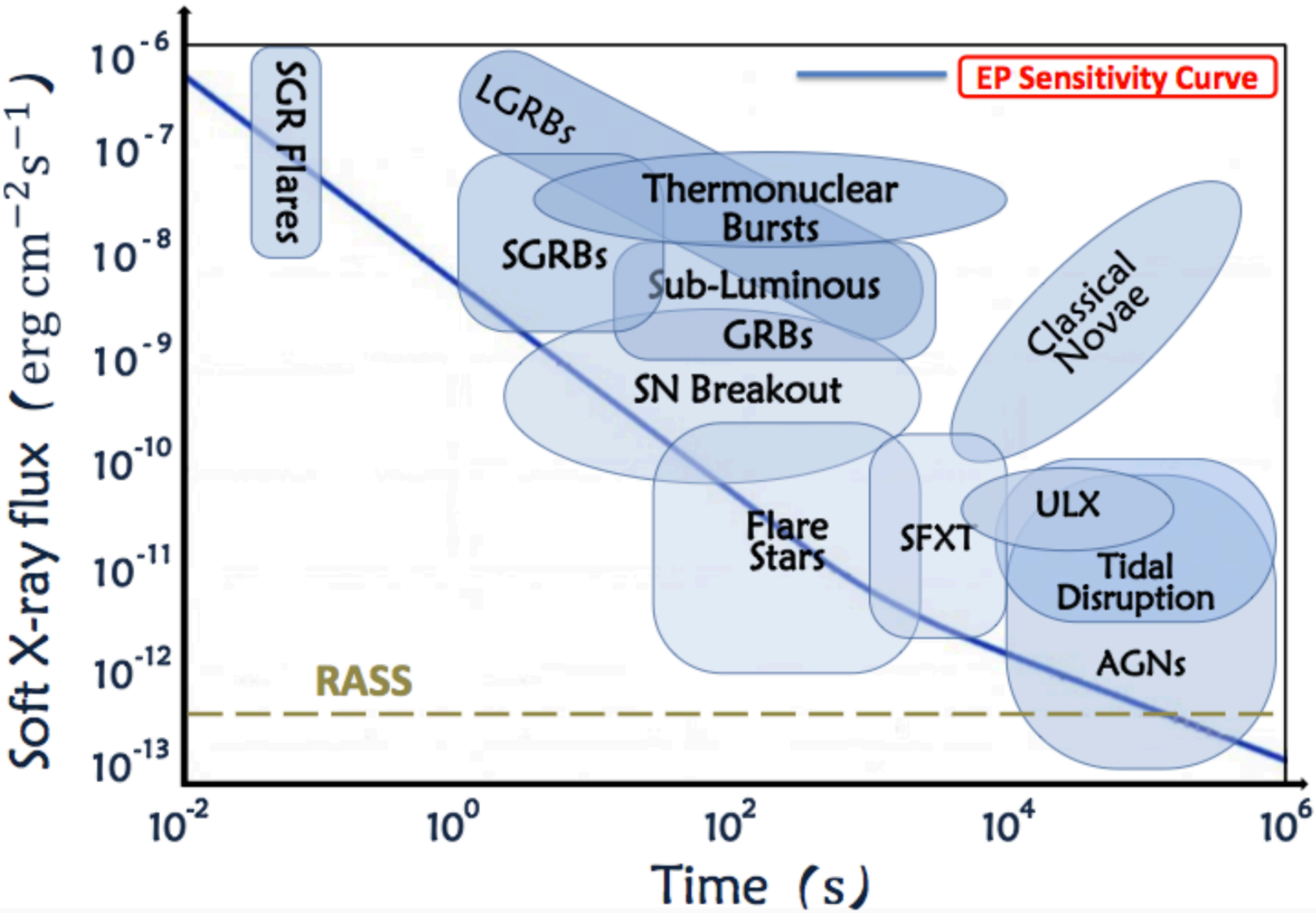
	LAD	WFM
Energy band (keV)	2–30(80)	2–50
Effective area	8.5 m^2 (at 6 keV)	90 cm^2 (peak)
FOV	1 deg	4.1 sr
Sensitivity (5σ)	0.1 mCrab in 100s	0.6 Crab in 1 s
		2.1 mCrab in 50 ks
Energy resolution	180–240 eV	300 eV
Timing resolution	10 μs	10 μs
Source location	–	0.5 – 1 arcmin



Slide by W. Yuan

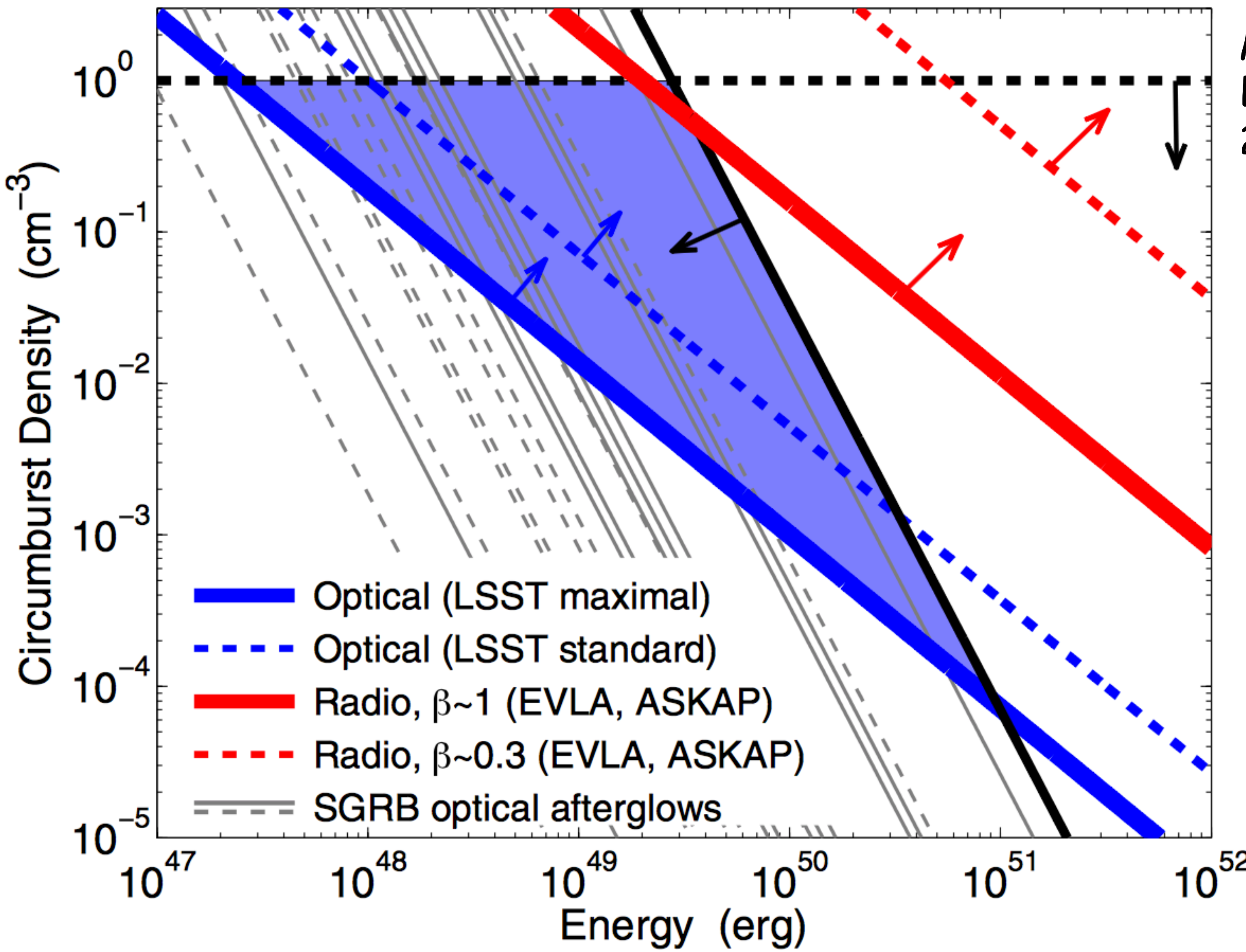


PL(Γ=4,N_H=3e20 cm^-2)
PL(Γ=2,N_H=3e20 cm^-2)
Thermal(kT=0.5keV)
EP discovery space
MAXI
RASS
ROSAT all-sky survey sensitivity
Limiting Flux (erg/s/cm²)
Limiting Flux (mCrab)
Accumulative Exposure Time(Second)
10.00
1.00
0.10
0.01



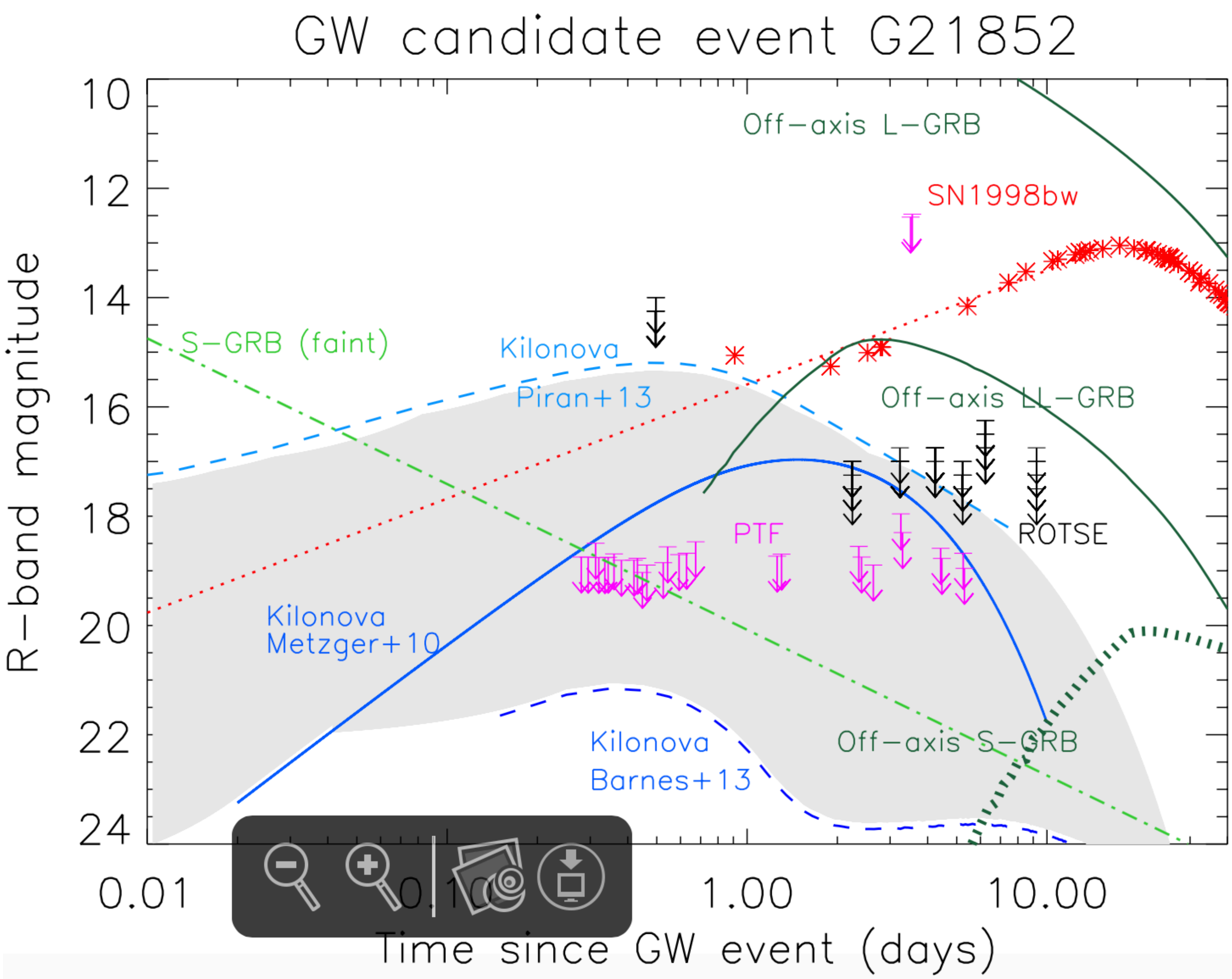
EP Sensitivity Curve
SGR Flares
LGRBs
Thermonuclear Bursts
SGRBs
Sub-Luminous GRBs
SN Breakout
Classical Novae
Flare Stars
SFXT
ULX
Tidal Disruption
AGNs
RASS
Soft X-ray flux (erg cm^{-2}s^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Time (s)

Expected EM counterparts



Metzger & Berger, 2012

Optical Counterparts (TBM)



Aasi et al. 2014, 30 Mpc

Modify picture to dL=100 Mpc

Radio Counterparts