GRAVITATIONAL WAVE ASTRONOMY

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1. GW: physics & astronomy
2. Current- & next-gen detectors & searches
3. **Burst sources: CBC, SN → GR, cosmology**
4. Periodic sources: NS → subatomic physics

LECTURE THREE

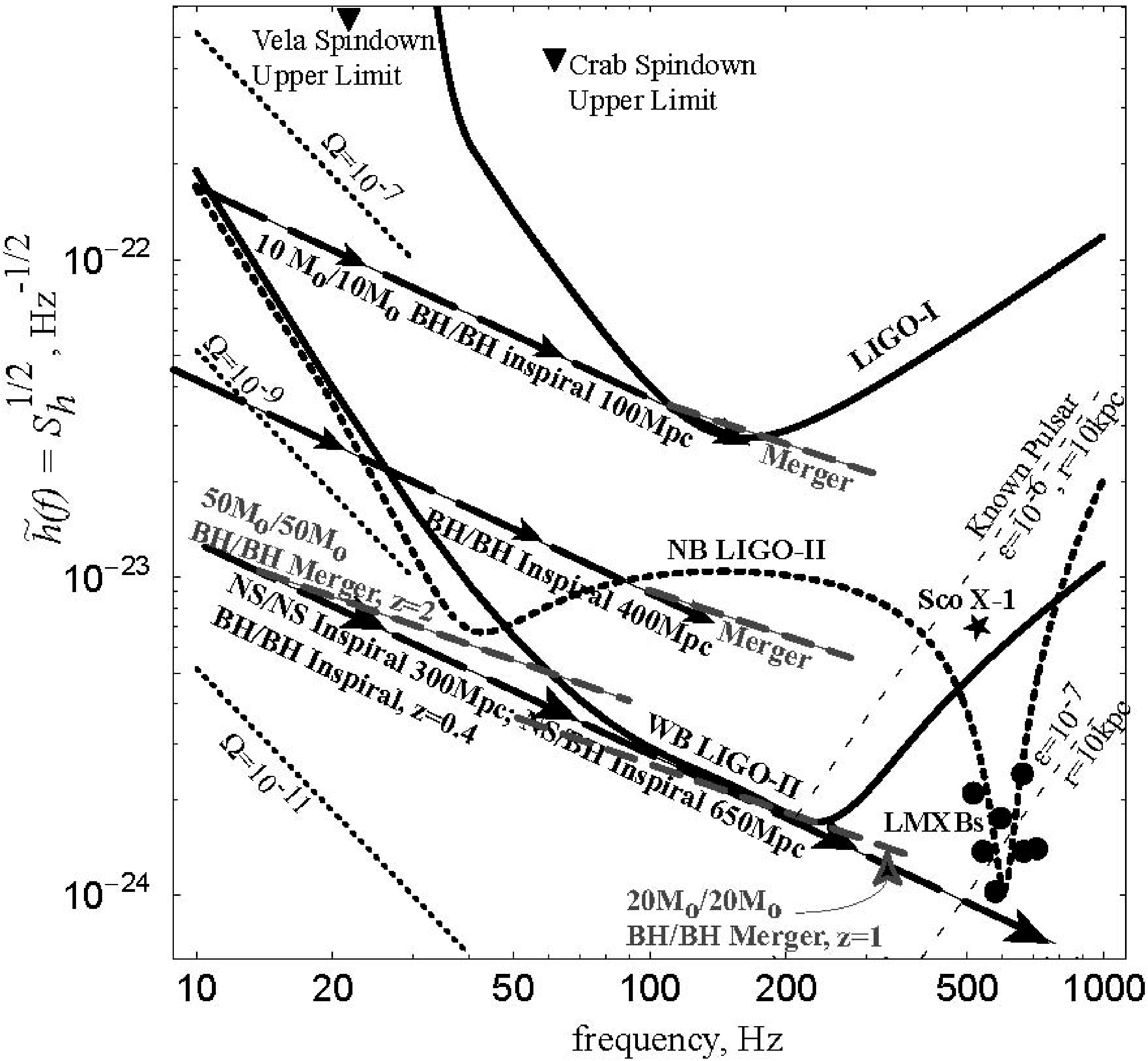
- Overview of LIGO sources

- **CBC: compact binary coalescence**
- Latest upper limits, predicted rates

- Bursts from core-collapse **supernovae**
- Bursts from **magnetars**

LIGO SOURCES

Source ↔ Search	Waveform
• CBC (NS or BH)	• 1-min chirp per wk
• Primordial: Big Bang	• Stochastic b'gnd
• Explosion: SN, GRB	• 1-s broadband burst
• Fast-spinning NS	• Periodic (with drift)



Vela Spindown
Upper Limit
Crab Spindown
Upper Limit
Ω=10-7
10 Mo/10Mo BH/BH inspiral 100Mpc
LIGO-I
Merger
Ω=10-9
Known Pulsar
ε=10-6, r=10kpc
50Mo/50Mo
BH/BH Merger, z=2
BH/BH Inspiral 400Mpc
NB LIGO-II
Merger
Sco X-1
NS/NS Inspiral 300Mpc; NS/BH Inspiral 650Mpc
BH/BH Inspiral, z=0.4
WB LIGO-II
ε=10-7
r=10kpc
Ω=10-11
LMXBs
20Mo/20Mo
BH/BH Merger, z=1
10−22
10−23
10−24
10
20
50
100
200
500
1000
frequency, Hz

HUNTING FOR CBCs

- **In-spiral** (chirp), **merger** (plunge inside ISCO), **ring-down** (quasi-normal modes relax to Kerr)

- NS-NS: $2 \;\; 10^3$ orbits in band, up to 1.5 kHz
- Heavier systems terminate at lower frequency

- Post-Newtonian waveforms $h(m_1,m_2;t)$
- Optimal **matched filtering** on (m_1,m_2) domain
- $(10^4)^2$ templates to cover $2\text{-}35\ M_{\mathrm{Sun}}$

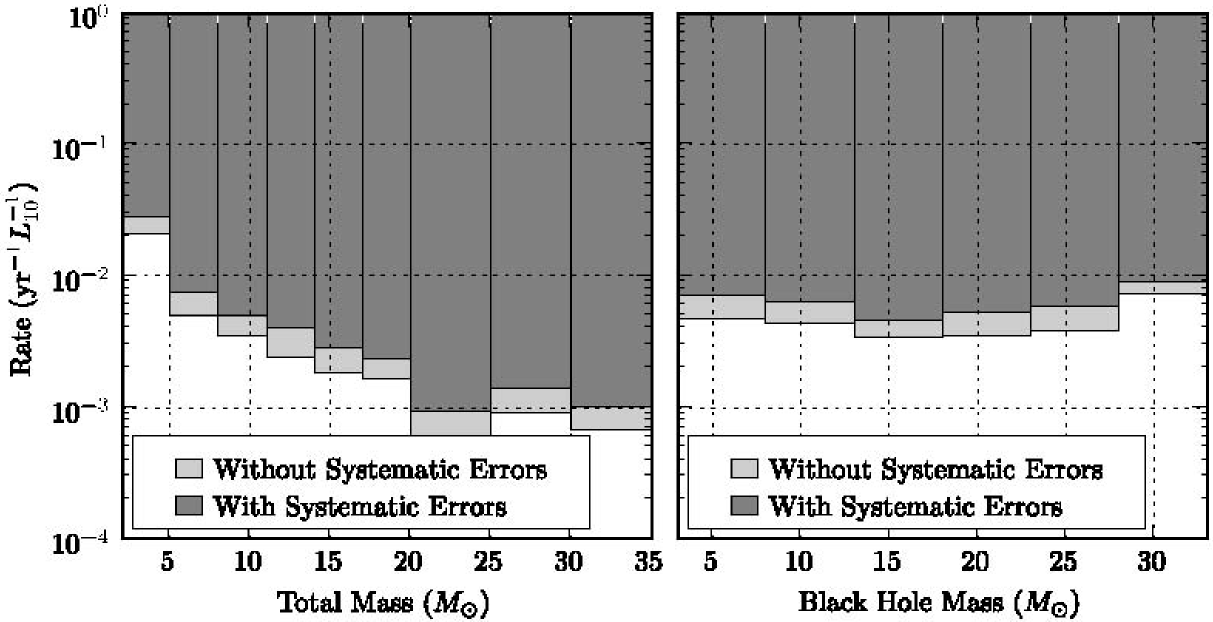
- **Now:** independent triggers from each IFO
- Coincidence check plus consistency tests, e.g. χ^2, r^2
- Thousands of survivors per month even now
- **Future:** coherent multi-detector analysis

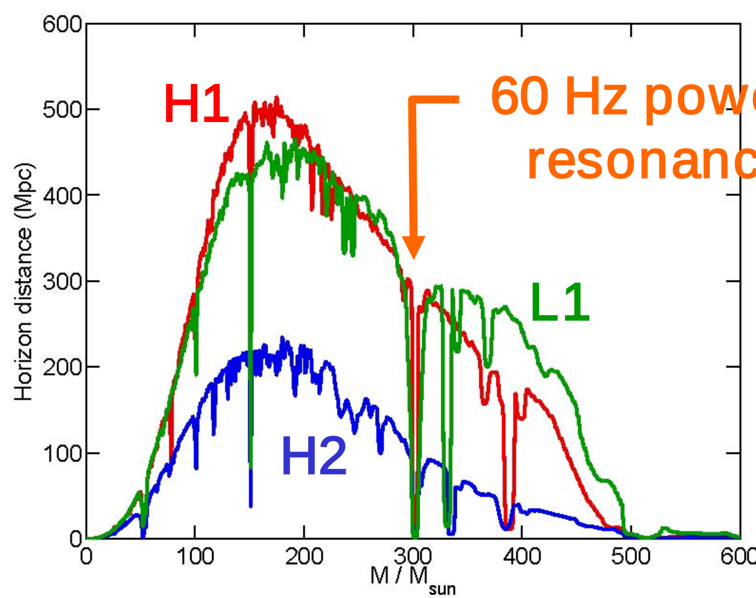
- Insert **time shifts** in data streams between detectors to estimate false alarm rate
- **Software injections**
- Secret **hardware injections**, e.g. Big Dog ☺

LIGO S5 BH-BH SEARCH
(Abbott et al. 09, RPPh)

BH-BH rate
uniform mass ratio

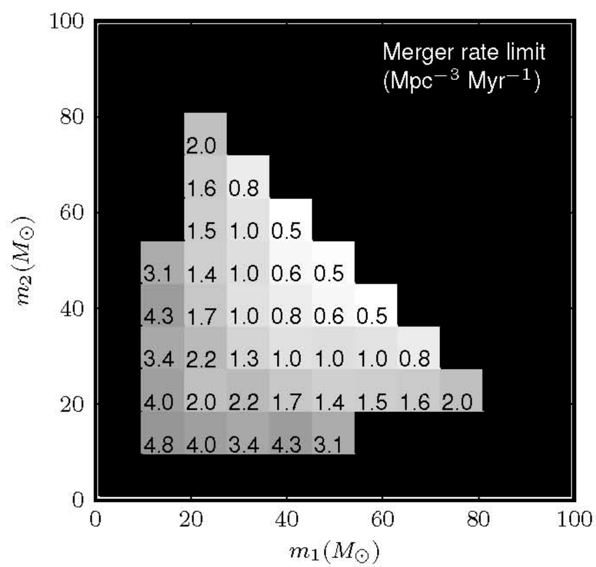
BH-NS rate
M_{NS}=1.35 M_{Sun}

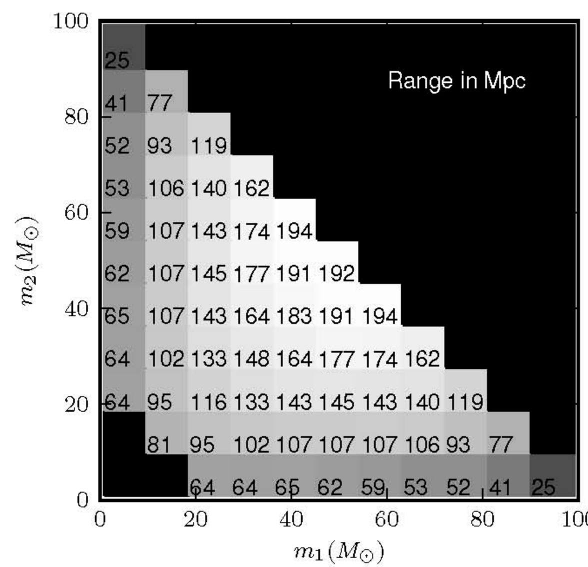




BH-BH ring-down
horizon

- **Latest** S5 analysis (Abadie et al. 11; arXiv:1102.3781)
- **Three** events with false alarm rate **$< 1.4\ \mathrm{yr}^{-1}$**, multi-detector **SNR ≈ 10**
- To get **merger rate upper limits:**
  → inject 10^6 signals, “detect” if FAR < loudest event in search
  → uniform in log(distance) 1-750 Mpc, total mass 25-100 M_{Sun}





$$\mathrm{Mpc}^{-3}\ \mathrm{Myr}^{-1} = 50 L_{10}^{-1}\ \mathrm{Myr}^{-1}$$

HOW MANY DO WE EXPECT?

- How many NS-NS binaries coalesce in a given volume of space per annum? (Phinney 91)

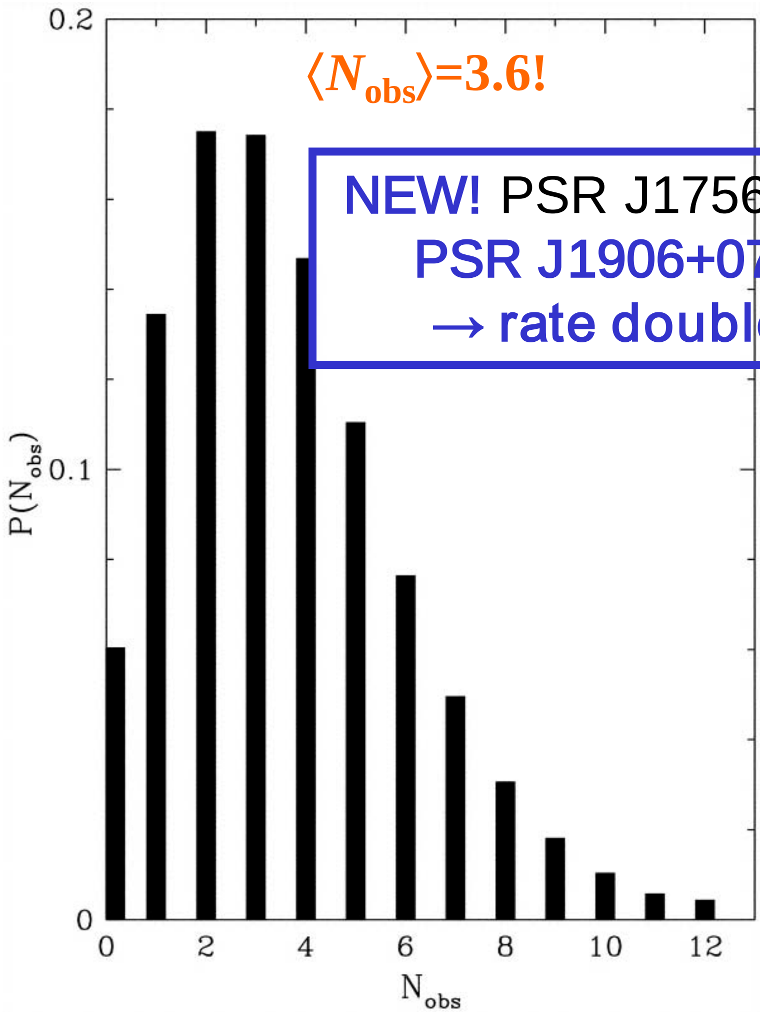
- Bayesian statistics + survey selection effects (e.g. small number & faint object biases)
- New double PSR J0737-3039 coalesces in just 85 Myr → boosts rate six-fold (Kalogera et al. 04)

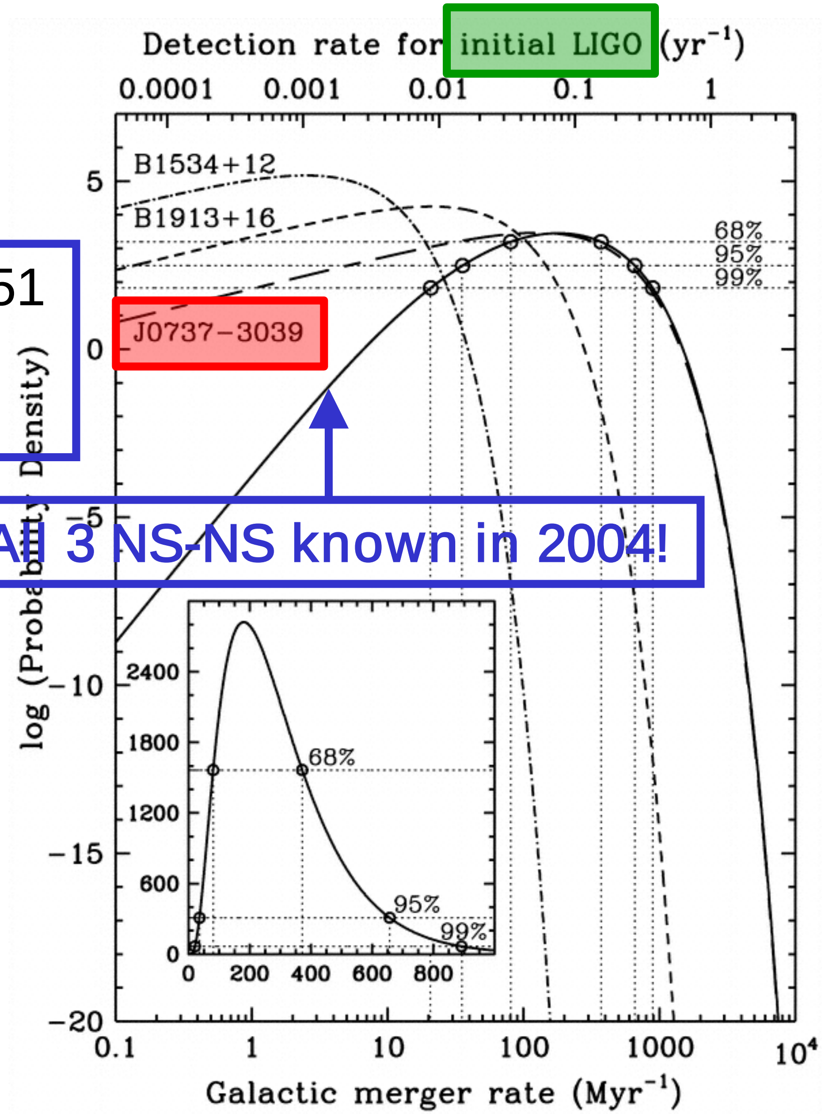
Initial / Advanced LIGO

$0.1 / 360\ \mathrm{yr}^{-1}$ @ $(20 / 350\ \mathrm{Mpc})^3$

probability distribution of annual event rate

INITIAL LIGO!!!





NEW! PSR J1756-2251
PSR J1906+0746
→ rate doubles

All 3 NS-NS known in 2004!

(Kalogera et al. 04; Kim et al. 06)

LATEST RATE PREDICTIONS

- **Adv LIGO:** sensitivity $\mathbf{10} \rightarrow$ volume $\mathbf{10^3}$, not $10^{1.5}$ (measure amplitude not intensity)

- "Ugly" astrophysics: natal kicks, winds from massive stars, unstable **common envelope** accretion, mass ratio distribution, …
- "Ugly" engineering: network configuration, noise colour, **search strategy** (coincidence or coherent), …

Pessimistic, realistic, optimistic, maximum rates
(arXiv:1003.2480)

FOLLOW THE BLUE LIGHT

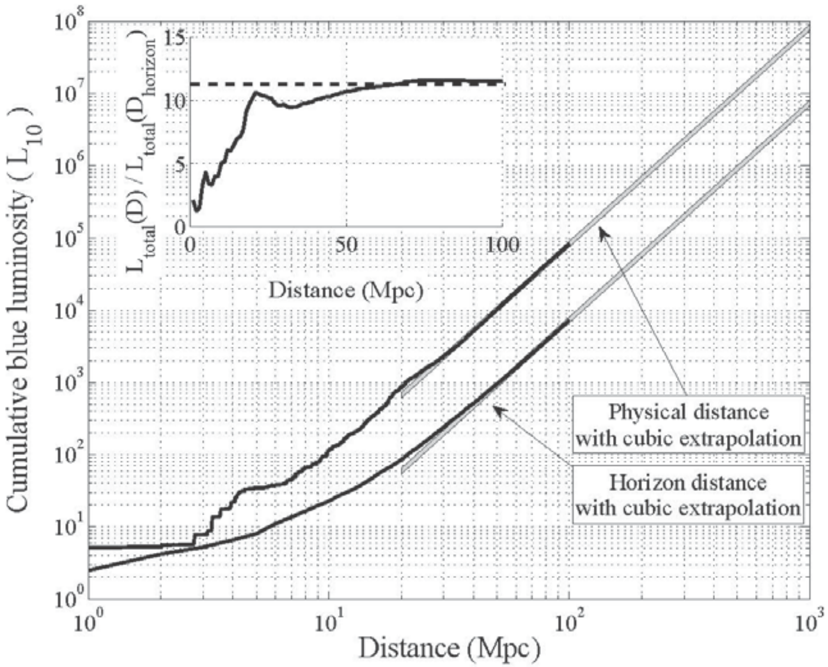


TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS ($MWEG^{-1}$ Myr^{-1})	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH ($MWEG^{-1}$ Myr^{-1})	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH ($MWEG^{-1}$ Myr^{-1})	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19][k]	20 [19][l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20][m]	0.07 [20][n]

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	N_{low} yr^{-1}	N_{re} yr^{-1}	N_{high} yr^{-1}	N_{max} yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

- Blue light = current SF not history
- Ignores old stars in ellipticals

- Single IFO, SNR > 8
- No red shift included

RATE ISSUES: NS-NS, NS-BH

Pop'n synthesis: Star Track (O'Shaugnessy et al. 08)

- **Kick ‖ pre-SN spin** → reduce rate 5-fold
- Best constrained by Galactic **pulsar binaries** → **NOT** independent of Bayesian approach
- **Common envelope?** (Voss & Tauris 03)

Bayesian inference: observed binaries

- **Short GRB:** unknown beaming, selection bias
- **Pulsar binaries:** radio L_{min} unknown

RATE ISSUES: BH-BH

Dynamical processes in **globular clusters** form BH-BH pairs (O'Leary et al. 07; Sadowski et al. 08)

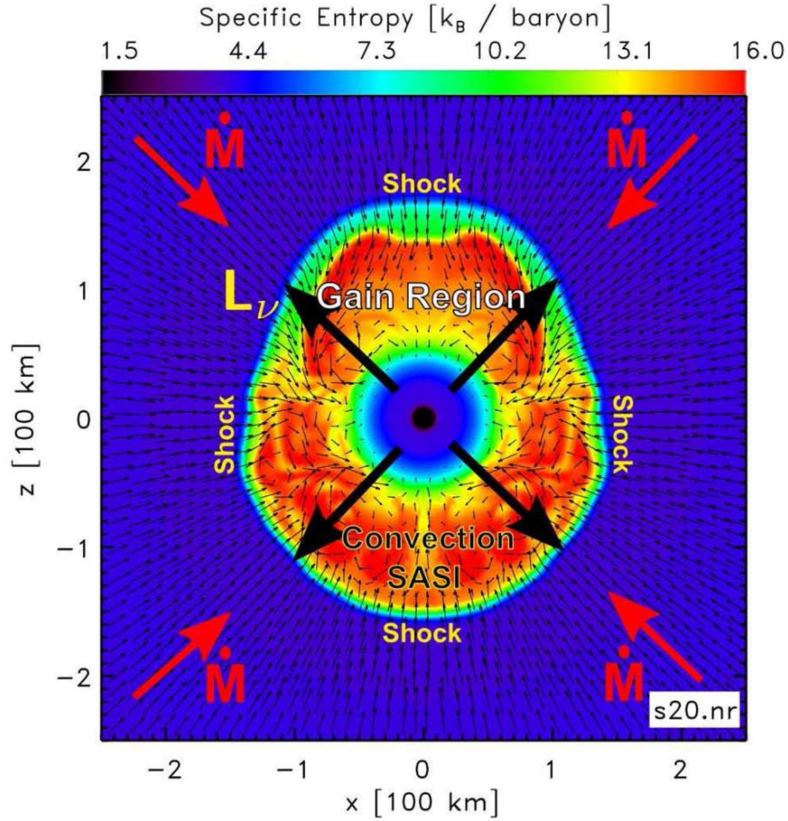
- Importance set by initial mass in clusters
- Central BHs → sub-cluster…?
- Intermediate-mass in-spirals (?) into IMBH (?)

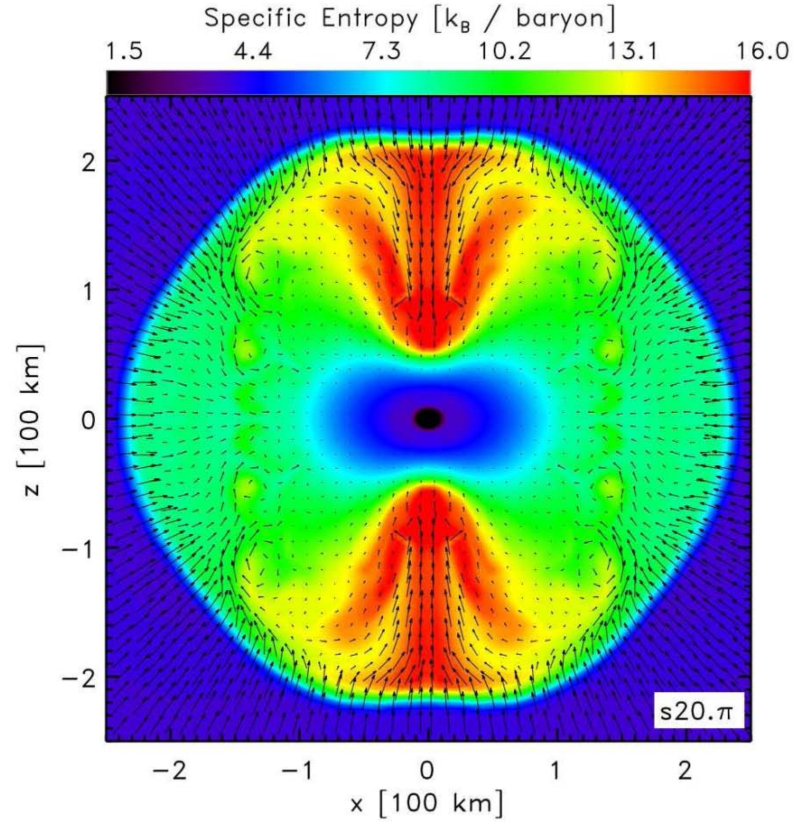
Common envelope: donor in Hertzsprung gap
→ **merge** instead of forming tight binary
→ **suppress BH-BH** rate (Belczynski et al. 07)

BURSTS: I

Multi-messenger studies of core-collapse supernovae

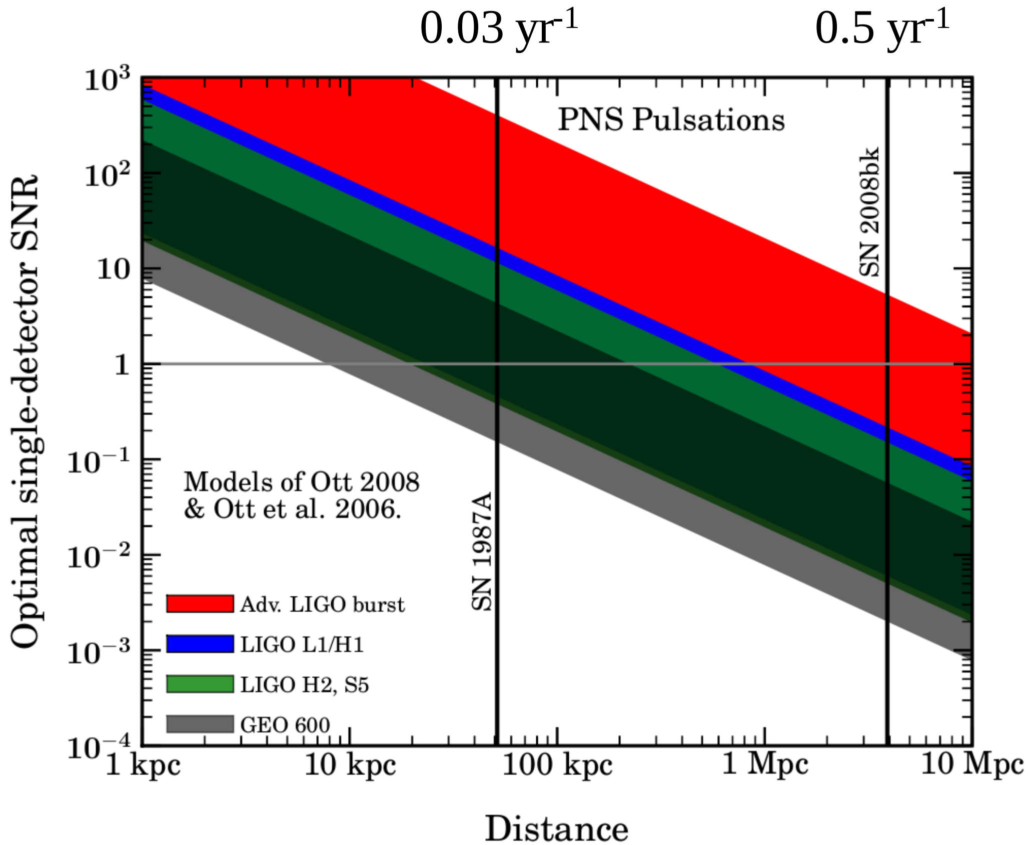
(Ott 09)





NON-ROTATING

ROTATING

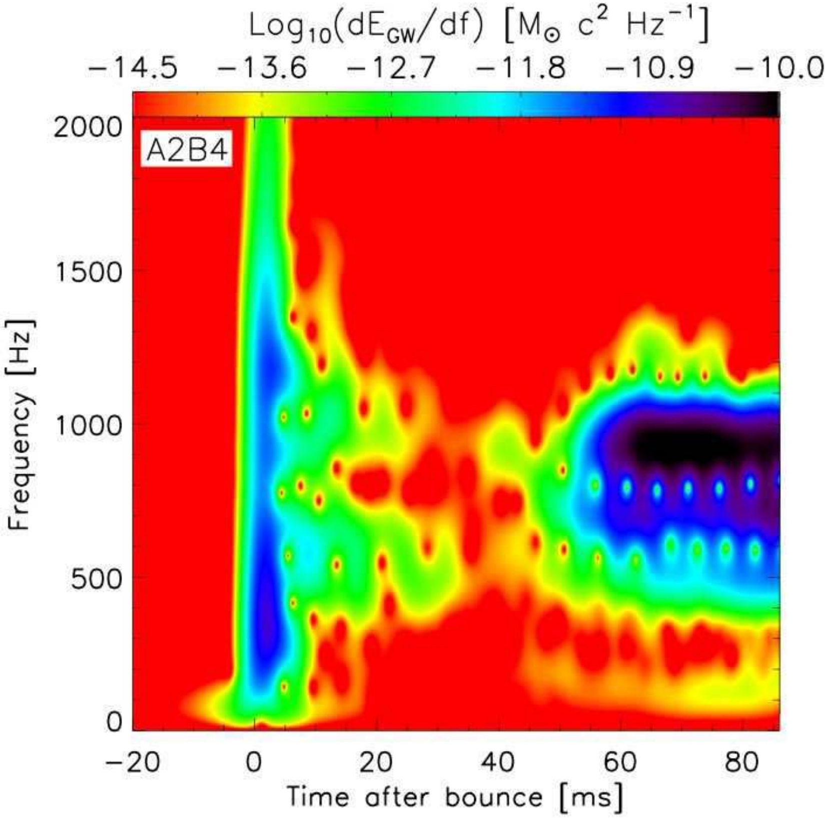


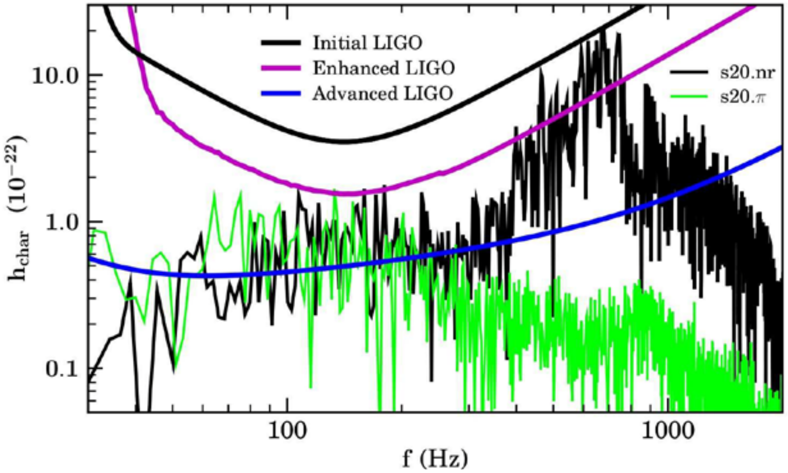
Convection & PNS g-modes @ 0.7 kHz (Ott 09)

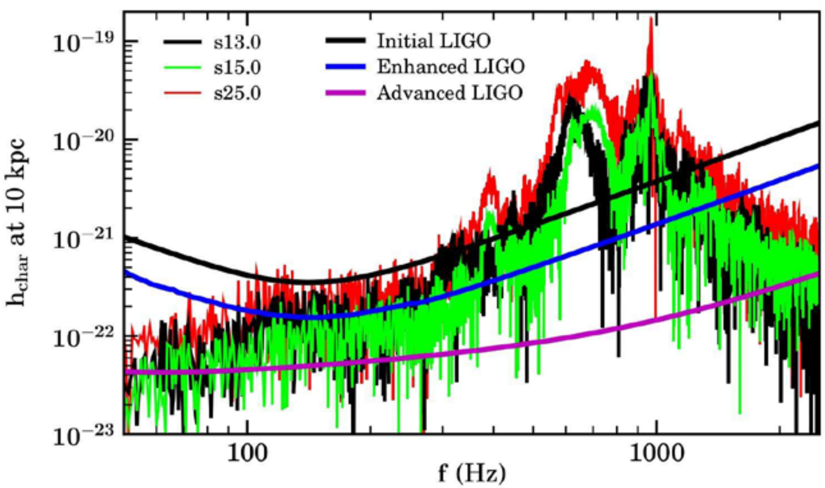
→ neutrinos injected behind stalled shock

→ magneto-centrifugal jet (B amplified)

→ acoustic (PNS modes steepen into shocks) g-modes







spectrogram

(Ott 09)

acoustic

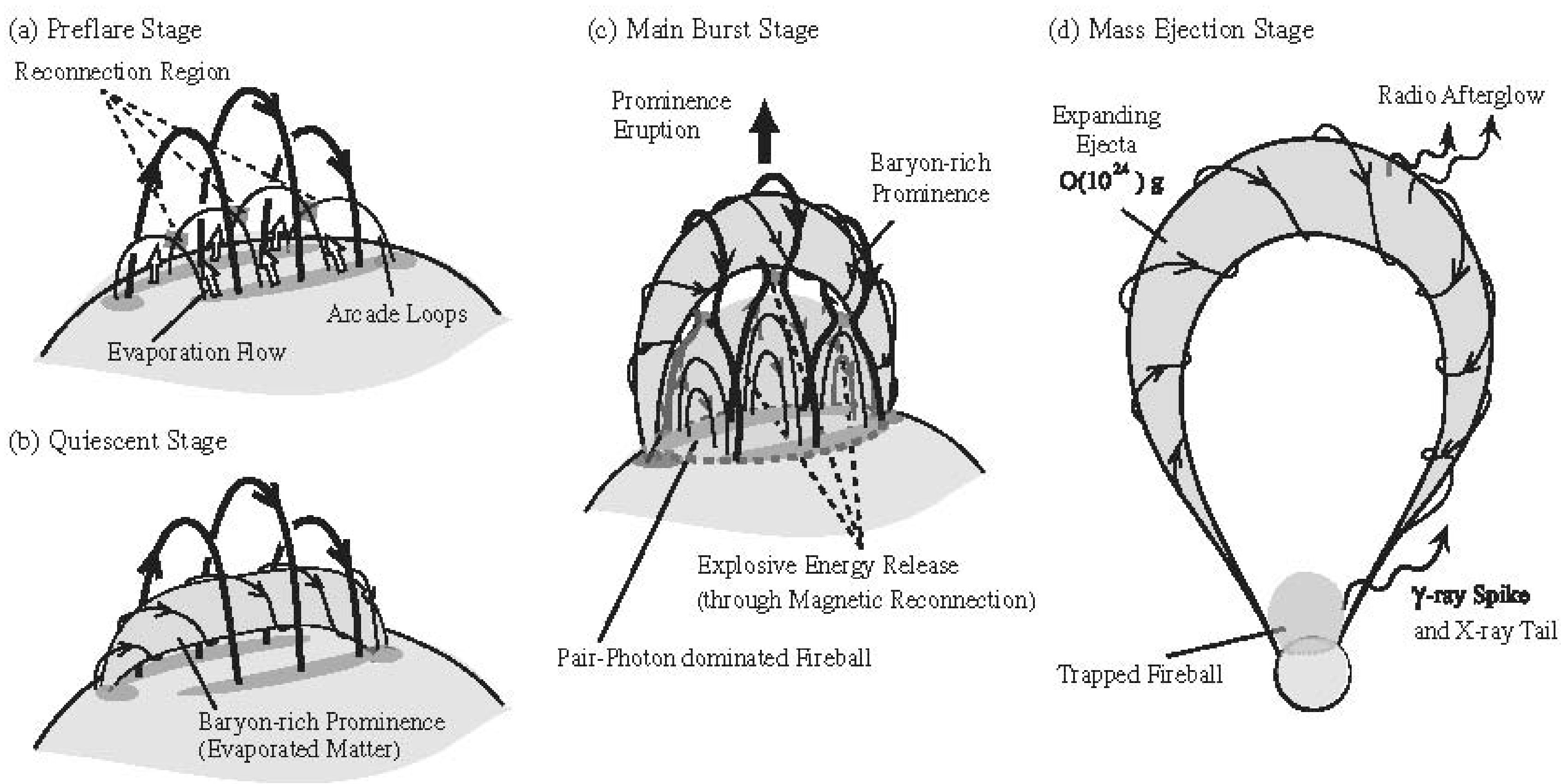
BURSTS: II

Multi-messenger studies of
magnetar flares

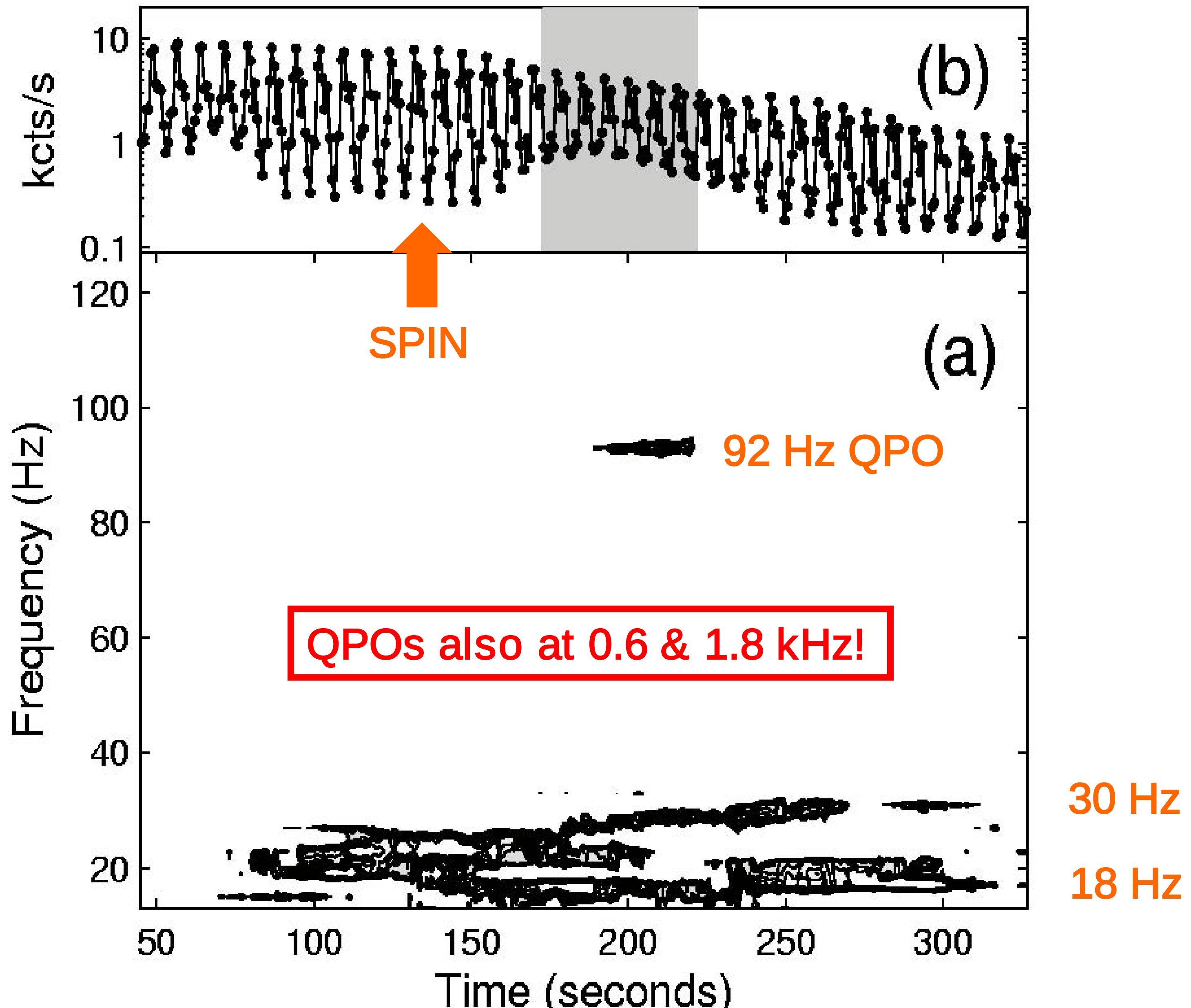
MAGNETARS

- Ultra-magnetized neutron stars; 20 known
- SGRs and AXPs
- Frequent X-ray flares $< 10^{42}$ erg
- Three giant broadband flares $\sim 10^{44\text{-}46}$ erg

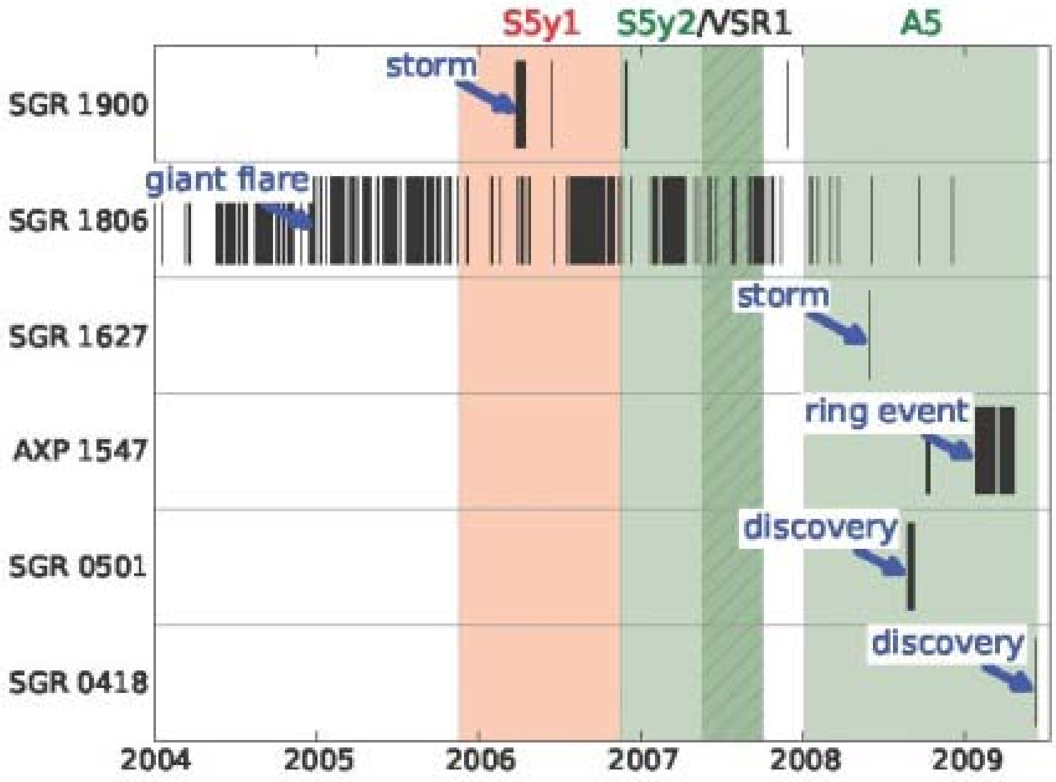
- Internal $\rightarrow$ *f*-modes ($f \sim 2$ kHz for ~ 0.2 s)
  (Passamonti et al. 10; Corsi & Owen 11)
- Magnetospheric $\rightarrow$ surface modes (Lyutikov 06)



Cf. Yohkoh X-ray images of **solar flares** (Masada 09)



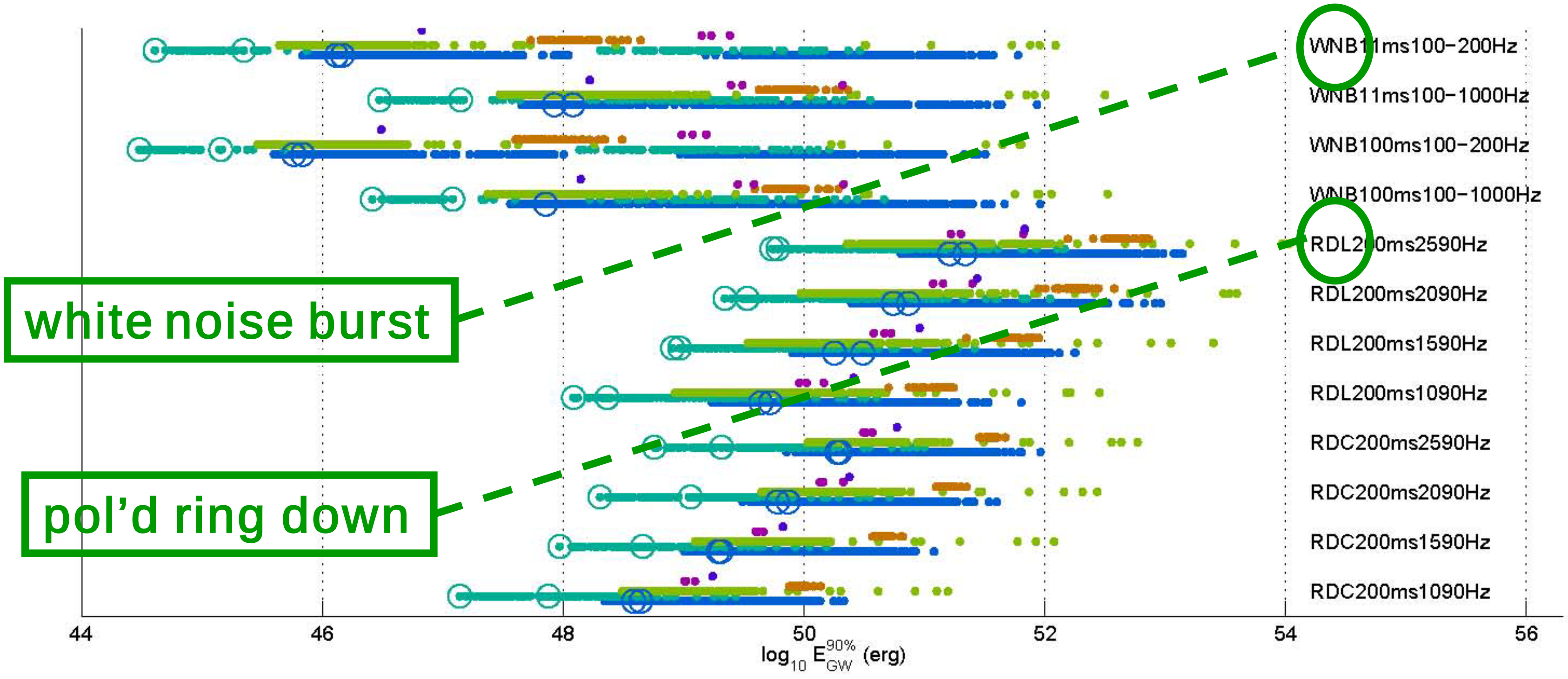
(Watts & Strohmayer 06)



EM triggers:
IPN, Fermi GRB

(Abadie et al. 11; arXiv:1011.4079)

- S5y2 inc. VSR1: **1217 bursts** from 6 objects
- Two in Perseus arm at ~ 1 kpc… **close!**
- AXP with expanding dust rings (inferred from X-ray scattering) → 5 kpc → $\mathbf{10^{44\text{-}45}}$ **erg**

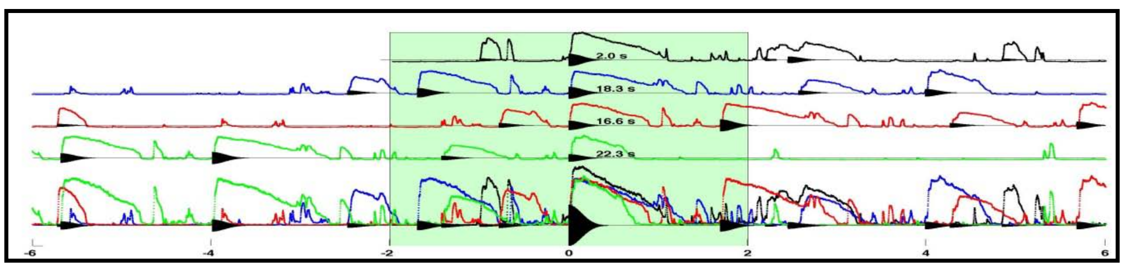


- Look for excess power in *t*-*f* **spectrogram**
- **4 s** around EM trigger, **10^3 s** background
- Model-dependent, Monte-Carlo **maximum GW energy** $E_{GW}^{90\%}$ (90% detection rate)

- “Best” WNB give $\gamma = E_{GW}^{90\%} / E_{EM} \approx 10$ **(!)**
- AXP ring events promising but E_{EM} uncertain

- Probe **elasticity** & **composition** (crust & core)

- Will get $\gamma < 1$ with ALIGO by **stacking flares** (Kalmus et al. 09) (if emission physics repeats)



SUMMARY

- Overview of LIGO sources

- **CBC: compact binary coalescence**
- Latest upper limits, predicted rates

- Bursts from core-collapse **supernovae**
- Bursts from **magnetars**