1. GW: physics & astronomy

2. Current- & next-gen detectors & searches

3. Burst sources: CBC, SN → GR, cosmology

4. Periodic sources: NS → subatomic physics
• 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**
- CBC (NS or BH)
- Primordial: Big Bang
- Explosion: SN, GRB
- Fast-spinning NS

**Waveform**
- 1-min chirp per wk
- Stochastic b’gnd
- 1-s broadband burst
- Periodic (with drift)
HUNTING FOR CBCs

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

- NS-NS: $2 \times 10^3$ 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 2-35 $M_{\text{Sun}}$
• **Now:** independent triggers from each IFO
• Coincidence check plus consistency tests, e.g. $\chi^2$, $r^2$
• 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 😎
BH-BH rate
**uniform mass ratio**

BH-NS rate
\[ M_{\text{NS}} = 1.35 \, M_{\odot} \]

BH-BH ring-down horizon

LIGO S5 BH-BH SEARCH

(Abbott et al. 09, RPPh)

60 Hz power line resonance! 😊
• **Latest** S5 analysis (Abadie et al. 11; arXiv:1102.3781)
• **Three** events with false alarm rate < 1.4 yr$^{-1}$, multi-detector SNR $\approx 10$
• 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 $M_{\text{Sun}}$

\[ \text{Mpc}^{-3} \text{Myr}^{-1} = 50L_{10}^{-1} \text{Myr}^{-1} \]
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 yr\(^{-1}\) @ (20 / 350 Mpc)\(^3\)
probability distribution of annual event rate

\[ \langle N_{\text{obs}} \rangle = 3.6! \]

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 $10 \to$ volume $10^3$, 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), …
• 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’Shaughnessy 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 $L_{\text{min}}$ unknown
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)
spectrogram

(Ott 09)

g-modes

acoustic
BURSTS: II

Multi-messenger studies of magnetar flares
• **Ultra-magnetized** neutron stars; 20 known
• SGRs and AXPs
• Frequent **X-ray flares** $< 10^{42}$ erg
• Three **giant broadband flares** $\sim 10^{44-46}$ erg

• **Internal** $\rightarrow f$-modes ($f \sim 2$ kHz for $\sim 0.2$ s) (Passamonti et al. 10; Corsi & Owen 11)
• **Magnetospheric** $\rightarrow$ surface modes (Lyutikov 06)
Cf. Yohkoh X-ray images of solar flares (Masada 09)
QPOs also at 0.6 & 1.8 kHz!
• S5y2 inc. VSR1: **1217 bursts** from 6 objects
• Two in Perseus arm at $\sim 1$ kpc… **close**!
• AXP with expanding dust rings (inferred from X-ray scattering) → 5 kpc → $10^{44-45}$ erg

EM triggers: IPN, Fermi GRB

(Abadie et al. 11; arXiv:1011.4079)
• Look for excess power in $t$-$f$ spectrogram
• $4 \, \text{s}$ around EM trigger, $10^3 \, \text{s}$ background
• Model-dependent, Monte-Carlo maximum GW energy $E_{GW}^{90\%}$ (90% detection rate)
• “Best” WNB give $\gamma = \frac{E_{GW}^{90\%}}{E_{EM}} \approx 10$ (!)

• 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

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- Bursts from *magnetars*