Astrophysics with LIGO

R. O'Shaughnessy (PSU)

Columbia physics seminar

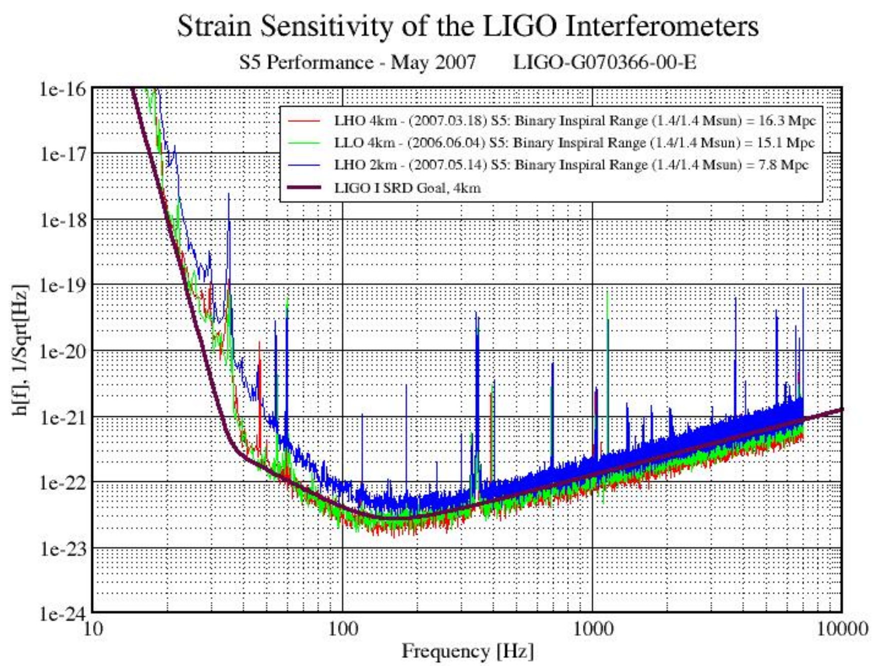
April 16, 2008

LIGO-G080276-00-Z

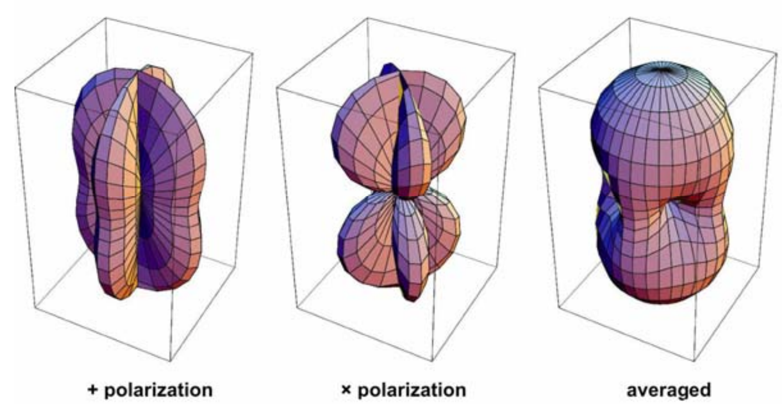
What can LIGO do?

"Hear"

- Narrow frequency sensitivity
  ~ 100 Hz
- Weak orientation dependence
  (each "ear" like dipole radio antenna)
- Good hearing!
  - **"loud"** (NS binaries) :
    - O(15 Mpc) now, O(30) Mpc soon, O(160) Mpc in 8 yrs
  - **"faint"** (pulsars) :
    - Nearby (Milky Way only)



LIGO DCC:070366-00



What can LIGO+VIRGO do?

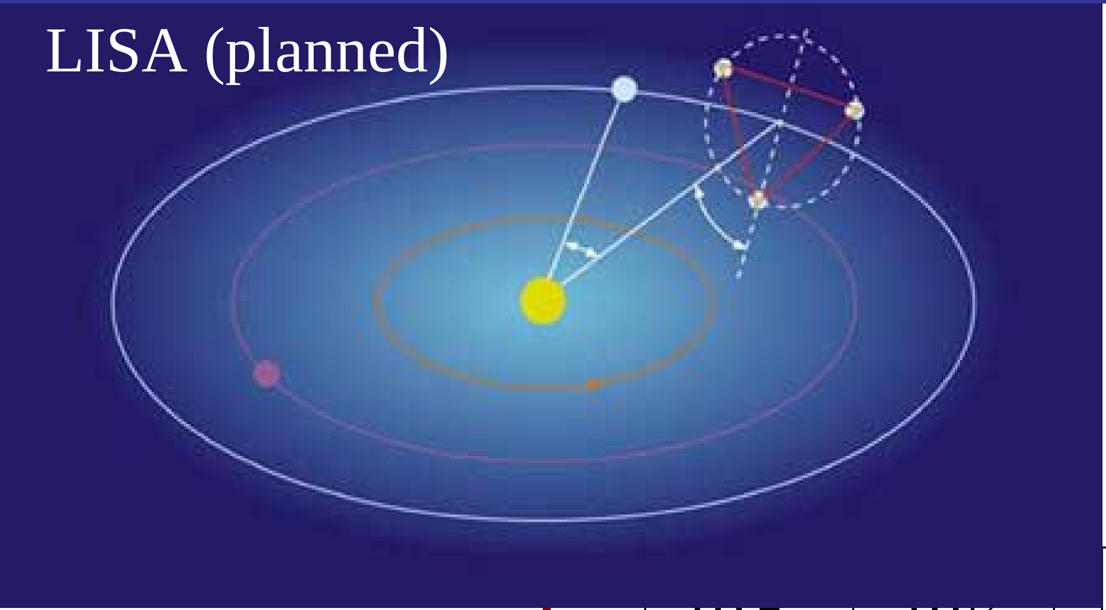
Locate:

- Triangulation!

- Just accurate timing

+ coherent multidetector search/joint likelihood (e.g., synthetic aperture)
stronger signals -> better location

What is out there to see?



Detectors

Pulsar timing
CMB fluctuations

Space-based interferometers
(LISA)

LIGO (running)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Ground-based interferometers
(LIGO/VIRGO/GEO/TAMA)

What is out there for it to see?

Lots:

- Stochastic background (inflation)
- Cosmic strings
- Supernova
- GRBs
- Parabolic BH-BH encounters

…

Known sources,

Right frequency,

Good detection probability

- Mergers

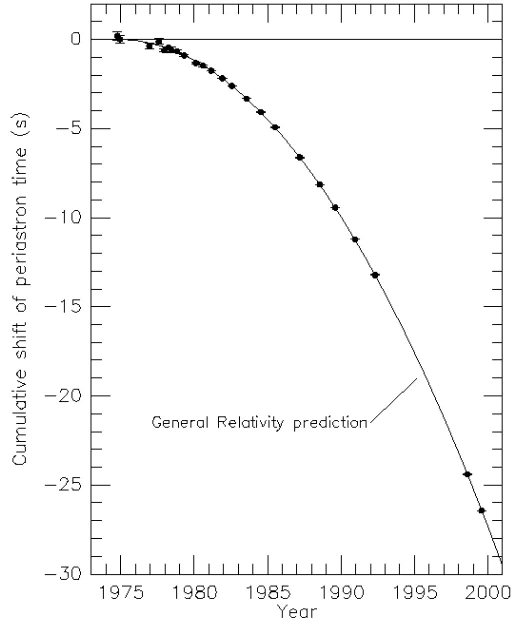
  Hulse taylor pulsar

  Endpoint of binary stellar evolution

- Neutron stars

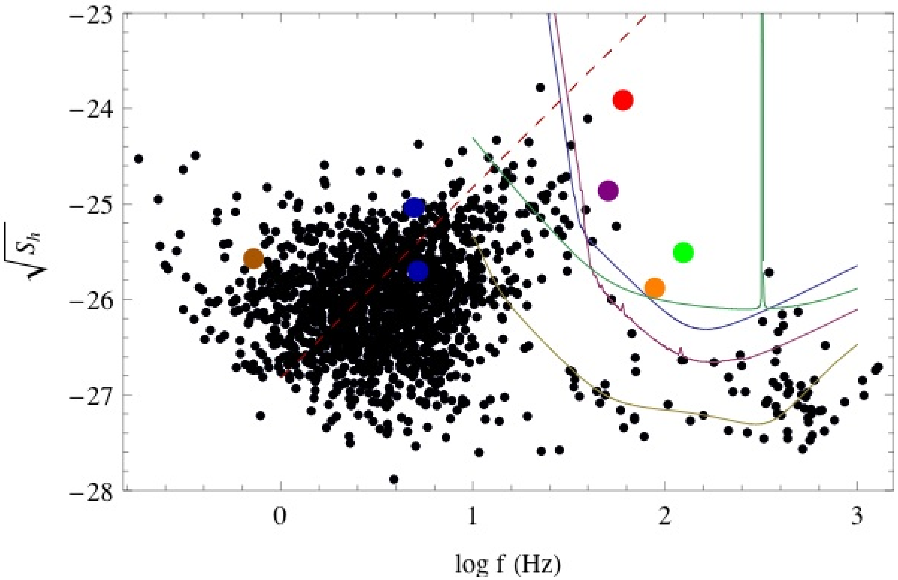
  Mergers

  Spin : isolated, accreting, glitching



Hulse-Taylor

Energetic limits on steady pulsar emission



What can we learn?

Three examples:

- Mystery of short GRBs (briefly)
- What is neutron star matter? (longer)
- How do paired stars evolve? (longest)

…**and a fourth (if time)**:

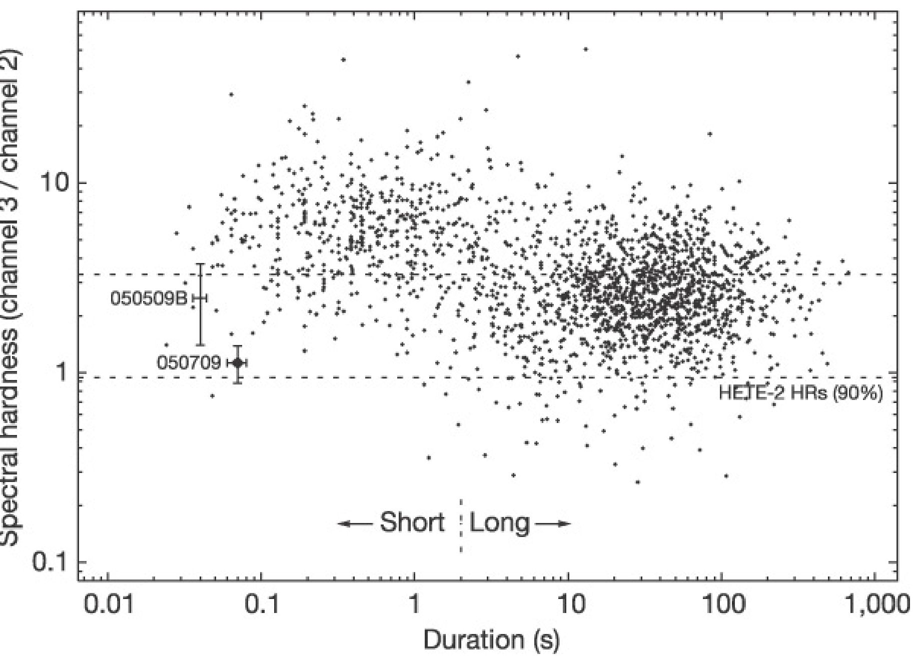
- Constraining star clusters and star formation

1: Short GRBs

GRBs generally

- "Fireball model":
  central engine hidden
  (unless post-blast wave signature: SN = long?)
- Non-fireball post- or pre-burst signal needed

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Swift website

Two classes

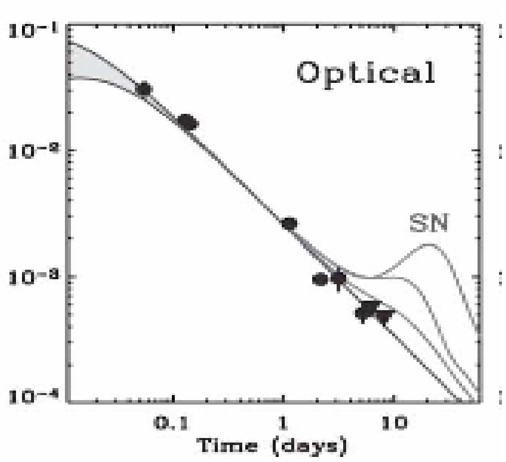
Long : Post-burst (some) are SN;
correlate to early SFR; …

Short : ….

What are short GRBs?

Merger motivation?

- No SN structure in afterglow



GRB 051221 (Soderberg et al 2006)

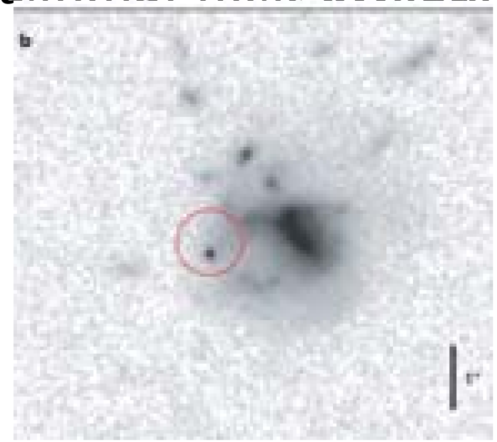
- In both **old**, young galaxies

Selected short GRBs

GRB	Host	L/L_*	SFR $M_\odot$/yr
050509b	E	3	< 0.1
050709b	Sb/Sc	0.1	0.2
050724	E	1.5	< 0.03
051221	S	0.3	1.4
060502	E	1.6	0.6

(Nakar, 2006 : Table 3)

- Occasional host **offsets**



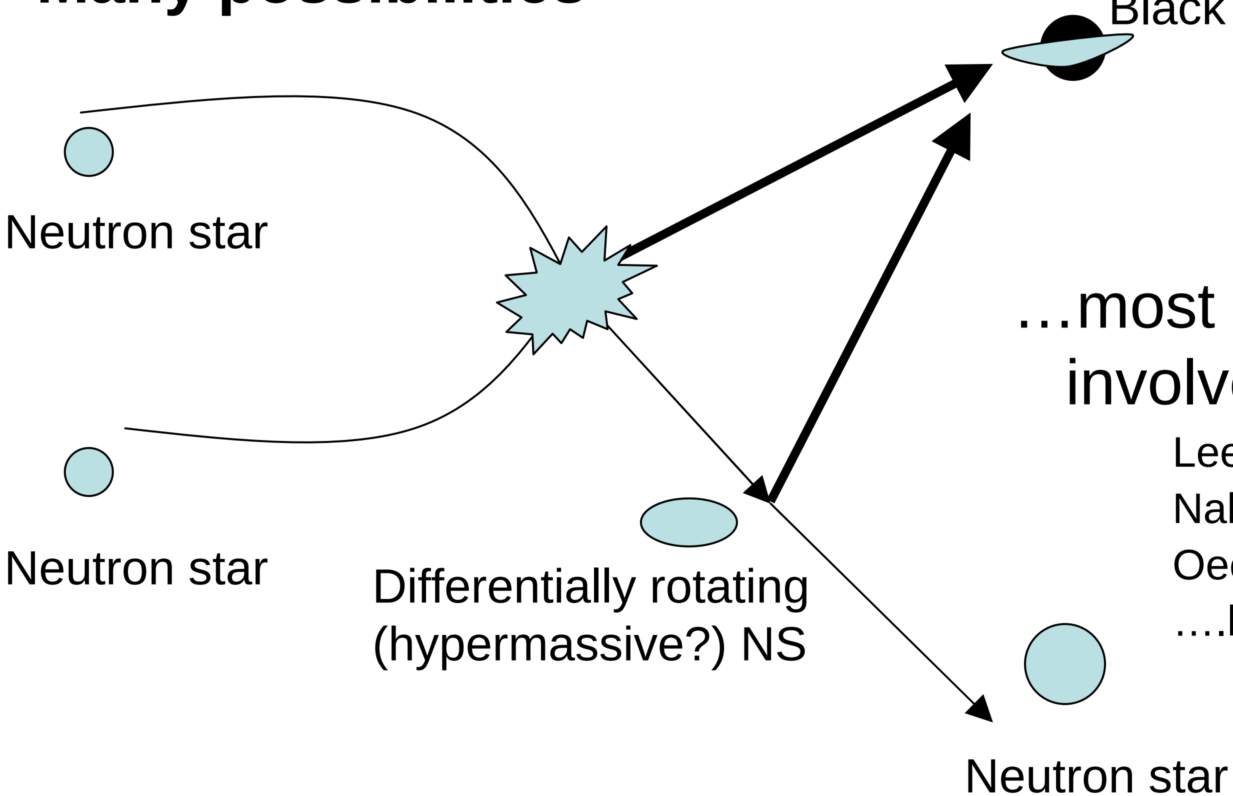
GRB 050709 (Fox et al Nature 437 845)

- Energetics prohibit magnetar for **all** …

[more later]

How do merger models work?

Many possibilities



…most popular NS+NS
involves BH torus

Lee and Ramirez Ruiz 2007
Nakar 2007
Oechslin and Janka 2006
….lots more …

Sociological? Unifies

- collapsar
- short bursts?

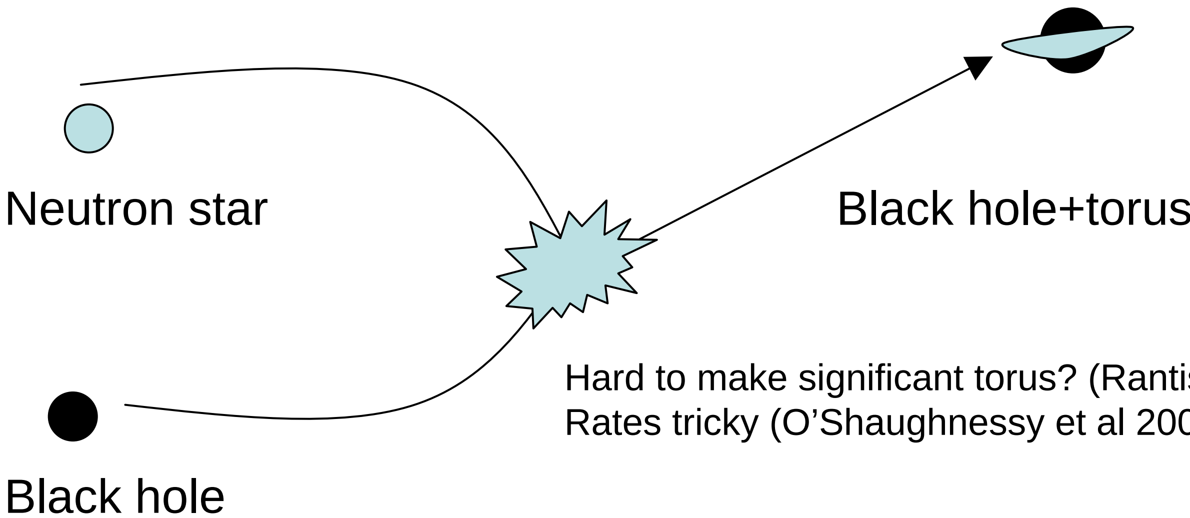
Other channel(s)

Hypermassive star (Faber et al 2006; Duez et al 2007; Liu et al 2008)
+ B, accretion, baryonic wind, tidal tail …. [extended emission]

Other merger models…

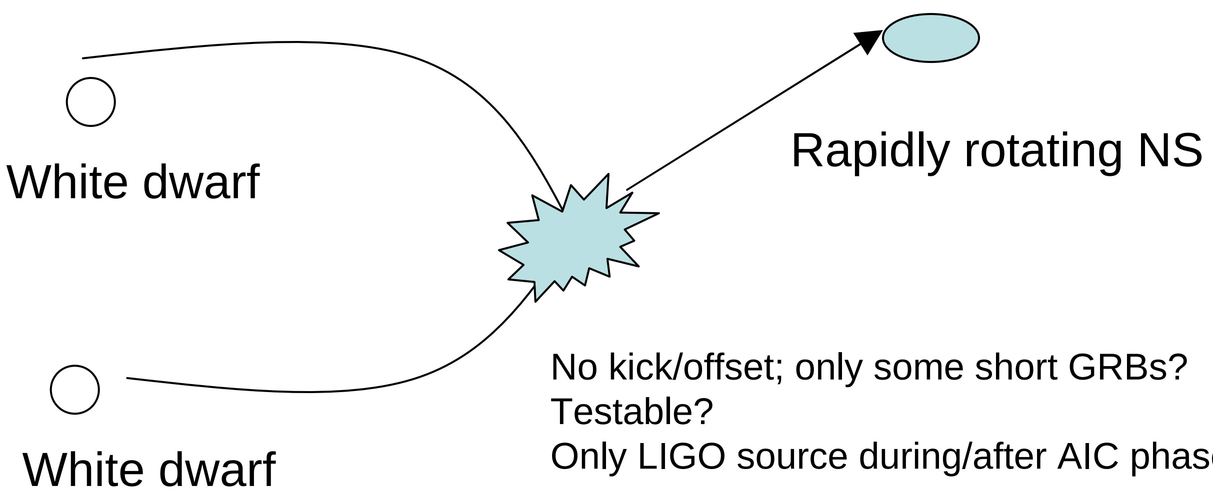
Not just NS-NS…

Oeschslin and Janka 2006
Faber et al 2006
Shibata et al 2006, 2007
….



Hard to make significant torus? (Rantisou et al 2007)
Rates tricky (O'Shaughnessy et al 2008; Belczynski et al 2007)

Metzger et al 2008
Chapman et al 2006
Levan et al 2006
Kluzniak and Ruderman 1992



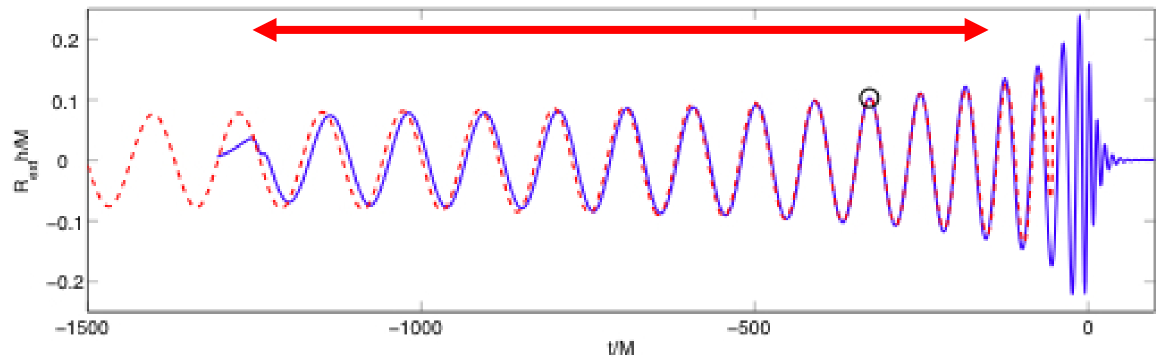
No kick/offset; only some short GRBs?
Testable?
Only LIGO source during/after AIC phase

Checking GRBs with LIGO?

Using only 'inspiral' phase
____[avoid tides, disruption!]

- Mass
  Must match!
  df/dt -> mass

- Distance



Hey…why just look at inspiral? (=point-particle approximation)

…for part 2:
Most NS mergers "slosh"
GW - clues to structure?

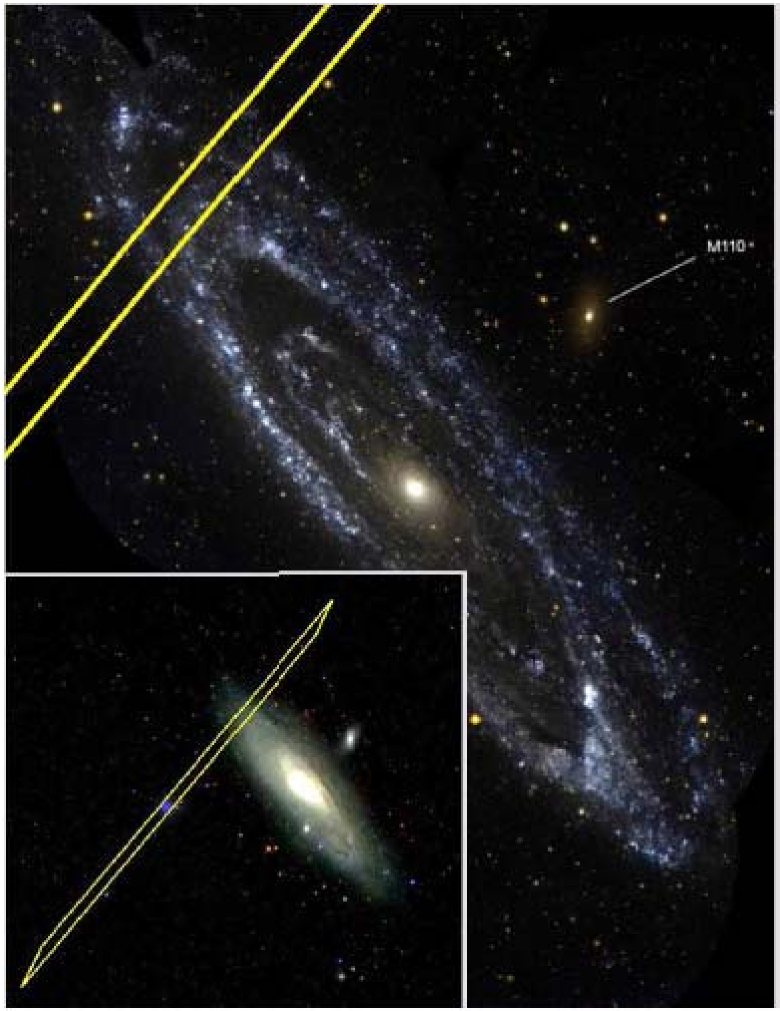
…but for now, *mostly* NS disruption frequency out of band

$$\Omega_{disrupt} \simeq \Omega_{kepler} \leftrightarrow f \simeq 1000 Hz$$

Predominant effect is point-particle mechanics

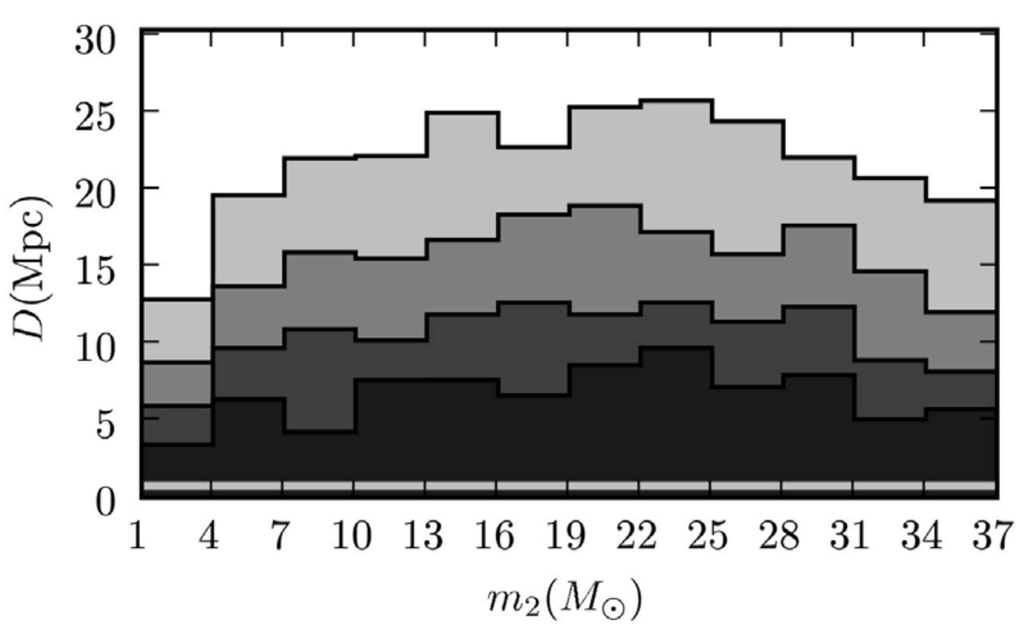
Example: GRB 070201

Burst coincident with (some of) Andromeda



…but no inspiral signal

- Range >>> d(M31)=770 kpc
- Exclude at > 99%



Abbott et al

2: Neutron star matter

Challenge of nuclear matter

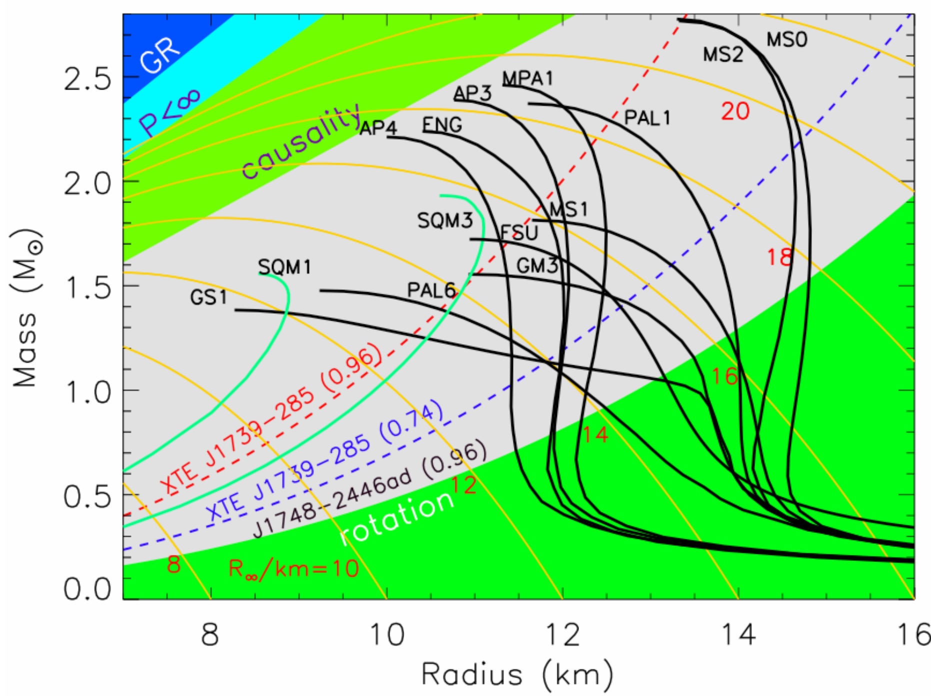
- Density ~ few * nuclear
  - Mildly relativistic
  - Fermi energy permits more particles (hyperons, kaons, …). Quark/strange matter?
- Highly asymmetric (n>>p) : unlike usual nuclei
- Nontrivial nuclear extrapolations required

--> wide range of predictions

Observations?

- M, R relation…hard
  - [e.g., Ozel (2006)]

Lattimer and Prakash, astro-ph/0612440



Method 1: Merger waves

Tidal disruption point

Disruption terminates signal

[Faber et al PRL 89 1102f]

Not in band (f~ $f_{breakup}$ ~1000 Hz)

Golden binaries? + aLIGO

Lee and Ramirez-Ruiz 2007

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Sloshing of hypermassive transient/remnant disk

Not in band

Weak

- need implausibly close (20 Mpc)

+ aLIGO

Oechslin and Janka PRL 99 1102 (2007)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Tidal-orbit coupling Flanagan and Hinderer, PRD 75 1502 (2008)

Change **early** part of signal

Limit “Love number” : aLIGO can weakly constrain

Method 2: Supernova waves

Supernova "kicks" young NS:

- Obvious problem:
  SN rare in MW
  won't see outside MW

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

C. Ott APS 2008-04-14

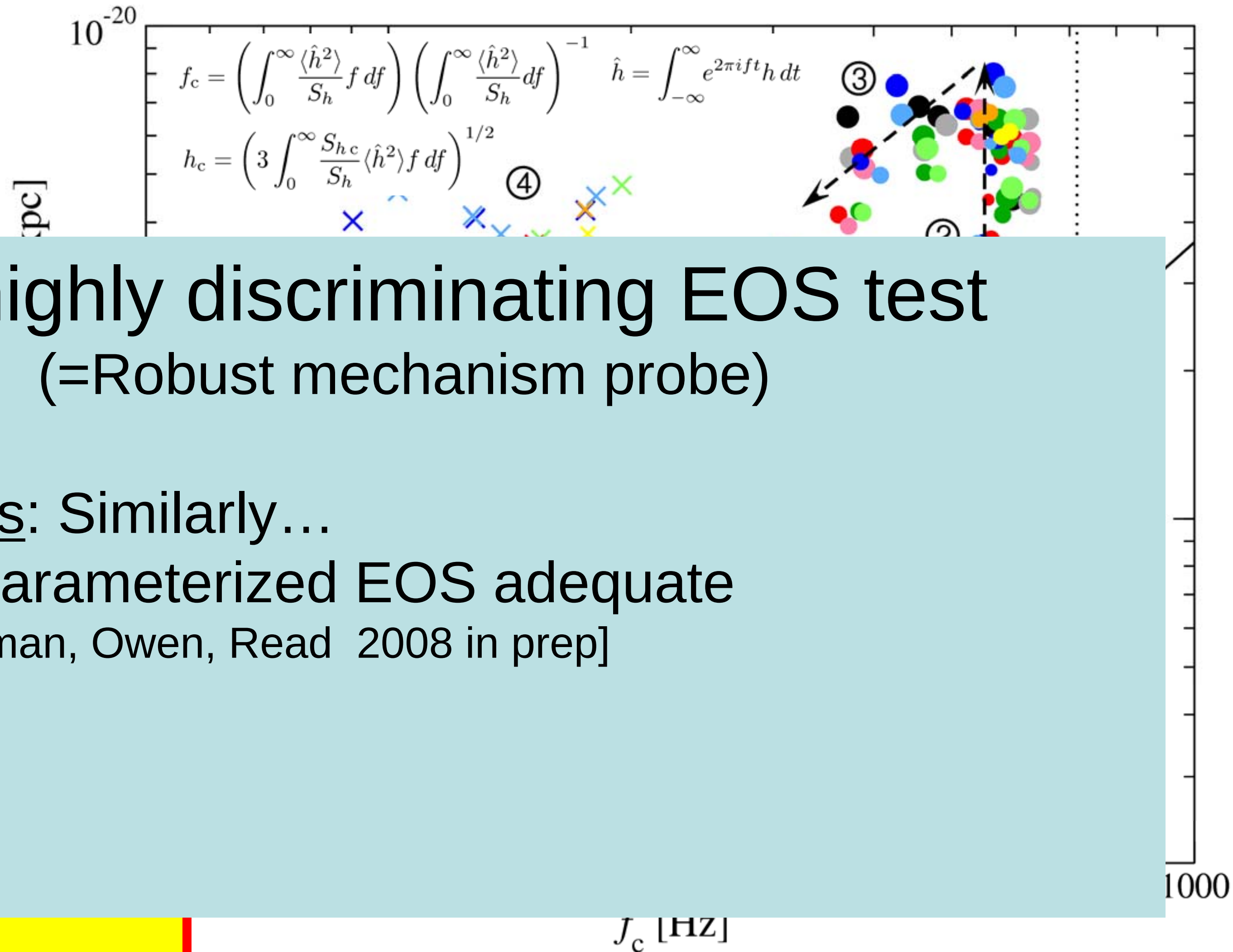
http://stellarcollapse.org/talks/Ott_APS_April_2008.pdf

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

New Extended 2D GR Model Set

[Dimmelmeier, Ott, Marek, and Janka 2008 in preparation, Dimmelmeier et al. 2007ab, Ott et al. 2007]

- >140 2D GR models with Y_e(⇧) parametrization.
- 6 presupernova mod[els]
- Slo[w] rota[tion]
- Sol[id] mo[dels] diff[erential] rota[tion]
- 2 fi[nite] nuc[lear]



Not highly discriminating EOS test

(=Robust mechanism probe)

<u>Merger waves</u>: Similarly…

- Simple parameterized EOS adequate

[Lackey, Friedman, Owen, Read 2008 in prep]

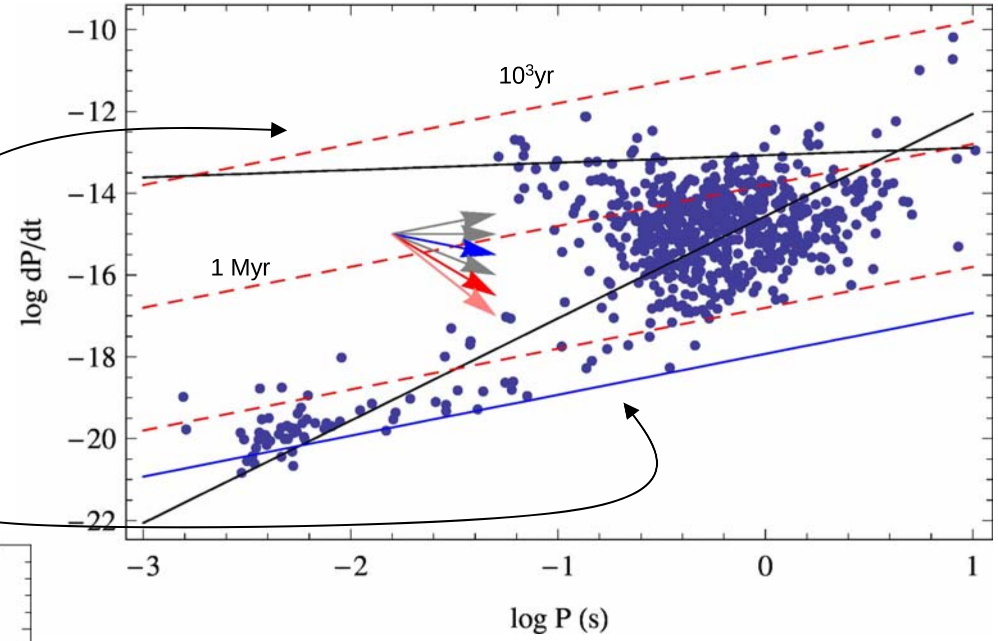
•GW s[ignal] multi-degenerate.
•Key parameters:
- Precollapse central ⩓.
- Precollapse iron-core entropy.

1) slow rotation, pressure-dominated bounce, prompt convection
2) moderately-rapid rotation, pressure-dominated bounce
3) rapid rotation, pressure-dominated, rotation-influenced bounce
4) single centrifugal bounce.

Method 3: Spindown

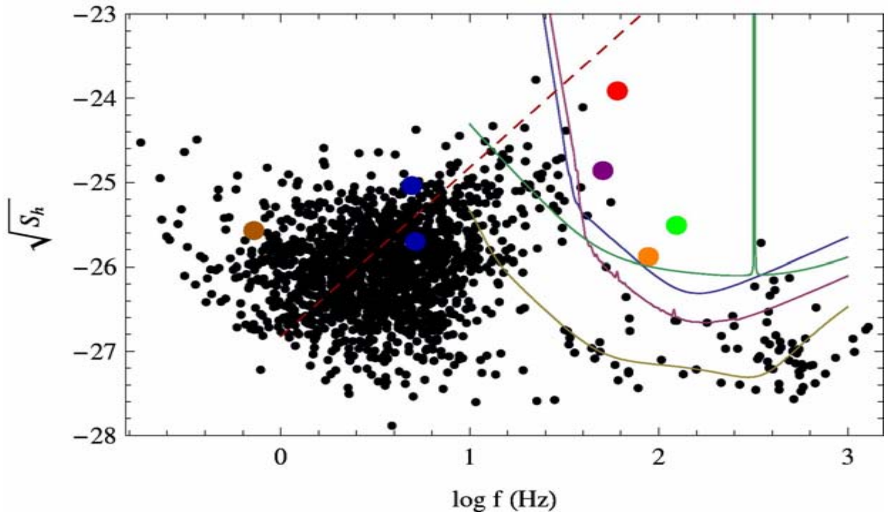
Quick pulsar review:

- Spindown diagram
  - "B" evolution
  - Recycled pulsars



lines of constant age

age of universe



GW spindown bound

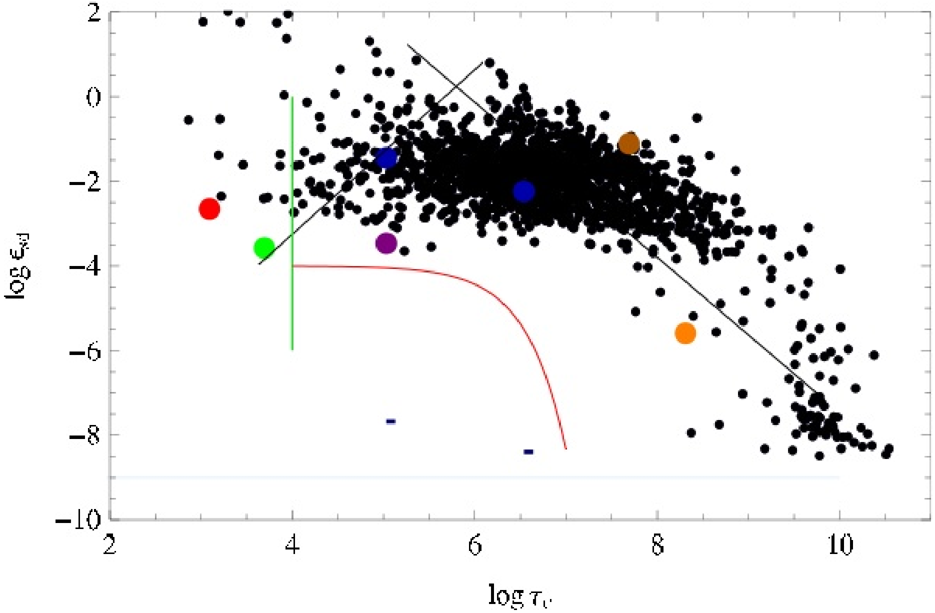
$$h_{sd} = \left(\frac{5}{2}\frac{G}{c^3}\frac{I_{zz}}{r^2 2\tau_c}\right)^{1/2}$$

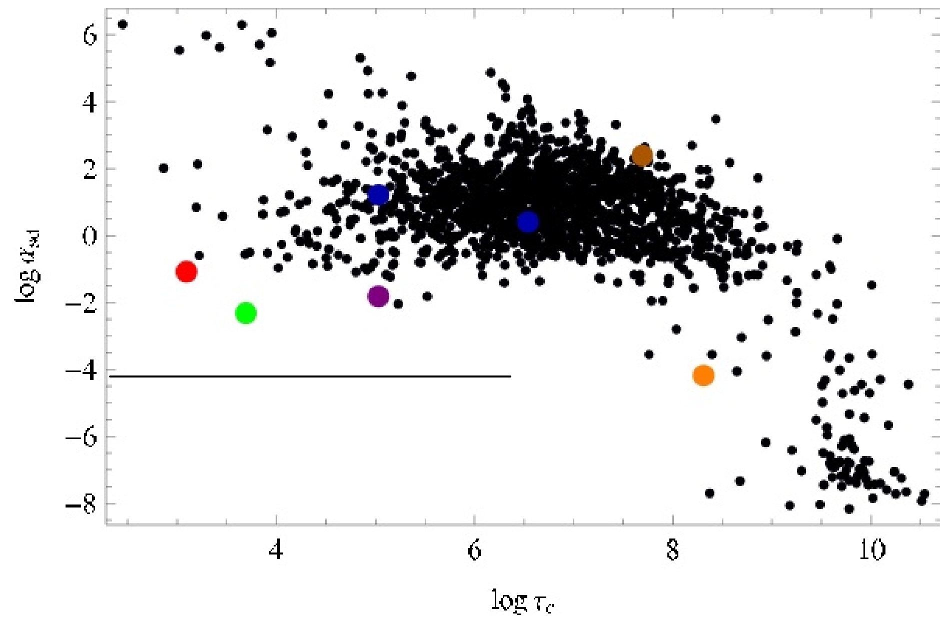
- Ellipticity bounds

$$\epsilon_{sd} = \sqrt{\frac{5}{32}\frac{c^5}{G}\frac{1}{I_{zz}}\frac{(-\dot{\Omega})}{\Omega^5}}$$

Method 3: Spindown

Spindown limit on mountains, r-modes





Spindown limits

Mountains

<u>can</u> rule out long-lived "large" ellipticity

<u>can't</u> rule out decaying "large" ellipticity

(e.g., viscoelastic; annealing; …)

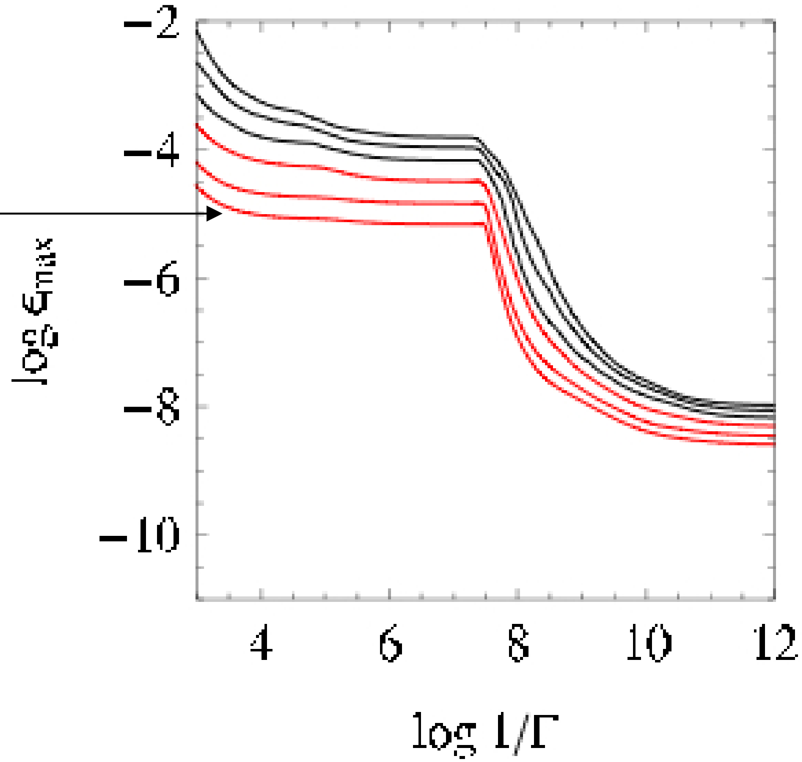
…don't forget:
mountain **distribution**
(EOS != guarantee!)

O'Shaughnessy and Owen, in preparation

Method 3: Spindown

aLIGO improvements

90% confidence
(if no detections)



Mountains:

Sensitive to "large"
mountains on young pulsars
at 10^{-5}

R-modes:

Sensitive to ~ (few)x10^{-2}

Close to parametric instability threshold

[Bondarescu et al 2008]

O'Shaughnessy and Owen, in preparation

And more!

Accreting NS:

- Why are spins not near breakup? [Bildsten]
  - R-modes? Mountains?
- Are modes excited by accretion and flares?

Bursty NS:

- Magnetar bursts excite internal modes?

  SGR1806-20 : observed oscillations
- NS “glitches”

3: How do stars evolve?

Complex

- Outline of (typical) evolution:
  - Evolve and **expand**
  - Mass transfer (perhaps)
  - Supernovae #1
  - Mass transfer (perhaps)
  - Supernovae #2

Note

•Massive stars evolve faster
•Most massive stars supernova, form BHs/NSs
•Mass transfer changes evolutionary path of star

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Movie: John Rowe

Why a challenge?

Lots of unknown physics inputs

1. “Supernova kicks”

   Pulsar tranverse velocities require

   Observed distribution used

2. Wind mass loss

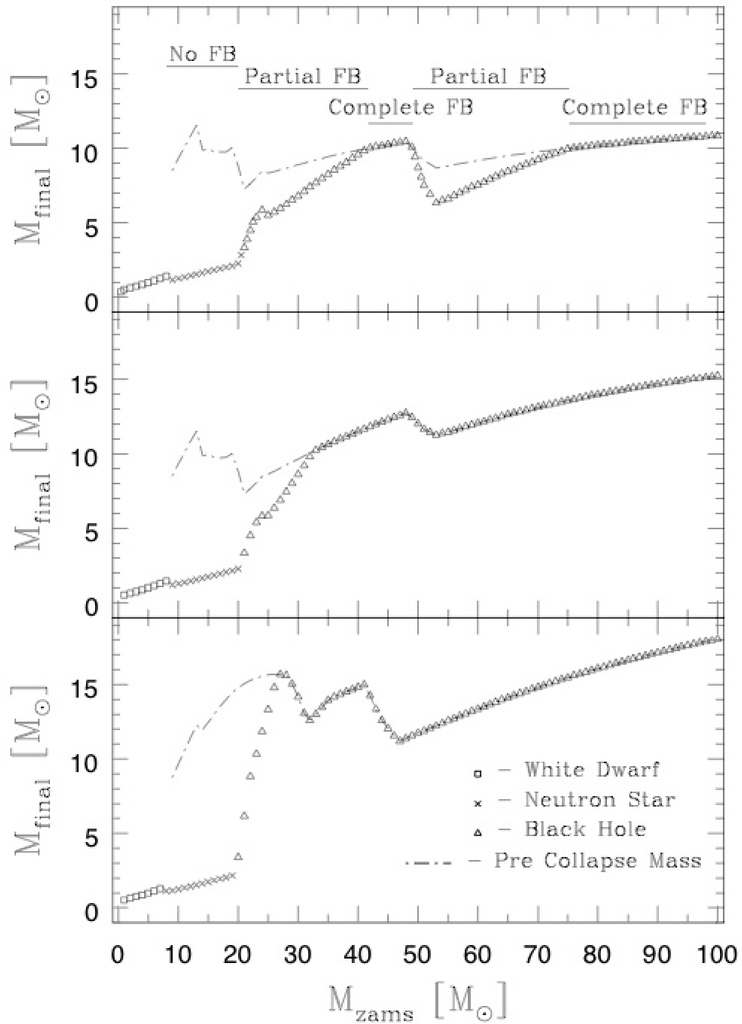
   Massive stars hard to observe

   Sets mass of final BH

   Recent observations : suggest preferred value

   Bulik et al 2008;

   Orosz et al



Belczynski et al 2002

Many parameters (like this)

change results by **x10** (each!)

Not one answer but many…

Distribution of results

Find subvolume

to match obervations?

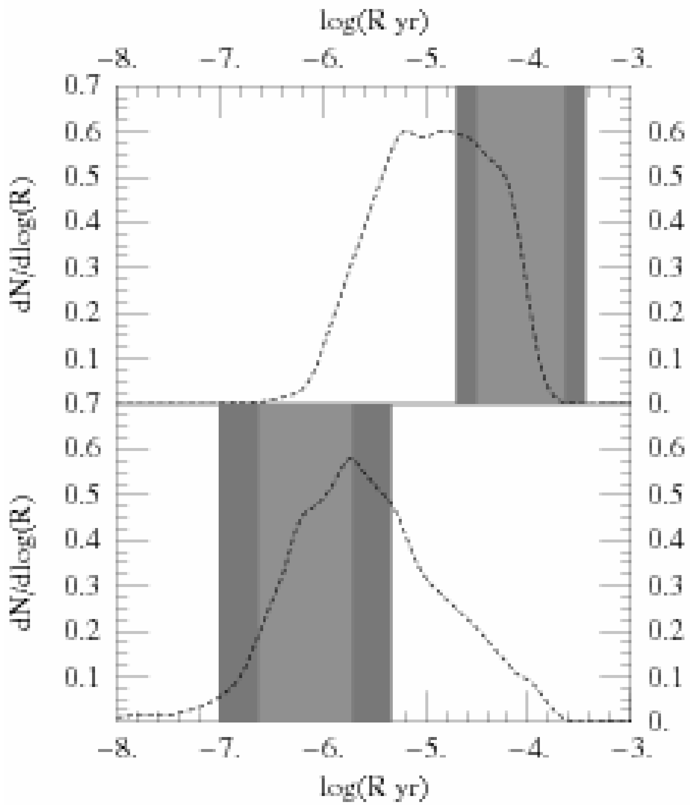
Computational challenge

- O(weeks/CPU) per model
  - Longer if more info needed
    (e.g., mass, spin distributions)

- Practical balance:
  - Explore (~ 7d) space
  - Know predictions of any model

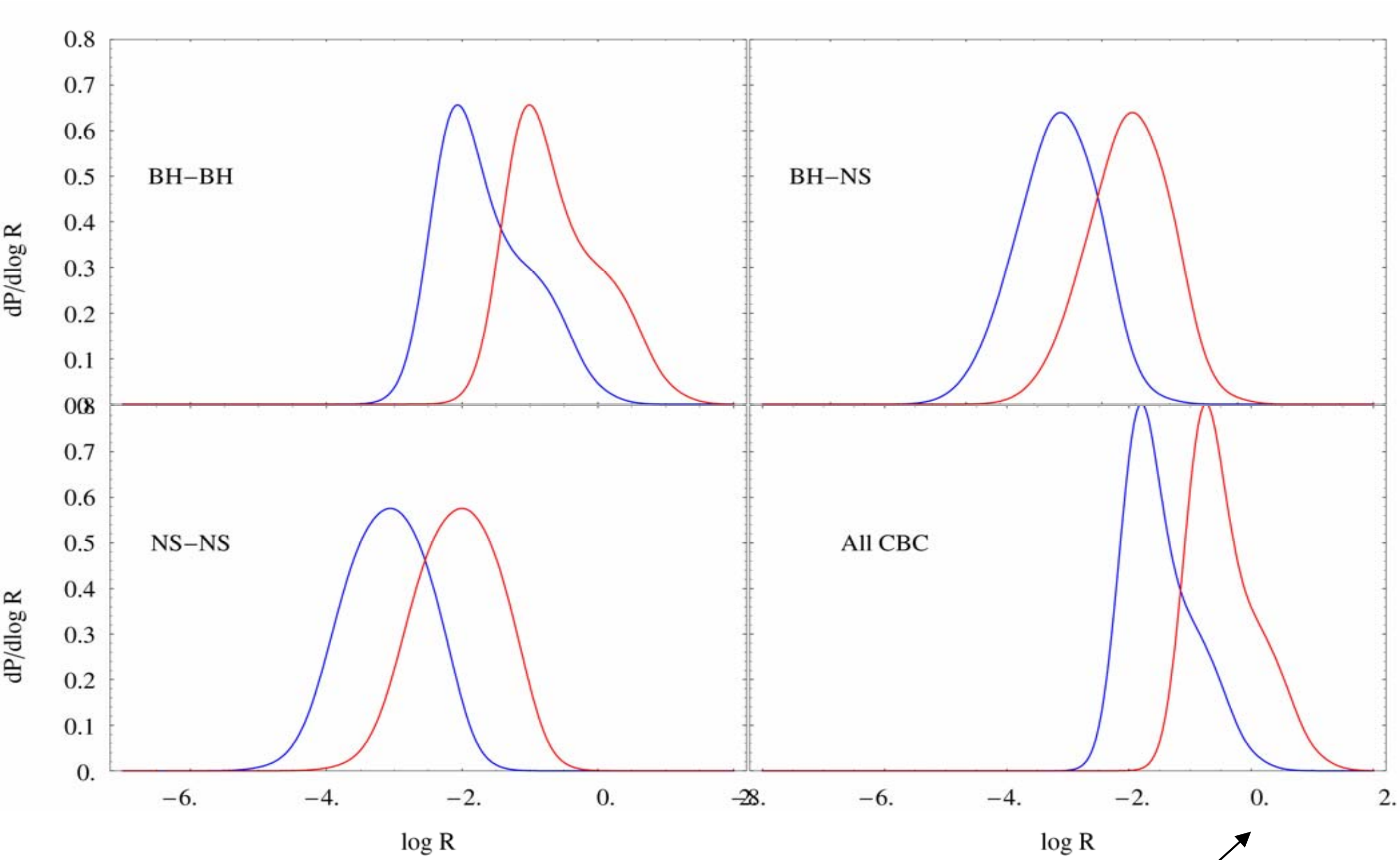
: we estimate detection rates

O'Shaughnessy et al 2005,2007,2008



Plot
Merging (top), wide (bottom
NS-NS binaries

Best estimates for detection rates



Key

Blue : D_{bns} =15 Mpc

Red : D_{bns} =27 Mpc

One detection/year

O'Shaughnessy et al in prep

How much will LIGO help?

Information extracted about rate depends on rate

Case 1: No detections: (eLIGO)

"Information" =p= prior probability of no detections

Detection rate PDF
(w/ preferred range)

Detection rate
(based on $D_{bns,0}$)

Range to BNS

Observation time

$$P_{\rm detect}(D_{bns}, T) = \int d\log R_D \, p(\log R_D) \times \left[1 - \exp\left(-R_D\left(\frac{D_{bns}}{D_{bns,0}}\right)^3 T\right)\right]$$

$$P_{\rm detect} = 0.34 + 0.64 \log \frac{VT}{V_c {\rm yr}}$$

Rare exceptional models much less plausible
Others biased against slightly

How much will LIGO help

Case 2: Most likely detection rate (aLIGO)

R= 27/yr : $\frac{dN}{dtdV} \simeq \frac{10^{-6}}{\text{Mpc}^3\text{yr}}$ + D_{bns}~ 169 Mpc [Shoemaker LSC 3-08]

$$\sigma_{before} \simeq 0.5$$

$$\sigma_{after} \simeq 1/\sqrt{27}\ln 10$$

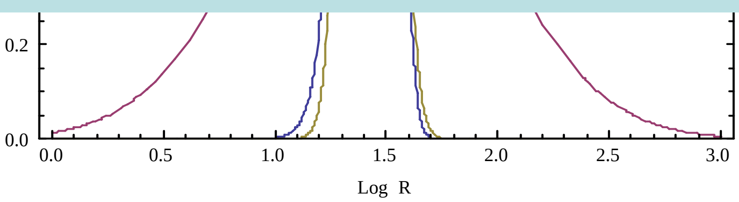
x 3

20% !

Better than relevant astrophysical uncertainties!

- Galaxy catalog
- Star formation uncertainties
- Inhomogeneous metallicities

Limit may require more GR model accuracy (moderate M_{bh})



Plus: Mass distribution of mergers (wind, CE)

Spin orientations of mergers (kicks)

(information extraction: **under development**)

What might we learn?: EXAMPLE

Parameter distributions

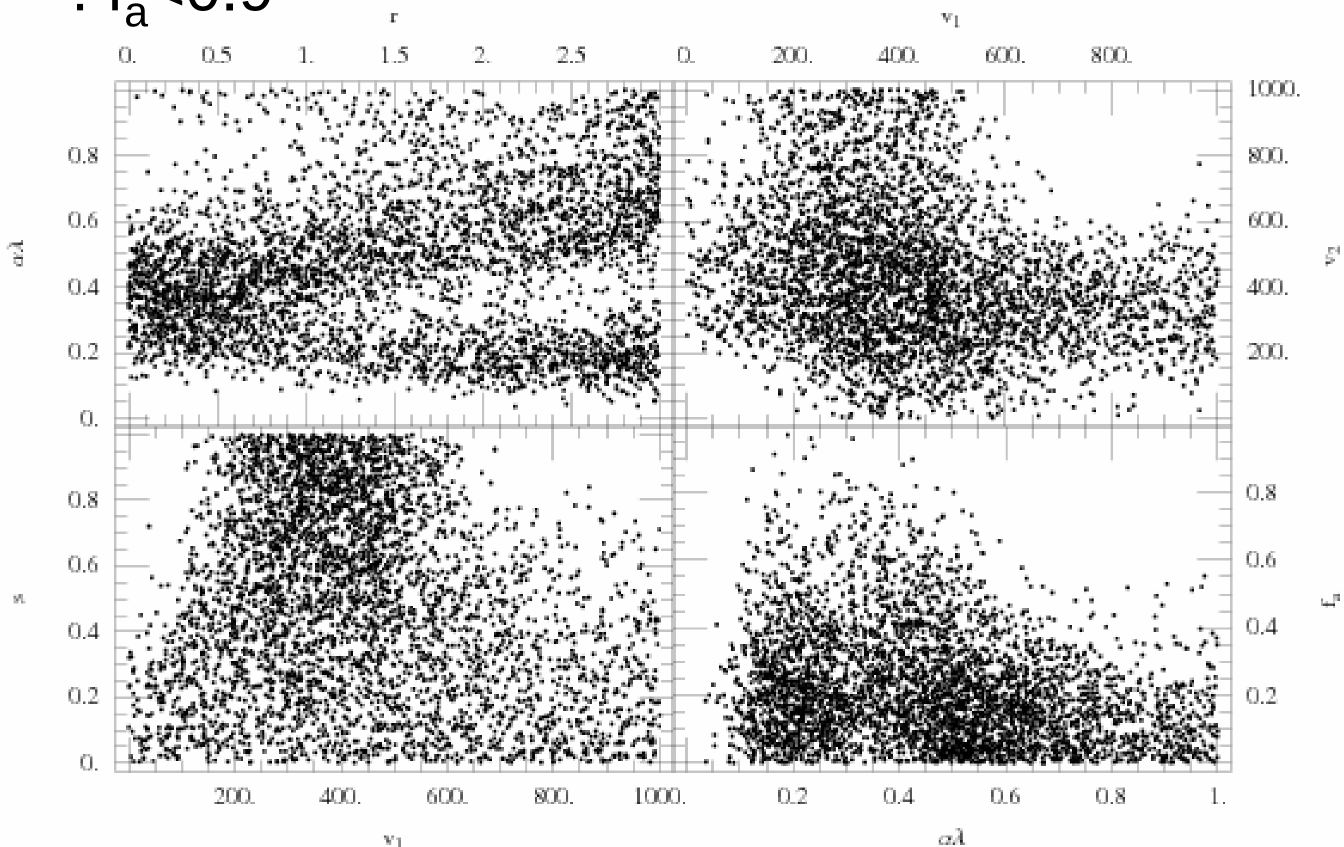
- Not all parameter combinations allowed

Examples:

- – Kick strength: v_1,v_2~ 300 km/s
- – CE efficiency: $\alpha\lambda$>0.1
- – Mass loss : f_a<0.9

Lots of physics in correlations

<u>Example</u>:
Reproducing Milky Way NS binaries



Conclusions

GW enable unique astrophysics

- Reveals the endpoint of the life of massive stars
  - How they get there
  - What they're like (NS, BH)
  - What happens when two collide
- Tells us about hard problems
  - Nuclear matter
  - Supernova (kicks via rates, waves, …)

Theoretical challenges

Models already (GC)/will soon (others) lag observations

Challenge I : <u>more concrete predictions</u> relevant to <u>what observables are accessible</u>

Challenge II: "Big picture" -- cross-correlate LIGO w/ other astro observables, models

It helps to have friends…

Outside information (triggers, etc) improves reach

Complement existing constraints

Ellipticity vs NS mass-radius constraints

Extragalactic young clusters ("infant mortality")

NS population: Mass spectrum, binarity, extreme masses

Short GRBs: rates, subpopulations (?), hosts, ….

4: Star formation in clusters (*)

Clusters are important…

- Much of SFR : Fall & Zhang
- Cluster mass distribution flat in log…
- Lots of mass formed in high-mass, high-density regions…

…but they don’t stick around

- Infant mortality : lots go away
- Long term tidal disruption

…very weak theory constraints

- What can happen?

What happens in dense clusters?

Point particle model

- Contraction and segregation, binary burning, core collapse

  Still finding surprises now!

  - Full Nbody slow for binaries (timescales)
  - Approximate codes just getting full few-body numerical collisions

  Fregeau; Freitag; Portegies Zwart; McMillan; Sigurdsson; Hut; Heggie; Aarseth;…

+ Stellar evolution

- Supernovae and Density switch:
  - Runaway collisions -> IMBH? [Gurkan; Fregeau; Freitag; …]
  - **BH segregated subcluster?**
- Size changes and full evolution

…*very* early stage [Ivanova; PZ & “MUSE”; Fregeau…]

} suggest high rates

+ “Initial conditions” - gas dynamics, IMF, …

…ideas being proposed…early…

What processes can LIGO see? (*)

Stellar mass BHs from subcluster

- Runaway mergers?
  - Nope, GR kicks
- Ejected mergers?
  - Evaporating segregated cluster
- Parabolic encounters?

What processes can LIGO see? (*)

IMBH binaries

- Formation: Runaway collisions
- Drive close via stars -- merge quickly

IMBH-stellar mass captures [Mandel Brown Gair Miller]

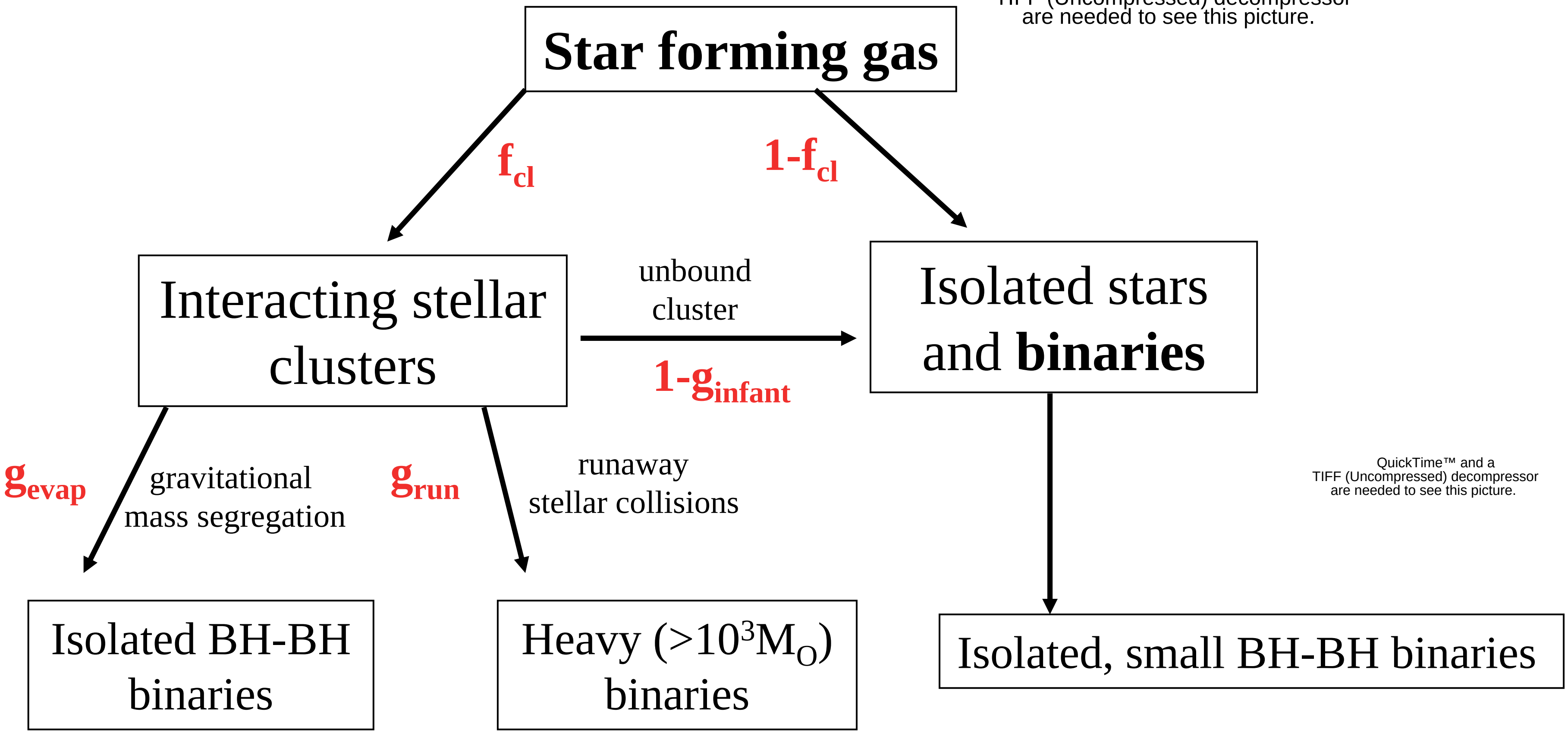
- Optimistic: IMBH growth by mergers ~ few/cluster/Gyr
- aLIGO : 1/few yrs?

Binary mergers: Big picture

Constrain "branching ratios"

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

<u>References include</u>
- O'Leary, O'Shaughnessy, Rasio PRD 76 061504 (2005)
  O'Leary et al astro-ph/0508224

<u>References include</u>
- Fregeau et al astro-ph/0605732

<u>References include</u>
- Belczynski, Kalogera, Bulik 2002
- O'Shaughnessy et al. in prep

+ astro-ph/0610076; 0609465; 0504479

Binary mergers: Big picture

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Constrain channel details:

Different mass distributions

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

gravitational mass segregation

runaway stellar collisions

Isolated stars and **binaries**

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Isolated BH-BH binaries

Heavy (>$10^3 M_O$) binaries

Isolated, small BH-BH binaries