Precessing binaries:
Selection biases and astrophysics

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2010-12-03 UWM

High mass: D. Shoemaker, J. Healy, B. Vaishnav, arXiv:1007.4213
Low mass: D. Brown, A. Lundgren in prep

Outline

- Motivation: Selection biases in GW astrophysics
  - Practical context: Distinguish formation channels …
    with low-statistics, low-amplitude inferences
  - Injections vs analysis: Galactic pulsars as example

- Spin and waveforms by example: BH-NS binaries
  - Kinematics, waveforms with precession
  - Intrinsic vs search-dependent selection biases

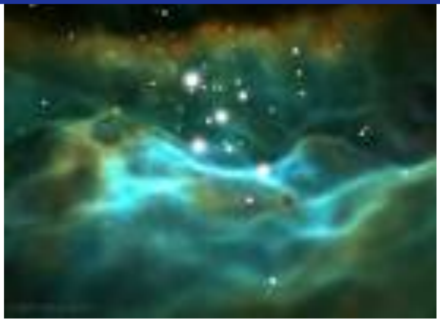
- High mass mergers (IMBH-IMBH binaries)
  - Practical context: GW signal (large spin effects) & Astrophysics (random spins)
  - Averaging vs rare aligned spins

- Low-mass precessing BH-BH ($M_{tot} < 15 M_\odot$)
  - Practical context: L dominated; aligned-spin-sensitive searches
  - Mismatch for standard vs "extended" searches

- Low-mass precessing BH-NS ($M_{tot} < 15 M_\odot$)
  - Practical context: Large misalignments, high rate, bias astrophysically useful
  - "Lighthouse model": separation of timescales
- Selection biases for astrophysics:
  - Options: analytic; zero-noise "bank simulation"; real injections?

Sources of compact binaries

Constrain “branching ratios”



Star forming gas

f_{cl}

$1-f_{cl}$

Interacting stellar clusters

unbound cluster

$1-g_{infant}$

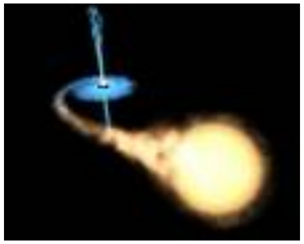
Isolated stars and **binaries**

g_{evap}

gravitational mass segregation

g_{run}

runaway stellar collisions



Isolated BH-BH binaries

Heavy ($>10^3 M_O$) Binaries or IMRI captures

Isolated, small compact binaries

References include

- O’Leary et al astro-ph/0701887
  O’Leary et al astro-ph/0508224
  Sadowski et al arXiv:0710.0878

References include

- Fregeau et al astro-ph/0605732
- A. Seone et al CQG 24, 113 (2007)
- Mandel arXiv:0707.0711

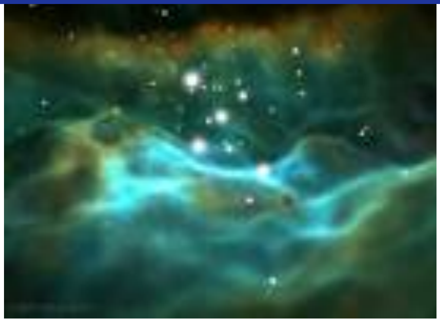
References include

- Belczynski, Kalogera, Bulik 2002
- O’ Shaughnessy et al. 0908.3635; astro-ph/0610076; 0609465; 0504479

Sources of compact binaries

Constrain channel details:

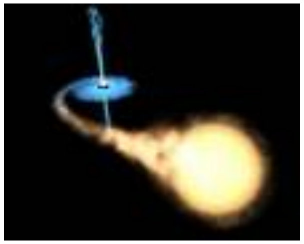
Different mass distributions



gravitational
mass segregation

runaway
stellar collisions

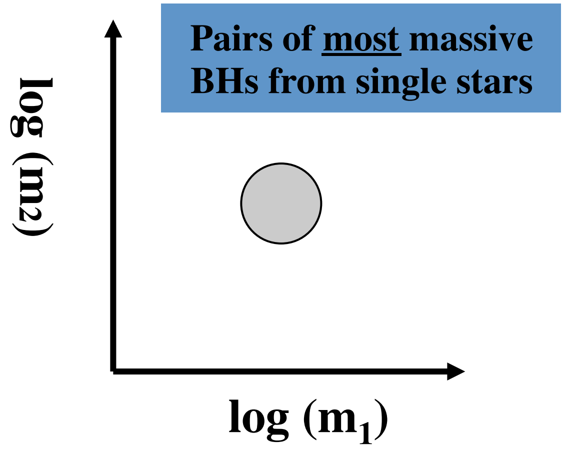
Isolated stars and **binaries**



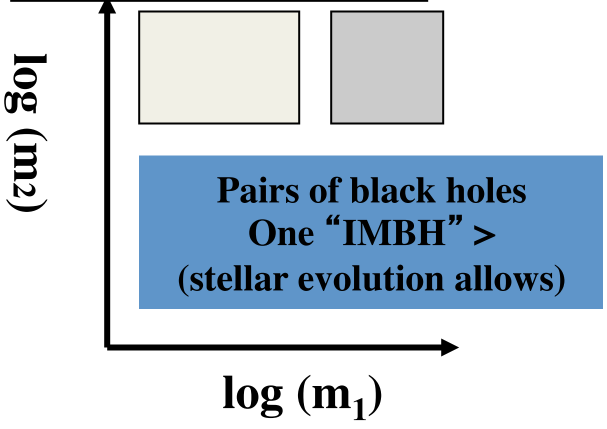
Isolated BH-BH binaries

Heavy ($>10^3 M_O$) binaries + IMRI captures

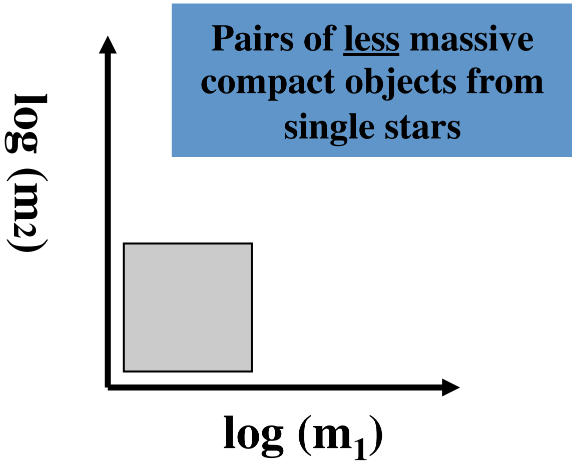
Isolated, small BH, NS binaries



Pairs of most massive BHs from single stars



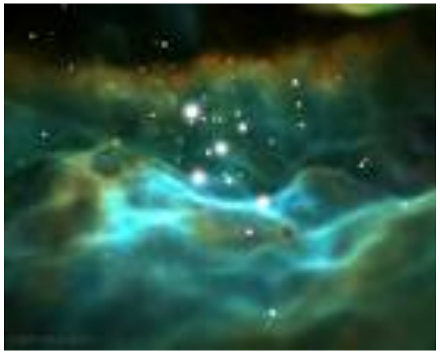
Pairs of black holes One “IMBH” > (stellar evolution allows)



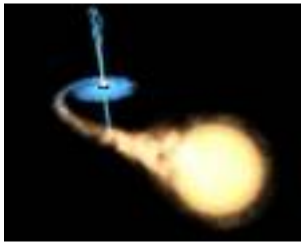
Pairs of less massive compact objects from single stars

Sources of compact binaries

Constrain channel details:
Different spin-orbit **alignment**



Star forming gas



Isolated binaries
Aligned spins

Small residual misalignment
<-> SN kick strength

What we want [right=reconstructible bias]

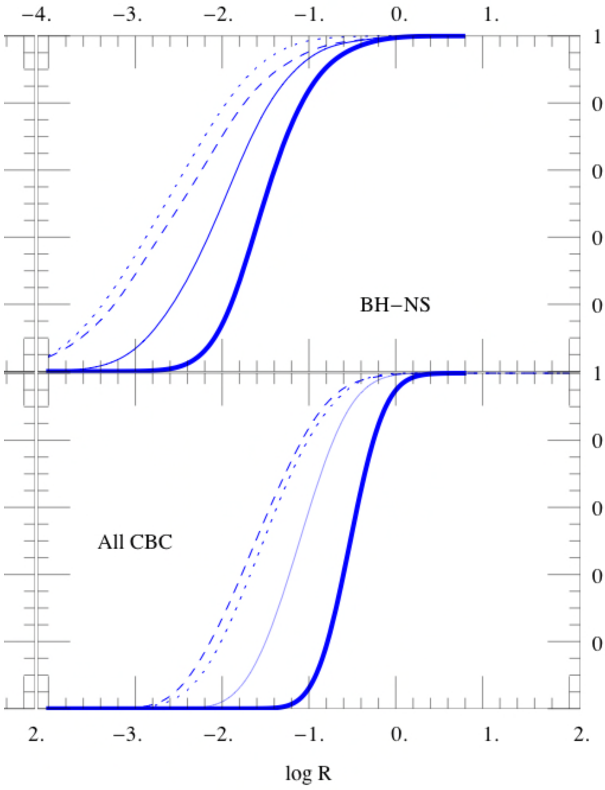
1) "right #" of sources
2) "right" masses
3) "right" spin-orbit distribution

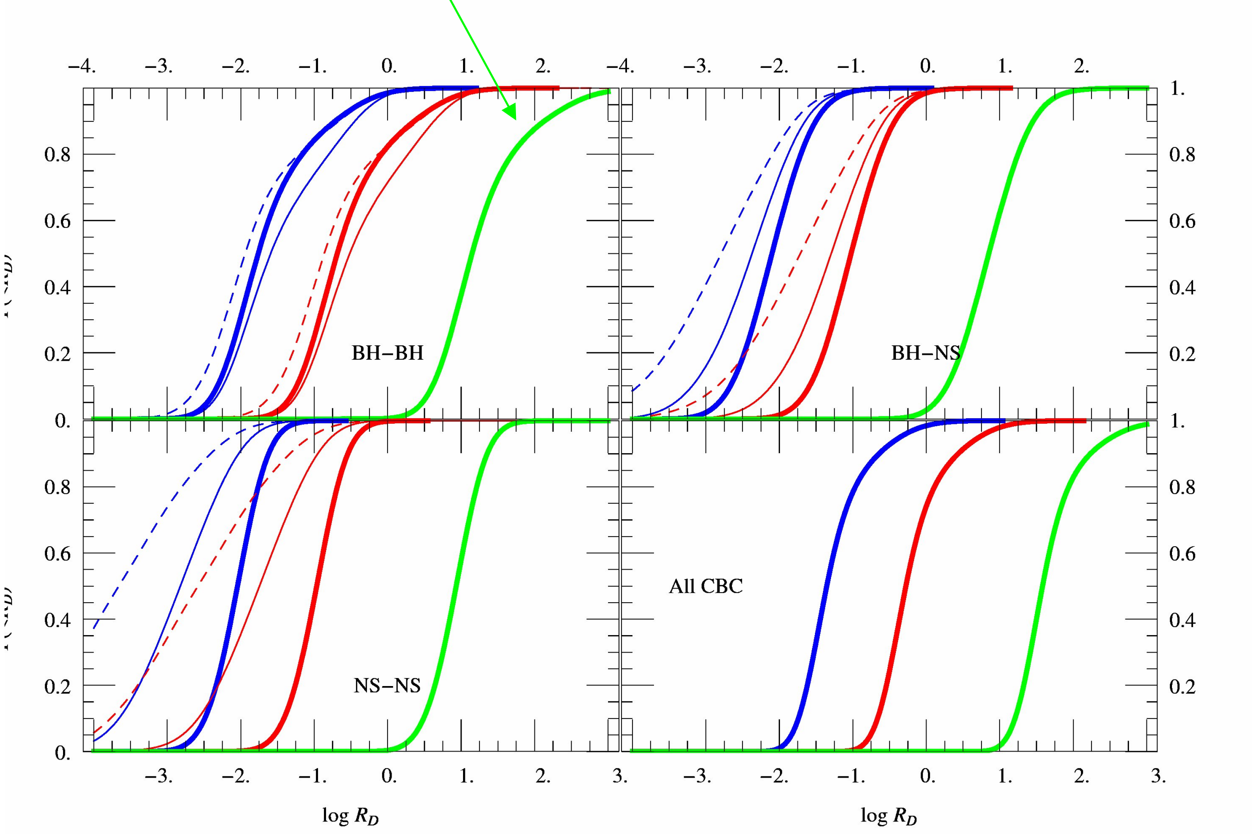
Interacting clusters' BH binaries (all masses)
Random spin alignment

Only a few detections to work with…

Birthrate reconstruction:
Intrinsic (poisson) error, **best case:** 1/ sqrt(N) > O(10%)

Focus on large biases!





log (rate*Myr), single detector

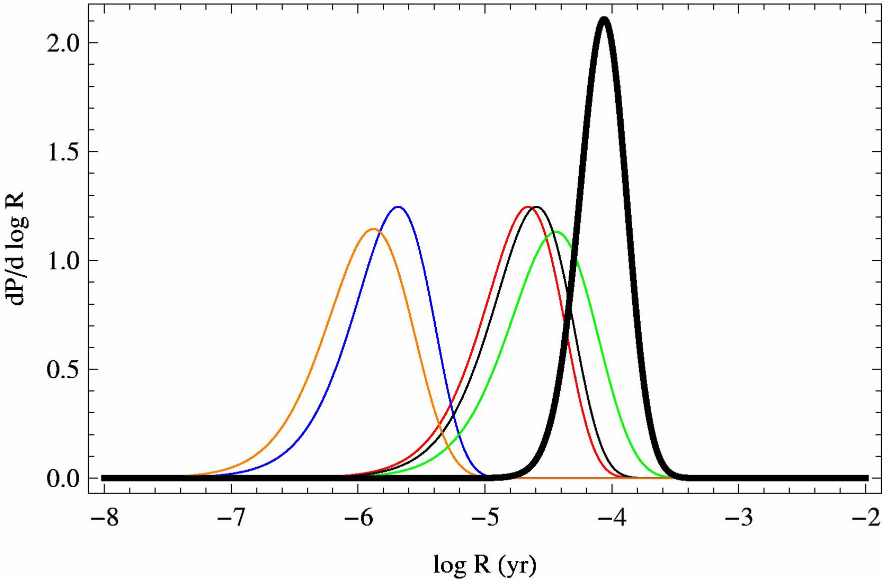
Injections vs analysis: Galactic PSRs

Galactic pulsar-NS birthrate:

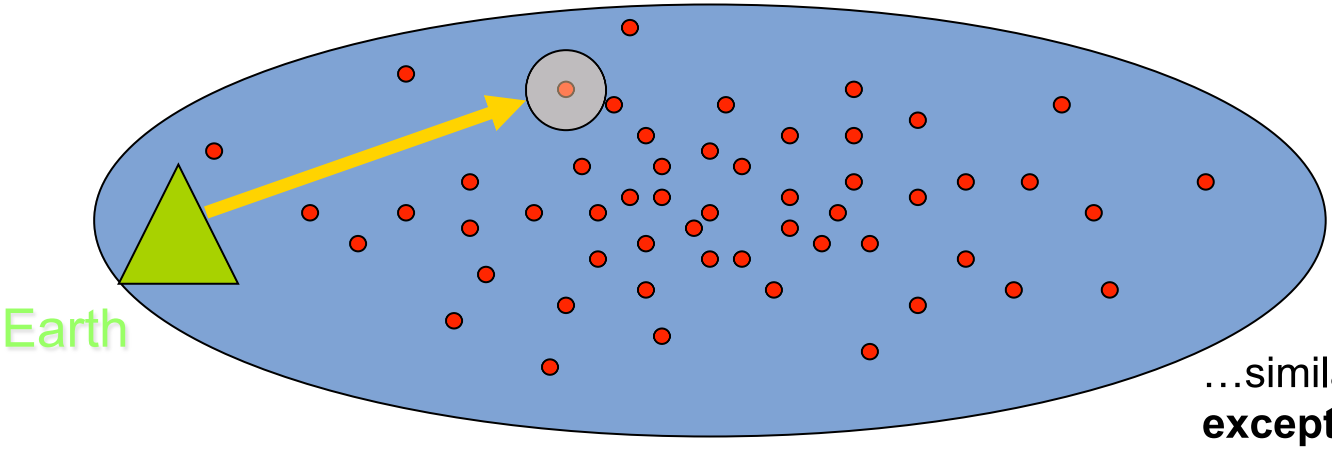
- Synthetic population:
  - Assume pulsar spin, beaming
  - Draw from luminosity, position distribution
  - Predict # seen in surveys vs # available

    (via sky brightness, distance, sky coverage, …

- Reconstruct # available from # seen



- Reconstruct birthrate



NS-NS merger rate in Milky Way
ROS and Kim, ApJ 715 230 (2010)
Kim et al ApJ 584 985 (2003)
Kim et al astro-ph/0608280
Kim et al ASPC 328 261 (2005)
Kim et al ApJ 614 137 (2004)

…similarly for GW sources, **except** only LSC can inject. Different populations/assumptions?

Injections vs analysis: Analysis?

Disadvantages: Analysis: = approximate

- Hard/impossible to capture all complexity
  (nonstationary detector noise & environment, analysis approximations; complex pipelines)
- Can't use for *high-precision* result

…but

- not much precision possible with few detections at low SNR

…and

Disadvantages: Injections

- Real-world complexity & computation-limited # can **obfuscate reasons for missed vs found**

  Unsatisfying astrophysical data product

Advantages: Analysis

- Understand which parameters missed & why
- *For real results:* Tools to interpret injections, understand biases
- *For astrophysicists:* **"Adequate" (?)** models for selection biases, reinterpreting results

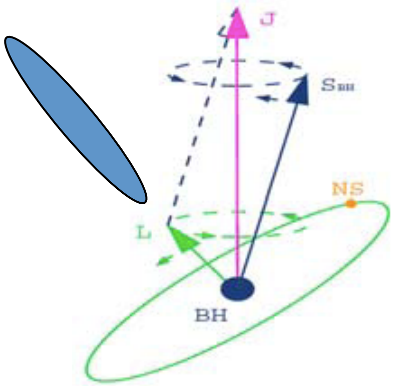
Spin and waveforms

Generic precession:

Misaligned binaries precess [ACST]

$$\partial_t X = \Omega_X \times X \qquad X = S_{1,2}, L$$

…often around nearly-constant **J** direction



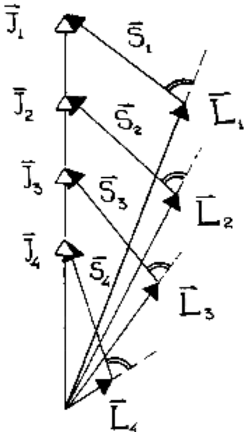
(Leading order): Propagation of L modulates waveform

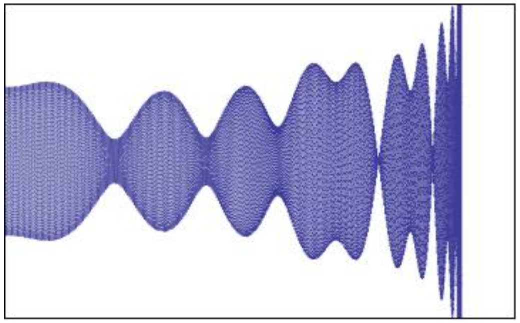
J loss decreases L:

More spin-dominated

More “freedom” for L at late times…

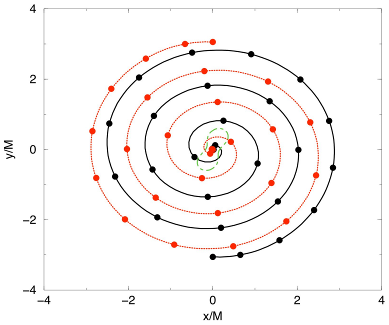
less freedom early on

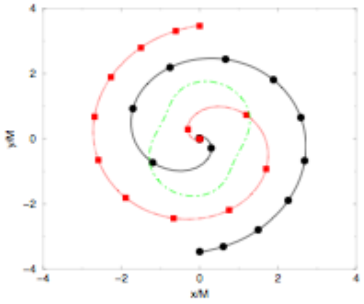




Other spin effect: Duration (=SNR,amplitude)

Angular momentum “barrier”, more emission





Two kinds of bias: Inspiral example

Intrinsic bias

Single event:

One line of sight: "Louder"/ "quieter" signal along line of sight

Biases for/against some directions (=modulations!)

Overall: Energy conservation limits increase

Larger detection volume ~ requires larger dE/df <->

large kinematic effect <-> duration change; aligned spins

Population: #, distribution bias is ~ kinematics (<-> spin-orbit coupling) [almost true]

Search bias: (here, template mismatch w/ nonspinning; χ^2 studies underway)

Single event:

Modulations (and/or secular) not fit by search model

Highly line of sight dependent, search dependent

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High-mass mergers

Physical scenario:

Cluster: Runaway collisions -> supermassive stars-> two IMBHs -> merger (dynamical friction)

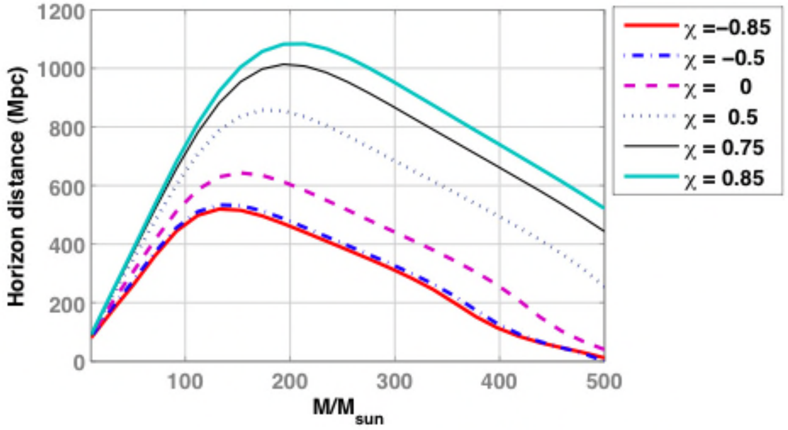
Short waveform: No templates; study “intrinsic” bias

Spin effects huge, *if* aligned:

Range increases strongly with “average aligned spin”

Random spins: as if no spin (*on average*, to range)

…**but** two large, aligned spins are **rare**



Range vs aligned spin:

Ajith et al : 0909.2867
Santamaria et al : 1005.3306
Reisswig et al : 0907.0462

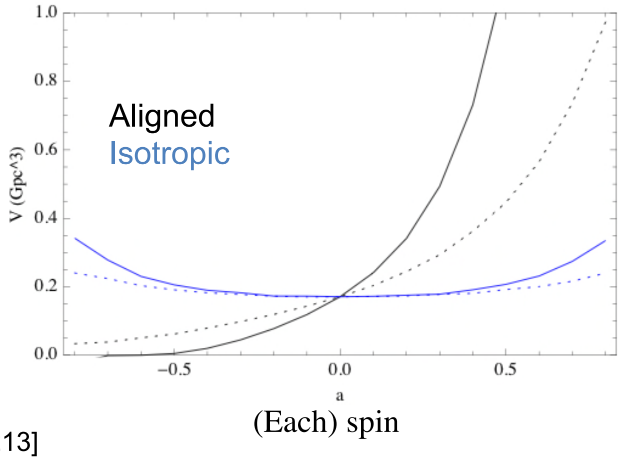
Astrophysics: Detection volume for generic spins

- Method: Fit SNR vs spin vectors. Volume ~ SNR^3,

$$\begin{aligned} V(S_1,S_2) &\propto \bar{\rho}_0^3[1+3\mathcal{X}_1(\chi_+\cdot\hat{z})+3(\mathcal{X}_1^2+\mathcal{X}_2)(\chi_+\cdot\hat{z})^2 \\ &+ 3\mathcal{X}_{02}(P\chi_+)^2+O(\chi^3)]\,. \end{aligned}$$

- Result: suppress linear-order term in *average* volume

$$\begin{aligned} \langle V(S_1,S_2)\rangle &\propto \bar{\rho}_0^3[1+3(\mathcal{X}_1^2+\mathcal{X}_2)\left\langle(\chi_+\cdot\hat{z})^2\right\rangle \\ &+ 3\mathcal{X}_{02}\left\langle(P\chi_+)^2\right\rangle+O(\chi^3)]\,. \end{aligned}$$



ROS et al: PRD 82 4006 (2010) [1007.4213]

Low-mass BH-BH Mergers

Physical scenario:

Origin: Isolated evolution (only at low mass)

Misalignment: SN kick produces (weak) misalignment; suppressed by BH inertia

Birth spin: large?

Precession amplitude:

In LIGO band, **J** dominated by **L** – precession amplitude small, *no matter what*

Aligned case: Fixable:

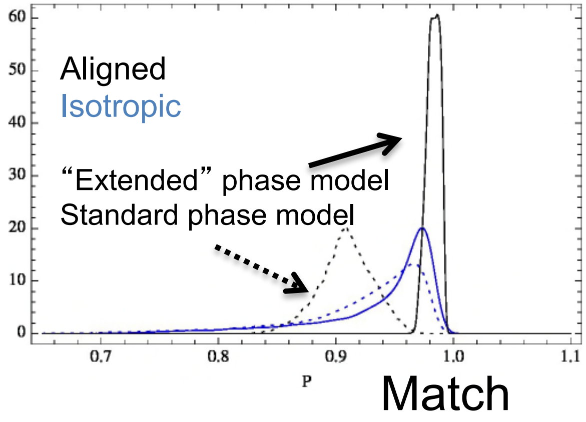
Intrinsic (range) bias: increases slightly (O(10%)) with “average aligned spin”

longer duration; predictable

Mismatch: Phase not like **standard** nonspinning templates…but fixable:

Extend mass ratio to “unphysical” (match > 0.95) : no new parameters!

Add “spin terms”, as high-mass phenomenological



…to astrophysical accuracy, **BH-BH searches are “good enough”** (if extended) for what we are **likely to see** (most of the time)…and **predictable**

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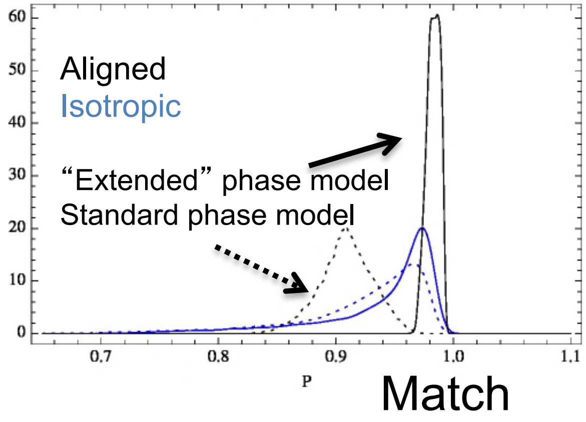
Generic spins:

Intrinsic (range) bias: Same formula (vs in-band spins)…some spread, but <u>unbiased</u>

Mismatch: Worse typical fits…but not many more

…worst cases are less likely to be seen (low amplitude)



…to astrophysical accuracy, **BH-BH searches are "good enough"** (if extended)
for what we are **likely to see** (most of the time)…and **predictable**

Low-mass BH-NS Mergers

Physical scenario:

Origin: Isolated evolution (say)

Misalignment: SN kick on 2nd-born NS produces misalignment

Valuable probe of SN kick strength!

Precession amplitude:

Depending on masses, spins, L or S can dominate

Understanding emission: Lighthouse model

- *Steady cone:* in-band,(very) simple precession
  - fixed opening angle
  - Transitional precession rare (<10% of time)

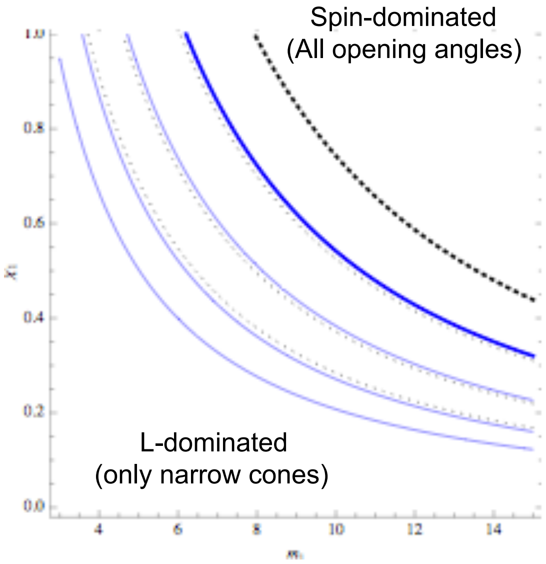
    […and transitional precession is *easier* to match!]

- *Polarized "lighthouse" (l=|m|=2) emission:*

  ~ circular on axis

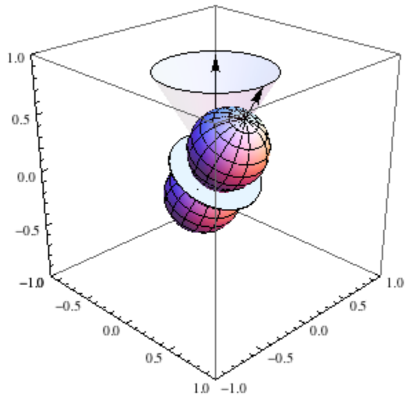
  ~ linear in orbital plane

BH-NS: Dominant part of J (vs m, S)



Spin-dominated (All opening angles)

L-dominated (only narrow cones)



Precession: modulated wave

Secular part:

- phase:
  - chirps, but at different rate
  - **depends on line of sight**
  - (somewhat)

Modulating part:

- magnitude depends on **opening cone only,** not mass, spin (once cone known)
  - good approx: **precession cone opens slowly**
  - model:
    - **complex** (fourier) **amplitude** z
- usually several cycles in band
  - number depends on mass, spin, NOT geometry

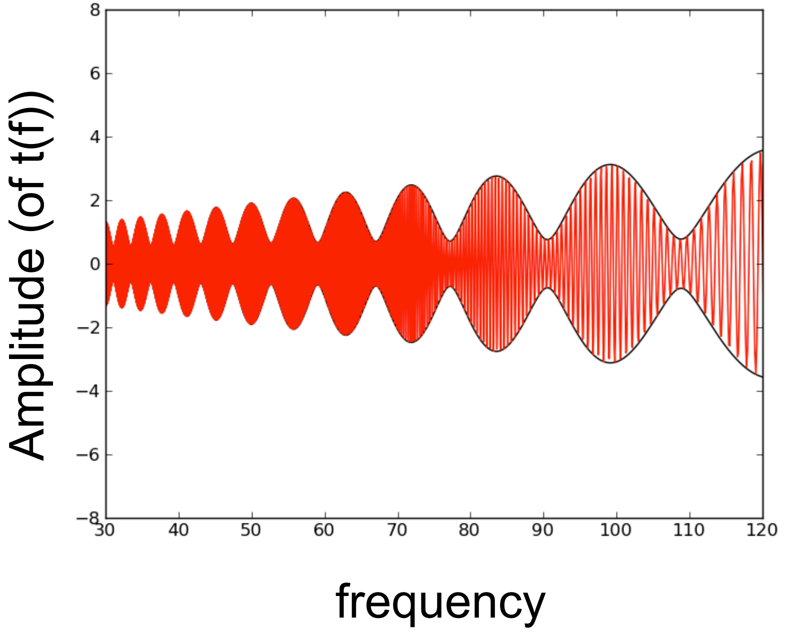
Separation of timescales:

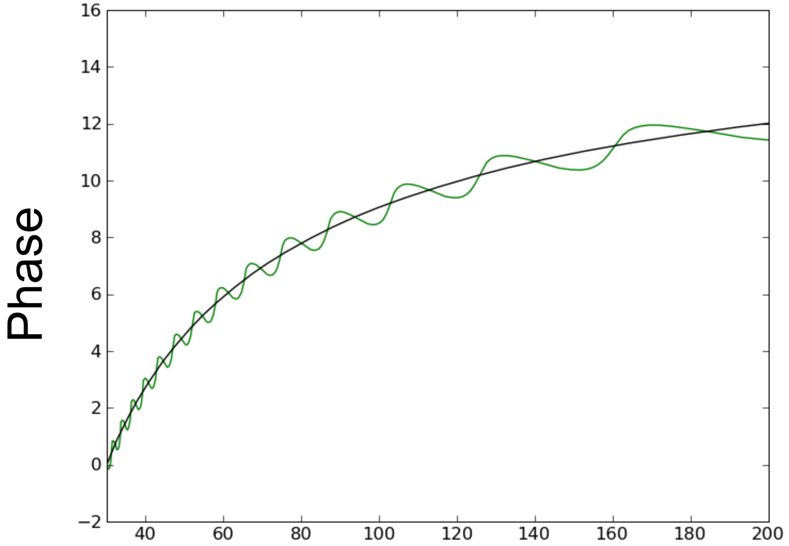
…+ use LIGO-like detectors (relatively) narrowband

-> a) ignore increasing opening angle (usually suppressed below radiation time)

b) average SNR across the lighthouse

c) factor overlap: masses, geometry





Physically separable coordinates

Intrinsic parameters:

What: Masses and $P_J S_{1,2}$

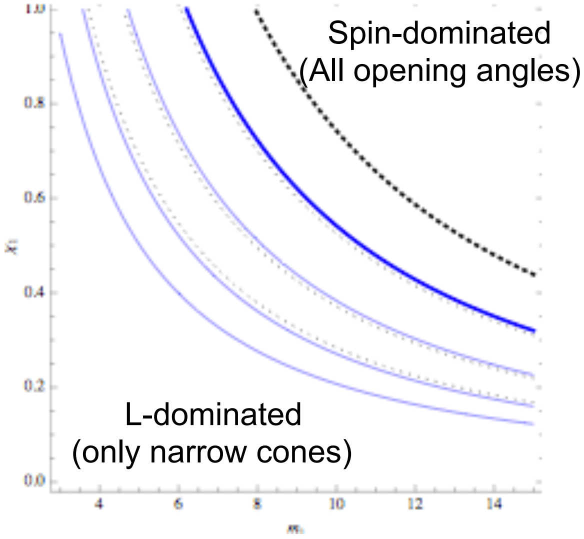
(aligned component of spin)

Why: Determine orbital kinematics (# of cycles)

Determine if L or S dominated in band →

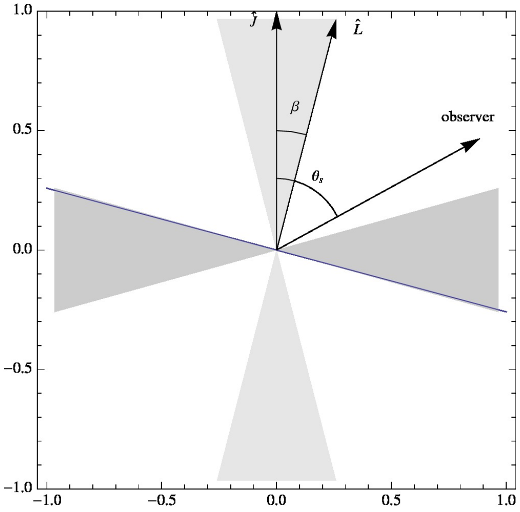
degree to which cone can open

BH-NS: Dominant part of J (vs m, S)



(In-band) extrinsic parameters:

- Orientation of **J** (ψ_J, θ_s)
- Opening angle of cone (β)
- ..+ usual (tc,phic)



- Comments
  - **Least-favorable orientation:**
    orbital plane vs line of sight; divides into 3 regions

Precession vs nonspinning searches

Nonspinning searches:

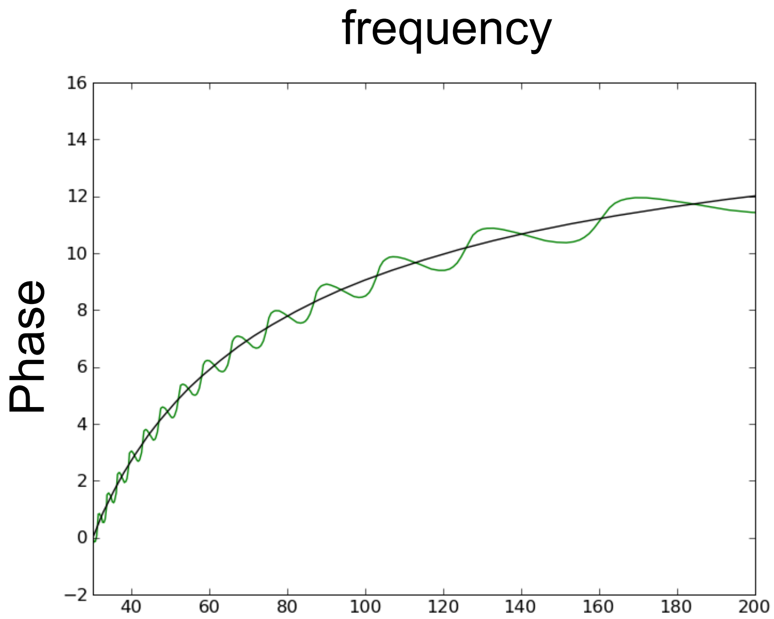
- Overlap:

  Can't fit oscillations

- Maximize over masses:

  Can fit any (reasonable) **secular phase**
  (in band)

  Still can't fit oscillations; **large** mismatches



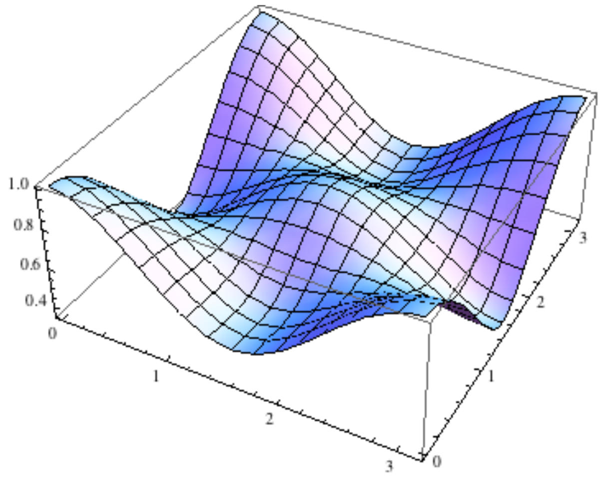
Implies: 1 precession cycle integral -> answer!

- **SNR**: average lighthouse power

$$
\begin{aligned}
s^2(\theta_s,\beta,\psi_J) &= \left\langle \frac{(1+(\hat{L}\cdot n)^2)^2}{4}\cos^2 2\psi_L(t) + (\hat{L}\cdot n)^2 \sin^2 2\psi_L(t) \right\rangle \\
&= \left\langle \frac{(1+(\hat{L}\cdot n)^2)^2}{4} \right\rangle - \left\langle (\hat{L}\cdot\hat{x})^2(\hat{L}\cdot\hat{y})^2 \right\rangle
\end{aligned}
$$

- **Best overlap**: integrate **known** residual oscillation

$$\text{overlap} \propto \max_{t,\phi} \int A\cos 2\delta\Psi$$



Amplitude (geometrical terms, psi=0)

Closed forms!

SNR

- Geometrical term (from “lighthouse” average)

$$\hat{s}^2 = \frac{1}{1024}\left[\{c_p(x-1)^2 + x^2\}(35y^2 + 10y - 13) + 2x\left(5y^2 + 166y + 53\right) - 13y^2 + 106y + 451\right]$$

- Kinematic term (from aligned spins giving longer orbits)
  - Standard SPA

Mismatch:

$$\hat{P}(\theta_s, \beta, \psi) \equiv |I(\theta, \beta, \psi)|/s(\theta_s, \beta, \psi)$$

$$I \equiv \begin{cases} -\frac{3}{4}\cos 2\psi \sin^2\beta \sin^2\theta & n_{wind} = 0 \\ \frac{(2\sin\beta \mp \sin 2\beta)(\mp\cos 2\psi \sin 2\theta - 2i\sin\theta \sin 2\psi)}{8} & n_{wind} = \pm 1 \\ \frac{(1\mp\cos\beta)^2}{8}\left[\cos 2\psi(1+\cos^2\theta) \mp 2i\cos\theta \sin 2\psi\right] & n_{wind} = \pm 2 \end{cases}$$

It works, empirically

Calculation:

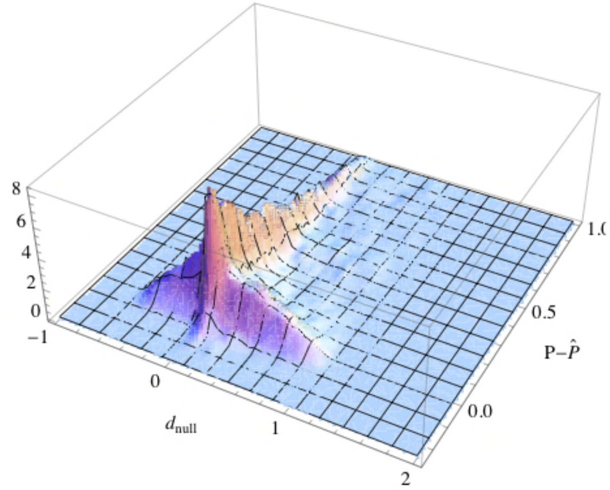
Real TaylorF2 3.5 PN bank vs SpinTaylor (3.5PN)

All BH-NS binary masses, spins

Figures:

2d: small error, except near special surface

3d, interactive



Mismatch error

Success:

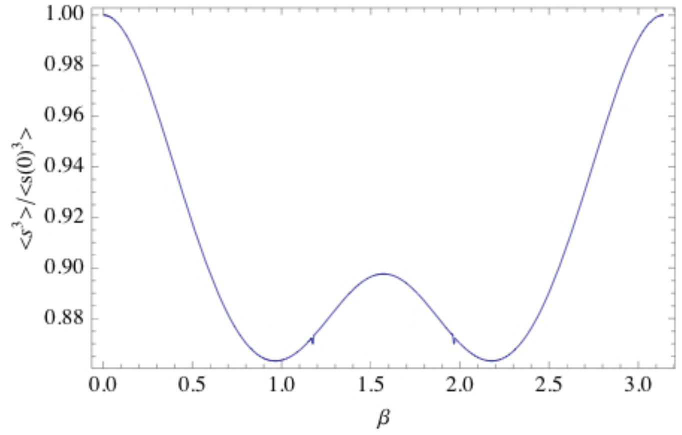
- SNR:
  - Good, except for: transitional-precession outliers
- Mismatch:
  - Good, except for: discrete jumps in secular phase rate, near special geometries

Selection biases for BH-NS?

Selection bias: Method

Zero-noise simulations (discrete real bank)

[can rescale overhead results to all-sky, etc]

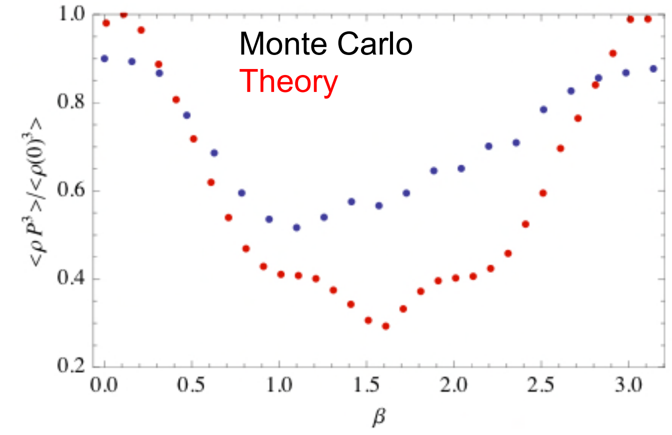


Selection bias: Results

- Intrinsic: Small change (volume: 10%)
- Search: **Can be** large (volume: x2!)

  Theory ~ agrees [preliminary]

  Transitional precession does *better* (less modulation)



Note:

Bias largest for (some) **spin**-dominated (=certain masses, spins)

Easy to wash out from injection population

Summary

Astrophysics:

- *High mass*: Rates “as if” no spin
- *Low mass*: Occasional bias.

  As needed (BH-NS), correct via tabulated Monte Carlo.

Data analysts: Low mass:

- *New coordinates*: Relative to J easier, never used (??)
- *Worst fits found*: closed form. Targets for hierarchical (PTF) followup?
- *Spin parameter biases found*: May help spin search tuning.
- *Future directions: Single-detector*: single-stage χ^2 fits; real data
- *Coherent bias*: So far, just single-detector formulae

Theory: Low mass:

- two-timescale expansions

HOLDING MATERIAL

BONUS SLIDES: GW features

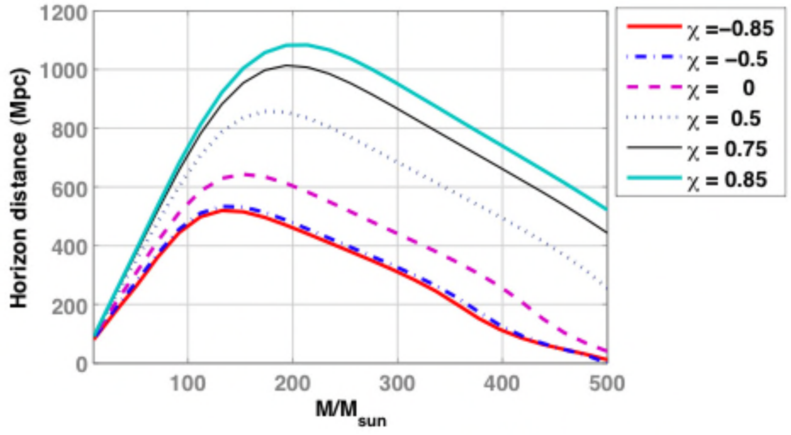
What makes GW?

Example: Two black holes with spin (aligned)

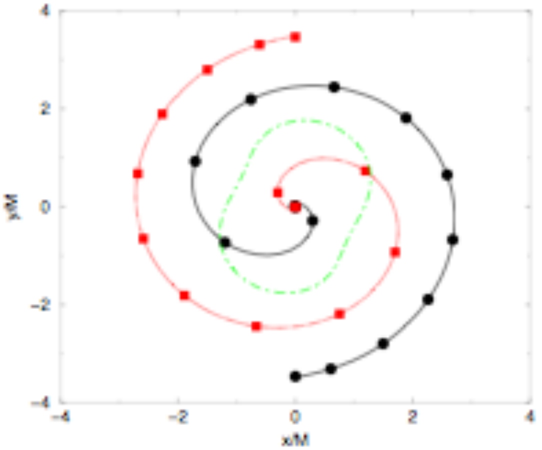
Like nonspinning

Spin-orbit couplings change duration, phasing

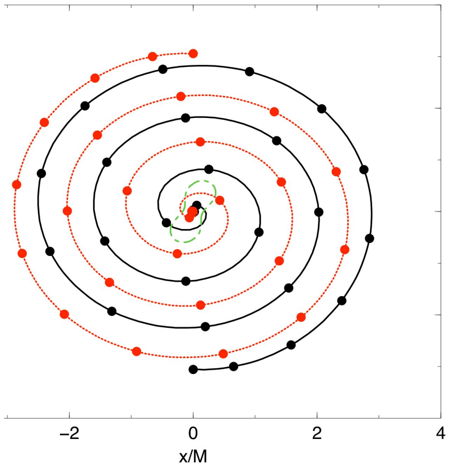
[Campanelli et al gr-qc/0604012]



Initial LIGO, range vs mass (m1=m2)



Both down



Both up

What makes GW?

Example: Two black holes with spin

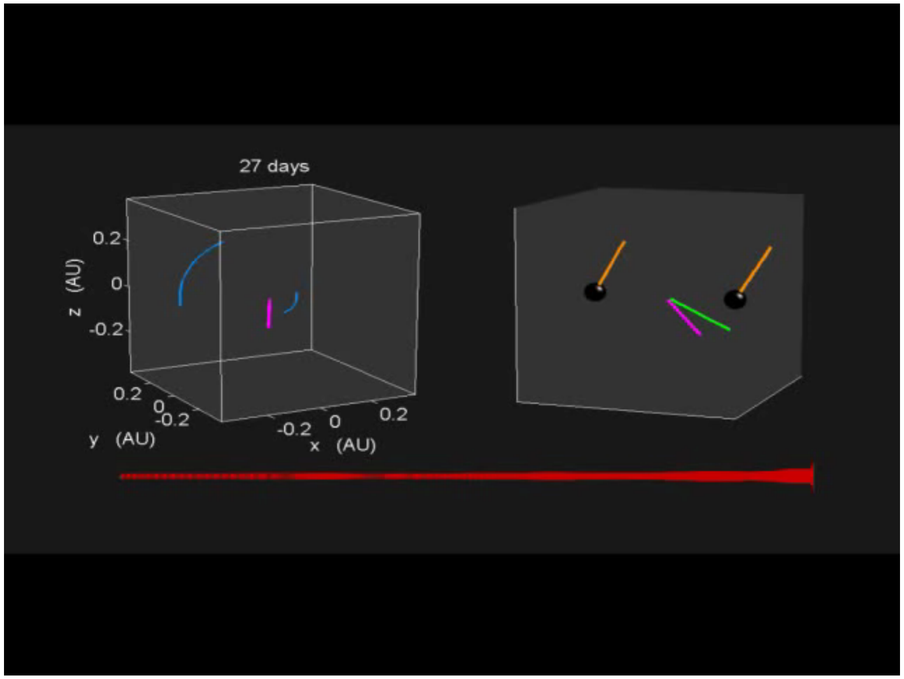
Precession:

$H = H_{orbit} + O(L.S) + O(S1.S2)$

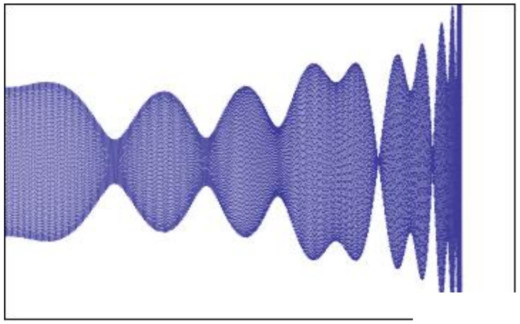
J exchange between spins, L

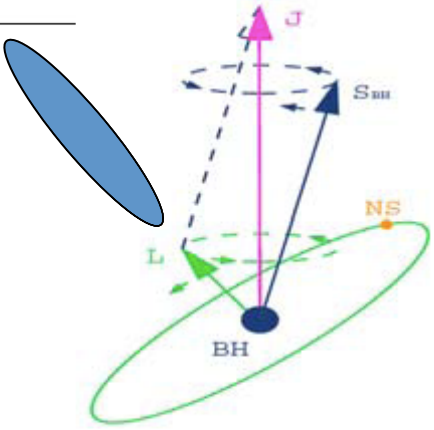
Orbit plane & beaming rotates

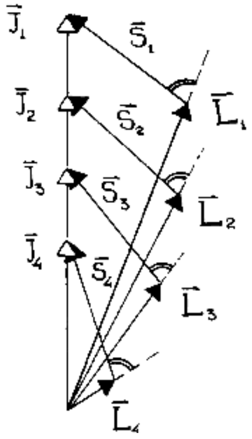
modulations



Movie: S. Hughes (gmunu.mit.edu))







Measurables?: Inspiral

- Mass

  Must match!

  df/dt -> mass

  [mass *ratio* : fine structure]

- Distance

$$SNR \propto \frac{M^{5/6}}{d}$$

- Orbit orientation:

  Measure beaming?...but

  - Distance-inclination degeneracy

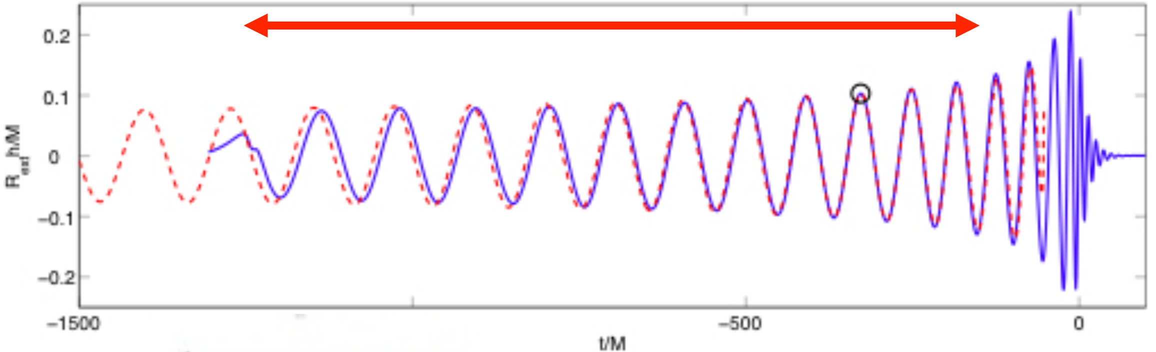
$$\delta X/X \simeq O(1)/\rho$$

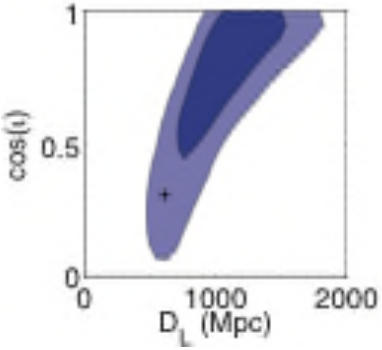
  significant vs beaming angle

- (Black hole) spin

  Precession

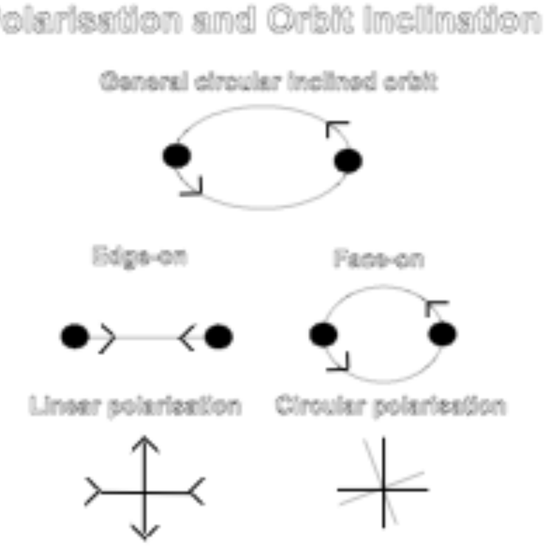
  Only if extreme





Nissanke et al 0904.1017

Beamed, polarized emission

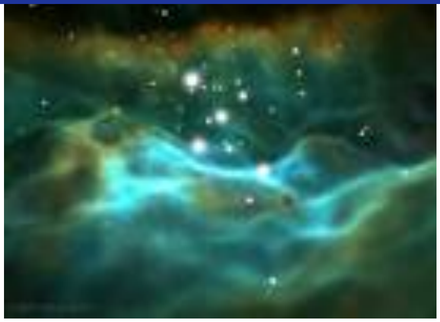


Spin-orbit coupling

BONUS SLIDES: Cartoon channels

Sources of compact binaries

Constrain "branching ratios"



Star forming gas

f_{cl}

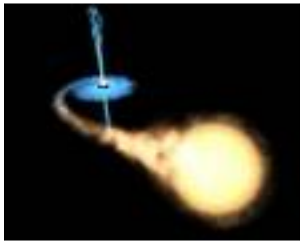
$1-f_{cl}$

Interacting stellar clusters

unbound cluster

$1-g_{infant}$

Isolated stars and **binaries**



g_{evap}

gravitational mass segregation

g_{run}

runaway stellar collisions

Isolated BH-BH binaries

Heavy ($>10^3 M_O$) Binaries or IMRI captures

Isolated, small compact binaries

<u>References include</u>

- O' Leary et al astro-ph/0701887
  O' Leary et al astro-ph/0508224
  Sadowski et al arXiv:0710.0878

<u>References include</u>

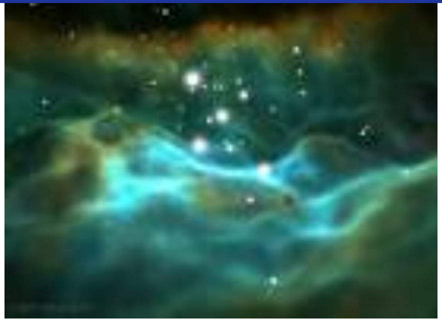
- Fregeau et al astro-ph/0605732
- A. Seone et al CQG 24, 113 (2007)
- Mandel arXiv:0707.0711

<u>References include</u>

- Belczynski, Kalogera, Bulik 2002
- O' Shaughnessy et al. astro-ph/0610076; 0609465; 0504479

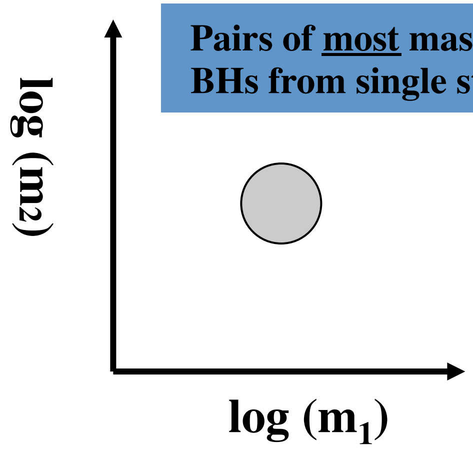
Sources of compact binaries

Constrain channel details:
Different mass distributions



gravitational mass segregation

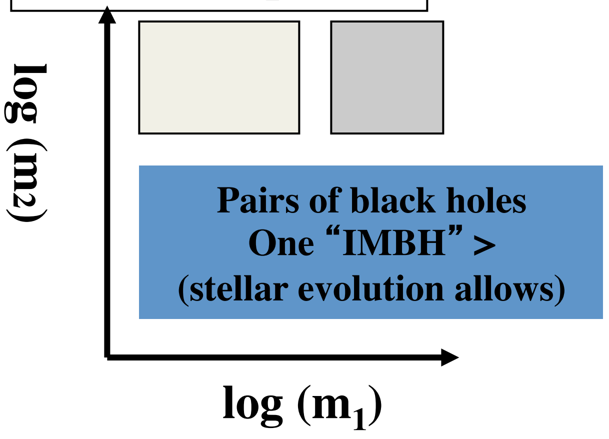
Isolated BH-BH binaries



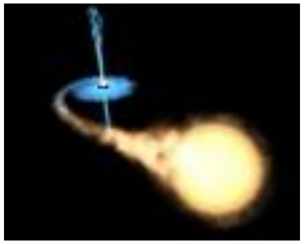
Pairs of most massive BHs from single stars

runaway stellar collisions

Heavy ($>10^3 M_O$) binaries + IMRI captures

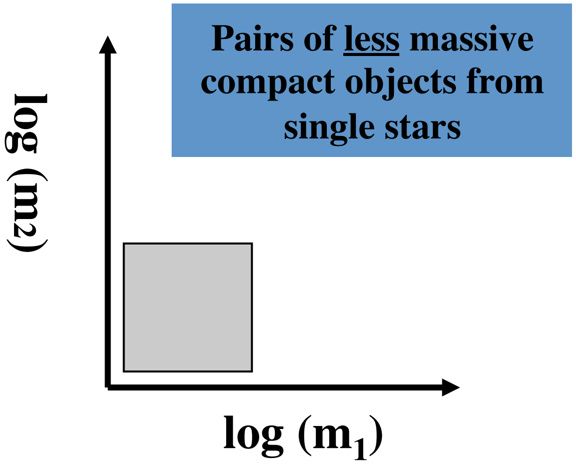


Pairs of black holes One “IMBH” > (stellar evolution allows)



Isolated stars and **binaries**

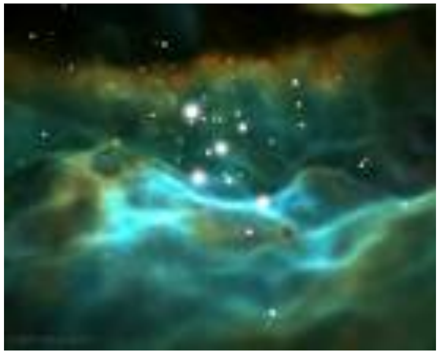
Isolated, small BH, NS binaries



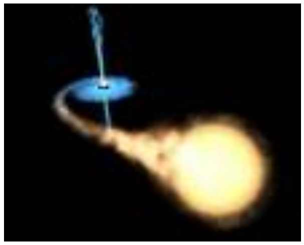
Pairs of less massive compact objects from single stars

What about dynamical sources?

Alignment = signature!



Star forming gas



Isolated binaries
Aligned spins

References include

- •Belczynski, Kalogera, Bulik 2002; Belczynski
- •O’ Shaughnessy et al. in prep

\+ astro-ph/0610076; 0609465; 0504479

Interacting clusters’ stellar mass binaries
Random spin alignment

References include

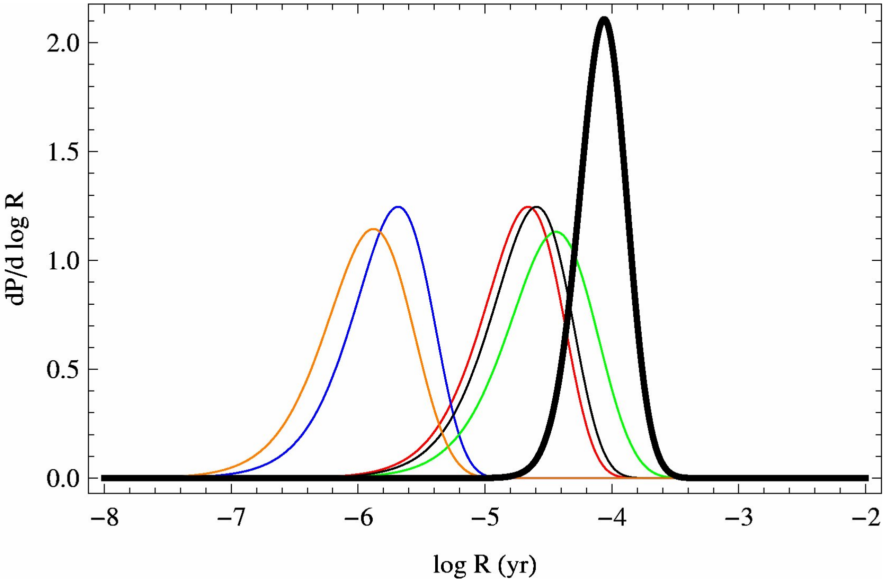
- • Sadowski et al 2008
- •O’ Shaughnessy et al PRD 76 061504
  O’ Leary et al astro-ph/0508224

BONUS SLIDES: PSR

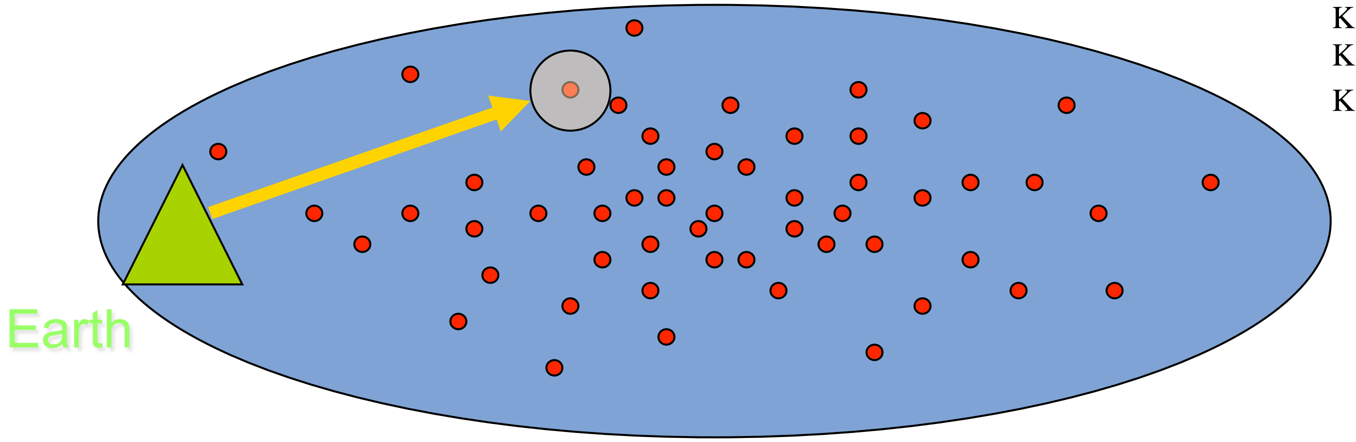
Pulsar "injections"

Galactic pulsar-NS birthrate:

- Synthetic population:
  - Assume pulsar spin, beaming
  - Draw from luminosity, position distribution
  - Predict # seen vs # available
- Reconstruct # available from # seen
- Reconstruct birthrate



NS-NS merger rate in Milky Way
ROS and Kim, ApJ 715 230 (2010)
Kim et al ApJ 584 985 (2003)
Kim et al astro-ph/0608280
Kim et al ASPC 328 261 (2005)
Kim et al ApJ 614 137 (2004)



BONUS SLIDES: Isolated evolution

- Formation channels
- Rates
- Key uncertainties
  - Sn kicks
  - Evolutionary issues: [Initial-final mass relation (improving - Ott);
  - Winds

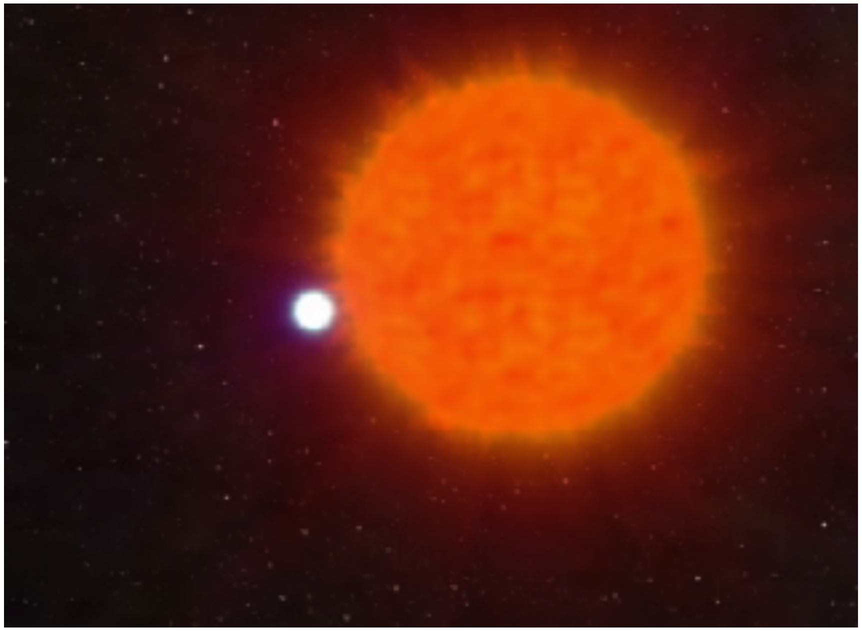
Example: Isolated evolution

Complex process

- 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



Models hard

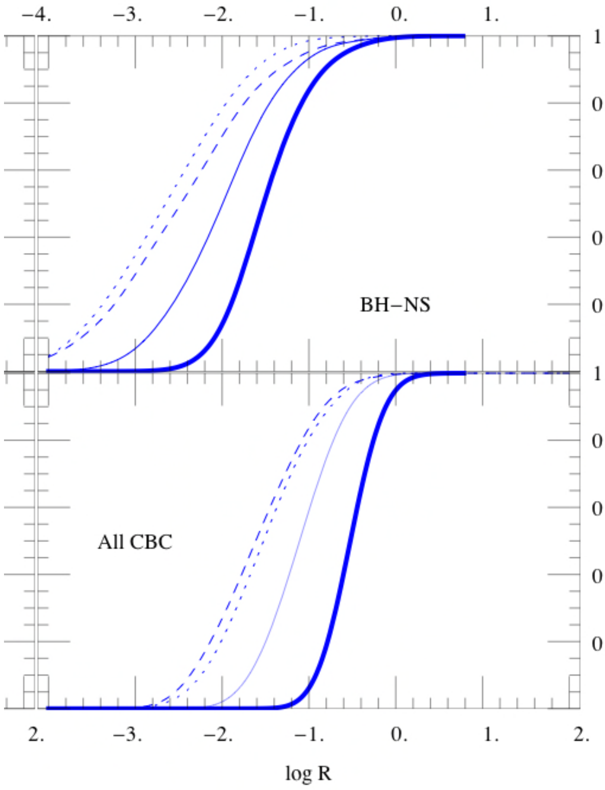
- supernova
- long mass transfer

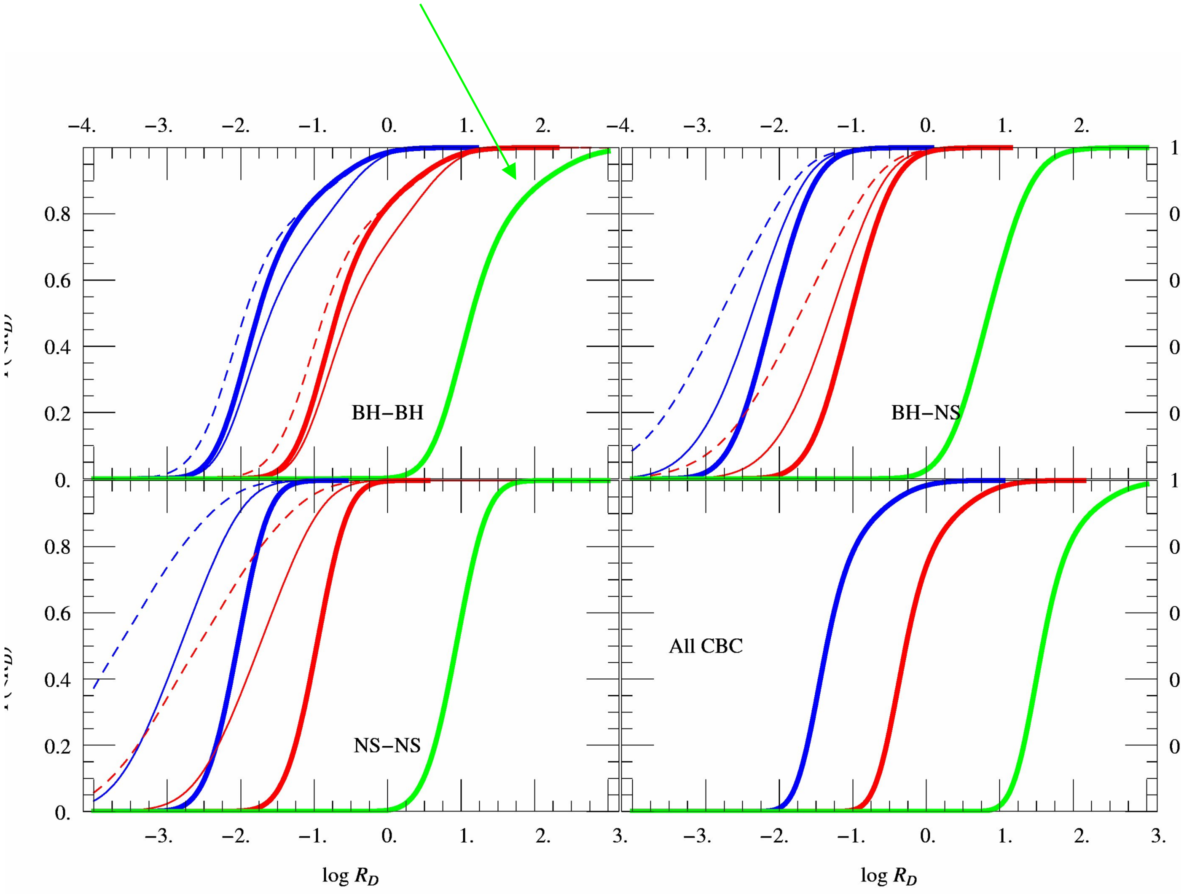
Movie: John Rowe

Predicted merger,GW detection rates

Mergers: <10/gal/Myr [ROS et al 0908.3635]

Detections: O(30/yr), aLIGO network





log (rate*Myr), single detector

Formation model: Key points

- **Mass transfer**:

Small orbit-> MT essential

GW radiation "fast" (< 10 Gyr)

only for tight orbits

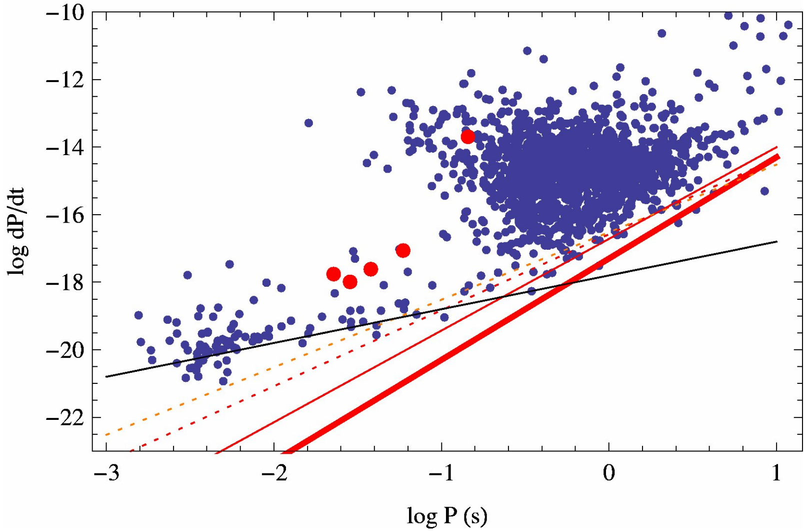
Example: Hulse-Taylor

$$\tau_{gw} \simeq 0.3\mathrm{Gyr}$$

$$a \simeq 2.7R_\odot \ll O(10^3 R_\odot) \simeq R_{\rm giant}$$

Mass transfer phenomenological:

parameterized (via energy or J) to unbind envelope



Visible connections!:

- (recycled?) Pulsar binaries
  - *Good*:
    - Long-lived remnants!
    - Precise measurements
  - *Challenges*:
    - Pulsar population statistics challenging:

      many potential (time-evolving?) biases: L distrib; galaxy distrib; beaming, B/L evolution, accn, …

      P-dP/dt diagram flow/popsyn still phenomenological
    - Theory: PSR-BH binaries should ~*never* be recycled

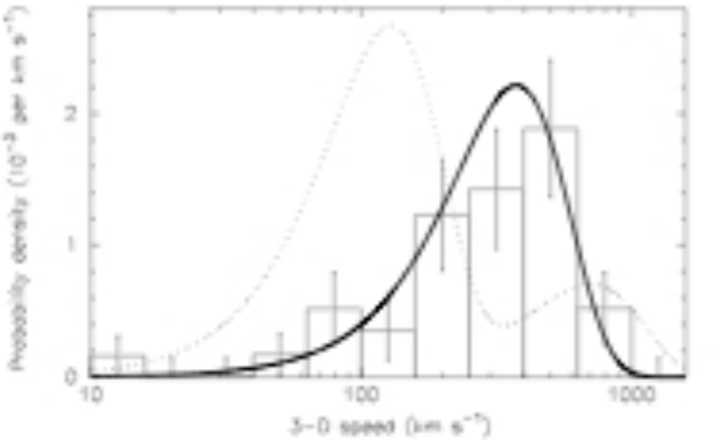
Formation model unknowns

- <u>Supernova kicks</u>

Isotropic kicks?

Hobbs vs Arzoumanian

<u>Group</u>: <u>explore all</u>



Hobbs et al

Polar?

Motivation: Spin-kick alignment?

(e.g., neutrino/B/.. kick)

For: obs claims (Lai et al 2001; Wang; Ng Romani Kaplan et al 2008);

Against: Willems et al 2008 (low kicks required to fit PSR-NS e;

high kicks seem required for others)

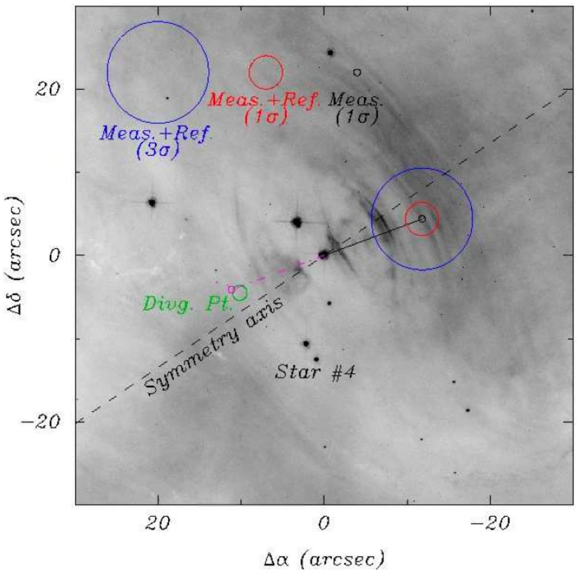
Impact for us:

huge rate reduction b/c never "kicking closer"

Kuranov et al 0901.1055; Postnov & Kuranov 0710.4465

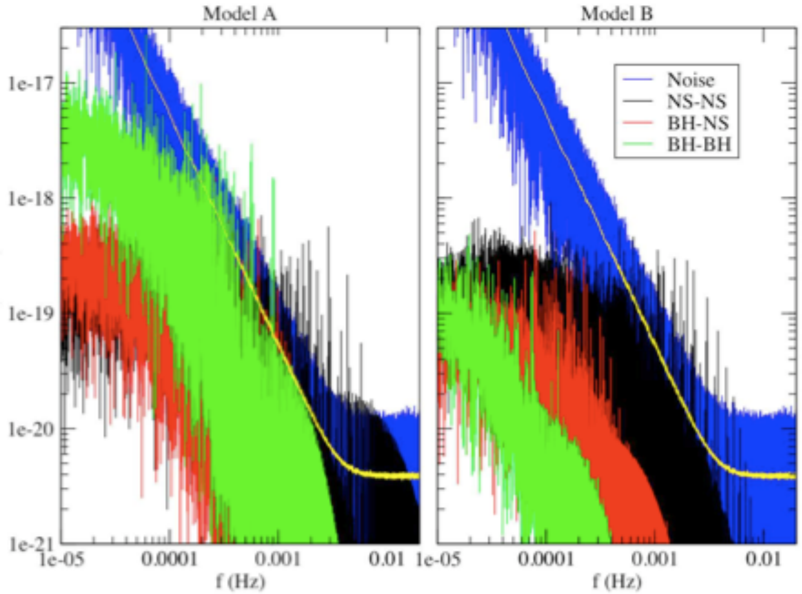
<u>Group</u>:<u>not explored extensively now</u>; could be

Crab motion

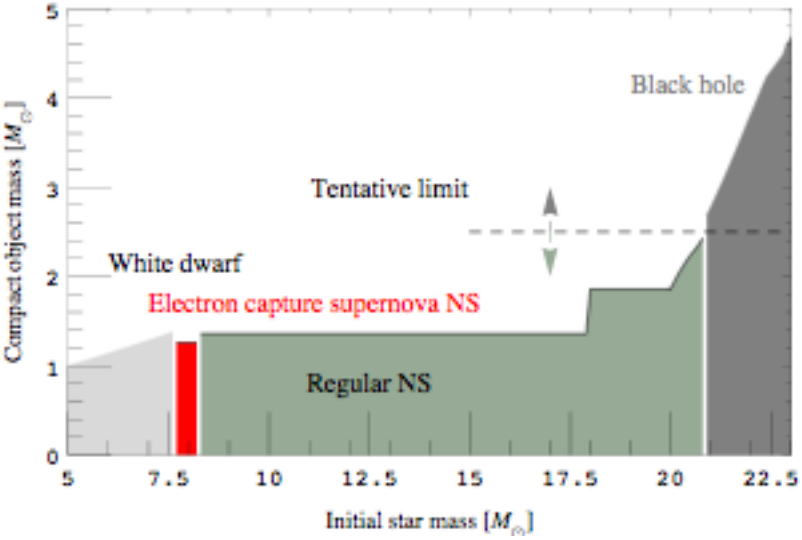


Formation model unknowns

- Supernova kicks
- Evolution model
  - Hertzprung gap merger
    - ultracompacts survive/not
    - **big** effect on BH rate
    - Changes background
      LISA binary #
  - NS maximum mass
  - Bondi rate in CE; AIC



Belczynski 0811.1602



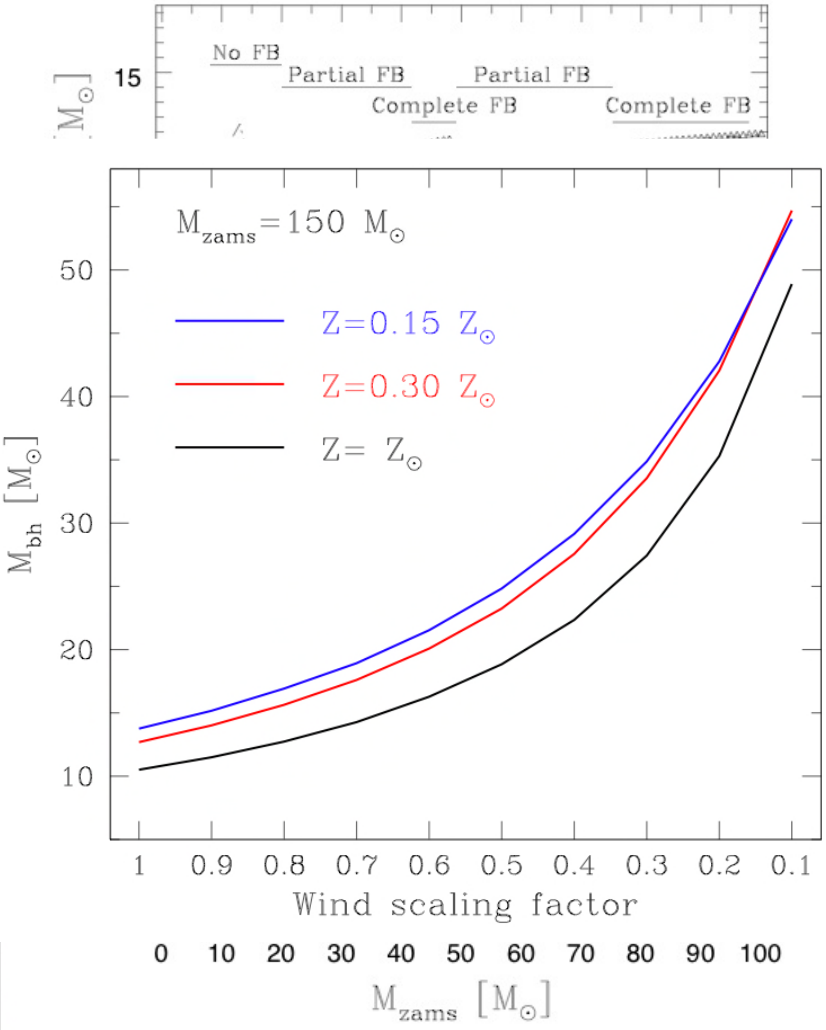
Belczynski, ROS, et al ApJ 680 129

Formation model unknowns

- Evolution model
- Supernova kicks
- <u>Winds</u>

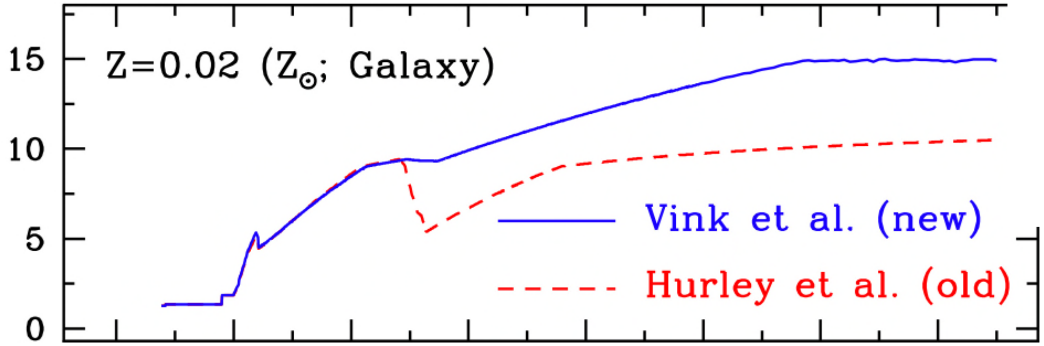
  Strong effect on star->BH mass

  Recent update



Belczynski et al 2002

“original” winds + scale factor

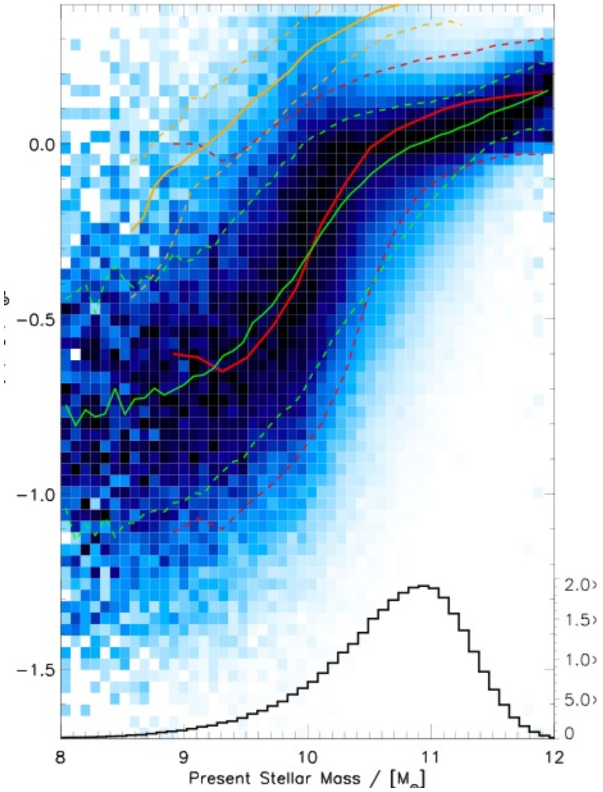


Belczynski et al 2009

“revised” winds

Formation model unknowns

- Evolution model
- Supernova kicks
- Winds
- <u>Metallicity distribution</u>: (input uncertainty)
  - Formation, detection rate *sensitive*
  - Wide distribution of conditions
  - Metallicity evolves strongly with z (Pei, Fall, Hauser)



=> typical detected binary from *highly atypical* region?

Panter et al 2008

[ROS and Koparappu, 0812.0591]