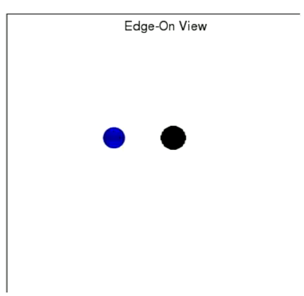
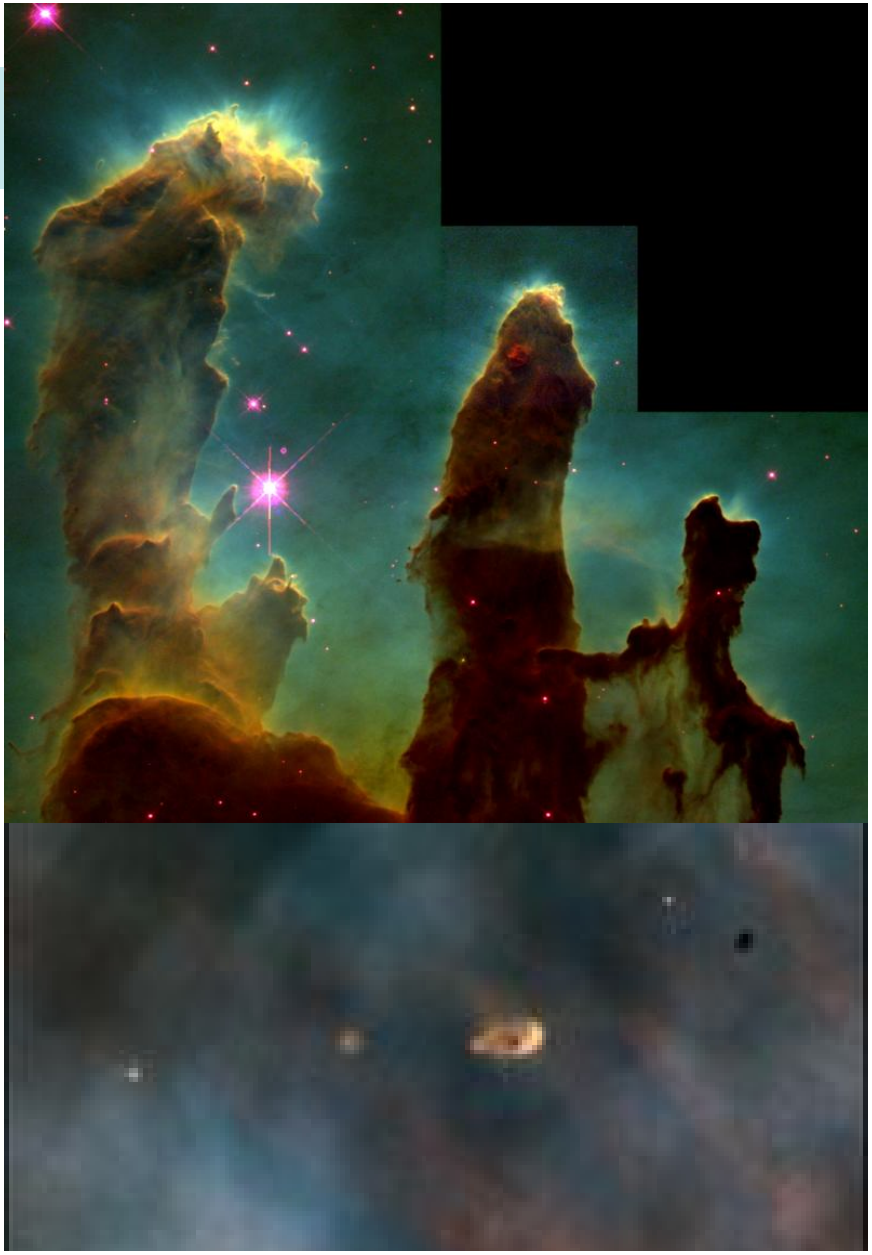
Gravitational wave astronomy and BH-NS mergers:
Uses for an astrophysical multitool



R. O' Shaughnessy

2010-06-23 Stony Brook

Why use GW?



EM Waves

Source:

~any accelerating charge

screening limits size…

Strong coupling:

Imaging often practical:

(common sources)

>> wavelength

- Easy to make & detect
- Easy to **obscure**

Outline

What happens in a BH-NS merger?

- Dynamics
  - Precession and inspiral
  - Merger
  - Post-merger (disk; fallback; wind)
- Emission
- Gravitational waves
  - Precession and inspiral
  - Merger

What can we measure?

Formation processes and Event rates

- Isolated evolution
- Short GRBs

What do we learn?

GR tests: Parity violation in gravity; …

Astrophysics: Progenitor models; short GRB engine mechanism; …

Nuclear: Nuclear matter; r-process nucleosynthesis (?)

Hidden: Internal outline(*)

THINGS TO ADD

- Pictures of G. Brown articles on HCE

------

what happens in a bh-ns merger

- - cartoon
- - early time: gw and precession
- - movie w distrupted dynamics. point: time of disrupt, residual as probe
- lehner fallback time
- manou movies: emphasize
- - what next? : em, other signatues, poss with delayed em emission
- - short grb
- - r process in disk

GW astronomy and mergers: what we learn

BH-NS merger movies

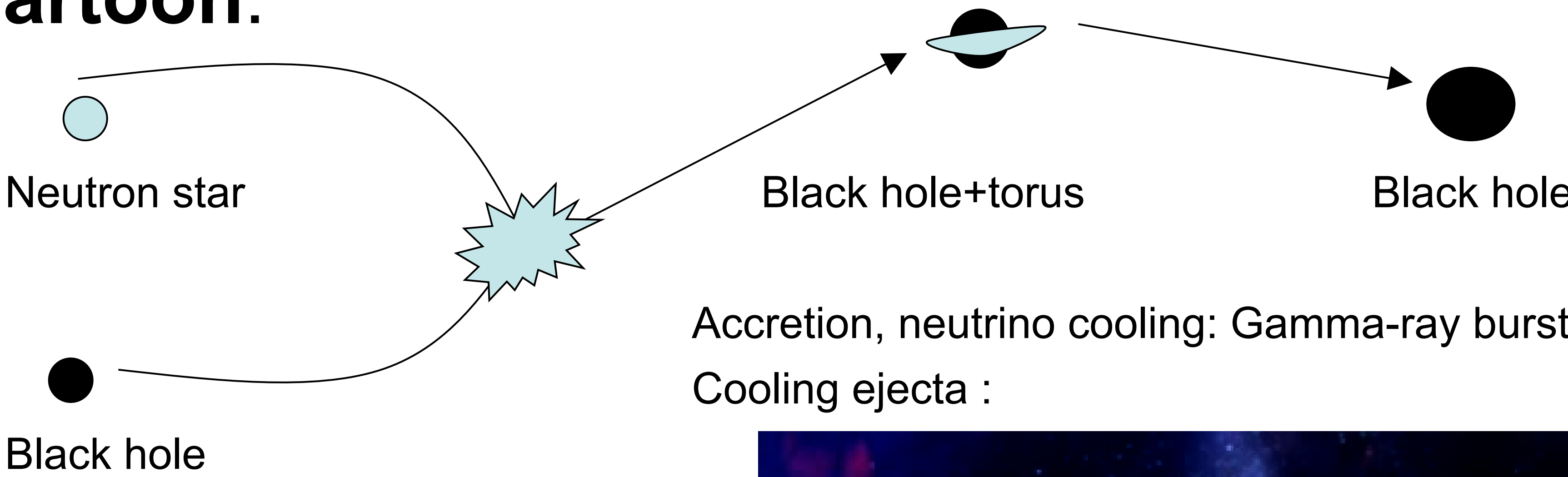
See script ‘open-youtube-movies.sh’

Campanelli:

- * with precession : http://www.youtube.com/user/Lazarus135#p/a/u/1/89EWKM7e6YQ
  - See http://www.black-holes.org/explore2.html
- * without precession: more boring
- http://www.youtube.com/user/Lazarus135#p/u/3/n3ueqgsEz_Y

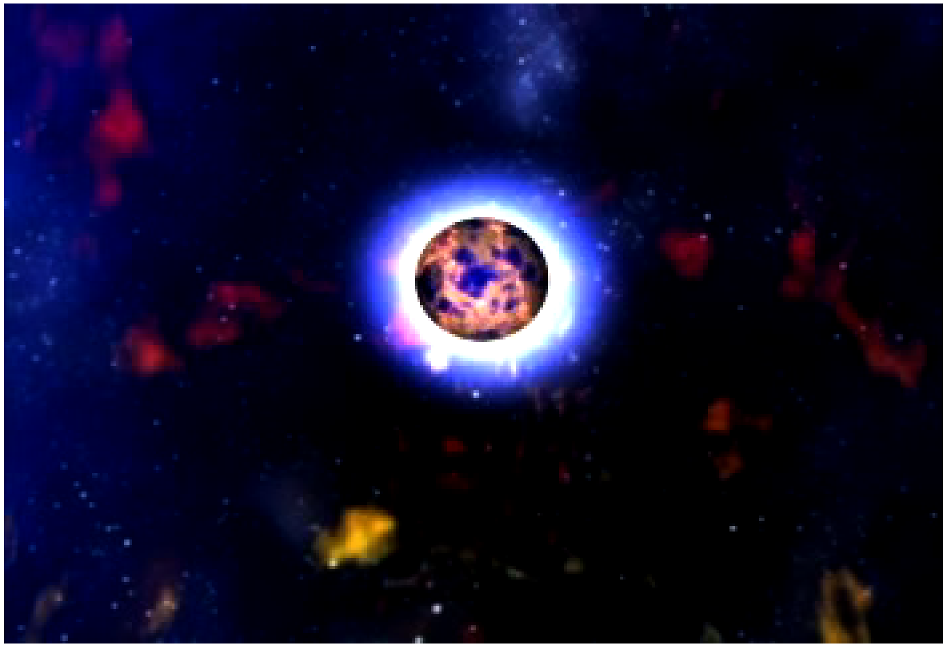
What happens in a BH-NS merger?

Cartoon:



Accretion, neutrino cooling: Gamma-ray burst?

Cooling ejecta :



Lee and Ramirez Ruiz 2007
Nakar 2007
Oeschslin and Janka 2006
Faber et al 2006
Shibata et al 2006, 2007
….

What happens: Dynamics

Early : [ACST]

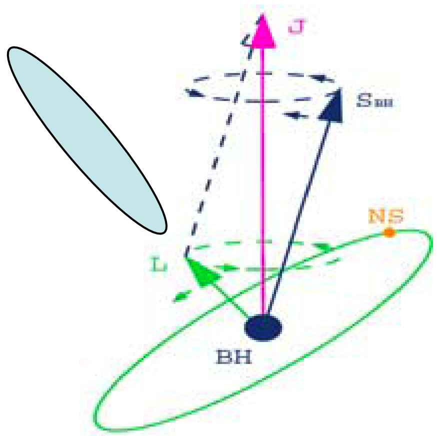
Precession:

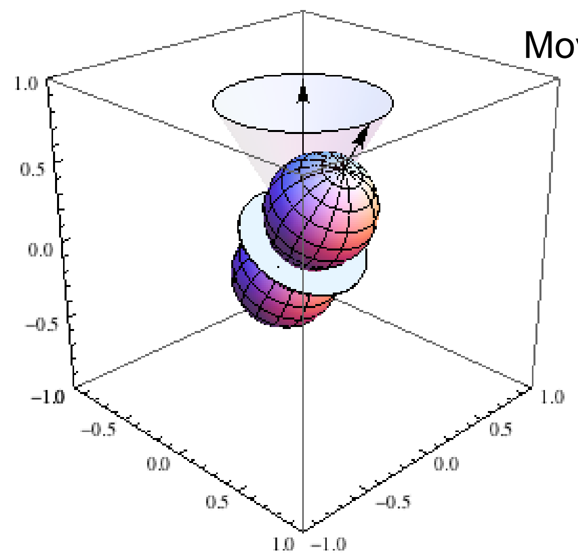
$H = H_{orbit} + O(L.S)$

L.S ~ conserved

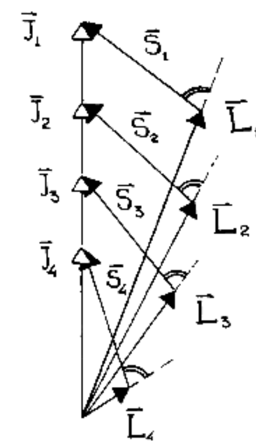
L ~ cone around J, widening

Orbit plane rotates





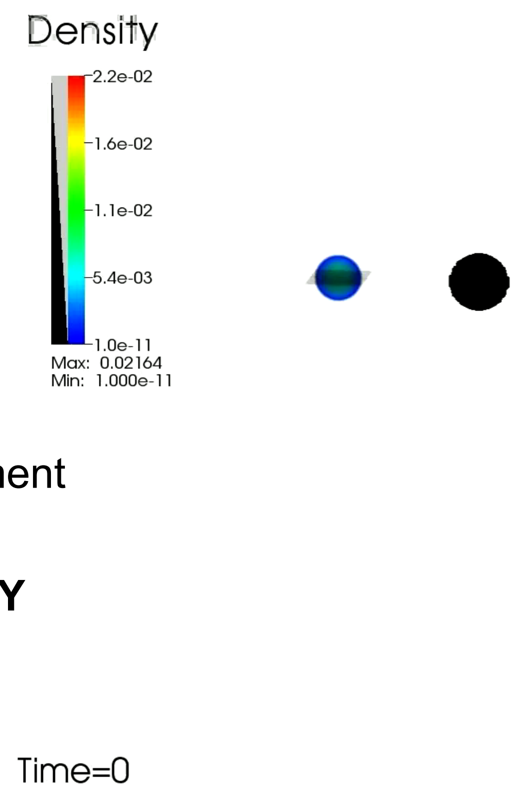
Movie: S. Hughes (gmunu.mit.edu)
[two black holes]

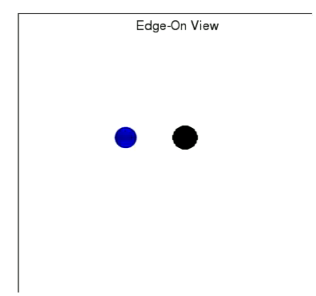


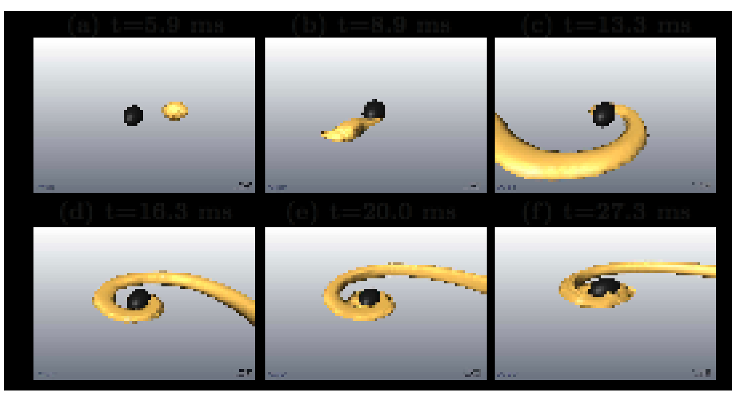
What happens: Dynamics

Tidal disruption:

- BH tides disrupt
- Orbit along BH equator:
  - Disruption radius, ejected mass depend on BH spin
  - Tidal tail in plane
- Generic orbits
  - Disruption time depends on BH spin, alignment
  - Tidal tail fills volume [Rantsiou et al]
  - Ejected, fallback mass depends **STRONGLY** on spins a>0.7, alignment

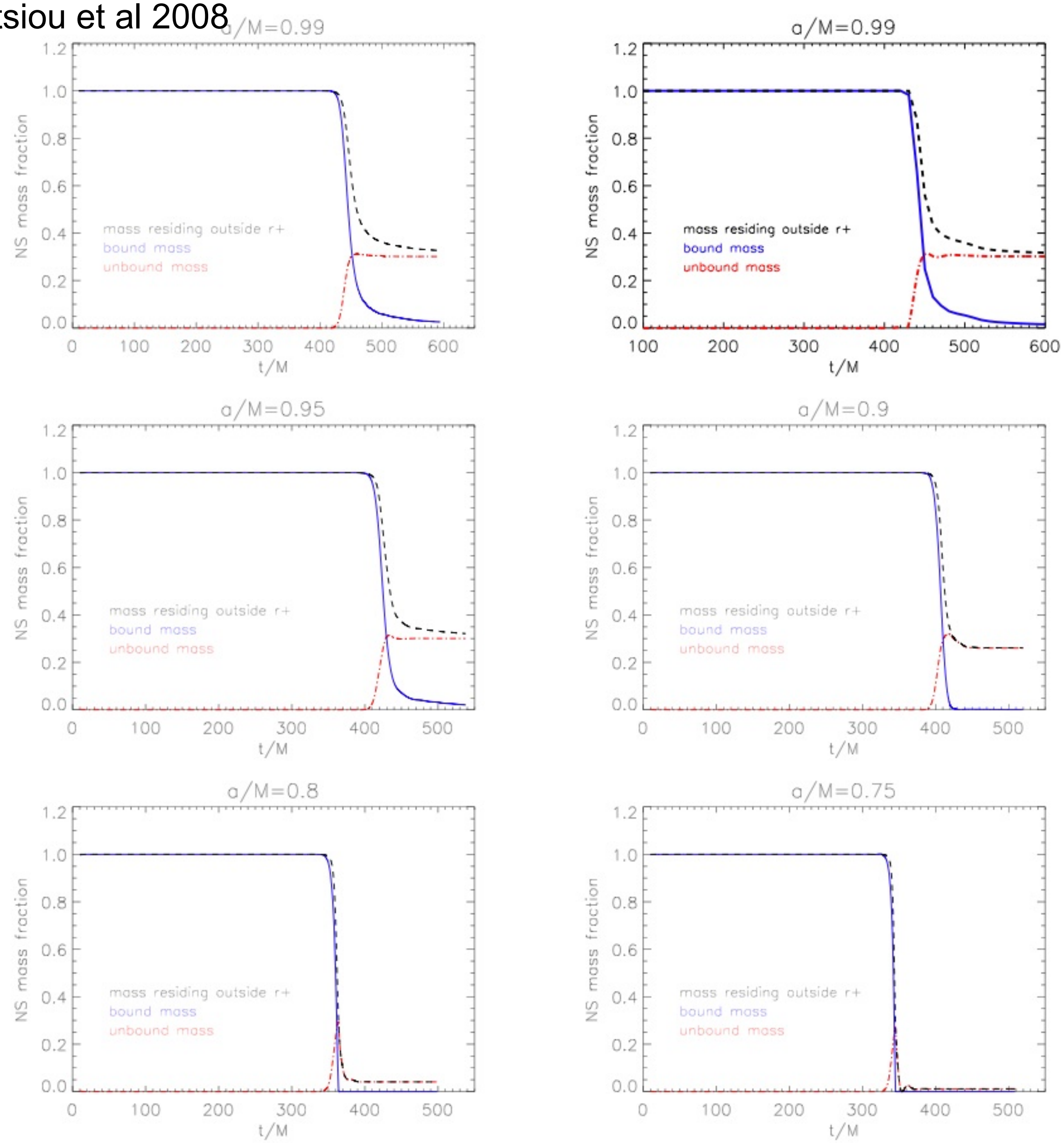






Example: Mass vs spins (aligned)

Rantsiou et al 2008



a=0.99

Lots ejected

a=0.75

Little ejected

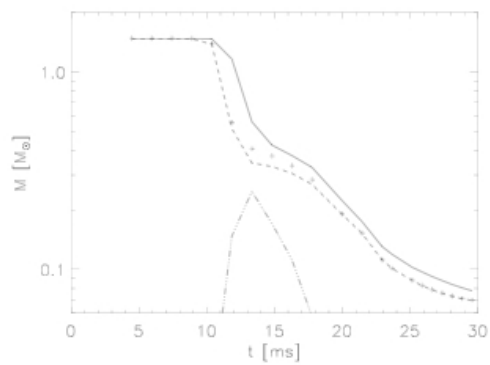
What happens: Dynamics

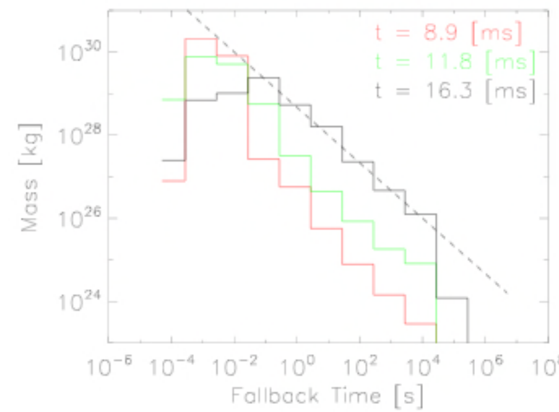
Accretion; fallback; winds

Prompt capture, disk: see movie

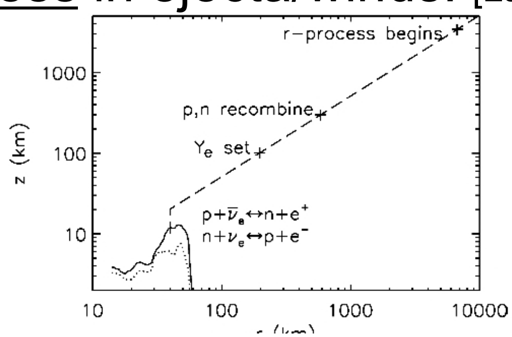
Fallback : $dM/dt \sim t^{-5/3}$ (Newtonian: Rosswog ; GR+MHD, a=0.7: Chawla et al 1006.2839)

Bursty (?) accretion ~ hours later



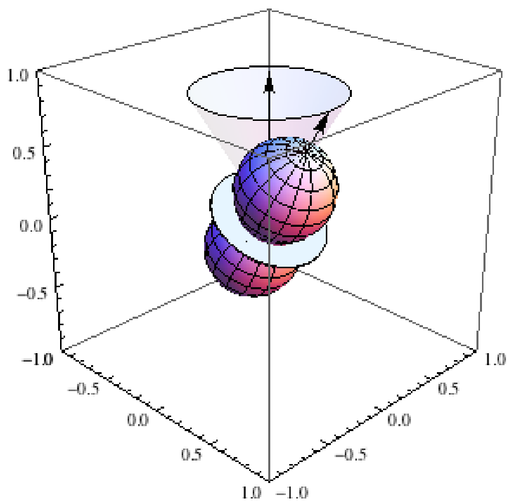


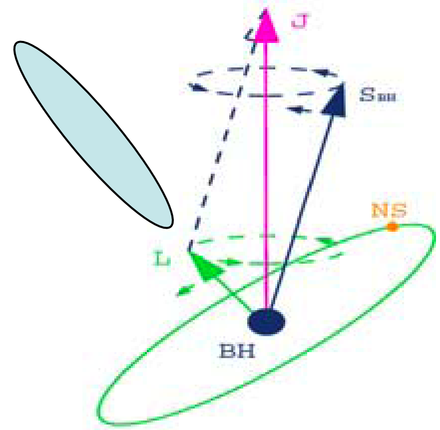
R-process in ejecta/winds: [Lattimer & Schramm 1974; Surman et al 2008; Metzger et al 2010]

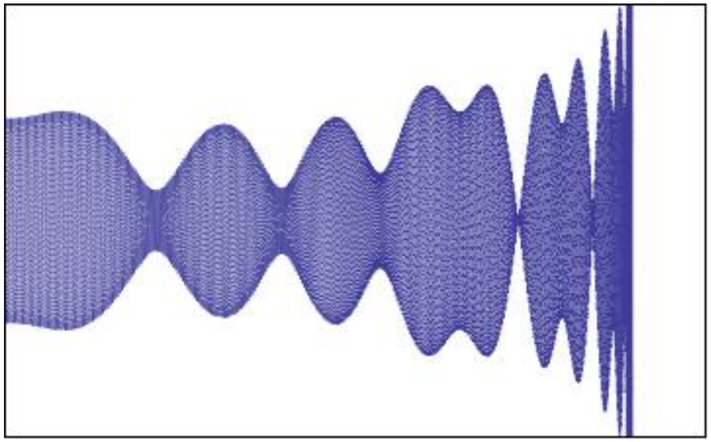


What happens: GW

Early precession, modulation:







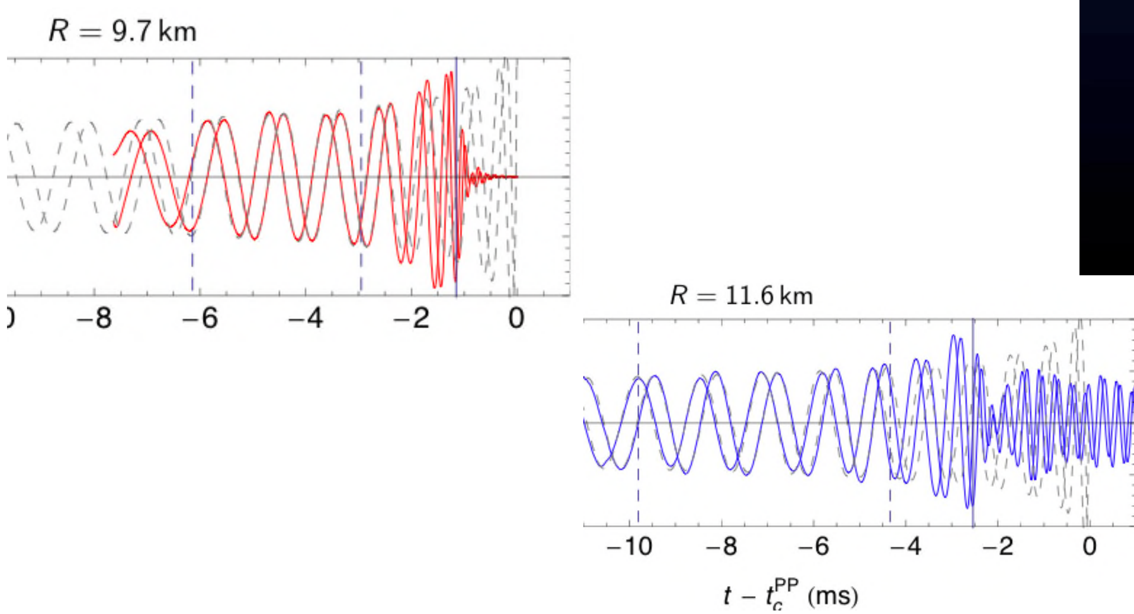
- occurs ~ at peak LIGO/Virgo sensitivity

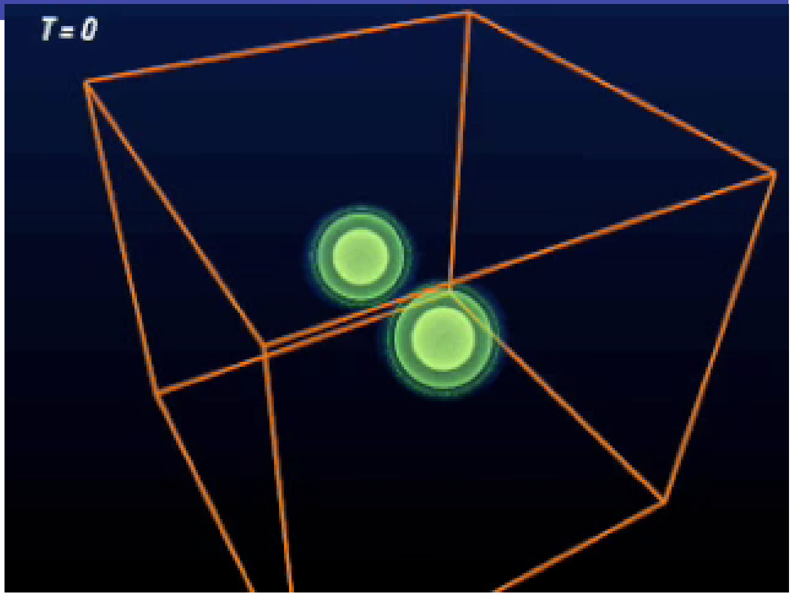
What happens: GW

Tidal termination [example: NS-NS]

~ Terminates at tidal radius

Radius depends on nuclear matter EOS





BH, fluid ringdown modified vs BH-BH, NS-NS:

- less excited by smooth merger
- Weakly (!) driven by accretion

Problem:

Both occur at high frequency

Need future detetors (ET)

What can we measure?

Each event, GW only:

- <u>Mass</u>

  Must match!

  df/dt -> mass

  [mass *ratio* : fine structure]

- <u>Distance</u>

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

- <u>Orbit orientation</u>:

  Measure beaming?…but

  – Distance-inclination degeneracy

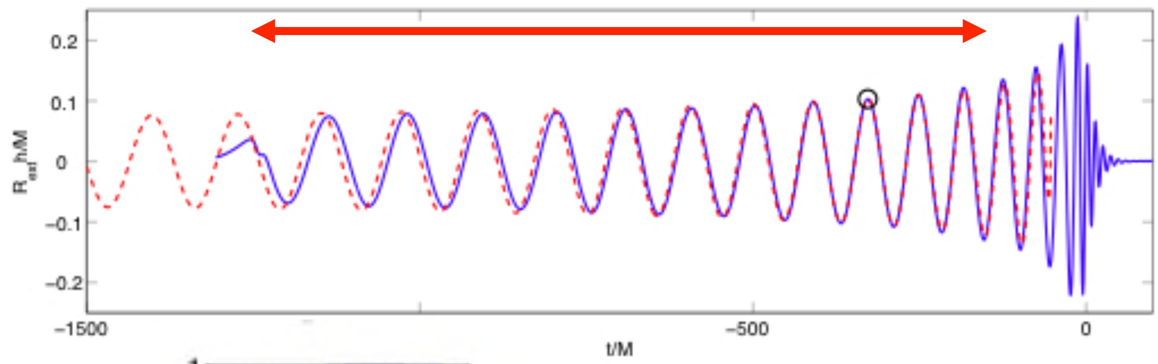
$$\delta X/X \simeq O(1)/\rho$$

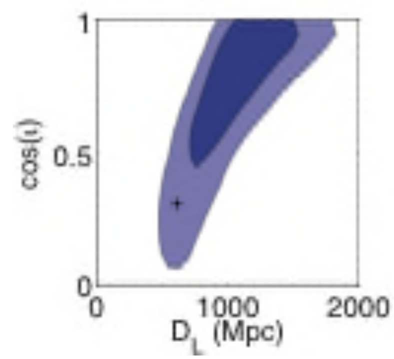
  significant vs beaming angle

- <u>(Black hole) spin</u>

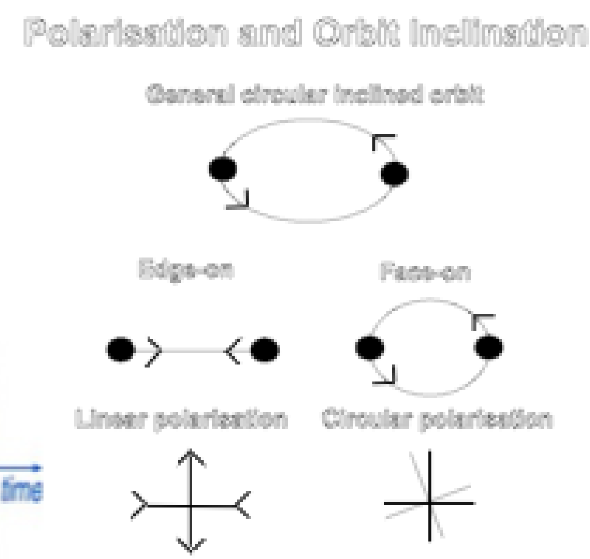
  Precession

  Only if extreme





Nissanke et al 0904.1017



Beamed, polarized emission

Spin-orbit coupling

Support: Sky localization

Rule of thumb:

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

Real calculation:

Van der Sluys et al 0710.1897

a=0.5,Θ=20°

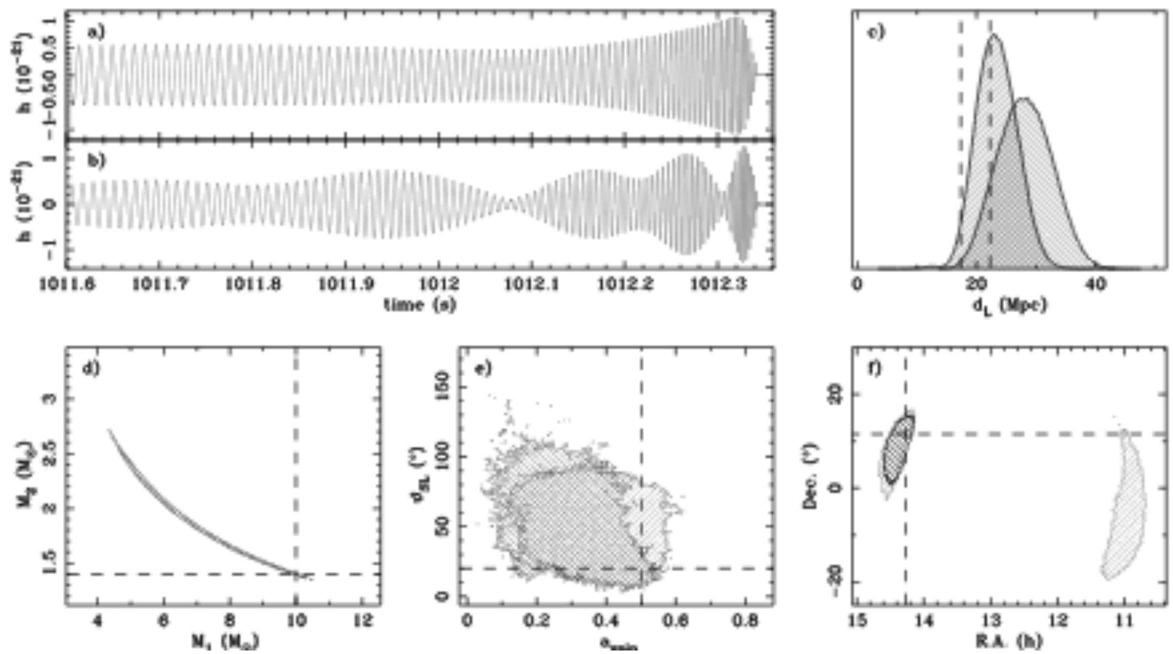


Table (SNR 17, 2-detector)

TABLE 1
INJECTION DETAILS AND WIDTHS OF THE 90%-PROBABILITY INTERVALS OF THE MCMC RUNS DESCRIBED IN THE TEXT

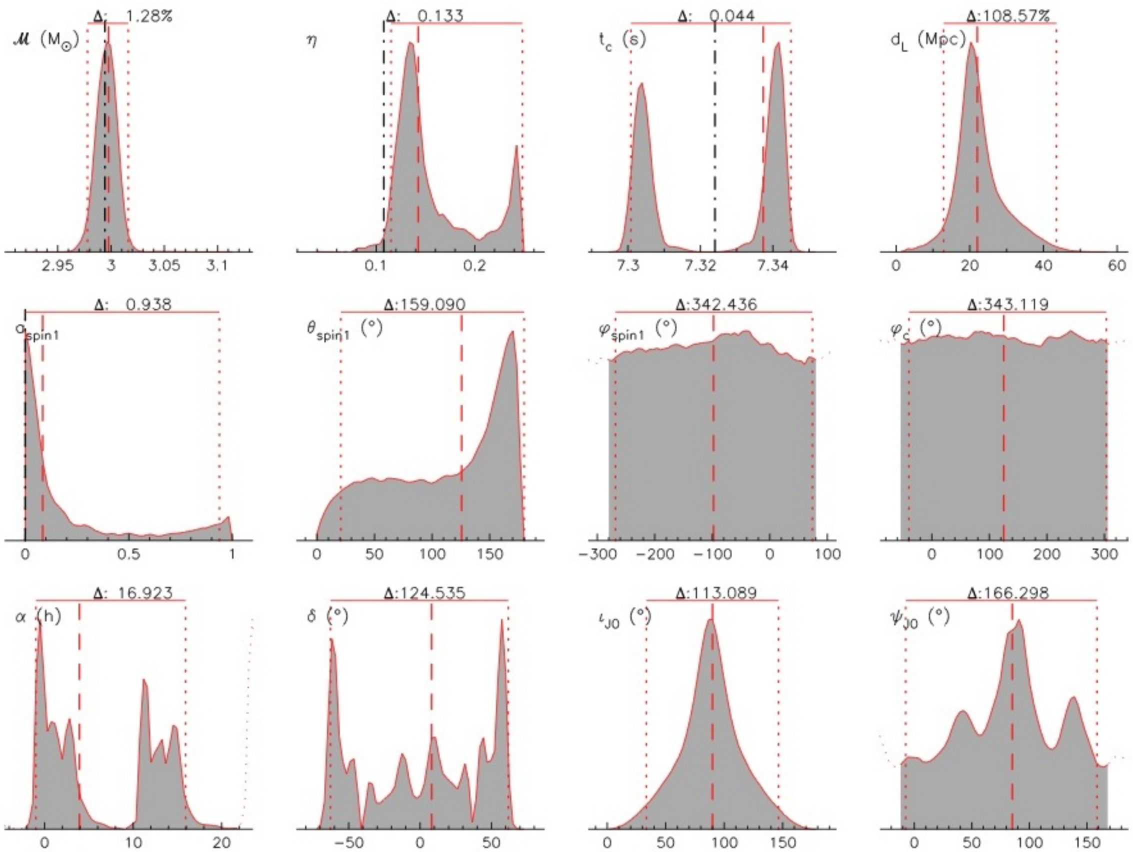
n_{det}	a_{spin}	θ_{SL} (°)	d_L (Mpc)	M_1 (%)	M_2 (%)	$\mathcal{M}$ (%)	η (%)	t_c (ms)	d_L (%)	a_{spin}	θ_{SL} (°)	ϕ_c (°)	α_c (°)	Pos. (°²)	Ori. (°²)
2	0.0	0	16.0	95	83	2.6	138	18	86	0.63	—	323	—	537	19095
2	0.1	20	16.4	102	85	1.2	90	10	91	0.91	169	324	326[a]	406	16653
2	0.1	55	16.7	51	38	0.88	59	7.9	58	0.32	115	322	326	212	3749
2	0.5	20	17.4	53[b]	42[a]	0.90	50[b]	5.4	46[a]	0.26	56	330	301[b]	111[a]	3467[a]
2	0.5	55	17.3	31	24	0.62	41	4.9	21	0.12	24	323	269[a]	19.8	178[a]
2	0.8	20	17.9	54[a]	42[a]	0.86[a]	54[a]	6.0	56	0.16	25[a]	325	319	104[a]	1540
2	0.8	55	17.9	21	16	0.66	29	4.7	22	0.15	15	320	323	22.8	182[a]

Roever et al gr-qc/0609131
Cutler and Flanagan
Van den Broeck and Sengupta
Bose and Ajith 0901.4936

Orientation

Spin: Example of new parameter

- Coupling parameter (a)
- Transition vs SNR: localize parameters with loud sources, not otherwise



Example

vdS et al 0905.1323

What we can measure?

Example: Orbital phase (beta, sigma)

$$\begin{aligned}
\psi_f(t_f) &= 2\pi f t_{\rm ref} - \phi_{\rm ref} + \psi_N \sum_{k=0}^{5} \psi_k (\pi m f)^{(k-5)/3} \\
\psi_N &= \frac{3}{128\eta}, \quad \psi_0 = 1, \quad \psi_1 = 0, \\
\psi_2 &= \frac{5}{9}\left(\frac{743}{84} + 11\eta\right), \quad \psi_3 = -16\pi, \\
\psi_4 &= \frac{5}{72}\left(\frac{3058673}{7056} + \frac{5429}{7}\eta + 617\eta^2\right), \\
\psi_5 &= \frac{5}{3}\left(\frac{7729}{252} + \eta\right)\pi + \frac{8}{3}\left(\frac{38645}{672} + \frac{15}{8}\eta\right)\ln\left(\frac{v}{v_{\rm ref}}\right)\pi.
\end{aligned}$$

… if narrowband,

~ “modified η”

$$\begin{aligned}
v &= (\pi M f)^{1/3} \\
\Psi(f) &= 2\pi f t_c - \phi_c - \pi/4 \\
&+ \frac{3}{128}(\pi M_c f)^{-5/3}\left[1 + \frac{20}{9}\left(\frac{743}{336} + \frac{11}{4}\eta\right)v^2\right. \\
&-4(4\pi - \beta)v^3 \\
&10\left(\frac{3058673}{1016064} + \frac{5429}{1008}\eta + \frac{617}{144}\eta^2 - \sigma\right)v^4 \\
&+\left(\frac{38645\pi}{252} - \frac{65}{3}\eta\right)\ln v \\
&+\left(\frac{11583231236531}{4694215680} - \frac{640\pi^2}{3} - \frac{6848\gamma}{21}\right)v^6 \\
&+\eta\left(\frac{15335597827}{3048192} + \frac{2255\pi^2}{12} + \frac{47324}{63} - \frac{7948}{9}\right)v^6 \\
&+\left(\frac{76055}{1728}\eta^2 - \frac{127825}{1296}\eta^3 - \frac{6848}{21}\ln 4v\right)v^6 \\
&\left.+\pi\left(\frac{77096675}{254016} + \frac{378515}{1512}\eta - \frac{74045}{756}\eta^2\right)v^7\right]
\end{aligned}$$

$$\begin{aligned}
\beta &= \frac{\hat{L}}{M^2}\cdot[(\frac{113}{12} + \frac{25m_2}{4m_1})S_1 + (\frac{113}{12} + \frac{25m_1}{4m_2})S_2 \\
&= \frac{1}{12}[(113(m_1/M)^2 + 75\eta)\hat{L}\cdot\hat{a}_1 + (1 \leftrightarrow 2)] \\
\sigma &= \frac{\eta}{48}[-247\hat{a}_1\cdot\hat{a}_2 + 721(\hat{L}\cdot\hat{a}_1)(\hat{L}\cdot\hat{a}_2)]
\end{aligned}$$

What can we measure?

NS specific (hard)

Tidal disruption point (degenerate: a, EOS) Ferrari 2010 PRD 81 4026

Each event with EM counterpart:

EM emission vs

spin-orbit misalignment (beaming)

Masses, spins (~ disk mass; "central engine")

Host galaxy

Metallicity & star formation: past and present

Optical counterpart, non-afterglow [Metzger 2010]

r-process in mergers or not?

Ejecta, disk mass vs BH mass, spin

GW not required (just trigger)

Population:

M,m2/m1, |S| distribution (BH masses & spins)

EM counterpart: m1 vs Z : BH mass vs metallicity

spin-orbit misalignment (SN kicks)

Rate (common envelope, etc)

What can we **eventually** measure?

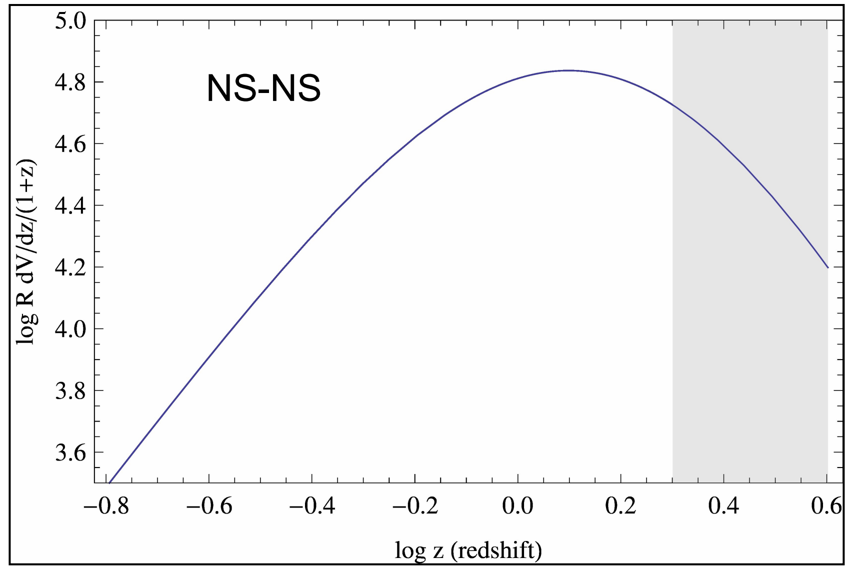
Third-generation: tomography

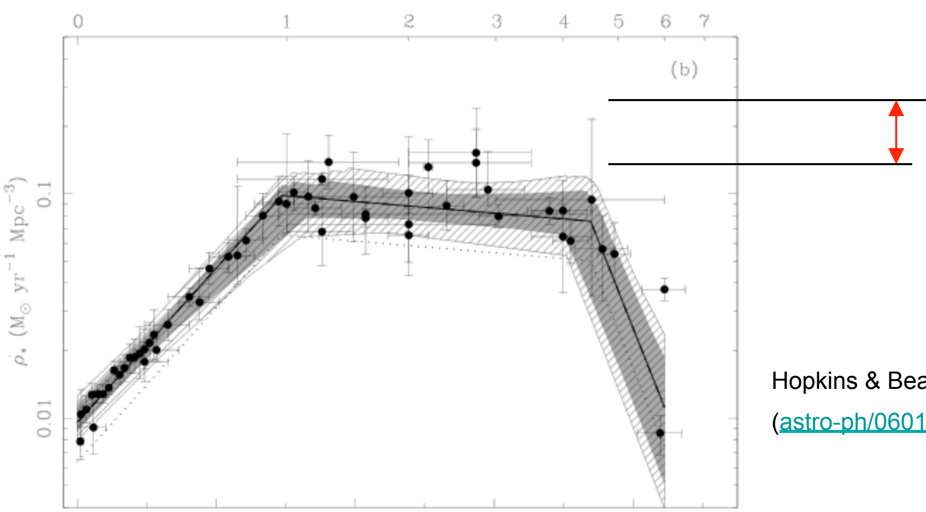
Example: NS-NS:

- dVolume(z)* rate(z)/(1+z)
  = “rate per redshift bin”

- O(10^5-10^6) detections
  - **Rate** vs distance
  - **Mass distribution** vs distance

- Reach ~ peak SFR





~ x2

Hopkins & Beacom ApJ 651 142 2006

(astro-ph/0601463): Fig. 4

Mass distribution versus redshift

Example: BH mass (via BH-NS)

Idea: Chirp mass traces BH mass

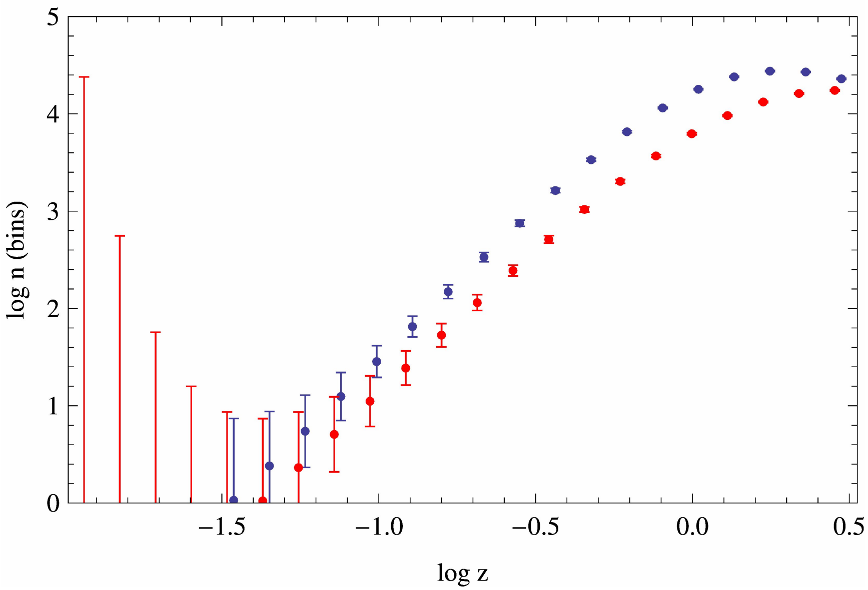
Typical BH mass evolves with z

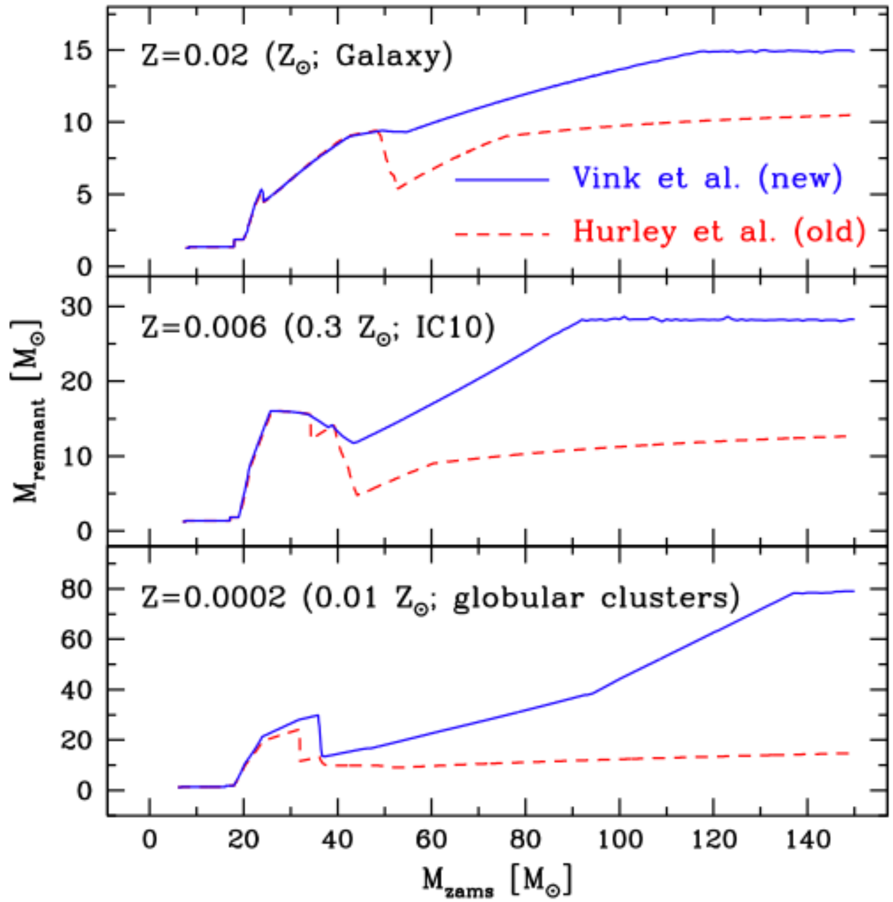
Qualitative:

O(10^4/bin) -> O(1%) accuracy!

Important!: Metallicity evolves, irregular

Initial->final relation uncertain (winds)





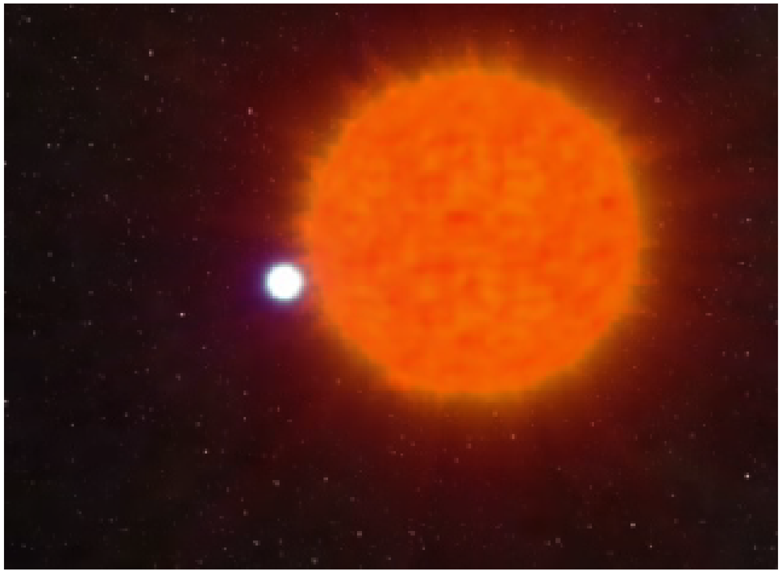
Belczynski et al 0904.2784

Formation model

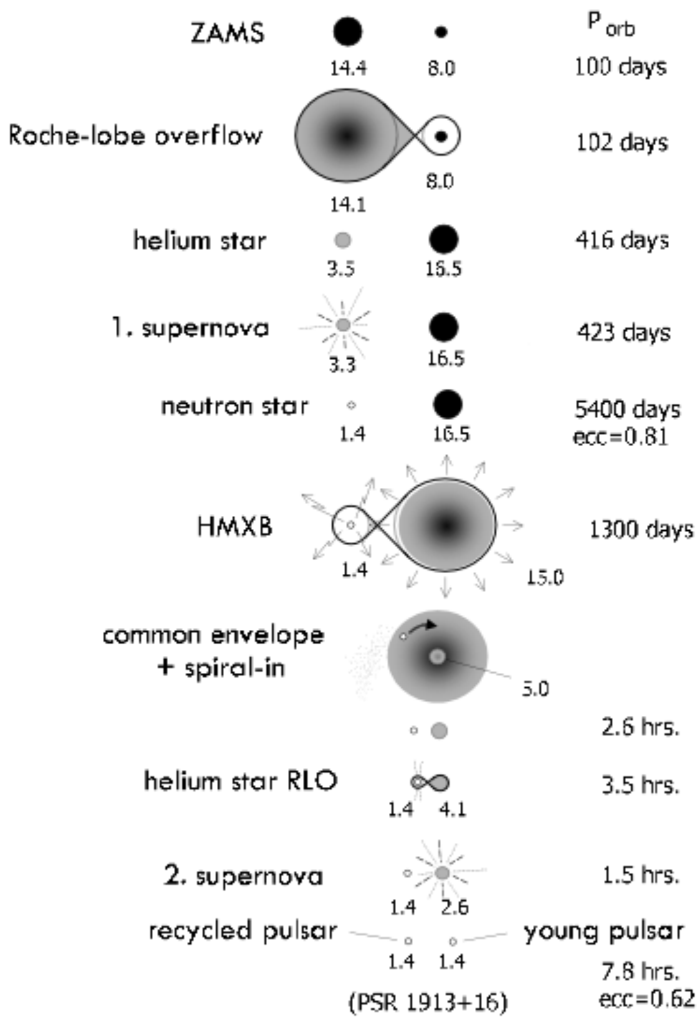
Isolated binary evolution

Outline of typical evolution

- –Evolve and **expand**
- –Mass transfer (perhaps)
- –Supernovae #1
- –Mass transfer (perhaps)
- –Supernovae #2



Movie: John Rowe



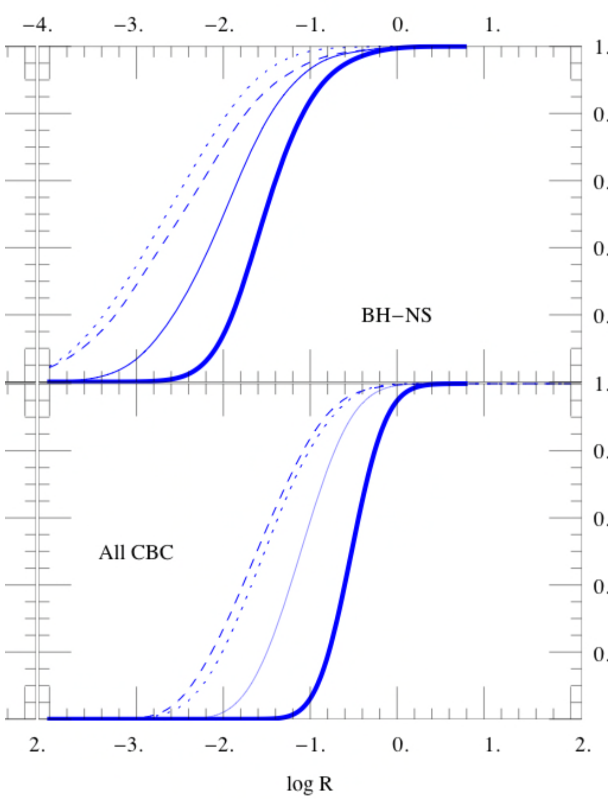
Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

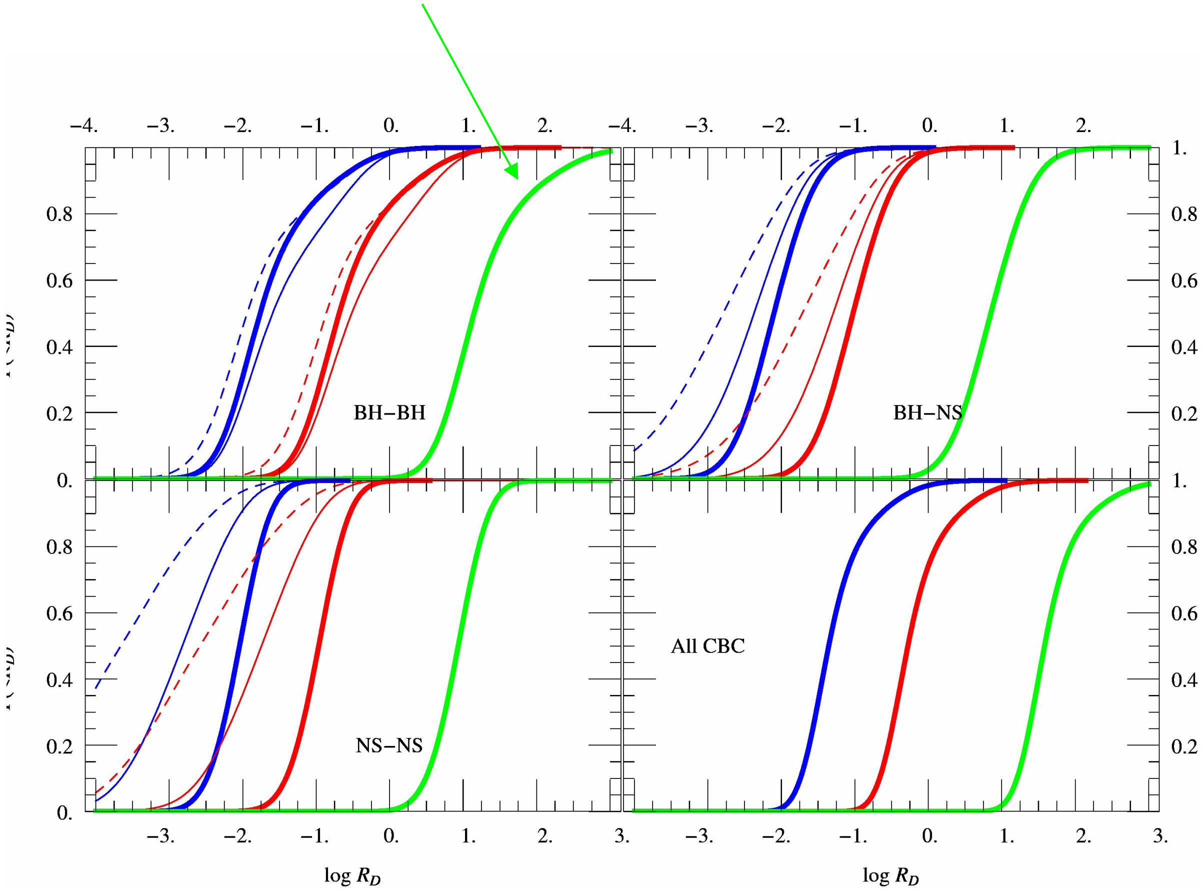
Predicted merger,GW detection rates

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

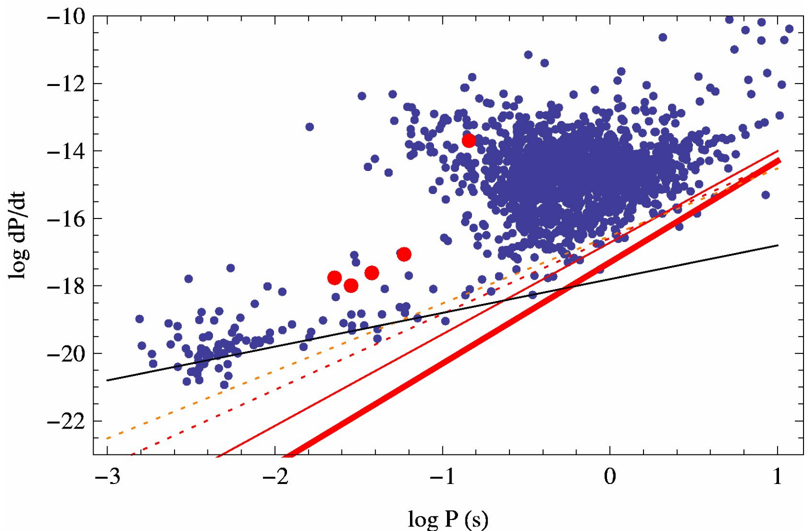
Example: Hulse-Taylor

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

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

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

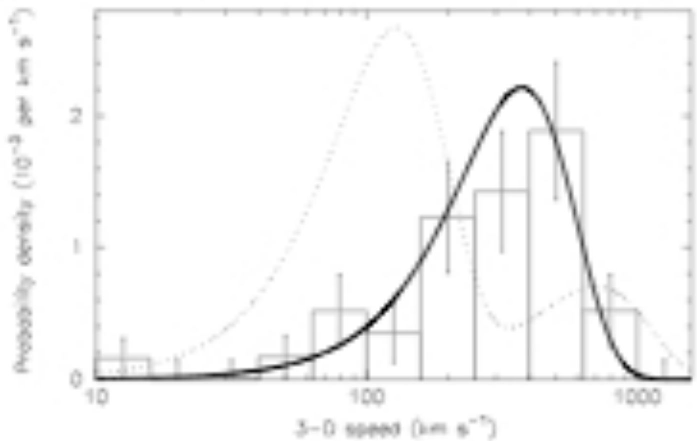
Formation model unknowns

- <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)

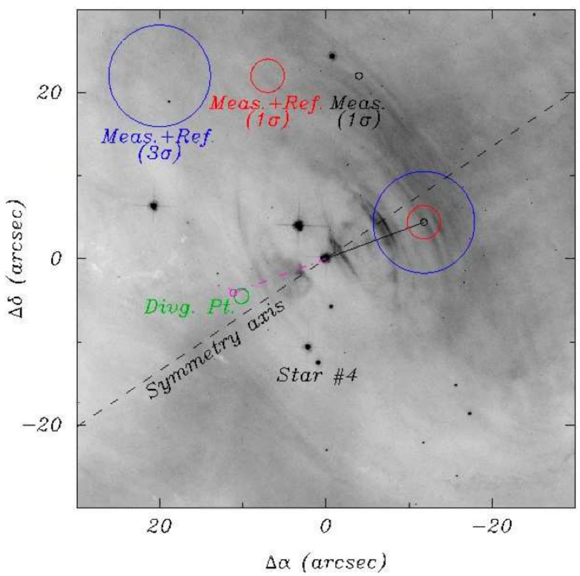
Impact for us:

huge rate reduction b/c never “kicking closer”

Kuranov et al 0901.1055; Postnov & Kuranov 0710.4465

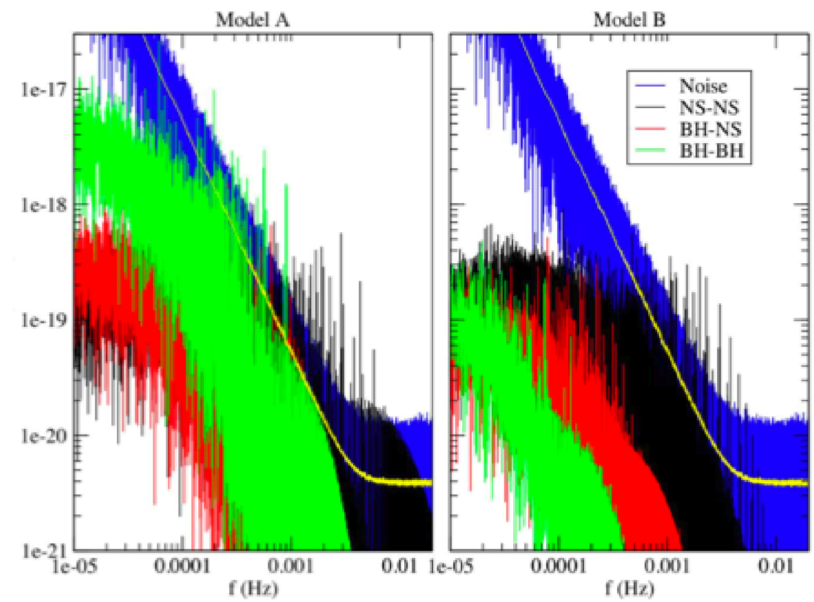
<u>Group</u>:<u>not explored extensively now</u>; could be

Crab motion

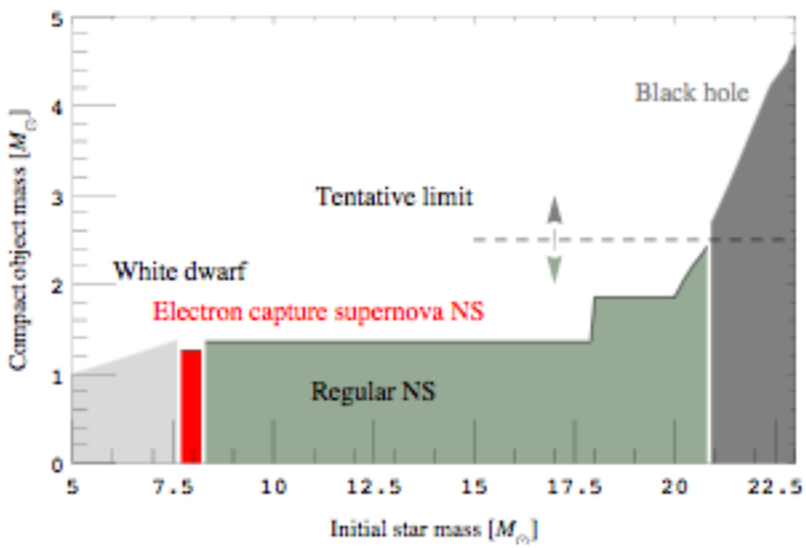


Formation model unknowns

- 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



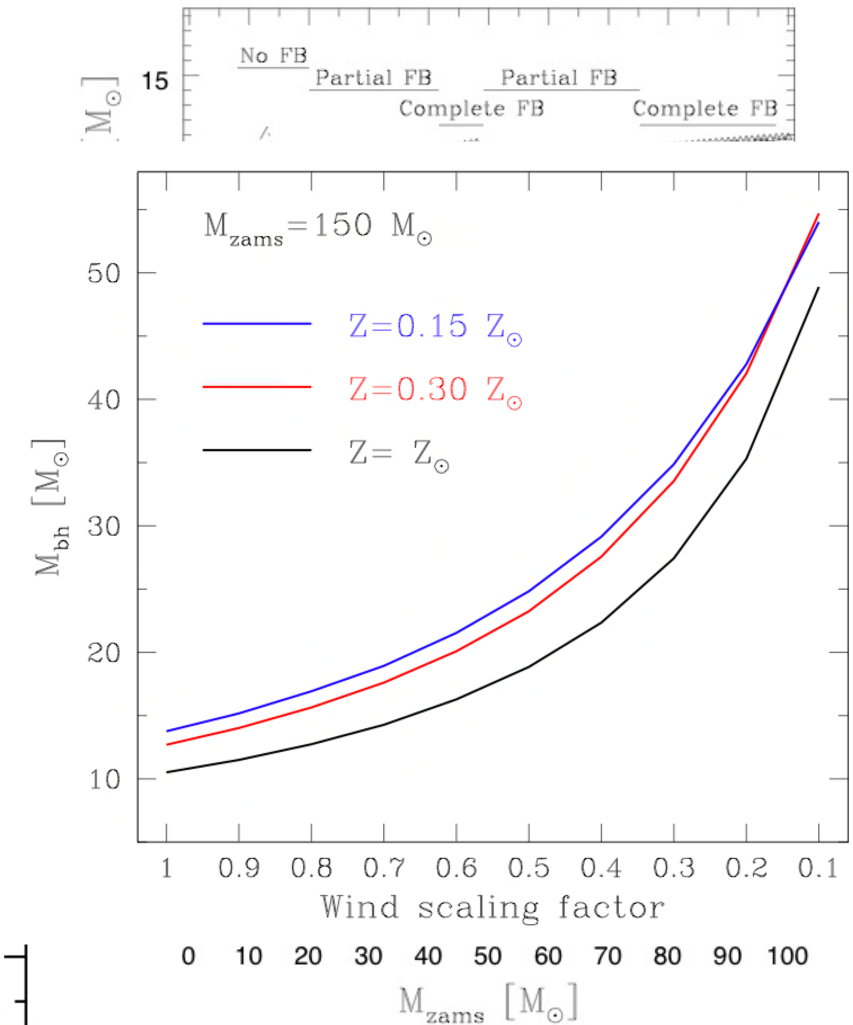
Belczynski, ROS, et al ApJ 680 129

Formation model unknowns

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

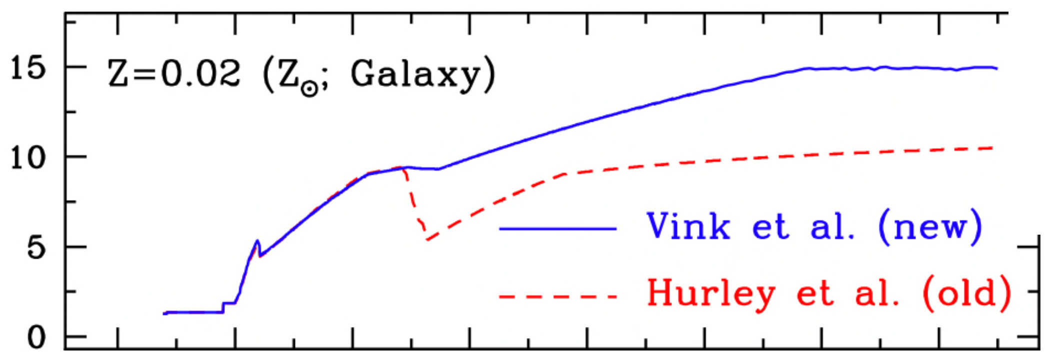
  Strong effect on star->BH mass

  Recent update



Belczynski et al 2002

“original” winds + scale factor

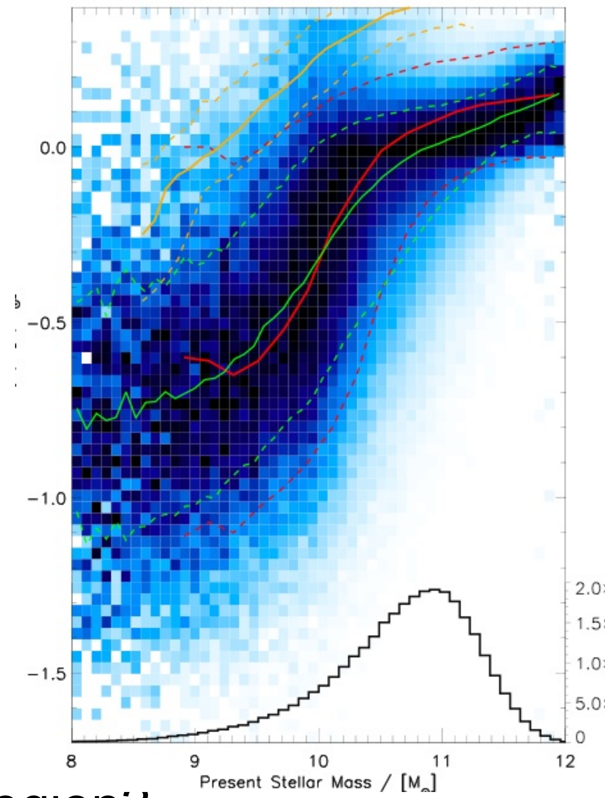


Belczynski et al 2009

“revised” winds

Formation model unknowns

- Evolution model
- Supernova kicks
- Winds
- Metallicity distribution: (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]

Merger physics

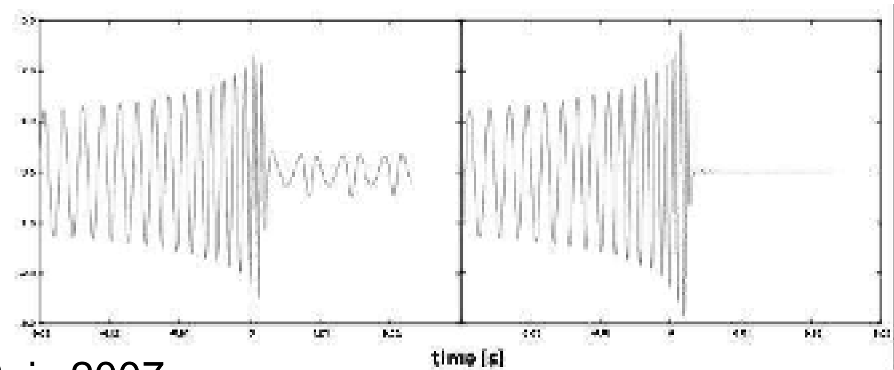
Tidal disruption point

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

Sloshing of hypermassive transient/remnant disk

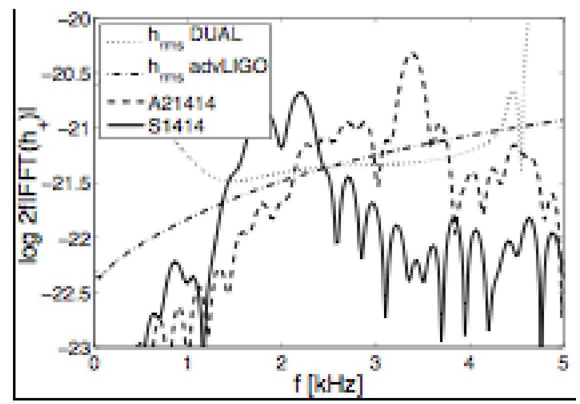
Not in band

Weak

- need implausibly close (20 Mpc)

+ aLIGO

Oechslin and Janka PRL 99 1102 (2007)



Tidal-orbit coupling

Change **early** part of signal Flanagan and Hinderer, PRD 75 1502 (2008)

Limit "Love number" : aLIGO can weakly constrain

What can we learn?

Does gravity violate parity? [Yunes, ROS et al arXiv:1005.3310]

- Many theoretical GR extensions add "Chern-Simons" parity-violating term

$$S = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\left(R + \frac{1}{4}\theta\,\mathbf{R}\,{}^*\mathbf{R} + (\nabla\theta)^2 + V(\theta)\right)$$

- Weak effect: **preferrred handedness** : amplifies over cosmological distances

- Test:
  - Short GRB: source of circularly polarized GW of "known" amplitude (if host known)
  - Test if any source (or population of all L, R handed) agrees with predictions:

$$\begin{aligned}\frac{\rho^2}{\rho^2_{GR}} &= 1 + 2\,\langle v\rangle \\ &= 1 + 2\,\langle f\rangle\, D\pi\,\frac{\delta(\dot\theta/a)}{\delta D}\end{aligned}$$

$$\frac{\delta(\dot\theta/a)}{\delta D} \equiv H_o\dot\theta q$$

$$q \simeq O(1)$$

  - Only propagation test. Better than (non-propagating) solar system tests

What will we learn?

Example: Reproduce # of MW NS-NS binaries

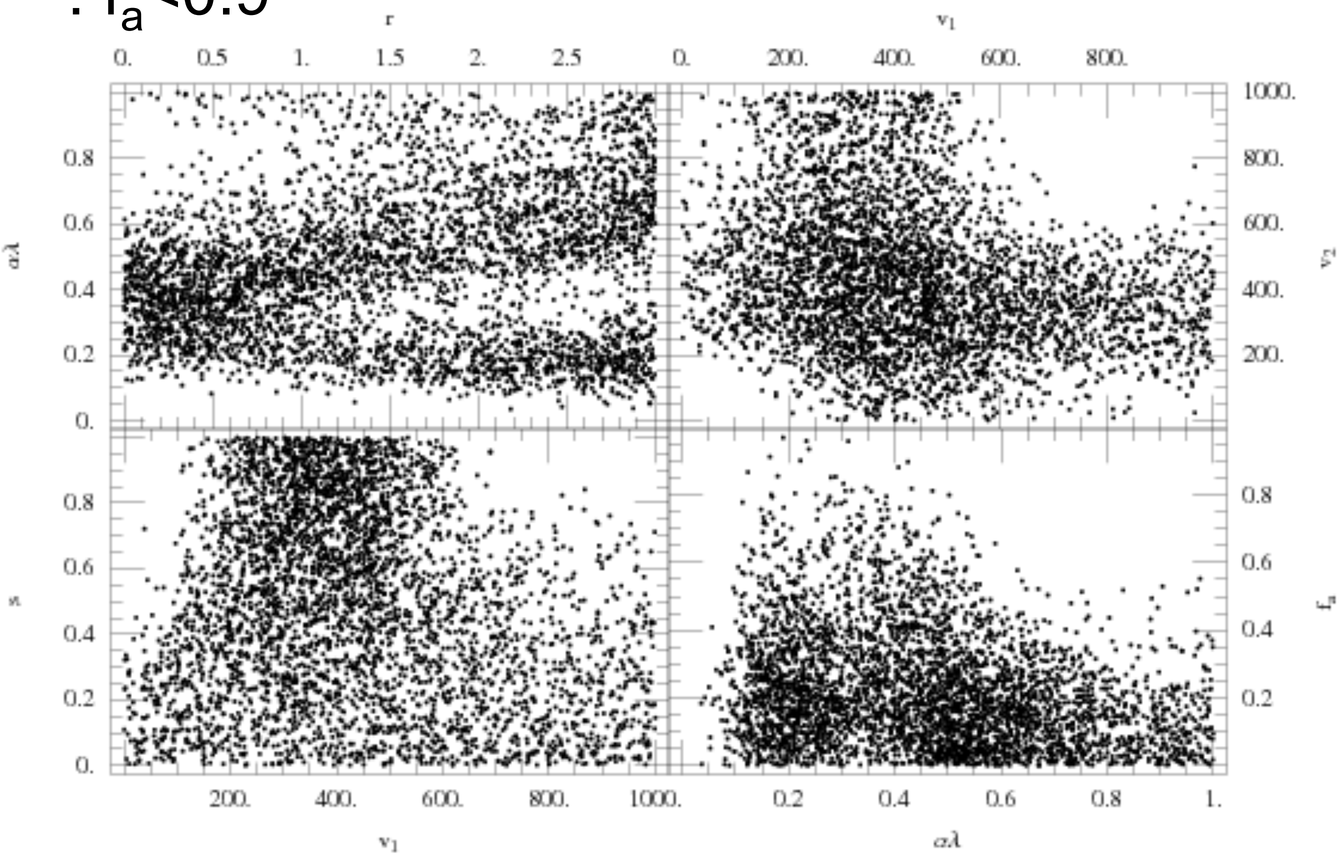
- Not all parameter combinations allowed

Examples:

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

ROS et al astro-ph/0610075

Lots of physics in correlations



..similarly for GW detections with **first few**

What will we learn?

First O(30) detections:

- What are the masses, spins of BHs at birth?
- Are some short GRBs BH-NS mergers? If so,
  - how does the central engine work?
  - What trends with host Z?
- Roughly what processes make them?
- Is there weak gravitational parity violation? MOND? Graviton mass? Modified gravity in strong field?

Third generation:

- Mass, spin distributions versus redshift
  - EM counterpart: confirm trends with host Z
- What progenitor-model parameters reproduce the observed population?

What will we learn?

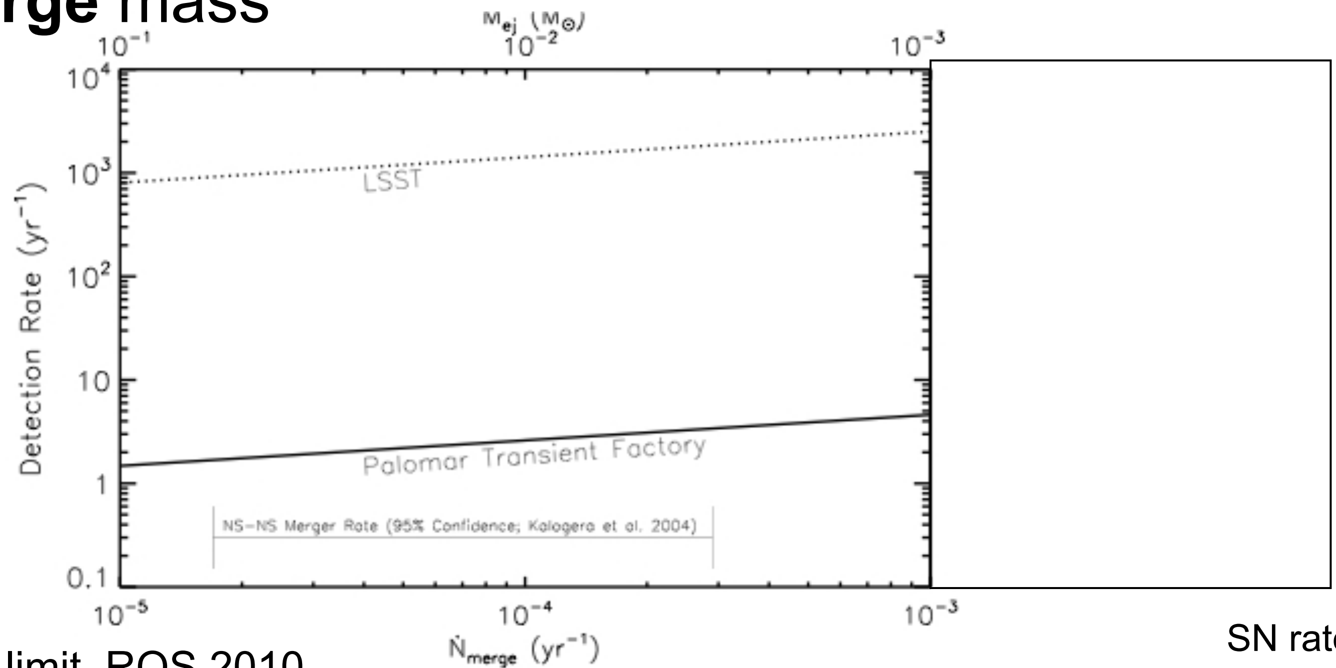
R-process via mergers?

- Bright, isotropic EM counterparts expected [Metzger 2010]
- Easy to see with transient sky surveys (PTF; LSST)
- Detection rate ~ constant; set by average r-process dM/dt from mergers

If all r-process from mergers

$$10^{-6} M_\odot/yr = dM/dt = \langle R_{mgr} M_{ej} \rangle$$

Large mass

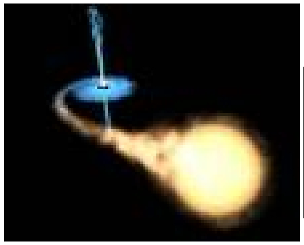


Upper limit, ROS 2010

SN rate

Spin?

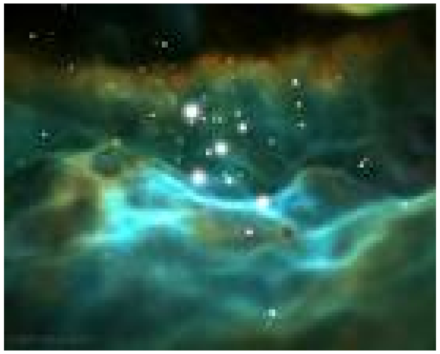
Alignment = signature!



Isolated binaries
Aligned spins

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

+ astro-ph/0610076; 0609465; 0504479



Star forming gas

Interacting clusters' stellar mass binaries
Random spin alignment

<u>References include</u>
• Sadowski et al 2008
•O' Shaughnessy et al PRD 76 061504
O' Leary et al astro-ph/0508224

Conclusion

- Gravitational waves turn BH-NS population from mystery to tool:
  - Known population

  -> Better known formation process

  -> Constrained GRB engine, nuclear matter, r-process

  -> “Standard candle” enabling pure-GR tests

Even valuable by their absence…

Quiz: GRB 070201

Quiz: GRB 070201

Overlaps M31

($d<1Mpc<<d_{LIGO}$)

What could you learn if

– Detection?

– No detection?

- Could be farther away merger
- Could be non-merger in M31

Point: GW from BH-NS isolate multiple GRB progenitors!

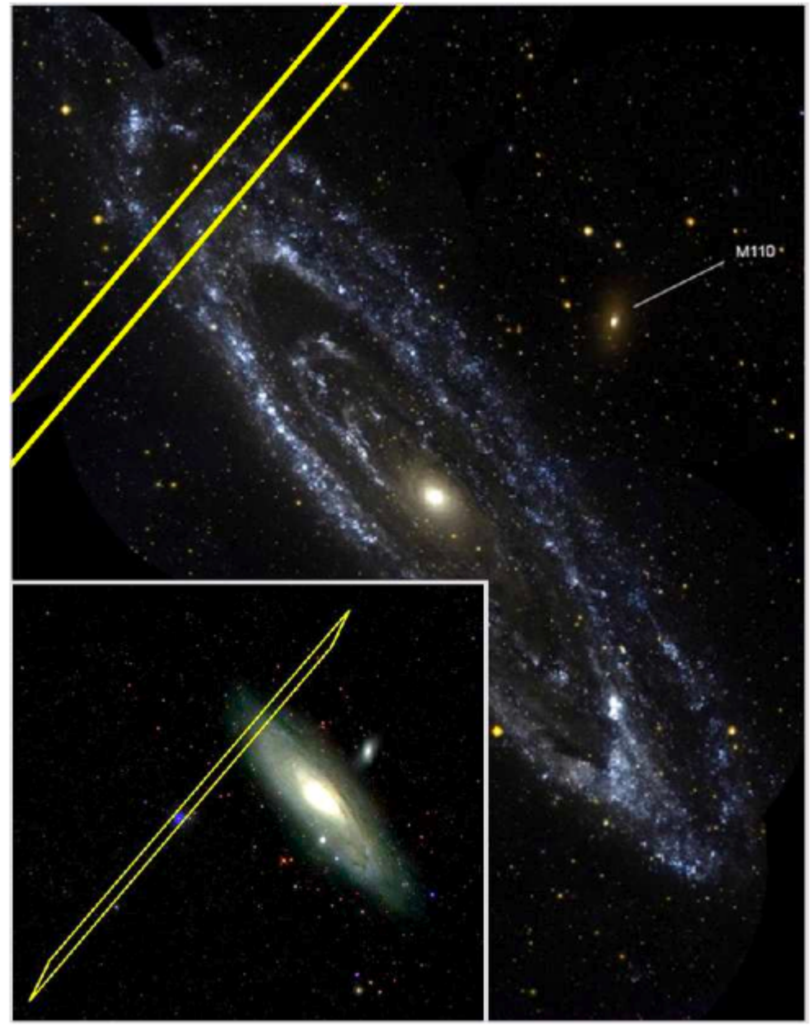
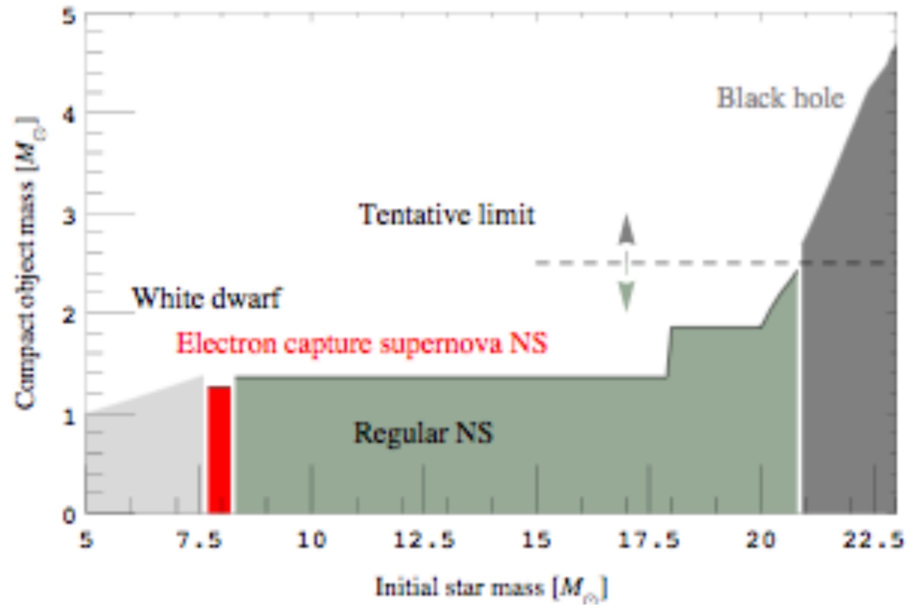


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

HOLDING MATERIAL

Masses of compact remnants



Theory

- Most NS born ~ 1.4 M_o [Fryer & Kalogera 2001; Timmes, Woosley, & Weaver 1996]
- Final compact mass ~ constant [Timmes et al 1996]
- Small fraction at higher masses
- Accretion (binary evolution) rarely increases mass much [Belczynski et al 2006]

…all standard

Young/proto NS models

Excellent multimessenger candidate:

EM, GW, neutrino signatures

GW emission modes:

Magnetar Perturbations (crust/EM: Duncan-Thompson)

_______…K. Kokkotas talk

+ LIGO SGR storm paper 0905.0005

NS merger-> hypermassive: (Shapiro; Rezzolla; …)

- Disruption radius & EOS [Faber; Read; ..]
- Bar modes of remnant
- Caveats: B field; neutrino cooling

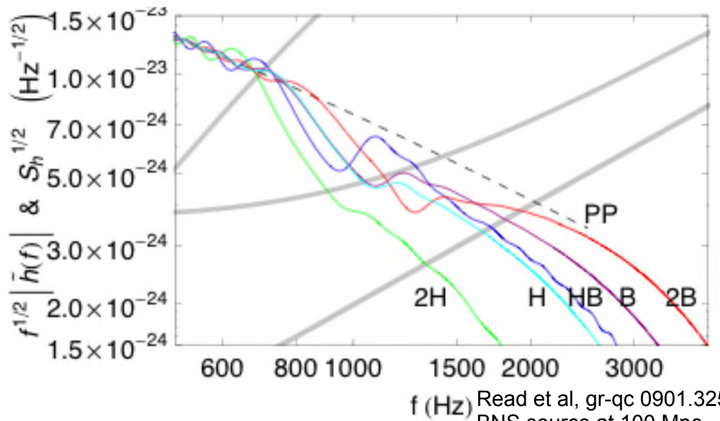
AIC: WD->NS:

- Very like SN:
  - 1-parameter family vs rotation
- Observations constrain mechanism (not EOS)

Problem: Short GW range

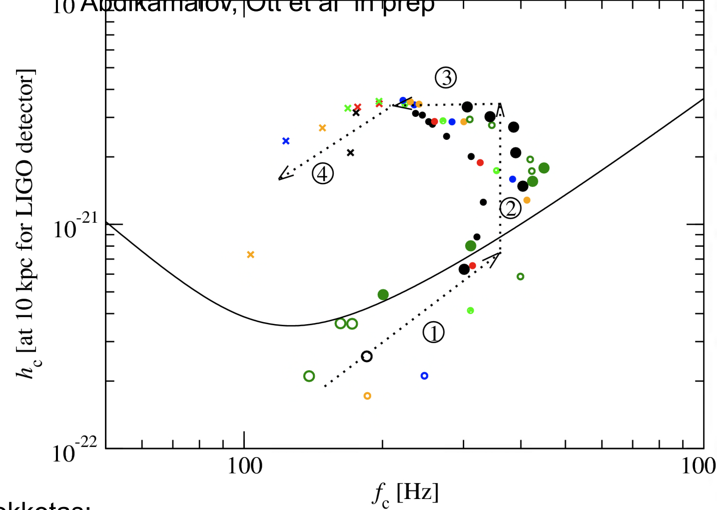
Range low -- often only MW…hard

Not all short GRBs



Read et al, gr-qc 0901.3258
BNS source at 100 Mpc
aLIGO and ET shown

Abdikamalov, Ott et al in prep



Further references

–*Isolated NS modes*: Kokkotas;
LIGO SGR papers : 0808.2025; 0905.0005
LIGO GRB 070201: 0711.1163

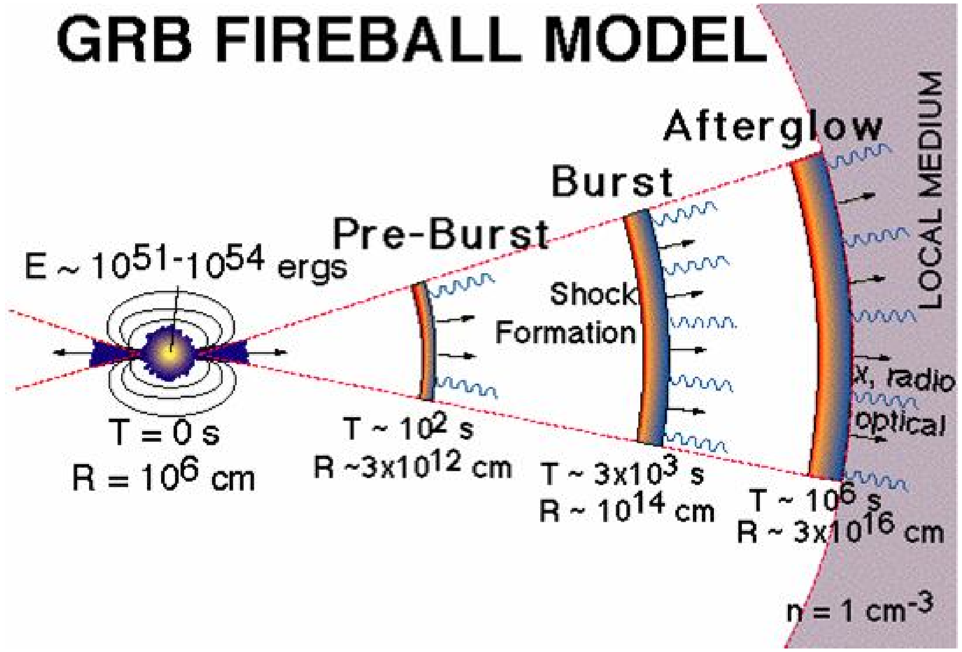
– *Isolated proto-NS (merger/AIC):* Thompson talks;
Metzger et al 0712.1233; Dessart et al 0705.3678

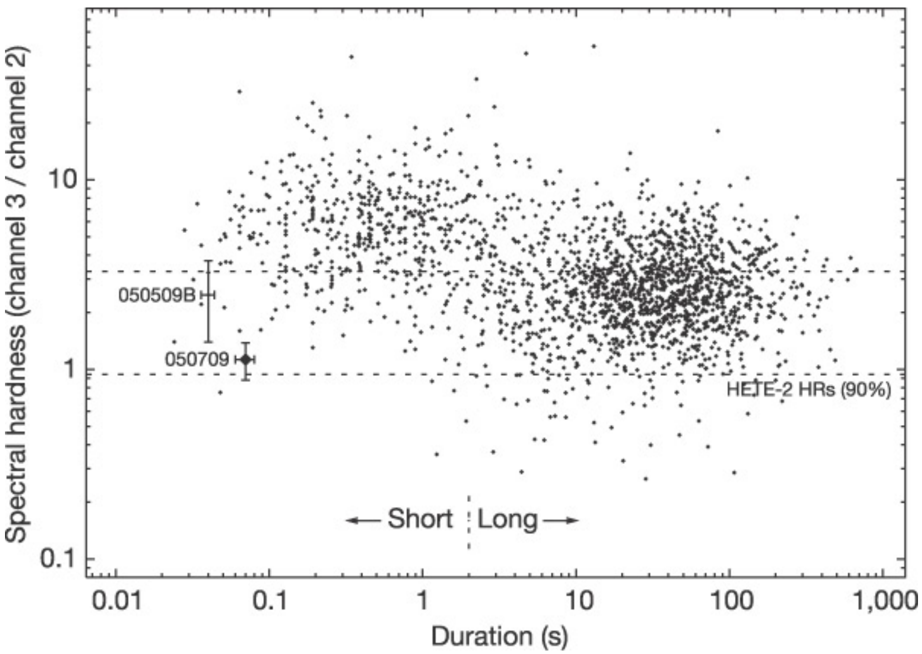
–*NS mergers:* Read et al & refs therein

Short GRBs: Review

GRBs generally

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





Two classes

Swift website

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

Short : ….

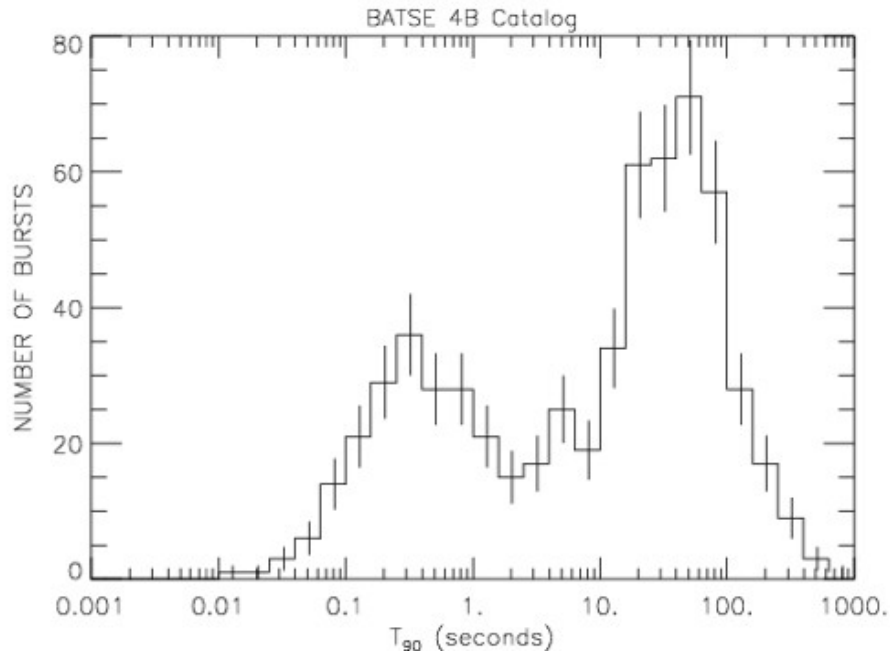
Short GRBs: Review

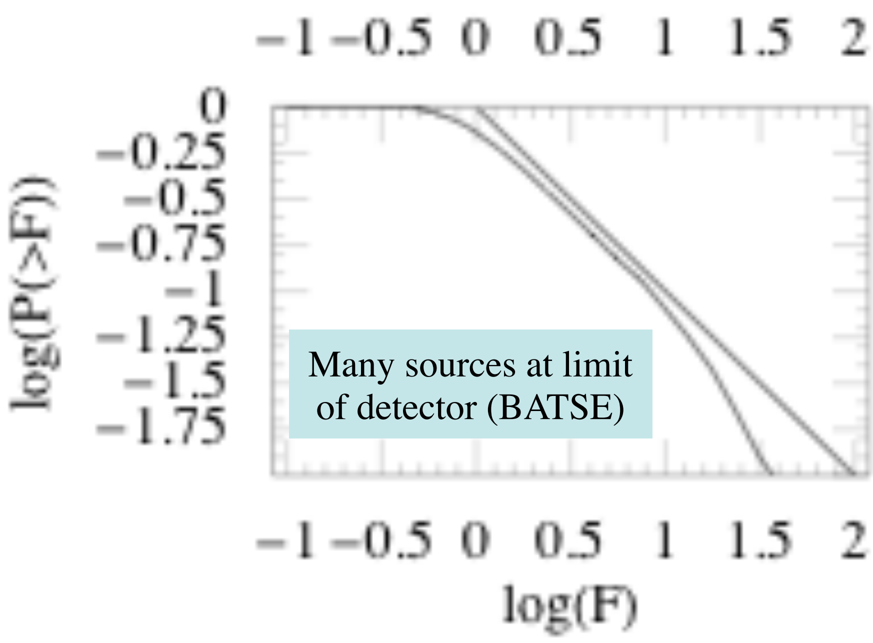
Short GRBs (BATSE view)

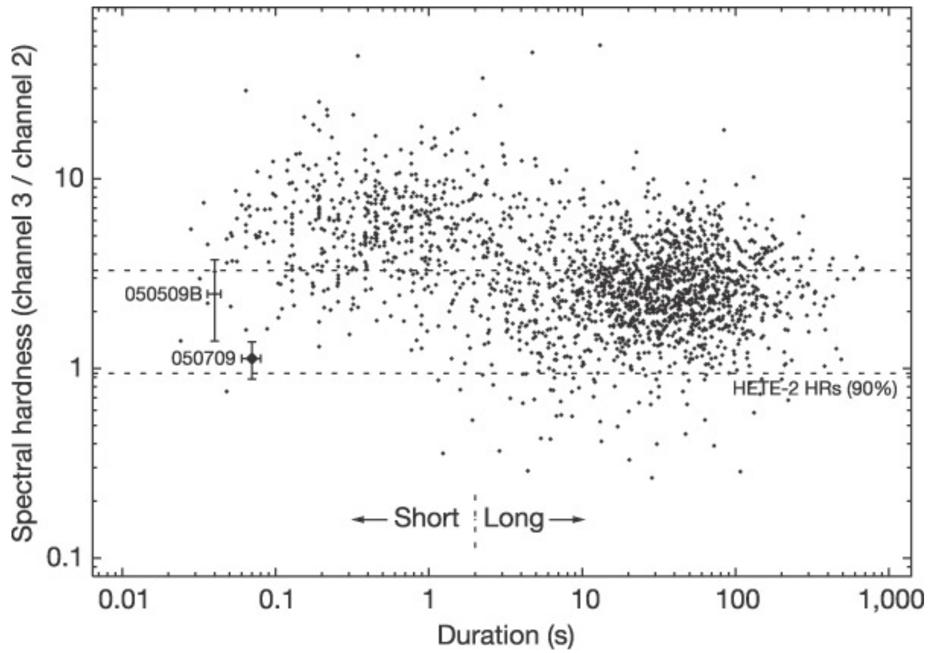
- Cosmological
- One of two classes
- Hard: often peaks out of banc
- Flux power law

$dP/dL \sim L^{-2}$

--> **most** (probably) **unseen**



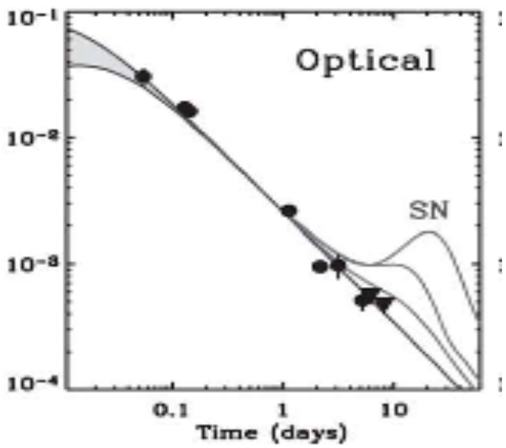




Short GRBs: Review

Merger motivation?

- No SN structure in afterglow



GRB 051221 (Soderberg et al 2006)

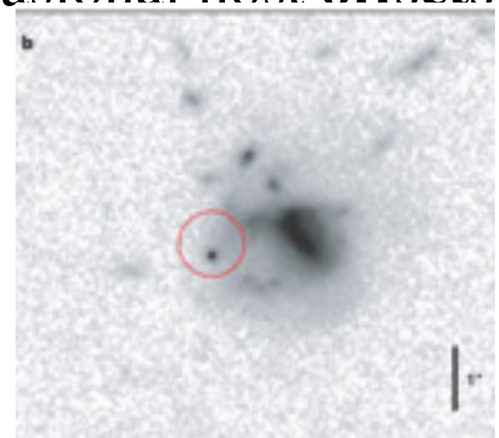
- In both **old**, young galaxies

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

Short GRB event rates?

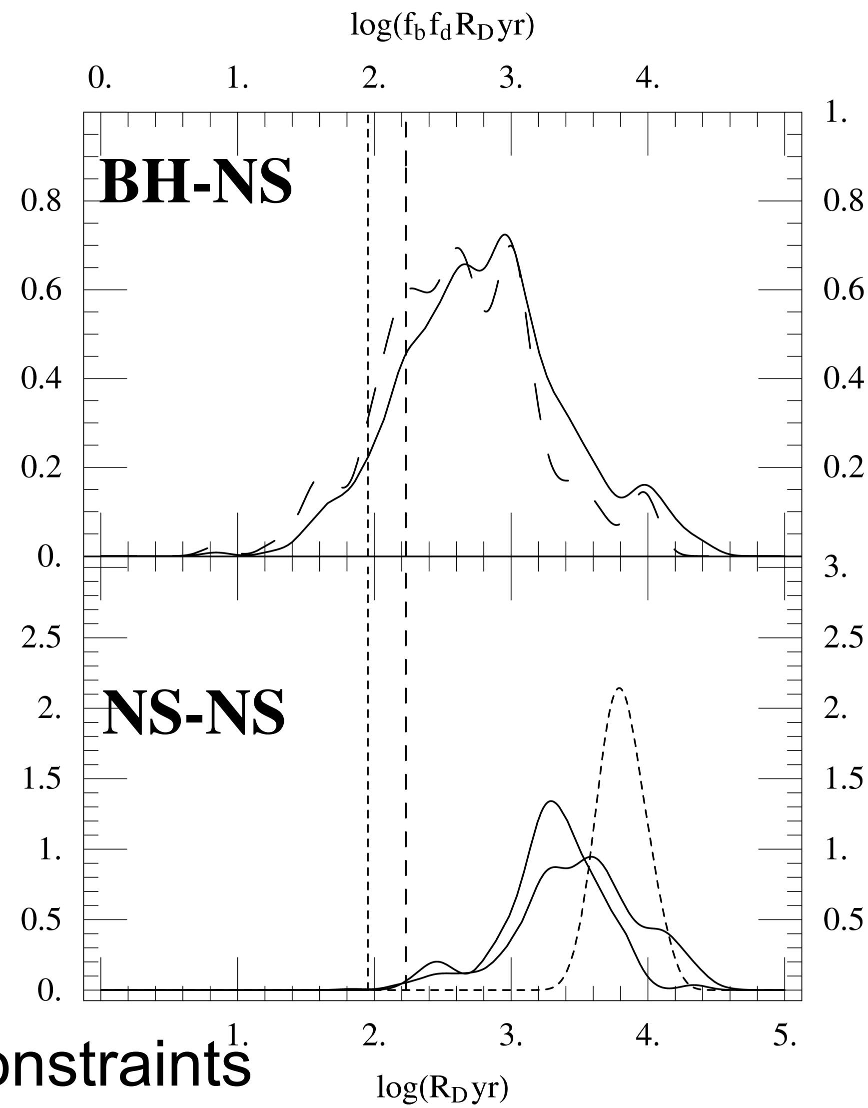
Luminosity & beaming

Method:

- Ratio (triggered/blind)~
  "Fraction that aren't seen"
  ~ low limit of luminosity function
  & beaming

Plot:

- Expected all-sky sGRB detection rates
  If none fainter & no beaming
- Ratio between dotted line,
  model =>
  Reduction factor:
  beaming + luminosity

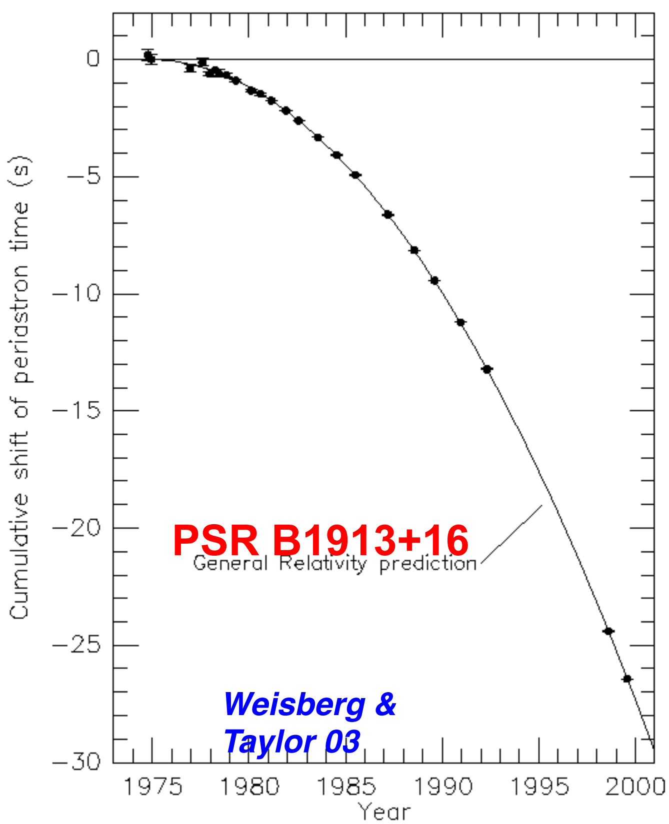


…application of GW+GRB rate constraints
degenerate w/ beaming, luminosity

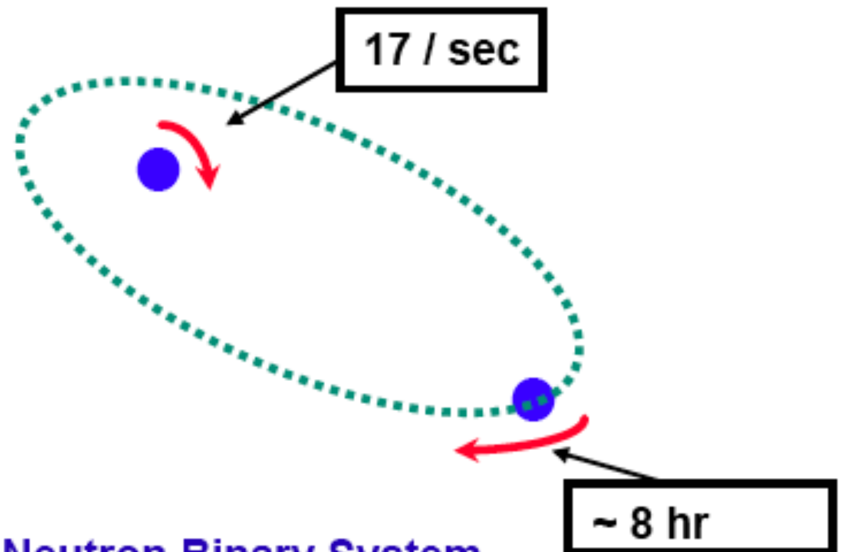
O' Shaughnessy et al 0706.4139

Event rates: Empirically

- <u>Hulse-Taylor binary</u>: (Nobel Prize, 1993)



PSR 1913 + 16 -- Timing of pulsars



<u>Neutron Binary System</u>

- separated by 10^6 miles
- $m_1 = 1.44m_{\odot}$; $m_2 = 1.39m_{\odot}$; $\varepsilon = 0.617$

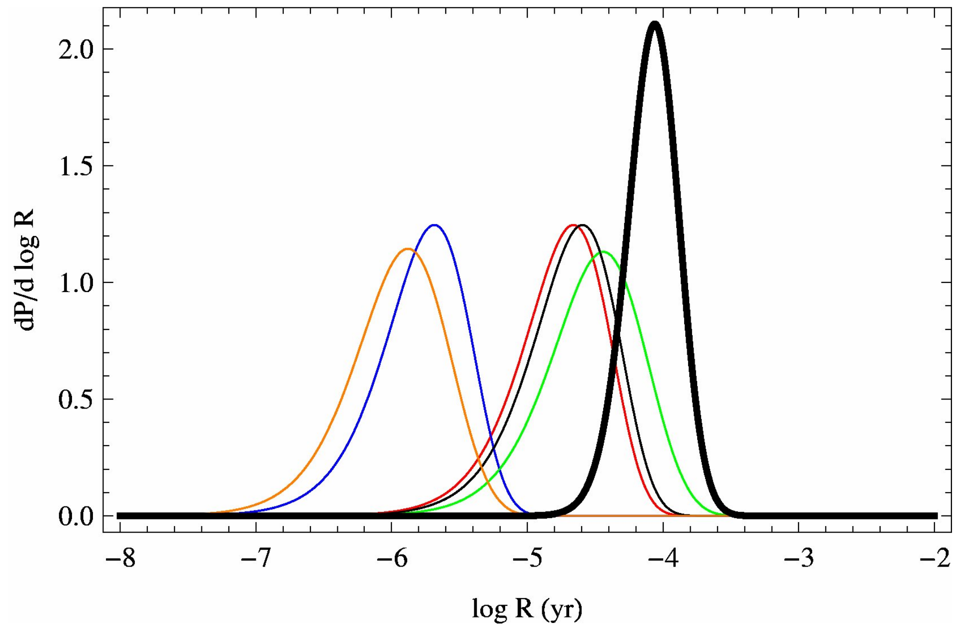
<u>Prediction from general relativity</u>

- spiral in by 3 mm/orbit
- rate of change orbital period

Event rates: Empirically

PSR statistics

- Known selection bias
- Model for
  - Luminosity
  - MW distribution
  - Beaming
  - Lifetime…



NS-NS merger rate in Milky Way
ROS and Kim, in prep; see also
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)

…see Ilya Mandel's talk yesterday

Event rates: Short GRBs

sGRB coincident signals?

Overall: O(70-200/yr) all sky (above BATSE/Swift photon count cut cut)

Estimate: Roughly **uniform** in z : **luminosity function**

Horizon range limits (aligned)

$$\begin{aligned} R_{GRB+GW} &\simeq D_{LIGO} H_o \frac{R_{GRB}}{\Delta z} \\ &\simeq 0.1 R_{GRB} \simeq O(7-20/\mathrm{yr}) \\ &\simeq 0.2 R_{GRB} \simeq O(14-40/\mathrm{yr}) \end{aligned}$$

cf Dietz 0904.0347
Beware short-distance/
low-L extrapolation

HOLDING MATERIAL: PARITY VIOLATION