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

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

Astrophysical constraints on BH-NS and NS-NS mergers and the short GRB redshift distribution

Richard O'Shaughnessy

U. Chicago, KICP

Feb 23, 2007

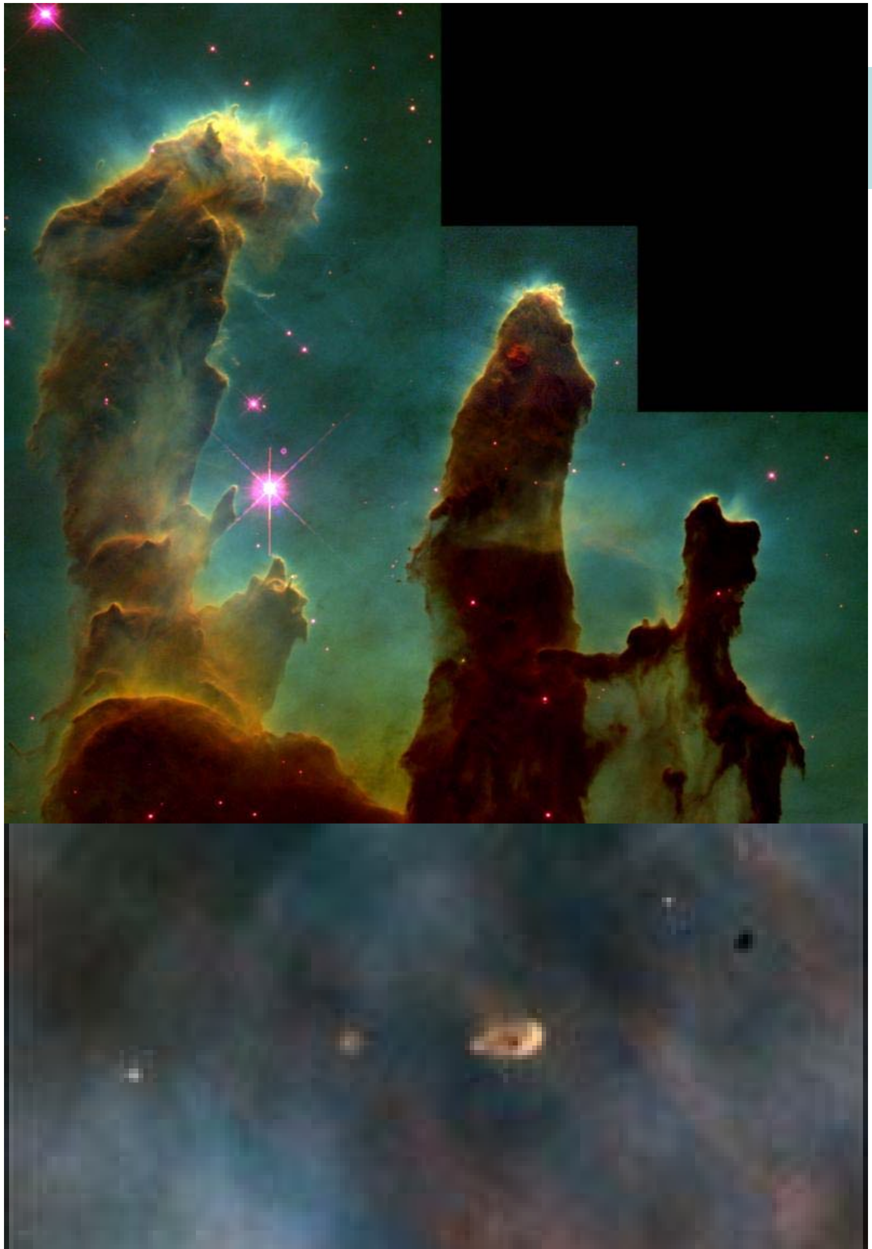
Outline

- Gravitational Wave Searches for Binaries
- How to Make Compact Binaries
  - Population synthesis
- Predictions and Constraints: Milky Way
  - Comparing predictions to observations
  - Physics behind comparisons : what we learn
  - What if a detection?
- Why Ellipticals Matter
  - Two-component star formation model
- Predictions and Constraints Revisited
  - Prior predictions
  - Reproducing Milky Way constraints
- Short GRBs
- Conclusions

Collaborators

• V. Kalogera	Northwestern
• C. Kim	Cornell
• K. Belczynski	New Mexico State/Los Alamos
• T. Fragos	Northwestern
• J. Kaplan	Northwestern
• LSC	(official LIGO results)

Big Picture



EM Waves

Source:

~any accelerating charge

Strong coupling:

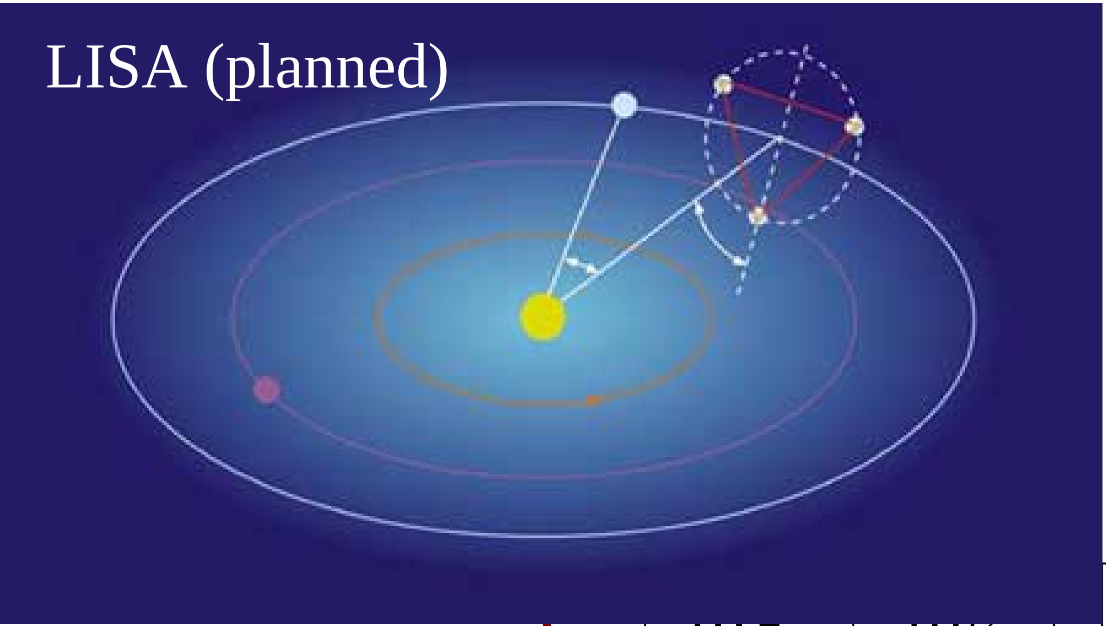
Imaging often practical:

(common sources)

>> wavelength

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

Big Picture: Spectrum



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)

Big Science Payoff

<u>Test GR (in detail)</u>

- Orbits agree — EMRI mergers
- Spacetime agrees — EMRI mergers

<u>Cosmology</u>

- Trace galaxy mergers? — Binary mergers
- Waves from inflation? — Stochastic

<u>Nuclear physics</u>

- Compressibility of nuclear matter — NS disruption, NS surface bumps

<u>Supernovae</u>

- Constrain asymmetry and kick — Supernovae bursts, Binary mergers
- Spin imparted? — Binary mergers

<u>Stars near galaxy centers</u>

- Capture rates

<u>Small compact binaries</u>

- Map all faint, close (“white dwarf”) binaries
- Mass transfer, tidal coupling,

<u>Understand stellar evolution</u>

- Mass transfer rates — Binary mergers
- Maximum NS mass — Binary mergers

<u>Reveal mystery : GRB engines</u>:

- Hypermassive NS?
- Merger-driven?

…and much more

Small effect at earth!

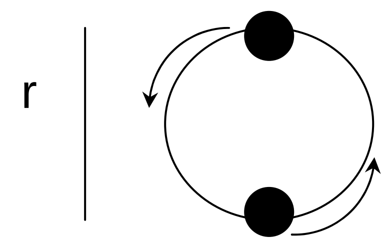
- **Example**:

Two black holes

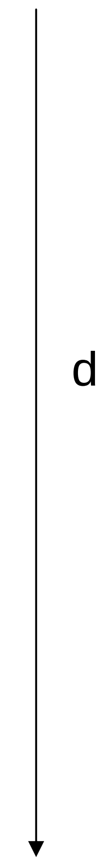
Newtonian circular orbit

$$f = 2 f_{orb} = 2(\Omega / \pi)$$

$$f = 10^3\, Hz (M / 8M_o)^{-1} (r / 6M)^{-3/2}$$



$$\Omega \sim \sqrt{M / r^3}$$



- **Characteristic relative length changes**

~ (kinetic energy)/(distance)

$$h \sim \frac{1}{d}\frac{d^2 I}{dt^2} \sim \frac{Mv^2}{d} \sim \frac{M}{d}(M$$

$$h \sim 10^{-21} (M / 8M_0)^{5/3} (d / 3$$

<u>Sensitivity needed? (LIGO)</u>

ΔL ~ h L ~ 10^{-21} 4km

~ 4 x 10^{-16} cm

laser light ~ 10^{-4}cm

atom ~ 10^{-8}cm

proton ~ 10^{-13}cm

Sensitivities of detectors

- **Present sensitivities: LIGO**

Reached

~ design sensitivity

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

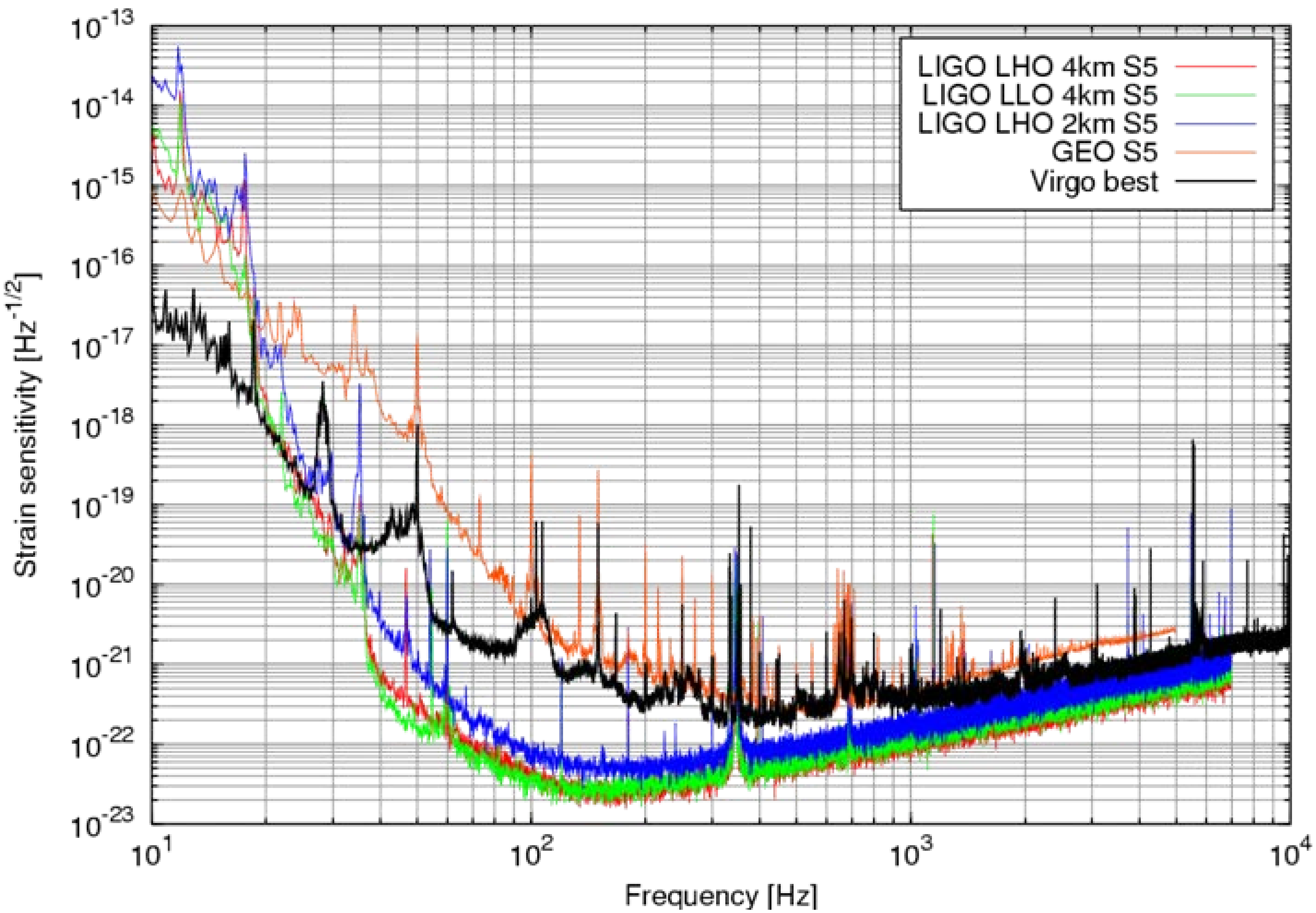
LIGO:

- at target
- **taking data** (~2 calendar yr)

LIGO sensitivity page

Sensitivities of detectors

- **Present sensitivities: Others**



GEO

- at target
- much less sensitive

VIRGO

- near target
- target: noise < LIGO at low, high f

Valiente, GWDAW-11

Sensitivities of detectors

- Lots of astrophysically relevant data:

Example: Average distance to which 1.4 M_O NS-NS inspiral range (S/N=8) *visible*

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

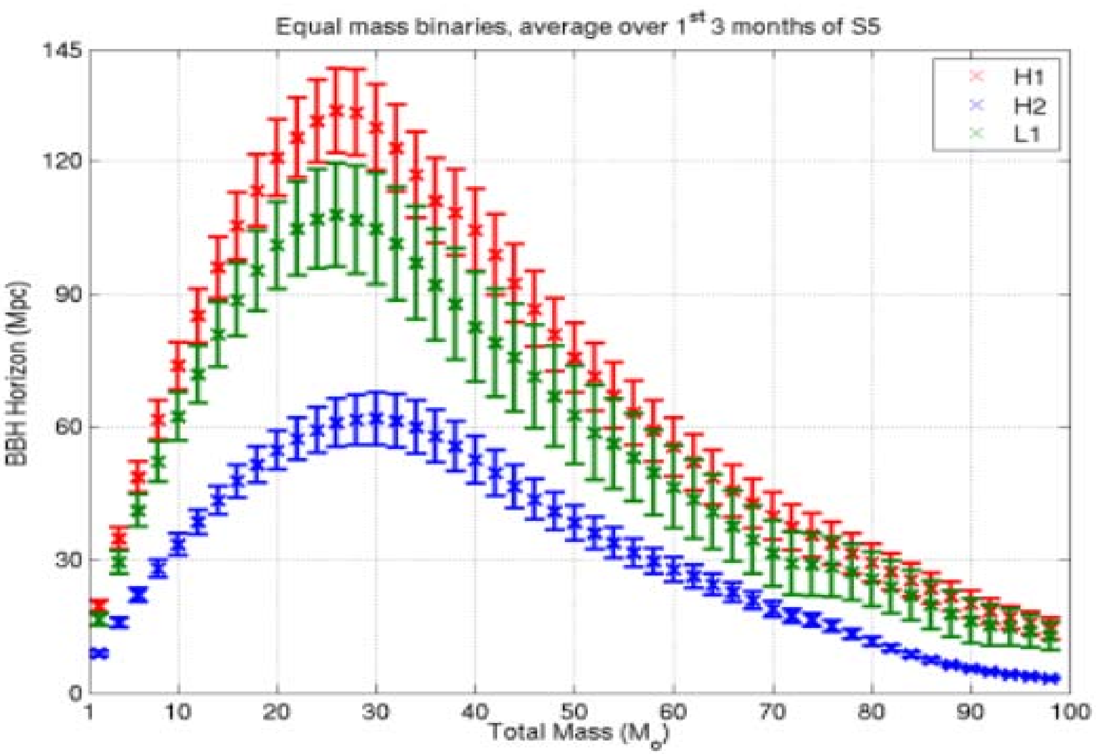
Marx, Texas symposium

Sensitivities of detectors

Range depends on mass

- For 1.4-1.4 M_o binaries, ~ 200 MWEG (# of stars <-> our galaxy) in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range
- <u>Plot</u>: Inspiral horizon for equal mass binaries vs. total mass

  (horizon=range at peak of antenna pattern; ~2.3 x antenna pattern average)



…using only the
'inspiral signal' (=understood)
• no merger waves
• no tidal disruption influences

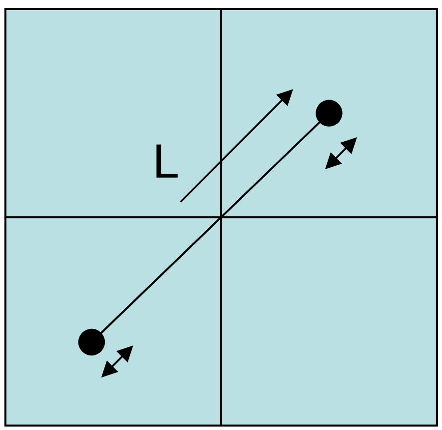
Gravitational plane waves

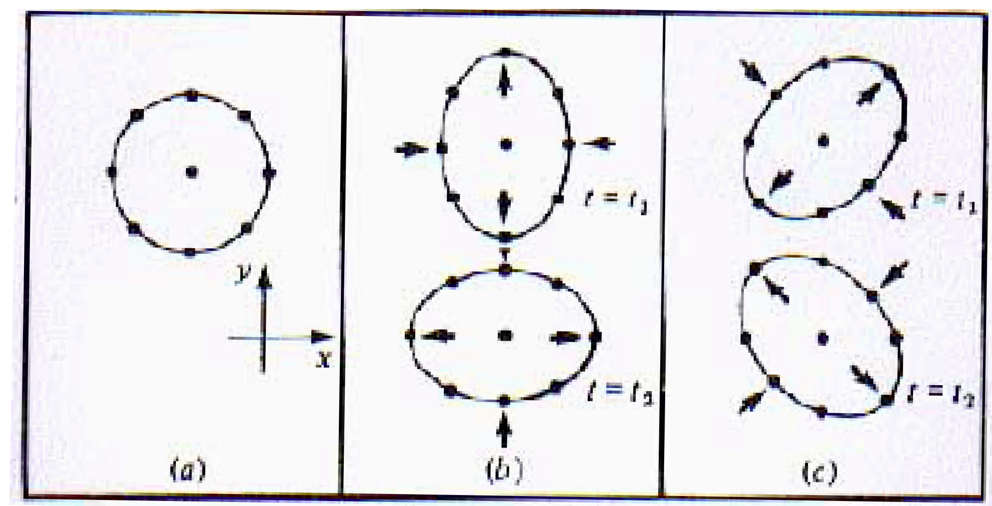
- Stretching and squeezing
  Perpendicular to propagation
- Two spin-2 (tensor) polarizations

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

$$h \sim \Delta L / L$$

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





$h_{xx} = -h_{yy}$ $\quad h_{xy} = -h_{yx}$

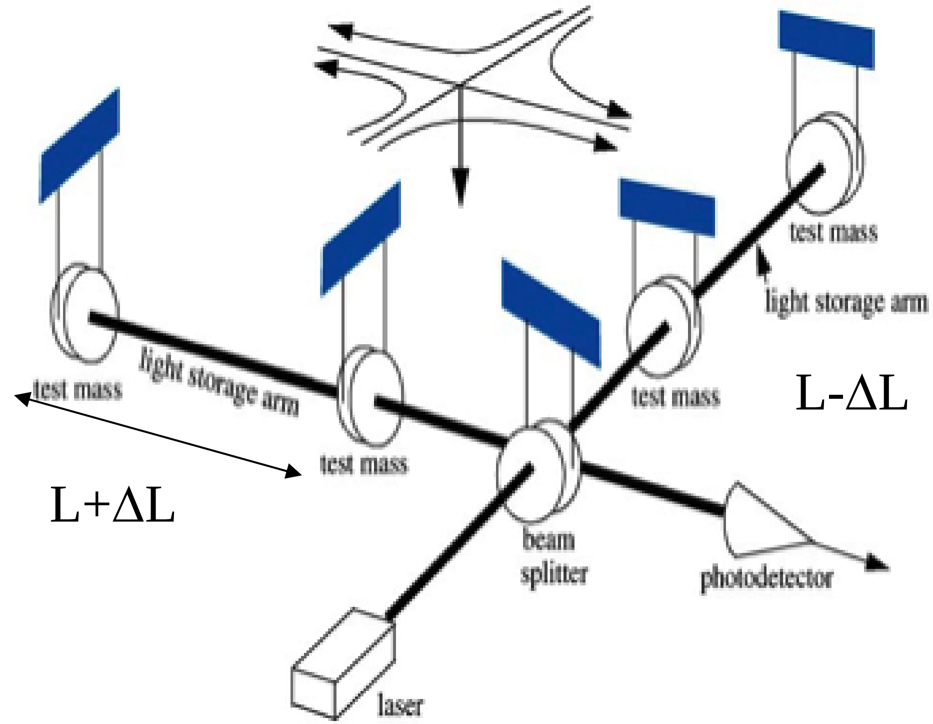
Detecting gravitational waves

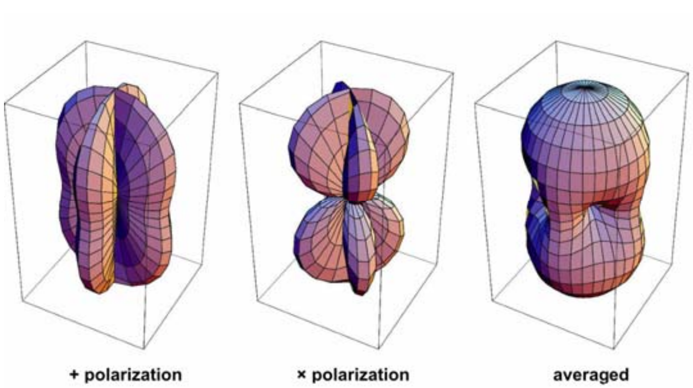
- <u>Interferometer</u>:
  - Compares two distances
  - Sensitive to

$$f \approx 1/t_{store}$$

[tunable]

  - Each interferometer = (weakly) directional antenna





Jay Marx, Texas symposium 2006

Measuring inspiral sources

Using only ‘inspiral’ phase

___[avoid tides, disruption!]

- Mass

  Must match!

  df/dt -> mass

- Distance

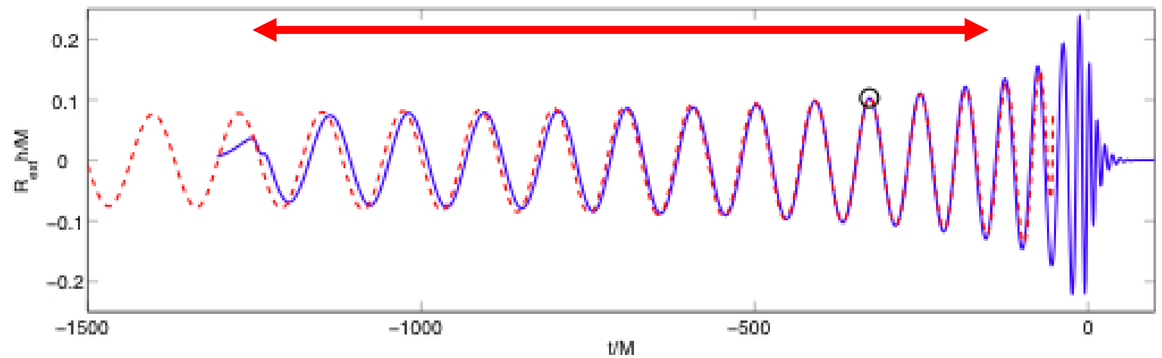
$$SNR \propto \frac{M^{5/6}}{d}$$

- Location on sky
- Orbit orientation

- (Black hole) spin

  Precession

  Only if extreme



Sample uses: short GRBs

1) Easily distinguish certain short GRB engines:

- ‘High’ mass BH-NS merger
- NS-NS merger

2) Host redshifts w/o afterglow association

sor
ure.

d a
ressor
picture.

-Z

Interpretation Challenge

"We saw three binary mergers…now what?"

Preparing to interpret measurements (detections *and* upper limits)

sometimes many are needed

Statistics of detection:

- If we detect several binary mergers we need to know how likely we are to see this many:
  - How many binary stars are in range?
    [Galaxy catalogs, normalization]
  - What formation channels could produce mergers this often?
  - What channels could produce these *specific* mergers?

better than 30%??

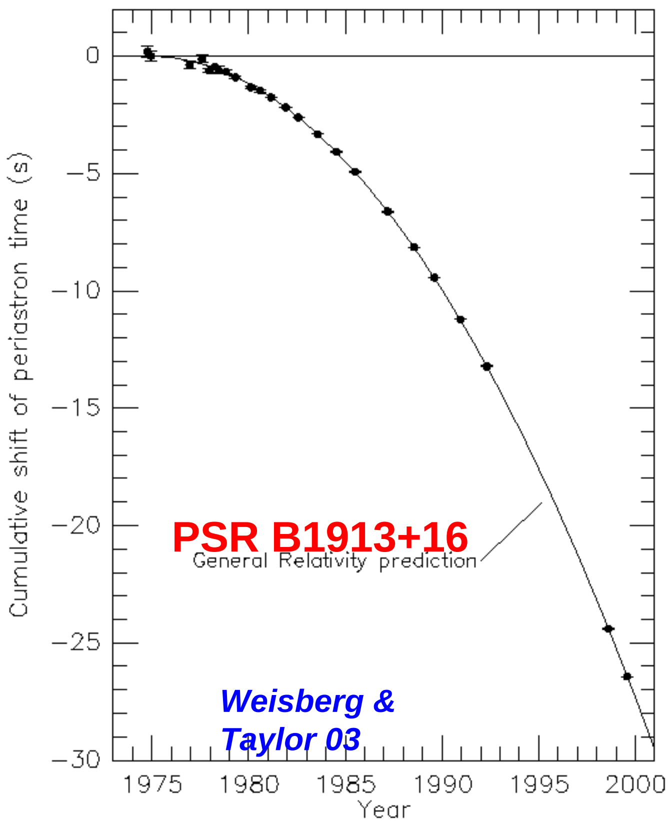
…most of this talk

Outline

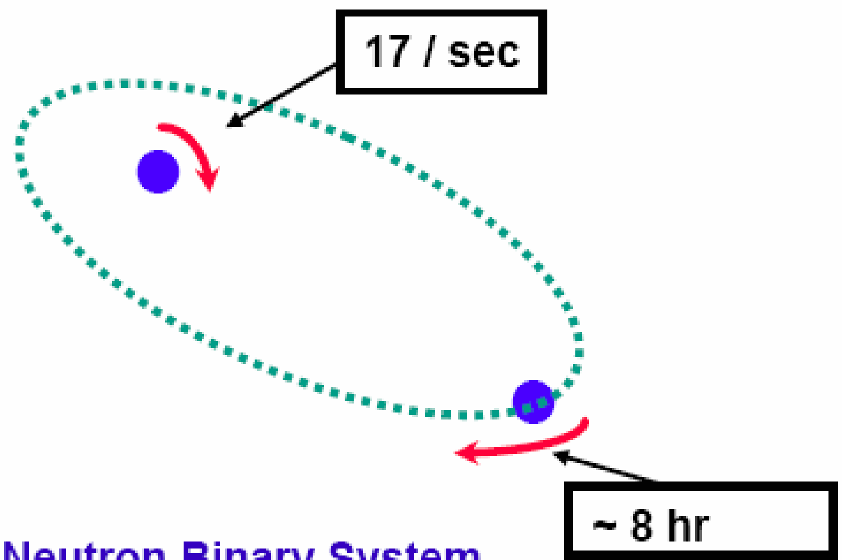
- Gravitational Wave Searches for Binaries
- How to Make Compact Binaries
  - Evolution of gas to merger
  - Observable phases
  - Population synthesis and *StarTrack*
- Predictions and Constraints: Milky Way
- Why Ellipticals Matter
- Predictions and Constraints Revisited
- GRBs
- Conclusions

Observed pulsar binaries

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



PSR 1913 + 16 -- Timing of pulsars



<u>Neutron Binary System</u>
- separated by 10^6 miles
- $m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$

<u>Prediction from general relativity</u>
- spiral in by 3 mm/orbit
- rate of change orbital period

Binary stellar evolution

Complex process

- <u>Outline of (typical) evolution</u>:
  - 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

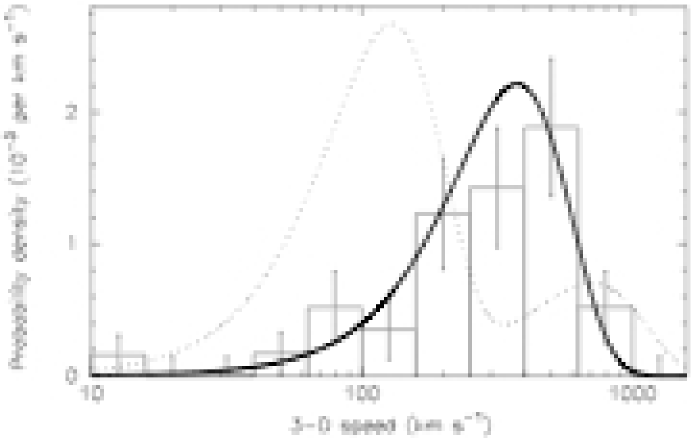
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Movie: John Rowe

Binary stellar evolution

Parameterized (phenomenological) model

- Example: Supernovae kicks
  - Neutron stars = supernovae remnants
  - Observed moving **rapidly** :
    - Supernovae asymmetry --> kick



  - Model:

    "Two-temperature thermal" distribution

Hobbs et al

- Many parameters (like this)

  change results by **x10**

Observations suggest preferred values
conservatively: explore plausible range

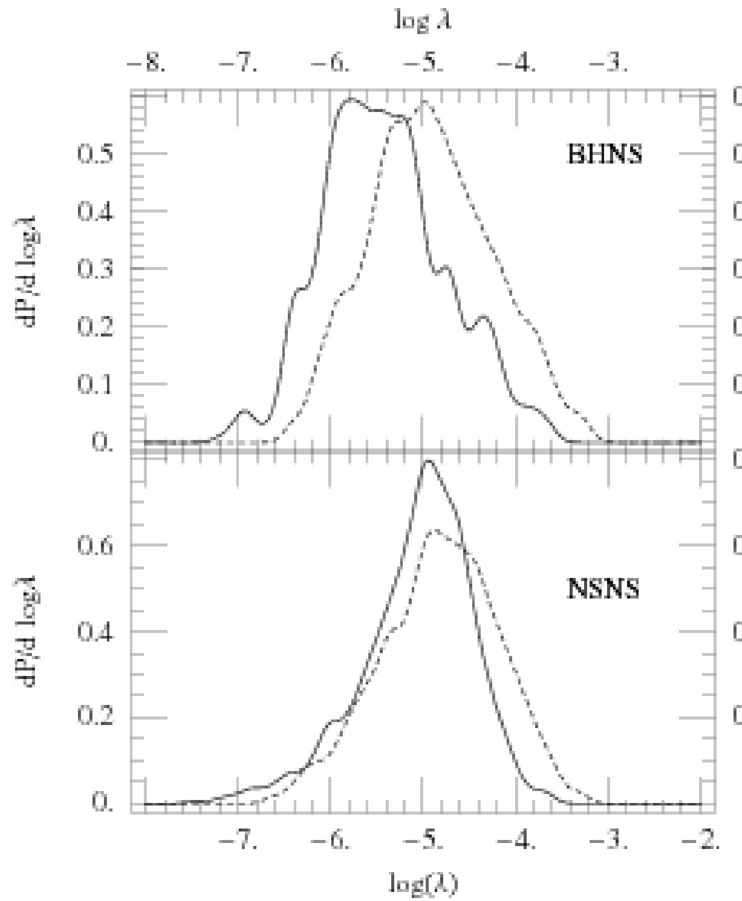
StarTrack and Population Synthesis

Population synthesis:
- Evolve *representative sample*
- See what happens

Variety of results

Depending on parameters used…
- Range of *number of binaries per input mass*

Plot: Distribution of mass efficiencies seen in simulations



More binaries/mass

Priors matter

a priori assumptions about what parameters likely influence *expectations*

O'Shaughnessy et al (in prep)

StarTrack and Population Synthesis

Population synthesis:
- Evolve *representative sample*
- See what happens

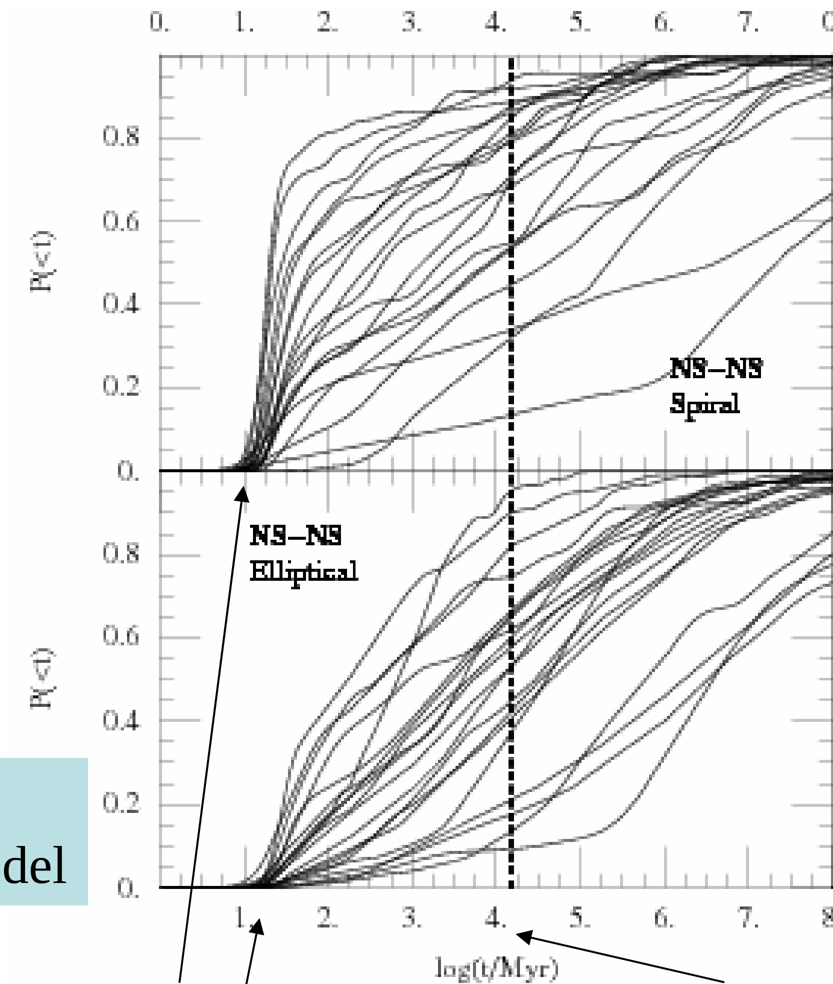
Variety of results

Depending on parameters used…
- Range of *number of binaries per input mass*
- Range of *delays between birth and merger*

Plot: Probability that a random binary merges before time ‘t’, for each model

Priors matter

a priori assumptions about what parameters likely influence *expectations*



Merging after 2nd supernova

Merging after 10 Gyr

O’Shaughnessy et al (in prep)

: changed priors since last paper

Outline

- Gravitational Wave Searches for Binaries
- How to Make Compact Binaries
- Predictions and Constraints: Milky Way
  - Observations (pulsars in binaries) and selection effects
  - Prior predictions versus observations
  - Constrained parameters
  - Physics behind comparisons : what we learn
  - Revised rate predictions
  - What if a detection?
- Why Ellipticals Matter
- Predictions and Constraints Revisited
- GRBs
- Impact of detection(s)?
- Conclusions

Observations of Binary Pulsars

Observations

- 7 NS-NS binaries
- 4 WD-NS binaries

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)

Rate estimate Kim et al ApJ 584 985 (2003)
(*steady-state approximation*)

Number + ‘lifetime visible’ + lifetime
+ fraction missed

=> **birthrate**

+ error estimate (number-> sampling error)

Note:

- **Only possible** because many single pulsars seen:
  Lots of knowledge gained on selection effects
  Applied to *reconstruct* N_{true} from N_{seen}

Predictions and Observations

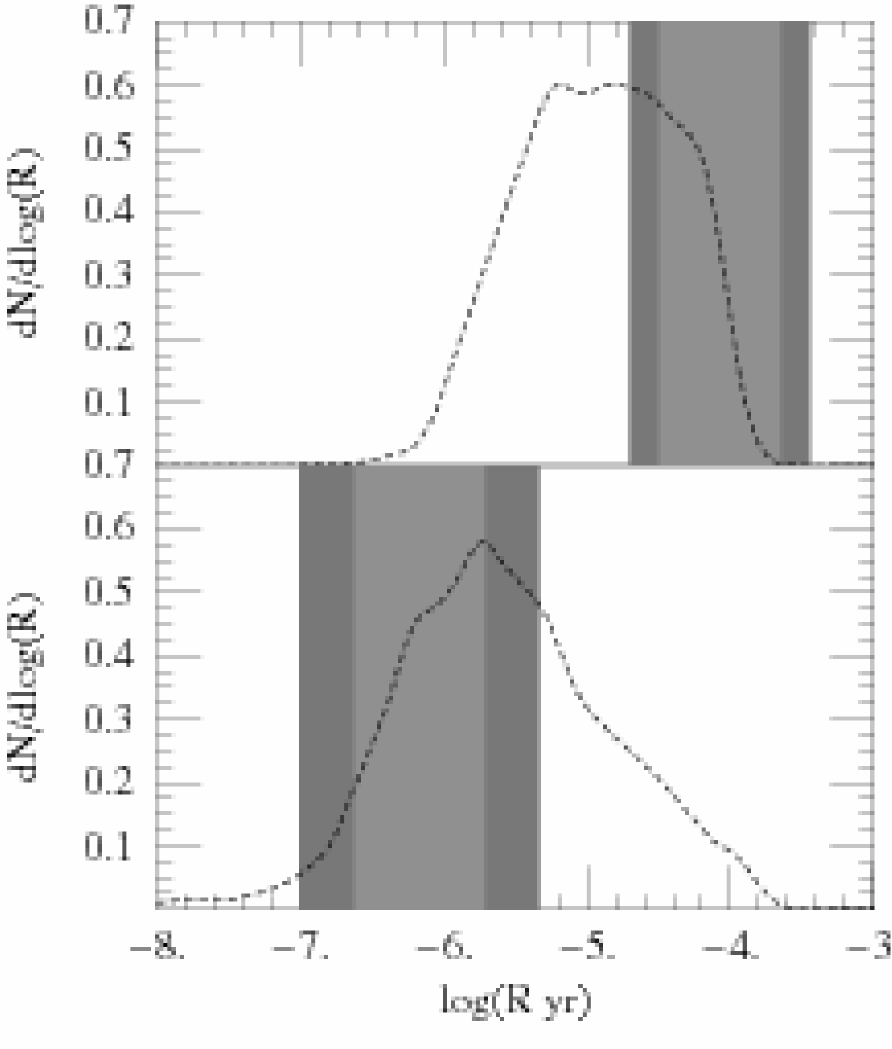
Formation rate distributions

- Observation: shaded
- Theory: dotted curve
- Systematics : dark shaded

Allowed models?

- Not all parameters reproduce observations of
  - NS-NS binaries
  - NS-WD binaries (massive WD)

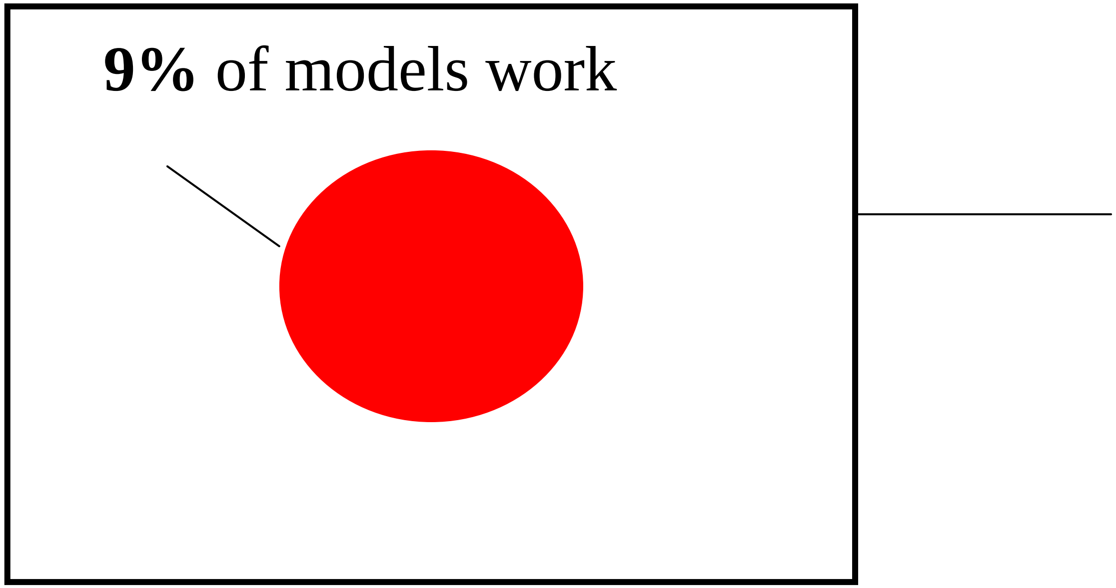
--> potential constraint



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

Accepted models

Constraint-satisfying volume



7d grid

= 7 inputs to StarTrack

7d volume:

- Hard to visualize!
- Extends over ‘large’ range:

characteristic extent(each parameter):
$0.09^{1/7}$~**0.71**

Accepted models

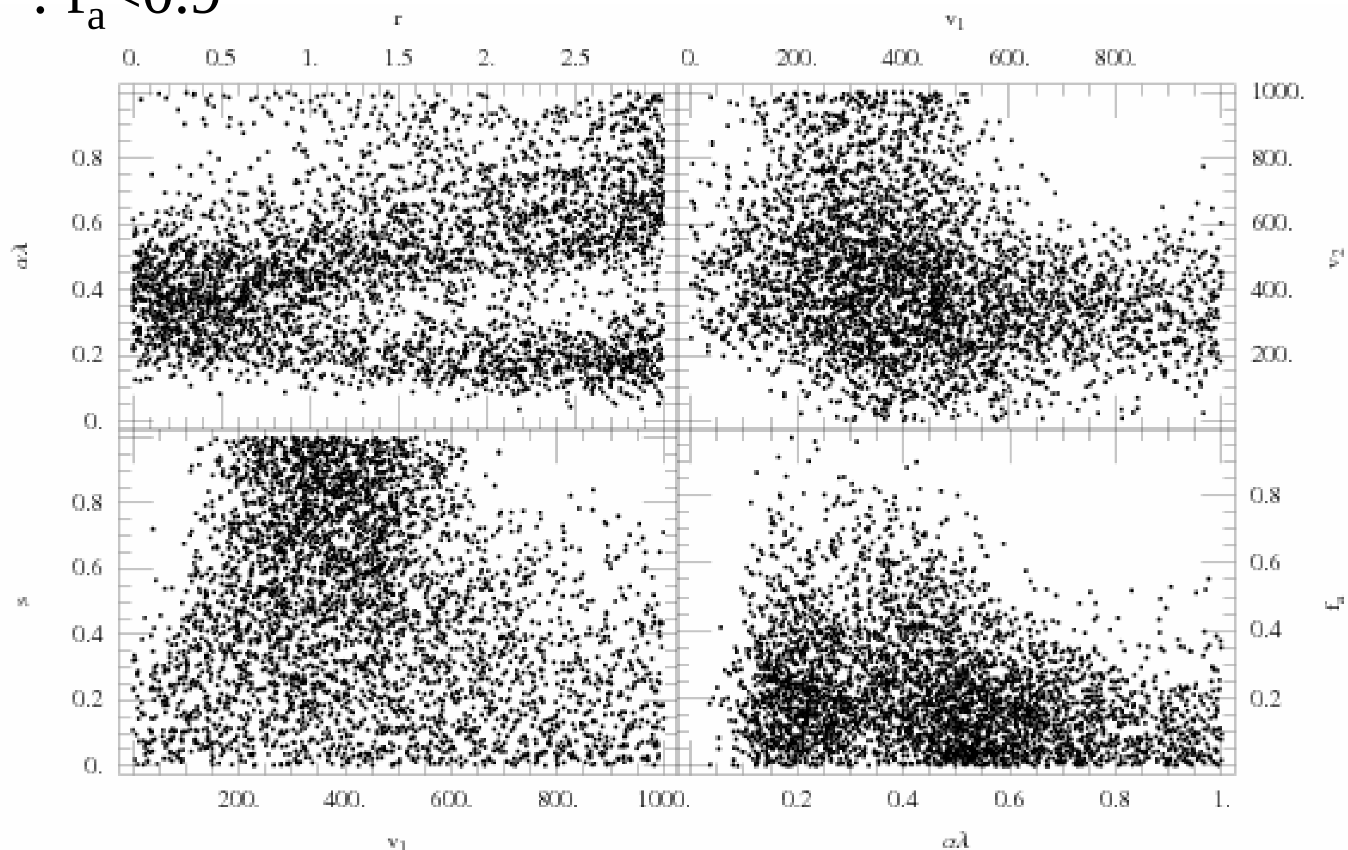
Parameter distributions

- Not all parameter combinations allowed

Examples:

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

Lots of physics in correlations

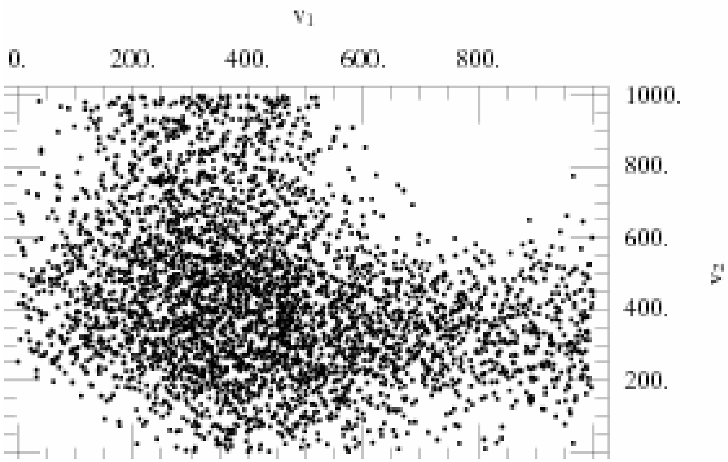


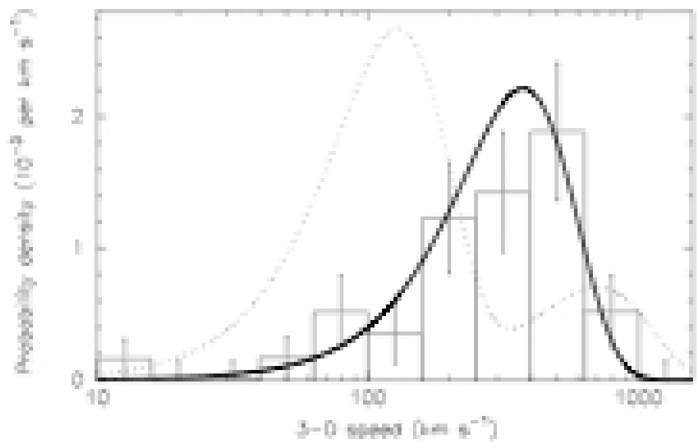
Physics of comparison

Physics implied by constraints

- <u>Kick strength</u>: $v_1, v_2 \sim 300$ km/s

  Pulsar motions ~ measure supernova kicks [e.g., Hobbs 2006]





Preferred kicks ~ **consistent with observations**
(*without* imposing that as a constraint)

Physics of comparison

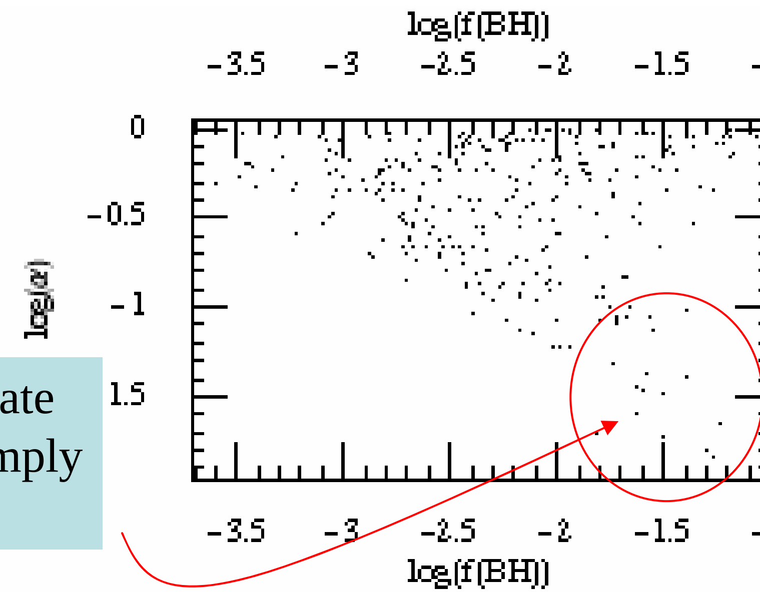
Physics implied by constraints

- <u>CE efficiency</u>: $\alpha\lambda > 0.1$

  CE efficiency = fraction of orbit energy needed to eject envelope surrounding two cores

  Low $\alpha\lambda$:
  - closer final orbit needed to eject envelope
  - some binaries merge in CE phase!
    - NS-NS rate down
    - BH-NS rate up (often)
    - BH-BH rate up

      brings together distant holes



Plot: BH-BH merger rate versus $\alpha\lambda$; low $\alpha\lambda$ imply high rate

<u>Excluding low</u>:
- High NS-NS rate needed to match observations

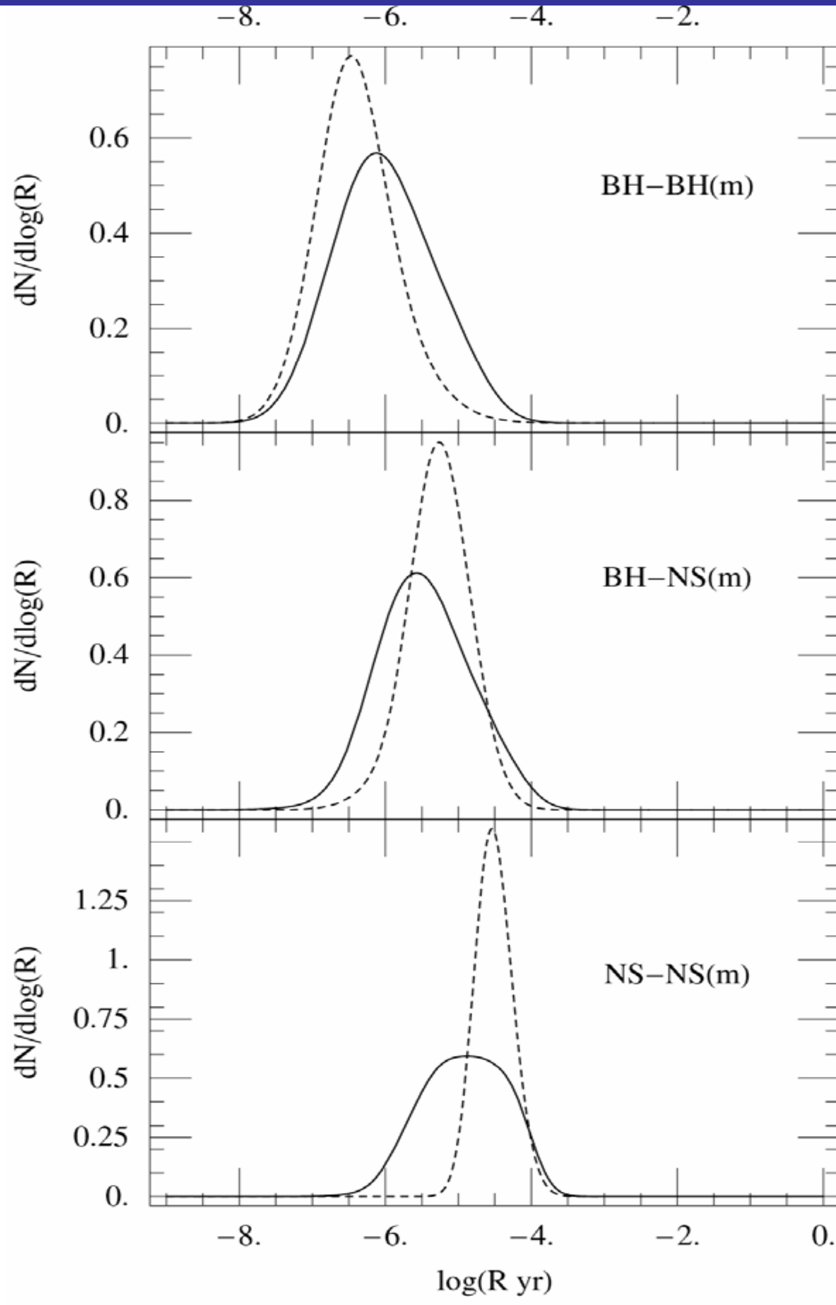
  Low $\alpha\lambda$ can't make it
- Posterior rate prediction:

  lower BH-BH rate

Revised rate predictions

Rate predictions change…

- Solid: Prior
- Dashed: After constraint



Warning: Priors matter

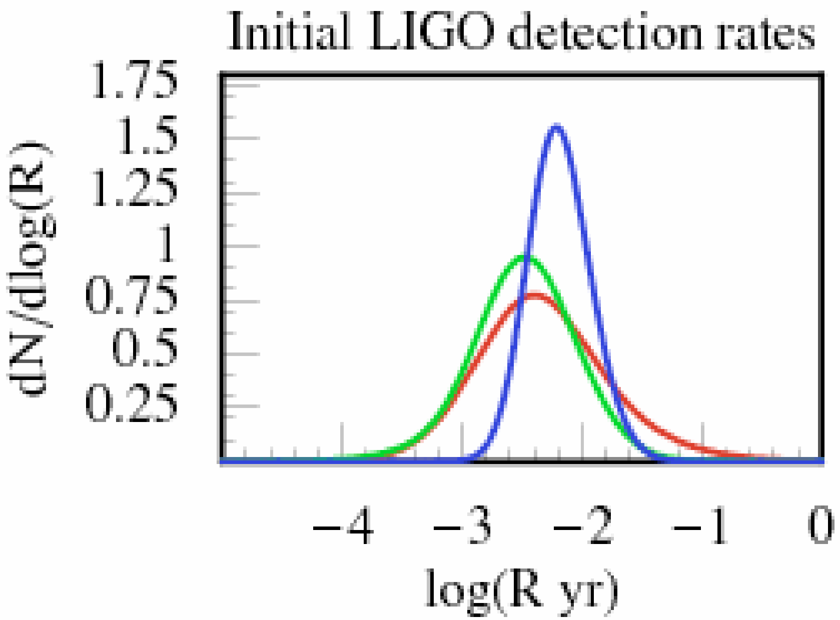
- Exact mean, probabilities depend on priors/assumptions
  (= range of parameters allowed)

- *Trend* of change (before vs after) rather than specifics
  - **Fewer BH-BH**
  - **More NS-NS** (of course)

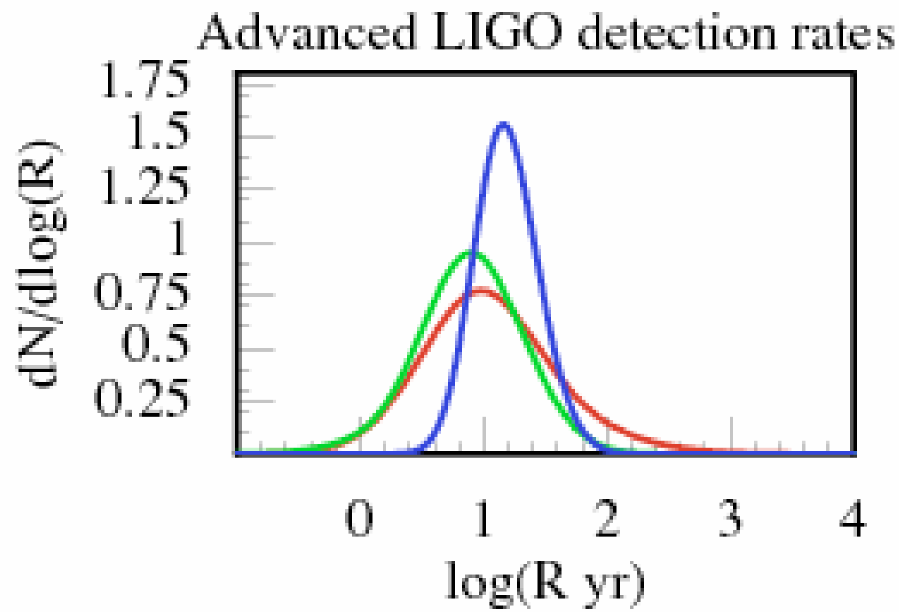
LIGO detection rates

Constrained LIGO detection rates

Assume all galaxies like Milky Way, density 0.01 Mpc^{-3}



Detection unlikely



Detection assured

Key
NS-NS
BH-NS
BH-BH

Detection: A scenario for 2014

Scenario: (Advanced LIGO)

- Observe n ~ 30 BH-NS events [reasonable]

Potential

•Stringent test of binary evolution model already!

•Stronger if

  •**Orbit distribution consistency**

  •**More constraints**

- independent channels (each depends differently on model params)->

Volume	$[0.09\ (0.08)^3] \sim$ **(4×10^{-5})** **!!**
Params	$[0.09\ (0.08)^3]^{1/7} \sim 0.24$

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  - Prior predictions
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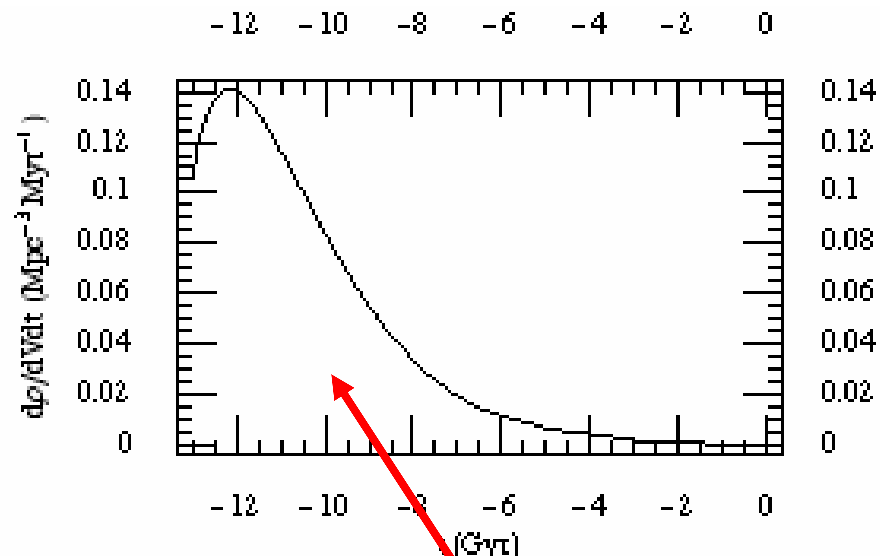
Importance of early SFR

Long delays allow mergers in ellipticals now

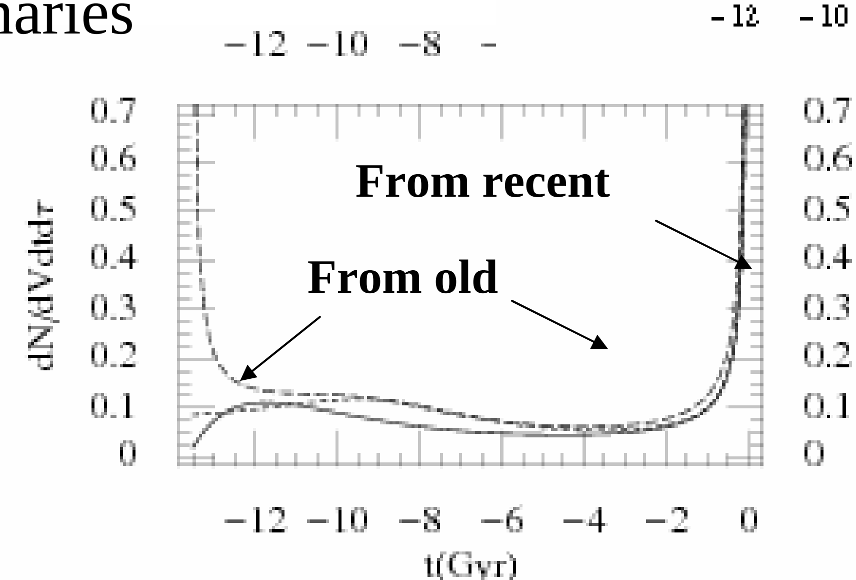
- Merger rate from starburst: R ~ dN/dt~1/t
- SFR higher in past:



Nagamine et al astro-ph/0603257\

- Result:
  - Many mergers *now* occur in ancient binaries

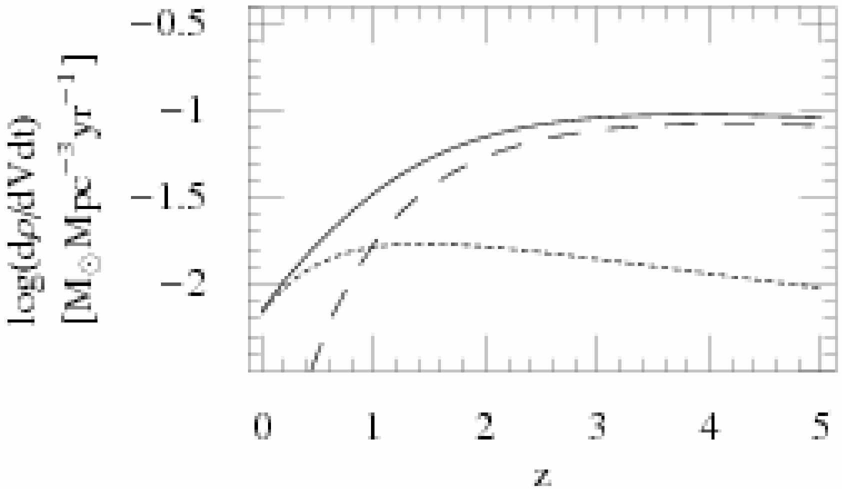
Plot:
Birth time for present-day mergers



ancient SFR
= ellipticals
(mergers, …)

Two-component SFR

SFR
[Nagamine et al 2006]
- Separate elliptical, spiral!



Nagamine et al astro-ph/0603257

Reliable?
- Normalization ok
- Spiral/elliptical ratio ok
- Time dependence reasonable

…uncertainty **smaller than popsyn**

Predictions and constraints

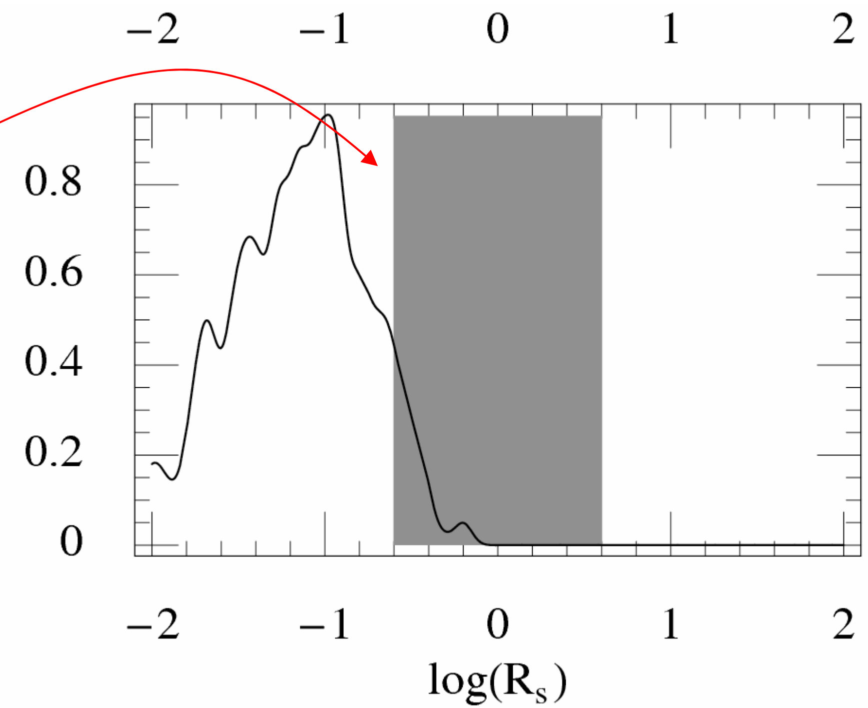
Two-component predictions:

– Each prediction =
Rate density (/vol/time) versus time
for **each** of ellipticals, spirals

…mostly **unobservable** (except now in Milky Way)

Example: NS-NS merger rate in spirals

- Rate extrapolated from Milky way:
  R_s=0.25-4 $Myr^{-1}Mpc^{-3}$



→consistent parameters
unfinished / pending
→revised merger & LIGO rates
discuss in context of short GRBs

Outline

- Gravitational Wave Searches for Binaries
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- Predictions and Constraints: Milky Way
- Why Ellipticals Matter
- Predictions and Constraints Revisited
- GRBs
  - Review + the short GRB merger model
  - Short GRB observations, the long-delay mystery, and selection effects
  - Detection rates versus L_{min}
  - Predictions versus observations:
    - If short GRB = BH-NS
    - If short GRB = NS-NS
  - Gravitational waves?
- Conclusions

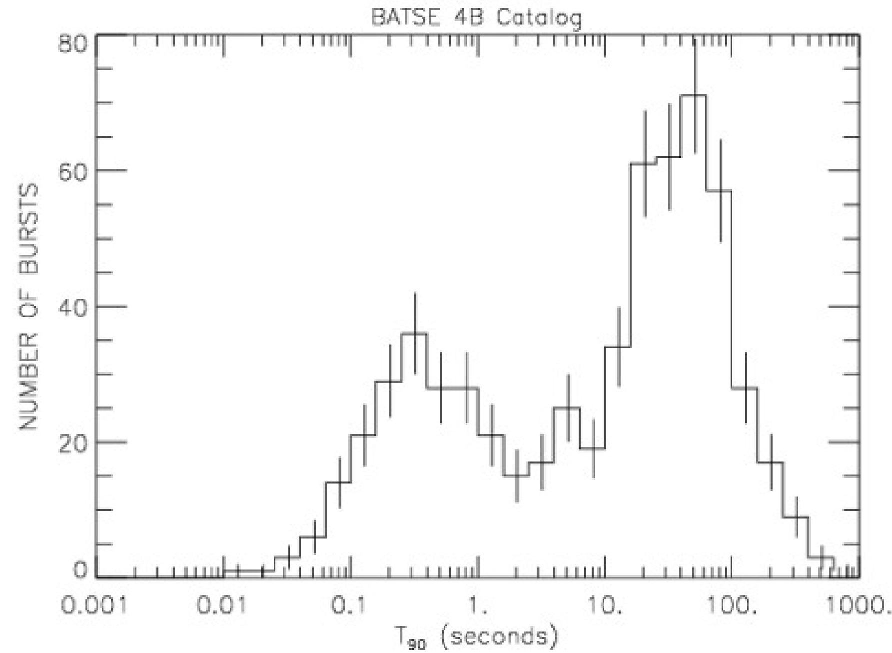
Short GRBs: A Review

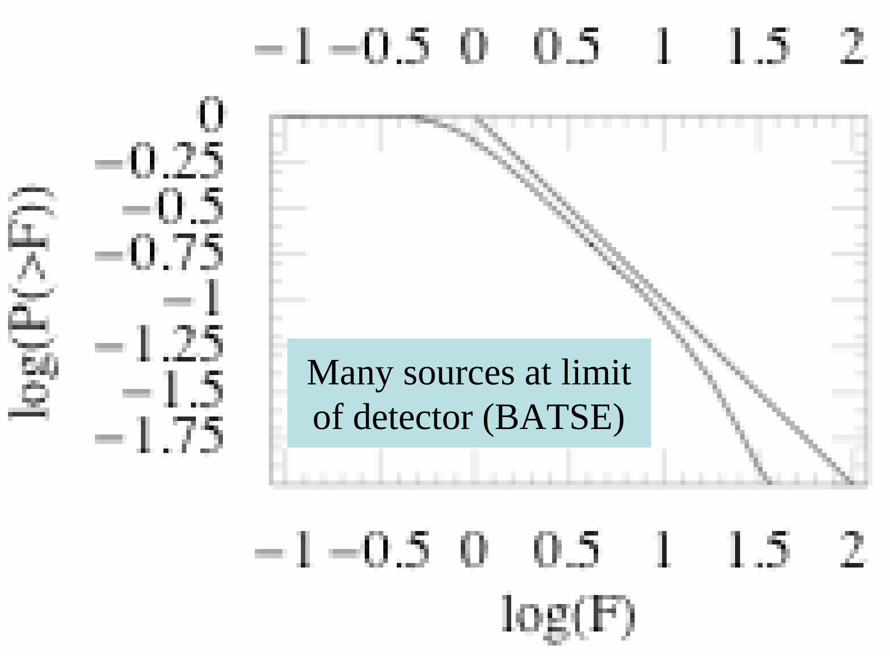
Short GRBs (BATSE view)

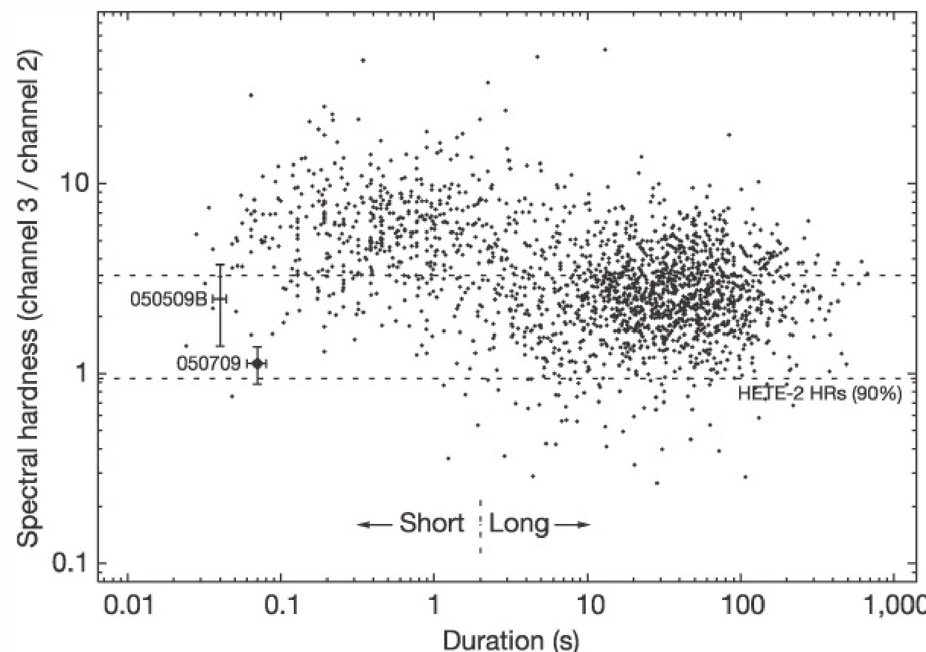
- Cosmological
- One of two classes
- Hard: often peaks out of band
- Flux power law

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

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



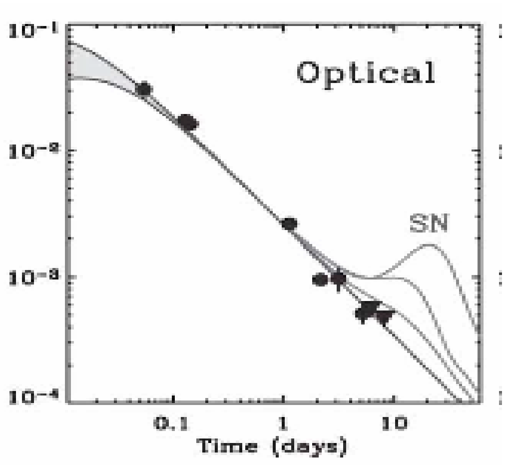




Short GRBs: A Review

Merger motivation?

- No SN structure in afterglow



GRB 051221 (Soderberg et al 2006)

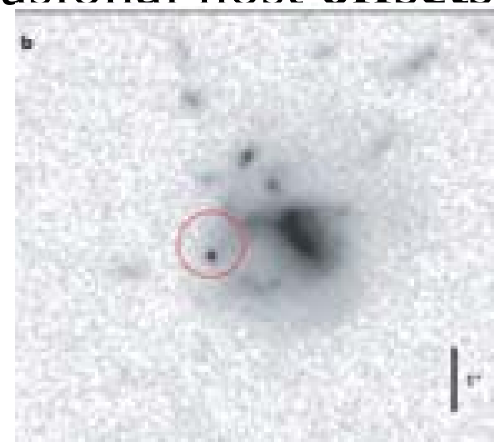
- In both **old**, young galaxies

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

Observables: Detection rate?

Binary pulsars

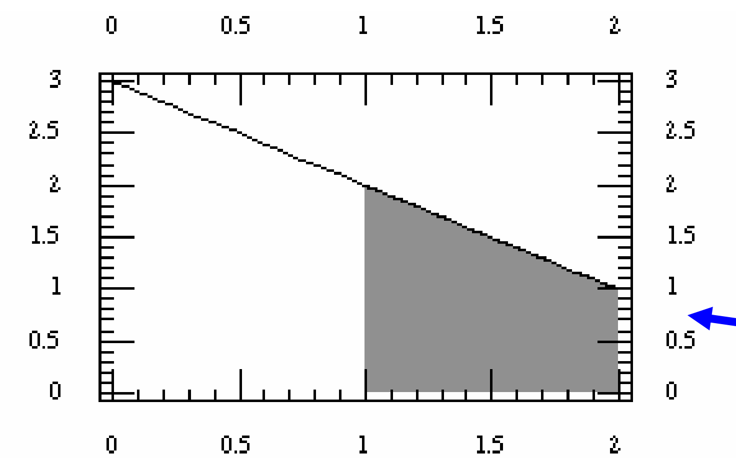
- Many (isolated) observed
- **Minimum luminosity** ~ known
- Observed number

--> **rate** (+ ‘small’ error)

Short GRBs

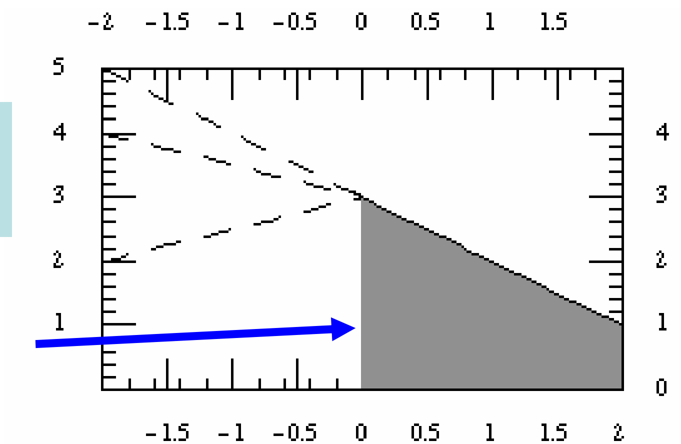
- Few observations
- **Minimum luminosity** ~ **unknown**
- Observed number

--> **rate upper bound**



Plots:
Cartoon on L_{min}

observed



Conclusion:
The number (rate) of short GRB observations is a <u>weak</u> constraint on models

Observables: Redshift distribution

Redshift distribution desirable

- Low bias from luminosity distribution
- Well-defined statistical comparisons

  Kolmogorov-Smirnov test (=use maximum difference)

Observed redshift sample

- Need sample with *consistent selection effects*

  (=bursts from 2005-2006, with Swift)

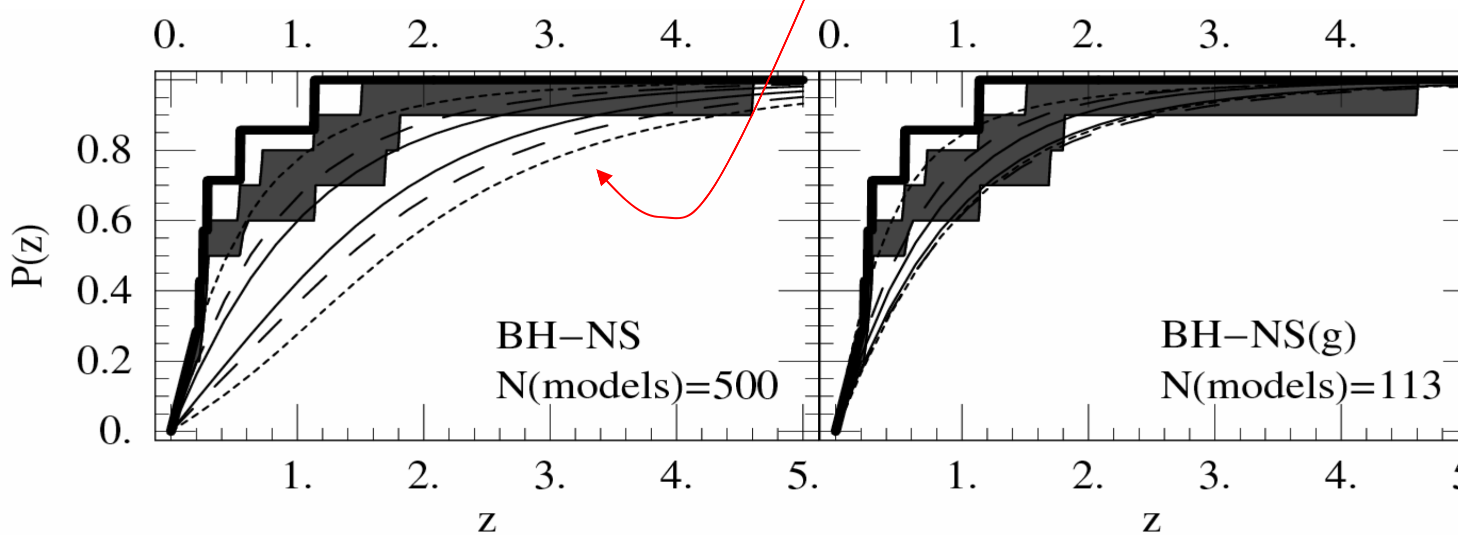
Problem: Possible/likely bias towards low redshifts

Merger predictions <-> short GRBs?

BH-NS?:

- Predictions:
  - 500 pairs of simulations
  - Range of redshift distributions
- Observations:
  - Solid: certain
  - Shaded: possible

Key
Solid: 25-75%
Dashed: 10-90%
Dotted: 1%-99%

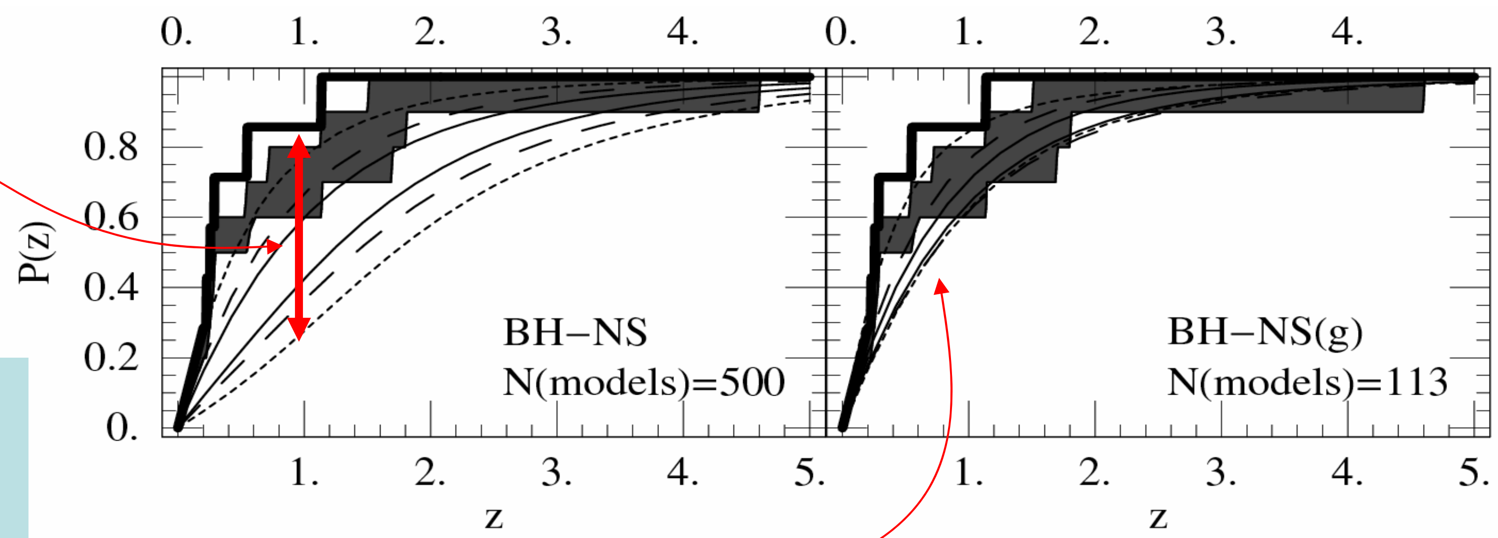


O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

BH-NS?:

- Predictions that agree?
  - Compare *cumulative distributions*:
    maximum difference < 0.48 everywhere [95% Komogorov-Smirnov given GRBs]
  - Compare to **well-known** GRB redshifts since 2005 [consistent selection effects]
    - dominated by low redshift



Result:
Distributions which agree = mostly at *low* redshift

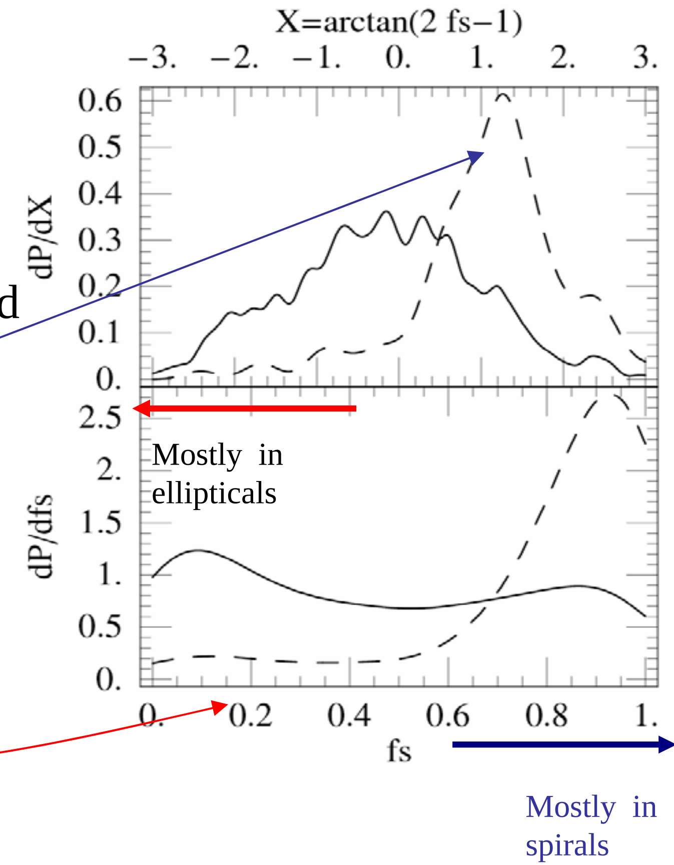
O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

<u>BH-NS?</u>:

- Physical interpretation
  - Observations : Dominated by **recent** events
  - Expect:
    - Most mergers occur in spirals (=*recent* SFR) and High rate (per unit mass) forming in spirals
    - **or** Most mergers occur in ellipticals (=*old* SFR) and High rate (per unit mass) forming in elliptical and **Extremely** prolonged delay between formation and merger (**RARE**)

Plot: f_s : fraction of mergers in spirals (z=0)



- **Consistent**…but…

  Short GRBs appear in ellipticals!

  BH-NS **hard to reconcile** with GRBs??

O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

<u>BH-NS?</u>:

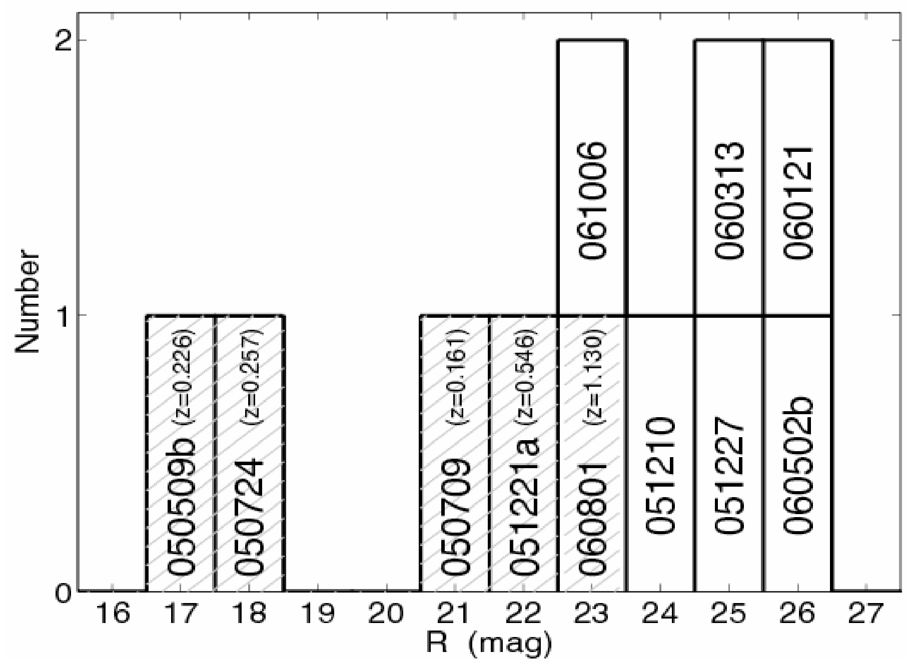
- Conclusion = confusion
  - Theory + redshifts : Bias towards recent times, **spiral** galaxies
  - Hosts: Bias towards **elliptical** galaxies

- What if observations are *biased* to low redshift?
  - strong indications from deep afterglow searches [Berger et al, astro-ph/0611128]

15

  - Makes fitting **easier**
    Elliptical-dominant solutions ok then (=*agree* w/ hosts)

Point: Too early to say
waiting for data;
more analysis needed



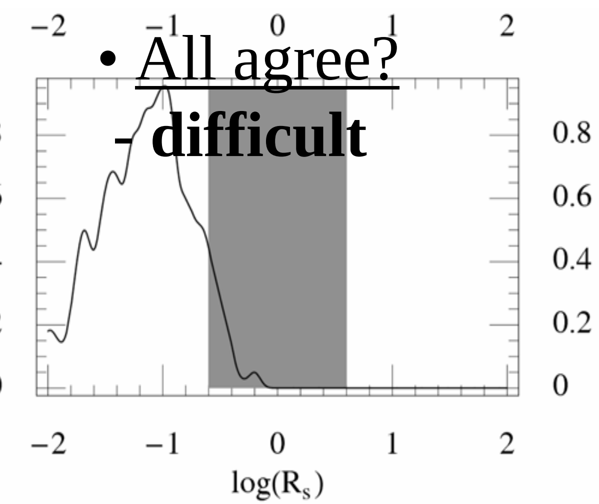
Merger predictions <-> short GRBs?

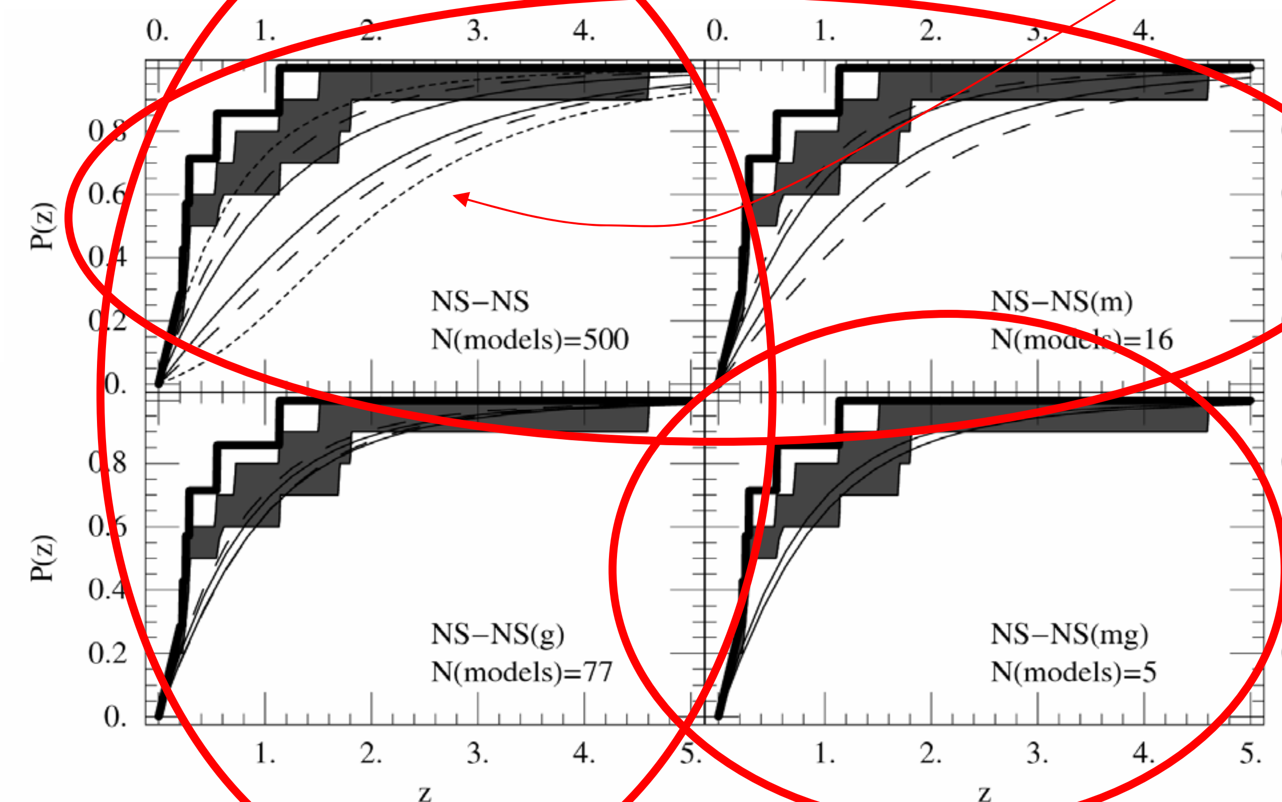
Key
Solid: 25-75%
Dashed: 10-90%
Dotted: 1%-99%

NS-NS?:

- Predictions & observations

- Matching redshifts
- Observed NS-NS (Milky Way)
- All agree?
  - difficult





O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

NS-NS?:

- Physical interpretation
  - Observations : GRBs
    - Dominated by **recent** events
  - Expect:
    - Recent spirals dominate or
    - **or** Ellipticals dominate, with long delays

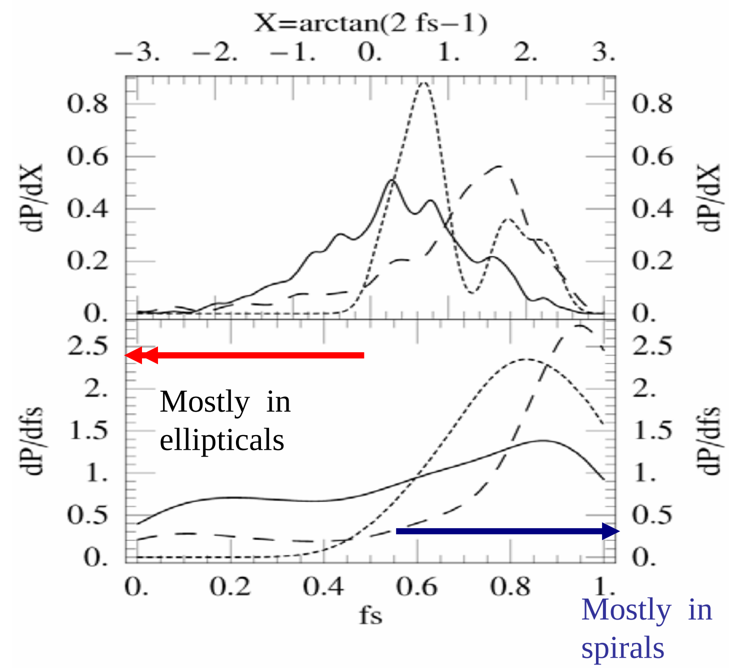
-Observations: Galactic NS-NS

- High merger rate

-Expect

-High merger rate in spirals

Plot: f_s : fraction of mergers in spirals (z=0)



- **Consistent**…but…

Short GRBs appear in ellipticals!

NS-NS **hard to reconcile** with GRBs

and problem *worse* if redshifts are biased low!

Conclusions

Present:

- Useful comparison method **despite** large uncertainties
- Preliminary results
  - Via comparing to pulsar binaries in Milky V
    - Low mass transfer efficiencies forbidden
    - Supernovae kicks ~ pulsar proper motions
    - BH-NS rate closely tied to min NS mass/CE
  - Via comparing to short GRBs?
    - Conventional popsyn **works** : weak const
    - Expect GRBs in **either host** : spirals form
      - Spirals now favored; may change with new
    - Short GRBs = NS-NS? **hard** : few c
    - Short GRBs = BH-NS? **easier** : fewer
- Observational recommendations
  - Galactic :
    - Minimum pulsar luminosity & updated sele
    - Pulsar opening angles
    - Model : Size and SFR history
  - Short GRBs :
    - **Ratio** of spiral to elliptical hosts at z<0.5

(Long term) Wishes

(critical)

-reliable GRB classification

-short burst selection bias?

-deep afterglow searches

(less critical)

-formation history

-formation properties (Z, imf) [mean+statistics] for **all** star-forming structures

Conclusions

Future (model) directions:

- More comparisons
  - Milky Way
    - Pulsar masses
    - Binary **parameters** (orbits!)
    - Supernova kick consistency?
  - Extragalactic
    - Supernova rates

Some examples:
Belczynski et al. (in prep)

- Broader model space
  - Polar kicks?
  - Different maximum NS mass

    [**important**: BH-NS merger rate sensitive to it!]
  - Different accretion physics

Goal:

- show predictions *robust* to physics changes
- if changes matter, understand why

  (and devise tests to constrain physics)