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

Unravelling short GRBs with **LIGO**, Swift and **GLAST**

Richard O'Shaughnessy

ANL GLAST Workshop

April 13, 2007

Warning:
Flight: 1pm @ O'Hare
Leaving at 11.30

Email: oshaughn@northwestern.edu

LIGO-G070250-00-0

Outline

- Short GRBs: Where are we now with Swift?
  - Good
  - Bad : Biases
- How can LIGO help?
  - Detections are powerful (in coincidence)
  - Merger detections unlikely
  - Nondetections still useful
- Big picture: Swift+GLAST+LIGO
- Scientific payoff near…
  - **Example**: Swift/BATSE vs theory *alone* + BH-NS mergers
  - **Further examples** (if time permits)
    - Galactic pulsars vs theory
    - Pulsars+LIGO vs theory
    - GRBs+pulsars vs theory : GRBs

Collaborators

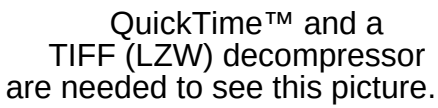
- V. Kalogera — Northwestern
- C. Kim — Cornell
- K. Belczynski — New Mexico State/Los Alamos
- T. **Fragos** — Northwestern **[he's here!]**

- LSC — (official LIGO results)

Short GRBs: Where are we with Swift?

See Nakar 2007

astro-ph/0701748



)

close

LIGO can help?

- 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.

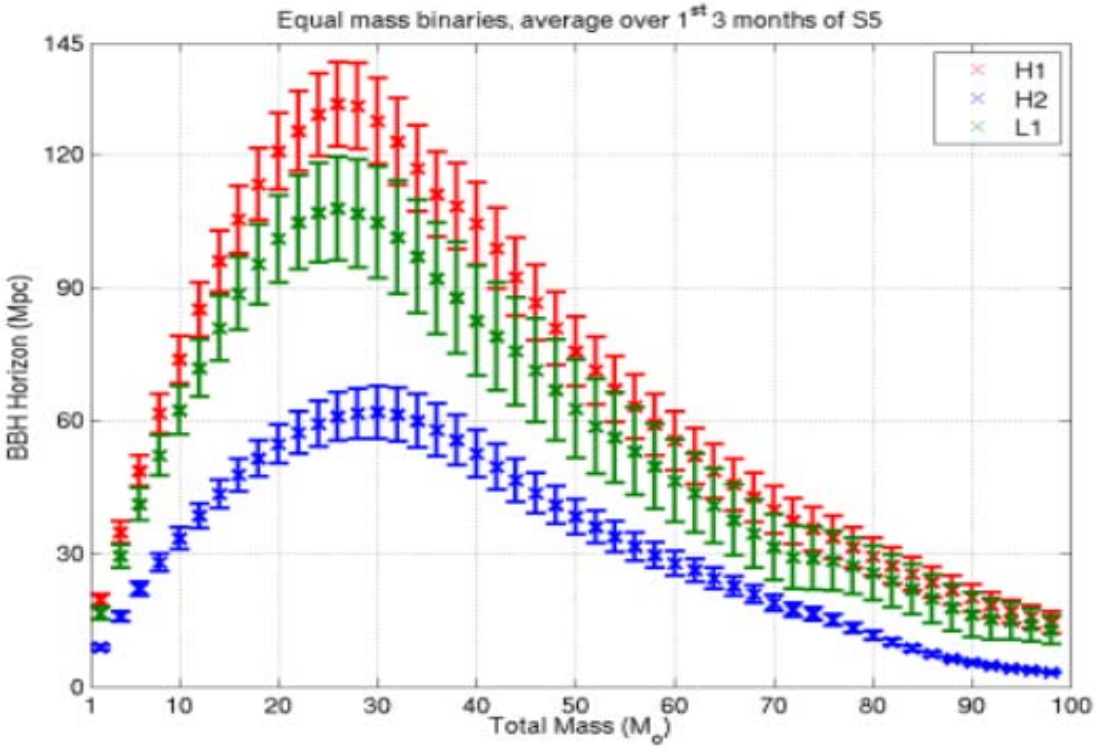
Marx, Texas symposium

LIGO: 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
- Plot: 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

Measuring inspiral sources

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

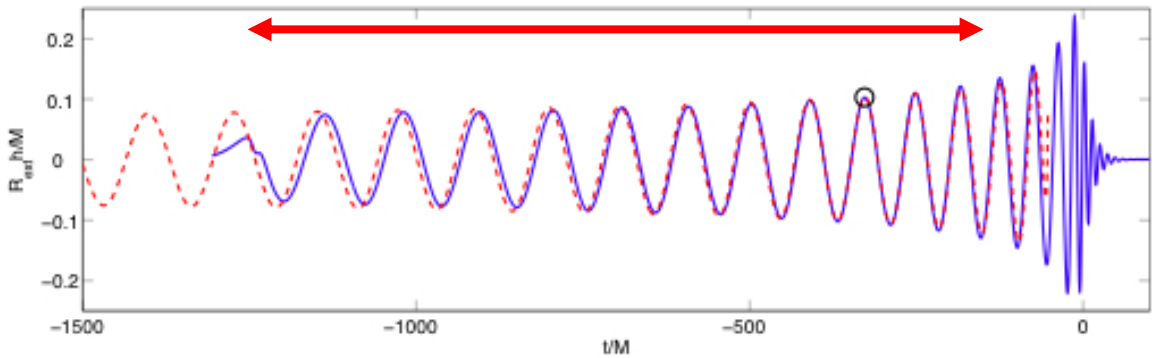
- Mass
  Must match!
  df/dt -> mass

- Distance

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

- Location on sky
- Orbit orientation

- (Black hole) spin
  Precession
  Only if extreme



Sample uses: short GRBs

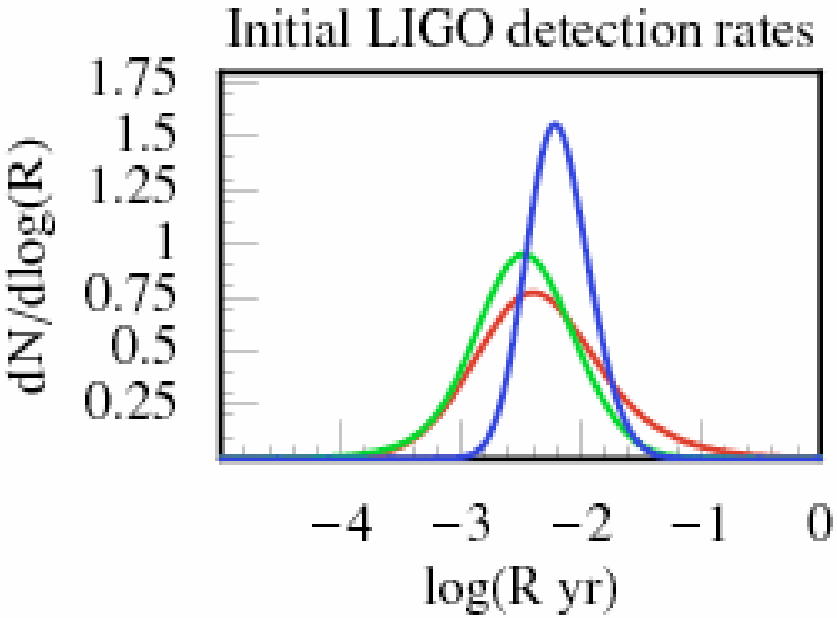
1) Easily distinguish certain short GRB engines:
- 'High' mass BH-NS merger
- NS-NS merger

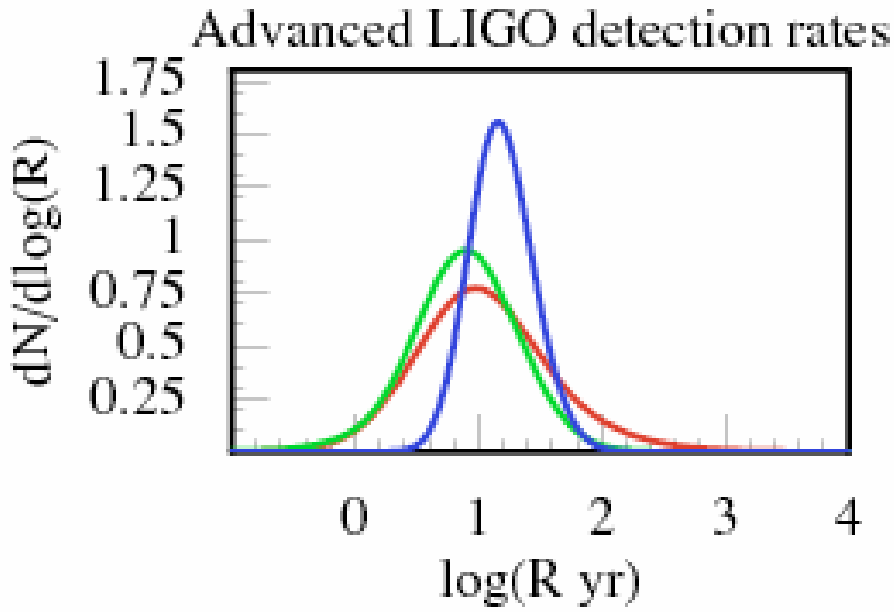
2) Host redshifts w/o afterglow association

Detection unlikely

Constrained LIGO detection rates

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





Detection unlikely

Key
NS-NS
BH-NS
BH-BH

Detection assured

Note: old plots,
published versions will change

Nondetection still useful

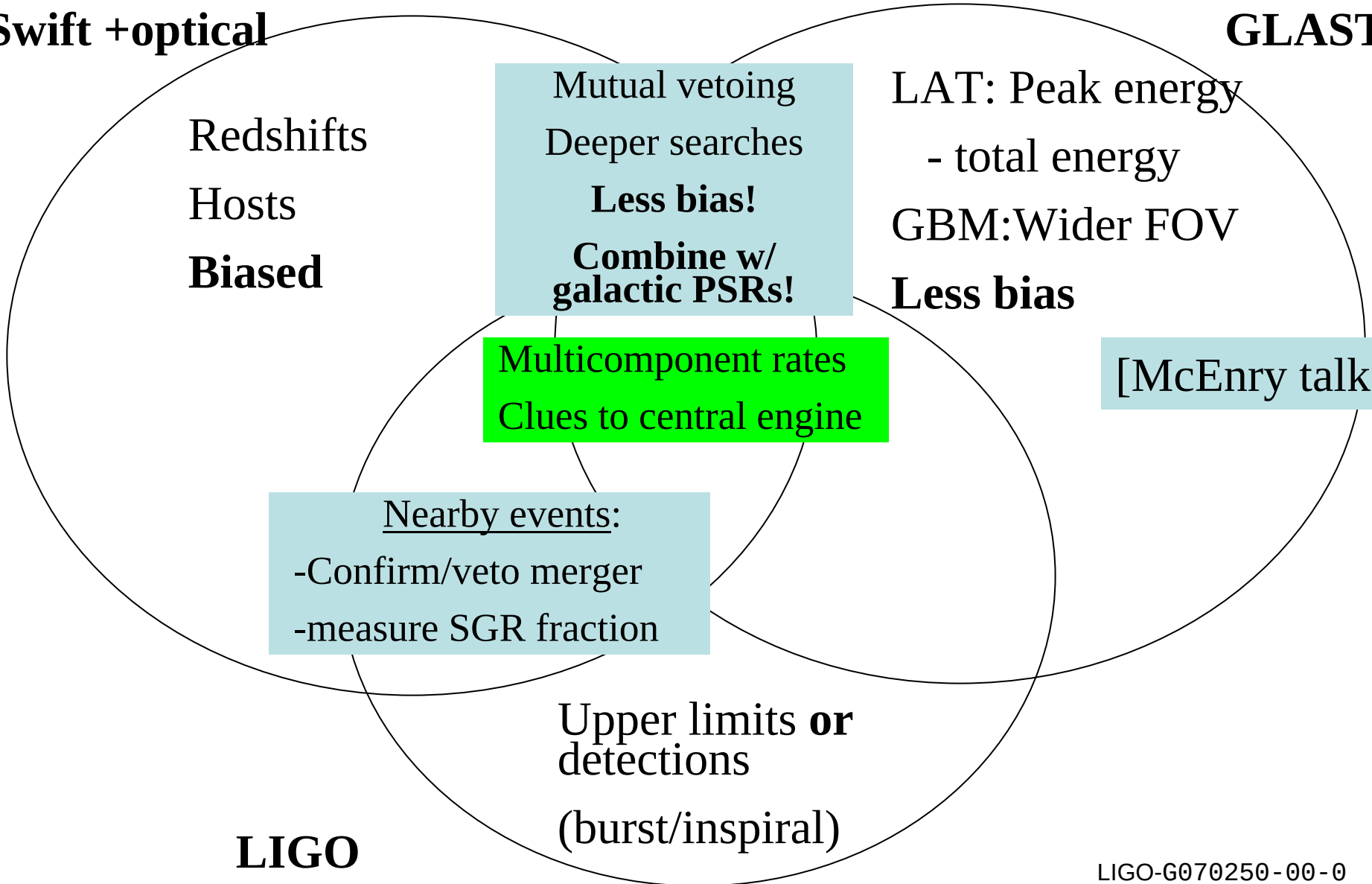
SGRs are GRBs

- Known galactic/nearby source : SGR 1806
- *Unknown* (small?) contribution to short GRB rate

LIGO can "distinguish":

- Short GRB nearby (e.g., <15 Mpc)
  - Merger : Detectable
  - SGR : Marginally/not detectable
- **Application**
  - **Assist** host galaxy searches (i.e., minimum distance to merger)
  - **estimate** SGR contribution

Key point: Cooperate!



Sample Payoff: Swift vs Theory

Constraints on channels (despite large uncertainties)

- Compare:
  - Theoretical (population synthesis) predictions for merger rates

    with very conservative accounting of uncertainties

    (I.e., explore lots of model parameters)

    + (two-component) star formation history of universe
  - Short GRB observations

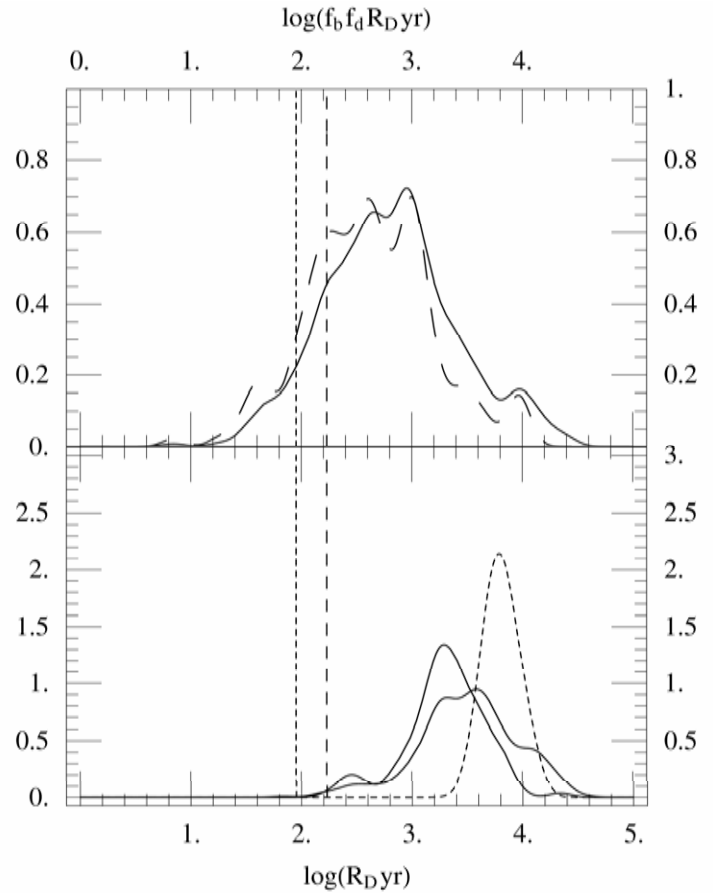
Sample payoff: Detection rates?

Predicted detection rate vs observed:

- Assume:
  - **No bursts fainter than observed!**

  Point:
  - Power law luminosity **suggests** not much freedom left for BH-NS (alone)

    ---> many mergers must make GRBs *and* many mergers must be visible *and* not too much beaming



If time permits…

More comparisons

- Pulsars vs theory
- Pulsars+LIGO vs theory : **estimate**
- Swift short bursts + pulsars vs theory

Otherwise?

Questions?

Leaving **immediately** after talk…if further questions,

Email: oshaughn@northwestern.edu

Chicago resident -- local visits easy

StarTrack and Population Synthesis

Population synthesis:

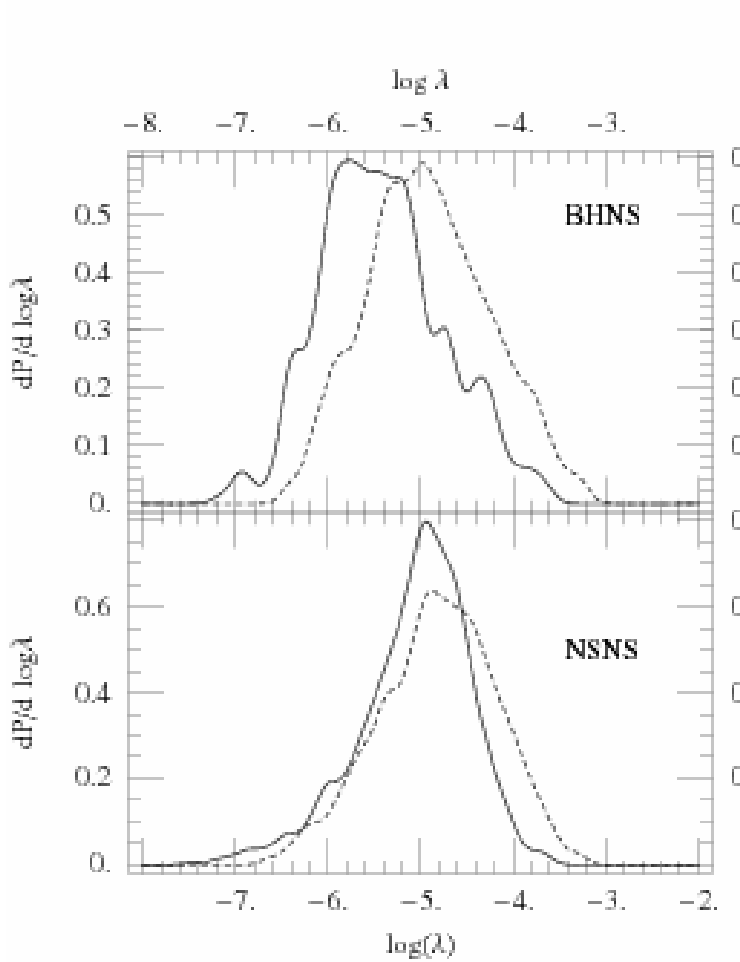
- Evolve *representative sample*
- See what happens

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:

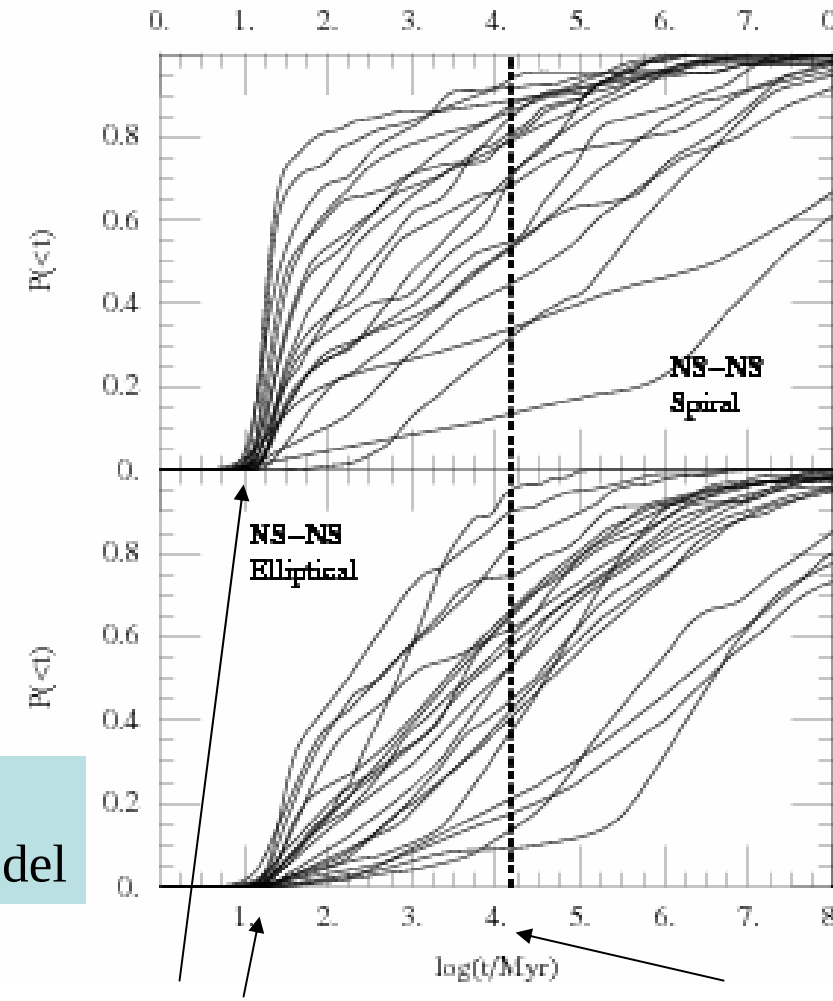
- Evolve *representative sample*
- See what happens

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*

O’Shaughnessy et al (in prep)

: changed priors since last paper

Outline

- 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

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

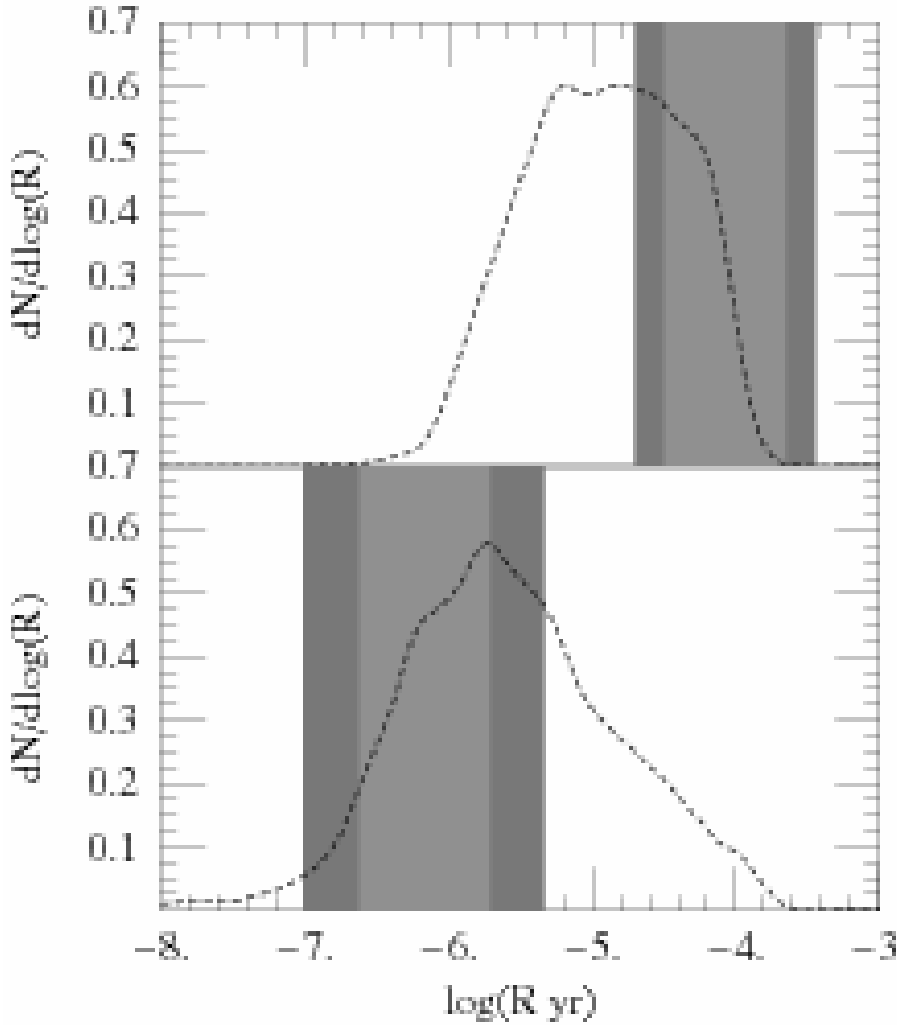
Formation rate distributions

- 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**

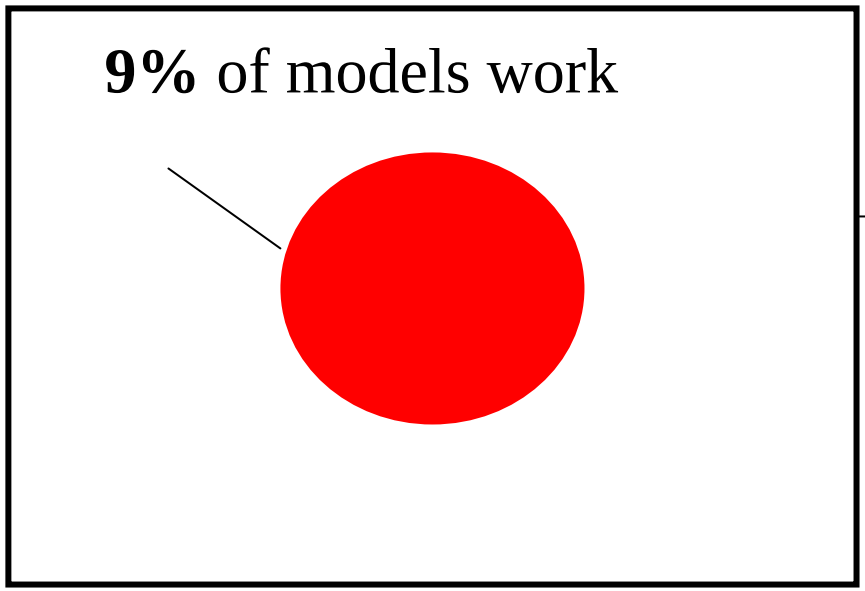


Plot

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**

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	$[0.09\ (0.08)^3]^{1/7} \sim 0.24$

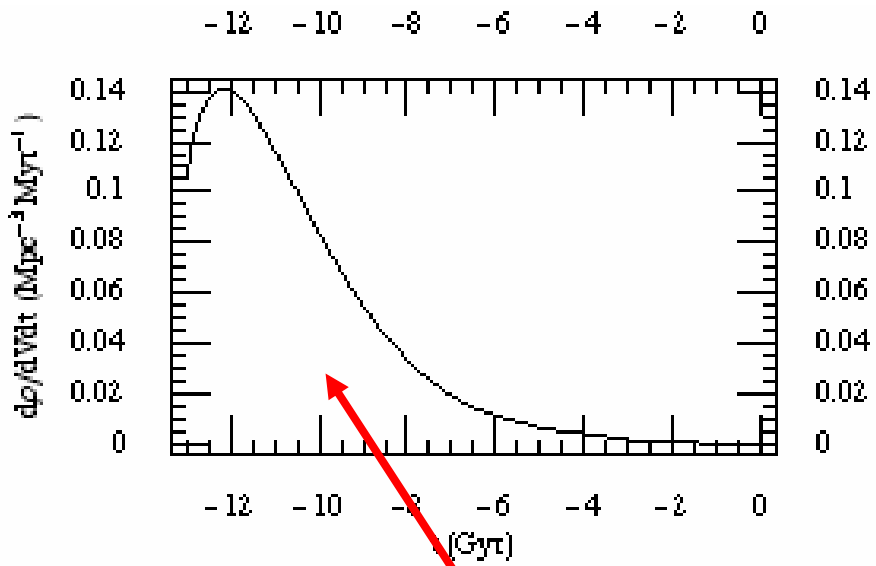
Outline

- Predictions and Constraints: Milky Way
- Why Ellipticals Matter
  - Two-component star formation model
- Predictions and Constraints Revisited
  - Prior predictions
  - Reproducing Milky Way constraints

Importance of early SFR

Long delays allow mergers in ellipticals now

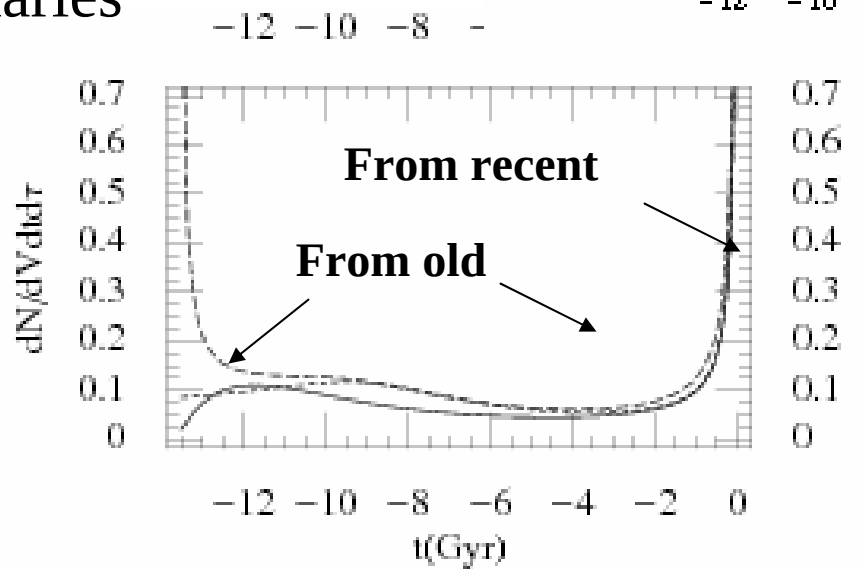
- Merger rate from starburst: R ~ dN/dt~1/t
- SFR higher in past:



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

Nagashine et al astro-ph/0603257\

Plot:
Birth time for present-day mergers



ancient SFR = ellipticals (mergers, …)

Outline

- 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

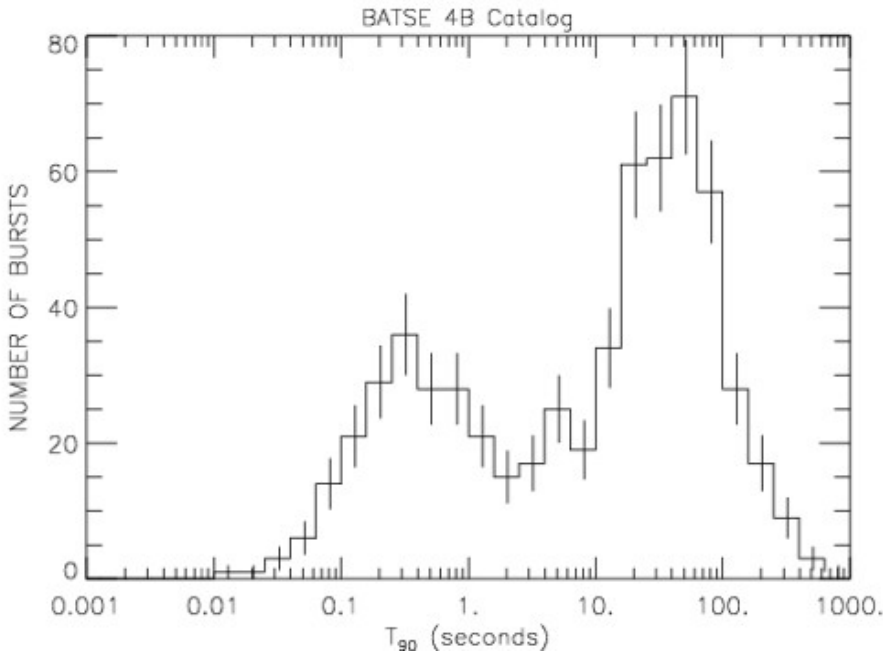
Short GRBs: A Review

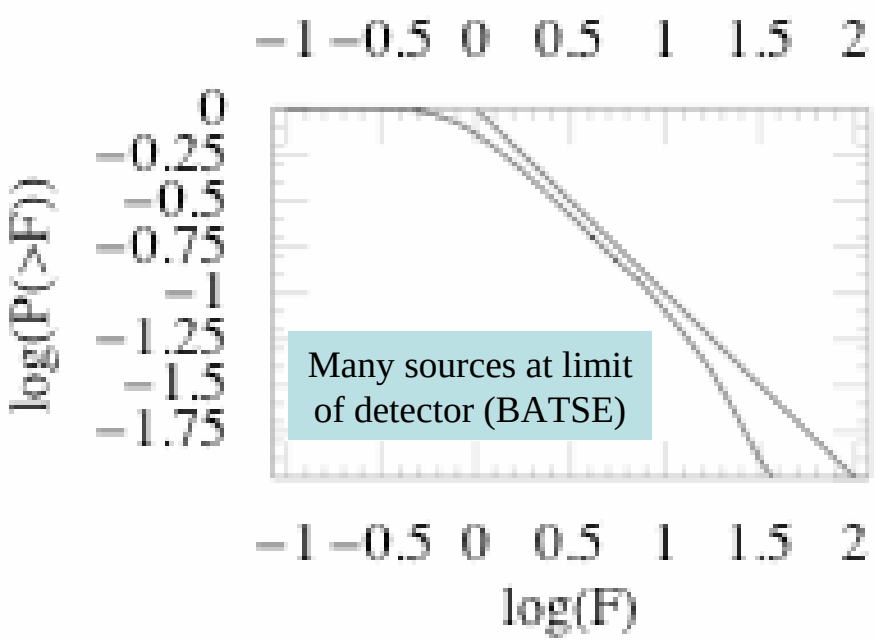
Short GRBs (BATSE view)

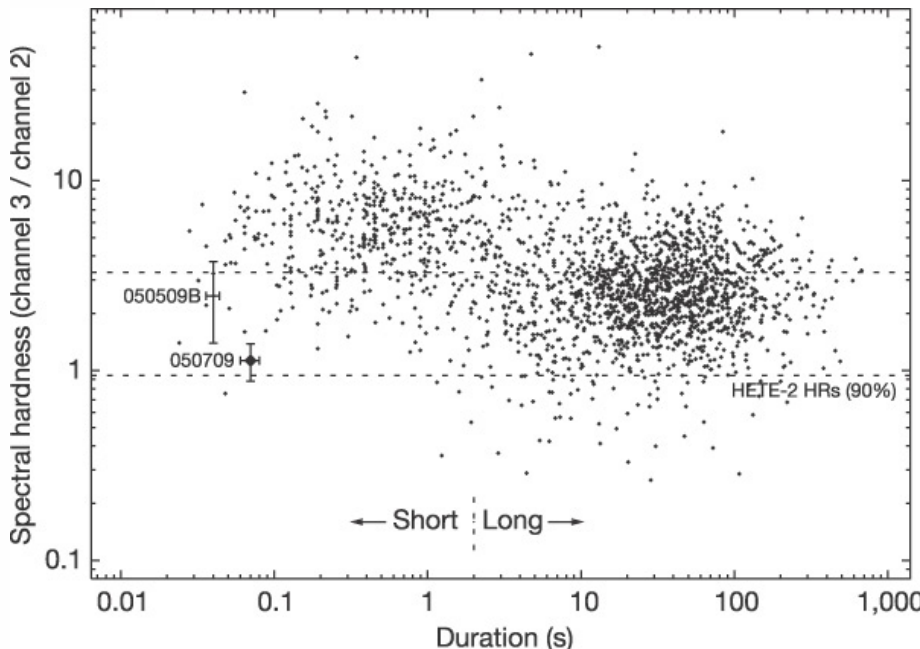
- Cosmological
- One of two classes
- Hard: often peaks out of band
- Flux power law

dP/dL ~ L^{-2}

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



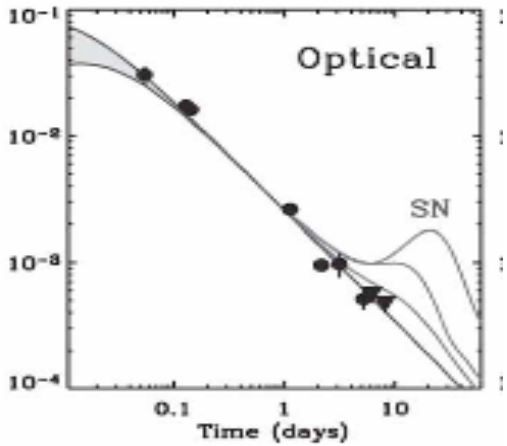




Short GRBs: A Review

Merger motivation?

- No SN structure in afterglow



GRB 051221 (Soderberg et al 2006)

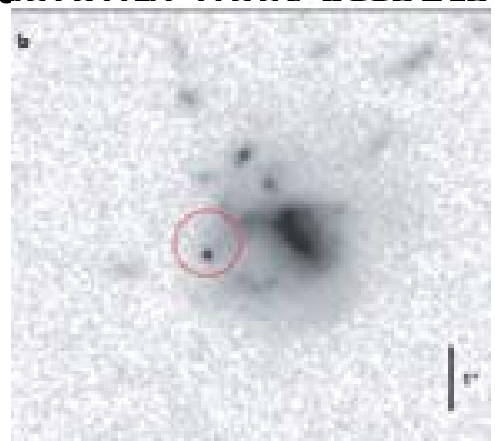
- In both **old**, young galaxies

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)

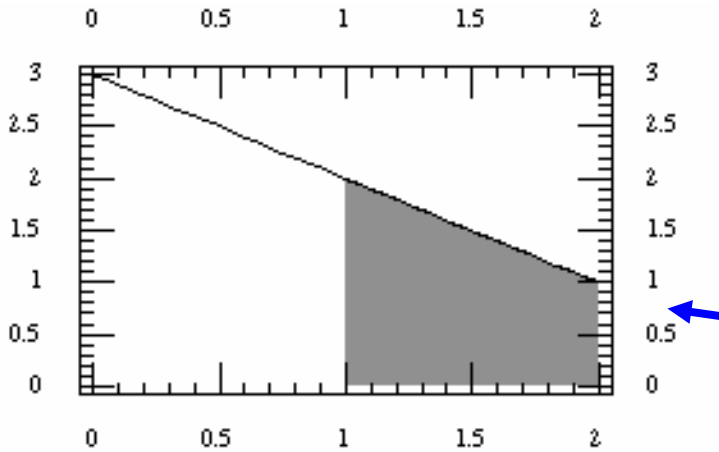
- Energetics prohibit magnetar

Observables: Detection rate?

Binary pulsars

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

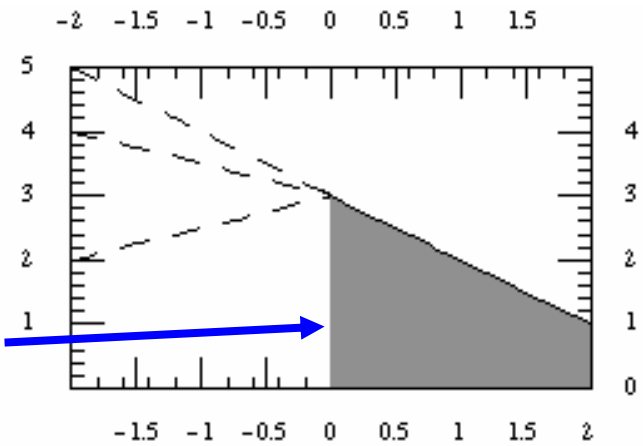
--> **rate** (+ 'small' error)



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 weak 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)

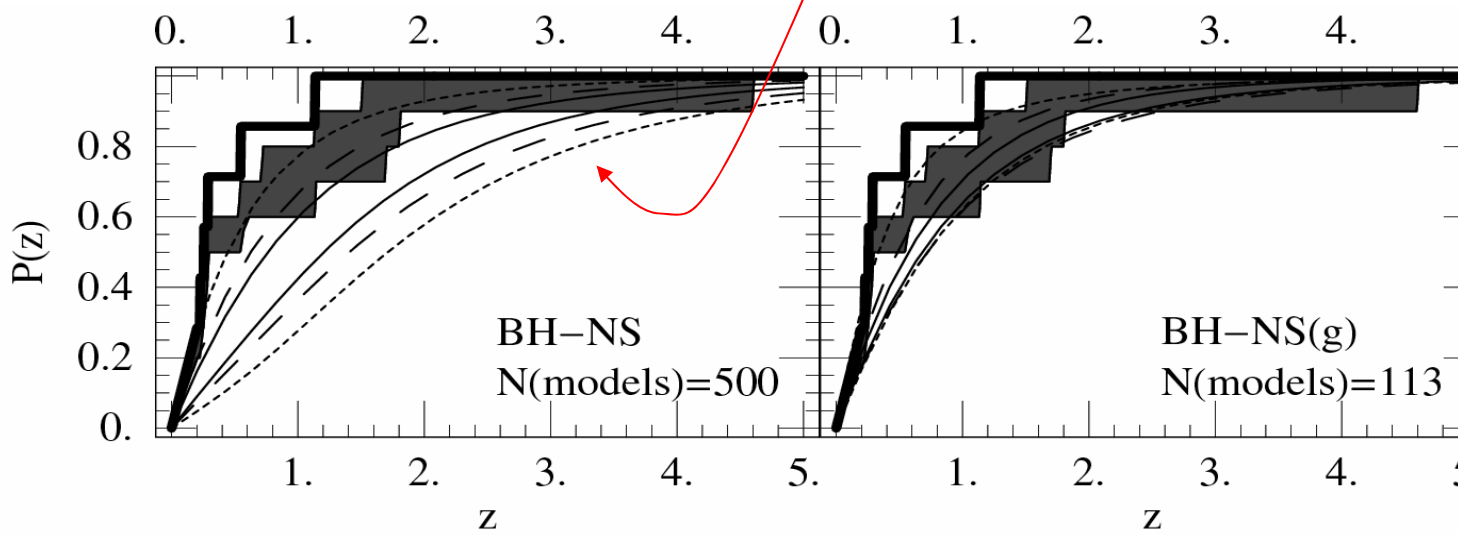
Problem: Possible/likely bias towards low redshifts

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%



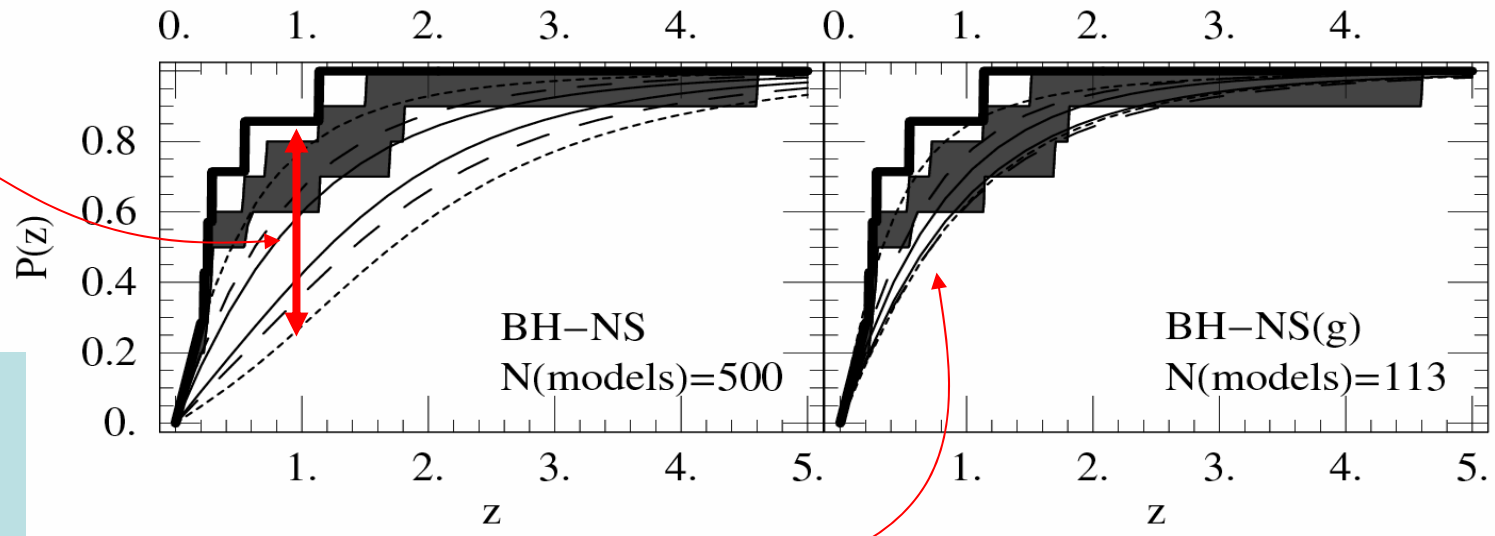
O'Shaughnessy et al (in prep)

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

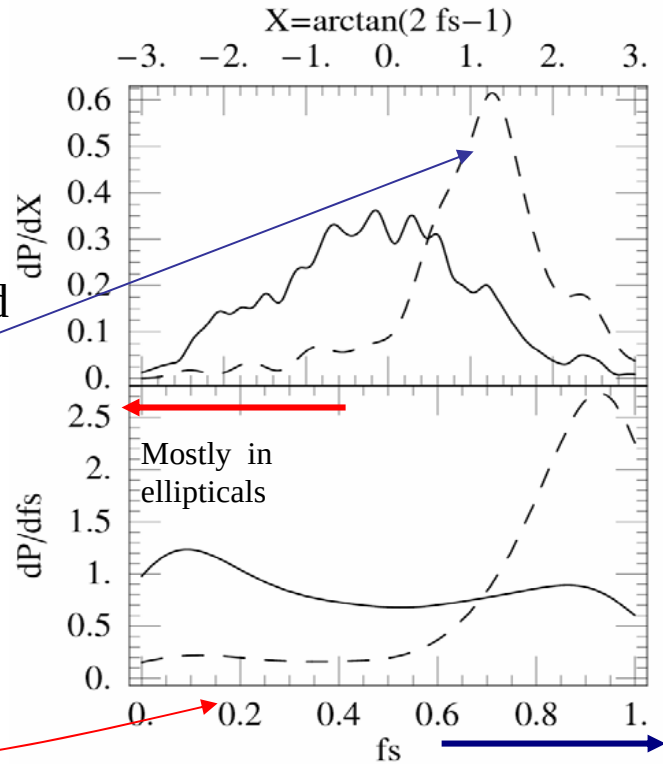
O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

BH-NS?:

- 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)



Mostly in spirals

- **Consistent**…but…

  Short GRBs appear in ellipticals!

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

O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

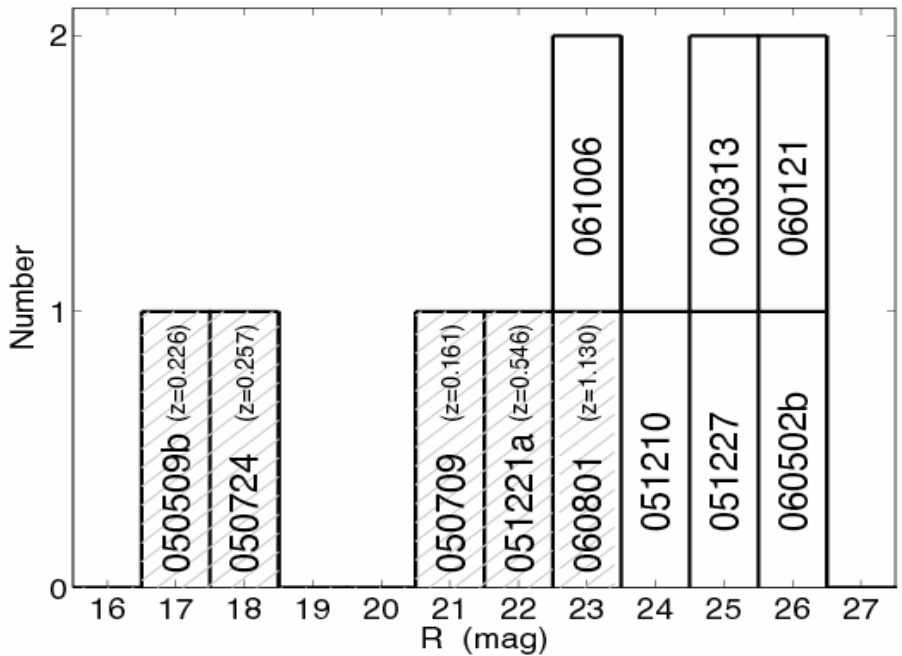
BH-NS?:

- 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]

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

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



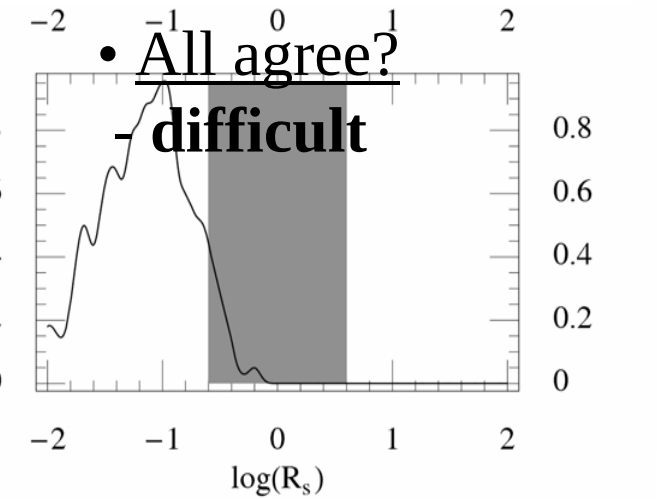
Merger predictions <-> short GRBs?

NS-NS?:

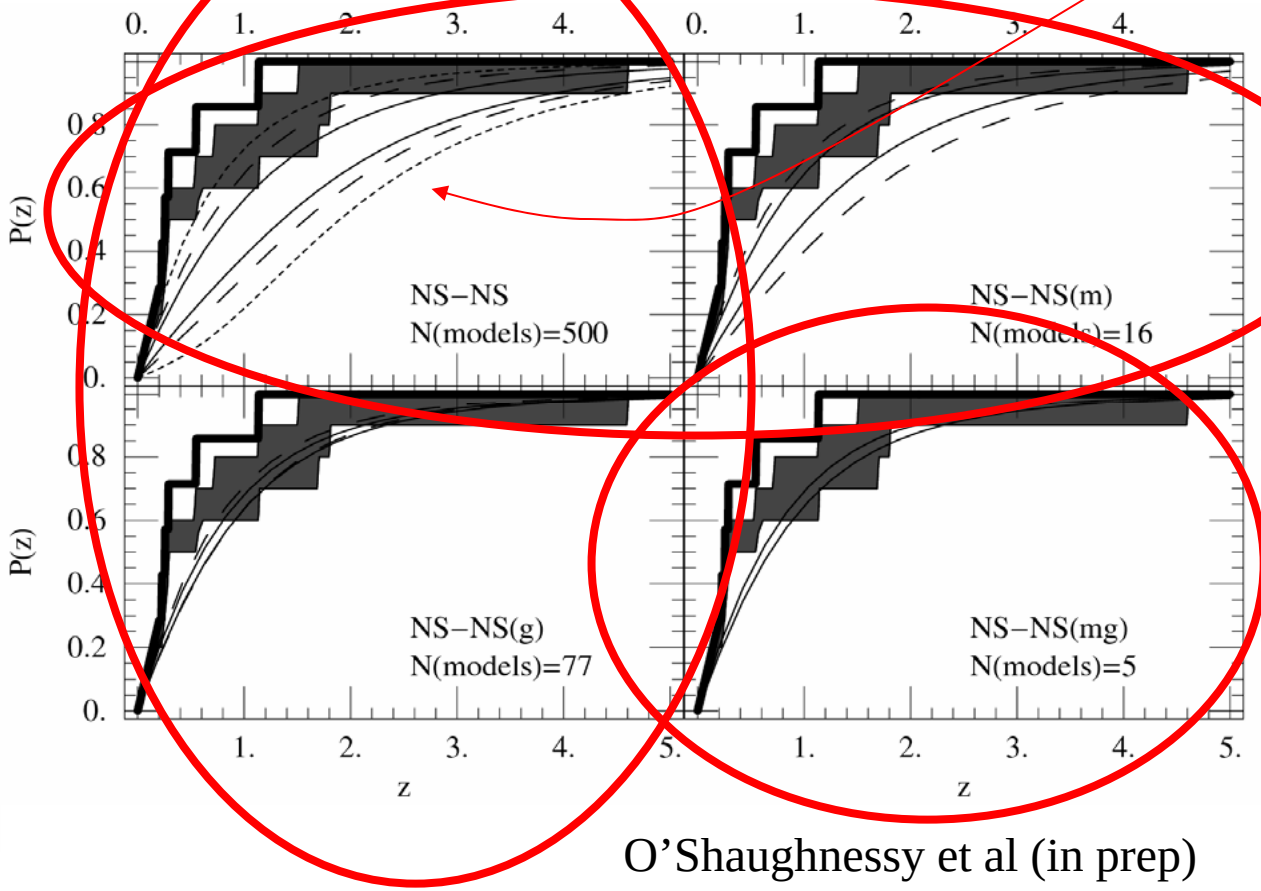
- Predictions & observations

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

- Matching redshifts
- Observed NS-NS (Milky Way)



- All agree? - **difficult**



O'Shaughnessy et al (in prep)

Merger predictions <-> short GRBs?

NS-NS?:

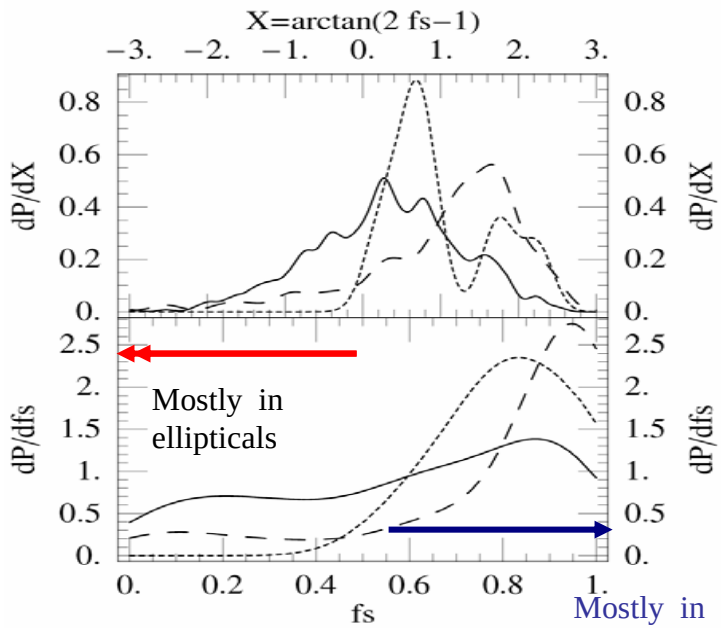
- Physical interpretation
  - Observations : GRBs
    - Dominated by **recent** events
  - Expect:
    - Recent spirals dominate or
    - **or** Ellipticals dominate, with long delays

-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 :

(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
- 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)

Some examples:
Belczynski et al. (in prep)