Title: Low Metallicity Star Formation: a Nursery for Compact Binary Mergers?

Date: Oct 06, 2011 01:00 PM

URL: http://pirsa.org/11100049

Abstract: Most predictions for binary compact object formation are normalized to the present-day Milky Way population. In this talk, I suggest the merger rate of black hole binaries could be exceptionally sensitive to the ill-constrained fraction of low-metallicity star formation that ever occurred on our past light cone. I discuss whether and how observations might distinguish binary evolution uncertainties from this strong trend, both in the near future with well-identified electromagnetic counterparts and in the more distant future via third-generation gravitational wave detectors.

Low metallicity star formation: the birthplace of binary mergers?

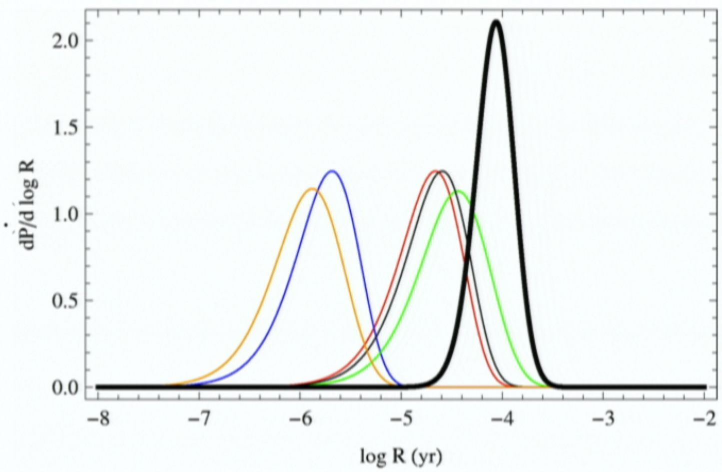
R. O'Shaughnessy
for **M. Dominik,** K. Belczynski, C. Fryer,
I. Mandel, E. Berti, D. Holz
and J. Bellovary, S. Shen

Belczynski et al 2010 [arxiv:1004.0386]

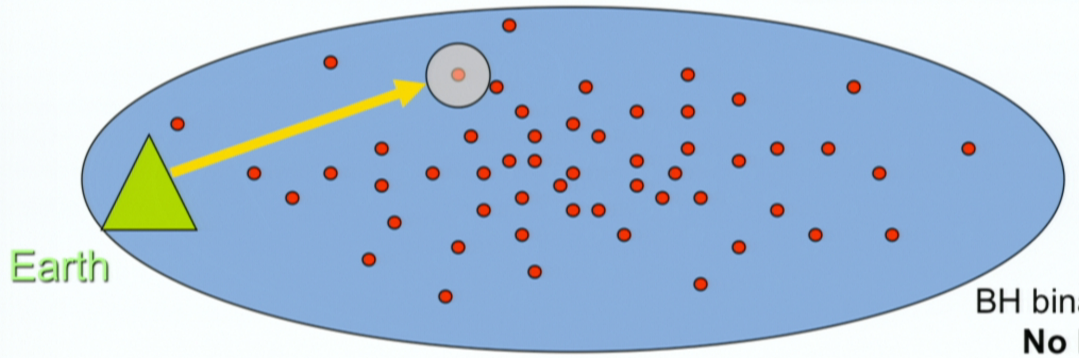
Galactic PSR merger rate

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



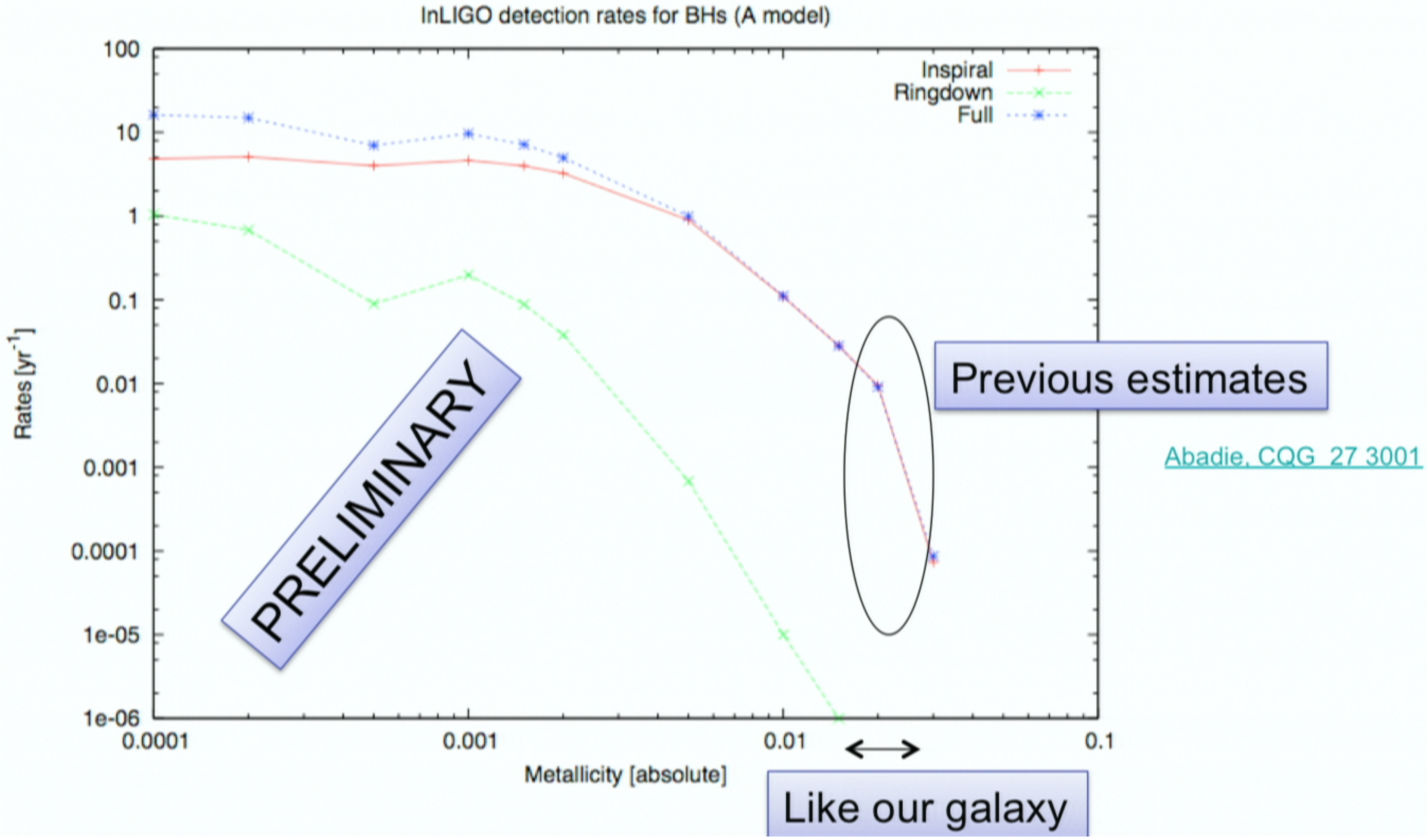
NS-NS merger rate in Milky Way
ROS and Kim, ApJ 715 230 (2010)
Kim et al ApJ 584 985 (2003)
Kim et al astro-ph/0608280
Kim et al ASPC 328 261 (2005)
Kim et al ApJ 614 137 (2004)



BH binary sources:
No known

Outline

Event rate versus metallicity



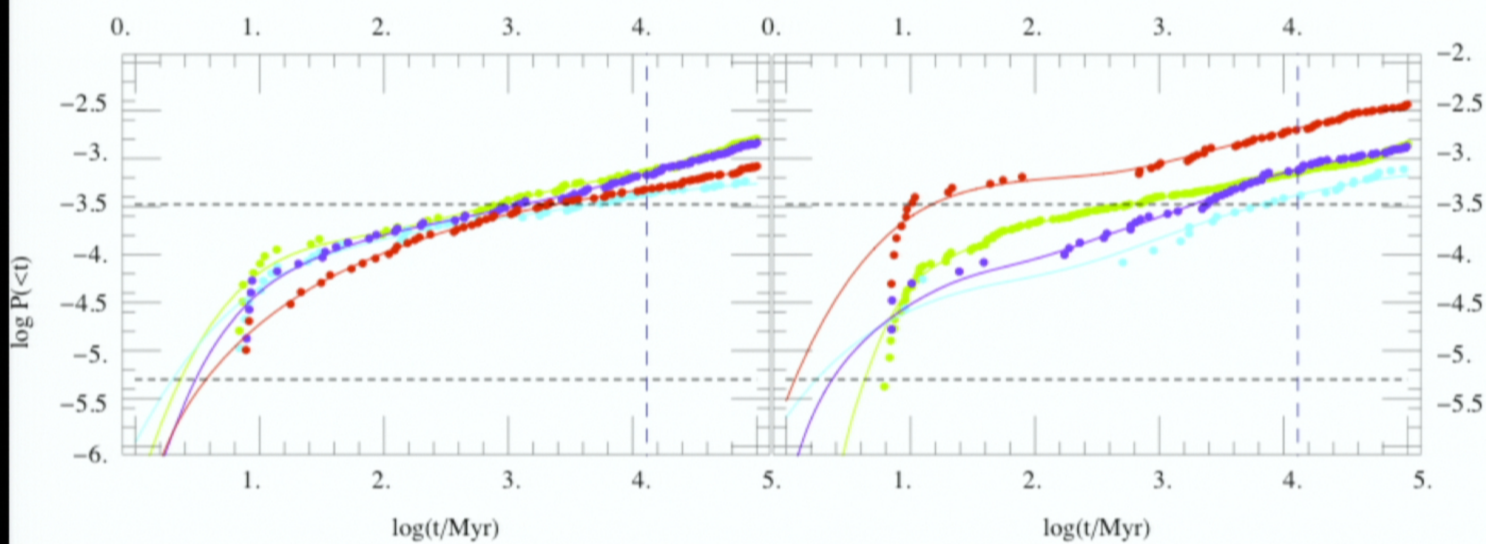
Abadie, CQG 27 3001

Outline

BH-BHs often **merge <u>long</u> after formation**

Most just barely close enough to merge via GW

“Naturally” produced in early universe (low Z!)



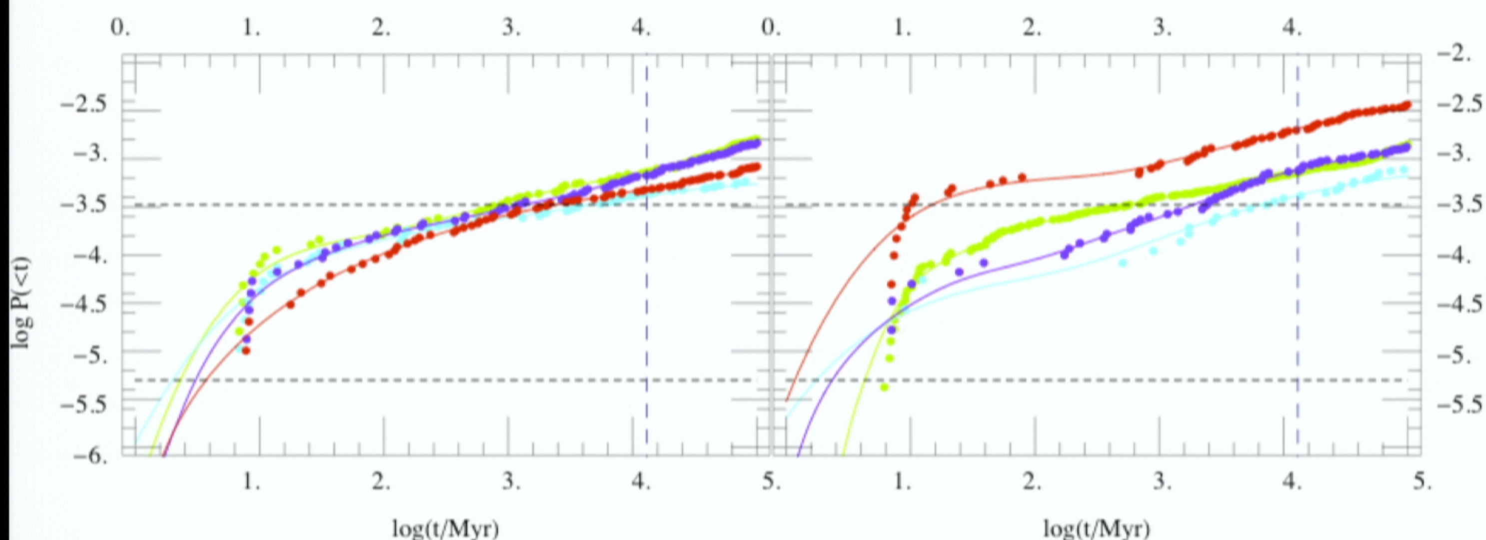
ROS et al 0908.3635

Outline

BH-BHs often **merge <u>long</u> after formation**

Most just barely close enough to merge via GW

"Naturally" produced in early universe (low Z!)

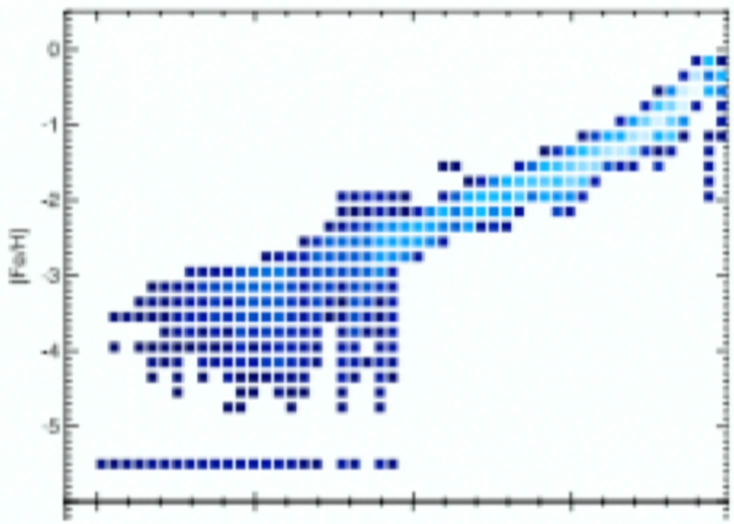


ROS et al 0908.3635

Outline

Metallicity distribution

- Metal content doesn't grow uniformly between (M-Z), within halos **even at fixed age**: halo capture, filaments



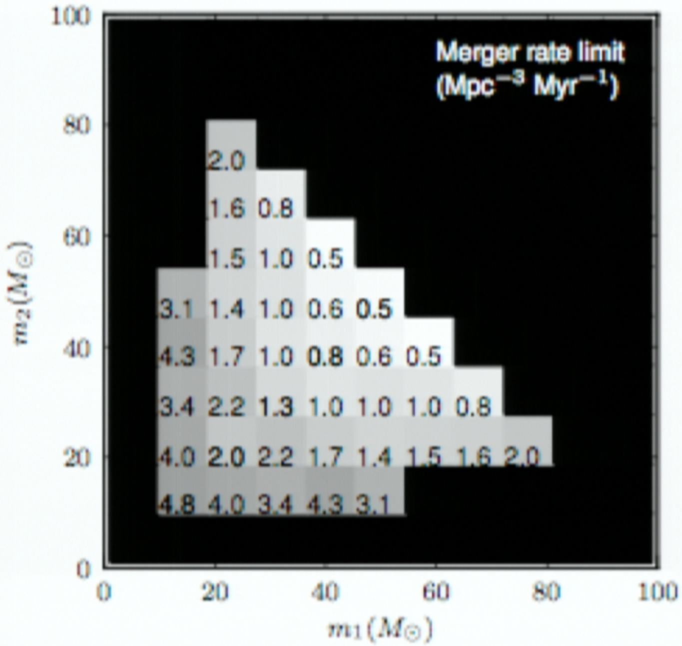
Milky way halo model

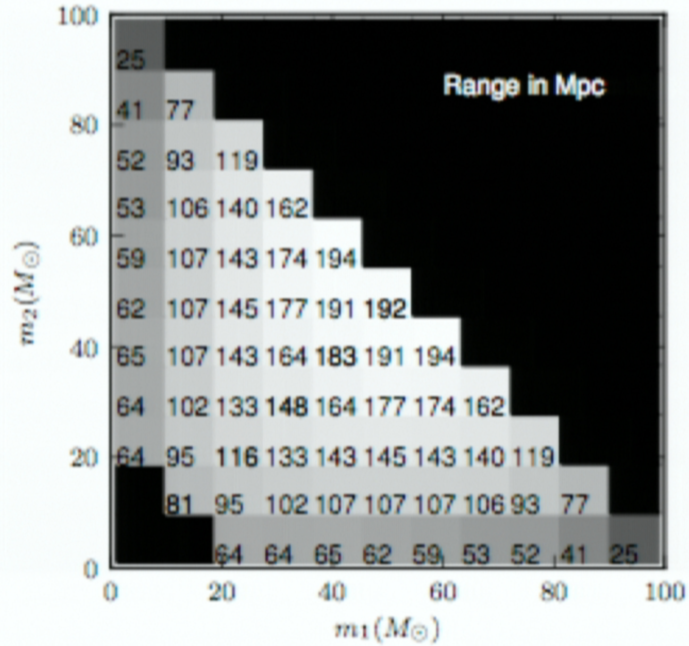
z=5

Tumlinson 0911.1786

Outline

Existing, future upper limits





LIGO S5 highmass upper limit [arXiv:1102.3781]

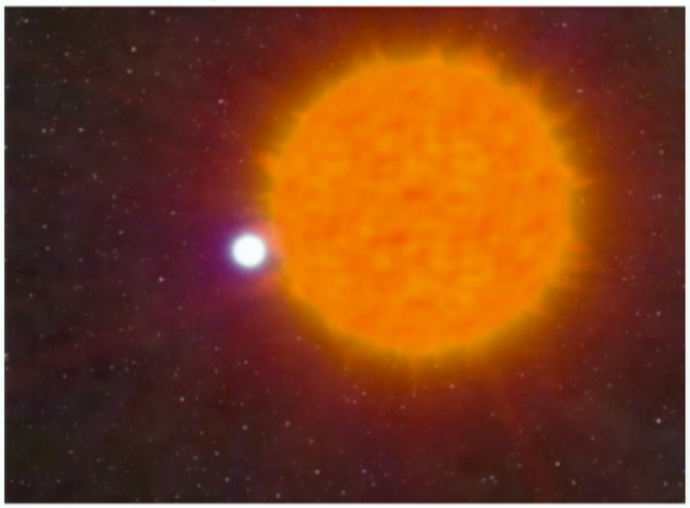
Outline

- Motivation: Metallicity (Z) matters
- Why so sensitive to Z?
- Z distribution?
- Implications for
  - LIGO?
  - Short GRBs
- Current challenges, future directions

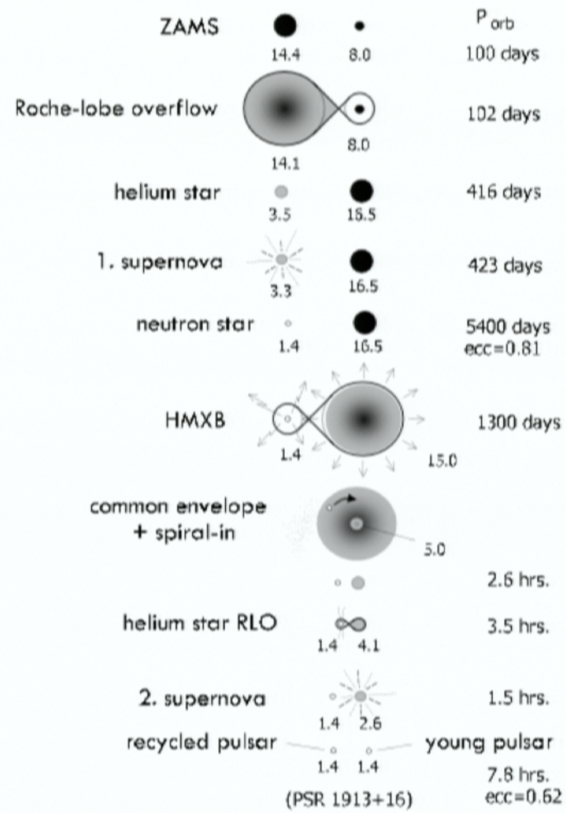
Stars evolve, interact

Complex process

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



Movie: John Rowe



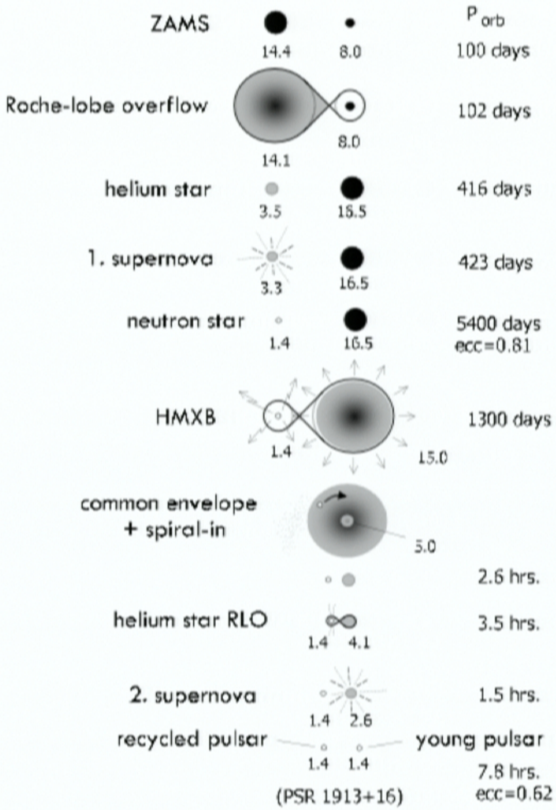
Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

Stars evolve, interact

Complex process

- 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

Interaction needed

- **Mass transfer**:

  <u>Small orbit-> MT essential</u>

  GW radiation "fast" (< 10 Gyr) only for tight

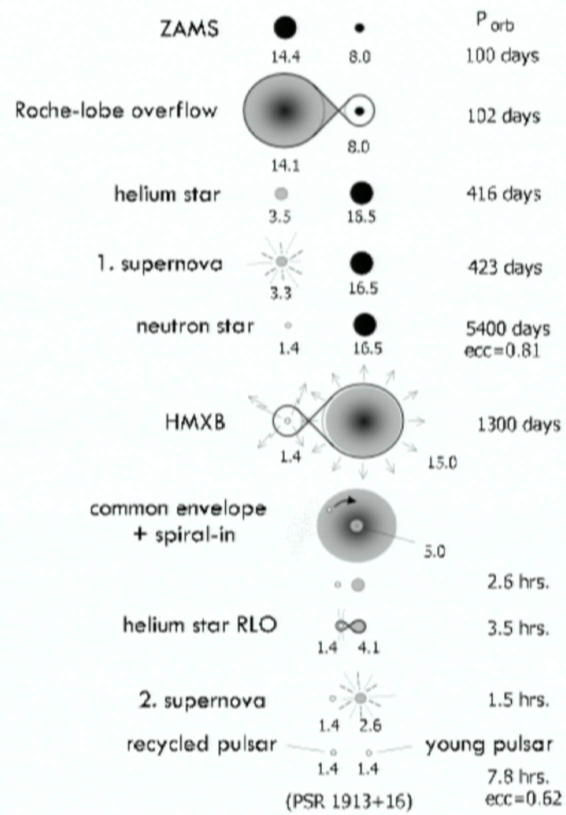
  Example: Hulse-Taylor PSR

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

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

Common envelope (<u>phenomenological</u>) parameterized (via energy or J) to unbind envelope

$$E_{bind} = \alpha \Delta E_{orb}$$



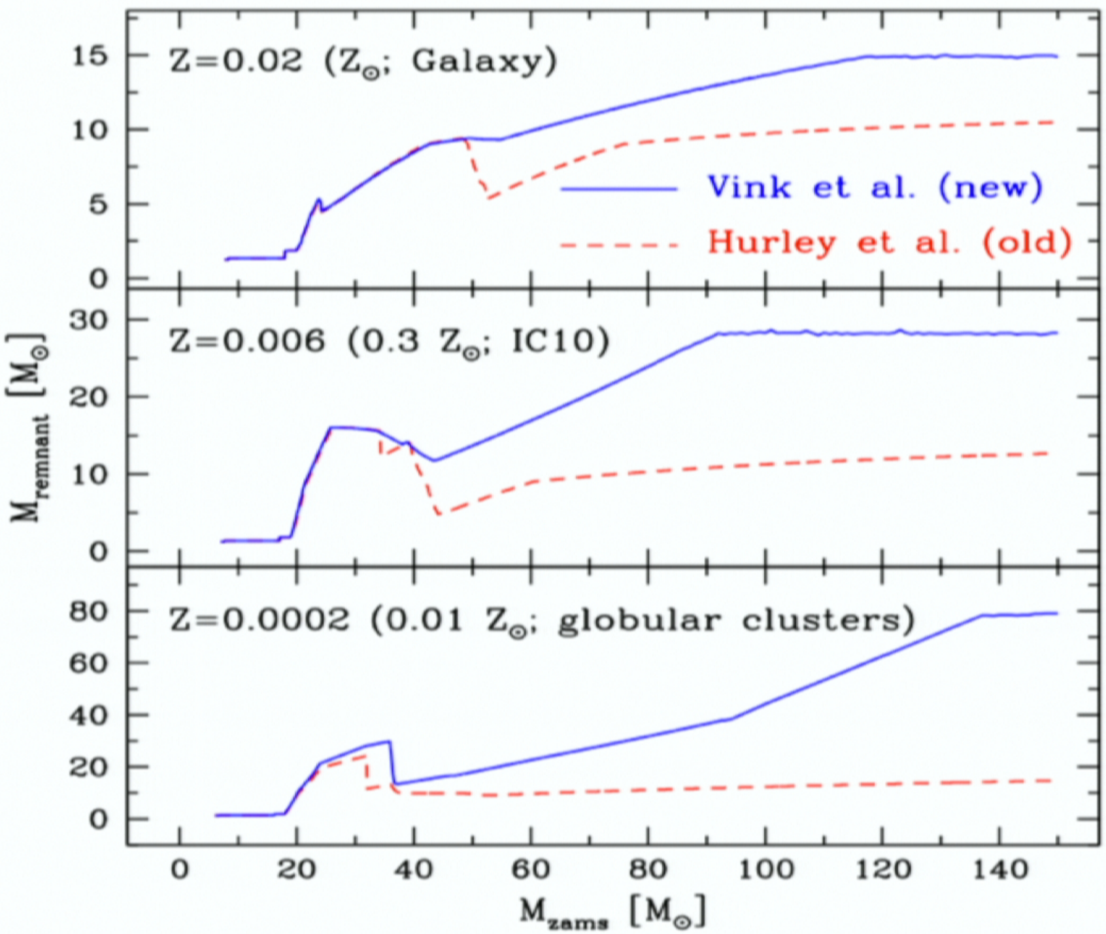
Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

Low metallicity changes….

- <u>Winds</u>

  Less mass lost

  Bigger BHs



Belczynski et al 2009

“revised” winds

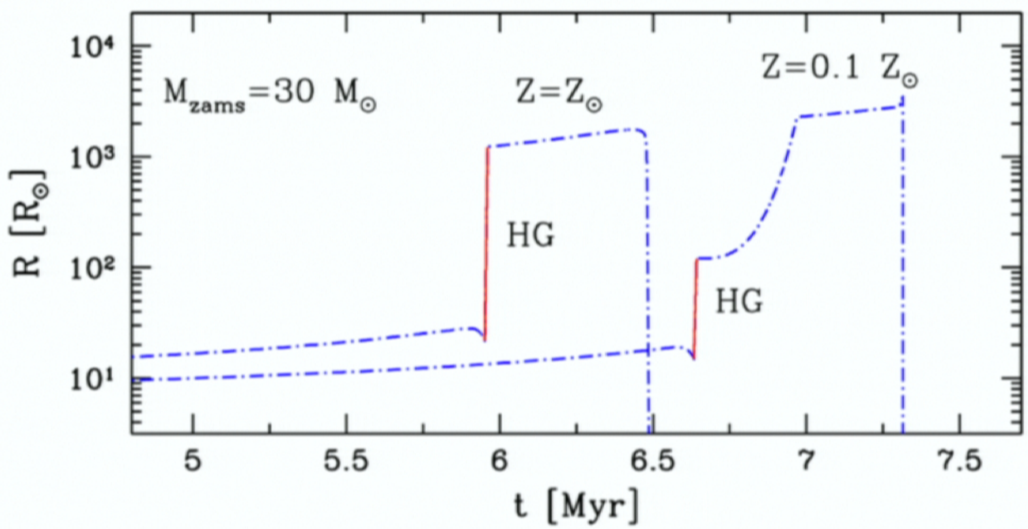
Low metallicity changes….

- Evolution, expansion:

Smaller radius

Less (& less dramatic) expansion

Contact less likely in rapid expansion phase (Hertzprung gap; "HG")



Other unknowns too…

- Supernova kicks
  - Less effective on more massive BHs (with more fallback)

- Evolution model: Common-envelope phase
  - Efficiency of mass transfer (vs ejection): Bondi; suppressed?
  - Sufficient envelope to terminate?

Belczynski et al 2010 [arxiv:1004.0386]

A: CE in HG terminates, leaves remnant

B: CE in HG merges

  - Binding energy of envelope?

- Initial conditions (IMF; binary mass, periods)
  - Ill-determined; variation with Z?

-

First estimate

Method

Variables: Z, CE merger only

Constant SFR (3.5 Msun/yr)

TABLE 1
GALACTIC MERGER RATES [MYR^{-1}][a]

Type	$Z_\odot$ (100%)	0.1 $Z_\odot$ (100%)	$Z_\odot$ + 0.1 $Z_\odot$ (50% + 50%)
NS-NS	40.8 (14.4)	41.3 (3.3)	41.1 (8.9)
BH-NS	3.2 (0.01)	12.1 (7.0)	7.7 (3.5)
BH-BH	1.5 (0.002)	84.2 (6.1)	42.9 (3.1)
TOTAL	45.5 (14.4)	138 (16.4)	91.7 (15.4)

Belczynski et al 2010 [arxiv:1004.0386]

First estimate

Method

Variables: Z, CE merger only

Constant SFR (3.5 Msun/yr)

TABLE 1
GALACTIC MERGER RATES [MYR^{-1}][a]

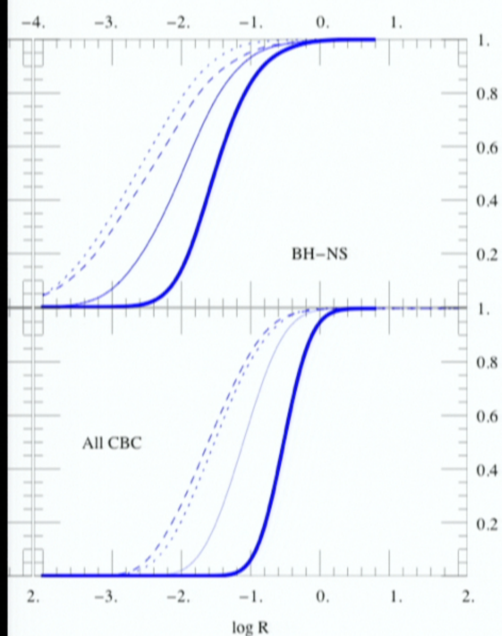
Type	$Z_\odot$ (100%)	0.1 $Z_\odot$ (100%)	$Z_\odot$ + 0.1 $Z_\odot$ (50% + 50%)
NS-NS	40.8 (14.4)	41.3 (3.3)	41.1 (8.9)
BH-NS	3.2 (0.01)	12.1 (7.0)	7.7 (3.5)
BH-BH	1.5 (0.002)	84.2 (6.1)	42.9 (3.1)
TOTAL	45.5 (14.4)	138 (16.4)	91.7 (15.4)

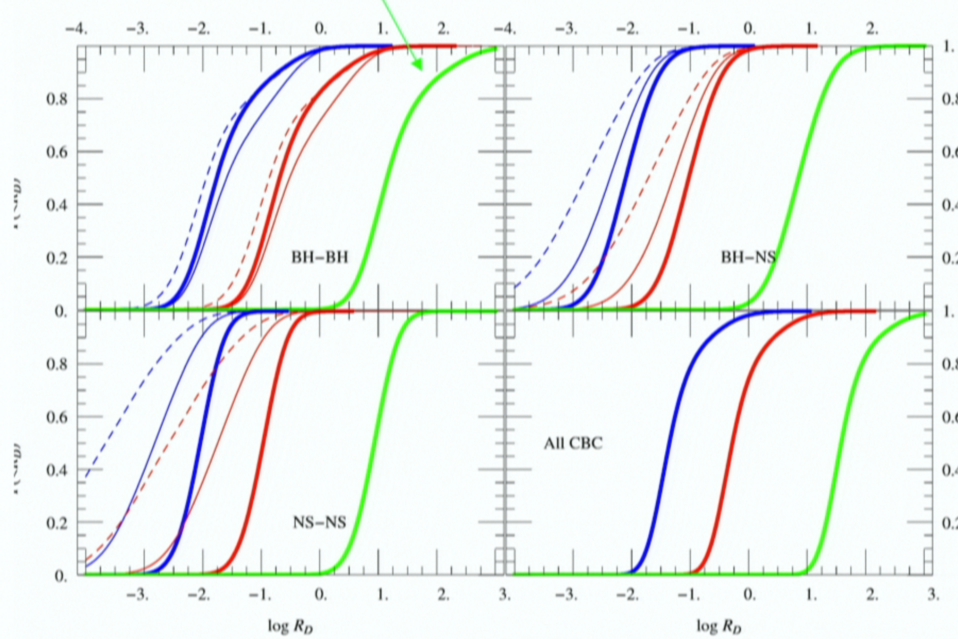
Belczynski et al 2010 [arxiv:1004.0386]

Previous calculations: BH-BH

Mergers: <10/gal/Myr [ROS et al 0908.3635; *one* channel]

Detections: O(30/yr), aLIGO network





log (rate*Myr), single detector

First estimate

Method

Variables: Z, CE merger only

Constant SFR (3.5 Msun/yr)

TABLE 1
GALACTIC MERGER RATES [MYR^{-1}][a]

Type	$Z_\odot$ (100%)	0.1 $Z_\odot$ (100%)	$Z_\odot$ + 0.1 $Z_\odot$ (50% + 50%)
NS-NS	40.8 (14.4)	41.3 (3.3)	41.1 (8.9)
BH-NS	3.2 (0.01)	12.1 (7.0)	7.7 (3.5)
BH-BH	1.5 (0.002)	84.2 (6.1)	42.9 (3.1)
TOTAL	45.5 (14.4)	138 (16.4)	91.7 (15.4)

Belczynski et al 2010 [arxiv:1004.0386]

First estimate

Method

Variables: Z, CE merger only

Constant SFR (3.5 Msun/yr)

TABLE 1
GALACTIC MERGER RATES $[\mathrm{MYR}^{-1}]^{a}$

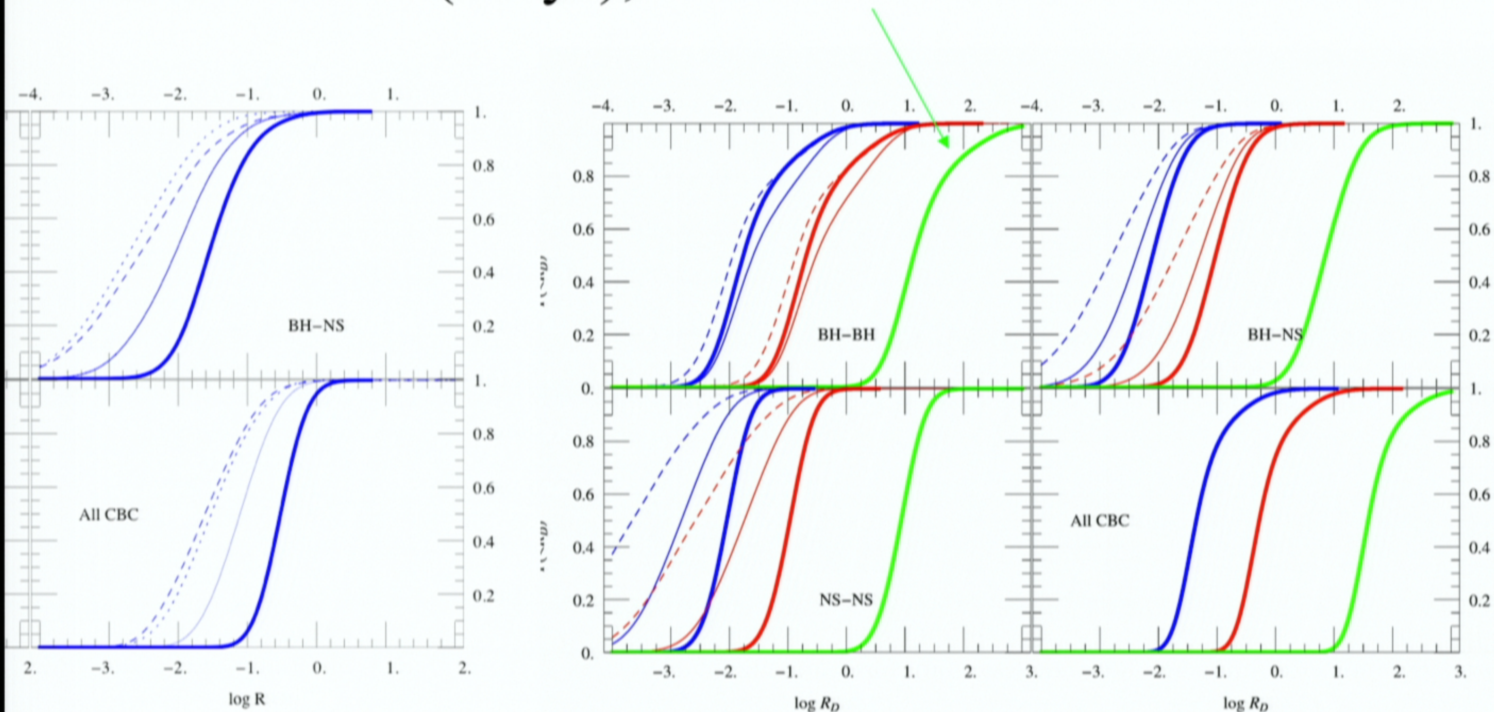
Type	$Z_{\odot}$ (100%)	0.1 $Z_{\odot}$ (100%)	$Z_{\odot}$ + 0.1 $Z_{\odot}$ (50% + 50%)
NS-NS	40.8 (14.4)	41.3 (3.3)	41.1 (8.9)
BH-NS	3.2 (0.01)	12.1 (7.0)	7.7 (3.5)
BH-BH	1.5 (0.002)	84.2 (6.1)	42.9 (3.1)
TOTAL	45.5 (14.4)	138 (16.4)	91.7 (15.4)

Belczynski et al 2010 [arxiv:1004.0386]

Previous calculations: BH-BH

Mergers: <10/gal/Myr [ROS et al 0908.3635; *one* channel]

Detections: O(30/yr), aLIGO network



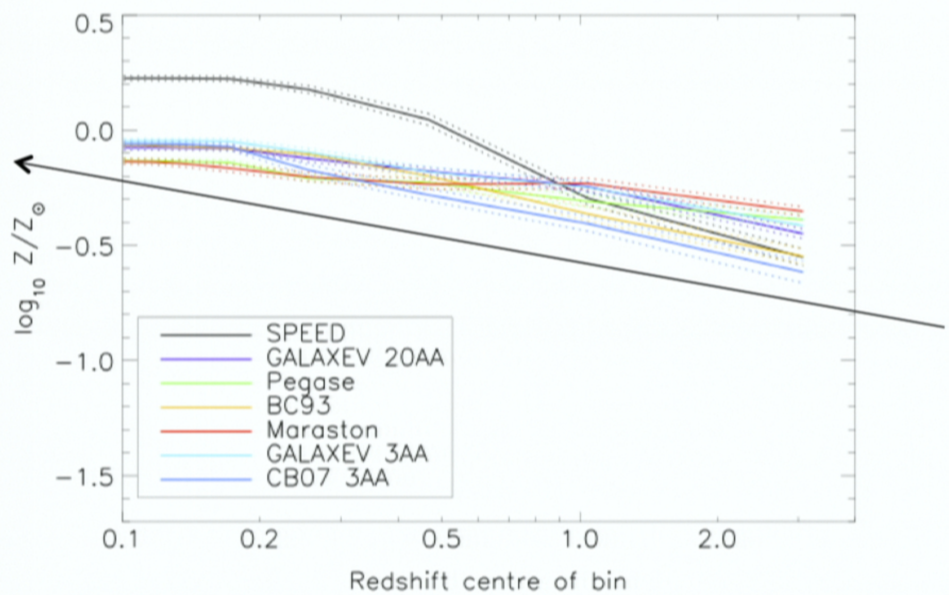
log (rate*Myr), single detector

Metallicity distribution

Metallicity distribution

- Stellar reprocessing:

  Metal content increases with time



Panter 2008, MNRAS 391 117
Across galaxies, **total Z**

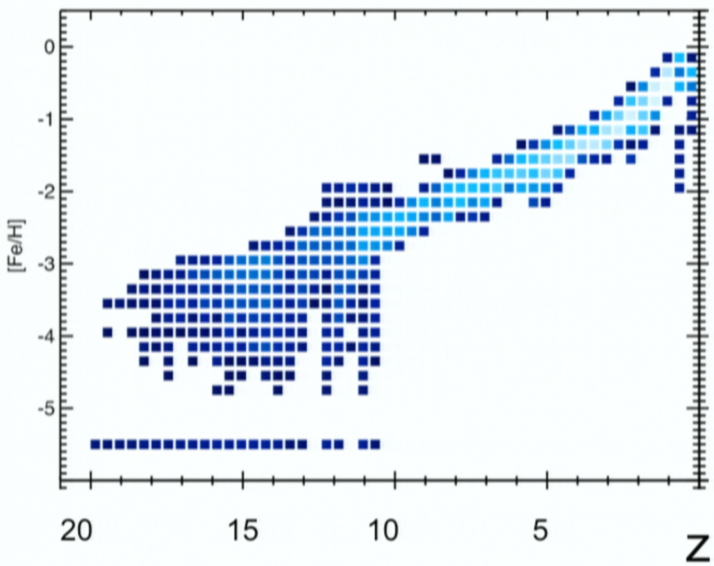
Z increases with time
(several methods consistent)

Metallicity distribution

Metallicity distribution

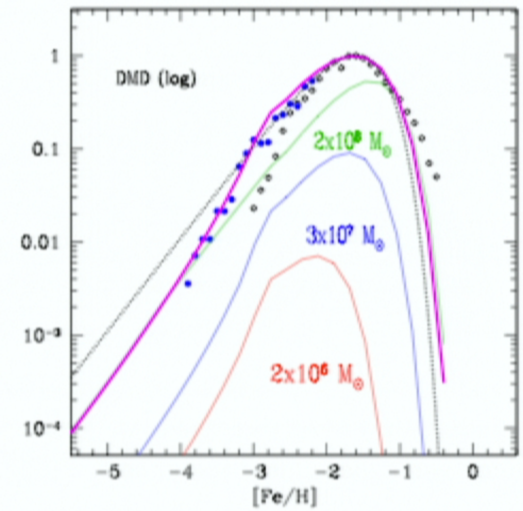
- Metal content doesn't grow uniformly

even at fixed age: halo capture, filaments



Tumlinson 0911.1786

Milky way halo models

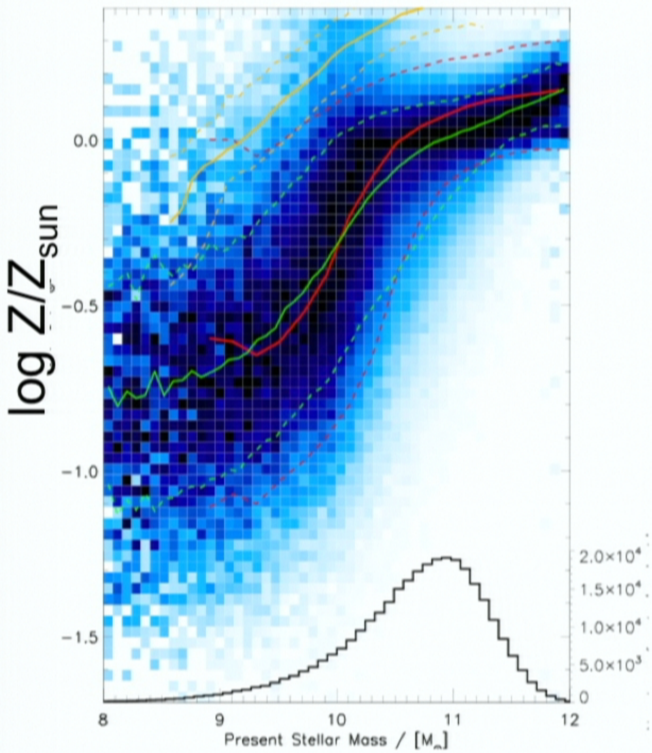


Prantzos 2008

Metallicity distribution

Metallicity distribution

Metal content doesn't grow uniformly



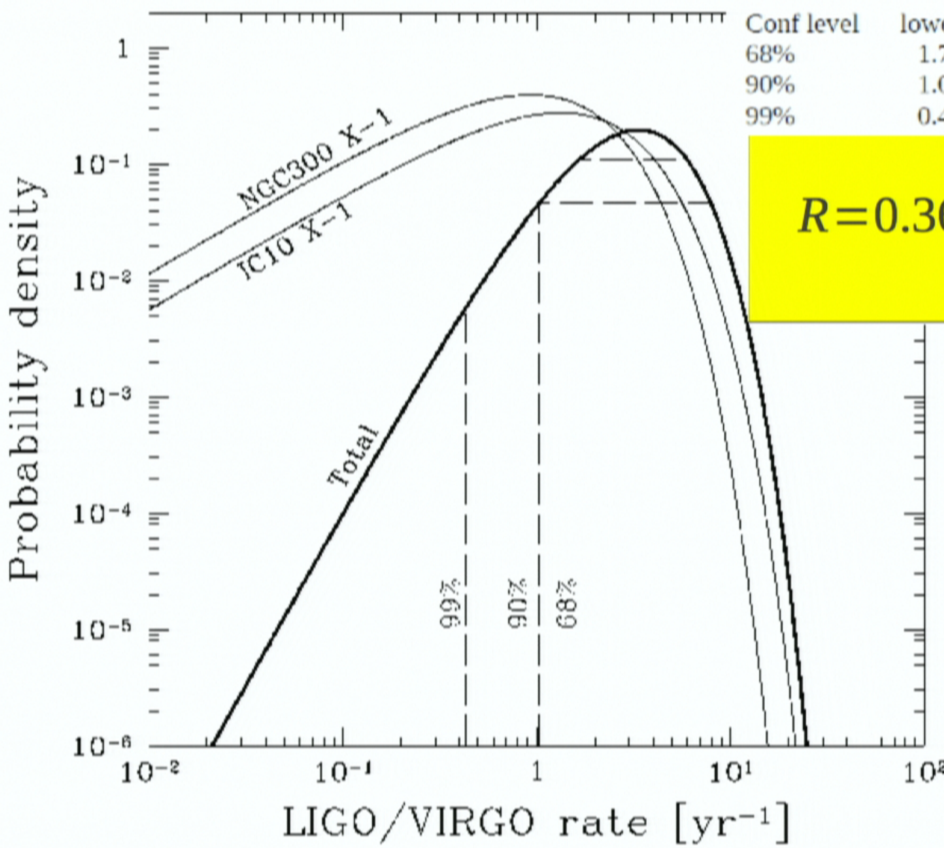
"mass-metallicity relation"

Panter 2008, MNRAS 391 117
Across galaxies; all stellar mass

Low Z now?
- Blue compact dwarfs
- "Green peas"
- 1 ZW 18

Corroboration?

Detection rates



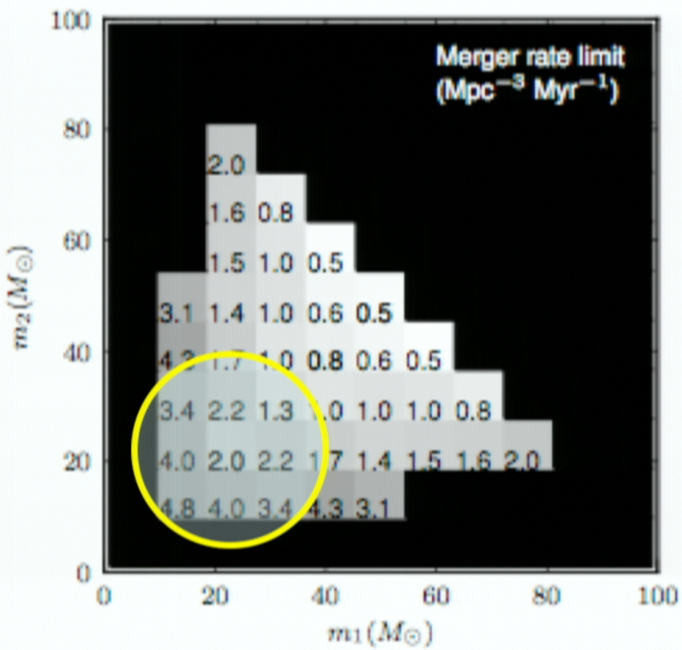
Conf level	lowest rate	highest rate per year
68%	1.73	5.80
90%	1.03	7.91
99%	0.43	11.6

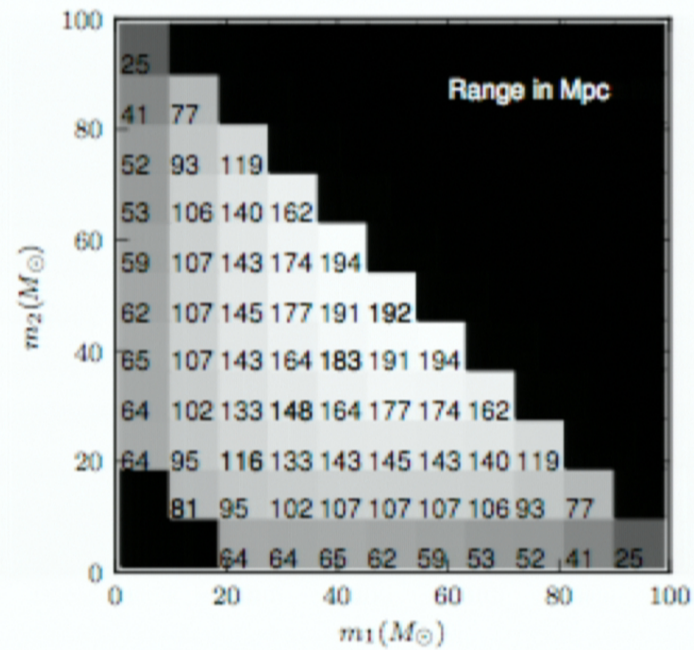
$$R = 0.36 \pm^{0.50}_{0.26} Mpc^{-3} Myr^{-1}$$

Bulik, GWPAW

Implications for LIGO

Close…



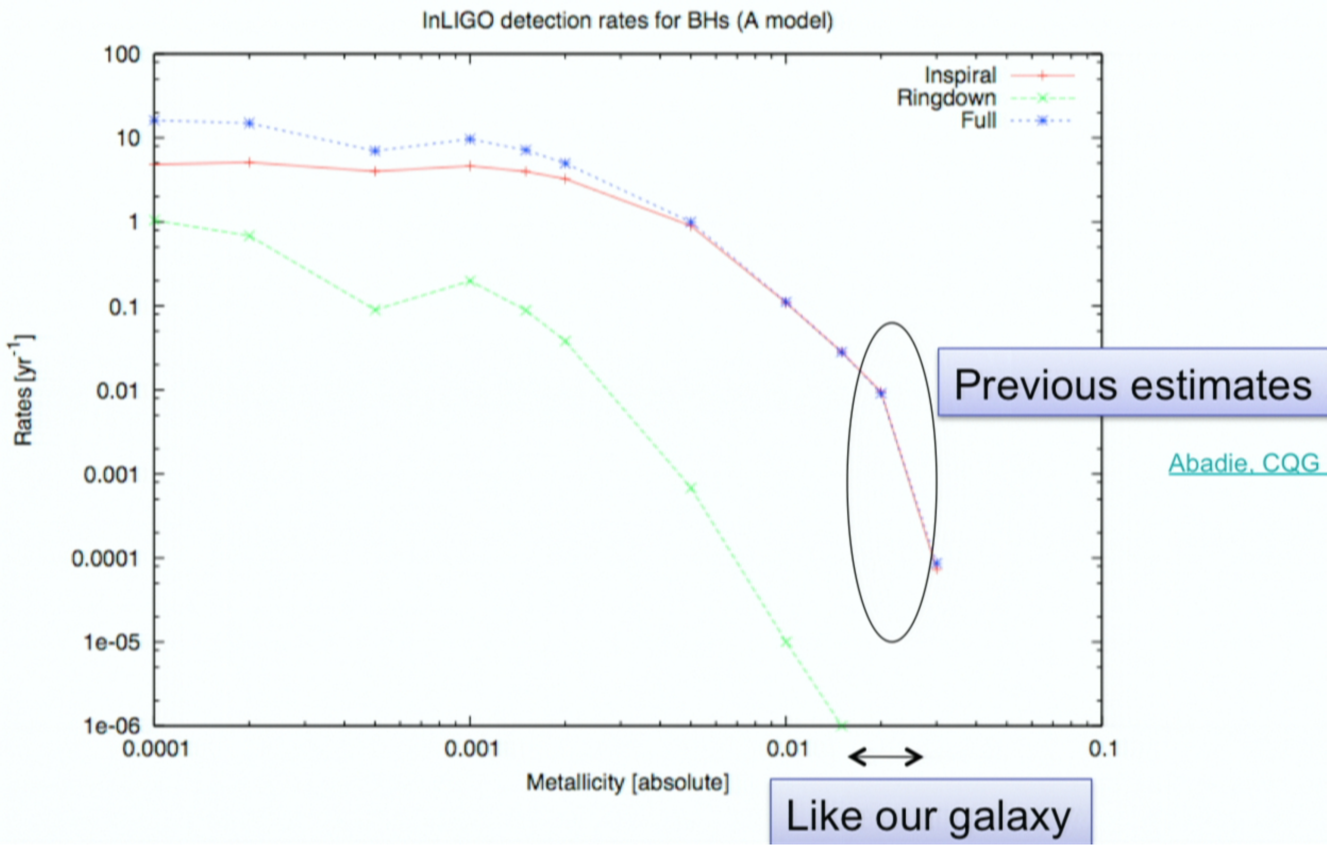


$$R = 0.36 \pm^{0.50}_{0.26} Mpc^{-3} Myr^{-1}$$

LIGO S5 highmass upper limit [arXiv:1102.3781]

Implications for LIGO

Event rate versus metallicity



Abadie, CQG 27 3001

What can we **eventually** measure?

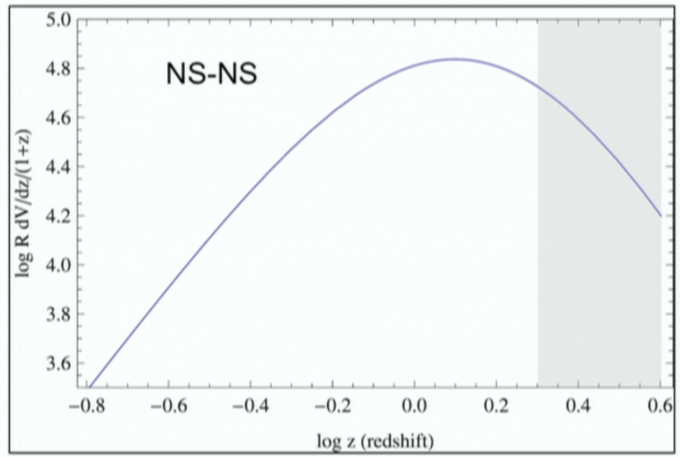
Third-generation: tomography

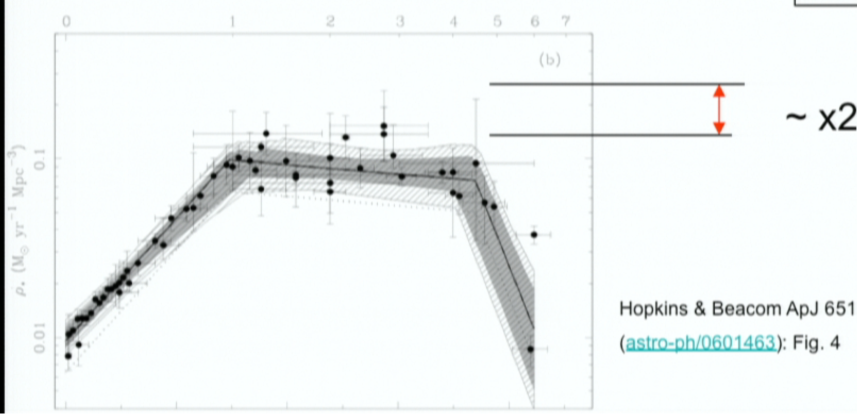
Example: NS-NS:

- 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





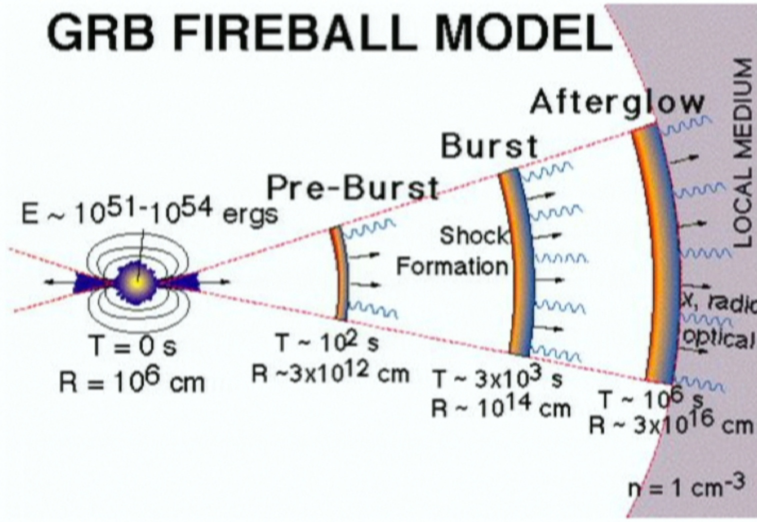
Hopkins & Beacom ApJ 651 142 2006
(astro-ph/0601463): Fig. 4

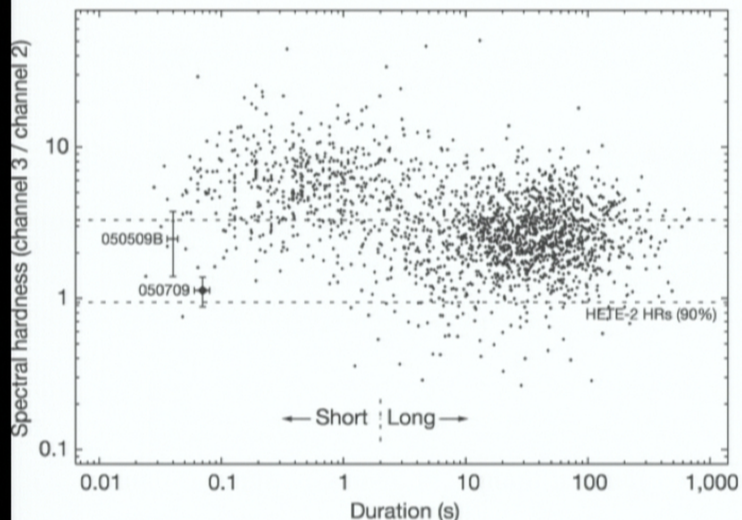
Short GRBs: Review

GRBs generally

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

GRB FIREBALL MODEL





Two classes

Swift website

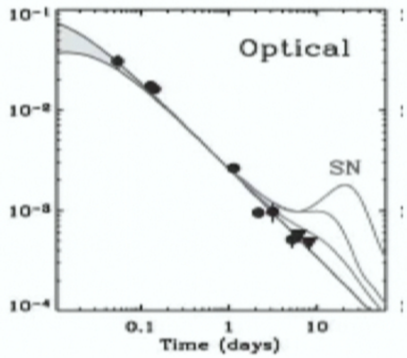
Long : Post-burst (some) are SN; correlate to early SFR; …

Short : ….

Short GRBs: Review

Merger motivation?

- No SN structure in afterglow



GRB 051221 (Soderberg et al 2006)

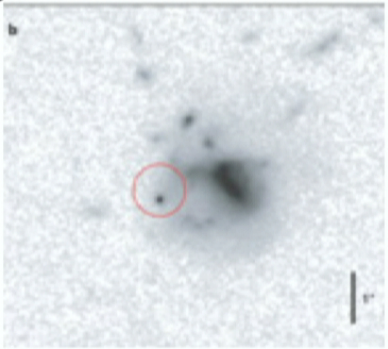
- In both **old**, young galaxies

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



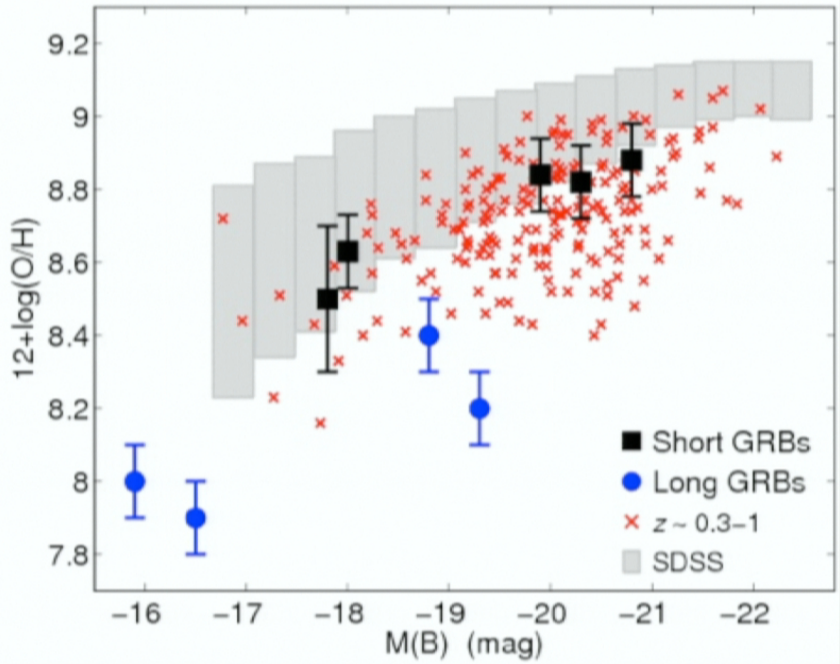
GRB 050709 (Fox et al Nature 437 845)

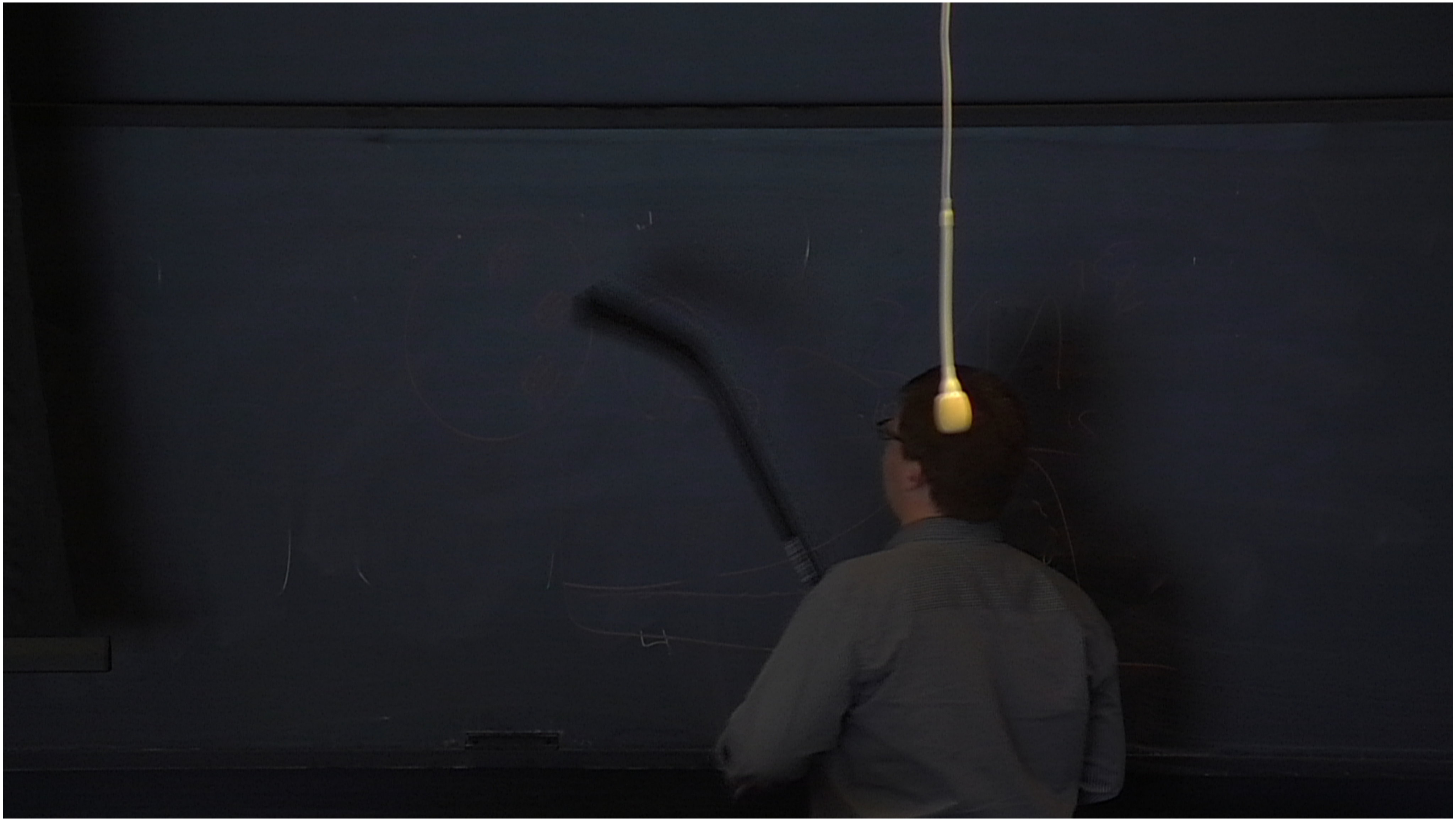
- Energetics prohibit magnetar

Short GRBs and dwarfs

- Implications: Low-Z bias for short GRBs?
  - Low Z bias? (no?)
    - Lower than *now*, Typical at z ~ 0.3-1
  - Dwarf galaxies [mass metallicity relation]
  - Kicks and no hosts (25%: Berger 2010)
- Issue:
  - "Average" vs "birth" Z [ROS, Bellovary et al in prep]

Berger 2009

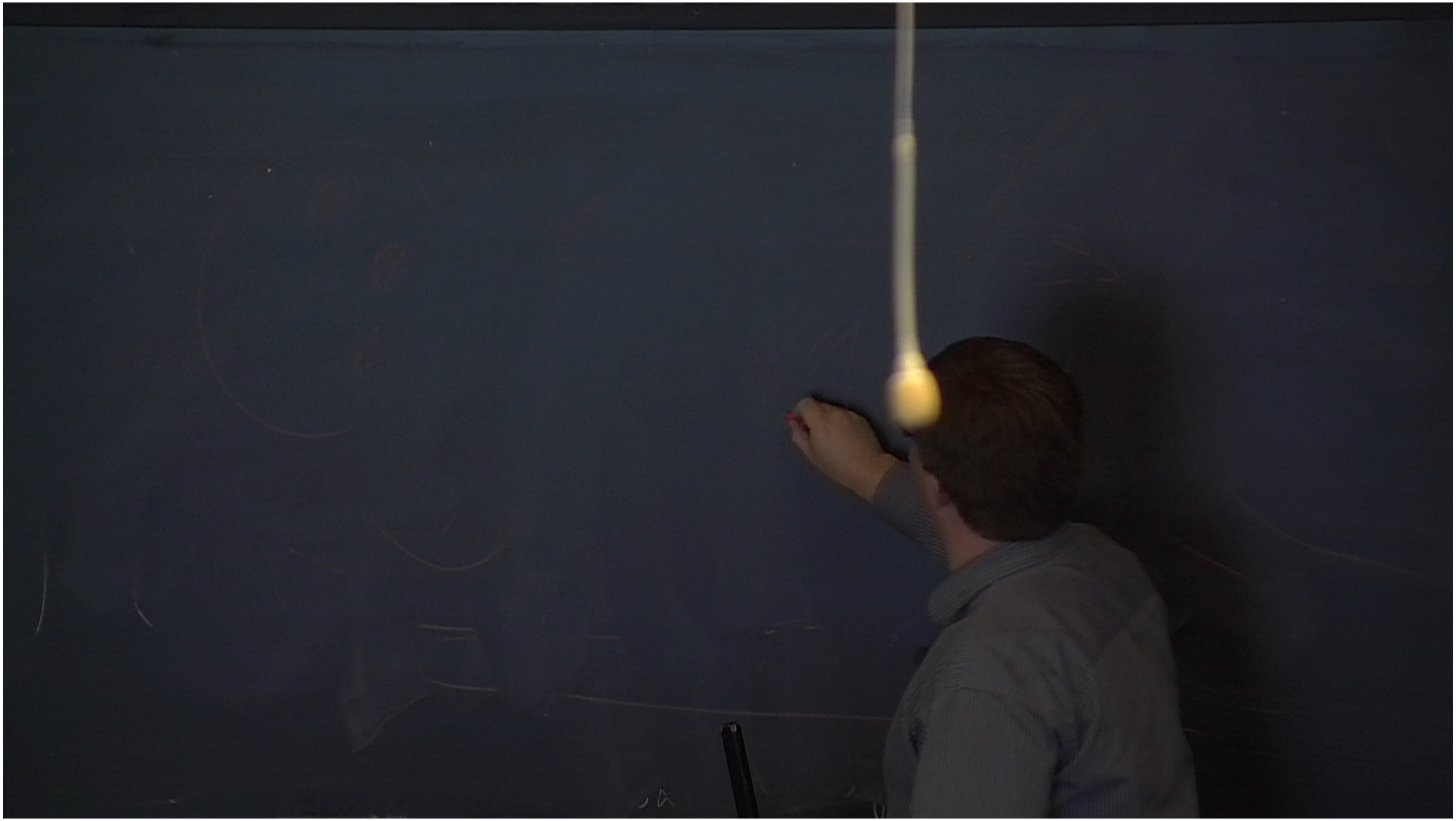




Concluding comments

- High GW detection rate likely…given our assumptions
  - Kicks on BHs
  - Winds of high-mass stars
  - Mass transfer in CE phase
  - Binding energy of envelope

- Current directions:
  - Technical improvements (envelope model); parameter study
  - Predicting, testing metallicity dependence (short GRBs)
  - Complimentary constraints and total consistency (PSRs,XRBs, sdBs, …)



Short GRBs and dwarfs

- Implications: Low-Z bias for short GRBs?
  - Low Z bias? (no?)
    - Lower than *now*, Typical at z ~ 0.3-1
  - Dwarf galaxies [mass metallicity relation]
  - Kicks and no hosts (25%: Berger 2010)
- Issue:
  - "Average" vs "birth" Z [ROS, Bellovary et al in prep]

Berger 2009