Critically assessing Binary mergers as short hard GRBs

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Outline

- Short GRBs & compact mergers
- Review: ‘Classical’ route to merger rates
- Revised: Modeling net merger and GRB rates
  - Ingredients
  - Predictions
- Experimental perspective:

  Directly measuring merger rates with GRBs?
- GRBs and GW: Testing the model…

Goal: Details !

- Theoretical GRB ‘predictions’?

__ **uncertain**

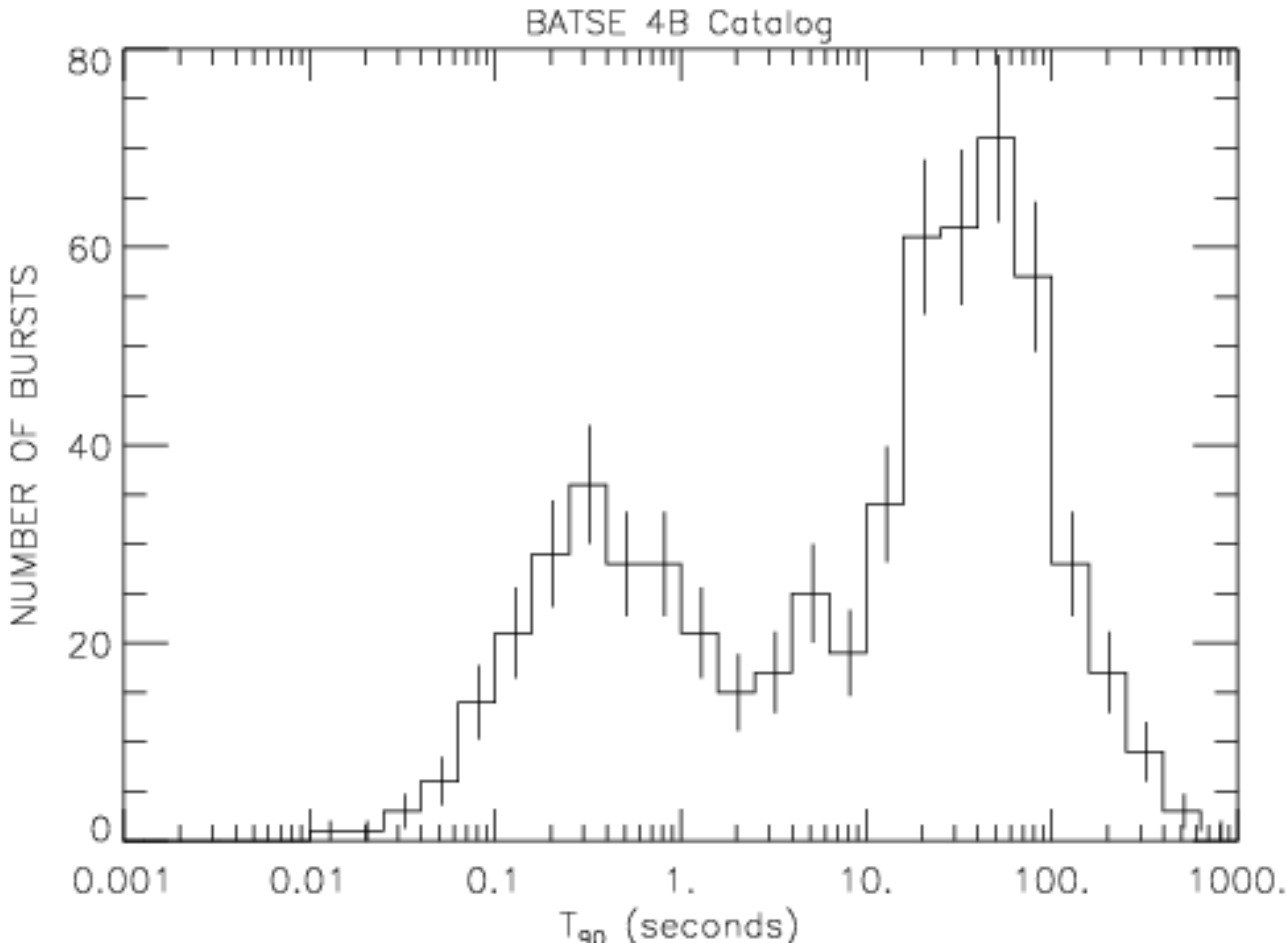
… an **opportunity** to constrain astrophysics !

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

GRBs: Experimental view

- Multiple classes:

  Duration diagram

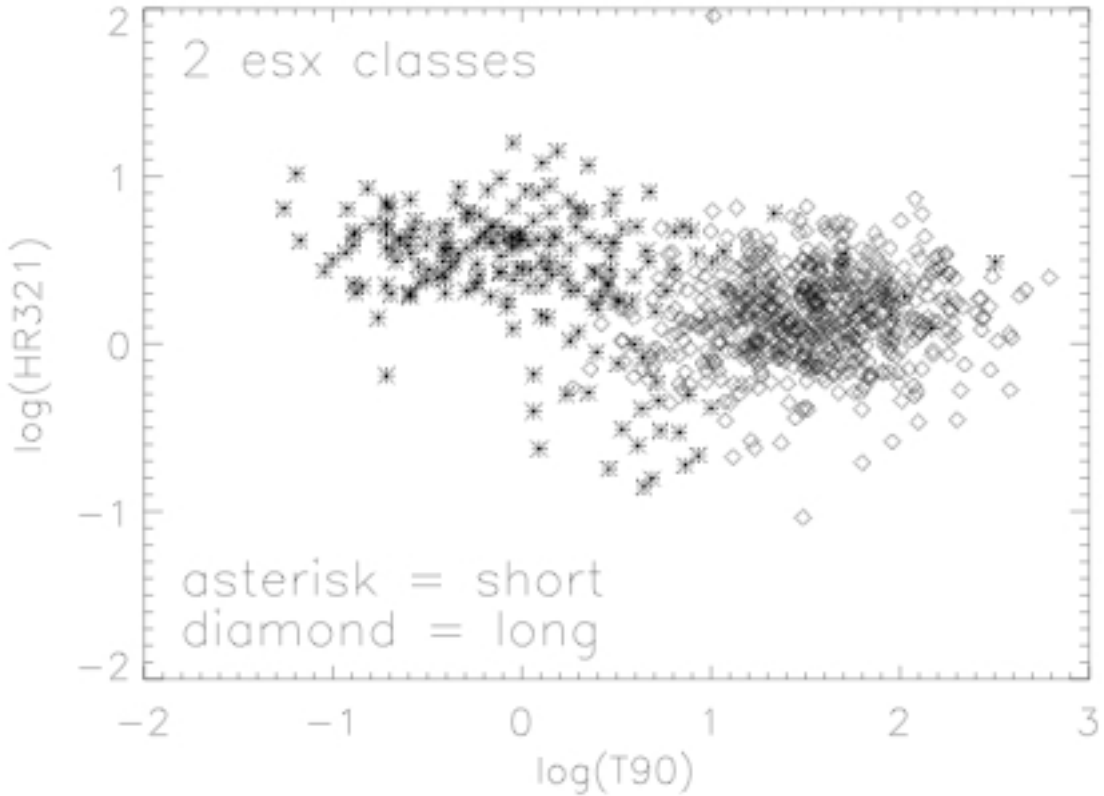


Kouveliotou et al. 1993

GRBs: Experimental view

- Multiple classes:

  Hardness-duration diagram



[hints of more than 2?
"intermediate" bursts? …]

Hakkila et al 2003

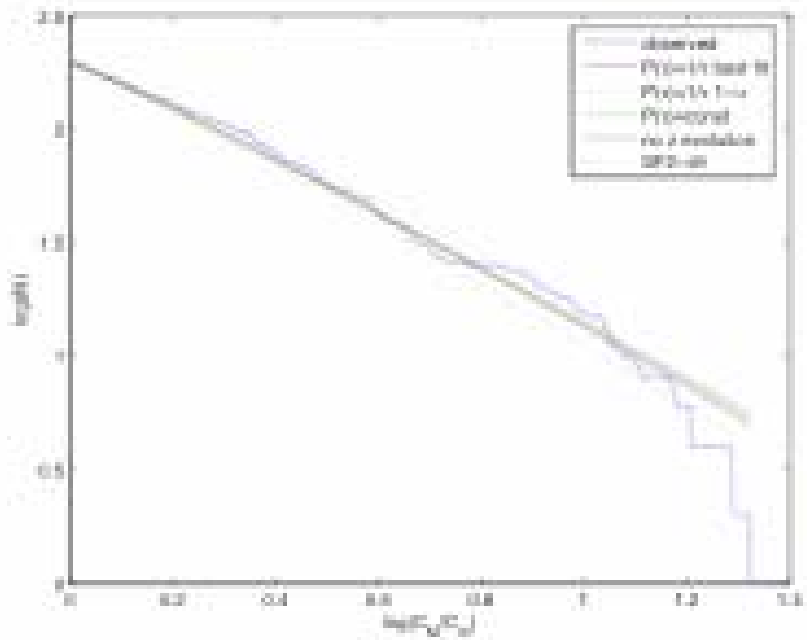
Short GRBs

- Unresolved:
  - **Number counts**

    Many faint, few strong

    Power law

    [--> missing faint ones]



  - **Detection rates** (instrument-dependent)
    - 1/(2-3 month) [Swift @ flux limit 0.1 ph/cm^2/s 50-300 keV]

Short GRBs

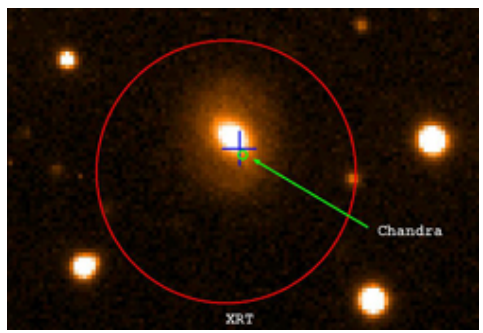
- Isolated:
  - **Associations + afterglows**

Examples

050709 : dwarf

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

050724 : elliptical



NASA press

Short GRBs

- Isolated:
  - **Associations**

Short GRB	Host galaxy	Redshift	Energy
050509b	Very old (E)	0.22 (~900 Mpc)	4.5×10^{48}
050709	Young (Sb/Sc)	0.16 (~660 Mpc)	6.9×10^{49}
050724	Old (E)	0.26 (~1 Gpc)	4×10^{50}
050813	Very old (cluster)	1.8 / 0.72[?]	
051221	young	0.547	9×10^{50}

E. Berger (review article)
Gehrels (KITP talk) **[link]**
Nakar (LIGO talk) **[link]**

…**suggests** rate ~ 1/(2 month)$(\mathrm{Gpc})^3$

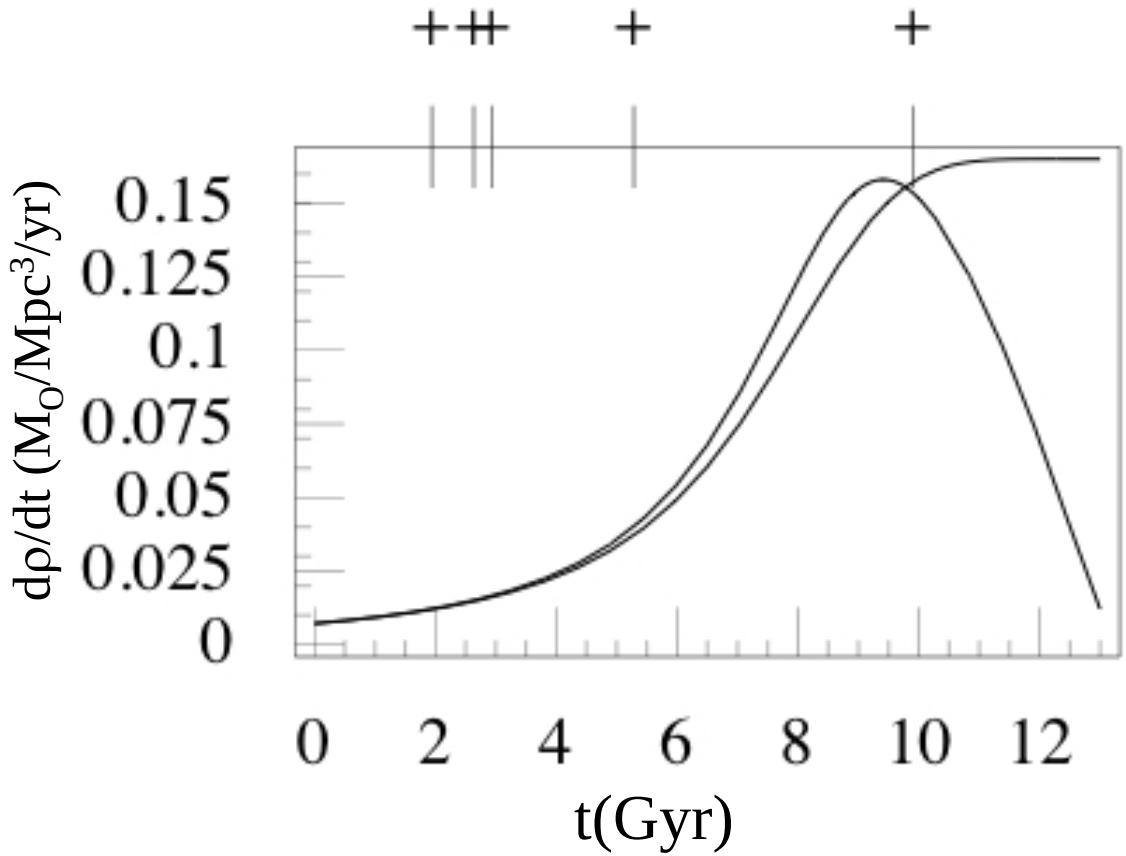
Short GRBs

- Isolated:
  - **Associations: Implications**
    - Redshifts

      …**lags** SFR

(plenty of range for bright;
larger redshifts **favored**
+ SFR
+ volume)

(=biased towards weak
or delay)



Short GRBs

- Isolated:
  - **Afterglows : Implications**
    - Jet opening angles

      $\theta \sim 10\text{-}20^{o}$

…**suggests** rate ~ 50x higher
~ 50/ $(\text{Gpc})^3$/year

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

Soderberg, 2006 **(link)**

Short GRBs

- Isolated:
  - **Afterglows : Implications**
    - ISM density at merger

      low

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

Soderberg, 2006 **(link)**

Merger rates: Review: 'Classical' approach: Method

- Population synthesis:

  = evolve **representative sample** of **MW stars** with **best knowledge**

  uncertainties
  - Supernovae (kicks)
  - Max NS mass
  - IMFs; metallicities; …

  …--> **repeat many times** (vary parameters)

LIGO inspiral injections
N_G
Blue light normalization

- SFR model of universe:

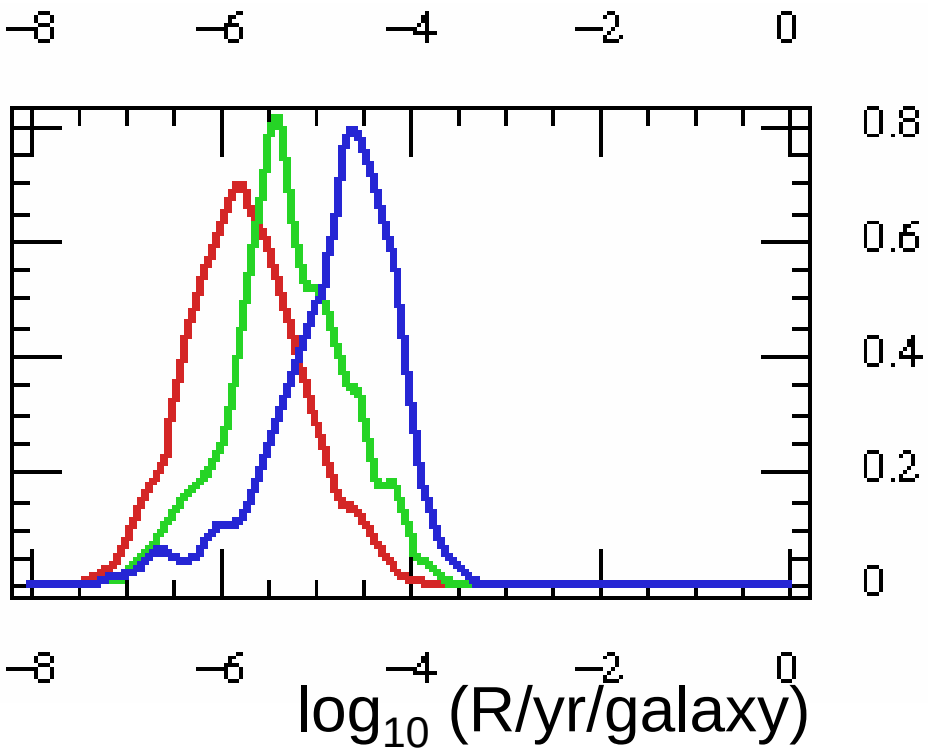
$$\rho_{gal} = 0.01 Mpc^3$$

$$SFR_{mw} = 3 M_O yr^{-1}$$

  - Populate universe with (i) **spirals** with (ii) **MW SFR**

‘Classical’ results

- Results slide



(a priori popsyn result)

- $<R_{BH\text{-}BH}>$= 1.8 / Myr * $4^{\pm1}$
  --> 18 / Gpc^3/yr
- $<R_{BH\text{-}NS}>$= 5 / Myr * $4^{\pm1}$
  --> 50 / Gpc^3/yr
- $<R_{NS\text{-}NS}>$= 16 / Myr *$(4.4)^{\pm1}$
  --> 160 / Gpc^3/yr

Not requiring agreement
w/ NS-NS observations in MW

Limitations

- Time delays:
  - Madau plot

    most stars form long ago
- Heterogeneity:
  - Ellipticals

    big, old, **different IMF/conditions**

    (cf. Regimbau et al)
  - Starbursts

    Dominate star formation (over disk mode)

    different IMF/conditions

Ingredients and Predictions

- Birth and merger history
  - Heterogeneous models used
- Population synthesis
  - Mass efficiencies
  - Delay time distributions (=since birth)
  - Merger time distributions (=after 2nd SN)
  - Recoil velocities
- Source model
- Detector model
- Host model (gravity, gas)

•Formation history (intrinsic)
•Event rate/volume (intrinsic)

•Host types

•Detection rate
•Detected z distribution

(not this talk)

•Offsets from hosts (intrinsic)
•Afterglows

Ingredient:
Galaxy heterogeneity I

- Heterogeneity:
  - Galaxies **obviously** differ…
    - Ellipticals
    - Spirals
    - Dwarfs (e.g. satellites)
    - …

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

Andromeda

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

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

M32

M87
(cD)

via Goddard archive

Ingredient:
Galaxy heterogeneity I

- Heterogeneity:
  - Galaxies **obviously** differ…
    - Ellipticals (+bulges)
    - Spirals (=disks only)
    - Dwarfs (satellites)

Mass fractions:
~65%
~35%
~ 0%

Census info

Panter et al 2004, Read & Trentham 2005

Fukugita, Hogan, Peebles 1998, 2004

Ingredient:
Galaxy heterogeneity I

Heterogeneity details

$$\Omega_{\text{spheroid stars}} = \left(0.00180\,^{+0.00121}_{-0.00085}\right) h^{-1},$$

$$\Omega_{\text{disk stars}} = \left(0.00060\,^{+0.00030}_{-0.00024}\right) h^{-1},$$

$$\Omega_{\text{stars in Irr}} = \left(0.000048\,^{+0.00033}_{-0.00026}\right) h^{-1},$$

Census info

Fukugita, Hogan, Peebles 1998, 2004

	Ω_b	Ω_*
E	0.00064	0.00064
S0	0.00073	0.00068
Sa+Sab	0.00036	0.00032
Sb+Sbc	0.00056	0.00040
Sc+Scd	0.00072	0.00047
Sd+Sdm+Sm	0.00037	0.00021
Irr+dIrr	0.00013	0.00007
dE	0.00002	0.00002
total	0.0035	0.0028

Census info

Read & Trentham 2005

Ingredient:
Galaxy heterogeneity II (*)

…can *reconstruct* star formation history from snapshot(?)
+ theory of evolution + spectral models…

- Mass (in stars):
- IMF:
  - Salpeter (elliptical)
  - Kroupa (disk)
- Metallicity:
- Time dependence (intrinsic):

Ingredient: Galaxy heterogeneity III

- Time dependence:
  - Clustering !

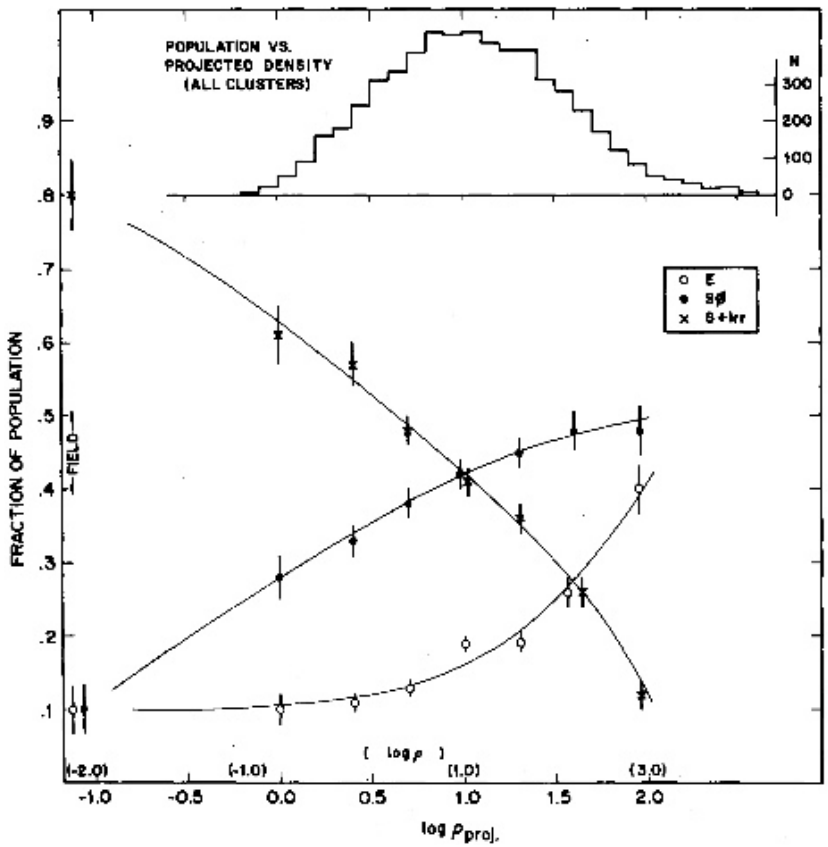
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Hubble cluster images

Ingredient:
Galaxy heterogeneity III

- Time dependence:
  - Ellipticals = **old interaction product** :

    …density-morphology relation



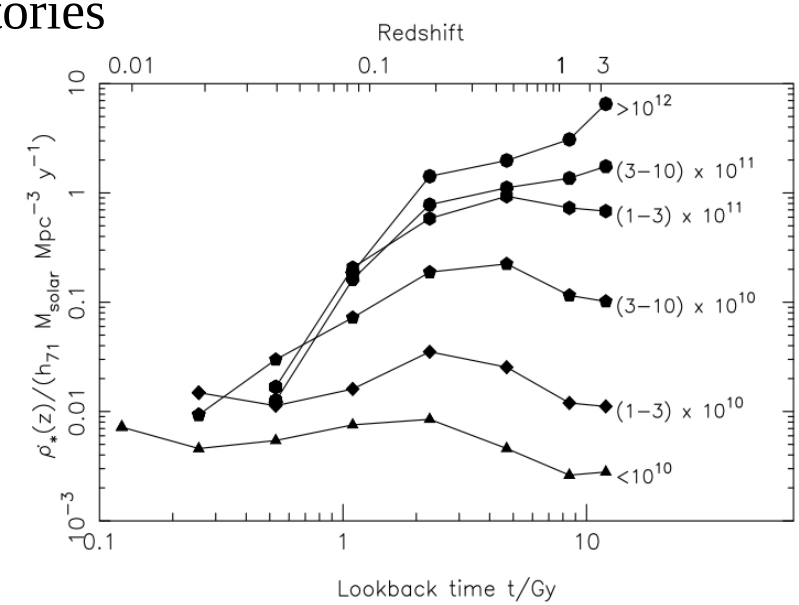
Dressler 1980

Ingredient: Galaxy heterogeneity III

- Time dependence:
  - Ellipticals = **old interaction product** :
    - Time-evolving density-morphology?
      - Only changes in **densest** clusters since z ~ 1

Smith et al 2005

    - Mass-dependent star-formation histories
      - Big = old burst
      - Small = continuous

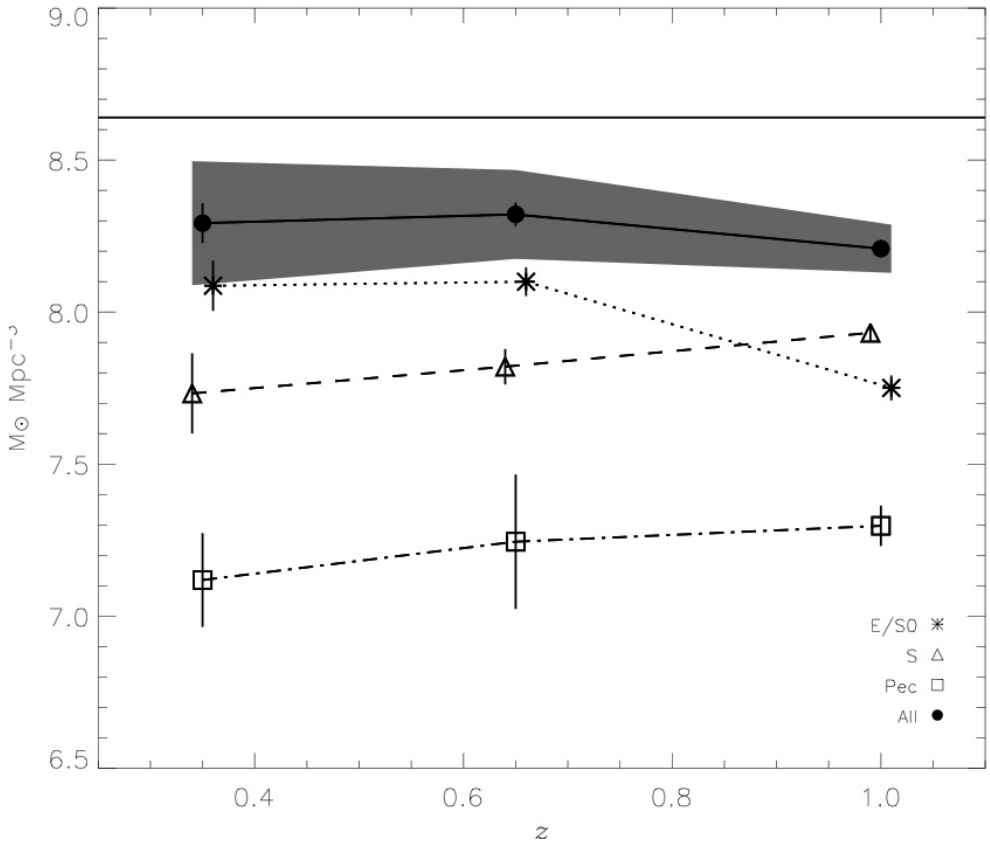


Heavens 2004

Ingredient:
Galaxy heterogeneity III

- Time dependence:
  - Variable ratios

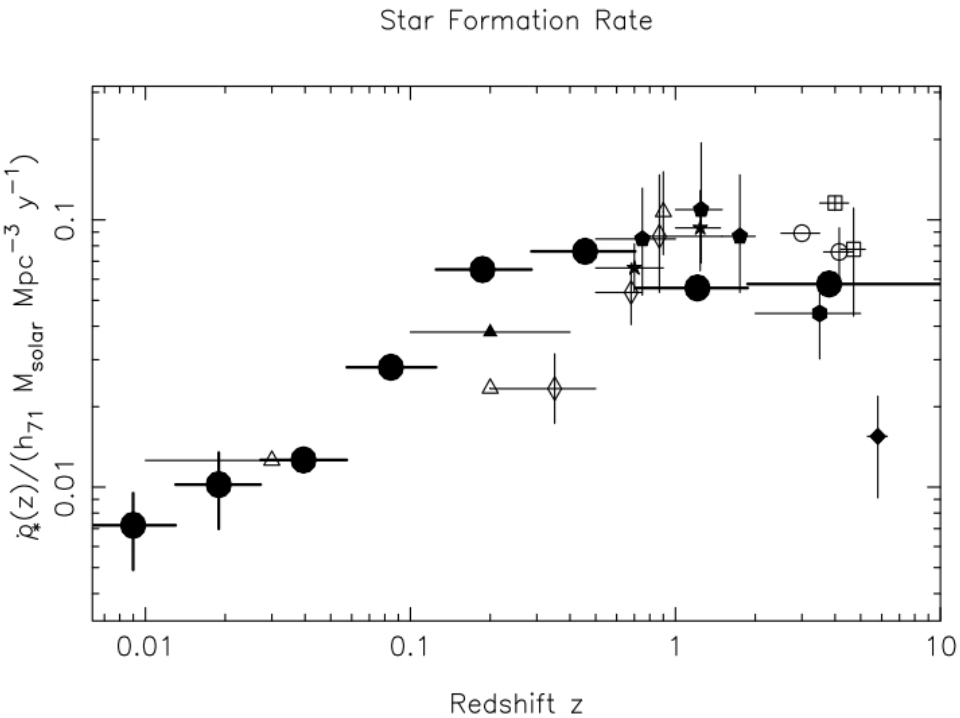
Example (Bundy et al 2004)
z ~ 0.4 - 0.8



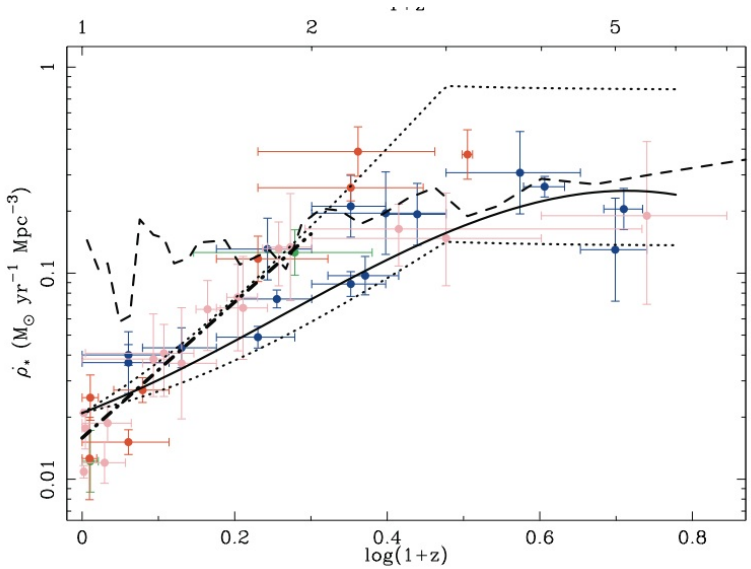
- z>2 **messy** (t> 10 Gyr)
  [~ theory only]

Ingredient:
Star formation history: Experiment

- Overall:
  - z < 2 : ~ ok
  - z ~ >2 : ??



Heavens 2004



Hopkins 2004

Ingredient:
Star formation history: Models

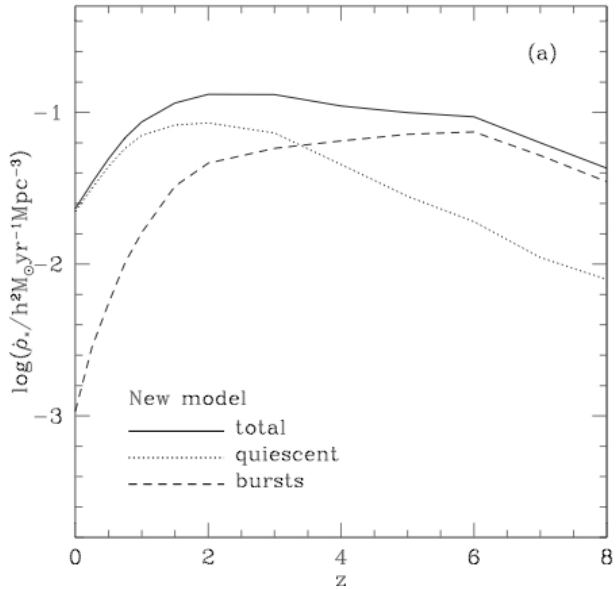
- Understood?

  …can **fit** it

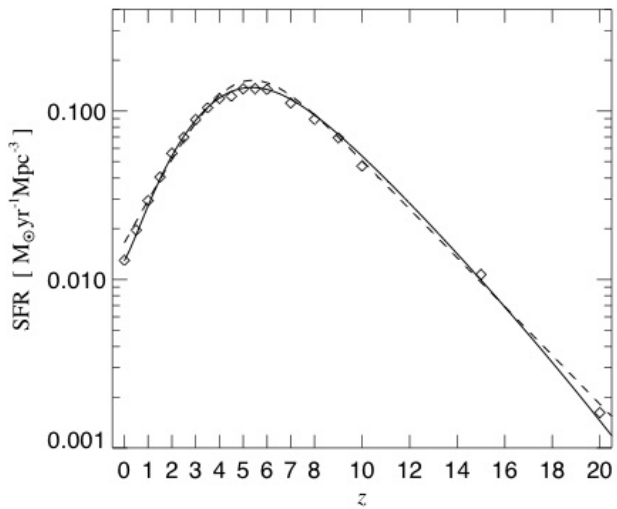
  [Λ-CDM with (crude) galaxy physics]

… gradual progress;

not well constrained



Baugh et al 2005



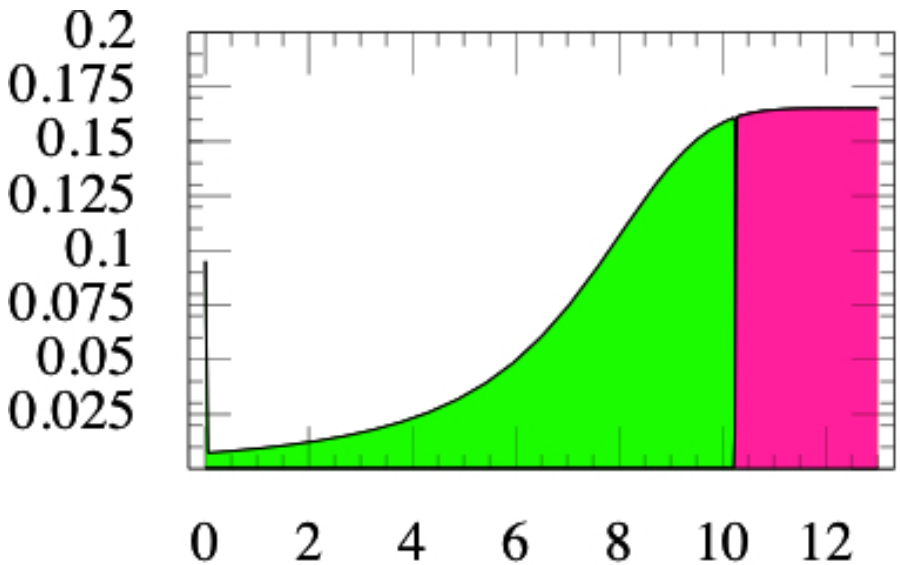
Hernquist and Springel 2003

Ingredient:
Star formation history: Summary

- Key features:
  - More formation long ago
  - Recently (z<2) ~ ok; early = ??
  - Ellipticals all old

Expect
Few mergers fine-tuned
for t_{mgr} ~ 10-13 Gyr (z>2)

…exact age may not matter



- Model used:
  - Sharp transition

    …in development…
  - **Issues**:
    - **Match** present-day normalization (!!)
    - Type conversion (collisions)
    - Reusing gas

Disk (spiral) **Elliptical**

Ingredient:
Popsyn: Overview

- Goals:
  - Mass efficiencies
  - Delay time distributions (=since birth)
  - Merger time distributions (=after 2nd SN)
  - Recoil velocities

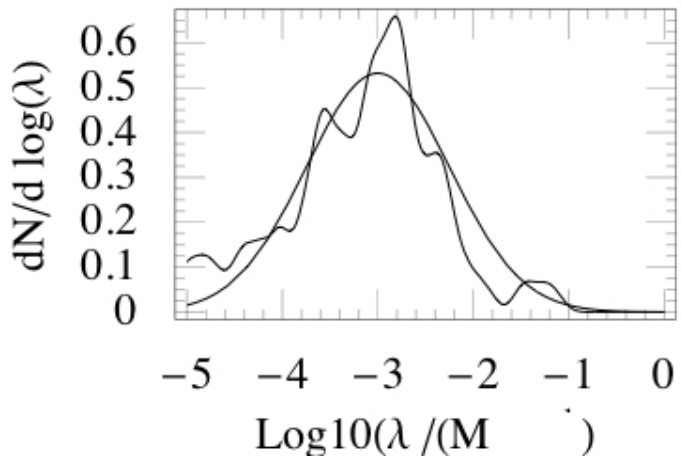
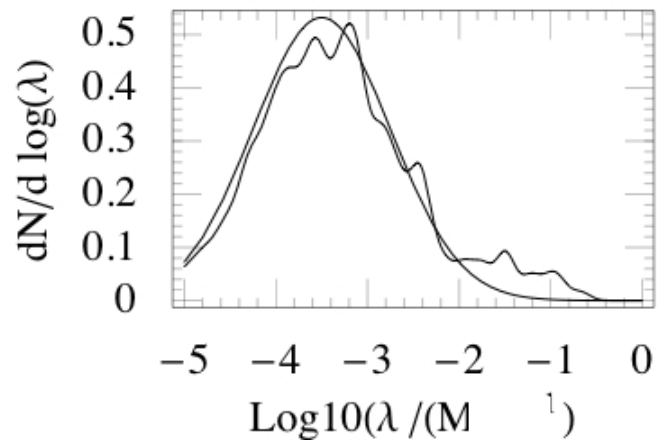
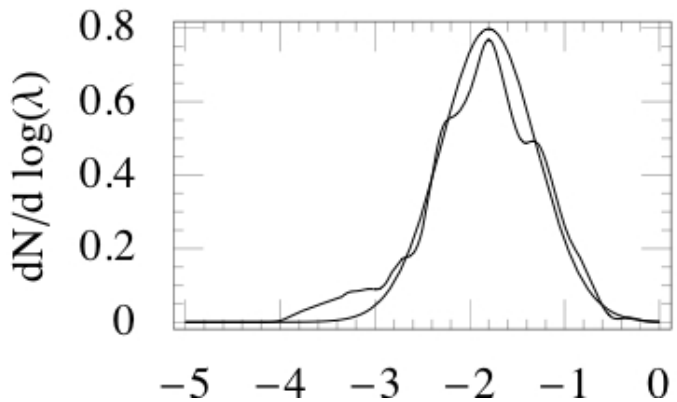
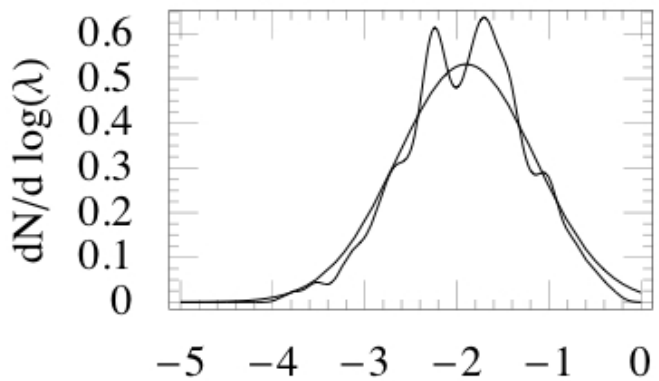
- Method:
  - As before…for **both** ellipticals/spirals

Ingredient:
Popsyn: Mass efficiencies

- Defined:
  - Number of binaries per input (star-forming) mass

- Heterogeneity:
  - Ellipticals make **more** high-mass stars than spirals!

Ingredient:
Popsyn: Mass efficiencies

	NS-NS	BH-NS
Spiral		
Elliptical		

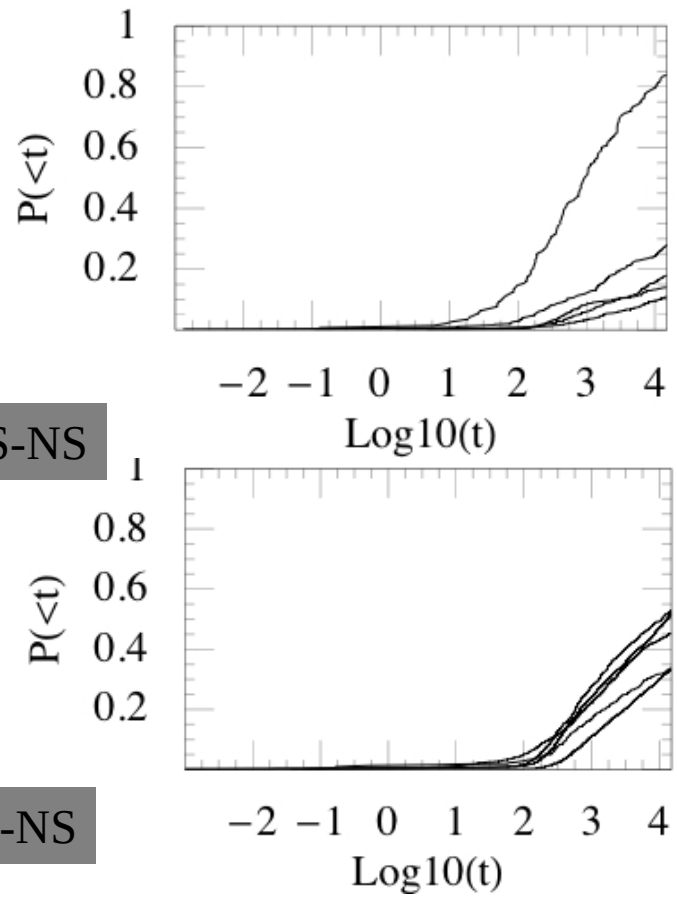
Ingredient:
Popsyn: Merger, Delay time distributions

- Definitions:
  - Merger : Time **after last SN**
  - Delay : Time **since binary birth**

- Variability?
  - Often **simple**

    (resembles 1/t closely !)

Merger time distributions
(Elliptical conditions)



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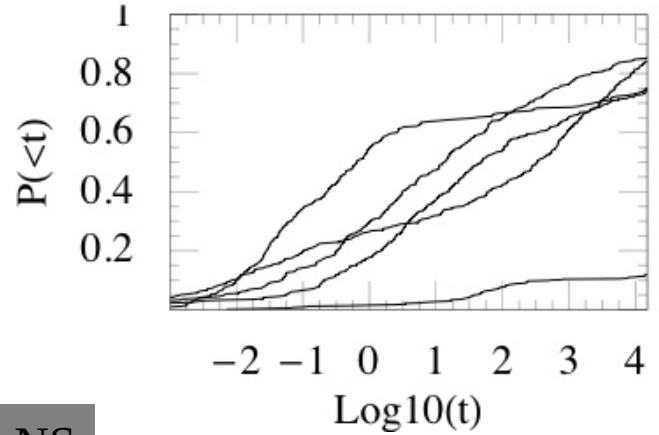
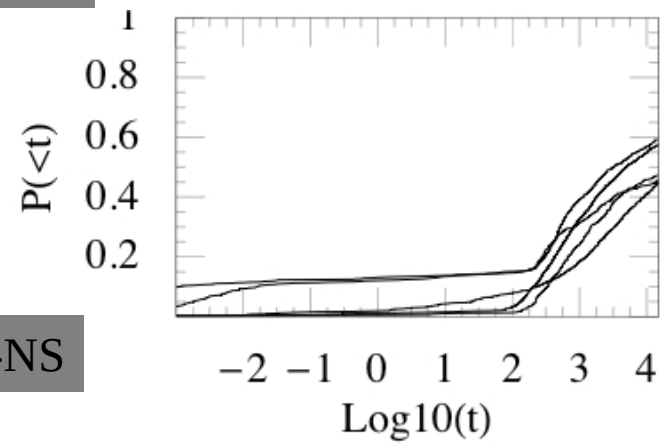
    … but not always

    (NS-NS, spiral, merger times)

Merger time distributions
(Spiral conditions)



NS-NS



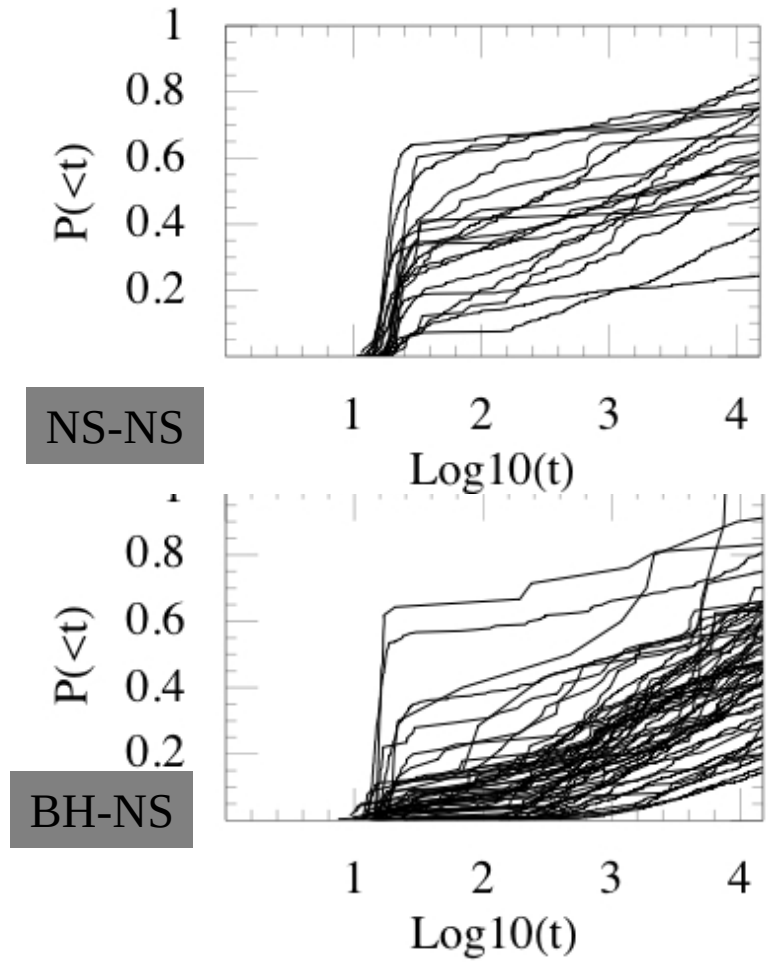
BH-NS

Ingredient:
Popsyn: Merger, Delay time distributions

- Definitions:
  - Merger : Time **after last SN**
  - Delay : Time **since binary birth**

- Variability?
  - Merger times often **simple**
    … but not always
    (NS-NS, spiral, merger times)
  - Delay times **always simple**

Delay time distributions
(Spiral conditions)



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Popsyn: Merger, Delay time distributions

- Definitions:
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- Variability?
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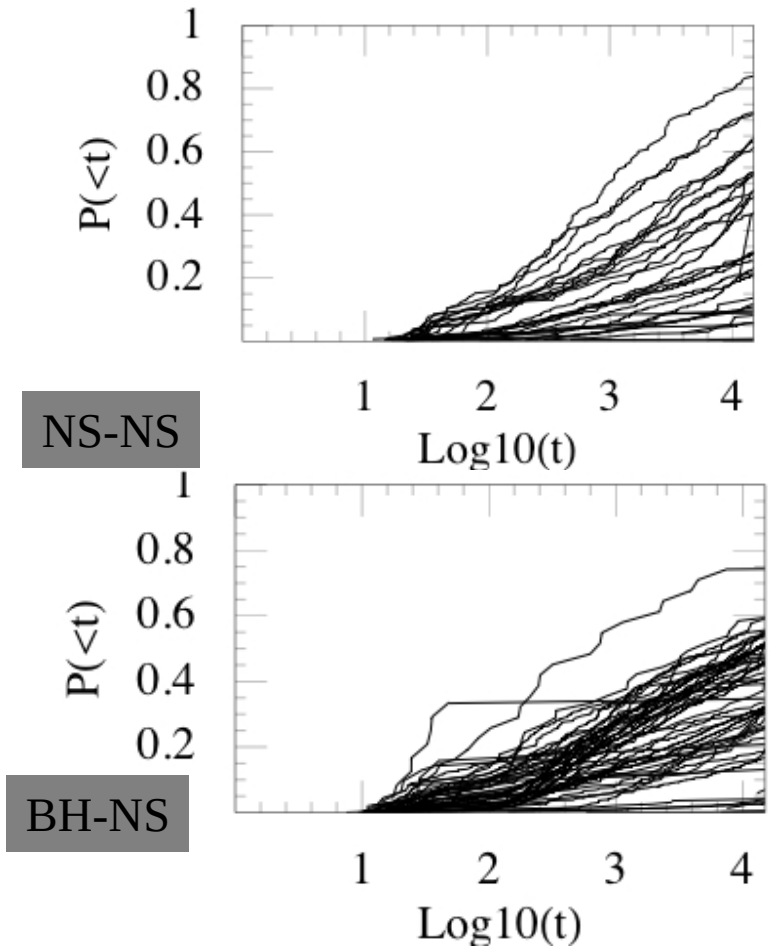
    … but not always
    (NS-NS, spiral)
  - Delay times **always simple**

Delay time distributions
(Elliptical conditions)



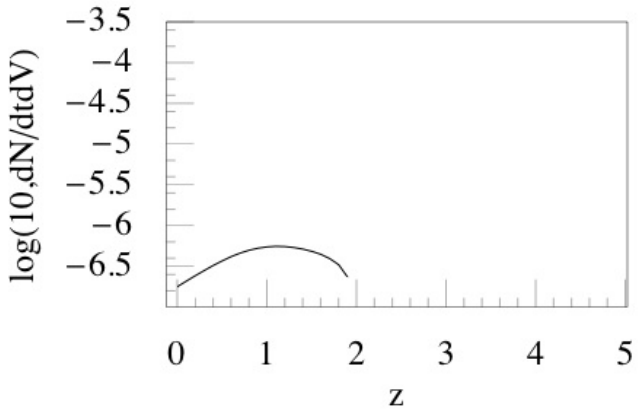
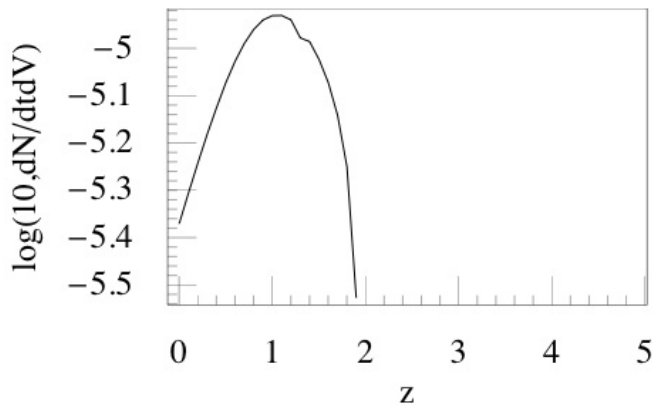
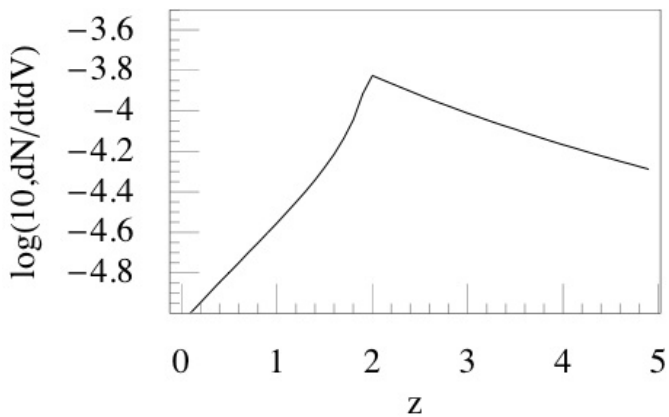
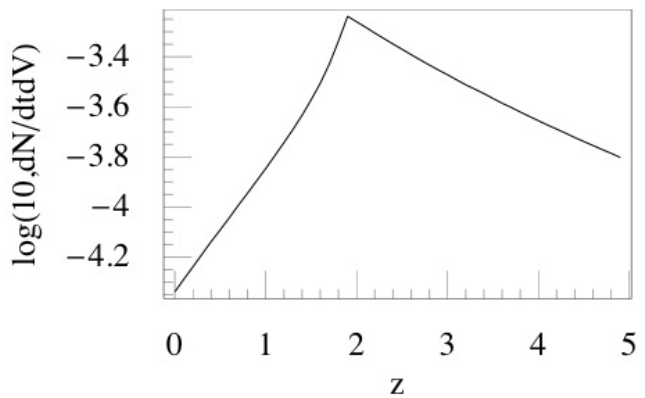
Ingredient:
Popsyn: Merger, Delay time distributions

- Key points:
  - dP/dt ~ 1/t is ok approx, NOT for NS-NS
  - Old mergers (>1Gyr) **significant** fraction
  - Elliptical fine-tuning (>10 Gyr, <14 Gyr)
    rare, not impossible

Predictions

- Event rate/volume (intrinsic)
  - Overall
  - Decomposed by host type
- Host ‘offsets’
- Detection rate [not this talk]

Predictions:
GRB event rate/volume (vs z)

sample	NS-NS	BH-NS
Spiral		
Elliptical		

Predictions:
GRB event rate/volume (vs z)

- Understanding features:
  - **Elliptical dominance**:
    - Flatter IMF
    - Higher SFR early
  - **Preferred redshift?**
    - Ellipticals dominate, yet **old**
    - ~ 1/t rate (roughly) + cutoff timescale
    - ‘fine-tuning’ needed for 1 Gyr

Predictions:
GRB event rate/volume (vs z)

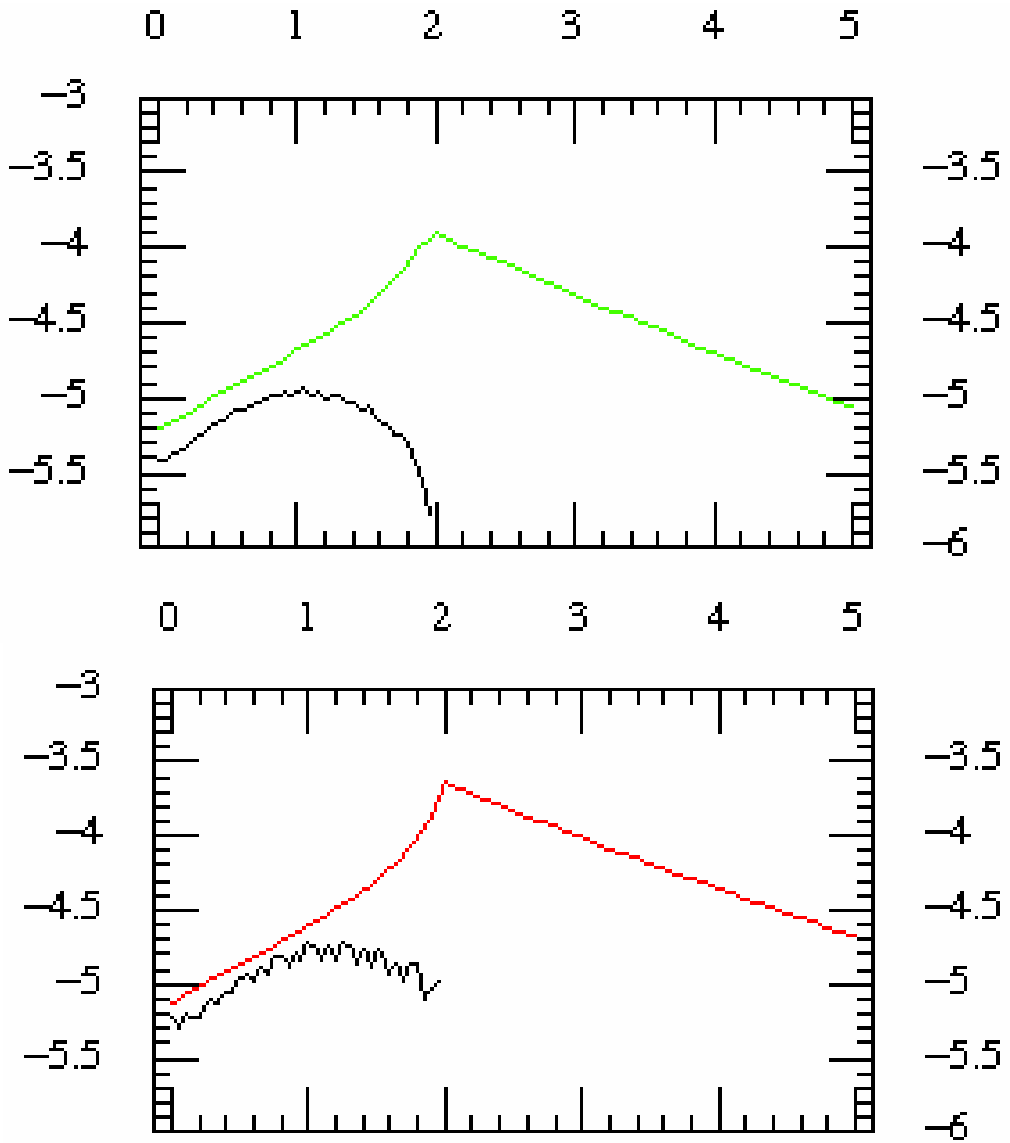
- Average results:
  'canonical' values

BH-NS

- Variability?:
  - +/- 1 order

[given SFR assumptions]

NS-NS



Predictions:
GRB detection rate

- Beaming distribution?
- Distribution of source energies?

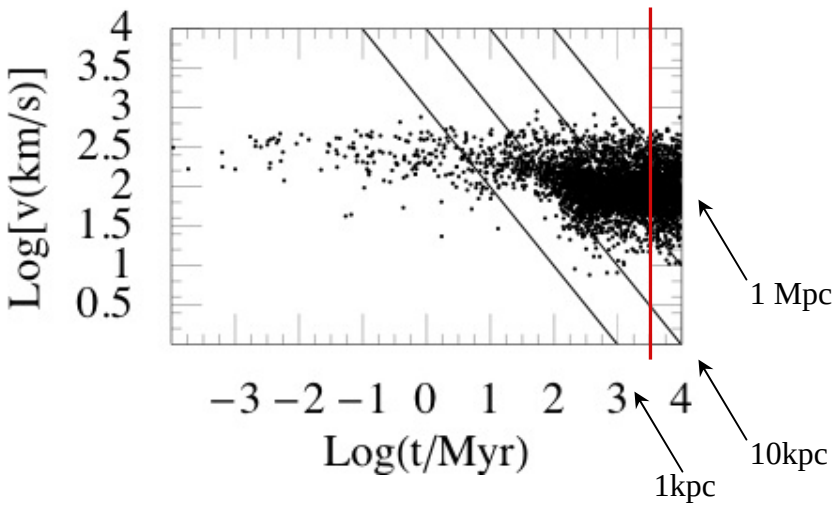
--> **still too uncertain**

Predictions:
Host offsets: Kinematics

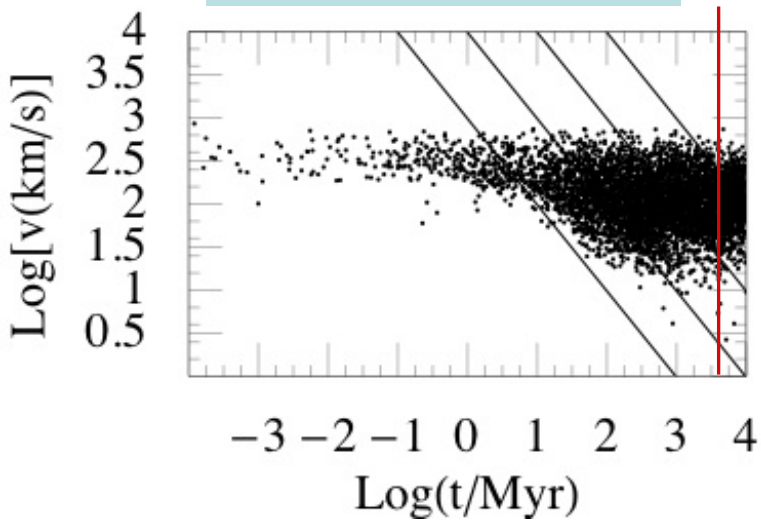
- Ballistic kinematics:
  - **Velocity-merger correlation**

    Stronger recoil -> closer orbit -> faster merger

Elliptical BH-NS



Elliptical NS-NS



average all models

Predictions:
Host offsets: Kinematics

- Ballistic kinematics:
  - **Velocity-merger correlation**

    Stronger recoil -> closer orbit -> faster merger

Elliptical BH-NS

Survival fractions:
P(>10 kpc) ~ 90%
P(>100 kpc) ~ 53%
P(>1 Mpc) ~ 7%

Elliptical NS-NS

Survival fractions
P(>10 kpc) ~ 75%
P(>100 kpc) ~ 42%
P(>1 Mpc) ~ 7%

average over all models

Predictions:
Host offsets: Kinematics

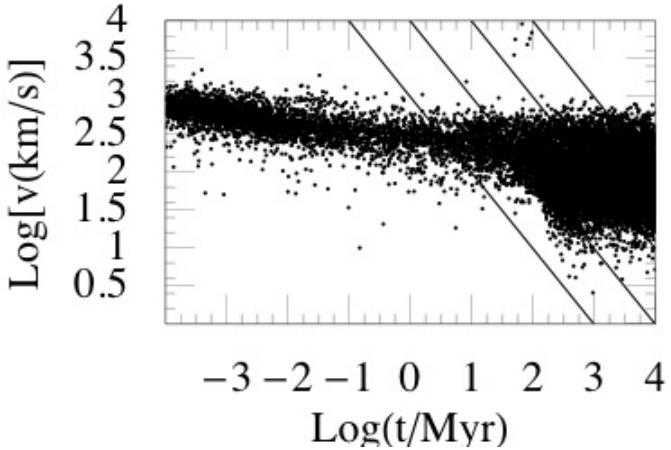
- Ballistic kinematics:
  - **Velocity-merger correlation**

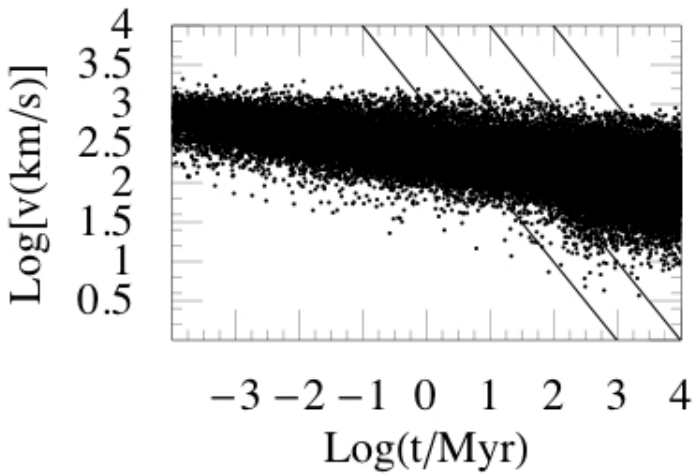
    Stronger recoil -> closer orbit -> faster merger

Spiral BH-NS

Highly variable

Spiral NS-NS





Many early mergers
very likely
(=most models)

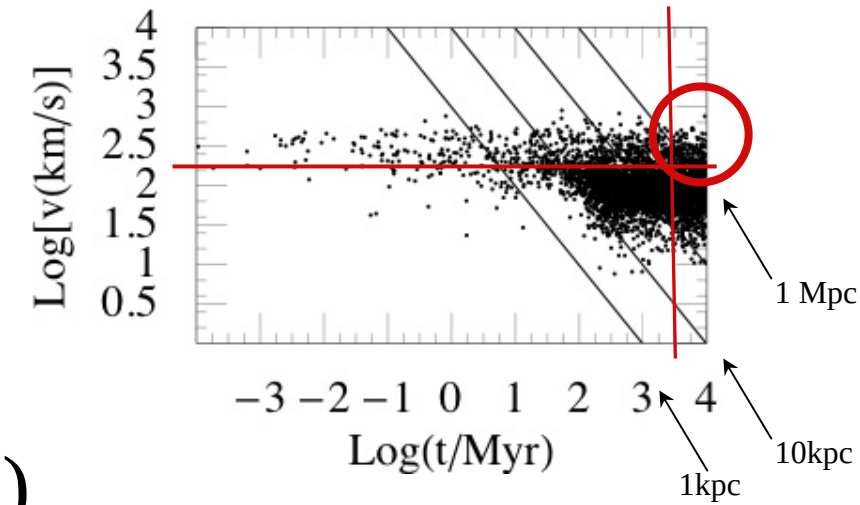
Predictions:
Host offsets: Using host model

- Escape velocities:

  $M \sim 10^{11}$ -->

  $v_{esc} \sim$ 200 km/s (10kpc)

Elliptical BH-NS



- Ballistic estimate: (sample)
  - …**fraction** (<< 1/3) of now-merging BH-NS escape large ellipticals

[very crude estimation technique]

Caveat…
BH-NS birth during galaxy assembly?

Predictions:
Host offsets: Using host model

- Sample:

  continuous SFR

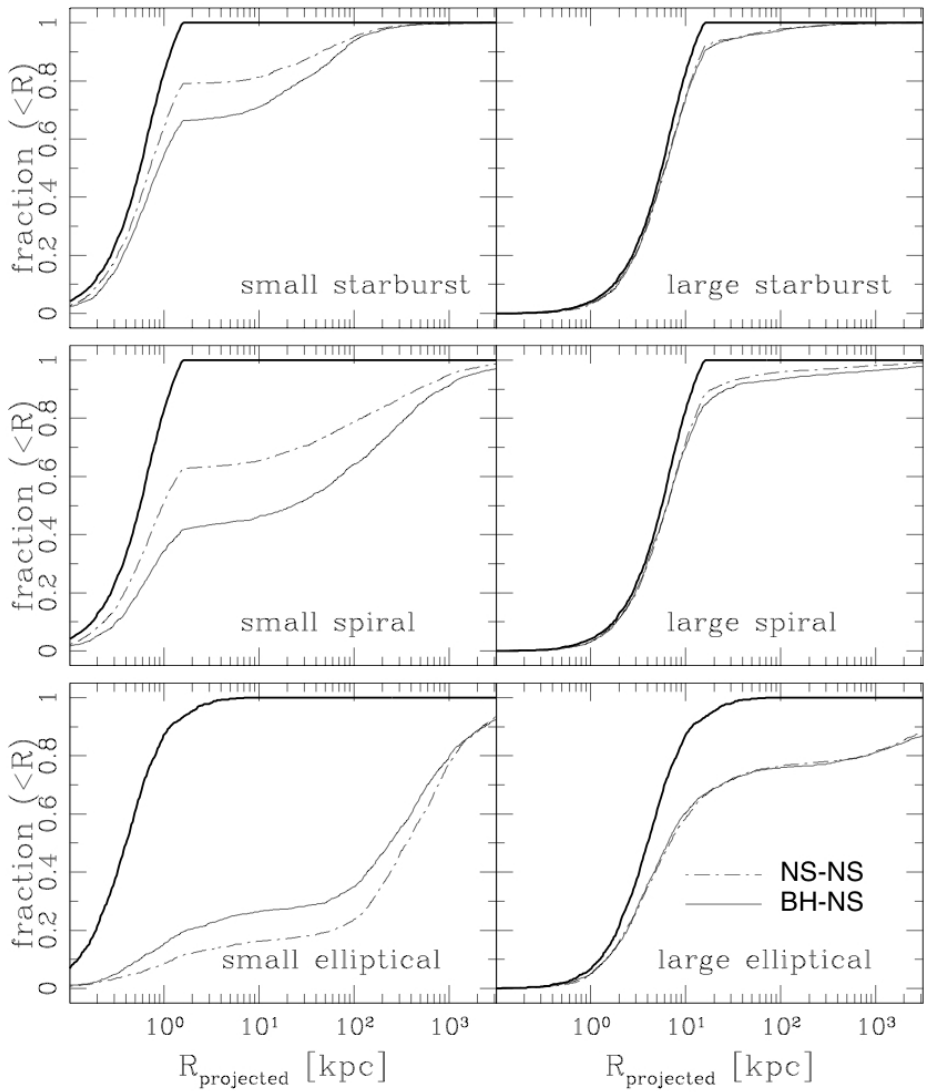
  – Spiral (MW-like)
    - Bulge+disk = $10^{11}\,M_O$
    - Halo (100 kpc) = $10^{12}\,M_O$

  – Small spiral (10x linear)

  continuous SFR t> 1Gyr

  – Elliptical
    - $5x10^{11}\,M_O$, 5kpc

  – Small elliptical



Belczynski et al 2006

Predictions: Afterglows

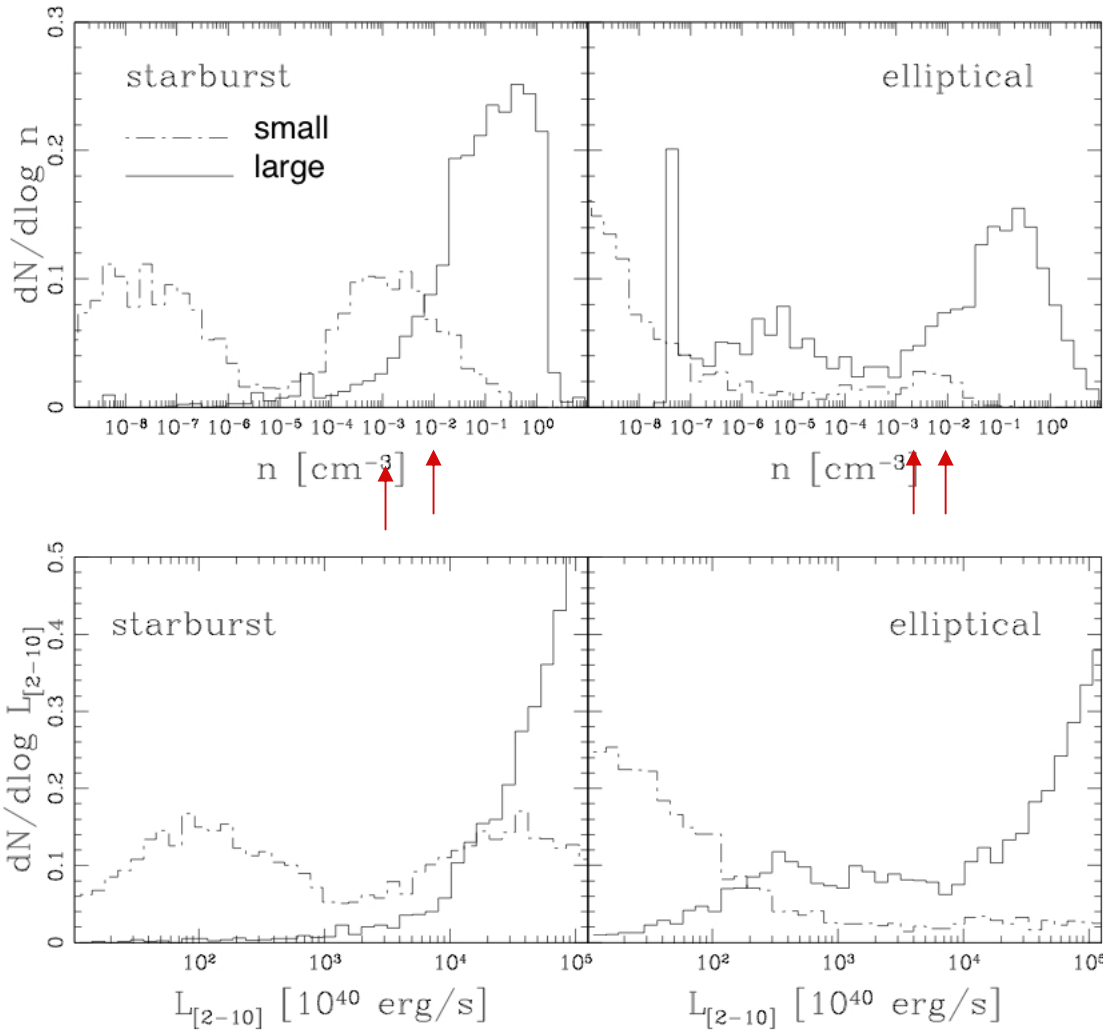
Kick + merger delay + galaxy gas model (r-dependent) + afterglows

Belczynski et al 2006

specific popsyn model

+

– Standard GRB candle (5×10^{49}erg)



Predictions vs reality: Rates

- Merger rate (local universe):

  $10^{-5.5\pm1}$ /Mpc^3/yr ~ 3000 / Gpc^3/yr **(10x higher than before)**

  [b/c early universe SFR much higher]

- GRB rates:
  - No beaming or faint correction : ~ 30 / Gpc^3/yr
  - Beaming correction : x 5-70 [10-40^o beams]

Correcting for 'unseen' --> experimental input

Experimental constraints?

- N(<P) for unresolved [number counts]:

- Observed bursts:
  - redshift distribution
  - peak flux

Applying experimental constraints I: N(<P)

- Matching:

  SFR history

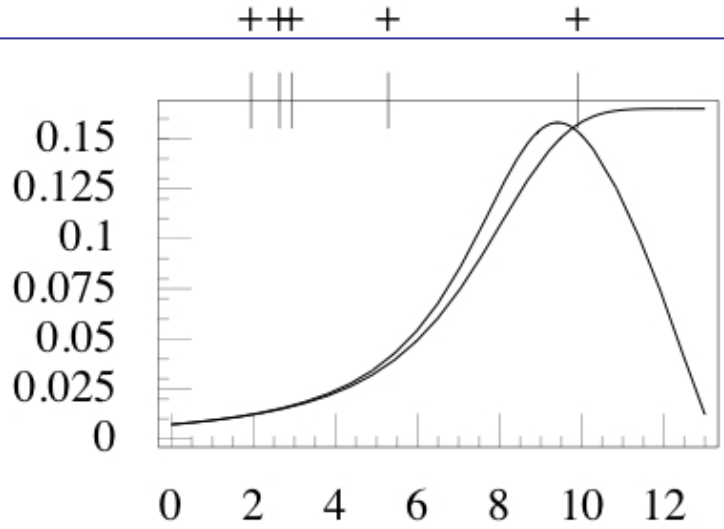
  + (homogeneous)

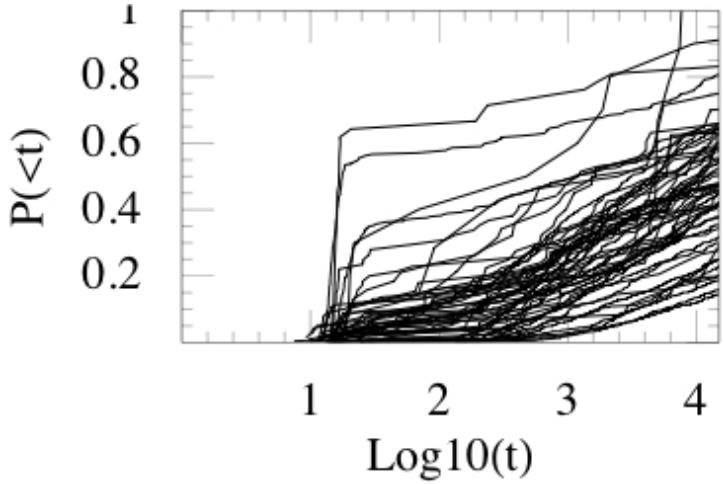
  + **delay time distribution**

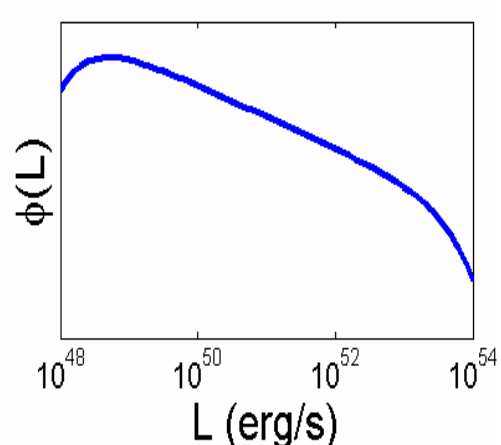
  (try a few)

  + **apparent LF**

  BEAMING MIXED IN (try a few)







Guetta and Piran 2005/6
Ando 2004

Applying experimental constraints I: N(<P)

- Matching:

  SFR history

  + (homogeneous)

  + **delay time distribution**

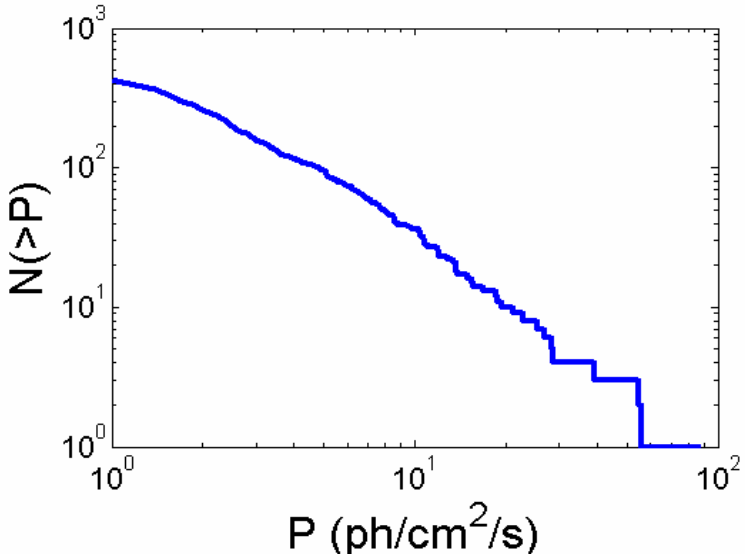
    (try a few)

  + **intrinsic LF**

    (try a few)

  = guess

  FIT TO OBSERVED



Results:

rate ~ O(0.1-10 / Gpc^3/yr)

[depends on model]

Guetta and Piran 2005/6

Ando 2004

Applying experimental constraints I: N(<P)

- Degeneracy problem:

  many weak **or** many long-lived ??

  – Many delay time histories work equally well !

Guetta and Piran 2005/6
Ando 2004

Applying experimental constraints II: N(<P) + beaming correction (*)

- Beaming correction (estimated):
  - Angle ~ 10-40^{o}
  - Rate up x 5 - 60

Guetta and Piran 2005/6
Ando 2004

Applying experimental constraints III: N(<P) + observed 'z'

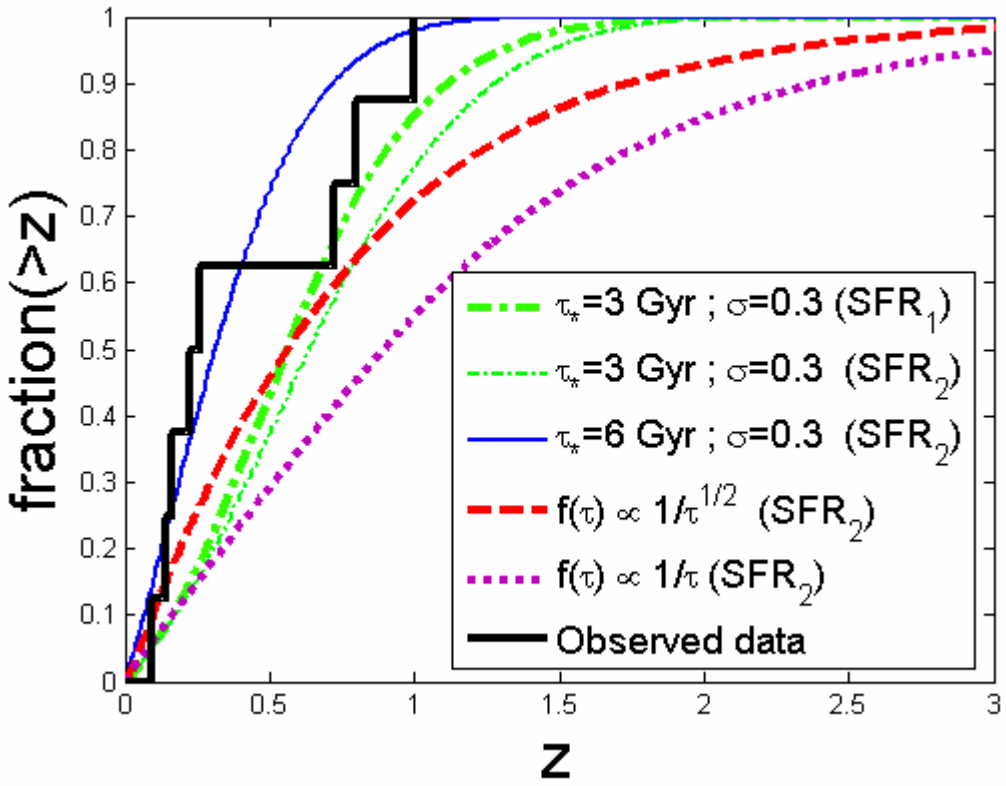
- Method:
  - Previous
  - + match z distrib
  - + limit faint end

    [else too many nearby]

- **Odd claims**:
  - 1/t excluded (!?)

    [what is tmin?]
  - 6 Gyr lifetime preferred?

Nakar et al 2005



Results

(i) No beaming: $10/Gpc^3/yr$

(ii) Beaming, faint: $10^5/Gpc/yr$

(~x30) (~ $3x10^3$)

Applying experimental constraints: Summary

- Loose agreement:
  - Rates ~ $10^{3.5}$-ish/Gpc^3/yr [w/ beaming + faint corrections]

- Theory limits experiment:
  - Fitting required to interpret results
  - Too many d.o.f. in **realistic** models
    - Heterogeneity (!)
    - Realistic merger time distributions
    - ….
  - Degeneracy/instability in fitting

I don't trust
•delay times
•LFs

Prospects for GW?

- Updated merger rates:
  - 10x higher likely
  - O(>10/yr) LIGO-II probable, O(>100/yr) possible

- GW-GRB coincidence (LIGO-II)
  - Need close burst (< 300 Mpc (NS-NS))
  - Expect plenty

Summary: State of the evidence

- Agreements:
  - **Merger rates**: Theory + GRB ~ agree w/ $10^{3.5}$/Gpc/yr
  - **Host populations**: Roughly as expected
  - **Offsets**: Roughly as expected
  - **ISM densities**: roughly as expected

- Disagreements:
  - **Faint bursts**: Suggest L_{min} small -> many nearby -> huge rate [Tanvir et al 2005 ; close to SN-based limit !]
  - **Lags** : Fits suggest long lags (rather than weak bias in LF), contrary to expectations

Summary: Key points

- Heterogeneity matters:

  Different IMF + high early SFR (rate up)

  wins over long lag (rate down)

- Significant uncertainty everywhere:
  - **Uncertain:** SFR (overall + by type)

    source model (beaming, LF, mass/spin?, BH-NS vs NS-NS) ;

    host model (gas+gravity) ;

    popsyn ingredients (IMF, (a,e) distribs) --> merger time delays;

  Opportunity to learn…

  … **many ingredients**, information correlated

Summary: Key points

- Main obstacles to progress:
  - **Source model** : intrinsic LF and beaming angle distrib
    …main limit (experimentally, theoretically)
  - **Starburst-**mode SFR critical [IMF], but not constrained
    [=overestimating ‘spiral’ part]
    Rates **may go up again**
  - **Early universe** constraints (high SFR)
  - Merger time distribution (popsyn)

Speculations

- Beaming and LF
  - How does beam angle distrib influence LF?
  - in ‘off-axis’ limit?:
    - Faintness-duration correlation?

      [wide-angle should be visible longer at similar luminosity]

- Per-component rate estimate: