LIGO’s BBH mergers in field binary scenarios
and
Macronova/Kilonova candidates and radio

Kenta Hotokezaka
(CCA, Flatiron Institute)

Outline

- Binary black hole spins and the field binary scenario

- kilonova/macronova candidates and late-time radio

Binary black holes detected by LIGO

Abbott et al 2016, 2017

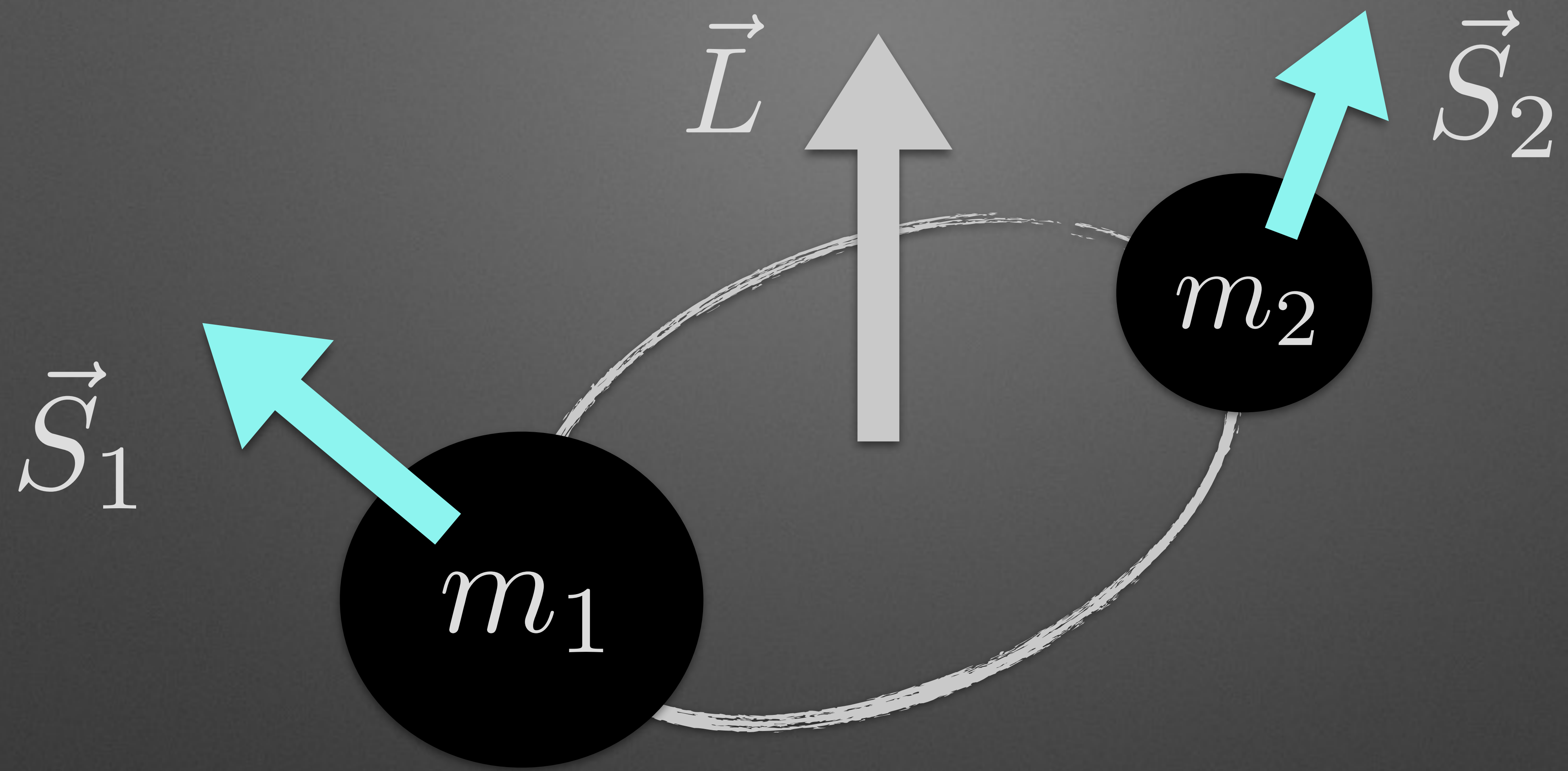
- 3 (4) events: the mass range of 7.5Msun to 36Msun.

- The event rate is 103^{+110}_{-63} /Gpc^3/yr. ~0.1% ccSNe

- The primary mass function is consistent with the Salpeter, alpha = $2.3^{+1.3}_{-1.4}$.

- The spins are low: -0.12 < effective chi < 0.21

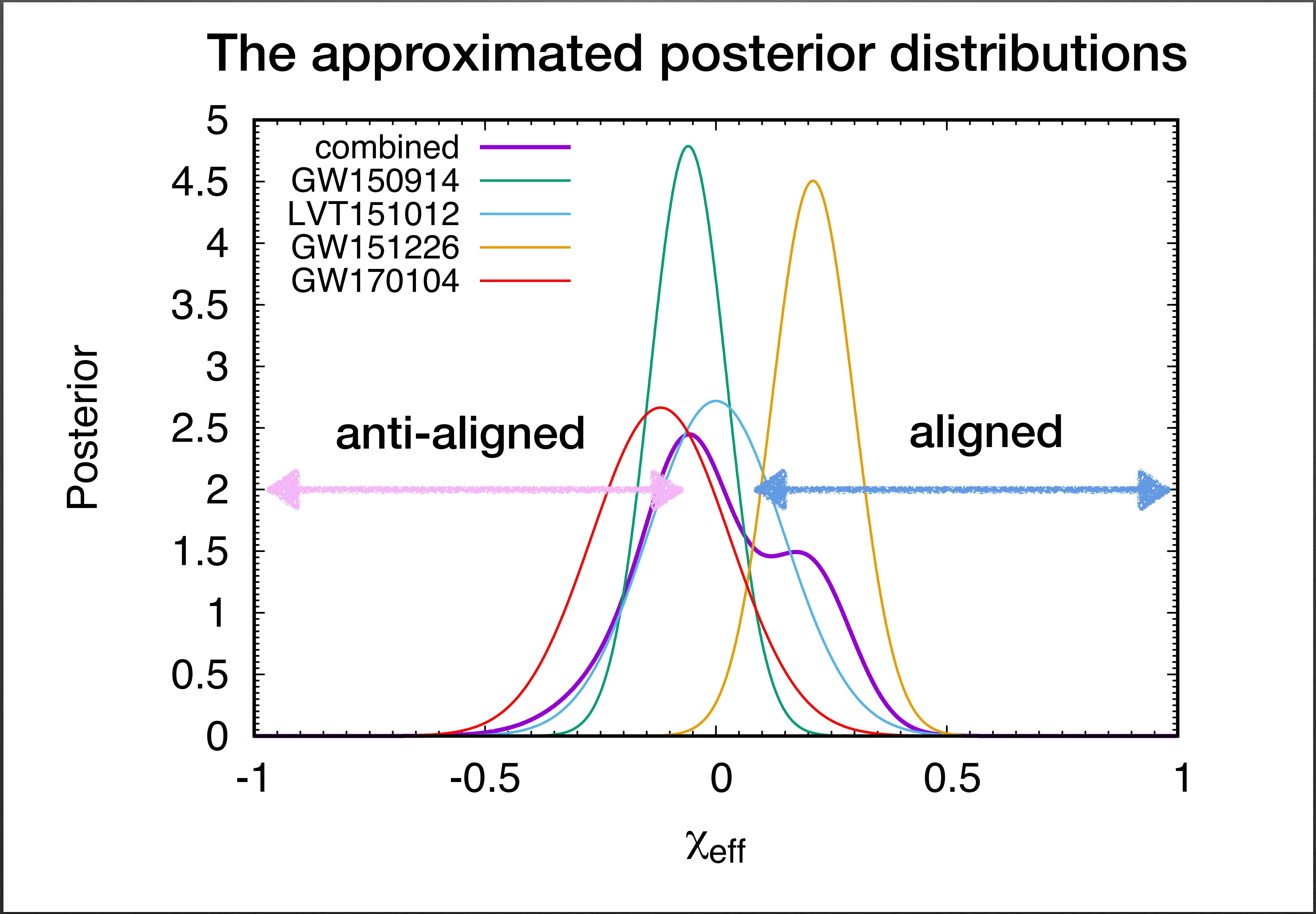
Effective spin parameter



$\chi_{\rm eff} = \frac{m_1\chi_1+m_2\chi_2}{m_{\rm tot}}$ **where** $\chi_{1,2} \equiv \frac{c\vec{S}_{1,2}\cdot\hat{L}}{Gm_{1,2}^2}$

$$-1 \le \chi_{\rm eff} \le 1$$

The effective spins of the LIGO events



KH & Piran 2017, Farr et al 2017

Low BBH aligned spins

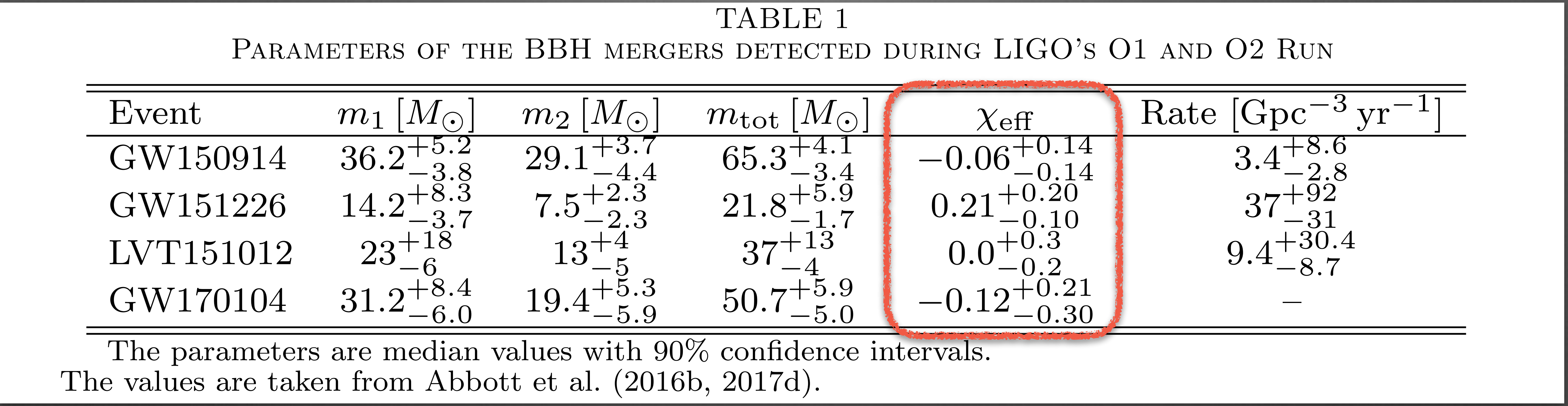


TABLE 1
PARAMETERS OF THE BBH MERGERS DETECTED DURING LIGO'S O1 AND O2 RUN

Event	$m_1\ [M_\odot]$	$m_2\ [M_\odot]$	$m_{\rm tot}\ [M_\odot]$	$\chi_{\rm eff}$	Rate $[{\rm Gpc}^{-3}\,{\rm yr}^{-1}]$
GW150914	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$	$65.3^{+4.1}_{-3.4}$	$-0.06^{+0.14}_{-0.14}$	$3.4^{+8.6}_{-2.8}$
GW151226	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$	$21.8^{+5.9}_{-1.7}$	$0.21^{+0.20}_{-0.10}$	37^{+92}_{-31}
LVT151012	23^{+18}_{-6}	13^{+4}_{-5}	37^{+13}_{-4}	$0.0^{+0.3}_{-0.2}$	$9.4^{+30.4}_{-8.7}$
GW170104	$31.2^{+8.4}_{-6.0}$	$19.4^{+5.3}_{-5.9}$	$50.7^{+5.9}_{-5.0}$	$-0.12^{+0.21}_{-0.30}$	–

The parameters are median values with 90% confidence intervals.
The values are taken from Abbott et al. (2016b, 2017d).

- chi_eff < 0.1?
  - The Sun (P ~ 26 days, v_surf ~ a few km/s):

$$\chi_\odot \sim 0.2$$

  - Typical O stars (P ~ 5 days, v_surf ~ 100 km/s):

$$\chi \sim 30$$

=> The spin of BBHs is significantly reduced or misaligned.

Scenarios of the BBH formation

(1) Evolution of field binaries

Our focus

e.g. Belczynski et al 16, 17, van den Heuvel et al 17, Mandel & de Mink 16, Stevenson et al 17, Kinugawa et al 14

→ Aligned spin

(2) Dynamical capture in stellar clusters

e.g. Rodorigez et al 2016, O'Leary et al 2016

(3) Formation in galactic nuclei

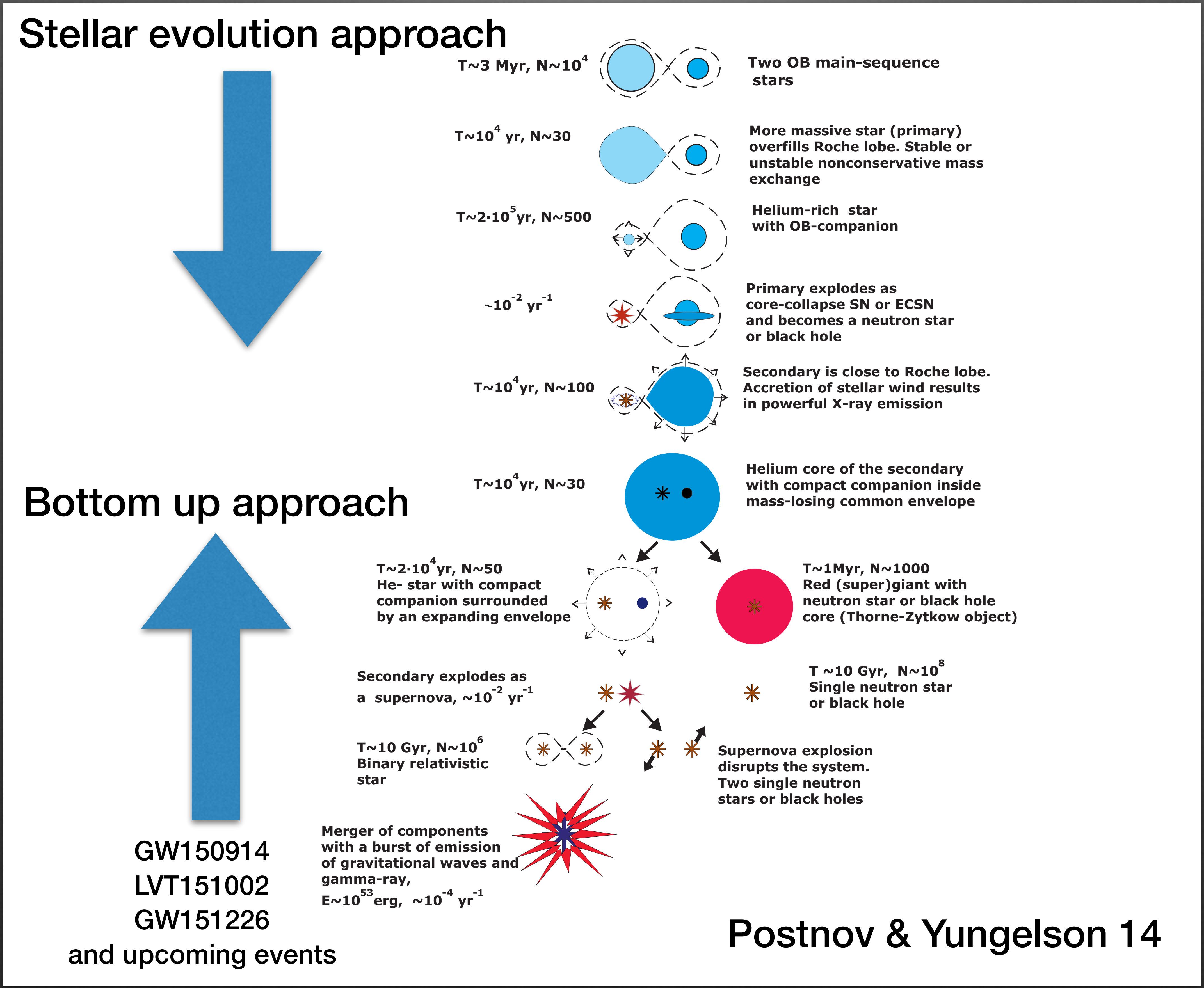
e.g. Antonini & Rasio 2016, Bartos et al 2016, Stone et al 2016

(4) Primordial black holes

e.g. Sasaki et al 2016, Bird et al 2016, Blinnilov et al 2016

→ Isotropic spin

Field binary evolution



Stellar evolution approach

$T\sim3$ Myr, $N\sim10^4$ — Two OB main-sequence stars

$T\sim10^4$ yr, $N\sim30$ — More massive star (primary) overfills Roche lobe. Stable or unstable nonconservative mass exchange

$T\sim2\cdot10^5$yr, $N\sim500$ — Helium-rich star with OB-companion

$\sim10^{-2}$ yr^{-1} — Primary explodes as core-collapse SN or ECSN and becomes a neutron star or black hole

$T\sim10^4$yr, $N\sim100$ — Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission

$T\sim10^4$yr, $N\sim30$ — Helium core of the secondary with compact companion inside mass-losing common envelope

$T\sim2\cdot10^4$yr, $N\sim50$
He- star with compact companion surrounded by an expanding envelope

$T\sim1$Myr, $N\sim1000$
Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)

Secondary explodes as a supernova, $\sim10^{-2}$ yr^{-1}

$T\sim10$ Gyr, $N\sim10^8$
Single neutron star or black hole

$T\sim10$ Gyr, $N\sim10^6$
Binary relativistic star

Supernova explosion disrupts the system. Two single neutron stars or black holes

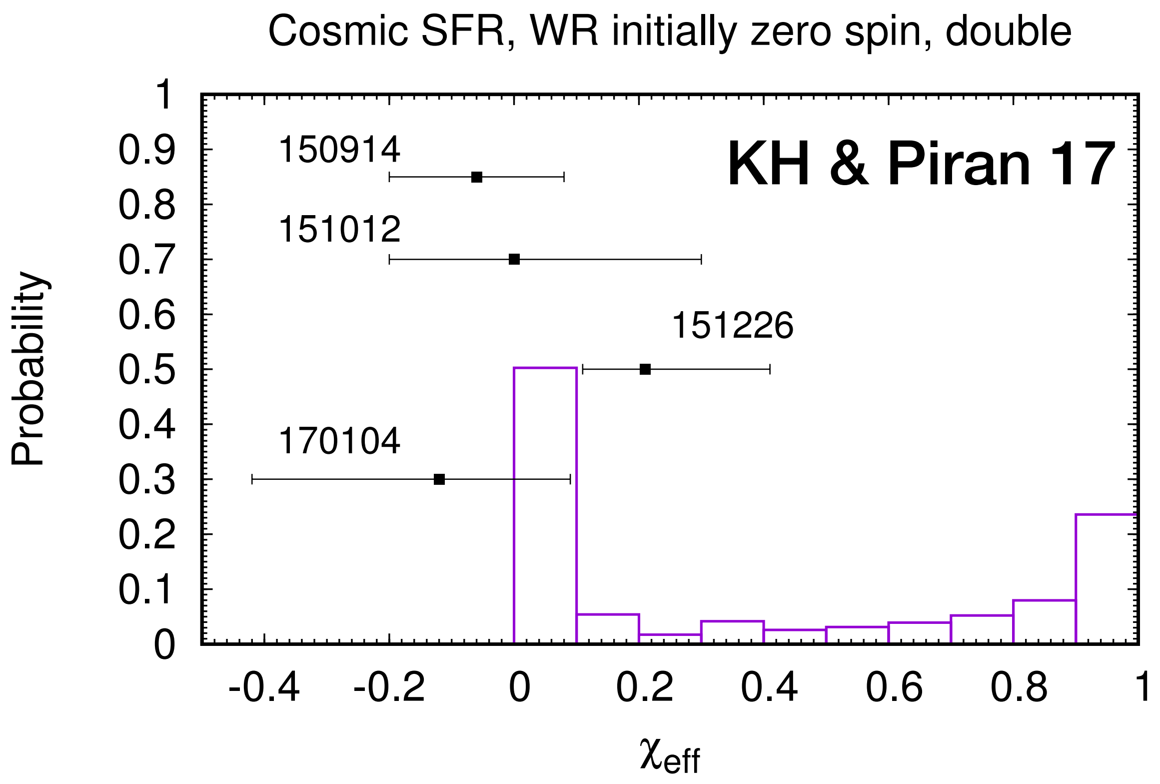
Merger of components with a burst of emission of gravitational waves and gamma-ray,
$E\sim10^{53}$erg, $\sim10^{-4}$ yr^{-1}

Bottom up approach

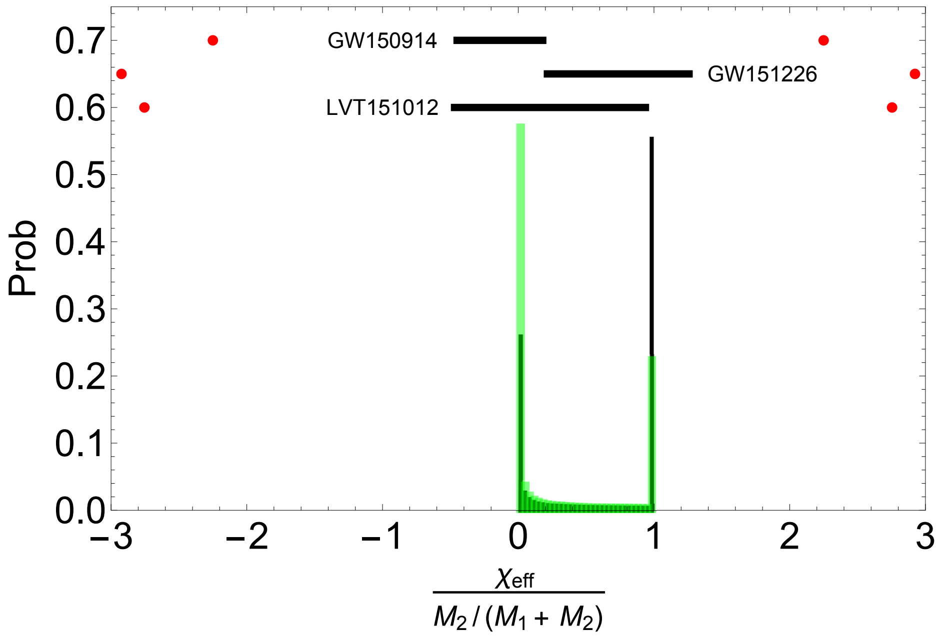
GW150914
LVT151002
GW151226
and upcoming events

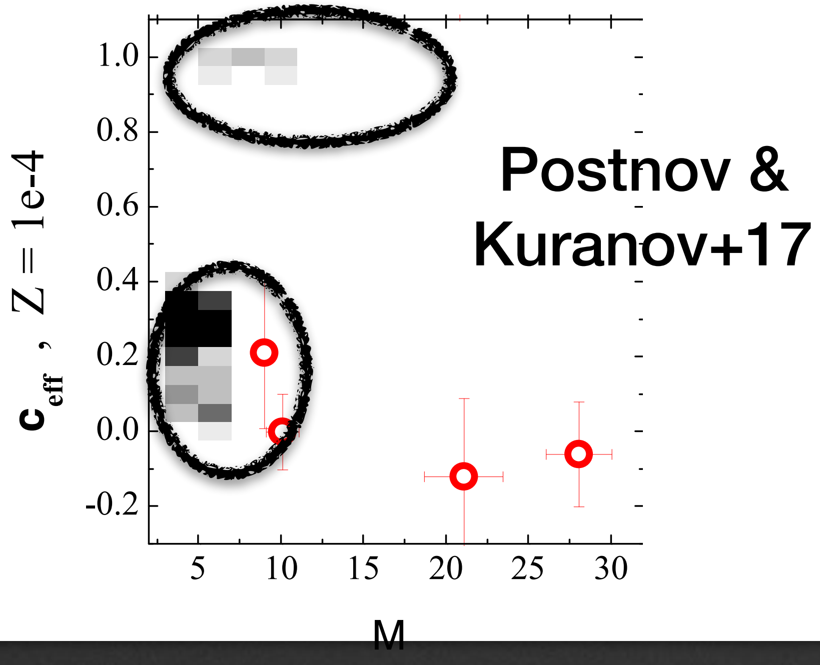
Postnov & Yungelson 14

Spin distribution

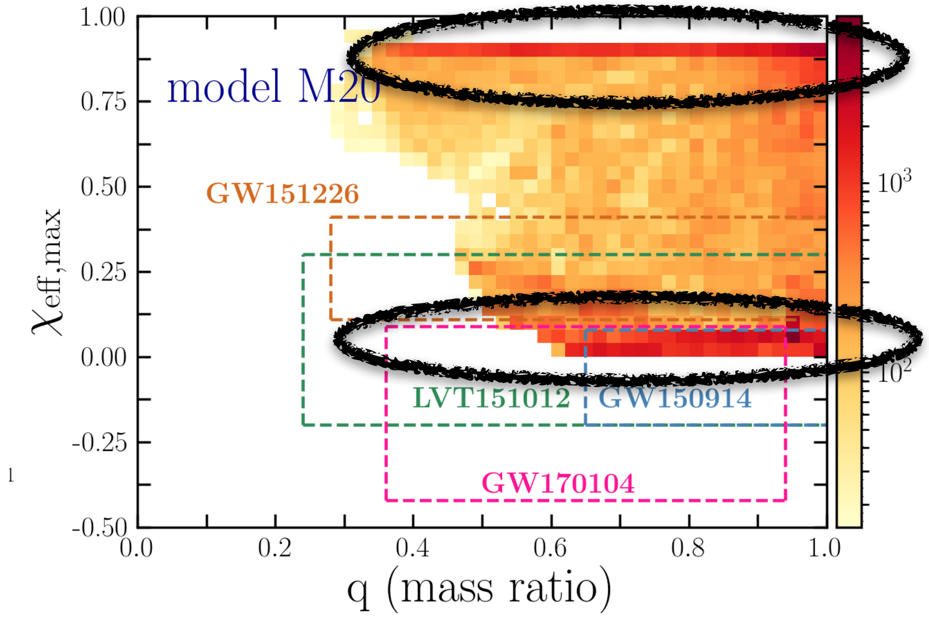


Zaldarriaga + 17



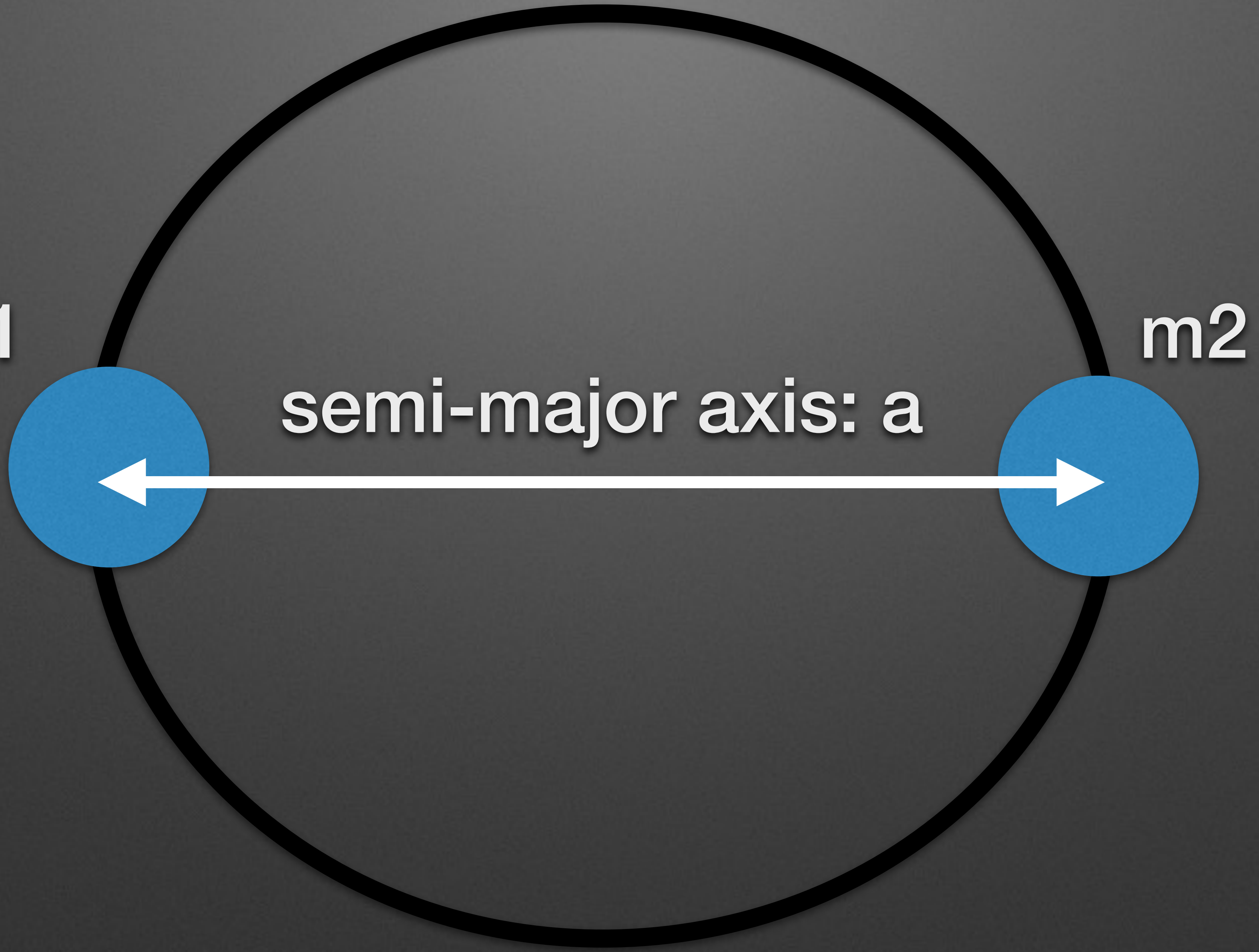


Belczynski + 17

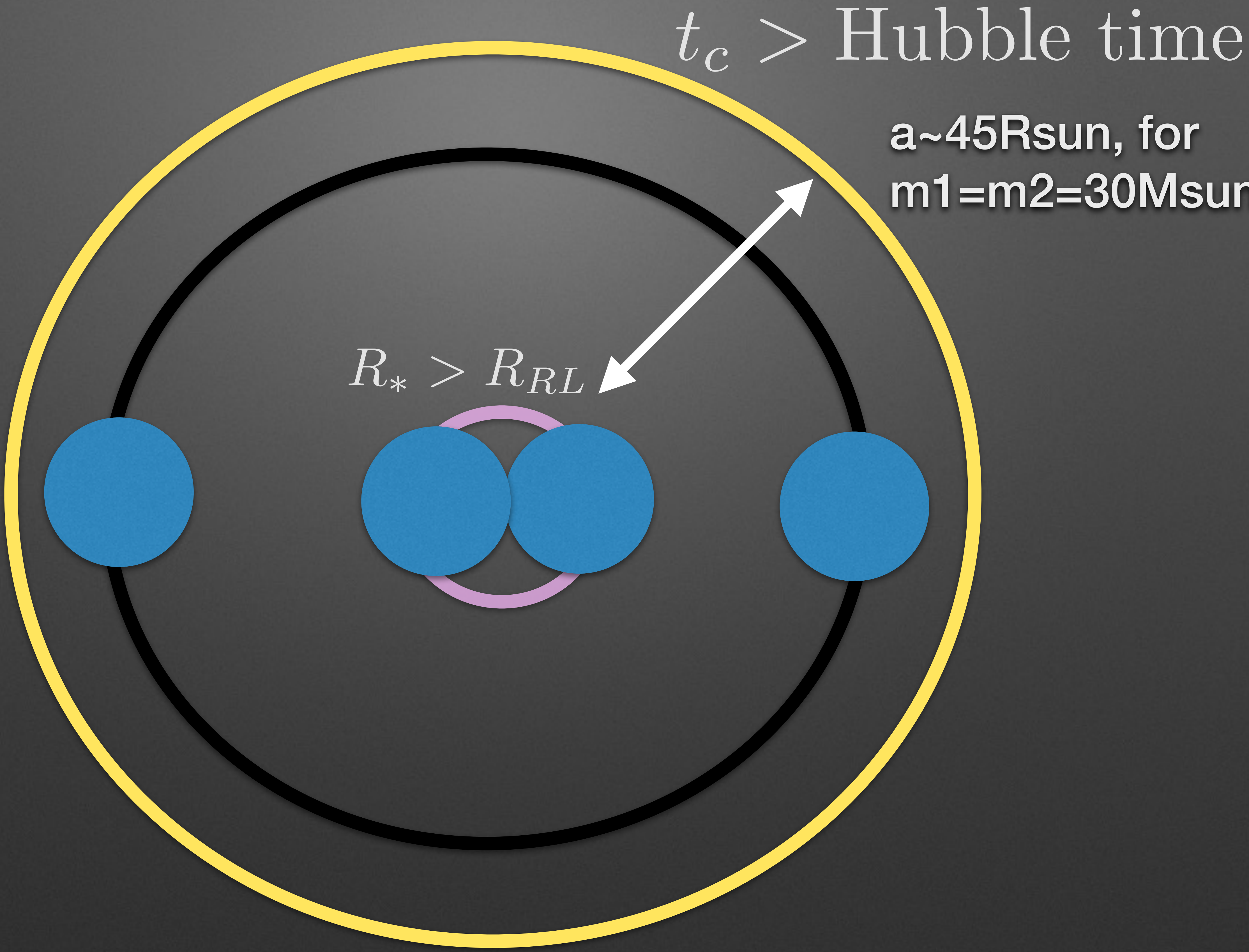


Field binary scenarios generally predict a bimodal spin distribution.

Characteristic scales of BBH progenitors



Characteristic scales of BBH progenitors

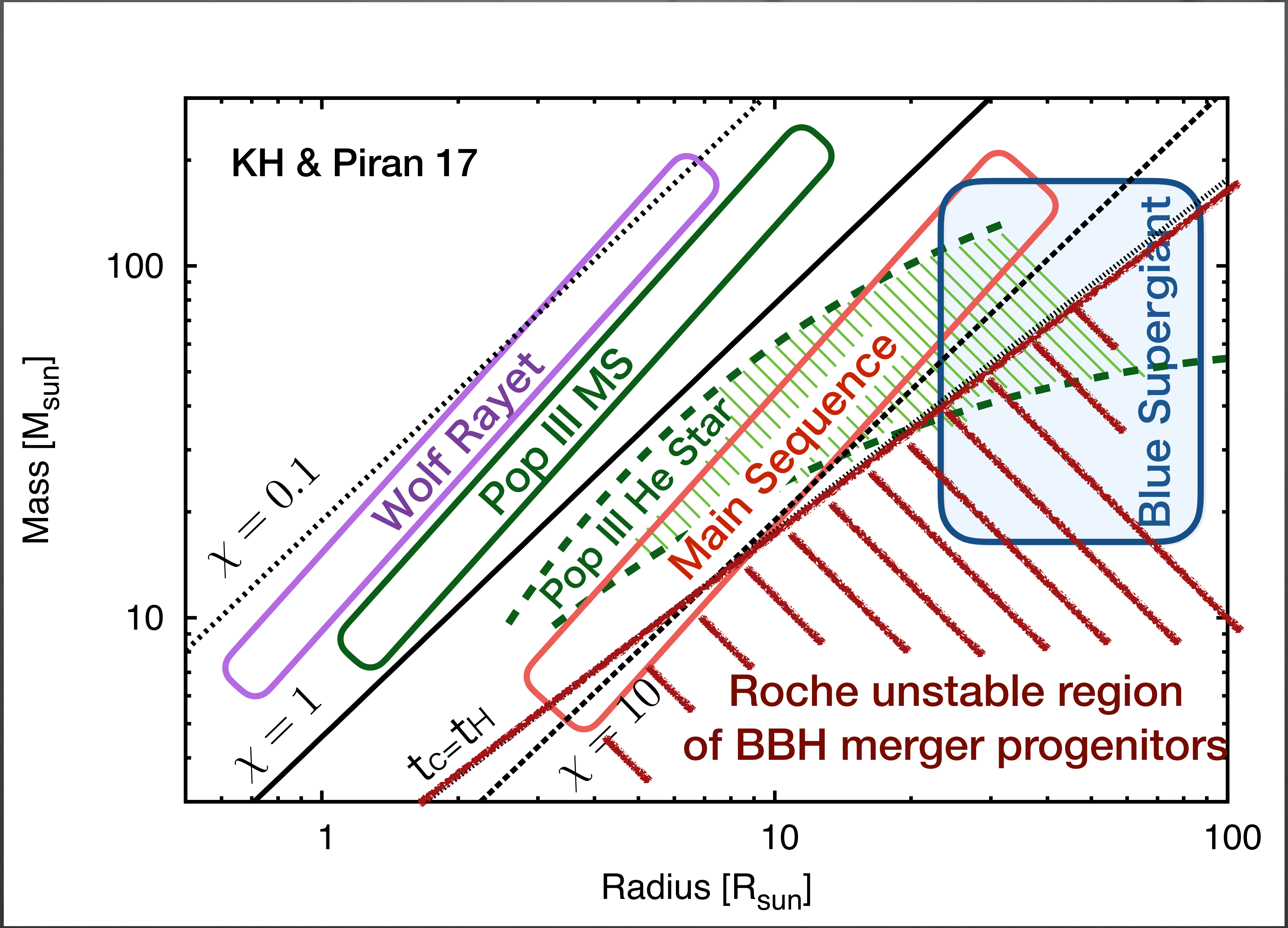


$t_c > \text{Hubble time}$

a~45Rsun, for
m1=m2=30Msun

$R_* > R_{RL}$

What kind of stars can be the progenitors of merging BBHs?

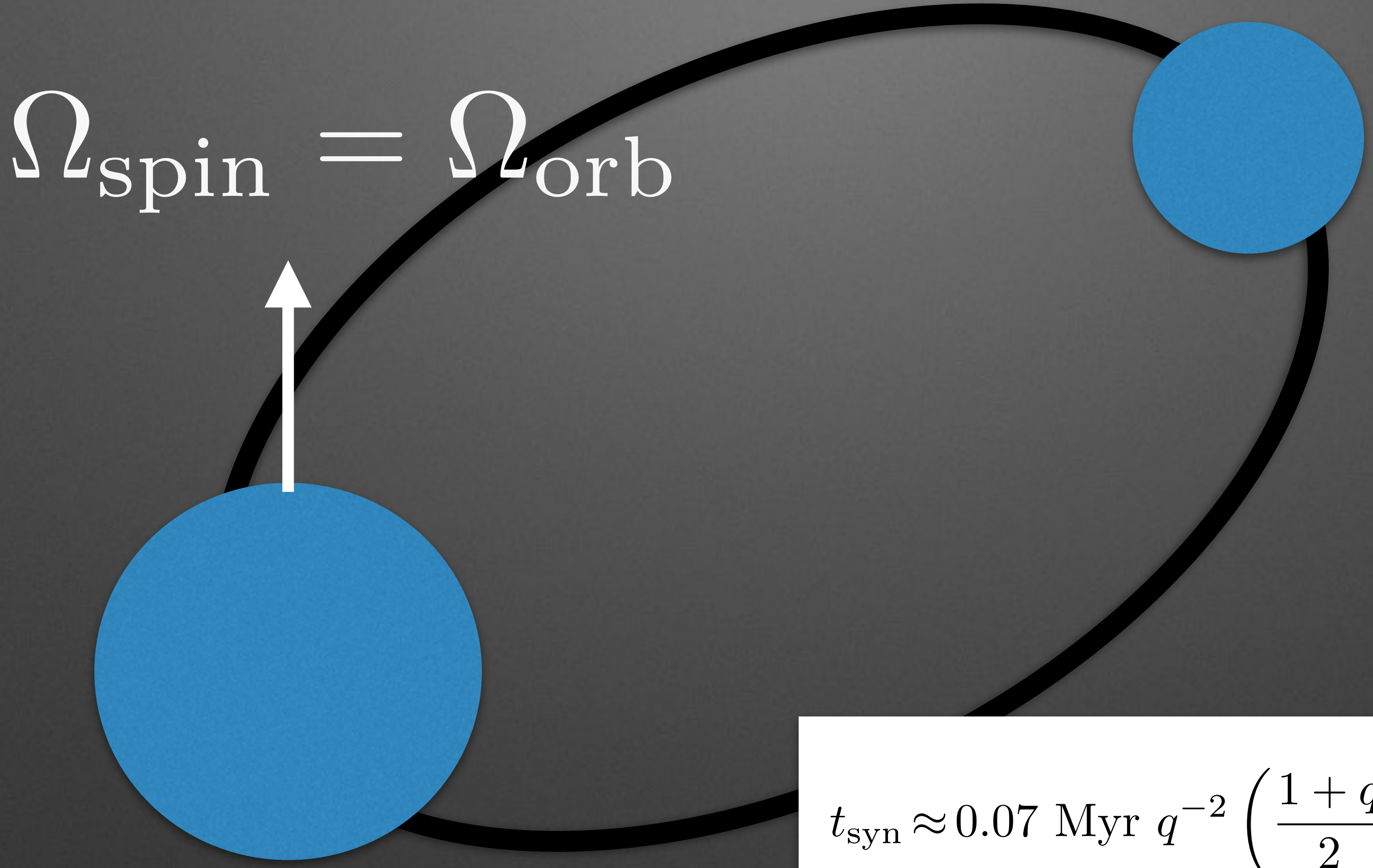


$t_c < H^{-1}$ →

If they evolve to red supergiants, there must be common envelope phases.

Tidal Synchronization

Tides + dissipation => Synchronization (e.g. Moon)



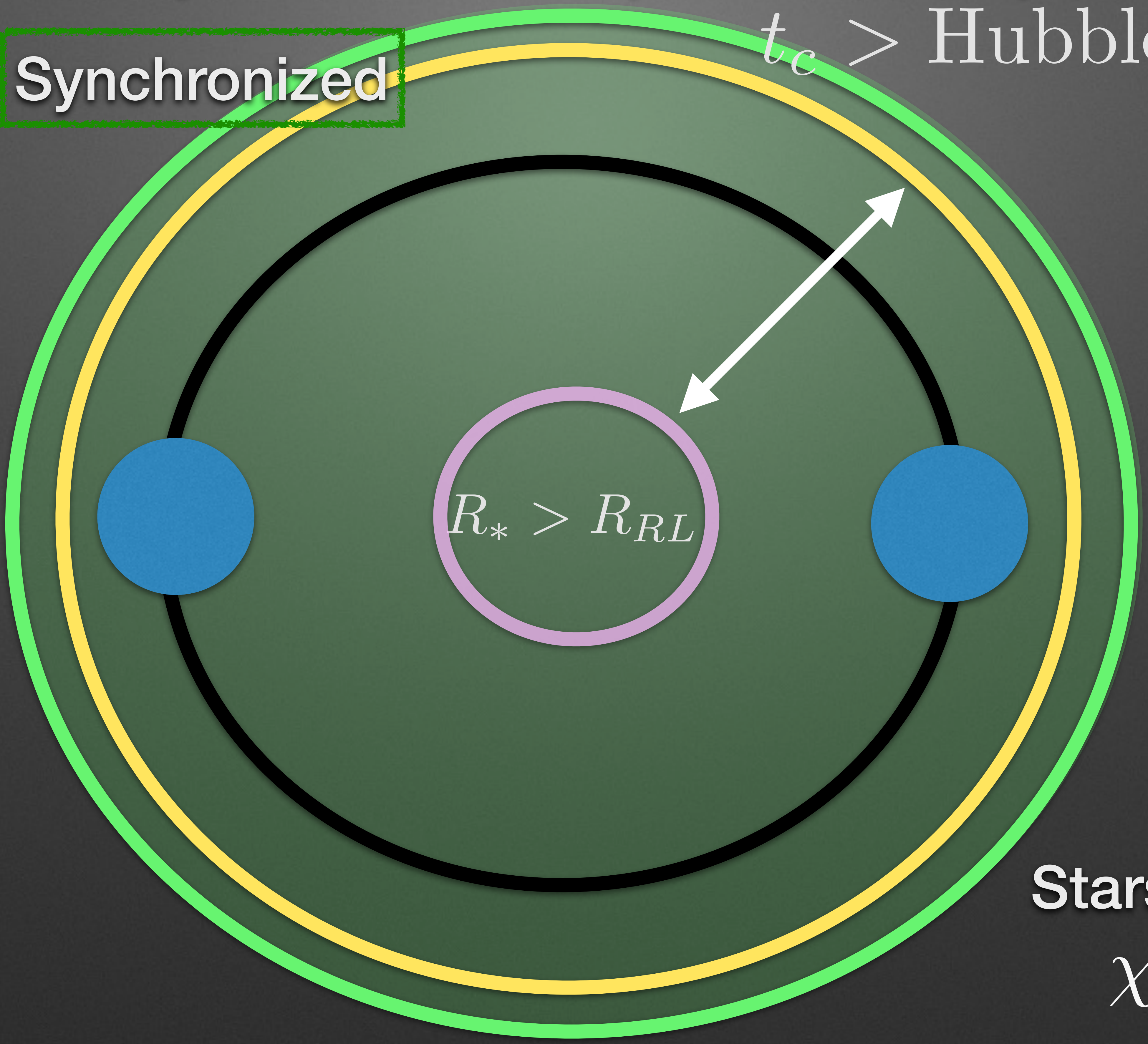
$$\Omega_{\rm spin} = \Omega_{\rm orb}$$

see Kushnir+16 for a discussion on BBH progenitors.

$$t_{\rm syn} \approx 0.07\ {\rm Myr}\ q^{-2} \left(\frac{1+q}{2}\right)^{-5/6} \left(\frac{\epsilon}{0.075}\right) \left(\frac{R}{14R_\odot}\right)^{-7} \times \left(\frac{M}{30M_\odot}\right)^{-1/2} \left(\frac{a}{44R_\odot}\right)^{17/2} \left(\frac{E_2}{10^{-6}}\right)^{-1}, \qquad (6)$$

Zahn 1975, 1977, Goldreich & Nicholson 89, Goodman & Dickson 98, Kushnir+16

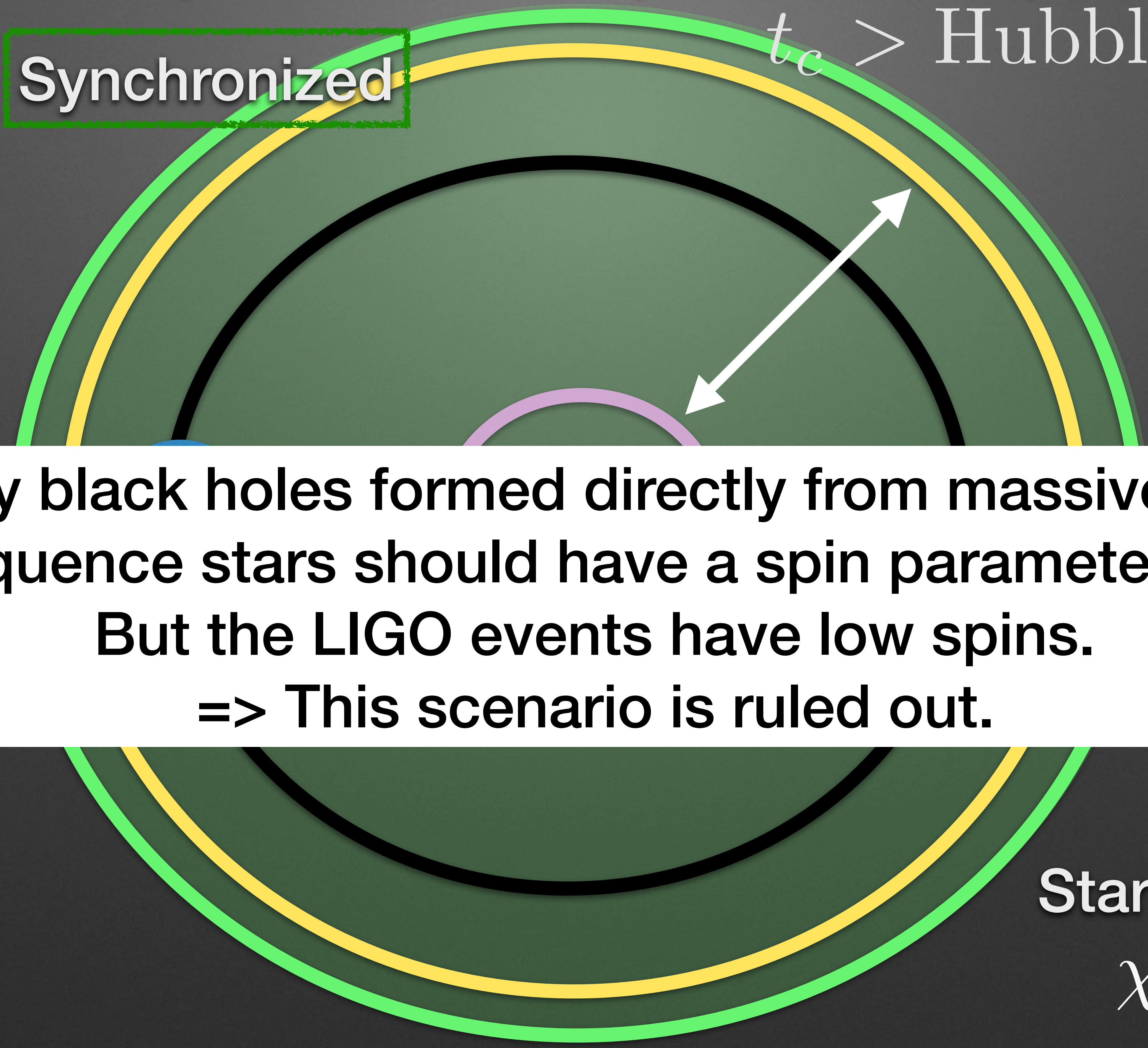
Main-sequence stars (R~10 Rsun)



Stars have

$\chi_* > 1$

Main-sequence stars (R~10 Rsun)



Synchronized

$t_c >$ Hubble time

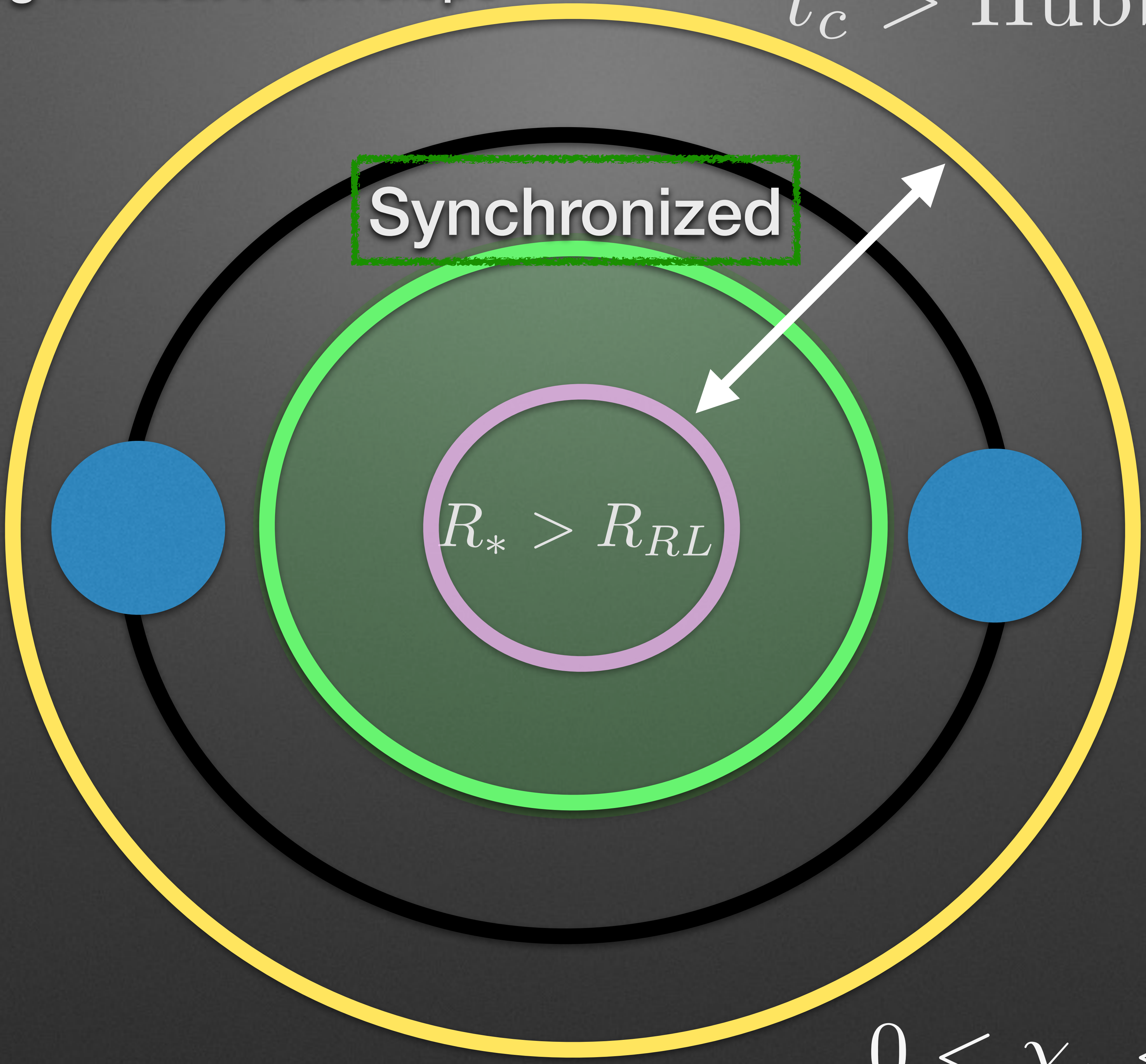
Binary black holes formed directly from massive main-sequence stars should have a spin parameter ~1.
But the LIGO events have low spins.
=> This scenario is ruled out.

Stars have

$\chi_* > 1$

Wolf-Rayet stars (R~2Rsun)

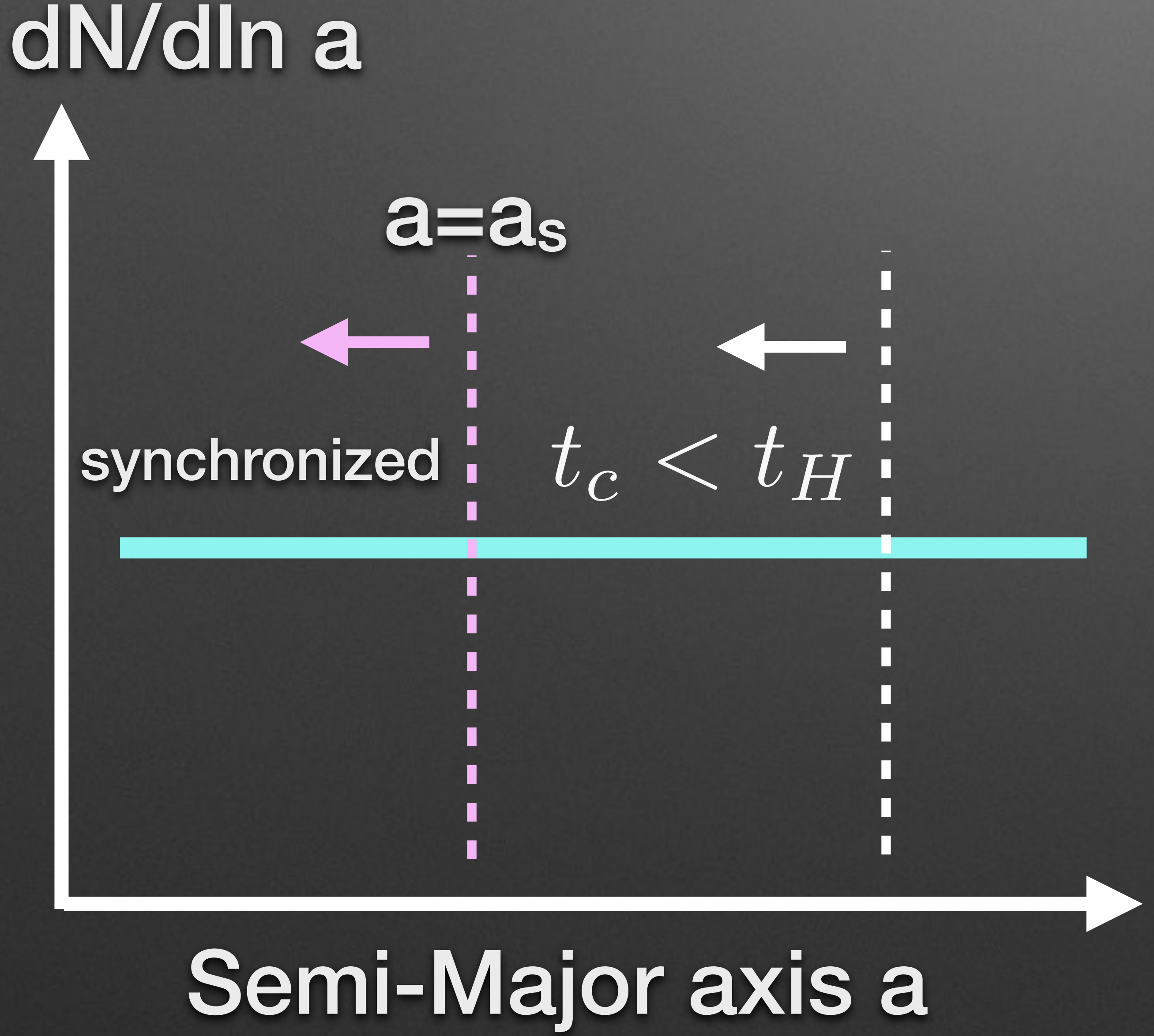
He burning without H envelope

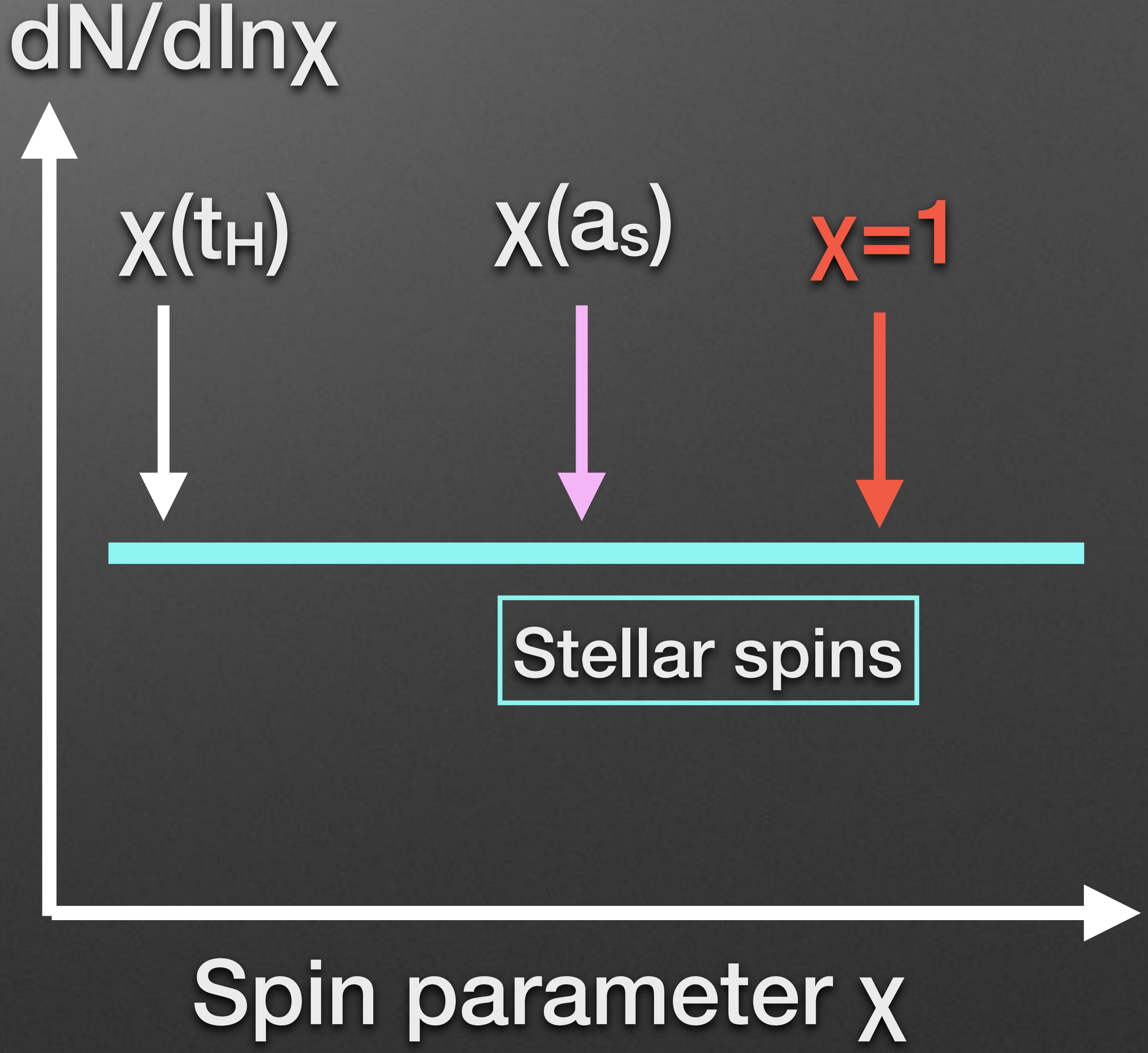


BBH spin distribution

For example,

- BBH formation is constant with time.
- The semi-major axis distribution is flat.
- Wolf-Rayet progenitors (initially non-spin).

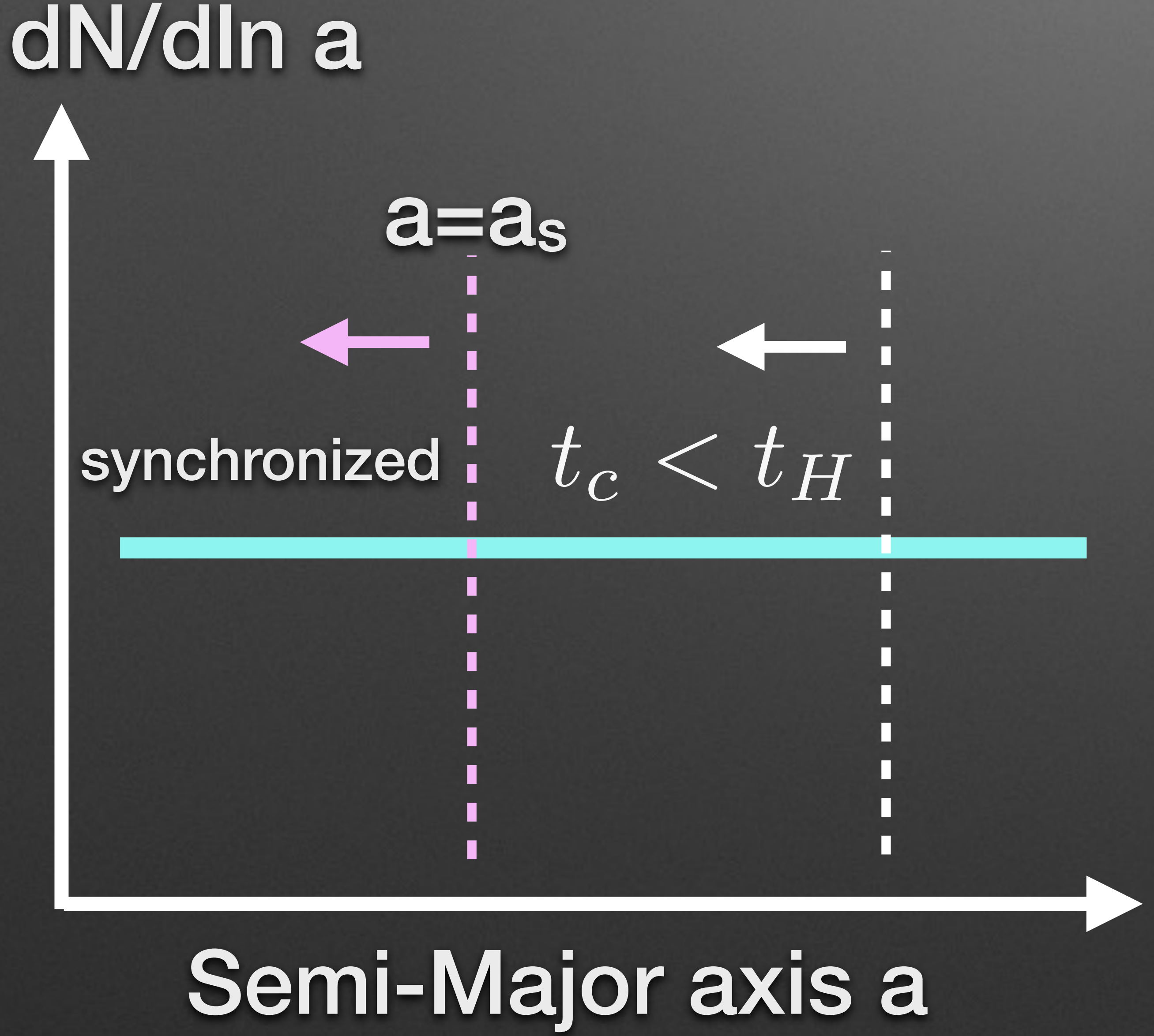


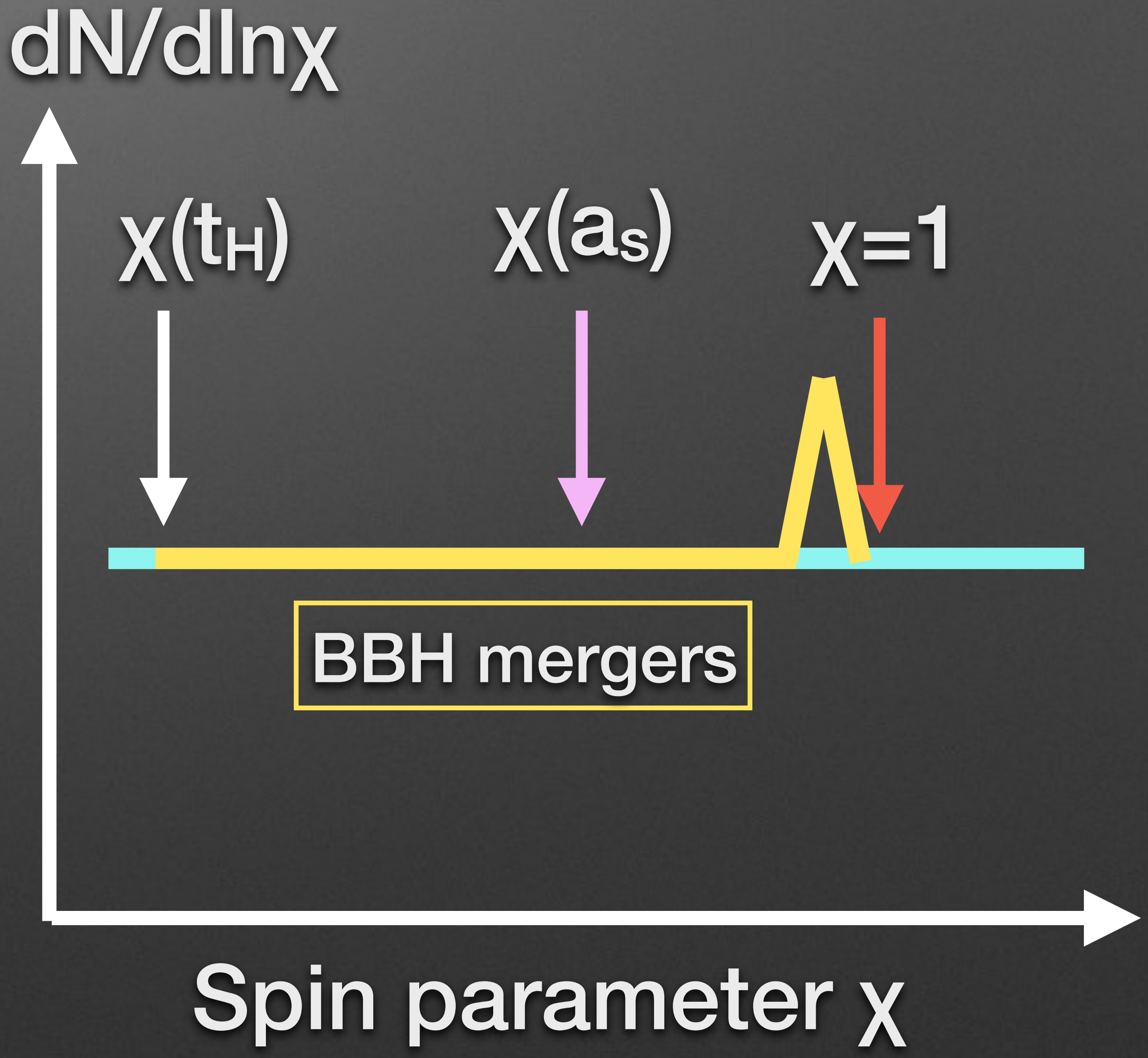


BBH spin distribution

For example,

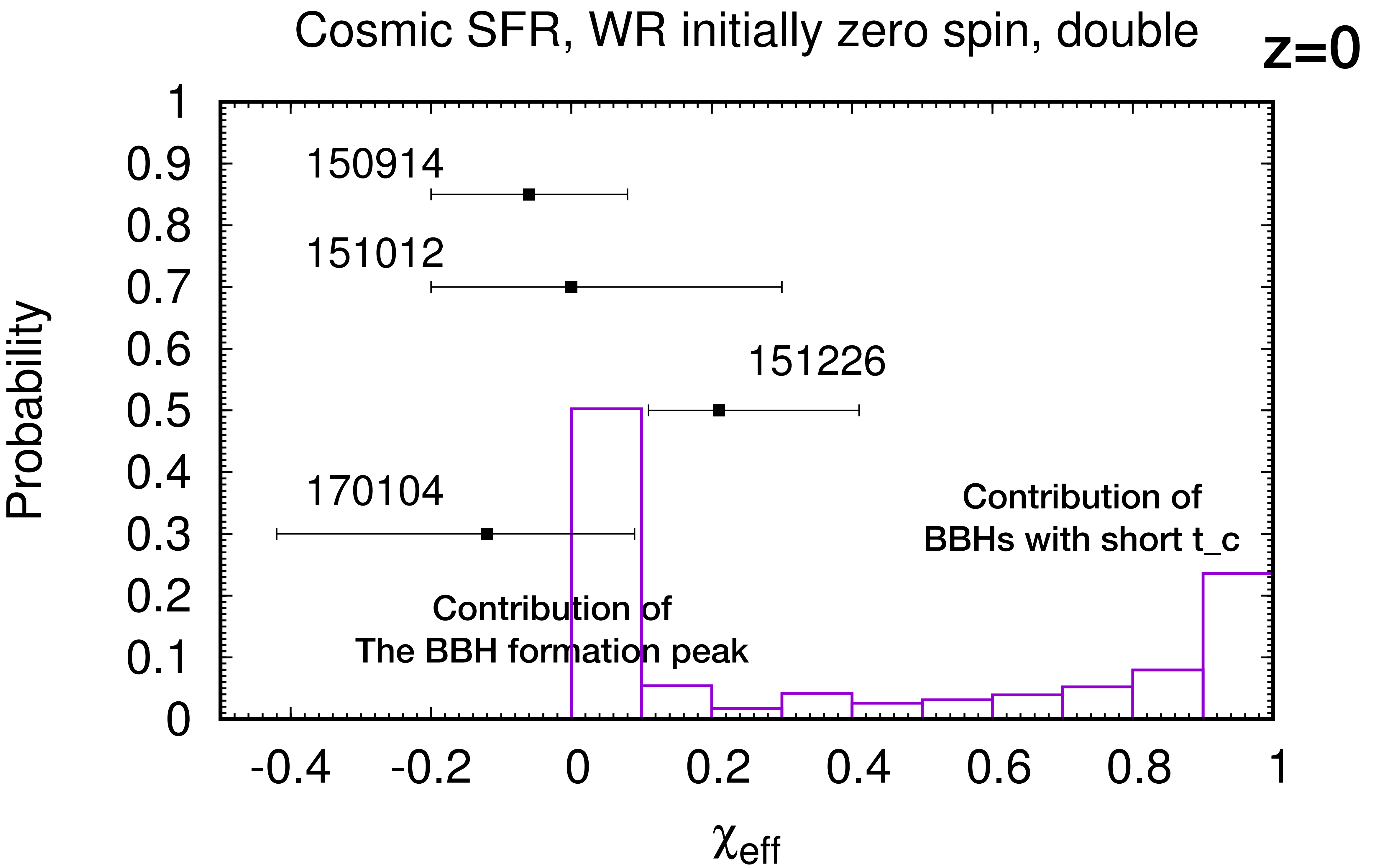
- BBH formation is constant with time.
- The semi-major axis distribution is flat.
- Wolf-Rayet progenitors (initially non-spin).





Spin distribution of BBH mergers

Two peaks in the spin distribution



Zaldarriaga et al 2017 also get a similar bimodal distribution.

Basic parameters of Wolf-Rayet Model

- The initial spin of Wolf-Rayet stars:

  (1) synchronized or (2) zero spin.

- The spin angular momentum loss time scale due to winds:

$$t_{\rm wind} \equiv \frac{J_{\rm spin}}{\dot{J}_{\rm spin}}$$

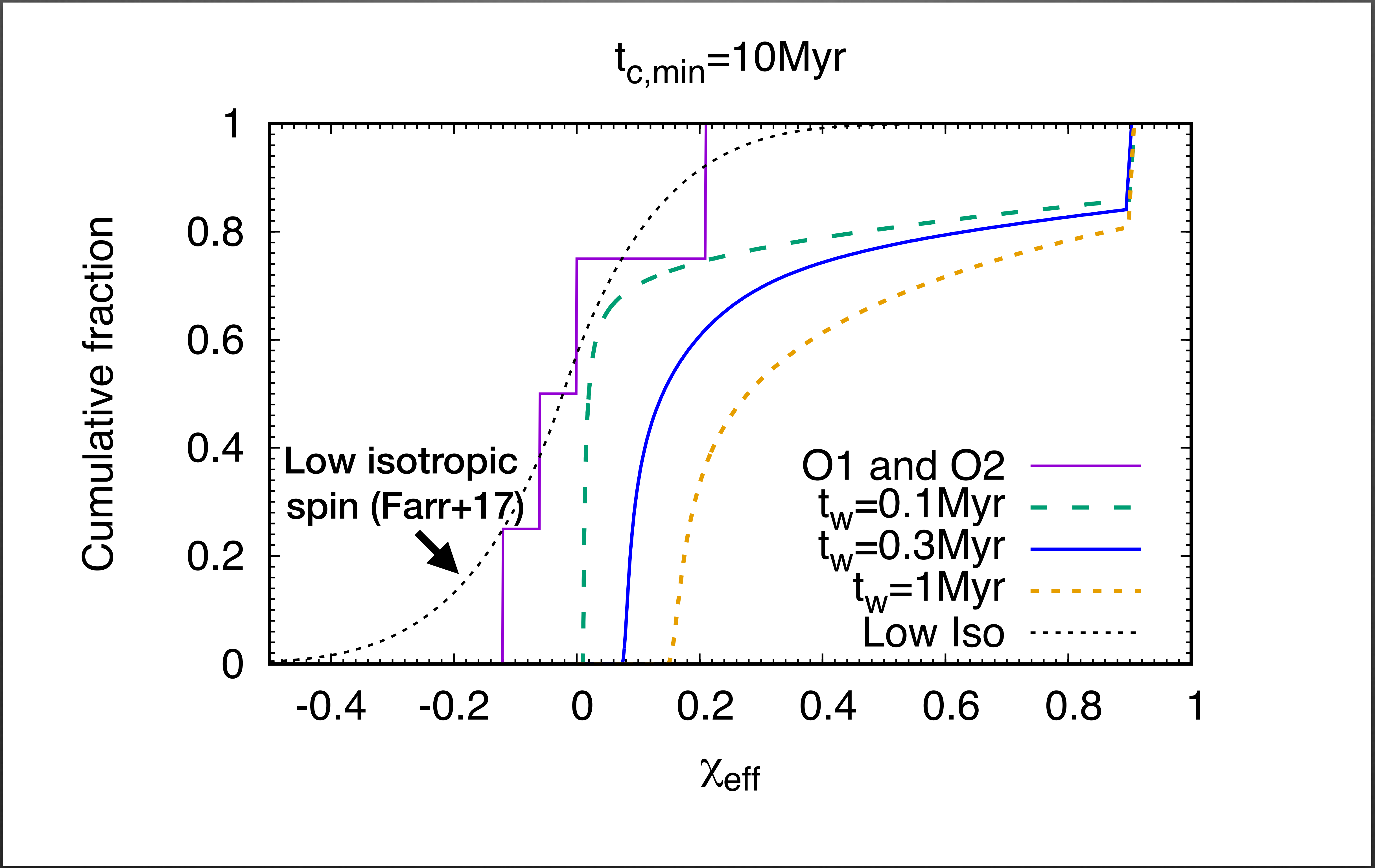
- The minimum coalescence time:

$$t_{c,\rm min} > 1 \ \rm Myr$$

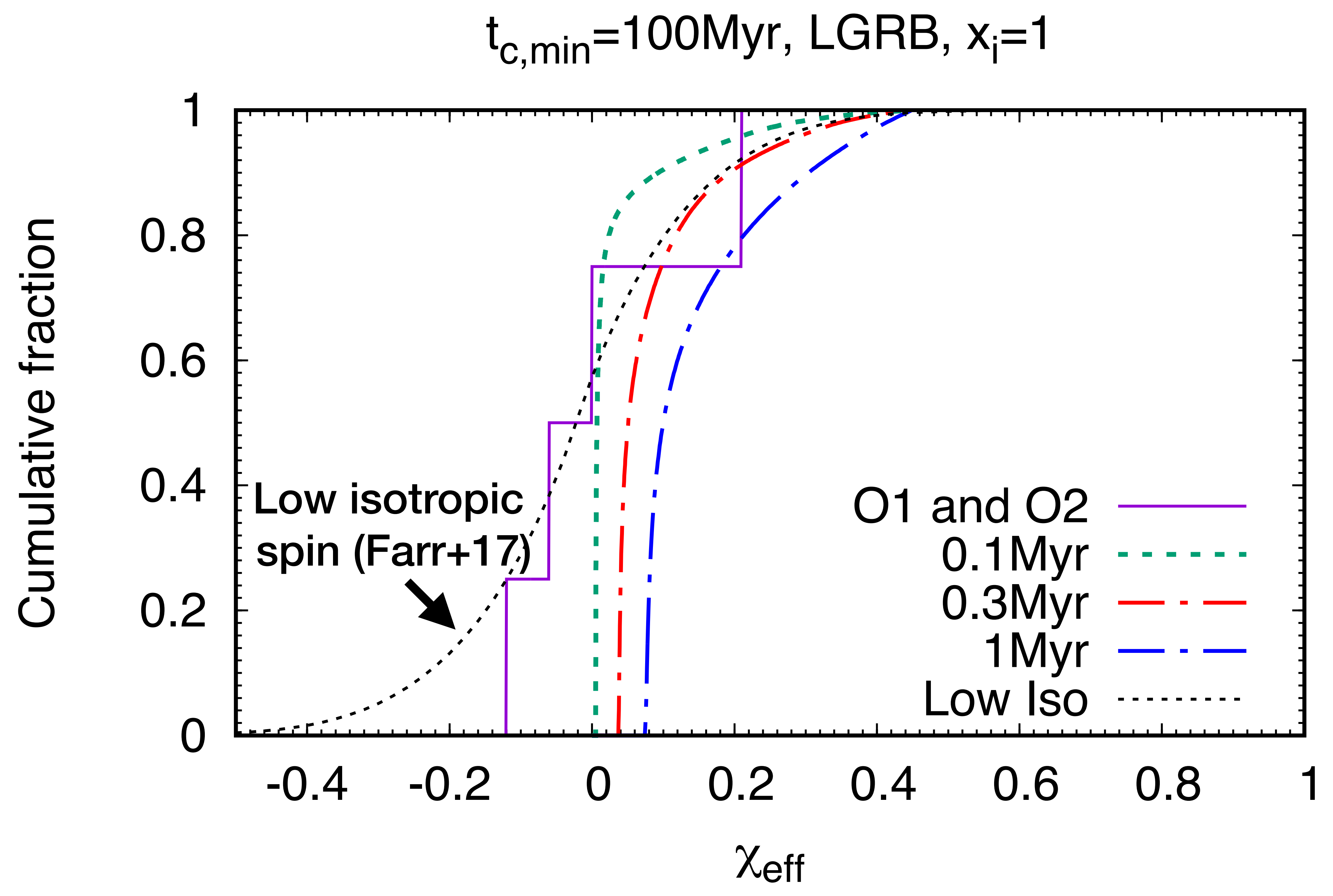
The formation history of binary black holes:

(1) cosmic star formation rate (SFR),
(2) Long Gamma-Ray Burst (LGRB),
(3) constant with redshift.

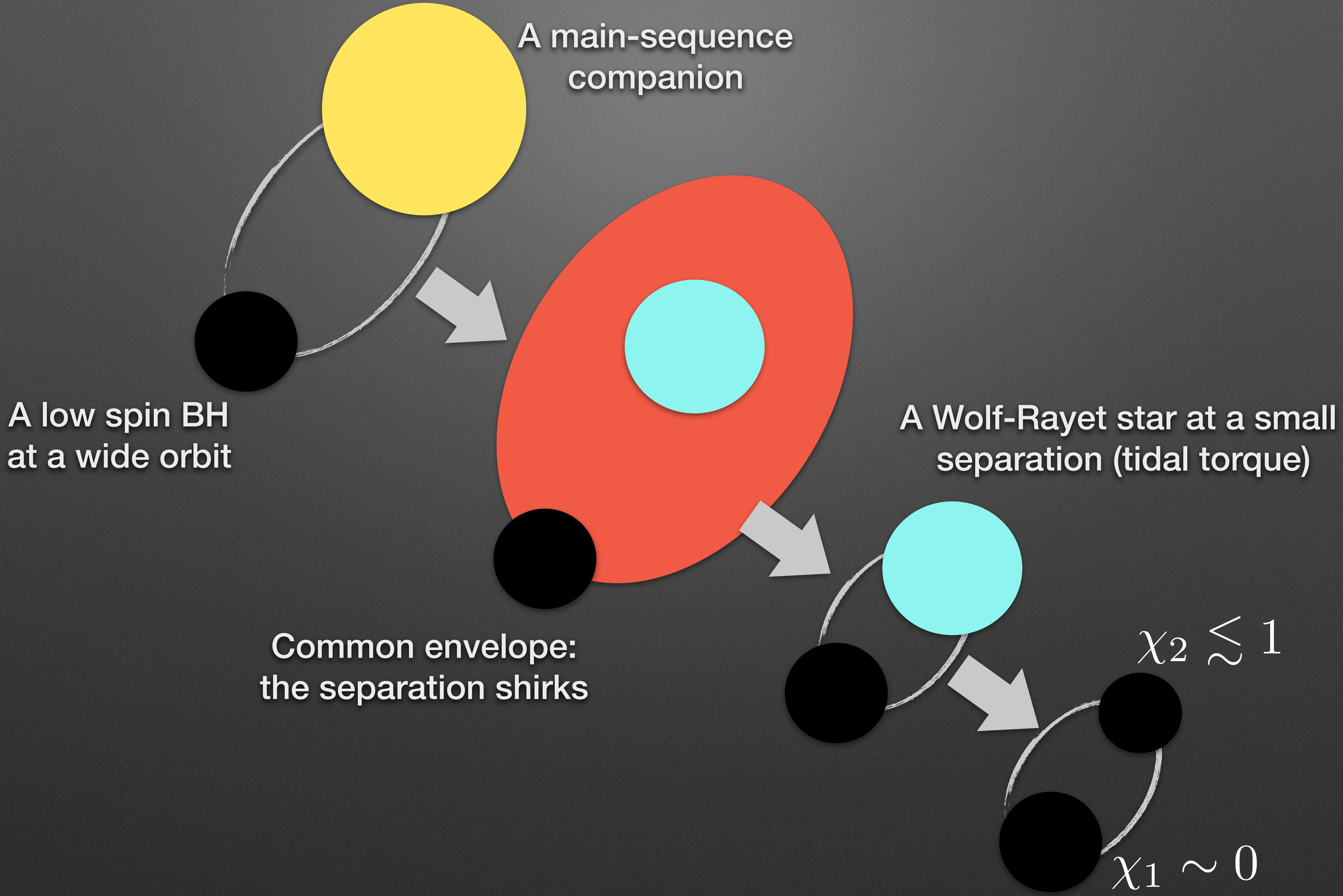
Cumulative distribution of chi effective



A longer minimal delay time 100Myr



The role of common envelope phases?



A main-sequence companion

A low spin BH at a wide orbit

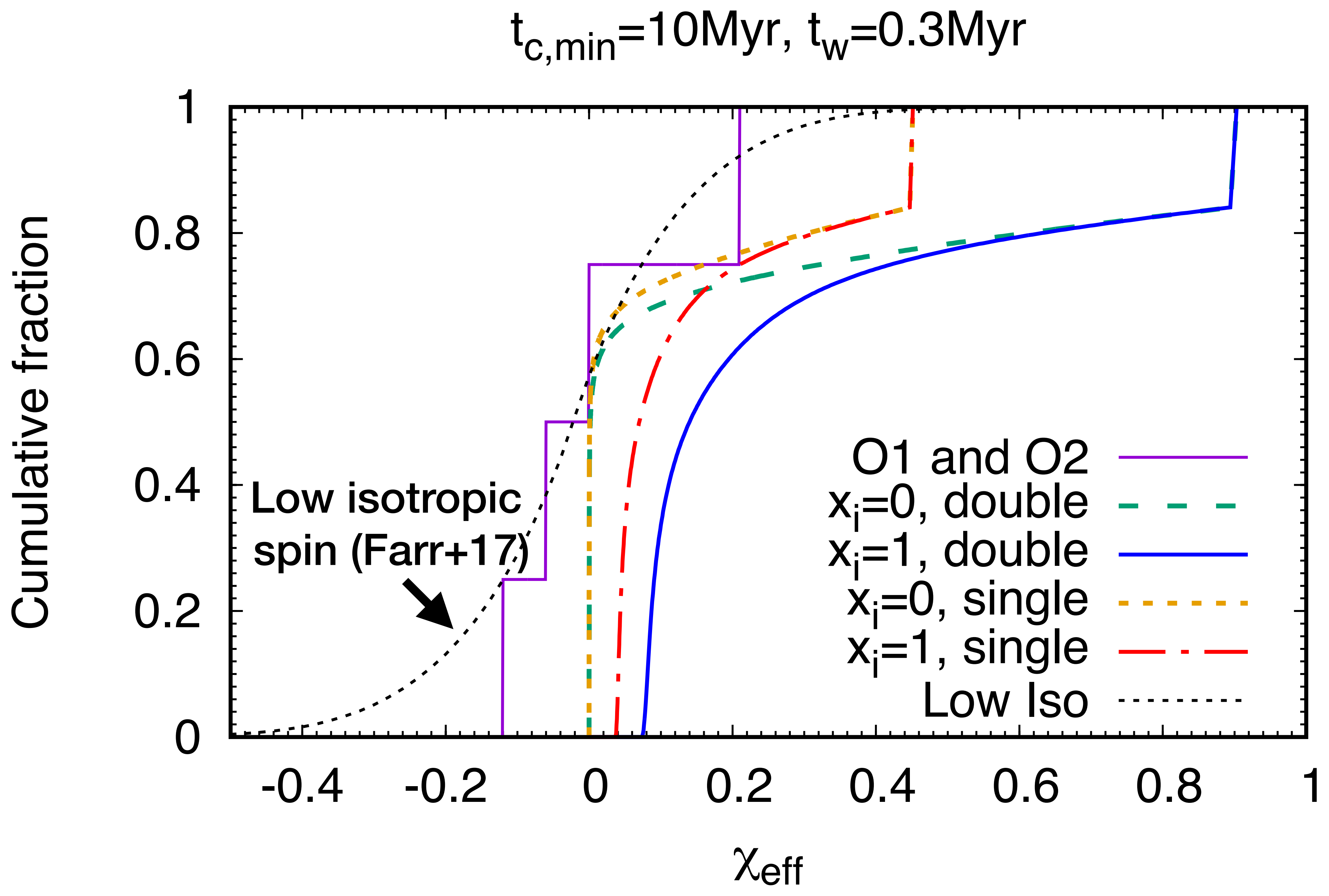
Common envelope: the separation shirks

A Wolf-Rayet star at a small separation (tidal torque)

$\chi_2 \lesssim 1$

$\chi_1 \sim 0$

Common envelope or not?



Summary 1

- Wolf-Rayet stars formed around the cosmic star formation peak can be consistent with the observed low aligned spin BBHs.

- But the low-isotropic spin model is more preferred.

- Prediction: a non-negligible fraction of BBH mergers have chi ~ 1,

Discussion

- Low spins of BBH mergers are not good news for BH-NS mergers.

- GW151226, The secondary spin can be maximal, if the primary has zero spin.
  => if neutron star and such a black hole merge, we expect large mass ejection.

Outline

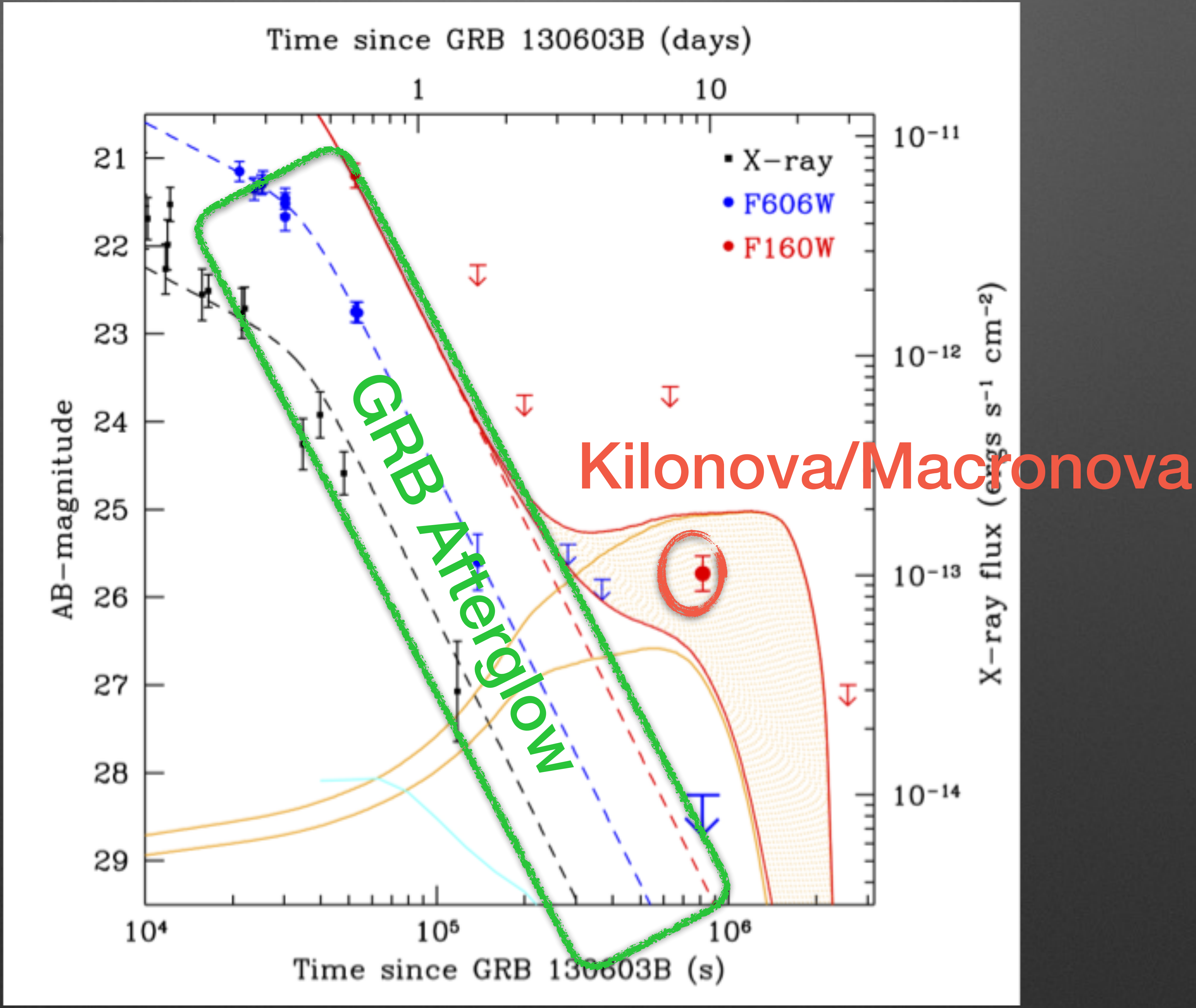
- Binary black hole spins and the field binary scenario
- kilonova/macronova candidates and late-time radio

Macronova candidates have already been reported.

The first Macronova candidate: after short GRB 130603B

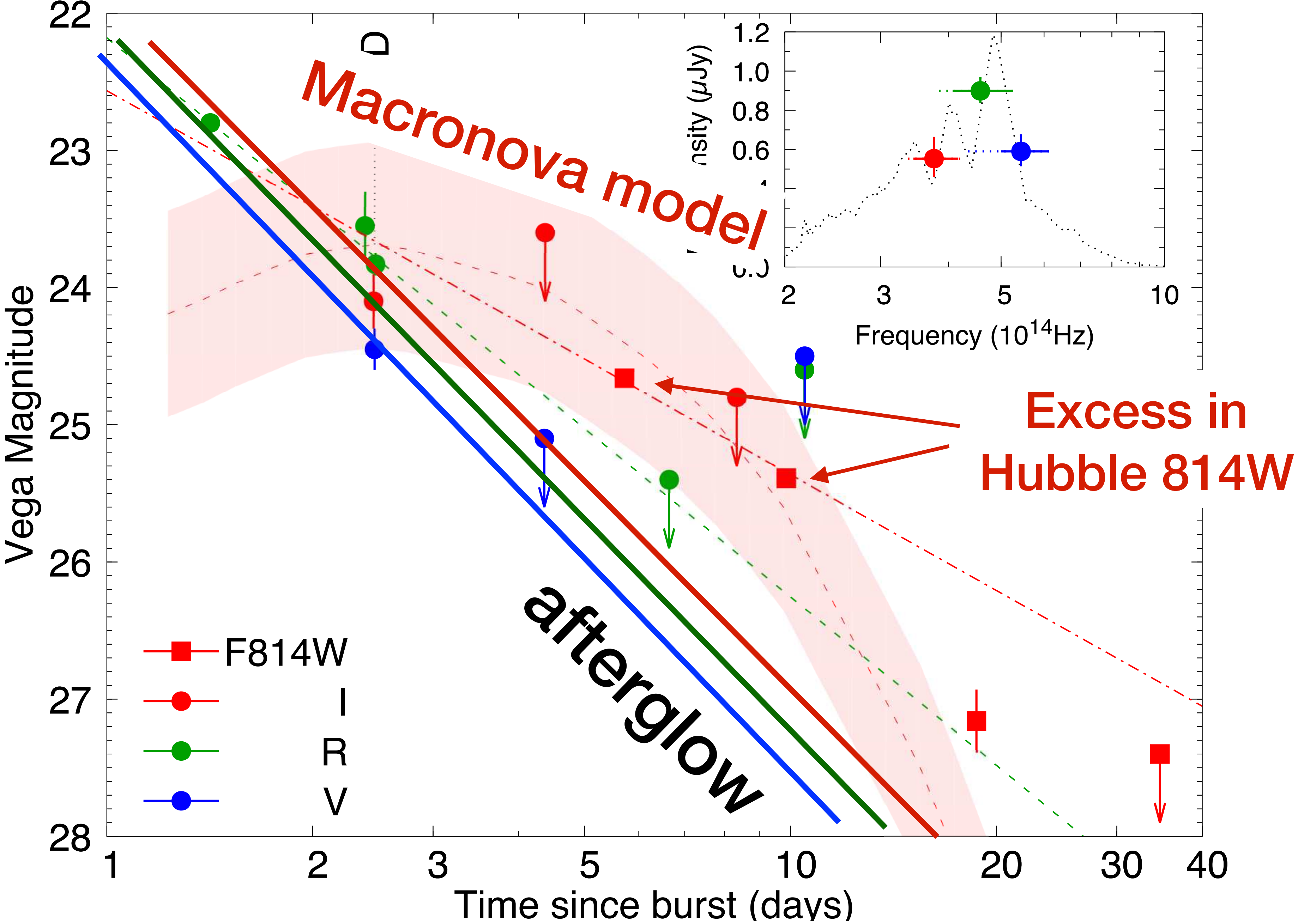
Tanvir+13
Berger+13

Masaomi's Talk
Edo's Talk
Mansi's Talk



Another candidate
in a historical short GRB 050709

Jin, KH + 16, see also Fox +05 and Watson + 06

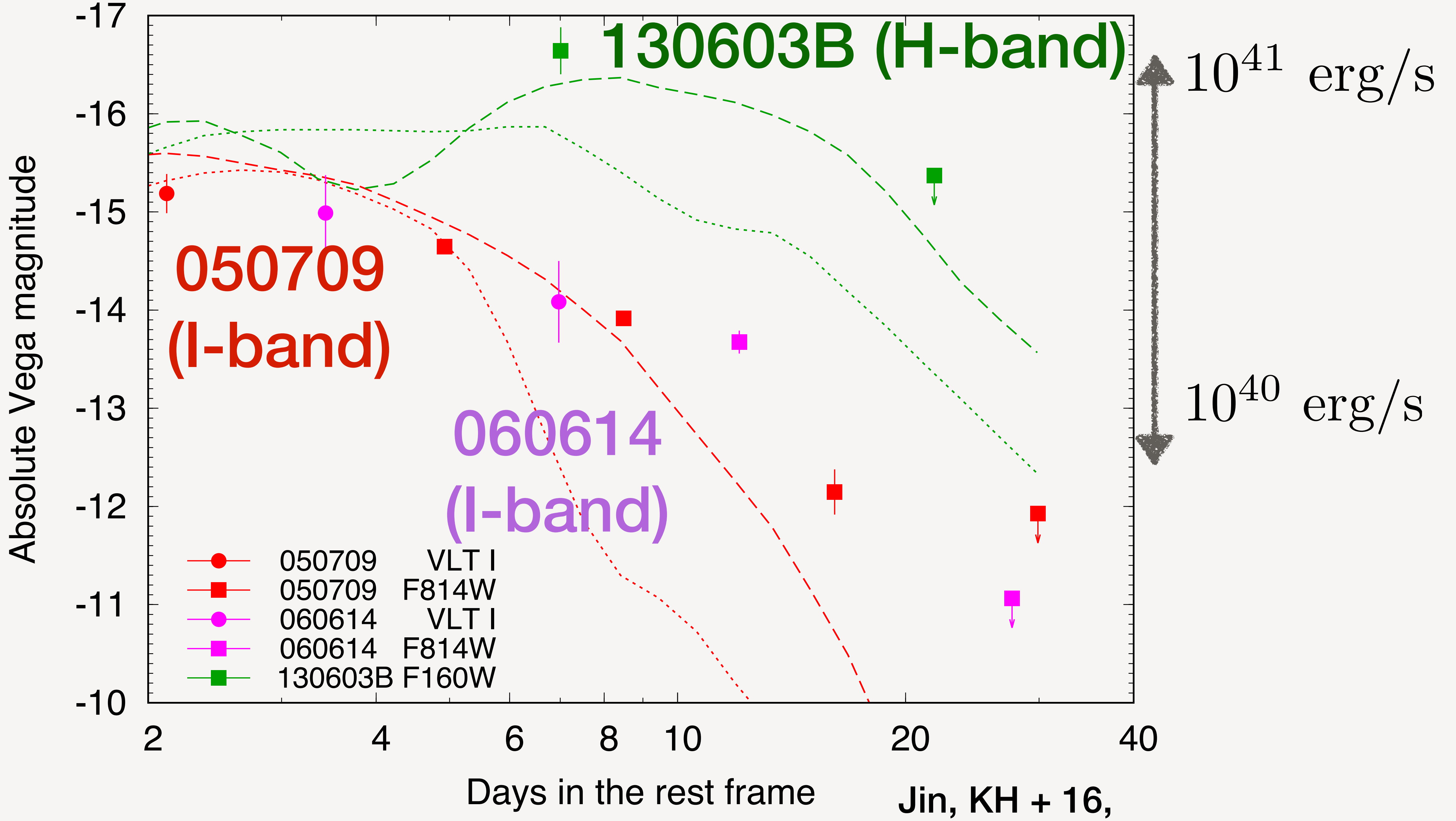


Macronova model

afterglow

Excess in Hubble 814W

Three macronova candidates after nearby short GRBs



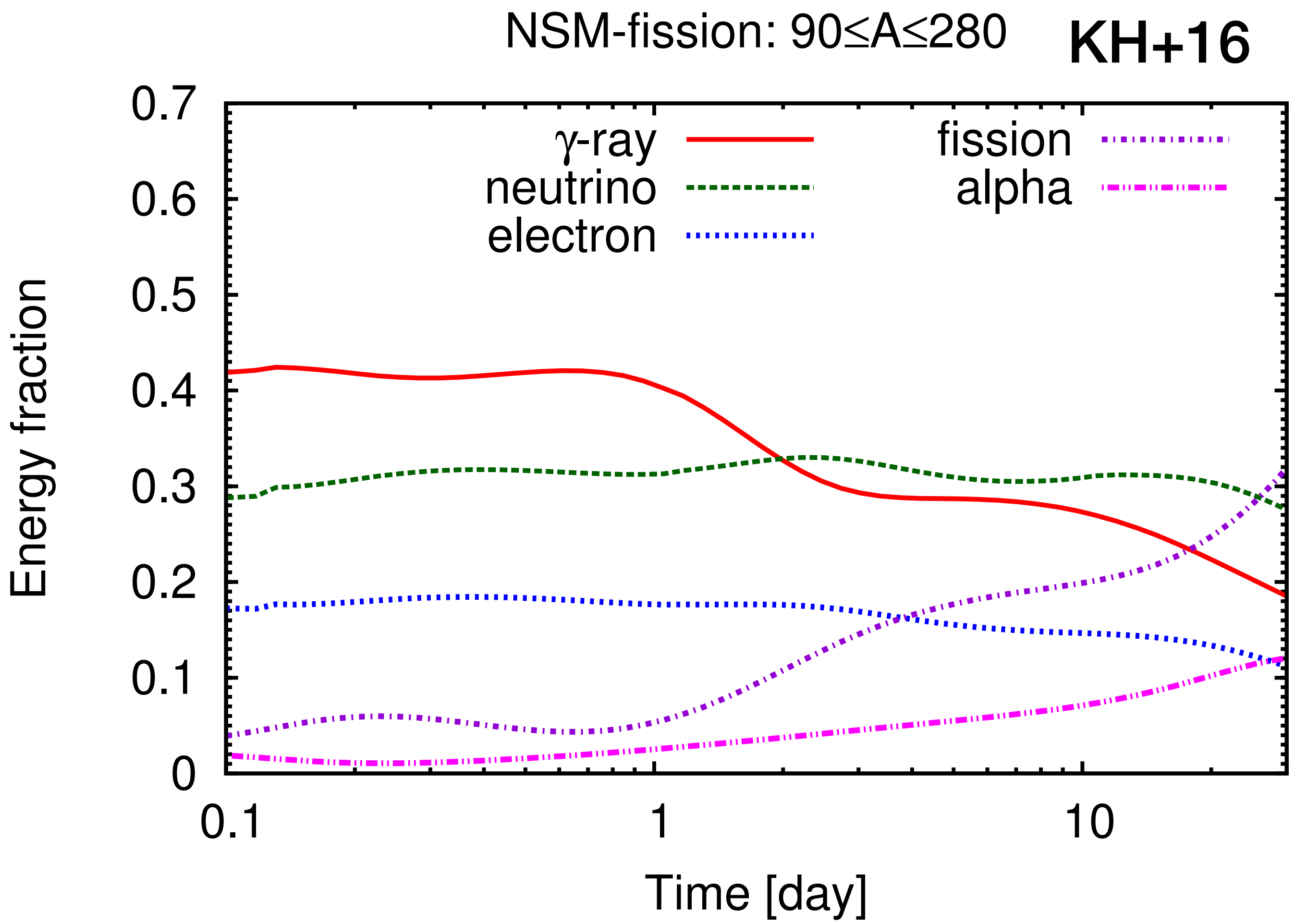
Jin, KH + 16,

see also Tanvir+13, Berger+13, Yang+15

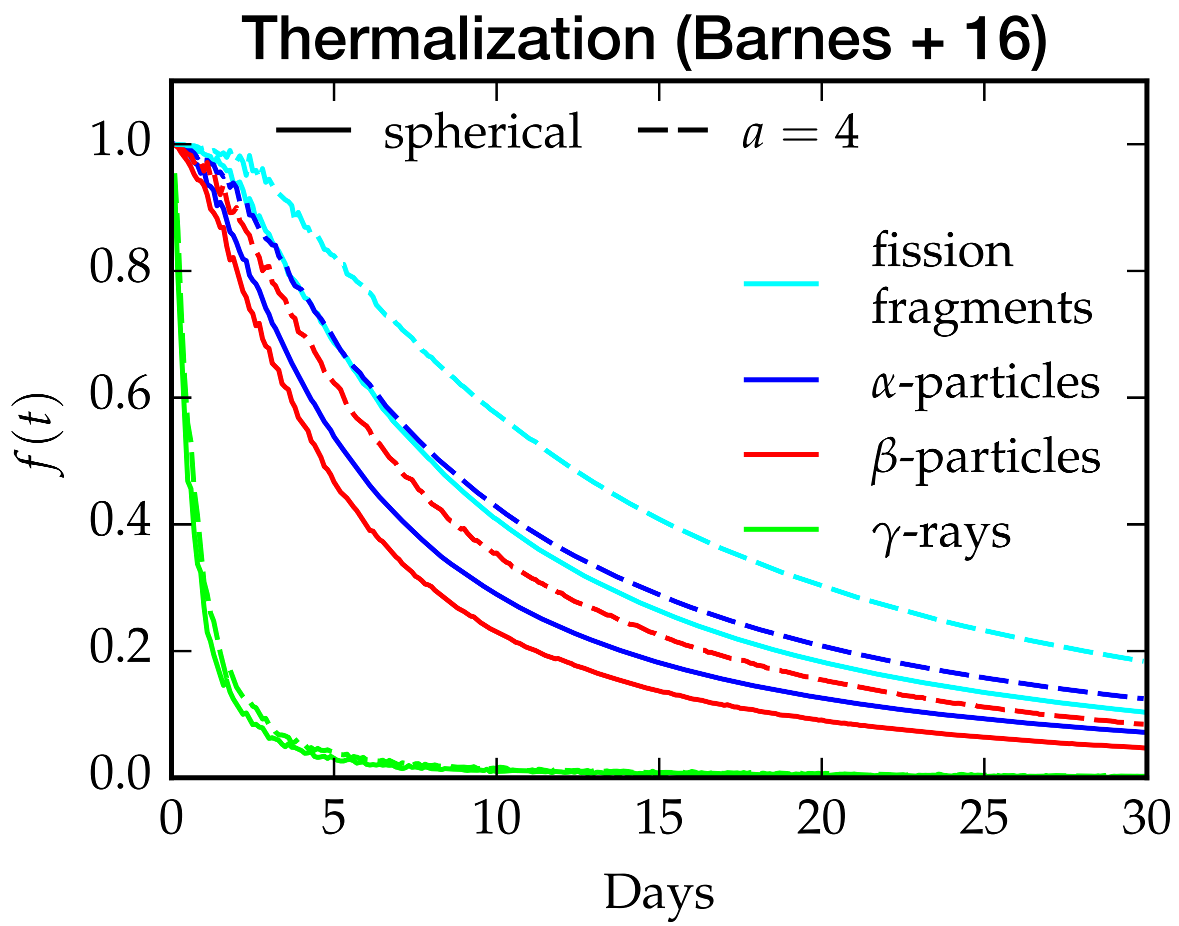
- Peak luminosity ~ 10^41 erg/s.
- The I-band light curves of 050709 and 060614 are very similar.
- Required a lot of ejecta mass ~ 0.05Msun if kilonova.

Energy partition to different products

Oleg Meng-Ru, Marius's Talk



NSM-fission: 90≤A≤280 **KH+16**



Thermalization (Barnes + 16)

At late times (t >~ 5 days),

- alpha decay and spontaneous fission potentially produce significant heats.
- Big questions are how much such nuclei are produced,
  what we can do for nuclides without experimental data.

Synchrotron Radio Flare from expanding ejecta

High velocity ejecta colliding with the ISM
=> particle acceleration=> Synchrotron Radiation
+ B amplification

Nakar & Piran 11

$$t_{peak} \approx 80\ day\ E_{50}^{1/3} n^{1/3} \beta_i^{-5/3}$$

p=2.5

$$F_{peak} \approx 3\ mJy\ \boxed{E_{50} \beta_i^{11/4} n^{7/8}}\, \epsilon_{B,-1}^{7/8} \epsilon_{e,-1}^{3/2} D_{27}^{-2} \nu_9^{-3/4}$$

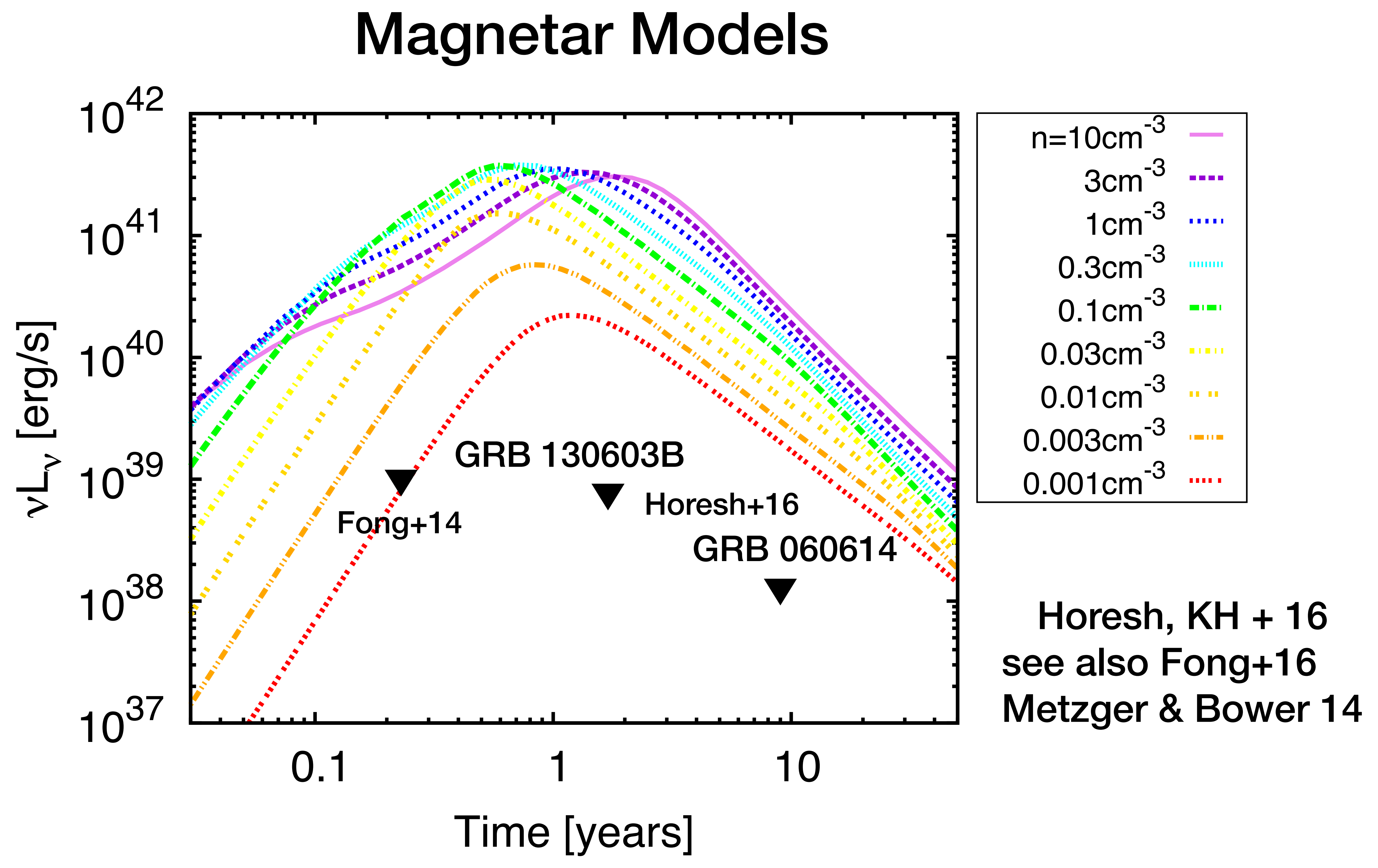
$$\nu_m \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} \boxed{\beta^5}$$

- The strong dependence on the ejecta velocity.

=> Fast components are very important.

- The peak flux and frequency also depend on n*e_b.

Limits on radio remnants

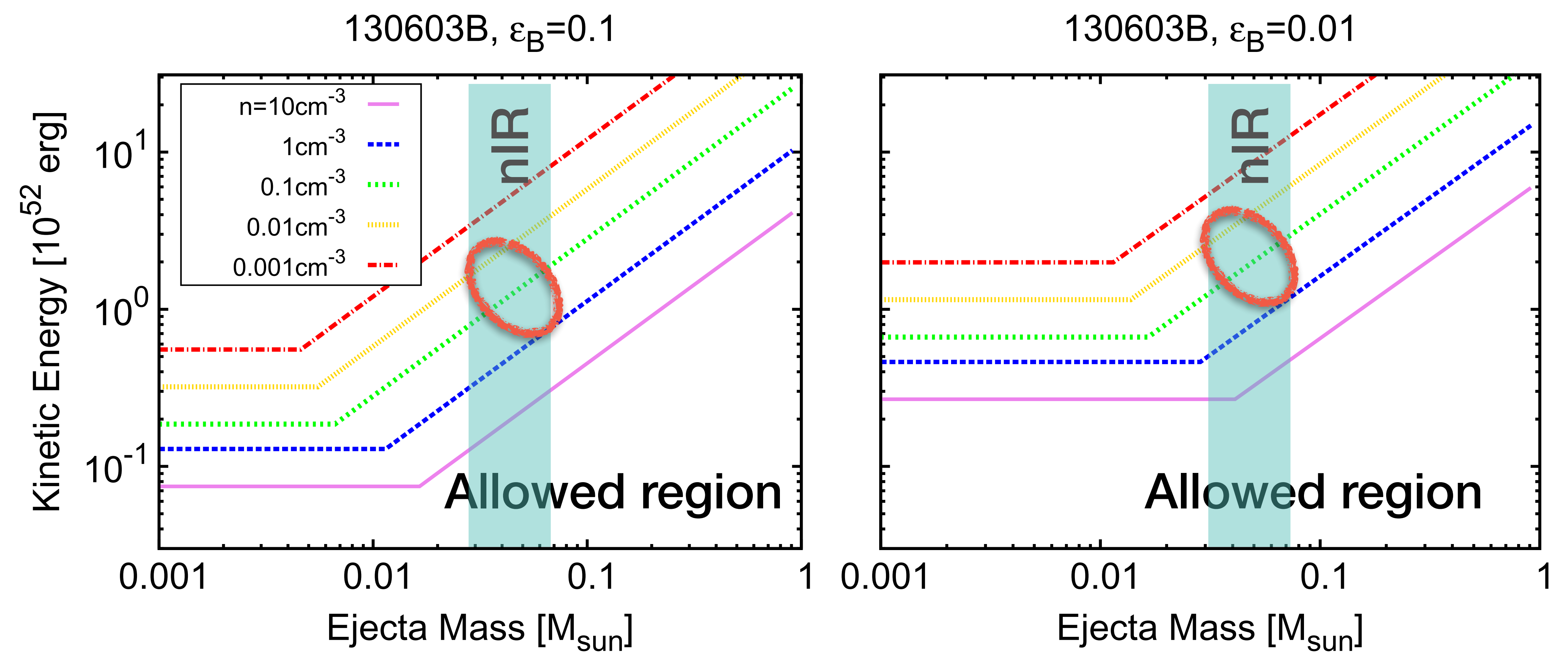


Horesh, KH + 16
see also Fong+16
Metzger & Bower 14

There are limits on the late-time radio flux after short GRBs.

Radio limits on E-M plane

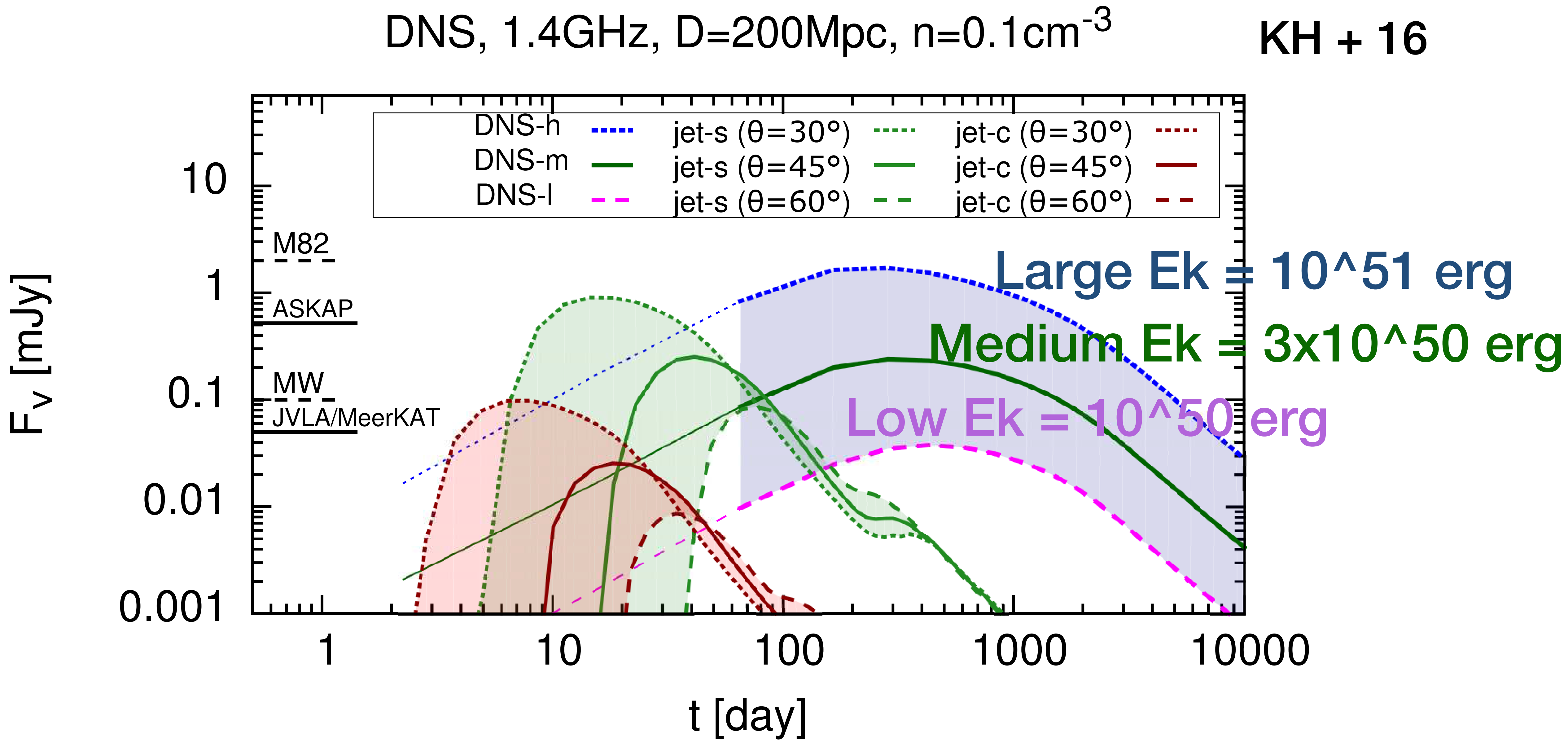
Horesh, KH + 16,
see also Fong + 16 for more samples



The macronova flux requires >~ 0.03Msun & the density from the GRB afterglow.

=> the radio limits put Ek ~< 10^52 erg.

Expected Radio Light Curves after a GW event



KH + 16

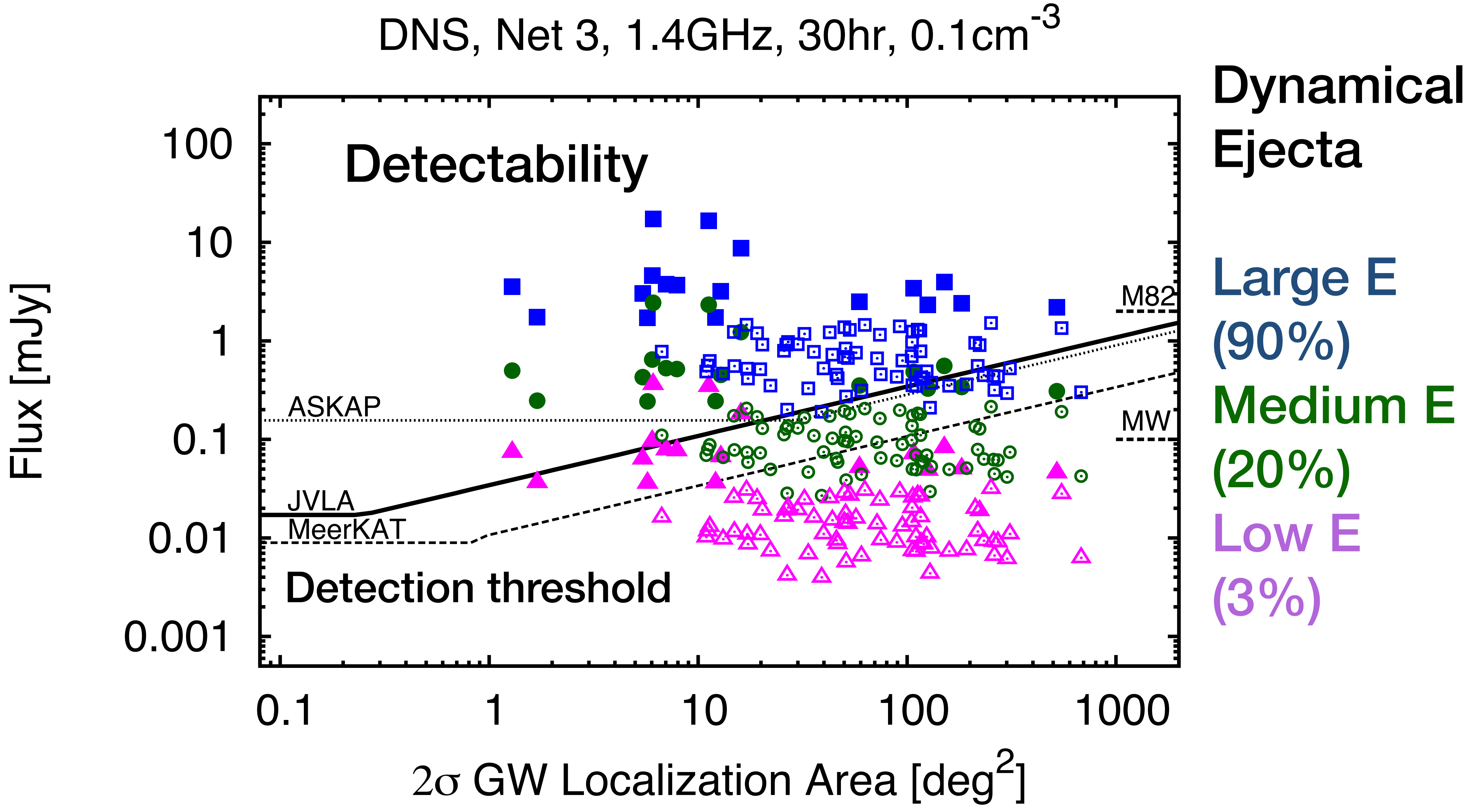
Large Ek = 10^51 erg

Medium Ek = 3x10^50 erg

Low Ek = 10^50 erg

There is chance to see the radio counterparts with the current telescopes.

Radio Macronovae as GW counterparts



KH+16

Filled points: nearby events D<200Mpc

Note also that radio false positives are relatively rare.

Summary 2

- The macronova candidates require somewhat large mass ejection ~0.05Msun.
- Red bumps at ~week may be ubiquitous for short GRBs?
- Alpha and spontaneous fission may increase the heating at late times > 5days.
- Late radio non-detections suggest Ek< 10^52 erg.
- Radio detectability will increase once GW area < 100 deg^2