"Binary black holes detected by LIGO: astrophysical and cosmological implications"

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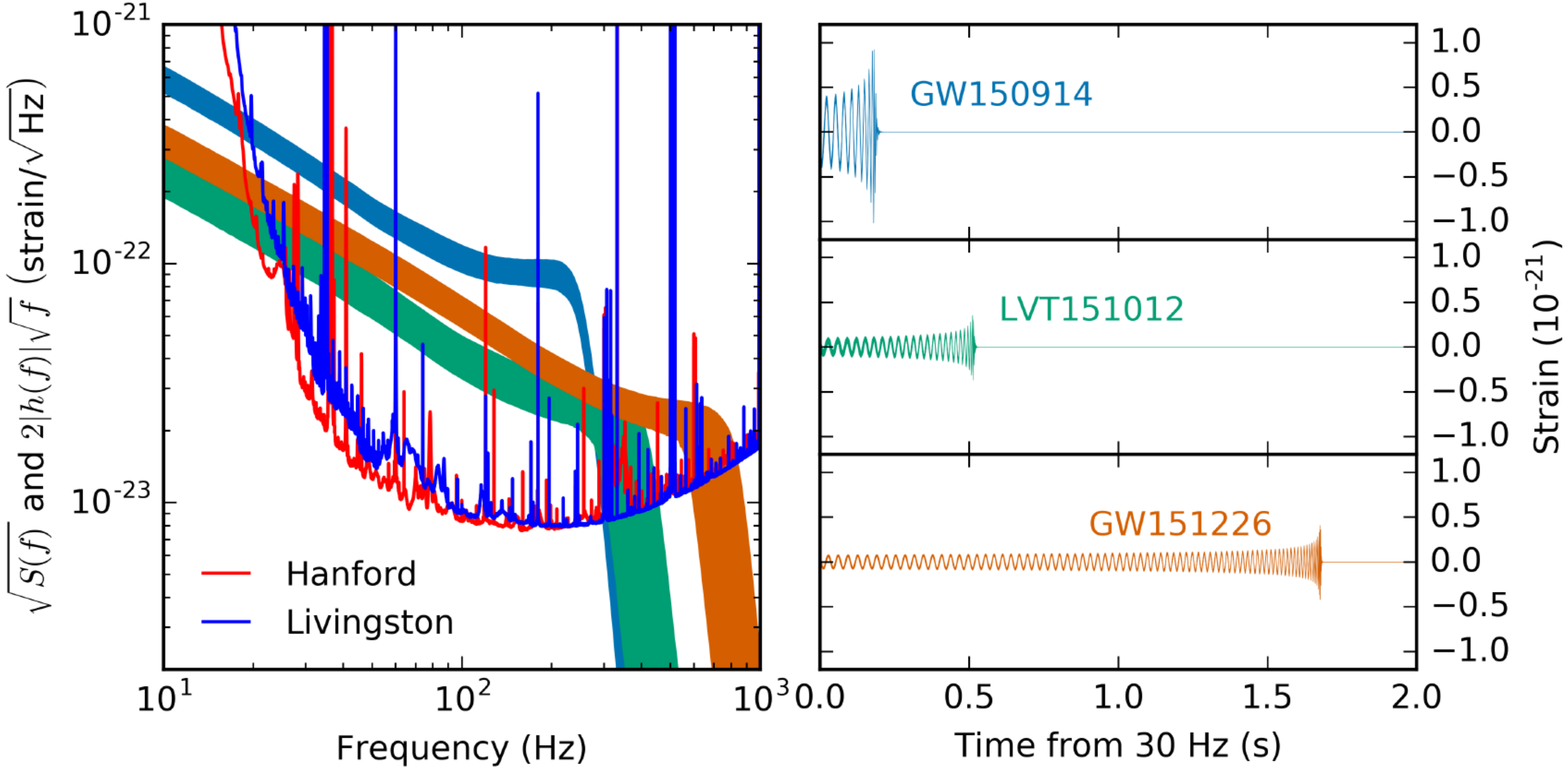
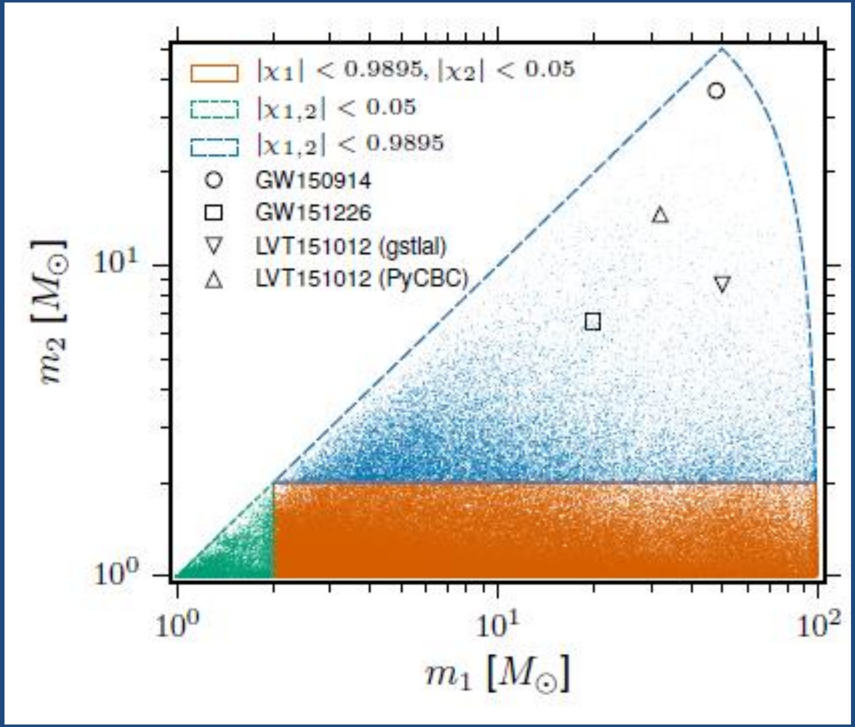
Blinnikov, Dolgov, PK 1409.5736, Blinnikov, Dolgov, Porayko, PK 1611.00541,
Dolgov, PK 1702.07621

2015 – start of GW astronomy



Abbott+ 2016, LIGO/VIRGO Collab.

Properties of BH systems measured from GW observations



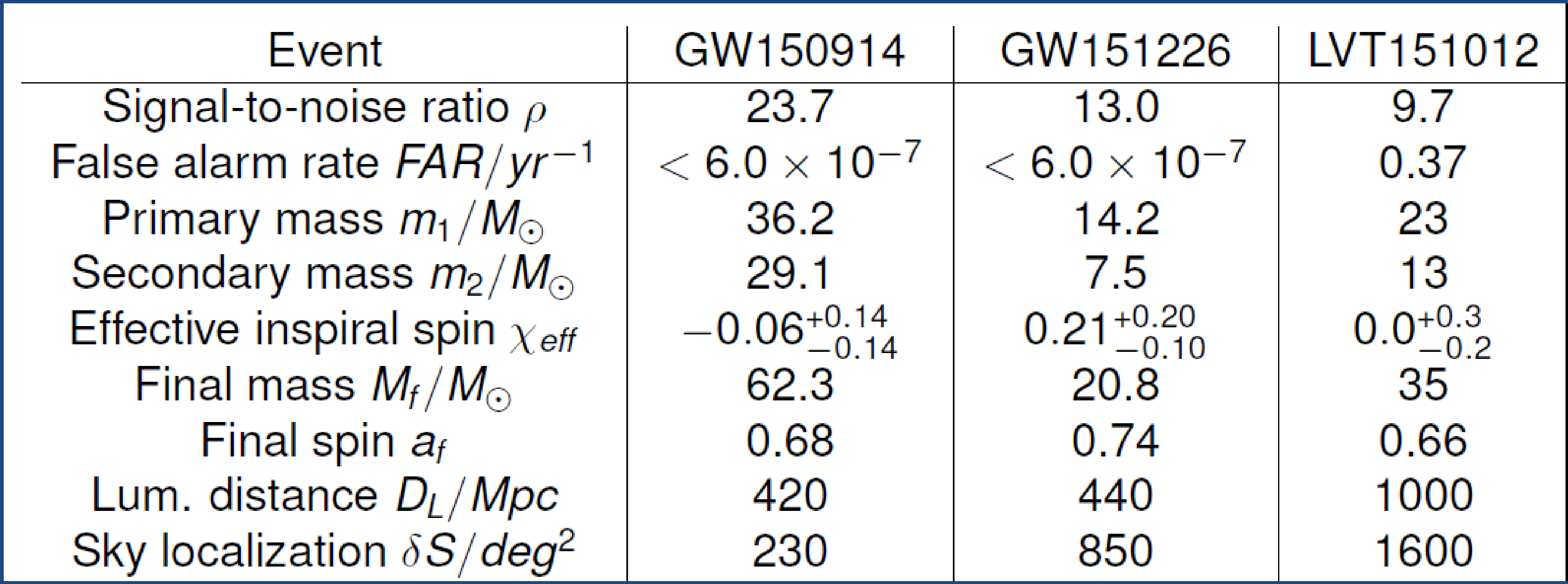
$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

$$a_{1,2} = \frac{c}{G m_{1,2}^2} |S_{1,2}|$$

$$\chi_{1,2} = \frac{c}{G m_{1,2}^2} S_{1,2} \cdot \hat{L}$$

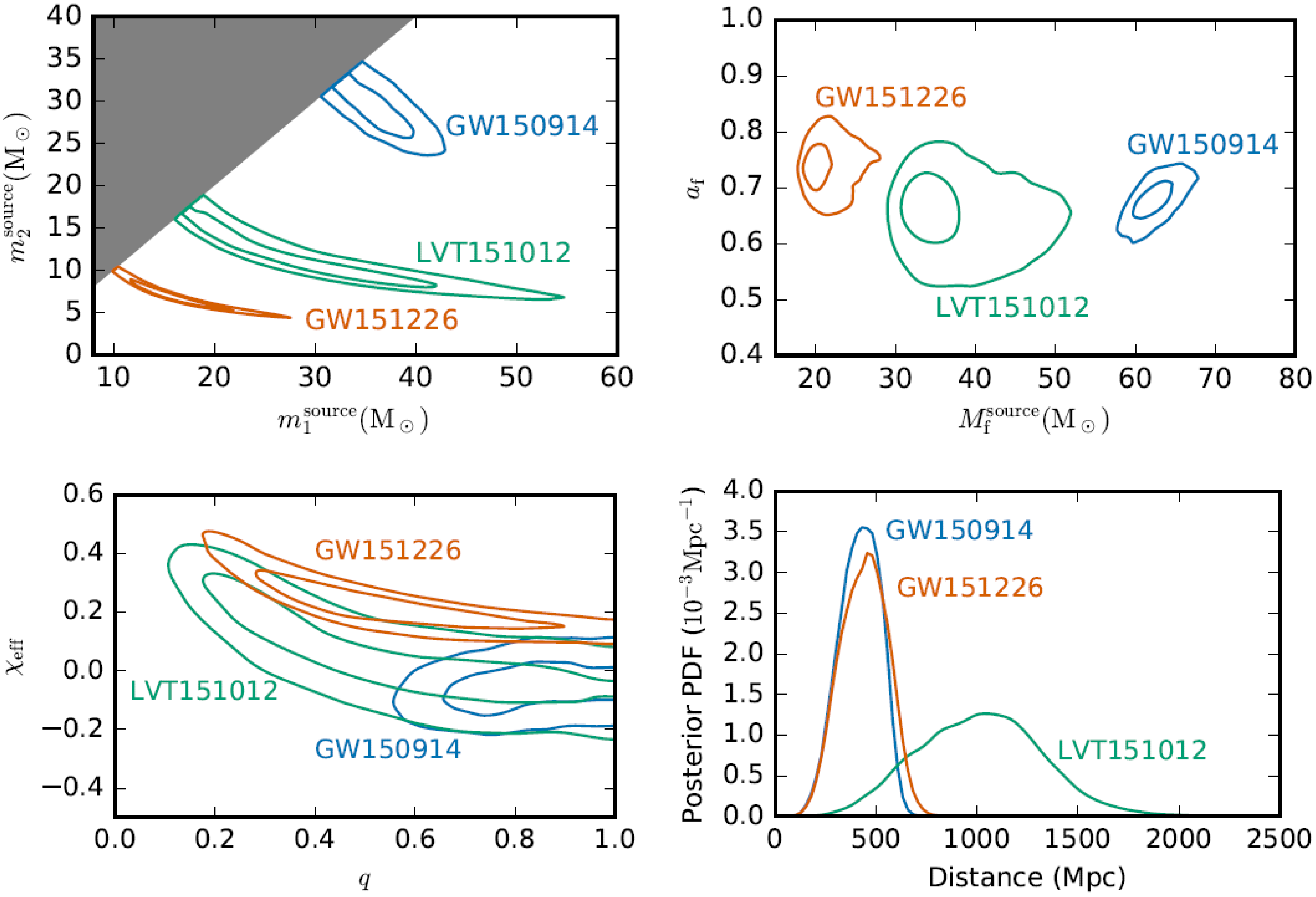
$$\chi_{\mathrm{eff}} = \frac{m_1 \chi_1 + m_2 \chi_2}{M}$$

aLIGO O1 run results



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
Primary mass $m_1/M_\odot$	36.2	14.2	23
Secondary mass $m_2/M_\odot$	29.1	7.5	13
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f/M_\odot$	62.3	20.8	35
Final spin a_f	0.68	0.74	0.66
Lum. distance D_L/Mpc	420	440	1000
Sky localization $\delta S/deg^2$	230	850	1600

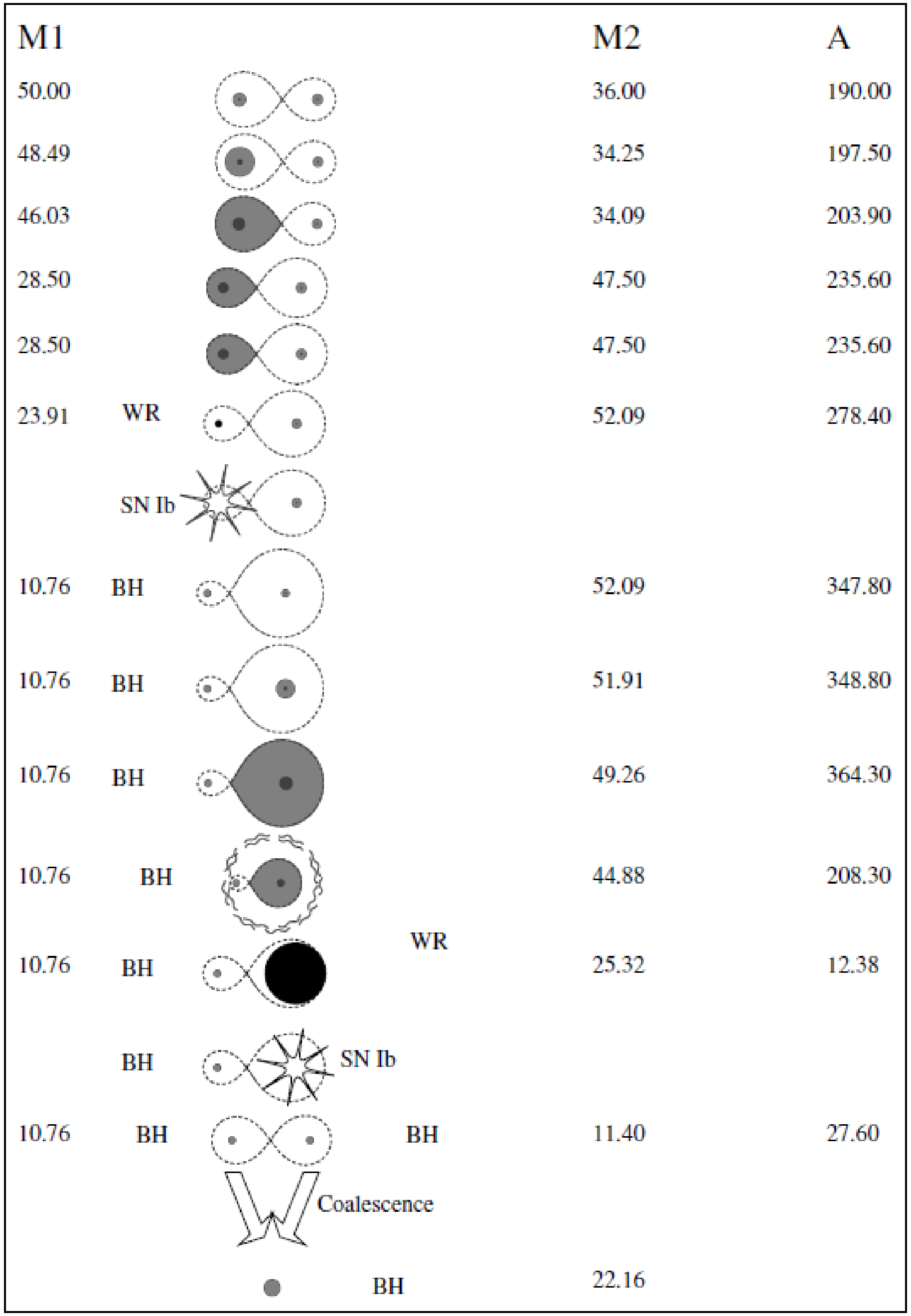
- In LIGO O2 run, 6 new events have been found from on-line analysis (as of April 23, 2017)


40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
$m_2^{\rm source}(\rm M_\odot)$
$m_1^{\rm source}(\rm M_\odot)$
GW150914
LVT151012
GW151226
1.0
0.9
0.8
0.7
0.6
0.5
0.4
$a_{\rm f}$
20
30
40
50
60
70
80
$M_{\rm f}^{\rm source}(\rm M_\odot)$
GW151226
GW150914
LVT151012
0.6
0.4
0.2
0.0
−0.2
−0.4
$\chi_{\rm eff}$
0.0
0.2
0.4
0.6
0.8
1.0
q
GW151226
LVT151012
GW150914
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Posterior PDF $(10^{-3}\rm Mpc^{-1})$
0
500
1000
1500
2000
2500
Distance (Mpc)
GW150914
GW151226
LVT151012

- Can these BH-BH systems be drawn from one distribution or originate from different progenitors?

Astrophysics

- **Stellar evolution channels**:
  - – From massive binary systems (Tutukov, Yungleson 73, Lipunov, PK, Prokhorov 87, 97…Fryer+ 02, Kinugawa+ 14,16, Belczynski+16, Eldridge&Stanway 16…)
  - – Dynamical formation in dense globular clusters (Sigurdsson, Hernquist 1993…Rodriguez+16)
- **Primordial BH binaries** (Nakamura+97, Ioka+, Sasaki+16, Eroshenko 16, Blinnikov+ 16)



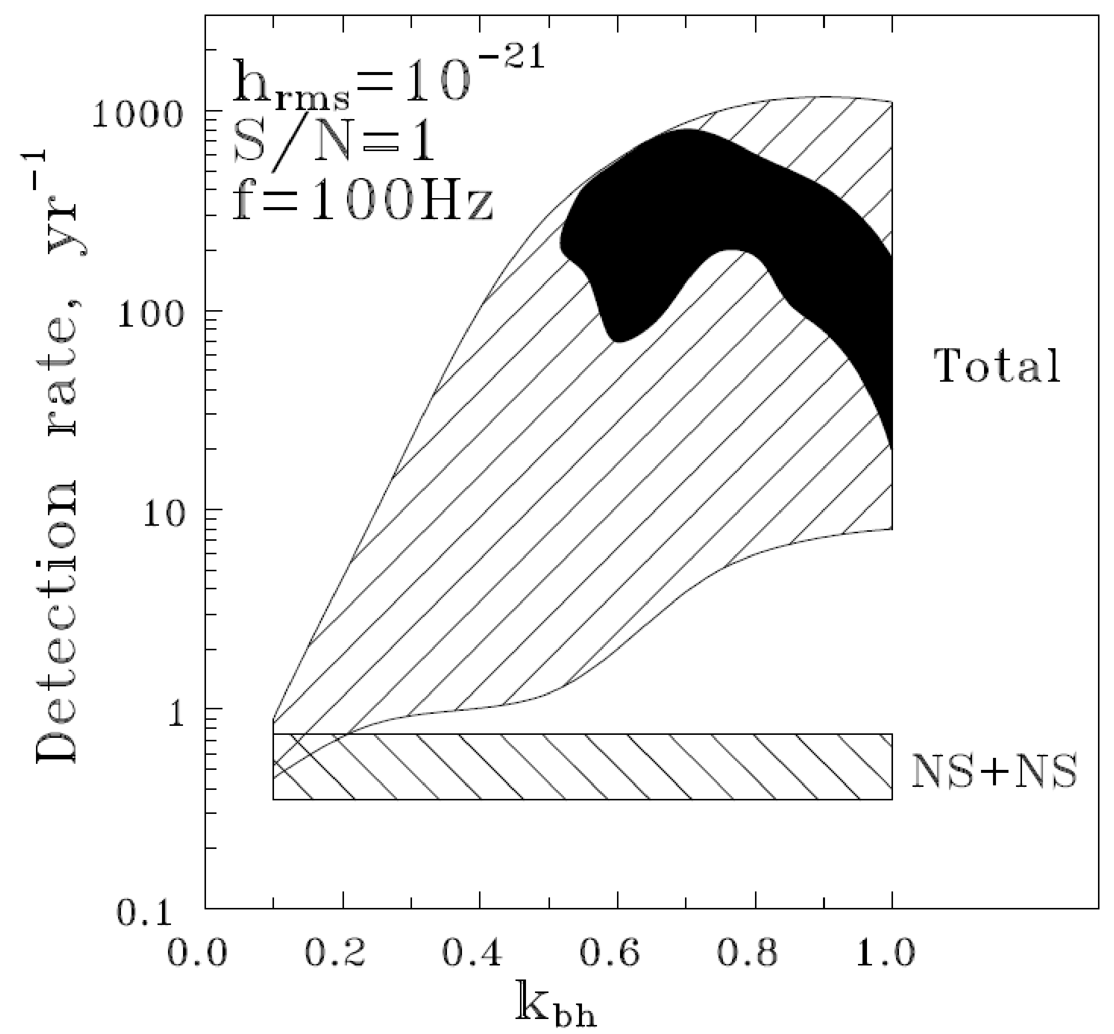
- **BH formation parameters**
  - initial mass (>20 $M_\odot$)
  - Collapsing mass fraction

$$k_{BH} = M_{BH}/M_*$$

  - Possible BH kick velocity

$$\frac{w_{BH}}{w_{NS}} = \frac{M_* - M_{BH}}{M_* - M_{OV}} = \frac{1 - k_{BH}}{1 - M_{OV}/M_*}$$

Lipunov PK Prokhorov 1987 MNRAS)



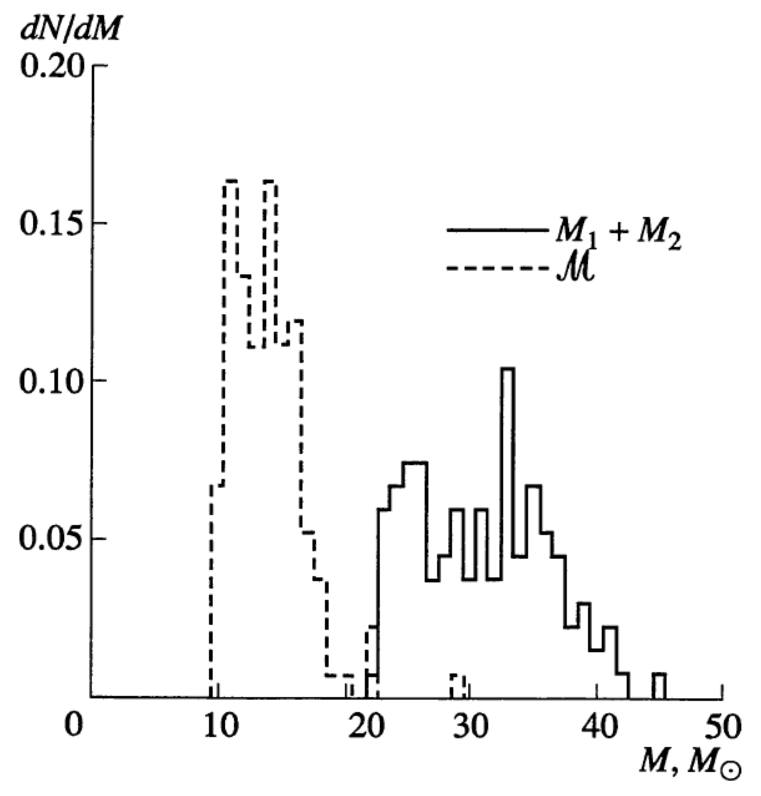


Fig. 4. The distributions of the total mass and the "chirp mass" for merging binary black holes for $M_* = 35M_\odot$ and $k_{bh} = 0.3$ and for a Lyne–Lorimer velocity distribution with $w_0 = 400$km s^{-1}.

Lipunov, PK. Prokhorov, 1997 Ast. Lett, MNRAS, New Astronomy

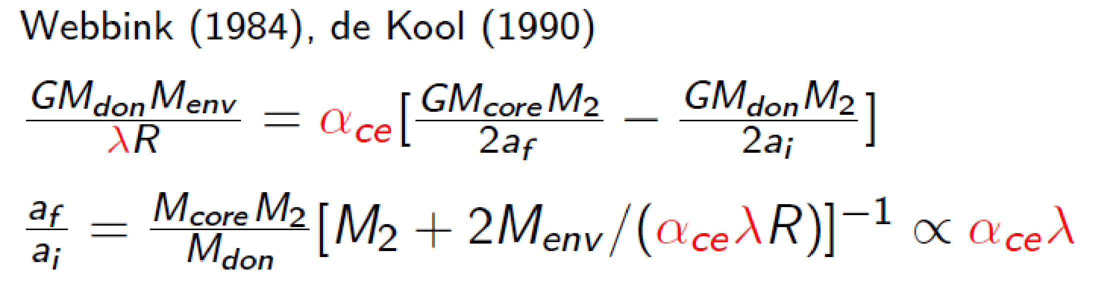
Major uncertainties

- BH formation parameters
  - mass-loss of progenitors (small at low metallicity)
  - Mass of the BH formed (tuned to produce required BH mass), additional kick…

- Binary evolution parameters
  - Non-conservative stages (common envelop treatment…)

Common envelope

- Compare binding energy of stellar envelope and orbital energy:

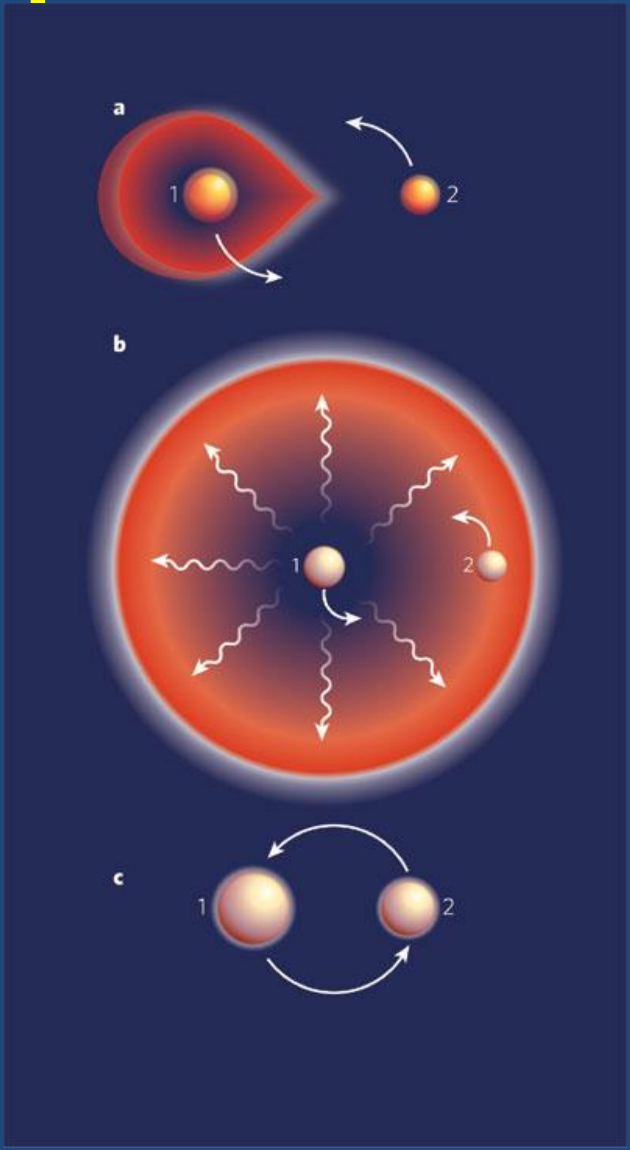


Webbink (1984), de Kool (1990)

$$\frac{GM_{don}M_{env}}{\lambda R} = \alpha_{ce}\left[\frac{GM_{core}M_2}{2a_f} - \frac{GM_{don}M_2}{2a_i}\right]$$

$$\frac{a_f}{a_i} = \frac{M_{core}M_2}{M_{don}}[M_2 + 2M_{env}/(\alpha_{ce}\lambda R)]^{-1} \propto \alpha_{ce}\lambda$$

- Hydro calculations give controversial results (Ohlman+16)



Metallicity effects

- No strong mass loss when low metal abundance ➔ higher BH mass

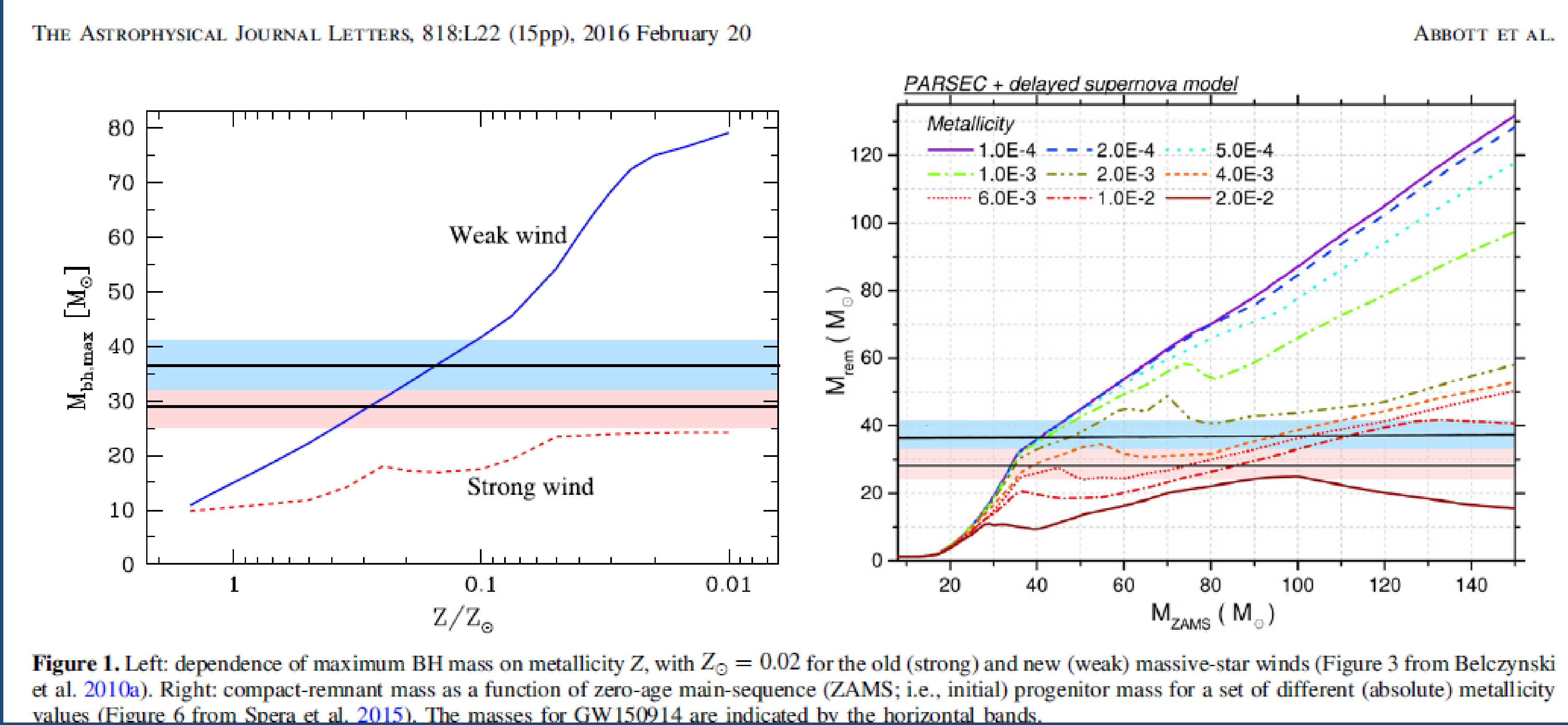


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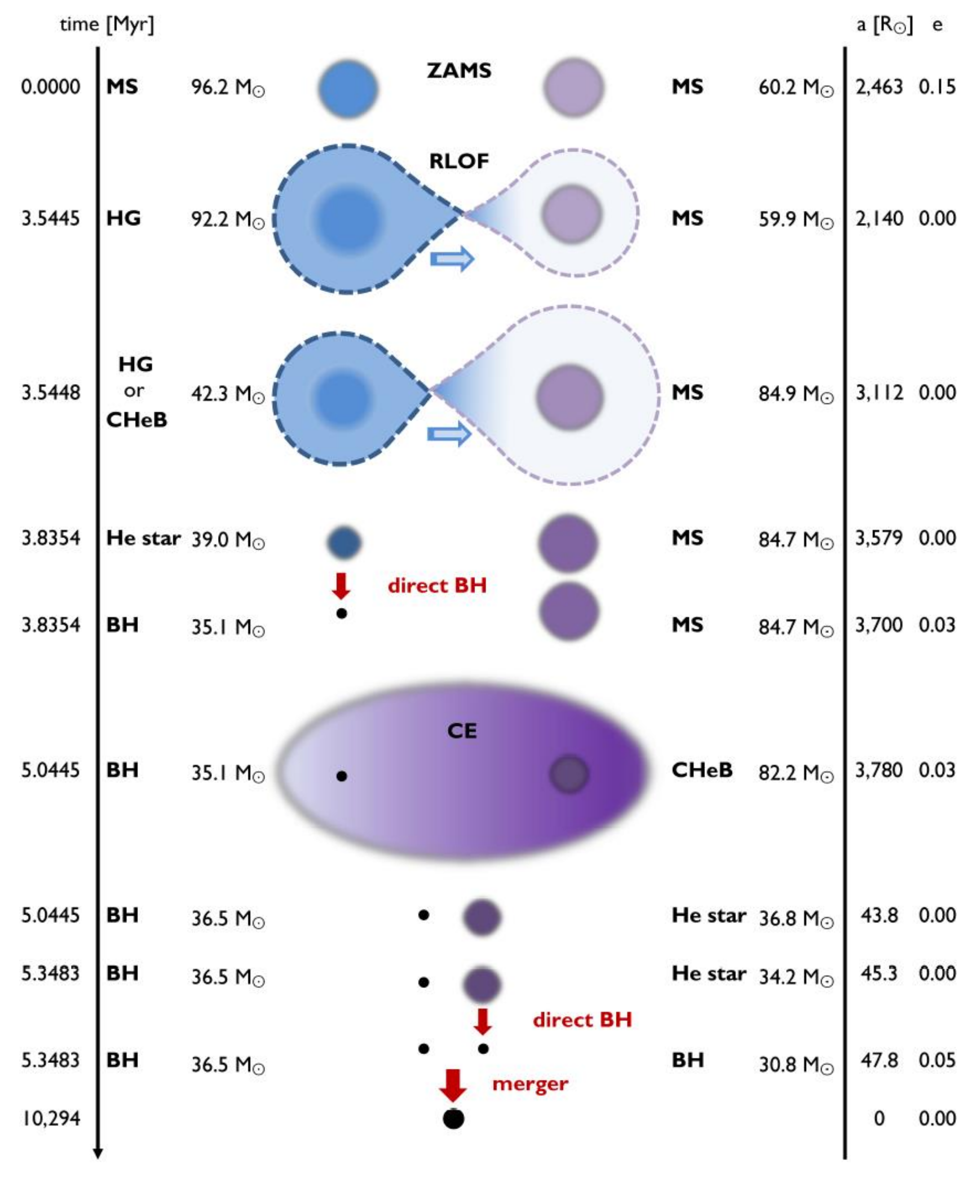
Figure 1. Left: dependence of maximum BH mass on metallicity Z, with $Z_\odot = 0.02$ for the old (strong) and new (weak) massive-star winds (Figure 3 from Belczynski et al. 2010a). Right: compact-remnant mass as a function of zero-age main-sequence (ZAMS; i.e., initial) progenitor mass for a set of different (absolute) metallicity values (Figure 6 from Spera et al. 2015). The masses for GW150914 are indicated by the horizontal bands.

Standard binary scenario for GW150914



- <0.1 solar metallicity
- 40-100 $M_\odot$
- No SN explosion
- Common envelope
- Original spin directions

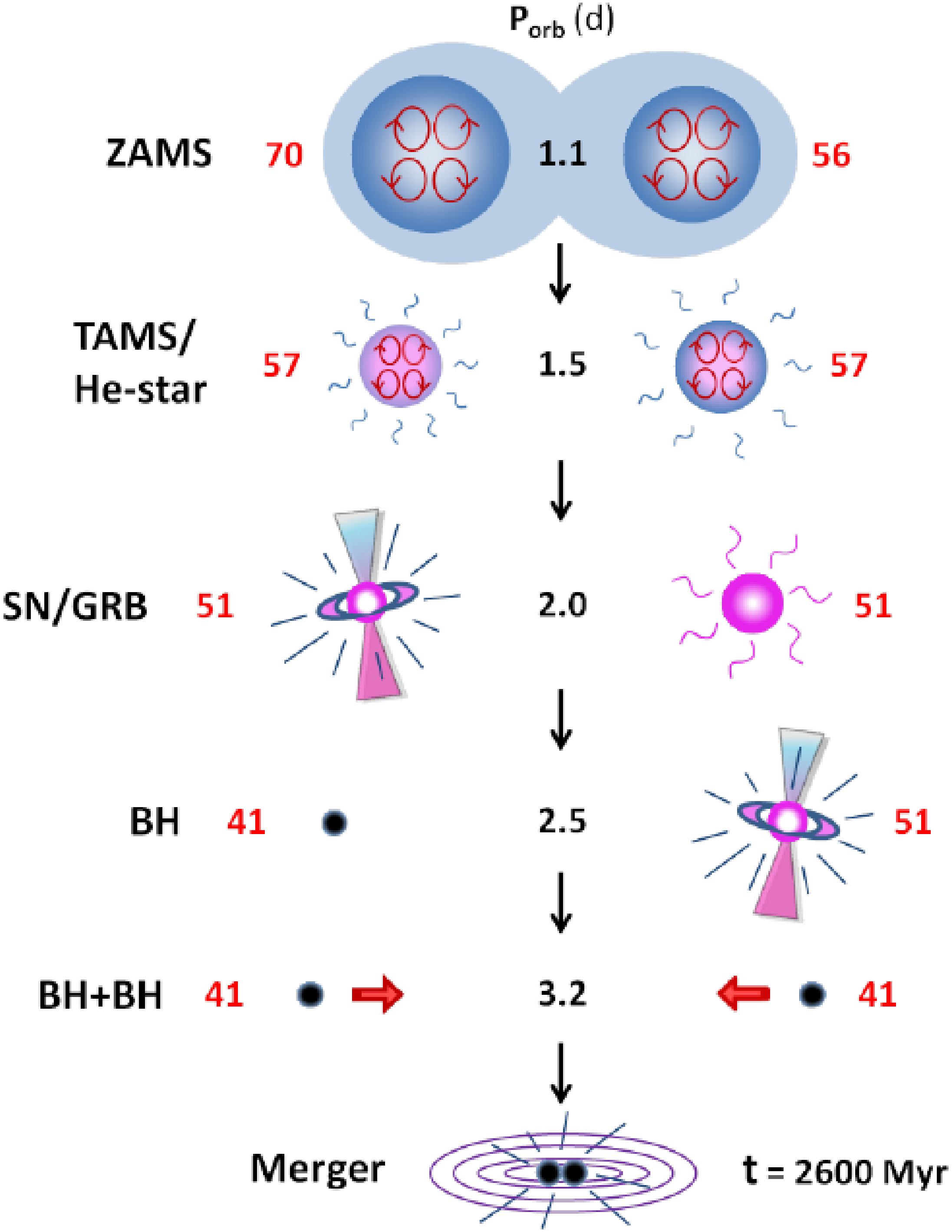
Belzcynski+ 2016

Problems in binary formation scenario

- BH components should have substantial rotation before merging, which is not observed in GW150914 (see also Kushnir+16)
- PopIII low-metallicity stars may be subdominant channel of GW150914 formation (Hatrtwig+16, Dvorkin+ 16)

Can CE be avoided?

- Yes, at the expense of fast rotation leading to quasi-homogeneous evolution (Marchant+16, Mandel & deMink 16)



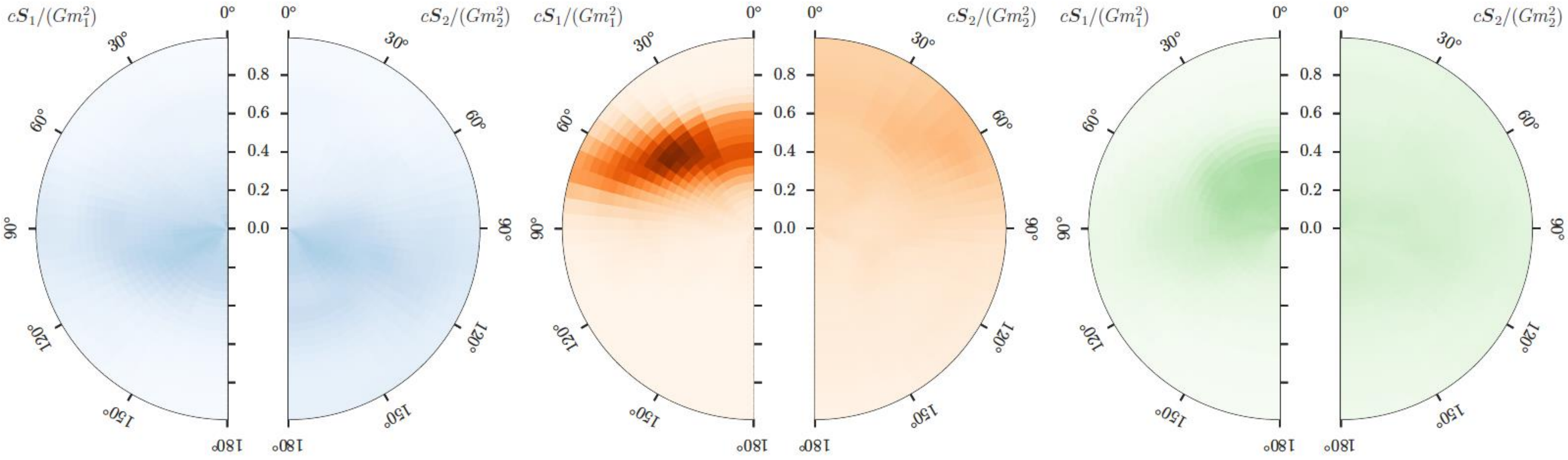
New scenarios (fast rotation and chemically homogeneous evolution to avoid uncertain common envelope stage

arXiv:1601.03718

- But rapid rotation of BH remnant cannot be avoided
- Or substantial kick velocity during BH formation should be assumed to have small BH spin projections onto orbital angular momentum

BHs in GW150914 had (almost) zero spins prior to merging

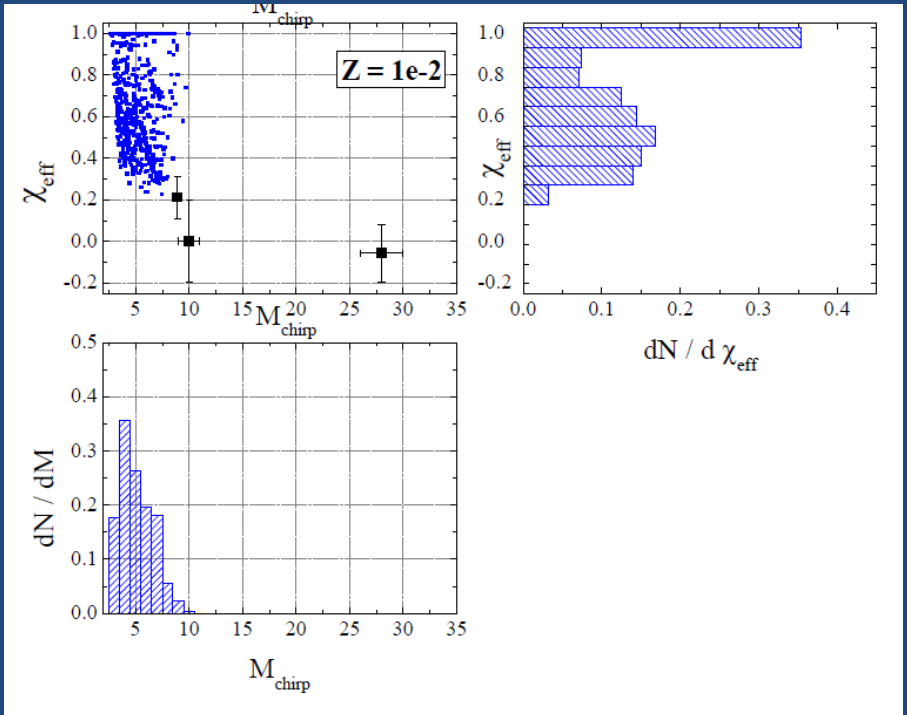
Spins

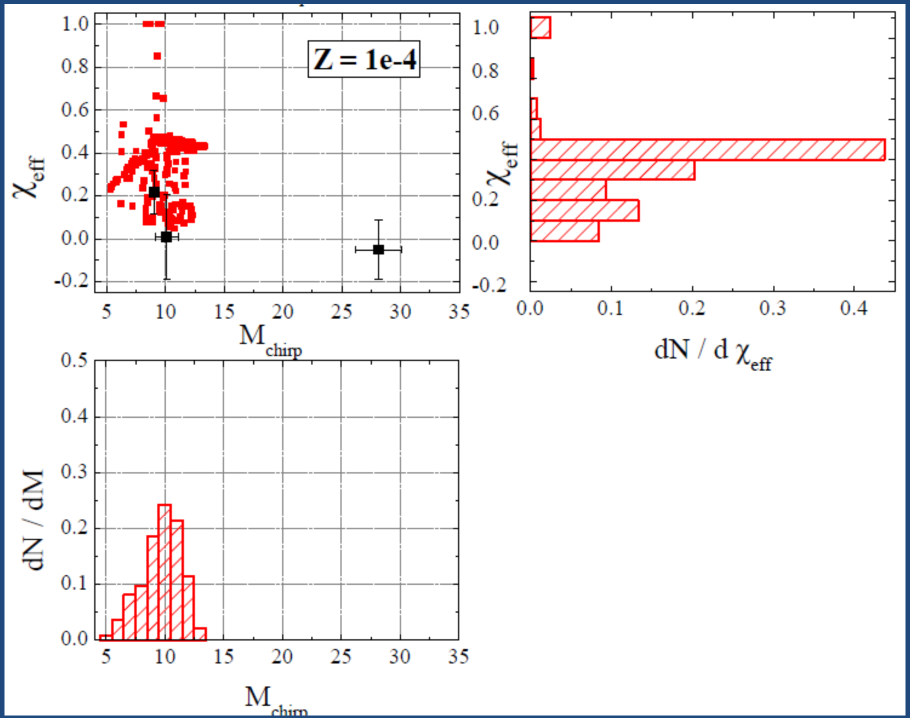


GW150914, GW151126, LVT151012

Credit: S.Babak, for LIGO collab.

Evolution of stars with solar abundance cannot produce massive BH



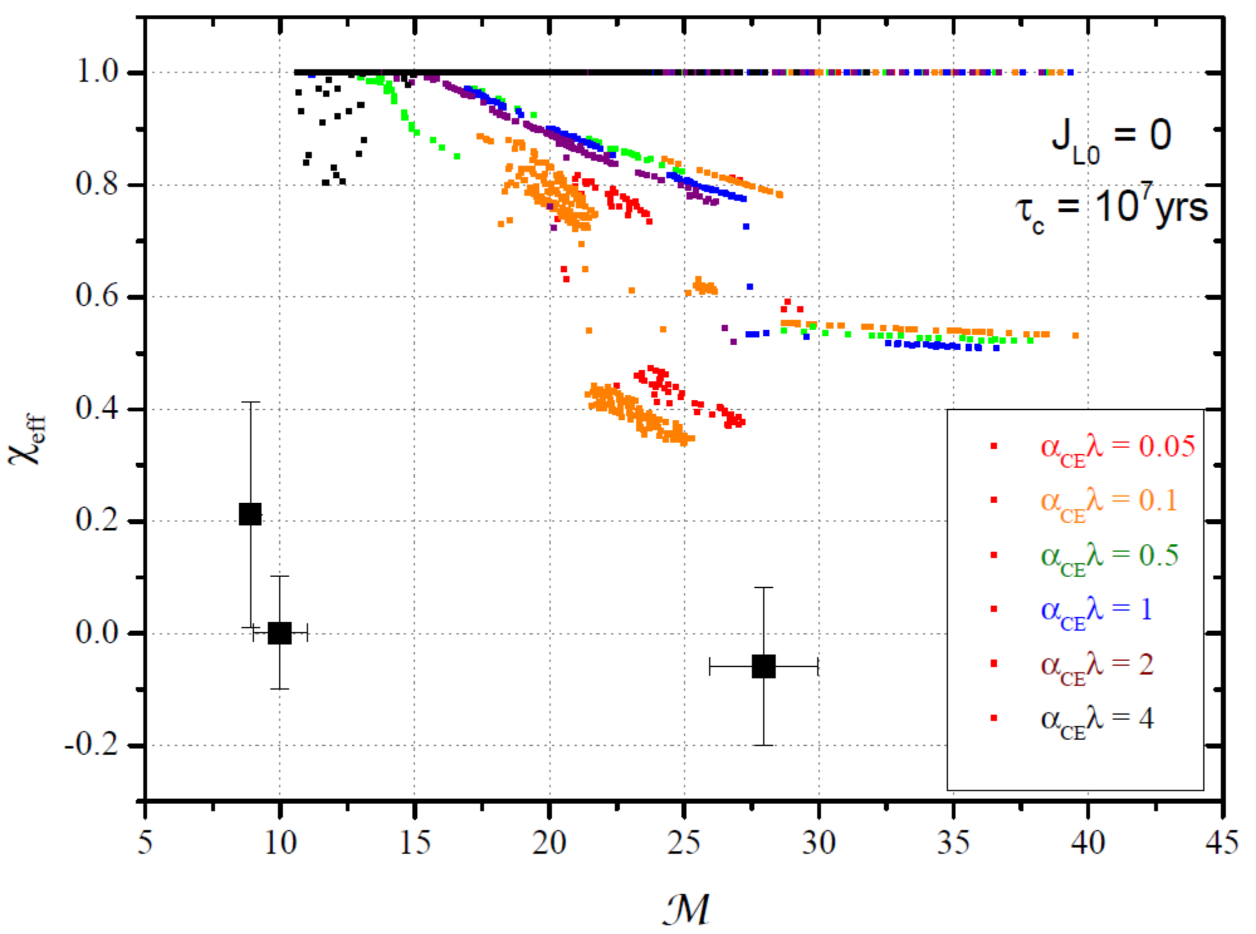


PK, Kuranov 1702.08056

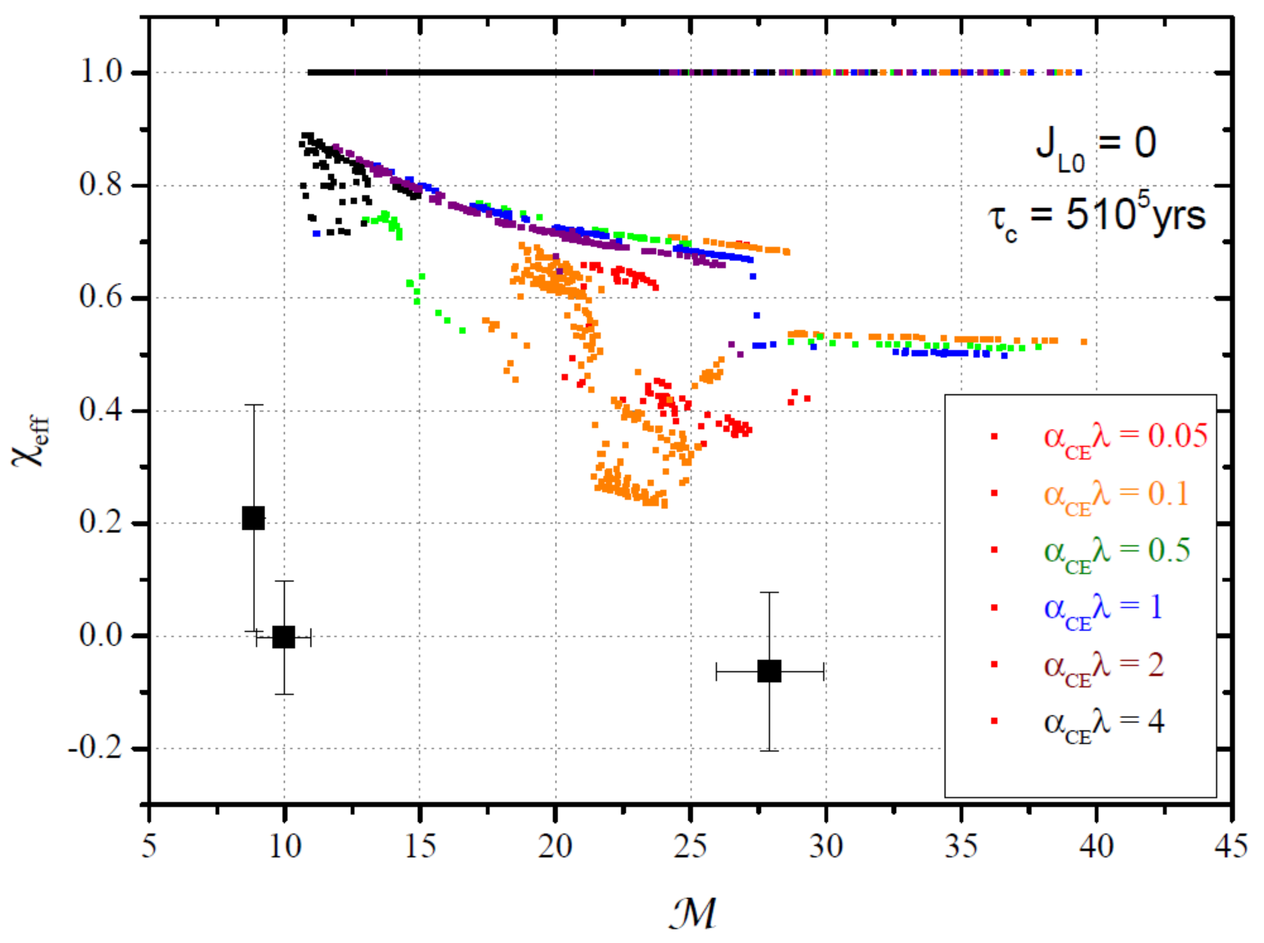
Evolution of stars with zero metal abundance (primordial, PopIII stars) can produce massive BH

- Under assumptions that
  - (i) All mass of the pre-collapse star goes into BH
  - (ii) Common envelope stage is very effective
  - (iii) Core-envelope rotation coupling is very strong

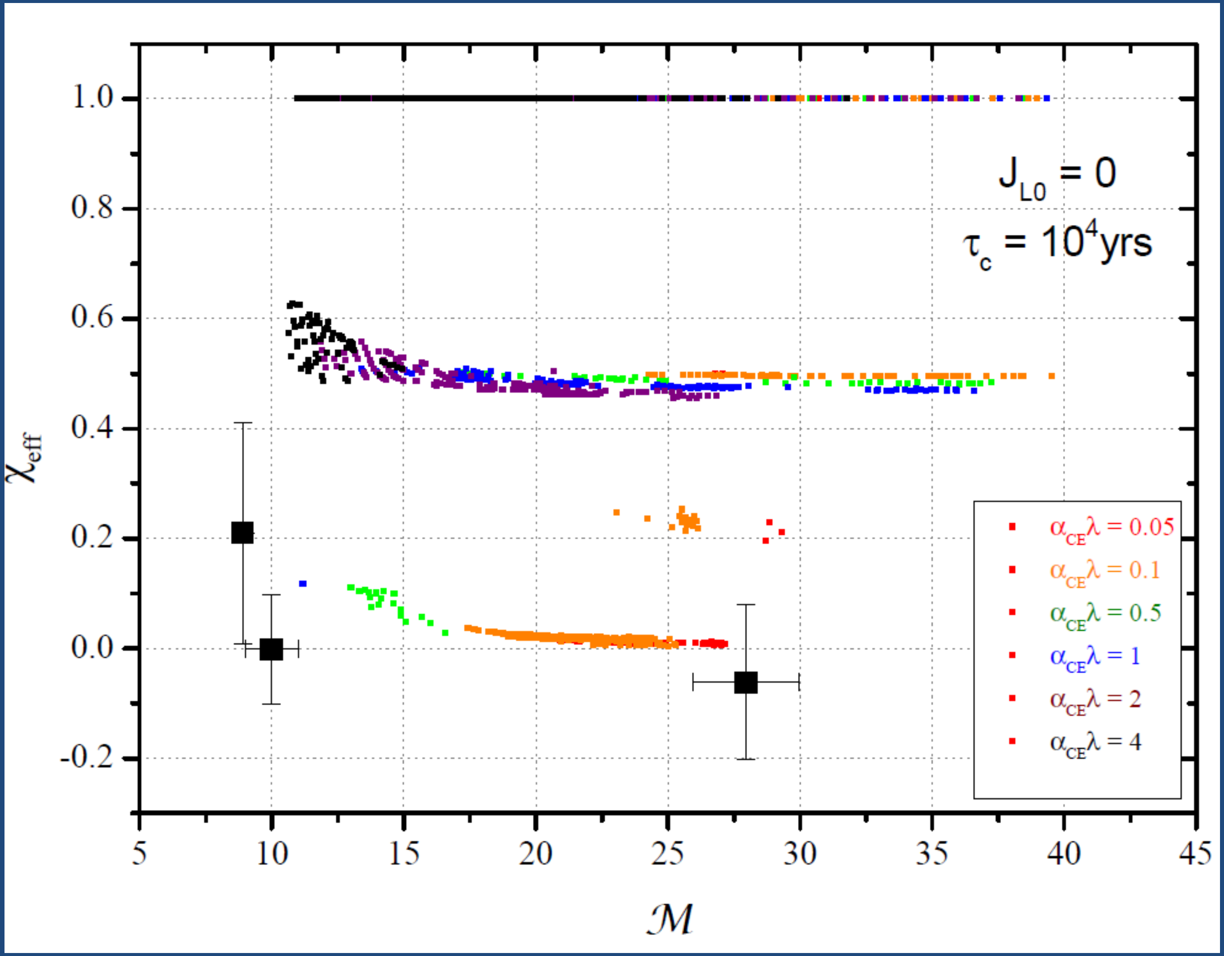
Weak core-envelope coupling



Moderate core-envelope coupling



Strong core-envelope coupling



Viable alternatives/complementary channels

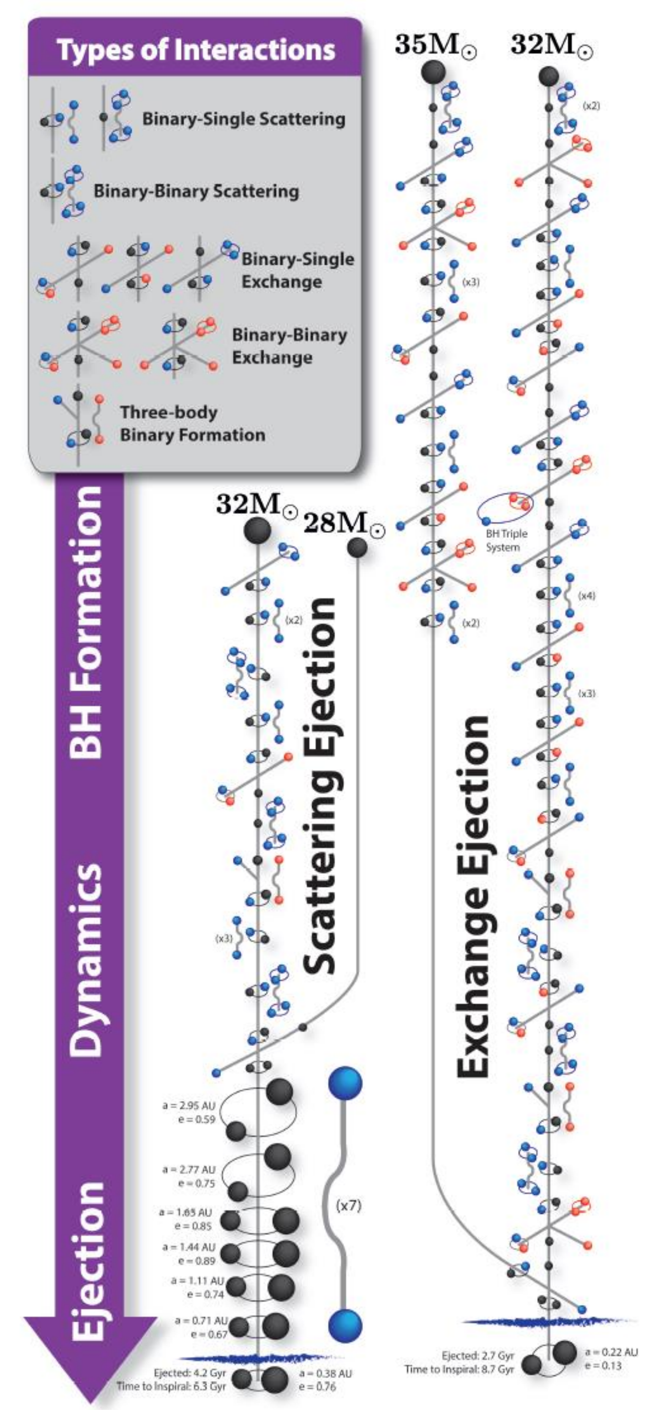
- Dynamical formation in globular clusters
- Primordial binary black holes

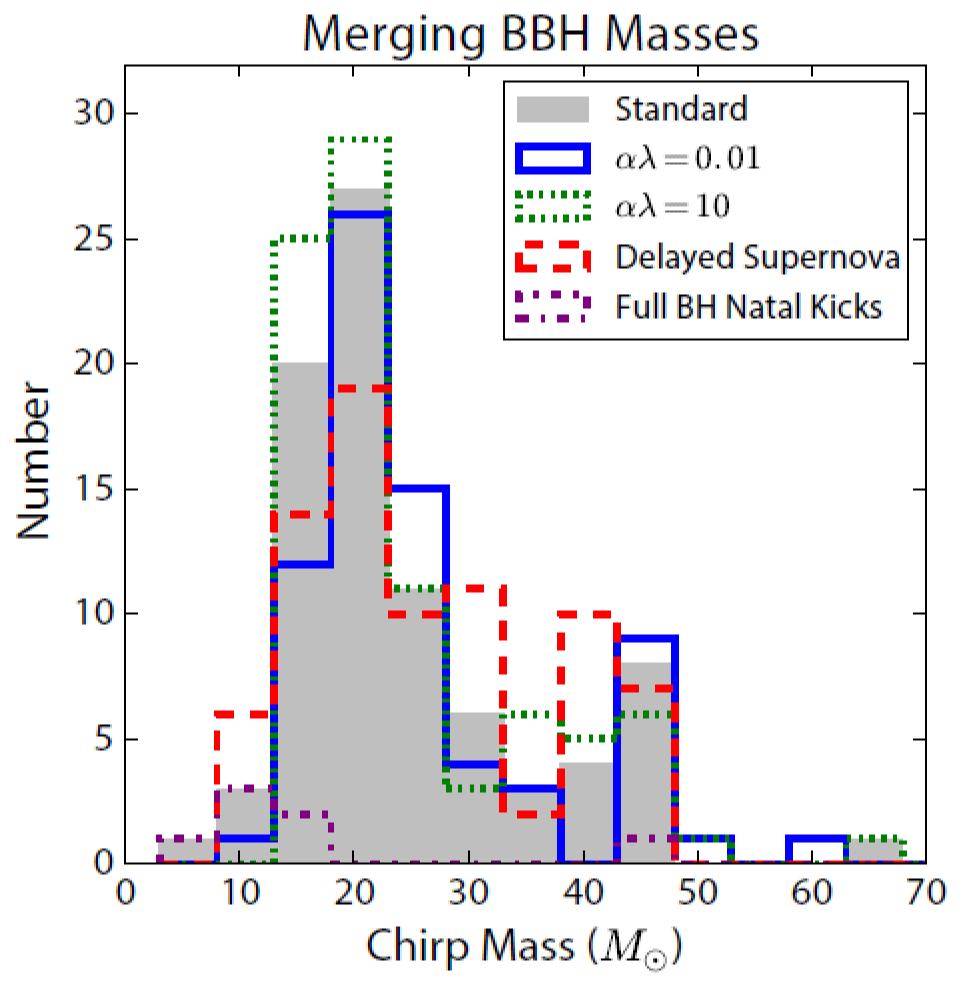
Schwarzschild (almost) BH can be formed → no problem with angular momentum excess

Dynamical BBH formation in globular clusters

- Globular clusters formed @ z=3.5
- M_{gc}=3-5 x 10^5 $M_{\odot}$
- Low-metallicity 0.01-0.05 of Z_{solar},
- Dynamical interactions lead to BBH formation and ejection from the cluster

Rodriguez+ 16





Rodriguez+ 16

Primordial BHs

- Can form in the early Universe (Carr, Hawking 74) and significantly contribute to DM
- Can be seeds for early galaxy formation
- Can form merging binary BHs (Nakamura+ 97)
- GW150914 can be a PBH (Bird+ 16, Blinnikov, Dolgov, PK, Porayko 16…)

Can a universal PBH mass distribution be responsible?

Particular model: primordial BH in the modified supersymmetric baryogenesis scenario (Affleck-Dine mechanism)

- Dolgov + (1993, 2009): inflation field coupled with renormalizable scalar baryon field

$$U(\chi,\Phi) = U_\Phi(\Phi) + U_\chi(\chi) + \lambda_1(\Phi - \Phi_1)^2|\chi|^2,$$

- High-B bubbles with almost model-independent mass distribution

$$\frac{dn}{dM} = C\exp\left[-\gamma\ \ln^2(M/M_{\max})\right]$$

- Small-scale B –number fluctuations originally are isocurvature perturbations, but after QCD phase transition @ 100-200 MeV are transformed into large density perturbations at astrophysically large but cosmologically small scales (Dolgov, Silk, **PRD47 (1993) 4244**)

- High-B bubbles could form **primordial BHs**, compact stellar-mass objects or dense primordial gas clouds. Primordial BHs can be seeds for early galaxy formation (Dolgov+ Nucl.Phys. B807 (2009) 229, Dolgov, Blinnikov PRD89 (2014) 021301)

Estimate of mass distribution

$$\varrho_c = 1.4 \times 10^{11} M_\odot \mathrm{Mpc}^{-3}$$

$$\varrho_m = 4 \times 10^{10} M_\odot \mathrm{Mpc}^{-3}$$

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_{max})\right]$$

$$\mu = \mu_{43} \times 10^{-43} / \ \mathrm{Mpc}$$

(in units c=h=1)

- A. Fraction of DM in MACHOs is 0.1 for mass range 0.1-1 Msun
- B. Primordial BH make up to all cosmological DM
- C. Density of primordial BH with M> 10^4 = density of observed large galaxies

Total energy density in the mass range M_1, M_2:

$$\varrho(M_1, M_2) = \mu^2 \int_{M_1}^{M_2} dM\, M \exp\left[-\gamma \ln^2\left(\frac{M}{M_{max}}\right)\right]$$

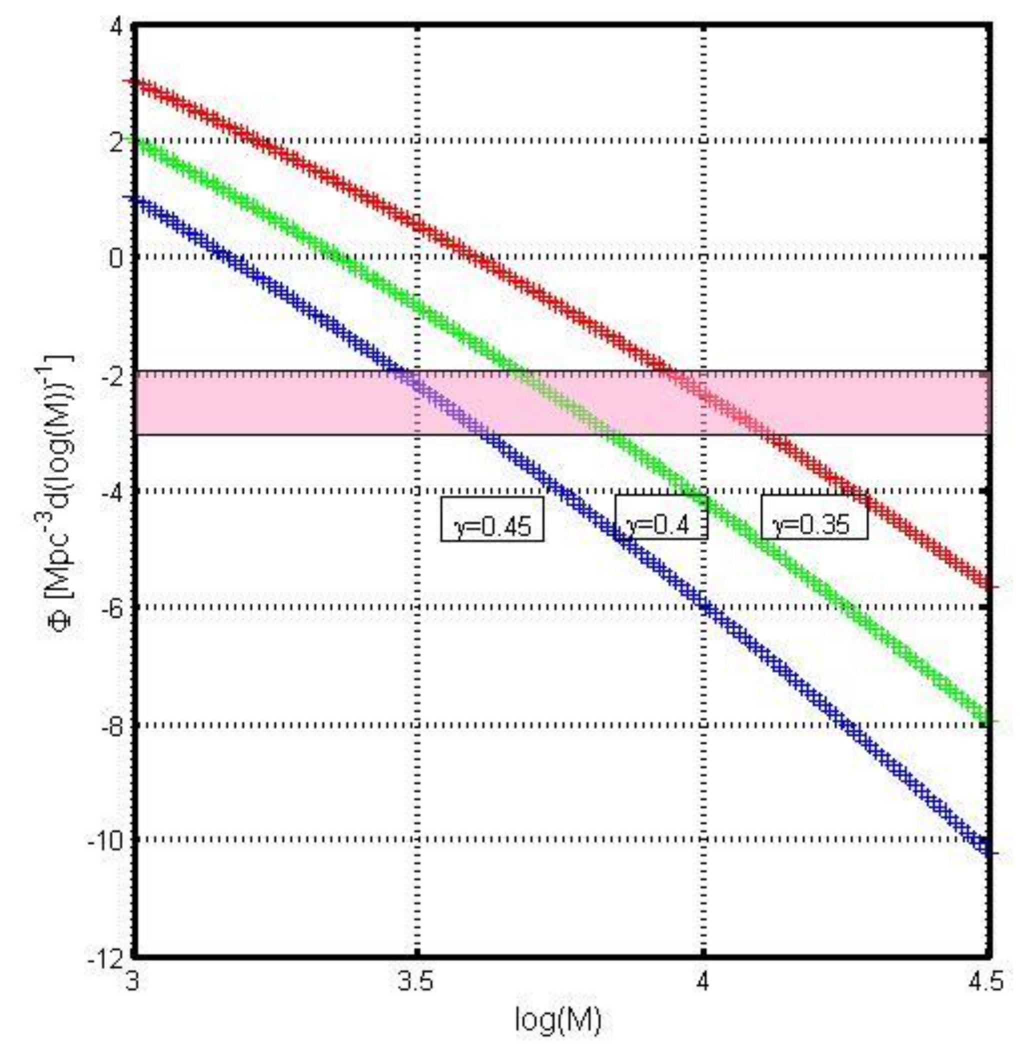
$$= 1.75 \cdot 10^9 \mu_{43}^2 M_\odot/\mathrm{Mpc}^3 \int_{x_1}^{x_2} dx\, x e^{-\gamma \ln^2(x/y)}$$

(A) holds independently of μ_{43} if $y \approx \gamma + 0.1\gamma^2 - 0.2\gamma^3$

MACHO fraction $r = \varrho(0.1, 1)/\varrho(0.01, 10^7)$ 0.1 → $\gamma = 0.4 - 1.6$

(B) $\Omega_{pbh} = \Omega_{dm}$ holds if $\mu_{43}^2 = 6$

(A)+(B) → (C) can be satisfied



- Space density of massive PBH with M> $10^4 M_\odot$
- Total PBH mass is normalized to 1/6 Ω_m

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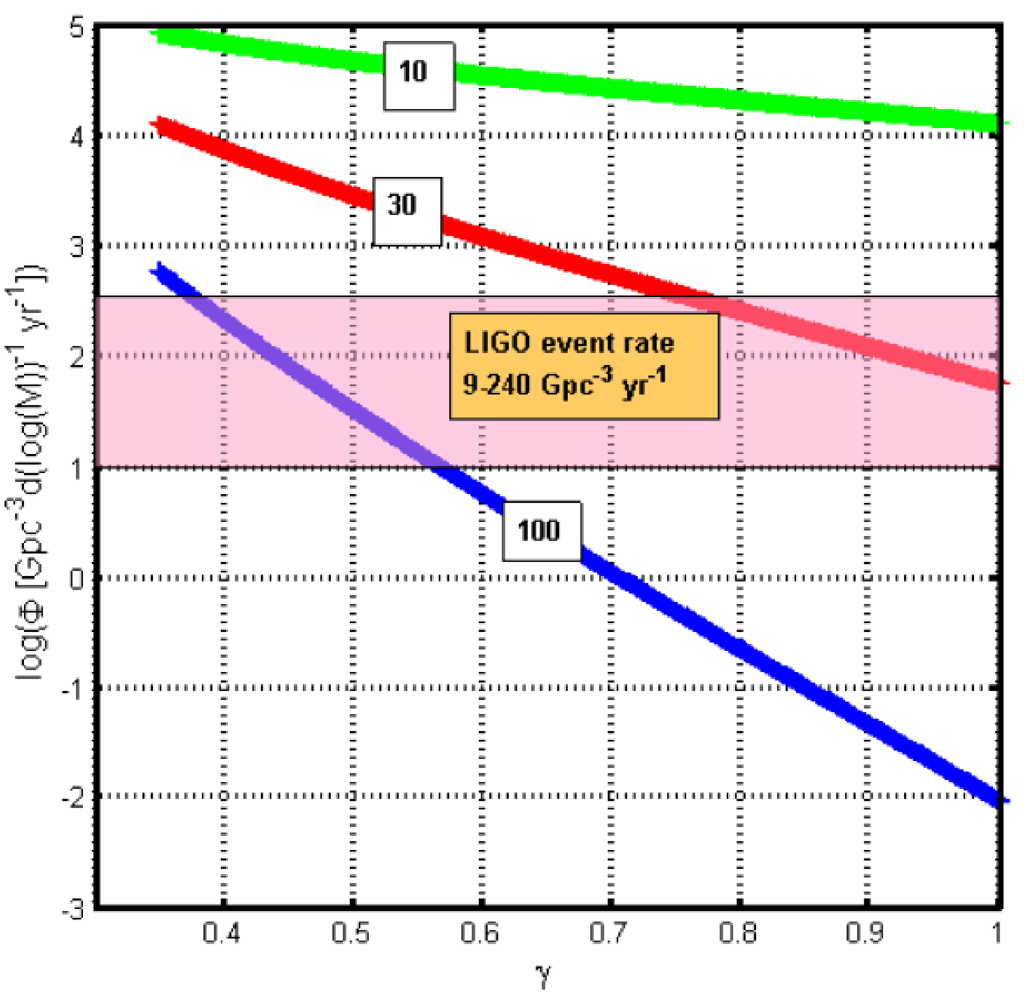
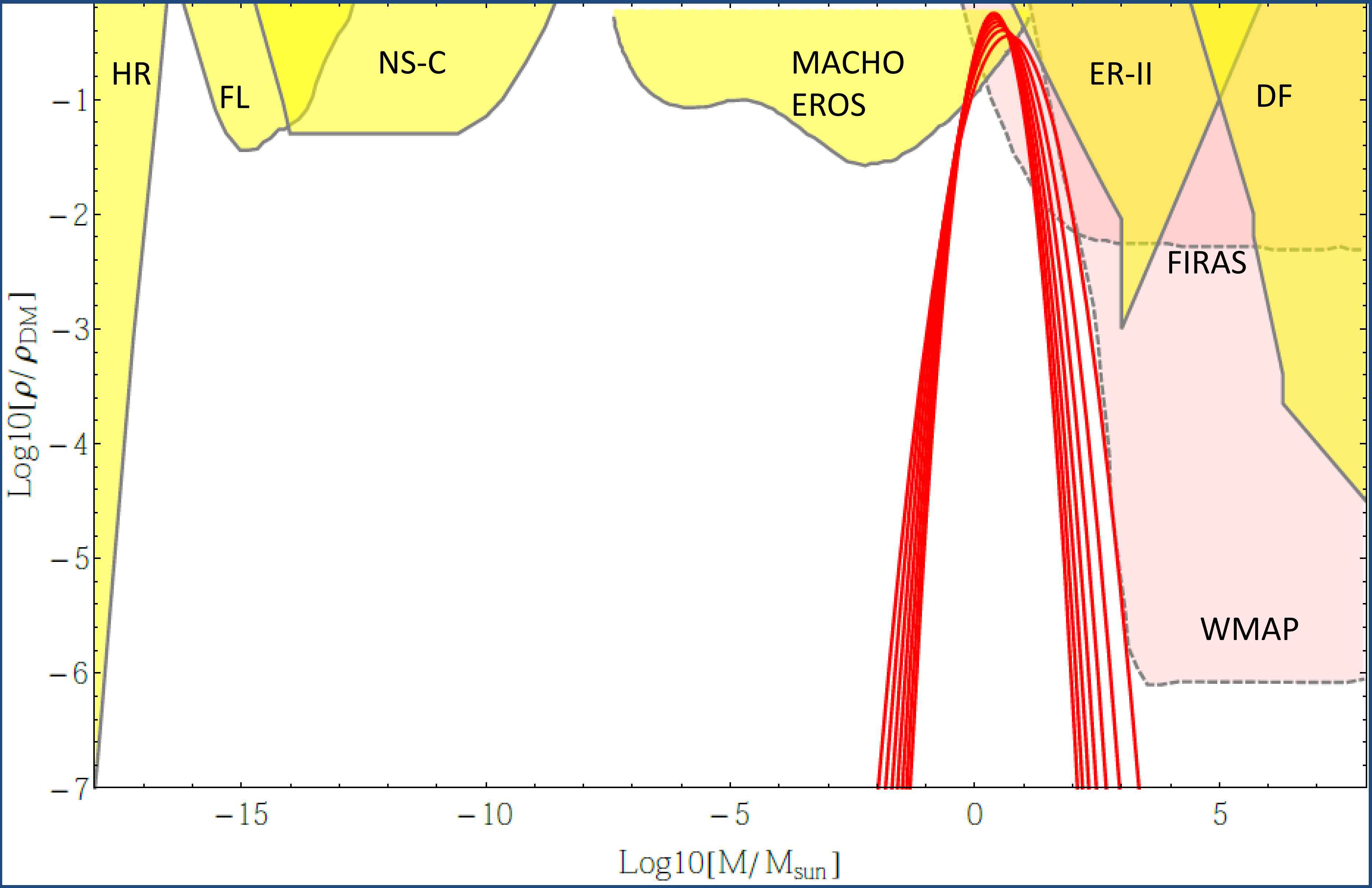
Merging rate of binary BH ($1/\mathrm{Gpc}^3/\mathrm{yr}$) per logarithmic mass interval over the universe age. The observed LIGO event rate is shown by the purple rectangle.



- GW150914
- 10-100 $M_\odot$



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Testable predictions

- Specific PBH mass spectrum peaked at a few – 10 $M_\odot$. Massive PBH ($>10^4$ $M_\odot$) as seeds of inverted galaxy formation (Dolgov, Silk 94, Dolgov+ 08, Bosch+ 12, etc.)
- Low spins (as in GW150914)
- Specific demographics: association with low-mass galactic halos where the binary PBH formation is dynamically favored (Bird+ 16)
- No (bright) electromagnetic, neutrino etc counterparts…
- Can be tested in the nearest LIGO observations!

Intermediate mass BHs

Stellar-mass BHs	**Intermediate-mass BHs**	**Supermassive BHs**
3-100$M_\odot$	100-$10^4M_\odot$	10^4 -$10^9M_\odot$
Core collapses	First supermassive stars, dynamical formation in GC	Growth (accretion, mergings) in galaxy centers
X-ray binaries	GC cores, ULX	Galaxy cores, AGNs

Modern SMBH growth simulations:

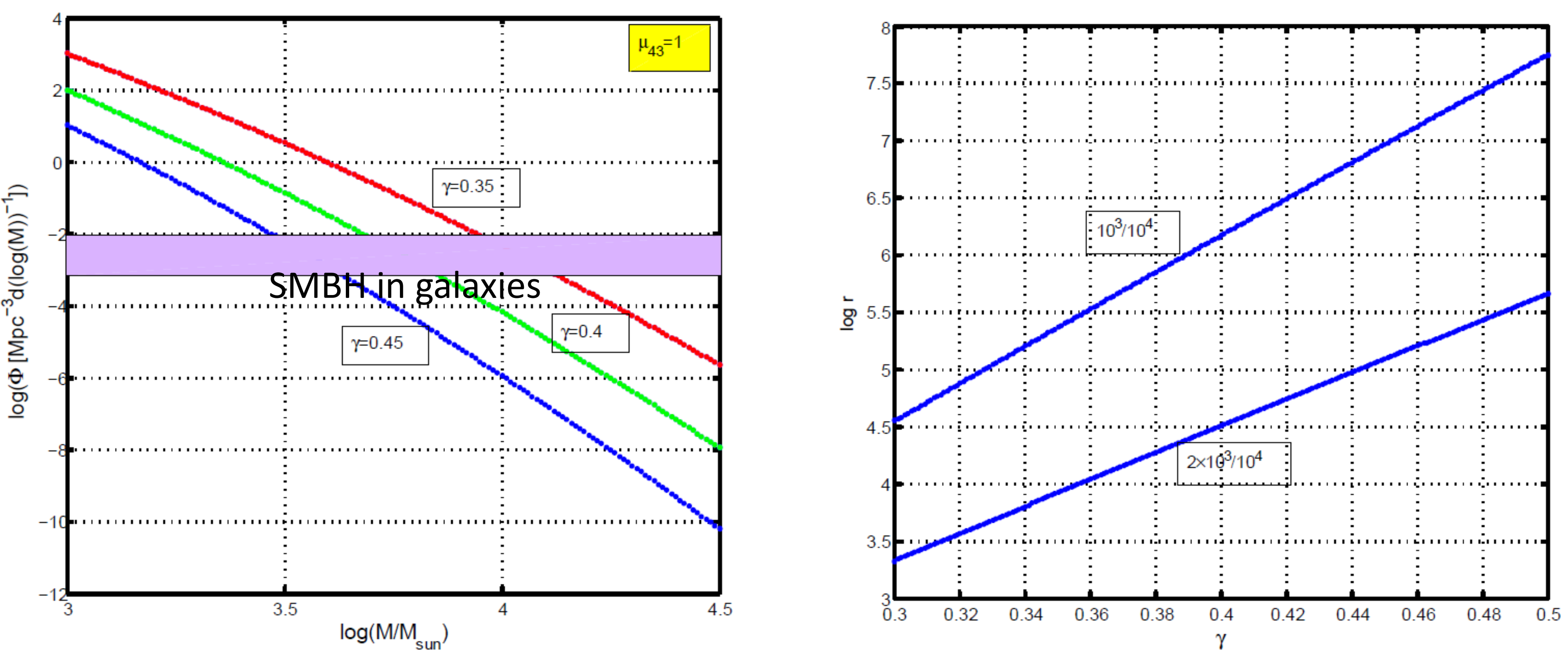
- M_{BH}~10^4-10^5 $M_\odot$ seeds rapidly grow due to gas accretion and galaxy mergings by z~5
- In DM halos <10^{12} $M_\odot$ no significant seed BH growth is observed. In more massive halos BH mass increases rapidly to form self-regulating M_{BH}-M_{DM} halo relation
- Shape of SMBH mass function does not change after z~5
- → primordial BH mass function shape is unimportant for M>10^4 -$10^5 M_\odot$

GC formation

- Globular clusters (GC) are oldest baryonic structures. Have no massive DM halos.
- In standard cosmogony are formed at z~12-5 from baryons filling DM minihalos, $M_b \sim M_h$
- Baryonic structures have initial mass about Jeans mass

$$M_b \sim M_{vir} \sim M_J \approx 10^4 M_\odot \left(\frac{1+z}{10}\right)^{3/2}$$

- At $z>20$ structures with $M<10^4\ M_\odot$ never collapse since $T_{vir} < T_{CMB}$



- If all PBH > 10^4 $M_\odot$ formed SMBH ➔ n_{IMBH} (z=0)~10^2-10^3 Mpc^{-3} ➔ n_{IMBH} (z=10))~10^5-10^6 Mpc^{-3} , comparable to expected DM halo number density with ~10^4 $M_\odot$ in Press-Shechter formalism

- primordial AD IMBHs with mass of a few thousand solar masses can be important additions to the standard paradigm of the early structure formation in the hierarchical cosmogony

Dolgov, PK 2017 JCAP 04 036

Conclusions

- First LIGO events confirm existence of binary BH
- Masses and merging rate can be explained by the standard astrophysical binary massive star evolution, but low (or zero) BH spins of GW150914 require special explanation.
- Dynamical formation in dense globular clusters is not excluded
- Primordial BH mass spectrum in modified Affleck-Dine scenario can explain both observed properties of GW150914, can provide significant fraction of DM, can explain present-day SMBH number density and be seeds of early globular cluster formation
- Increasing statistics of binary BH mergings can be used to test (constrain) PBH hypothesis

Bright future for GW astronomy!