

Madrid 2016 Cosmology with 21 cm Surveys,
Cosmic Microwave Background and Large Scale Structure

Gravitational waves from Massive Primordial Black Holes as Dark Matter

based on S. Clesse & JGB, arXiv:1603.05234
S. Clesse & JGB, Phys Rev D92 (2015) 023524
JGB, Linde & Wands, Phys Rev D54 (1996) 6040



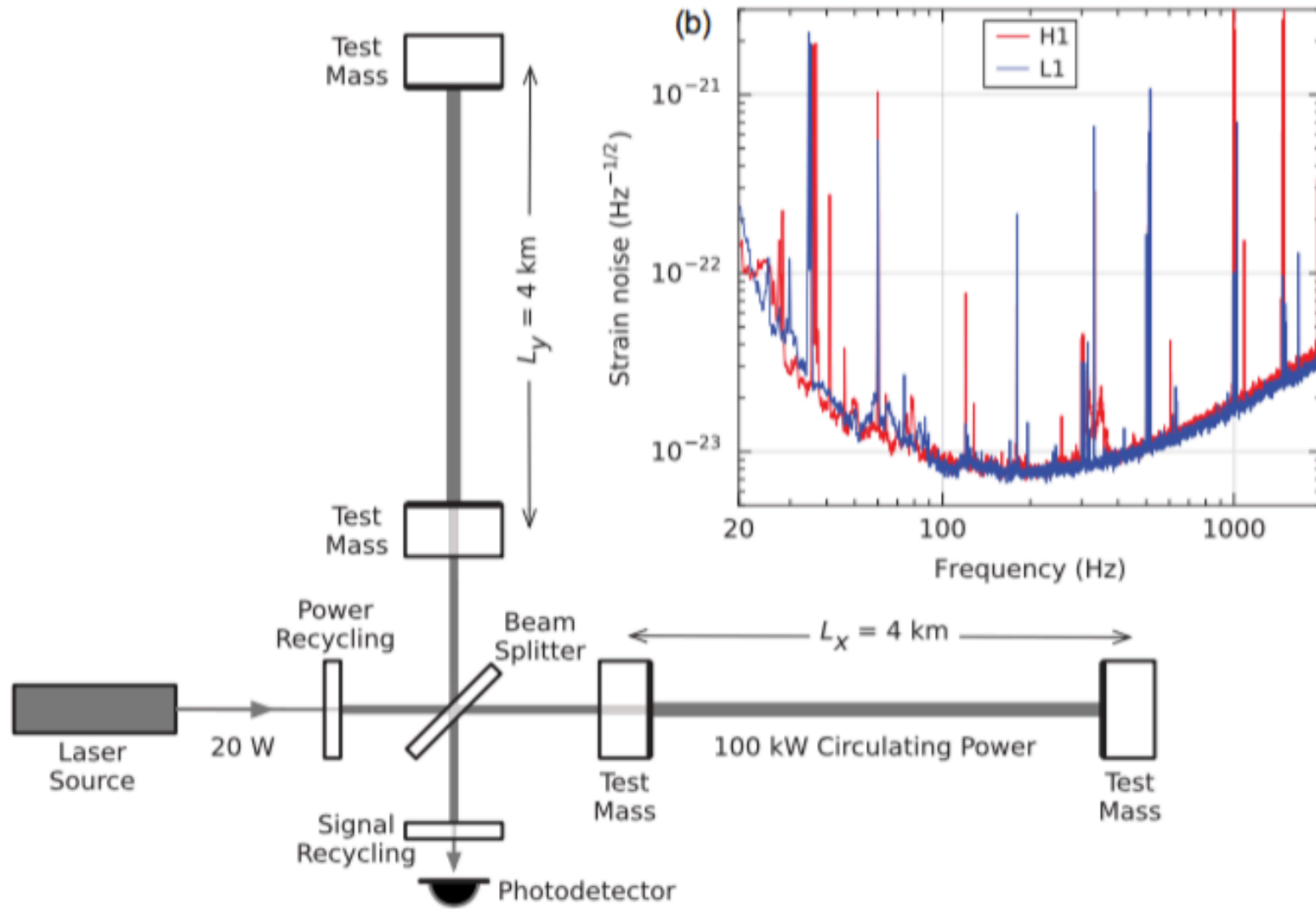
Juan García-Bellido
28th June 2016

Outline

- Discovery of 3 binary BH by aLIGO starts a new era of GW Astronomy
- Massive PBH could be the main component of Dark Matter
- Specific signatures of PBH
- Future: Testing the idea with cosmological observations
- Conclusions

Gravitational Wave Astronomy

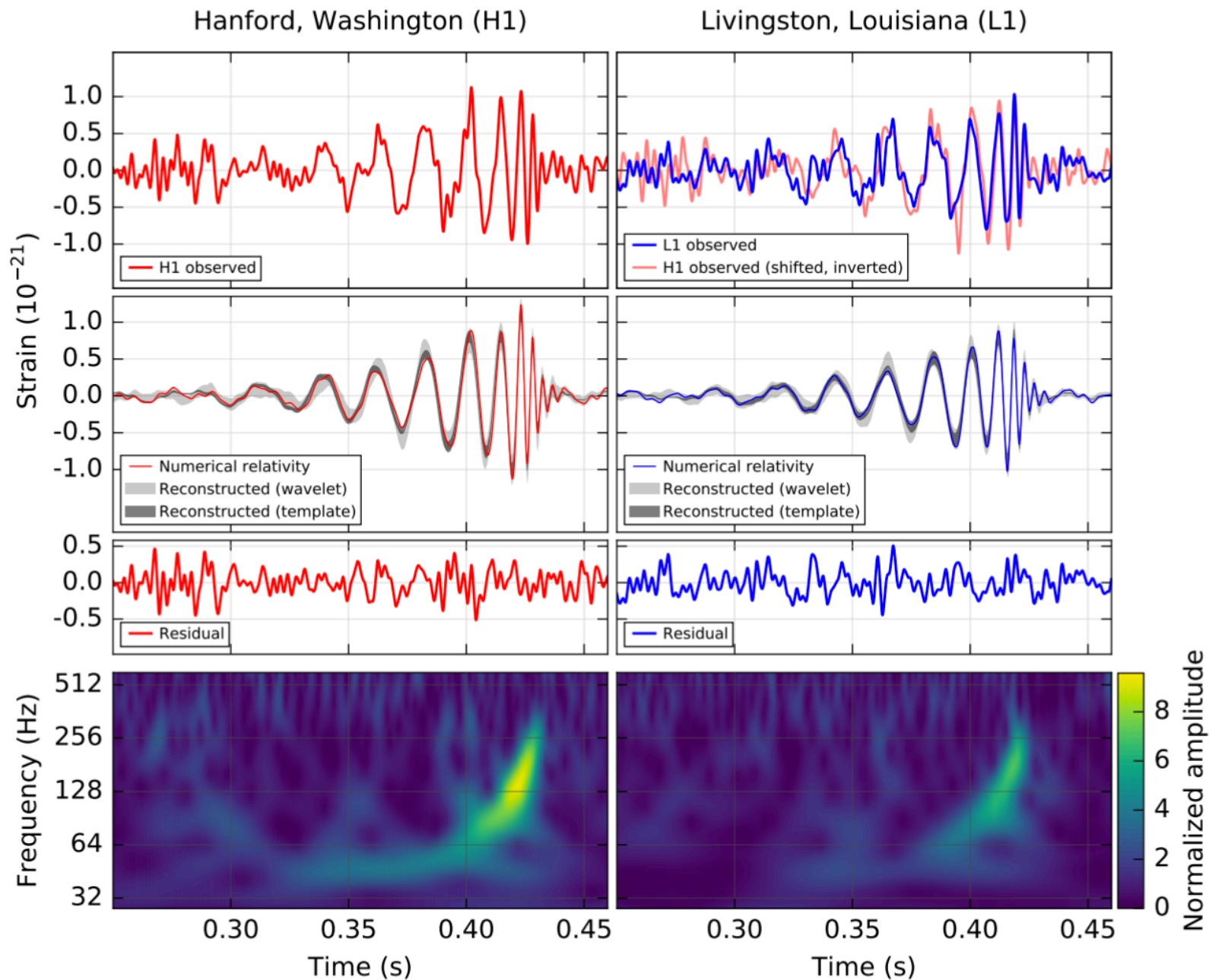
New Telescopes = Interferometers



aLIGO Collab. (2016)

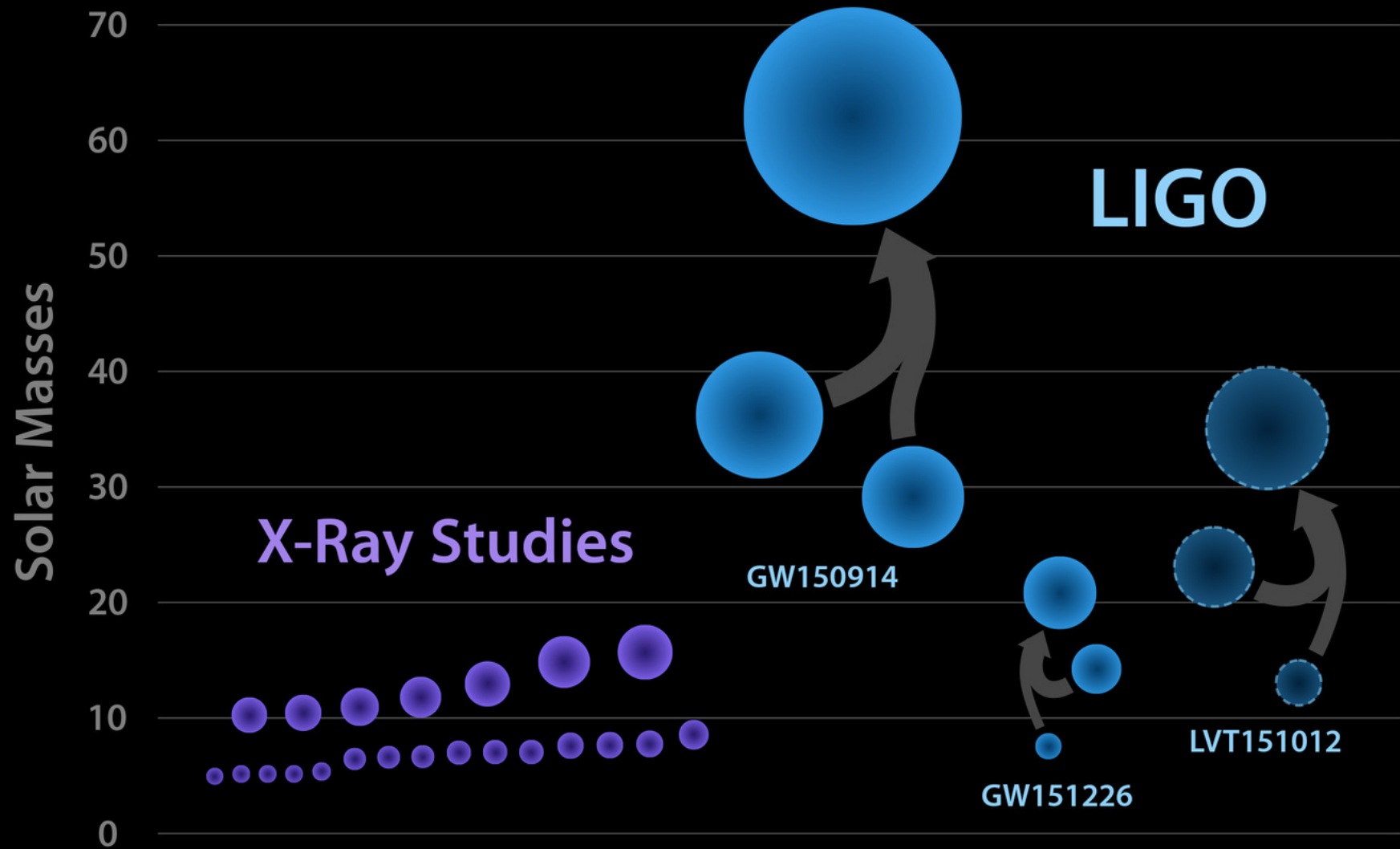
GW150914

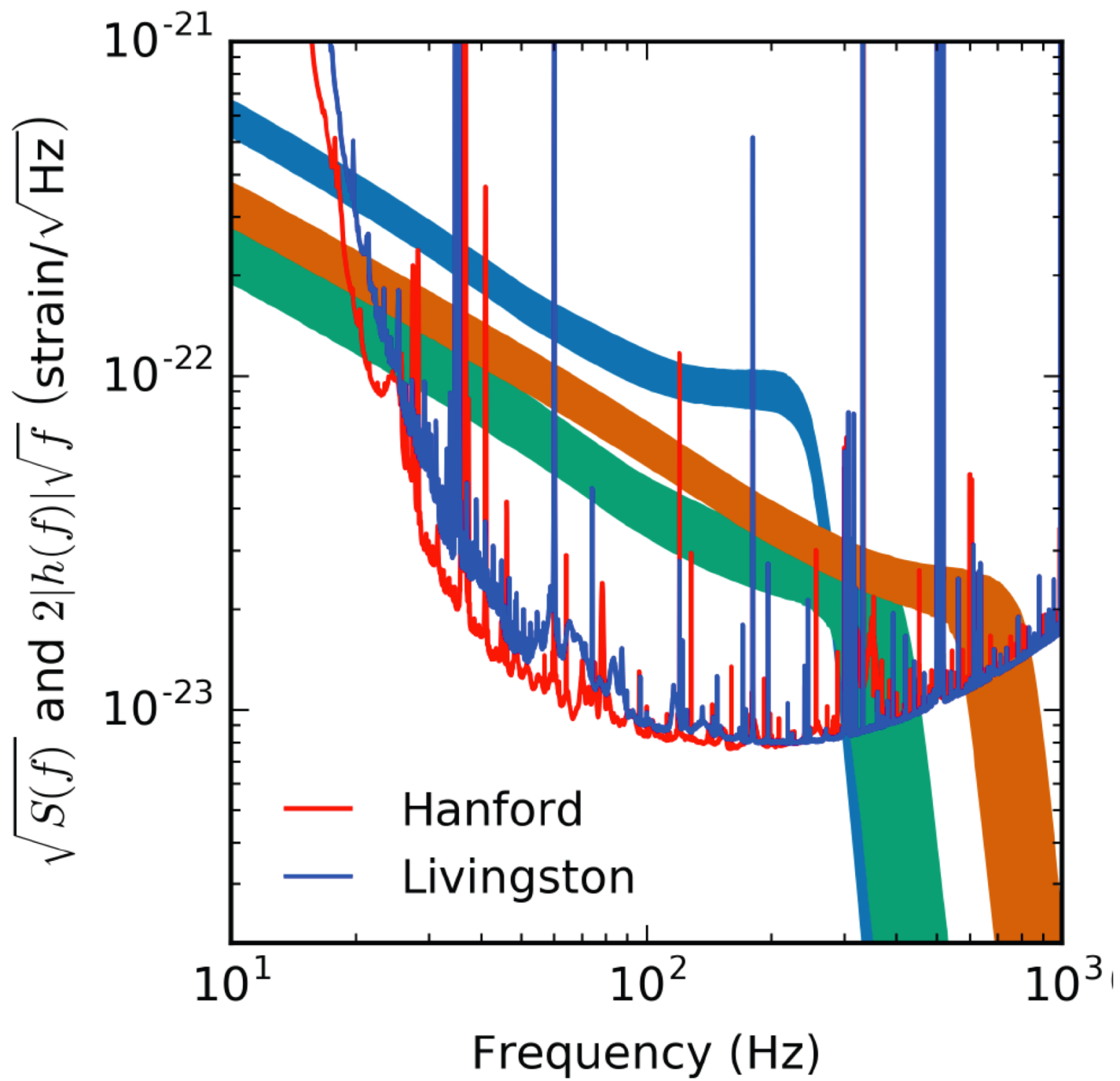
aLIGO Collab. (2016)

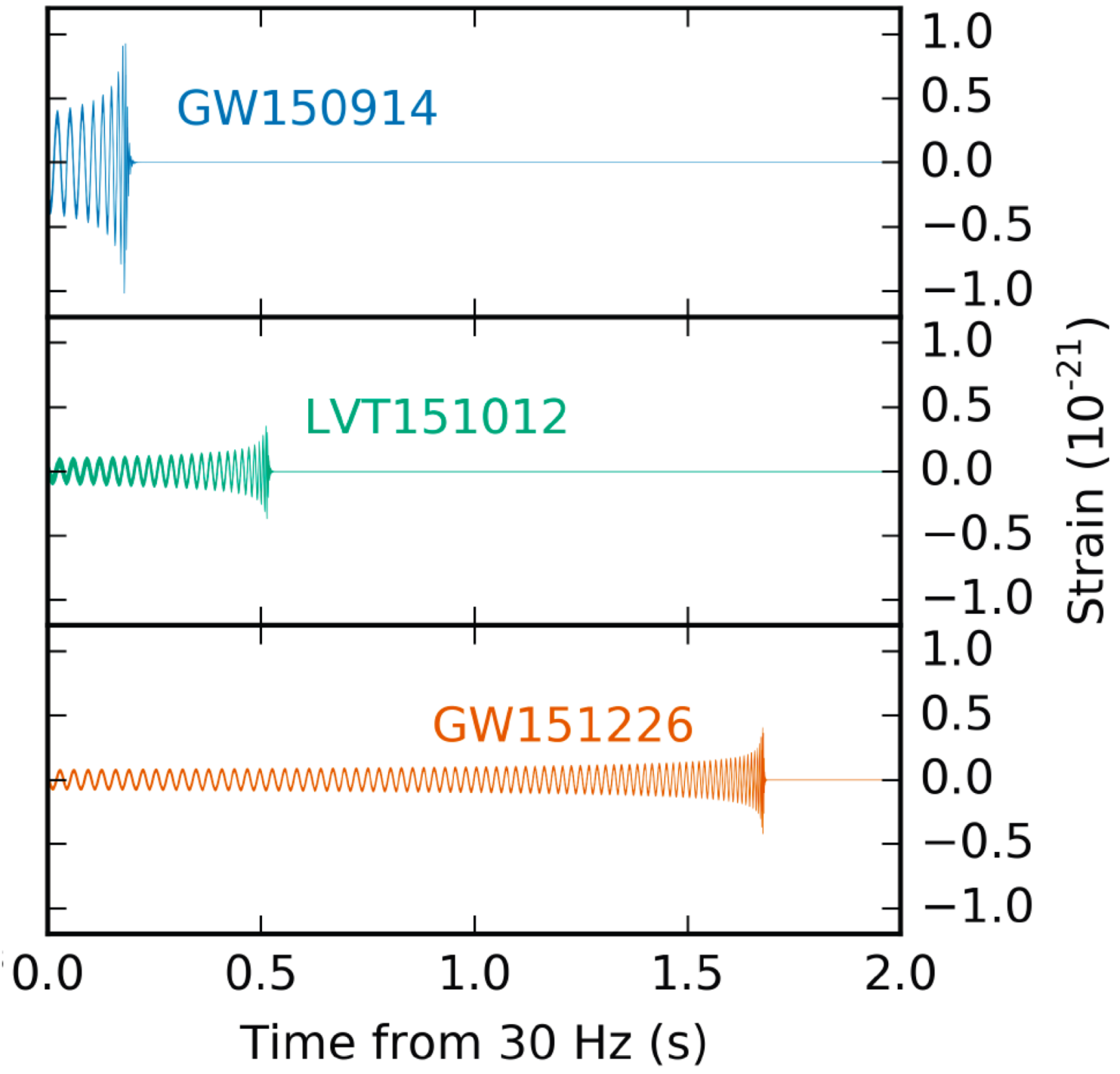


**Not just
one but
Three BBH!**

Black Holes of Known Mass



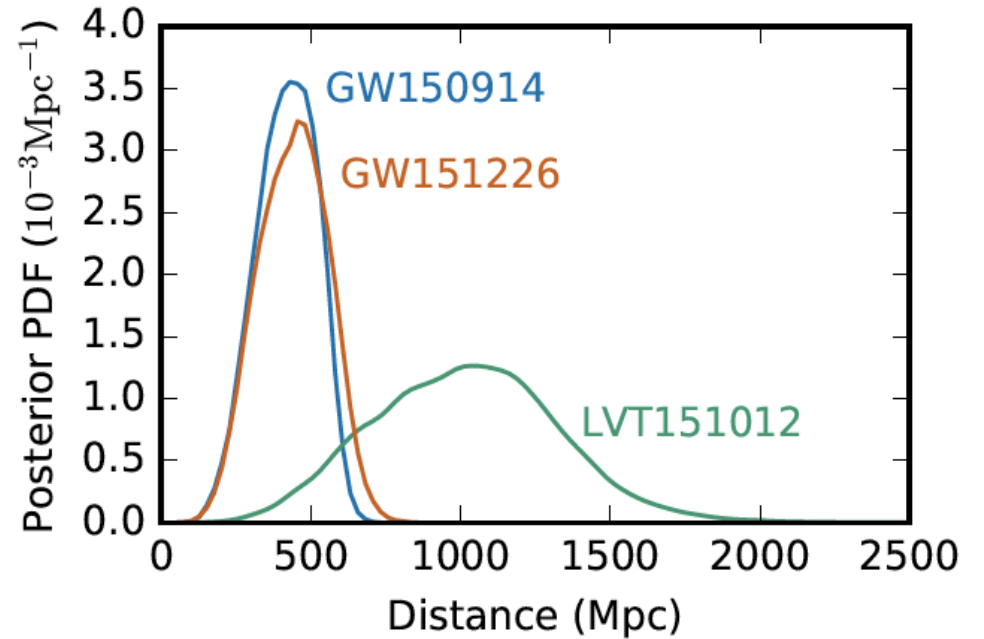
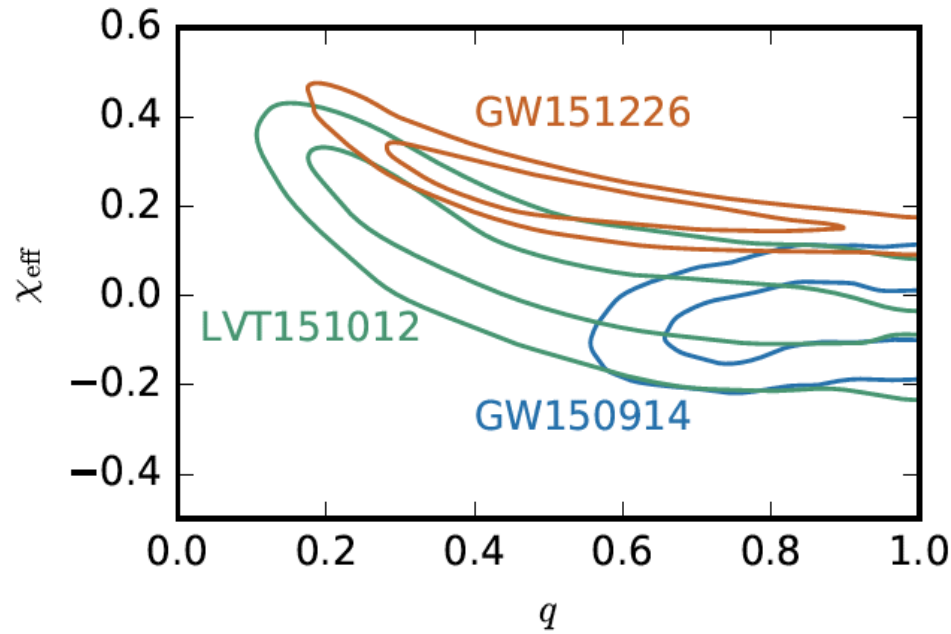
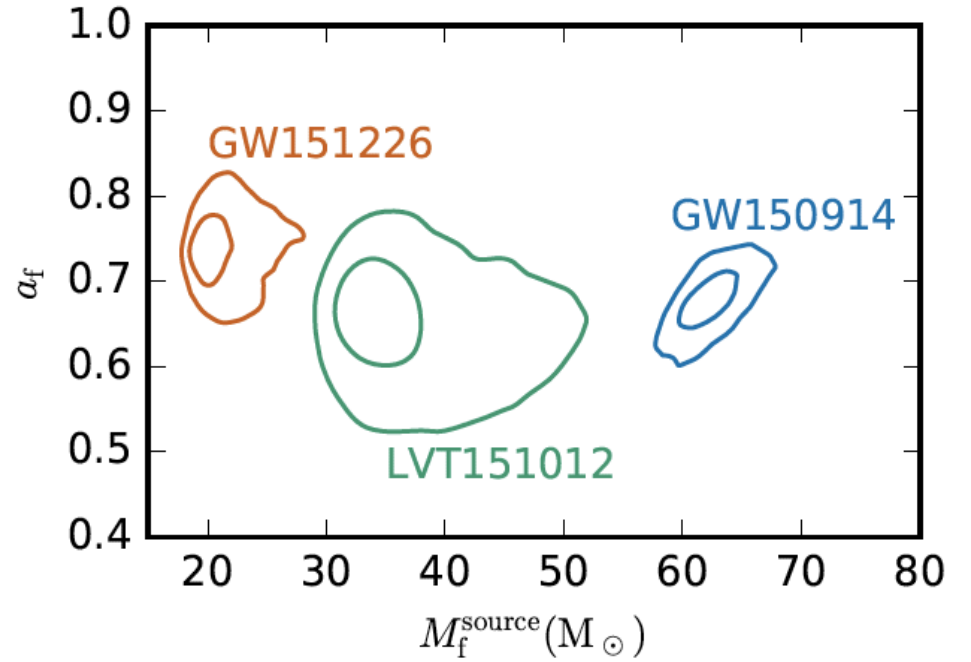
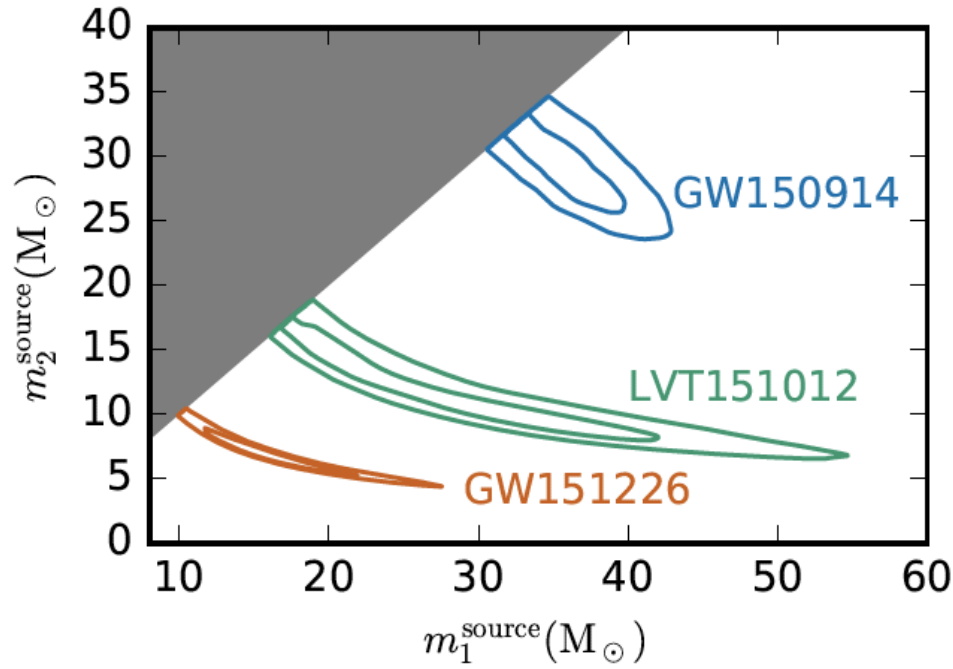


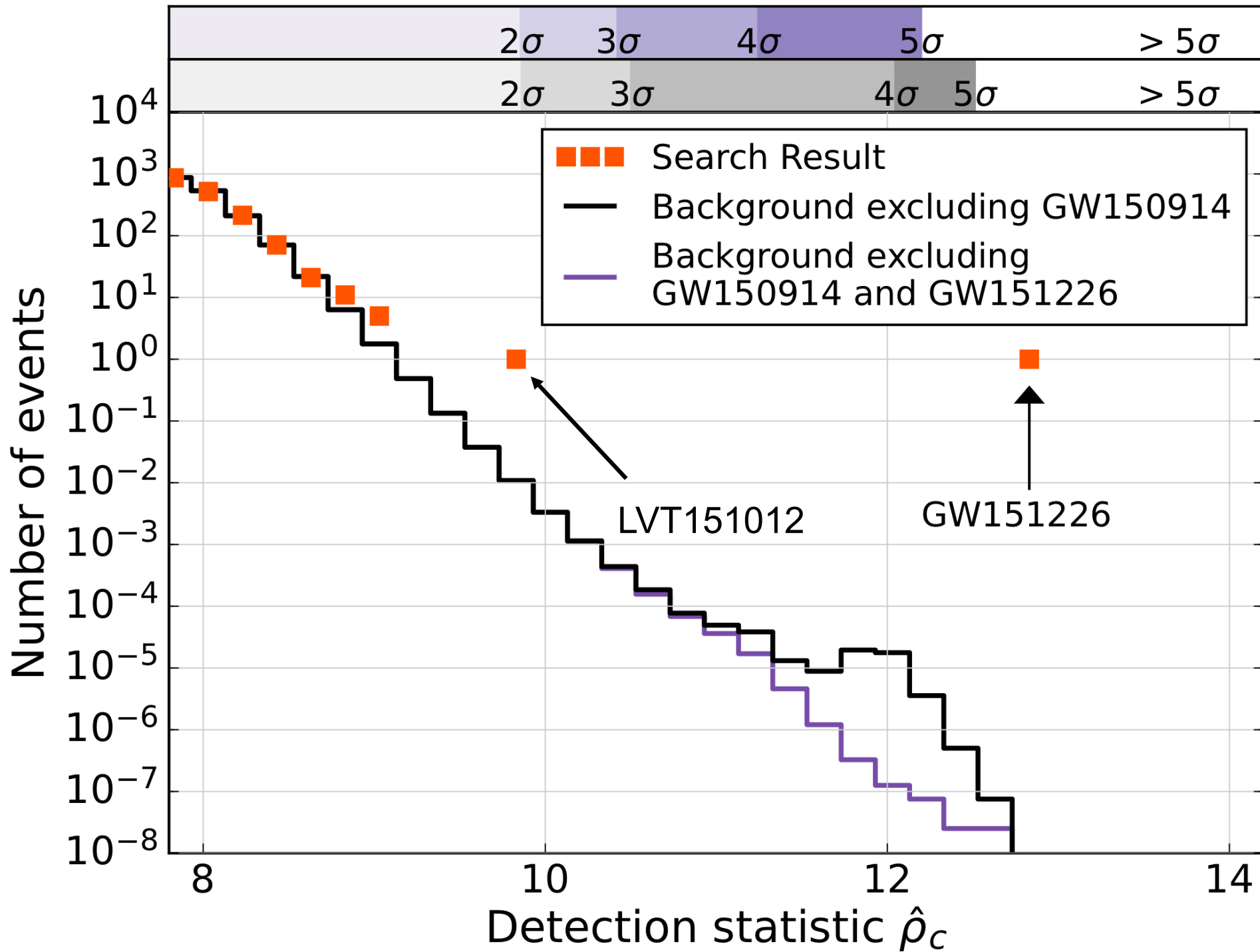


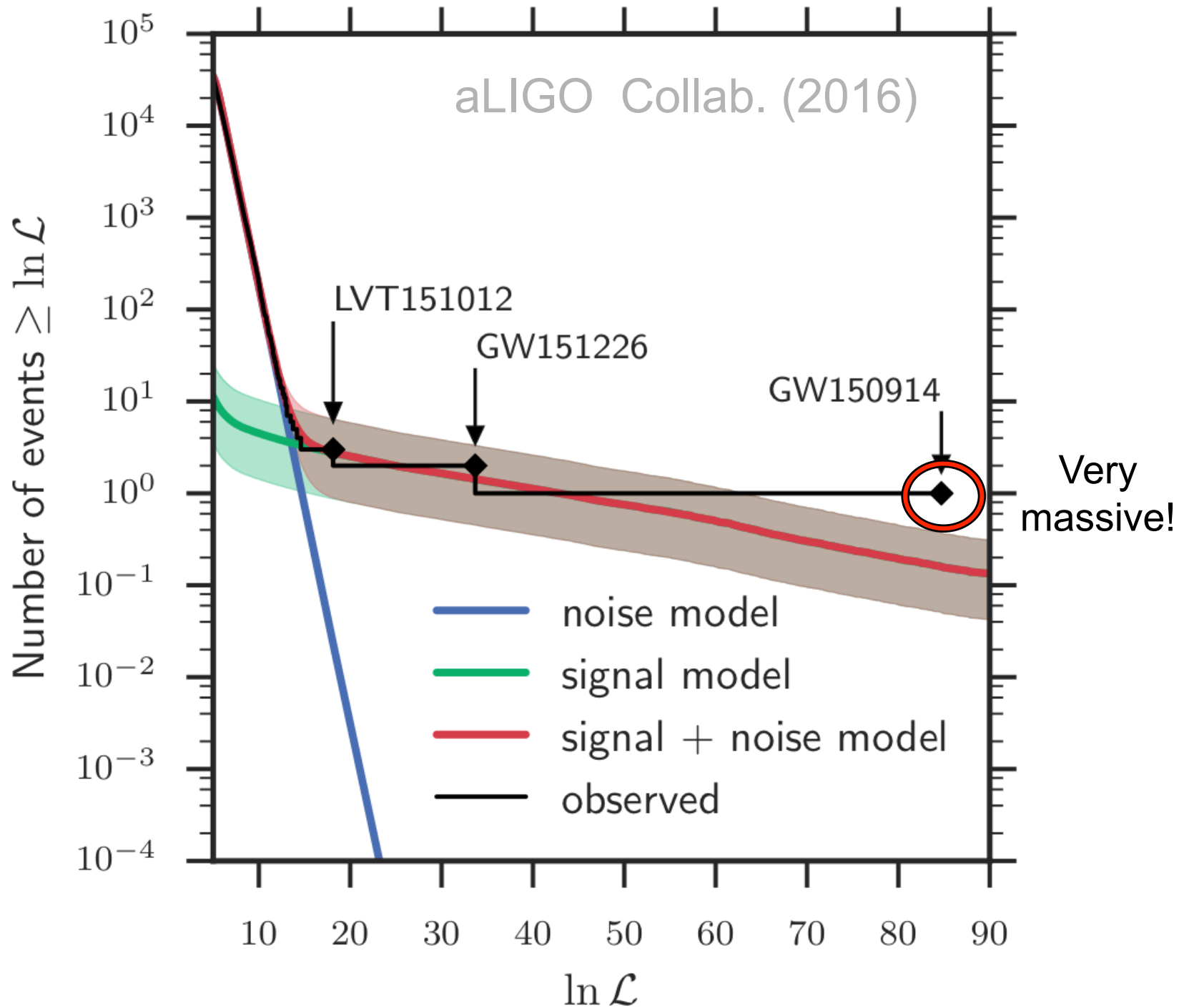
aLIGO Collab. (2016)

	GW150914			GW151226			LVT151012		
	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall
Detector frame									
Total mass M/M_{\odot}	71.0 ^{+4.6} _{-4.0}	71.2 ^{+3.5} _{-3.2}	71.1 ^{+4.1±0.7} _{-3.6±0.8}	23.6 ^{+8.0} _{-1.3}	23.8 ^{+5.1} _{-1.5}	23.7 ^{+6.5±2.2} _{-1.4±0.1}	45 ⁺¹⁷ ₋₄	44 ⁺¹² ₋₃	44 ^{+16±5} _{-3±0}
Chirp mass \mathcal{M}/M_{\odot}	30.4 ^{+2.3} _{-1.6}	30.7 ^{+1.5} _{-1.5}	30.6 ^{+1.9±0.3} _{-1.6±0.4}	9.71 ^{+0.08} _{-0.07}	9.72 ^{+0.06} _{-0.06}	9.72 ^{+0.07±0.01} _{-0.9}	18.1 ^{+1.3} _{-0.9}	18.1 ^{+0.8} _{-0.8}	18.1 ^{+1.0±0.5} _{-0.8±0.1}
Primary mass m_1/M_{\odot}	40.2 ^{+5.2} _{-4.8}	38.5 ^{+5.4} _{-3.3}	39.4 ^{+5.4±1.3} _{-4.1±0.2}	15.3 ^{+10.8} _{-3.8}	15.8 ^{+7.2} _{-4.0}	15.6 ^{+9.0±2.6} _{-4.0±0.2}	29 ⁺²³ ₋₈	27 ⁺¹⁹ ₋₆	28 ^{+21±5} _{-7±0}
Secondary mass m_2/M_{\odot}	30.6 ^{+5.1} _{-4.2}	32.7 ^{+3.1} _{-4.9}	31.7 ^{+4.0±0.1} _{-4.9±1.2}	8.3 ^{+2.5} _{-2.9}	8.1 ^{+2.5} _{-2.1}	8.2 ^{+2.6±0.2} _{-2.5±0.5}	15 ⁺⁵ ₋₆	16 ⁺⁴ ₋₆	16 ^{+5±0} _{-6±1}
Final mass M_f/M_{\odot}	67.8 ^{+4.0} _{-3.6}	67.9 ^{+3.2} _{-2.9}	67.8 ^{+3.7±0.6} _{-3.3±0.7}	22.5 ^{+8.2} _{-1.4}	22.8 ^{+5.3} _{-1.6}	22.6 ^{+6.7±2.2} _{-1.5±0.1}	43 ⁺¹⁷ ₋₄	42 ⁺¹³ ₋₂	42 ^{+16±5} _{-3±0}
Source frame									
Total mass $M^{\text{source}}/M_{\odot}$	65.5 ^{+4.4} _{-3.9}	65.1 ^{+3.6} _{-3.1}	65.3 ^{+4.1±1.0} _{-3.4±0.3}	21.6 ^{+7.4} _{-1.6}	21.9 ^{+4.7} _{-1.7}	21.8 ^{+5.9±2.0} _{-1.7±0.1}	38 ⁺¹⁵ ₋₅	37 ⁺¹¹ ₋₄	37 ^{+13±4} _{-4±0}
Chirp mass $\mathcal{M}^{\text{source}}/M_{\odot}$	28.1 ^{+2.1} _{-1.6}	28.1 ^{+1.6} _{-1.4}	28.1 ^{+1.8±0.4} _{-1.5±0.2}	8.87 ^{+0.35} _{-0.28}	8.90 ^{+0.31} _{-0.27}	8.90 ^{+0.32±0.01} _{-0.2±0.04}	15.2 ^{+1.5} _{-1.1}	15.0 ^{+1.3} _{-1.0}	15.0 ^{+1.5±0.3} _{-1.1±0.0}
Primary mass $m_1^{\text{source}}/M_{\odot}$	37.0 ^{+4.9} _{-4.4}	35.3 ^{+5.1} _{-3.1}	36.2 ^{+5.2±1.4} _{-3.8±0.4}	14.0 ^{+10.0} _{-3.5}	14.5 ^{+6.6} _{-3.7}	14.2 ^{+8.3±1.4} _{-3.7±0.9}	24 ⁺¹⁹ ₋₇	23 ⁺¹⁶ ₋₅	23 ^{+18±4} _{-6±0}
Secondary mass $m_2^{\text{source}}/M_{\odot}$	28.3 ^{+4.6} _{-3.9}	29.9 ^{+3.0} _{-4.5}	29.1 ^{+3.7±0.7} _{-4.4±0.2}	7.5 ^{+2.3} _{-2.6}	7.4 ^{+2.3} _{-2.0}	7.5 ^{+2.3±0.1} _{-2.3±0.0}	13 ⁺⁴ ₋₅	14 ⁺⁴ ₋₅	13 ^{+4±0} _{-5±0}
Final mass $M_f^{\text{source}}/M_{\odot}$	62.5 ^{+3.9} _{-3.5}	62.1 ^{+3.3} _{-2.8}	62.3 ^{+3.7±0.7} _{-3.1±0.2}	20.6 ^{+7.6} _{-1.6}	20.9 ^{+4.8} _{-1.8}	20.8 ^{+6.1±2.0} _{-1.7±0.1}	36 ⁺¹⁵ ₋₄	35 ⁺¹¹ ₋₃	35 ^{+14±4} _{-4±0}
Energy radiated $E_{\text{rad}}/(M_{\odot}c^2)$	2.98 ^{+0.55} _{-0.40}	3.02 ^{+0.36} _{-0.36}	3.00 ^{+0.47±0.13} _{-0.39±0.07}	1.02 ^{+0.09} _{-0.24}	0.99 ^{+0.11} _{-0.17}	1.00 ^{+0.10±0.01} _{-0.20±0.03}	1.48 ^{+0.39} _{-0.41}	1.51 ^{+0.29} _{-0.44}	1.50 ^{+0.33±0.05} _{-0.43±0.01}
Mass ratio q	0.77 ^{+0.20} _{-0.18}	0.85 ^{+0.13} _{-0.21}	0.81 ^{+0.17±0.02} _{-0.20±0.04}	0.54 ^{+0.40} _{-0.33}	0.51 ^{+0.39} _{-0.25}	0.52 ^{+0.40±0.03} _{-0.29±0.04}	0.53 ^{+0.42} _{-0.34}	0.60 ^{+0.35} _{-0.37}	0.57 ^{+0.32±0.01} _{-0.37±0.04}
Effective inspiral spin χ_{eff}	-0.08 ^{+0.17} _{-0.14}	-0.05 ^{+0.11} _{-0.12}	-0.06 ^{+0.14±0.02} _{-0.14±0.04}	0.21 ^{+0.24} _{-0.11}	0.22 ^{+0.15} _{-0.08}	0.21 ^{+0.20±0.07} _{-0.10±0.03}	0.06 ^{+0.31} _{-0.24}	0.01 ^{+0.26} _{-0.17}	0.03 ^{+0.31±0.08} _{-0.20±0.02}
Primary spin magnitude a_1	0.33 ^{+0.39} _{-0.29}	0.30 ^{+0.54} _{-0.27}	0.32 ^{+0.47±0.10} _{-0.29±0.01}	0.42 ^{+0.35} _{-0.37}	0.55 ^{+0.35} _{-0.42}	0.49 ^{+0.37±0.11} _{-0.42±0.07}	0.31 ^{+0.46} _{-0.27}	0.31 ^{+0.50} _{-0.28}	0.31 ^{+0.48±0.03} _{-0.28±0.00}
Secondary spin magnitude a_2	0.62 ^{+0.35} _{-0.54}	0.36 ^{+0.53} _{-0.33}	0.48 ^{+0.47±0.08} _{-0.43±0.03}	0.51 ^{+0.44} _{-0.46}	0.52 ^{+0.42} _{-0.47}	0.52 ^{+0.43±0.01} _{-0.47±0.00}	0.49 ^{+0.45} _{-0.44}	0.42 ^{+0.50} _{-0.38}	0.45 ^{+0.48±0.02} _{-0.41±0.01}
Final spin a_f	0.68 ^{+0.05} _{-0.07}	0.68 ^{+0.06} _{-0.05}	0.68 ^{+0.05±0.01} _{-0.06±0.02}	0.73 ^{+0.05} _{-0.06}	0.75 ^{+0.07} _{-0.05}	0.74 ^{+0.06±0.03} _{-0.06±0.03}	0.65 ^{+0.09} _{-0.10}	0.66 ^{+0.08} _{-0.10}	0.66 ^{+0.09±0.00} _{-0.10±0.02}
Luminosity distance D_L/Mpc	400 ⁺¹⁶⁰ ₋₁₈₀	440 ⁺¹⁴⁰ ₋₁₇₀	420 ^{+150±20} _{-180±40}	450 ⁺¹⁸⁰ ₋₂₁₀	440 ⁺¹⁷⁰ ₋₁₈₀	440 ^{+180±20} _{-190±10}	1000 ⁺⁵⁴⁰ ₋₄₉₀	1030 ⁺⁴⁸⁰ ₋₄₈₀	1020 ^{+500±20} _{-490±40}
Source redshift z	0.086 ^{+0.031} _{-0.036}	0.094 ^{+0.027} _{-0.034}	0.090 ^{+0.029±0.003} _{-0.036±0.008}	0.096 ^{+0.035} _{-0.042}	0.092 ^{+0.033} _{-0.037}	0.094 ^{+0.035±0.004} _{-0.039±0.001}	0.198 ^{+0.091} _{-0.092}	0.204 ^{+0.082} _{-0.088}	0.201 ^{+0.086±0.003} _{-0.091±0.008}
Upper bound									
Primary spin magnitude a_1	0.62	0.73	0.67 ± 0.09	0.68	0.83	0.77 ± 0.12	0.64	0.69	0.67 ± 0.04
Secondary spin magnitude a_2	0.93	0.80	0.90 ± 0.12	0.90	0.89	0.90 ± 0.01	0.89	0.85	0.87 ± 0.04
Lower bound									
Mass ratio q	0.62	0.68	0.65 ± 0.05	0.25	0.30	0.28 ± 0.04	0.22	0.28	0.24 ± 0.05
Log Bayes factor $\ln \mathcal{B}_{s/n}$	287.7 ± 0.1	289.8 ± 0.3	—	59.5 ± 0.1	60.2 ± 0.2	—	22.8 ± 0.2	23.0 ± 0.1	—
Information criterion DIC	32977.2 ± 0.3	32973.1 ± 0.1	—	34296.4 ± 0.2	34295.1 ± 0.1	—	94695.8 ± 0.0	94692.9 ± 0.0	—

aLIGO Collab. (2016)



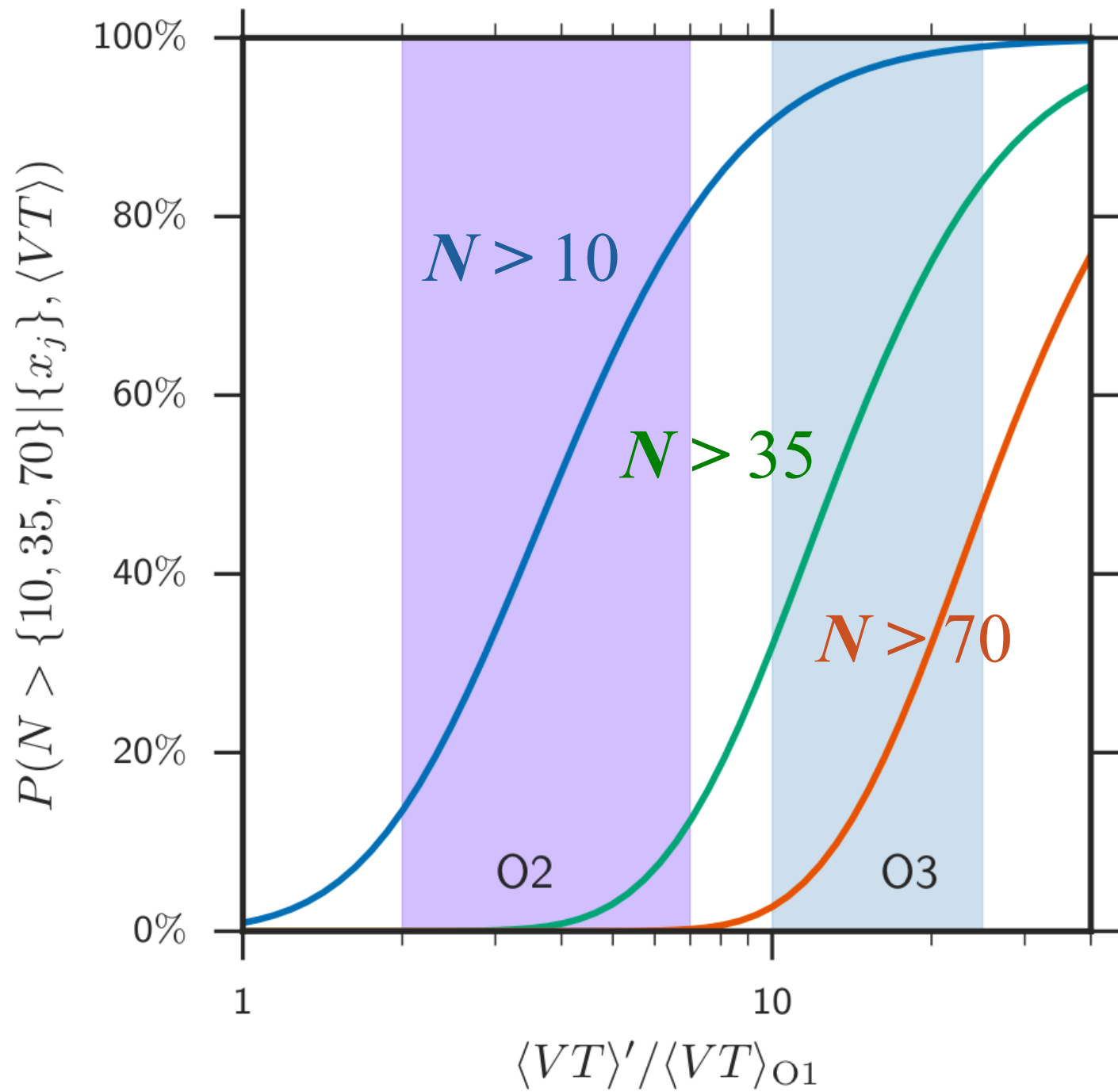




Mass distribution	$R/(\text{Gpc}^{-3}\text{yr}^{-1})$		
	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law (-2.35)	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

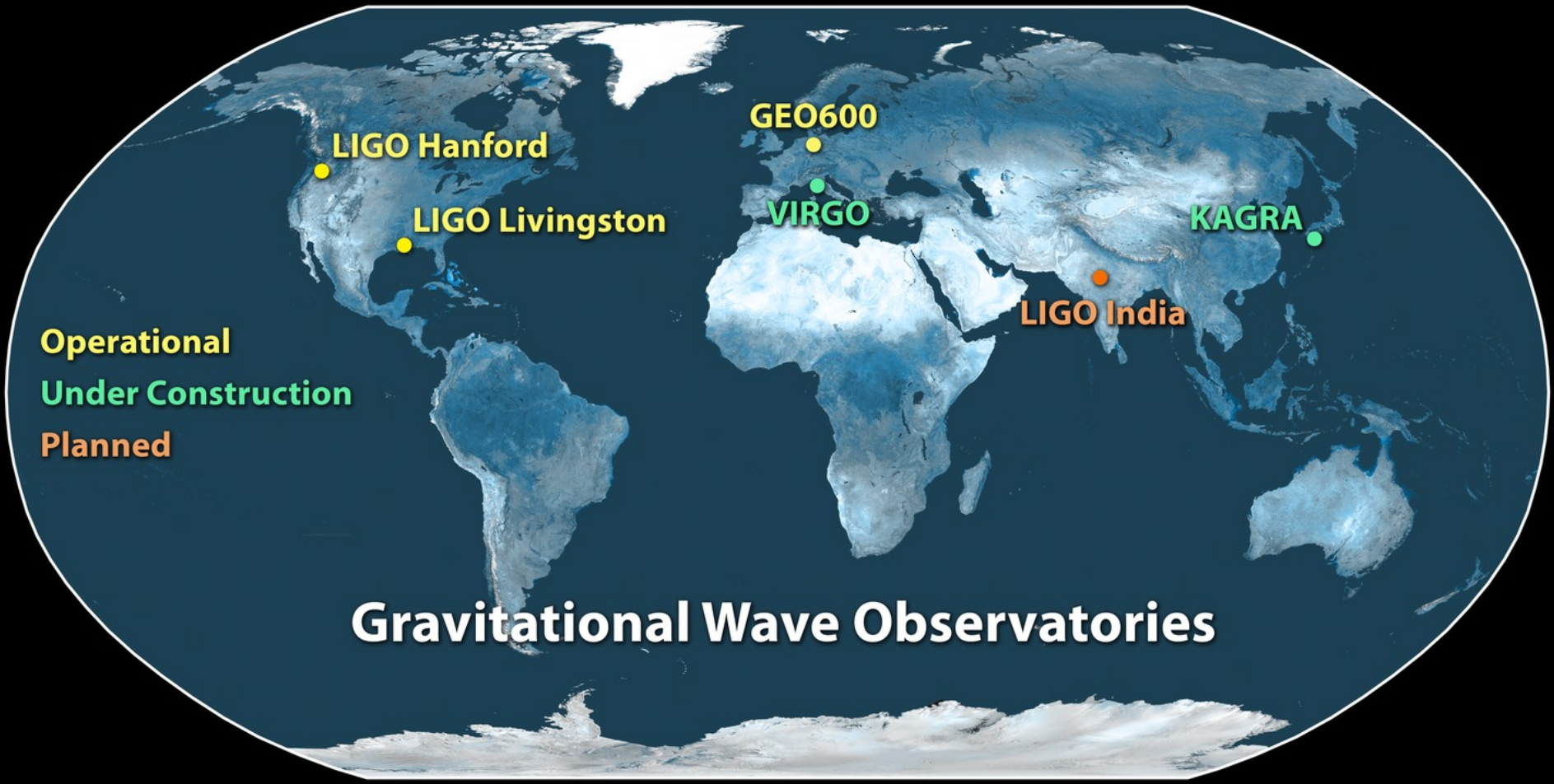
TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

6)



aLIGO
Collab. (2016)

expected
future no.
events



LIGO Hanford

LIGO Livingston

GEO600

VIRGO

KAGRA

LIGO India

Operational
Under Construction
Planned

Gravitational Wave Observatories

Gravitational Wave Astronomy

- Discovery of binary BH by aLIGO
- VIRGO, KAGRA, INDIGO = GW Astron
- GW150914 = 36 + 29 M_{sun} BH binary
- GW151226 = 14 + 8 M_{sun} BH binary
- LVT151012 = 23 + 13 M_{sun} “candidate”
- Expected $10^{1\pm 1}$ events/yr/Gpc
- aLIGO+ and eLISA can map the mass and spin of Massive BH ($M_{\text{BH}} > 20 M_{\text{sun}}$)

**Massive
Primordial
Black Holes
as DM**

Density perturbations and black hole formation in hybrid inflation

Juan García-Bellido

Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

The resulting density inhomogeneities lead to a copious production of black holes.

David Wands

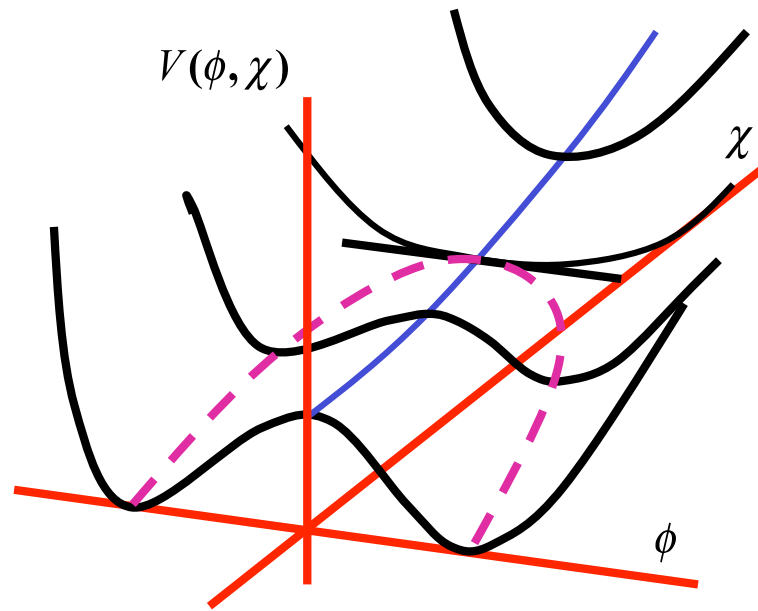
*School of Mathematical Studies, University of Portsmouth, Portsmouth PO1 2EG, United Kingdom
and Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*

for certain values of parameters these black holes may constitute the dark matter in the Universe.

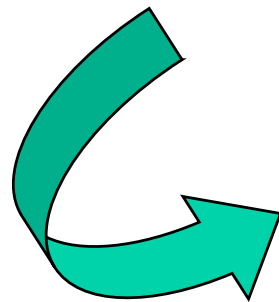
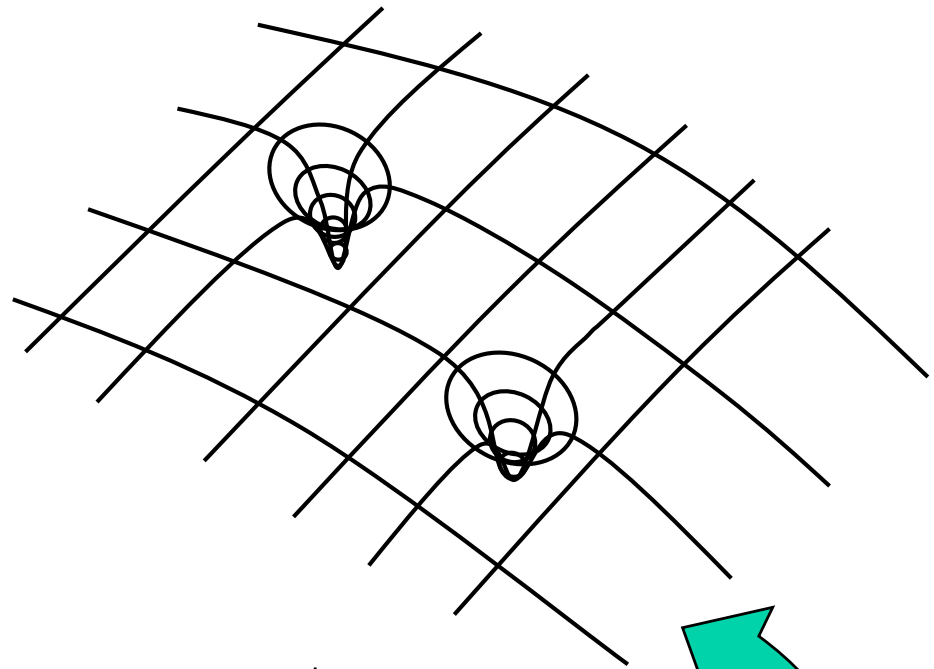
corresponding to the phase transition. The resulting density inhomogeneities lead to a copious production of black holes. This could be an argument against hybrid inflation models with two stages of inflation. However, we find a class of models where this problem can be easily avoided. The number of black holes produced in these models can be made extremely small, but in general it could be sufficiently large to have important cosmological and astrophysical implications. In particular, for certain values of parameters these black holes may constitute the dark matter in the Universe. It is also possible to have hybrid models with two stages of inflation where the black hole production is not suppressed, but where the typical masses of the black holes are very small. Such models lead to a completely different thermal history of the Universe, where postinflationary reheating occurs via black hole evaporation. [S0556-2821(96)00522-X]

PACS number(s): 98.80.Cq

Hybrid Inflation Model



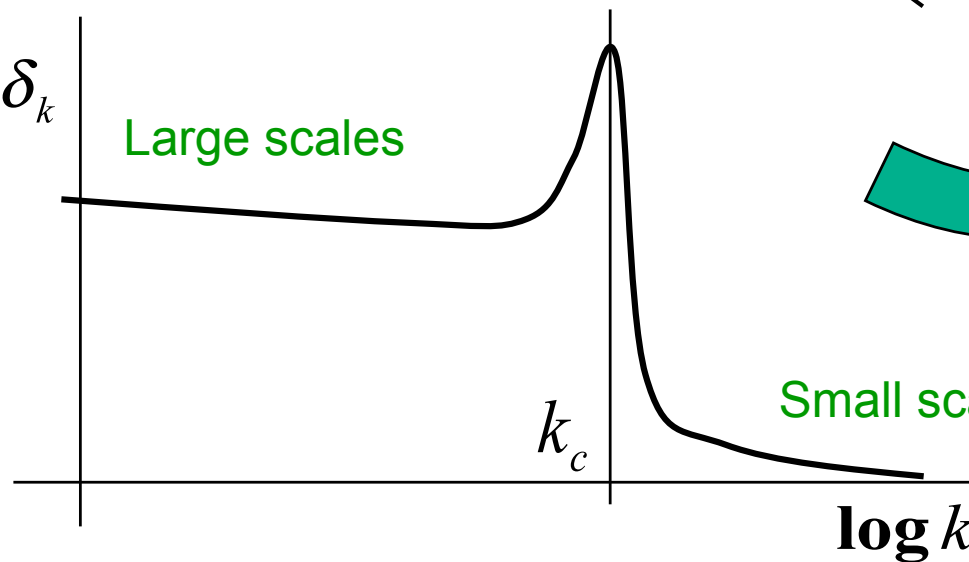
Primordial Black Hole Production



Peaked density
perturbation spectrum

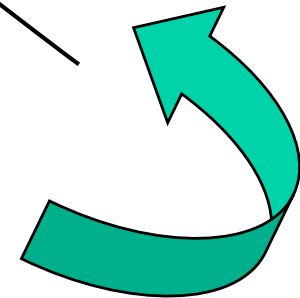
$\log \delta_k$

Large scales



Small scales

$\log k$



Steven Weinberg

“our problem is not that we
take our theories too seriously,
but that we
don't take them seriously enough”

Massive primordial black holes from hybrid inflation as dark matter

These PBHs could have acquired large stellar masses today, via merging, the model passes both the constraints from CMB distortions and microlensing. the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources.

planetary-mass PBHs at matter-radiation equality and producing abundances comparable to those of dark matter today, while the matter power spectrum on scales probed by cosmic microwave background (CMB) anisotropies agrees with Planck data. These PBHs could have acquired large stellar masses today, via merging, and the model passes both the constraints from CMB distortions and microlensing. This scenario is supported by Chandra observations of numerous BH candidates in the central region of Andromeda. Moreover, the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources. We find that our effective hybrid potential can originate e.g. from D-term inflation with a Fayet-Iliopoulos term of the order of the Planck scale but sub-Planckian values of the inflaton field. Finally, we discuss the implications of quantum diffusion at the instability point of the potential, able to generate a Swiss-cheese-like structure of the Universe, eventually leading to apparent accelerated cosmic expansion.

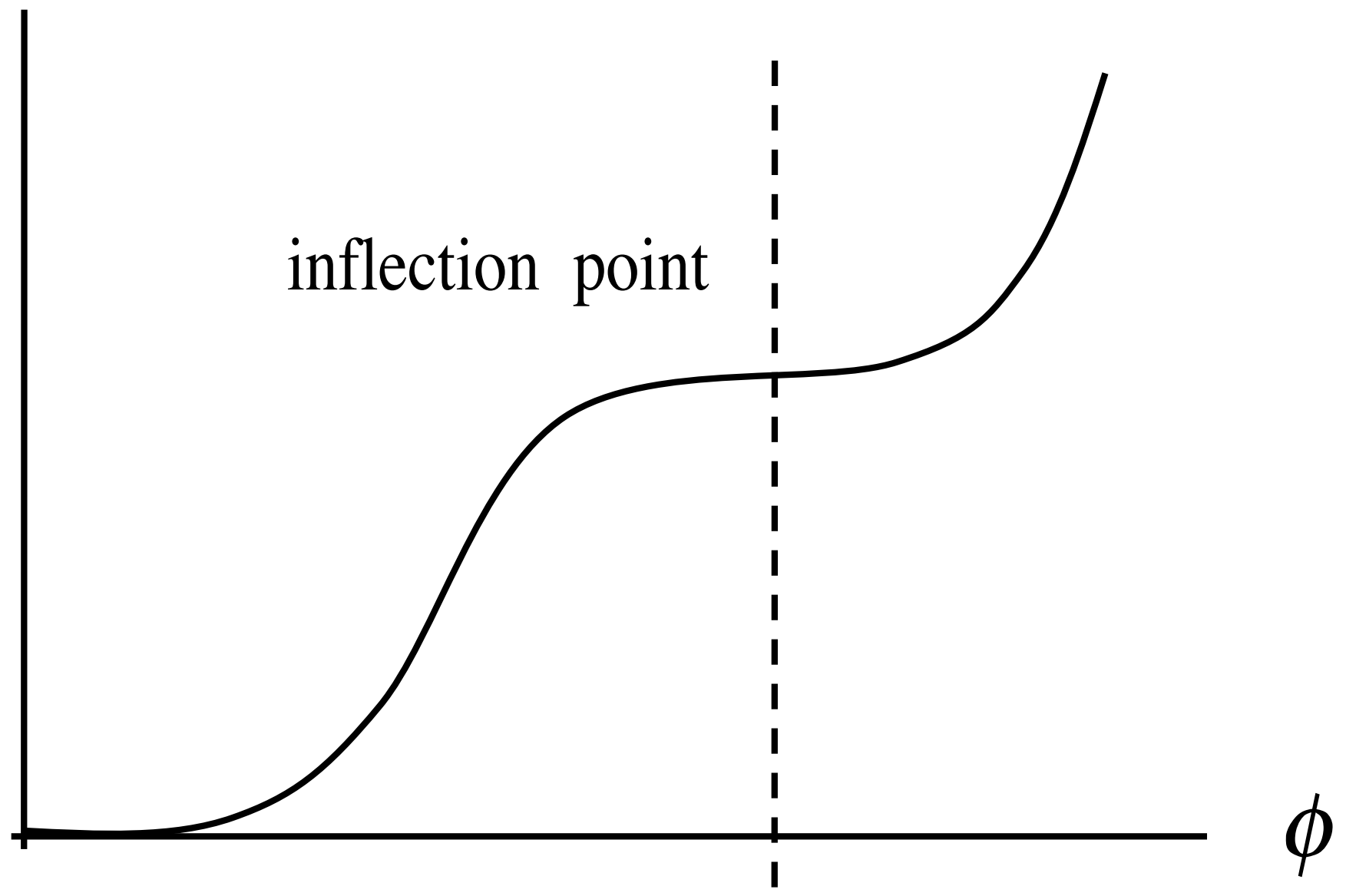
PHYSICAL REVIEW D **92**, 023524 (2015)

Moreover, PBH binaries should emit gravitational waves that could be detected by future gravitational wave experiments such as LIGO, DECIGO and eLISA [70,71].

Binaries of PBHs forming a fraction of dark matter should emit gravitational waves; this results in a background of gravitational waves that could be observed by LIGO, DECIGO and eLISA [70–72].

Potential

$V(\phi)$

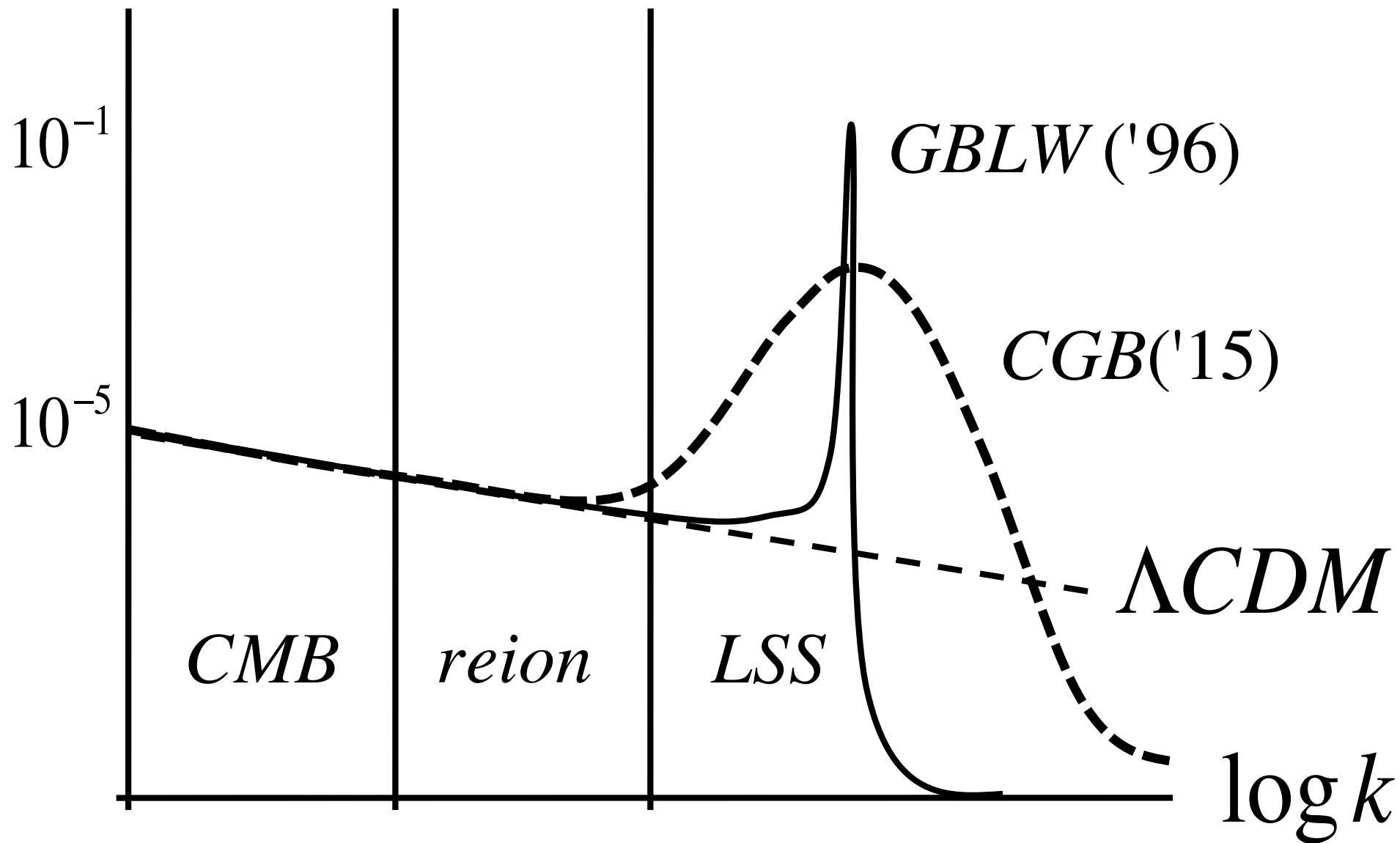


inflection point

ϕ

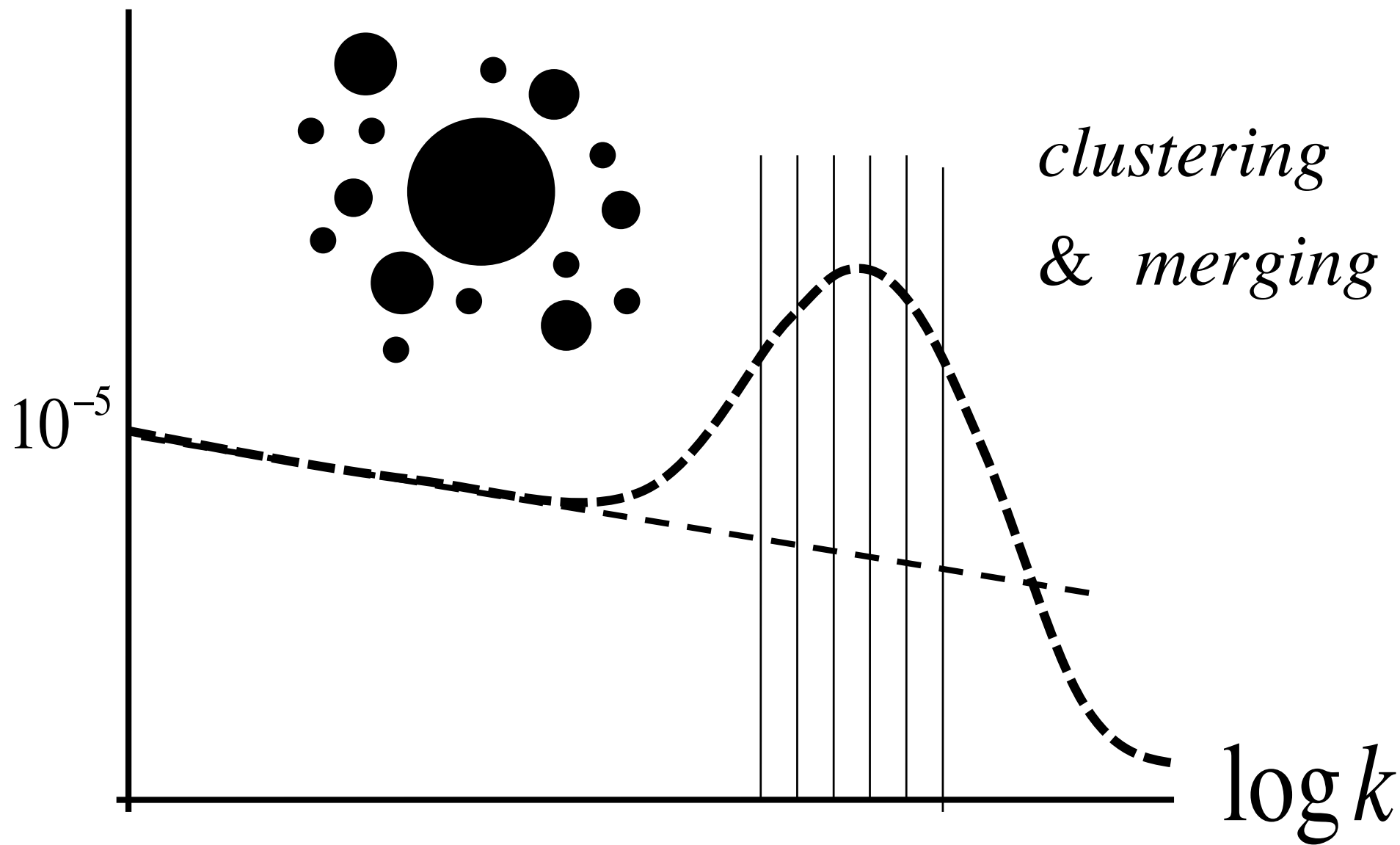
$\log P(k)$

Power spectrum



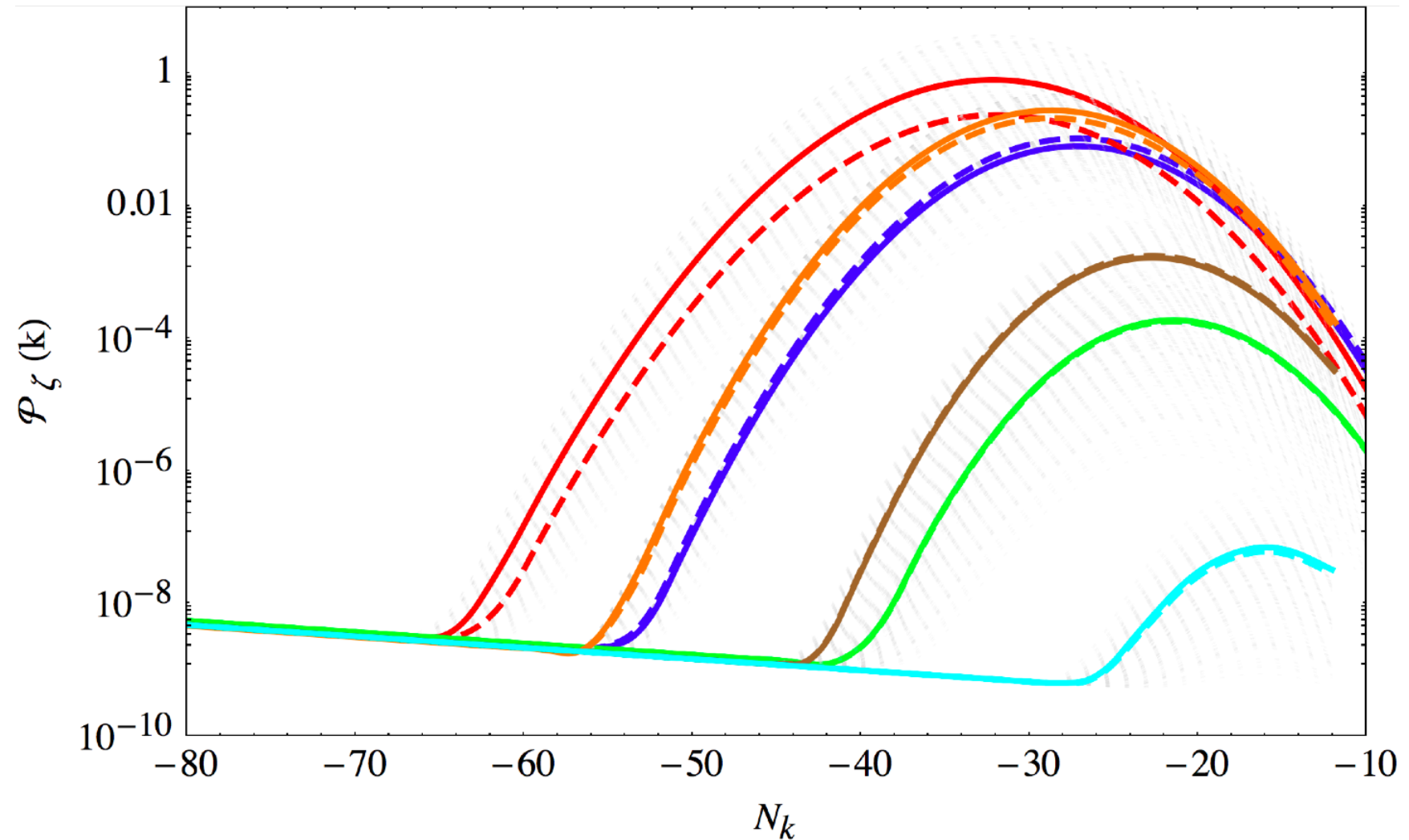
$\log P(k)$

Power spectrum

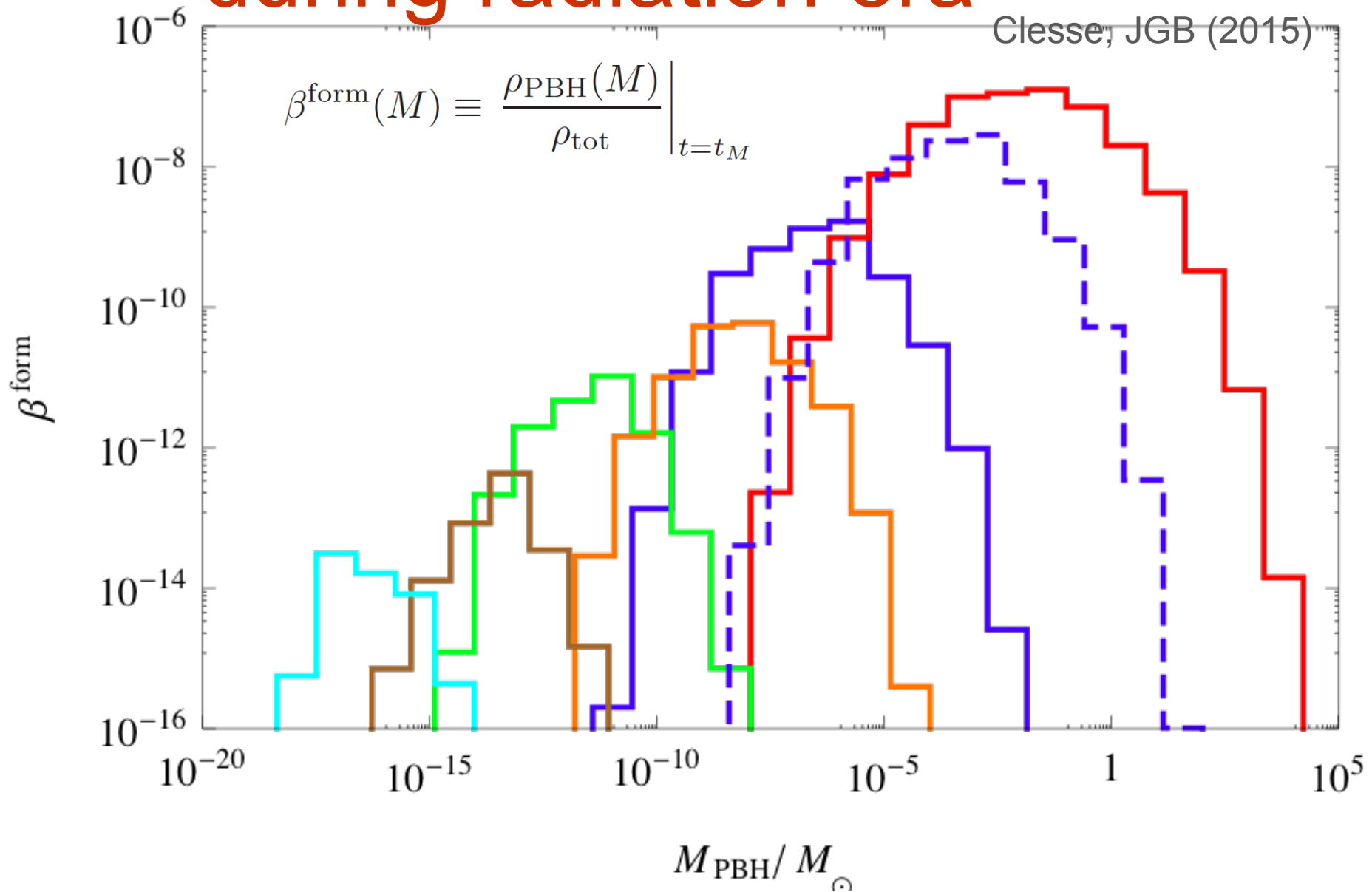


Primordial Spectrum for PBH

Clesse, JGB (2015)

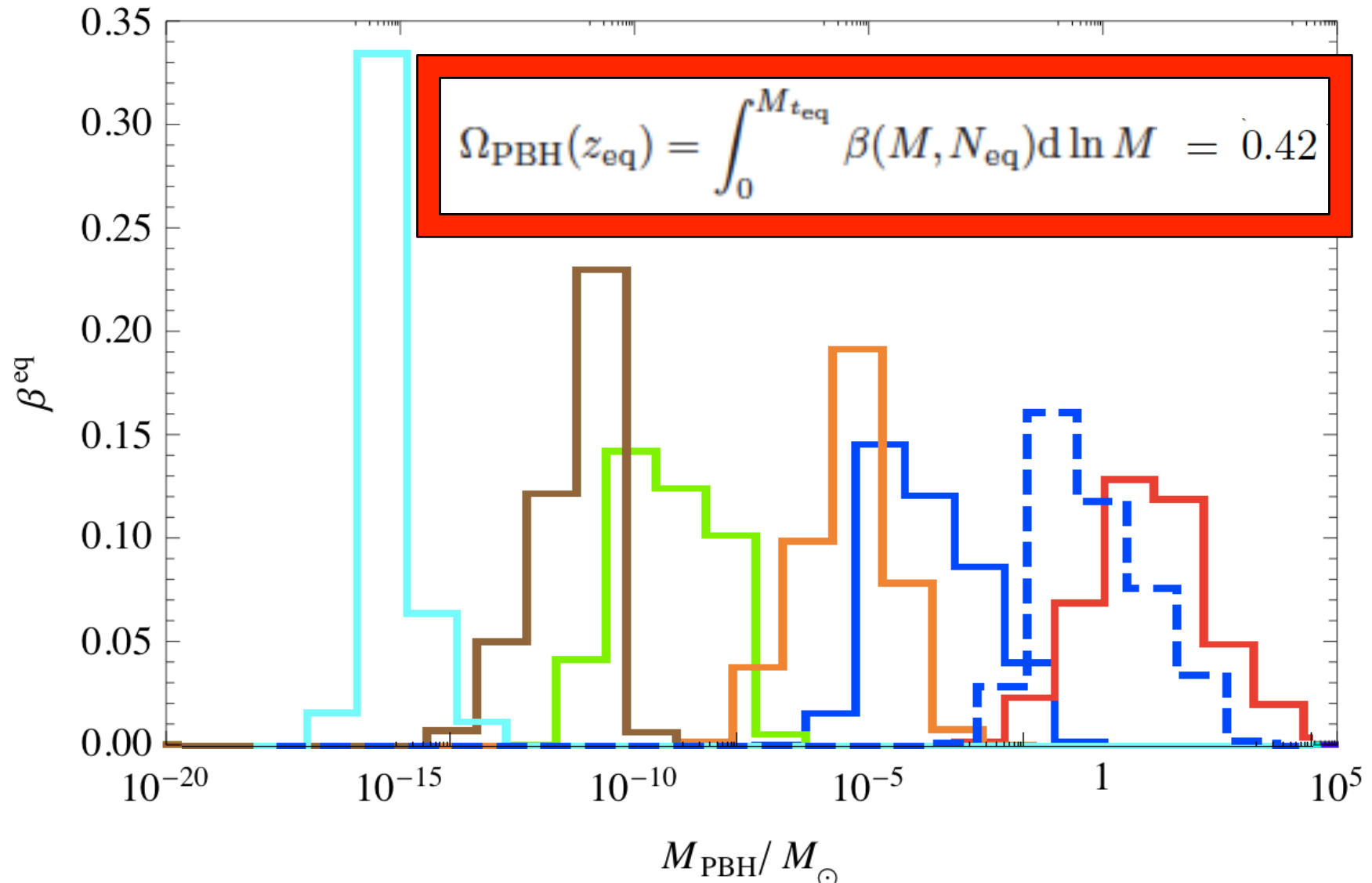


Mass Spectrum @ formation during radiation era



Mass Spectrum @ MR equality

Clesse, JGB (2015)



Constraints

on

Primordial

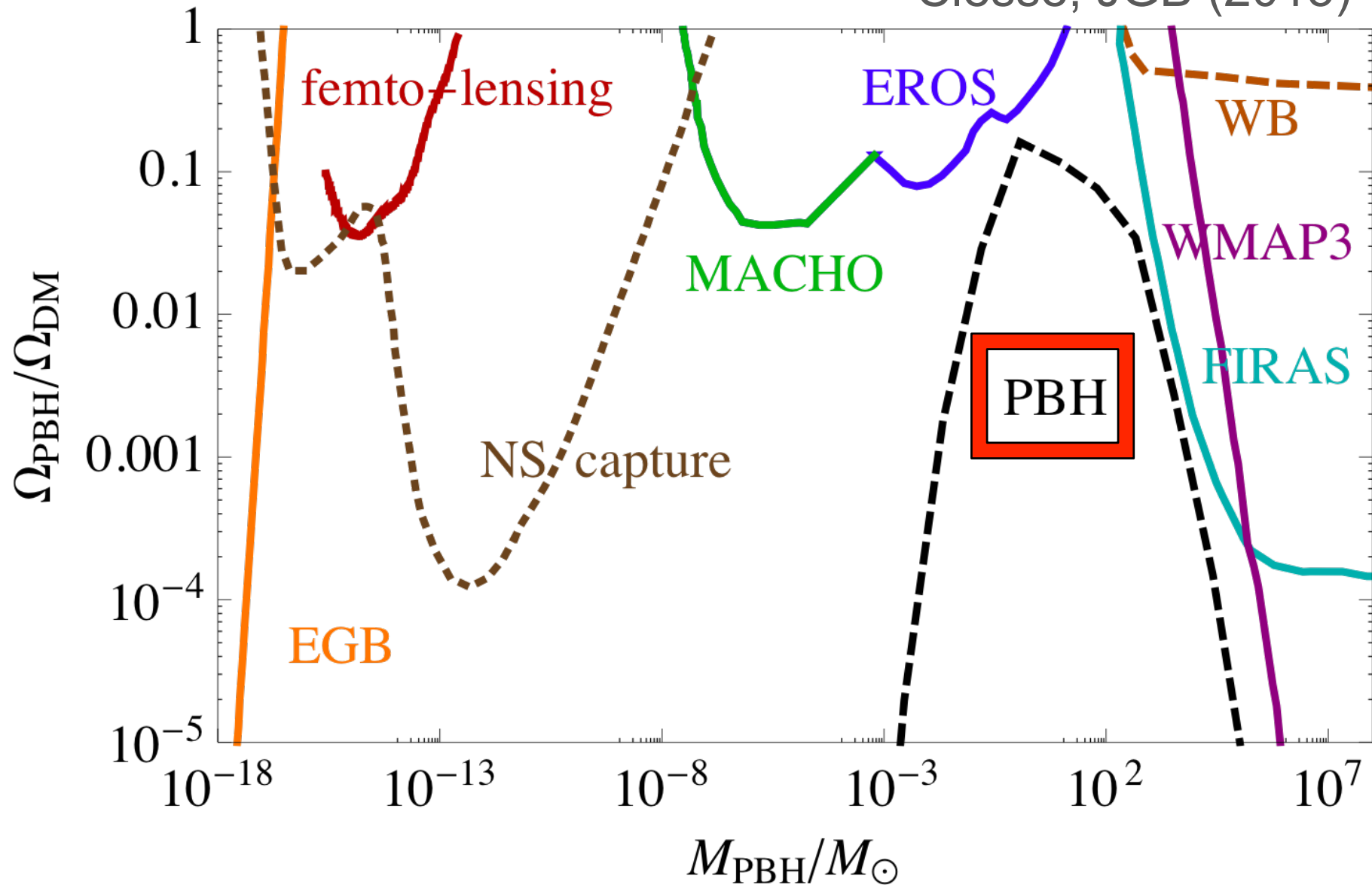
Black Holes

Constraints on PBH

- BBN light element abundance
- Extragalactic photon background
- Galactic Background Radiation
- Femtolensing of GRB
- Star formation rate
- Capture of PBH by neutron stars
- Disruption of wide binaries
- Microlensing
- CMB distortions

Present Constraints on PBH

Clesse, JGB (2015)



Massive Primordial Black Holes

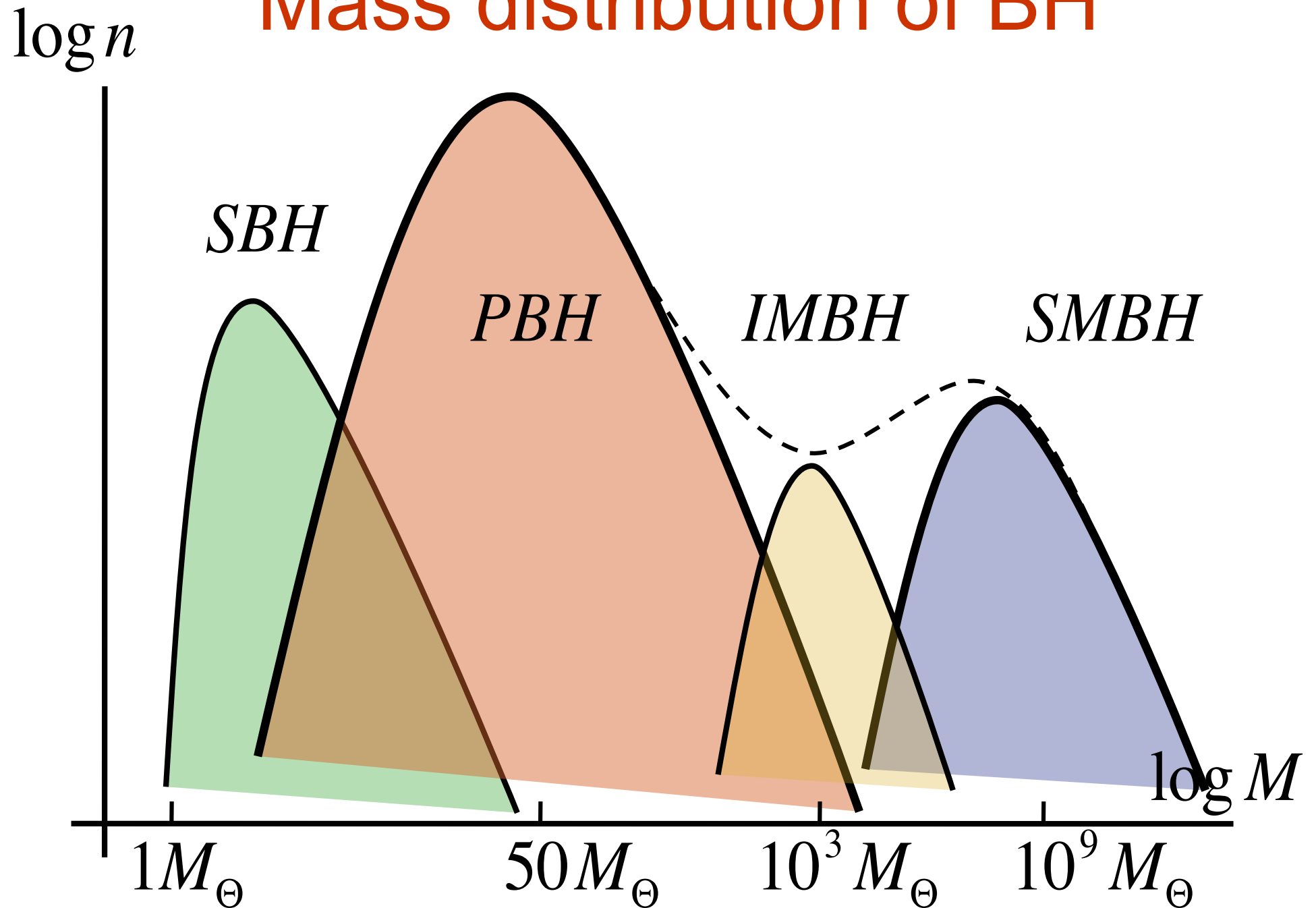
These are NOT the (small) PBH with
 $10^{-24} M_{\odot} < M_{\text{PBH}} < 10^{-6} M_{\odot}$ of Carr et al.

These are MASSIVE black holes with
 $10^{-2} M_{\odot} < M_{\text{PBH}} < 10^5 M_{\odot}$ which
cluster and merge and could resolve
some of the most acute problems of
 Λ CDM paradigm

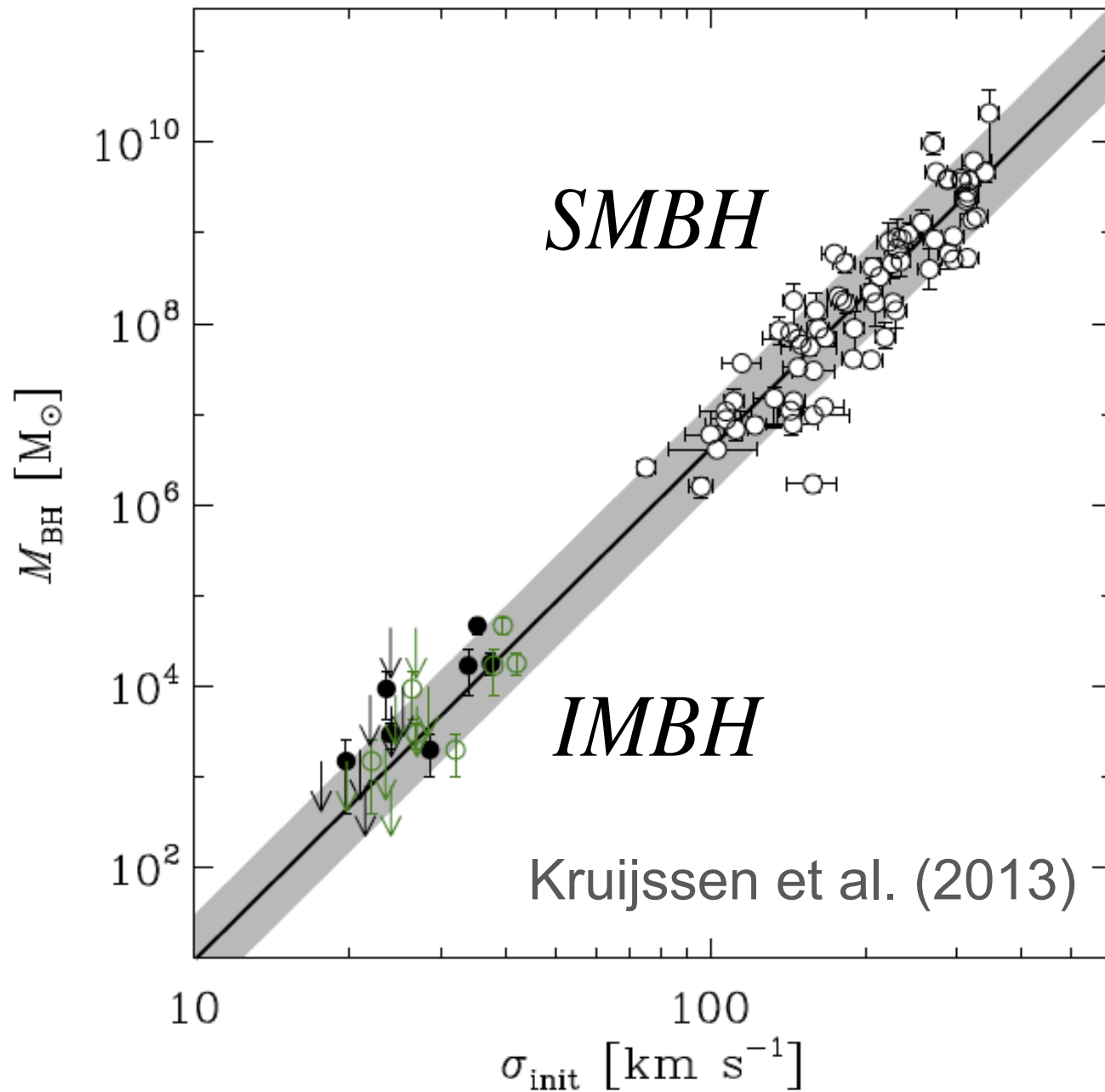
Λ CDM has difficulties explaining

- Fully formed galaxies & QSO at $z \sim 10$
- Very massive clusters at $z \sim 1$
- Intermediate Mass Black Holes
- Ultra Luminous X-ray Sources
- Large population BH seen by Chandra
- Unidentified sources in Fermi LAT
- Tidally disrupted stars by BH
- DM substructure and too-big-to-fail prob.

Mass distribution of BH



Mass- σ relation BH at G.C.

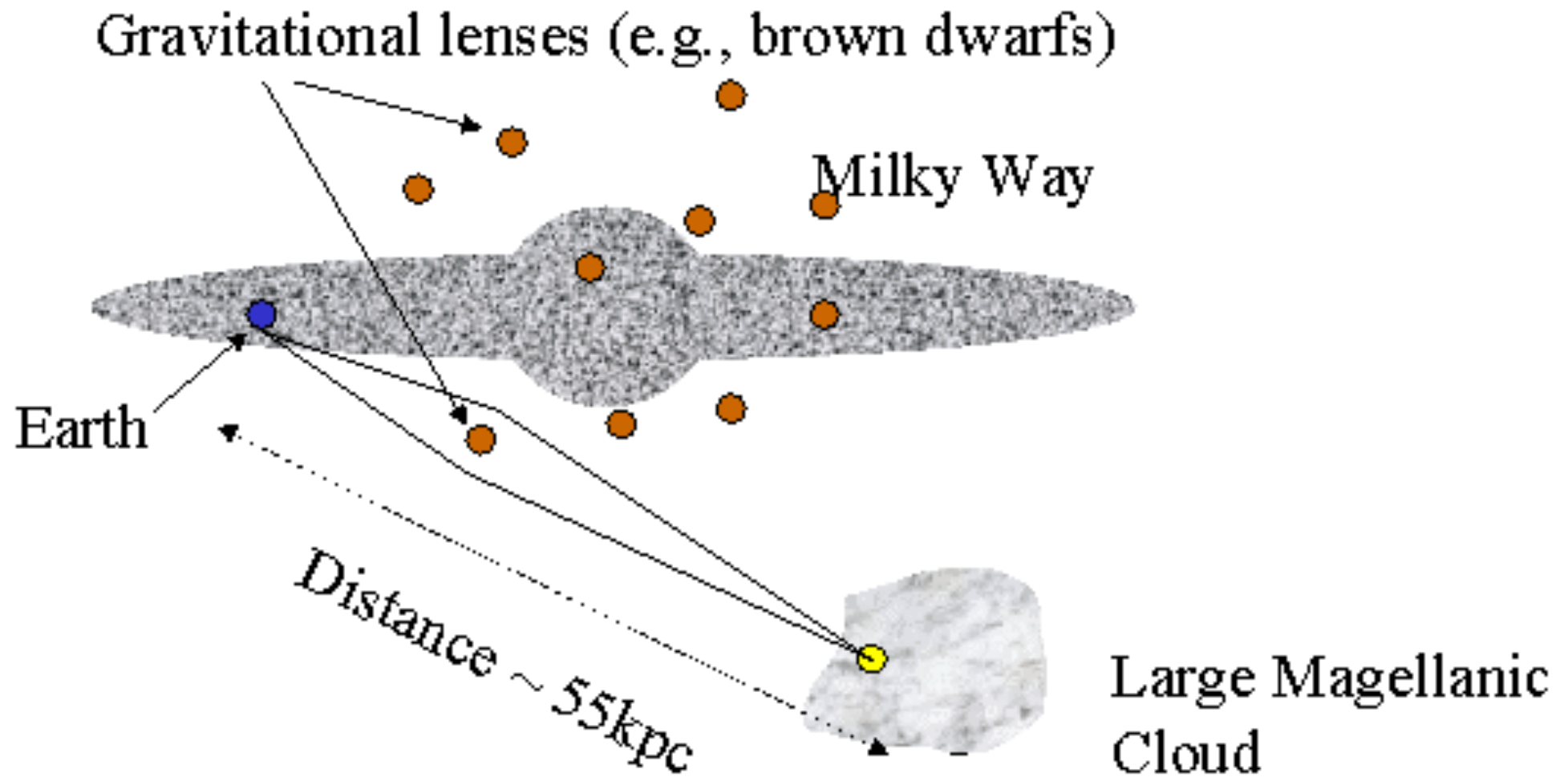


Distinguish MPBH from Stellar BH

- Accretion disks
- Distribution of spins
- Mass distribution \neq IMF
- SBH kicks at formation vs static PBH
- Galaxy formation rate \rightarrow gal. seeds
- Microlensing events of long duration
- GAIA anomalous astrometry
- CMB distortions with PIXIE/PRISM
- Reionization faster in the past
- N-body simulations below $10^2 M_{\text{sun}}$

Signatures of Primordial Black Holes

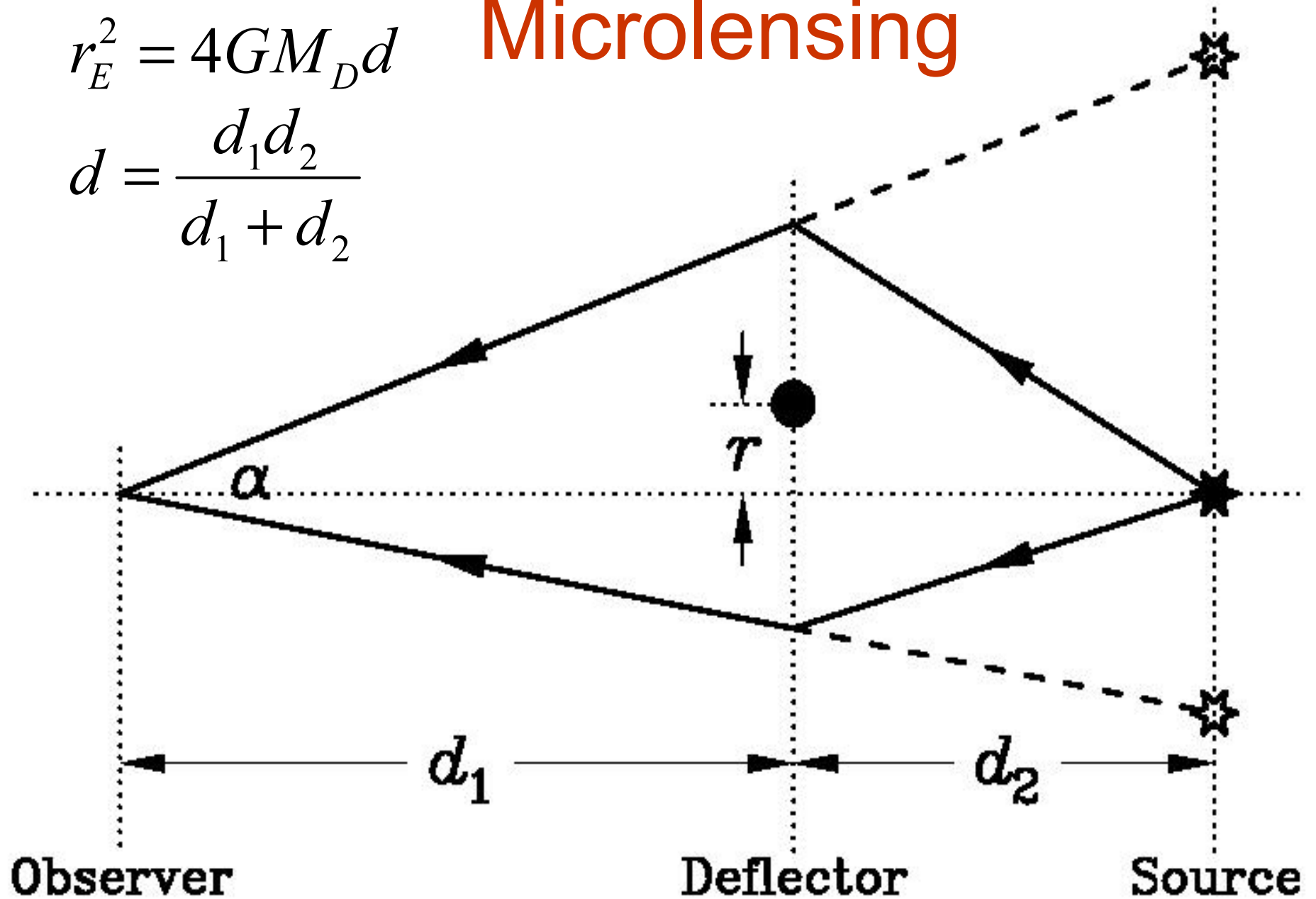
Microlensing



Microlensing

$$r_E^2 = 4GM_D d$$

$$d = \frac{d_1 d_2}{d_1 + d_2}$$



$$A = \frac{2 + u^2}{u\sqrt{4 + u^2}} \quad u = \frac{r}{r_E} \quad \text{amplification}$$

$$\overline{\Delta t} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v} \quad \text{average } \frac{1}{2} \text{ crossing}$$

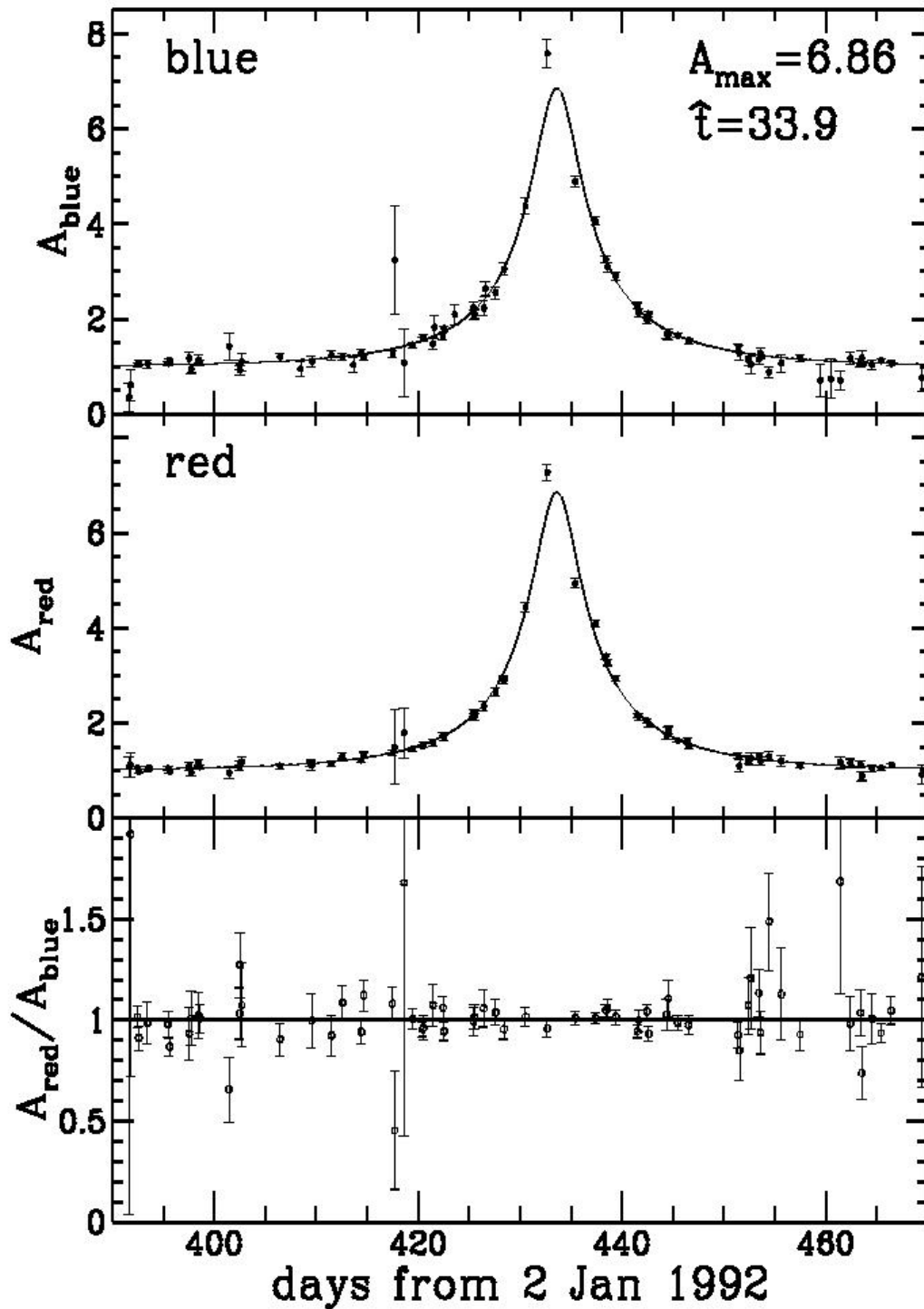
$$M_D = 10 M_{\odot} \quad \Rightarrow \quad \overline{\Delta t} = 1.23 \text{ years}$$

$$M_D = 1 M_{\odot} \quad \Rightarrow \quad \overline{\Delta t} = 5 \text{ months}$$

$$M_D = 0.1 M_{\odot} \quad \Rightarrow \quad \overline{\Delta t} = 1.5 \text{ months}$$

$$M_D = 10^{-2} M_{\odot} \quad \Rightarrow \quad \overline{\Delta t} = 2 \text{ weeks}$$

$$M_D = 10^{-4} M_{\odot} \quad \Rightarrow \quad \overline{\Delta t} = 1.5 \text{ day}$$



symmetric

$$A_{\text{max}} = 7.20 \pm 0.09$$

achromatic

$$\frac{A_{\text{red}}}{A_{\text{blue}}} = 1.00 \pm 0.05$$

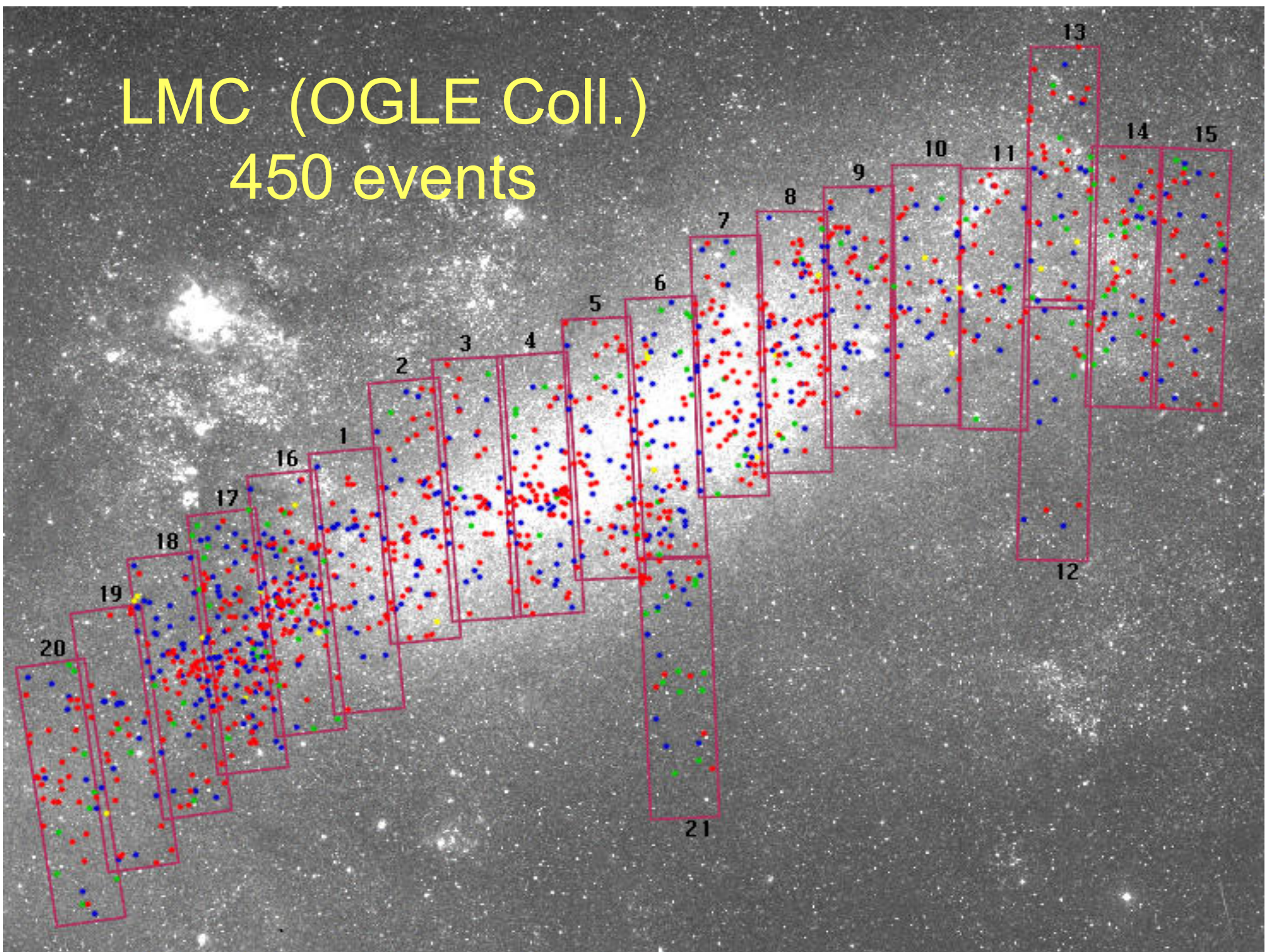
unique

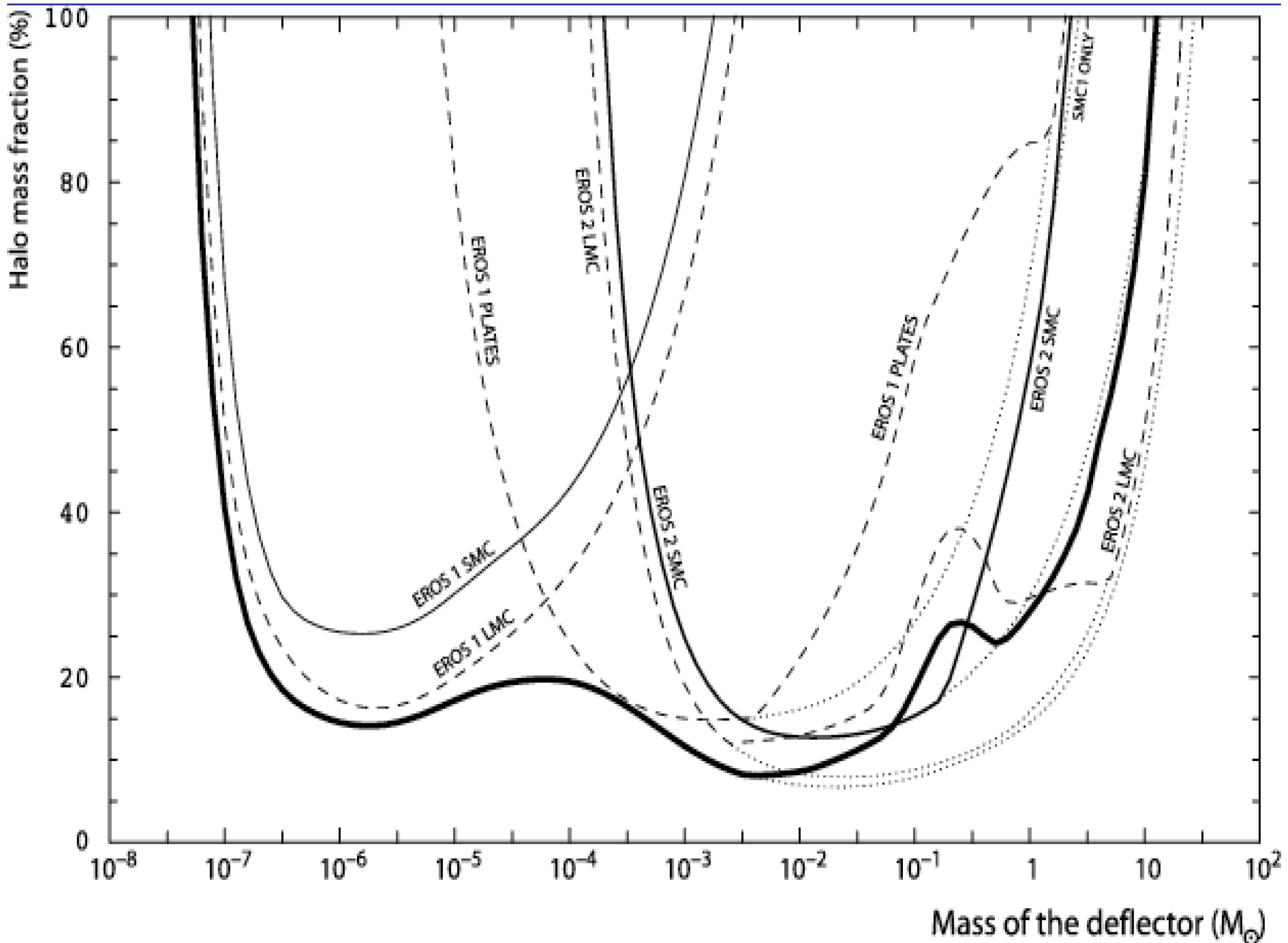
$$t = 34.8 \pm 0.2 \text{ days}$$

$$\Rightarrow M_D \approx 0.1 M_{\odot}$$

LMC (OGLE Coll.)

450 events

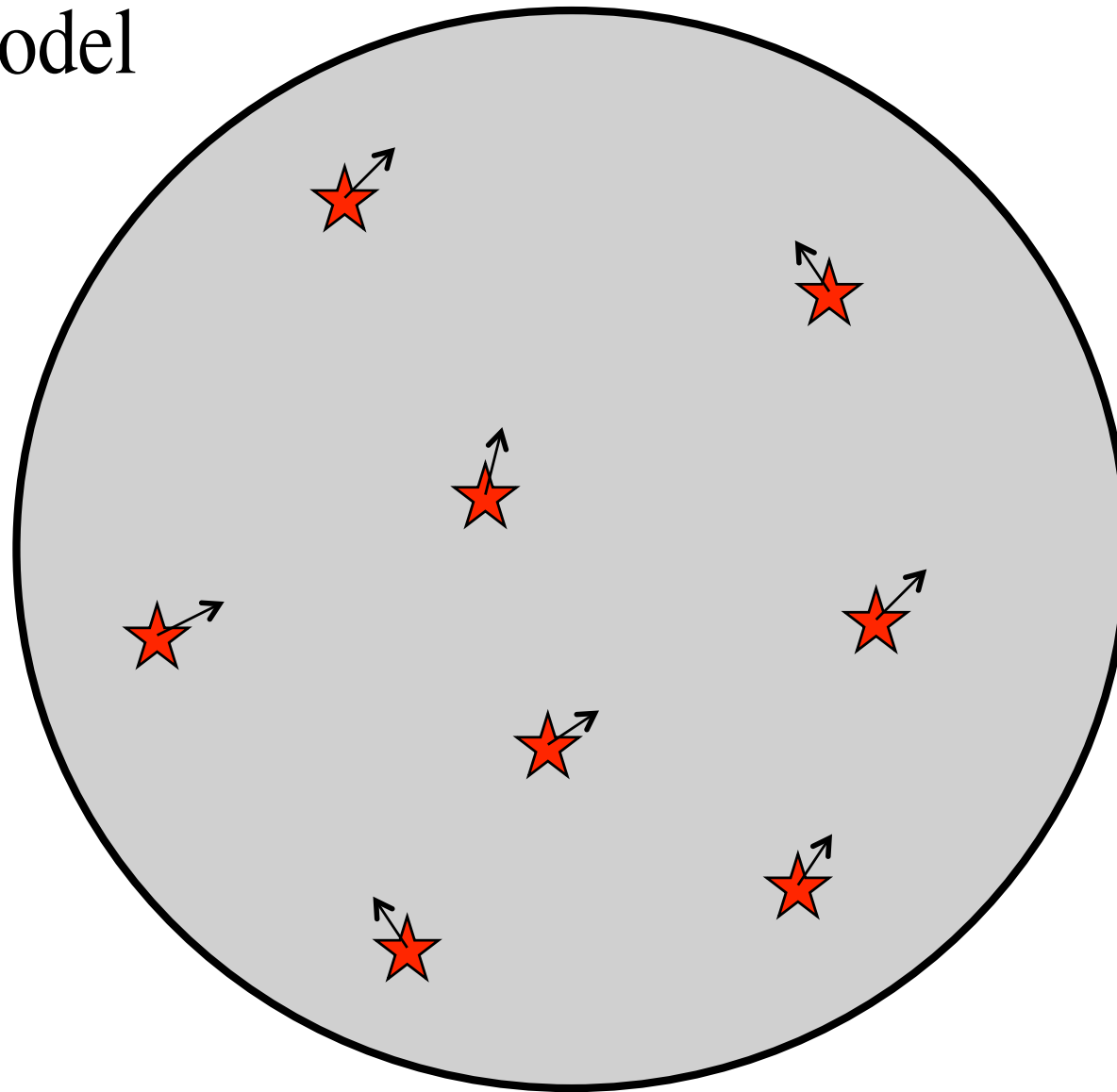




Astrometric Anomalies @ GAIA

GAI A position + velocity anomalies

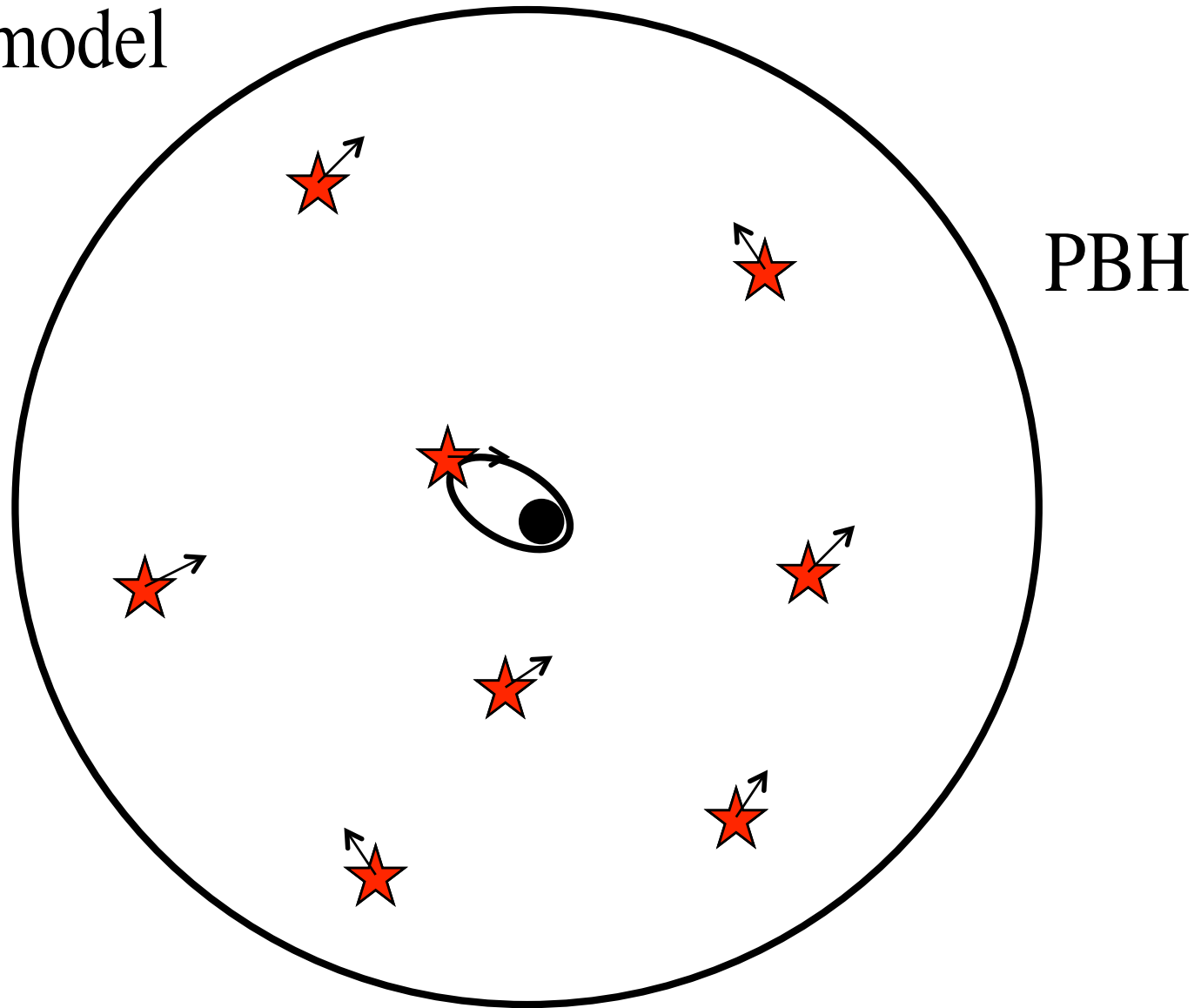
Thomson model



PDM

GAI A position + velocity anomalies

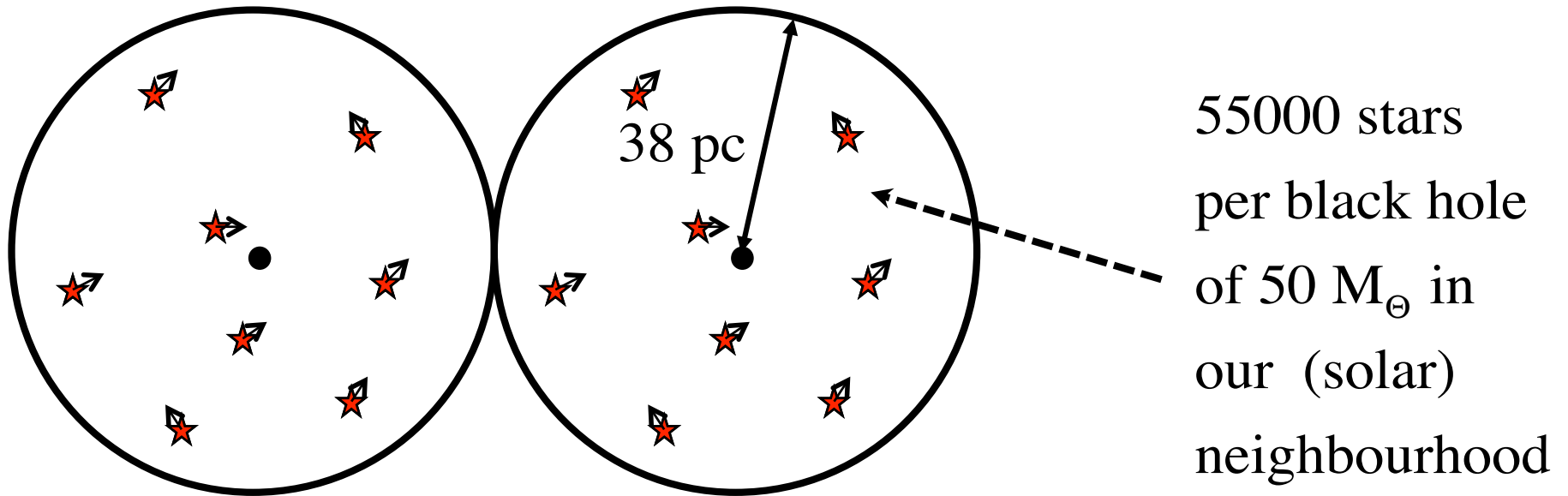
Rutherford model



Average distance between PBH

$$M_{halo MW} (< 50 kpc) = 5.4 \times 10^{11} M_{\odot}$$

$$\bar{\lambda}_{BH} \equiv (\bar{n}_{BH})^{-1/3} = 38 \text{ pc} \left(\frac{M}{50 M_{\odot}} \right)^{1/3}$$



Anomalous accelerations

The acceleration on any given star is due to the surrounding masses. A uniform DM field does not induce an extra force on \star . The \star only feels the presence of other \star s

$$a_i = \frac{GM_{BH}}{b^2} + \sum_j \frac{Gm_j}{r_{ij}^2} \hat{u}_{ij}$$

$$\Delta a = \frac{GM_{BH}}{b^2} = 4 \times 10^{-15} \text{ m s}^{-2} \left(\frac{M}{50 M_{\odot}} \right) \left(\frac{40 \text{ pc}}{b} \right)^2$$

Anomalous velocities & positions

The relative velocity change of a ★ due to PBH, for a 220 km/s relative motion is

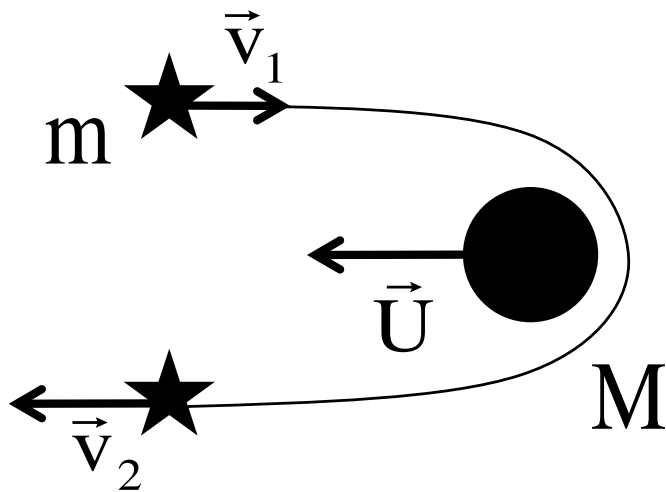
$$\frac{\Delta v}{v} = 2.7 \times 10^{-6} \left(\frac{M}{30 M_{\odot}} \right) \left(\frac{1 pc}{b} \right)^2$$

The relative displacement of a ★ at 1 kpc

$$\frac{\Delta x}{x} = 0.56 \text{ marcsec} \left(\frac{M}{30 M_{\odot}} \right) \left(\frac{1 pc}{b} \right)^2$$

Gravitational slingshot effect

Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the globular cluster.



$$\vec{v}_2 = \frac{2\vec{U} + (1 - m/M)\vec{v}_1}{(1 + m/M)}$$

It may explain large M/L ratios of dSph by ejection of stars in the cluster, $v > v_{\text{esc}}$.

**Grav. Waves
detections
@ aLIGO**

arXiv:1603.05234v1 [astro-ph.CO] 16 Mar 2016

The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

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(Dated: March 17, 2016)

The recent detection by Advanced LIGO of gravitational waves (GW) from the merging of a binary black hole system sets new limits on the merging rates of massive primordial black holes (PBH) that could be a significant fraction or even the totality of the dark matter in the Universe. aLIGO opens the way to the determination of the distribution and clustering of such massive PBH. If PBH clusters have a similar density to the one observed in ultra-faint dwarf galaxies, we find merging rates comparable to aLIGO expectations. Massive PBH dark matter predicts the existence of thousands of those dwarf galaxies where star formation is unlikely because of gas accretion onto PBH, which would possibly provide a solution to the missing satellite and too-big-to-fail problems. Finally, we study the possibility of using aLIGO and future GW antennas to measure the abundance and mass distribution of PBH in the range $[5 - 200] M_{\odot}$ to 10% accuracy.

PACS numbers: 98.80.Cq

Capture and merger rates of m_A and m_B

$$\tau_{\text{PBH}}^{\text{capt}} = (2\pi) n_{\text{PBH}}(m_A) \bar{v} \left(\frac{85\pi}{6\sqrt{2}} \right)^{2/7} \\ \times \frac{G^2 (m_A + m_B)^{10/7} (m_A m_B)^{2/7} c^{18/7}}{c^4 v_{\text{rel}}^{18/7}}$$

$$\tau_{\text{PBH}}^{\text{merg}} = n_{\text{PBH}}(m_A) \left(\frac{3}{2\pi \bar{v}^2} \right)^{3/2} \frac{8\pi^2 G}{3} m_B R_B \bar{v}^2 .$$

$$R_{\text{PBH}} = 2Gm_{\text{PBH}}/c^2.$$

Broad spectrum of masses

$$\rho(m_{\text{PBH}}) = \frac{E_{\text{factor}} \rho_{\text{DM}}^0}{\sqrt{2\pi\sigma_{\text{PBH}}^2}} \exp \left[-\frac{\log^2(m_{\text{PBH}}/\mu_{\text{PBH}})}{2\sigma_{\text{PBH}}^2} \right]$$

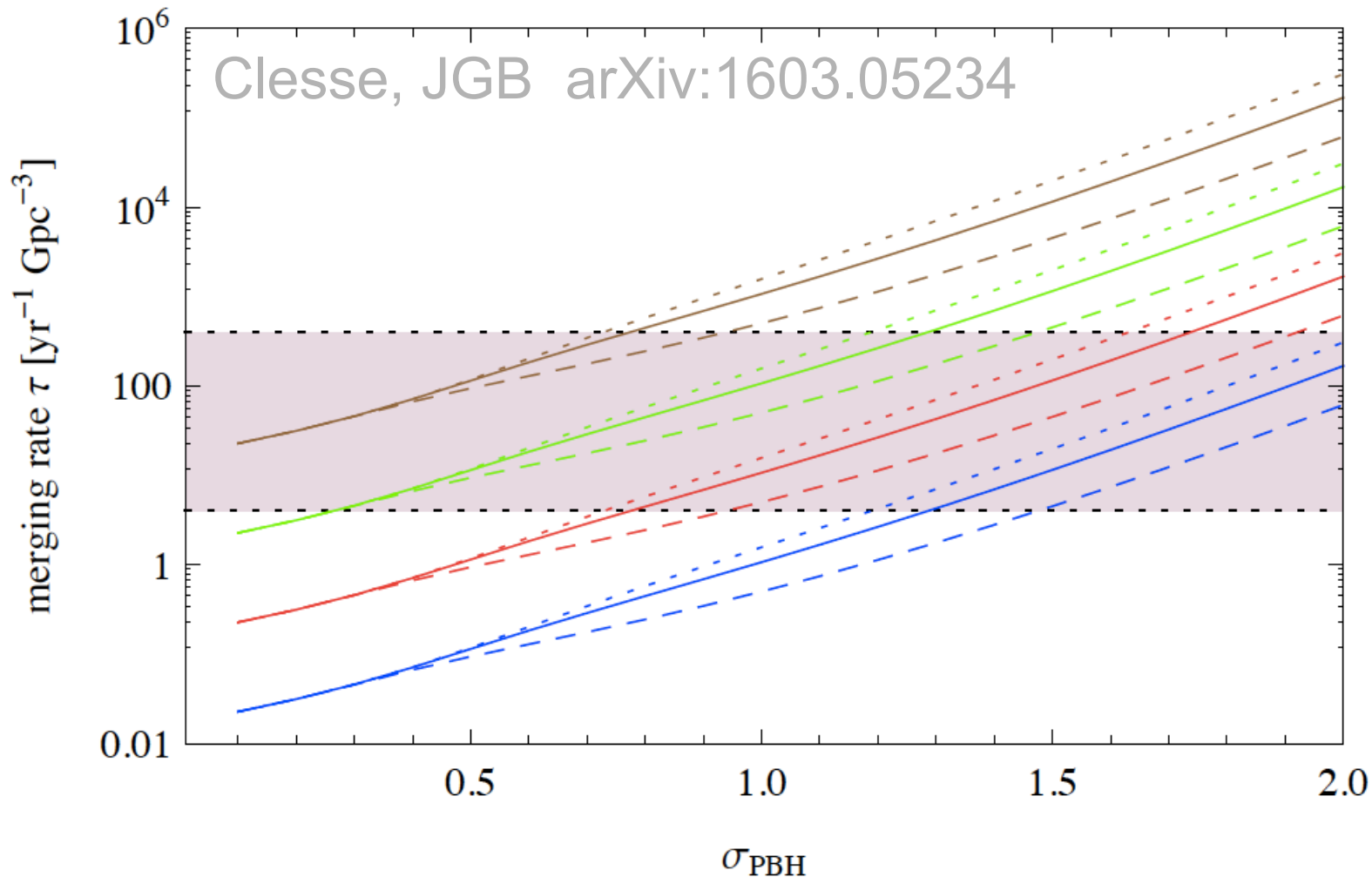
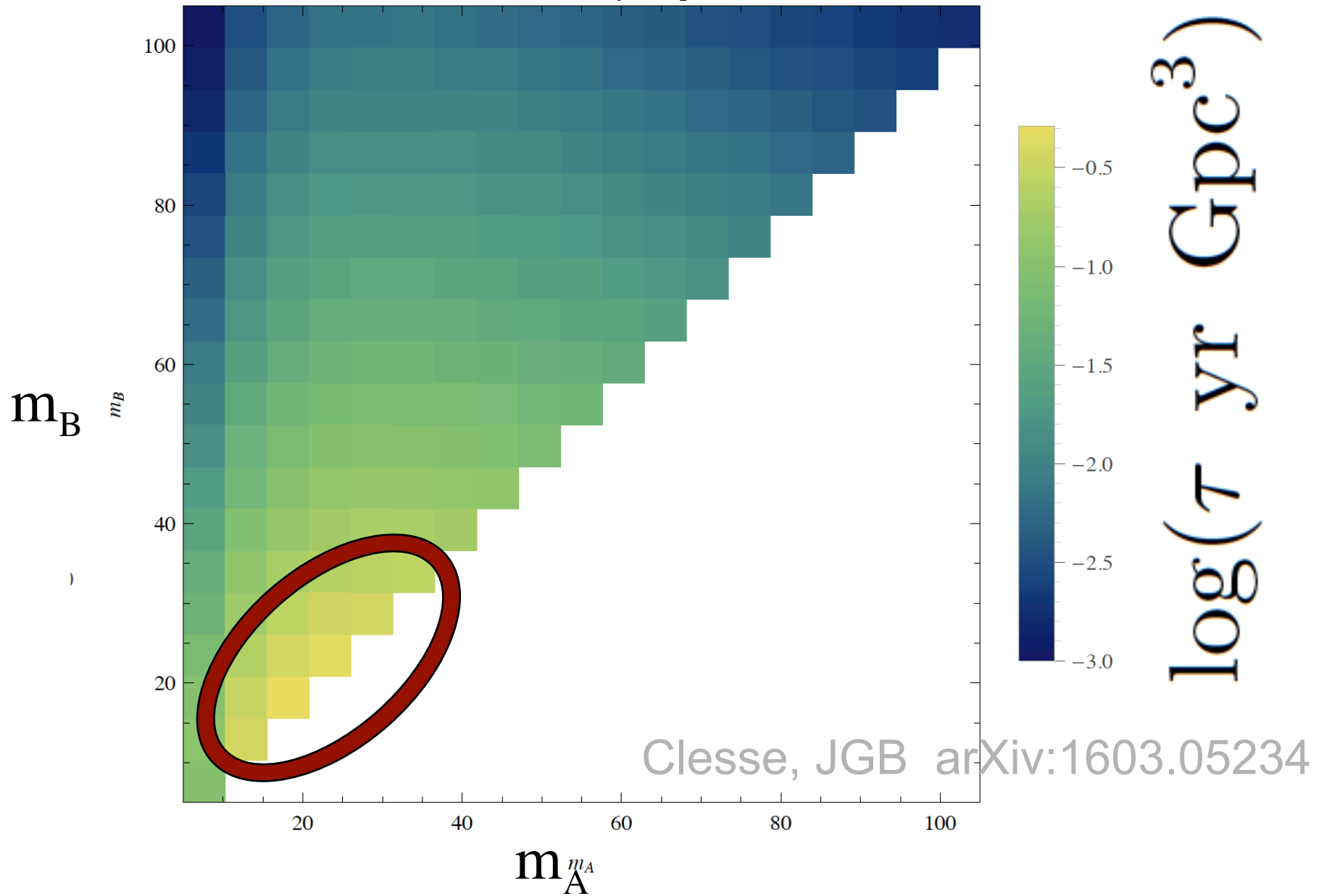


FIG. 2. Merging rate as a function of the width σ_{PBH} of the PBH density spectrum, for different values of the central mass of the distribution $\mu_{\text{PBH}} = 10/30/60M_{\odot}$ (respectively dotted, solid and dashed lines), and of the enhancement factor $E_{\text{factor}} = 10^7/10^8/10^9/10^{10}$ (respectively blue, red, green and brown lines). The colored band corresponds to the bounds inferred by aLIGO.

Merging rates of BHs with masses m_A and m_B

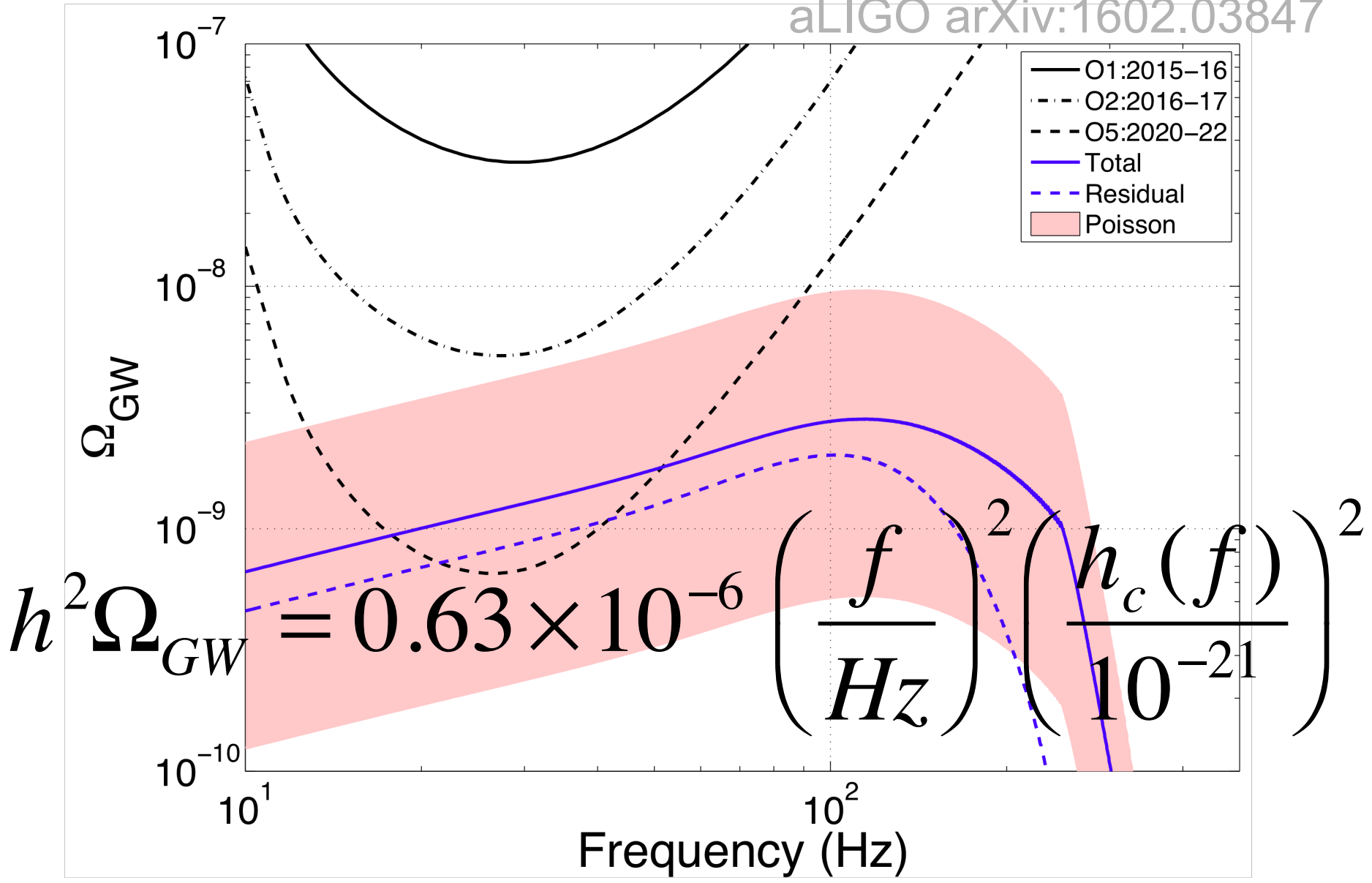
$$\sigma_{\text{PBH}}=0.3, \mu_{\text{PBH}}=30, E_{\text{factor}}=10^{10}$$
$$\text{total rate } \sigma = 10 \text{ yr}^{-1} \text{Gpc}^{-3}$$



Stochastic Background Grav. Waves

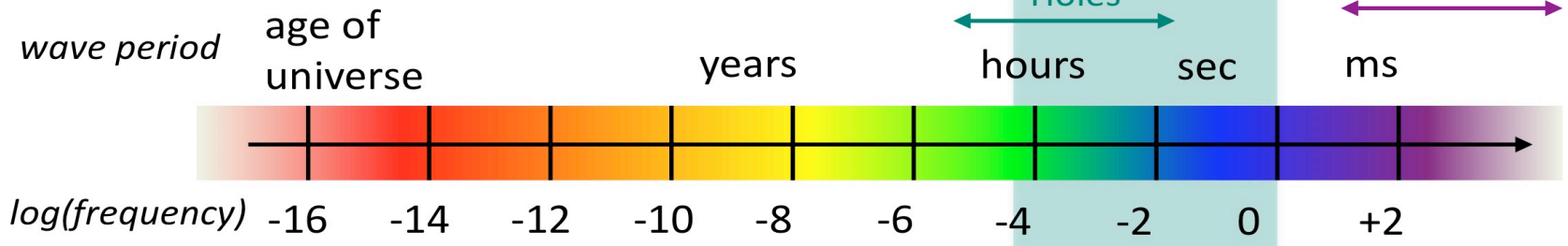
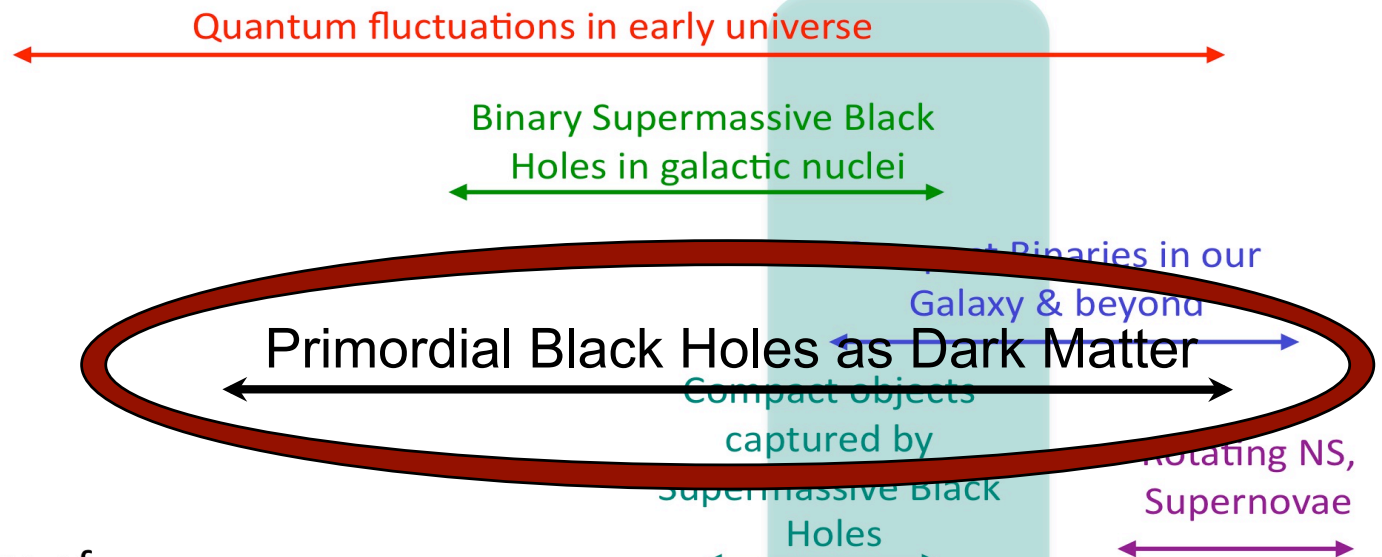
Stochastic Background from MPBH

aLIGO arXiv:1602.03847

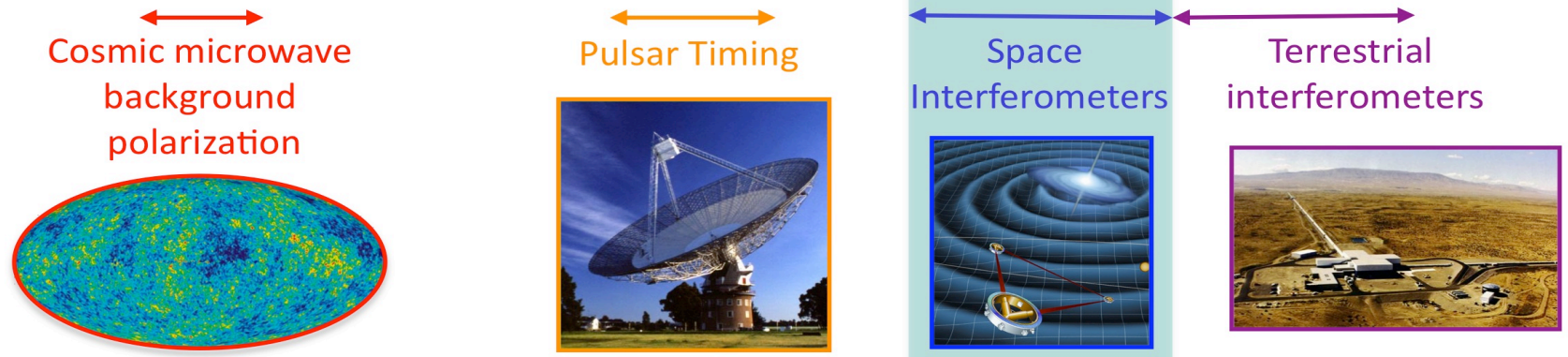


The Gravitational Wave Spectrum

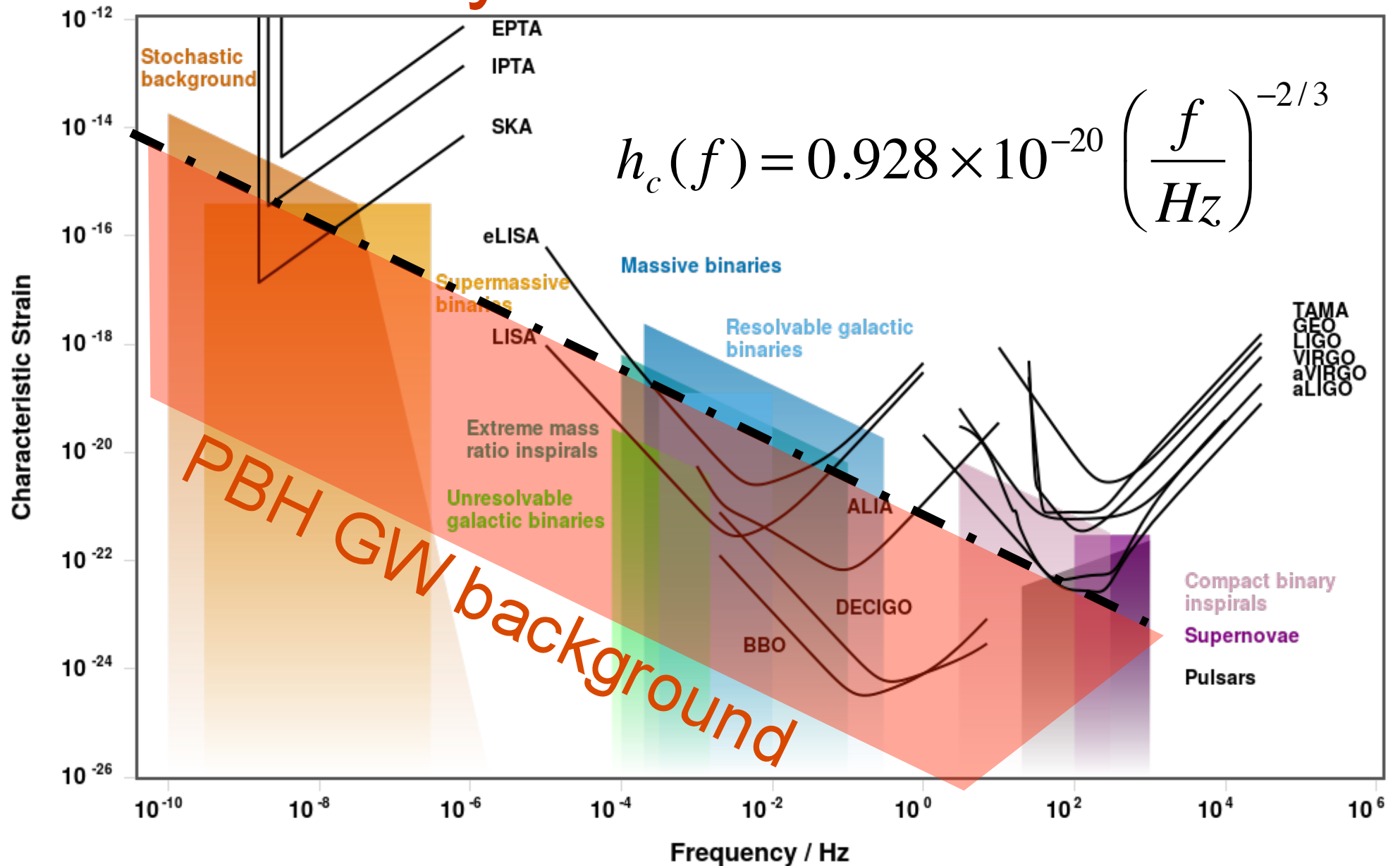
Sources



Detectors



Sensitivity of future GW antennas



Discussion

Signatures of MPBH as DM

- Seeds of galaxies at high- z
- Reionization starts early
- Larger galaxies form earlier than Λ CDM
- Massive BH at centers QSO @ $z > 6$
- Growth of structure on small scales
- Ultra Luminous X-ray Transients
- MPBH in Andromeda (Chandra)
- GW from inspiraling BH (LIGO)
- Substructure and too-big-to-fail probl.
- Total integrated mass = Ω_M

Future tests

- GAIA positions and velocities of stars
- CMB distortions with CORE+
- GW from PBH mergers with LIGO
- Growth of structure on small scales
- Reionization history with SKA
- Direct detection from astrophysics (GAIA, X-rays and gamma-rays)
- SN or GRB lensing on MPBH
- Microlensing (long duration events)
- Stochastic Grav. Wave Background

Conclusions

Massive Primordial Black Holes could account for all the DM we measure in rotation curves of galaxies and in clusters of galaxies and LSS.

Λ CDM N-body simulations never reach the 100 solar mass particle resolution, so for them PBH is as good as PDM.

There are many ways to test this idea in the near future from CMB, LSS, X-rays and GW.