Signatures of Primordial Black Holes as Dark Matter

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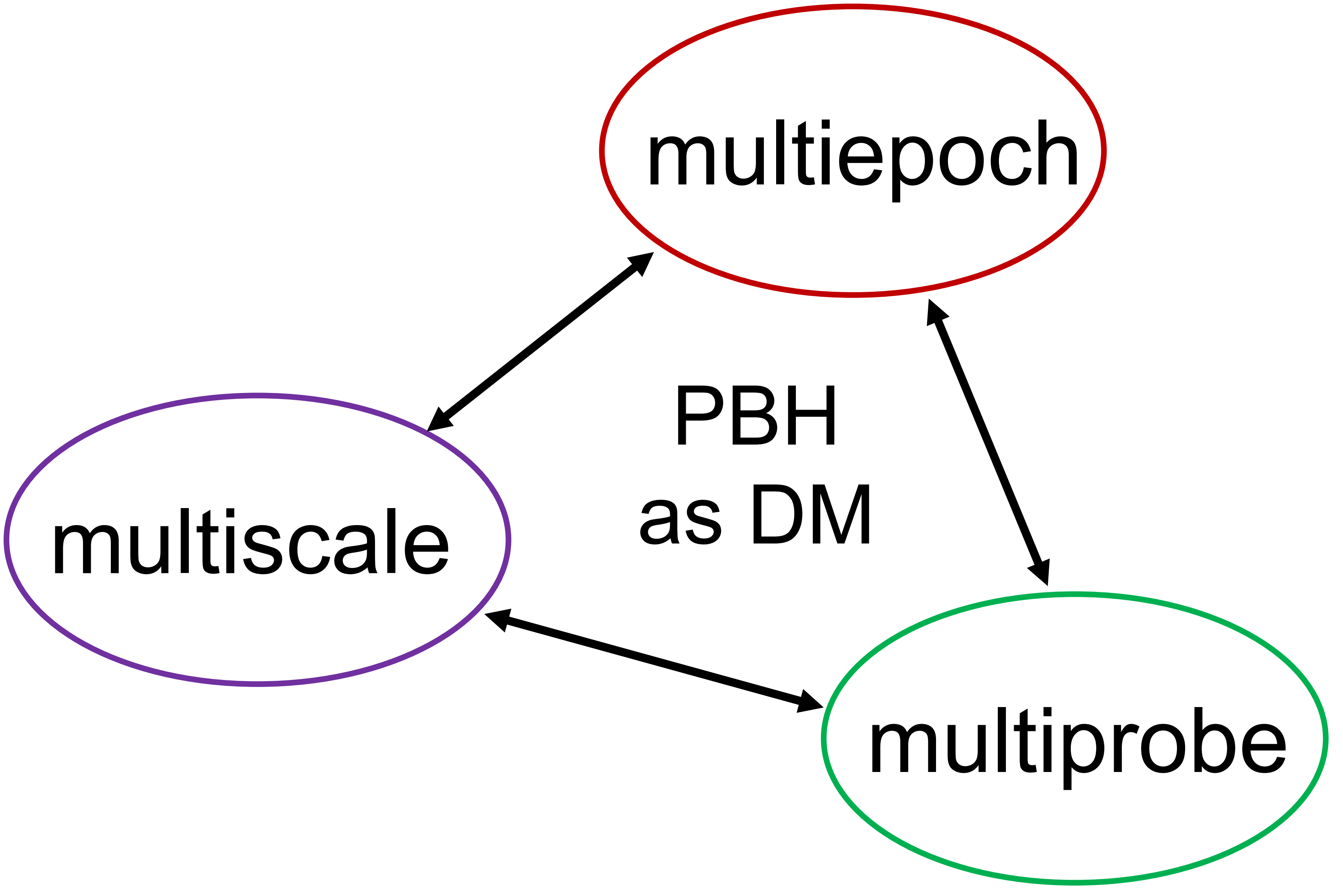
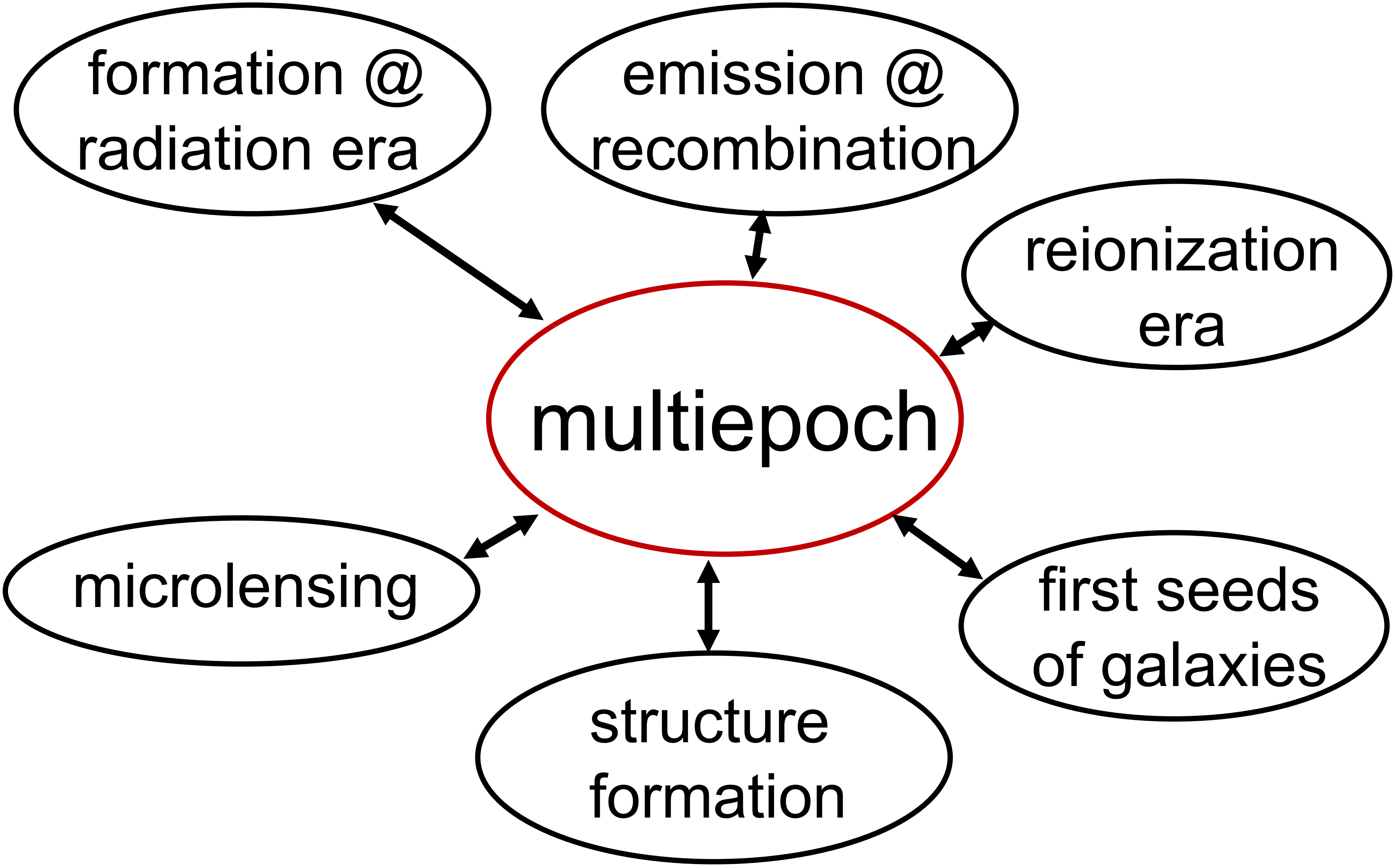
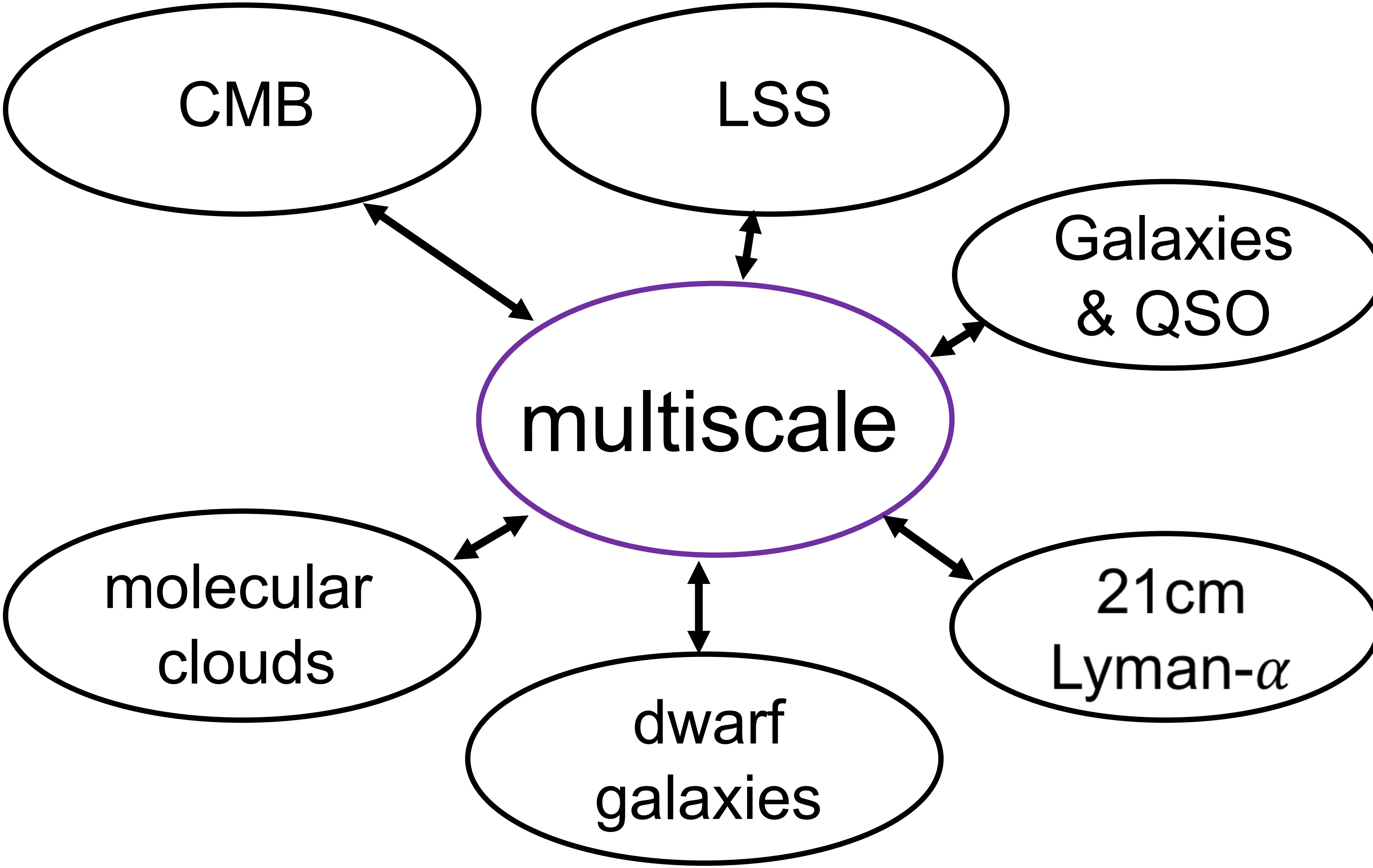
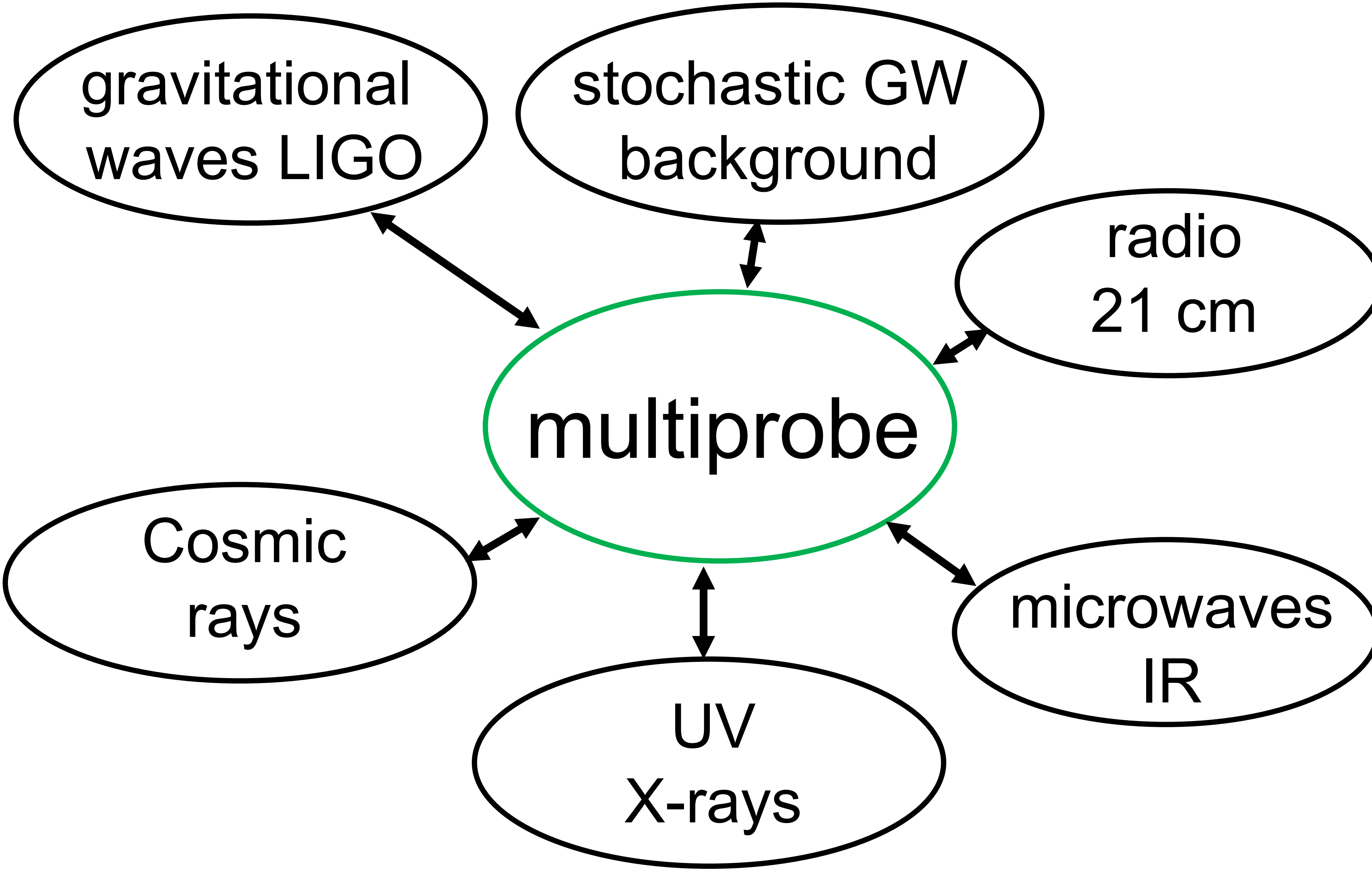
Outline

- PBH = multiepoch-multiscale-multiprobe
- Early universe formation scenarios
- Signatures of PBH as DM
- Gravitational waves (mergers & background)
- Small scale structure (e.g. dwarf spheroidals)
- Early Galaxy formation (origin SMBH)
- Gamma-ray + X-ray + CIR background
- Long duration microlensing events
- Summary


multiepoch
PBH
as DM
multiscale
multiprobe


formation @
radiation era
emission @
recombination
reionization
era
multiepoch
microlensing
first seeds
of galaxies
structure
formation


CMB
LSS
Galaxies & QSO
multiscale
molecular clouds
dwarf galaxies
21cm Lyman-α


gravitational waves LIGO
stochastic GW background
radio 21 cm
multiprobe
Cosmic rays
UV X-rays
microwaves IR

PBH

formation scenarios

PBH-genesis mechanisms

- Fluctuations in the Early Universe

Zeldovich-Novikov (1966), Carr-Hawking (1974), Chapline (1975)

- Phase transitions: e.g. Quark-Hadron 1 $M_\odot$

Khlopov et al. (1985), Dolgov-Silk (1993), Jedamzik (1997), Byrnes et al. (2018)

- Topological defects. $M_{PBH} \sim 10^{-10}\ M_\odot$

Deng-Garriga-Vilenkin (2017)

- BE Condensate fragmentation. $10^{-10}\ M_\odot$

Cotner-Kusenko (2017)

- Higgs vacuum instability. $10^{-10}\ M_\odot$

Espinosa-Racco-Riotto (2017)

PBH from inflation

- Large peaks in curvature power spectrum

  - Hybrid inflation. 1 $M_\odot$ + $10^{-2} – 10^{2}$ $M_\odot$

JGB-Linde-Wands (1996), Dimopoulos (2005), JGB-Clesse (2015)

  - Axion-gauge inflation. 10^{-10} $M_\odot$ + 1 $M_\odot$

Kawasaki-Kitajima (1996), Bugaev-Klimai (2014), JGB-Peloso-Unal (2016-17)

  - Single field (Higgs) inflation. $10^{-2} – 10^{2}$ $M_\odot$

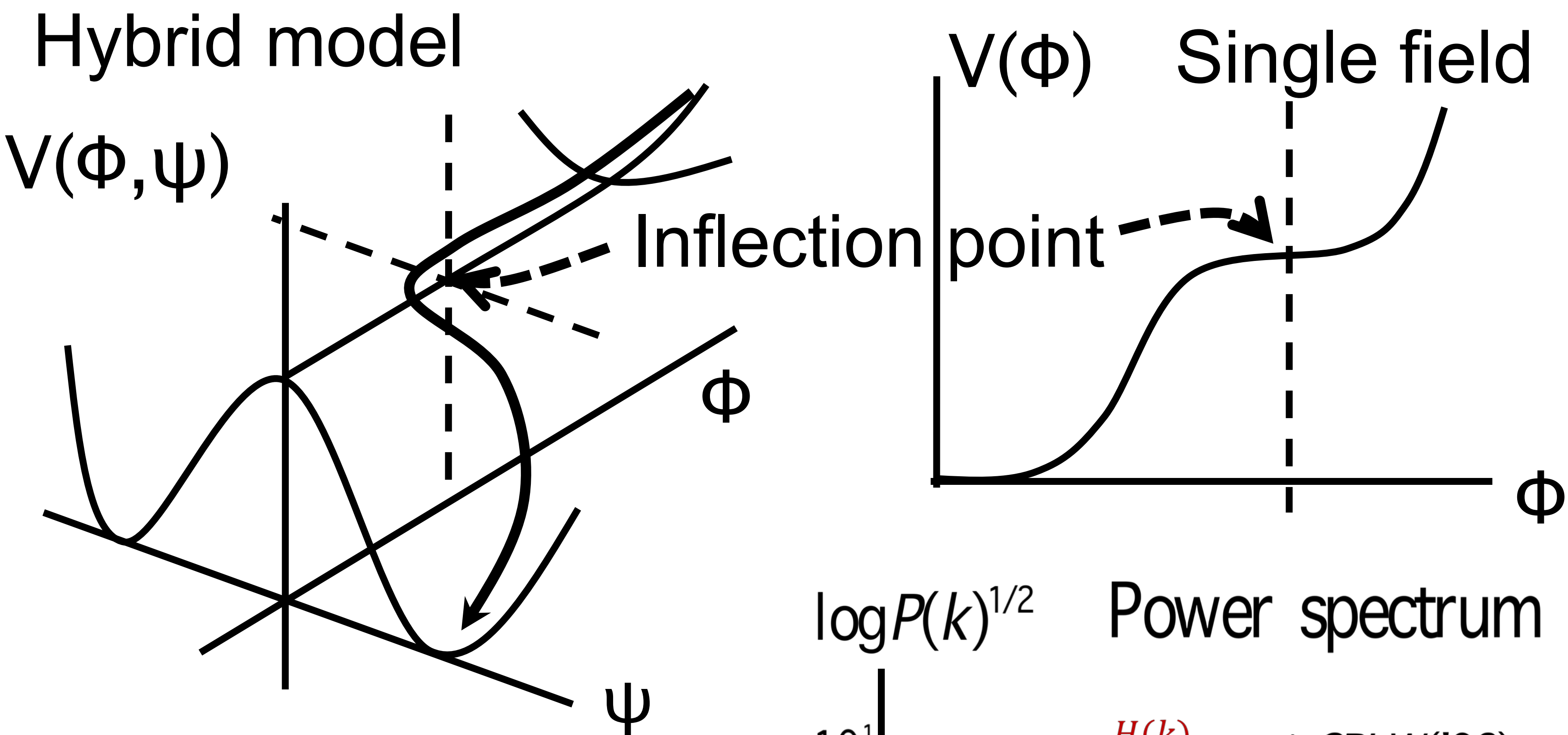
JGB-Ruiz Morales (2017), Ezquiaga et al. (2018)

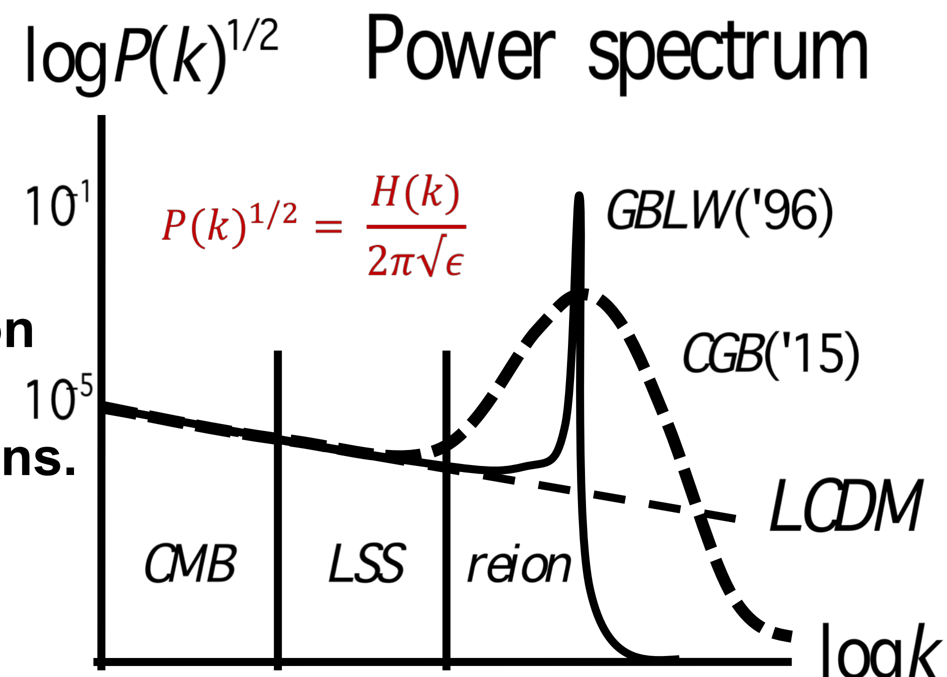
  - Axion-monodromy inflation. 10^{-10} $M_\odot$

Cheng-Lee-Ng (2018)

  - String-based Inflation. 10^{-14} - 10^{-10} $M_\odot$

Cicoli-Diaz-Pedro (2018), Dalianis-Kehagias-Tringas (2018)

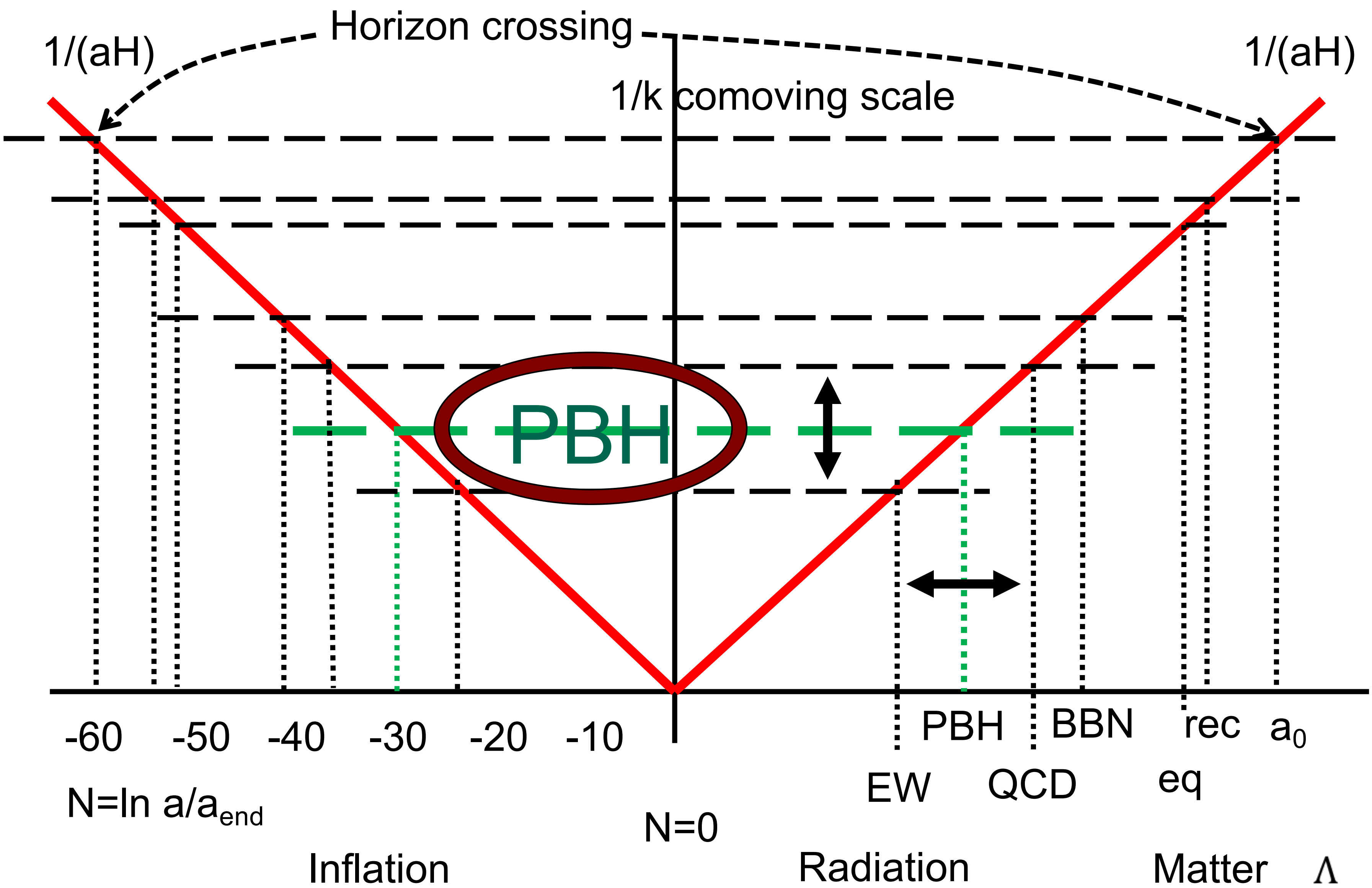




Quantum fluctuations during inflation may have enough amplitude to generate large curvature perturbations.

Quantum diffusion makes a narrow peak become a broad peak in k.

Inflation



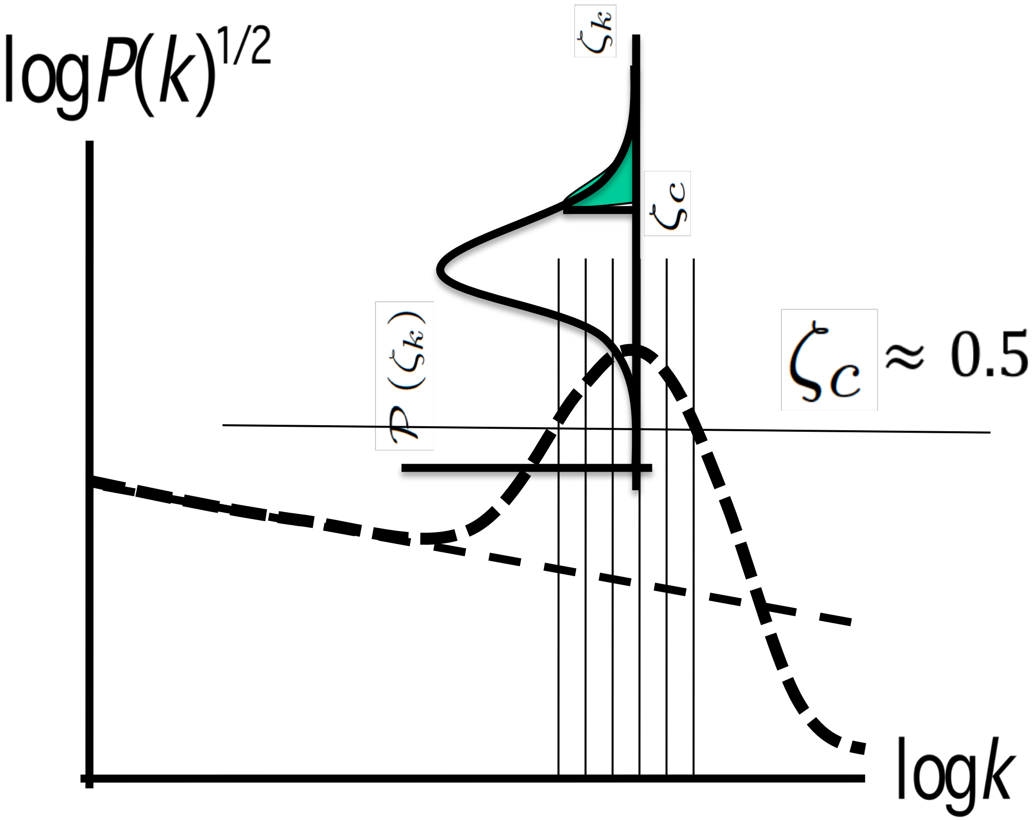
Horizon crossing
1/(aH)
1/(aH)
1/k comoving scale
PBH
-60
-50
-40
-30
-20
-10
N=ln a/a_end
N=0
PBH
BBN
rec
a_0
EW
QCD
eq
Inflation
Radiation
Matter
Λ

Clustering

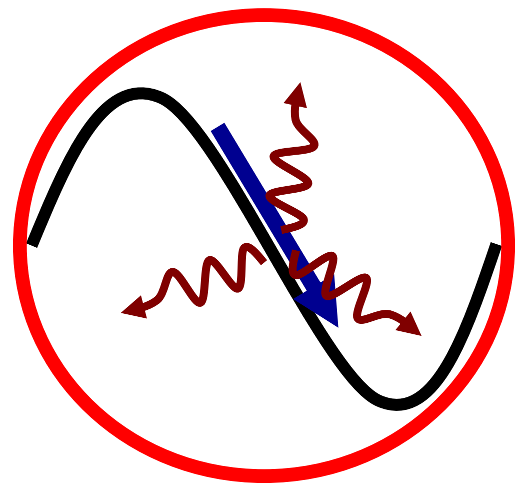
of

PBH

Gravitational Collapse of PBH



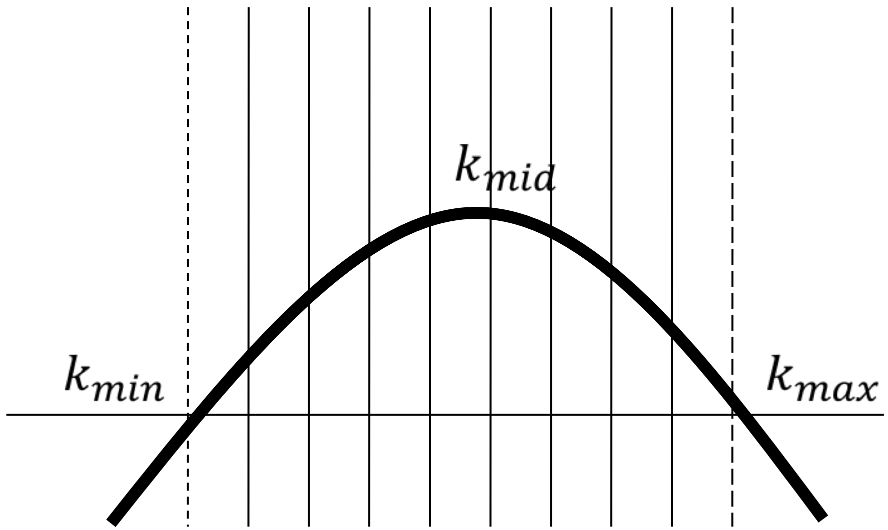
$$\beta^{\rm form}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k)\, d\zeta_k$$



$$M_{PBH} \approx 30 M_{\odot}\, e^{2(N-36)}$$

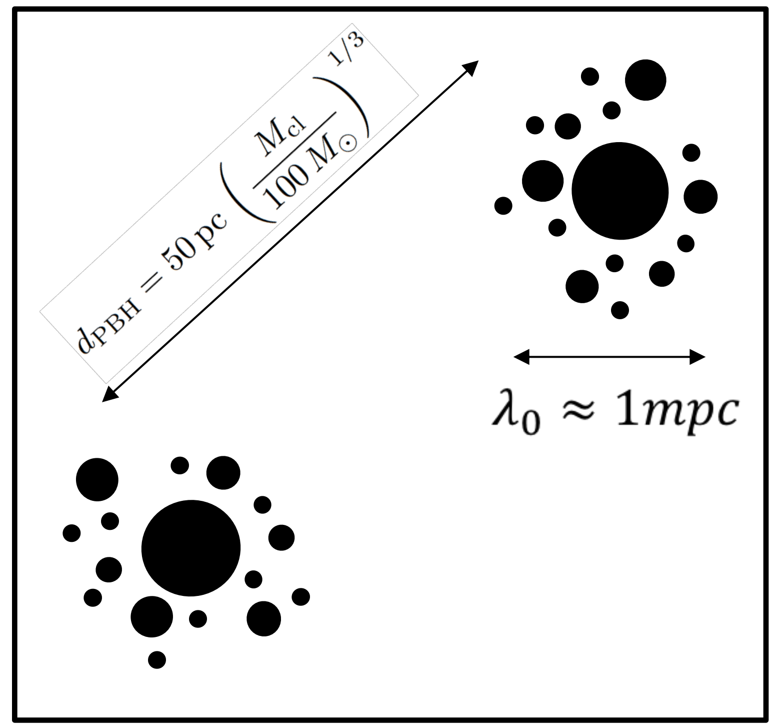
$$\beta(N) = \begin{cases} \mathrm{Erfc}\left(\frac{\zeta_c}{\sqrt{2P_\zeta(N)}}\right), & \text{Gaussian statistics}, \\ \mathrm{Erfc}\left(\sqrt{\frac{1}{2} + \frac{\zeta_c}{\sqrt{2P_\zeta(N)}}}\right), & \chi^2 \ \text{statistics} \end{cases}$$

Clustering properties of PBH



$$\beta(\nu) = \mathrm{erfc}\left(\nu/\sqrt{2}\right) \simeq \sqrt{\frac{2}{\pi}}\frac{e^{-\nu^2/2}}{\nu}$$

$$N_{\rm cl} = \frac{10}{7}\,\beta(\nu)\,e^{3\nu^2/4} \sim 2000 \qquad \nu = \frac{\zeta_c}{\sigma_k} \approx 6$$



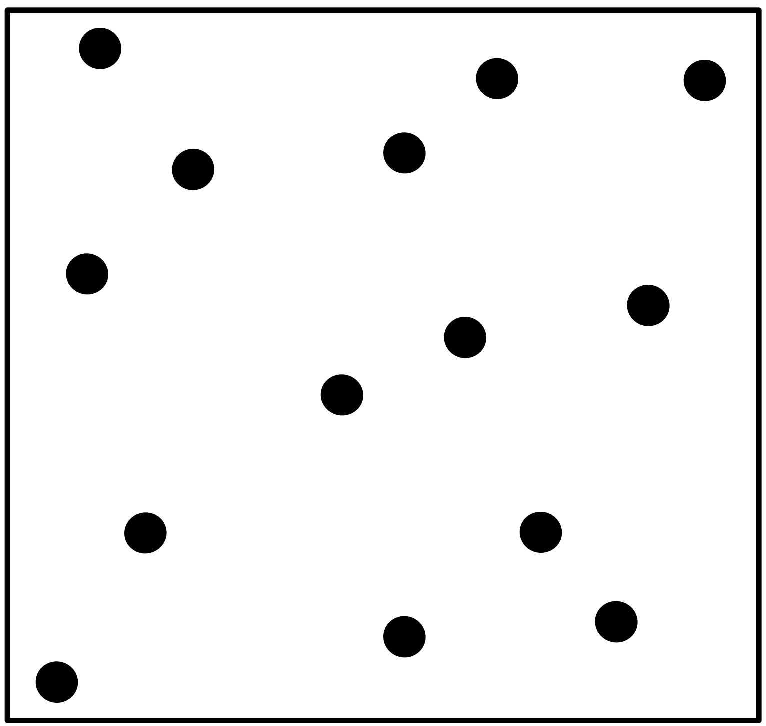
$$\lambda(z_f) = \frac{d_H(z_f)}{\beta(z_f)^{1/3}} \sim 1.2\times10^5\ {\rm km}\left(\frac{6\times10^{11}}{1+z_f}\right)^{5/3}$$

$$\beta(z_f) \sim 3\times10^{-9}\left(\frac{6\times10^{11}}{1+z_f}\right)$$

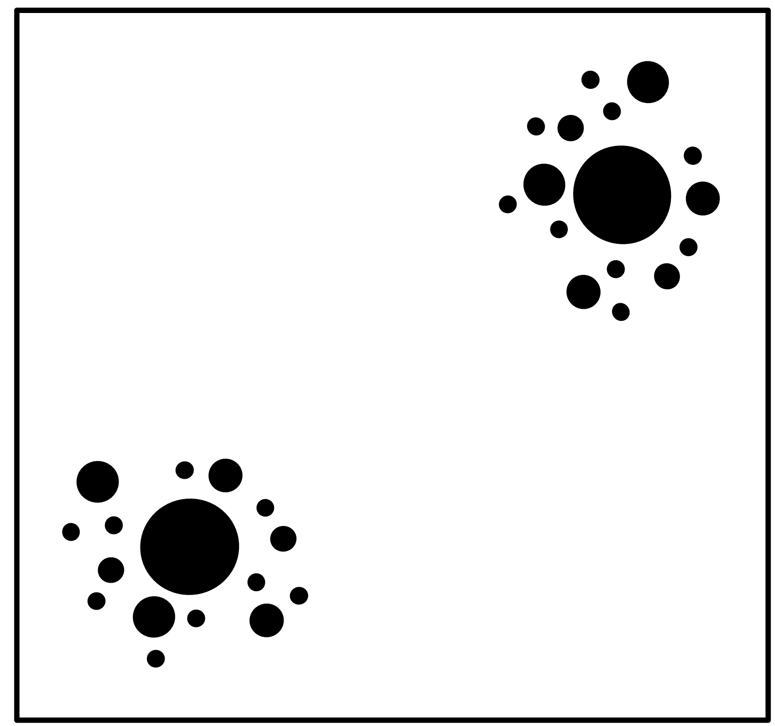
$$M_{\rm PBH} \sim 20\,M_\odot\left(\frac{6\times10^{11}}{1+z_f}\right)^2$$

Inflationary predictions

- Lognormal wide-mass distribution   JGB & Clesse (2017)
- Clusters of PBH: N_{cl} ~100-1000 , comoving size ~1mpc



uniform single-mass
is already ruled out



clustered wide-mass
is still viable

Future experimental tests of PBH

- Seeds of galaxies and QSO at high redshift
- Spectral distortions of the CMB
- Microlensing by uniform + clustered PBH populations
- Massive PBH slingshot stars out of Dwarf Spheroidals
- GAIA anomalies in tidal streams
- SN lensing magnification bias

EM ↑ GW ↓

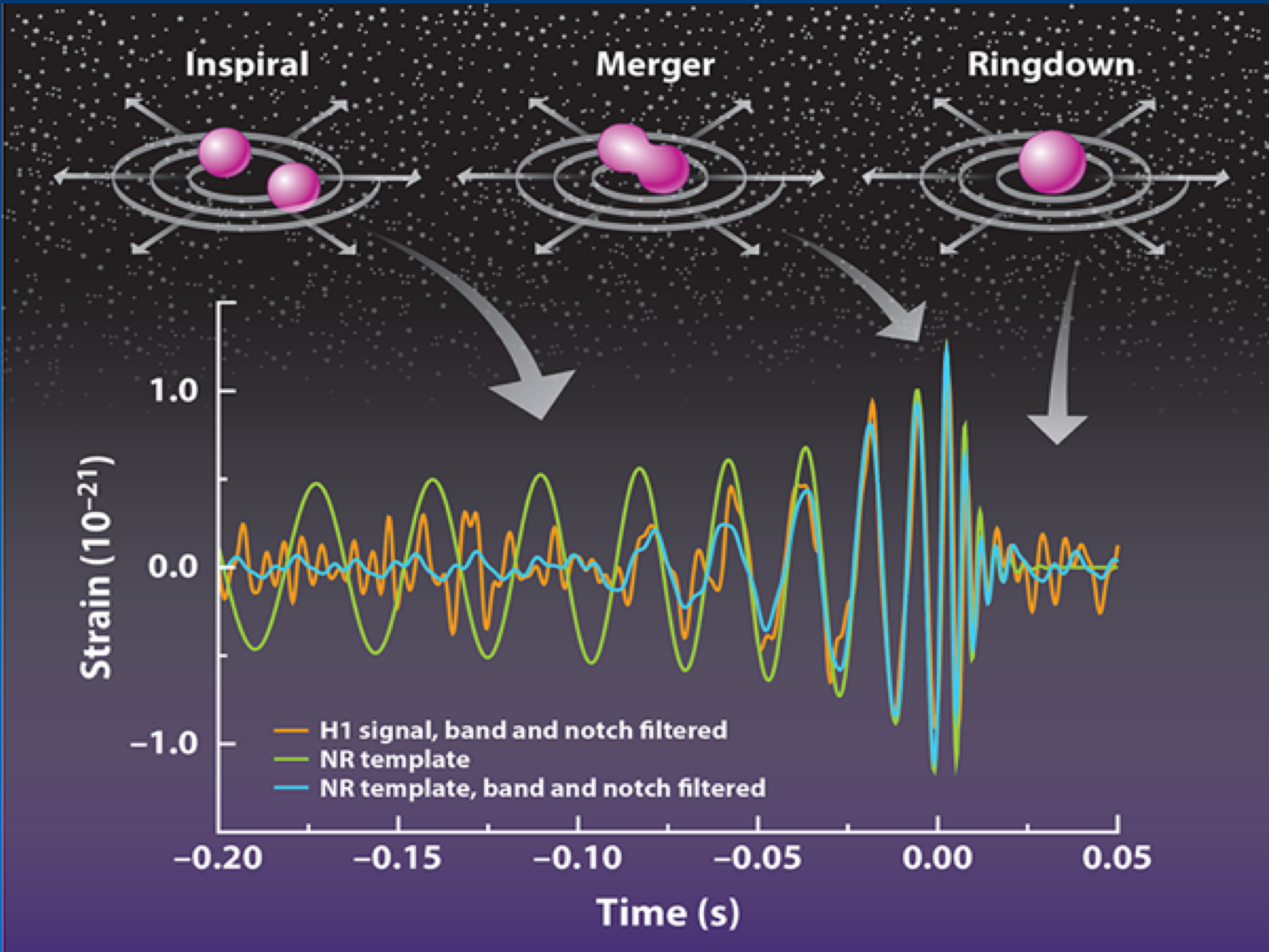
- Spin distribution of PBH in clusters and in background
- Second-order source of GW at PBH formation → LISA
- Stochastic BGW from PBH mergers since recombination
- Individual mergers in compact PBH clusters → LIGO
- GW bursts from hyperbolic close encounters of PBH

Signatures PBH as DM

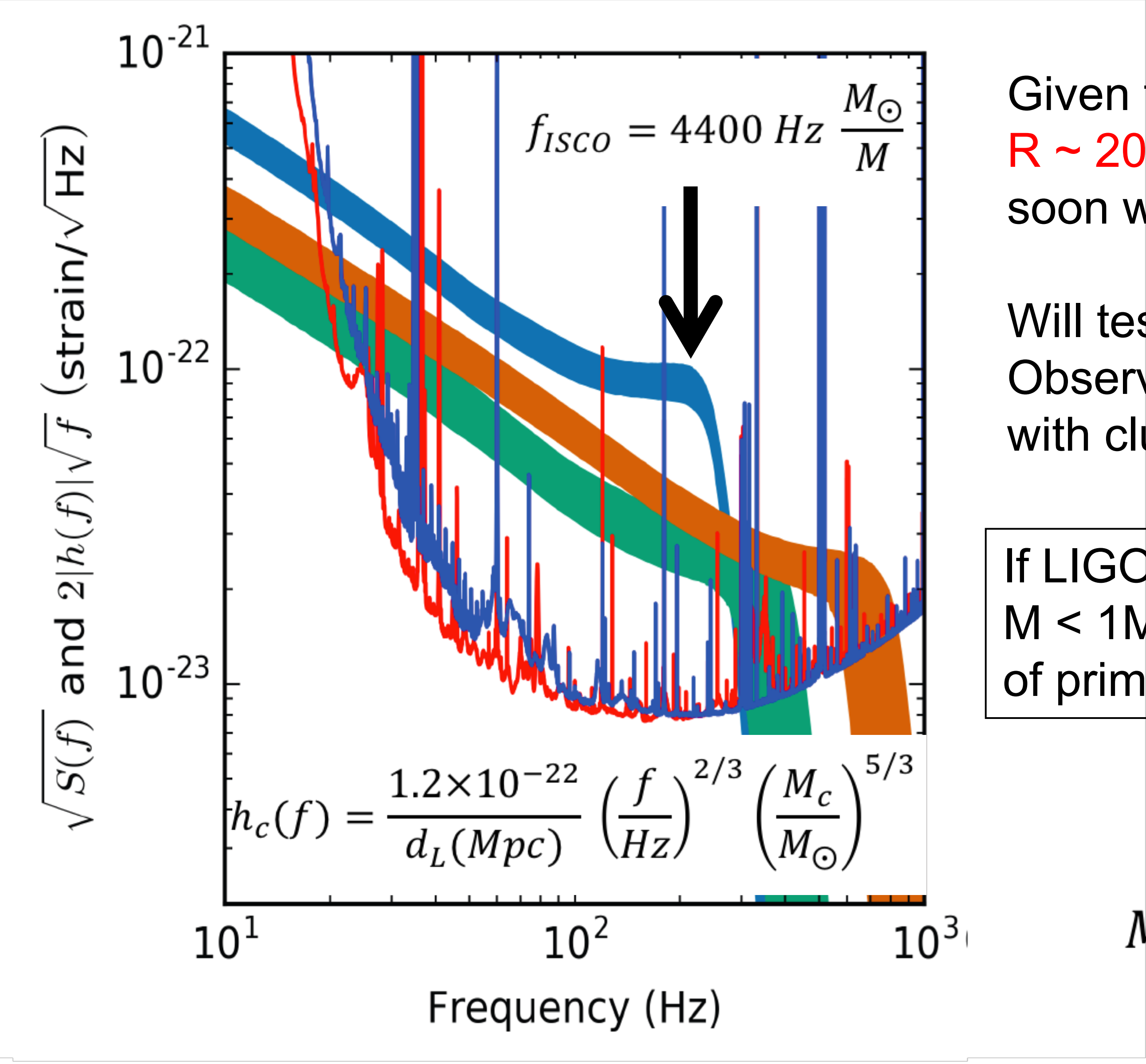
Signatures of PBH as DM

- GW emission by inspiralling BH in clusters
- Seeds for galaxy formation (SMBH in QSO)
- Origin of small scale structure (dwarf gals.)
- Chandra Deep Field (z ~ 10)
- Smooth reionization (z ~ 6-15).
- Correlations of X-ray and CIRB fluct.
- IMBH in dSph + Molecular clouds
- Long duration microlensing events

BBH mergers detected by LIGO



LIGO events



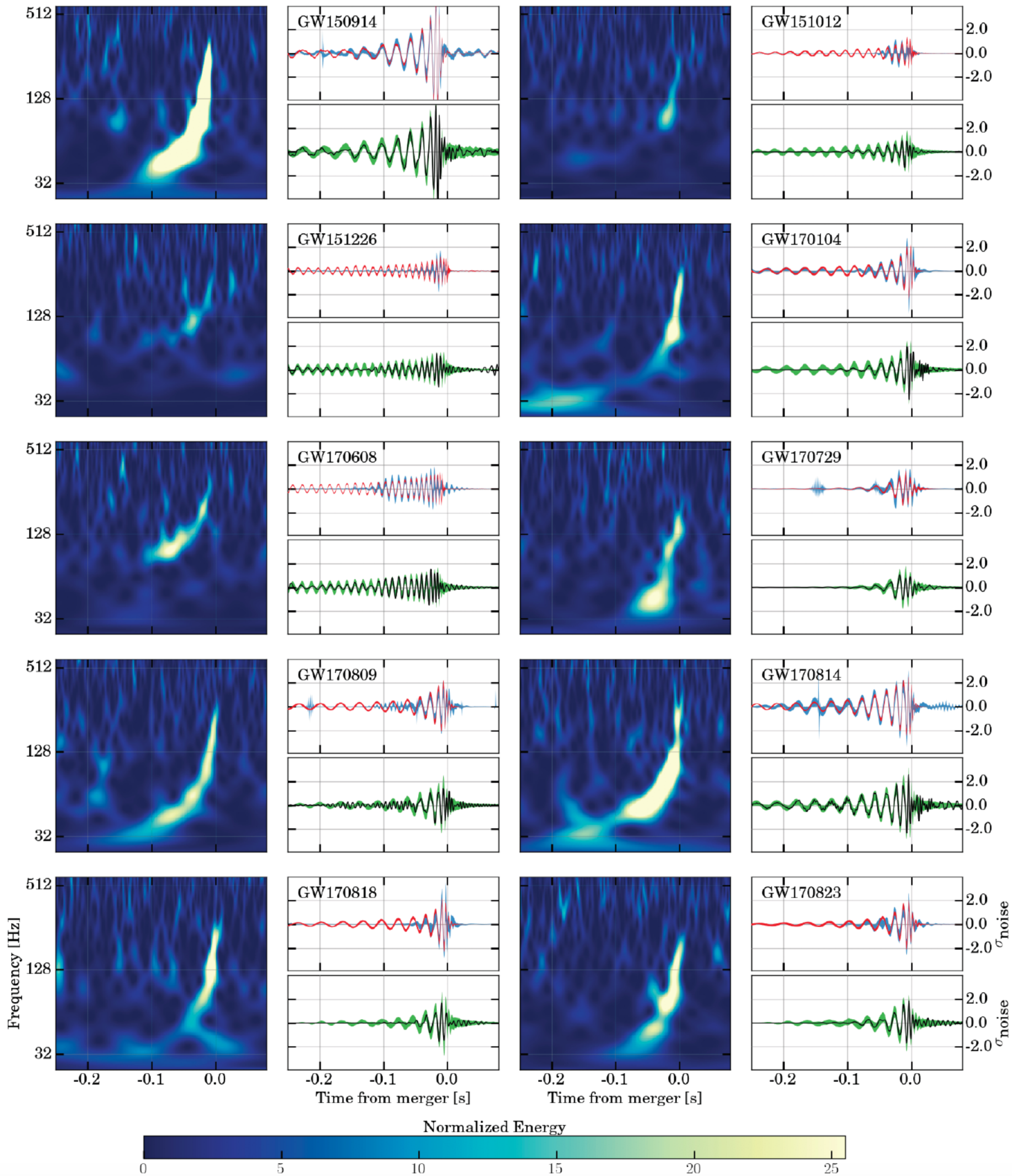
Given the present rate
R ~ 20-200 events/yr/Gpc^3
soon will have MANY events.

Will test lognormal distribution.
Observed rate of events is OK
with clustered wide-mass distr.

If LIGO detects a single BH with M < 1Msun it will necessarily be of primordial origin, not stellar.

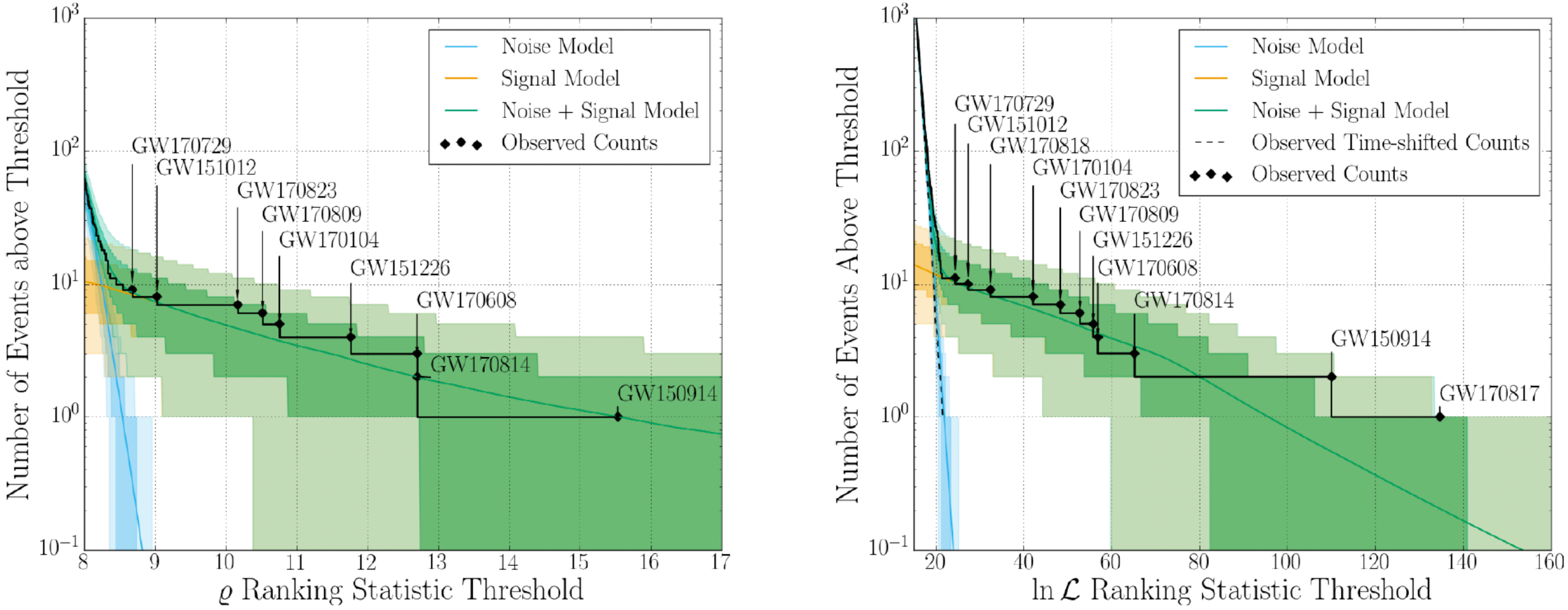
Chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$



GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
Frequency [Hz]
512
128
32
2.0
0.0
-2.0
σ noise
-0.2
-0.1
0.0
Time from merger [s]
Normalized Energy
0
5
10
15
20
25

Distribution of LIGO BHB

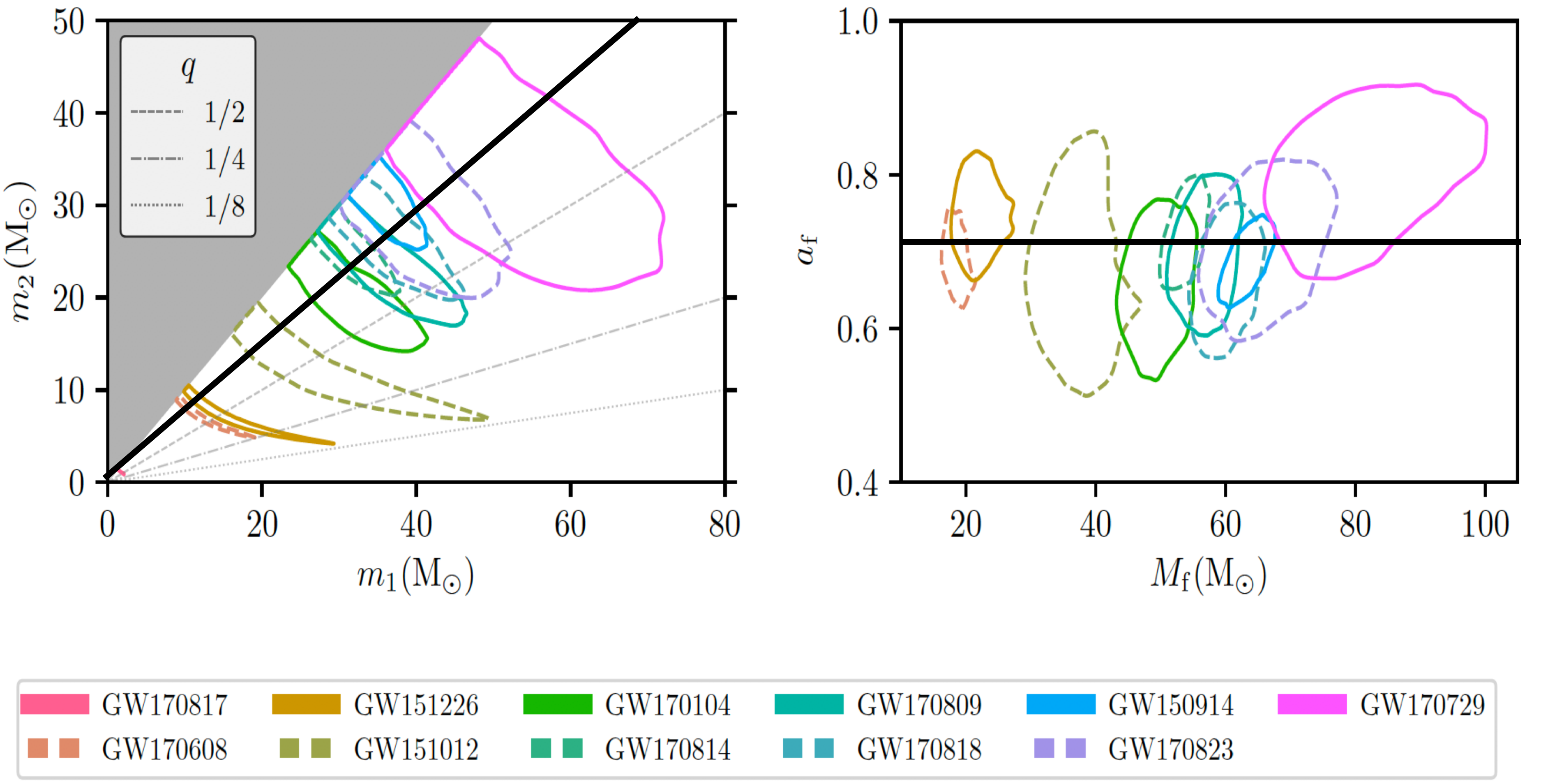


Distribution of LIGO BHB

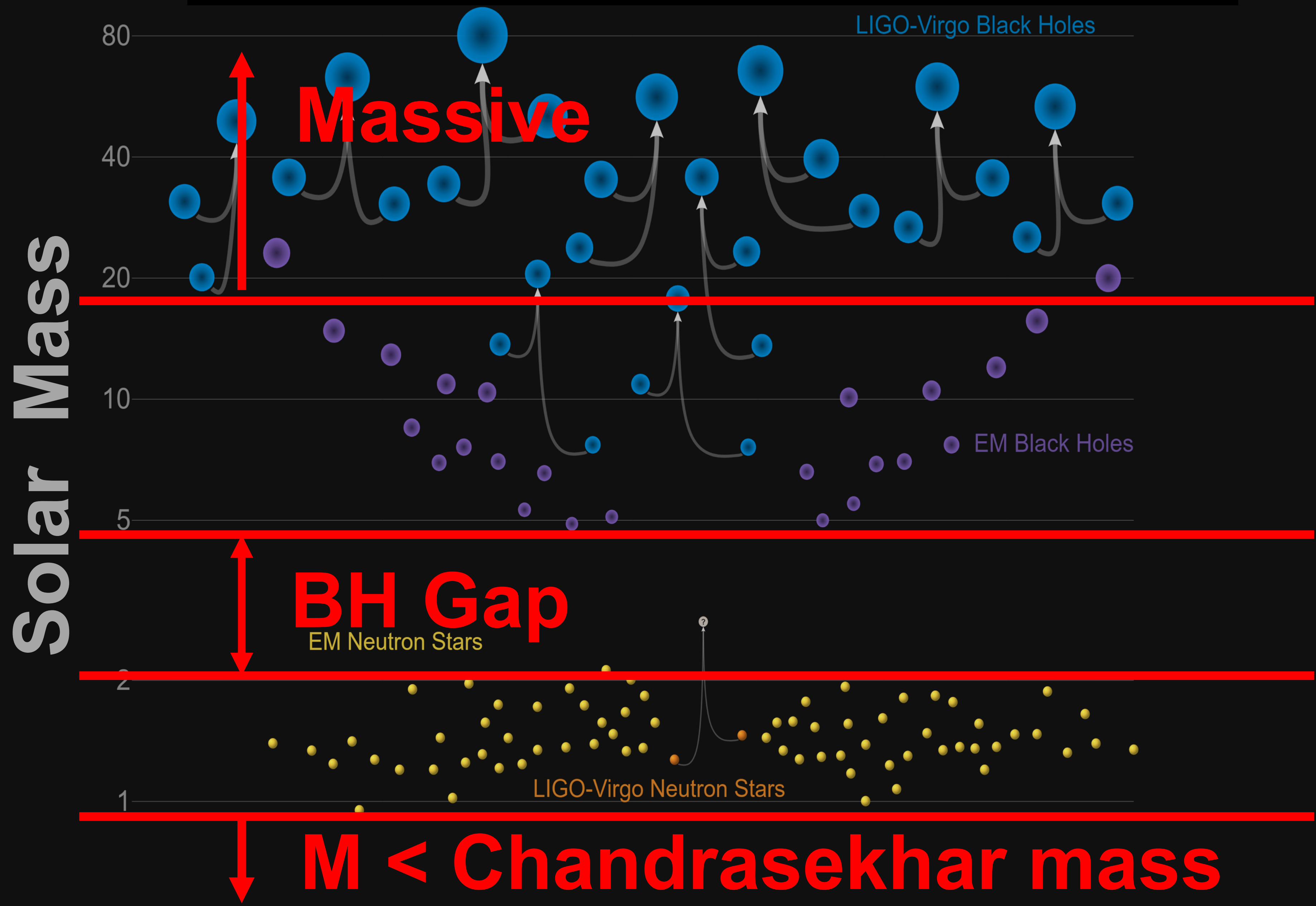
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_eff	$M_\mathrm{f}/\mathrm{M}_\odot$	a_f	$E_\mathrm{rad}/(\mathrm{M}_\odot c^2)$	$\ell_\mathrm{peak}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

TABLE III. Selected source parameters of the eleven confident detections. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of two waveform models for BBHs. For GW170817 credible intervals and statistical errors are shown for IMRPhenomPv2NRT with low spin prior, while the sky area was computed from TaylorF2 samples. The redshift for NGC 4993 from [87] and its associated uncertainties were used to calculate source frame masses for GW170817. For BBH events the redshift was calculated from the luminosity distance and assumed cosmology as discussed in Appendix B. The columns show source frame component masses m_i and chirp mass $\mathcal{M}$, dimensionless effective aligned spin χ_eff, final source frame mass M_f, final spin a_f, radiated energy E_rad, peak luminosity l_peak, luminosity distance d_L, redshift z and sky localization $\Delta\Omega$. The sky localization is the area of the 90% credible region. For GW170817 we give conservative bounds on parameters of the final remnant discussed in Sec. V E.

Mass distribution of LIGO BHB

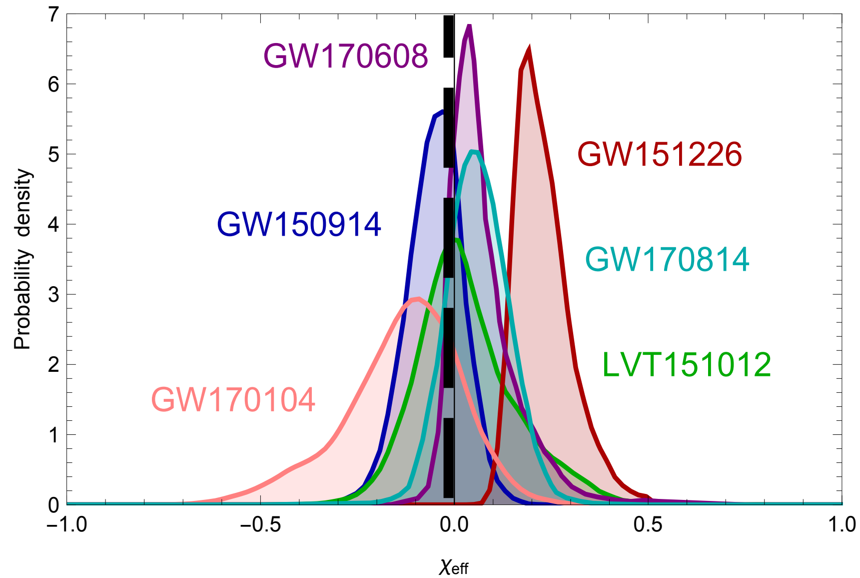


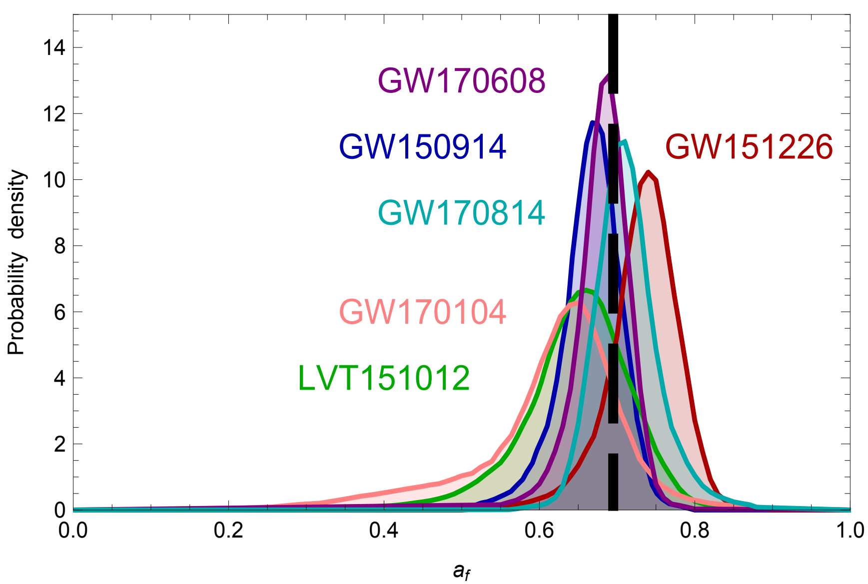
Black Holes and Neutron Stars

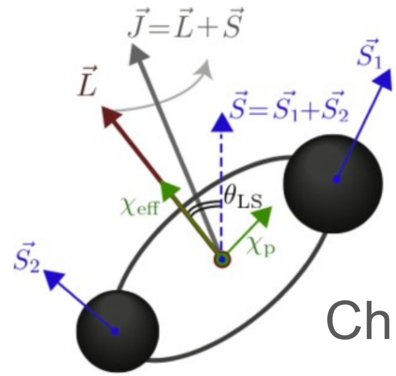


Spin distribution of LIGO BHB

Abbott et al. (2017)

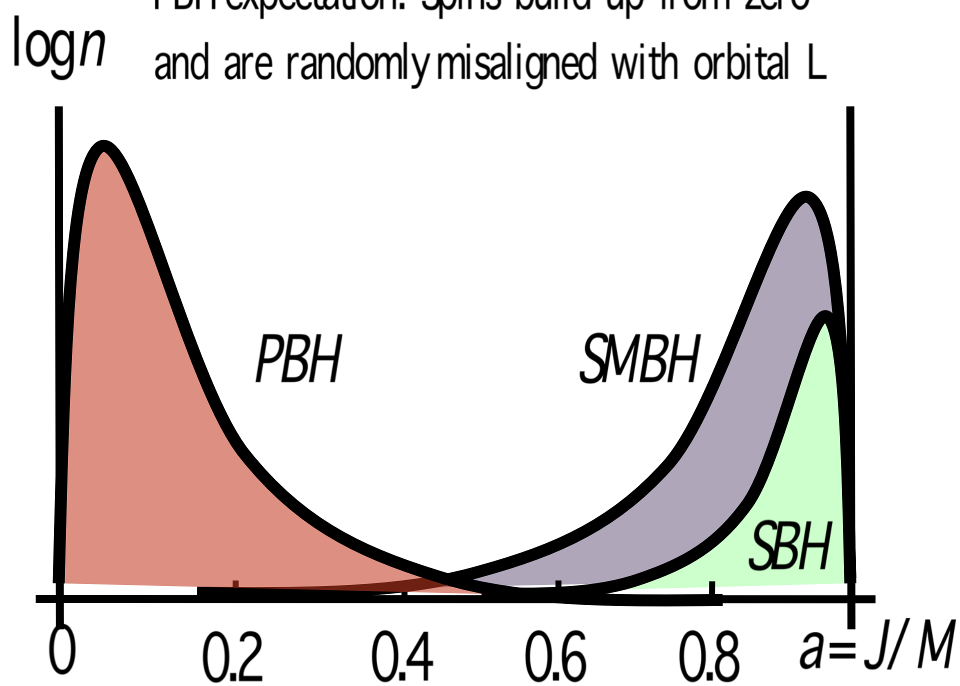


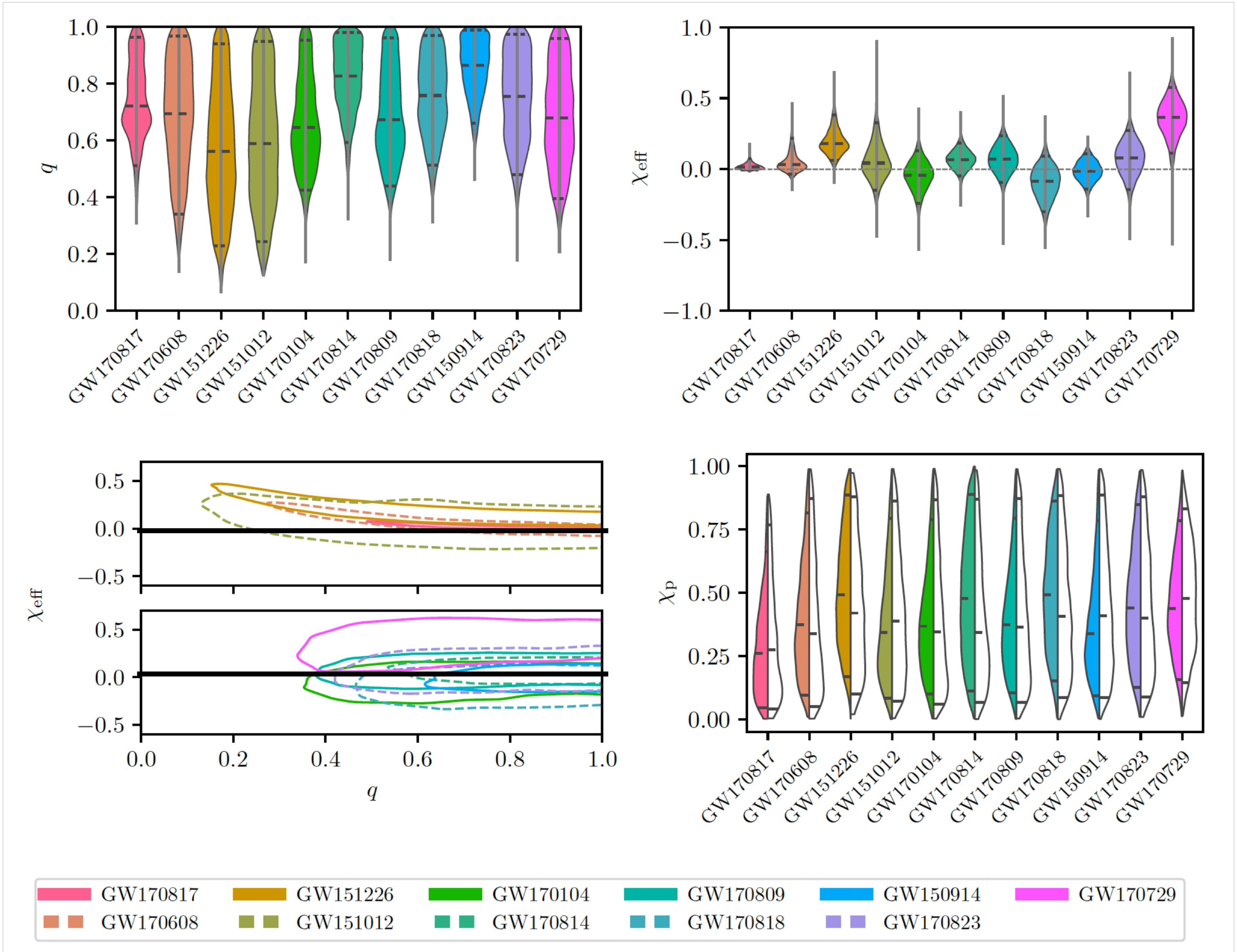




Chiba-Yokoyama (2017), Farr et al. (2017)

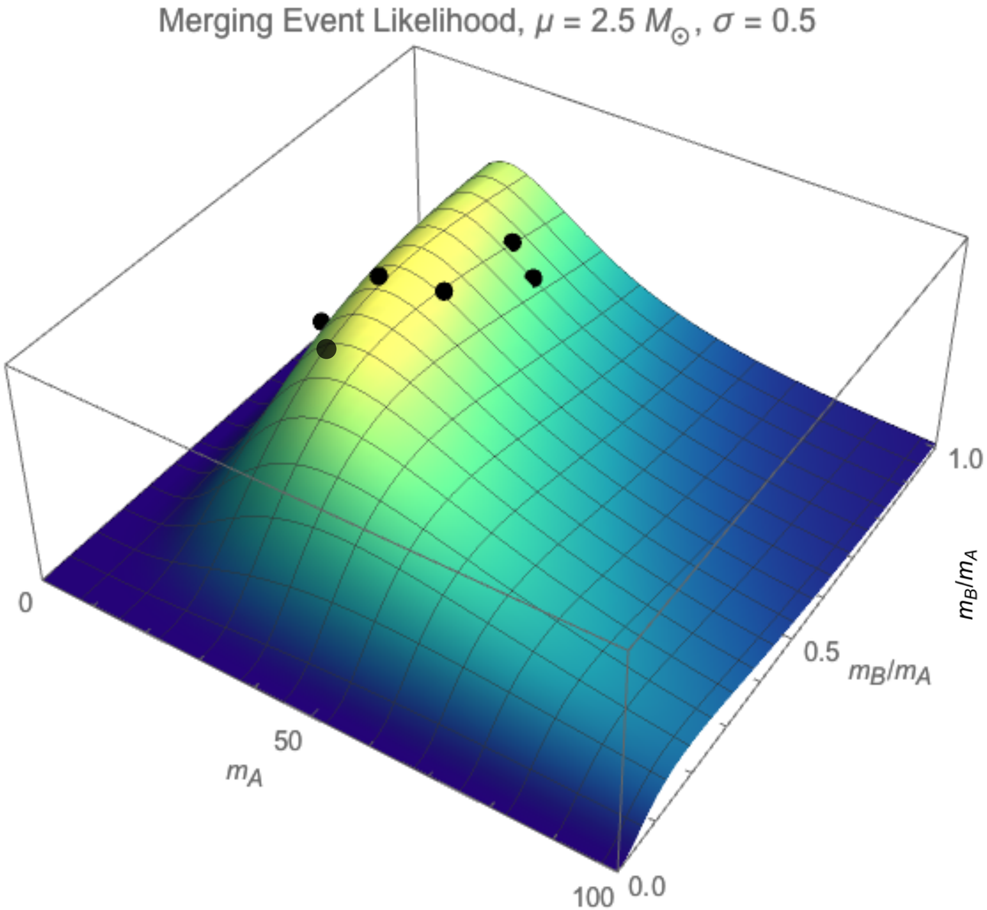
PBH expectation: Spins build up from zero and are randomly misaligned with orbital L



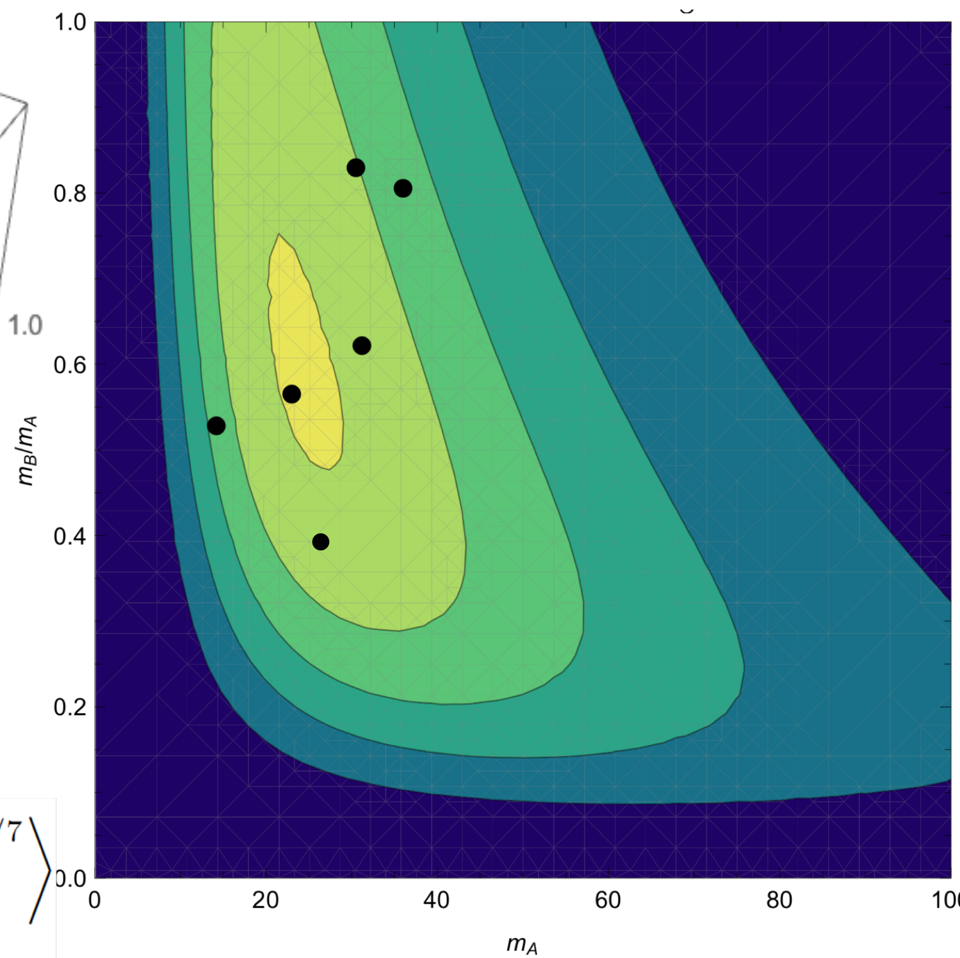


q
χeff
χp
GW170817
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729

AdvLIGO BBH event rate



Clesse & JGB (2017)



$$\frac{\mathrm{d}\tau_{\mathrm{merg}}}{\mathrm{d}m_{\mathrm{A}}\mathrm{d}m_{\mathrm{B}}} \simeq 2.9 \times 10^{-9}\ \langle \delta^2_{\mathrm{PBH}} \rangle^{1/2} \left\langle \left(\frac{v}{20\ \mathrm{km/s}} \right)^{-11/7} \right\rangle \times \frac{\psi(m_{\mathrm{A}})\psi(m_{\mathrm{B}})(m_{\mathrm{A}} + m_{\mathrm{B}})^{10/7}}{2^{10/7} \ln^2(10)\ \rho^2_{\mathrm{DM}} (m_{\mathrm{A}})^{12/7} (m_{\mathrm{B}})^{12/7}}\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3},$$

$$\psi \equiv \frac{\mathrm{d}\rho(m_{\mathrm{PBH}})}{\mathrm{d}\log_{10} m_{\mathrm{PBH}}} = \frac{\rho_{\mathrm{DM}}}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{\log^2_{10}(m_{\mathrm{PBH}}/\mu)}{2\sigma^2} \right]$$

Missing satellite

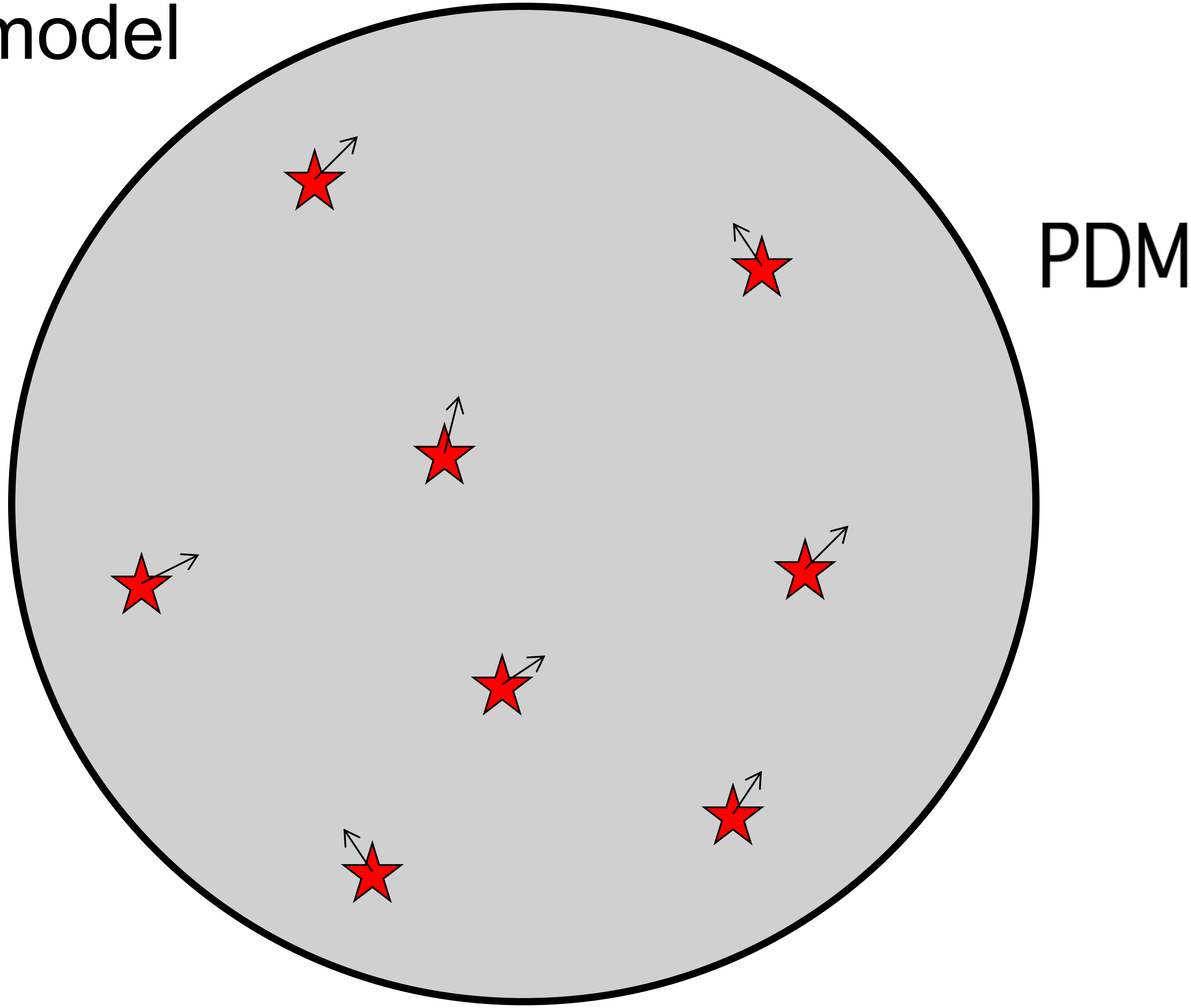
&

Too-big-to-fail

Problems ΛCDM

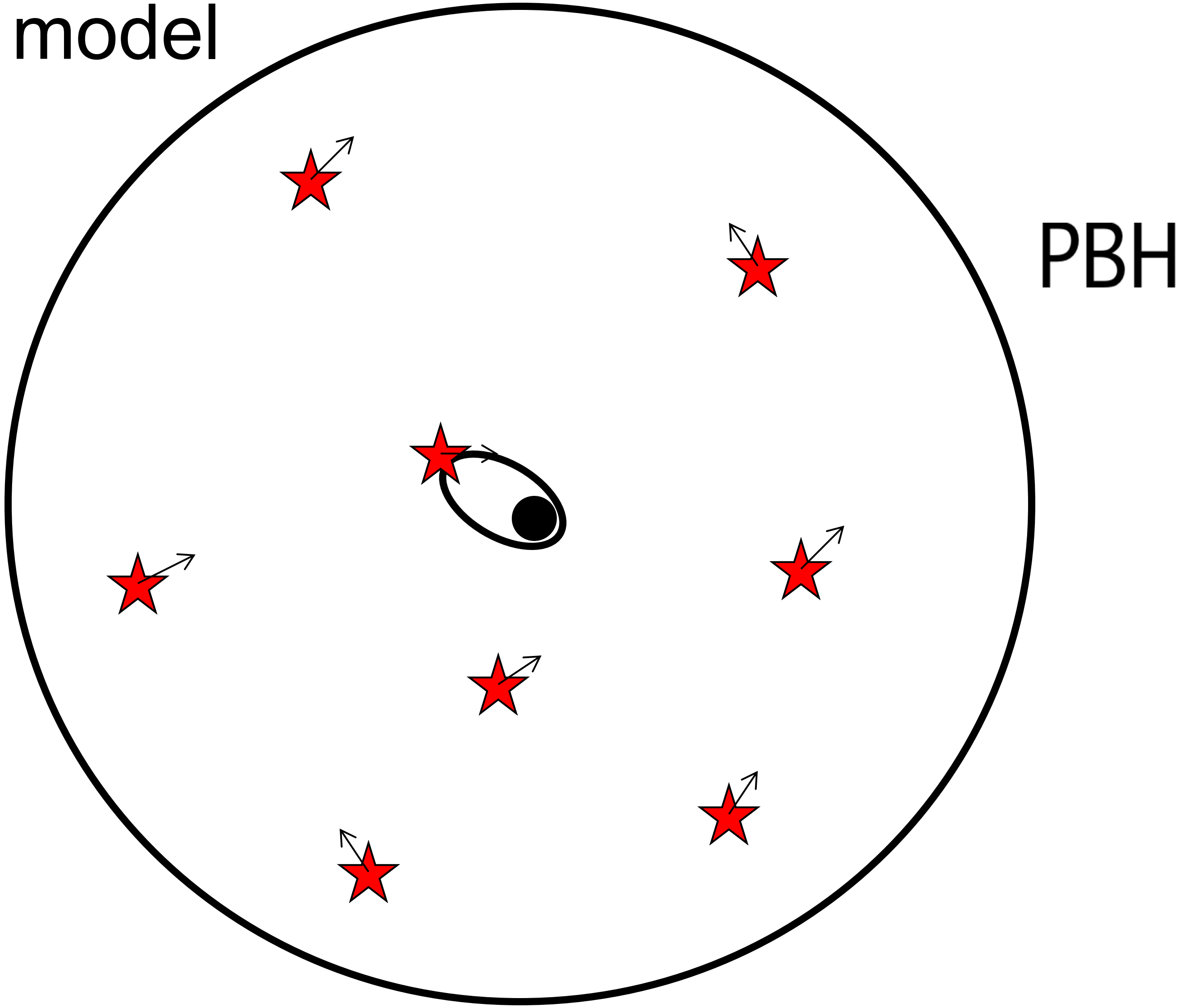
Spatial distribution of DM

Thomson model



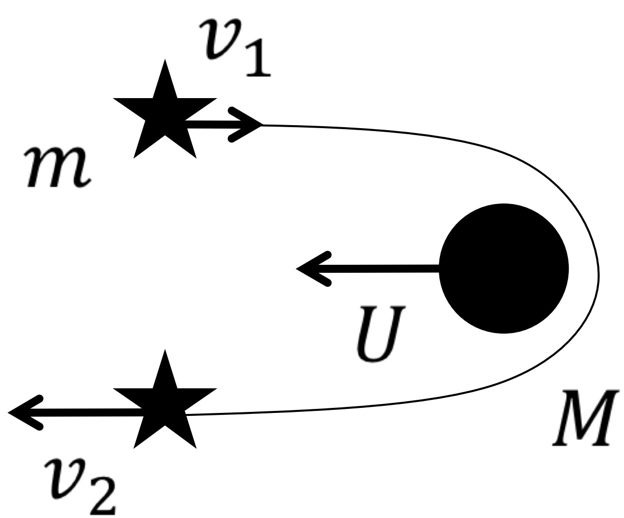
Spatial distribution of DM

Rutherford model



Gravitational slingshot effect

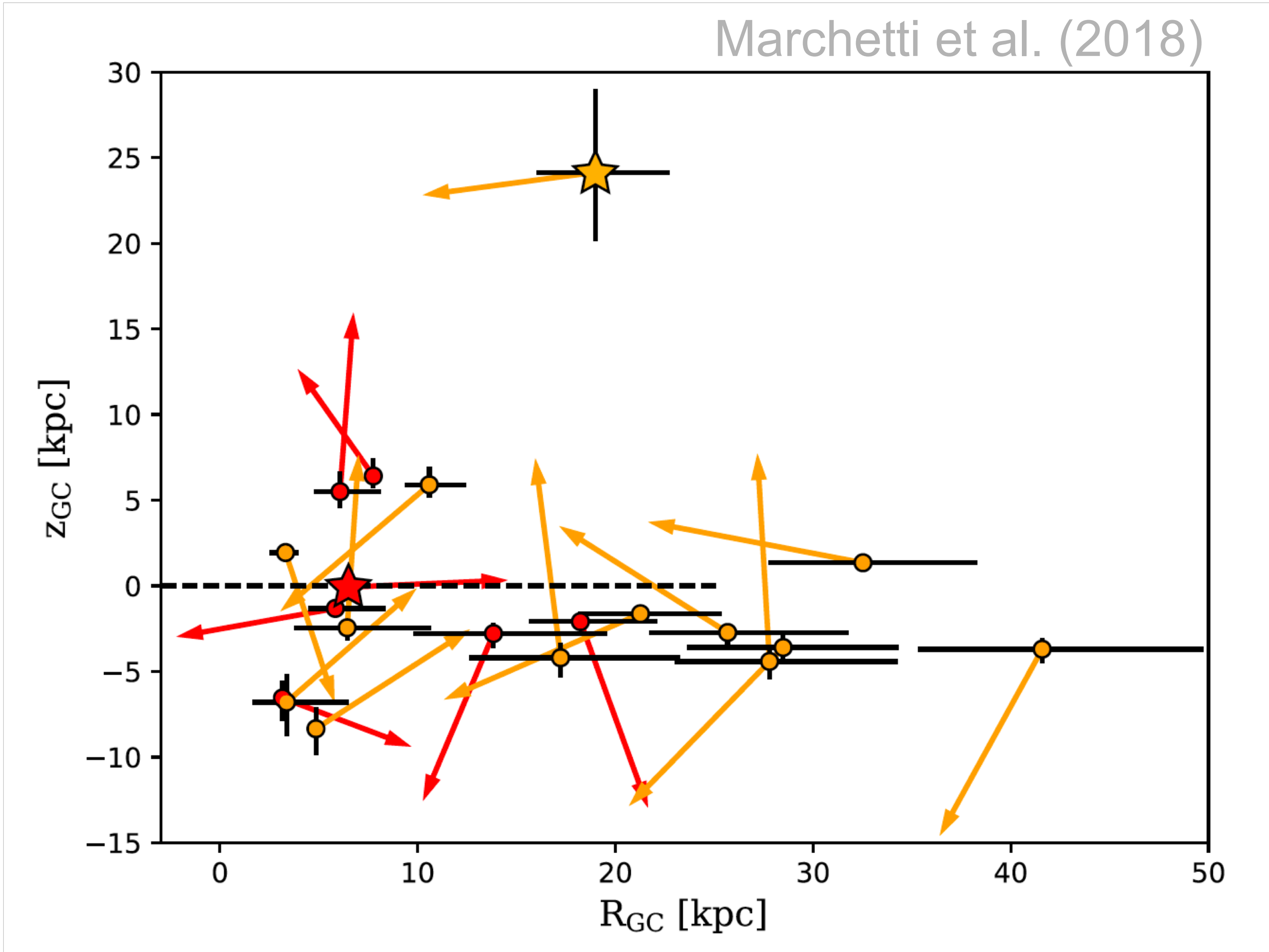
Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.



$$v_2 = \frac{2U + (1 - \frac{m}{M})v_1}{(1 - \frac{m}{M})}$$

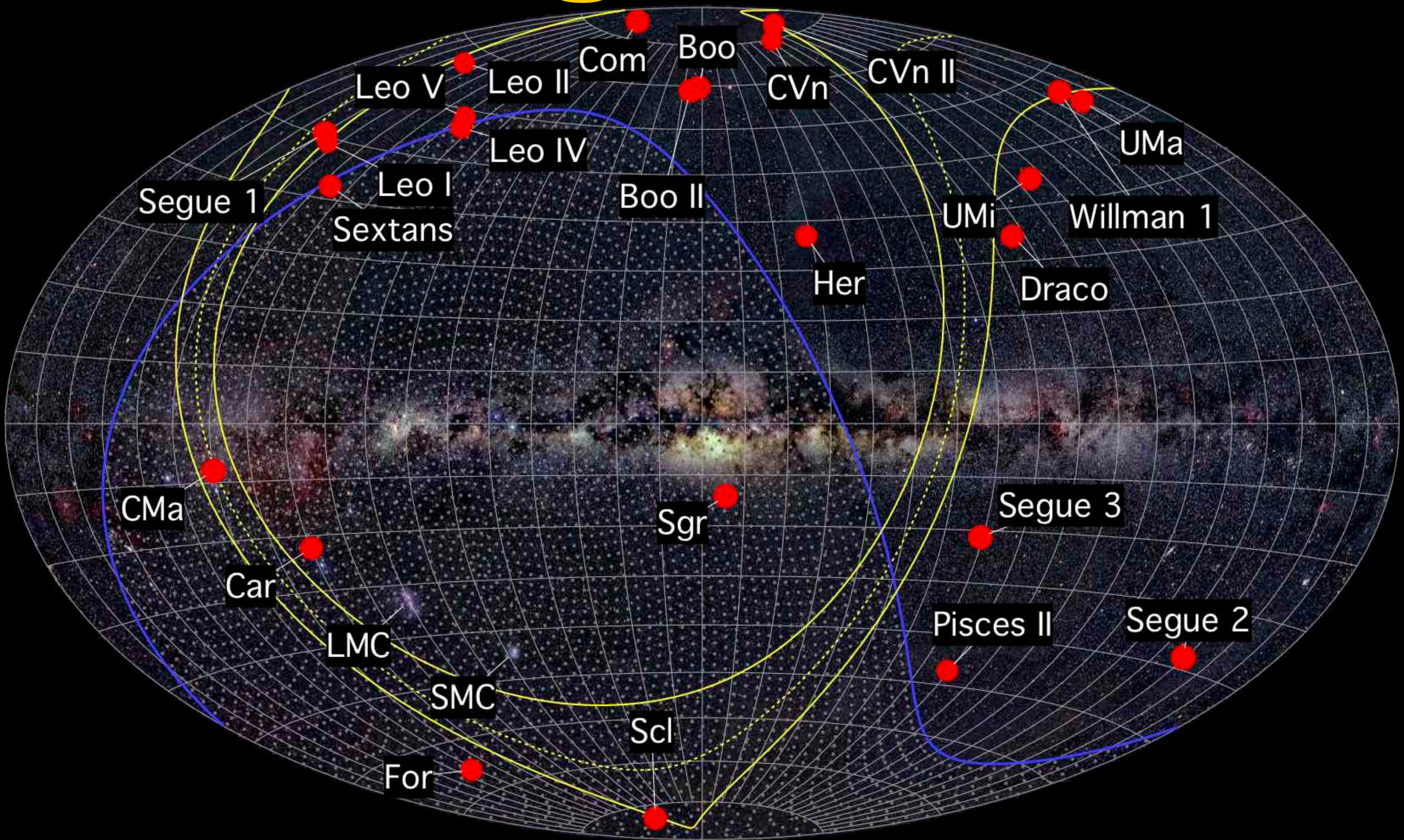
It may explain large M/L ratios of dSph by ejection of stars in the cluster, $v > v_{esc}$.

GAIA HyperVelocityStars in DR2

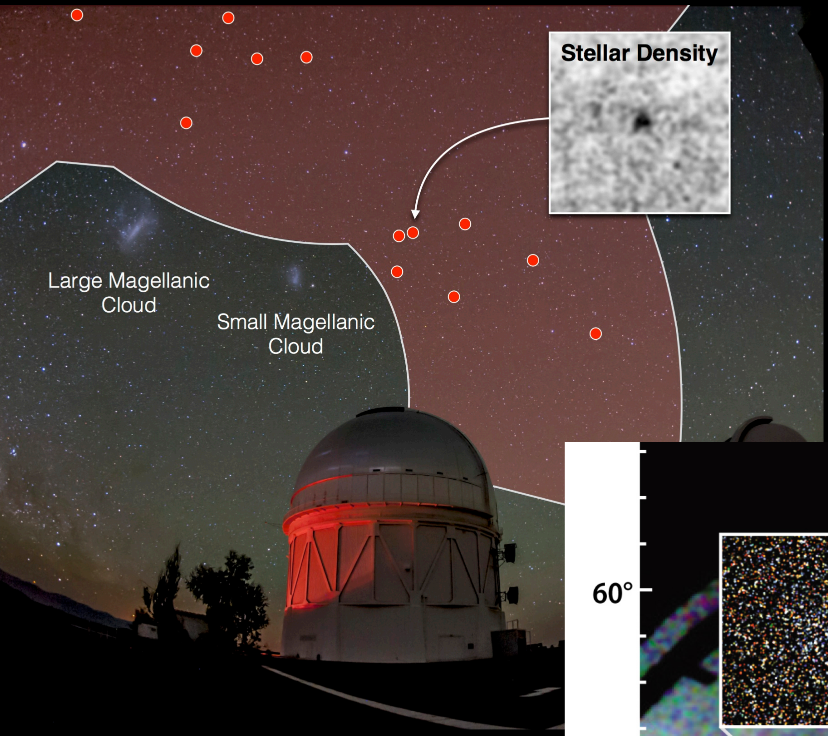


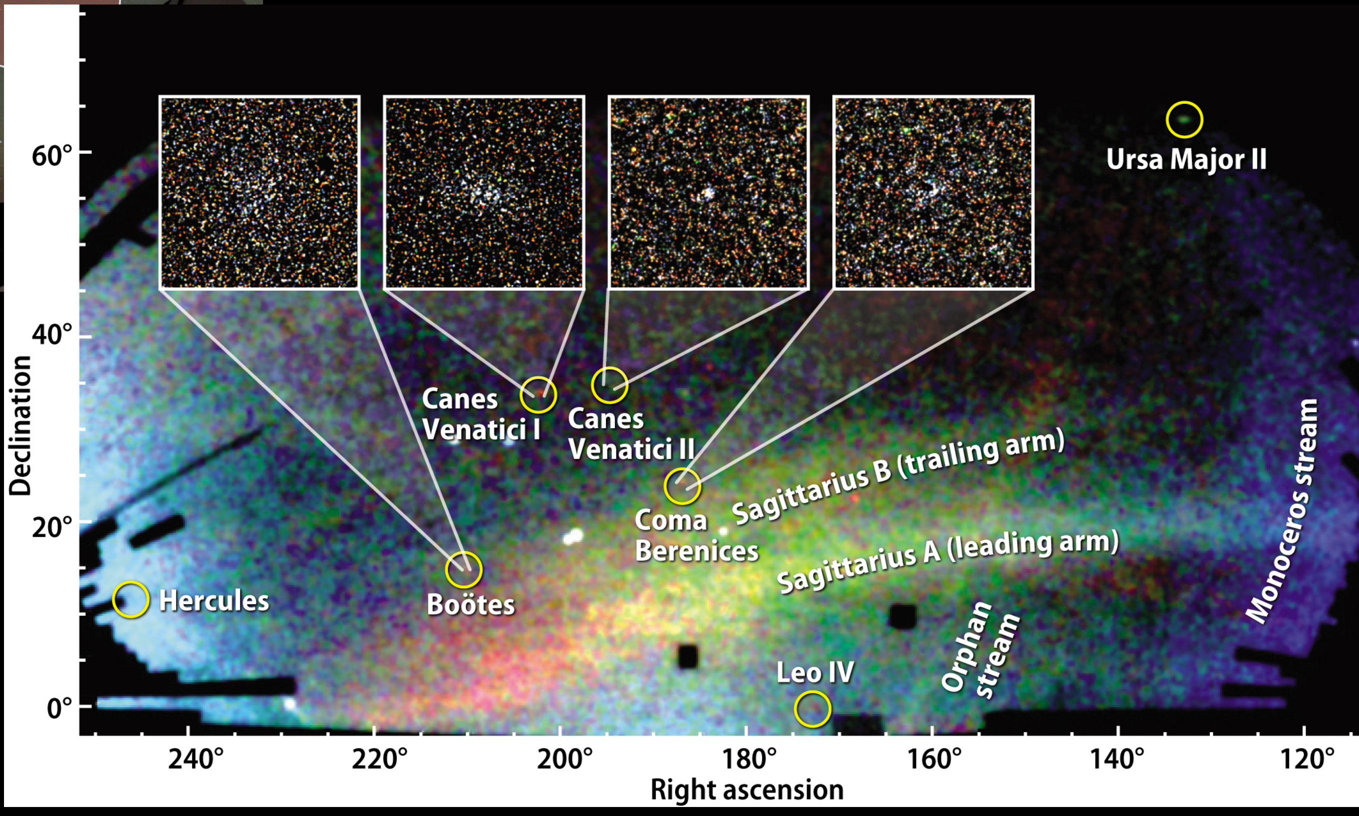
Missing Satellites

Missing Satellites

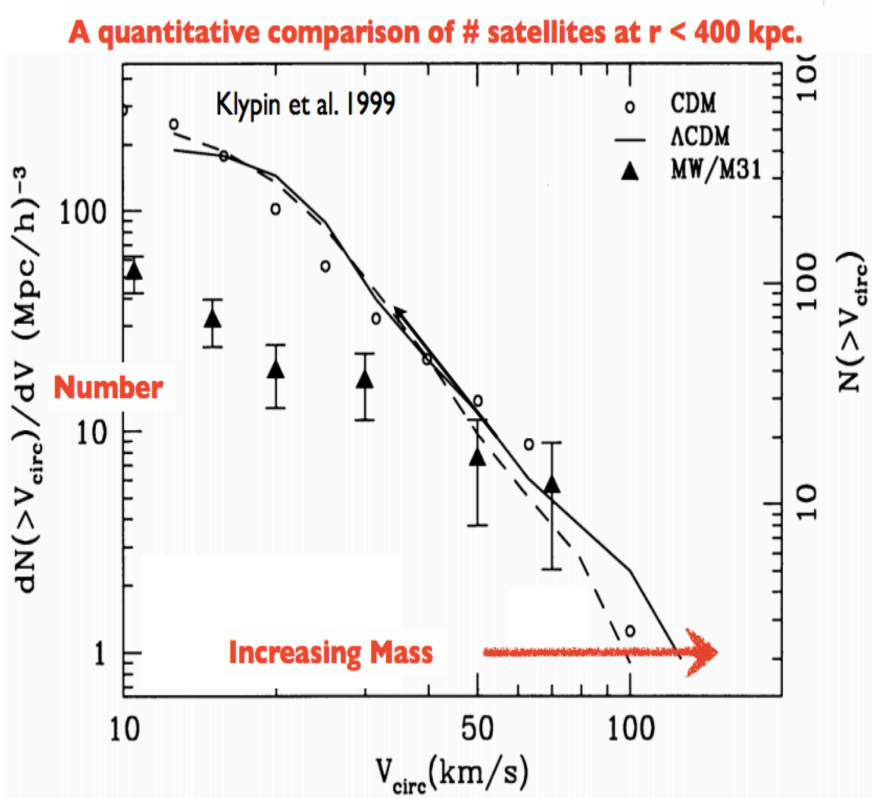


DES Dwarf Spheroidals

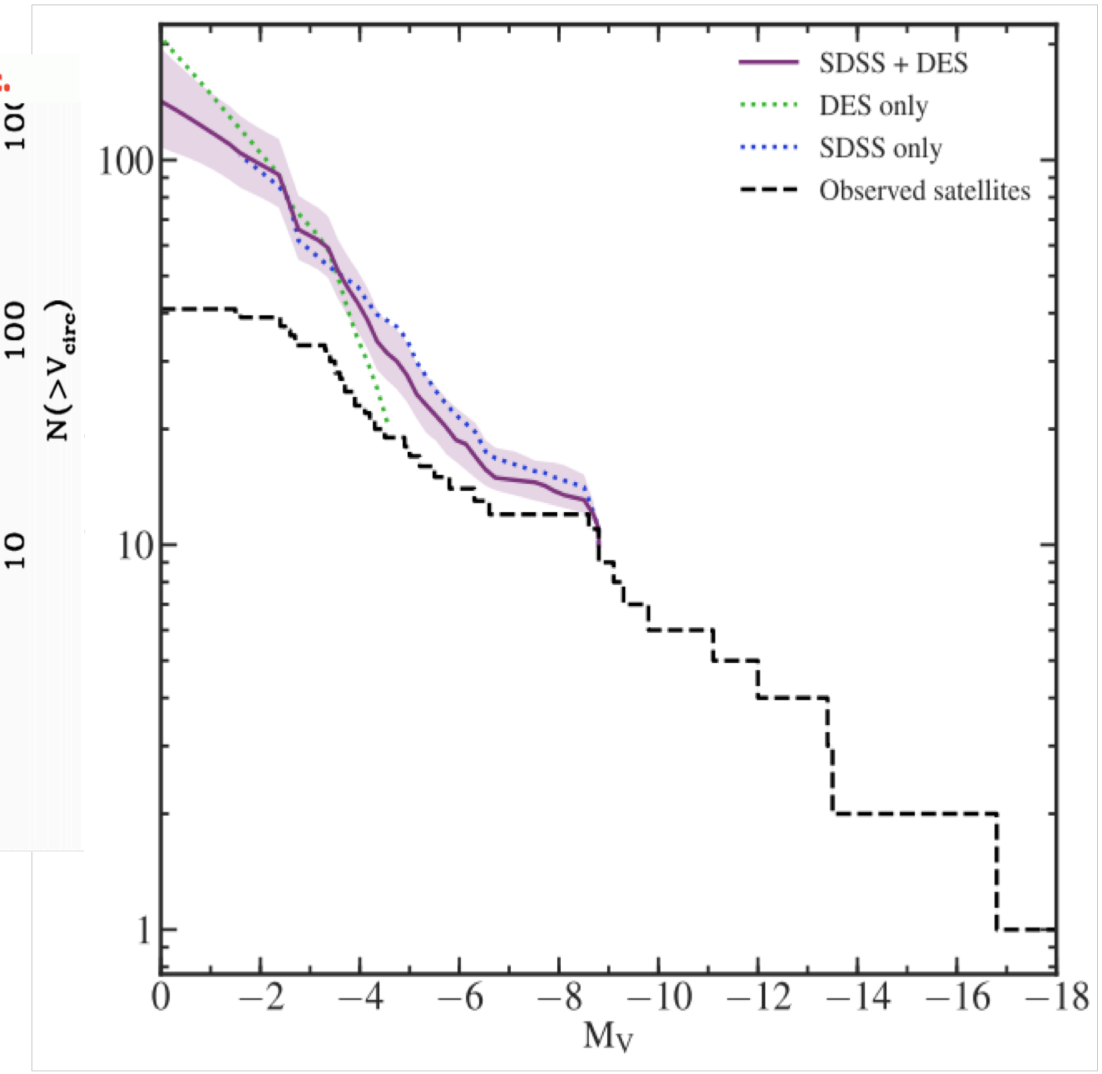




Missing Satellite problem is over



Newton et al. (2017)

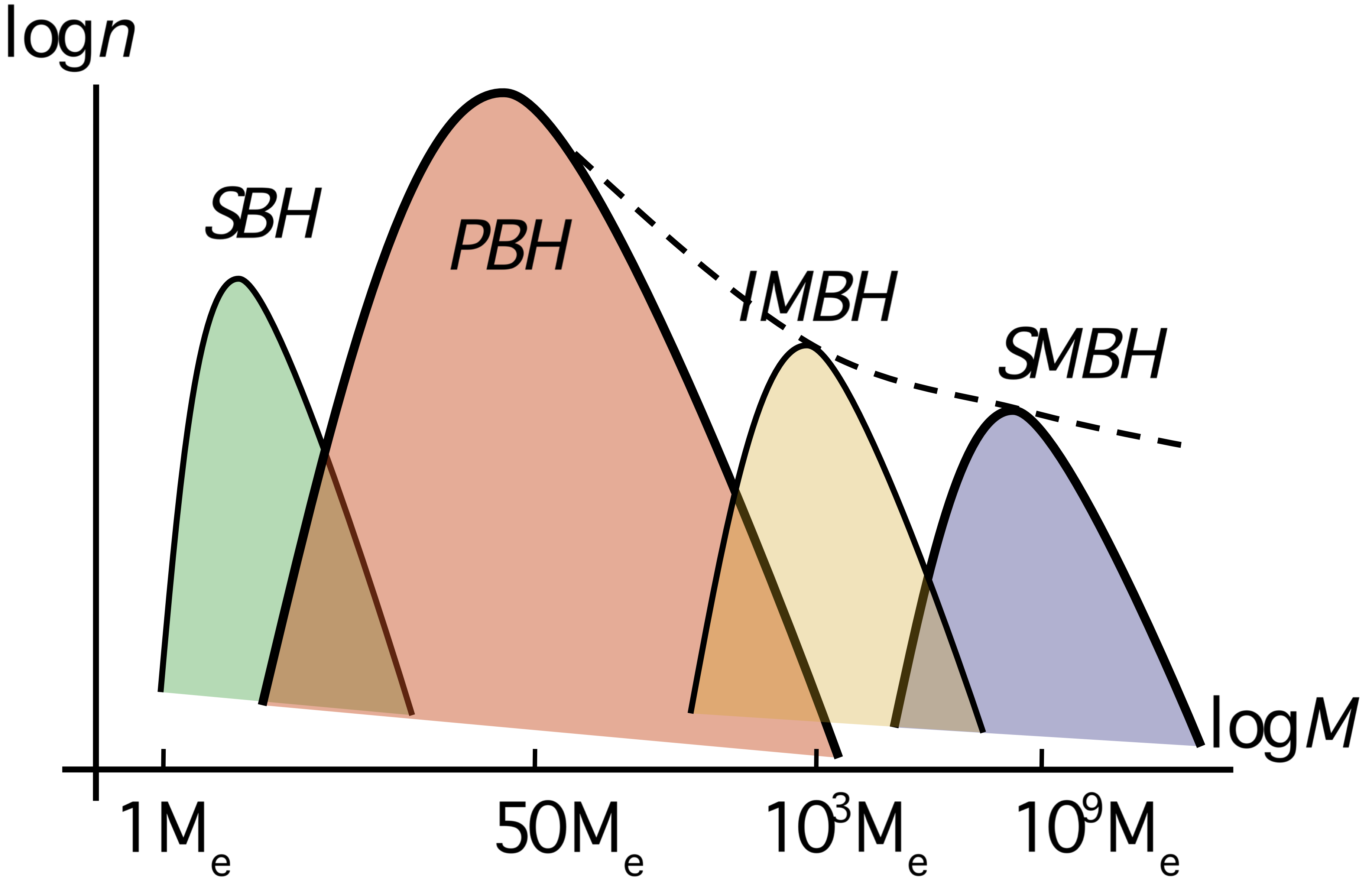


Early Galaxy Formation

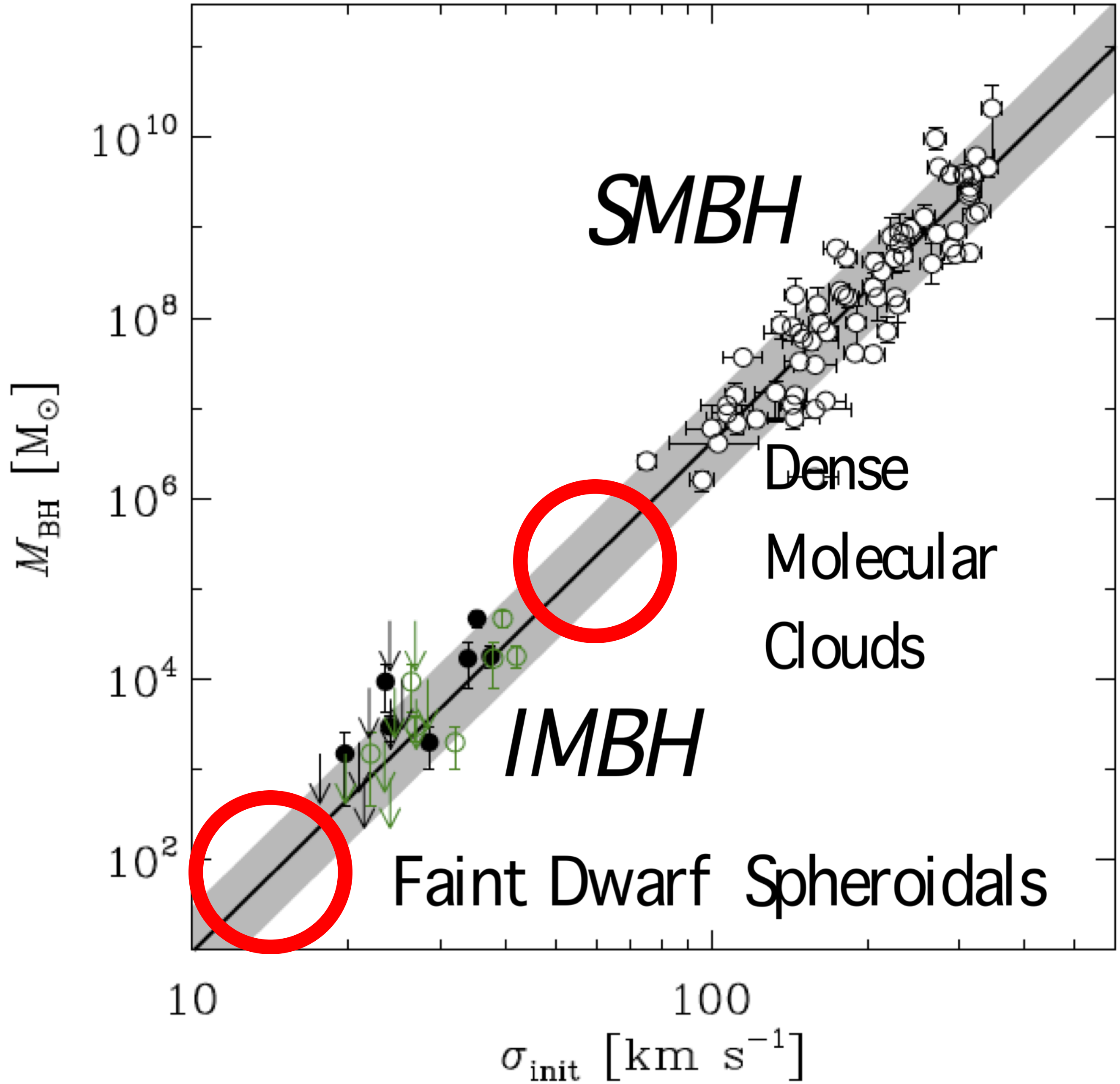
Massive PBH = seeds of structure

- Massive primordial black holes with $10^{-2}\ M_\odot < M_{PBH} < 10^{2}\ M_\odot$, which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.
- ΛCDM N-body simulations never reach the $100\ M_\odot$ particle resolution, so for them PBH is as good as PDM.
- PBH DM paradigm naturally incorporates all properties of collisionless CDM scenario on large scales but differs on small scales.

Mass distribution of BH

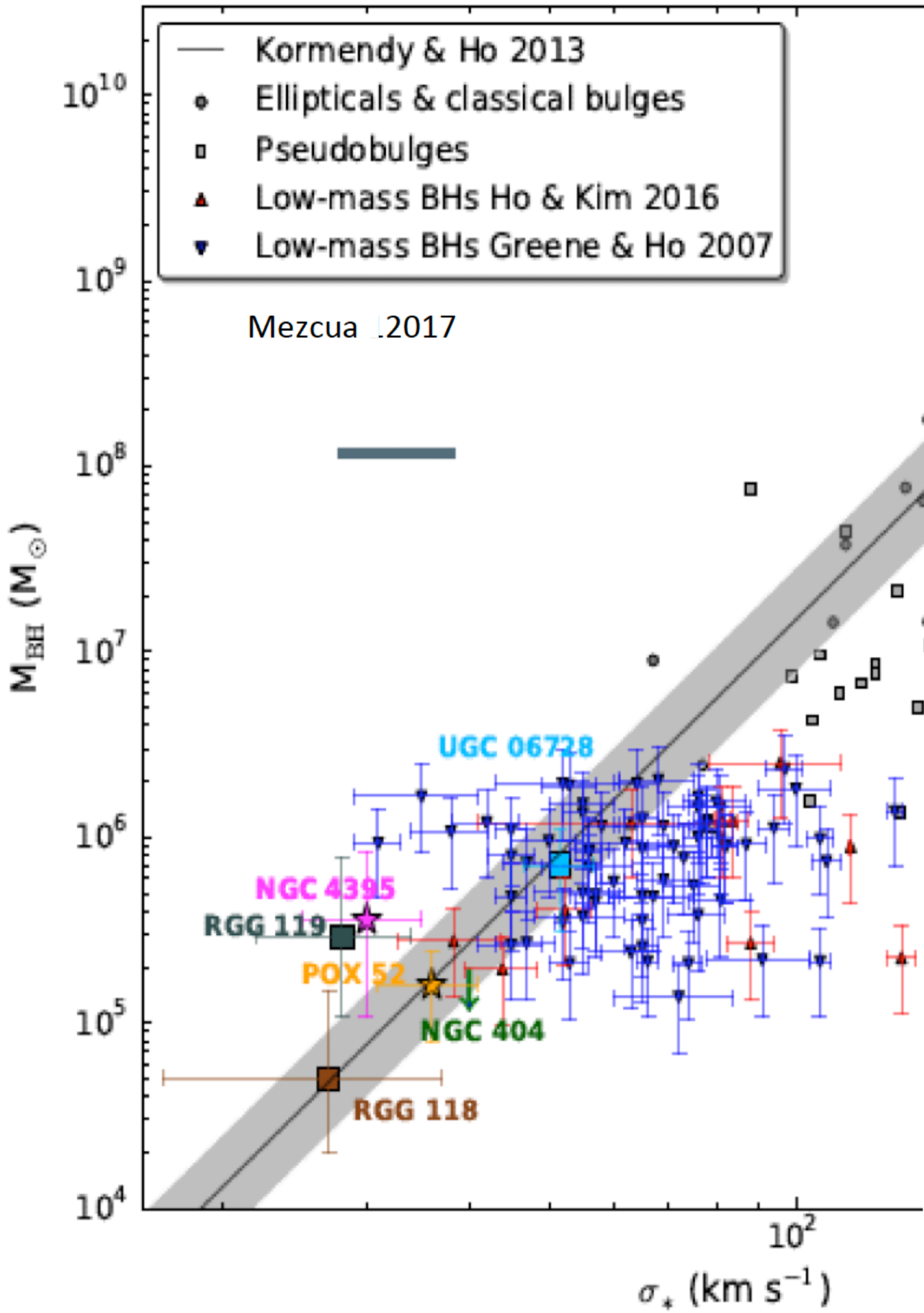


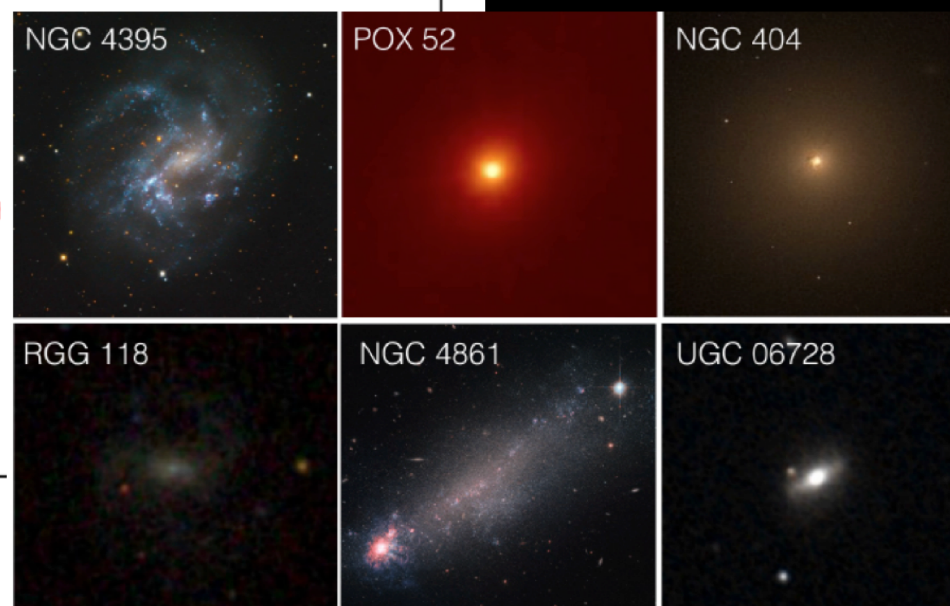
Kruijssen et al. (2013)



M_{BH} vs σ

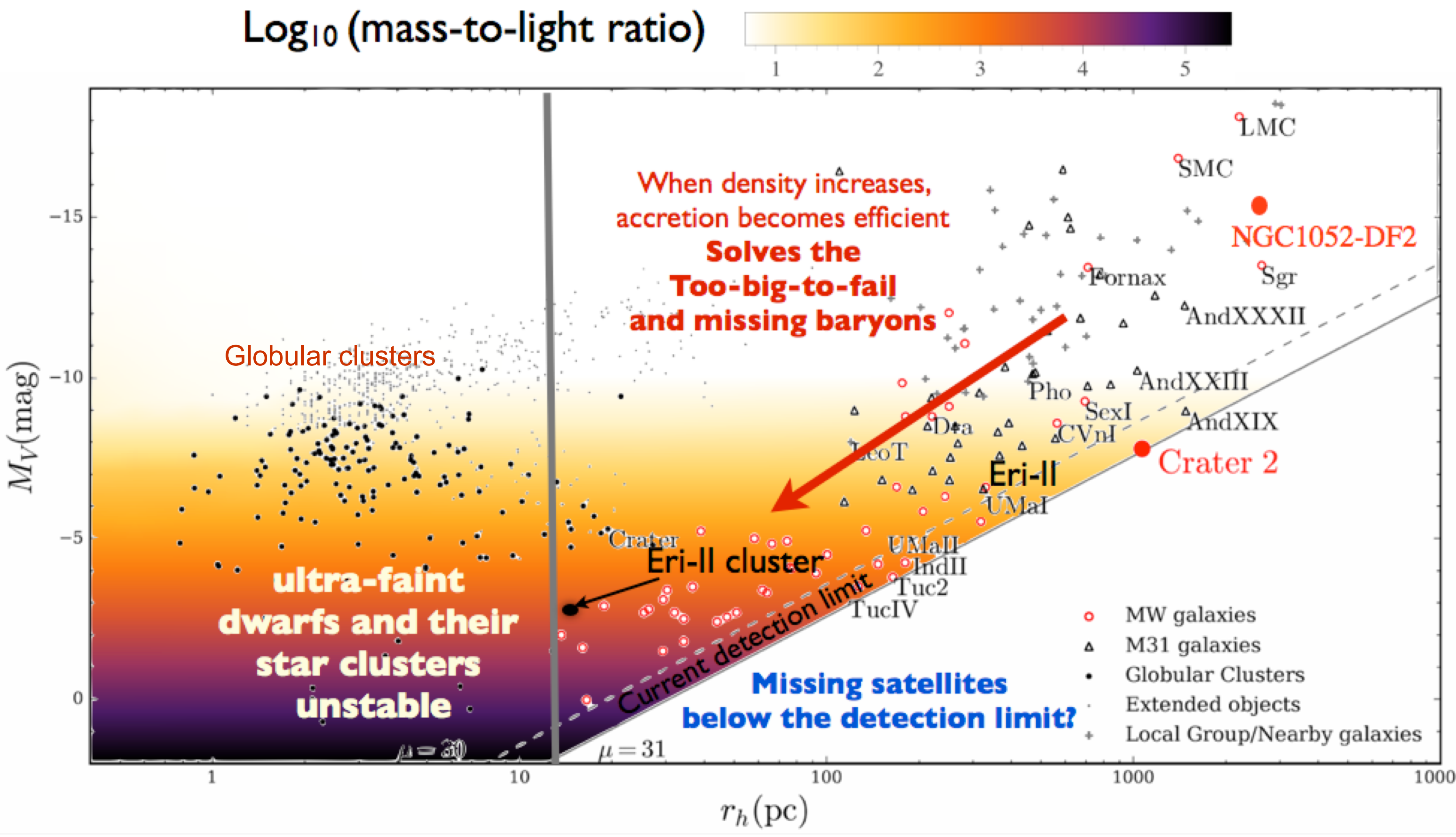
Silk (2018)





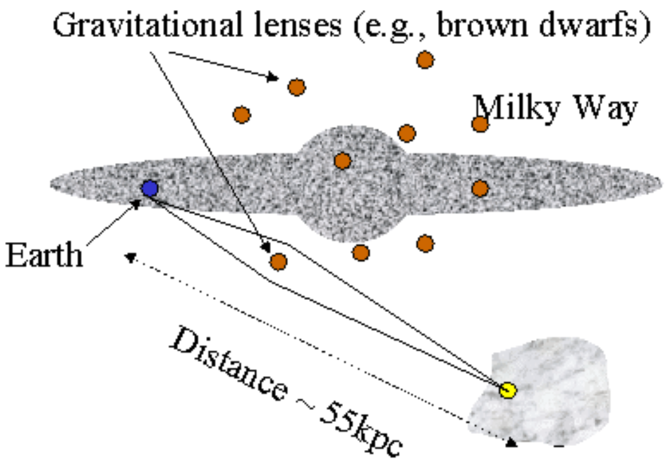
Understanding the MW satellites

Clesse & JGB (2017)

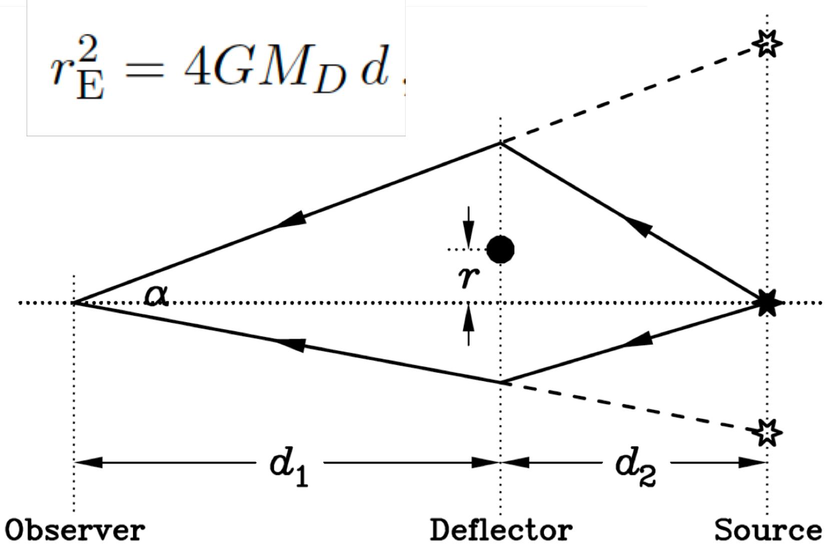


Long duration microlensing events EROS, MACHO, OGLE

Microlensing



$$r_E^2 = 4GM_D\,d$$



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

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

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

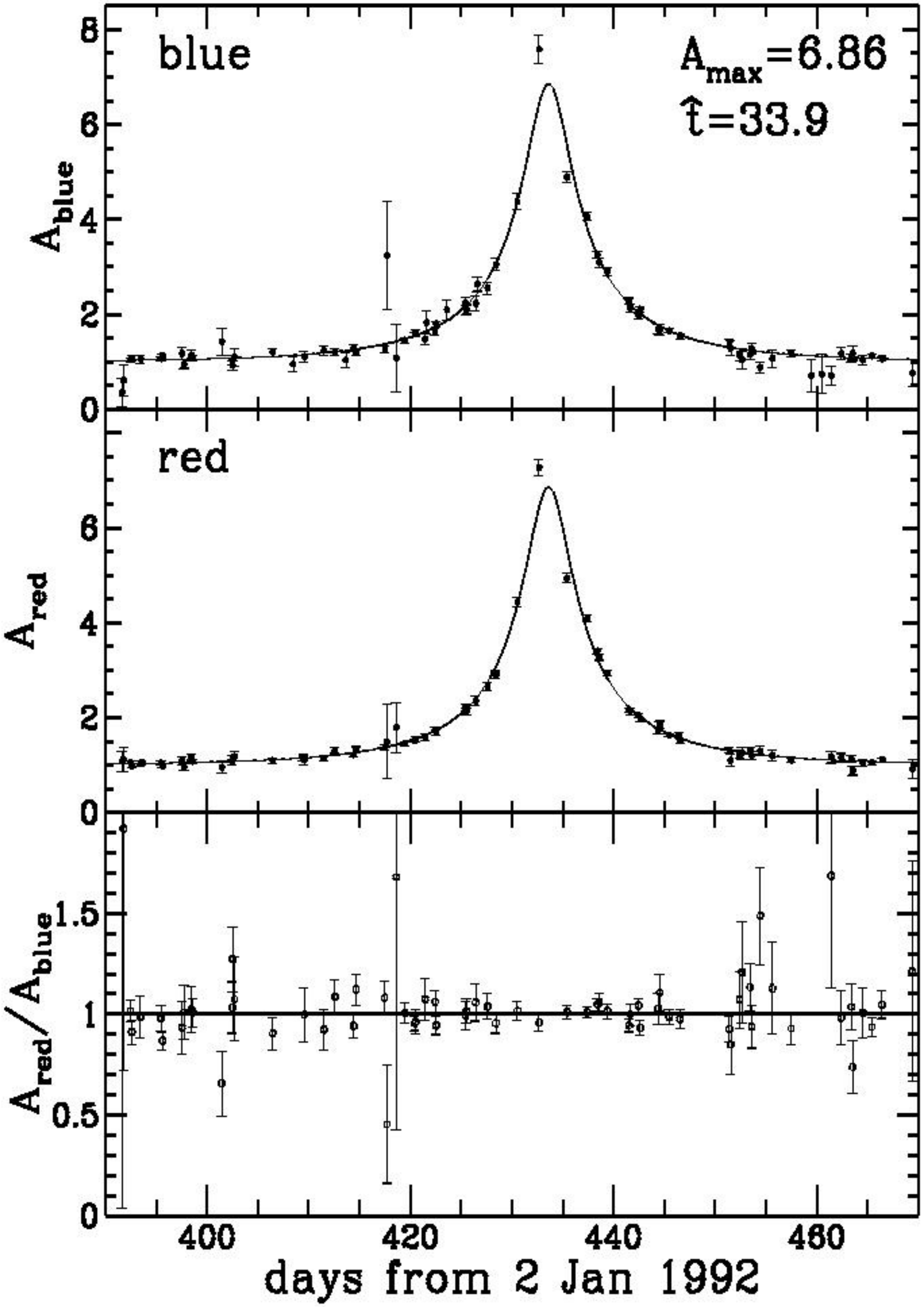
$M_D = 100\,M_\odot$ => $\overline{Dt} = 4$ years

$M_D = 10\,M_\odot$ => $\overline{Dt} = 1.23$ years

$M_D = 1\,M_\odot$ => $\overline{Dt} = 5$ months

$M_D = 0.1\,M_\odot$ => $\overline{Dt} = 1.5$ months

$M_D = 0.01\,M_\odot$ => $\overline{Dt} = 2$ weeks



Alcock et al. (2005)

symmetric

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

achromatic

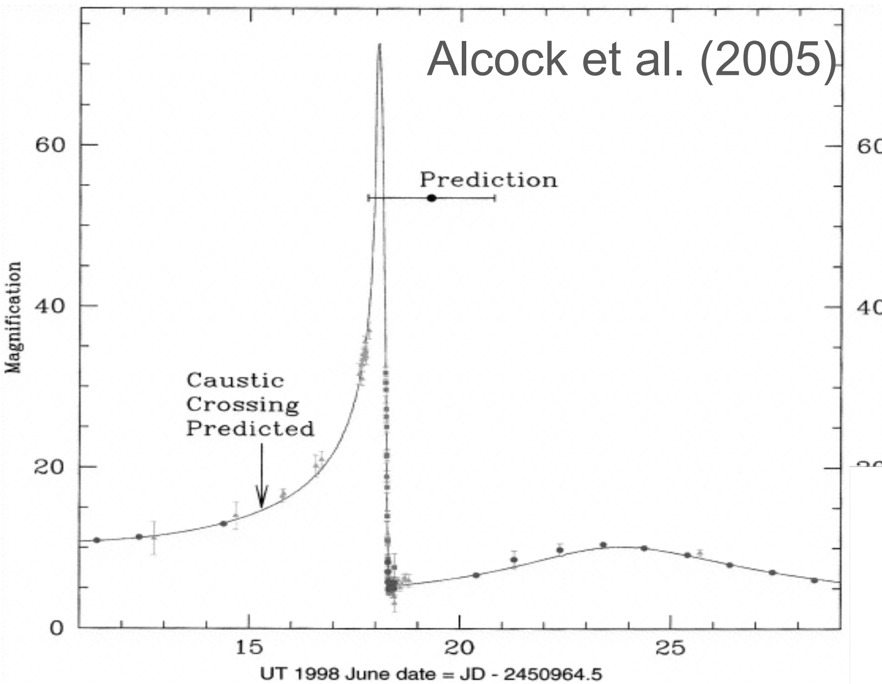
$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

unique

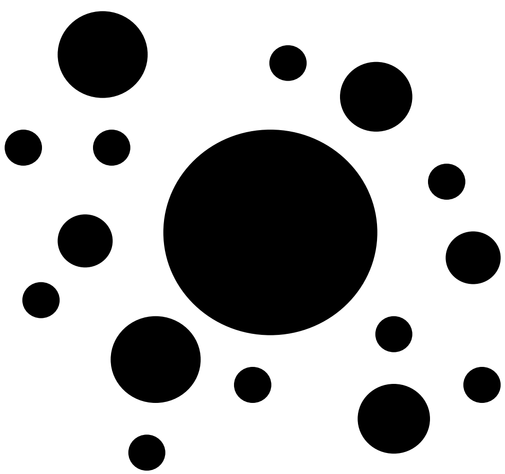
$$t = 34.8 \pm 0.2 \text{ days}$$

$$M_D = 0.1\, M_\odot$$

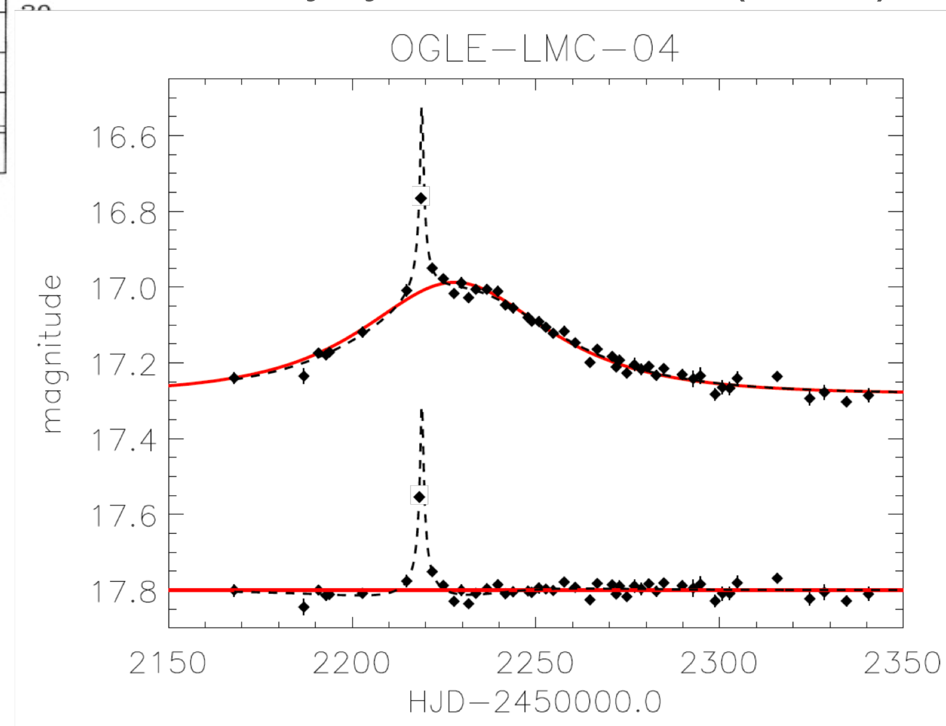
Signatures of clustering of PBH



Caustics!



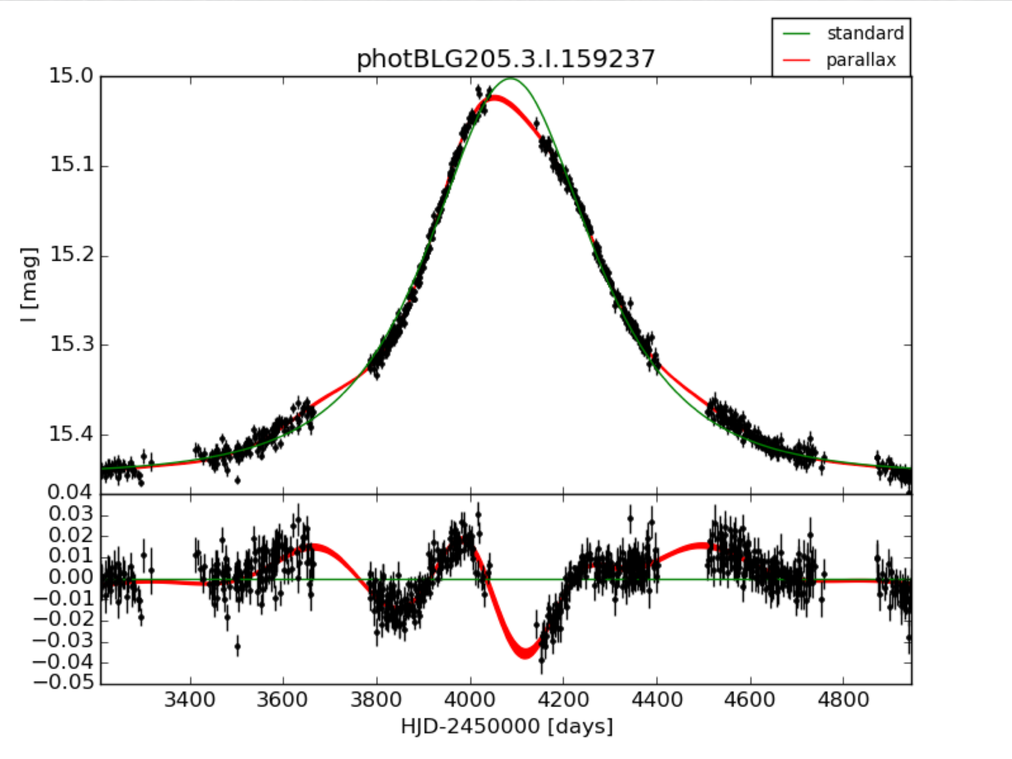
Wryzykowski et al. (2011)

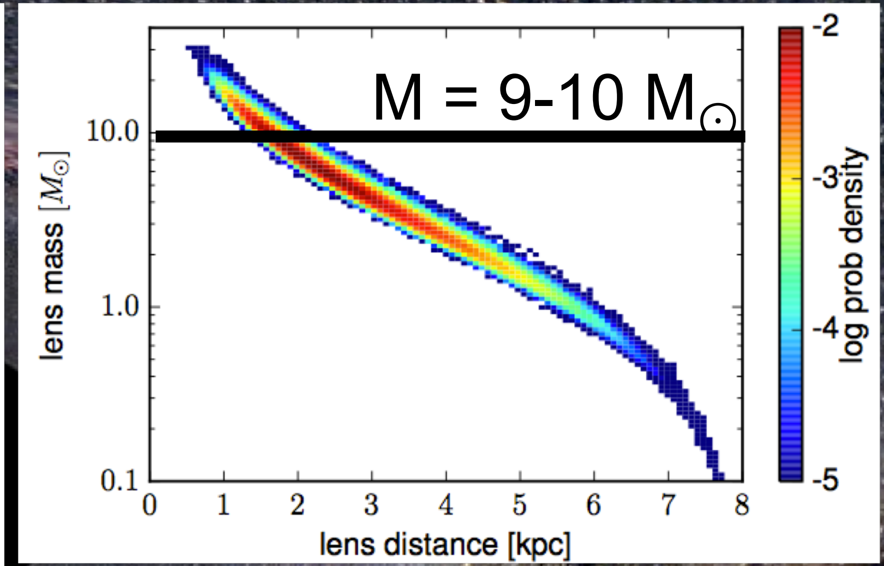


PBH @ CERN 2018

OGLE3-UL-PAR-02 - candidate ~9MSun BH

Wyrzikowsky (2018)





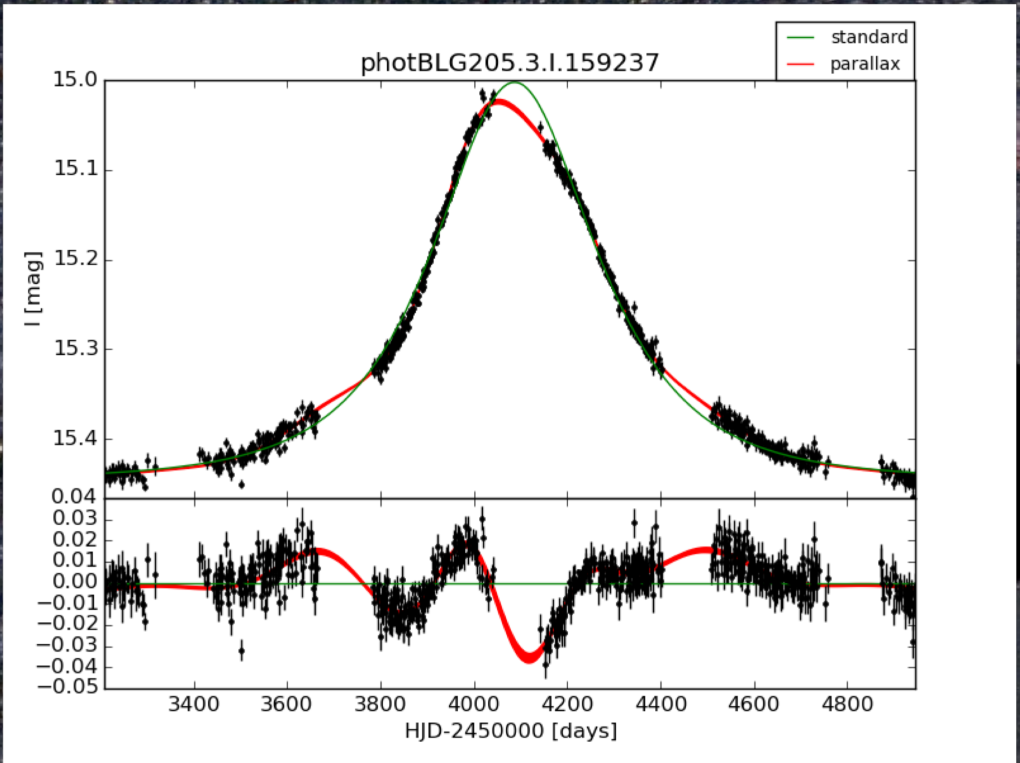
OGLE photometry
from 2001-2008
and microlensing model

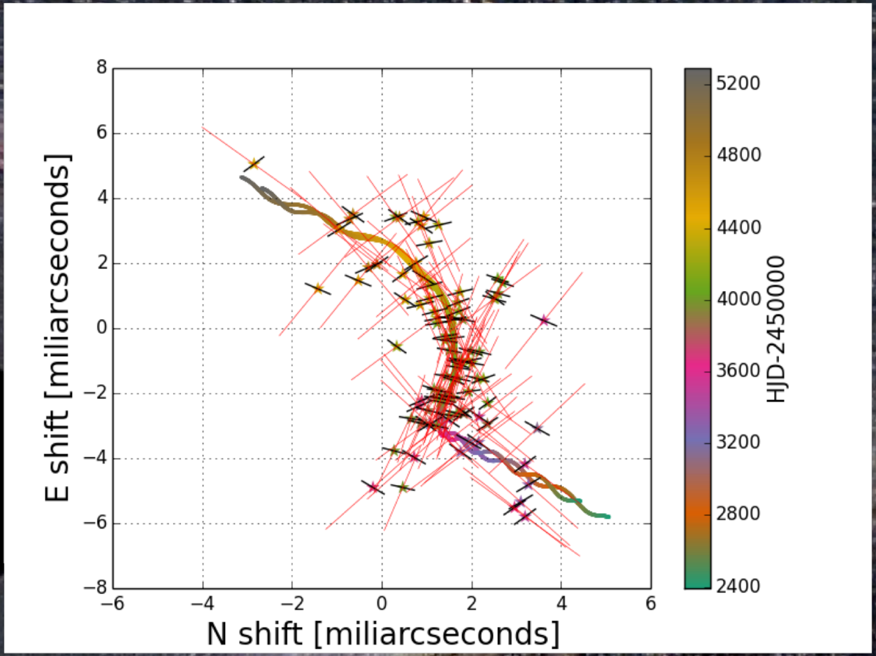
Mass, Distance (degenerated estimate)

PBH @ CERN 2018

OGLE3-UL-PAR-02 - candidate ~9MSun BH

Wyrzikowsky (2018)





OGLE photometry from 2001-2008 and microlensing model

predicted Gaia astrometry for similar event (real data in 2022)

Mass, Distance

Rybicki, Wyrzykowski+ 2018

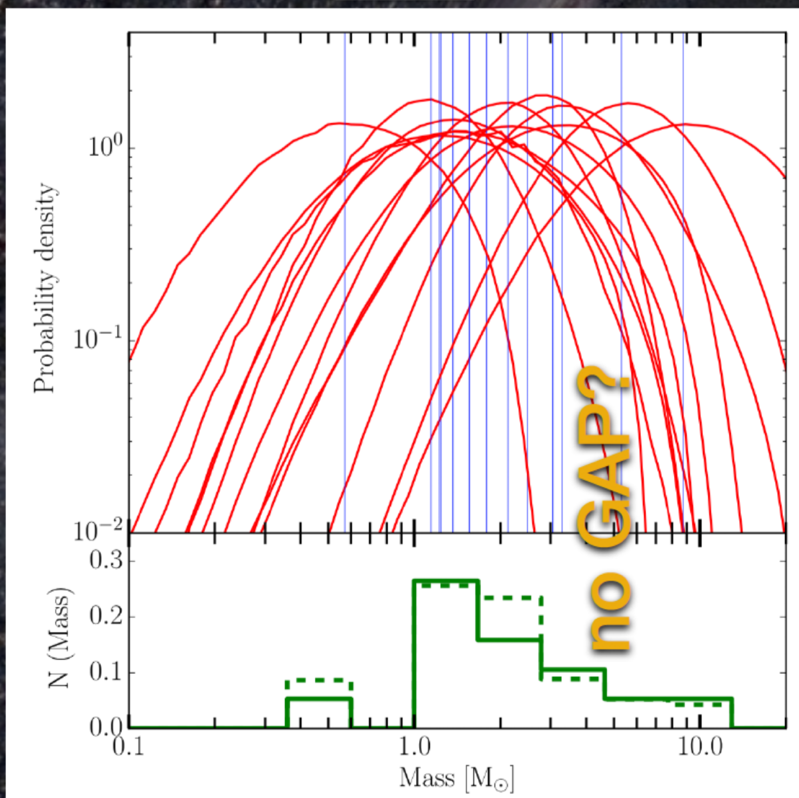
MASS FUNCTION

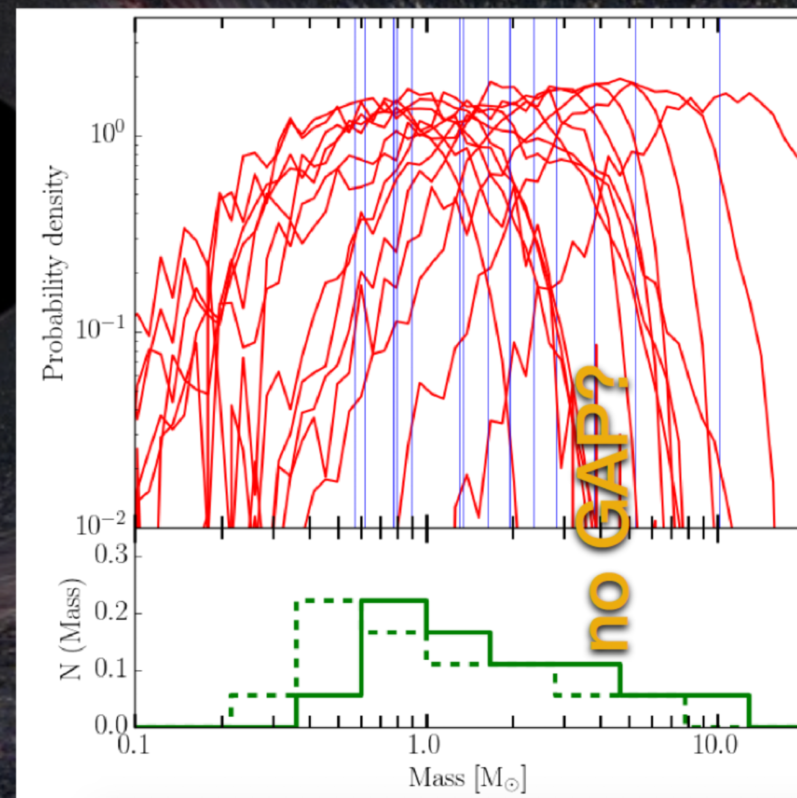
- using Gaia DR2 distances and proper motions of SOURCE stars
- only dark lenses selected
- new examples of mass-gap dark objects!

Wyrzikowsky (2018)

preliminary results!

single





Wyrzykowski+2016

Microlensing constraints

Calcino, JGB, et al. (2018)

For the semi-isothermal dark halo model

$$\frac{d\Gamma}{d\hat{t}} = \frac{512 L u_T\, G^2 M \rho_0 (R_\odot^2 + R_c^2)}{\hat{t}^4 v_c^2 c^4} \int_0^{x_h} \frac{x^2(1-x)^2}{A + Bx + x^2} e^{-Q(M,x)} dx,$$

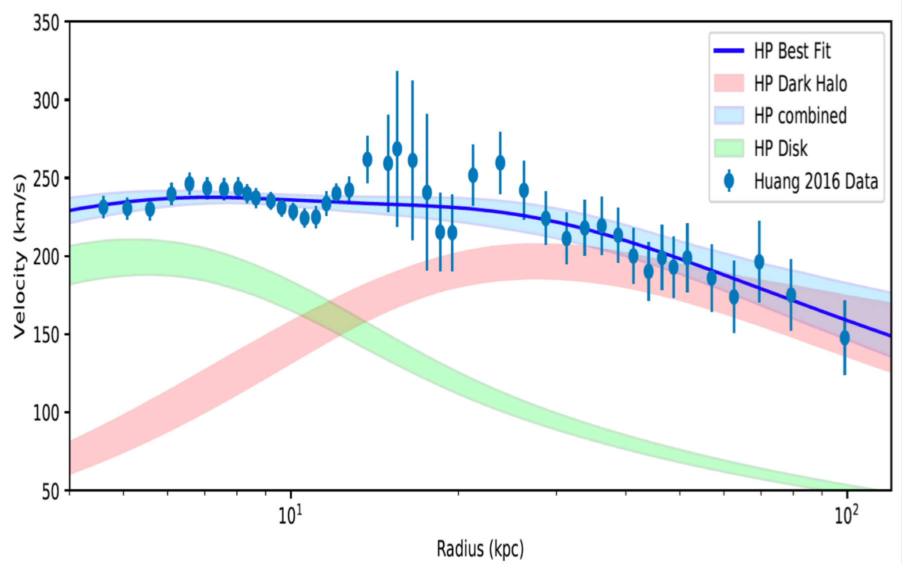
$\hat{t}$ is the time it takes for the lens to cross the Einstein ring

$$Q(x) = \frac{4 r_E^2(x) u_T^2}{\hat{t}^2 v_c^2},$$

$$A = \frac{R_c^2 + R_\odot^2}{L^2},$$

$$B = -2\frac{R_\odot}{L}\cos b \cos l,$$

$$r_E = \sqrt{\frac{4GMLx(1-x)}{c^2}}$$



The expected number of events is given by

$$N_{\rm exp} = E \int_0^\infty \frac{d\Gamma}{d\hat{t}} \xi(\hat{t}) d\hat{t},$$

E is the total exposure time in units of source years

$N_{\rm avg}$ is the upper limit on the average event rate

The Poisson distribution of microlensing events

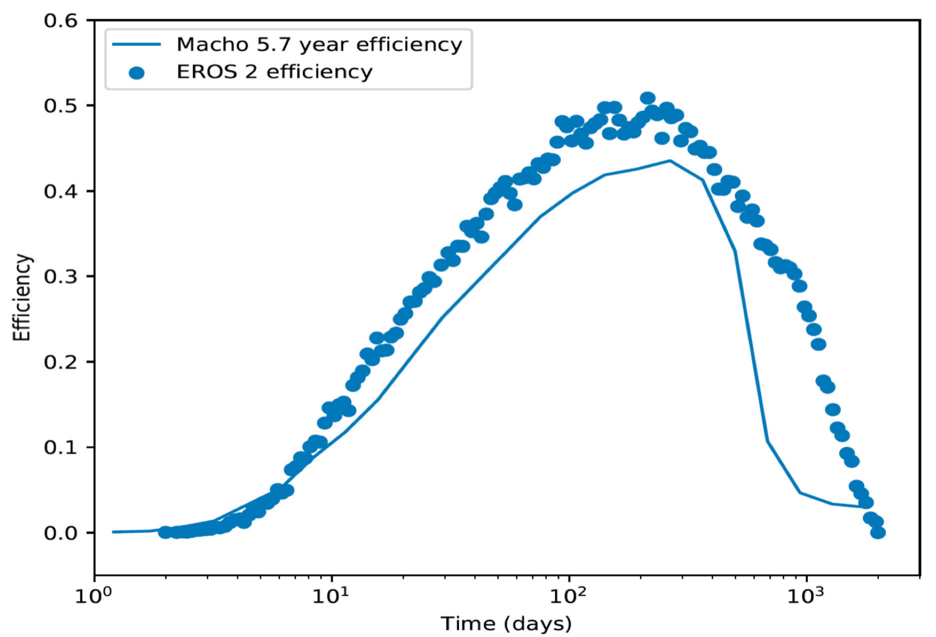
$$P(N_{\rm obs}) = e^{-N_{\rm avg}} \frac{N_{\rm avg}}{N_{\rm obs}!},$$

$N_{\rm obs}$ is the number of observed microlensing events

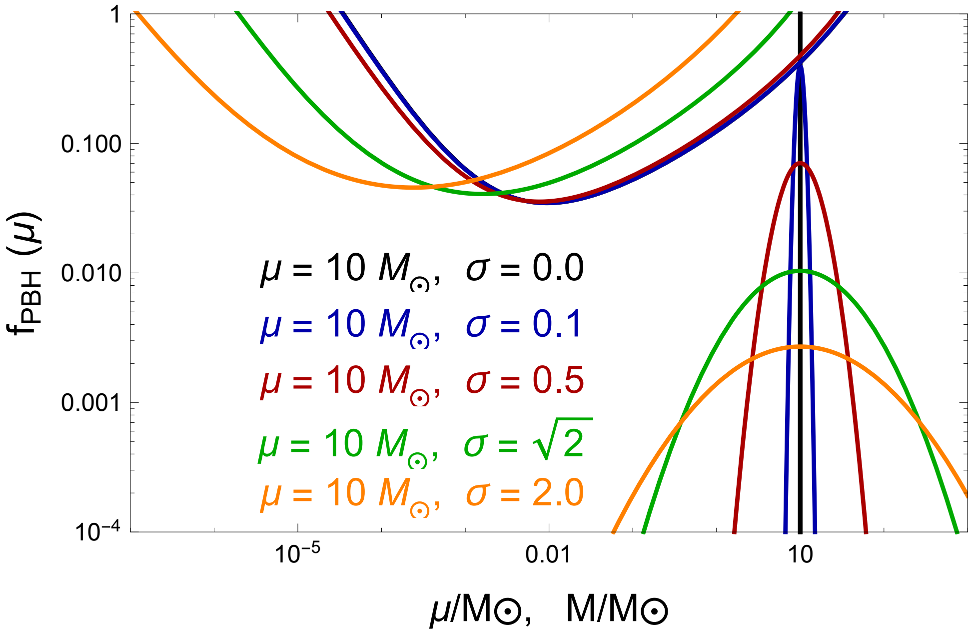
$P(N_{\rm obs}) = 0.95$ for some upper $N_{\rm avg}$.

$$C(M) = \frac{N_{\rm avg}}{N_{\rm exp}(M)} \leq 1$$

95% confident



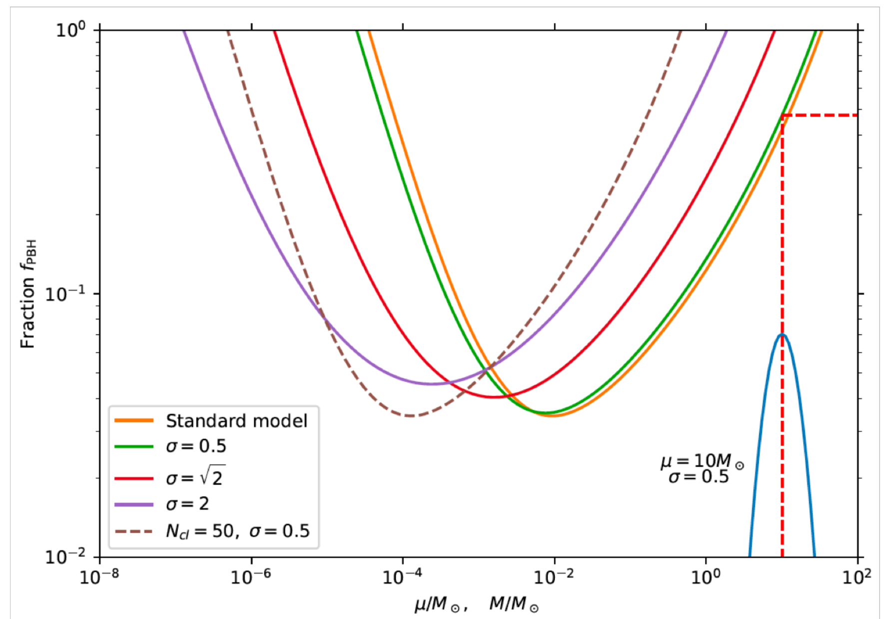
Microlensing constraints on clustered PBH with wide-mass distributions



$$\psi(M,\mu,\sigma) = \frac{f_{\rm PBH}\; e^{-\frac{1}{2}\sigma^2}}{\mu\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\ln^2 M/\mu}{2\sigma^2}\right)$$

Calcino, JGB et al. (2018)

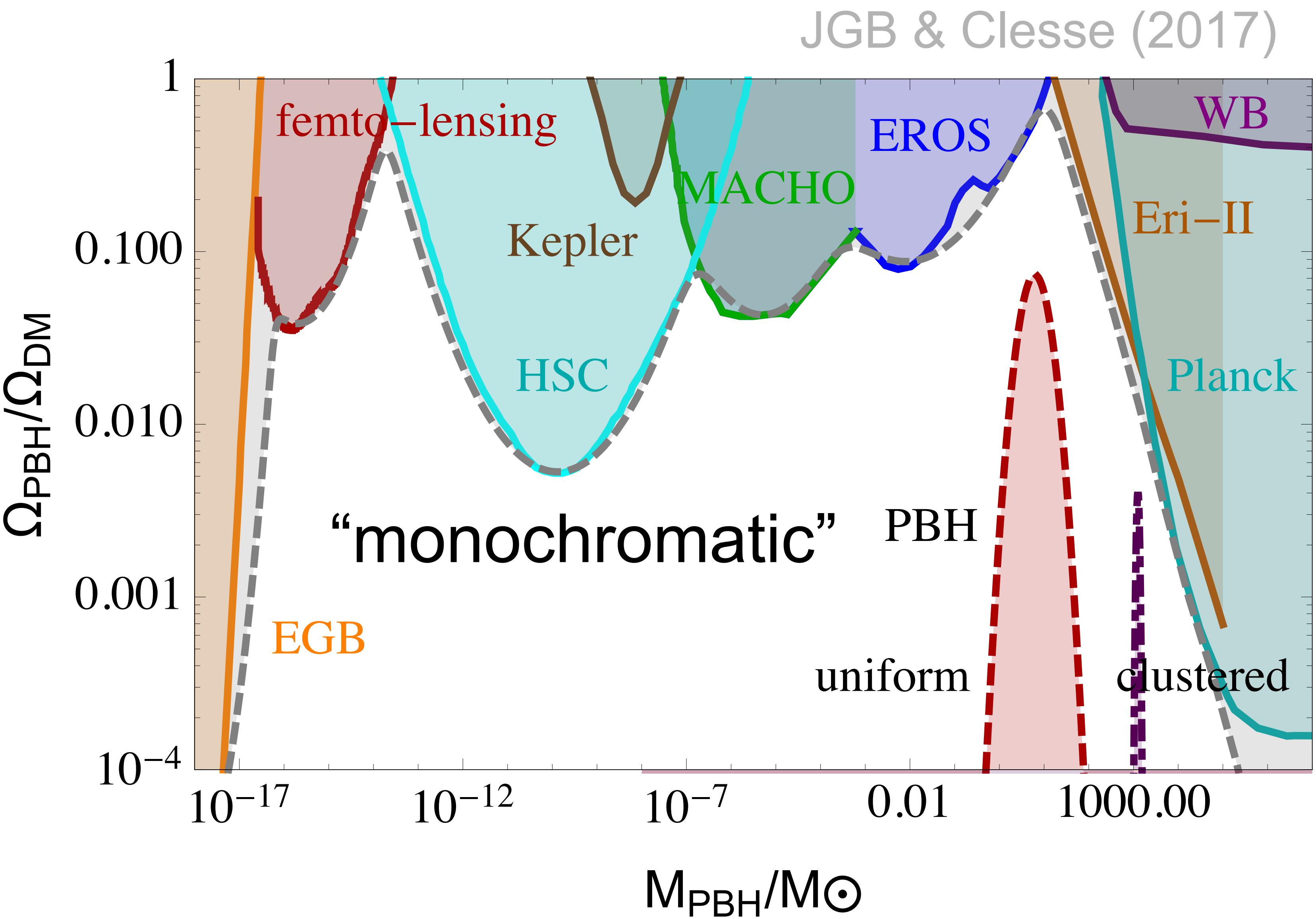
$$\psi = f_{\rm PBH}\bar{\psi}$$



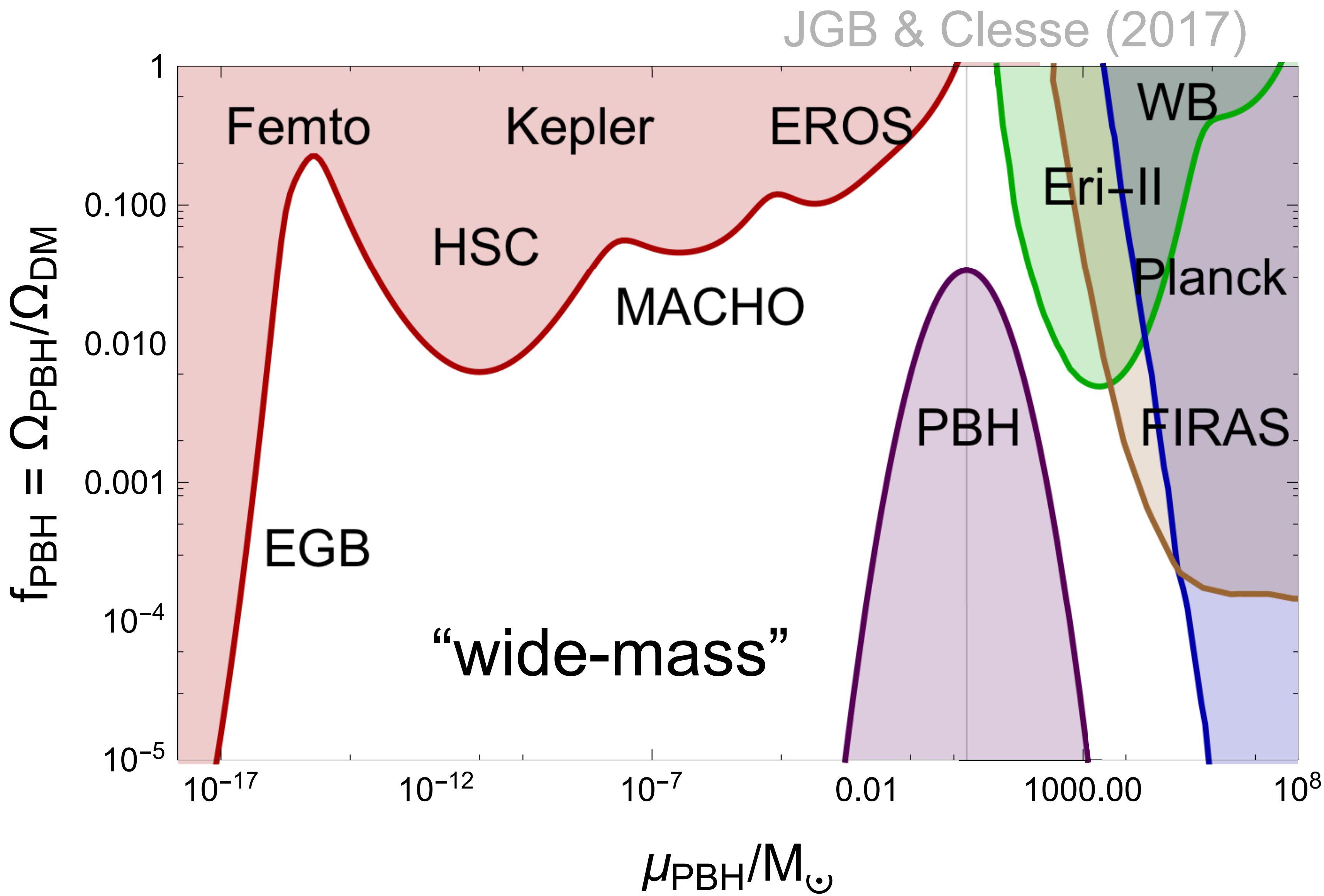
$$f_{\rm PBH}(\mu) \leq \left[\int_0^\infty dM\, \frac{\bar{\psi}(M,\mu,\sigma)}{C(M)}\right]^{-1}$$

Summary
Constraints
on PBH

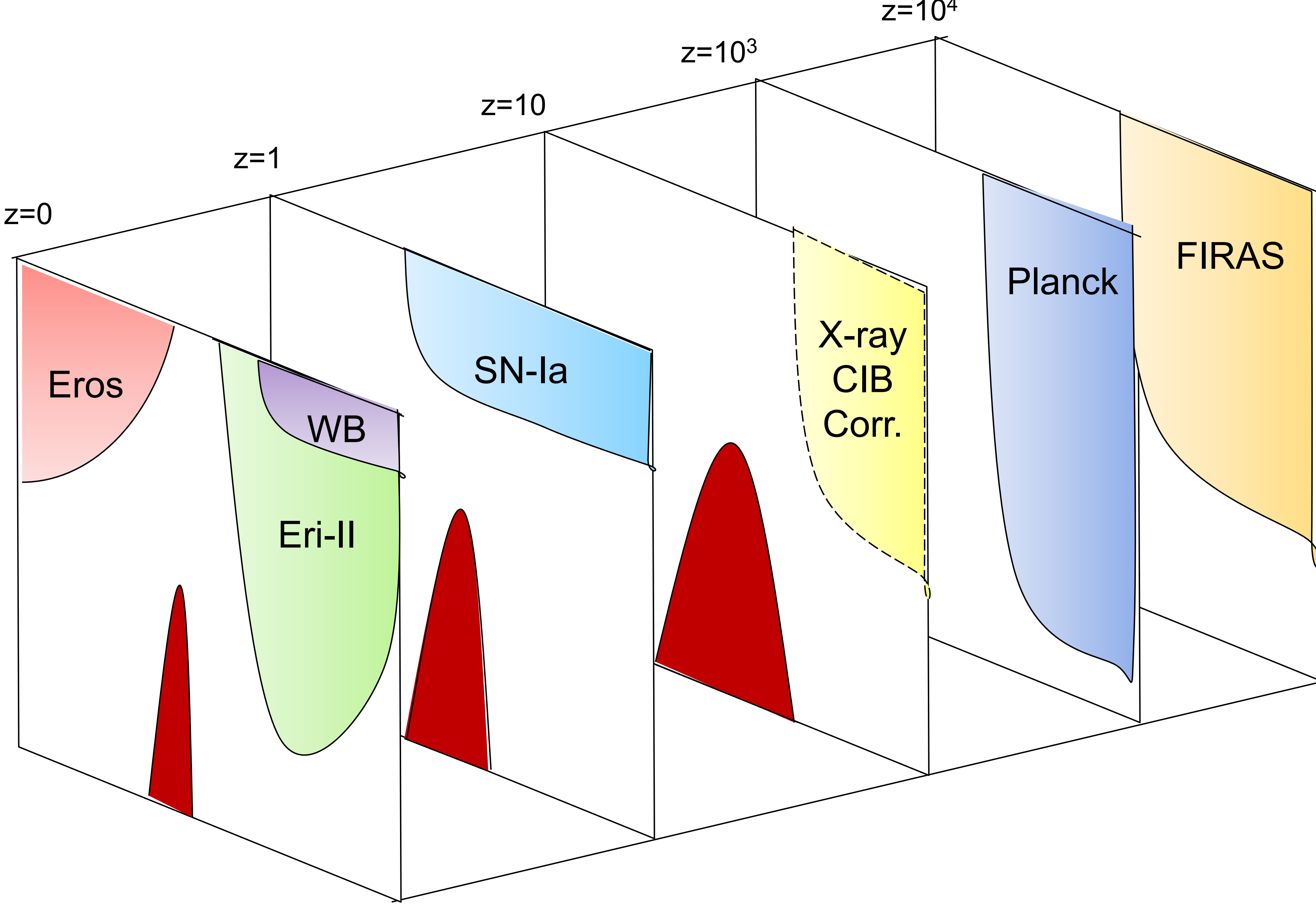
PBH constraints



PBH constraints



PBH constraints



Standing issues

- Evolution of clusters PBH with a wide-mass distribution
  - Why is $\Omega_{PBH} = \Omega_{DM} = 0.25$ today? Why is $\Omega_{PBH} = 5\ \Omega_B$?
  - Growth of individual BH masses in radiation & matter eras
  - Slingshot effect on PBH → evaporation of clusters of PBH
  - Few captures and mergers in the age of the universe
  - Gas accretion in dense baryonic environments => SMBH
  - PBH clusters disappear to form early galaxies
- Evolution of spin of BH inside massive PBH clusters
  - Initially spin-less PBH from isotropic collapse
  - Mergers and gas accretion induce spin on evolved PBH

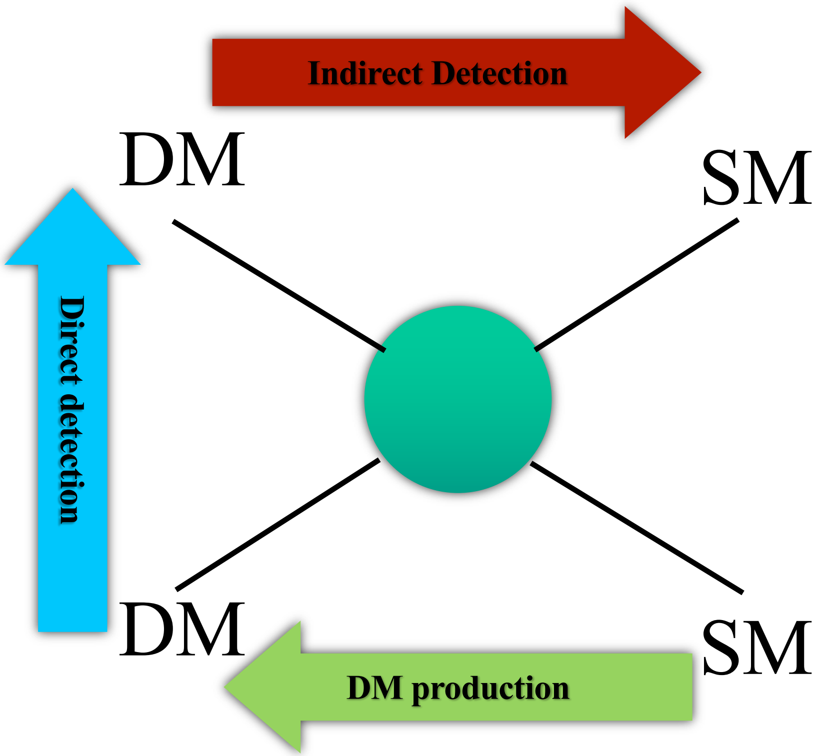
PBH

as

Dark Matter

Primordial Black Holes

Rethinking Dark Matter interactions:

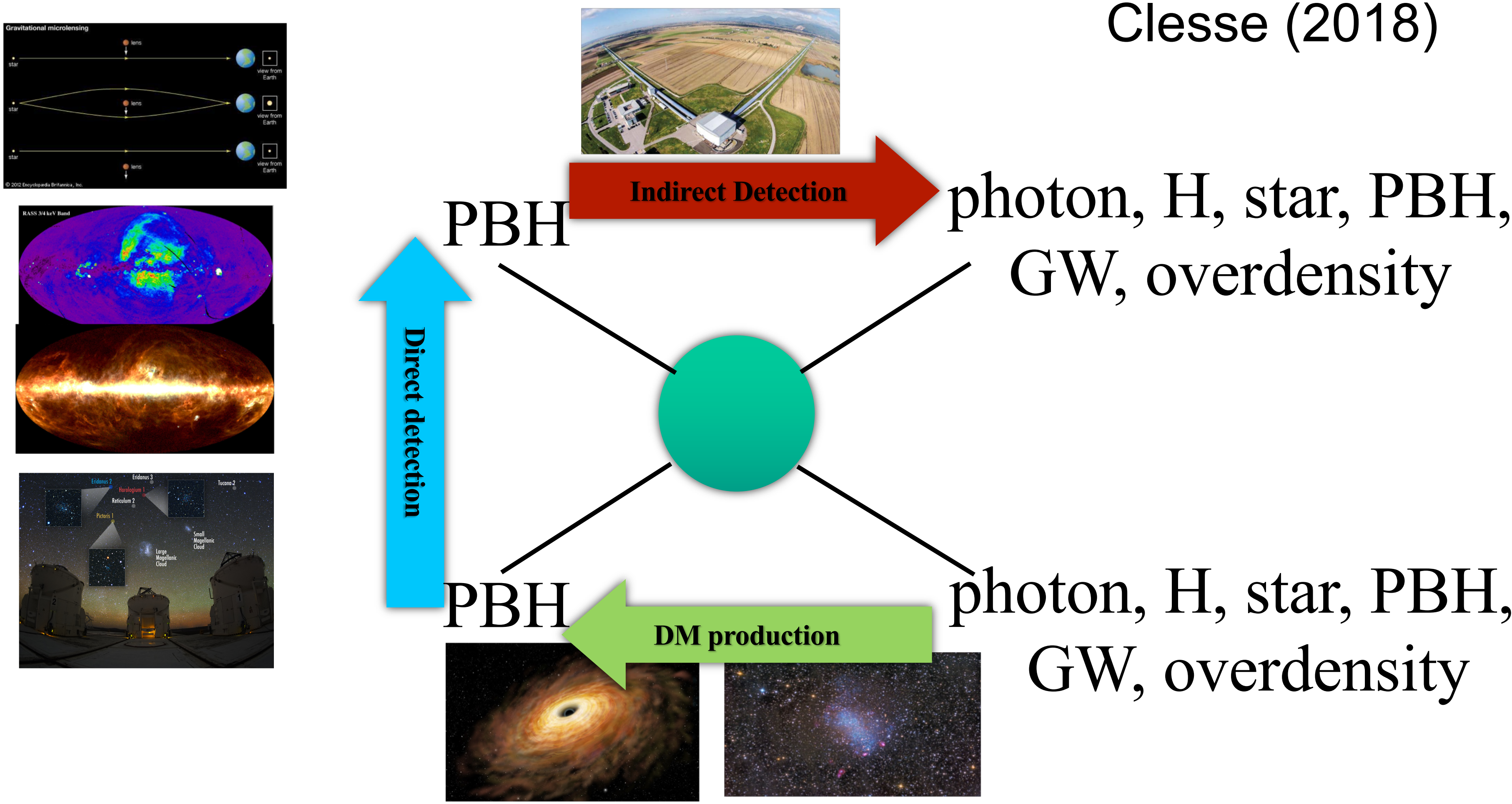


Clesse (2018)

Primordial Black Holes

Exciting times, very active, multi-disciplinary field, some clues in observations, upcoming experiments will challenge the scenario...

Clesse (2018)



Conclusions

- Massive Primordial Black Holes are the perfect candidates for collisionless CDM, in excellent agreement with CMB and LSS observations.
- PBHs could also resolve some of the most acute problems of ΛCDM paradigm, like early structure formation and (small scale) substructure problems.
- PBHs could arise from quantum fluctuations of curvature during inflation that collapse in rad. era.
- There are many ways to test this idea in the near future from microlensing, CMB, LSS and GW.
- Need a multiepoch, multiscale and multiprobe approach to the scenario of PBH as DM.

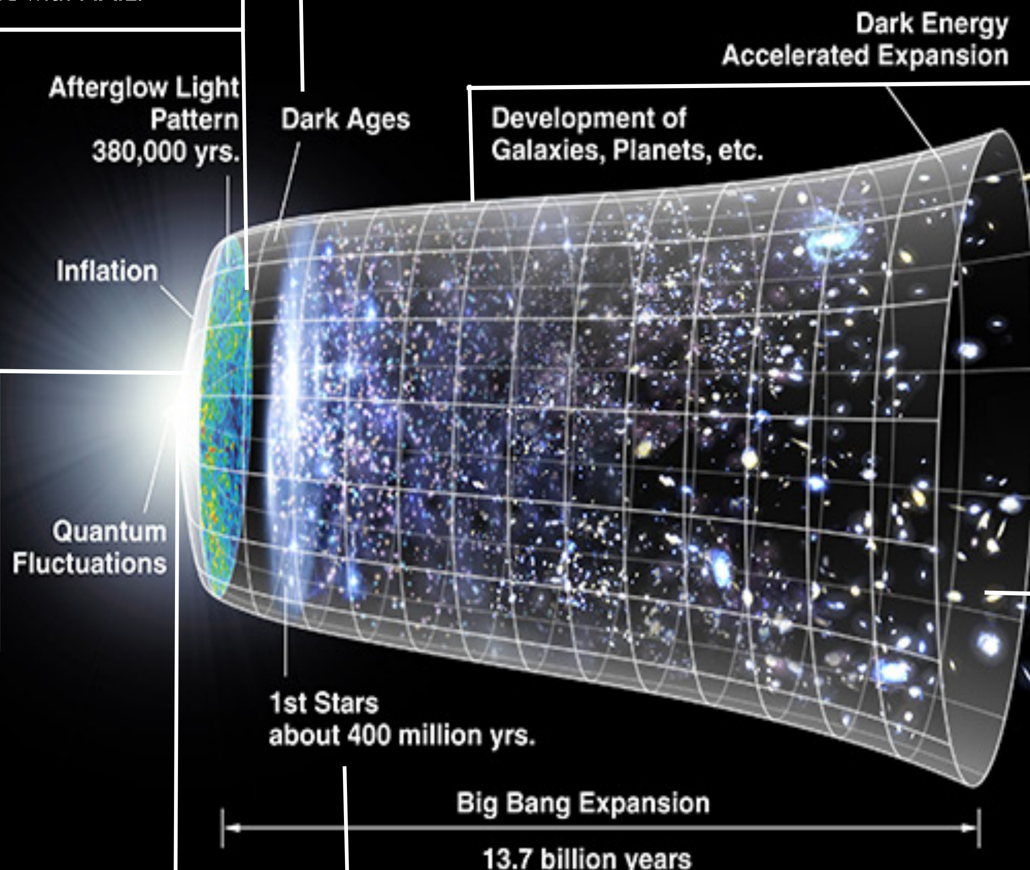
Cosmic Microwave Background: *380 000 years*
Massive primordial black holes induce distortions of the CMB,. These could be probed with PIXIE.

21cm signal *about 500 million years...*
X-rays emitted by accreting matter onto PBHs ionize the environment, leading to detectable signatures in the 21cm signal.

Over the cosmic evolution...

Binaries can form when PBH trajectories cross. After a spiraling phase, the two PBH merge and emit gravitational waves, such as the ones detected by LIGO.
PBH binaries also produce a background of gravitational waves, that will be probed by eLISA.

Halos of PBH induce anomalies in the Cosmic Infrared Background (CIB) and X-ray background, that have been observed by Spitzer.



Inflation : *10^{-35} second*
Quantum fluctuations are stretched by the exponential expansion.
In some models, large density fluctuations are generated

Local Universe:
PBH are regrouped in ultra-faint dwarf galaxies, orbiting around massive galaxies such as the Milky-Way and Andromeda.
Their existence could solve the *missing satellite* and *too-big-to-fail* problems.
Some of them have been detected by the DES experiment.

In the Milky-Way:
The presence of PBH should induce tiny variations in the position and velocity of stars that are being monitored by GAIA.

Formation of primordial black holes (PBH) :
less than one second after the end of inflation...
The large inhomogeneities produced during inflation collapse gravitationally and form massive primordial black holes, which could be already regrouped in dense halos.

The seeds of supermassive black holes (SMBH):
during the first billion years...
A subdominant fraction of very massive PBH could be the seeds of SMBH, then growing by successive merging and matter accretion.

Primordial Black Holes as Dark Matter

J. Calcino, JGB & T. Davis, MNRAS 479 (2018) 2889
S. Clesse & JGB, Phys. Dark Univ. 22 (2018) 137
JGB & S. Nesseris, Phys. Dark Univ. 21 (2018) 61
JGB, S. Clesse & P. Fleury, Phys. Dark Univ. 20 (2018) 95
JGB & S. Clesse, Phys. Dark Univ. 19 (2018) 144
Ezquiaga, JGB & Ruiz Morales, Phys. Lett. B776 (2018) 345
JGB & Ruiz Morales, Phys. Dark Univ. 18 (2017) 47
JGB & S. Clesse, Sci. Am. July (2017) 39 (review)
JGB, J.Phys.Conf 840 (2017) 012032 (scenario)
JGB & S. Nesseris, Phys Dark Univ. 18 (2017) 123
S. Clesse & JGB, Phys Dark Univ. 18 (2017) 105
JGB, M. Peloso & C. Unal, JCAP 1709 (2017) 013
JGB, M. Peloso & C. Unal, JCAP 1612 (2016) 031
S. Clesse & JGB, Phys Dark Univ. 10 (2016) 002
S. Clesse & JGB, Phys Rev D92 (2015) 023524
JGB, Linde & Wands, Phys Rev D54 (1996) 6040

Summary

1. PBH can be all of the Dark Matter
   - Solves ΛCDM problems with small scale structures.
   - Clustered wide-mass PBH scenario not yet ruled out
2. Natural PBH formation mechanism during inflation
   - Broad peaks in the curvature power spectrum
3. Already exist observational hints of PBH as DM
   - Gravitational waves from LIGO
   - Microlensing OGLE + QSO
4. Can be tested with future experiments (PIXIE, GAIA)
5. Present constraints are weakened for spatially clustered wide-mass distributed PBH

Backup slides

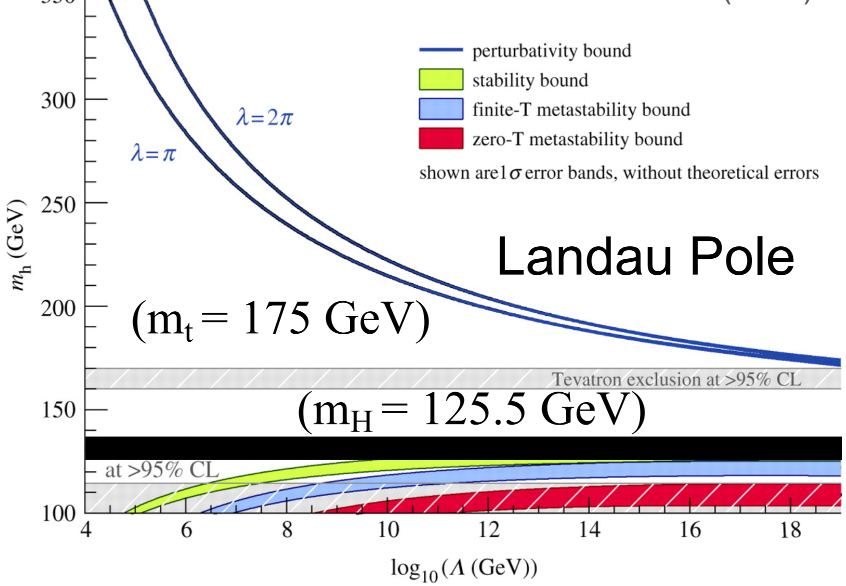
Critical Higgs Inflation

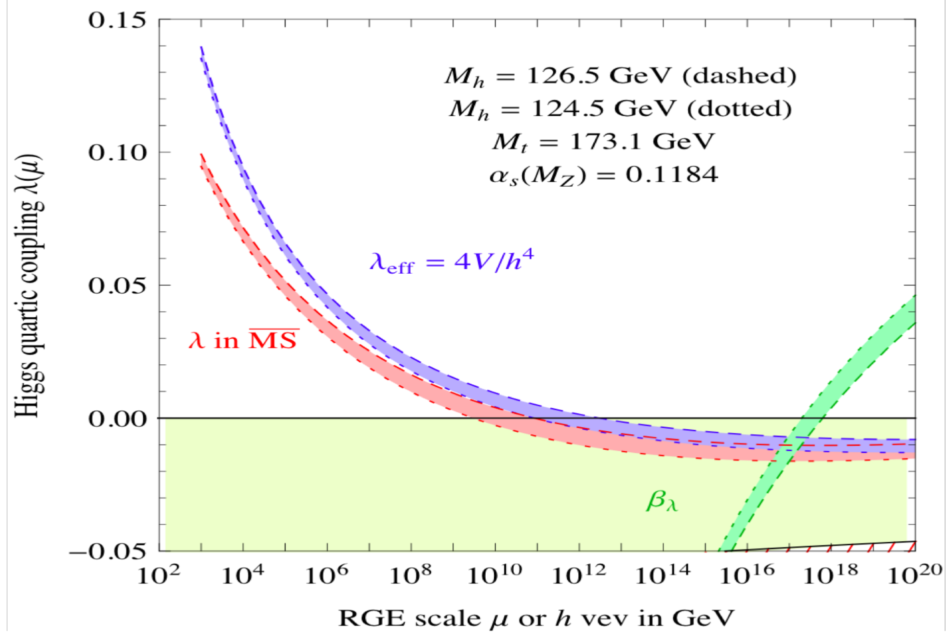
SM Higgs → Inflaton

↓

Dark Matter ← PBH

John Ellis (2012)





Ezquiaga, JGB, Ruiz Morales (2017)

$$S=\int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2}+\frac{\xi(\phi)}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu)\,,$$

$$\xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu)\,,$$

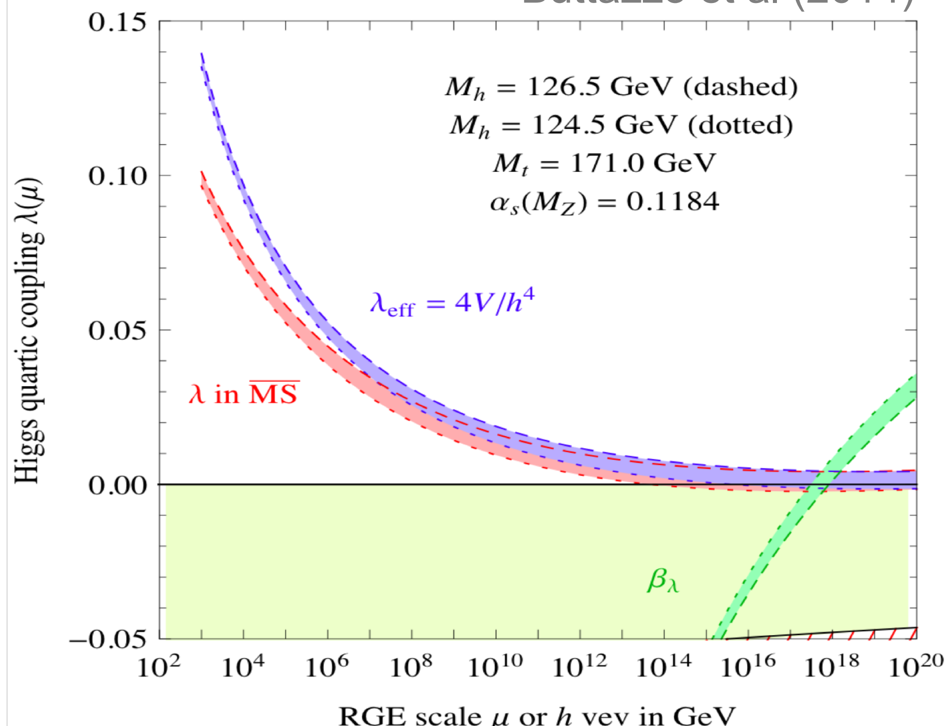
$$\frac{d\varphi}{d\phi}=\frac{\sqrt{1+\xi(\phi)\,\phi^2+6\,\phi^2\,(\xi(\phi)+\phi\,\xi'(\phi)/2)^2}}{1+\xi(\phi)\,\phi^2}$$

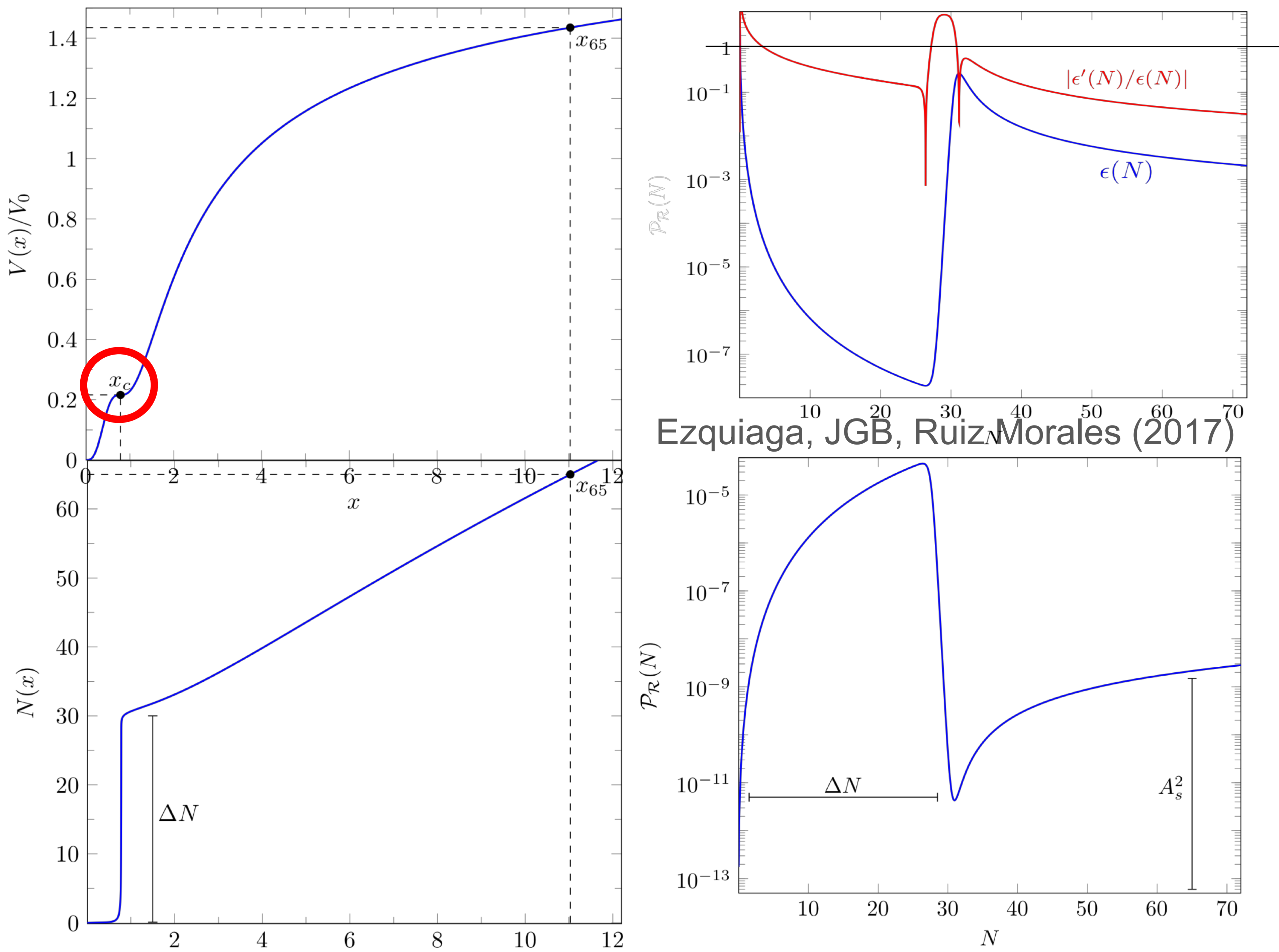
$$V(x)=\frac{V_0\,(1+a\,\ln^2 x)\,x^4}{(1+c\,(1+b\,\ln x)\,x^2)^2}$$

$$x = \phi/\mu$$

$$V_0=\lambda_0\mu^4/4,\; a=b_\lambda/\lambda_0,\; b=b_\xi/\xi_0 \text{ and } c=\xi_0\,\kappa^2\mu^2$$

Buttazzo et al (2014)

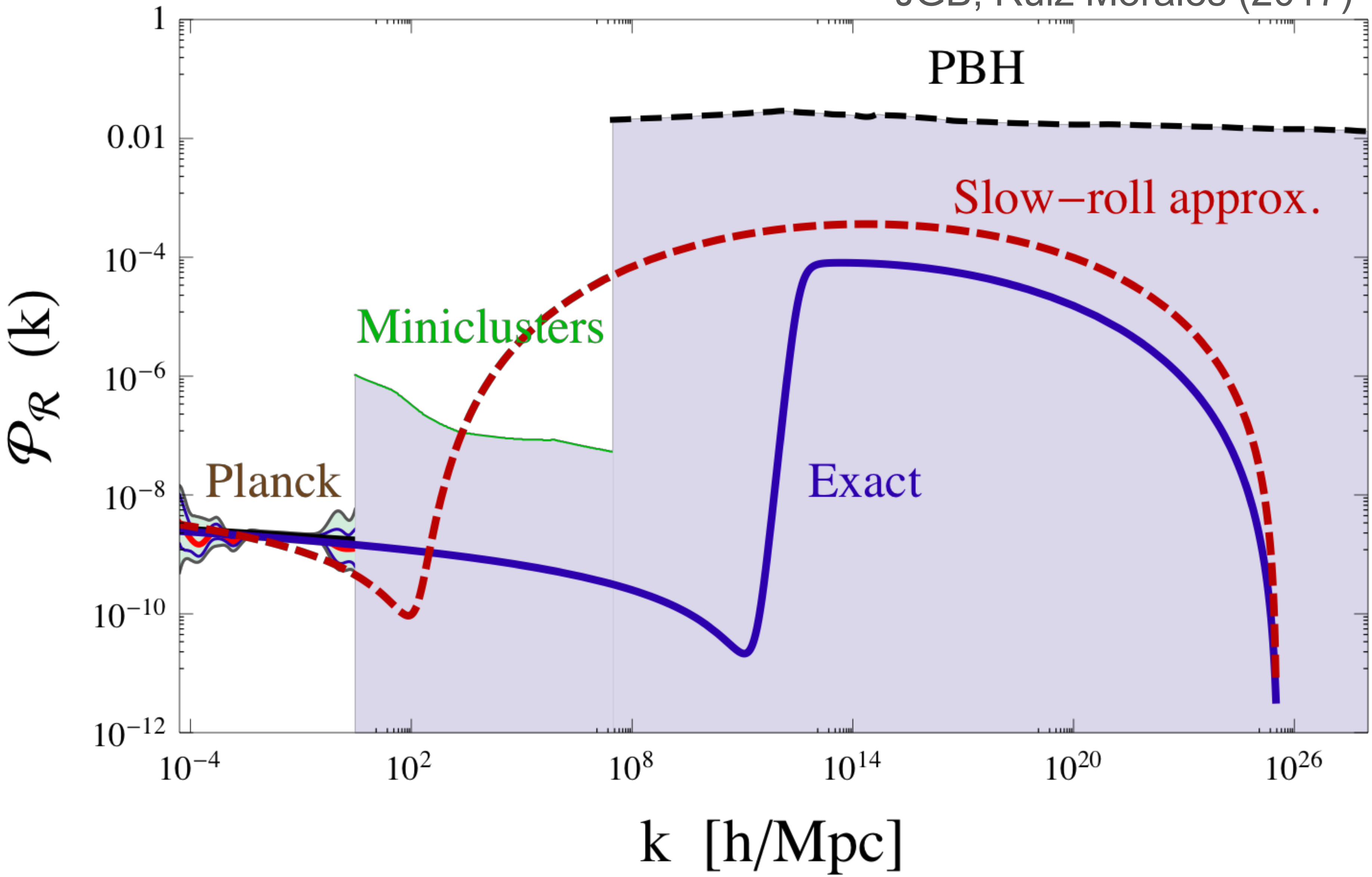




$V(x)/V_0$
x_c
x_{65}
x
$N(x)$
ΔN
$|\epsilon'(N)/\epsilon(N)|$
$\epsilon(N)$
$\mathcal{P}_\mathcal{R}(N)$
N
A_s^2
Ezquiaga, JGB, Ruiz Morales (2017)

Primordial Spectrum PBH in SFI

JGB, Ruiz Morales (2017)



Clustering of PBH at formation

Chisholm (2006)

Mass fraction Hubble domains / collapse to form PBH

$$\beta(\nu) = \mathrm{erfc}\left(\nu/\sqrt{2}\right) \simeq \sqrt{\frac{2}{\pi}}\frac{e^{-\nu^2/2}}{\nu}$$

$$\nu \equiv \delta_c/\sigma_H = \delta_c/\sqrt{P(k_H)} \gg 1 \qquad \nu \simeq 6.$$

The number of PBH in each cluster

$$N_{\rm cl} = \frac{10}{7}\,\beta(\nu)\,e^{3\nu^2/4} \sim 2000$$

A large fraction PBH will evaporate from the cluster via multiple 3-body interactions (Sigurdsson-Hernquist 1993)

Clustering of PBH at formation

The typical distance between PBH @formation

$$\lambda(z_f) = \frac{d_H(z_f)}{\beta(z_f)^{1/3}} \sim 1.2 \times 10^5 \text{ km} \left(\frac{6 \times 10^{11}}{1+z_f}\right)^{5/3}$$

and the horizon distance at formation

$$d_H(z_f) = d_H(z_{\rm eq}) \left(\frac{1+z_{\rm eq}}{1+z_f}\right)^2 \sim 240 \, \text{km} \left(\frac{6 \times 10^{11}}{1+z_f}\right)^2$$

$$\beta(z_f) \sim 3 \times 10^{-9} \left(\frac{6 \times 10^{11}}{1+z_f}\right)$$

$$M_{\rm PBH} \sim 20 \, M_\odot \left(\frac{6 \times 10^{11}}{1+z_f}\right)^2$$

Clustering of PBH today

The typical distance between PBH clusters in the outer halos of galaxies

$$d_{\rm PBH} = 50\,{\rm pc}\,\left(\frac{M_{\rm cl}}{100\,M_\odot}\right)^{1/3}$$

The local density contrast @ formation

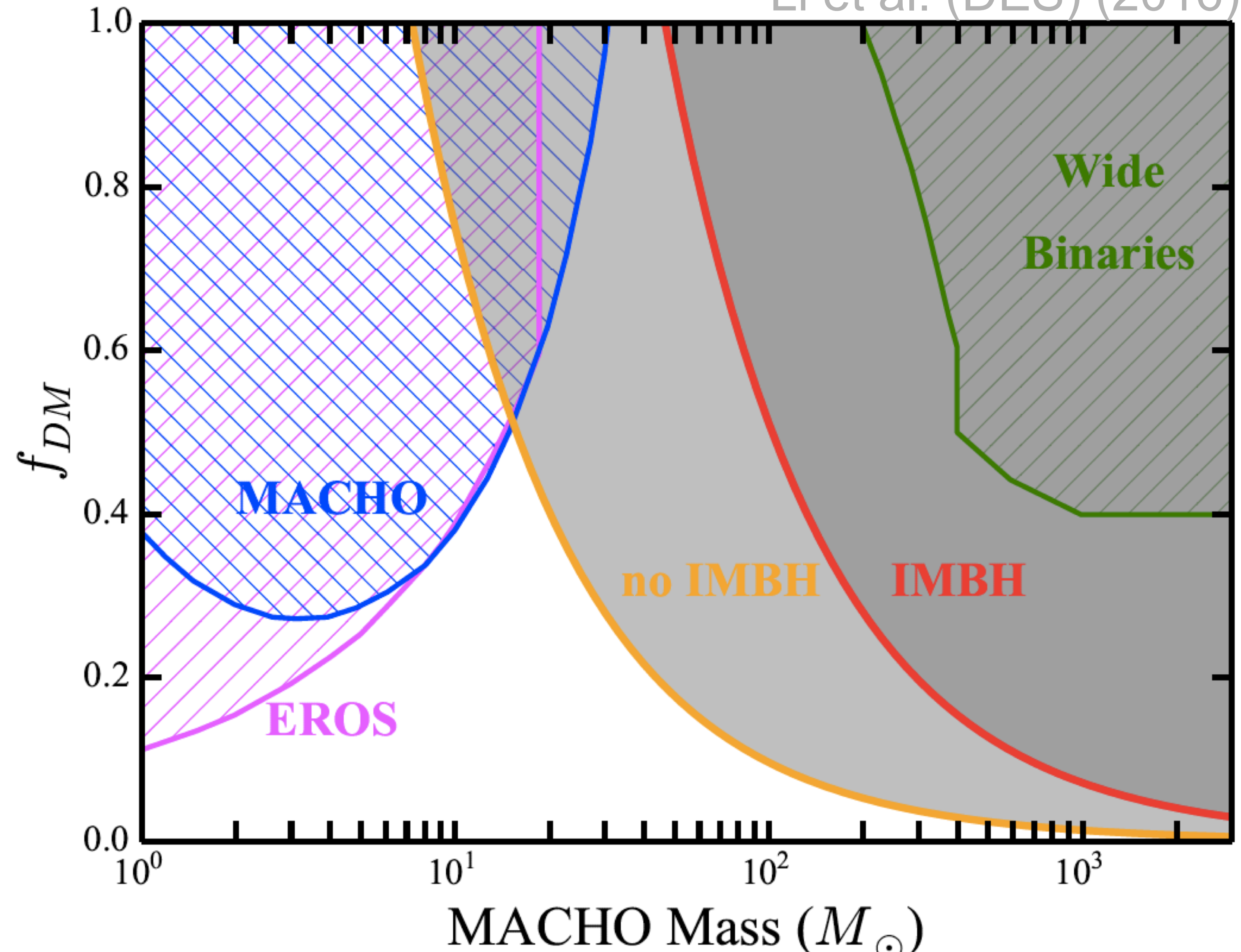
$$\delta \sim e^{\nu^2/2} \propto \beta(z_f)^{-1} \sim 6\times 10^7$$

today $\delta_{loc} \sim 10^{11}$

The typical size of a cluster of PBH today is of the order of a miliparsec to a parsec.

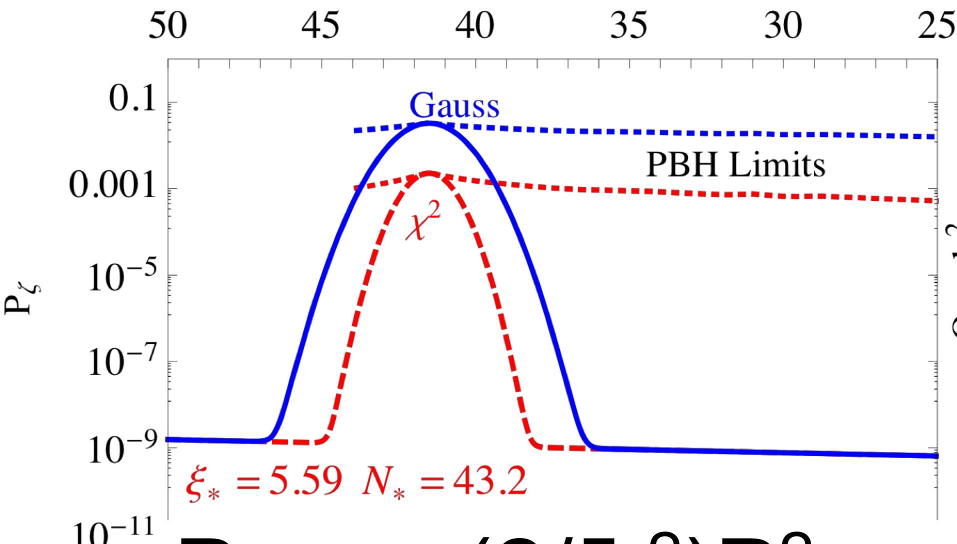
Eridanus II dwarf spheroidal

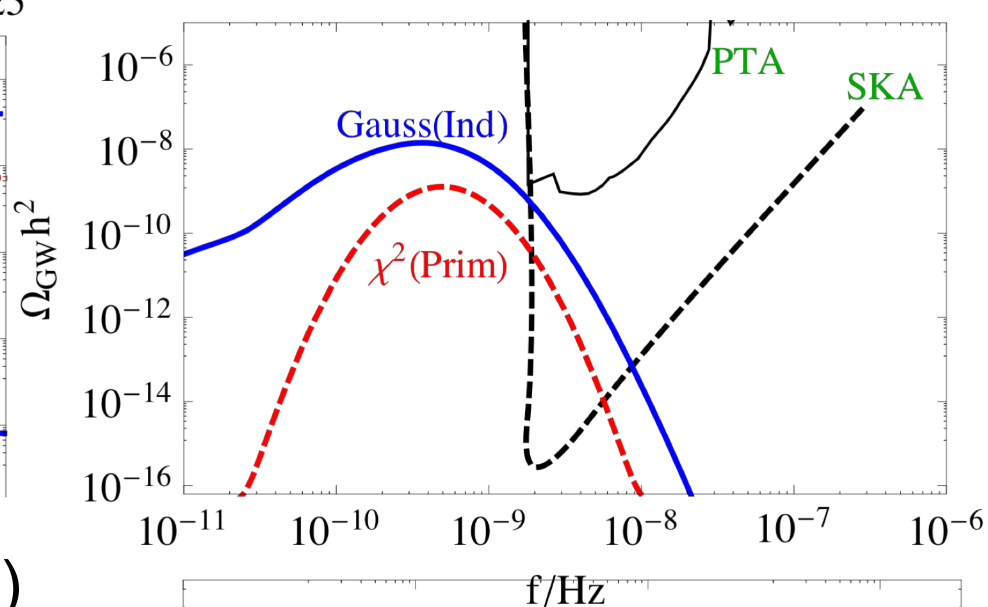
Li et al. (DES) (2016)



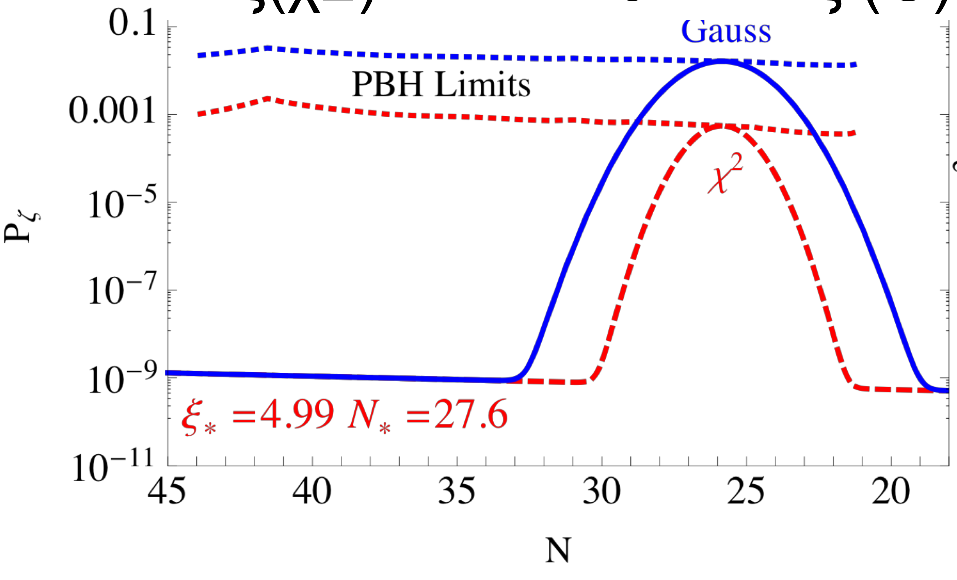
Second order background GW

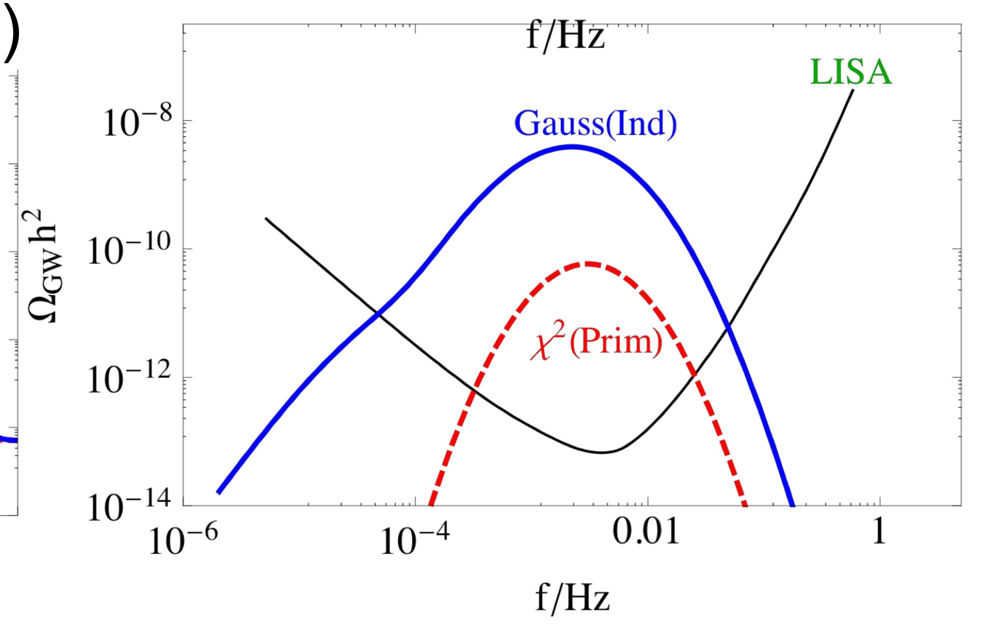
JGB, Peloso, Unal (2017)





$$P_{\zeta(\chi 2)} = (2/\zeta_c^{\,2}) P^2_{\zeta\,(G)}$$





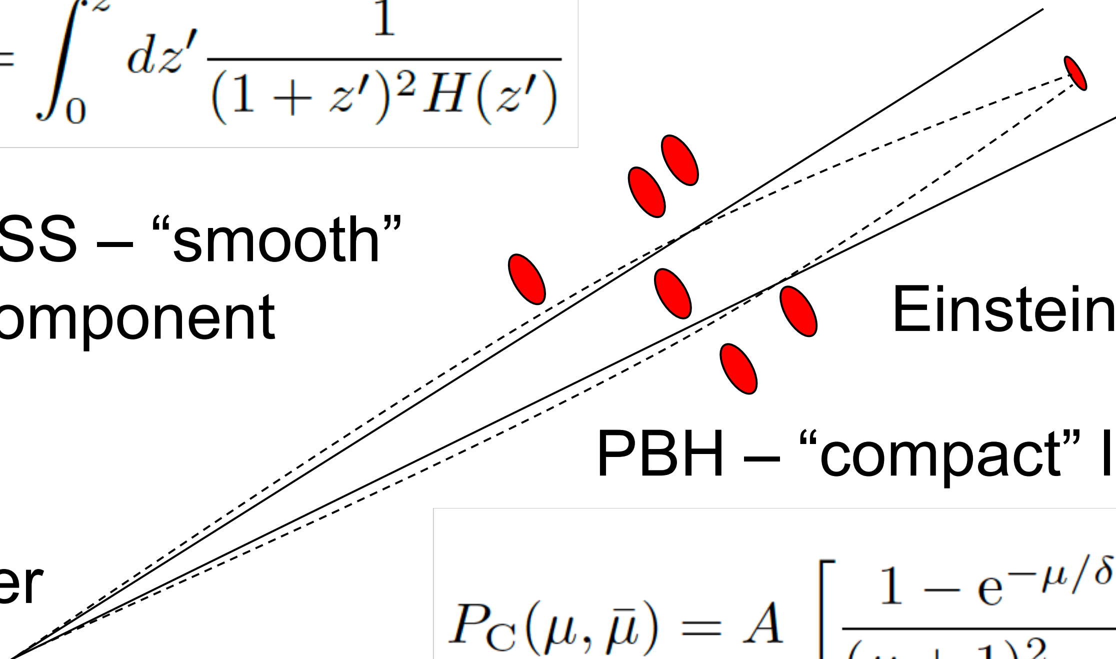
Supernova lensing magnification

Supernovae lensing

Magnification   Dyer-Roeder (1973)

$$\mu \equiv \left(\frac{D_{\rm EB}}{D}\right)^2 - 1,$$

$$D_E(z) = \int_0^z dz' \frac{1}{(1+z')^2 H(z')}$$



$\Omega_M = 1$

$\Omega_\Lambda = 0$

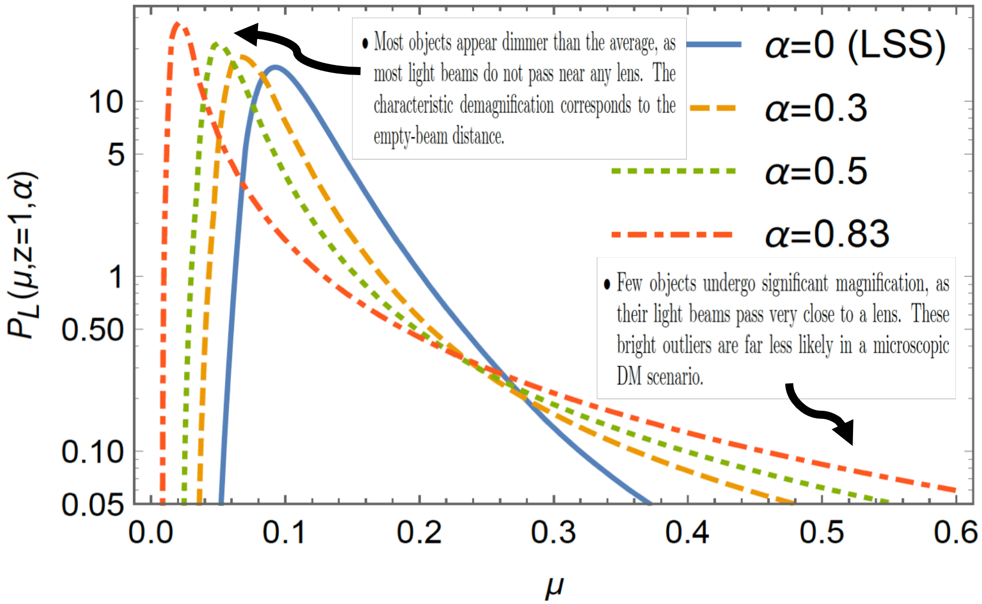
$$P_{\rm C}(\mu, \bar{\mu}) = A \left[\frac{1 - e^{-\mu/\delta}}{(\mu+1)^2 - 1}\right]^{3/2} \quad \text{for } \mu > 0,$$

$$P_{\rm L}(\mu; z, \alpha) = \int_0^{\frac{\mu}{1-\alpha}} d\mu' \; P_{\rm LSS}(\mu'; z) P_{\rm C}[\mu - (1-\alpha)\mu'; \alpha\mu'].$$

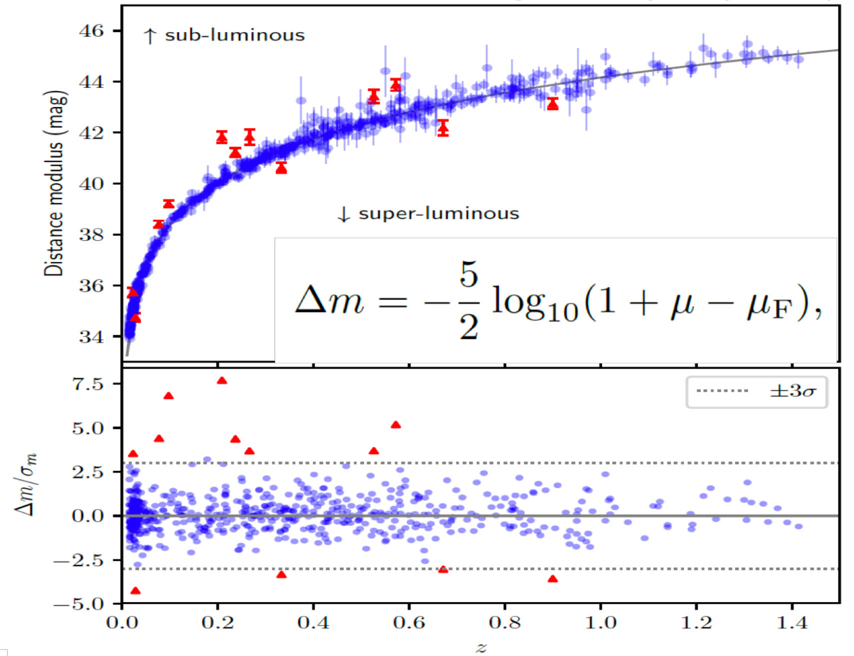
$$\mu = (1-\alpha)\mu' + \mu_{\rm c}[\alpha\mu']$$

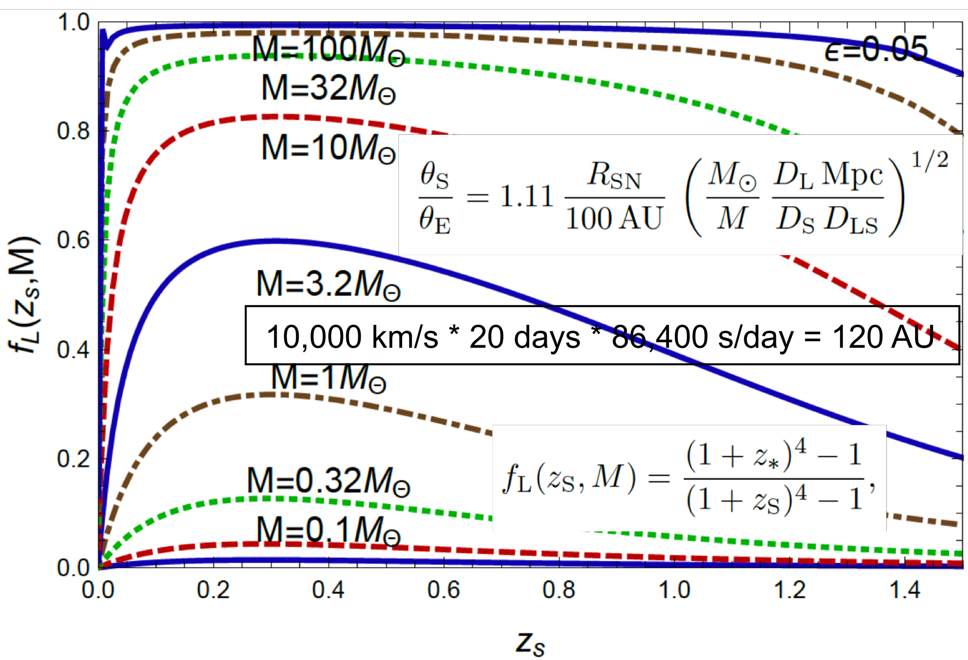
$$\alpha \equiv \rho_{\rm PBH}/\rho_{\rm M} = 0.83 f_{\rm PBH}$$

SN lensing

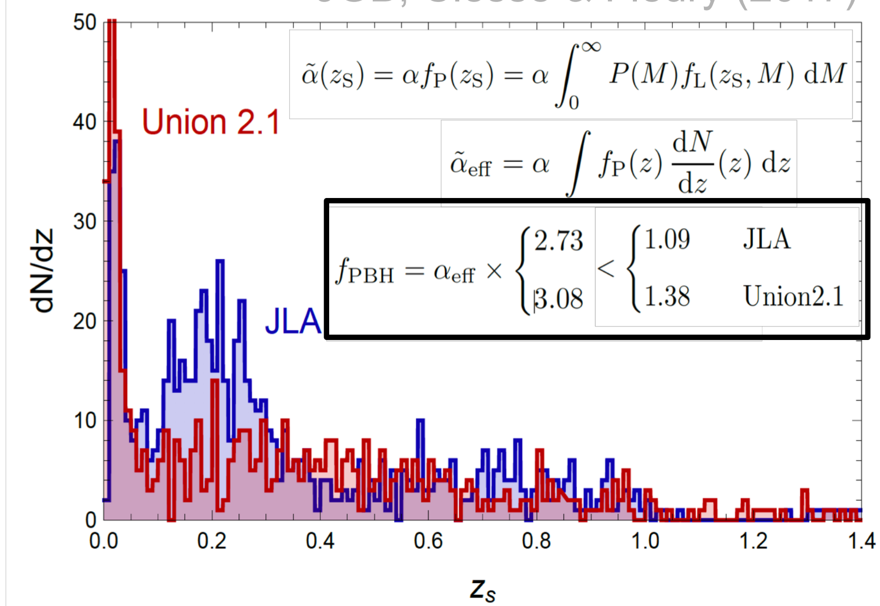


Zumalacarregui, Seljak (2017)



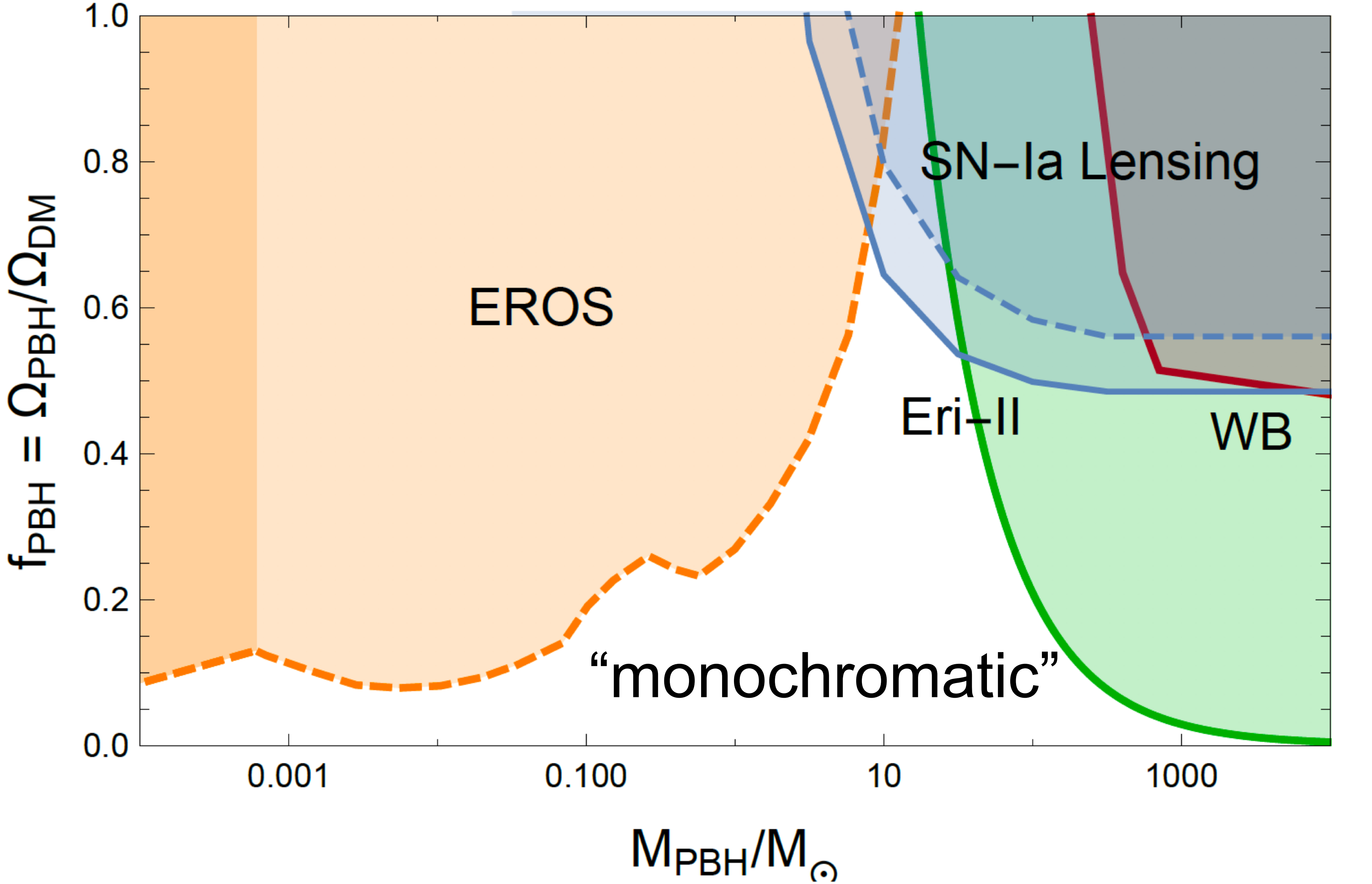


JGB, Clesse & Fleury (2017)

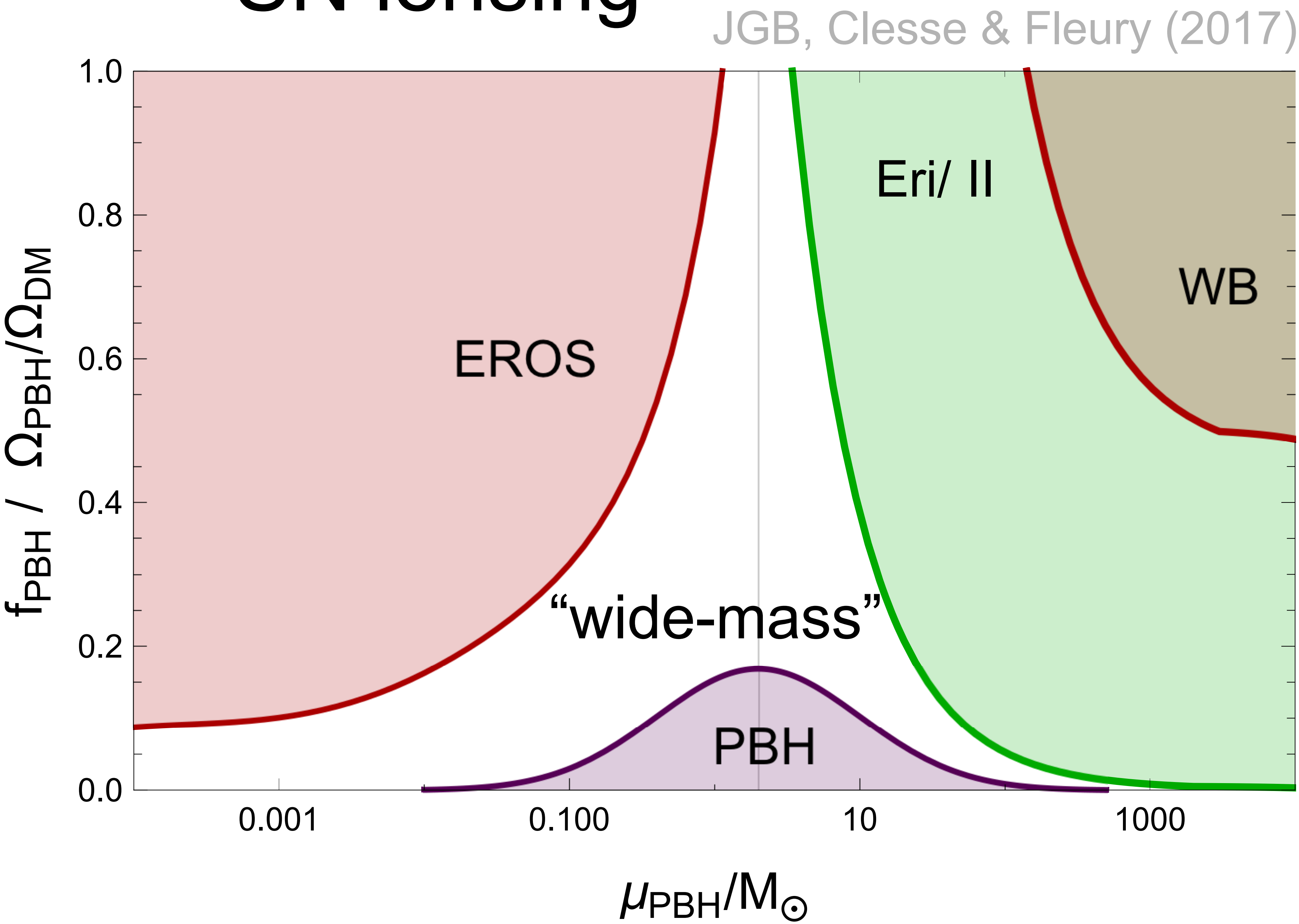


SN lensing

JGB, Clesse & Fleury (2017)



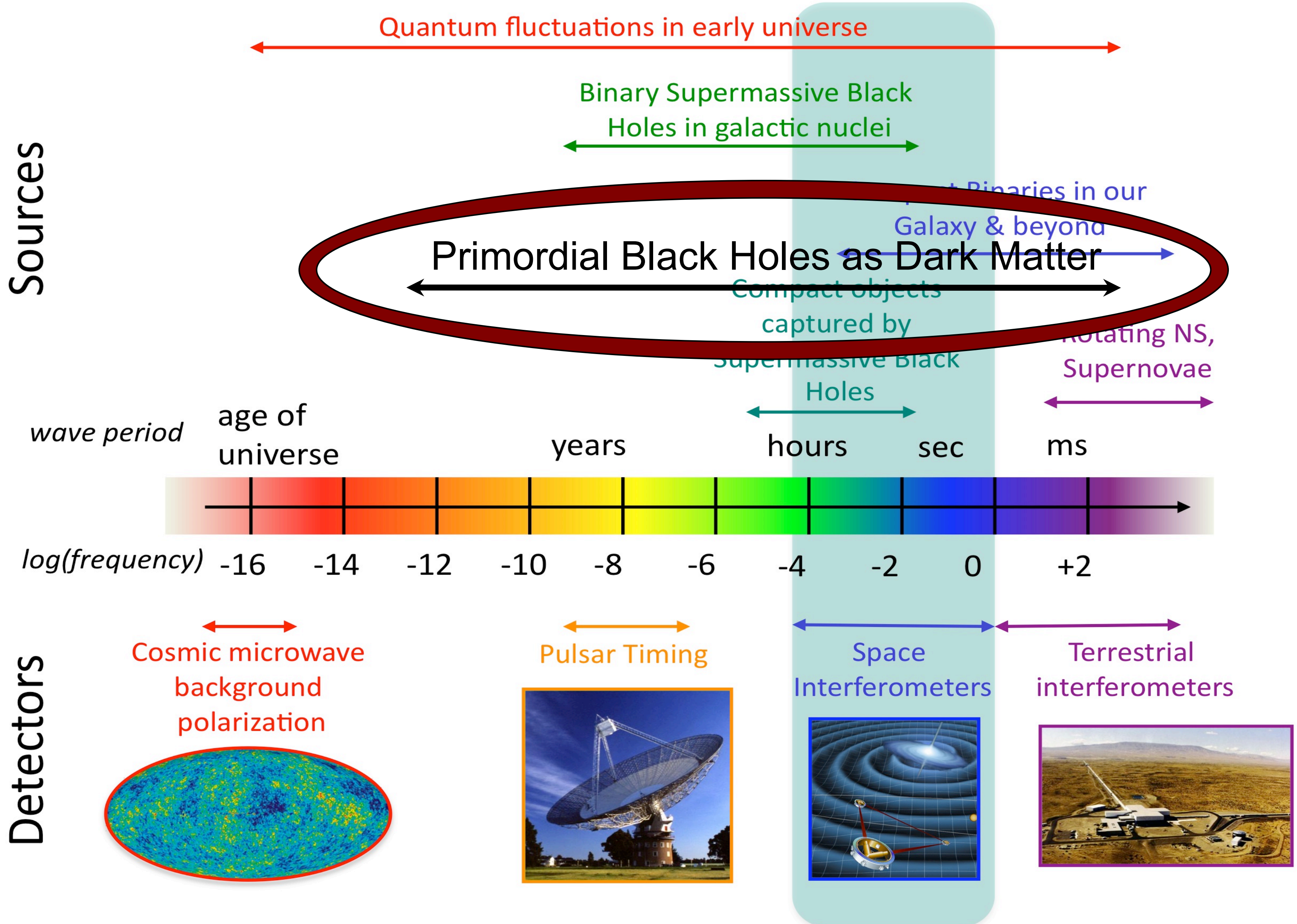
SN lensing



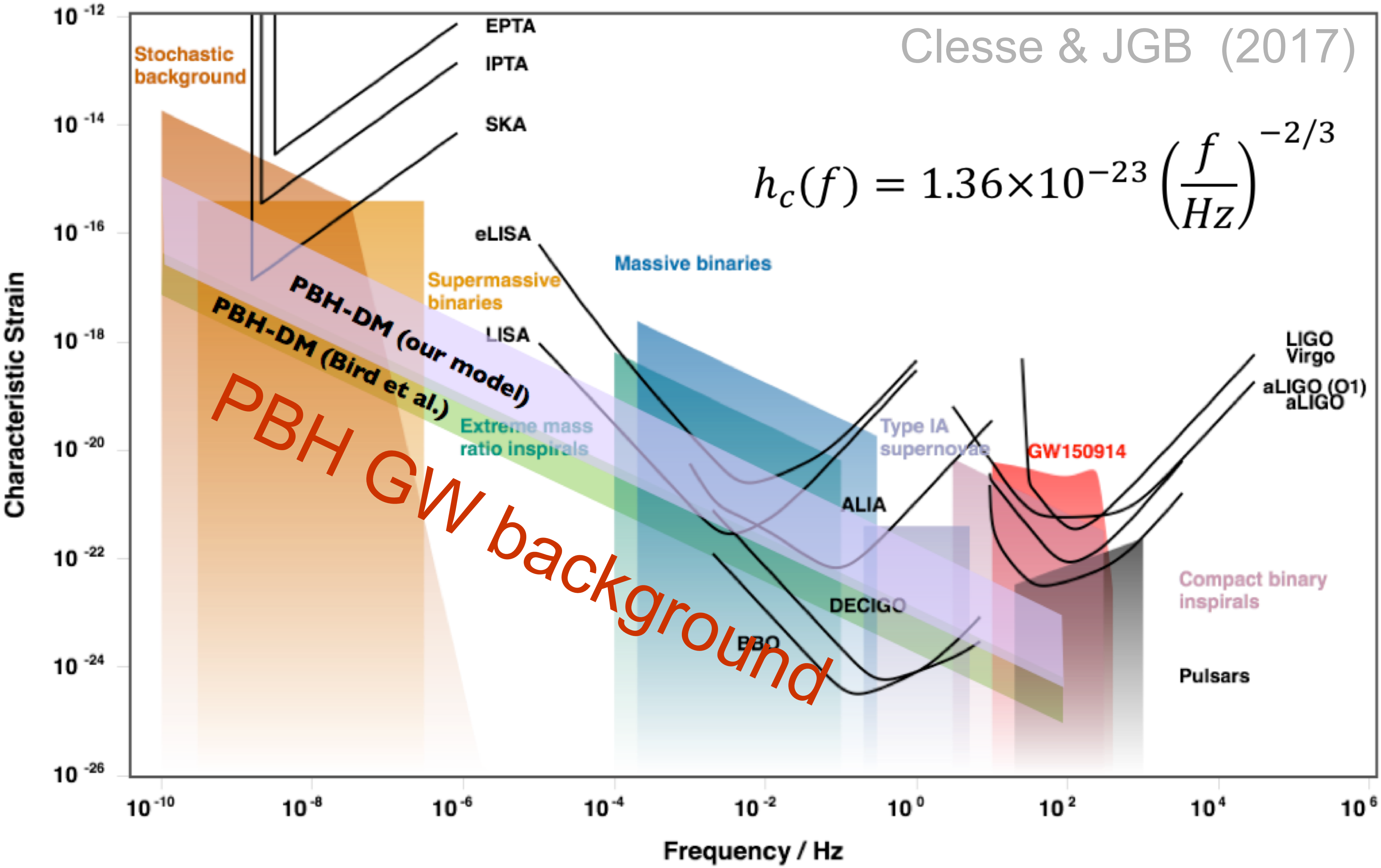
JGB, Clesse & Fleury (2017)
1.0
0.8
0.6
0.4
0.2
0.0
0.001
0.100
10
1000
f_{PBH} / Ω_{PBH}/Ω_{DM}
$\mu_{PBH}/M_{\odot}$
EROS
Eri/ II
WB
"wide-mass"
PBH

Stochastic Background Grav. Waves

The Gravitational Wave Spectrum

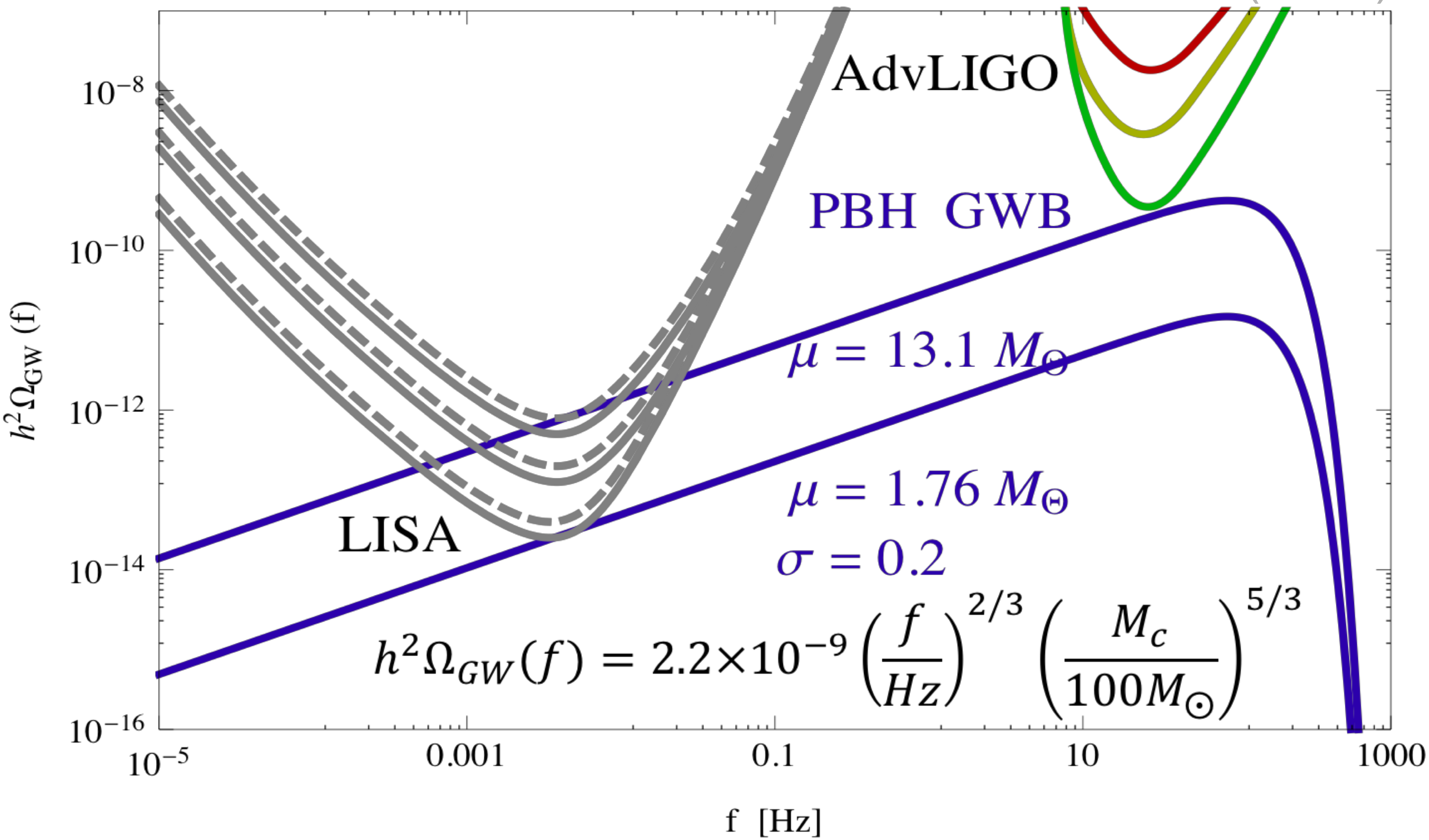


Sensitivity of future GW antenas



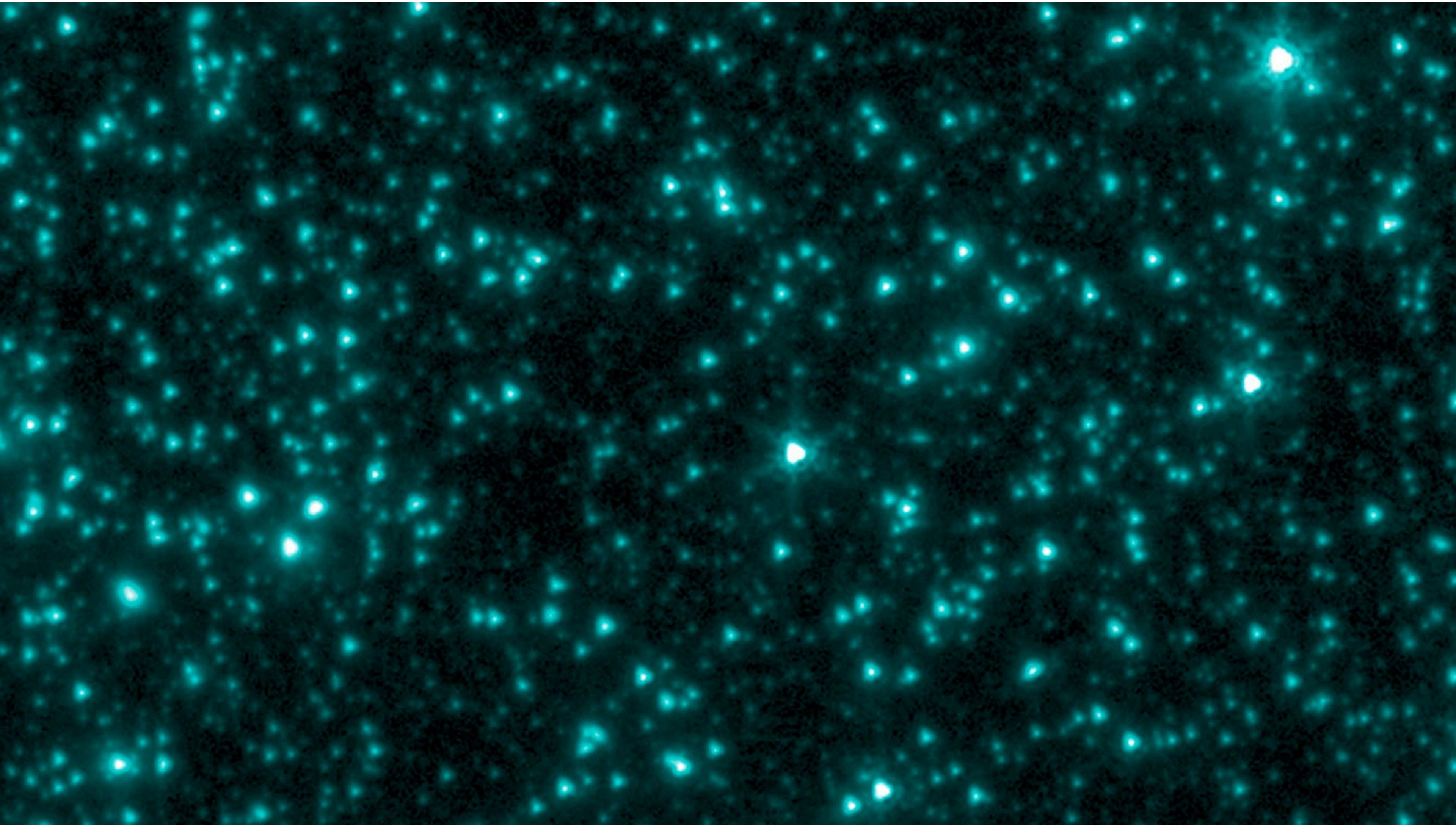
Stochastic Background from PBH

Clesse & JGB (2017)

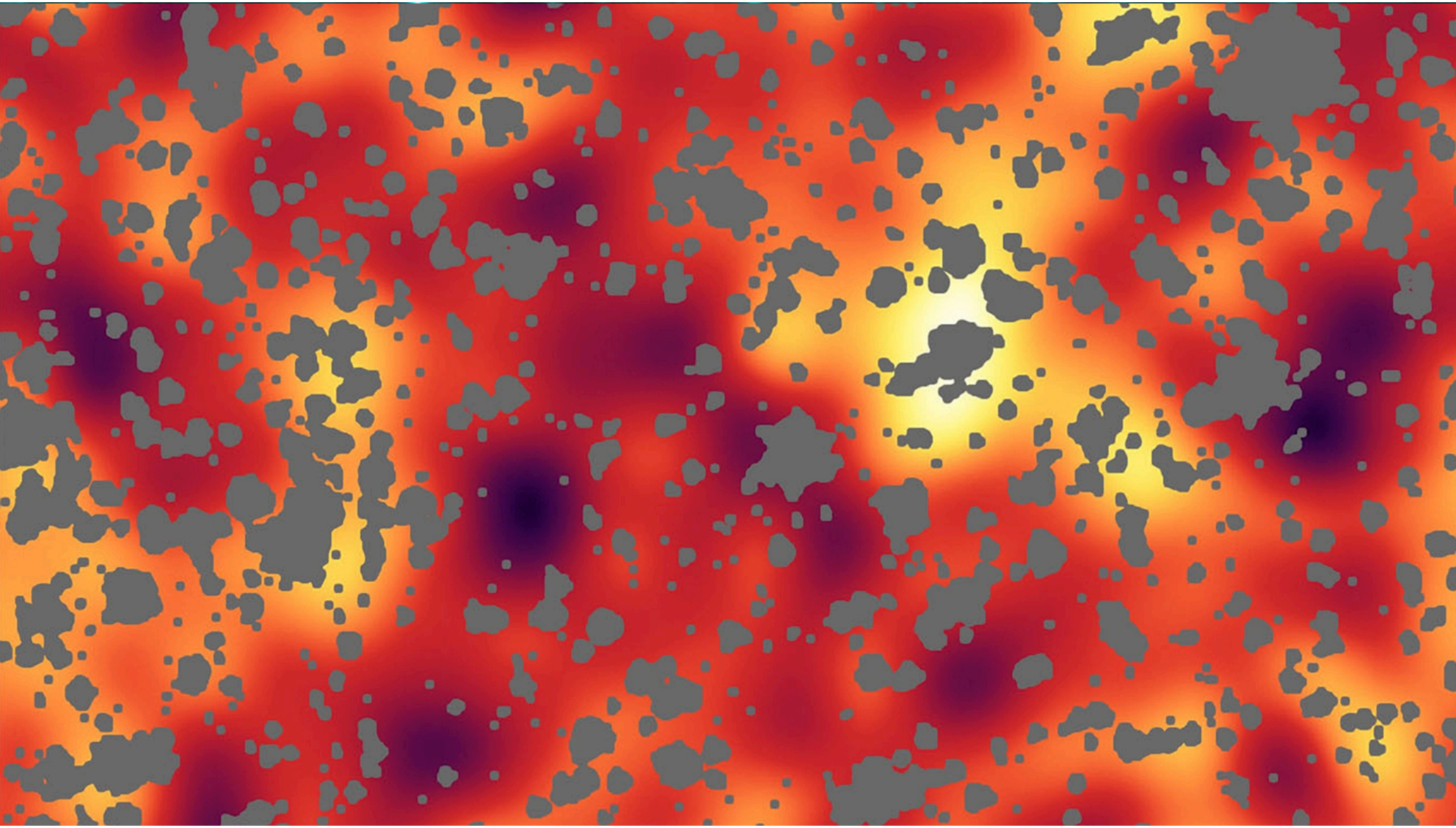


Fluctuations CIB & X-ray Background

Kashlinsky (2016)

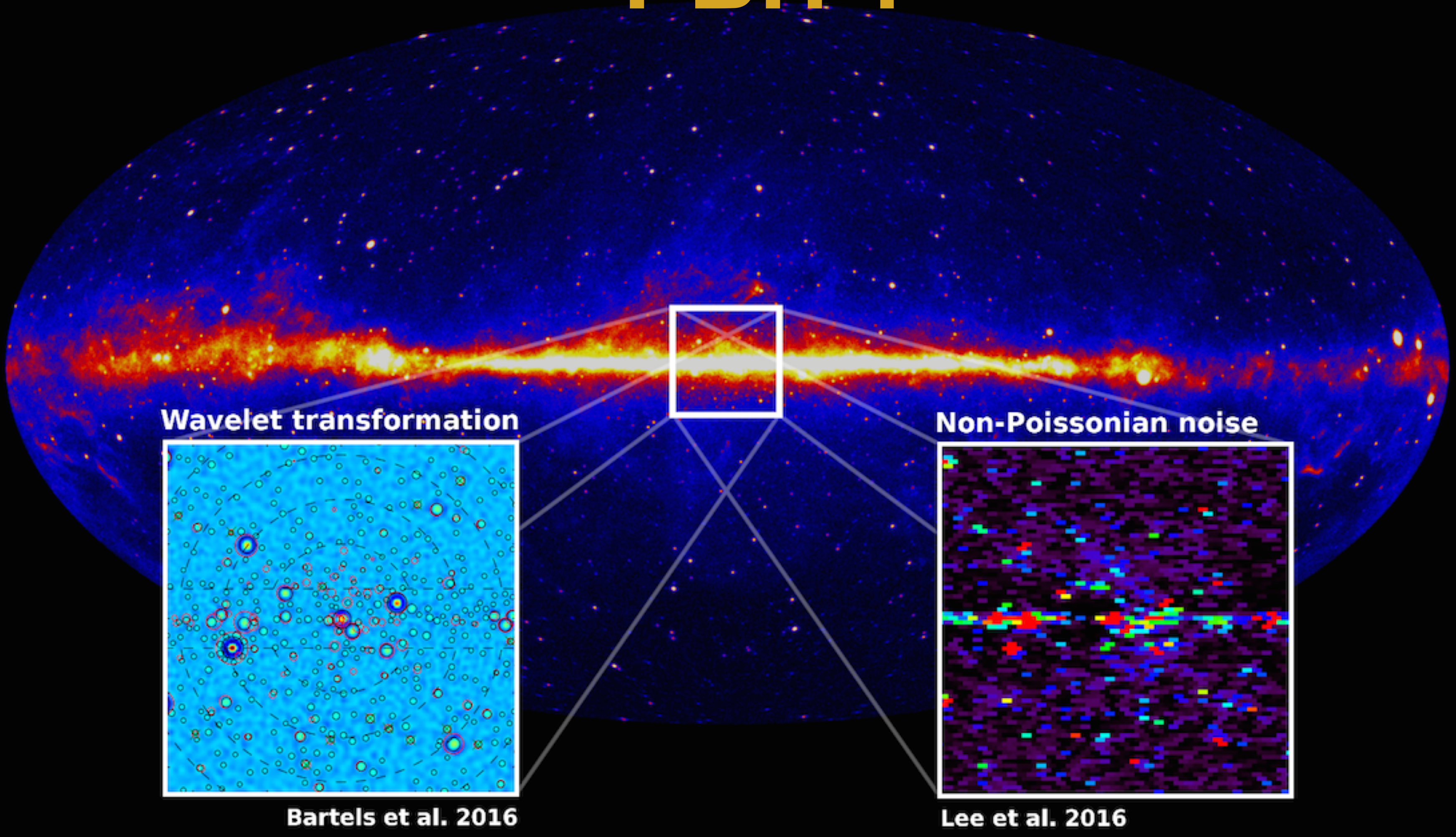


Kashlinsky (2016)

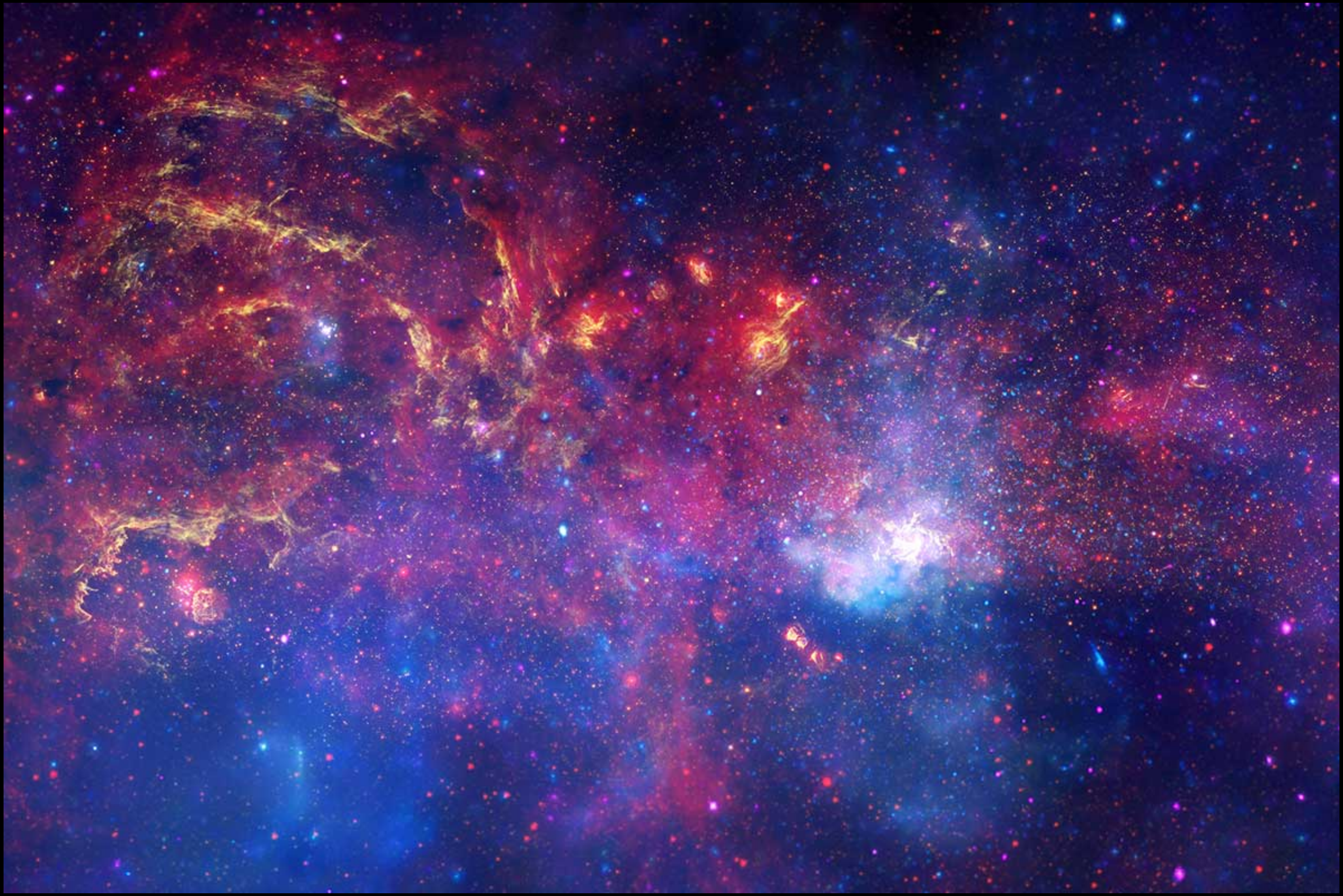


Gamma-ray Background

Fermi-LAT Point Sources = PBH ?



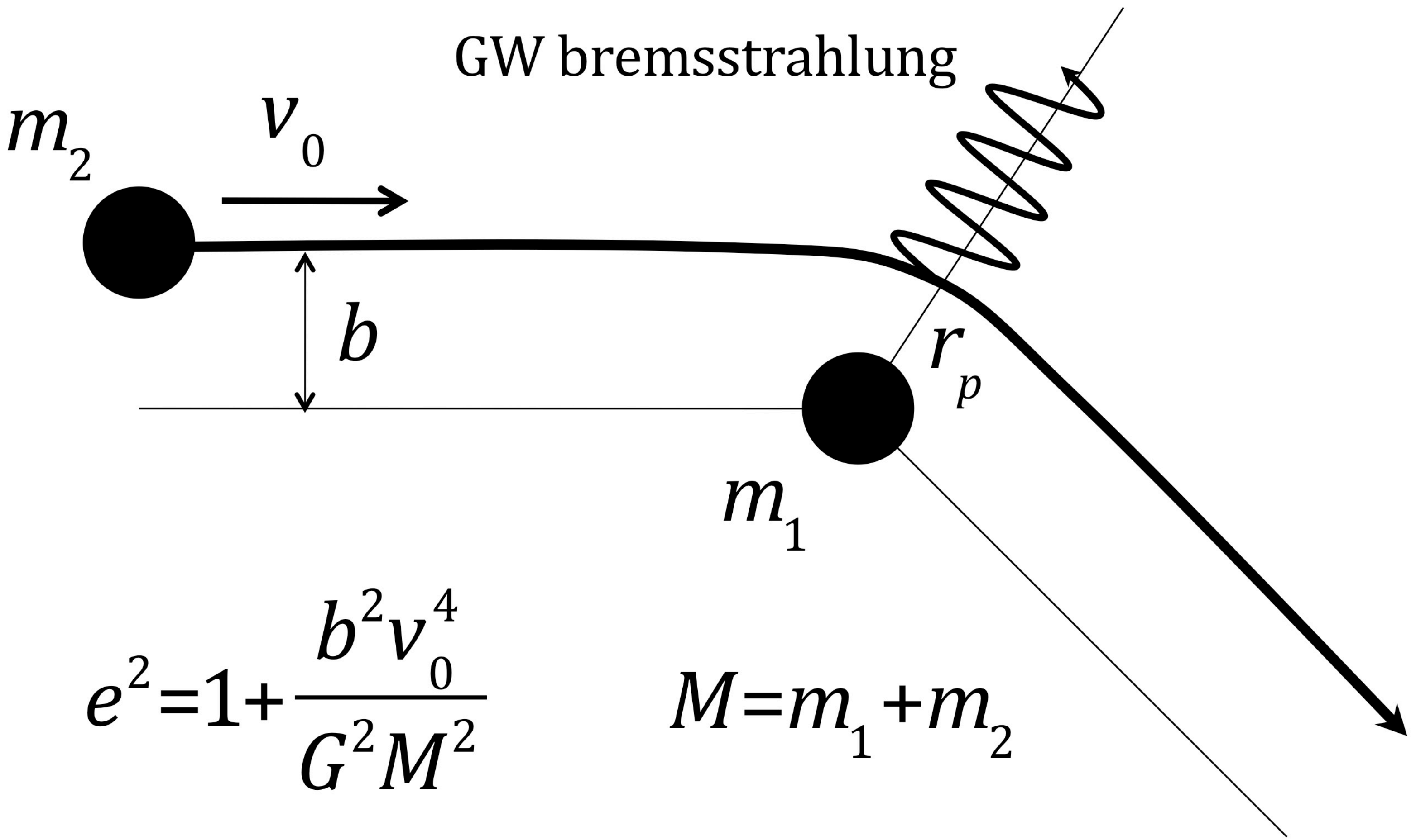
Chandra: 10,000 BH at GC



GW bursts from close encounters

GW bursts

JGB & Nesseris (2017)

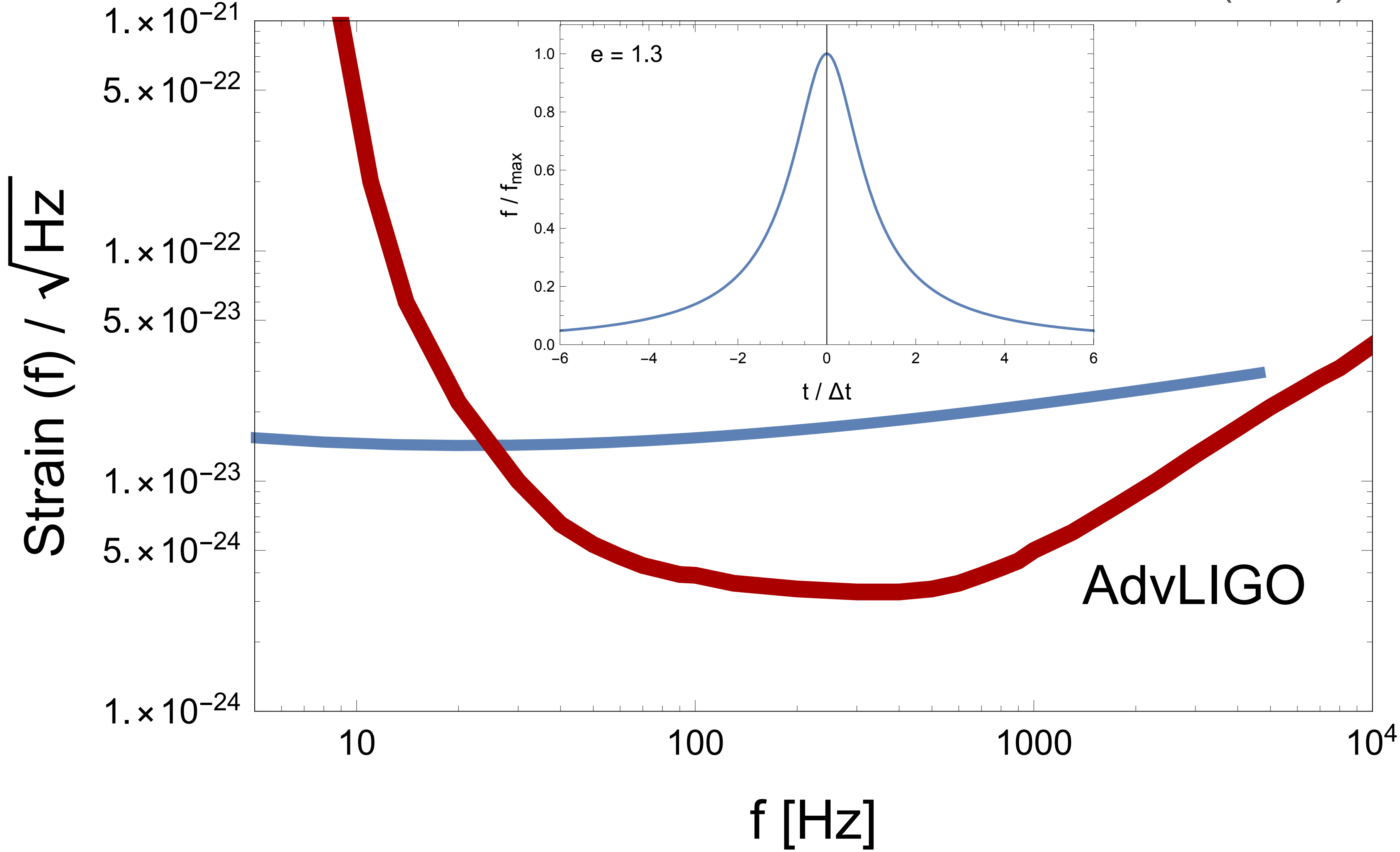


$$e^2 = 1 + \frac{b^2 v_0^4}{G^2 M^2}$$

$$M = m_1 + m_2$$

GW bursts

JGB, Nesseris (2017)



JGB, Nesseris (2017)