Summary of WG5

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Primordial black holes

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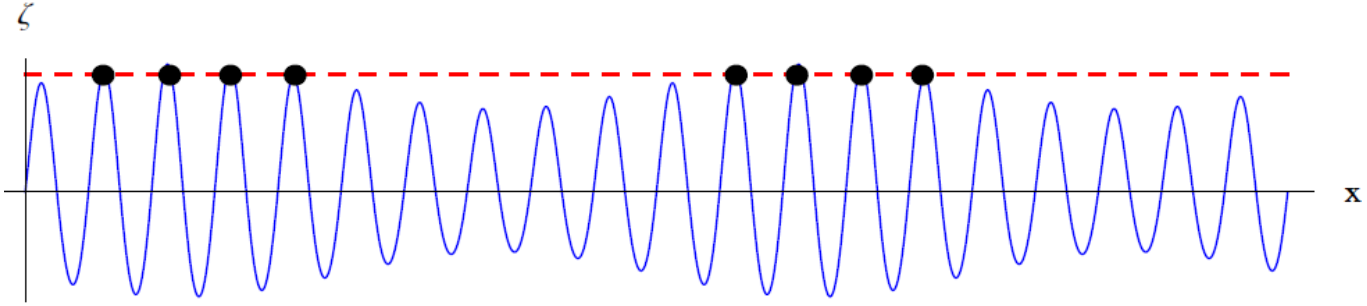
Primordial black hole formation

Press-Schecter formalism – $\beta = \int_{\Delta_c}^{\infty} P(\Delta) d\Delta$

β is the mass fraction of PBH's at the time of formation



$$P(\Delta) = \frac{1}{\sqrt{2\pi\langle\Delta\rangle^2}} \exp\left(-\frac{\Delta^2}{2\langle\Delta\rangle^2}\right) \qquad \langle\Delta^2\rangle = \int_0^{\infty} \frac{dk}{k} \mathcal{P}_{\Delta}(k)$$

Primordial black hole formation

Press-Schecter formalism – $\beta = \int_{\Delta_c}^{\infty} P(\Delta) d\Delta$

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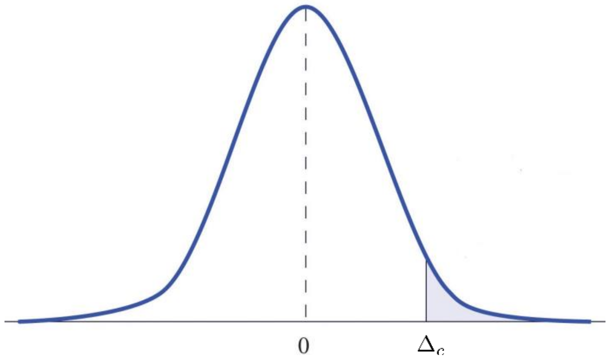
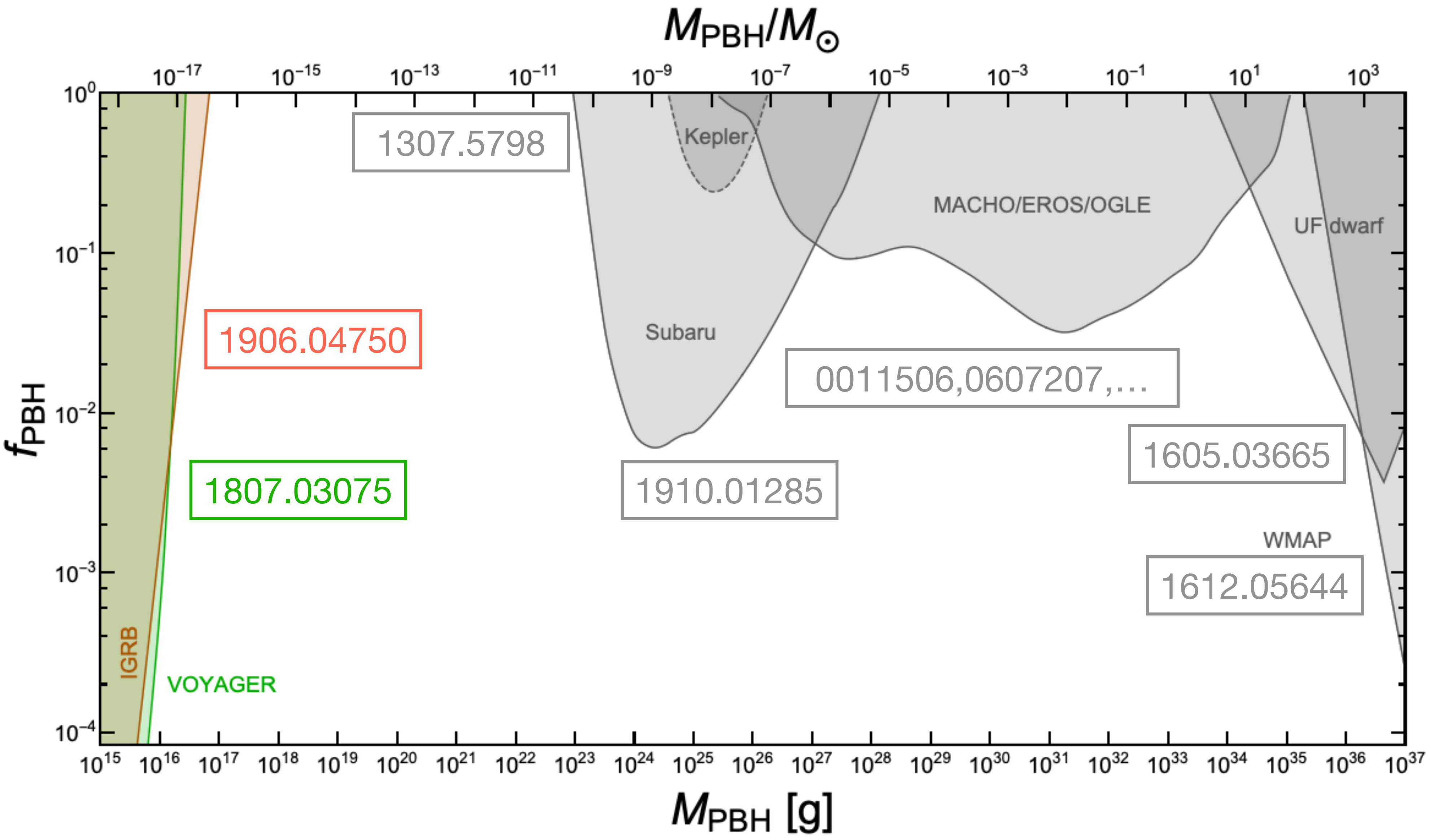


$$\mathcal{P}_{\Delta}(k) = \frac{4(1+w)^2}{(5+3w)^2} \left(\frac{k}{aH}\right)^4 \boxed{\mathcal{P}_{\mathcal{R}}(k)}$$

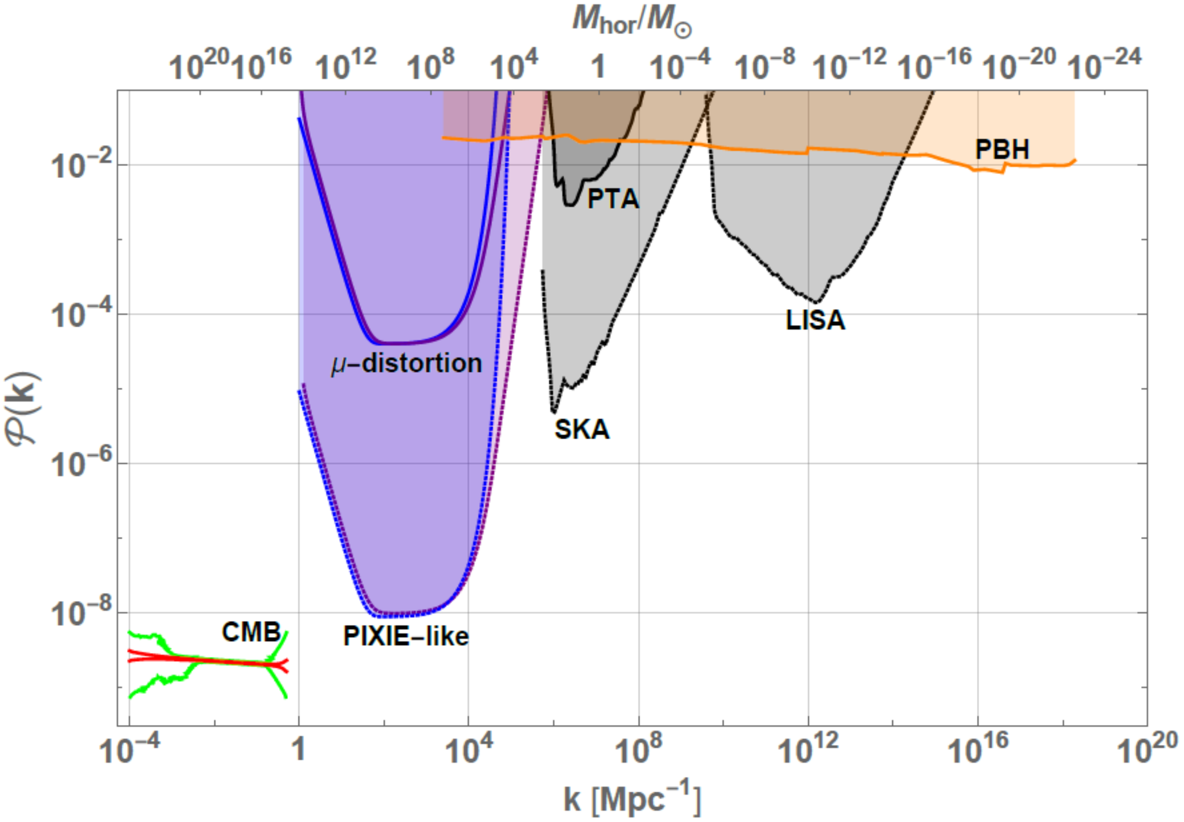
power spectrum of curvature perturbation from inflation

$$P(\Delta) = \frac{1}{\sqrt{2\pi\langle\Delta\rangle^2}} \exp\left(-\frac{\Delta^2}{2\langle\Delta\rangle^2}\right)$$

$$\langle\Delta^2\rangle = \int_0^{\infty} \frac{dk}{k} \mathcal{P}_{\Delta}(k)$$

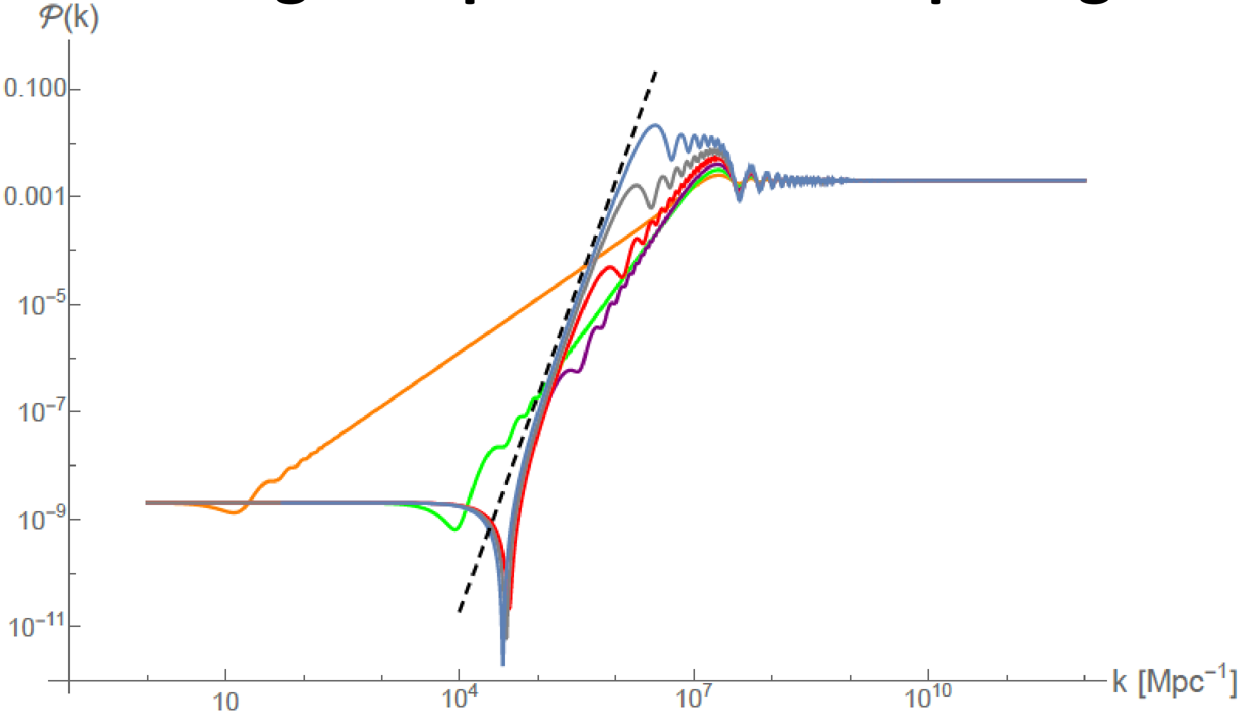

$M_{PBH}/M_\odot$
10^{-17}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
f_{PBH}
1307.5798
Kepler
MACHO/EROS/OGLE
UF dwarf
Subaru
1906.04750
0011506,0607207,…
1605.03665
1910.01285
1807.03075
WMAP
1612.05644
IGRB
VOYAGER
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
M_{PBH} [g]

Shape dependence of constraints on underlying power spectrum



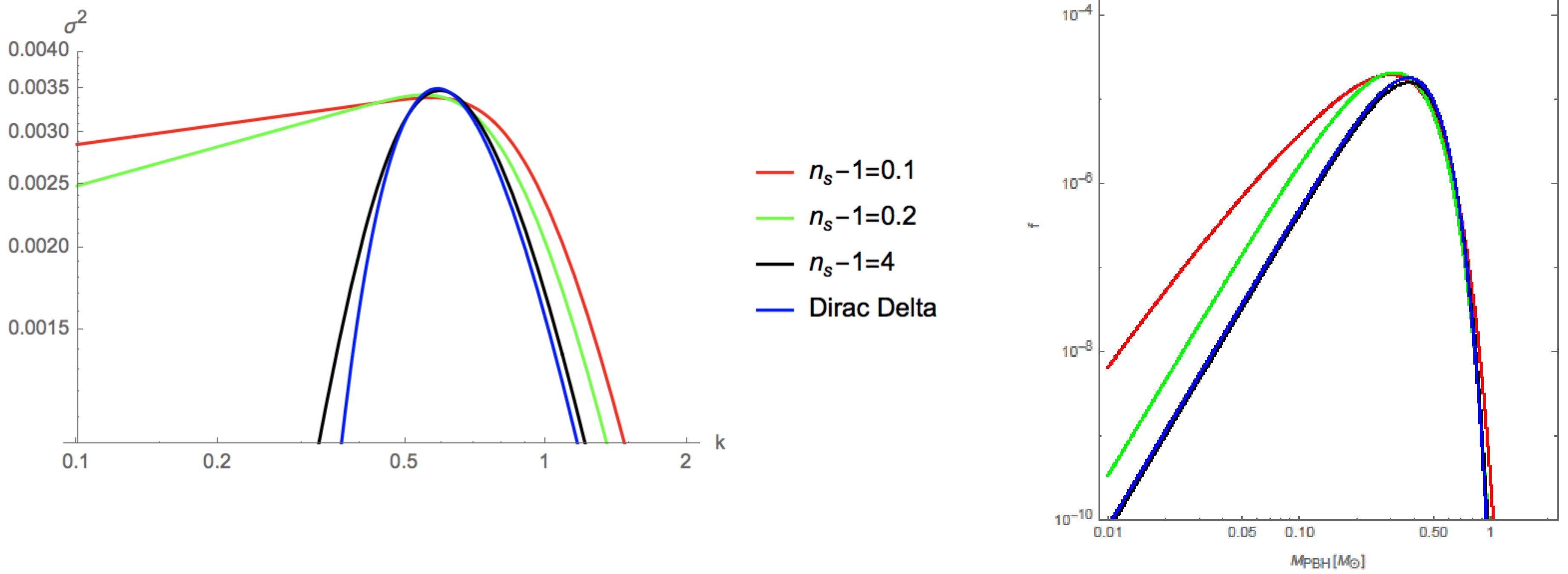
Byrnes, Cole, Patil (2018)

Analytic matching computation – steepest growth of $\propto k^4$



$$\frac{\mathcal{P}_\mathcal{R}(k)}{\mathcal{P}_\mathcal{R}(0)} = \left[1 - \frac{4}{5}\left(\frac{k}{k_\mathrm{u}}\right)^2 e^{3N_\mathrm{USR}}\right]^2 + 2\left(\frac{k}{k_\mathrm{u}}\right)^2 - 0.10\left(\frac{k}{k_\mathrm{u}}\right)^6 e^{6N_\mathrm{USR}} + 0.0075\left(\frac{k}{k_\mathrm{u}}\right)^8 e^{6N_\mathrm{USR}} + \cdots$$

Mass functions always extended to some extent…



However the underlying power spectrum is hard to extract from the PBH mass function due to degeneracies between the effect of the amplitude and shape of the power spectrum… The PBH mass function would have to be observed with very high precision in order to reconstruct the shape of the primordial power spectrum near the corresponding peak. (Byrnes, Cole, Patil 2018)

Primordial Black Holes and Gravitational Waves in a stiff pre-BBN epoch

Sukannya Bhattacharya

Physical Research Laboratory

1912.xxxx with

Priyank Parashari, Subhendra Mohanty

WHEPP, WG V, IIT Guwahati

02/12/2019

Introduction

- **What are PBHs?**
  Formed in the early universe when the density fluctuations of high amplitude ($\delta > \delta_c$) re-enter the Hubble horizon at post-inflationary epochs and collapse gravitationally.

$$M = \gamma M_H = \gamma \frac{4}{3}\pi (H^{-1})^3 \rho = \frac{\gamma}{2GH}$$

- **Why PBHs?**
  • Nonrelativistic and collisionless: Can be a significant component of DM.
  • GW experiments (LIGO, VIRGO, LISA etc.) will look at more binary black hole events: $M > M_\odot$ stellar black holes are rare $\Longrightarrow$ Massive PBH?
  • A tool to probe the epoch from the time the smaller scales ($k > k_{\rm CMB}^{\rm max}$) exit inflationary horizon - - - BBN.
- **Aim**
  • The effect of a modified evolution during stiff-domination $1/3 < w < 1$ on PBH formation.

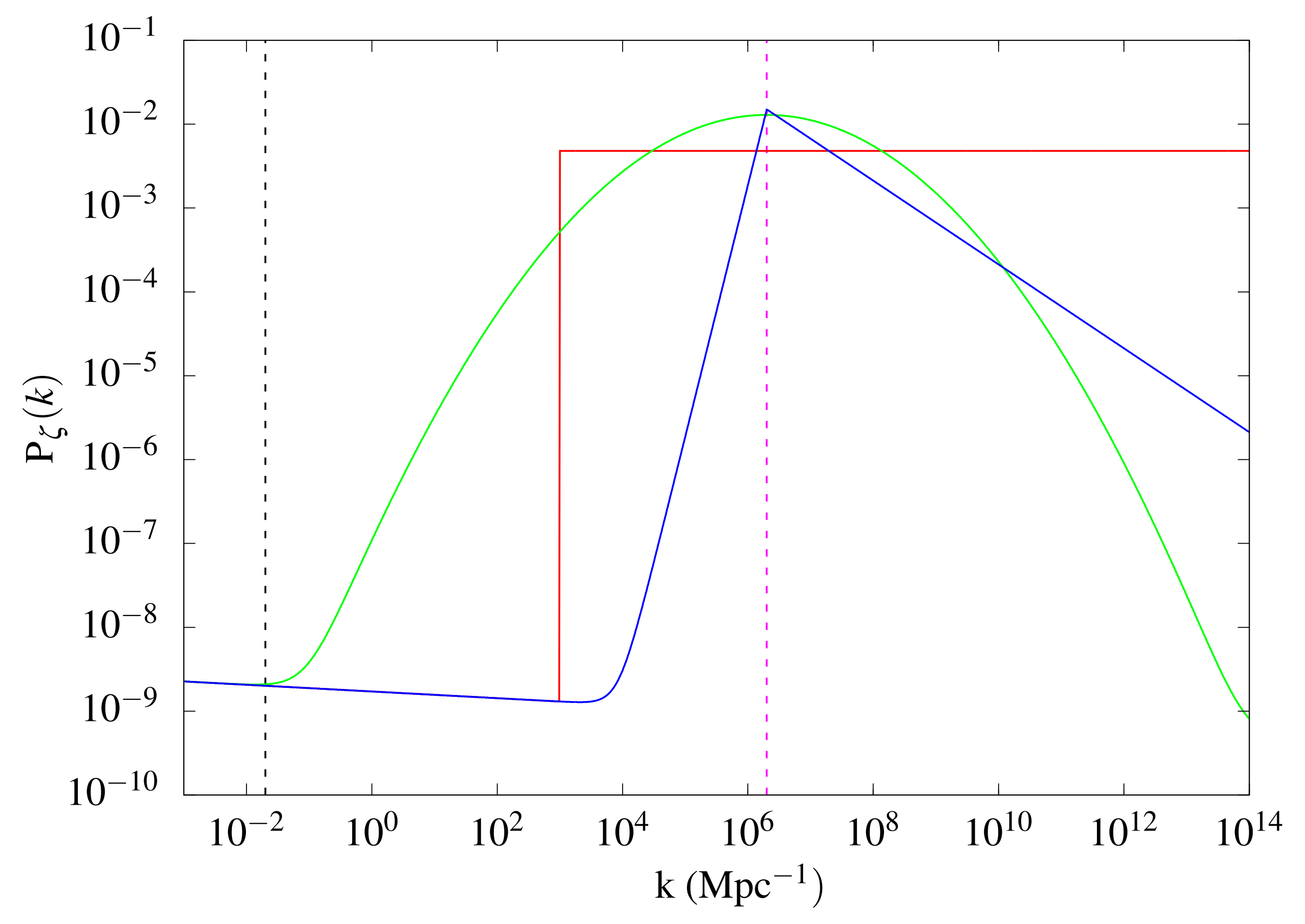
Results: Analysis with different power spectra

- 1. Scale-independent power spectrum: $P_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} + P_p \Theta(k-k_p)$: better understanding of the gain due to $w > 1/3$
- 2. Broken Power Law:

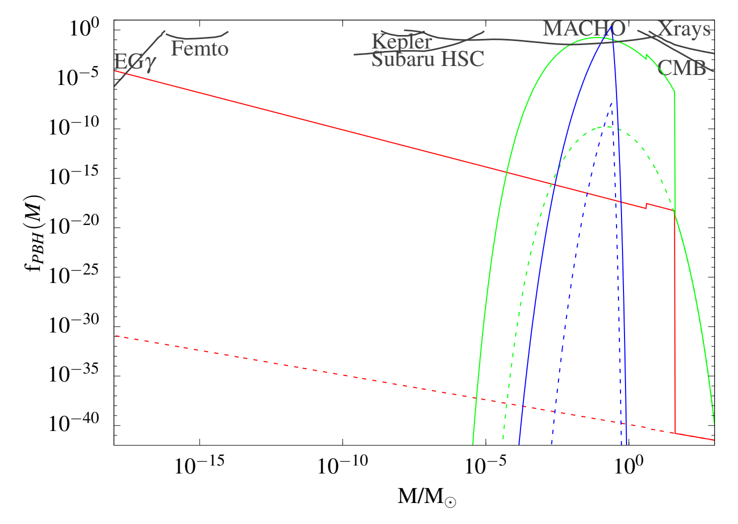
$$\begin{aligned} P_\zeta(k) &= A_s \left(\frac{k}{k_*}\right)^{n_s-1} + P_p \left(\frac{k}{k_p}\right)^{m} \quad k < k_p, \\ &= A_s \left(\frac{k}{k_*}\right)^{n_s-1} + P_p \left(\frac{k}{k_p}\right)^{-n} \quad k \geq k_p \end{aligned}$$

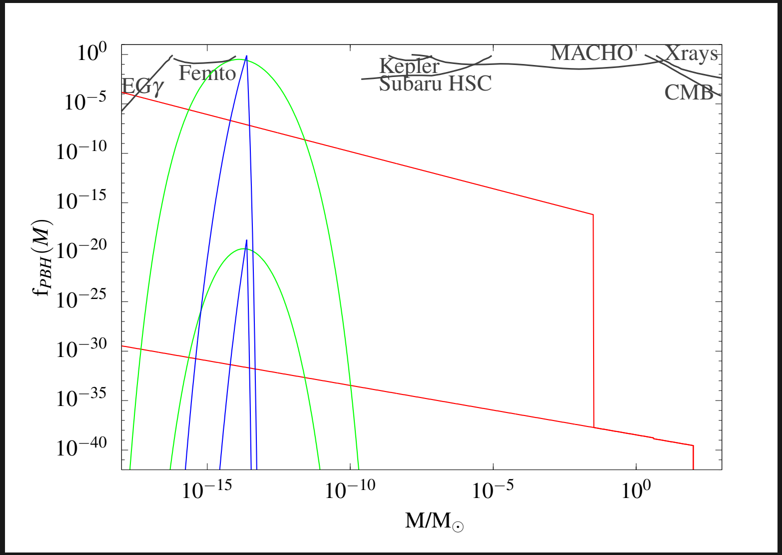
- 3. Gaussian Power Spectrum: $P_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} + P_p \exp\left[-\frac{(N_k - N_p)^2}{2\sigma_p^2}\right]$.
- 2 and 3 are theoretically motivated, e.g. Hybrid inflation leads to power 3.
- Analysis done for $k_p \sim 10^6 Mpc^{-1}$ (near solar mass PBH) and $k_p \sim 10^{12} Mpc^{-1}$ (frequency corresponds to LISA; $M \simeq 10^{-10} M_\odot$ where $f_{\rm PBH}^{\rm tot} = 1$ still allowed).

Power spectra



PBH Mass Spectra





k_p		Scale-inv P_p	Broken Power Law P_p	Gaussian P_p
$10^6 Mpc^{-1}$	RD	0.021	0.0275	0.025
$10^6 Mpc^{-1}$	$w = 1$	0.0048	0.015	0.0129
$10^{12} Mpc^{-1}$	RD			0.0163
$10^{12} Mpc^{-1}$	$w = 1$	0.0048	0.0069	0.0067

for comparison, check *1812.11011*

WHEPP-2019

Origin of Primordial Black Holes from Warm Inflation

Based on arXiv: 1910.05238

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2 December 2019

Warm Inflation

Warm Inflation is an alternate description of inflation in which,

- The inflaton dissipates to the other fields both during and after inflation.
- The Universe has a thermal bath of particles throughout.
- E.o.m of inflaton is modified

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} + V'(\phi) = 0$$

- Dissipation parameter $Q \equiv \frac{\Upsilon}{3H}$.

Primordial power spectrum for warm inflation

The primordial power spectrum for warm inflation is given as[1]

$$P_{\mathcal{R}}(k) = \left(\frac{H_k^2}{2\pi\dot{\phi}_k}\right)^2 \left[1 + 2n_k + \left(\frac{T_k}{H_k}\right)\frac{2\sqrt{3}\pi Q_k}{\sqrt{3+4\pi Q_k}}\right] G(Q_k).$$

- It has contributions from thermal bath with temperature T and the dissipation parameter Q.
- Here $G(Q)$ is the growth factor [2],

$$G(Q_k) = 1 + 4.981\, Q_k^{1.946} + 0.127\, Q_k^{4.330}.$$

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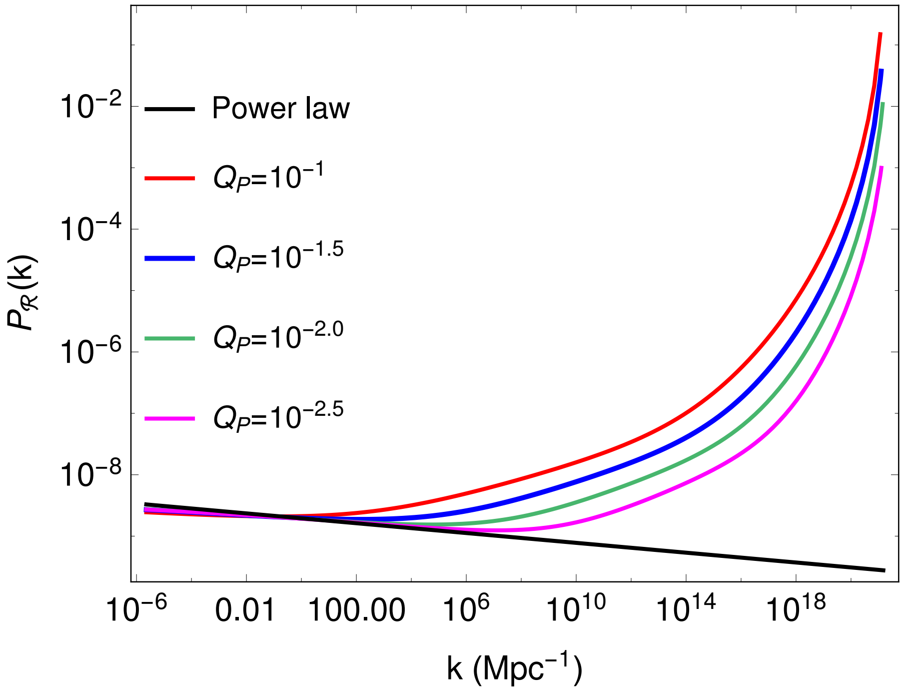
[1] S. Bartrum et al, PLB 732, 116 (2014).

[2] M. Benetti and R. O. Ramos, PRD 95 no. 2, (2017) 023517.

Our warm inflation model

We consider inflationary potential $\lambda\phi^4$ with $\Upsilon \propto T^3$.(Arya et al, JCAP02 (2018) 043)



- The primordial curvature power spectrum has a blue-tilt ($n_s > 1$) for the PBH scales (large k).
- For large dissipation, the amplitude of the primordial power spectrum is larger as compared to the smaller dissipation case.

Initial Mass Fraction versus Mass of the generated PBH

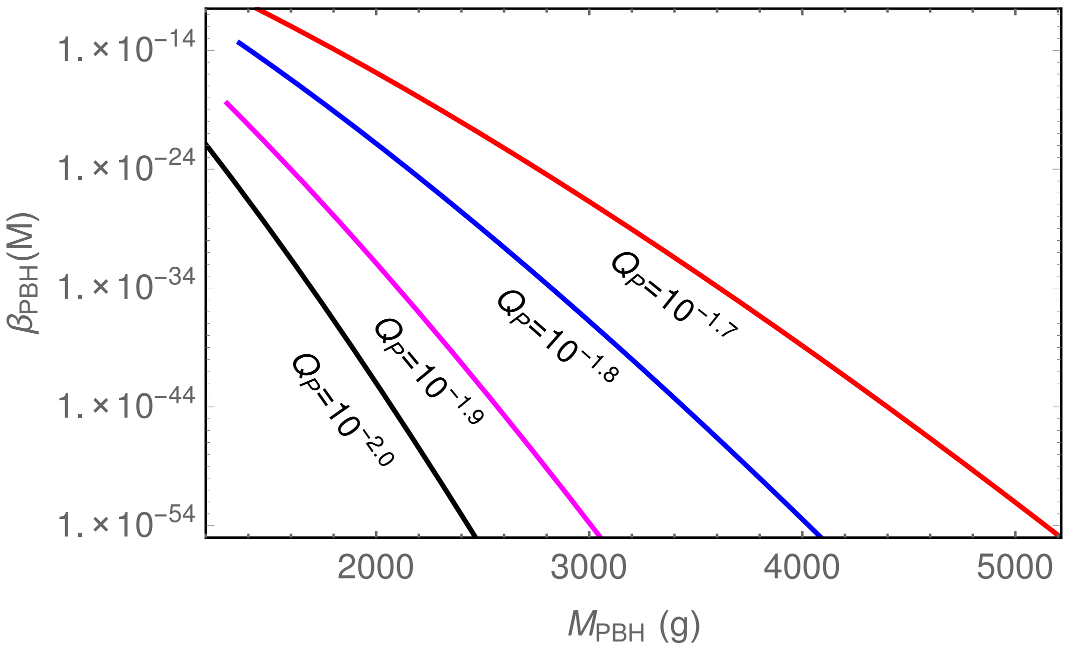


Figure : Plot of initial mass fraction $\beta(M)$ versus M_{PBH} (g).

- Large dissipation leads to more massive PBH formation, whereas small dissipation produces small mass PBHs.

Detecting gravitational waves with pulsars as Weber Detectors

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Institute of Physics
Bhubaneswar, India

Pulsars are incredibly accurate clocks

Example: period of the first discovered "millisecond pulsar" is:

$P = 0.00155780644887275$ sec

It is slowing down at a rate of 1.051054×10^{-19} sec/sec

Pulsar: J0437-4715

$P = 0.005757451936712637$ sec

Error of 1.7×10^{-17} sec.

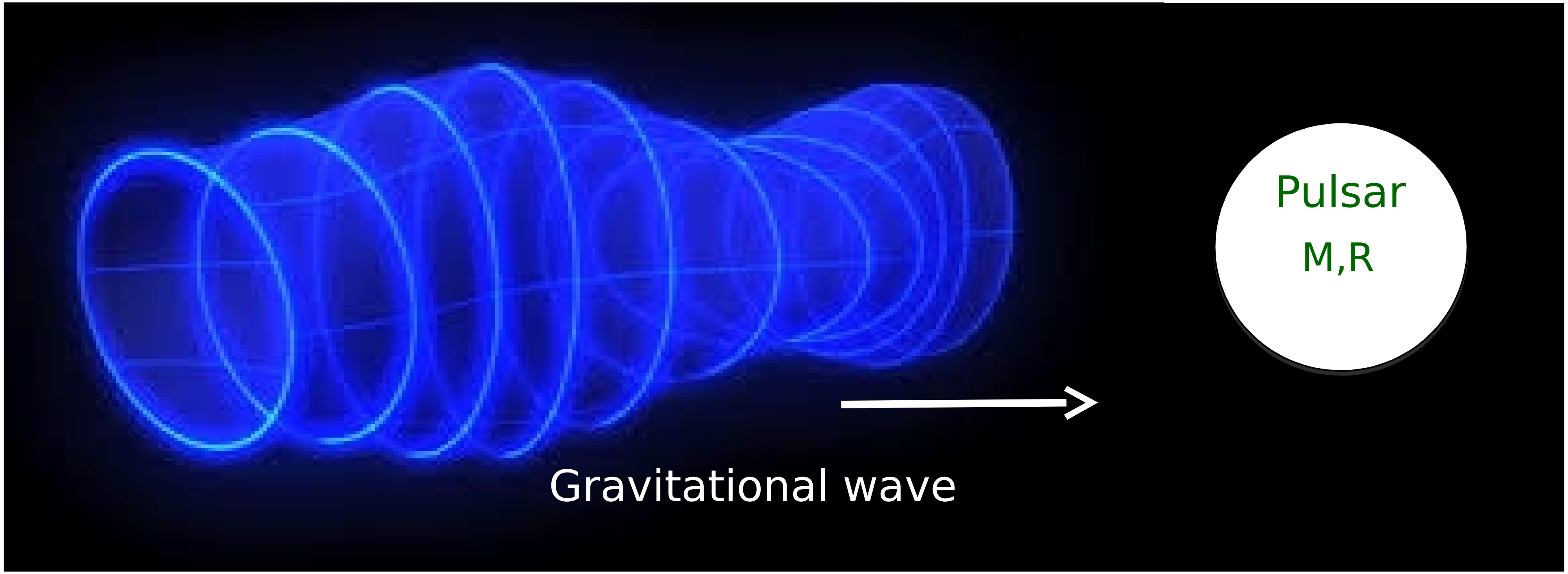
Our work: use this incredible precision for detecting changes occurring in the configuration of a neutron star.

Pulsars as Weber gravitational wave detectors:

In our earlier work, we discussed internal dynamics of pulsar (e.g. phase transition) leading to its deformations.

Now consider a pulsar under influence of external gravitational waves (GW) , coming, say, from a merger event far away.

For simplicity, take a spherical pulsar to begin with



We analyzed specific GW events detected by LIGO/Virgo and have identified specific pulsars whose perturbed signals will reach us, say, within next 50 years: Example:

GW source	Pulsar	Signal arrival time mm/dd/year	mean time max time
GW170814 (BH-BH)	J0437-4715	1/14/2035	2038-2043

Closest and brightest pulsar known, T ~ 5 ms, distance ~ 500 ly
X-ray, in binary with white dwarf, Pictor constellation (South)

Past Supernova events as GW sources:

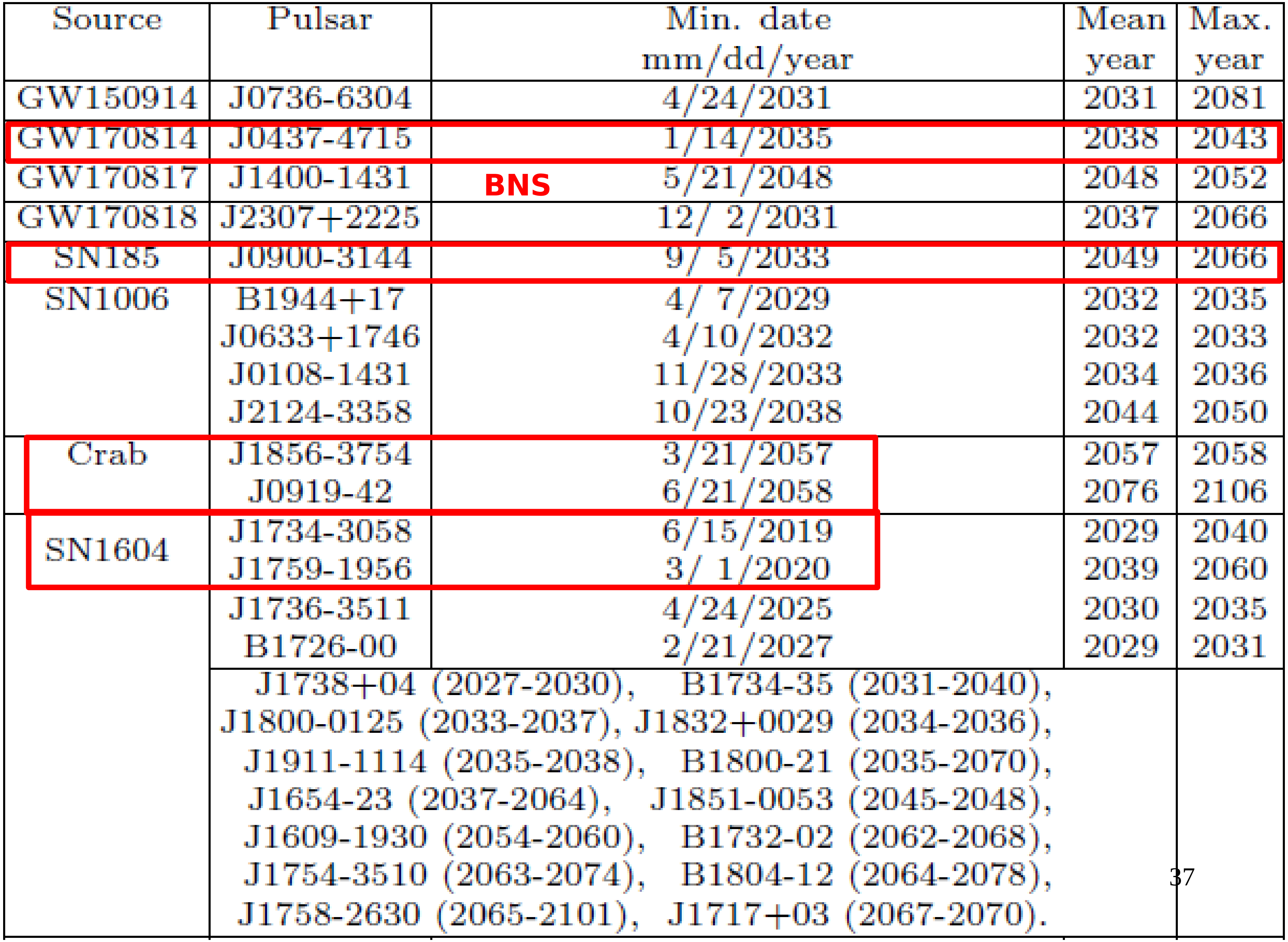
Estimated GW strain from a type-II supernova (even for a type 1A Supernova) can reach as high as 10^{-20} at a distance of 10 kpc.

We have analyzed recorded supernova events, GWs from these will leave imprints on the pulsars will perturbed signal arrival dates.
Example:

SN1604	J1759-1956	3/1/2020	2039-2060

(Note: In following tables, errors not available for all cases)

Table I: GW signal arrival dates for next 50 years



Source	Pulsar	Min. date mm/dd/year	Mean year	Max. year
GW150914	J0736-6304	4/24/2031	2031	2081
GW170814	J0437-4715	1/14/2035	2038	2043
GW170817	J1400-1431	**BNS** 5/21/2048	2048	2052
GW170818	J2307+2225	12/ 2/2031	2037	2066
SN185	J0900-3144	9/ 5/2033	2049	2066
SN1006	B1944+17	4/ 7/2029	2032	2035
	J0633+1746	4/10/2032	2032	2033
	J0108-1431	11/28/2033	2034	2036
	J2124-3358	10/23/2038	2044	2050
Crab	J1856-3754	3/21/2057	2057	2058
	J0919-42	6/21/2058	2076	2106
SN1604	J1734-3058	6/15/2019	2029	2040
	J1759-1956	3/ 1/2020	2039	2060
	J1736-3511	4/24/2025	2030	2035
	B1726-00	2/21/2027	2029	2031
	J1738+04 (2027-2030), B1734-35 (2031-2040), J1800-0125 (2033-2037), J1832+0029 (2034-2036), J1911-1114 (2035-2038), B1800-21 (2035-2070), J1654-23 (2037-2064), J1851-0053 (2045-2048), J1609-1930 (2054-2060), B1732-02 (2062-2068), J1754-3510 (2063-2074), B1804-12 (2064-2078), J1758-2630 (2065-2101), J1717+03 (2067-2070).			

Axion like particles- cosmological and astrophysical probes

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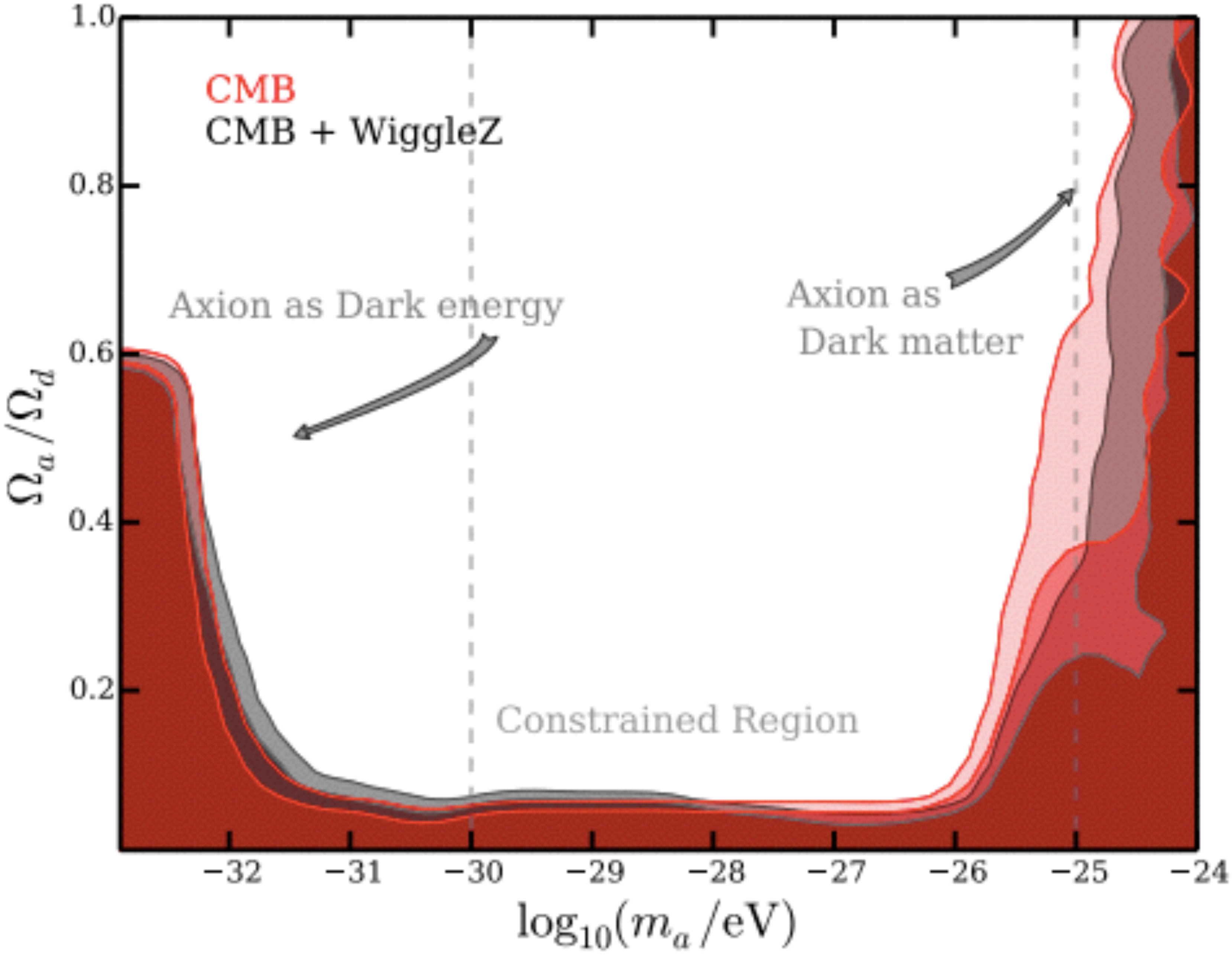
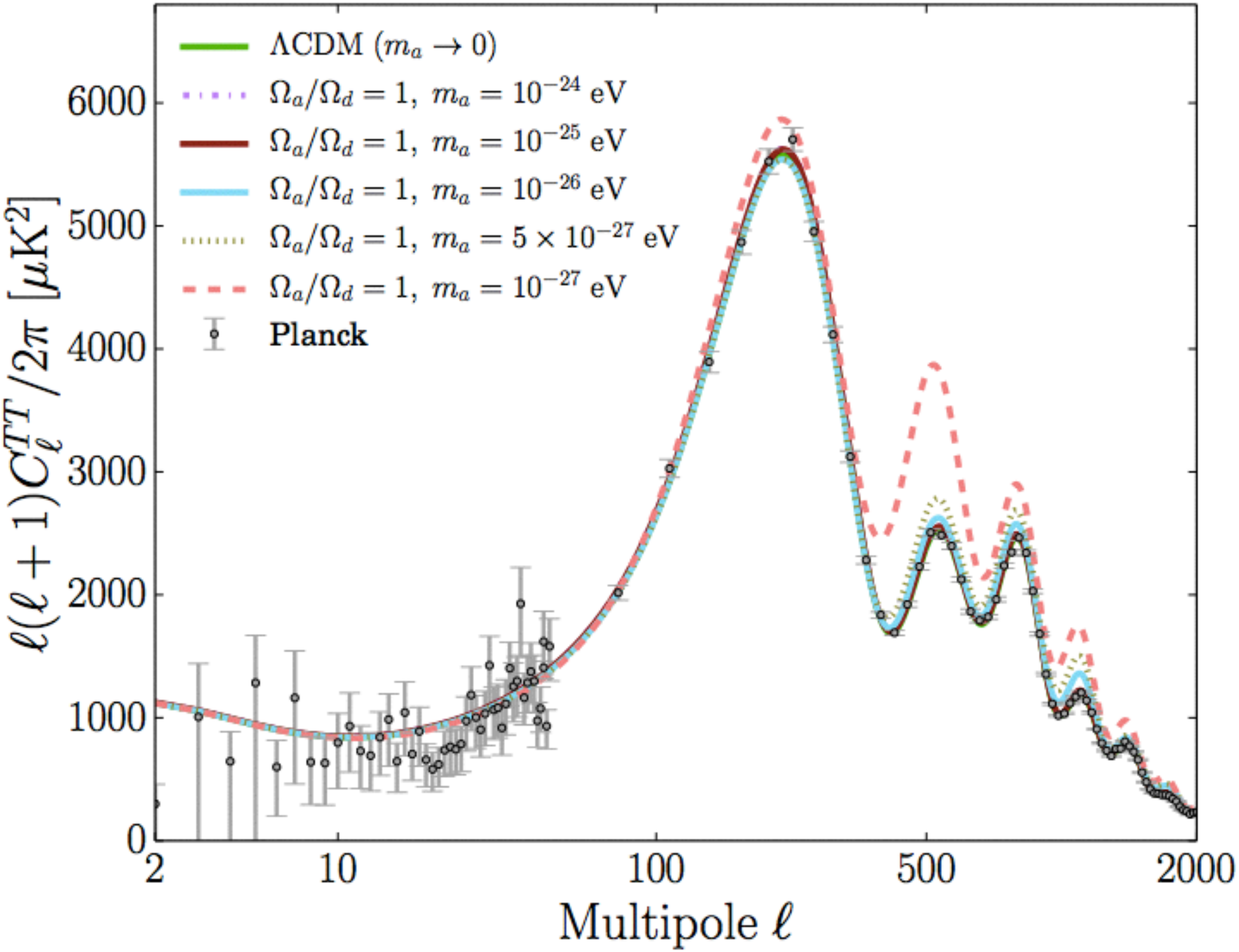
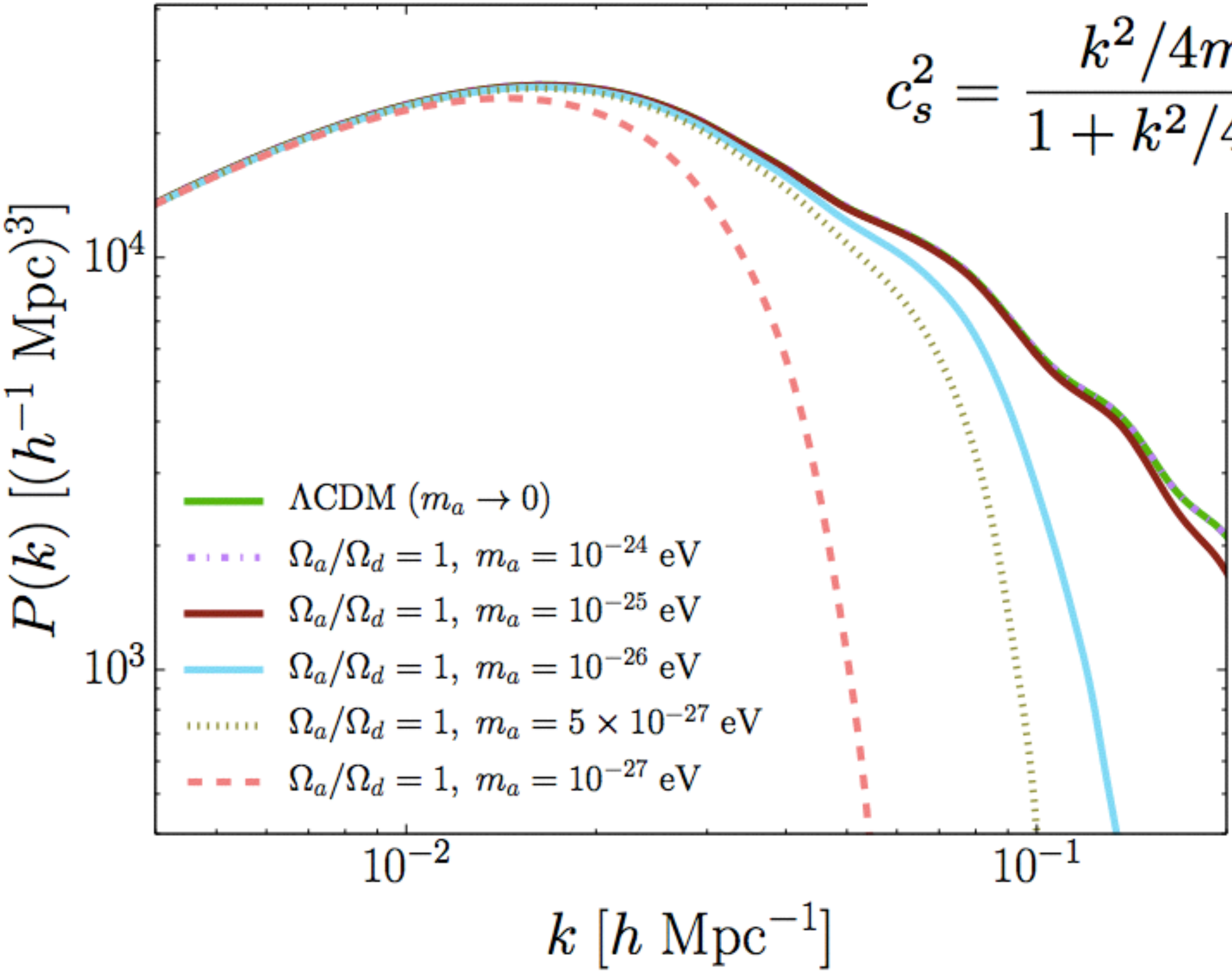
Constraints from CMB - Hlozek et al (2015).





ΛCDM ($m_a \to 0$)
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-24}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-25}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-26}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 5 \times 10^{-27}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-27}$ eV
Planck
$\ell(\ell+1)C_\ell^{TT}/2\pi\ [\mu\mathrm{K}^2]$
0
1000
2000
3000
4000
5000
6000
Multipole ℓ
2
10
100
500
2000

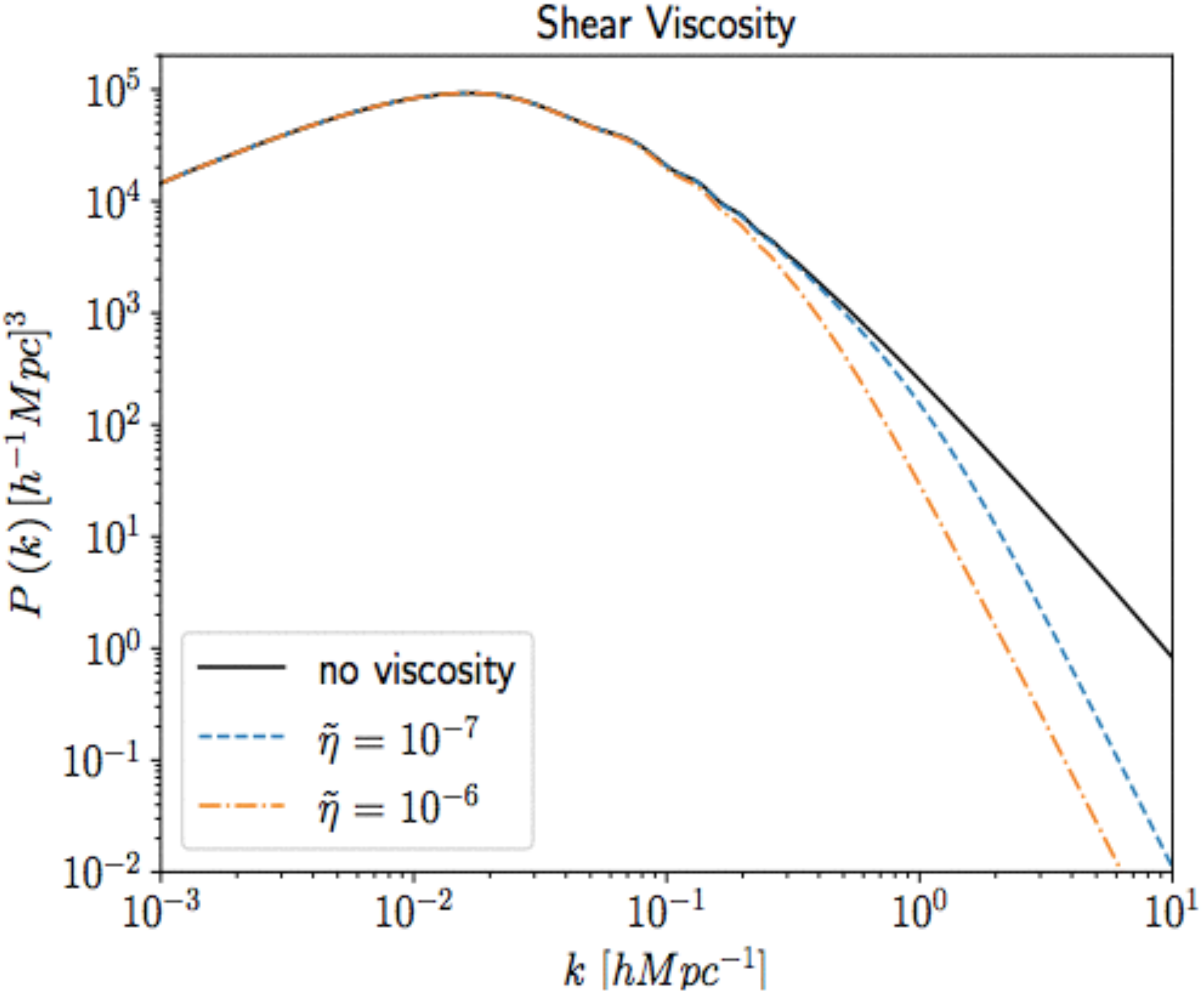
Matter power spectrum of FDM : power at small length scales suppressed.

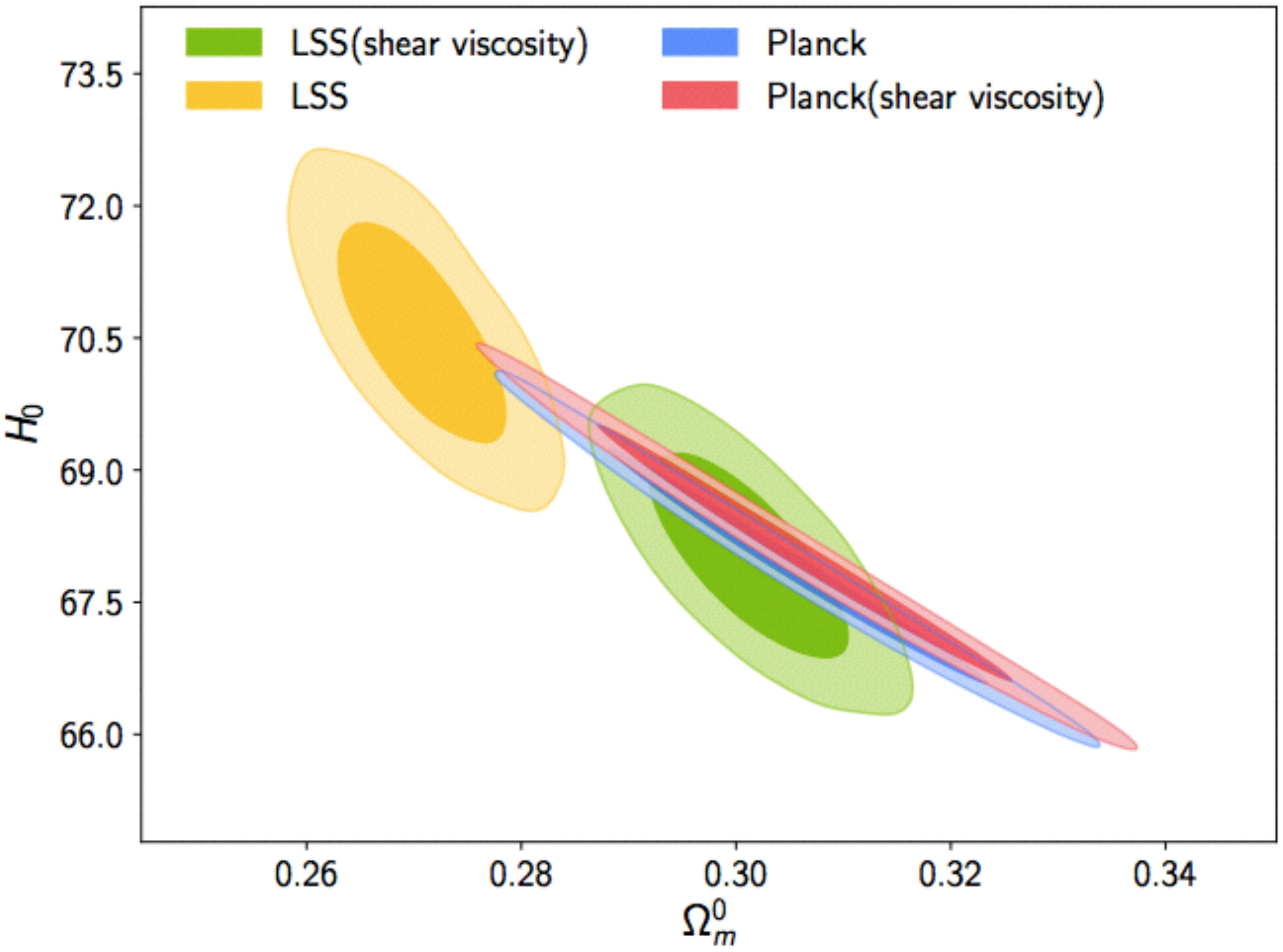


$$c_s^2 = \frac{k^2/4m_a^2a^2}{1 + k^2/4m_a^2a^2}$$

Hlozek et al 2015

Viscous ΛCDM cosmology: S.Anand, P.Chaubal, A.Mazumdar, SM (2017)

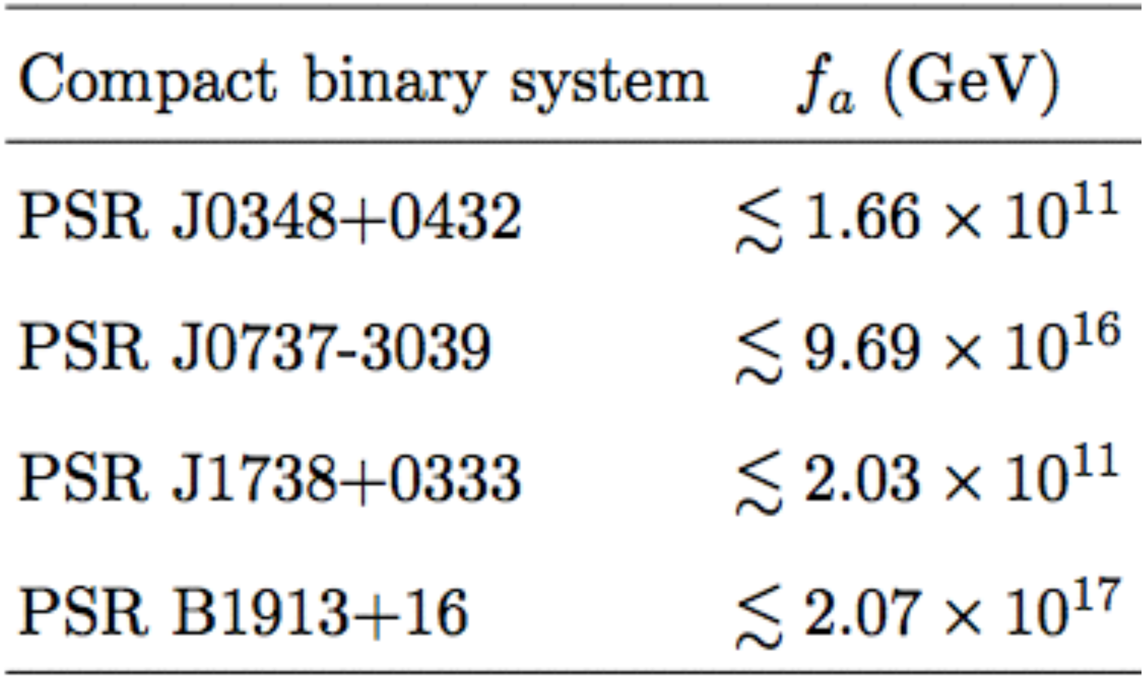




S.Anand, P.Chaubal, A.Mazumdar, SM (2017)

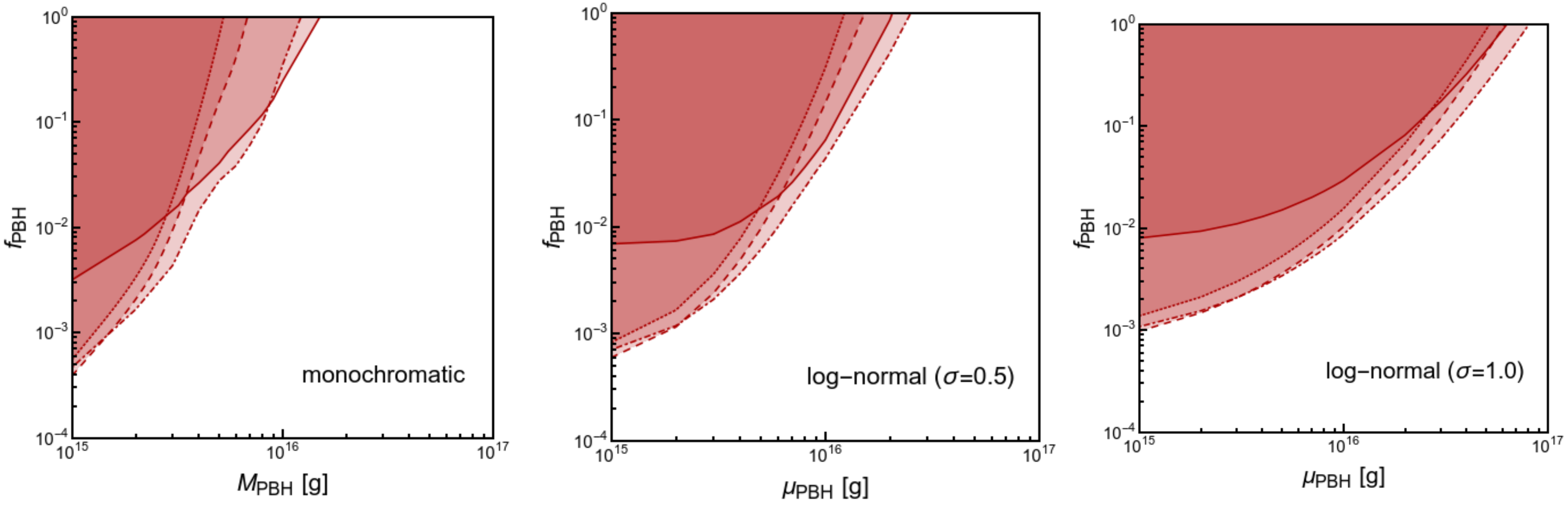
Soumya Jana, Tanmoy Poddar, SM 1906.00666

$$q_{eff} = -\frac{8\pi G M f_a}{\ln\left(1 - \frac{2GM}{r_{NS}}\right)}$$

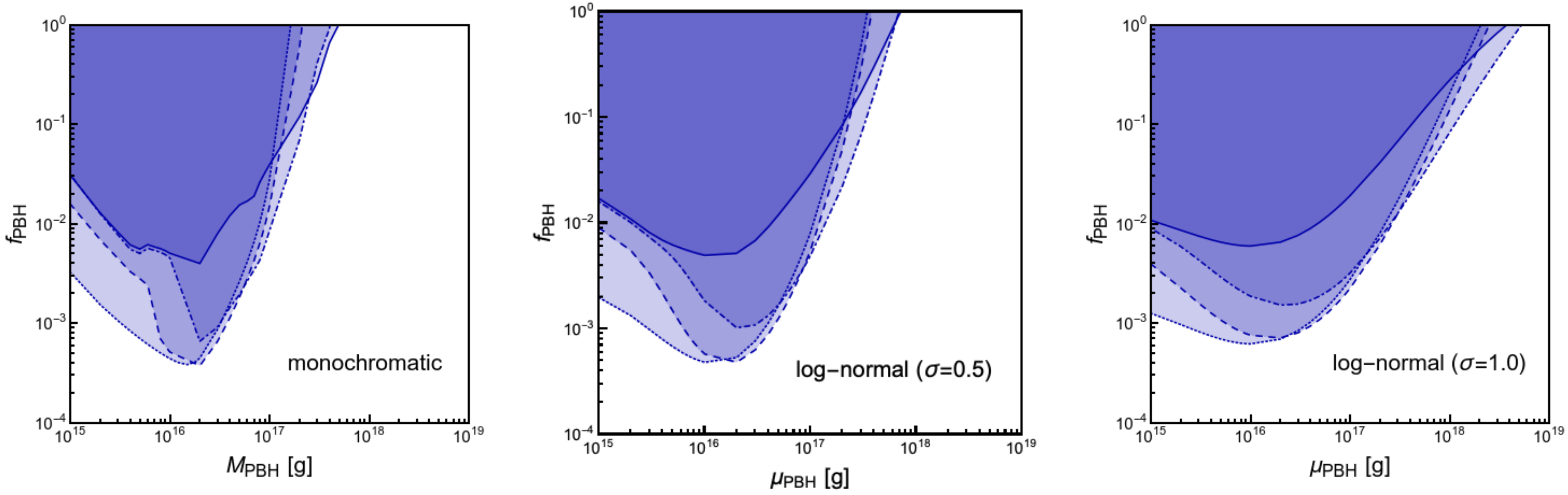


Compact binary system	f_a (GeV)
PSR J0348+0432	$\lesssim 1.66 \times 10^{11}$
PSR J0737-3039	$\lesssim 9.69 \times 10^{16}$
PSR J1738+0333	$\lesssim 2.03 \times 10^{11}$
PSR B1913+16	$\lesssim 2.07 \times 10^{17}$

FDM which couple with quarks ruled out



Upper limit on dark matter fraction of PBHs, from DSNB searches at Super-Kamiokande.



Upper limit on dark matter fraction of PBHs, from INTEGRAL 511 keV gamma-ray line measurement.

PBHs

- Anupam Ray

Constraints on low mass PBHs from non-observation of Hawking radiation as positrons and neutrinos. Dependence of these constraints on BH spin.

- Mostafizur Rahman

Can primordial vorticity lead to high spins of PBH?

DM in Stars

- Avik Paul

Strong bounds on axions through cooling of neutron stars

- Aritra Gupta

WIMPS can be captured in stars after multiple collisions. New formalism, and strong constraints at low and high mass end.

On WIMPs

- Devabrat Mohanta

Model with leptogenesis, DM freeze-out, and non-standard cosmology

- Pritam Sen

All-orders proof of IR-finiteness of fermion-scalar interactions. Possible application to freeze-out of Bino-like DM.

WIMPs

- Tarak Maity

New variants of the WIMP freeze-out, using semi-annihilation, assisted annihilation, exchange-driven annihilation.

- Bohdan Grzadkowski

Creating DM through a purely time-varying gravitational background

DM Models

- Dibyendu Nanda

Gauged B-L model with two Dirac DM candidates. Scalar sector chosen to stabilize DMs without any discrete symmetry.

- Piyali Banerjee

Extended superpotential in SO(10) SUSY GUTs as a way to eliminate pseudo domain walls

Discussion: Axions

- Mohanty discussed the possibility that DM is an ultralight (10^-22 eV) axion. Follow-up from plenary.
- Rishi Khatri discussed the possibility of axion-photon conversion as a probe of axions

Discussion: Hubble Tension

- Rishi Khatri gave an insightful summary of the Hubble tension and the ways to resolve this tension.

- Lot of interest, and ongoing project(s).