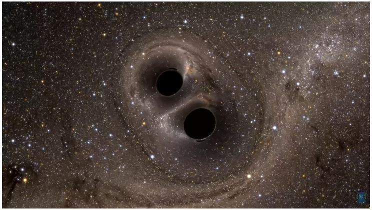
Primordial Black Hole Dark Matter



Valerie Domcke
DESY Hamburg

based partially on
arxiv[hep-ph] 1704.03464
in collaboration with
F. Muia, M. Pieroni
and L. Wittkowski

Outline

- Primordial Black Holes
  - ... in a nutshell
  - ... as dark matter?

- Primordial Black Holes from Inflation
  - scales: times, e-folds and masses
  - a worked example: pseudoscalar inflation

- Searching for PBHs with Gravitational Waves

Primordial Black Holes

see e.g. [Carr, Kühnel, Sandstad '16]

Spherical scalar fluctuations ζ with power spectrum $P(\zeta)$:

- gravitational collapse to PBHs (at horizon re-entry) if $\zeta > \zeta_c = \mathcal{O}(1)$
- primordial fluctuations: PBH mass set by horizon at re-entry,

$$M(N) = \gamma M_H \simeq \gamma \frac{4\pi M_P^2}{H_{\text{inf}}} e^{3N} \simeq 2\times 10^5\,\gamma \left(\frac{t}{1s}\right) M_\odot\,, \quad N = \int H\,dt$$

$\rightarrow$ spans many many orders of magnitude $\quad (M_\odot = 2\times 10^{33}\ g)$

- Hawking radiation:

$$M \lesssim 10^{15} g \rightarrow t_{\text{BH}} < t_{\text{Universe}}\,, \qquad M \gtrsim 10^{15} g \rightarrow t_{\text{BH}} > t_{\text{Universe}}$$

PBH mass $\leftrightarrow$ formation time, PBH formed after $10^{-20}\ s$ are stable

... as dark matter?

- formed before BBN ($t \simeq 3$ min): act as 'non-baryonic' DM
- fraction of energy density collapsing into PBHs at formation time t_N:

$$\beta(N) = \int_{\zeta_c}^{\infty} \frac{M(N)}{M_H(N)} P_N(\zeta) d\zeta = \int_{\zeta_c}^{\infty} \gamma P_N(\zeta) d\zeta \quad \to \beta(M)$$

- adiabatic universe, formation during radiation epoch ($n_{\text{PBH}}(t)/s(t) = $ const, $\rho(t_N) = 3/4 T(t_N) s(t_N)$):

$$\beta(M) = \frac{M\, n_{\text{PBH}}(t_N)}{\rho(t_N)} = \frac{4 M n_{\text{PBH}}(t)}{3 T(t_N) s(t)}$$

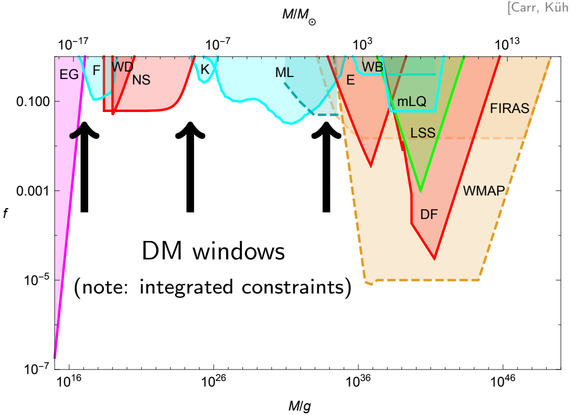
- $\to$ fraction of DM today:

$$f(M) = \frac{M\, n_{\text{PBH}}(t_0)}{\Omega_{\text{CDM}} \rho_c} \simeq 4.1 \cdot 10^8\, \gamma^{1/2} \left(\frac{g_*(t_N)}{106.75}\right)^{-1/4} \left(\frac{M}{M_\odot}\right)^{-1/2} \beta(M)$$

abundance set by $P_N(\zeta)$

Searches and constraints

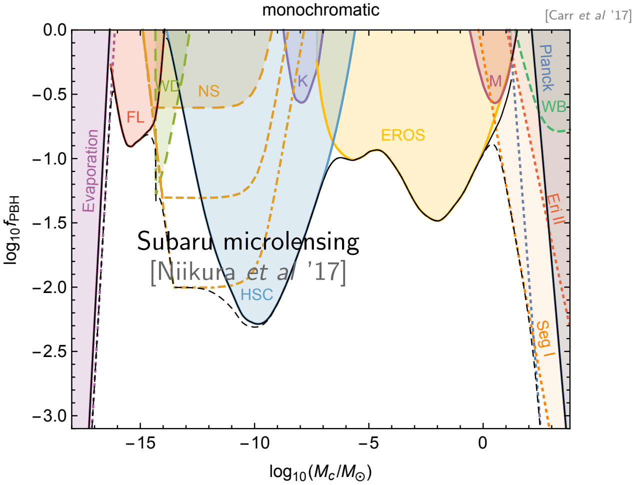
[Carr, Kühnel, Sandstad '16]



Lensing: **f**emtolensing of γ-ray bursts, **K**epler microlensing, MACHO/EROS/OGLE **m**icro**l**ensing of stars; dynamical constraints: **w**hite-**d**warf explosions, **n**eutron-**s**tar capture, **E**ridianus II, **d**ynamical **f**riction ; evaporation: **e**xtra-**g**alactic γ-rays, CMB; accretion effects

interesting range of $\sim$ 20 orders of magnitude in mass

Searches and constraints II



only very narrow windows left for 100% of DM

Caveats

- Non-gaussian fluctuations: PBH production very sensitive to high-ζ tail of $P(\zeta)$.
- Critical collapse: $M \sim M_H(N) \sim \exp(aN)$ not exact, better fit:
  [Choptuik *et al* '93]

$$M(\zeta, N) = \kappa M_H(N)(\zeta - \zeta_c)^y \quad \text{with } \kappa = 3.3, \zeta_c = 0.45, y = 0.36$$
$$\to \tilde{\beta}(N, M) dM = \frac{M}{M_H(N)} P_N(\zeta(M)) d\zeta(M)$$

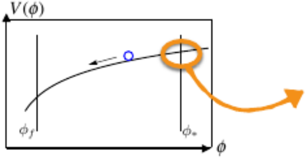
- Non-spherical collapse: overall decrease in amplitude of PBH spectrum [Kühnel, Sandstad *et al* '16].
- Mergers and accretion: Increase PBH masses, counteract Hawking radiation: see e.g. [Garcia-Bellido, Morales *et al* '17].

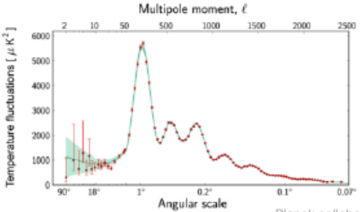
$$M_*^{\text{vac}} = 5 \cdot 10^{14}\, g \quad \to \quad M_*^{\text{eq}} = 3 \cdot 10^{12}\, g$$

Outline

- Primordial Black Holes
  - ... in a nutshell
  - ... as dark matter?
- Primordial Black Holes from Inflation
  - scales: times, e-folds and masses
  - a worked example: pseudoscalar inflation
- Searching for PBHs with Gravitational Waves

The (scalar) power spectrum of inflation





Planck collaboration

large vacuum energy	$\Rightarrow$ exponential expansion	$\Rightarrow$ homogeneity of CMB
quantum fluctuations	$\Rightarrow$ become classical	$\Rightarrow$ tiny anisotropies

- Two point function (variance of $P_N(\zeta)$):

$$\Delta_s^2 = \frac{V(\phi)}{24\,\pi^2\,\epsilon(\phi)}\,, \quad \epsilon(\phi) = \frac{\dot{\phi}^2}{2H^2} \simeq \frac{(V'(\phi))^2}{2V^2}$$

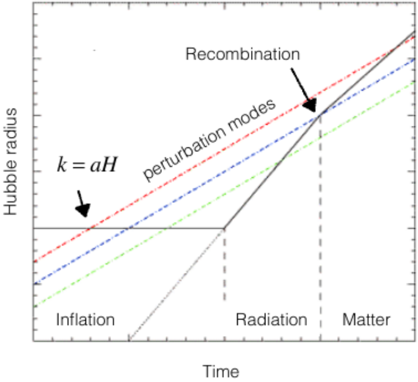
- E.g. Gaussian fluctuations: PBH production for $\Delta_s^2 \gtrsim 10^{-2}$

PBH constrain $V(\phi)$ at scales inaccessible to the CMB observations

Horizons and scales

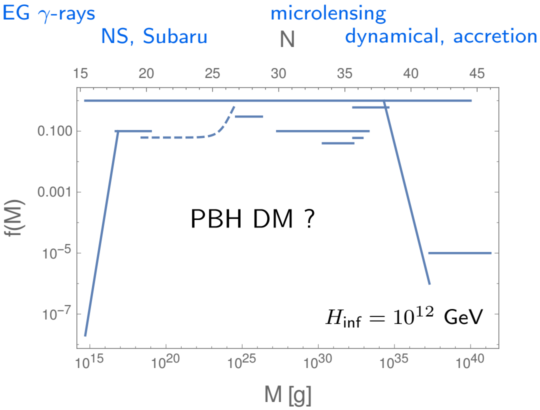
co-moving perturbation modes leave Hubble horizon during reheating, re-enter after reheating

perturbation with given scale today corresponds to fixed during inflation and re-entry



Different PBH masses probe different epochs of inflation / radiation era

PBHs from inflation



- $N = 50 - 60$ (CMB): $\Delta_s^2 = 2 \times 10^{-9}$
- $N < 14$ no DM
- $N < 18$ (PBH evaporation): $f \sim 10^{-20} (M_\odot / M)^{1/2}$;

  constant $\Delta_s^2(N)$ $\rightarrow f_{\text{tot}} \lesssim 10^{-11}$

PBH DM requires peaked spectrum at $15 < N_{\text{peak}} < 40$

PBHs from pseudoscalar inflation (I)

a generic coupling for a pseudoscalar inflaton:

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

[Turner, Widrow '88;
Garretson, Field, Caroll '92;
Anber, Sorbo '06/'10/'12;
Barnaby, Namba, Peloso '11;
Barnaby, Pajer, Peloso '12; ...]

resulting background equations of motion:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\alpha}{\Lambda}\langle\vec{E}\vec{B}\rangle$$

$$\frac{d^2}{d\tau^2}A_\pm(\tau,k) + \left(k^2 \pm 2k\frac{\xi}{\tau}\right)A_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot{\phi}}{2\Lambda H}$$

- tachyonic instability for the gauge field, controlled by $\xi \sim \sqrt{\epsilon} = \dot{\phi}/(\sqrt{2}H)$
- exponential growth of gauge field modes towards the end of inflation
- backreaction on inflaton eom, additional source for scalar and tensor fluctuations

enhancement of scalar (and tensor) power spectrum at small N

PBHs from pseudoscalar inflation (I)

a generic coupling for a pseudoscalar inflaton:

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

[Turner, Widrow '88;
Garretson, Field, Caroll '92;
Anber, Sorbo '06/'10/'12;
Barnaby, Namba, Peloso '11;
Barnaby, Pajer, Peloso '12; ...]

resulting background equations of motion:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\alpha}{\Lambda}\langle\vec{E}\vec{B}\rangle = \frac{\alpha}{\Lambda}2.4\cdot 10^{-4}H^4 e^{2\pi\xi}/\xi^4$$

$$\frac{d^2}{d\tau^2}A_\pm(\tau,k) + \left(k^2 \pm 2k\frac{\xi}{\tau}\right)A_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot{\phi}}{2\Lambda H}$$

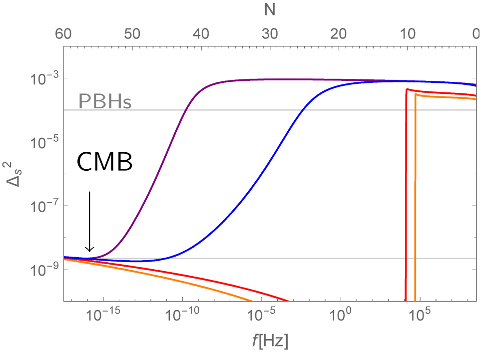
- tachyonic instability for the gauge field, controlled by $\xi \sim \sqrt{\epsilon} = \dot{\phi}/(\sqrt{2}H)$
- exponential growth of gauge field modes towards the end of inflation
- backreaction on inflaton eom, additional source for scalar and tensor fluctuations

enhancement of scalar (and tensor) power spectrum at small N

PBHs from pseudoscalar inflation (II)

a generic coupling for a pseudoscalar inflaton: [Binétruy, VD, Pieroni '16]

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$\epsilon \simeq \beta/N^p$: [Mukhanov '13]

$p = 1$ (chaotic)

$p = 2$ (starobinsky)

$p = 3$ (hill-top)

$p = 4$ (hill-top)

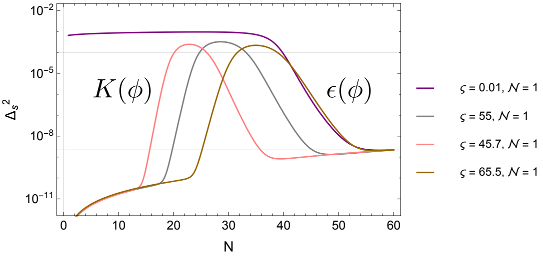
non-gaussian!

increase at small scales, sensitive to underlying class of inflation model

PBHs from pseudoscalar inflation (III)

consider non-minimal kinetic term [VD, Muia, Pieroni, Wittkowski '17]

$$\mathcal{L} = \Omega(\phi)\frac{R}{2} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$= \frac{R}{2} - \frac{1}{2}K(\phi)\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



'attractor' models:
$\Omega(\phi) = 1 + \varsigma h(\phi)$
$V_J(\phi) = V_0 h^2(\phi)$
[Kallosh, Linde, Roest '13]

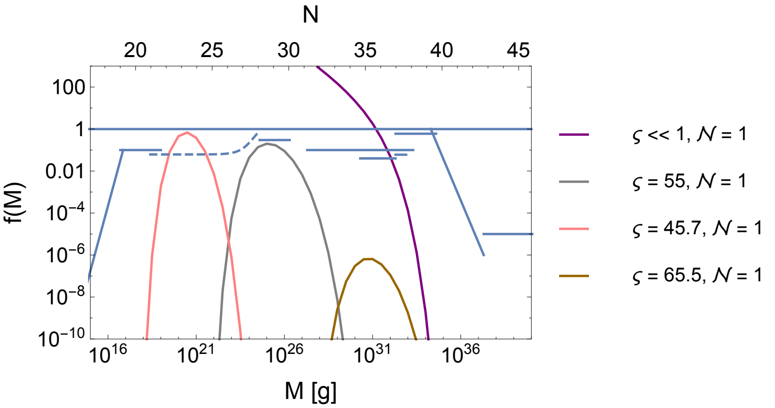
here: $h(\phi) = 1 - 1/\phi$

suitable $\epsilon(\phi)$ and $K(\phi)$ generate peak

PBHs from pseudoscalar inflation (IV)

resulting PBH spectrum:

[VD, Muia, Pieroni, Wittkowski '17]



sizable fraction of PBH DM possible

Other models for PBH production

A very flat inflaton potential enhances scalar perturbations, $\Delta_s^2 \sim V(\phi)/\epsilon(\phi) \sim V^3/V'^2$, e.g. in

- **hybrid inflation**: Garcia-Bellido, Linde, Wands '96 (two-stage inflation), Garcia-Bellido, Clesse '15 (mild waterfall)
- **critical Higgs inflation**: Ezquiaga, Garcia-Bellido, Morales '17
- ...

PBHs can further be produced in first-order phase transitions (Jedamzik, Niemeyer '99), during (p)reheating (Suyama, Tanaka, Basett, Kudoh '05, '06), in curvaton models (Kohri, Lin, Matsuda '12), from cosmic strings (Wichoski, MacGibbon, Brandenberger '98),...

PBHs can serve as messengers for the physics of the early Universe

Outline

- Primordial Black Holes
  - ... in a nutshell
  - ... as dark matter?

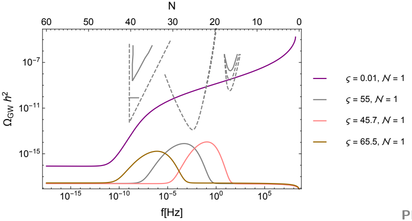
- Primordial Black Holes from Inflation
  - scales: times, e-folds and masses
  - a worked example: pseudoscalar inflation

- Searching for PBHs with Gravitational Waves

Searching for PBHs with GWs

see e.g. [Garcia-Bellido, Peloso, Unal '17]

- transcendent inspiral/merger signal (LIGO like event). (sensitive to mass distribution, merger rate)
- stochastic background (SGWB) of unresolved merger events (sensitive to PBH distribution today)
- SGWB sourced by scalar fluctuations at second order in perturbation theory (sensitive to statistics of scalar fluctuations and PBH distribution at formation)
- possibly first order GW production (sensitive to physics responsible for PBH formation)



more data to come...

Conclusion

- ranges for primordial black hole dark matter:

$$10^{15}\ g \lesssim M \lesssim 10^{37}\ g\,, \qquad 15 \lesssim N \lesssim 40$$

$\rightarrow$ encodes information on wide ranges of cosmological history, which is currently very poorly constrained observationally

- Searches (γ-rays, lensing, dynamical) are severely constraining the 100% PBH DM option, but a sizable DM fraction still possible. Gravitational waves could act as new search tools.

- Pseudoscalar inflation generically produces large scalar perturbations at ‘small’ scales with characteristic features linked to the underlying micro physics of inflation.