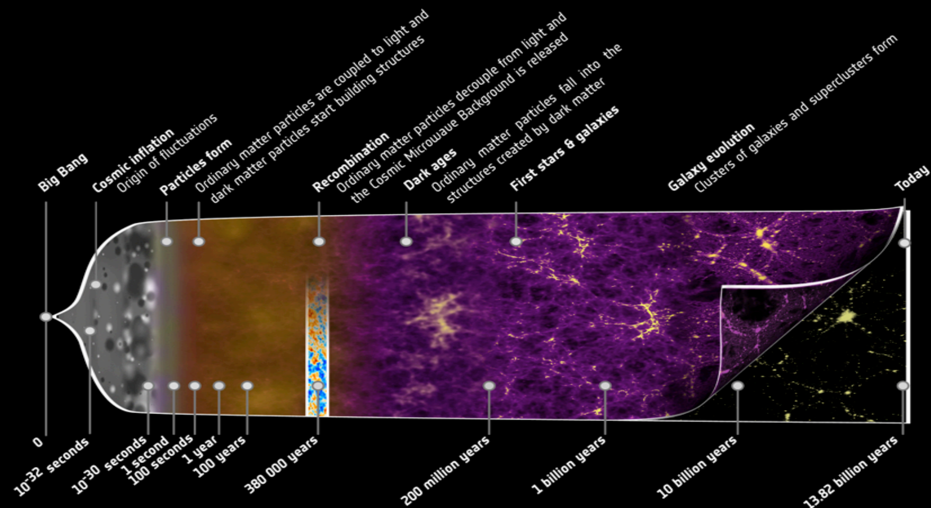
Searching for dark matter and dark energy in the dark ages

Photo Jongsun Lee

Luca Amendola

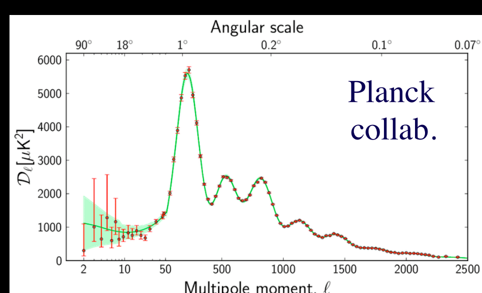
University of Heidelberg

Dark ages

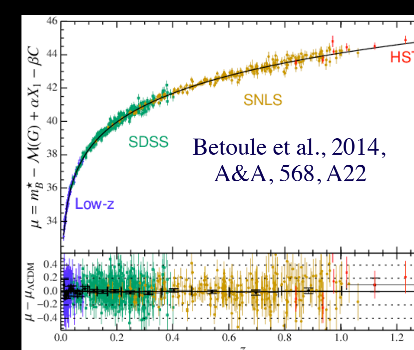


NASA

CMB



SNIa
Large-scale structure



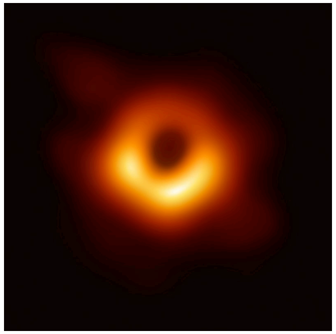
New directions in search of the dark

Searching in new domains
Primordial Dark Matter Halos

Searching with new probes
Testing gravity with the 21cm line

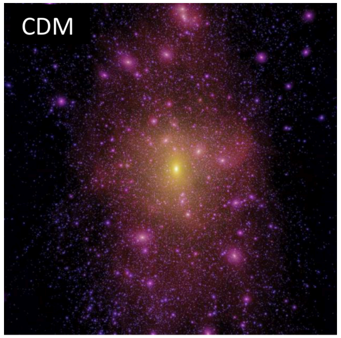
collaboration with C. Wetterich, J. Rubio, S. Savastano, C. Heneka, X.-W. Liu

Astrophysical motivation: From PBH to DMH



Primordial BH

$$\rho_{BH} \approx 10^{16} \left(\frac{M}{M_{\odot}} \right)^{-2} gr/cm^3$$



Ordinary DM (sub)halos

$$\bar{\rho}_{\rm clump}^{\rm min} \simeq 7 \times 10^{-22}\, {\rm gr/cm^3}$$

Anything in the middle ?

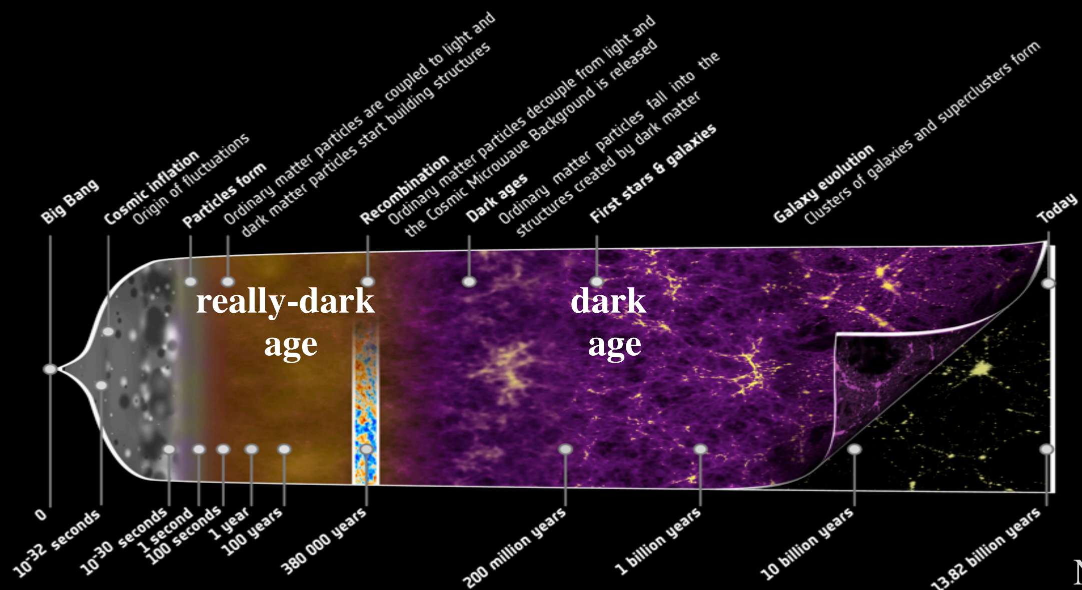
Fundamental physics motivation

One can continue this logic by deducing that the corresponding scalar field responsible for quintessence should interact strongly with the dark sector. This is because an extension of the Weak Gravity Conjecture would suggest that the scalar field has to couple stronger than gravity to some matter fields and we already know, by lack of violation of the equivalence principle in the visible matter sector, that this should be in the dark sector. It would be interesting to find evidence for such a picture by finding apparent violation of equivalence principle in the dark sector due to the force generated by this scalar.

Daniel Brennan, Federico Carta, Cumrun Vafa, 1711.00864

The really-dark age

- The dark age after recombination is not totally dark
- The evolution of the Universe before recombination is however really dark!
- Only two almost direct probes so far: BBN and CMB BB spectrum
- What else: B-modes, non-gaussianity, early structure formation, …?



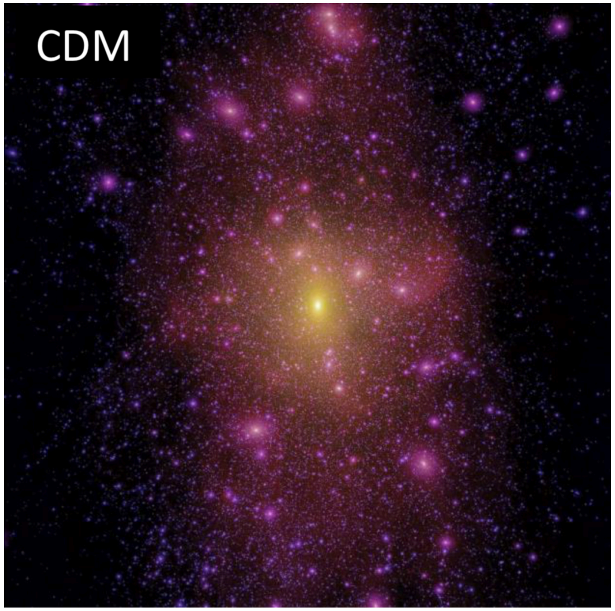
NASA

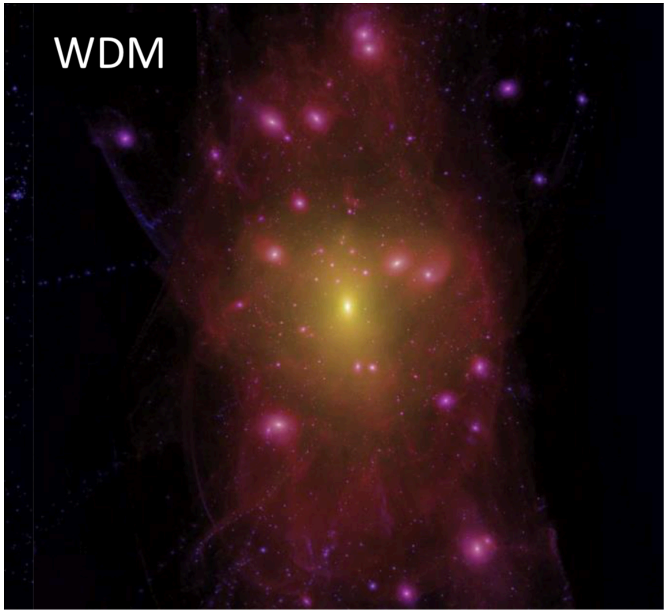
What is dark matter?

"Dark matter is a floating free particle"

. . . well, not really. . . it clumps by gravitational collapse!

Different cosmological histories → Different structures





Lovell et al (2014)

Slide courtesy of Javier Rubio

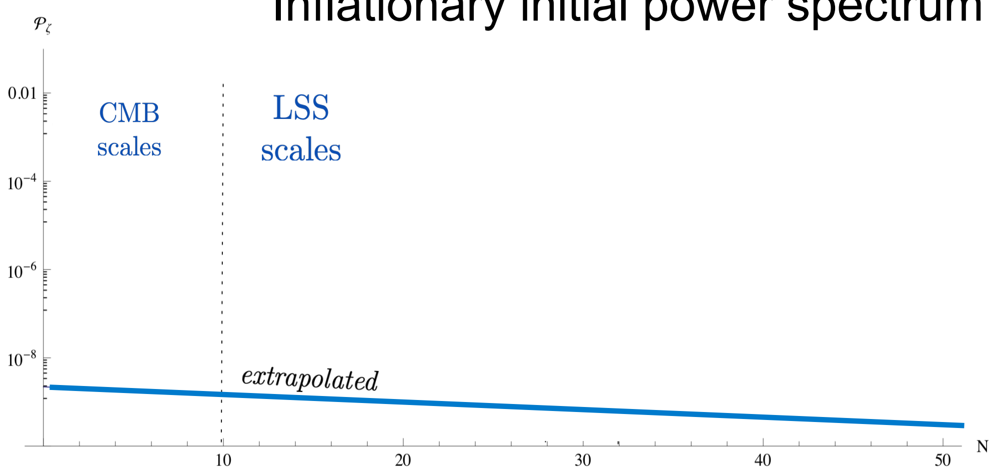
When does it cluster?

"The formation of bound objects is restricted to small redshifts"

This result is based on:

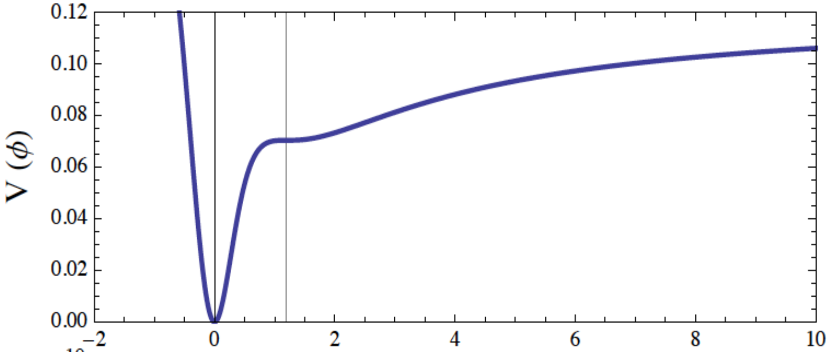
- Gravity is the only unscreened long-range force
- Primordial density fluctuations are scale-invariant
- Matter fluctuations do not grow during radiation era

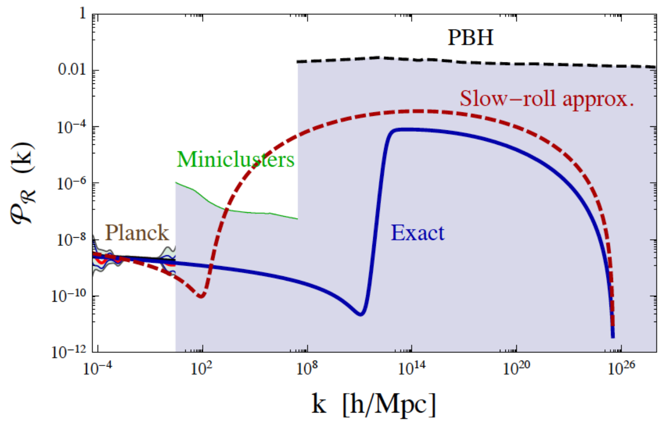
Inflationary initial power spectrum



Slide courtesy of Javier Rubio

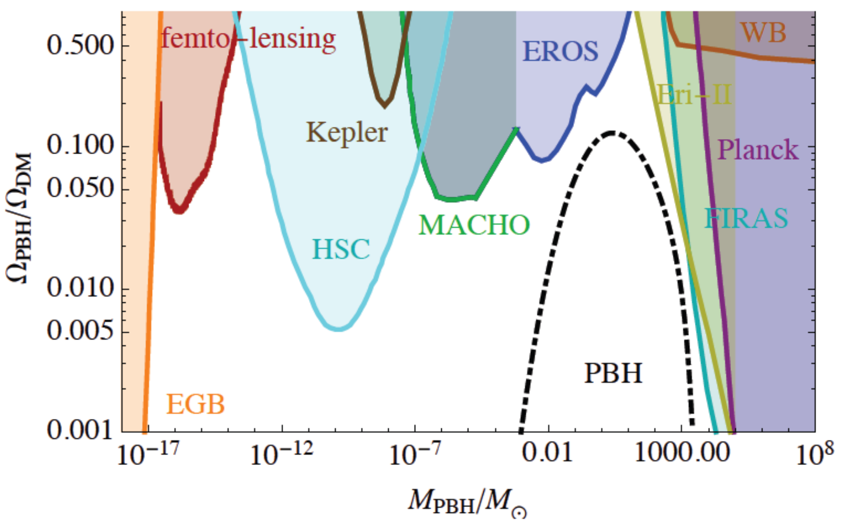
Structure formation after inflation





Primordial BHs are normally assumed to form from spectral peaks due to features in slow-rolling inflation
Eg *inflection* in the potential

$$P \sim \frac{H^2}{\varepsilon}$$



Garcia-Bellido & Ruiz Morales 2017, 1702.03901

When does it cluster?

"The formation of bound objects is restricted to small redshifts"

This result is based on:

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- Primordial density fluctuations are scale-invariant
- Matter fluctuations do not grow during radiation era

Growth during radiation era?

$$\delta = \text{matter density constrast}$$

Sub-hor matter growth equations $\delta_m'' + (1 + \frac{H'}{H})\delta_m' - \frac{3}{2}(\Omega_m \delta_m + \Omega_r \delta_r) = 0$

Perturbation do not grow because $\Omega_m \approx 0$, $\delta_r \approx 0$

$$\Rightarrow \quad \delta_m \approx \text{constant}$$

Interacting fields

Interacting fields ψ (heavy) and ϕ (light)

$$S=\int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R+\mathcal{L}_R+\mathcal{L}(\phi)+\mathcal{L}(\phi,\psi)\right],$$

$$\mathcal{L}(\phi,\psi)=i\bar{\psi}\left(\gamma^\mu\nabla_\mu-m(\phi)\right)\psi\,,$$

$$\beta(\phi)=-M_P\frac{\partial\ln m(\phi)}{\partial\phi}\,.$$

conservation equations

$$\dot{\rho}_\phi+3H(\rho_\phi+p_\phi)=\frac{\beta}{M_P}\left(\rho_\psi-3p_\psi\right)\dot{\phi}\,,$$

$$\dot{\rho}_\psi+3H\left(\rho_\psi+p_\psi\right)=-\frac{\beta}{M_P}\left(\rho_\psi-3p_\psi\right)\dot{\phi}\,,$$

interacting fields

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}\,,$$

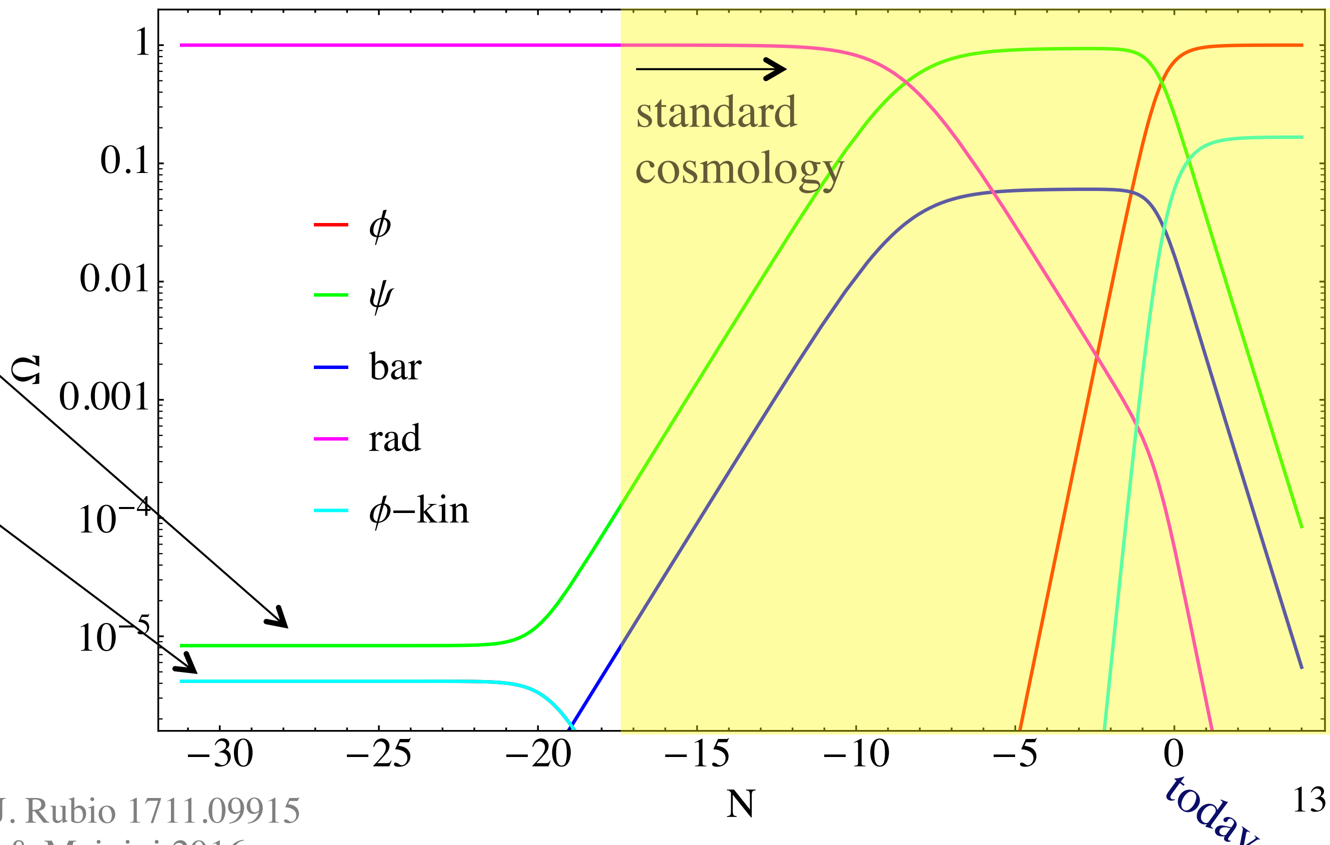
$$\dot{\rho}_\psi + 3H\,(\rho_\psi + p_\psi) = -\,\frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}\,,$$

after the ψ particle become non-relativistic…

$$\beta > \sqrt{\frac{2}{3}}$$

$$\Omega_\psi = \frac{1}{3\beta^2}$$

$$\Omega_\phi = \frac{1}{6\beta^2}$$



L.A., C. Wetterich and J. Rubio 1711.09915
see also Bonometto & Mainini 2016

Growth during radiation era!

$$\delta_m'' + (1+\frac{H'}{H})\delta_m' - \frac{3}{2}(\Omega_m\delta_m + \Omega_r\delta_r) = 0$$

$$\delta_\psi'' + \left(1+\frac{\mathcal{H}'}{\mathcal{H}} - \frac{\beta\phi'}{M_P}\right)\delta_\psi' - \frac{3}{2}(Y\Omega_\psi\delta_\psi + \Omega_R\delta_R) = 0.$$

$$\Omega_\psi = \frac{1}{3\beta^2}$$

$Y = 1+2\beta^2$

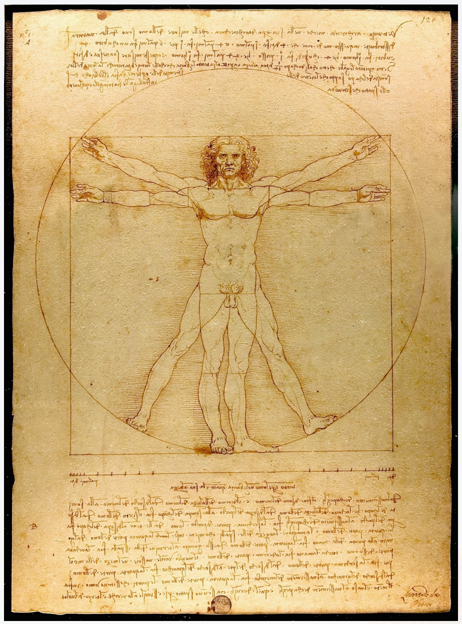
If ψ strongly interacts with coupling $\beta>>1$ with the field ϕ, then there are two consequences:

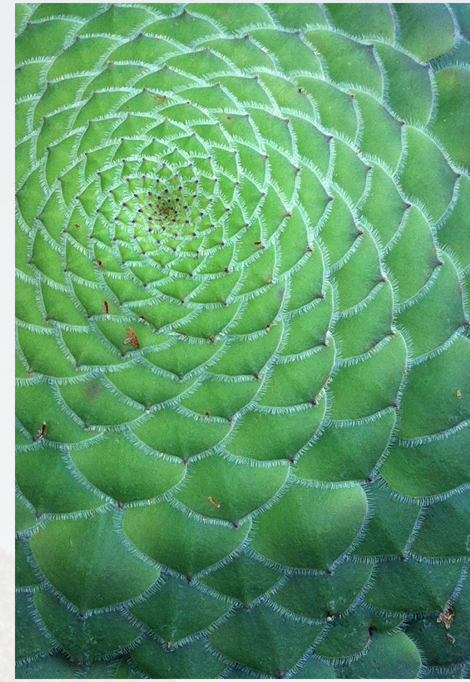
1) The effective gravitational force is large ($Y = 1+2\beta^2 >> 1$)
2) The amount of ψ during radiation is large ($\Omega_r >>\Omega_\psi >> \Omega_{bar}$)

$$\delta_\psi'' - \delta_\psi' - \delta_\psi = 0 \quad \Rightarrow \quad \delta_\psi = \delta_{\psi,\mathrm{in}}\left(\frac{a}{a_{\mathrm{in}}}\right)^{\frac{1+\sqrt{5}}{2}}$$

$$\frac{d\log\delta}{d\log a}=\frac{1+\sqrt{5}}{2}=1.618\ldots$$

The golden number !

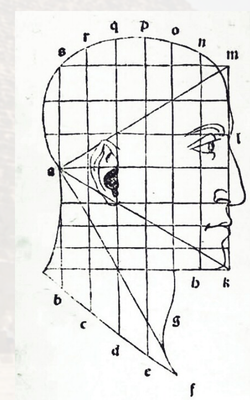




By Max Ronnersjö - Own work, wikipedia

$$\frac{d\log\delta}{d\log a} = \frac{1+\sqrt{5}}{2} = 1.618...$$

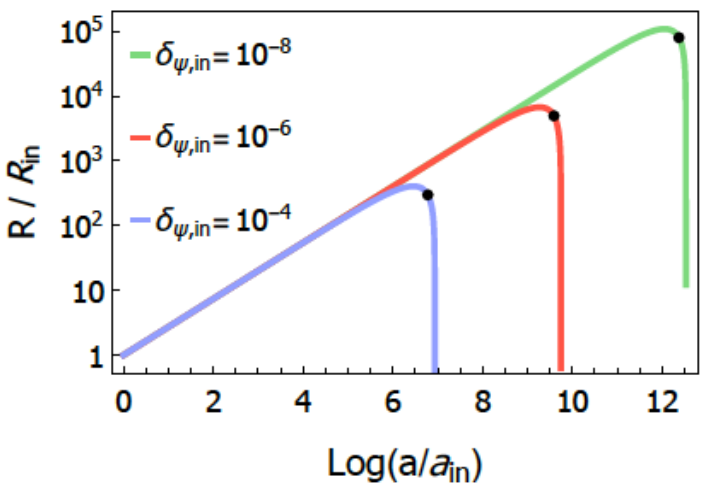
By Nina - Own work, wikipedia

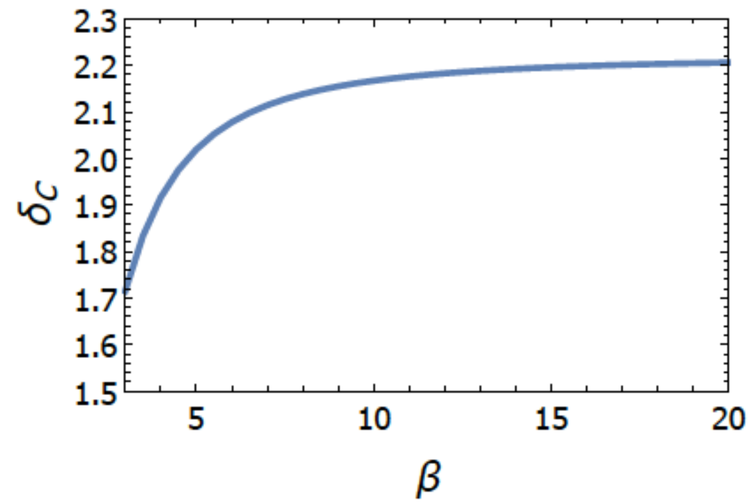


Spherical collapse: Virialization and Screening

non-linear growth

$$\delta_\psi'' - \delta_\psi' - (1+\delta_\psi)\delta_\psi - \frac{4}{3}\frac{\delta_\psi'^2}{(1+\delta_\psi)} = 0\,,$$

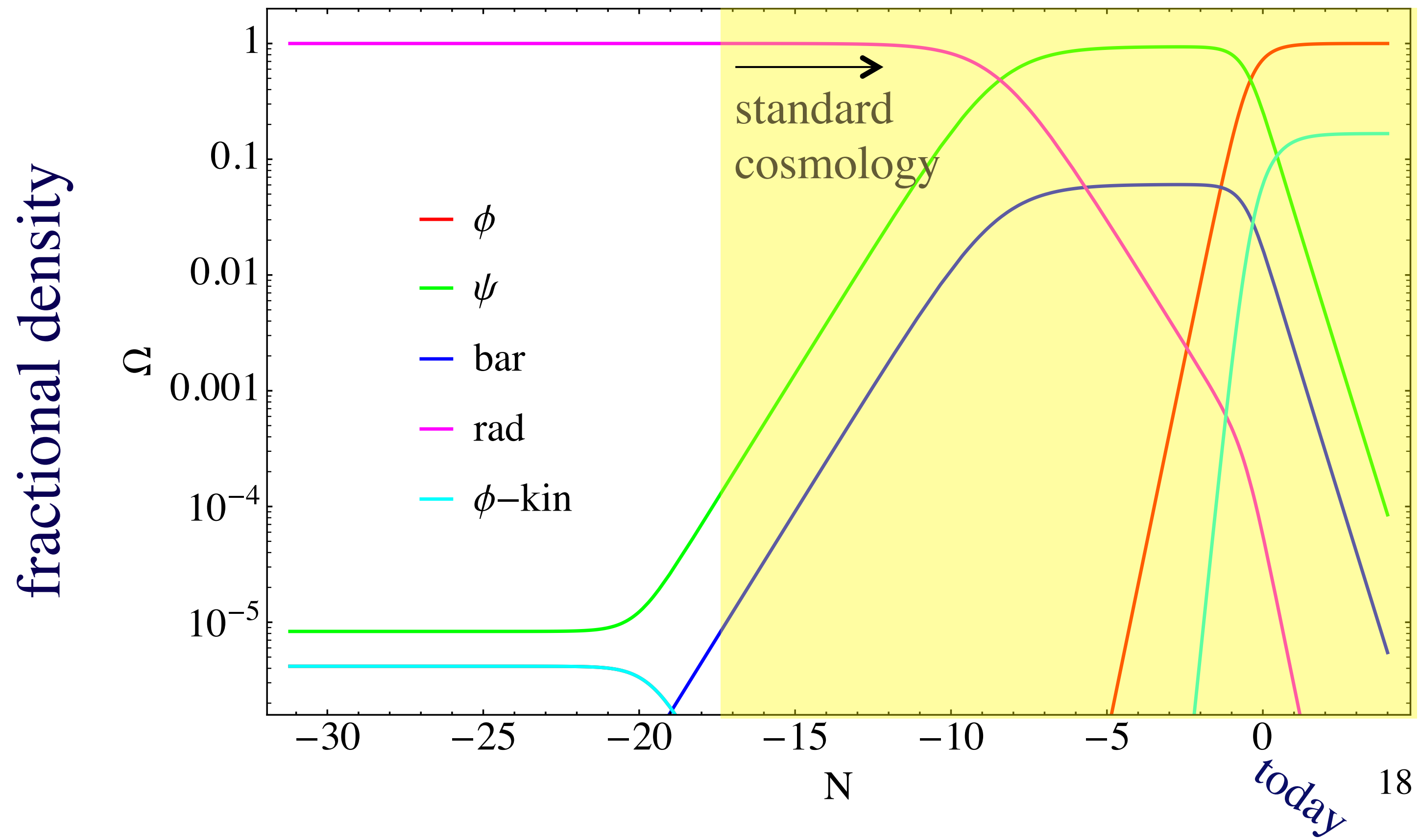




epoch of virialization $\dfrac{a_{\mathrm{V}}}{a_{\mathrm{eq}}} = \dfrac{2}{3\beta^2}\,,$

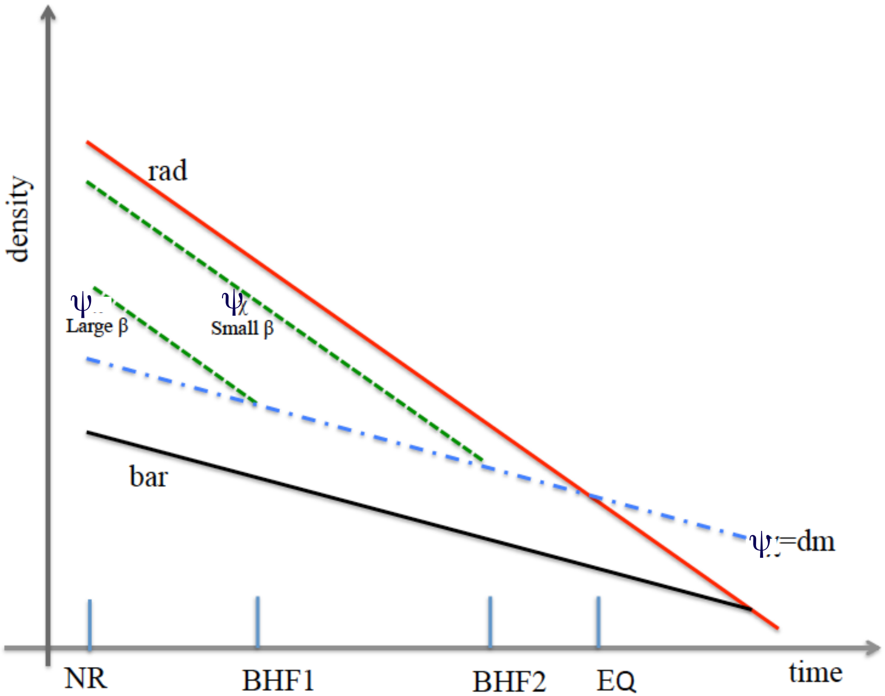
we assume screening to occur around virialization!

interacting fields



Growth during radiation era

Growth as $\delta_\chi \sim a^{1.6}$ after horizon reenter during radiation:
formation of virialized primordial DM halos



Simple relation between PDMH mass, radius and coupling parameter β

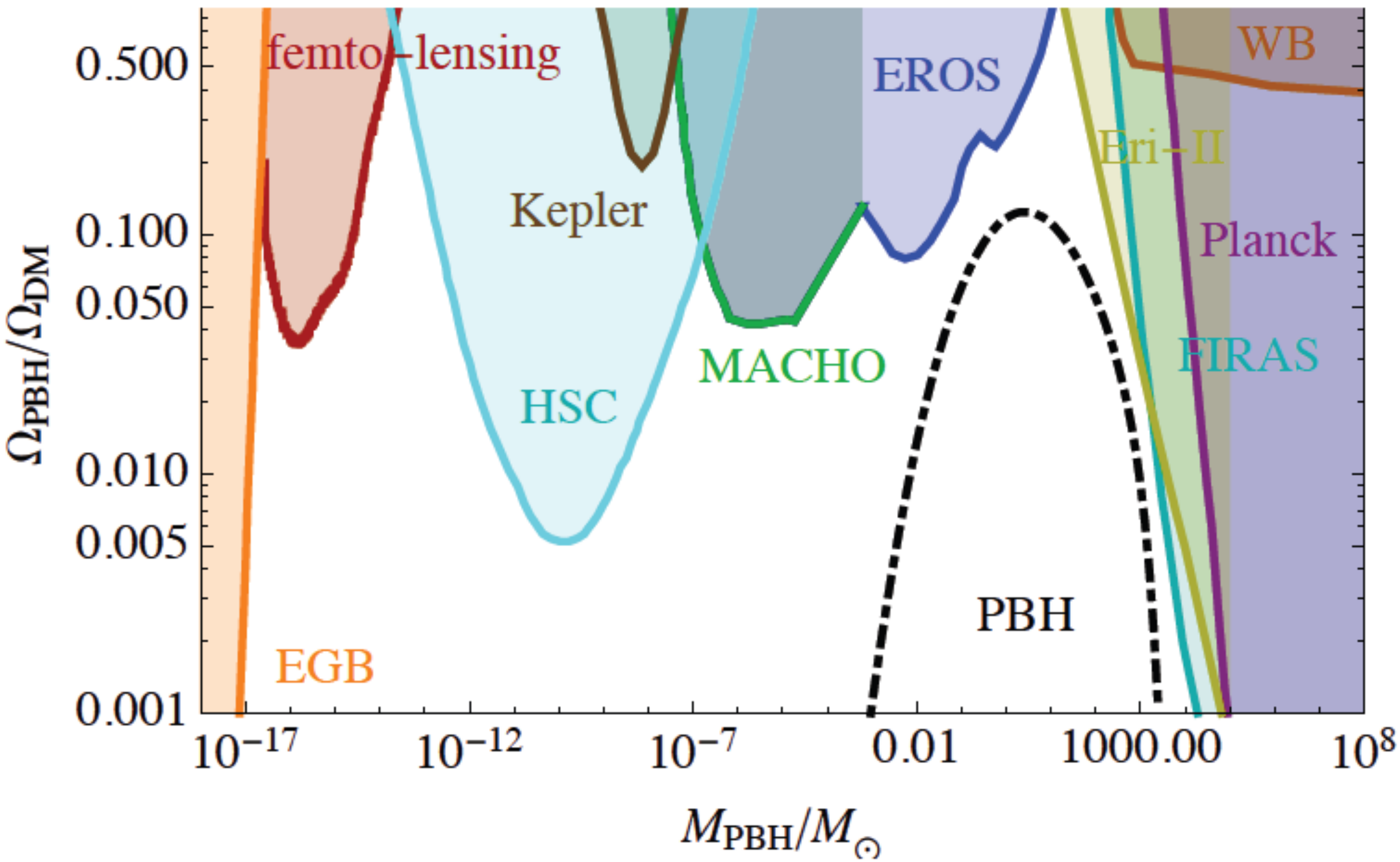
$$|\beta| \simeq 585 \left(\frac{\delta_c}{\delta_{\psi,\mathrm{in}}}\right)^{-1/2p} \left(\frac{M_{\mathrm{PDMH}}}{M_\odot}\right)^{-1/6} .$$

$$R_{\mathrm{PDMH}} = 100 \left(\frac{M_{\mathrm{PDMH}}}{M_\odot}\right)^{2/3} \mathrm{AU} ,$$

(1 solar mass = 3 x size of Neptune's orbit!)

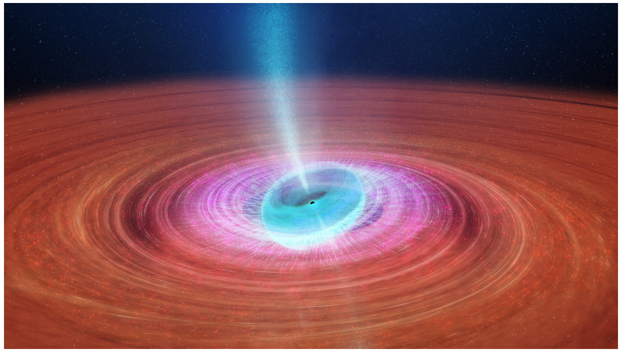
L.A., C. Wetterich and J. Rubio 1711.09915

Constraints



CMB constraints

- CMB constraints derive from the energy injection due to accretion
- The radiated energy changes the ionization history and distorts the temperature and polarization spectra
- This energy injection is very large for PBHs because it happens near the Schwarzschild radius, and scales as $(R/R_s)^{-1/2}$
- For our PDMHs, the radius is 10^9 larger, so the effect is negligible



ESA

See e.g. Y. Ali-Haimoud and M. Kamionkowski, Phys. Rev. D95, 043534 (2017), 1612.05644.

Microlensing constraints

Microlensing is the closest thing we have to a direct measurement

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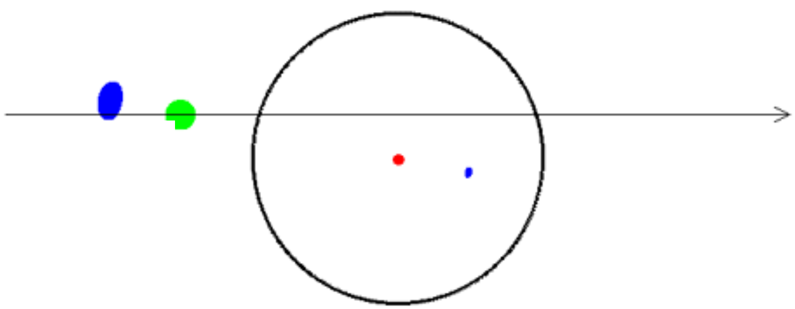
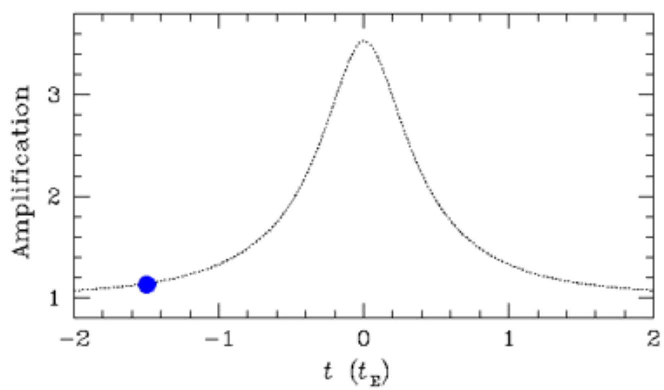
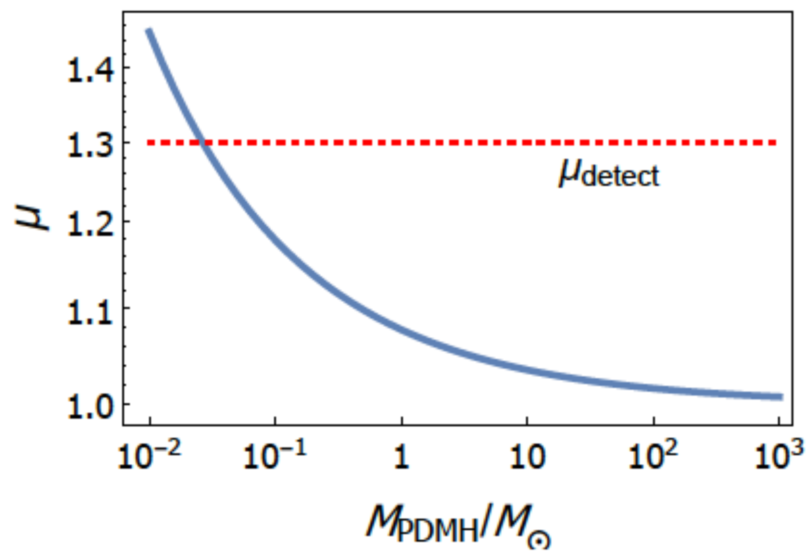




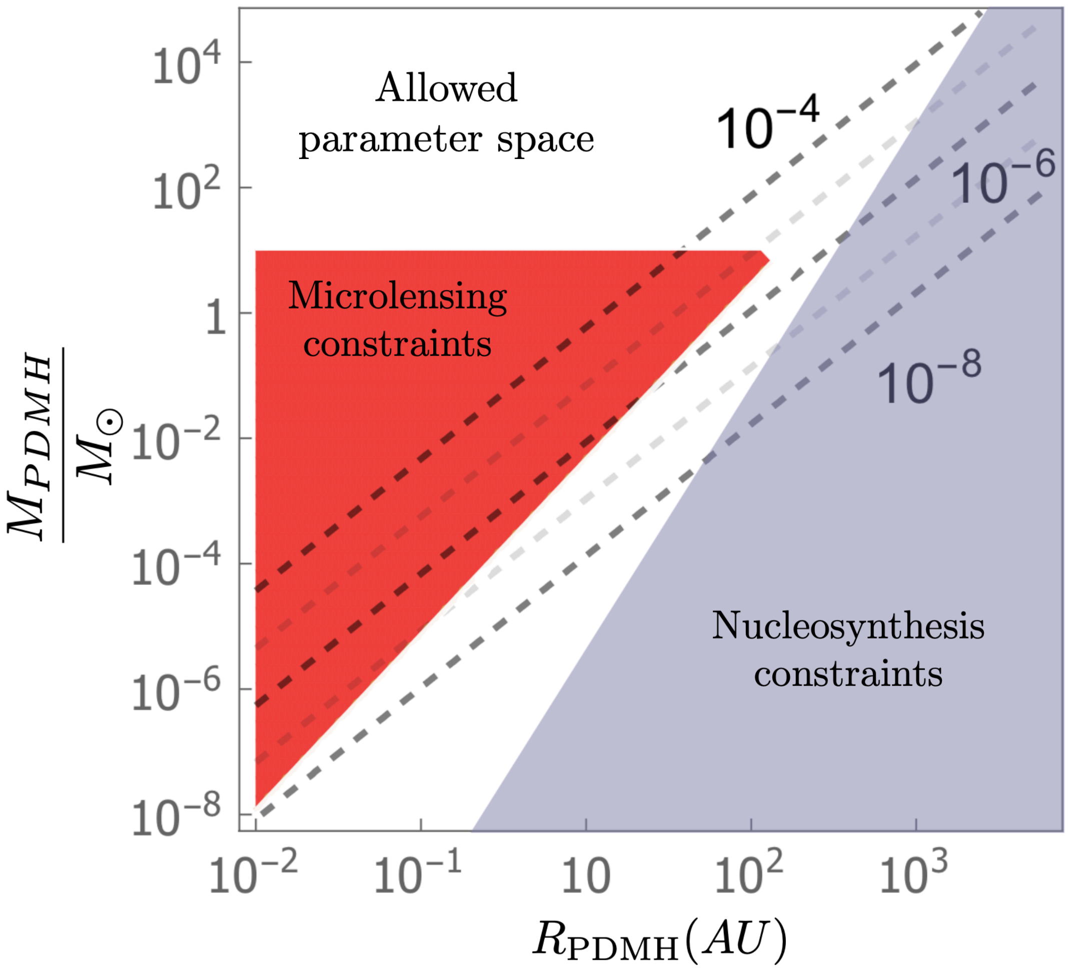


Magnification depends on the concentration

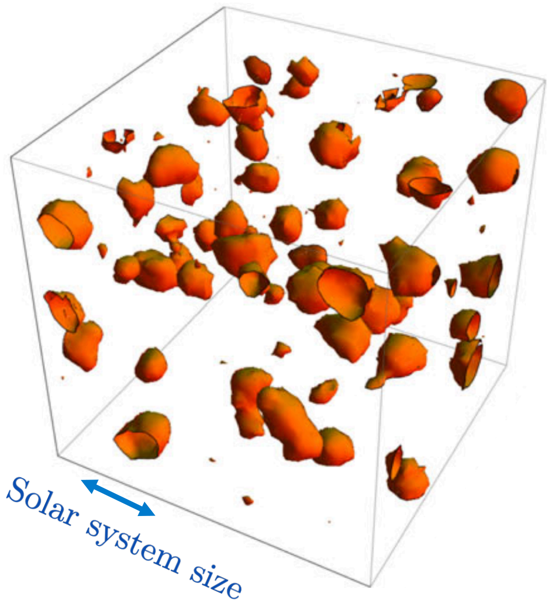
Savastano, S. J. Rubio, L.A., C. Wetterich, 1906.05300

Slide courtesy of Javier Rubio

PDMH constraints



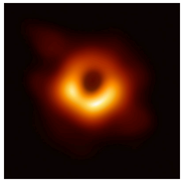
$$\delta_{\psi,\rm in} \sim 10^{-6}$$
$$M_{\rm PDMH} \simeq M_\odot$$
$$R_{\rm PDMH} \simeq 100\rm AU$$
$$\bar\rho_{\rm PDMH} \simeq 2.2\times10^{-13}\frac{\rm gr}{\rm cm^3}$$
$$H_{\rm in} \simeq 6\times10^{-26}\rm GeV$$
$$m_\psi(a_{\rm in}) \sim 1\,\rm MeV$$



Savastano, S. J. Rubio, L.A., C. Wetterich, 1906.05300

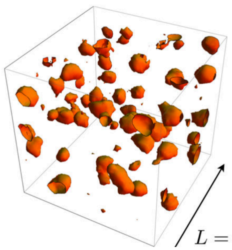
Slide courtesy of Javier Rubio

PDMH vs PBH vs DMH



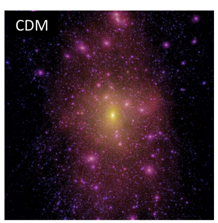
Primordial BH

$$\rho_{BH} \approx 10^{16} \left(\frac{M}{M_\odot} \right)^{-2} gr / cm^3$$



Primordial DM halos

$$\bar{\rho}_{\rm PDMH} \simeq 2.2 \times 10^{-13} \left(\frac{M_\odot}{M_{\rm PDMH}} \right) \frac{\rm gr}{\rm cm^3} \, ,$$

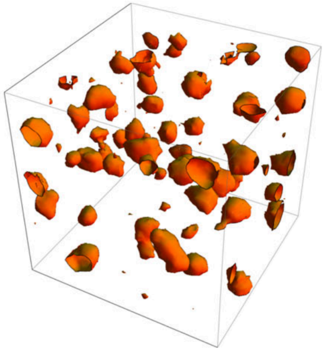


Ordinary DM (sub)halos

$$\bar{\rho}_{\rm clump}^{\rm min} \simeq 7 \times 10^{-22} \, {\rm gr/cm^3}$$

PDMH are intermediate between PBH and DMH !

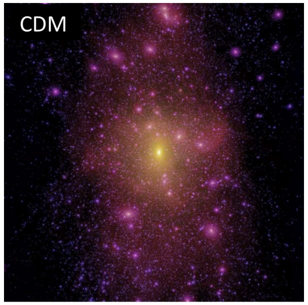
Distinguishing PDMH vs DMH



Primordial DM halos

$$R_{\rm PDMH} = 100 \left(\frac{M_{\rm PDMH}}{M_\odot}\right)^{2/3} {\rm AU}\,,$$

$$\bar{\rho}_{\rm PDMH} \simeq 2.2 \times 10^{-13} \left(\frac{M_\odot}{M_{\rm PDMH}}\right) \frac{\rm gr}{\rm cm^3}\,,$$



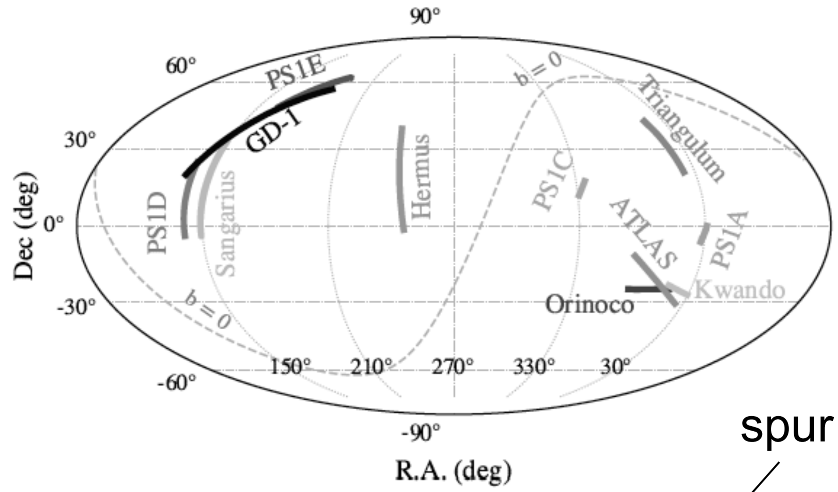
Ordinary DM (sub)halos

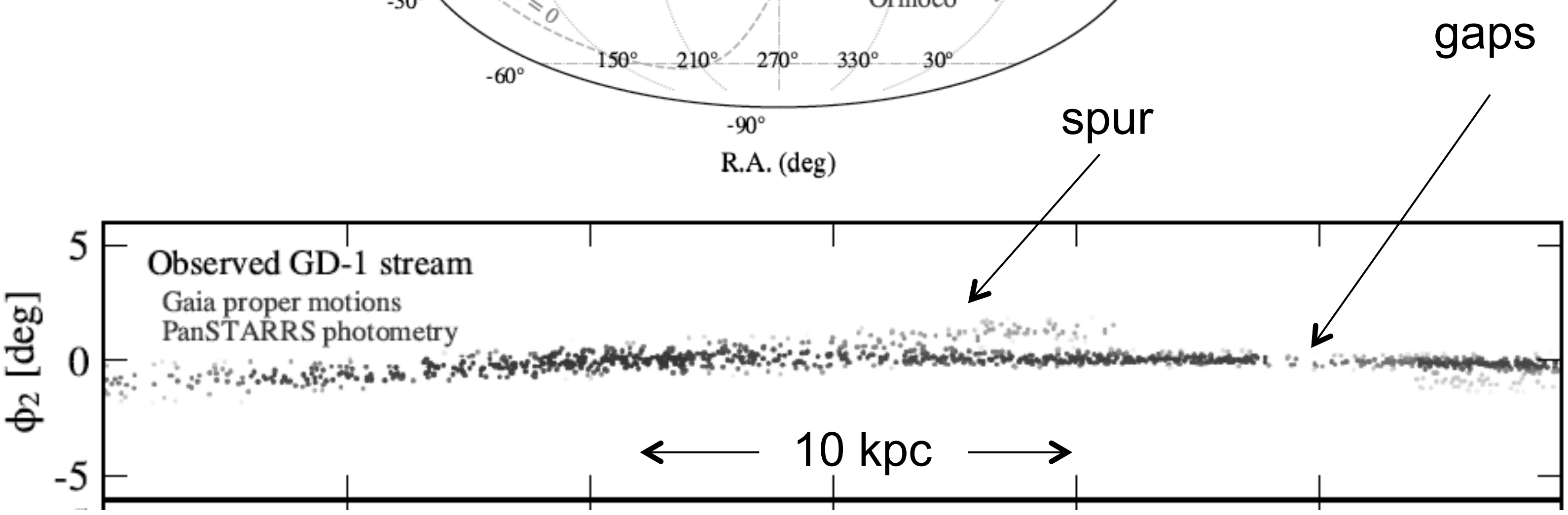
$$R_{DMH} = 10^3 R_{PDMH}$$

$$\bar{\rho}_{\rm clump}^{\rm min} \simeq 7 \times 10^{-22}\, {\rm gr/cm^3}$$

PDMH are smaller and more compact than ordinary DM subhalos
Mass distribution is also expected to be quite different

Stellar streams

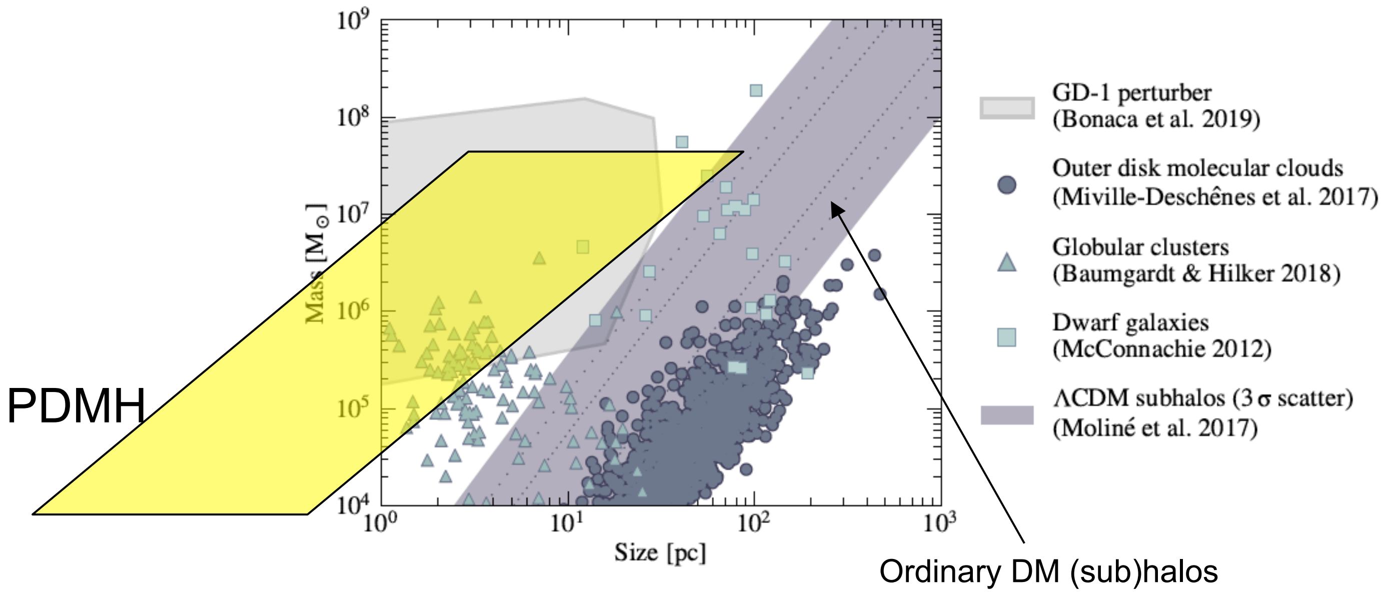




Bonaca et al. 1811.03631 and 1804.06854

Tidally disrupted globular clusters create very long and thin stellar streams

What objects hit stellar streams?



Bonaca et al. 1811.03631

Stellar streams seem to require more compact halos than ordinary DM ones…

Still many questions…

- **Dark matter remains mostly confined into PDMHs: is this the reason why no free DM particles have been detected?**
- No need of special features on the inflationary spectrum
- Is the coupling fully screened?
- Can PDMHs be distinguished from "ordinary" DM mini-halos?
- Can the "dark radiation" epoch have other visible effects?
- PDMH -> PBH? (see Flores and Kusenko, 2008.12456)