Первичные черные дыры как кандидаты на роль тёмной материи

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Overview

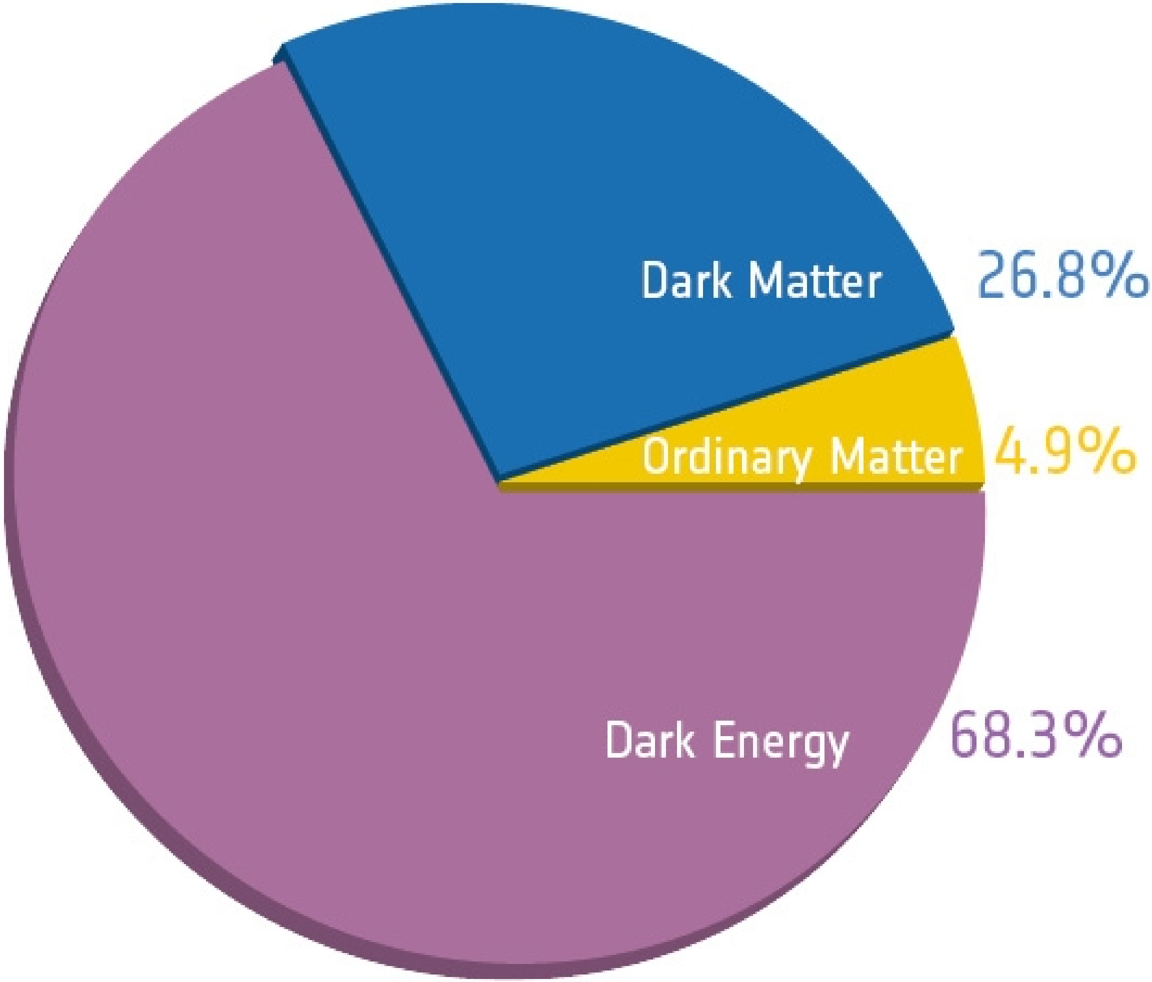
- PBH formation

- PBH as DM

  - Hawking evaporation
  - Femtolensing
  - Constraints from stellar evolution
  - Gravitational lensing constraints
  - CMB consraints

- Conclusions

DM paradigm



95% of constituting stuff is acting only gravitationally (to our best present knowledge)

DM paradigm

- 1846 – Le Verrier and Adams discover new planet Neptune via its action on the orbit of the Uranus

- 1859 – Le Verrier(!) reported that the precession of the Mercury orbit cannot be fully explained by the action of known matter distribution in the Solar system

- 2 ways out:
  - New “specie” of matter(“Neptune”)
  - Modification of the gravitation laws (“Einstein”)

DM paradigm

- So now we also should either add DM or modify the GR
- The problem is that there's no room for new particles in the Standard Model. And the SM is very well (up to 10^{-9} precision) tested experimentally—so any new extension is not so easy to plug in.
- GR is very well tested as well (although when we are dealing with the cosmological scales we are making a **huge leap forward**), so construction of viable MG theories is extremely challenging.

DM paradigm

- Let's follow the (C)DM path
- SM extension in a very broad mass range:

  - Axions and ALPs (10^{-9}-10^{-6} eV)
  - Sterile neutrinos (~keV)
  - Neutralinos, e.g. SUSY WIMPS (~GeV-TeV)
  - WIMPzillas (>~10^{12} GeV)
  - ...
  - More and more and more

OR

Primordial Black Holes

PBHs

- Perfect candidate:
  - Stable (if massive enough)
  - Cold
  - Very weakly interacting (i.e. **Dark**)

$$r_{bh} = \frac{2GM_{bh}}{c^2} = 3x10^{-8}\left(\frac{M_{bh}}{10^{20}g}\right)cm$$

e.g. Carr'06, Khlopov'10

PBHs: formation

- PBHs were formed in the very early Universe.
- Large overdensity ($\delta \sim 1$) with a horizon size
- In case of usual almost flat spectrum with gaussian fluctuations $\varepsilon \sim 10^{-5}$, the probability during RD is prohibitively low:

$$W(k) \sim \exp\left(-\frac{\delta^2}{\epsilon(k)^2}\right)$$

PBHs: formation

- Two ways out:
  - Non-flat spectrum of fluctuations $\varepsilon(k)$ could produce PBH in abundance at some scale. E.g. spike in inflationary spectrum could lead to narrowly distributed masses of PBHs.
  - EOS $p=\gamma e$ softening due to phase-transition (for example). PBHs would be mostly formed at the epoch of that transition

$$W \sim \exp\left(-\frac{\gamma^2}{\epsilon^2}\right)$$

PBHs: formation

- Alternatives:
  - Bubble collisions during phase transition. PBHs again would have mass defined by the time of the transition (QCD—1 M_{sol}, e^+e^- annihilation – 10^5 M_{sol}).
  - In general we are not expecting PBHs of much higher masses to be formed, because we more or less understand physics at these scales and excessive PBH formation could affect BBN
  - Last but not least: collapse of cosmic strings, domain walls

PBHs: formation

- Concluding remarks:
  - Considerable contribution of PBH into the Universe mass-energy budget comes from the fact that they are non-relativistic at any stage. Thus they are diluted only as a^{-3}, whereas other species as a^{-4}.

  - In some extensions PBHs could leave Planck mass relics after evaporation. These relics (10^{-5} g) could also be considered as DM candidates.

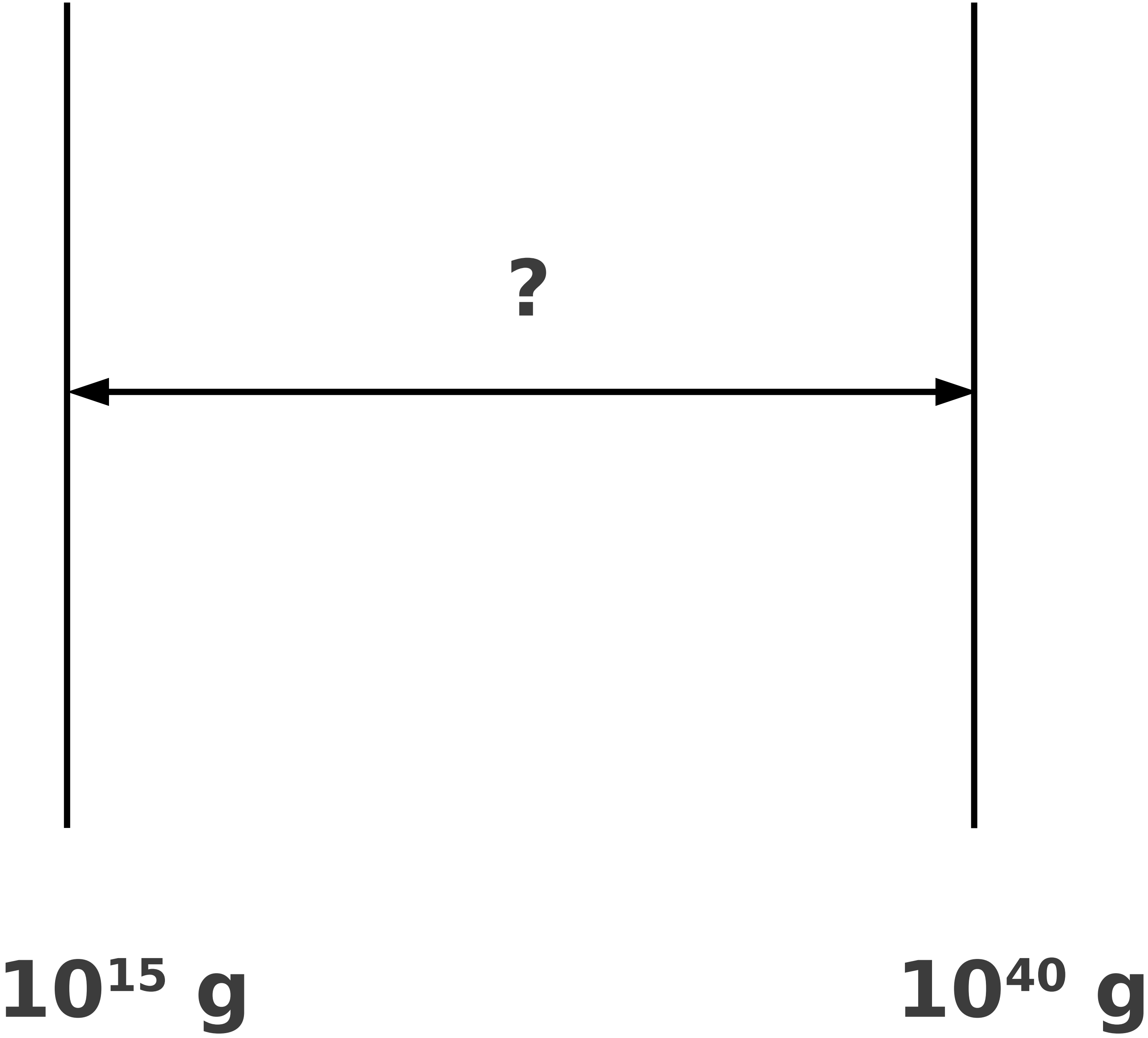
PBHs: Hawking evaporation

- Black holes are not entirely black
- They slowly evaporate due to the Hawking radiation at very long timescales:

$$\tau(M) \sim \frac{hc^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_{sol}}\right)^3 yr$$

- Only PBHs with masses larger than 10^{15} g survived until now

PBHs: mass range



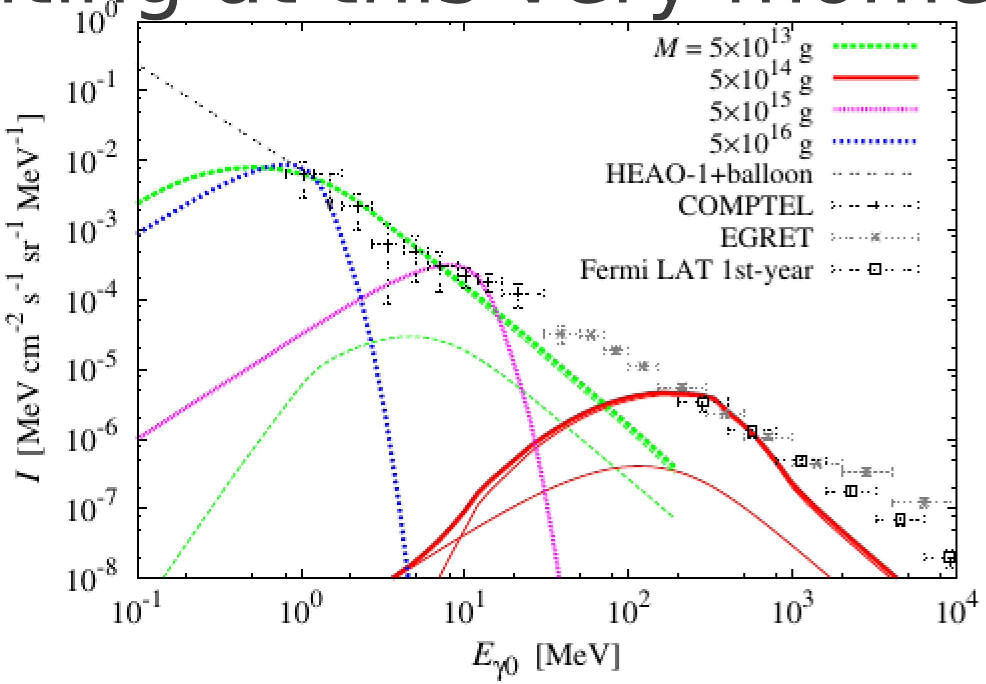
?

10^{15} g

10^{40} g

PBHs: constraints from evaporation

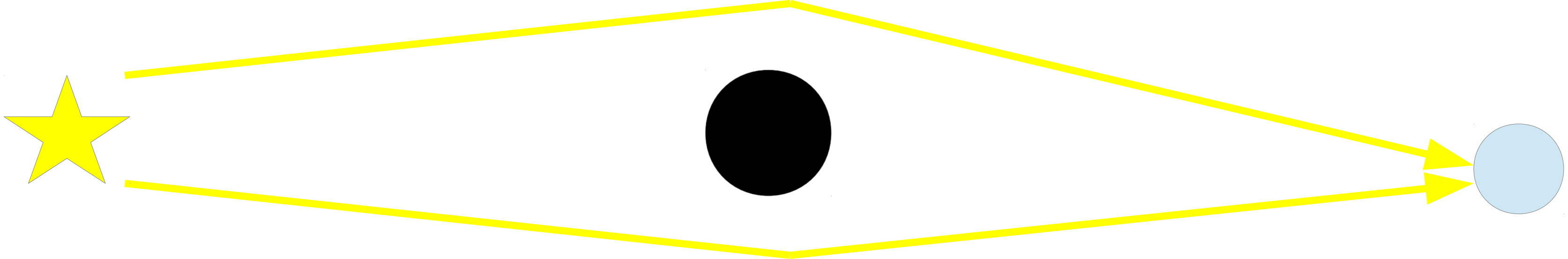
- At the lower boundary PBH abundance is severely constrained by non-observation of gamma-rays (and CRs) from PBHs evaporating at this very moment



From Carr et al.'10

- $\Omega_{PBH} < 10^{-9}$ at $M_{PBH} \sim 10^{15}$, however these constraints get relaxed very rapidly

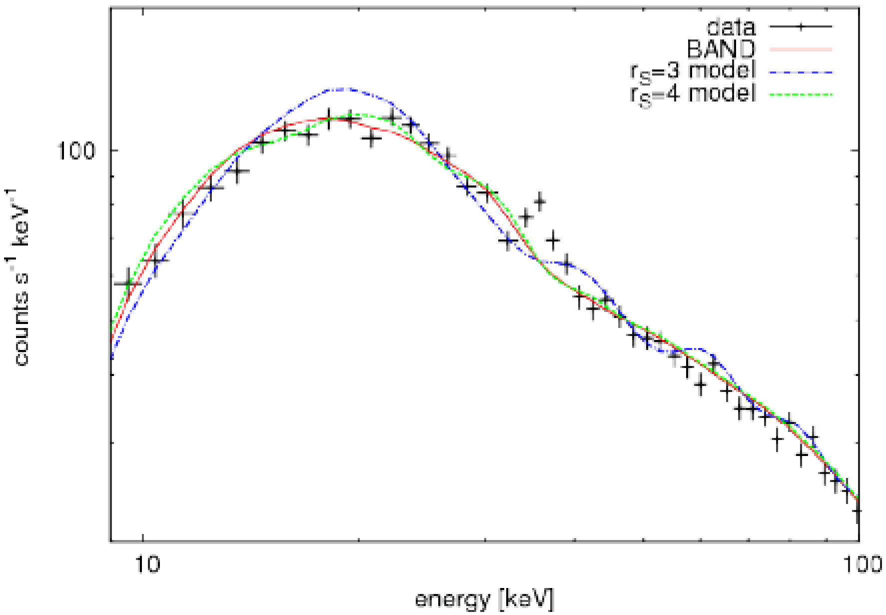
Constraints from femtolensing

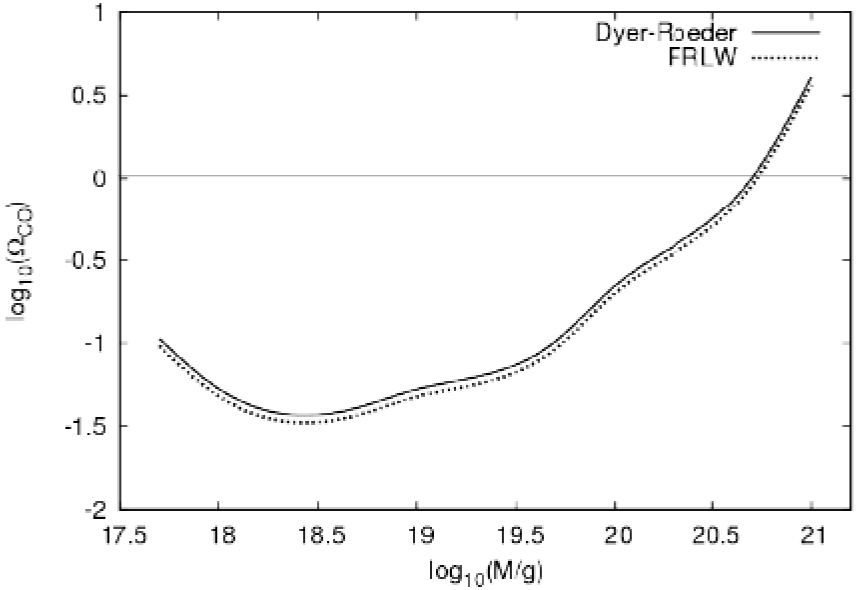


- Gravitational lensing (by PBH) cause emergence of two images
- Time delay τ between them would be $\sim r_g/c$
- If $M_{PBH} \sim 10^{18}$ g τ would be around one period length for a MeV gamma-ray==>we could expect some spectral features due to the constructive/destructive interference (Gould'92)
- As a rule of thumb, optical depth to lensing is $\sim\Omega$ for cosmological distances

Constraints from femtolensing

- Barnacka et al'12 used Fermi GBM data to constrain PBH abundance (from 500 bursts)





- Possible problems – non-finite size of the sources (GRBs). That could invalidate these claims

Constraints from stellar evolution

- PBHs could be captured by a protostar
- Due to the dynamic friction, they could fall down to the central regions of the star
- After some compact object (WD or NS) would form, PBH would rapidly devour it
- Thus, observation of these objects could put some constraints on PBHs abundance.

F.Capela, MP & P.Tinyakov, 2013a
(1209.6021,PRD 87 id. 023507)

Constraints from stellar evolution

- Star formation: GMC is fragmenting into denser clumps
  - $M_{\mathrm{GMC}} = 5\mathrm{x}10^5\ \mathrm{M}_{\mathrm{sol}}$
  - $R_{\mathrm{GMC}} = 20\ \mathrm{pc}$
  - $\rho_{\mathrm{GMC}} = 500\ \text{см}^{-3}$

→

$M_{\mathrm{PC}} = 1\ \mathrm{Msol}$
$R_{\mathrm{PC}} = 0.02\ \mathrm{pc}$
$\rho_{\mathrm{PC}} = 10^6\ \text{см}^{-3}$

- Some fraction of DM would be gravitationally bound to a forming star. In case of the Maxwellian distribution this fraction could be estimated as:

$$dn = \bar{n}_{\mathrm{DM}} \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} \exp\left\{\frac{-3v^2}{2\bar{v}^2}\right\} d^3v,$$

$$\rho_{\mathrm{DM,bound}} = \bar{\rho}_{\mathrm{DM}} \frac{4\pi}{3}\left(\frac{3|\phi_0|}{\pi\bar{v}^2}\right)^{3/2} = \bar{\rho}_{\mathrm{DM}} \frac{4\pi}{3}\left(\frac{6G\rho_0 R_0^2}{\bar{v}^2}\right)^{3/2}$$

F.Capela, MP & P.Tinyakov 2013a

Constraints from stellar evolution: AC

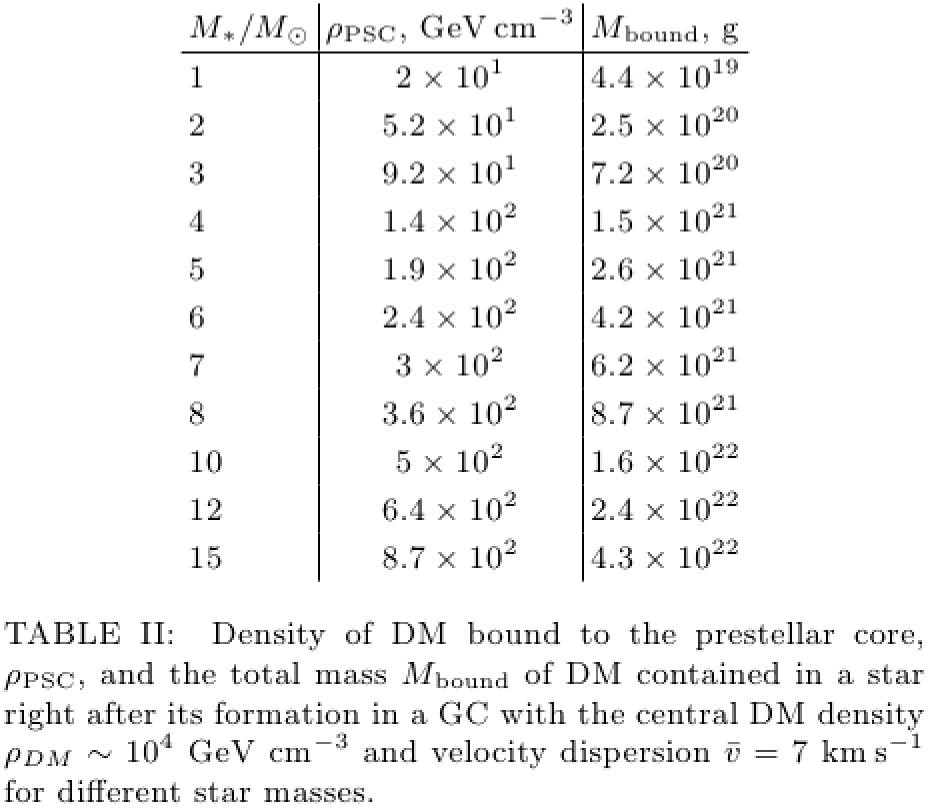
- Adiabatic contraction: DM is falling inside deepening potential well of the forming star
- $$I = \oint p\,dq = const$$
- Radial orbits, L conserved. ==> $rM(r)$=const
- This process would operate even when the collapse time scale is comparable to the free fall time
- However, there is no effective way for DM to lose its initial angular momentum, thus the final enhancement would be $\sim r^{-3/2}$ for initially uniform cloud

$$\rho_{DM}(r) = \frac{1}{2}\rho_{DM,bound}\left(\frac{R_0}{r}\right)^{3/2}$$

Constraints from stellar evolution

- We need to look for regions with large abundance of slowly moving (small velocity dispersion) DM

- Old globular clusters of the galactic halo (?)
- Simulations show that they were formed at *z*=10-12 in rare density peaks and the initial DM density could reach 10 000 GeV/cm^3



$M_*/M_\odot$	$\rho_{\rm PSC}$, GeV cm^{-3}	$M_{\rm bound}$, g
1	2×10^1	4.4×10^{19}
2	5.2×10^1	2.5×10^{20}
3	9.2×10^1	7.2×10^{20}
4	1.4×10^2	1.5×10^{21}
5	1.9×10^2	2.6×10^{21}
6	2.4×10^2	4.2×10^{21}
7	3×10^2	6.2×10^{21}
8	3.6×10^2	8.7×10^{21}
10	5×10^2	1.6×10^{22}
12	6.4×10^2	2.4×10^{22}
15	8.7×10^2	4.3×10^{22}

TABLE II: Density of DM bound to the prestellar core, $\rho_{\rm PSC}$, and the total mass $M_{\rm bound}$ of DM contained in a star right after its formation in a GC with the central DM density $\rho_{DM}\sim10^4$ GeV cm^{-3} and velocity dispersion $\bar{v}=7$ km s^{-1} for different star masses.

Constraints from stellar evolution: constraints

- If $N_{BH}<1$, no constraints arise
- If $N_{BH}>1$, then we could constrain PBH fraction

$$\frac{\Omega_{PBH}}{\Omega_{DM}} \leq \frac{1}{N_{BH}}$$

$$N_{BH} = M_{DM}(r_c)/m_{BH}$$

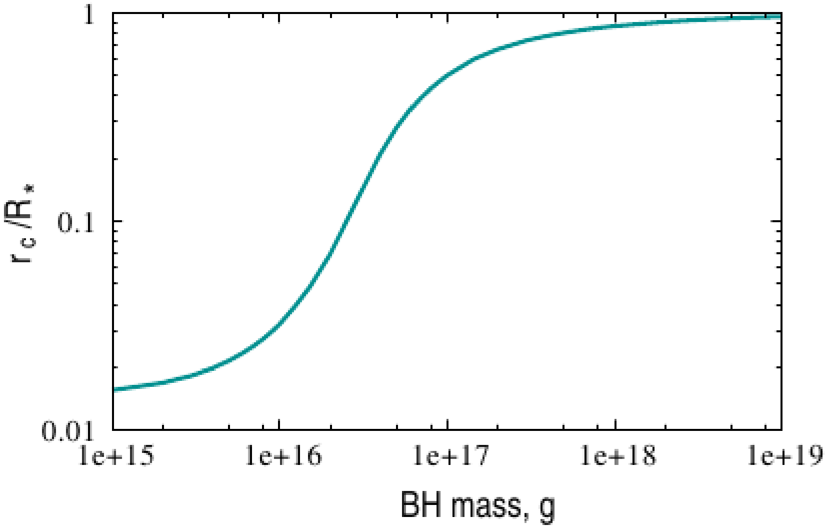


FIG. 2: The dependence of the size r_c of the collection region (the region from which the PBHs captured by the star at its formation have enough time to sink to within the radius of the future compact remnant, WD or NS) on the PBH mass, corresponding to the case of WD for $M_* = M_\odot$.

- More massive PBHs would sink faster but their number is much lower (we have fixed density of PBHs)

Constraints from stellar evolution: dynamic friction

- When a massive body is moving through a medium some drag force would emerge. Some density enhancement would be formed behind a moving body due to the effect of gravitational focussing. Thus this body would experience action of an additional attractive force, i.e. dynamical friction

$$\frac{\mathbf{f}}{m_{\rm BH}} = -\gamma(v)\mathbf{v}$$

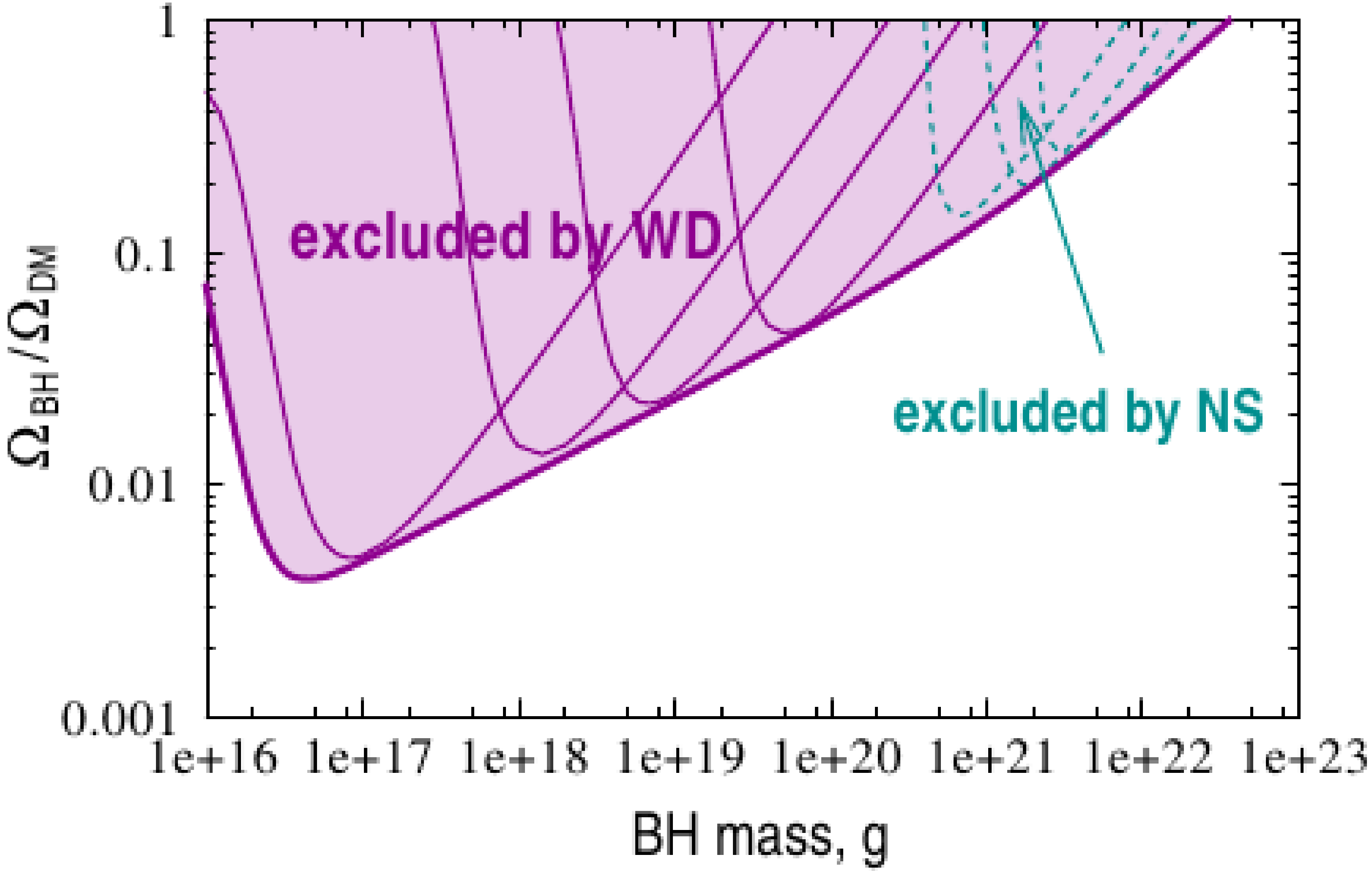
$$\gamma(v) = 4\pi G^2 \rho(r) m_{\rm BH} \ln(\Lambda) \frac{F(X)}{v^3},$$

$$F(X) = \mathrm{erf}(X) - 2X\exp(-X^2)/\sqrt{\pi},$$

$$X = v/(\sqrt{2}\sigma),$$

- Friction is more effective for **massive** bodies
- We are interested in the fraction of PBHs that would have spiralled down to the radius of future NS/WD in the star lifetime

Constraints from stellar evolution: constraints



Constraints from stellar evolution: revisited

- Previous estimates were based onto clear distinction: DM inside/outside a star always remains inside/outside
- Clearly insufficient—most of the orbits are radial
- Enhancement factor is ~2x10^3

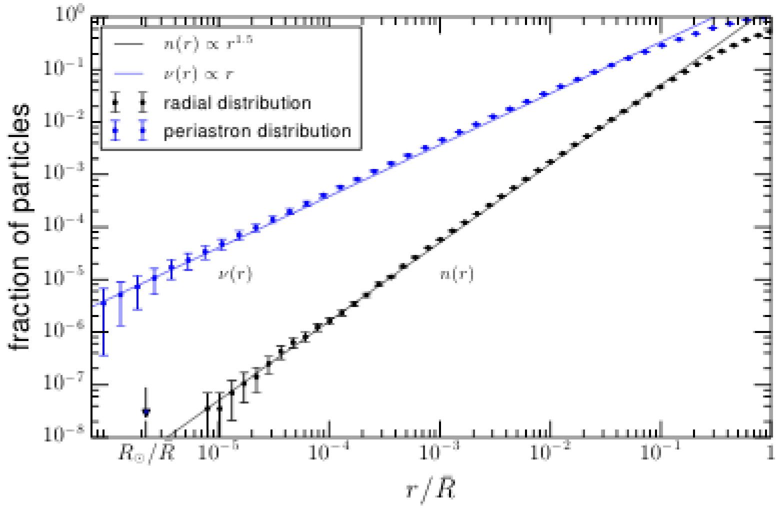


FIG. 1: *Lower curve:* The fraction of particles $n(r)$ that are found within radius r at the end of the adiabatic contraction. $\bar{R}$ is the initial radius of the prestellar core. *Upper curve:* The fraction of particles $\nu(r)$ whose orbits have the periastron smaller than r. Lines show the power laws $n(r) \propto r^{1.5}$ and $\nu(r) \propto r$. The errorbars represent statistical errors.

Constraints from stellar evolution: revisited

- Much more DM could be captured (depends on DM-nucleon interaction strength)
- Again, taking PBH:

$$t_{\rm capt} \simeq 2\tau\sqrt{\xi_0} \sim 2\times 10^8 \text{ yrs} \left(\frac{10^{22}\text{ g}}{m_{\rm BH}}\right) \qquad \tau = \frac{\pi R_*^{5/2} v^2}{4Gm_{\rm BH}\sqrt{GM}\ln\Lambda},$$

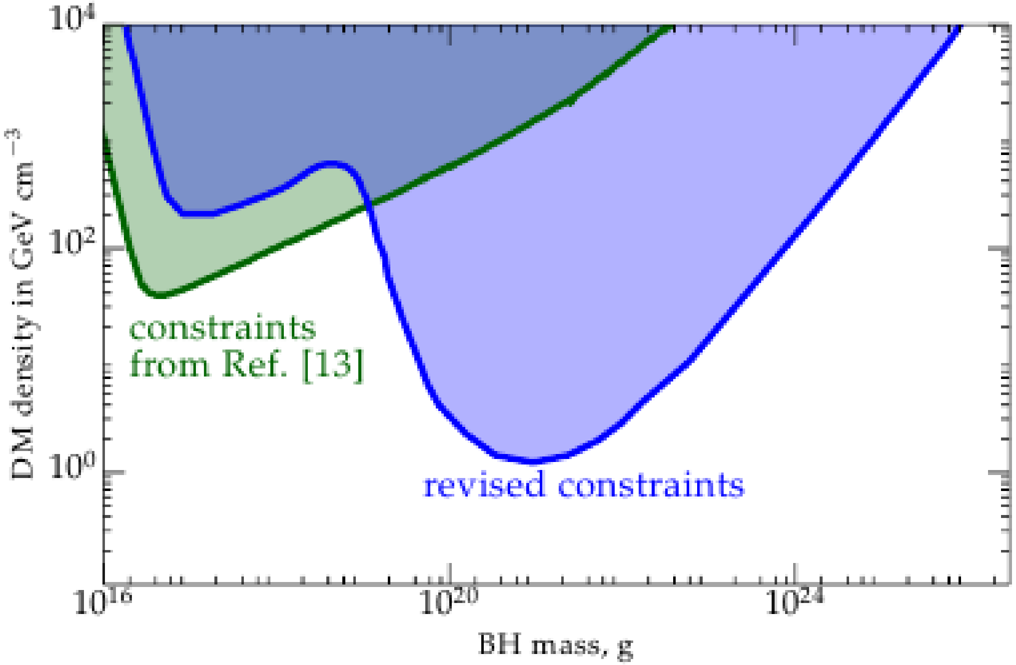


FIG. 2: Constraints on the abundance of PBHs assuming the DM velocity dispersion of 7 km/s. The constraints derived in Ref. 13 are in green, while the revised ones are in blue.

FC,MP&PT, 2014
(1403.7098)

PBH capture by NSs

- Idea is quite similar – if a NS could capture a PBH, then the latter one would rapidly sink down to the centre of a NS and after that quickly destroy it.

- NSs in GCs are about 10 billion years old and we adopt high DM density ~10^3 GeV/cm^3

- Again we would employ the dynamic friction—if a PBH could lose enough energy to become bound ($E_{tot}<0$), all the subsequent fly-throughs would quickly (~several million years) would bring a PBH to the center

- Direct accretion is not as effective as a drag force (~ 25% contribution)

F. Capela, MP &P. Tinyakov 2013b
(1301.4184,PRD 87 id. 123524)

PBH capture by NSs

$$\mathbf{f}_{\rm dyn} = -4\pi G^2 m_{\rm BH}^2 \rho \ln\Lambda \frac{\mathbf{v}}{v^3}$$

$$\boxed{E_{\rm loss} = \frac{3Gm_{\rm BH}^2 \ln\Lambda}{R}}$$

- During every subsequent passage, the PBH would lose the same amount of energy and gradually its orbit would shrink

$$\dot{\xi} = -\frac{1}{\tau}\frac{\xi^{3/2}}{\xi - 1}; \qquad \tau = \frac{\pi M R^{3/2}}{3m_{\rm BH}\sqrt{GM}\ln\Lambda} \simeq 6.1\times 10^5 {\rm s}\left(\frac{m_{\rm BH}}{10^{22}{\rm g}}\right)^{-1}$$

$$\boxed{t_{\rm loss} \simeq 1.8\times 10^3 {\rm yr}\left(\frac{m_{\rm BH}}{10^{22}{\rm g}}\right)^{-3/2}}$$

- Evolution time scale is comparable with the Universe age for PBHs with masses $3\text{x}10^{17}$ g

PBH capture by NSs

$$E_{\mathrm{loss}} = \frac{3Gm_{\mathrm{BH}}^2 \ln\Lambda}{R}$$

- Only PBHs with asymptotic energy less than E_{loss} could be captured

- Rate would be determined by the distribution parameters

- Maxwellian:

$$F_0 = 2\sqrt{6\pi}\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{BH}}}\frac{GMR}{\bar{v}}\left(1-\exp\left(-\frac{3E_{\mathrm{loss}}}{m_{\mathrm{BH}}\bar{v}^2}\right)\right)$$

$$F_0 = 6\sqrt{6\pi}\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{BH}}}\frac{GMR}{\bar{v}^3}\frac{E_{\mathrm{loss}}}{m_{\mathrm{BH}}}$$

PBH capture by NSs

- Coulomb logarithm value is crucial for the DF effect to play any role

$$\ln \Lambda = \ln \frac{b_{max}}{G_N M_{BH}} \approx \ln \frac{M_{star}}{M_{BH}}$$

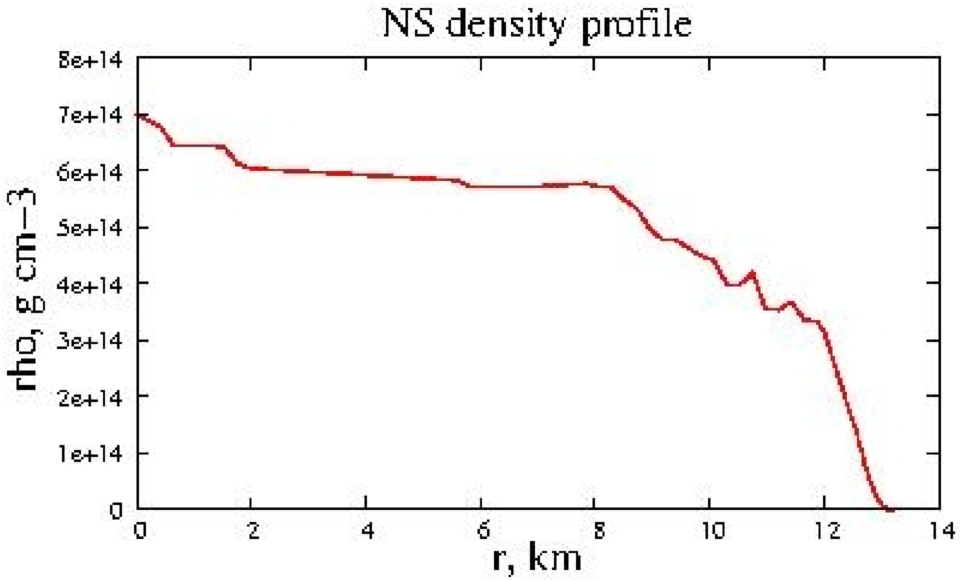
- Usual star: $\ln \Lambda \sim 30$

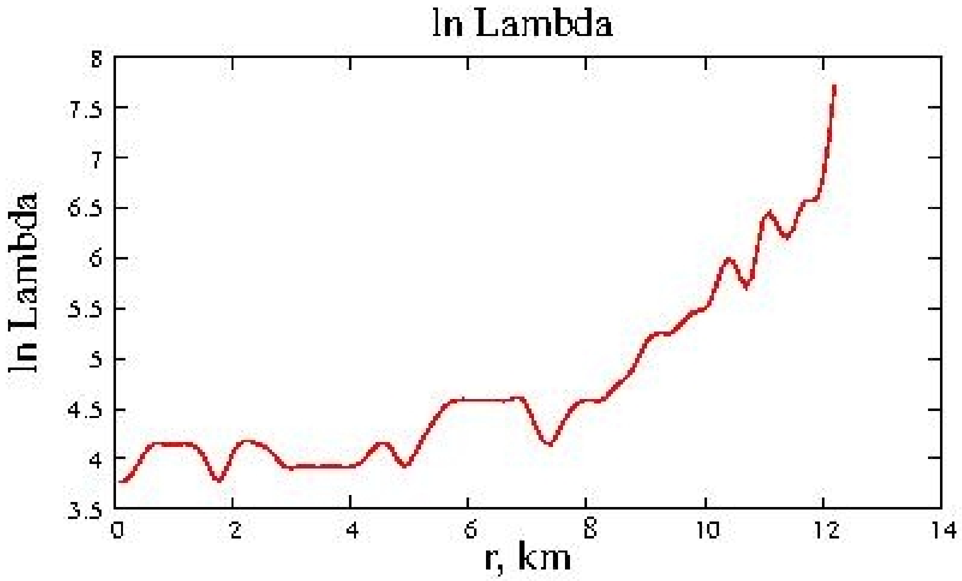
- When we are dealing with NS (degenerate matter) it's not so simple now—$b_{\text{max}} << R_{\text{star}}$. Impact parameter should be small enough in order to transfer more than Fermi momentum to the particles constituting NS

$$k_F(r) = \left(3\pi^2 \frac{\rho(r)}{m_n} \right)^{1/3}$$

PBH capture by NSs

- We used Belvedere et al' 12 model but results proved to be rather robust and model-independent

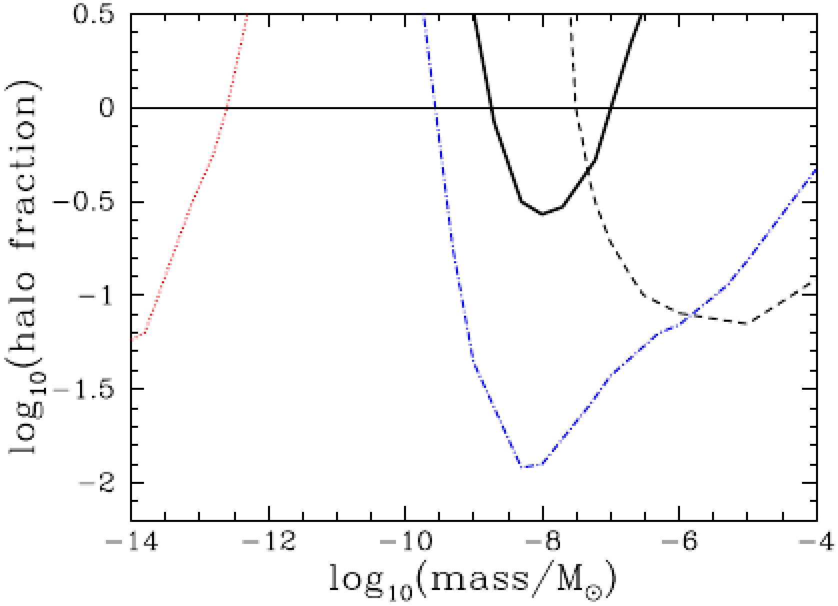




- Taking into account drag due to the direct accretion we finally got that in the degenerate case the effect is weaker in *k*=4.5 times.

Constraints from microlensing

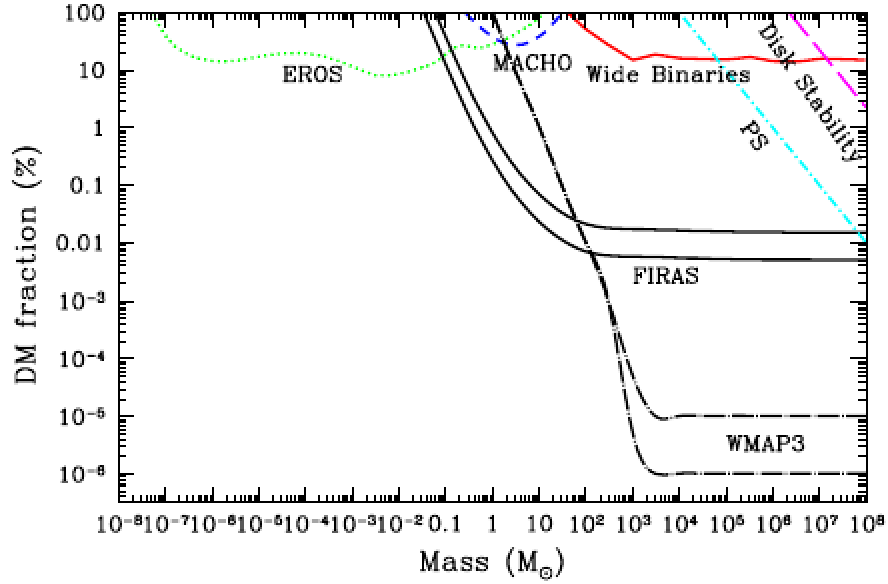
- For heavier PBHs more stringent constraints come from microlensing experiments (EROS, MACHO). e.g. Tisserand et al'07
- For masses 10^{26} g – 10^{33} g PBHs are excluded as a main contribution to the DM density (*f*<0.1)
- In Cieplak&Griest'13, Griest et al.'13 this analysis was performed using Kepler data, thus lowering limit down to 10^{24} g



from Griest et al.'13

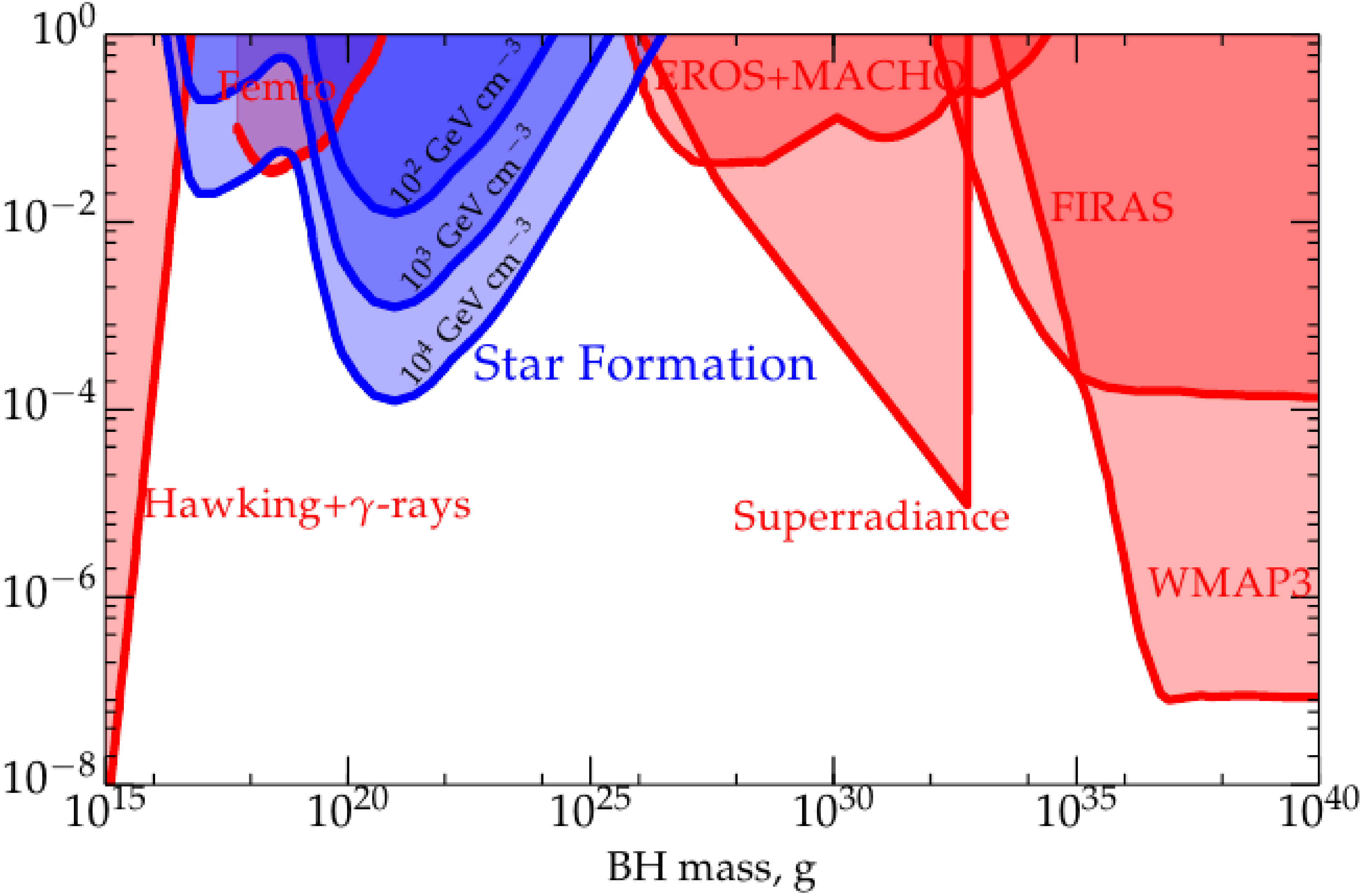
Still heavier PBHs

- > tens solar masses are excluded in the wide range by wide binaries survival (Yoo et al'04)
- Also there are strong constraints from reionization history (absence of early reionization) and CMB spectrum (no significant spectral deviations) 'Ricotti et al'08
- For very heavy PBHs (>millions of solar masses)--no GRB-echo (Nemiroff et al'93), no disk destruction (Lacey&Ostriker'85) and all that...



From Ricotti et al'08

Conclusions



THANK YOU!