Constraining PBH of asteroid masses from stars in dwarf galaxies

P. Tinyakov

ULB

N. Esser, PT, PRD 107 (2023) 10, 103052

Esser, De Rijcke, PT, MNRAS 529 (2024) 1, 32-40

Marseille, 13-15 Nov 2024

Primordial black holes

Zel'dovich, Novikov, Astronomy 10 (1967) 602

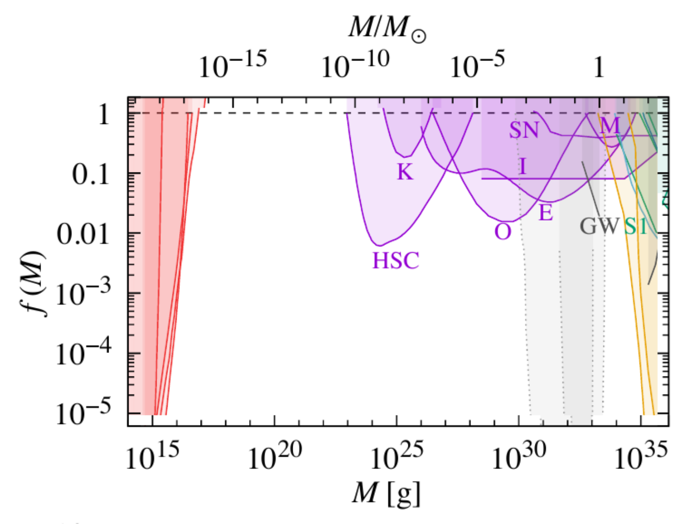
Hawking, MNRAS 152 (1971) 75

- BH may be produced in the early Universe in collapse of large matter fluctuations with masses ranging from M_{Pl} to tens of $M_\odot$
- The total PBH abundance may typically be tuned to match all or a fraction of the total DM
- $\Longrightarrow$ Attractive candidate for the DM as it requires no new stable particles
- May perhaps explain (some of) the LIGO-VIRGO merger events

Existing constraints

Key question: can all of the DM be in PBH?

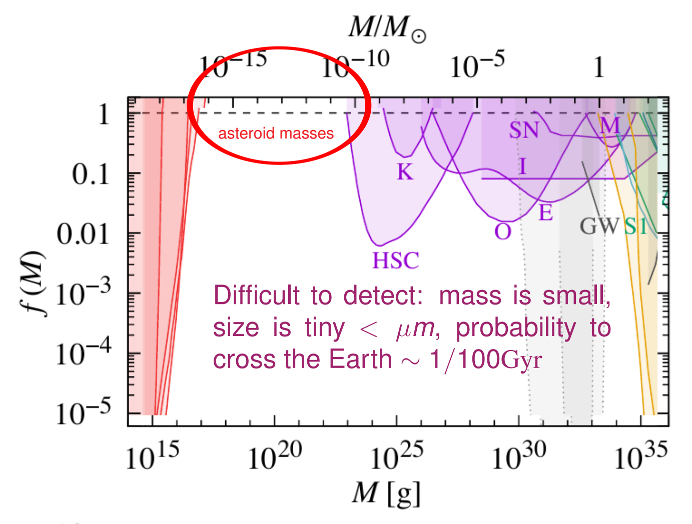
Fig. from: Carr, Rept.Prog.Phys. 84 (2021) 11



Existing constraints

Key question: can all of the DM be in PBH?

Fig. from: Carr, Rept.Prog.Phys. 84 (2021) 11



Difficult to detect: mass is small, size is tiny $< \mu m$, probability to cross the Earth $\sim 1/100\text{Gyr}$

Constraints from capture of PBH by stars?

- In this mass range PBH abundance may be constrained from their capture by stars
- If a PBH is captured by a star it accretes the matter and eventually destroys the star
  $\Longrightarrow$ A mere existence of stars may be used to constrain the PBH abundance.
- Previous studies concentrated on NS and WD because they capture PBH more easily.

  Capela, Pshirkov, PT, PRD87 (2013) 023507
  Capela, Pshirkov, PT, PRD87 (2013) 123524
  Capela, Pshirkov, PT, PRD90 (2014) 083507

  However, NS and WD themselves are much harder to observe.
- Here we focus on main sequence stars

Destruction of ordinary stars by PBH

How fast an ordinary star gets destroyed by a PBH?

- Assume Bondi accretion (spherically symmetric inflow of gas). The Bondi rate is

$$\dot{m}_{\rm BH} = \frac{4\pi\rho_* G^2 m_{\rm BH}^2}{c_s^3}$$

- Accretion time

$$t_{\rm acc} = \frac{c_s^3}{4\pi\rho_* G^2 m_{\rm BH}} = 5\times 10^6 {\rm yr}\left(\frac{10^{20}{\rm g}}{m_{\rm BH}}\right) \Longrightarrow {\rm OK}$$

- Note:
  - initial stages are the longest
  - Bondi radius $r_B = 2Gm/c_s^2 \sim 5\times 10^{-3}$ cm
    $\Longrightarrow$ gas approximation OK

Capture of PBH in stars

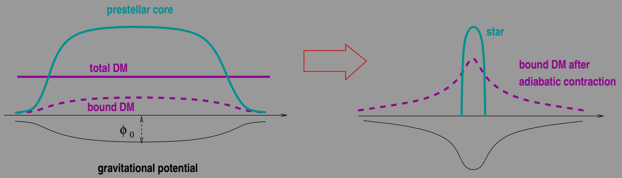
Basically, two different mechanisms:

- Capture during lifetime
  - only efficient for NS and WD
  - key quantity — energy loss by dynamical friction
- Capture at star formation
  - efficient for all stars
  - dominant in case of ordinary stars

Capture at star formation

Capela, Pshirkov, PT, PRD87.023507, PRD90.083507

- The stars are formed in the collapse of giant molecular clouds. These clouds have some DM (PBH) density gravitationally bound to them with $\rho_{\rm bound} \propto \rho_{\rm DM}/\sigma^3$.
- Collapsing baryons gravitationally drag the DM along



- After contraction some PBH end up inside the star, and even more settle on star-crossing orbits
- The latter gradually loose energy and finally get captured as well.

Simulation of capture

Esser, PT, PRD 107(2023)10, 103052 [arXiv:2207.07412]

Two stages:

A initial capture by adiabatic contraction
- simulated as in previous studies, except we accounted for the star density profile

B sinking into newly formed star
- time constraint
- constraint from perturbers

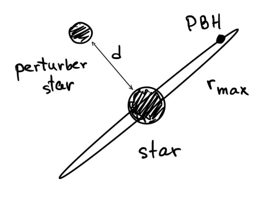
A. Adiabatic contraction

- Baryons are contracted from a uniform sphere of $R_c = 4300$AU to the actual star density profile
- PBH trajectories are simulated one by one in the baryon gravitational field. Those with apastron $< R_*$ are retained.
- The initial conditions of PBH uniformly sample the DM distribution. The sampled phase space:

$$r < 20 R_C, \quad v < v_{\rm esc} = \sqrt{3GM_\odot/R_C} = 0.79 \mathrm{km/s}$$

- The ambient DM distribution is assumed to be uniform in space with $\rho = 100 \mathrm{GeV/cm}^3$ and Maxwellian in velocity with dispersion $\sigma = 7$km/s (reference parameters typical of dwarf galaxies).

B. Sinking conditions



Each successful trajectory was checked for two extra conditions:

- *Cooling time.* Rough analytic estimate:

$$t_{\text{cool}} = \frac{\pi M_* R_*}{m_{\text{BH}} \ln \Lambda} \sqrt{\frac{r_{\text{max}}}{R_G}} \sim 10^{10}\text{yr} \sqrt{\frac{r_{\text{max}}}{100\text{AU}}} \frac{10^{20}\text{g}}{m_{\text{BH}}}$$

  Calculated numerically for each trajectory. Those with $t_{\text{cool}} > 10^{10}\text{yr}$ were discarded.

- *Perturbations* by nearby stars are not too big,

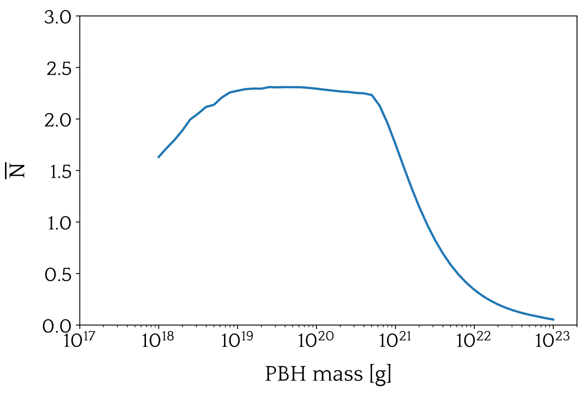
$$r_{\text{min}} = r_{\text{max}} \left(\frac{r_{\text{max}}}{d} \right)^6 < R_*,$$

  otherwise the trajectory was discarded.

Mean captured mass

From simulations:

- total DM mass in the sampled region of phase space
- fraction of successful (captured) trajectories $\Longrightarrow$ determine the mean captured number $\bar{N} = \bar{M}/m_{\rm BH}$
- Result for reference conditions, star of $1M_{\odot}$, all of DM is composed of PBH ($f = 1$):



Direct constraints

The probability to capture 0,1,2,.. PBH has the Poisson distribution with the mean $\bar{N} = f\bar{M}/m_{\rm BH}$, f being the PBH abundance. In an ensemble of stars, the fraction ξ of destroyed stars is therefore

$$\xi = 1 - \exp(-f\bar{M}/m_{\rm BH})$$

Requiring that no more than given fraction ξ of stars is destroyed gives the constraint on the PBH fraction f in DM

$$f < \frac{m_{\rm BH}}{\bar{M}} \ln \frac{1}{1-\xi}$$

The max allowed fraction ξ has to come from observations. The smaller ξ, the stronger the constraints.

Some observed dwarf galaxies

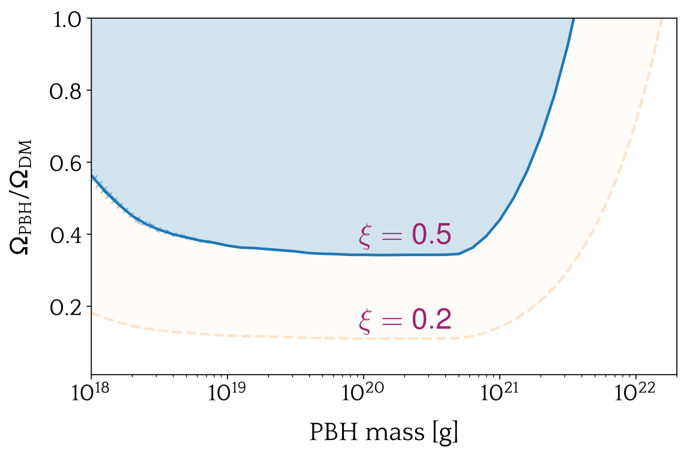
	$R_{1/2}$ [pc]	σ [km/s]	$\rho_{\rm DM}$ [GeV/cm^3]	n_* [10^{-3}pc^{-3}]	η
Triangulum II	16	< 5.9	161	9.2	0.95
Tucana III	37	< 2.1	3.7	0.67	0.51
Draco II	19	< 10.2	343	2.6	0.39
Segue 1	24	6.4	85	2.1	0.39
Grus I	28	5.0	38	9.6	0.37

Here the merit factor

$$\eta = \frac{\rho_{\rm DM}}{100{\rm GeV/cm^3}} \left(\frac{7{\rm km/s}}{\sqrt{2}\sigma} \right)^3$$

shows how the concrete galaxy is doing with respect to our reference values $\rho = 100{\rm GeV/cm^3}$ and $\sigma = 7{\rm km/s}$.

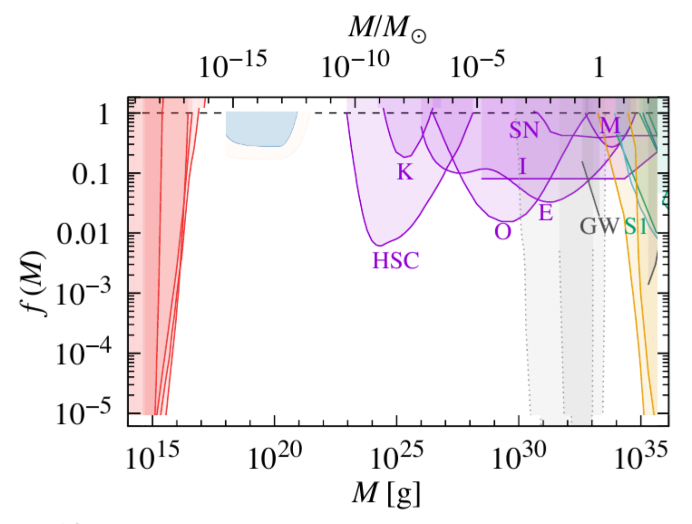
Would-be constraints from Triangulum II



Constraining PBH of asteroid masses from stars in dwarf galaxies

P. Tinyakov

Would-be constraints from Triangulum II

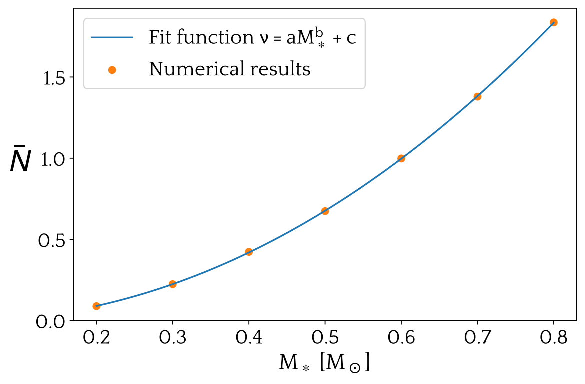


STATISTICAL APPROACH

De Rijcke, Esser, PT, MNRAS 529(2024)32

- The fraction ξ of destroyed stars is difficult to know experimentally $\Longrightarrow$ a better observable is needed
- In many dwarf galaxies the star distribution in masses is (a) measured and (b) quantitatively modeled
- Key point: the probability of PBH capture depends on the star mass $\Longrightarrow$ the presence of PBH alters the star mass function.
  This may be used to constrain the abundance of PBH

Mean PBH captured number $\bar{N}$ as a function of the star mass, for $m_{\rm BH} \sim 10^{20}$g:



$\Longrightarrow$ PBHs preferentially destroy heavier stars

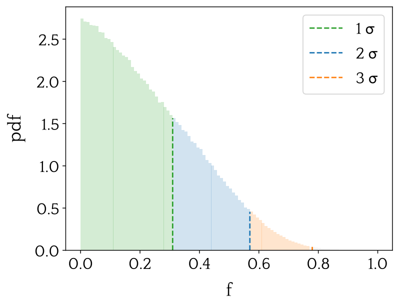
Is this approach sensitive enough?

Esser, De Rijcke, PT, MNRAS 529 (2024) 1, 32-40

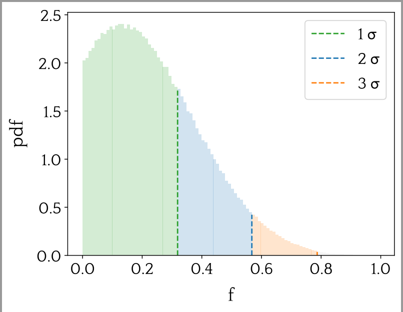
Make a numerical experiment:

- Generate a sample of stars that resembles the one observed in a typical dwarf galaxy: 1000 stars with masses $(0.2 - 0.8)M_\odot$ distributed as observed ones. Pretend this is the real data.
- Take a model star mass function typically used in UFD population studies: broken power law or log-normal distribution. Add the modifications due to the destruction of stars by PBH, with the PBH fraction f a free parameter
- Run the Bayesian analysis to see how well the fraction f can be constrained from these "data".

Probability distribution marginalized over all parameters except f:



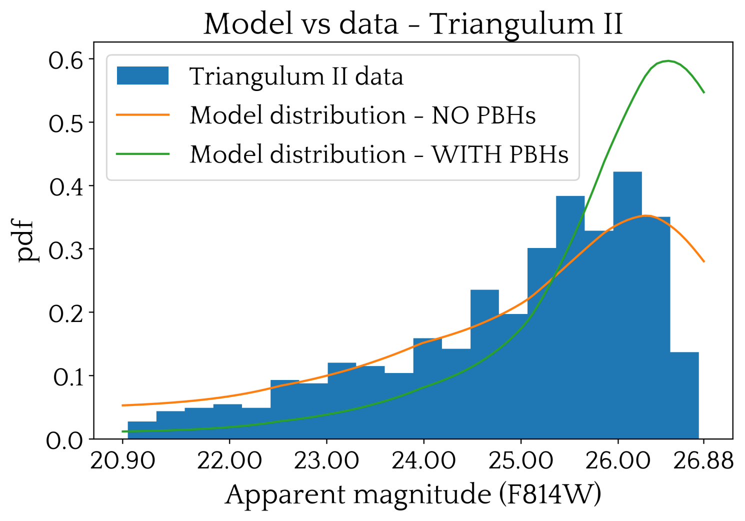
broken power law



log-normal

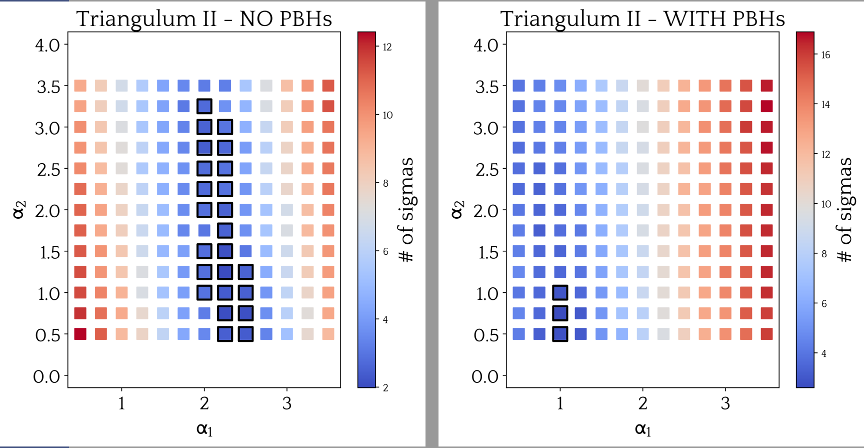
$\Longrightarrow$ Looks promising!

Applying to real data: Triangulum II



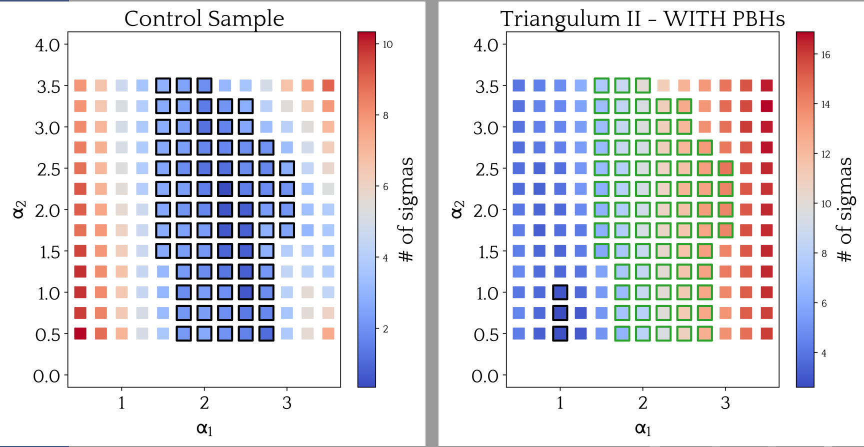
Preliminary results

- Model: broken power law with slopes α_1 and α_2; PBH fraction either $f = 1$ of $f = 0$.
- KS test of mass distributions: model vs. data



Control sample strategy

- There is data for several UFDs: Segue I, Triangulum II, Bootes I, Reticulum II and Ursa Major II (last 3 have small merit factor)
- $\Longrightarrow$ map out allowed region of parameters



Summary

- Constraints form capture of PBH in stars fall right in the unconstrained mass range
- Measurement of stellar mass function in many dwarf galaxies (already existing for several of them) may be sufficient to firmly exclude $f = 1$ in some range of PBH masses.
- Quantitative analysis is in progress!