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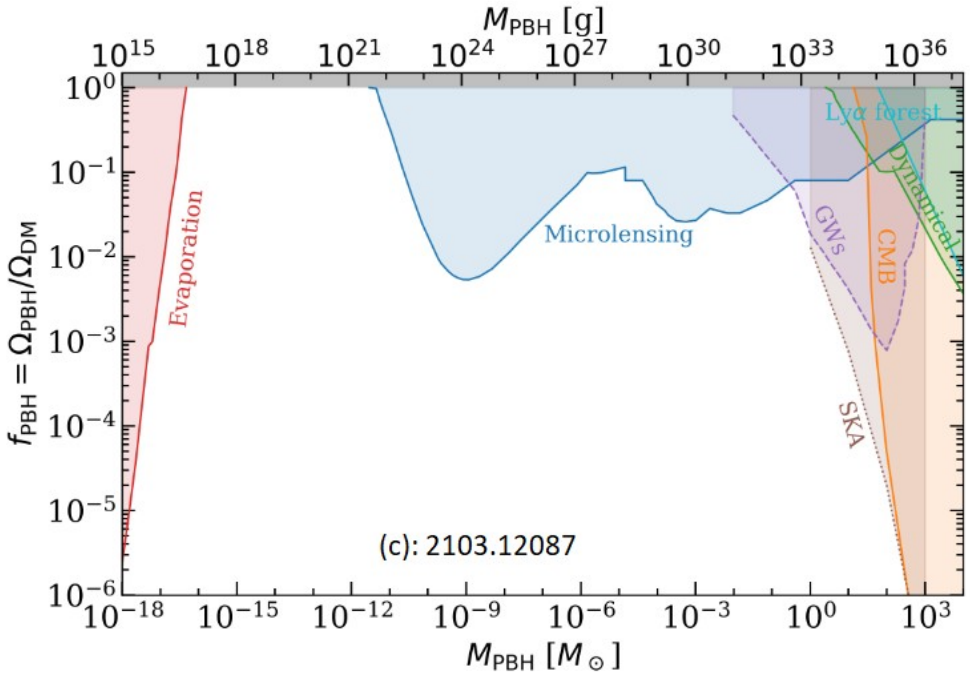
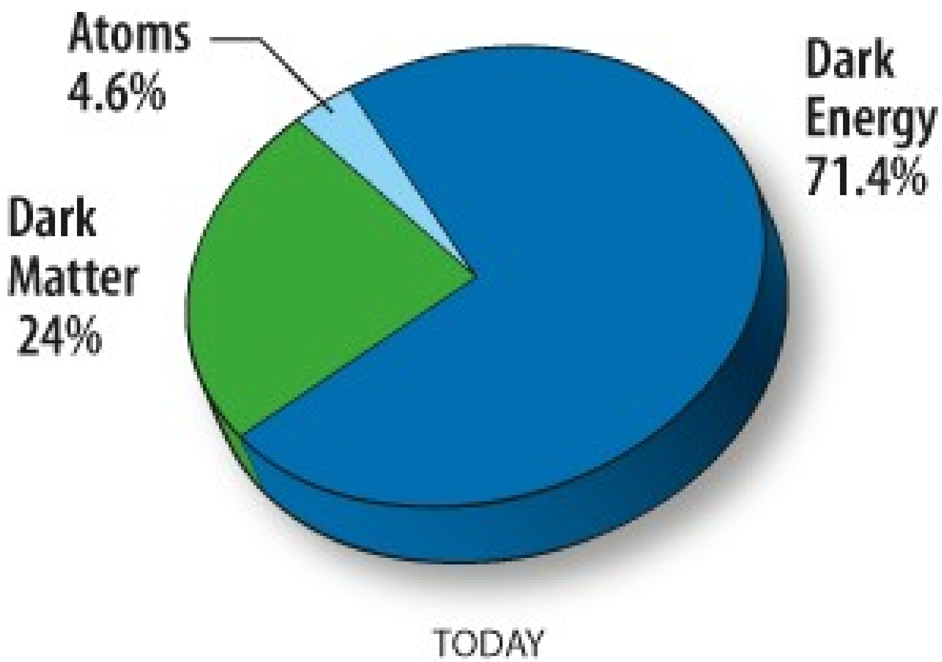


Search for primordial black hole dark matter with x-ray spectroscopic and imaging satellite experiments and prospects for future satellite missions

D. Malyshev, E. Moulin, A. Santangelo

Friedrich-Alexander-Universität Erlangen-Nürnberg, November 16th 2023

Dark Matter – Introduction

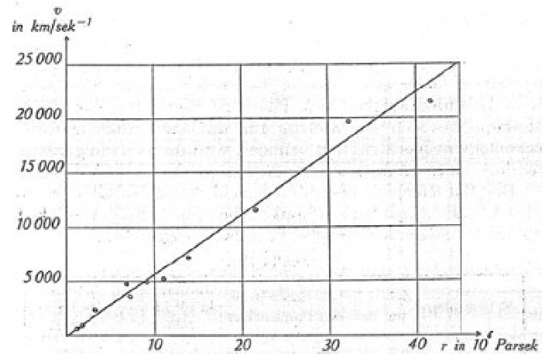


The «standard» particle-DM talk outline:

- The Universe is dark:
  - dark energy
  - dark matter
  - SM particles make just a tiny fraction (~5%)

– How do we know this?

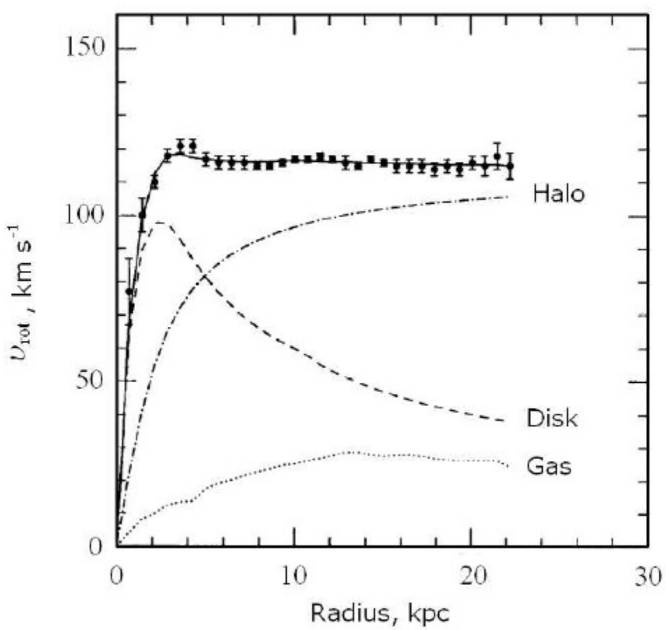
Dark Matter – Introduction



Apparent velocities in the Coma cluster

$v =$	8500 km/s	6900 km/s
	7900	6700
	7600	6600
	7000	5100 (?)

Helv. Phys. Acta **6** (1933) 110-127



– The number of evidences at ***different*** scales:
  - – *rotational curves* of the galaxies (DM)
  - – high *velocity dispersion* in galaxy clusters (DM)
  - – *temperature profiles* in galaxy clusters (DM)
  - – *Bullet cluster* (DM)
  - – *supernovae* observation (DE)
  - – *LSS*, Ly-alpha forest (DM + DE)
  - – *CMB* (DM + DE)

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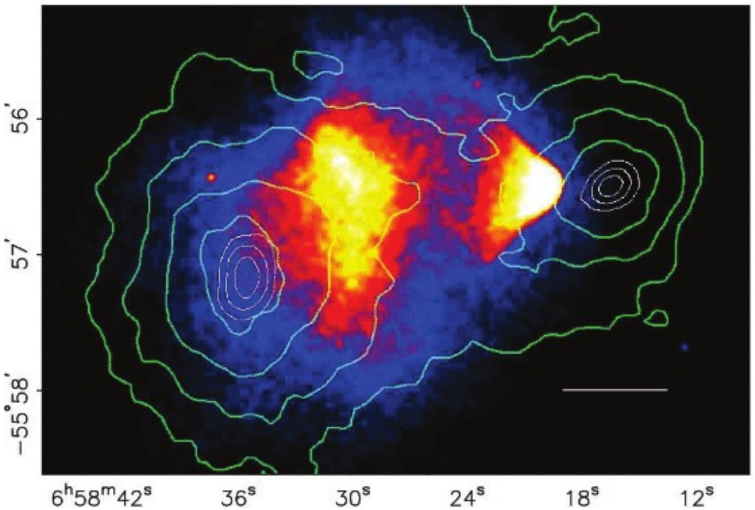

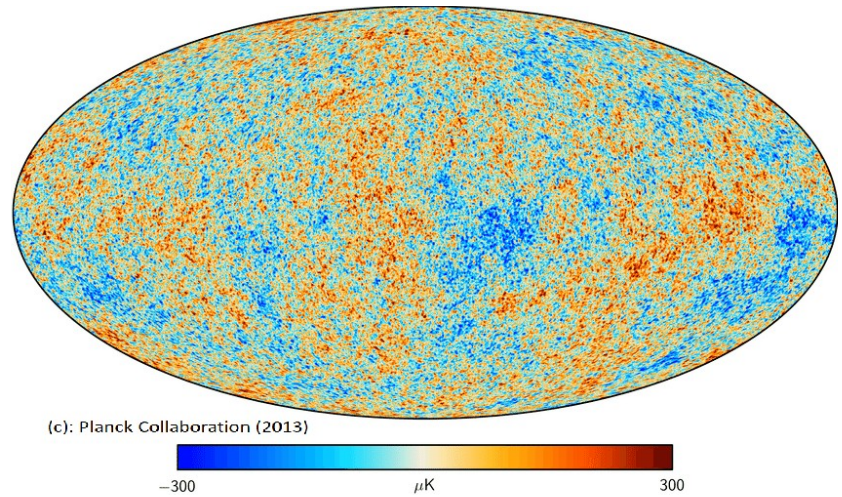

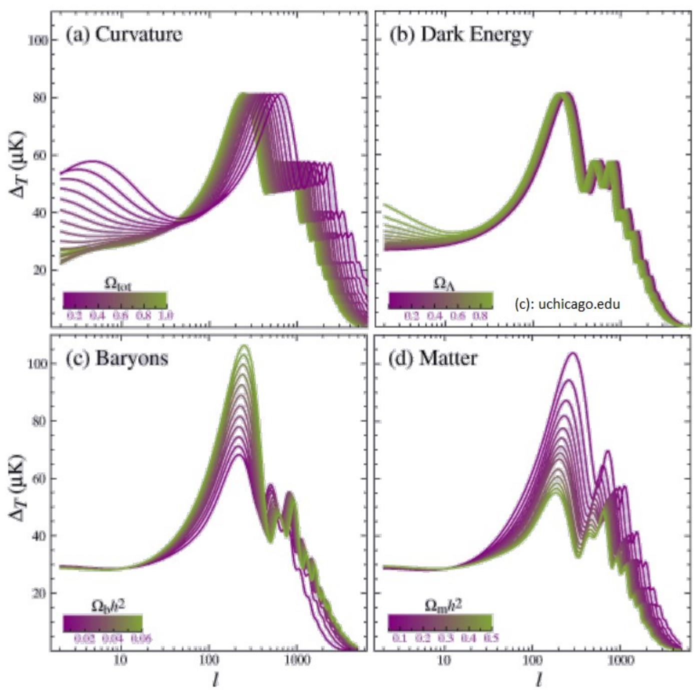

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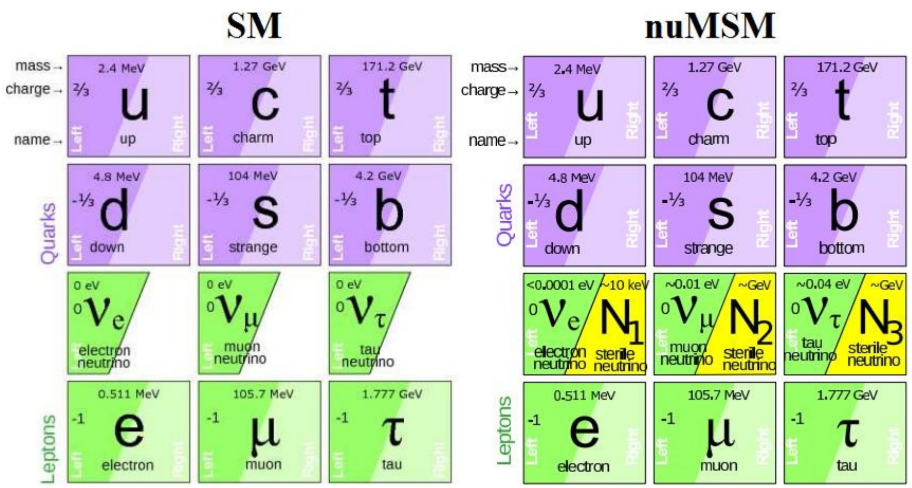

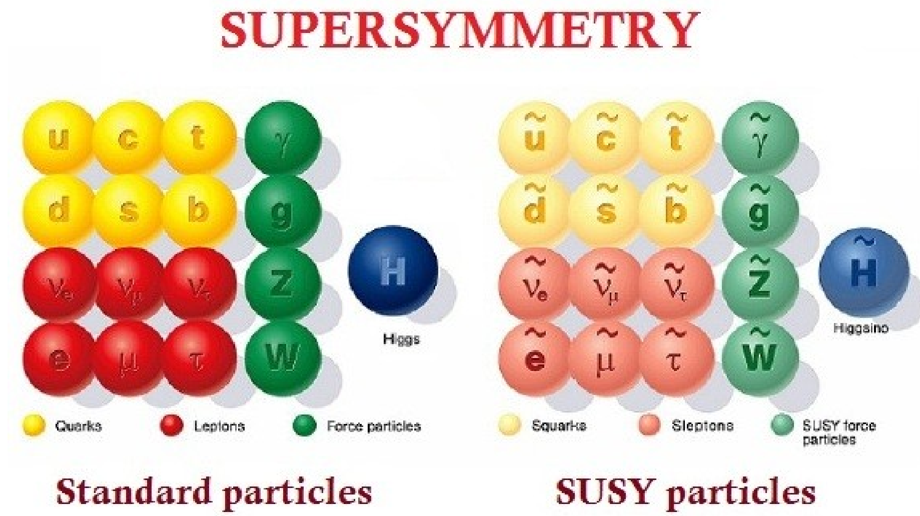

***Good dark matter candidate*:**

- *formed* in the *early* Universe (well before CMB, cold well before CMB)
- can *survive* cosmological times
- at most *weakly* (only gravitationally?) *interacts* with the normal matter
- *non-baryonic*
  - too few stars/hot gas
  - BBN limits on cold gas/baryonic DM (too few D, ^{3}He, ^{4}He, ^{7}Li)
- *non-SM*
  - SM hosts no stable, massive, un-charged particles
    - note: hexaquark-like particles still discussed (arXiv: 2201.01334)

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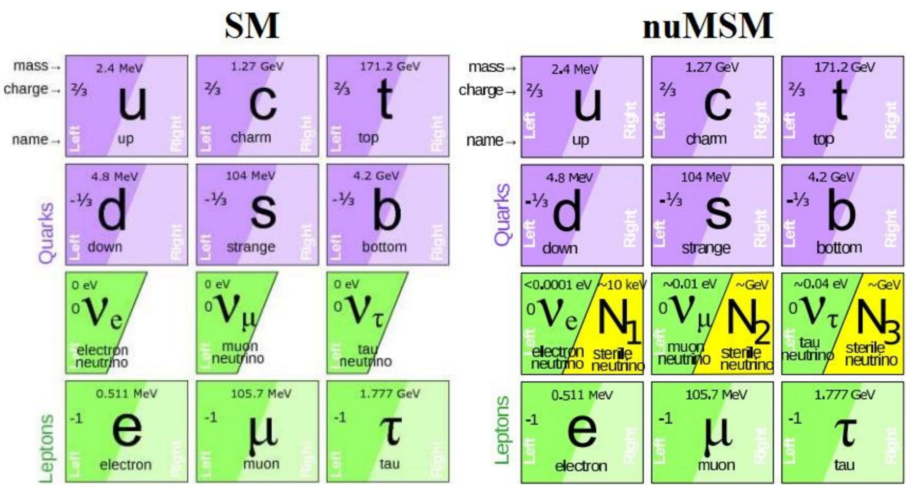

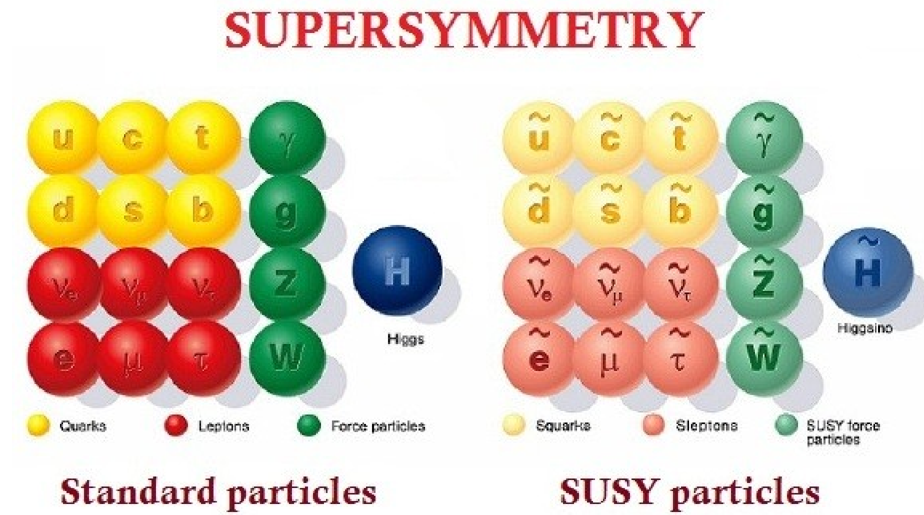

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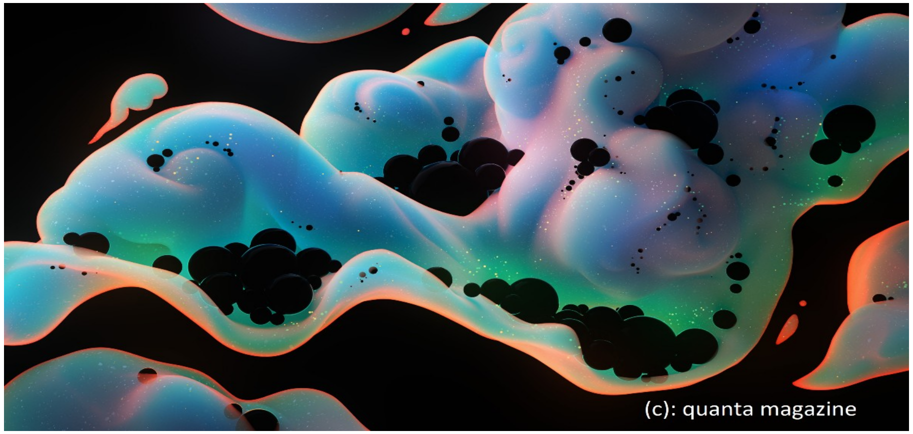
Dedicated *microlensing surveys* excluded *PBH* DM.
New physics is needed to explain DM! *Or not?*

Black holes and Dark Matter



NOT ALL PBHs are ***excluded*** by microlensing surveys!

– ***Primordial*** black holes are ***good*** DM candidates:
- – formed in the early Universe (well before CMB)
- – non-baryonic (interacts only gravitationally)
- – no SM interactions (*in some sense*)
- – can survive (*under some conditions*) and be present in nowadays galaxies/clusters

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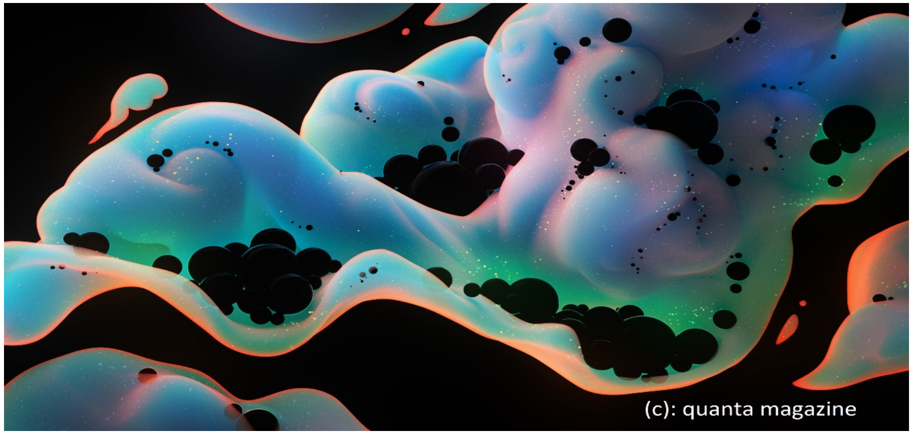

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– “***Normal***” black holes are ***bad*** DM candidates:
  – *recently* formed from massive stars or *BH collisions*

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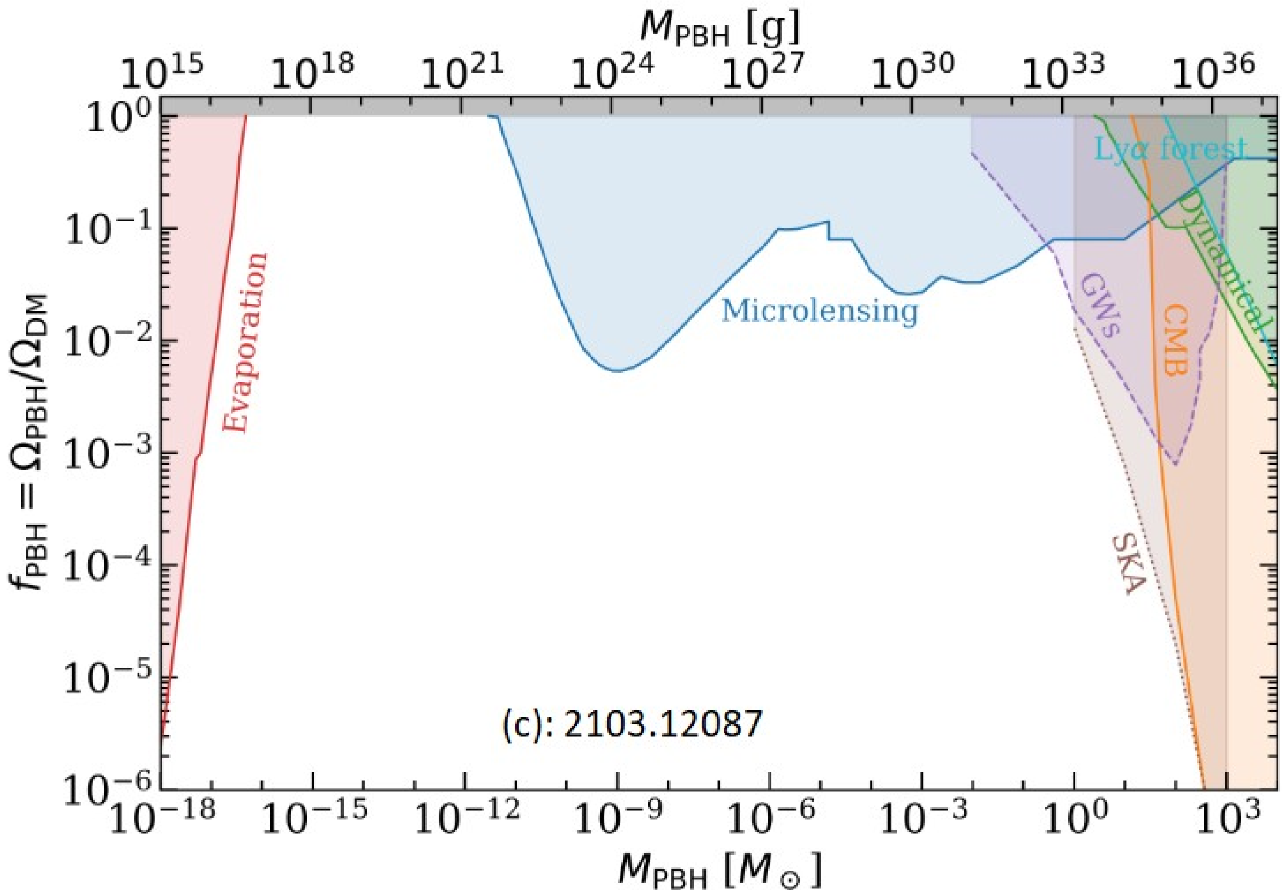
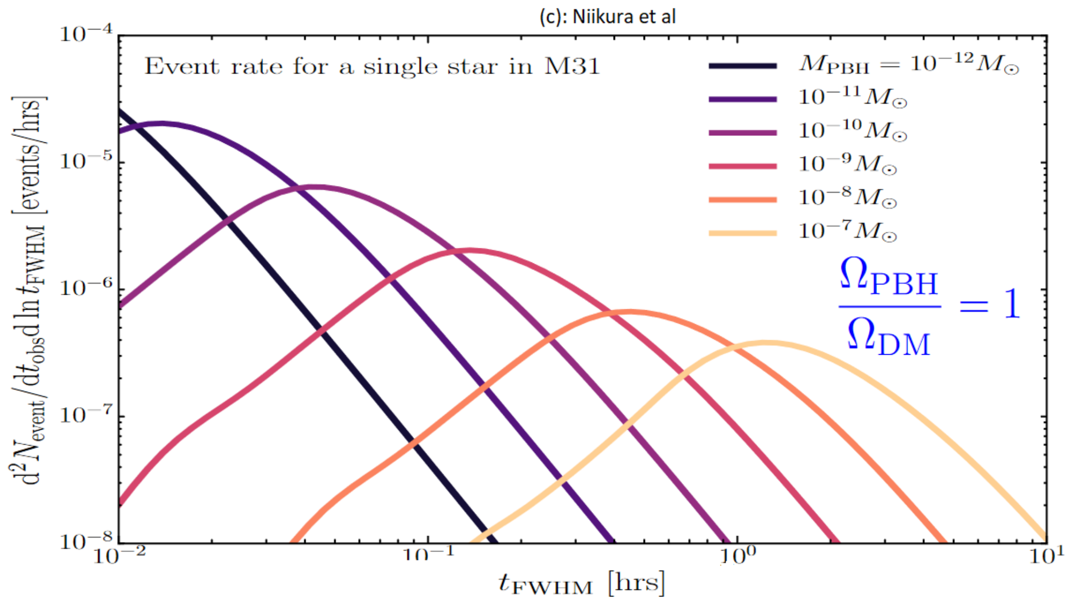
Black holes and Dark Matter

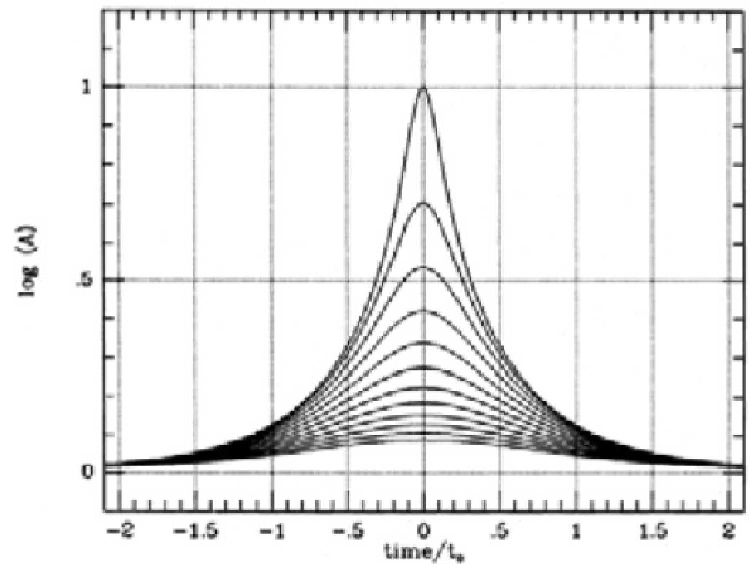


Not all PBHs are excluded by microlensing surveys!

But why?

Black holes and MicroLensing





Gravitational microlensing – increase of the brightness of the background star as relatively light object passes in front of it

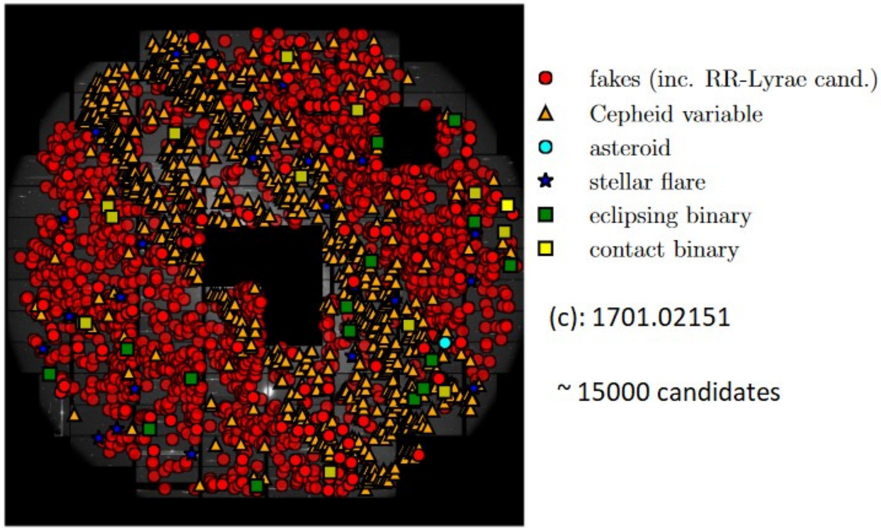
Microlensing magnification amplitude and time scale:

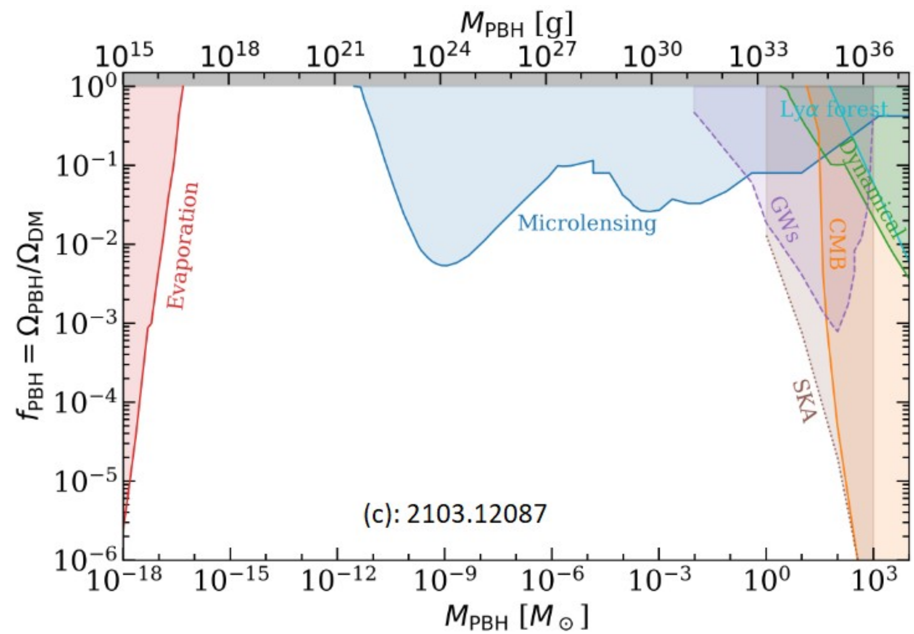
$$A(t) = \frac{u^2+2}{u\sqrt{u^2+4}}, \qquad u(t) = \sqrt{\beta^2 + \frac{(t-t_0)^2}{t_E^2}}. \qquad t_E \equiv \frac{R_E}{v} = \frac{\sqrt{4GMd_l d_{ls}/d_s}}{cv},$$

$$t_E \simeq 44 \text{ days} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{d_l d_{ls}/d_s}{4 \text{ kpc}}\right)^{1/2} \left(\frac{v}{220 \text{ km/s}}\right)^{-1}$$

The characteristic time of such event becomes too short and can be confused with the conventional variability for low mass PBHs. The times become too long for high-mass Bhs. The number of events drops strongly for high-mass Bhs

Black holes and MicroLensing





Several dedicated experiments:

– ***MACHO*** (***Ma***ssive ***C***ompact ***H***alo ***O***bjects) ~1993
– LMC observations

– ***EROS*** (***E***xpérience pour la ***R***echerche d'***O***bjets ***S***ombres) ~1990 – 2003
– LMC observations (*https://arxiv.org/abs/astro-ph/0607207)*

– ***OGLE*** (***O***ptical ***G***ravitational ***L***ensing ***E***xperiment) ~1992 – *present*
– LMC + *Galactic Bulge (https://arxiv.org/abs/1901.07120)*

– *Subaru/HSC ~2017*
– *6 hours of M31 observations (https://arxiv.org/abs/1701.02151)*

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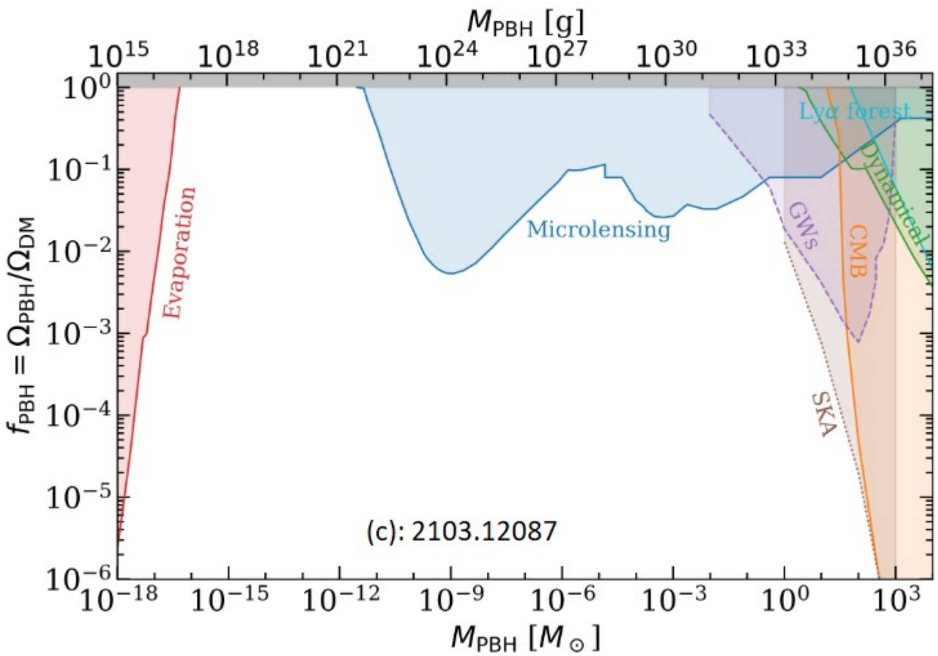
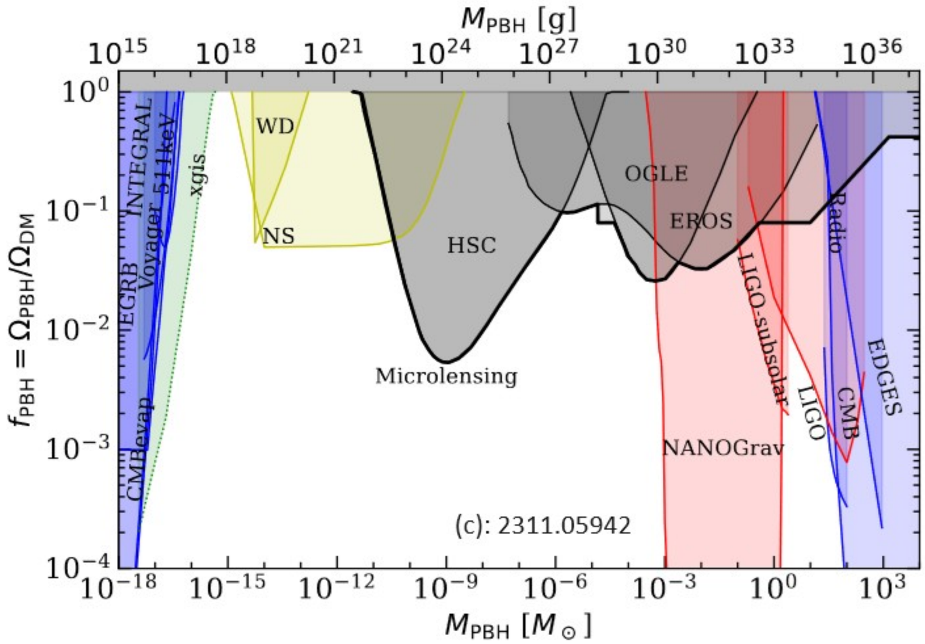
Black holes: Constraints



Other constraints:
- *Low masses* (< 10^{15}g)
  - temperature T~1/M
  - *evaporate* on timescales shorter than the age of the Universe
  - before evaporation can create a *burst* of VHE emission (detectable by e.g. HESS)

- *Heavy* black holes (> 100 Msun)
  - can *accrete* a lot of matter and produce visible effects on *CMB* (see e.g. arXiv:1612.05644)

Black holes: Constraints



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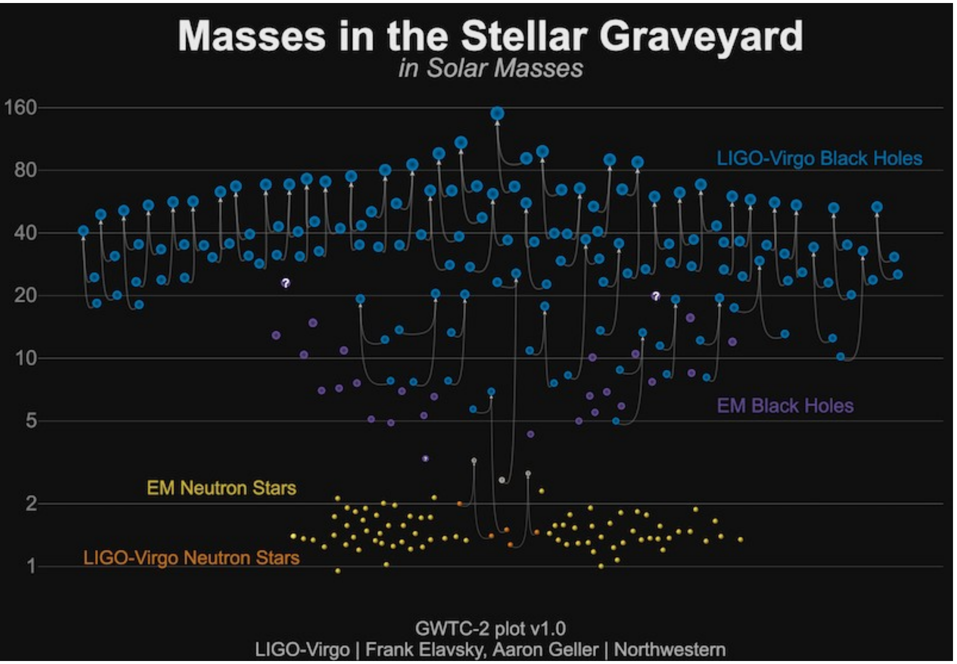
"Dynamical constraints":

- DM BH *accrete* gas or stars as travels through galaxy/globular cluster
- *Destruction* of NS or WD explosion as supernova (arXiv:1301.4984, 105.04444)

– *Dynamical constraints are strongly model-dependent and debated in the recent literature!*

Black holes and Gravitational Waves



2015 – 1st ever observation of merging BHs by LIGO/VIRGO

~90 events detected in total today (GWTC-3)

Majority of the events are BHs of ~20 Msun mass

Unexpectedly high masses! Did LIGO detect Primordial black holes?

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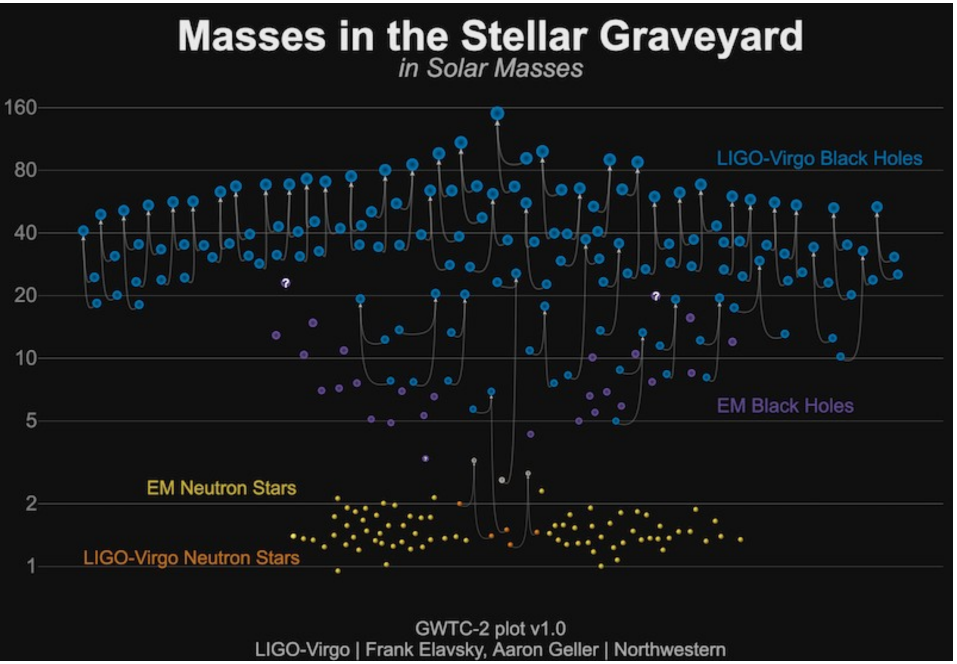

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https://arxiv.org/abs/1603.00464 – "Did LIGO detected dark matter?"

If primordial BHs forms binaries – much more events should be seen by LIGO/VIRGO

https://arxiv.org/abs/1603.08338 ; https://arxiv.org/abs/1709.06576 ; https://arxiv.org/abs/1709.09007

https://arxiv.org/pdf/2008.10743.pdf – "Eliminating the LIGO bounds on primordial black hole dark matter"

Did LIGO detected dark matter in form of ~20 Msun BHs? *Probably not*, but too early for firm conclusions!

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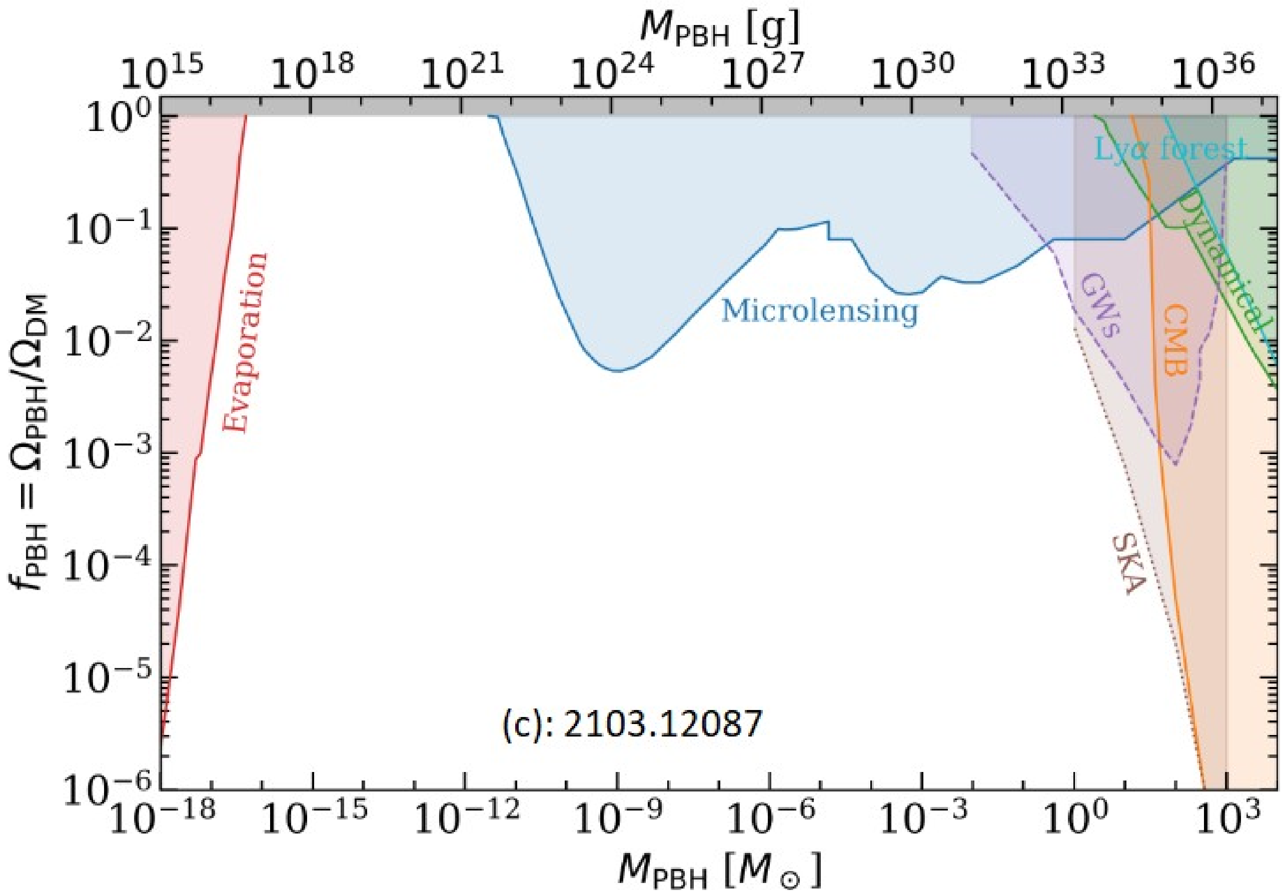
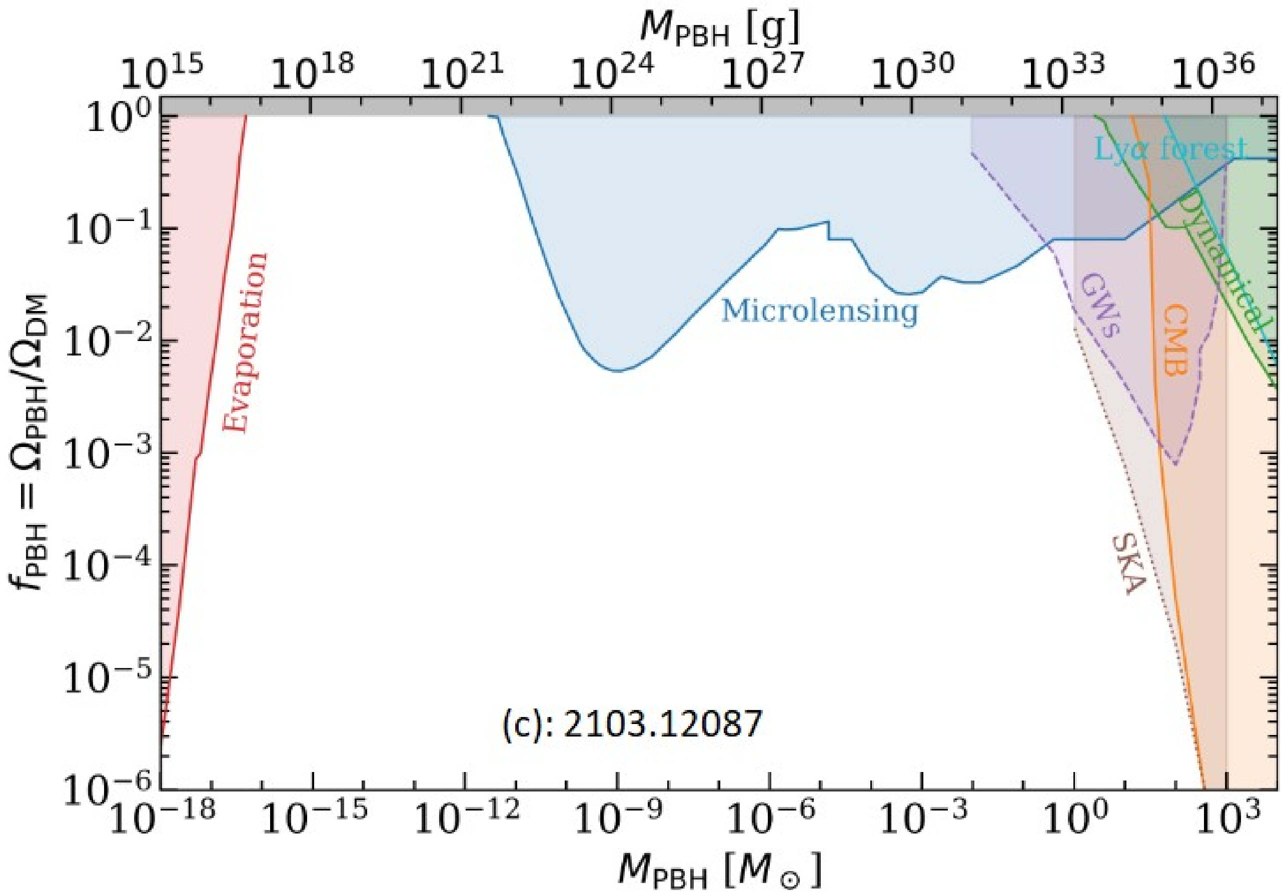
Black holes and Dark Matter



Modern (robust) constraints on fraction of primordial BHs which can make DM

Note: Femtolensing constraints (diffraction-like pattern can appear in keV-spectrum of GRBs if M_{pbh}~10^{20}g, see Gould, 1992ApJ) were strongly questioned (see Katz, 2018JCAP) and are not considered currently to be solid.

Black holes and Dark Matter



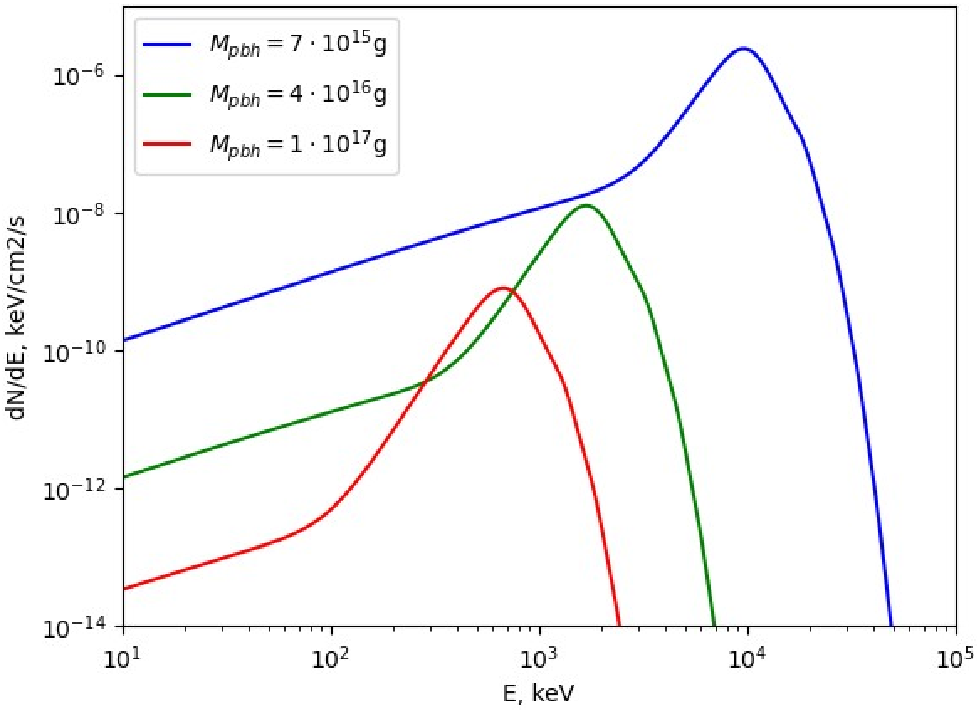
Modern (robust) constraints on fraction of primordial BHs which can make DM

The PBHs with masses 10^{16} – 10^{21}g are poorly constraint and can make all dark matter

Black holes and Dark Matter

The PBHs with masses 10^{16} – 10^{21}g are poorly constraint and can make all dark matter.

Is there any chance to constrain this mass range as well?



Peculiar fact:

– Hawking temperature of such black holes is in keV-MeV range:

$$T_H \sim (10^{16}g / M_{pbh}) , MeV$$

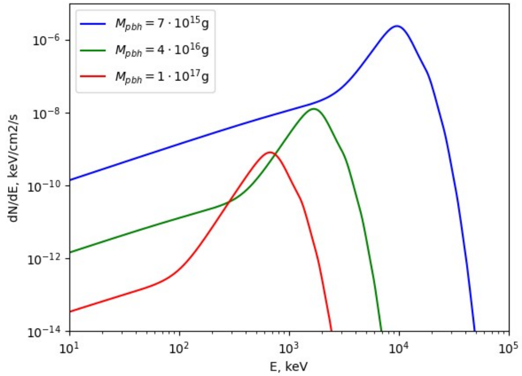
– X-rays observations could be used to find such PBHs!

– potential problem: the strength of the signal drops quickly with the increasing PBH mass

Black holes and Dark Matter

INTEGRAL [ESA]

XMM-Newton [ESA]



Evaporating PBHs ressemble standard decaying DM:

$$\frac{d^2 N_{\rm k}}{dE_{\rm k} dt} = \frac{1}{2\pi} \frac{\Gamma_{\rm k}(E_{\rm k}, M_{\rm BH}, m)}{e^{E_{\rm k}/T_{\rm BH}} - (-1)^{2s}} \, .$$

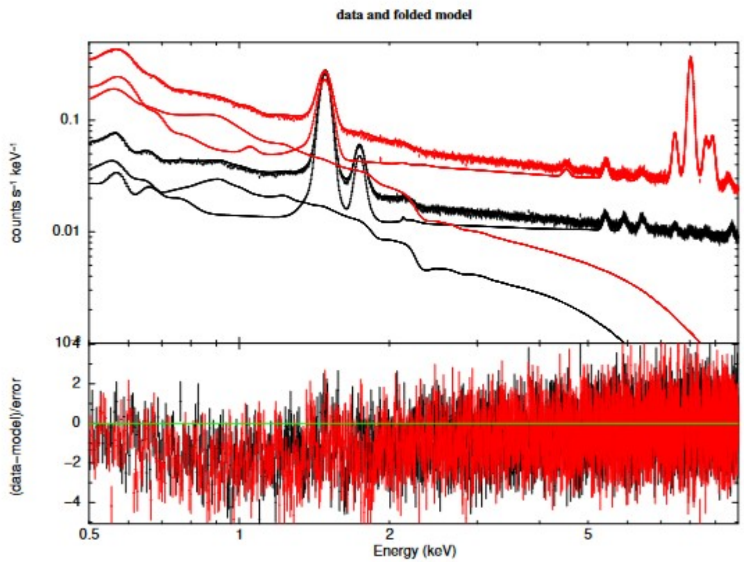
$$\frac{d^2\Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\rm LOS} ds \frac{f_{\rm pbh}\, \rho_{\rm DM}(r(s,d,\theta))}{M_{\rm pbh}} \frac{d^2 N_\gamma}{dE_\gamma dt}$$

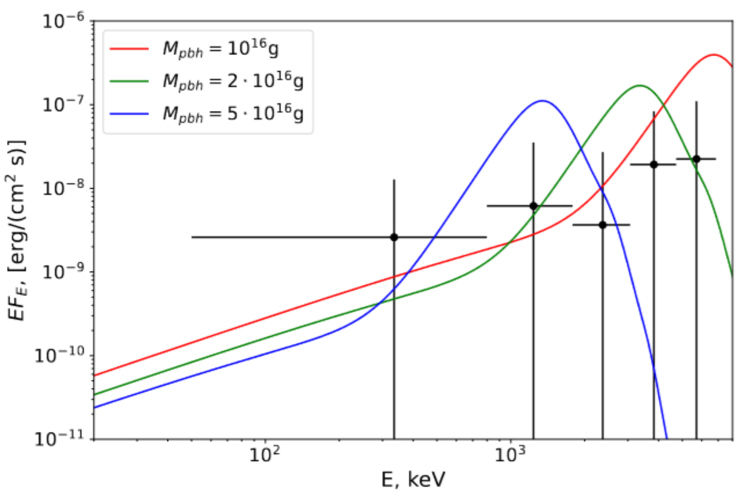
$$D(\Delta\Omega) = \int_{\Delta\Omega} \int_{\rm LOS} \rho_{\rm DM}(r(s,d,\theta))\, ds\, d\Omega.$$

Evaporating PBHs ressemble standard decaying DM:

– the strength ~ D-factor; the spectrum is hard in keV-MeV bands
– best targets – dSphs, GC, clusters...

PBH Dark Matter searches in X-rays





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Malyshev, Moulin, Santangelo, 2022PhRvD:

– used X-ray observations of Draco dSph with XMM-Newton (1 – 10 keV)

– used hard X-ray observations of MW with INTEGRAL/SPI (0.1 – 8 MeV)

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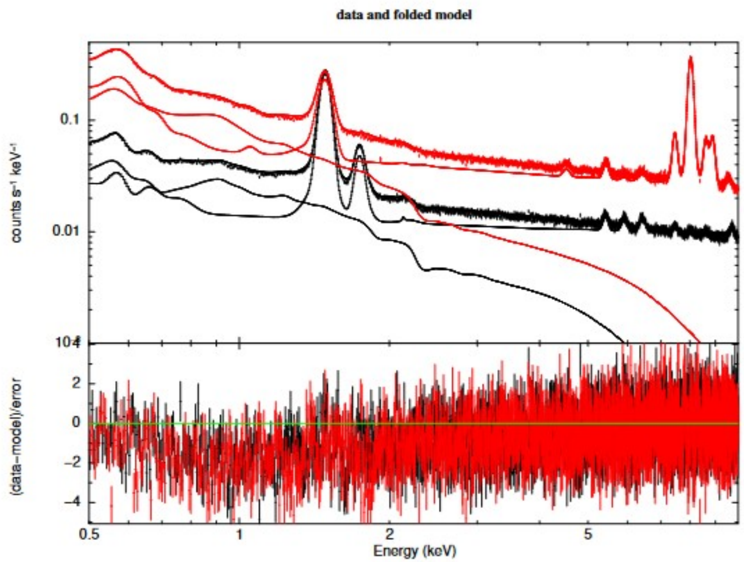

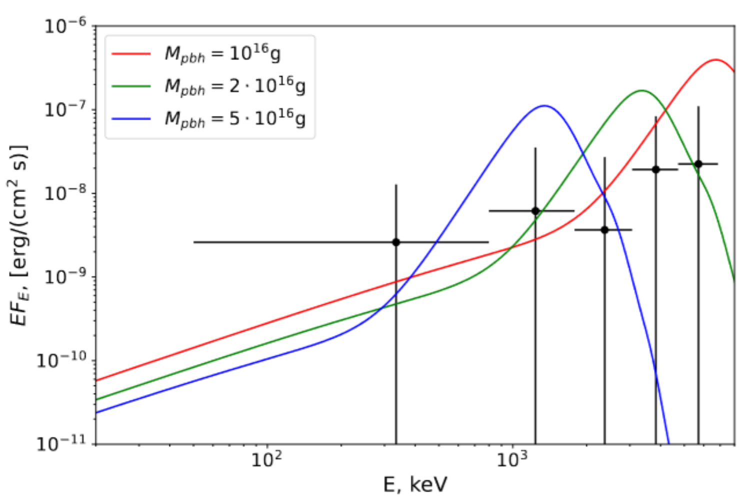

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Aiming to detect a ***Hawking*** radiation signal from PBHs assuming that they make majority of DM in these objects.

Non-detection of such a signal allowed us to put ***constraints*** on a fraction of DM that can consist of PBH (f_{pbh}).

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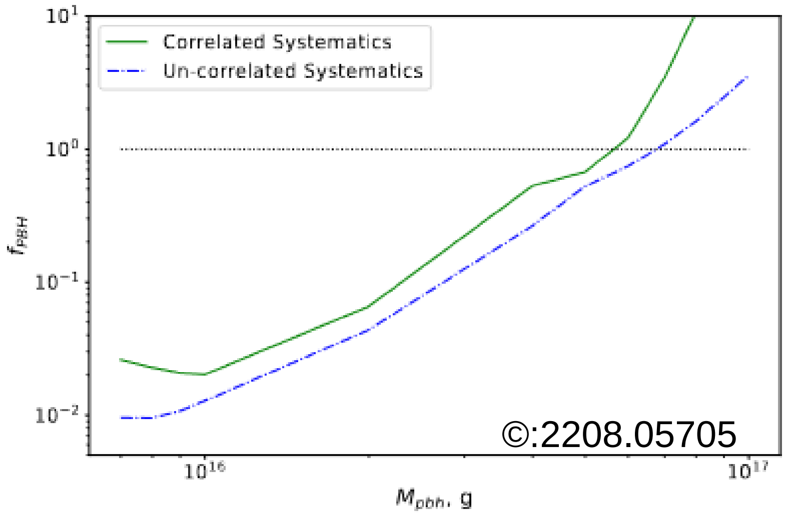

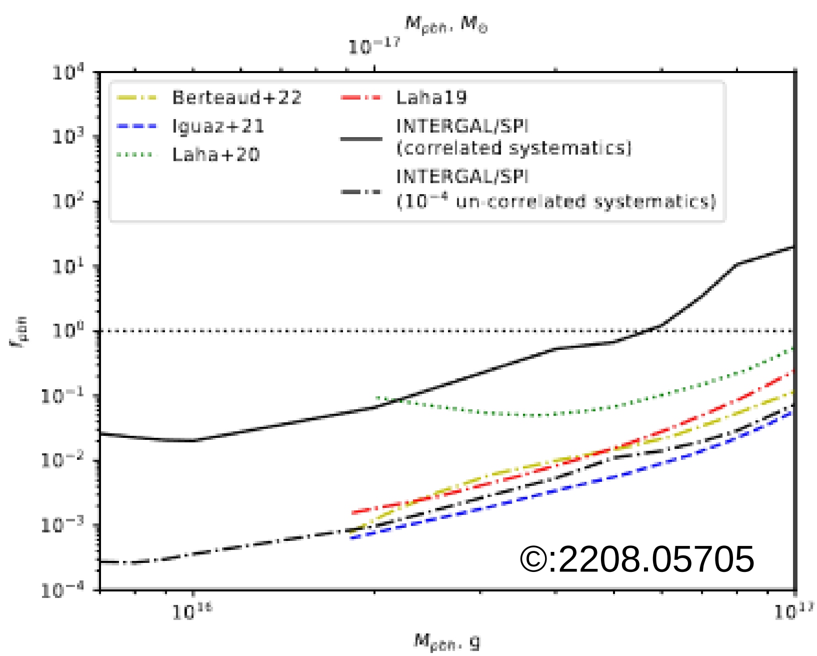

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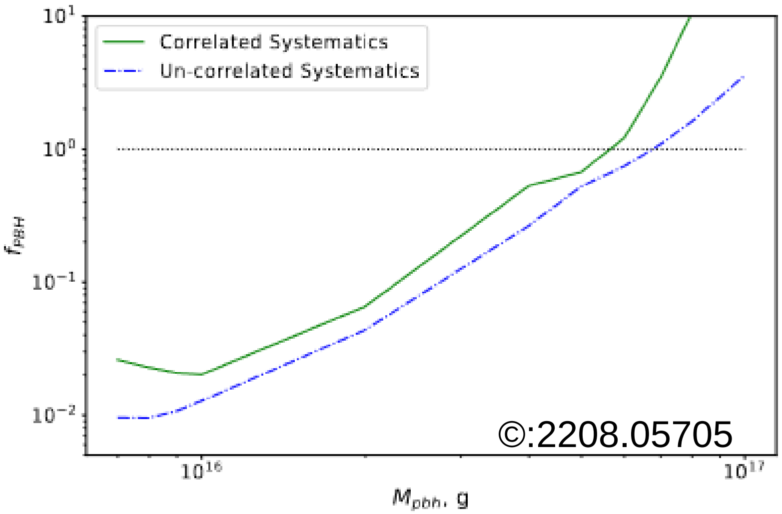

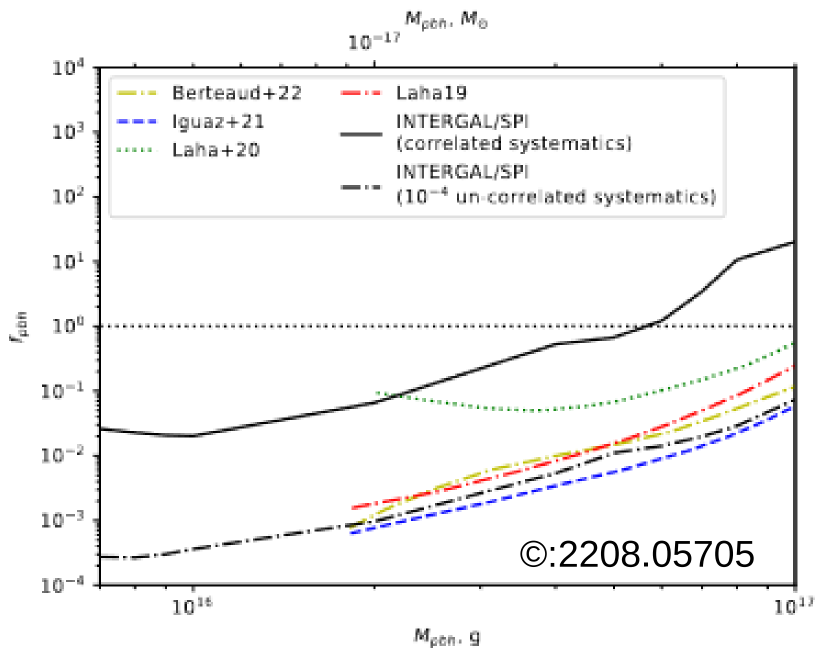

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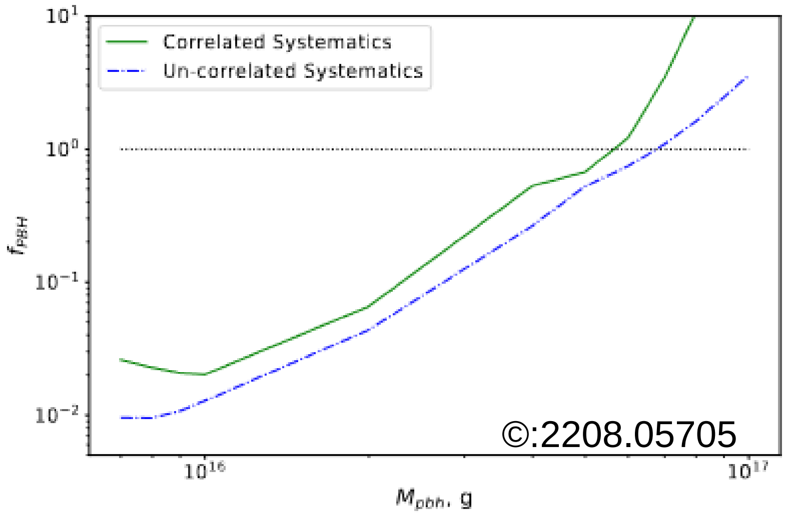
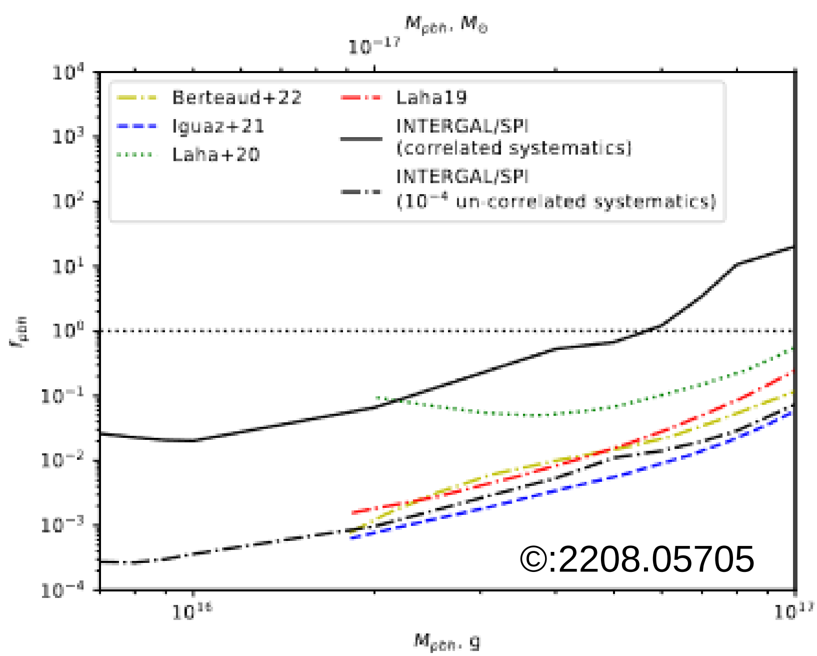
– ***Different*** observation ***stategies***:

– ***XMM-Newton***: small FoV, ~stable instr background; signal search on top of modelled (astrophysical+instr) background

– ***INTEGRAL/SPI***: large FoV, unstable instr background; ON-OFF observations.

PBH Dark Matter searches in X-rays





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Non-detection of such a signal allowed us to put ***constraints*** on a fraction of DM that can consist of PBH (f_{pbh}).

Note, that ***INTEGRAL/SPI*** is a *systematic-dominated* instrument. The constraints are defined mainly by systematic uncertainties (often ignored)!

Two types of limits for this instruments (assuming strongly energy-correlating systematics and energy un-correlated systematics) were derived.

PBH Dark Matter future searches

Instrument	Energy range [keV]	Peak A_{eff} [cm^2]	FoV [sr]	Launch date [year]	Target	Obs. Type	D-factor [GeV/cm^2]
XMM-Newton/PN	0.1-15	815	$4.5 \cdot 10^{-5}$	1999-**	Draco+MW	Model	$(1.1 + 0.74) \cdot 10^{18}$
INTEGRAL/SPI	20-8000	160	0.29	2002-**	MW	ON-OFF	$0.9 \cdot 10^{22}$
eXTP/SFA	0.5-10	8600	$9.6 \cdot 10^{-6}$	2027	Segue I + MW	Model	$(2.0 + 0.9) \cdot 10^{17}$
eXTP/LAD	2-30	$3.3 \cdot 10^4$	$2.4 \cdot 10^{-4}$	2027	Segue I	ON-OFF	$9.8 \cdot 10^{17}$
eXTP/WFM	2-50	77	2.5	2027	MW	ON-OFF	$2 \cdot 10^{22}$
THESEUS/SXI	0.3-5	1.9	1	2037	MW	ON-OFF	$1 \cdot 10^{22}$
THESEUS/XGIS-X	2-30	504	1	2037	MW	ON-OFF	$1 \cdot 10^{22}$
THESEUS/XGIS-S	20-2000	1060	1	2037	MW	ON-OFF	$1 \cdot 10^{22}$
Athena/X-IFU	0.2-12	$1.6 \cdot 10^4$	$3.3 \cdot 10^{-6}$	2035	Segue I+MW	Model	$(8.3 + 3.0) \cdot 10^{16}$
Athena/WFI	0.2-15	7930	$1.35 \cdot 10^{-4}$	2035	Segue I+MW	Model	$(0.98 + 1.2) \cdot 10^{18}$
Einstein probe/WXT	0.5-4	3	1.1	2023	MW	ON-OFF	$1 \cdot 10^{22}$
SVOM/MXT	0.2-10	37	$3.5 \cdot 10^{-4}$	2023-24	Segue I	ON-OFF	$0.98 \cdot 10^{18}$

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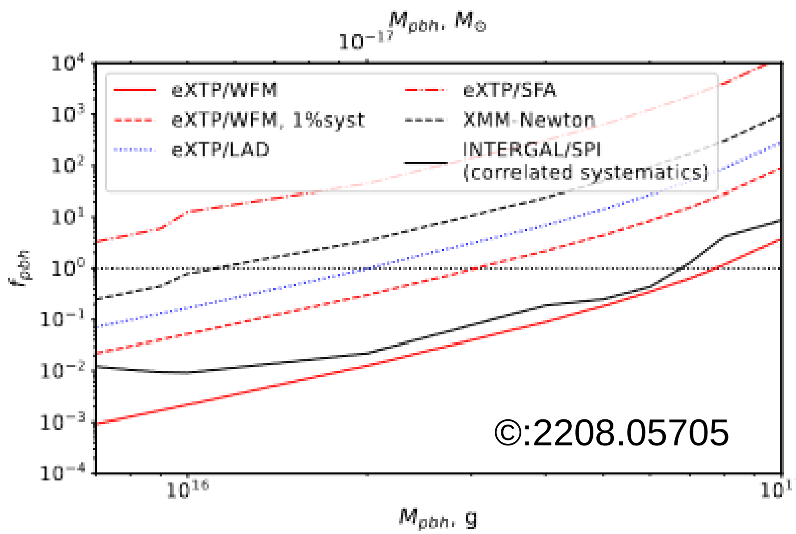
Malyshev, Moulin, Santangelo, 2022PhRvD:

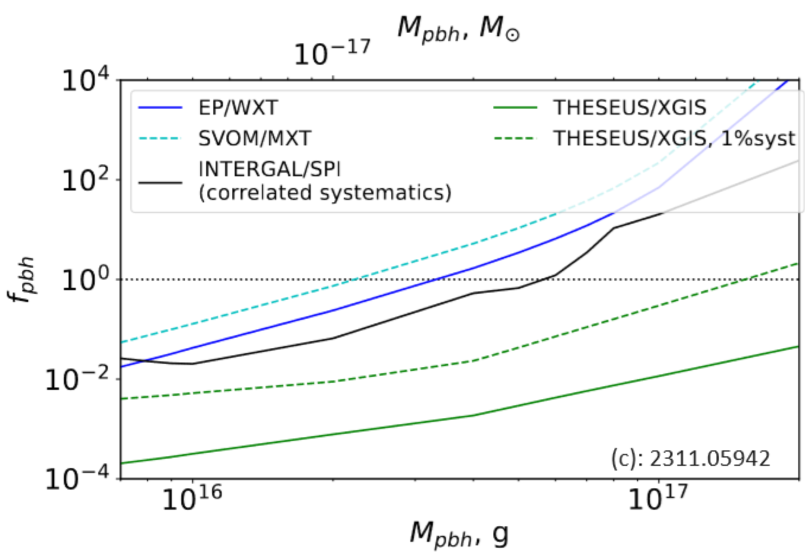
– Current constraints start to probe 10^{16} – 10^{17}g mass region

– Several new missions are expected within next decade: eXTP, THESEUS, Athena

– Current limits can be improved by up to 2 orders of magnitude and extended to 10^{18}g masses

PBH Dark Matter future searches





Malyshev, Moulin, Santangelo, 2022PhRvD:

– Current constraints start to probe 10^{16} – 10^{17}g mass region

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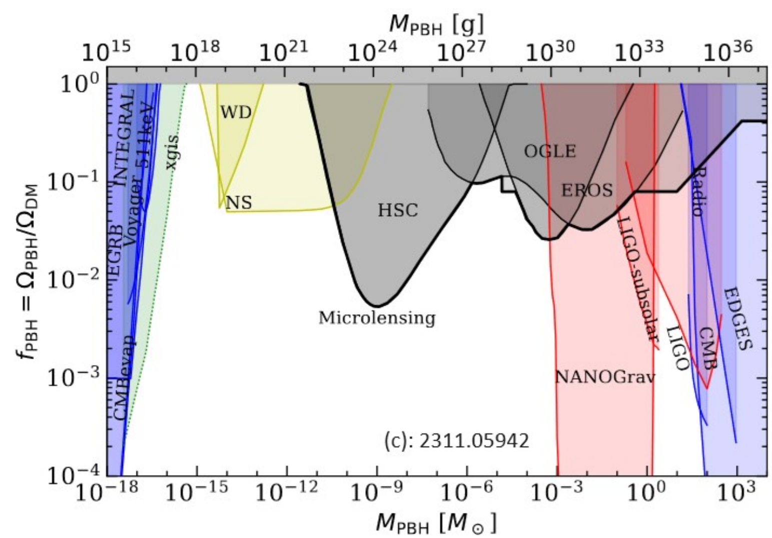
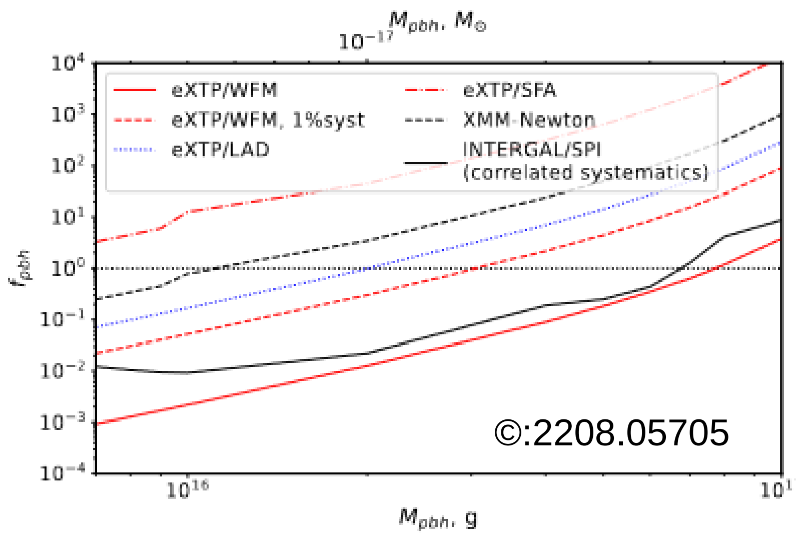
– The mass range of 10^{18} – 10^{21}g still remains un-probed



PBH Dark Matter future searches



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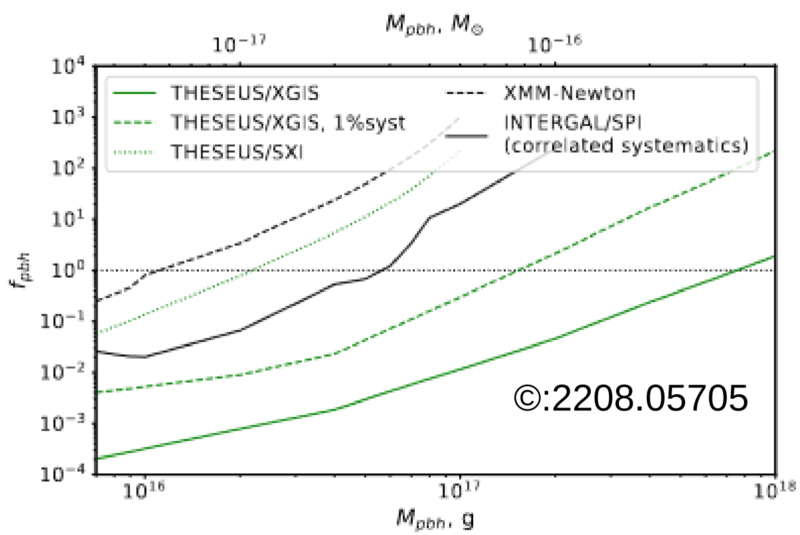
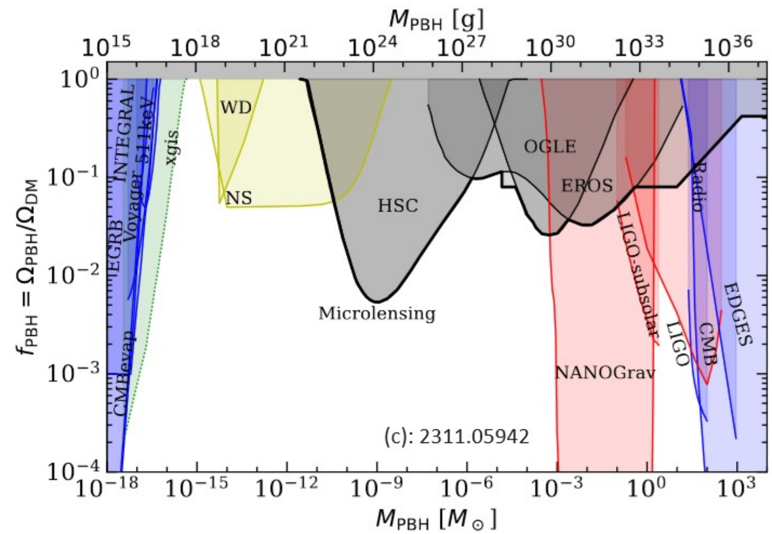
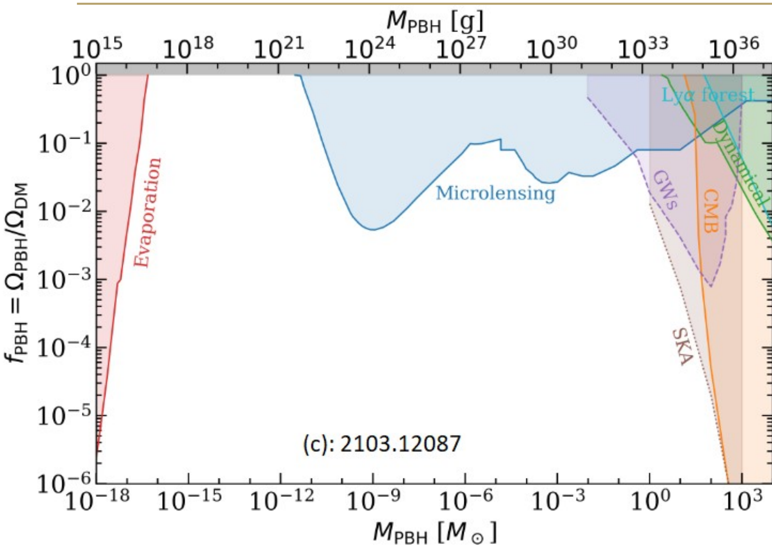
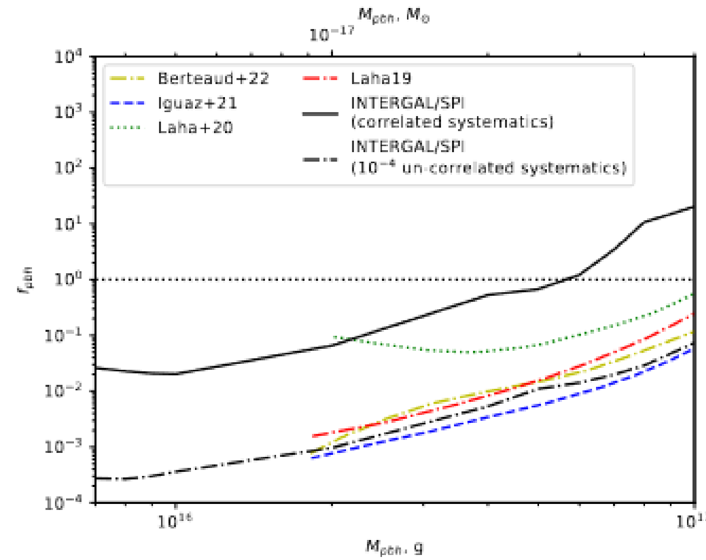


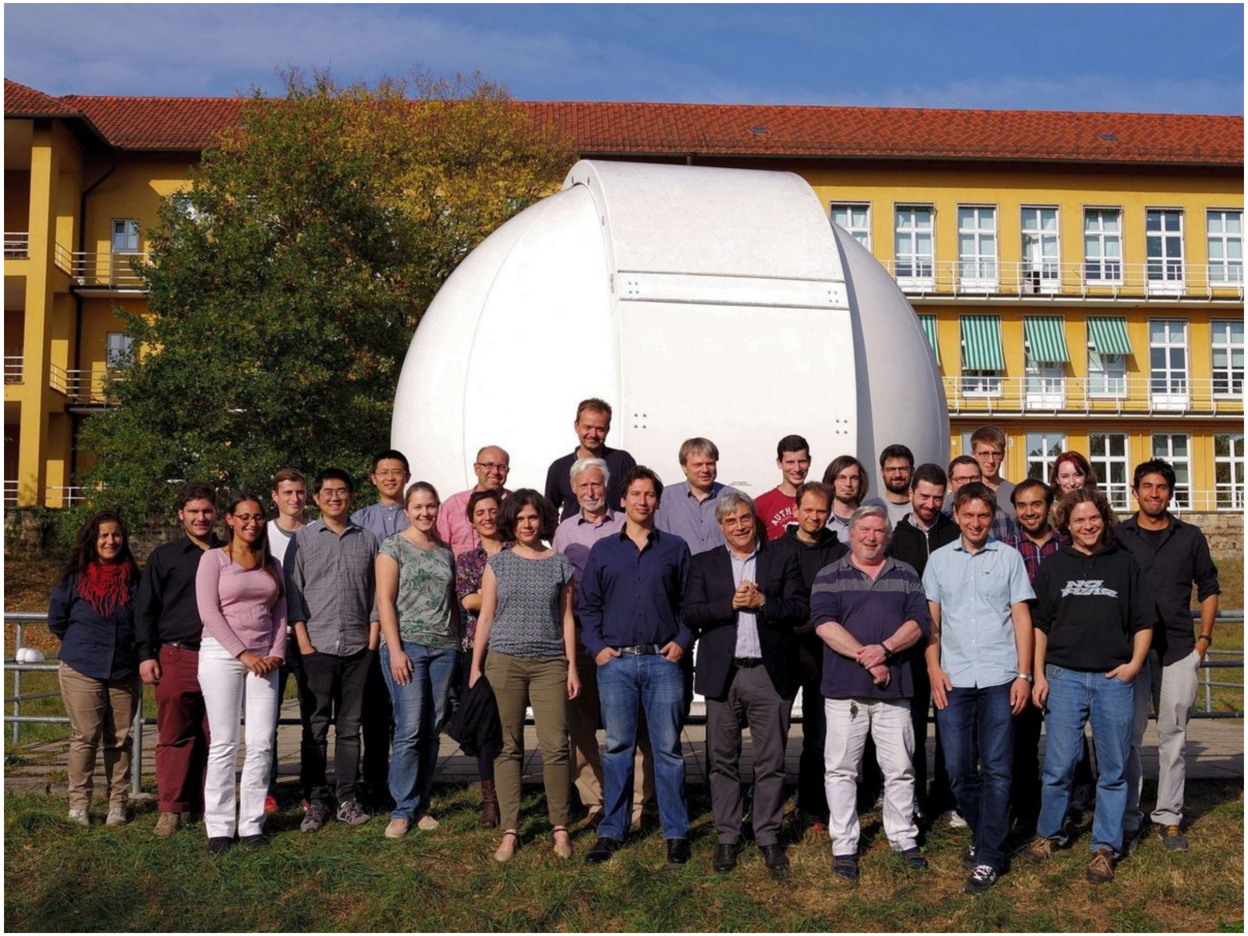


Short Conclusions





- DM PBHs with masses $10^{18} – 10^{21}$g are not currently constraint and can make up to 100% of the whole DM in the Universe
- Non-observations of Hawking radiation from evaporating PBHs in Draco dSph and in the MW in the X-ray band exludes PBHs $M_{PBH}<10^{17}$g as major contributors to DM
- Future X-ray missions planned to launch within next decade can extend exclusion range to $>10^{18}$g



Vielen Dank!