Dark Matter and/or (Primordial) Black Holes

Julien Lavalle
CNRS – LUPM – Montpellier

Atelier PNHE, IAP-Paris, September 2023

Menu

Shortly on:

* Status of dark matter paradigm

* Status of dark matter candidates

* Primordial black holes (PBHs)

* Coexistence of (P)BHs with particle DM

Dark matter on small scales

CDM at the core of structure formation theory
+ daily used in th. predictions + simulations without asking … what is it made of?

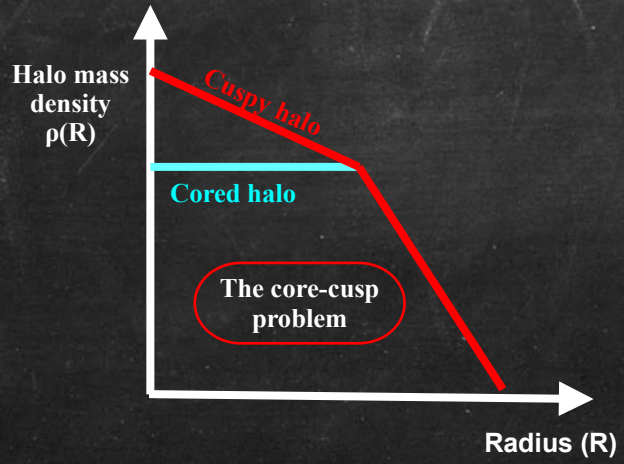
Not devoid of "**tensions**" on small scales

- ~~subhalo pb~~ (long solved from baryonic physics)
- **core/cusp pb** (e.g. de Blok'10) and its declension

Dark matter on small scales

CDM at the core of structure formation theory
+ daily used in th. predictions + simulations without asking … what is it made of?

Not devoid of "**tensions**" on small scales
- ~~subhalo pb~~ (long solved from baryonic physics)
- **core/cusp pb** (e.g. de Blok'10) and its declension



Mass density profiles of galactic halos:

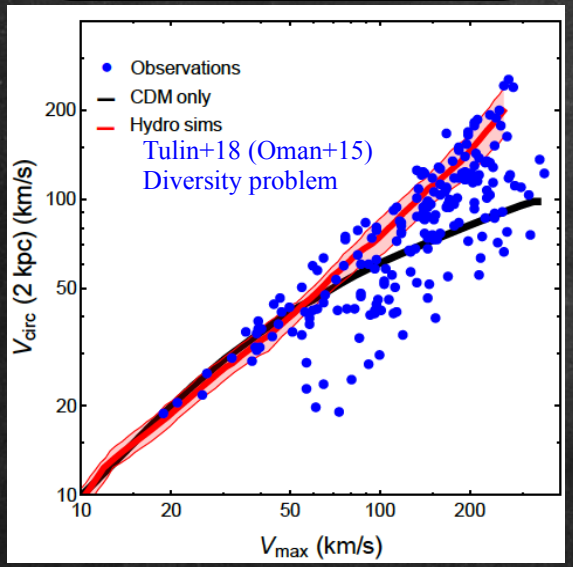
- predicted cuspy down to very inner parts (NFW, Einsato)
- 1-parameter model (mass), given redshift.

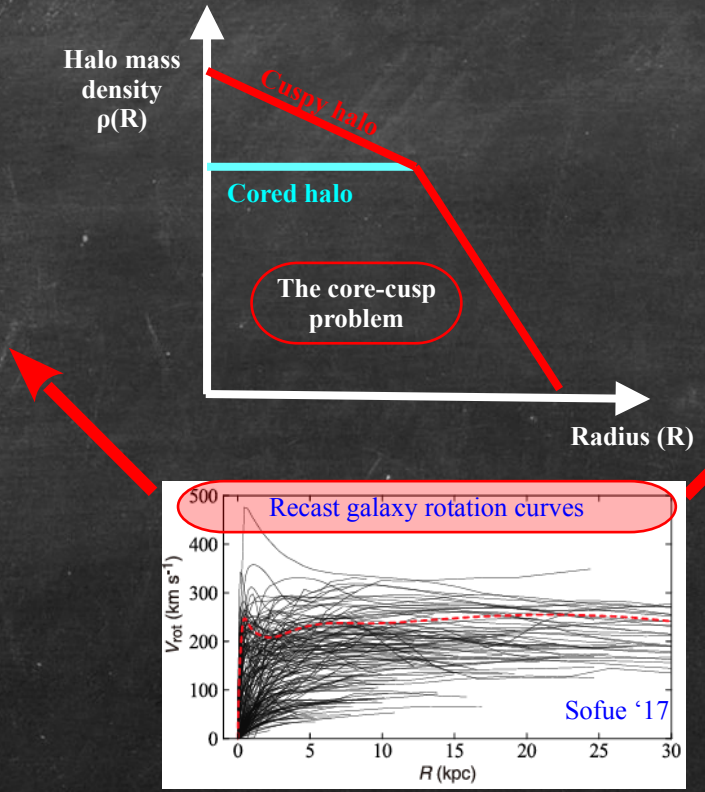
… but found cored in significant fraction of galaxies (not always).

Dark matter on small scales

Diversity problem

Halos of similar masses (V_{max}) have a large scatter in central properties (V_{circ})

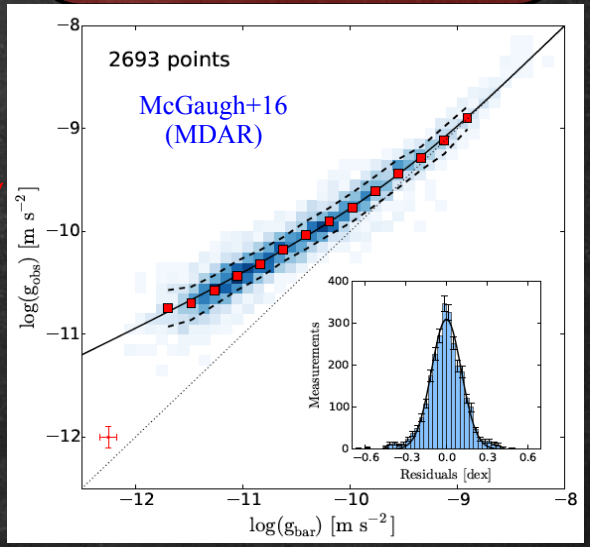




Regularity problem

Total acceleration correlates with baryonic acceleration
(Mass Discrepancy Acceleration Relation).

(NB: predicted by MOND)



Core-cusp problem ↔ Diversity/regularity problem

Potential solutions to core/cusp ↔ diversity pb

Baryonic physics

[Must be investigated anyway]

OR/AND ?

Dark matter properties

Self-interacting dark matter (SIDM)
[Spergel & Steinhardt'00]
→ heats the cusps away

Ultra-light [bosonic] dark matter (ULDM)
[Hu+'00]
→ solitonic cores

Come with different properties on small scales [e.g. subhalos or not, possible collapse or not]

DM on small scales: connecting fundamental unknowns

Origin of cosmological perturbations

→ Primordial power spectrum (PS)

(on scales much lower than CMB+LSS can touch)

Nature and origin of dark matter

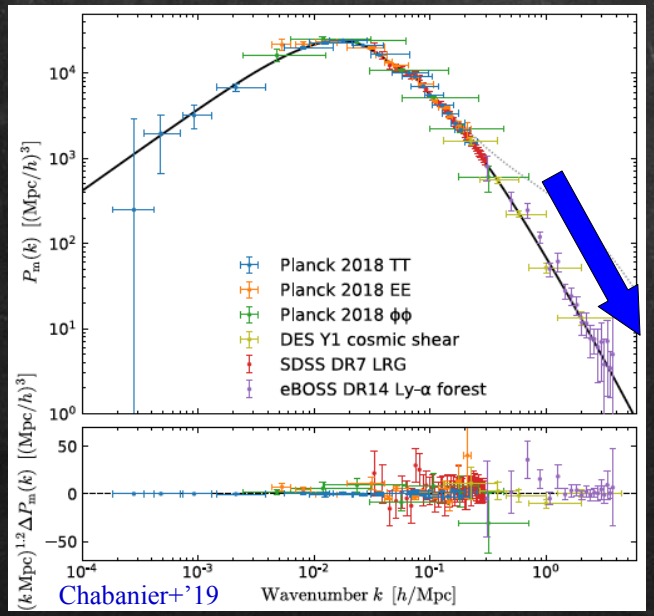
→ DM responds to primordial perturbations (matter PS)
→ Imprints its own features (interactions, etc.)
→ Might even generate additional perturbations
→ Smallest dark structures carry invaluable information

DM on small scales: connecting fundamental unknowns

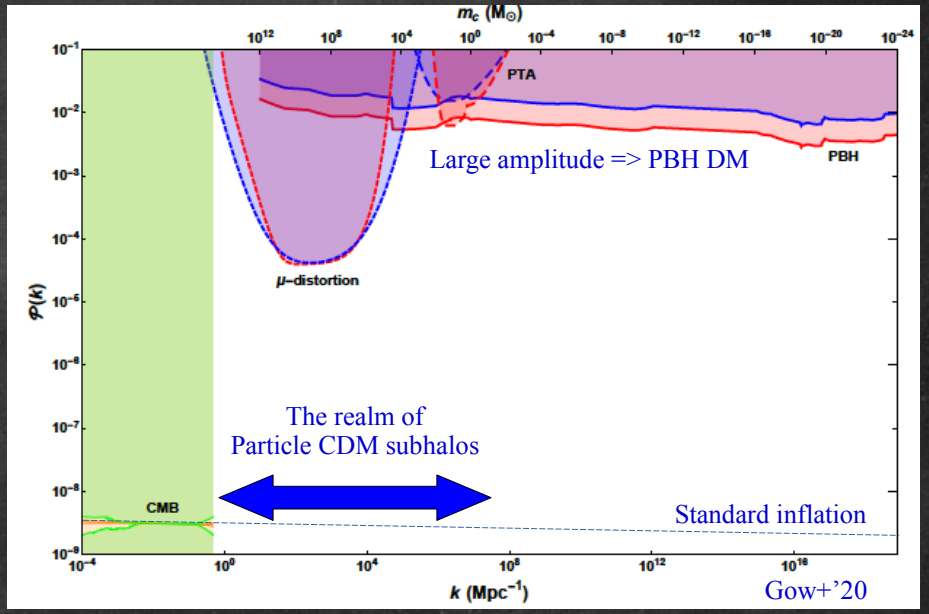
Origin of cosmological perturbations

→ Primordial power spectrum (PS)

(on scales much lower than CMB+LSS can touch)



Chabanier+'19



Gow+'20

Nature and origin of dark matter

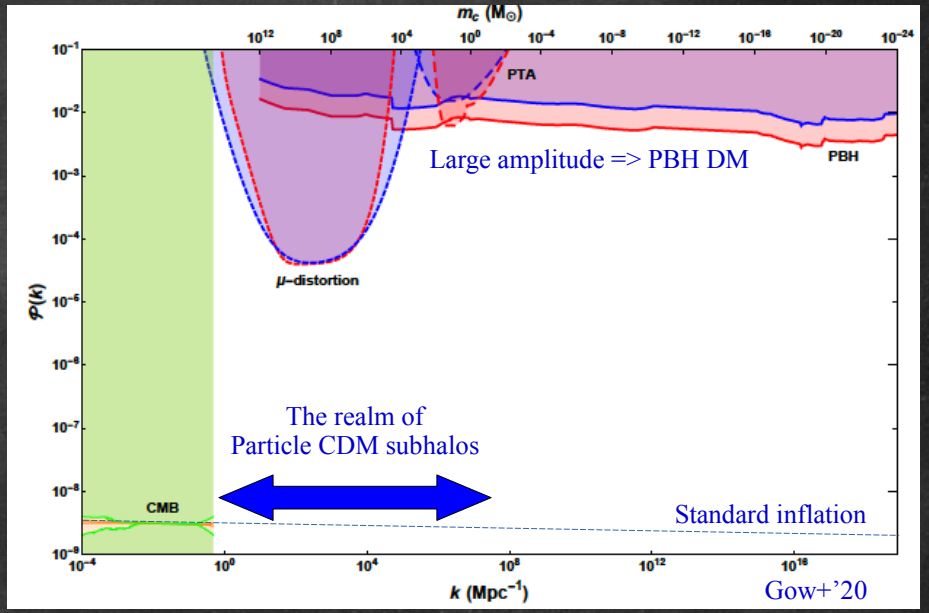
→ DM responds to primordial perturbations (matter PS)
→ Imprints its own features (interactions, etc.)
→ Might even generate additional perturbations
→ Smallest dark structures carry invaluable information

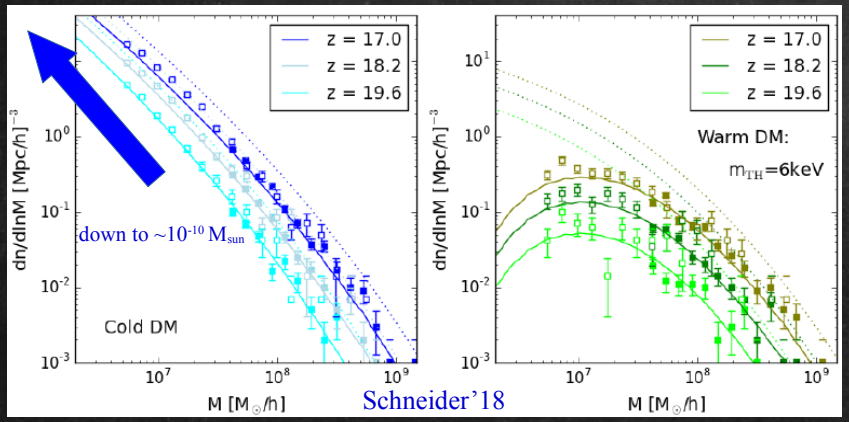
DM on small scales: connecting fundamental unknowns

Origin of cosmological perturbations

→ Primordial power spectrum (PS)

(on scales much lower than CMB+LSS can touch)



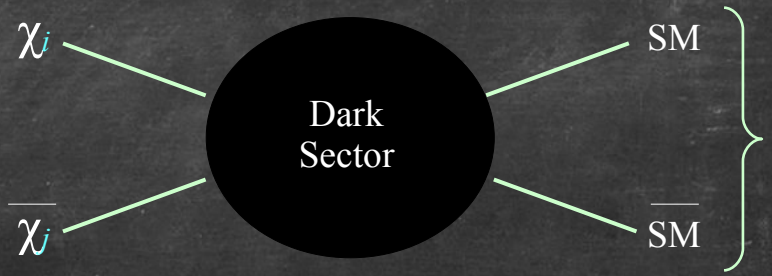


Nature and origin of dark matter

→ DM responds to primordial perturbations (matter PS)
→ Imprints its own features (interactions, etc.)
→ Might even generate additional perturbations
→ Smallest dark structures carry invaluable information

Typical DM candidates and small-scale properties

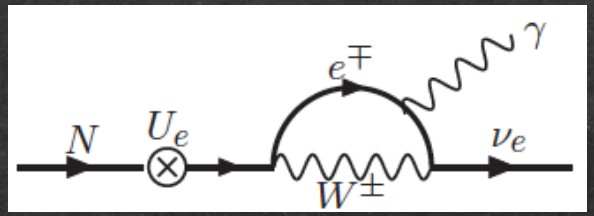
Thermal (non-neutrino) DM
[1 keV – 100 TeV]
Simple production mechanism
WIMPs, FIMPs, asymmetric, etc.



On small scales

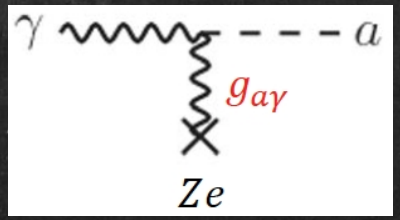
CDM with cutoff
WDM
SIDM

Sterile neutrinos
[1 – 50 keV]
Neutrino masses+leptogenesis
(production from mixing only)



WDM

Axions or axion-like
[1 μeV – 1 meV]
[10^{-22} eV for ALPs beyond QCD-axion]
Absence of CP violation in QCD
(misalignment or string decays)

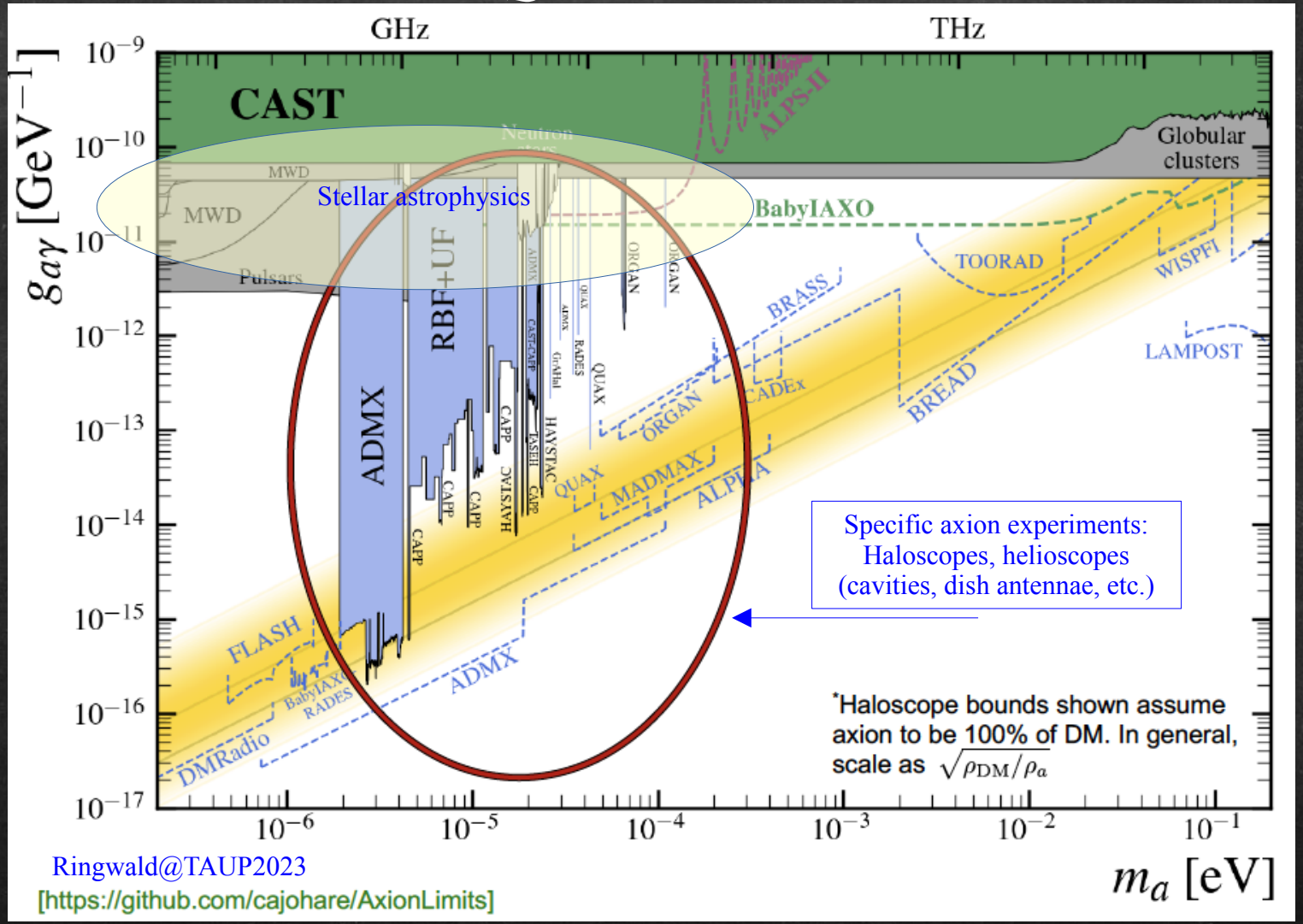


CDM / axion clusters/stars
ULDM
Solitons of different sizes

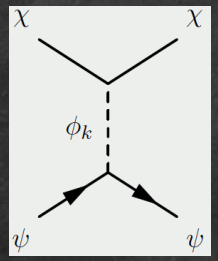
"QCD" axions

Also, for PQS breaking after inflation:

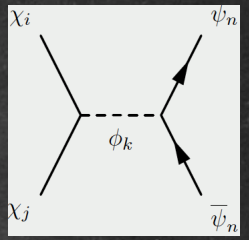
Astro radio-line signals from encounters of axionic solitons with neutron stars.
[e.g. Pshirkov&Popov '09, Witte+'23]

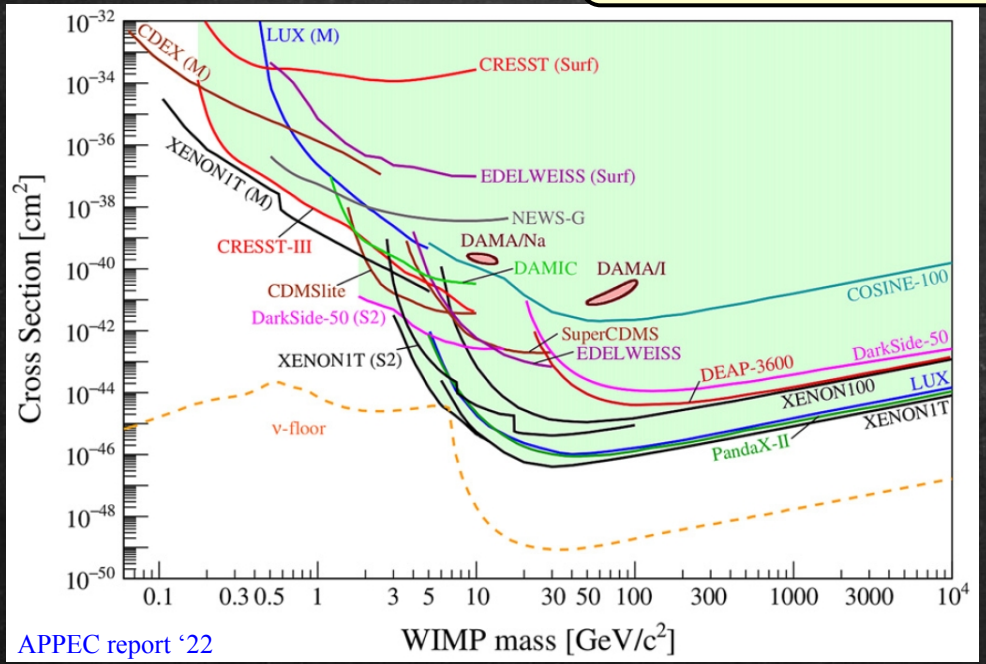


WIMPs: direct vs. indirect searches(no serious smoking gun signal so far)

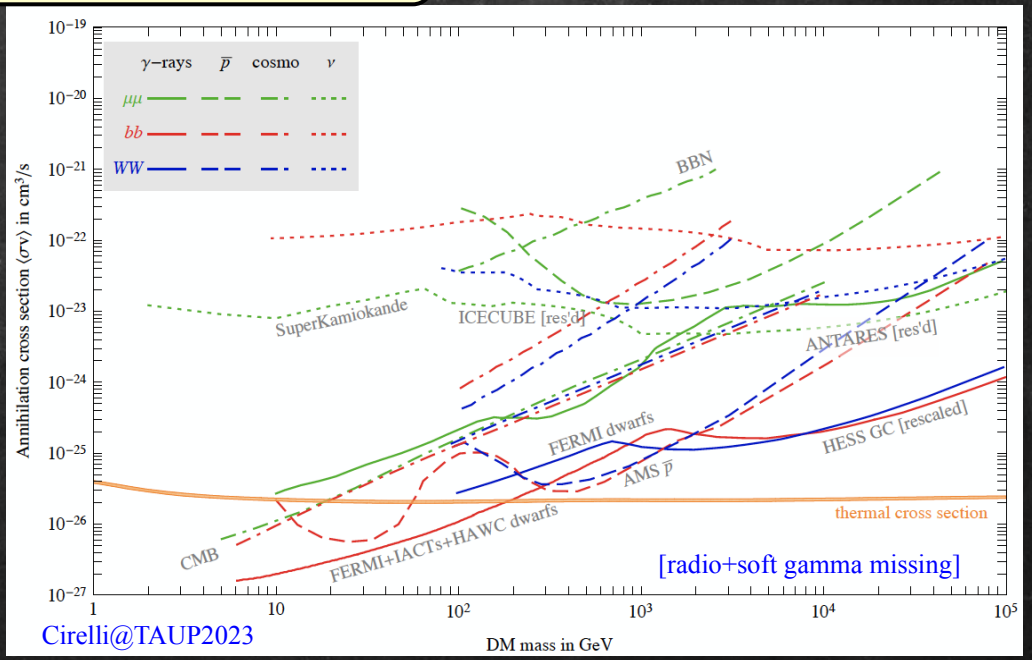


Complementarity
= not same parameter/theory space
[rotated diagrams have different velocity dependencies]
Example:
Scalar interaction @ direct searches
Pseudo-scalar interactions @ indirect searches
exclusion in DD ≠ excluded for ID (and conversely)



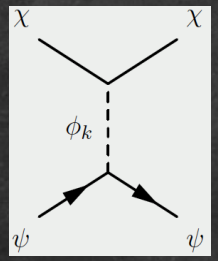


APPEC report '22

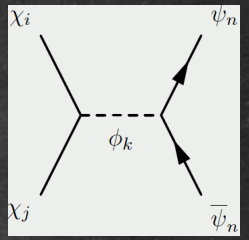


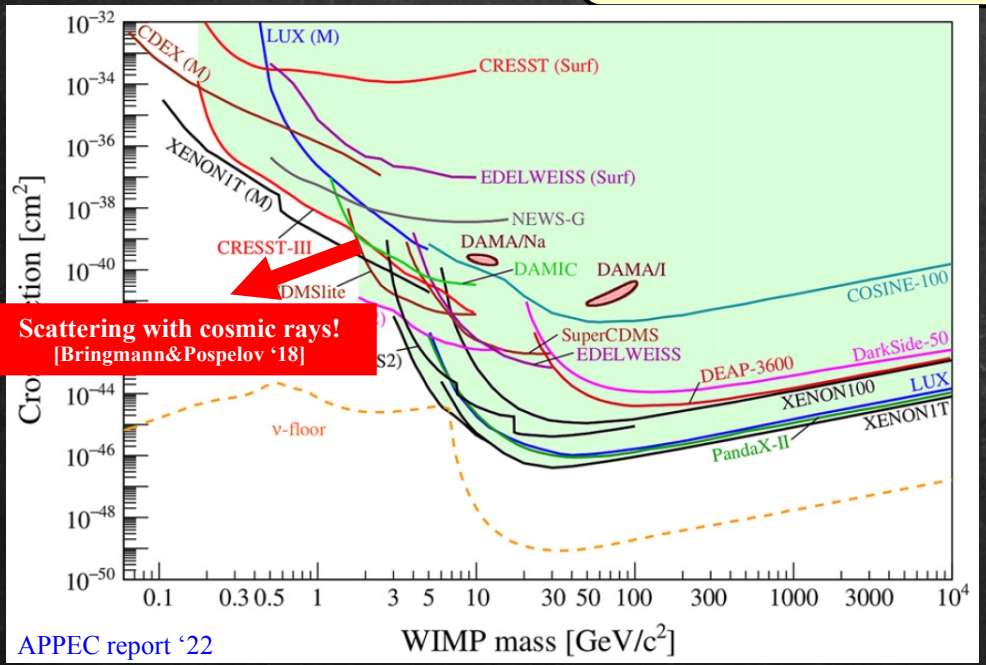
Cirelli@TAUP2023

WIMPs: direct vs. indirect searches(no serious smoking gun signal so far)

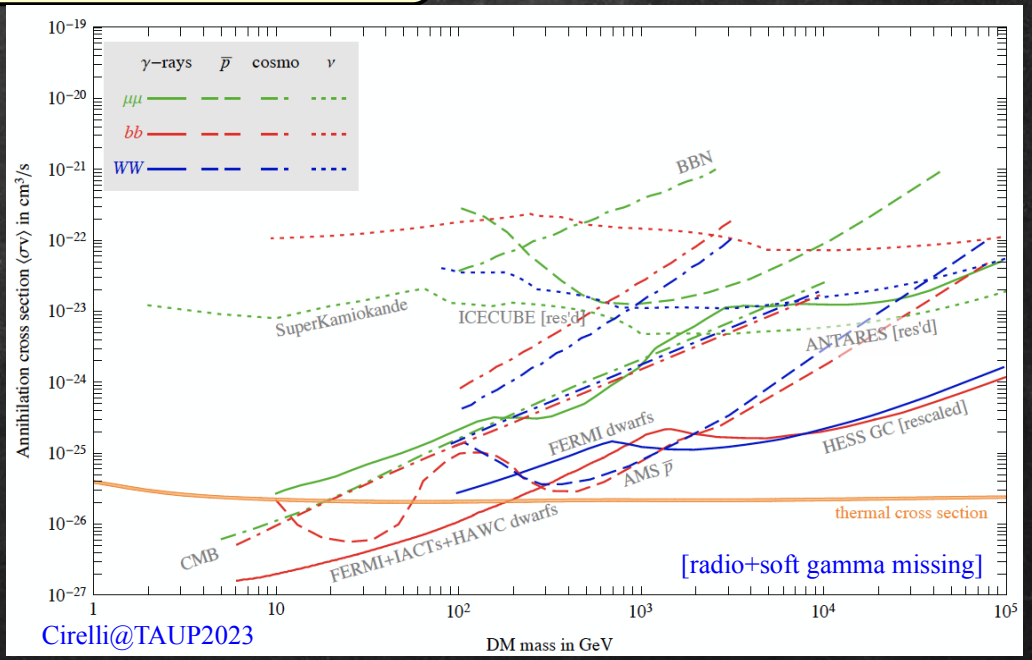


Complementarity
= not same parameter/theory space
[rotated diagrams have different velocity dependencies]
Example:
Scalar interaction @ direct searches
Pseudo-scalar interactions @ indirect searches
exclusion in DD ≠ excluded for ID (and conversely)



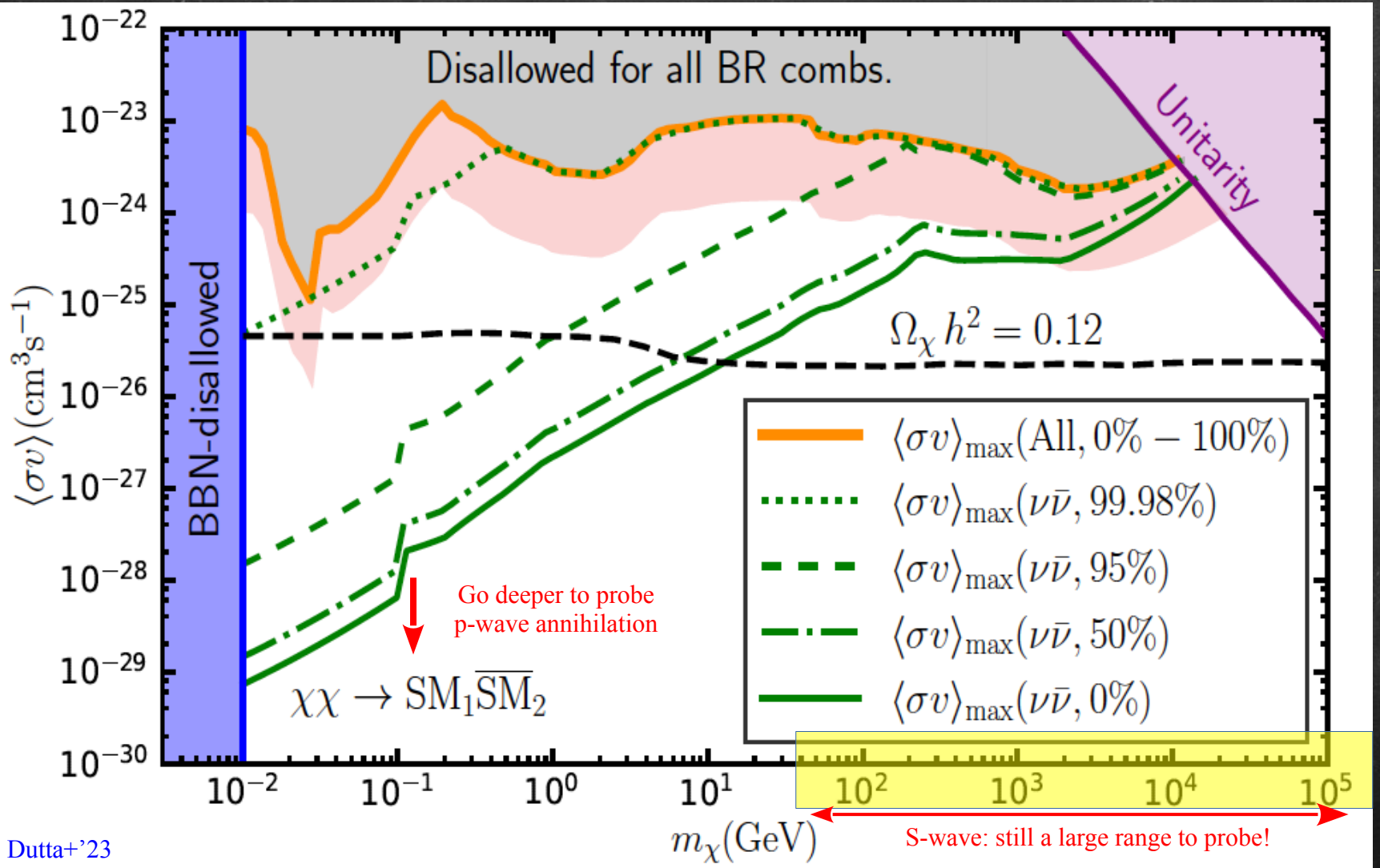


APPEC report '22



Cirelli@TAUP2023

Summary on s-wave production/annihilation (WIMPs)



PNHE participation: predictions+data analyses: integral+Fermi+HESS+ AMS02+Antares/Km3, etc.

A lot to improve:

* Understanding/control of astro bgs. (multimessenger+multi wavelength)

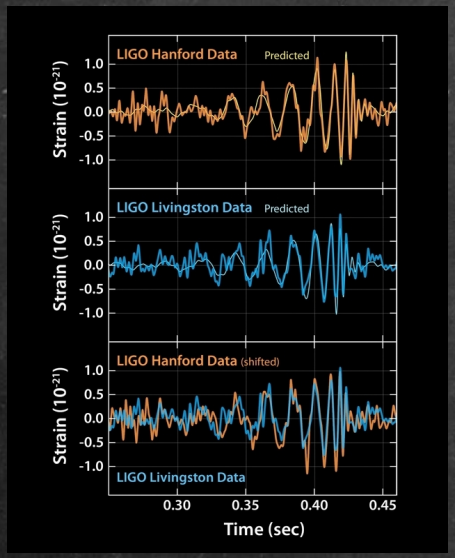
* Distribution of DM in targets + clumpiness

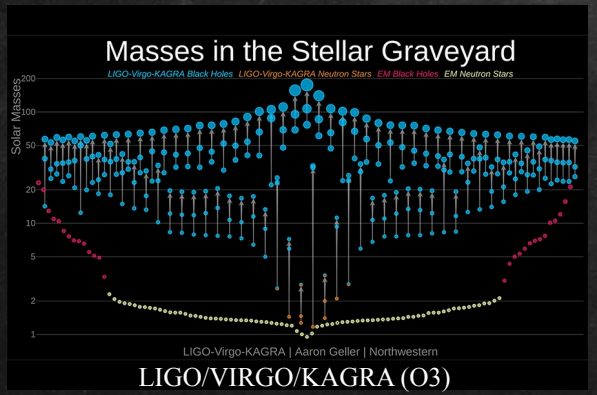
* Sensitivity >50 GeV

* p-wave yet to probe: MeV-TeV

An elephant in the room

LIGO+VIRGO ‘15-16





LIGO/VIRGO/KAGRA (O3)
arXiv:2111.03606 – 2111.03634

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

arXiv:1603.00464 (PRL)

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

arXiv:1603.08338 (PRL)

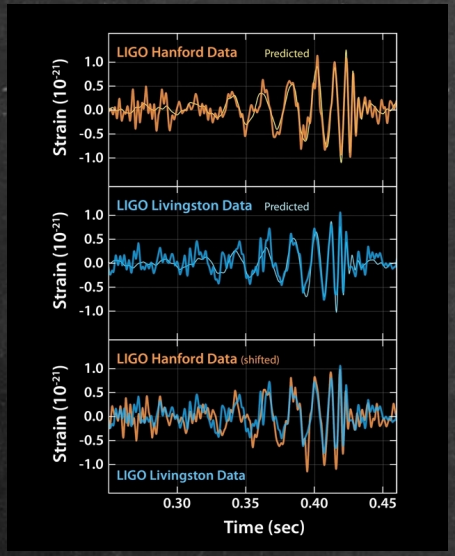
The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

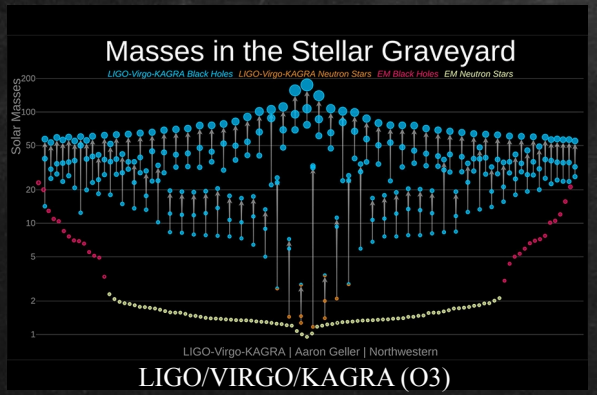
Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

arXiv:1603.05234 (PDU)

An elephant in the room

LIGO+VIRGO ‘15-16





LIGO/VIRGO/KAGRA (O3)
arXiv:2111.03606 – 2111.03634

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

arXiv:1603.00464 (PRL)

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

arXiv:1603.08338 (PRL)

The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

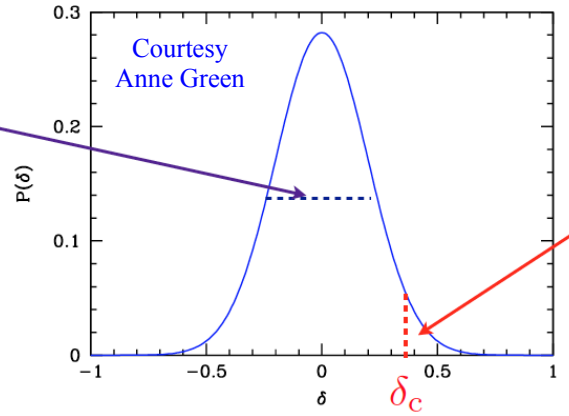
arXiv:1603.05234 (PDU)

NB: Merger rate has now turned to a constraint on PBH DM (clustering effects difficult to work out)
[Hütsi+, Ali-Haïmoud+, Jedamzik, etc.]

PBH links to power spectrum and constraints

σ(M_H) (mass variance)
typical size of fluctuations

Determined by amplitude
of primordial power spectrum



PBH forming
fluctuations

Critical threshold
[Zeldovich, Novikov, Hawking, Carr]

$$\delta \geq \delta_c \sim w = \frac{p}{\rho} = \frac{1}{3}$$

$$M_H \sim 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)$$

$$\beta(M) \sim \int_{\delta_c}^{\infty} P(\delta(M_H))\,\mathrm{d}\delta(M_H)$$

Gaussian spectrum →

$$\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$$

$$\sigma(M_H) \sim 10^{-5}$$

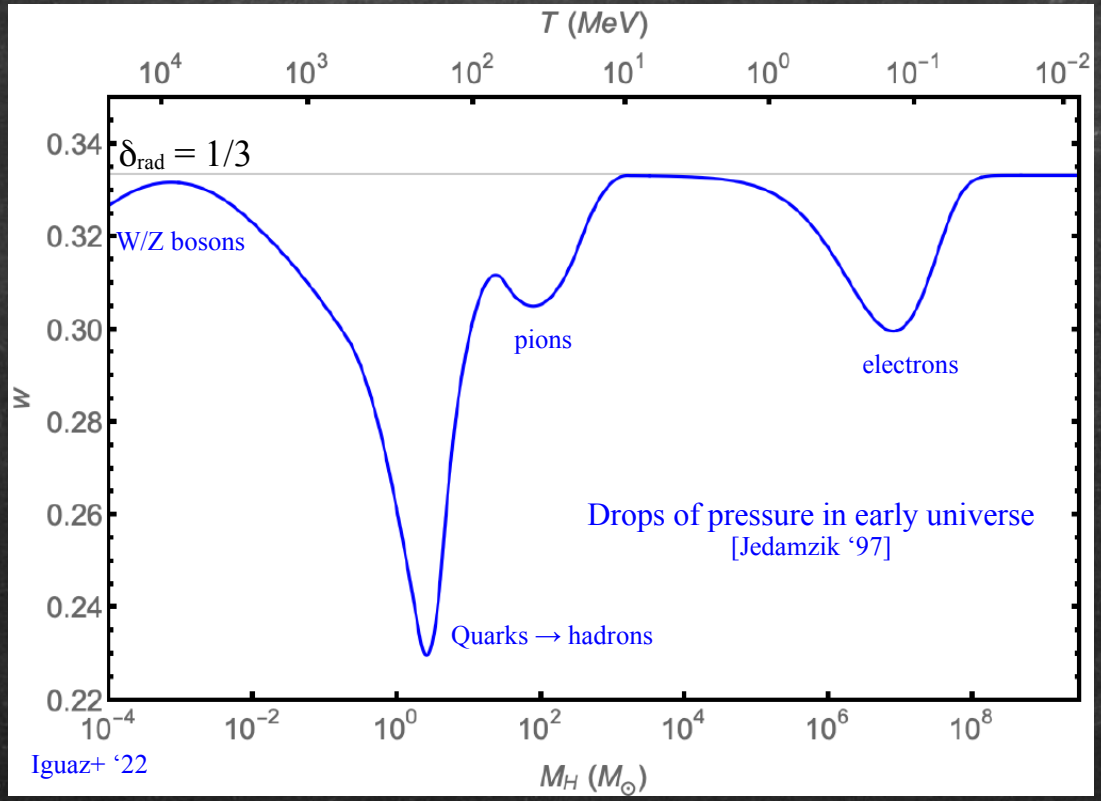
On CMB scales →

$$\sim 10^5 \exp\left[-(10^5)^2\right]$$

Mass fraction in PBHs strongly suppressed in standard inflation.

Caution: PBHs could also form out of phase transitions, topological defects, etc.

Favored mass windows for PBHs



Critical threshold

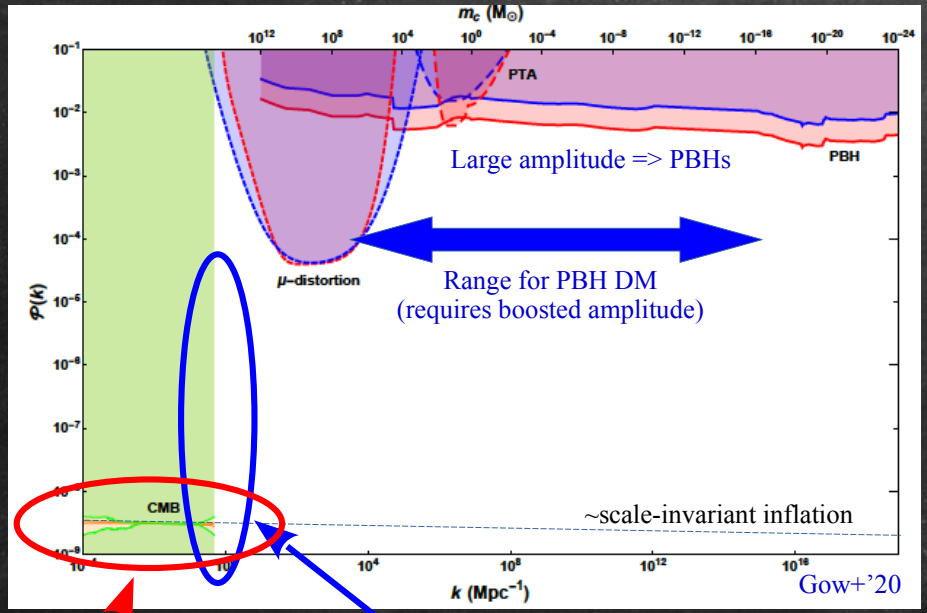
[Zeldovich, Novikov, Hawking, Carr]

$$\delta \geq \delta_c \sim w = \frac{p}{\rho} = \frac{1}{3}$$

$$M_H \sim 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)$$

PBH links to power spectrum and constraints

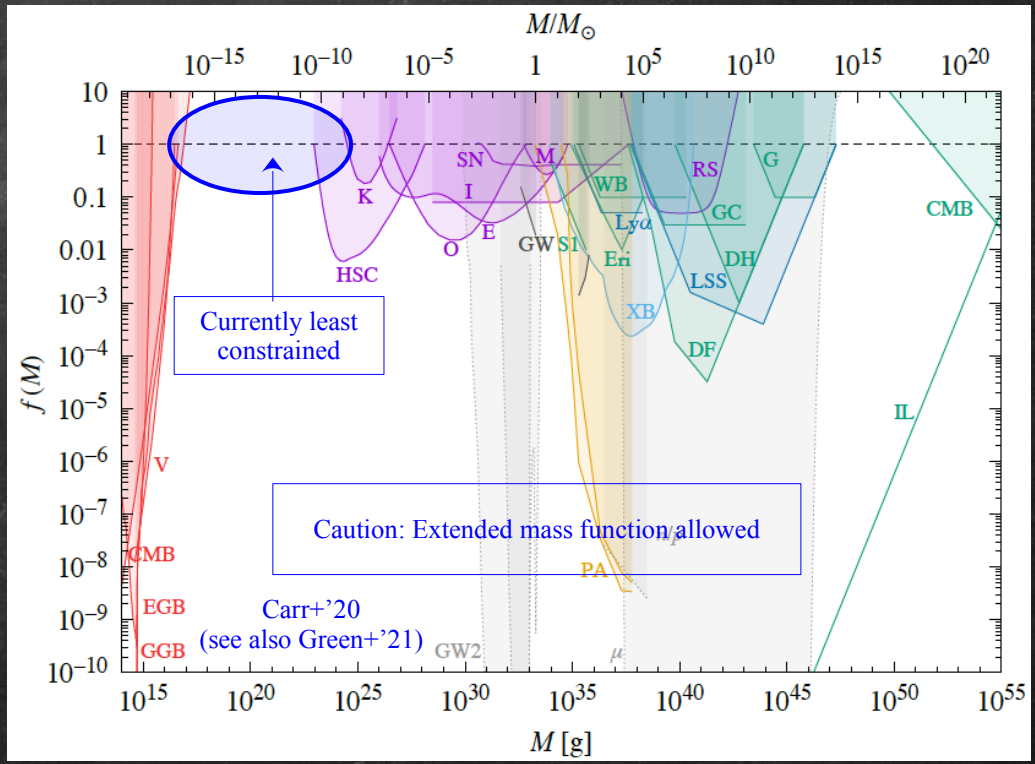
Primordial power spectrum



Current CMB constraints
[Planck+'18]

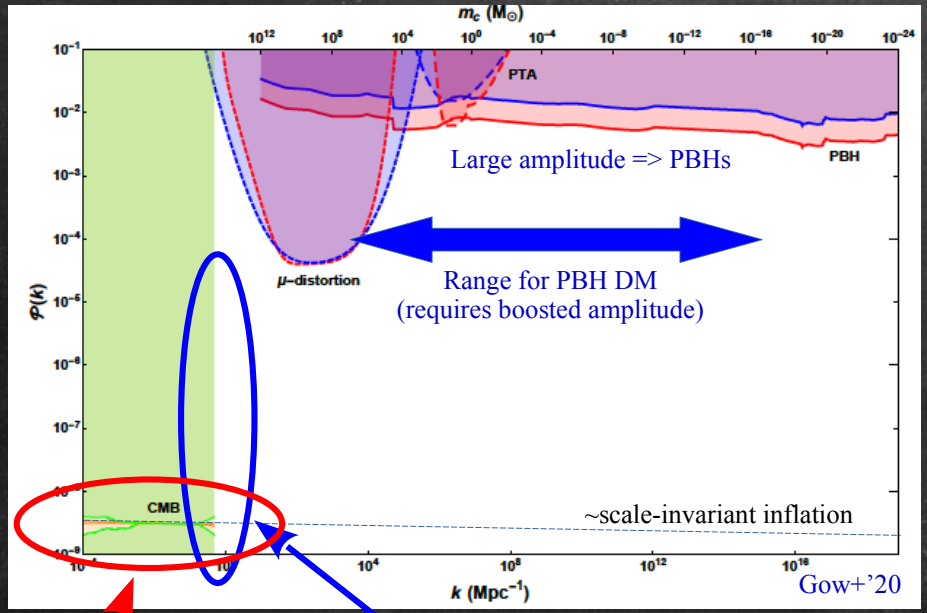
Current LSS constraints
[e.g. Ly-alpha]

Constraints on PBH DM fraction

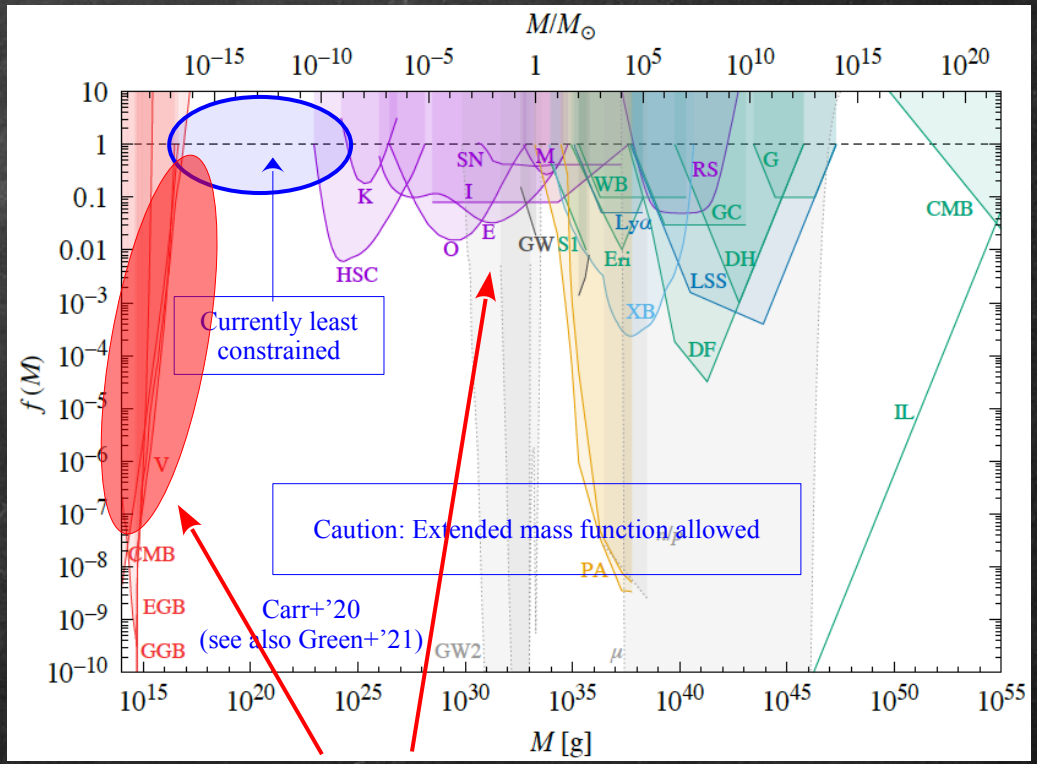


PBH links to power spectrum and constraints

Primordial power spectrum



Constraints on PBH DM fraction



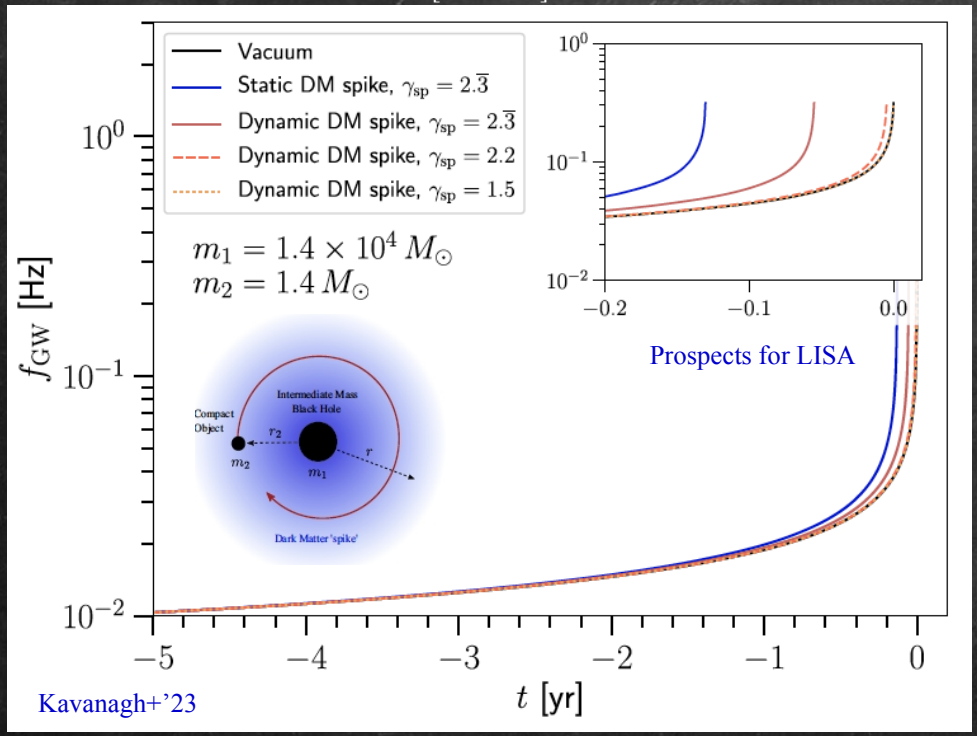
Current CMB constraints
[Planck+'18]

Current LSS constraints
[e.g. Ly-alpha]

PNHE input:
* PBH evaporation to HE messengers (photons MeV-TeV, neutrinos, antimatter)
* GW => look for subsolar mass PBHs

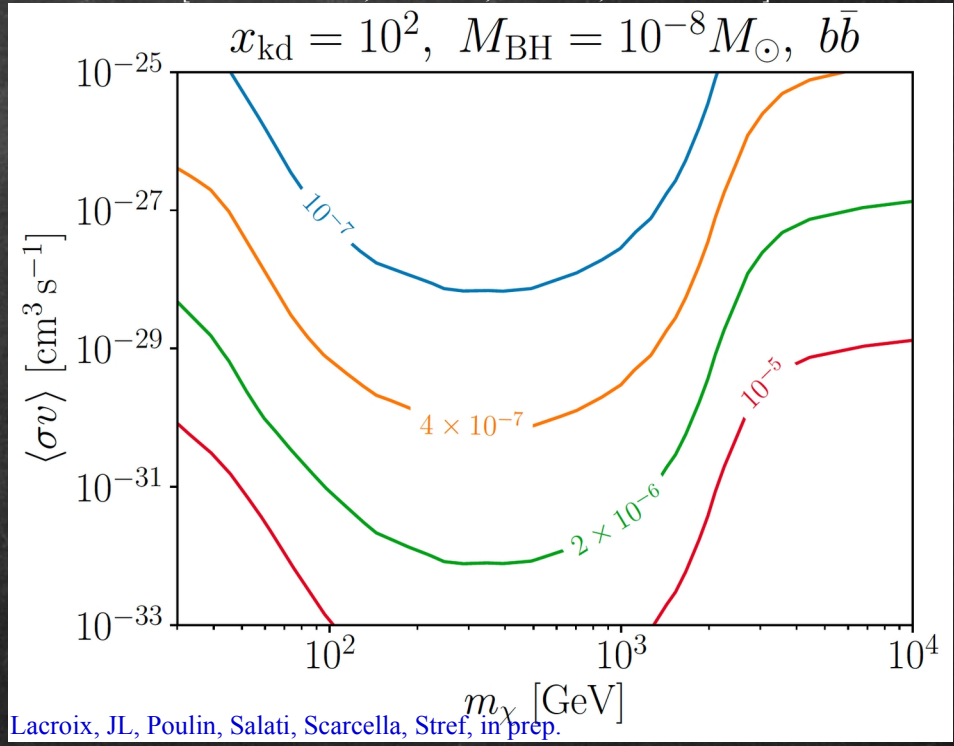
Coexistence of particle DM and (P)BHs

DM impact on inspiral: dynamical friction shortens coalescences time
[Eda+ '13]



Q: Impact of 3rd body + baryons + degeneracies?

DM accumulates as dense spikes around PBHs in radiation-dominated universe
[Dokuchaev+'03, Ricotti'07, Mck+'07, Eroshenko'16]



=> small fraction of PBHs may have dramatic impact
on s-wave annihilation WIMP scenario!
[See also Eroschenko'16, Boucenna+'18,Carr+'21, Boudaud+'21, Gines+'22]

Summary

- Origin of DM still unknown: several motivated candidates with specific theory/parameter spaces

- Structuring on small scales: can tell candidates apart, tests with gravitational/dynamical probes
=> important theoretical + observational work expected (e.g. Gaia, LSST, etc.)

- DM searches: PNHE has important role to play (most of interesting targets identified)
→ Multimessenger + multi-: EM (Mhz → 100 TeV), neutrinos, GWs
→ 50 GeV – 100 TeV: still to probe (WIMPs, s-wave)
→ 100 keV – 50 GeV: go deeper (p-wave, not probed with CMB)
→ GWs: subsolar mass PBHs + particle DM ↔ (P)BHs
=> IMPORTANT: understanding and control astrophysical backgrounds (= PNHE signals)
+++ new ideas

- Complementarity with other probes (e.g. direct searches) model-dependent

=> Long-term research (long-term follow up of identified targets)

All about theoretical devs. in the French community involved in dark/early universe+gravitation:
Atelier TUG @ LPENS 10-12 Oct. 2023