Some cosmological aspects of Dark Matter and their links to (exotic?) candidates

Julien Lavalle
CNRS – LUPM – Montpellier

Journée SFP, Paris-Jussieu, March 21, 2024

Menu

A few words on:

* Status of (cold) dark matter paradigm

* Setting scales for structure formation

* Some candidates

* (P)BHs and their co-existence with other candidates

* My two cents on modified gravity

* Conclusion and perspectives

Status of (cold) dark matter

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

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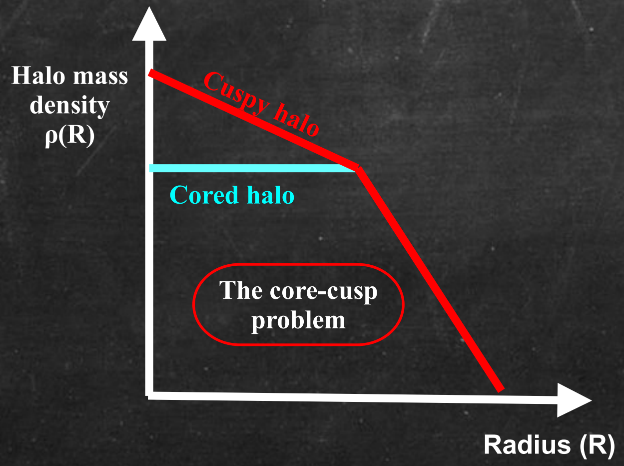


Mass density profiles of galactic halos:

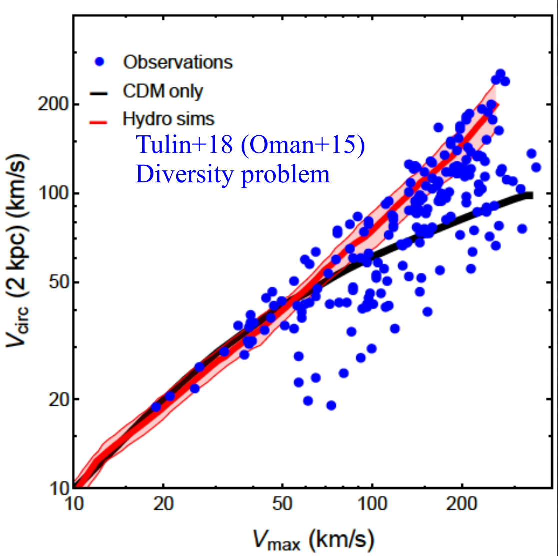
- predicted cuspy down to very inner parts (NFW, Einsato)
- 1-parameter model (mass), given redshift.

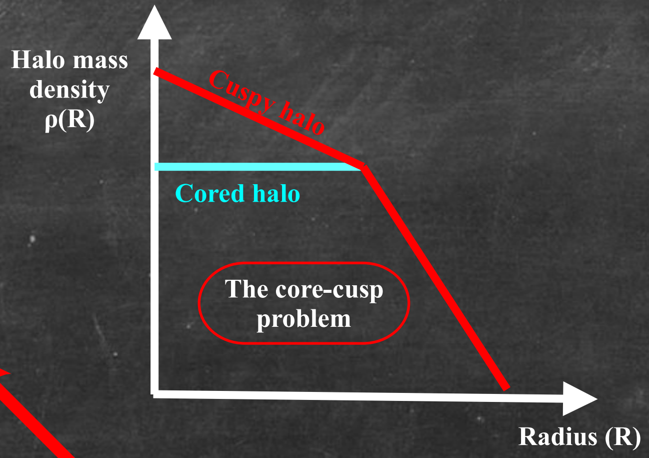
… but found cored in significant fraction of galaxies (not always).

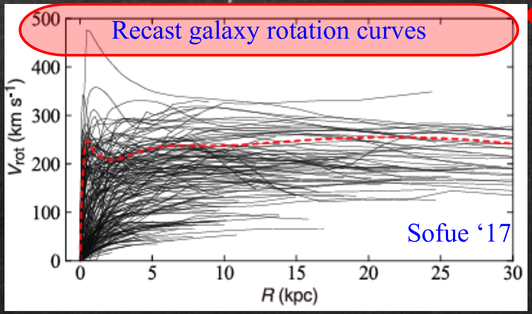
Status of (cold) dark matter

Diversity problem

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



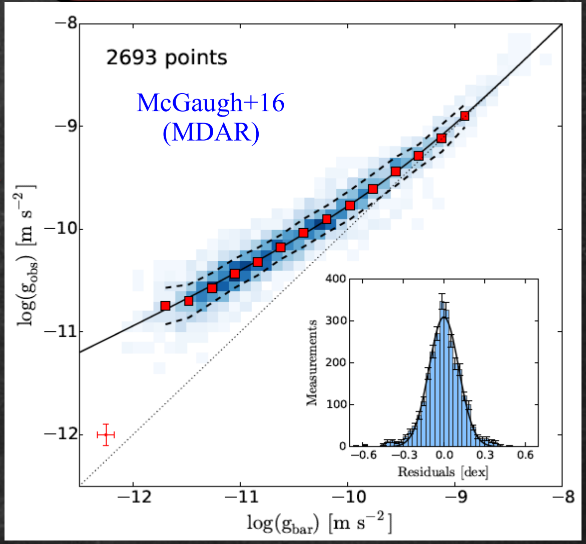




Regularity problem

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

(NB: predicted by MOND)



Core-cusp problem ↔ Diversity/regularity problem

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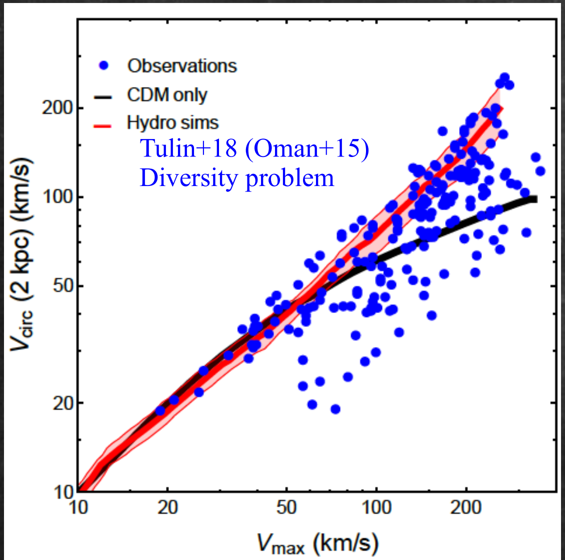

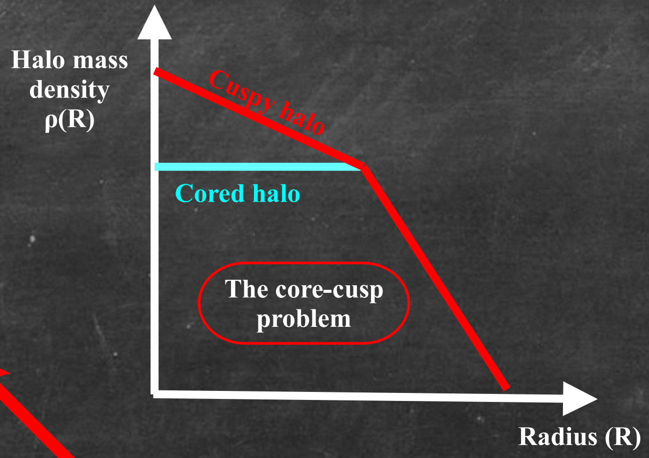

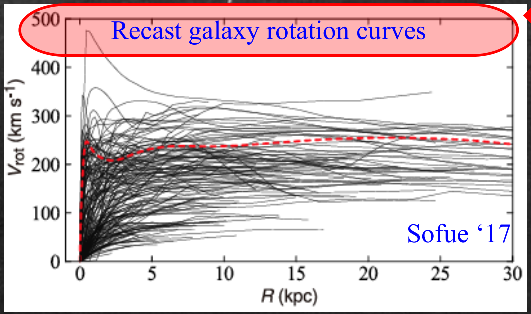

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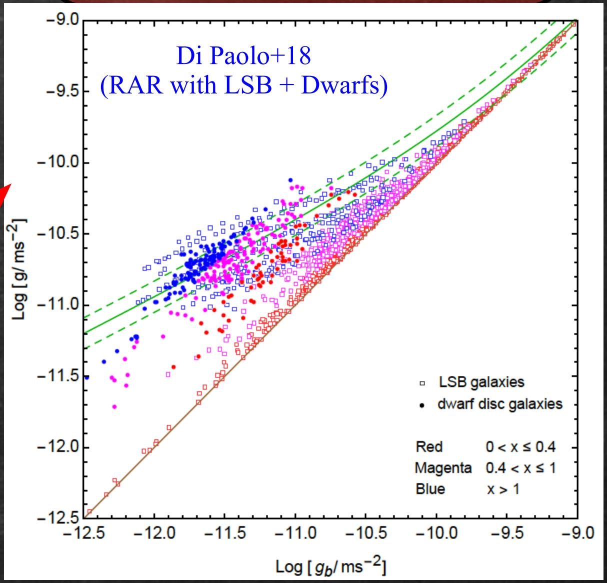

Core-cusp problem ↔ Diversity/regularity problem

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]

Potential solutions to core/cusp ↔ diversity pb

The formation of cores in galaxies across cosmic time - the existence of cores is not in tension with the ΛCDM paradigm

R. A. Jackson,[1,2,3★] S. Kaviraj,[2] S. K. Yi,[3] S. Peirani,[4,5] Y. Dubois,[5] G. Martin,[6,7,8]
J. E. G. Devriendt,[9] A. Slyz,[9] C. Pichon,[5,10] M. Volonteri,[5] T. Kimm[3] and K. Kraljic[11]

The Mass-Discrepancy Acceleration Relation: A Natural Outcome of Galaxy Formation in Cold Dark Matter Halos

Aaron D. Ludlow,* Alejandro Benítez-Llambay, Matthieu Schaller, Tom Theuns, Carlos S. Frenk, and Richard Bower
Joop Schaye Robert A. Crain
Julio F. Navarro,† Azadeh Fattahi, and Kyle A. Oman

MIND THE GAP: IS THE TOO BIG TO FAIL PROBLEM RESOLVED?

JEREMIAH P. OSTRIKER[1,2], ENA CHOI[1], ANTHONY CHOW[1], KUNDAN GUHA[1]

Baryonic solutions already found – many studies ongoing
[Caveats: controled subgrid physics? Same baryonic recipe for all pbs?]

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

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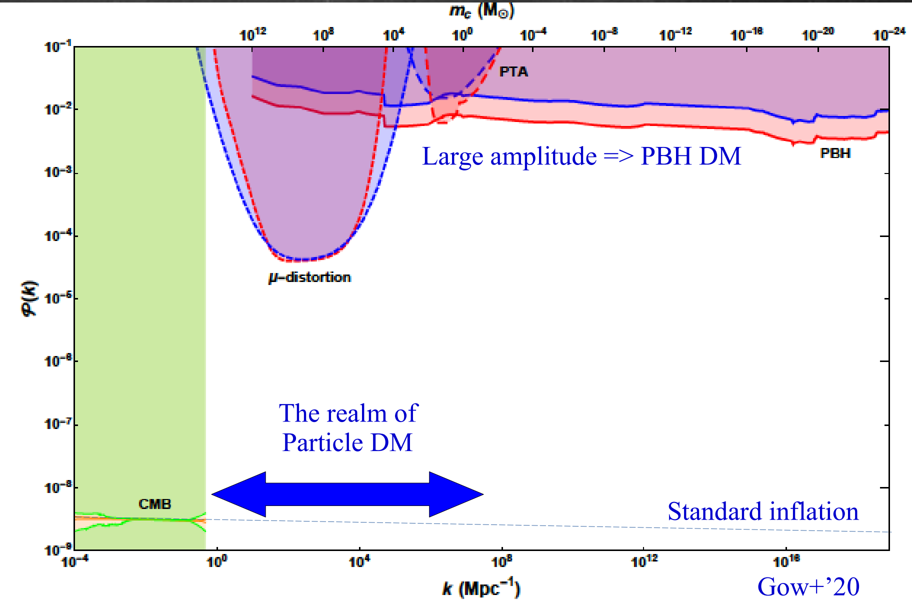

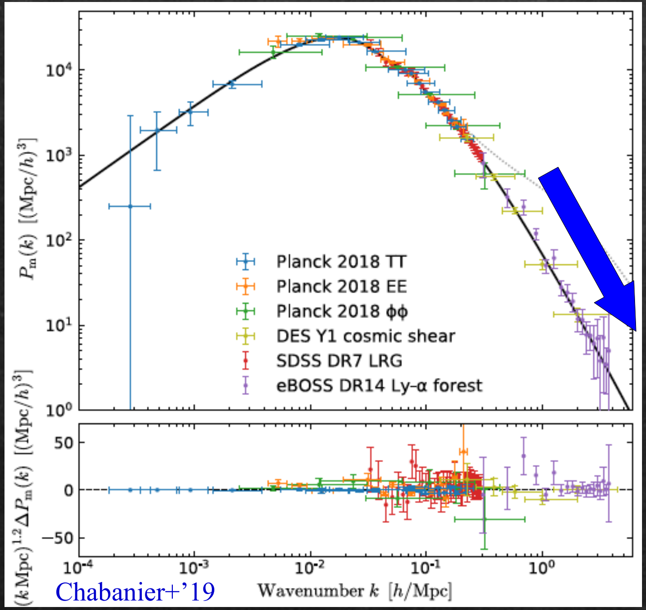

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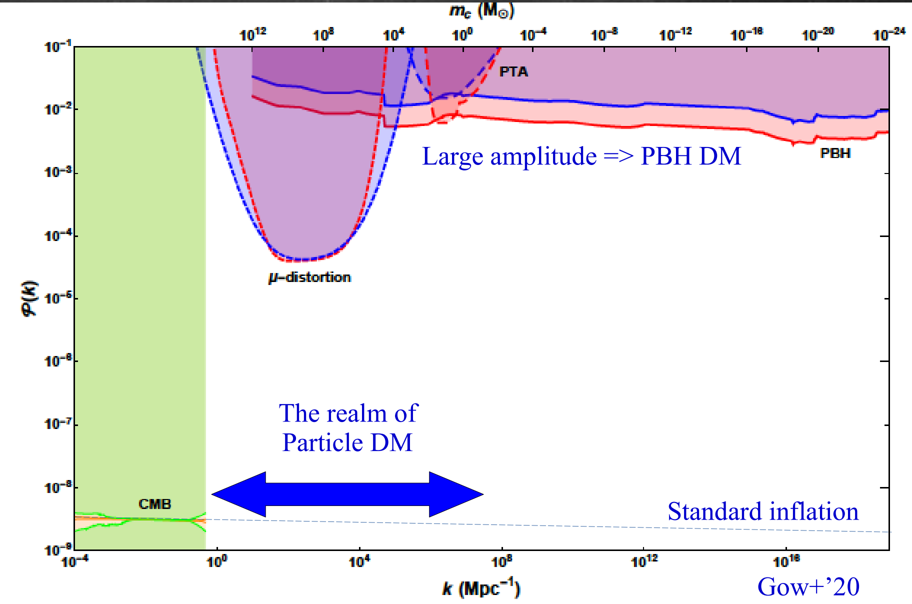

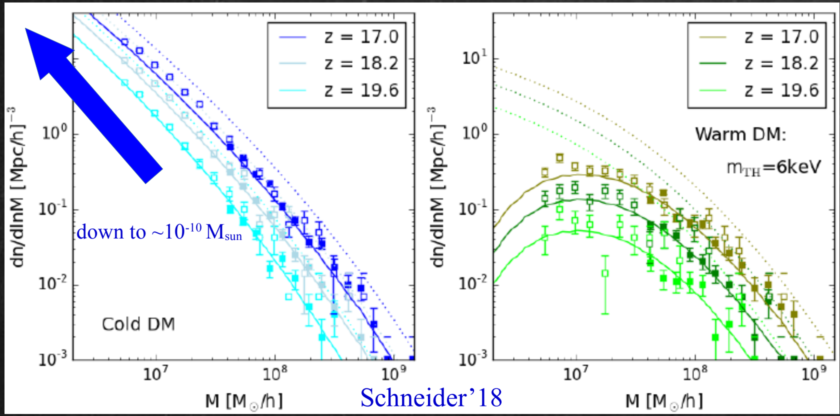

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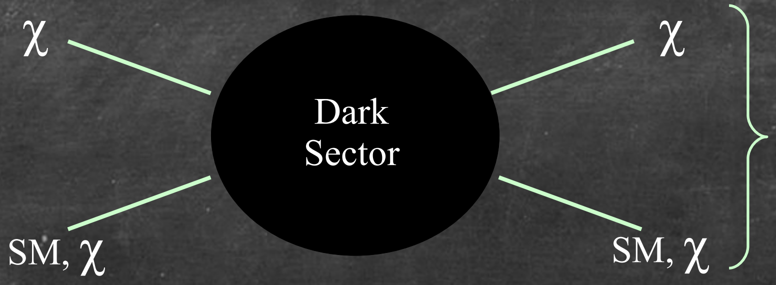
Setting scales in cosmological structures
1: before structure formation

Thermal DM (incl. rh neutrinos)
[1 keV – 100 TeV]
Elastic interactions with matter



On small scales

CDM with cutoff
WDM
SIDM

Kinetic decoupling
=> 2[nd] moment of Boltzmann eq.
++ acoustic damping if ate decoupling or strong self-interactions

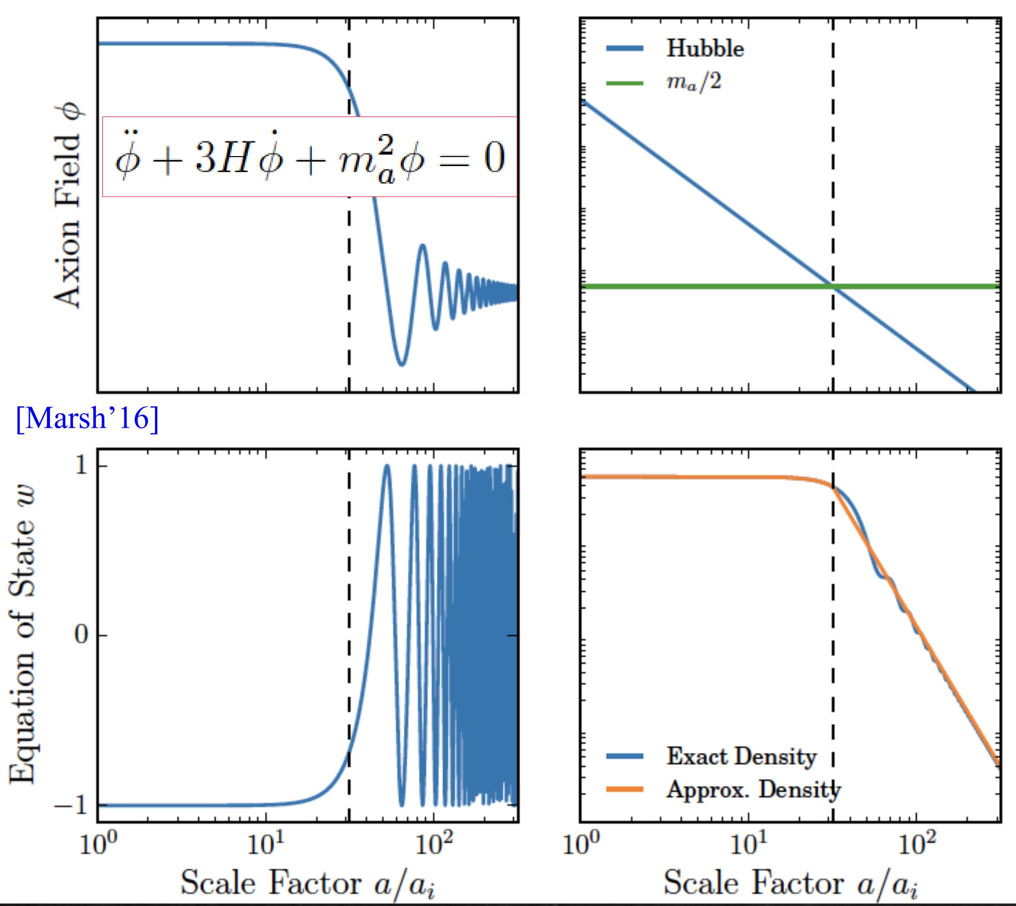
Free-streaming vs collisional damping

$$\lambda_{\rm fs} = a_{\rm eq} \int_{t_{\rm kd}}^{t_{\rm eq}} dt \frac{v(t)}{a(t)} \approx v_{\rm kd} (a_{\rm kd}/a_{\rm eq})/H_{\rm eq}$$

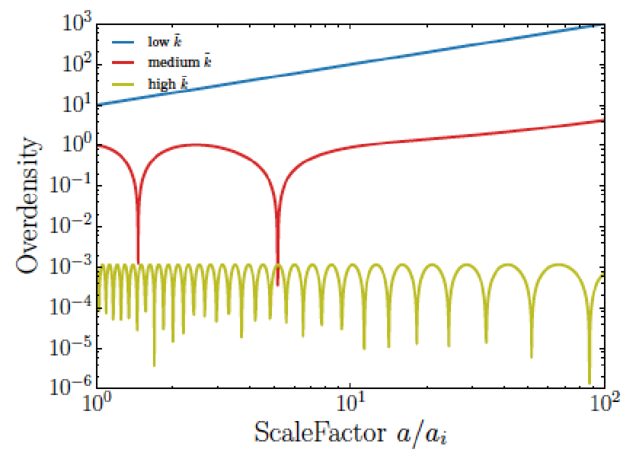
Slower <=> shorter mfp <=> colder

Faster <=> larger mfp <=> warmer

Setting scales in cosmological structures
1: before structure formation



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)

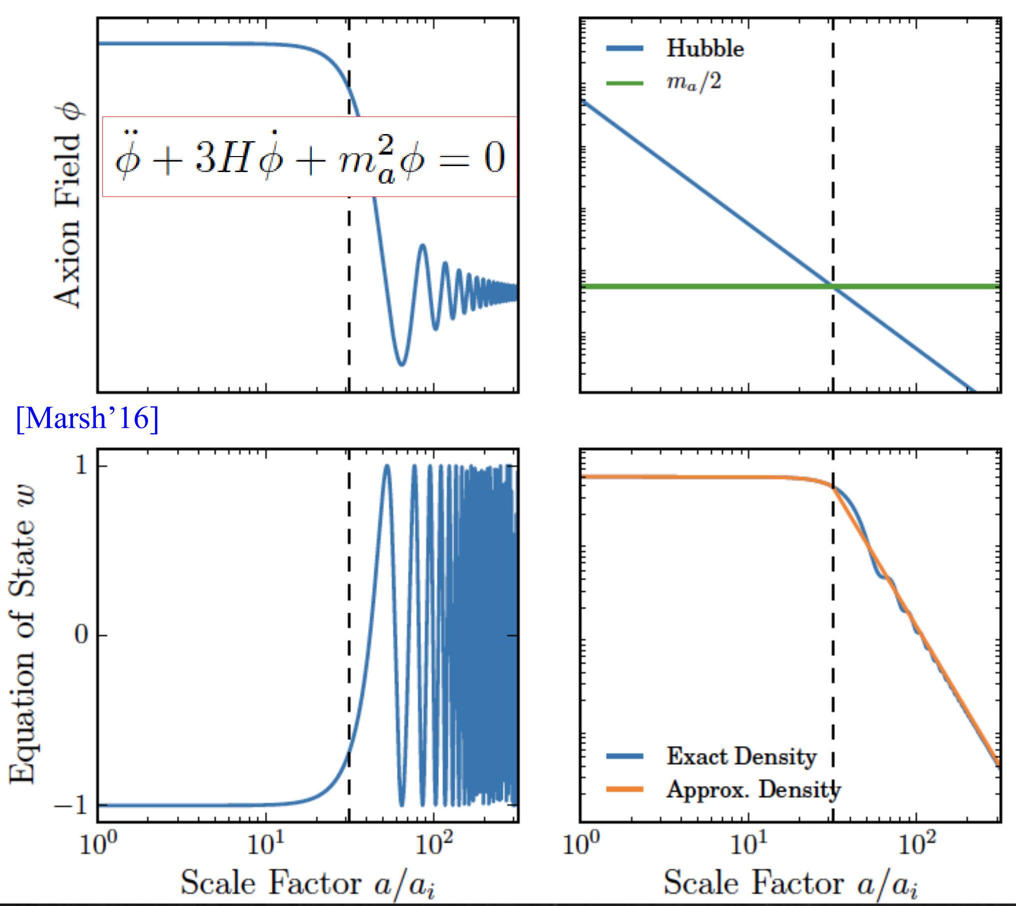


$$\ddot{\delta}_a + 2H\dot{\delta}_a + (k^2 c_{s,\text{eff}}^2/a^2 - 4\pi G\rho_a)\delta_a = 0$$

$$c_{s,\text{eff}}^2 \approx \frac{k^2}{4m_a^2a^2}$$

CDM / axion clusters/stars
ULDM
Solitons of different sizes

Setting scales in cosmological structures
1: before structure formation



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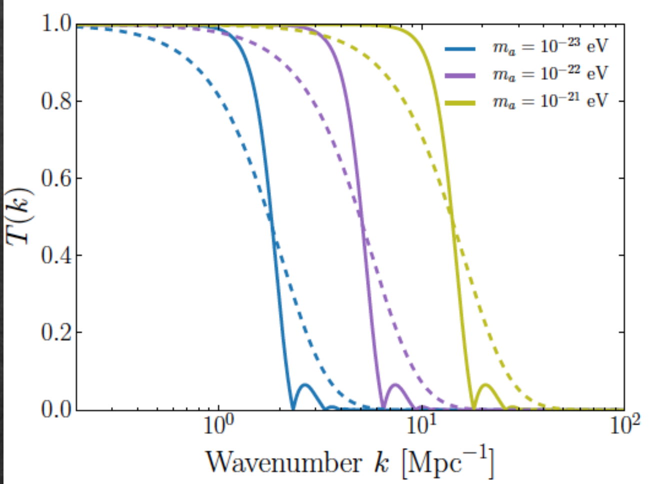

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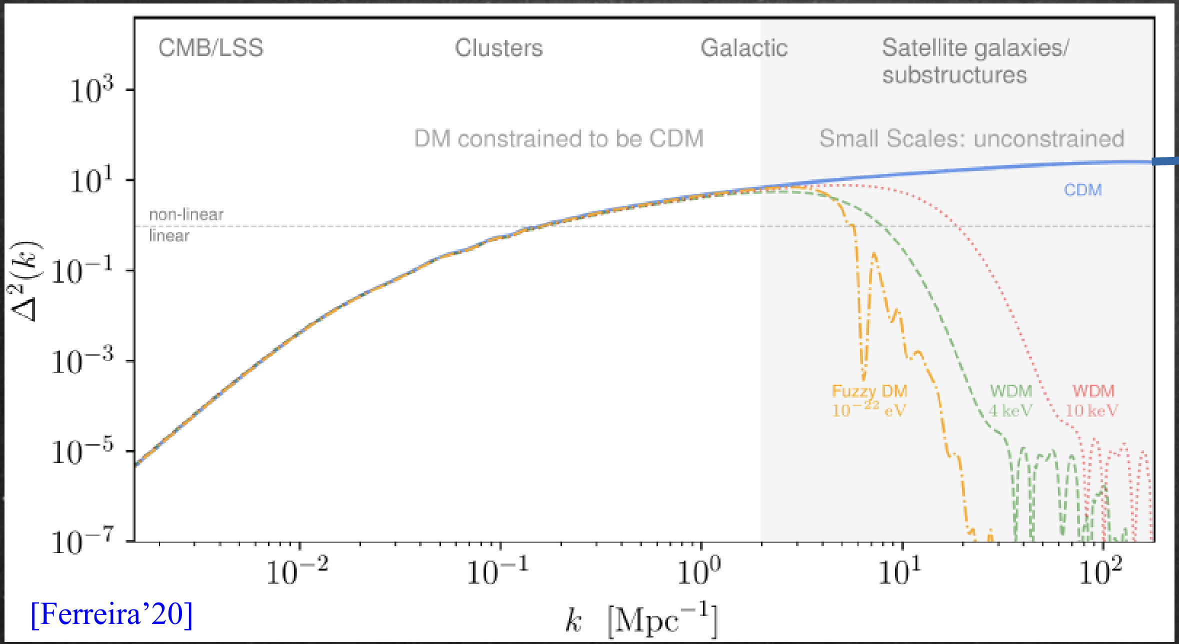
Setting scales in cosmological structures
1: before structure formation

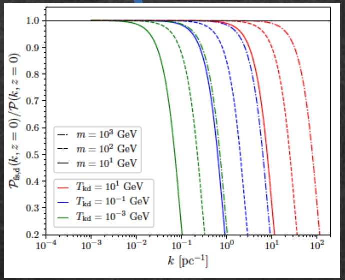
Linear matter power spectrum



[Ferreira'20]

WIMPs

QCD axions



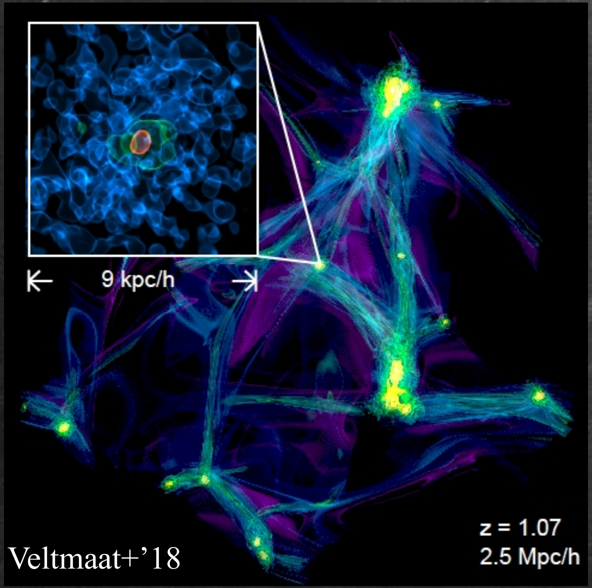
WDM

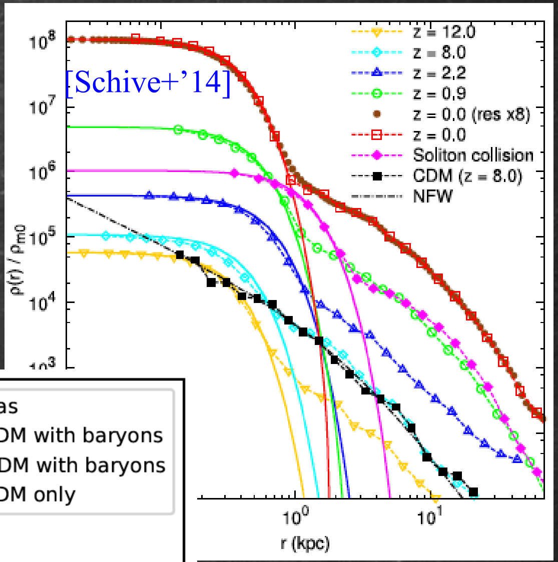
Fuzzy DM

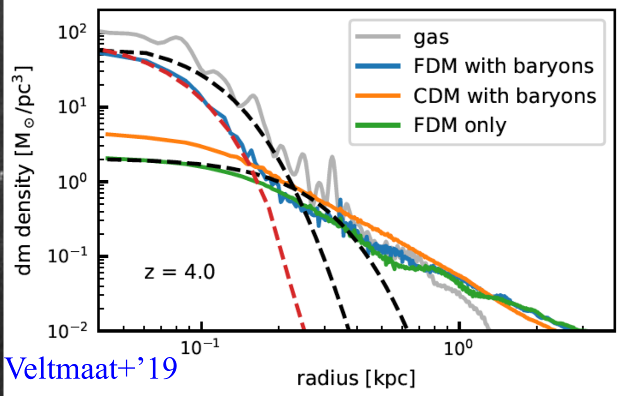
Setting scales in structures 2: after structure formation

Fuzzy, wave, ULS, etc.DM
Reviews in Ferreira'20, Niemeyer'20, Hui'21

g=0 => fuzzy DM
g<0 => ULA (attractive)
g>0 ULDM (repulsive)







$$\phi = \frac{1}{\sqrt{2ma^3}}\left(\psi\, e^{-imt} + \psi^*\, e^{imt}\right)$$

$$i\dot{\psi} = -\frac{3}{2}iH\psi - \frac{1}{2ma^2}\nabla^2\psi + \frac{g}{8m^2}|\psi|^2\psi + m\Phi\,\psi$$

$$\nabla^2\Phi = 4\pi G\,(\rho - \bar{\rho})$$

Scaling relations

$$M_{\rm soliton} \sim 6.7\times 10^7\,{\rm M_\odot}\,\frac{10^{-22}\,{\rm eV}}{m}\left(\frac{M_{\rm halo}}{10^{10}\,{\rm M_\odot}}\right)^{1/3}$$

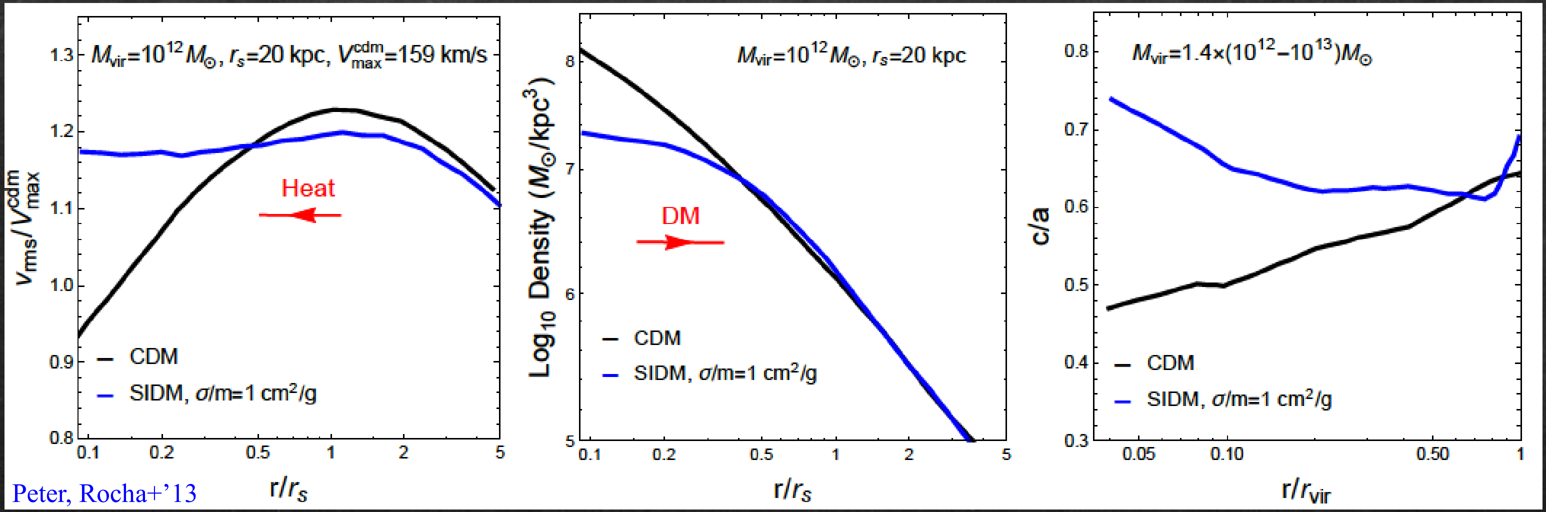
Extensive analytical work by Chavanis

Setting scales in structures 2: after structure formation

On small scales

Self-interacting DM
[e.g. Tulin&Yu'18, Adhikari+'22]

Cusps are flattened



Peter, Rocha+'13

$$R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ {\rm M_\odot/pc^3}}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm^2/g}}\right)$$

Setting scales in structures 2: after structure formation

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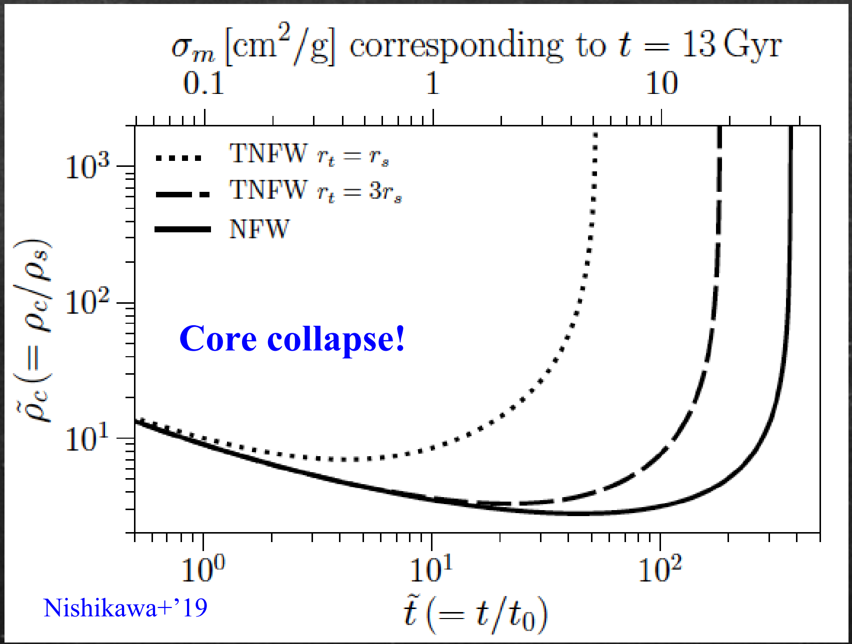
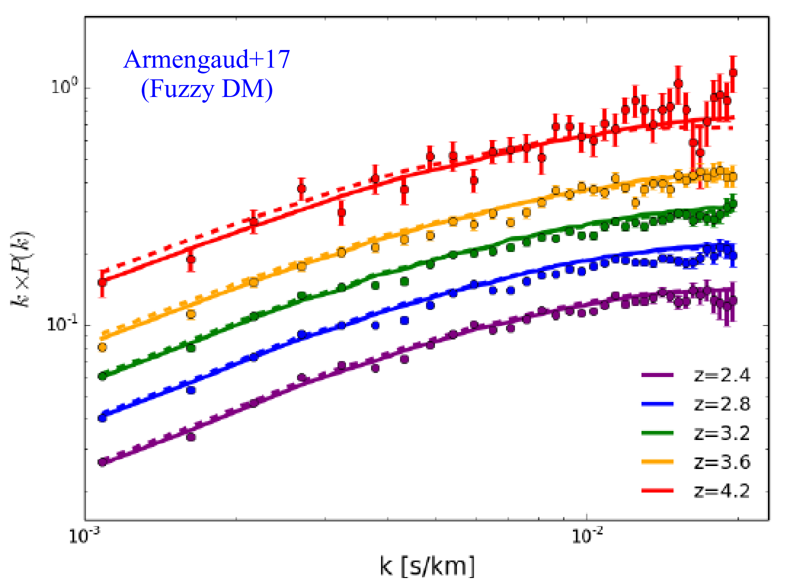


Gravothermal catastrophe possible

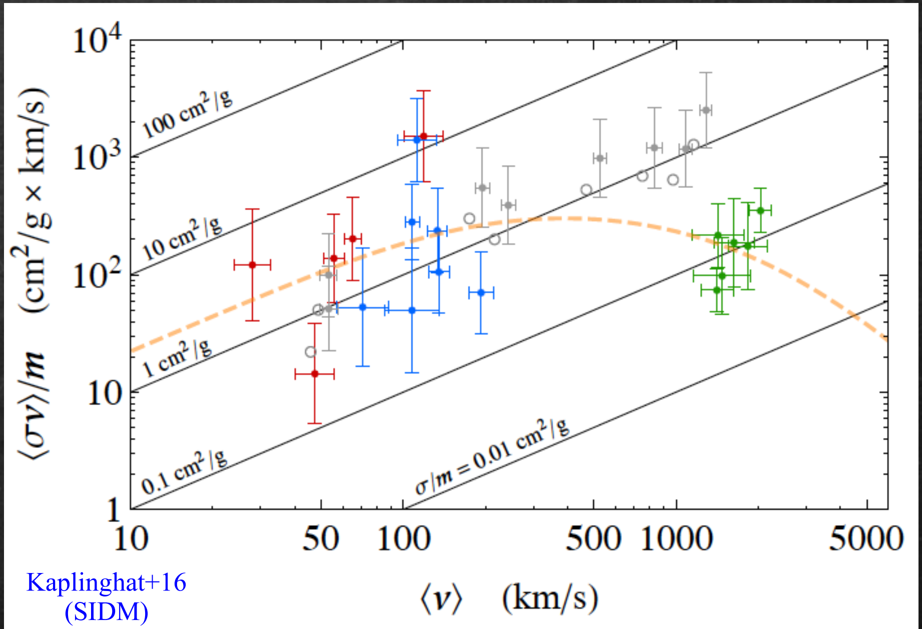
Seeds for SMBH formation?

Some constraints (ULDM & SIDM)



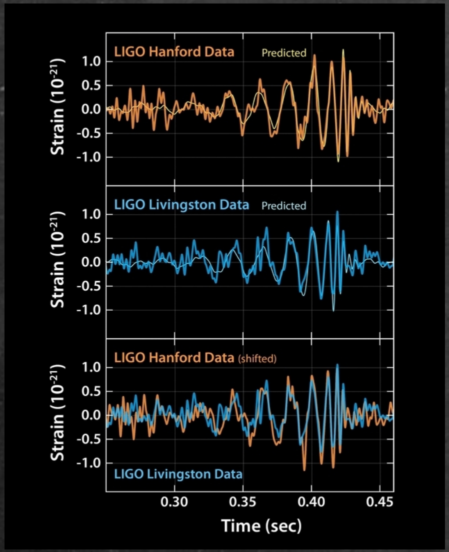
Excluded: $m_a < 2.3 \times 10^{-21}$ eV at 95 % CL

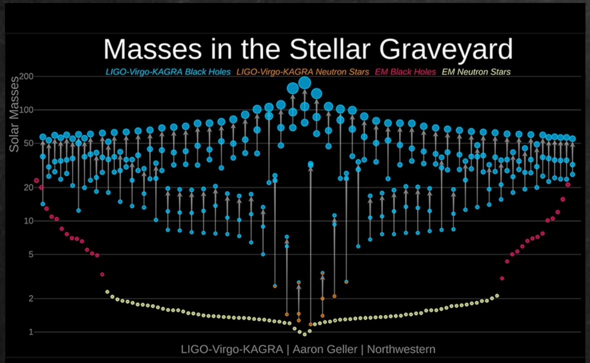
Many constraints, for example:
- Lyman-alpha power spectrum
- Rotation curves
- Dynamics/survival of dwarf galaxies
- Counting of satellites
- Cluster collisions (SIDM)
- Stability / core collapse
- Etc.



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)

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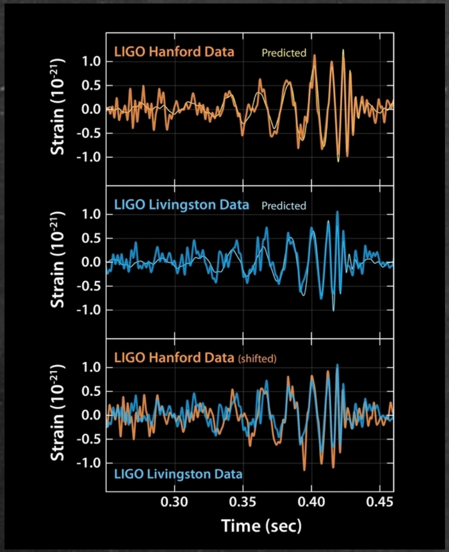
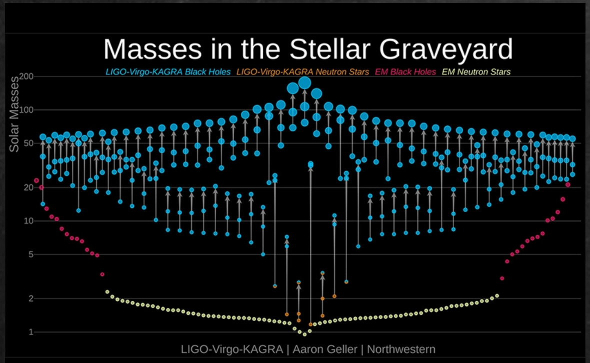
LIGO+VIRGO '15-16





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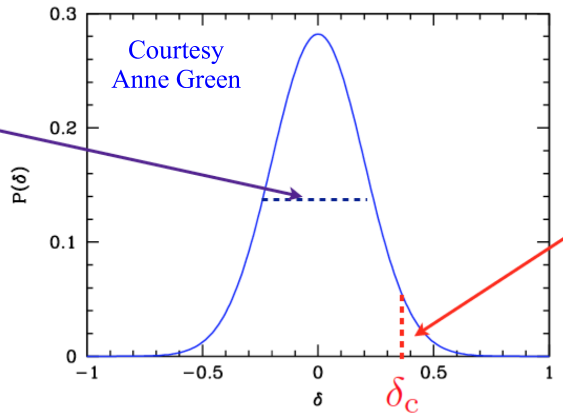
NB: Merger rate has now turned to a constraint on PBH DM
(clustering effects difficult to work out)
[Hütsi+, Ali-Haïmoud+, Jedamzik, etc.]

PBH links to power spectrum and constraints

$\sigma(M_H)$ (mass variance)
typical size of fluctuations

Determined by amplitude
of primordial power spectrum



PBH forming
fluctuations

Critical threshold
[Zeldovich, Novikov, Hawking, Carr]

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

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

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

Gaussian spectrum →

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

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

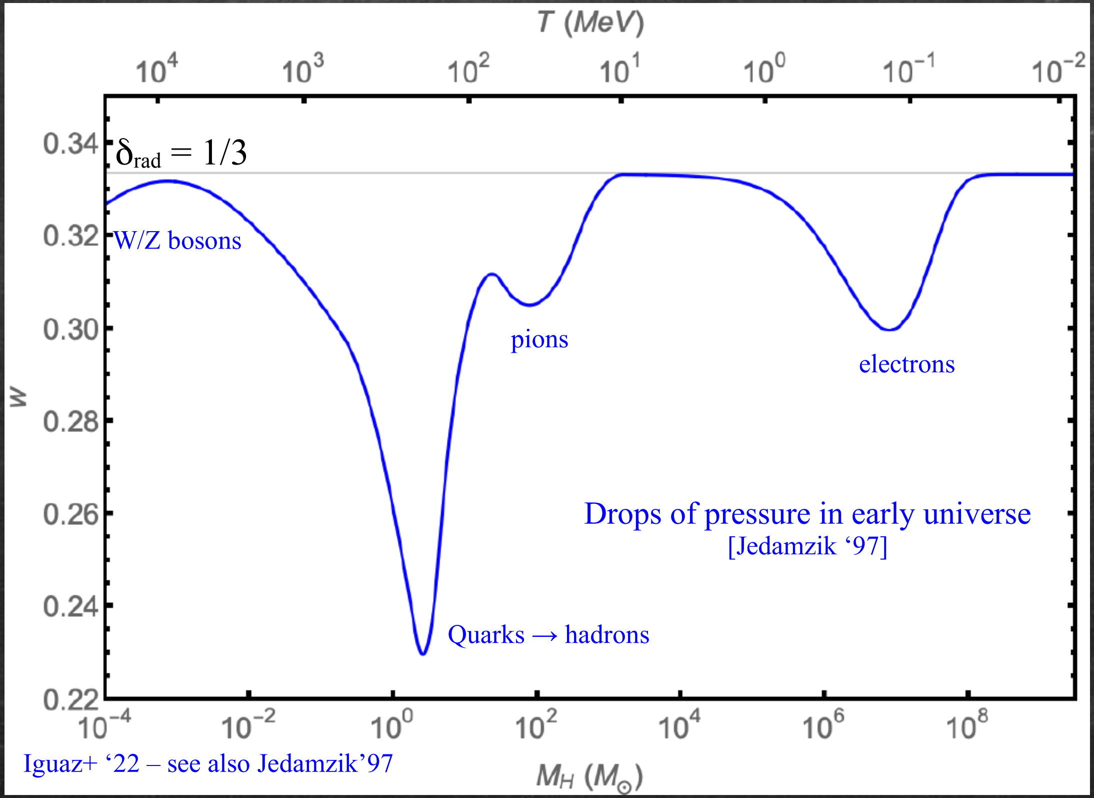
On CMB scales →

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

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



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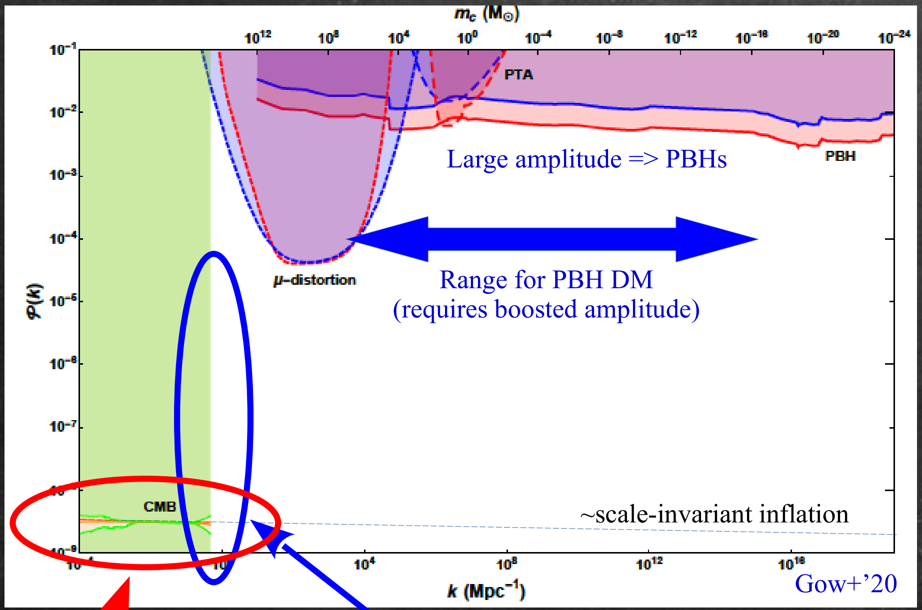
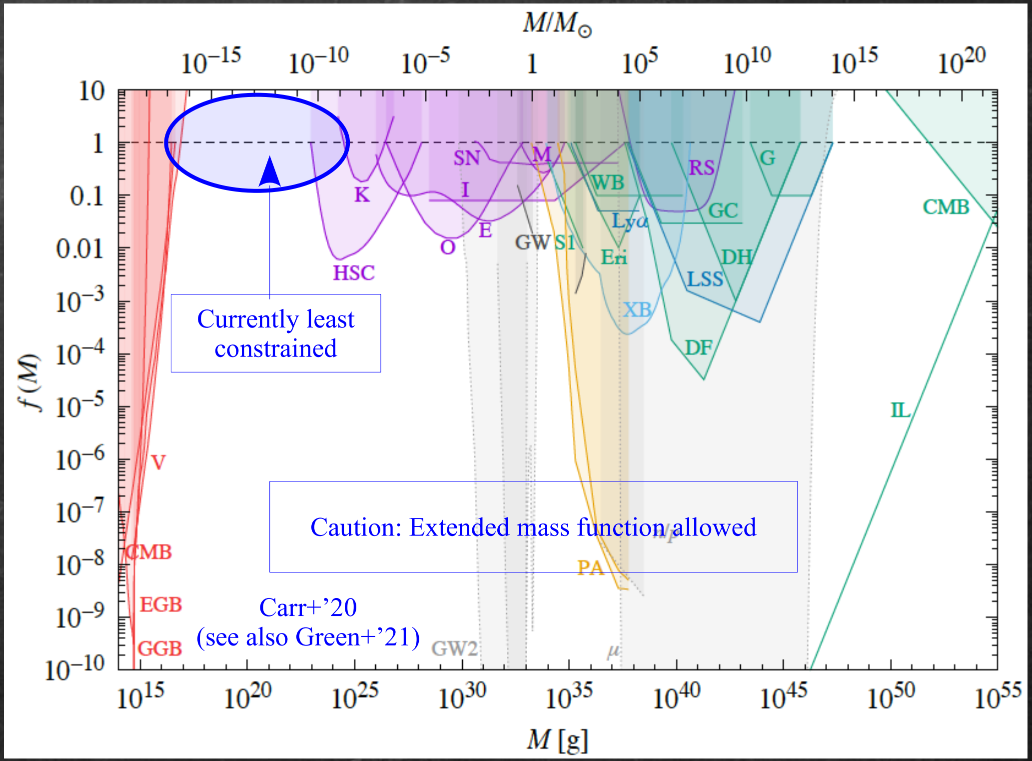
PBH links to power spectrum and constraints

Primordial power spectrum



Constraints on PBH DM fraction

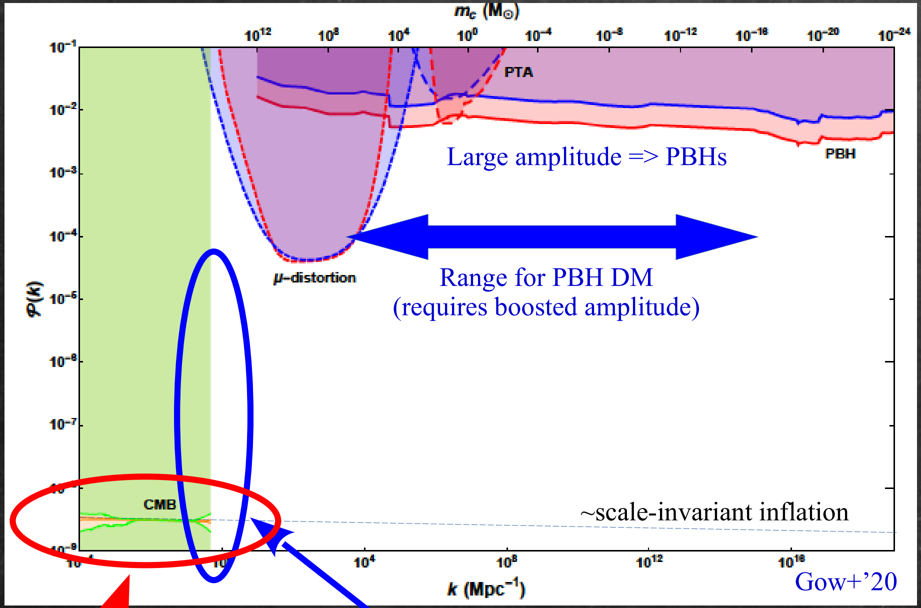


Current CMB constraints
[Planck+'18]

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

PBH links to power spectrum and constraints

Primordial power spectrum



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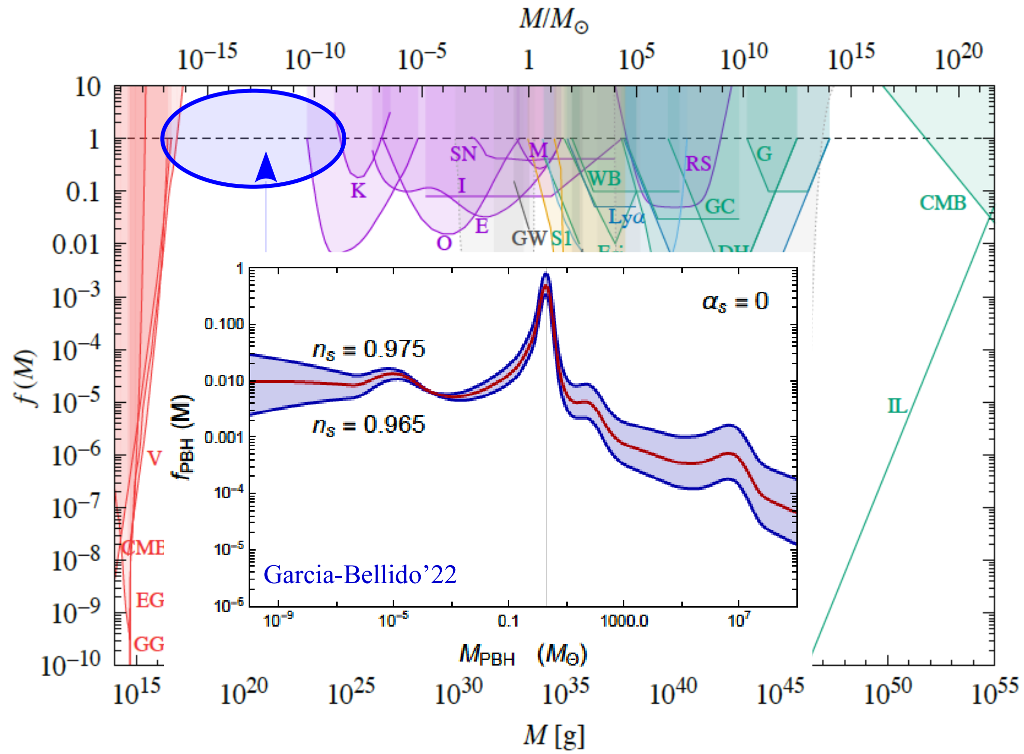


Current CMB constraints
[Planck+'18]

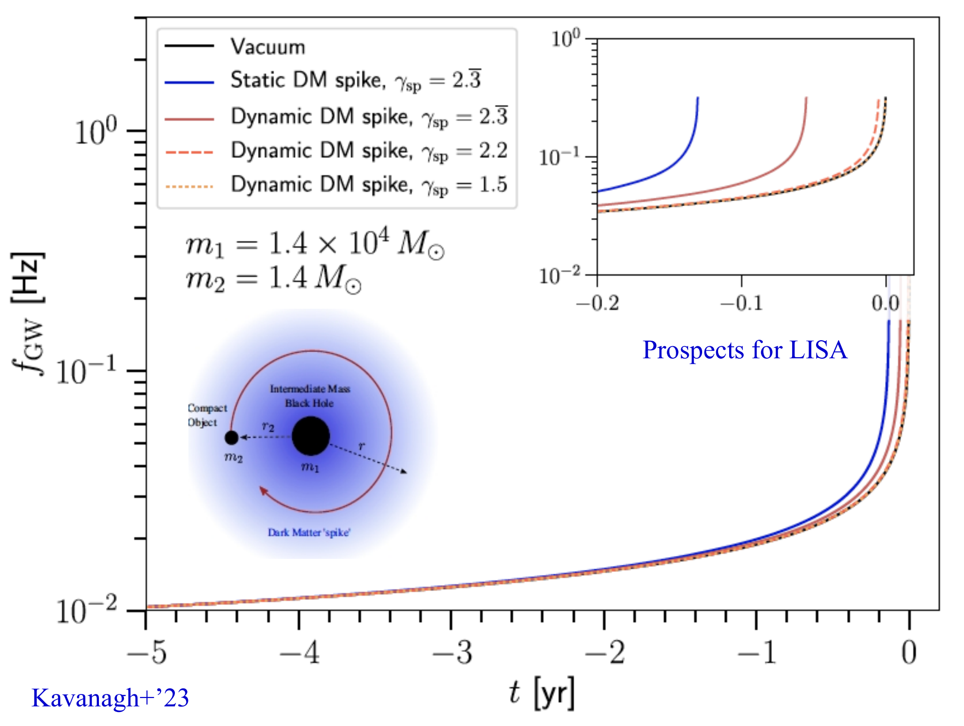
Current LSS constraints
[e.g. Ly-alpha]

Some activity in France, e.g. LPENS, IAP, etc.

Models exist that give f~1
e.g. Critical Higgs inflation
[e.g. Bezrukov+'14, Ezquiaga+'17]
→ Subsolar BH mergers expected!
++ Clusters of PBHs

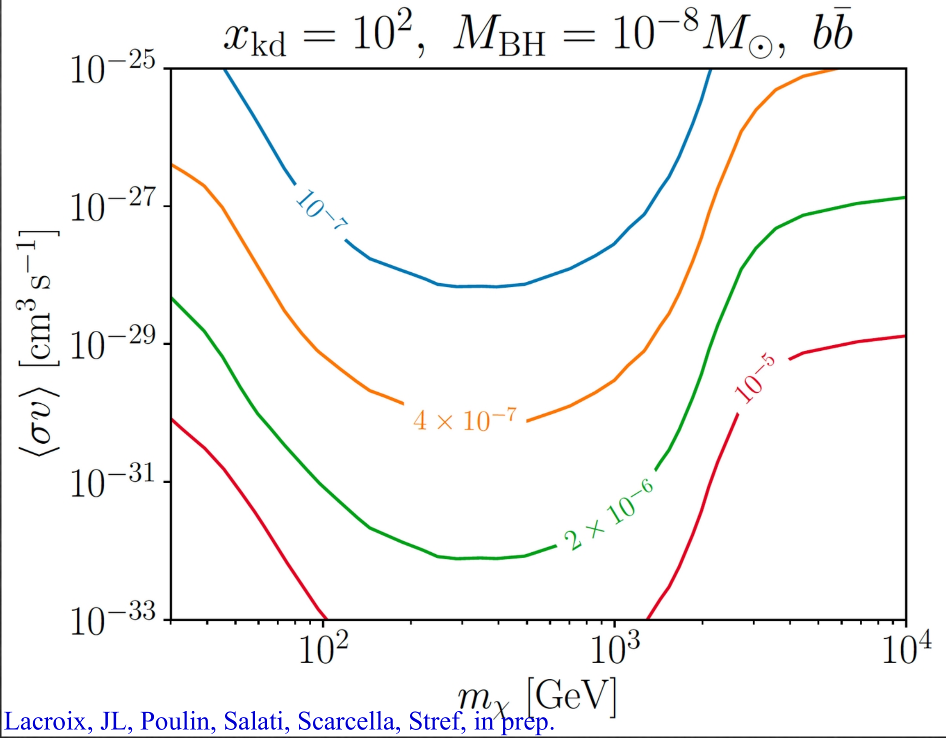
Coexistence of particle/wave DM and (P)BHs

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]

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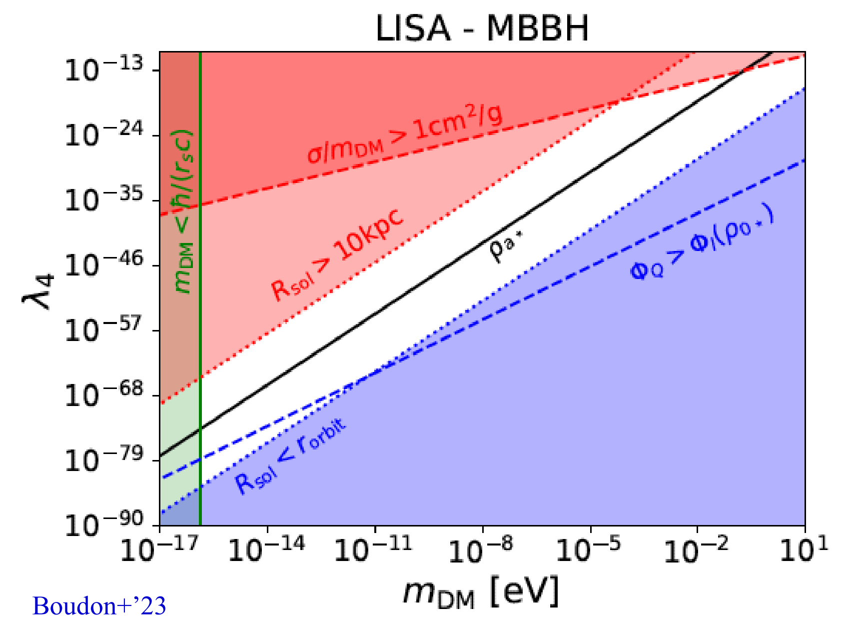
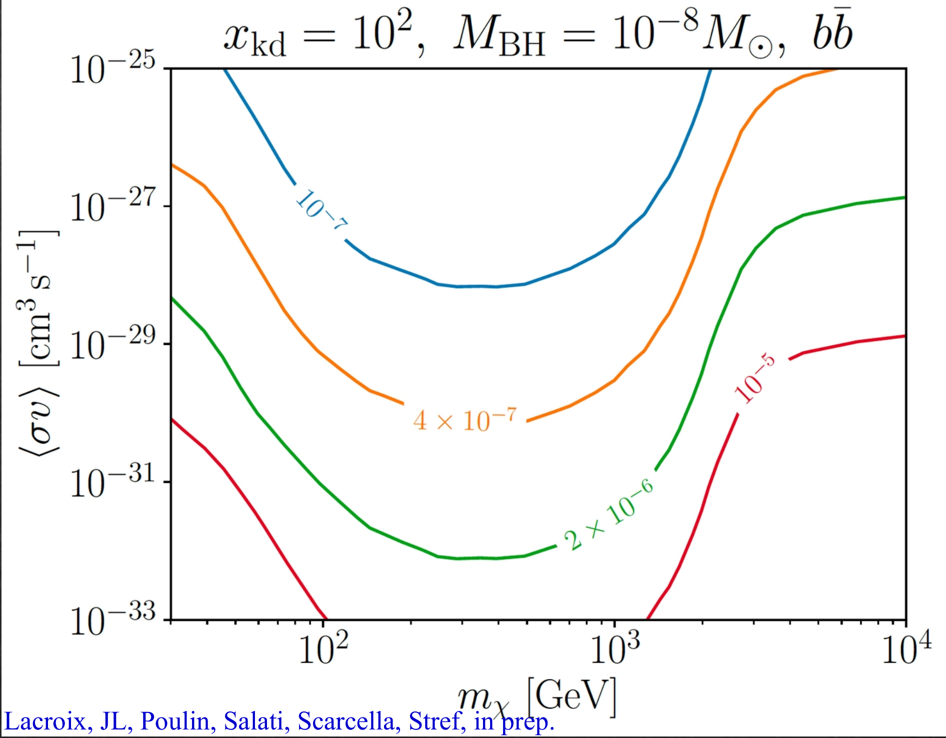


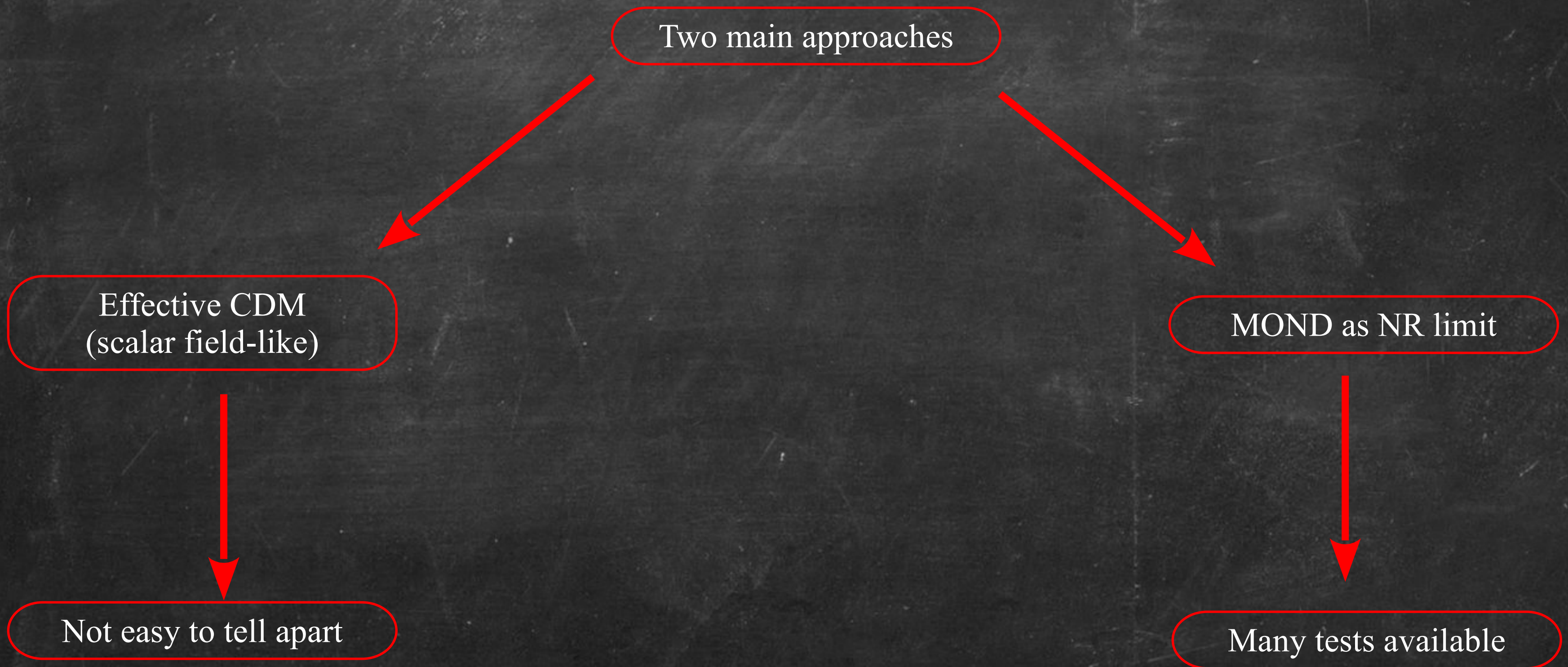
Active field also in France (e.g. IPhT group)

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



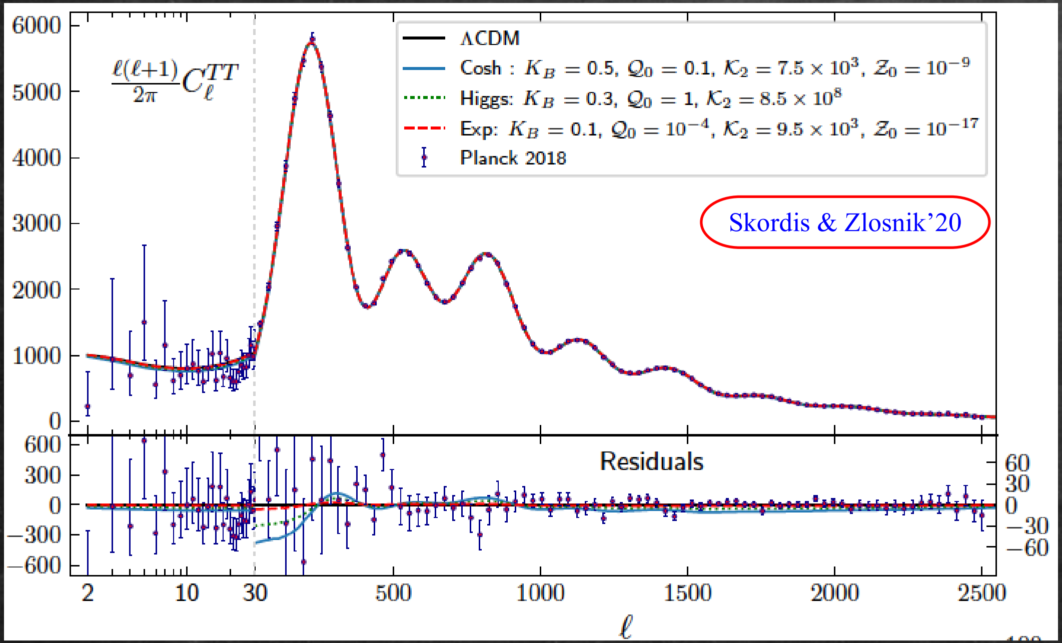
=> small fraction of PBHs may have dramatic impact
on s-wave annihilation WIMP scenario!
[See also Eroschenko'16, Boucenna+'18,Carr+'21, Boudaud+'21, Gines+'22]

Modified gravity as effective dark matter?



Modified gravity as effective dark matter?

MOND case: Some recent successes … but also growing issues



Strong constraints on the gravitational law from *Gaia* DR3 wide binaries

Indranil Banik[1⋆], Charalambos Pittordis[2], Will Sutherland[2], Benoit Famaey[3], Rodrigo Ibata[3], Steffen Mieske[4] and Hongsheng Zhao[1]

to the stars in each WB. We interpolate between the Newtonian and Milgromian predictions using the parameter $\alpha_{\rm grav}$, with 0 indicating Newtonian gravity and 1 indicating MOND. Directly comparing the best Newtonian and Milgromian models reveals that Newtonian dynamics is preferred at 19σ confidence. Using a complementary Markov Chain Monte Carlo analysis, we find that $\alpha_{\rm grav} = -0.021^{+0.065}_{-0.045}$, which is fully consistent with Newtonian gravity but excludes MOND at 16σ confidence. This is in line with the similar result of Pittordis and Sutherland using a

For now:
CMB passed ... but …
Structure formation a challenge + pbs on small scales
(solutions become involved: screening, etc.)

Summary

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

- Issues on small scales prompted new perspectives: Ultra-light DM and Self-Interacting DM (or both)
++ LHC? WIMPs/FIMPs not fashionable anymore? (caveat: fashion is not science)

- Baryonic physics? (must be better understood irrespective of DM)

- Structuring on small scales: can tell candidates apart, tests with gravitational/dynamical probes
=> Important theoretical + observational work expected (e.g. Gaia, LSST, etc.)
++ Small scales connect physics of inflation + nature of DM

- GWs revived interest in PBHs: direct links to inflation and/or phase transitions

- Active research on BH/DM interactions

- Modified gravity vs. particle/wave/BH dark matter still debated

- Structure formation a challenge to modified gravity asymptoting to MOND

BACKUP