Dark matter in astrophysics/cosmology

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1. A brief introduction to cosmology
2. Observational evidence for dark matter
3. Dark matter distribution
4. **Constraints on the properties of dark matter**
5. overspill/what would you like to hear more about?

Constraints on the properties of dark matter

Will focus on how DM particle interactions (deviations from 'vanilla' collisionless CDM) affect the DM distribution and hence how these interactions are probed by astronomical observations, see Tracey Slatyer's lectures for indirect detection.

Warm DM (WDM)

Self-interacting DM (SIDM)

Non-particle dark matter

Recommended further reading

- ‘Probing the fundamental nature of dark matter with the Large Synoptic Survey Telescope’, LSST dark matter group, arXiv:1902.01055. nb LSST now known as the Vera C. Rubin Observatory.

- ‘Gravitational probes of dark matter physics’, Buckley & Peter, arXiv:1712.06615, Phys. Rept.

- ‘Small-scale challenges to the ΛCDM paradigm’, Bullock & Boylan-Kolchin, arXiv. 1707.04256, Ann. Rev. Astro.

- ‘Dark matter self-interactions and small scale structure’, Tulin & Yu, arXiv:1705.02358, Phys. Rept.

How do dark matter particle interactions affect its distribution?

Particle interactions can lead to **primordial** and/or **evolutionary** deviations from vanilla CDM (c.f. Buckley & Peter):

Primordial: modifications to evolution of density perturbations $\longrightarrow$ modify (initial) halo mass function

Evolutionary: DM interactions within halos $\longrightarrow$ modify density profiles, sub-halo mass function & radial distribution, halo shapes,…

Will focus mainly on 2 widely studied cases:

warm dark matter

self-interacting dark matter

other possibilities include baryon scattering DM, and fuzzy DM (see Lam Hui's lectures).

Warm dark matter (WDM)

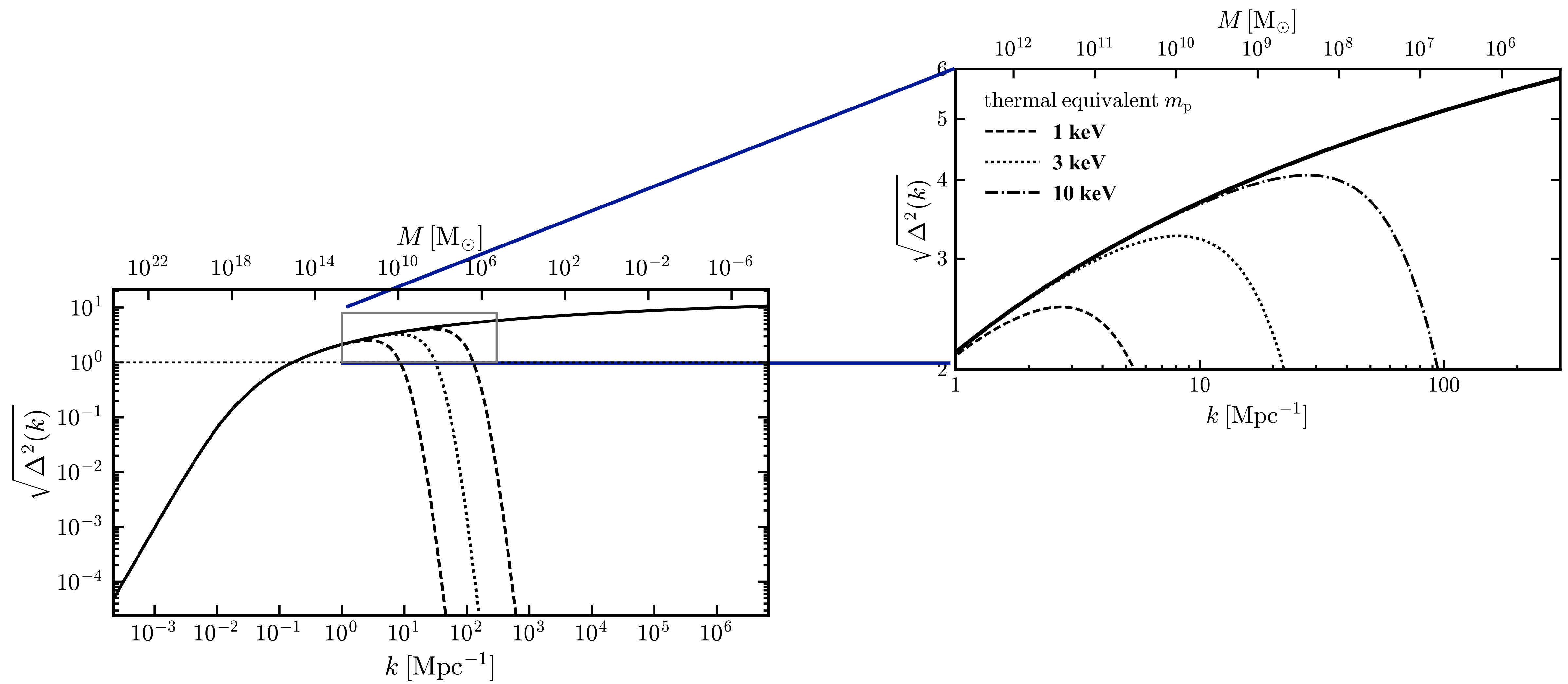
Semi-relativistic at creation, mass~keV, velocity dispersion today ~ $0.03\,\mathrm{km\,s^{-1}}$.
Bond & Szalay

Concrete candidate: sterile neutrino (see Abazajian and Joachim Kopp's lectures) see e.g. Bullock & Boylan-Kolchin and references therein

For *thermal** warm dark matter, free streaming erases perturbations and suppresses the power spectrum on scales smaller than

$$M_{\rm h} \sim 10^{10} \left(\frac{m_{\rm wdm}}{1\,{\rm keV}}\right)^{-3.33} M_\odot$$

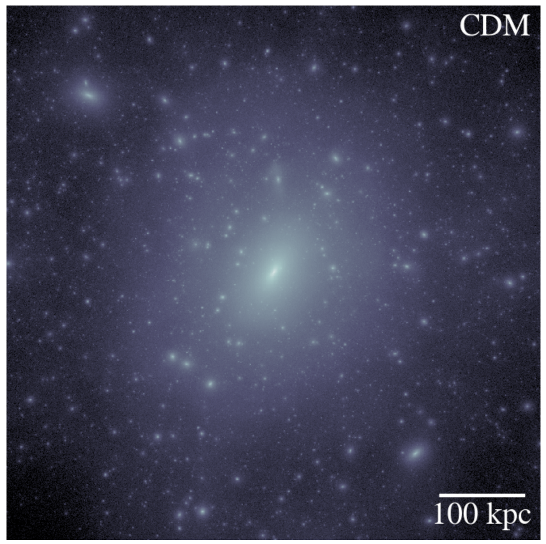
consequently structure formation is suppressed below this mass.

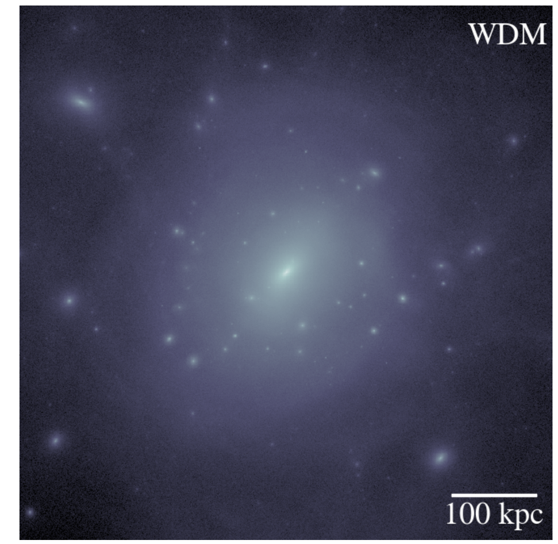


* depends on velocity distribution of particles, for sterile neutrinos (see Joachim Kopp's lectures) relationship depends on thermal history. e.g. Abazajian

Comparison of Milky Way mass halos simulated with
CDM and WDM

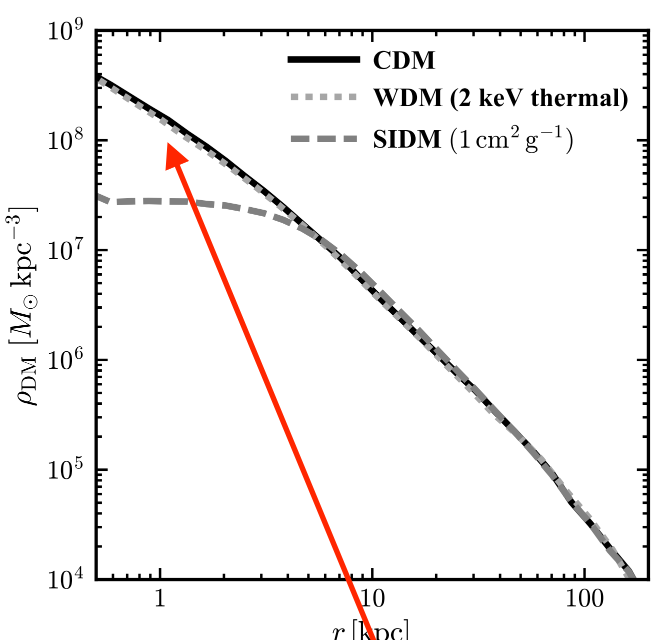
Bullock & Boylan-Kolchin

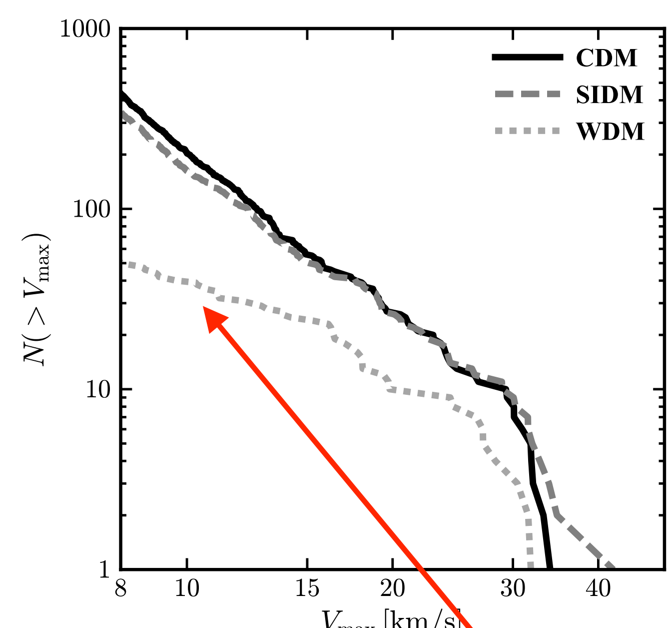




density profile, $\rho(r)$

sub-halo 'mass'-function





V_{max}=maximum value of circular speed

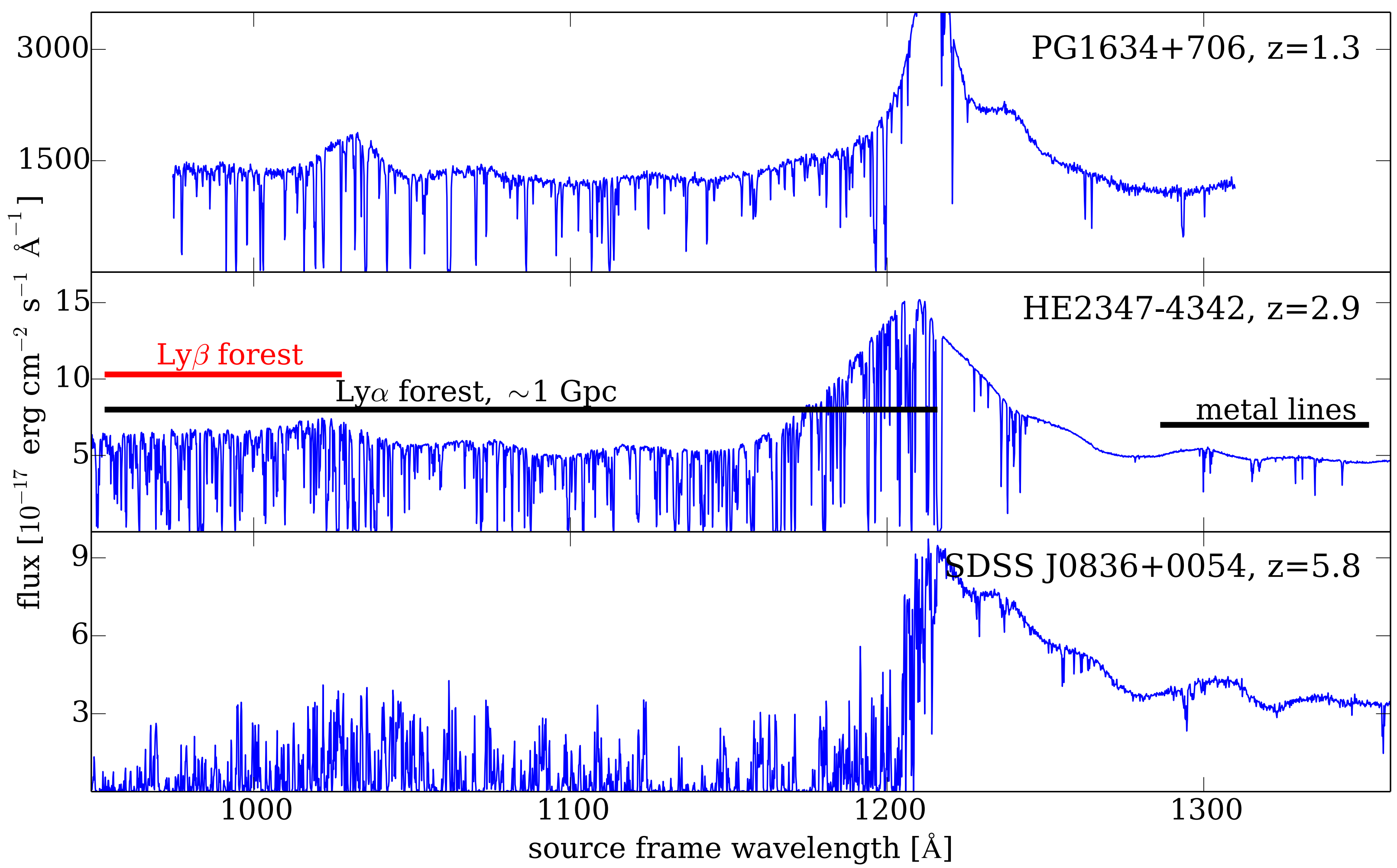
WDM halos have cuspy density profiles like CDM, but there are less light halos.

Probes of linear power spectrum/halo mass-function

i) Lyman-alpha forest

See e.g. McQuinn Sec. 2.1.1 and Gnedin Sec. 2.1.4

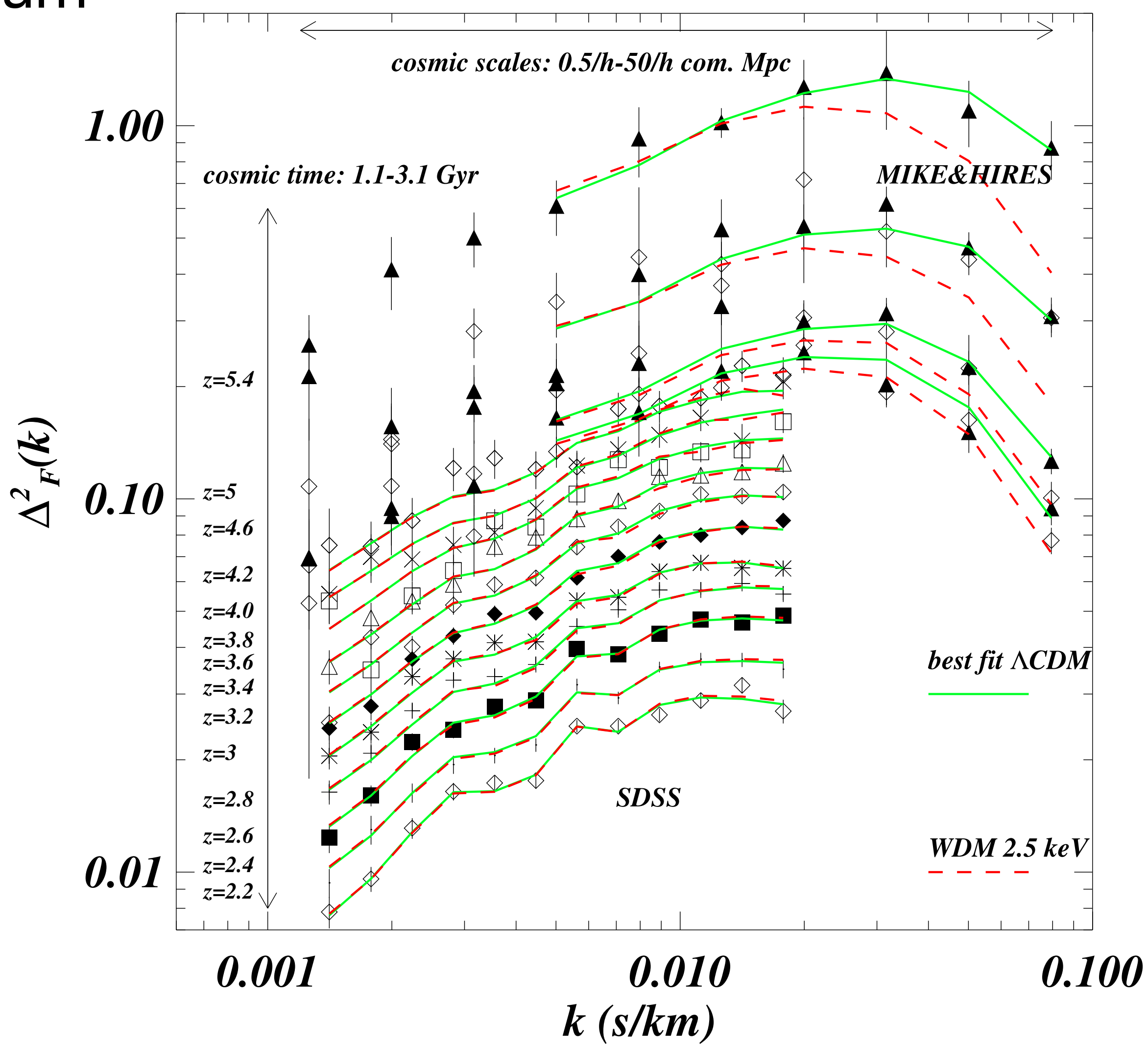
Absorption lines in spectra of galaxies and quasars from Lyman-alpha (n=1 to n=2) electron transition in intergalactic neutral hydrogen 'clouds'.



McQuinn

Absorption/transmission probability depends on matter density, and hence power spectrum. Can constrain WDM mass from (absence of) damping at high k.
Narayanan et al.

matter power spectrum



best fit ΛCDM

WDM m=2.5keV

increasing red-shift

wavenumber k

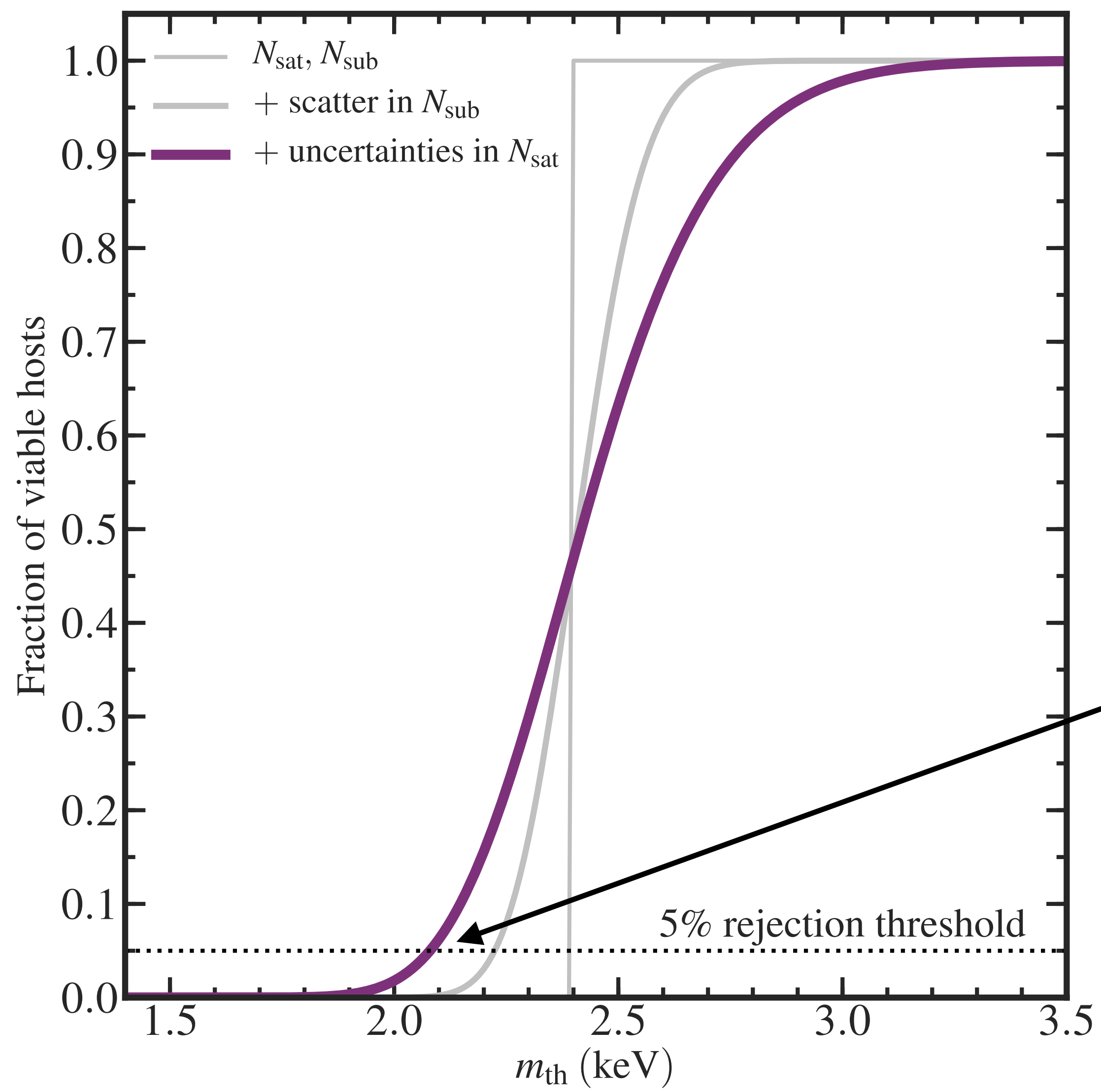
Gnedin

Limit on mass of thermal relic: m > (3-5) keV Irsic et al., Palanque-Delabrouille et al.

ii) Milky Way satellites

Compare predictions for abundance of satellite (dwarf) galaxies in MW-mass halos with observations (taking into account incompleteness of observations)
e.g. Polisensky & Ricotti, …, Newton et al.

Fraction of MW-mass WDM systems with at least as many satellites as inferred for the MW.



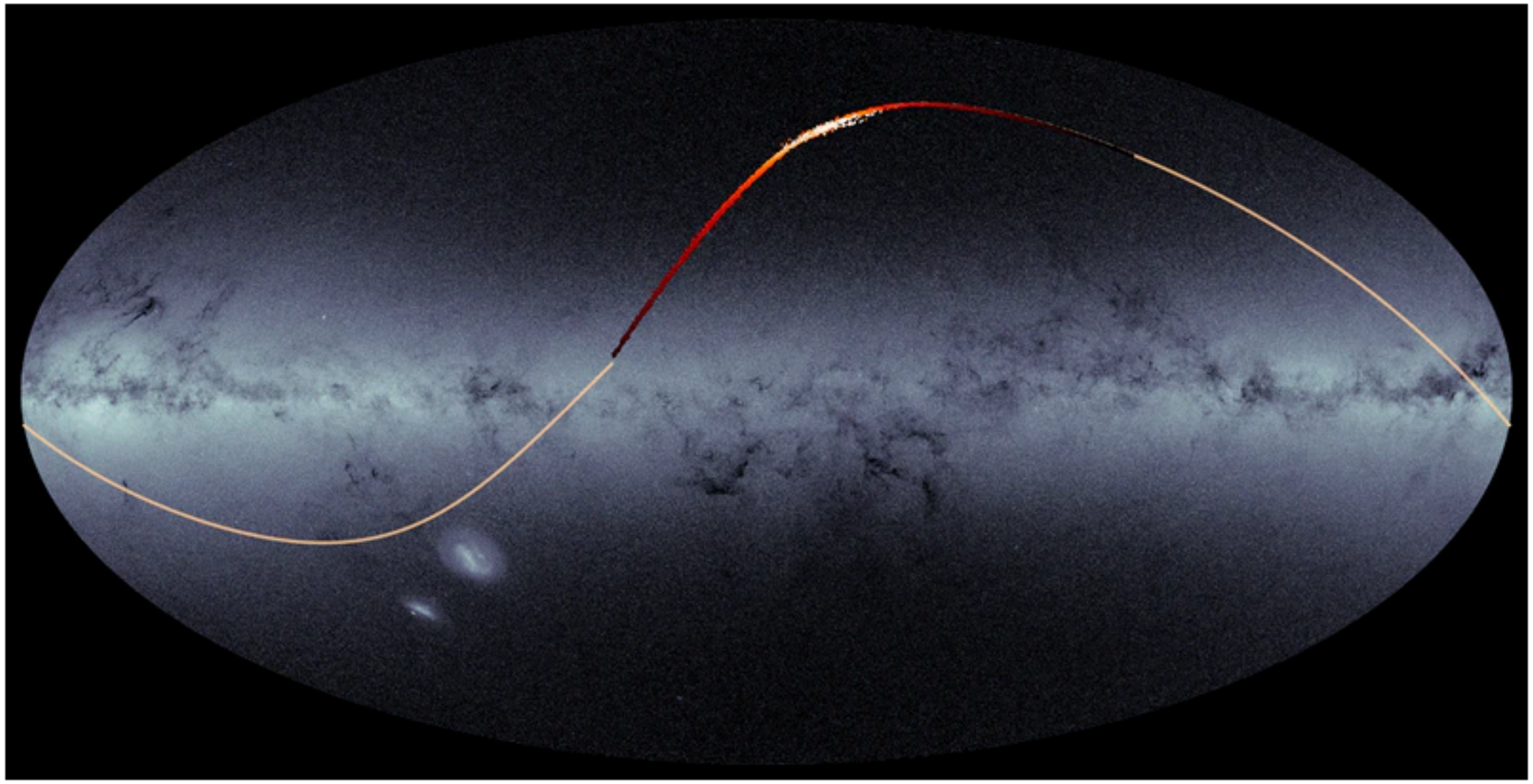
limit on mass of thermal relic m > 2 keV

Newton et al.

iii) gaps in stellar streams

A DM sub-halo passing by a stellar stream gives the stars a kick and perturbs their orbits $\longrightarrow$ gap in stream, observable if $M_{\rm sh} \gtrsim 10^5 M_\odot$. Carlberg

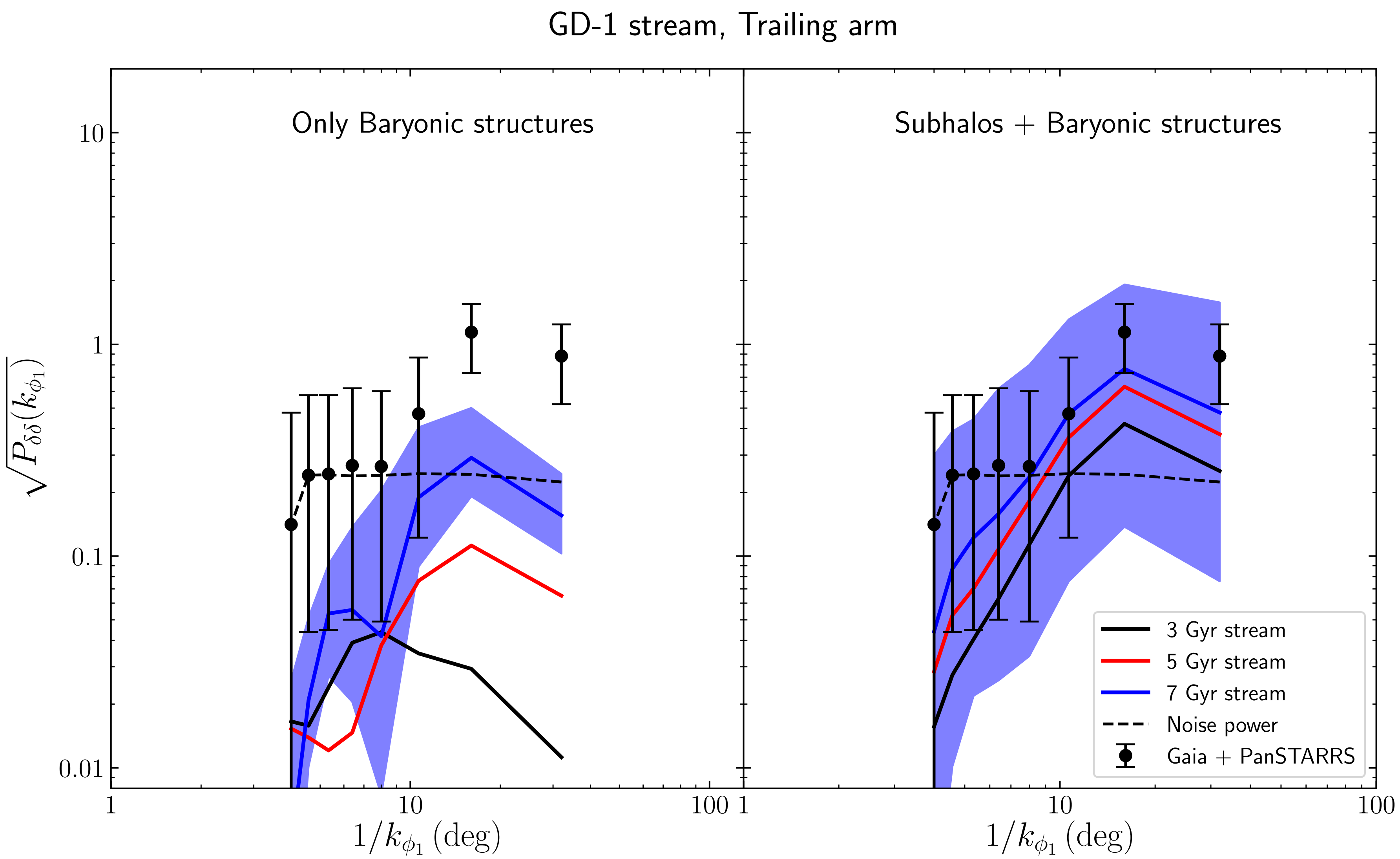
GD-1 stream



Bonaca, Gaia/ESA

Density power spectrum of trailing arm of GD-1 stream

Data compared with simulations without (left) and with (right) DM sub-halos.



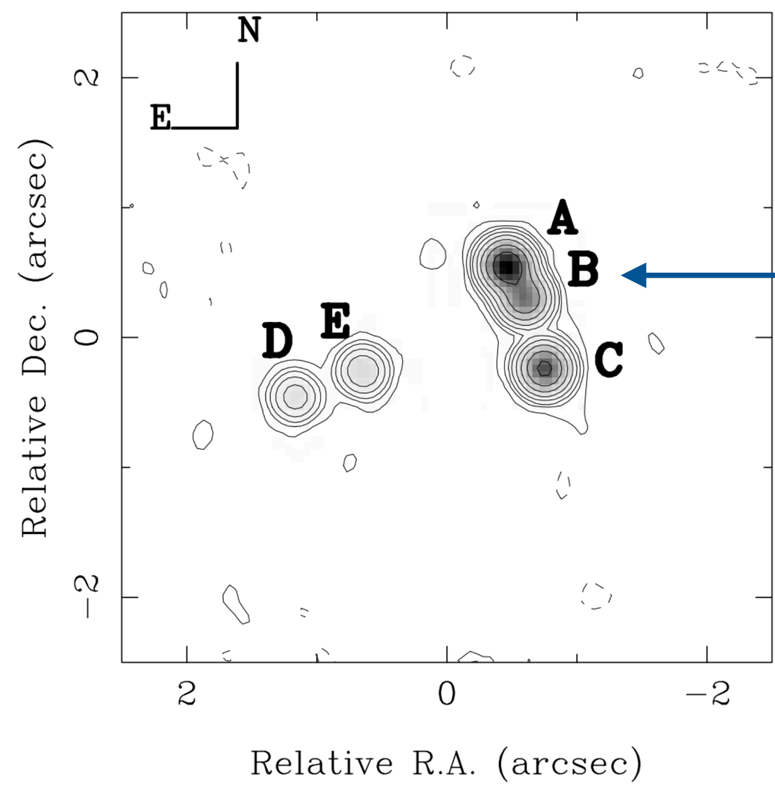
limit on mass of thermal relic: m > 4.6 keV.

Banik et al.

iv) strong lensing

flux ratio anomalies

In strong lensing systems with multiple images, substructure can affect one of the images, leading to anomalies in the relative fluxes of the images. Mao & Schneider, Dalal & Kochanek



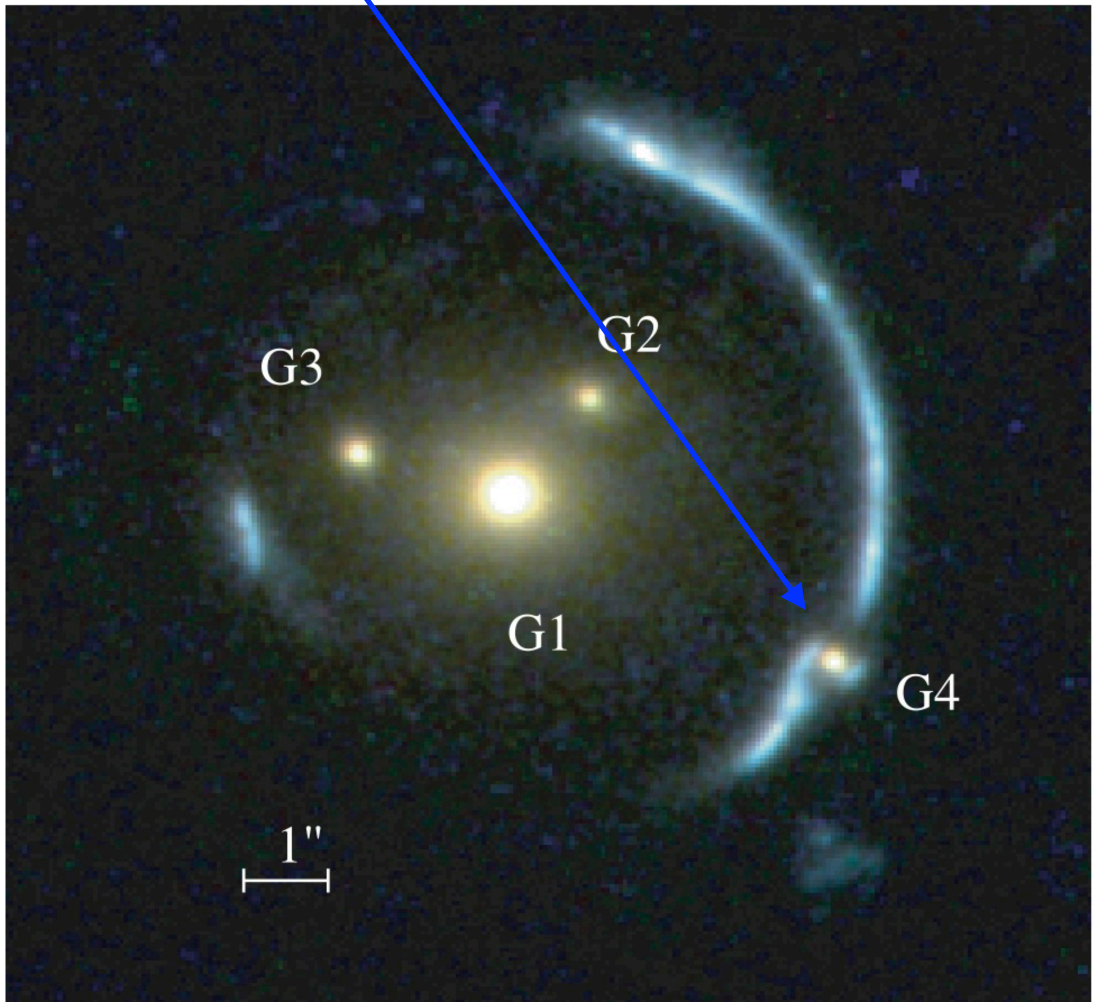
B should be brightest of A-C if lens is smooth, but is in fact dimmest.

Fassnacht et al.

Limit on mass of thermal relic from analysis of multiple systems: m > 5 keV
Gilman et al., Hsueh et al.

gravitational imaging

Substructure can change shape of lensed emission, detectable in strong lens systems where galaxy is lensed in long arcs. Koopmans



(in this case lens is luminous galaxy)

Vegetti et al.

Limit on mass of thermal relic from analysis of multiple systems: m > 0.2 keV
Vegetti et al., Rittondale et al.

Joint analysis Enzi et al.

Table 4. A summary of the lower limits reported on the thermal relic dark matter particle mass for a selection of past studies. Note that additional model assumptions and assumed parameter ranges can widely differ. When derived for different assumptions, we provide more than one of the limits.

Reference	Probe	$\frac{m_{\text{th}}}{\text{keV}}$ 95% c.l.
this work	see Section 3	6.048
Birrer et al. (2017)	Grav. Imaging	2.0
V18 (Original)	Grav. Imaging	0.3
R19 (Original)	Grav. Imaging	0.26
Gilman et al. (2019a)	Flux Ratios	3.1, 4.4
Gilman et al. (2019b)	Flux Ratios	5.2
Hsueh et al. (2019)	Flux Ratios	5.6
Banik et al. (2018, 2019)	Stellar streams	4.6, 6.3
Alvey et al. (2020)	Dwarf spheroidals	0.59, 0.41
Viel et al. (2005)	Lyman-α	0.55
Viel et al. (2006)	Lyman-α	2.0
Seljak et al. (2006)	Lyman-α	2.5
Iršič et al. (2017)	Lyman-α	3.5, 5.3
M18 (Original)	Lyman-α	2.7, 3.6
Polisensky & Ricotti (2011)	MW satellites	2.3
Kennedy et al. (2014)	MW satellites	1.3, 5.0
Jethwa et al. (2017)	MW satellites	2.9
Nadler et al. (2019b)	MW satellites	3.26
Nadler et al. (2020a)	MW satellites	6.5
Nadler et al. (2021)	MW satellites & Flux Ratios	9.7
N20 (Original)	MW satellites	2.02, 3.99

Self-interacting dark matter (SIDM)

Spergel & Steinhardt, and see e.g. LSST dark matter group + Tulin & Yu and references therein.

Dark matter particles scatter elastically with each other: DM + DM → DM + DM.

Interaction rate:

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

Mean-free path between interactions, $\lambda = (n\sigma)^{-1} = (\rho\sigma/m)^{-1}$, is of order kpc for $\sigma/m \sim (0.1 - 10)\,{\rm cm}^2/{\rm g}$ $\longrightarrow$ thermalisation in inner regions of halos, and formation of a **constant density core**.

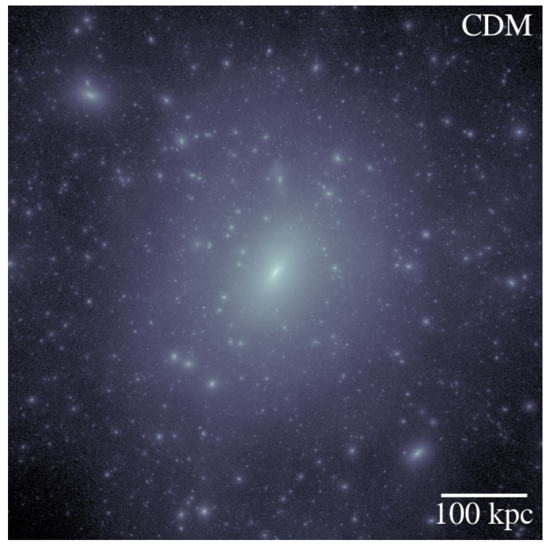
nb in specific particle physics (e.g. dark photon) models:

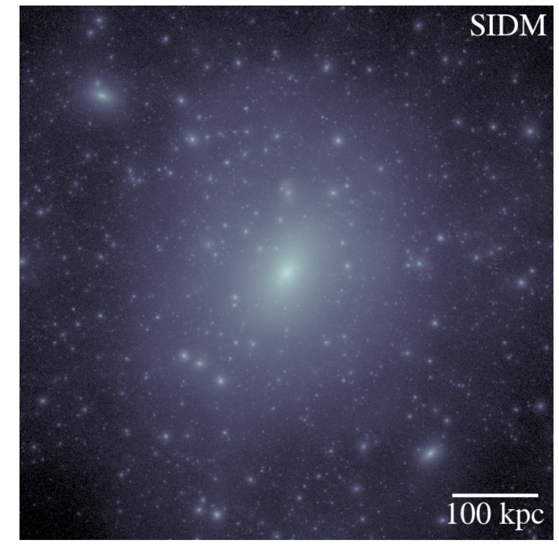
i) σ/m can be velocity dependent (so different in different mass halos),

ii) coupling with other particles in early Universe can suppress power spectrum (& hence structure formation) on small scales.

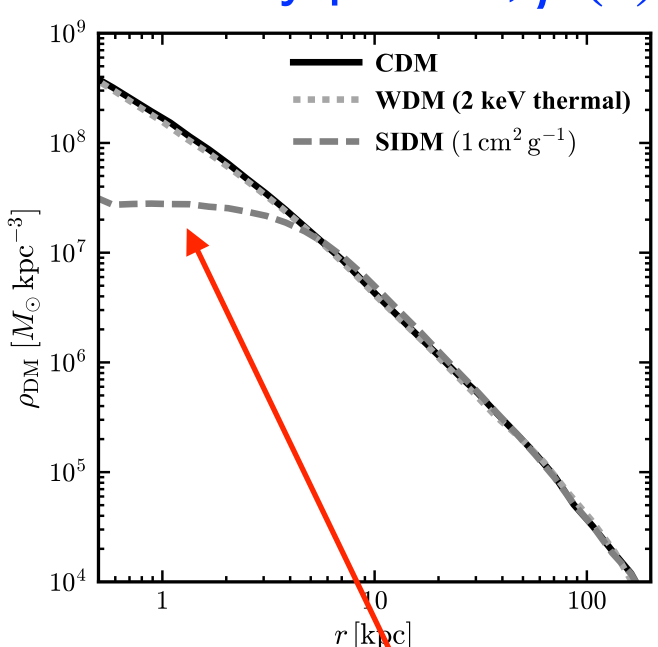
Comparison of Milky Way mass halos simulated with CDM and SIDM

Bullock & Boylan-Kolchin

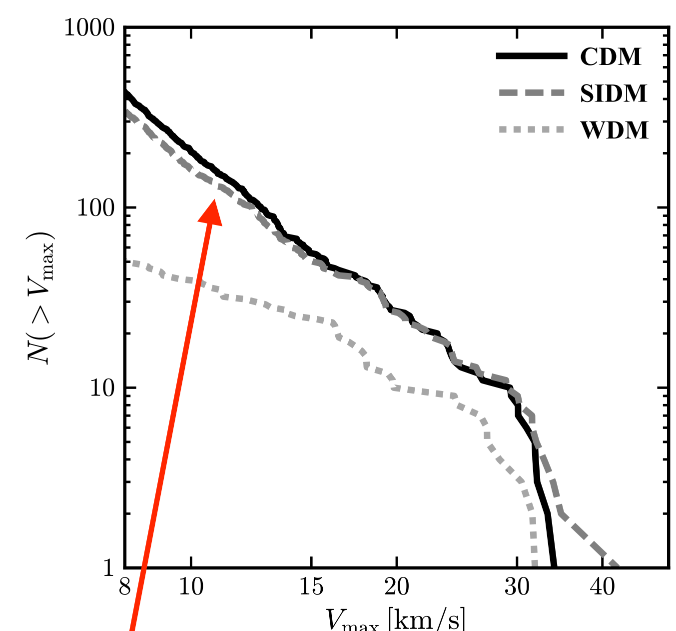




density profile, $\rho(r)$



sub-halo 'mass'-function



V_{max}=maximum value of circular speed

SIDM halos have constant density cores, but sub-halo mass function is similar to CDM.

bullet cluster (and other mergers)

See e.g. Tulin & Yu

X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

DM self-interaction transfer momentum between cluster halos, so they lag behind collisionless galaxies $\longrightarrow$ offset between DM and galaxies.

Also constraints from scattering depth & survival of the cluster, and changes to the mass-to-light ratio from mass loss.

SIDM can also be probed with minor mergers.

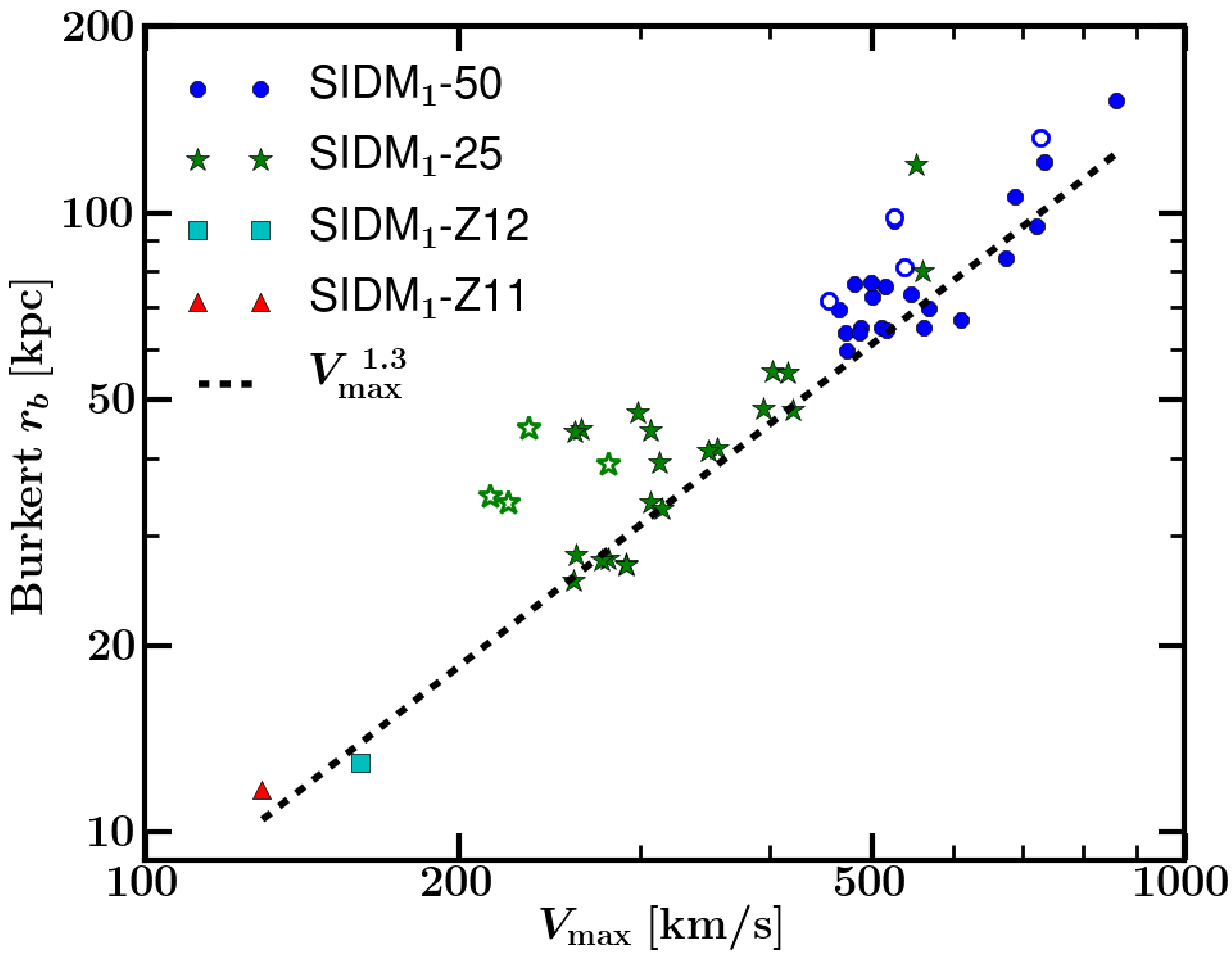
density profiles $\rho(r)$

More massive galaxies have larger constant density cores e.g. Rocha et al.:

core radius

Burkert profile

$$\rho(r) = \frac{\rho_\mathrm{b}}{(r + r_\mathrm{b})(r^2 + r_\mathrm{b}^2)}$$

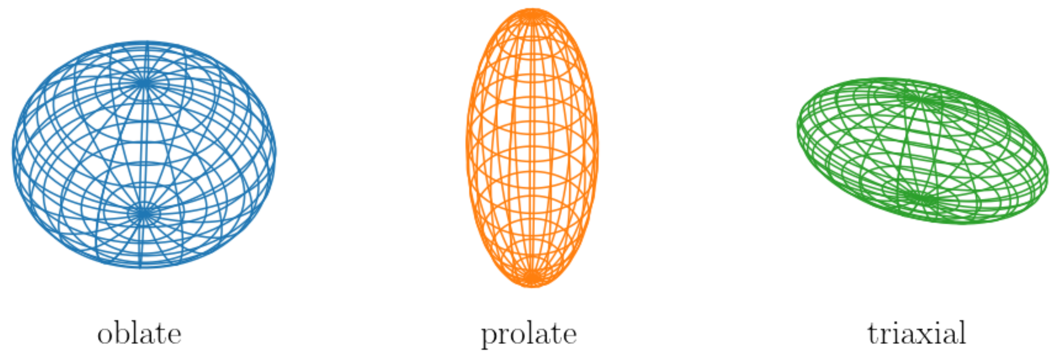


Milky Way size

Cluster size

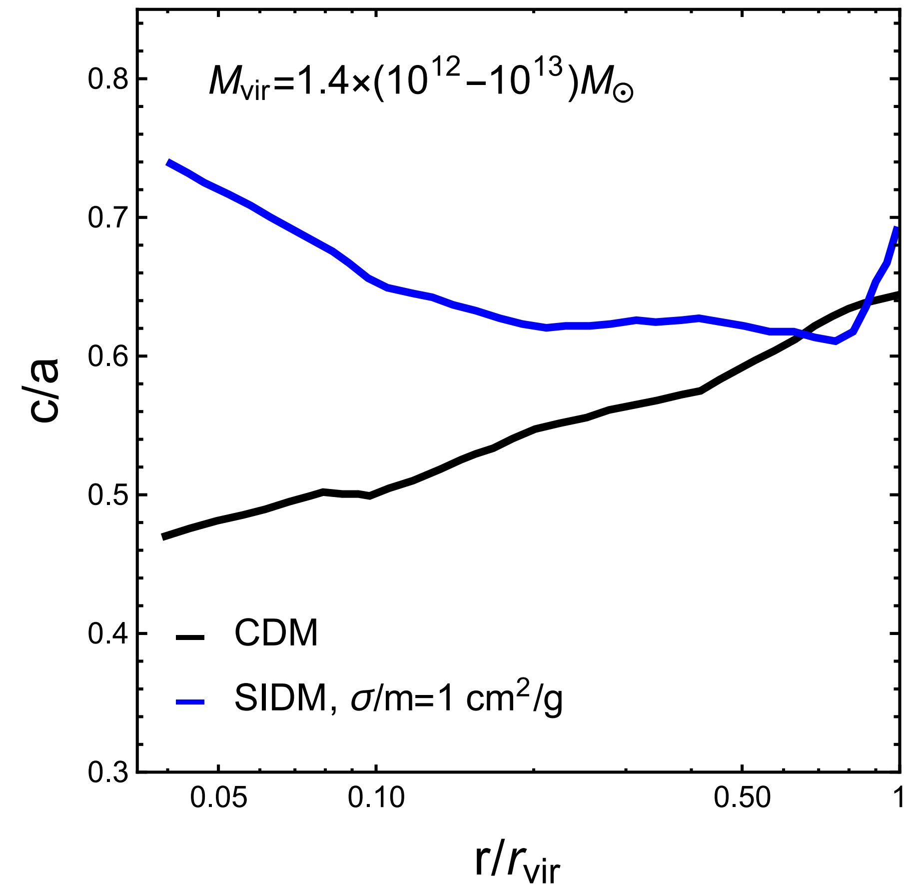
<u>ellipticity</u>

CDM halos are triaxial, self-interactions isotropize DM particle velocities, and erase ellipticity at small radii e.g. Peter et al.



Bovy

minor-to-major axis ratio



Tulin & Yu using data from Peter et al.

Shape of DM halos can be probed observationally via cluster strong lensing.

Compilation of SIDM constraints/observations c. 2017

Positive observations	σ/m	$v_{\rm rel}$	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm^2/g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[102, 116]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[110]
Local Group	$\gtrsim 0.5\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[111]
Cores in clusters	$\sim 0.1\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	$\sim 1.5\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset	[127]
Abell 520 cluster merger	$\sim 1\ \mathrm{cm^2/g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[128, 129, 130]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm^2/g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[95]
Substructure mergers	$\lesssim 2\ \mathrm{cm^2/g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[115, 131]
Merging clusters	$\lesssim \text{few}\ \mathrm{cm^2/g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm^2/g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[106]

Tulin & Yu

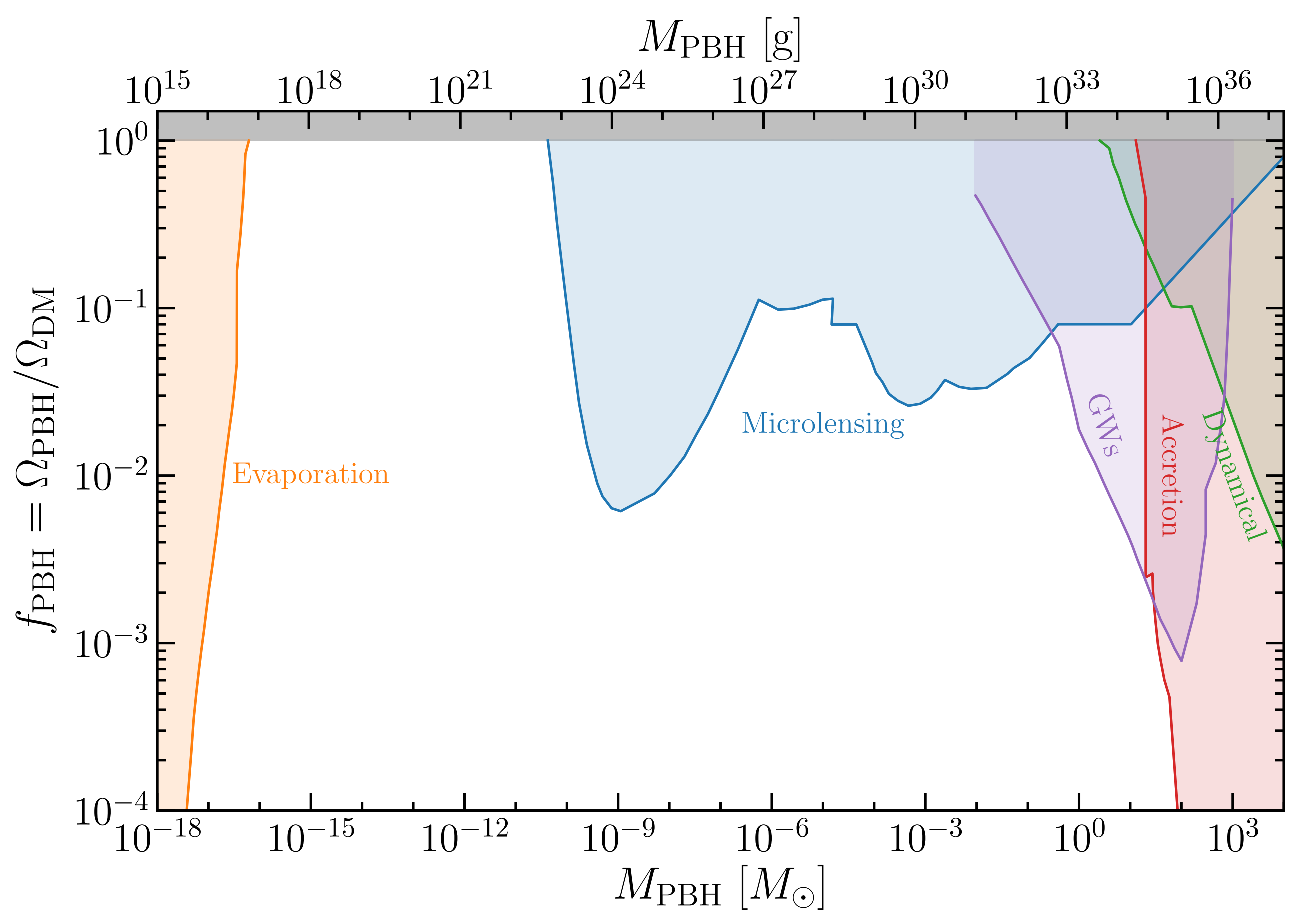
Non-particle dark matter

e.g. Primordial Black Holes (PBHs):
see Bernard Carr and Florian Khunel's lectures

Black holes that form in the early Universe, from the collapse of large over densities.

Mass ranges from 10^{15}g though to $> 1000\,M_{\odot}$.

Constraints from: evaporation, microlensing, gravitational waves from mergers, accretion, dynamical effects.



Green & Kavanagh
see also Carr & Kuhnel; Carr et al.

Summary

As well as providing evidence for dark matter, astronomical/cosmological observations can (combined with numerical simulations) probe the nature of dark matter e.g.

Self-interacting dark matter:

halos have constant density cores, also constraints from mergers and halo shapes: $\sigma/m \lesssim 1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$.

Warm dark matter:

power spectrum surpassed on small scales, less light subhalos, constraints from Lyman-alpha forest, stellar streams, MW satellites, strong lensing: $m \gtrsim 5\,\mathrm{keV}$.

non-particle dark matter:

e.g. primordial black holes, macros
various constraints: microlensing, dynamical, effects on stars…

Overall summary

The ΛCDM cosmological model, in which the Universe is flat, with ~25% of the energy density being in the form of cold, non-baryonic, dark matter is (overall) a good fit to observations (nucleosynthesis, CMB, large scale structure, type 1a supernovae…) But we don't (yet) know what dark matter is (or dark energy).

To detect DM we need to know how it's distributed, in particular in the Milky Way. Significant (and ongoing) progress from both observations and simulations.

We can also probe the nature of DM (i.e. deviations from cold dark matter which just interacts gravitationally) with astronomical and cosmological observations.

Hope you enjoy the weekend, and the rest of the School.

I'm happy to continue answering questions by email/on padlet: https://padlet.com/annegreen3/k33gx7aeoyggy61j

Mer de Glace, Chamonix

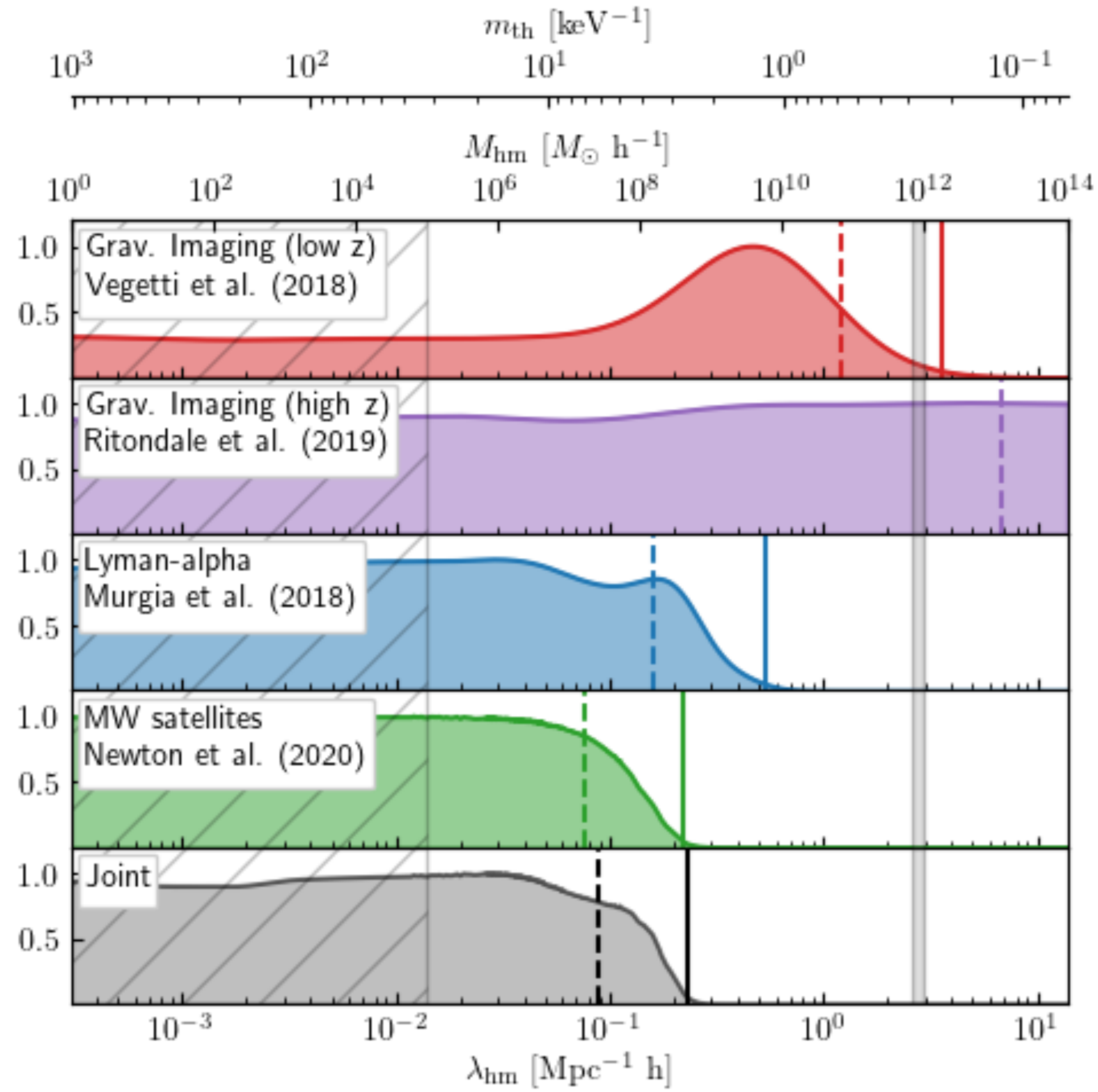
Peak District, UK

Back-up slides

posterior probability distributions

gravitational imaging low and high z, Lyman-alpha, MW satellites, combined

solid (dashed) vertical lines limits from Bayes factor (95%)

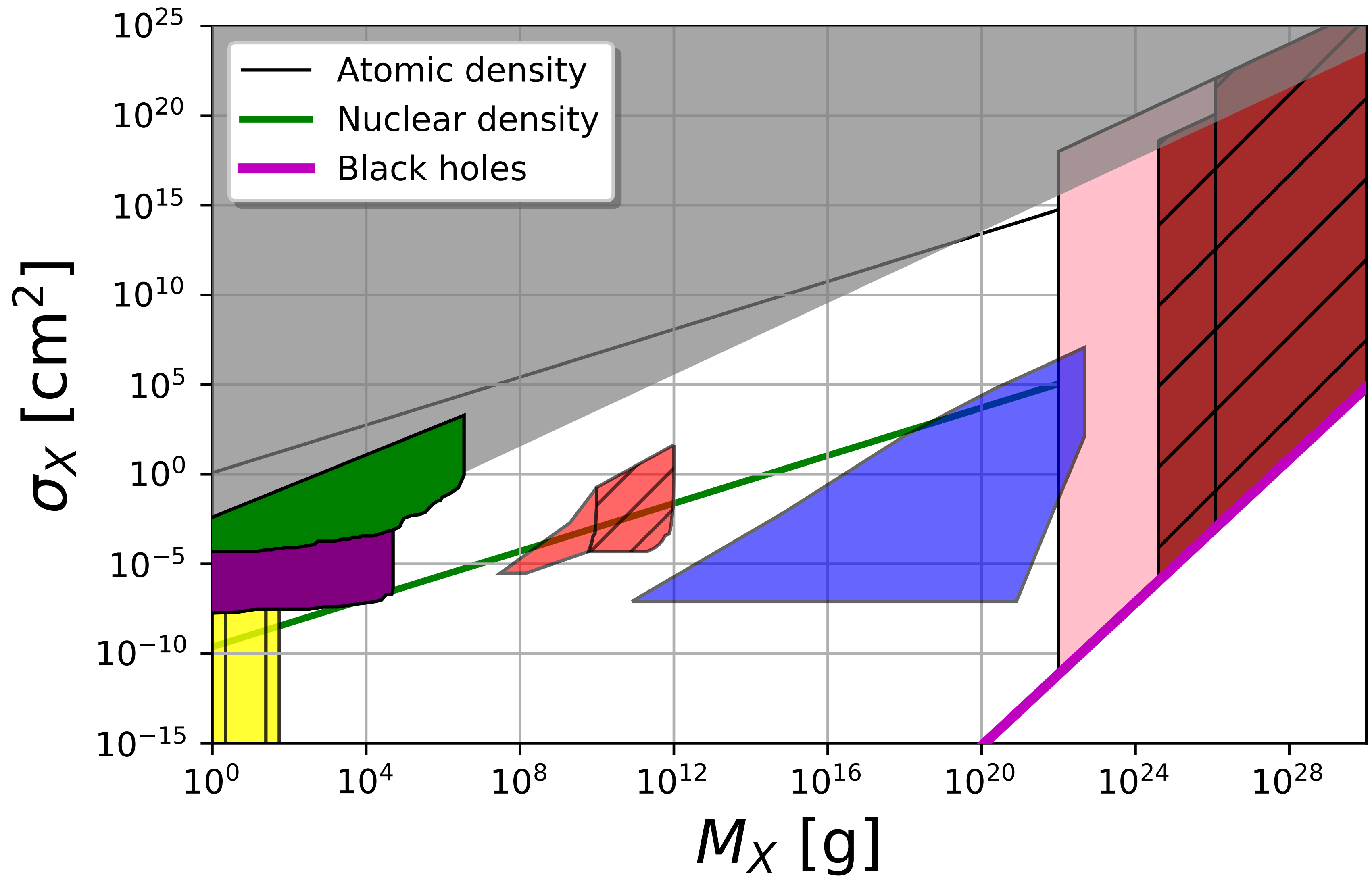


Limit on mass of thermal relic: m > 2.5 (6.0) keV.

MACROs:

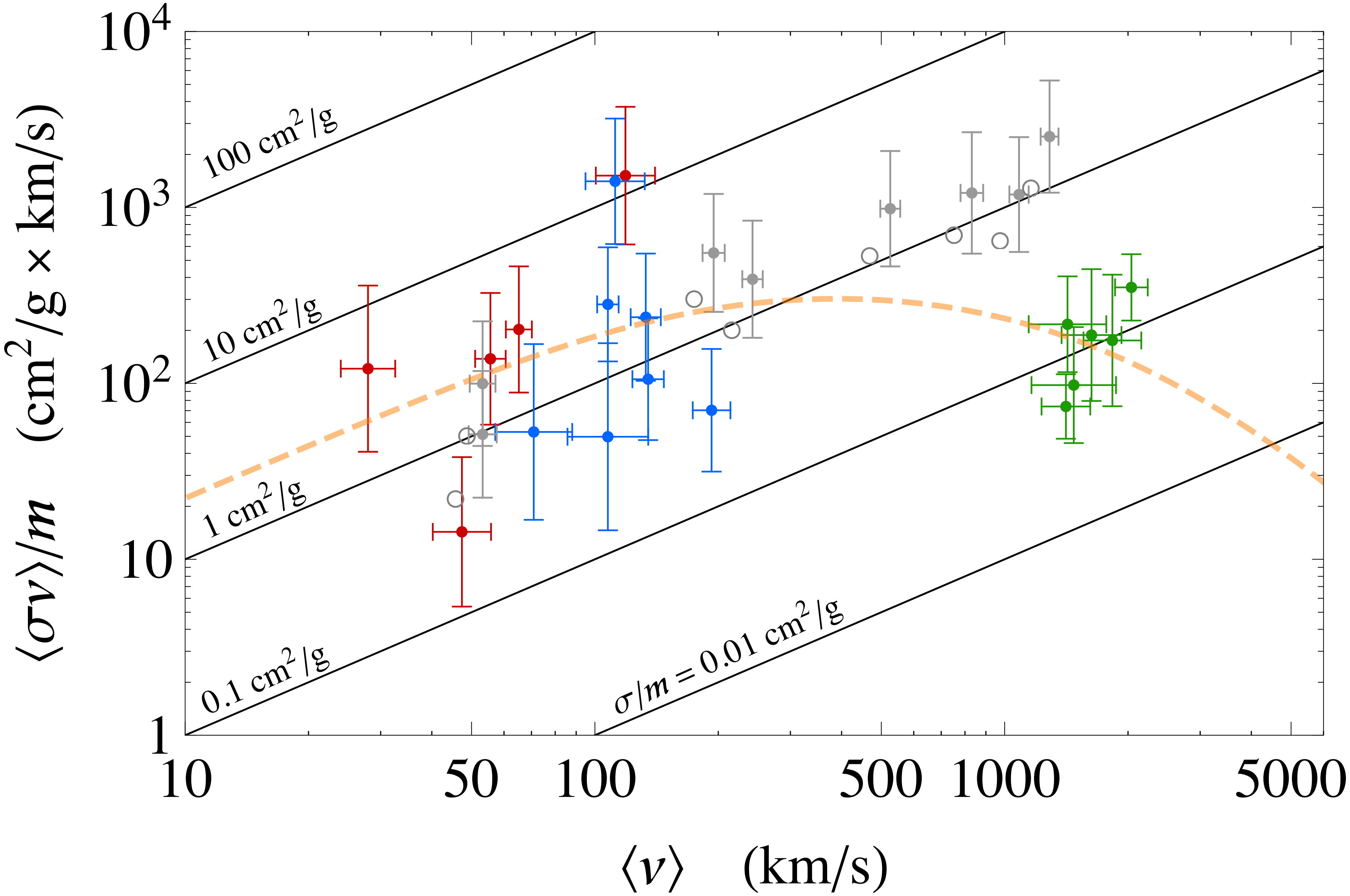
Bound states of fundamental particles with macroscopic mass ($\gtrsim$ g) and interaction cross section (cm²). see e.g. Sidhu & Starkman

Constraints from: structure formation, fast moving bolides (bright meteorites), effects on humans, tracks in ancient mica, superbursts in neutron stars, white dwarf SNe, microlensing (MW, M31),.



dwarf galaxies, low surface brightness spiral galaxies, clusters

(mock data from simulations with $\sigma/m \sim 1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$)

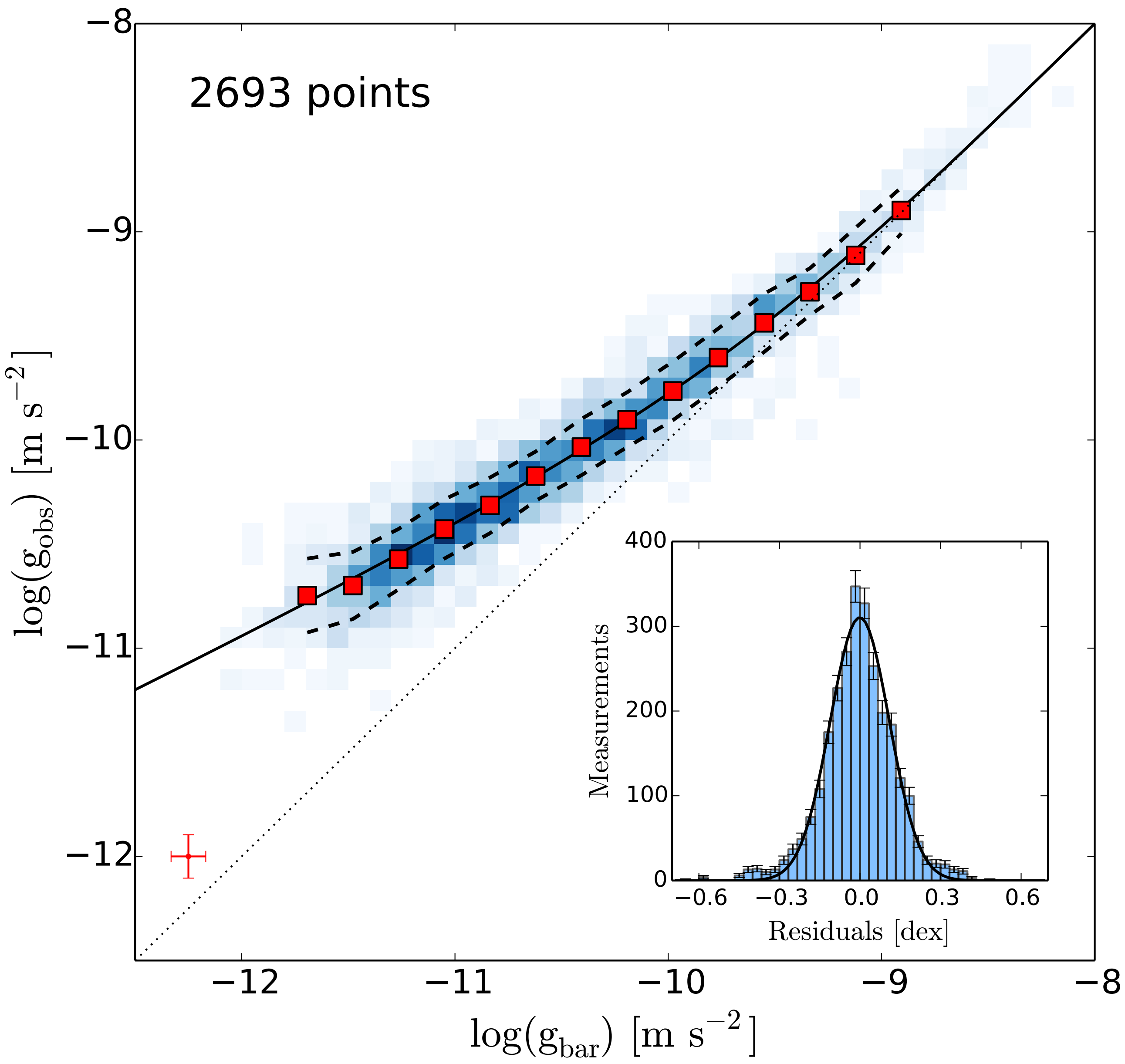


Kaplinghat, Tulin & Yu

Radial acceleration relation

observed radial acceleration: $$g_{obs} = \frac{v^2(r)}{r} = \left| \frac{\partial \Phi_{tot}}{\partial r} \right|$$

radial acceleration predicted by baryons: $$g_{bar} = \left| \frac{\partial \Phi_{bar}}{\partial r} \right| \qquad (\nabla^2 \Phi_{bar} = 4\pi G \rho_{bar})$$



McGaugh, Lelli, Schombert