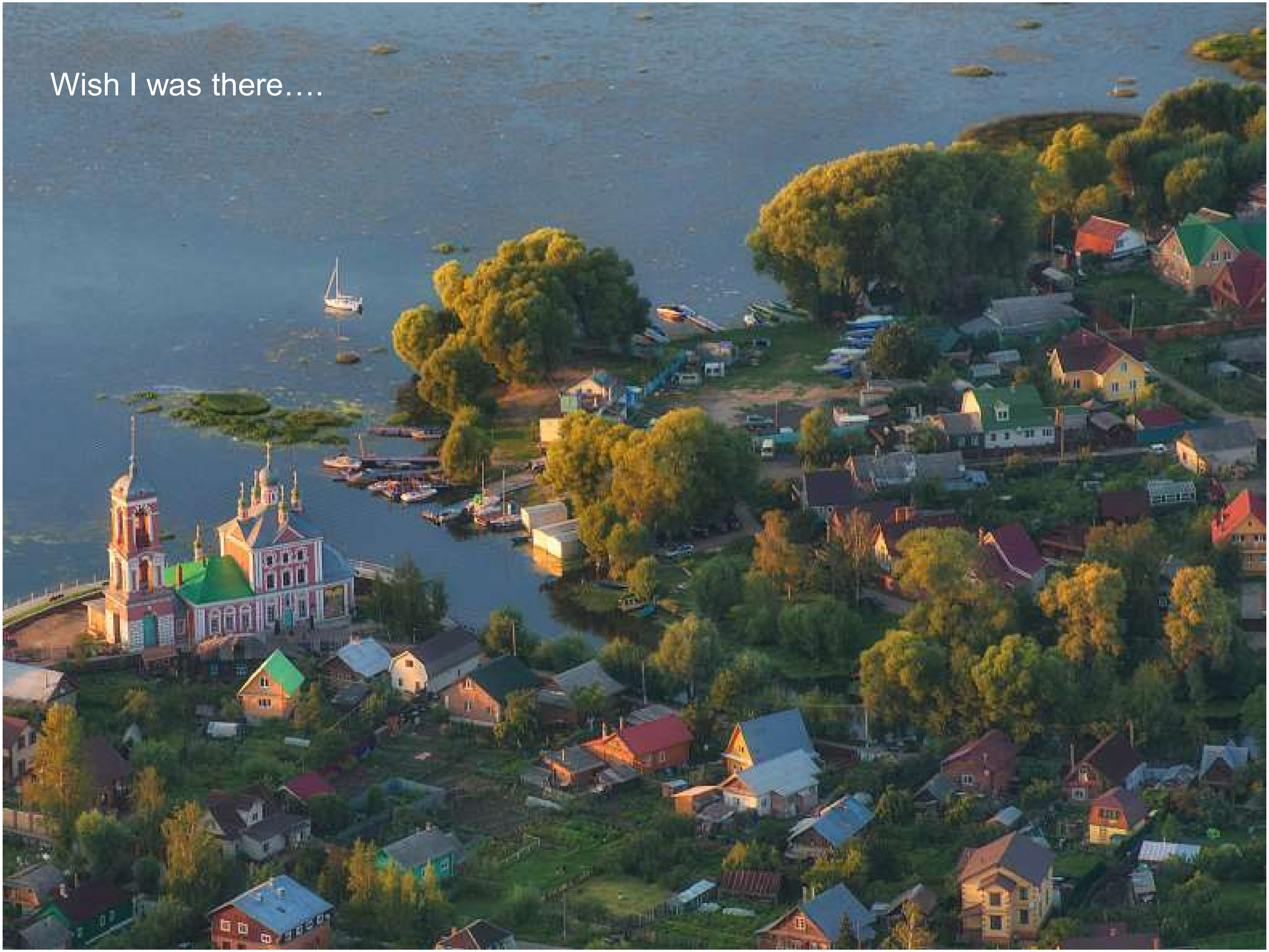
Astrophysical constraints on dark matter

Malcolm Fairbairn

Quarks 2021


Wish I was there….

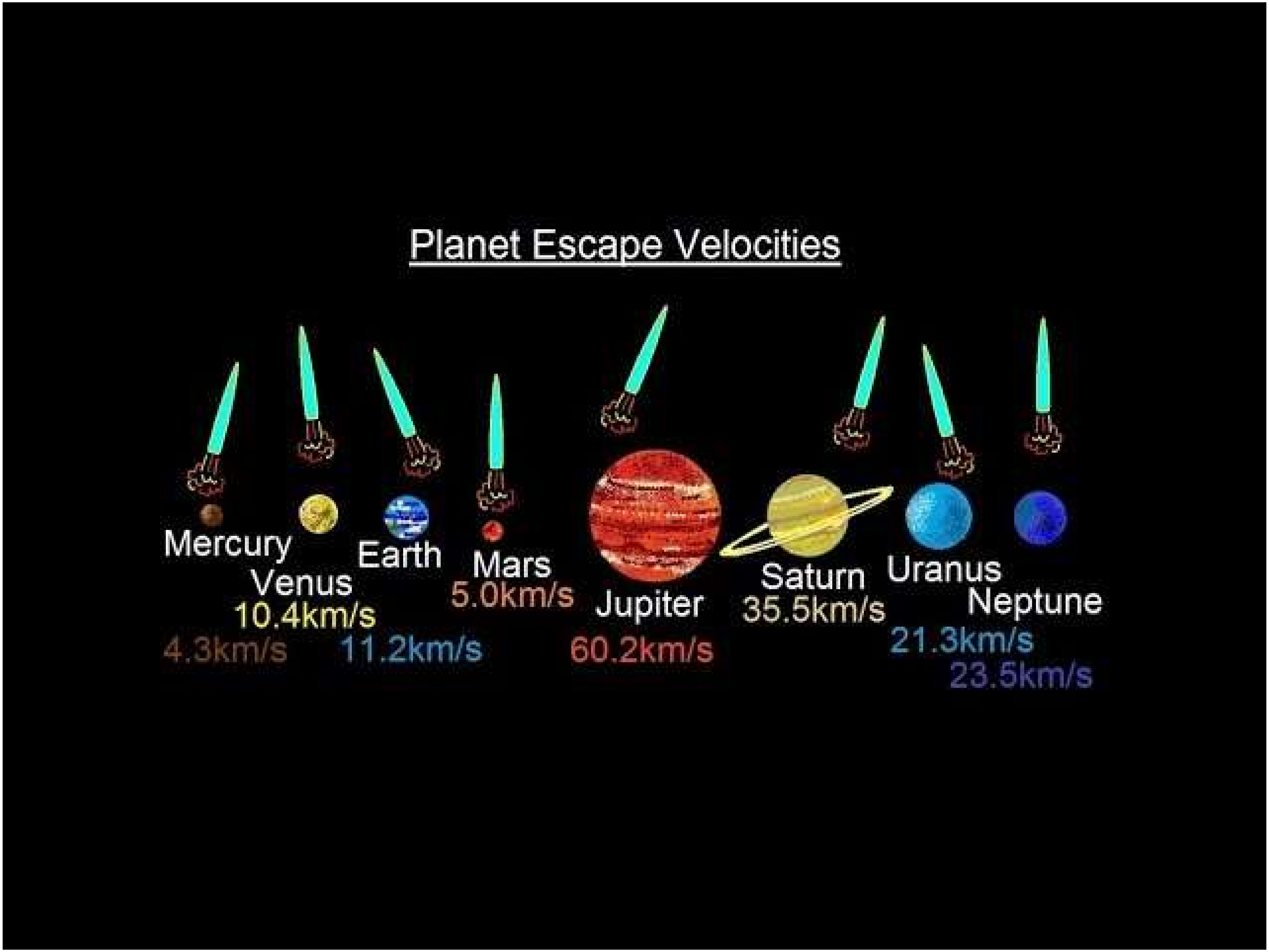
There is 6 times as much dark matter as normal matter.

No dark matter has been detected yet!

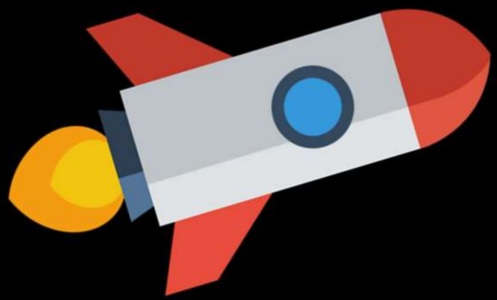
What can we find out about it without interacting with it directly?

Three methods to constrain dark matter without seeing it:-

- Strong Lensing probes of dark matter (how do we learn more about DM if we can’t see it)
- Effect of light dark matter on Nucleosynthesis
- Galactic Probes of fermionic dark matter


Planet Escape Velocities
Mercury
4.3km/s
Venus
10.4km/s
Earth
11.2km/s
Mars
5.0km/s
Jupiter
60.2km/s
Saturn
35.5km/s
Uranus
21.3km/s
Neptune
23.5km/s

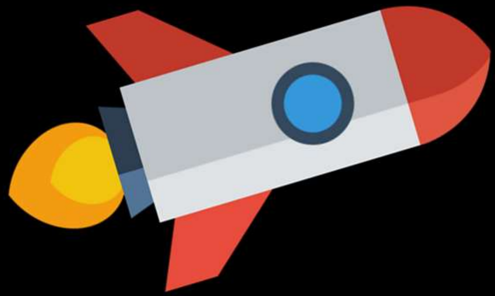
Milky Way Escape velocity



~ 500 km / s

We know dark matter must be travelling less quickly than this, since we know it is present in galaxies like the Milky Way

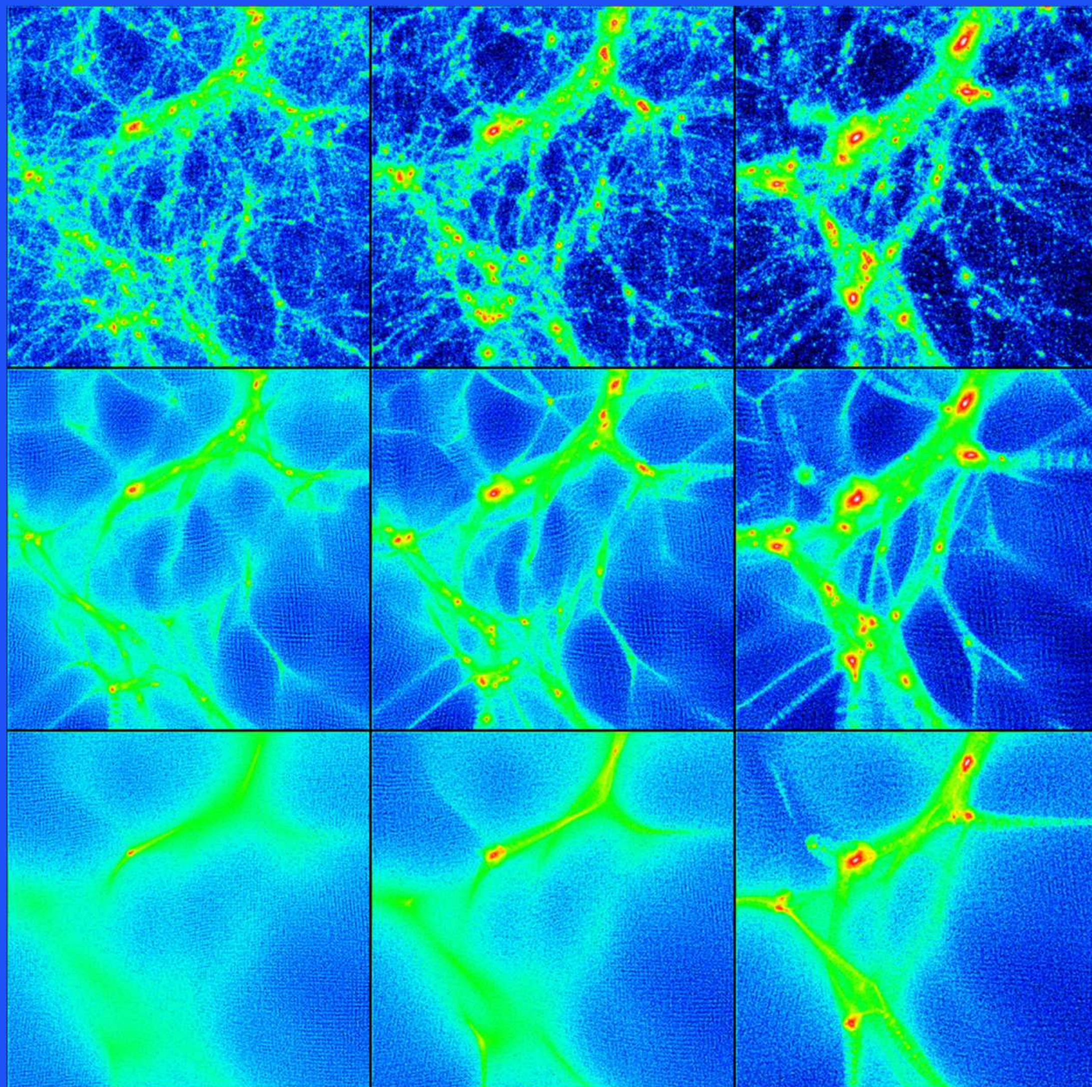
Dwarf Galaxy Escape velocity



~ 20 km / s

Dark Matter is also present in Dwarf galaxies, so we know it is moving at least this slow.

How Quickly was Dark Matter moving in the Early Universe?

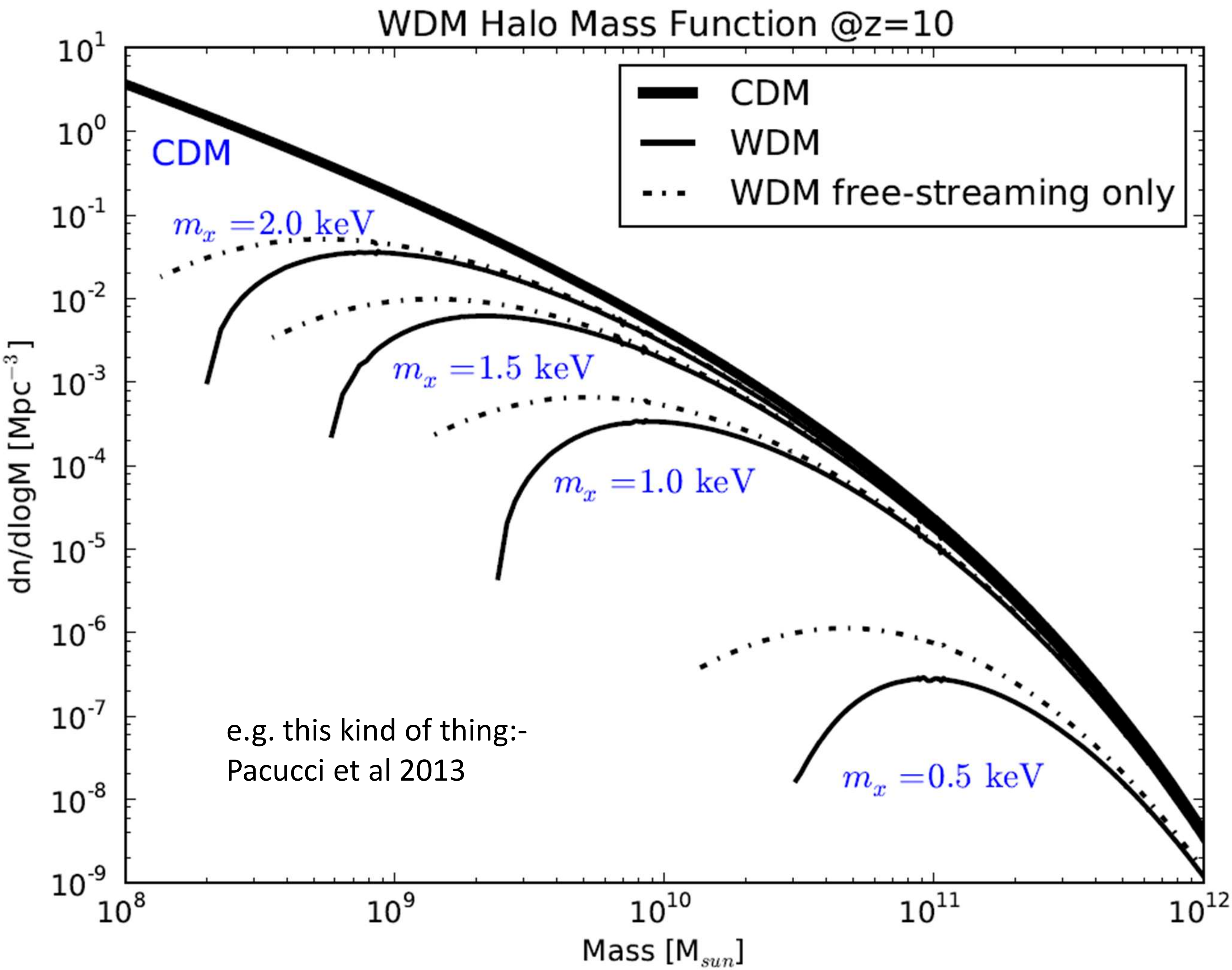


Slow moving dark matter

(computer simulations)

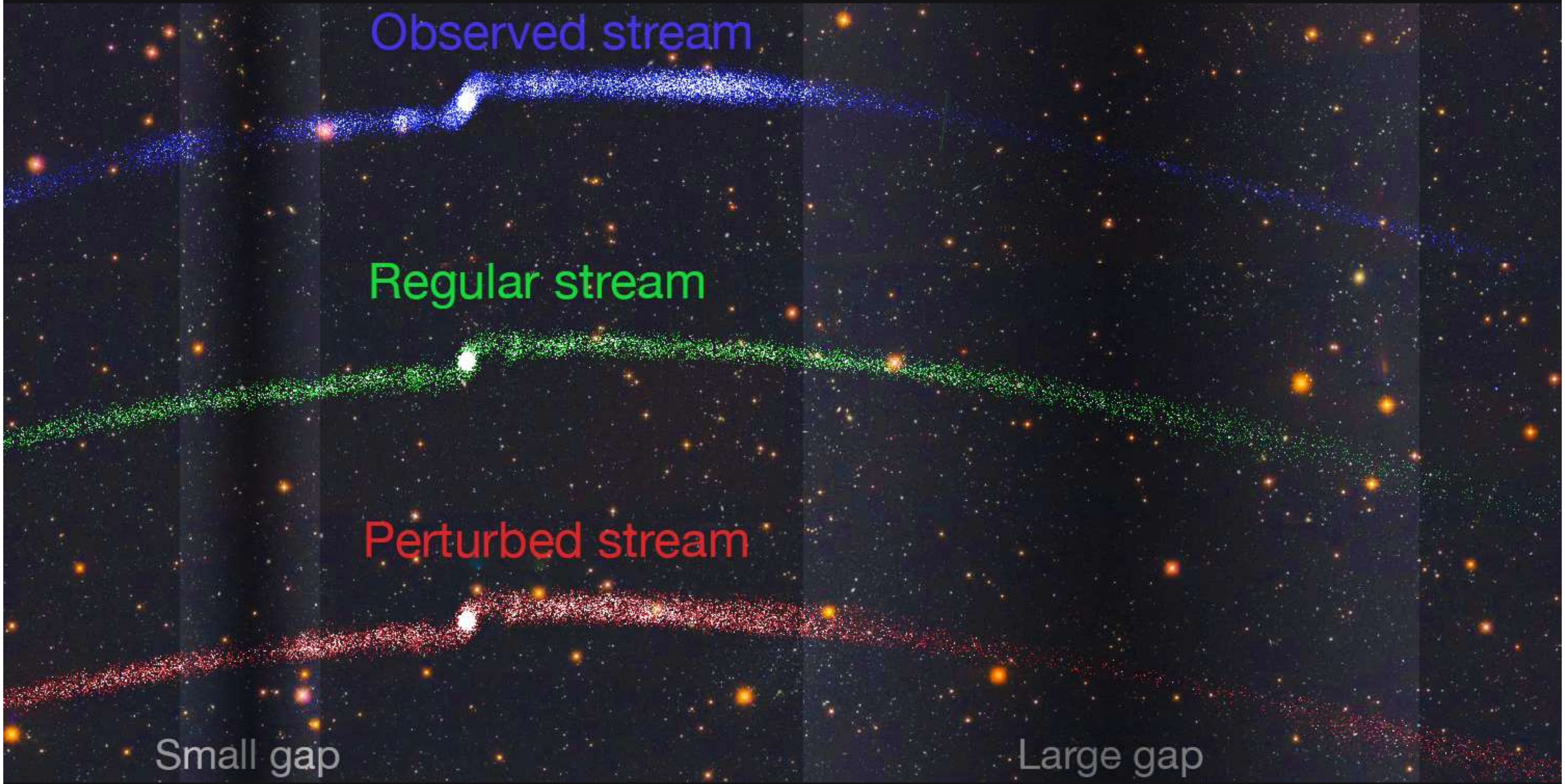
Fast moving dark matter

Different initial dark matter velocities lead to different amounts of substructure.

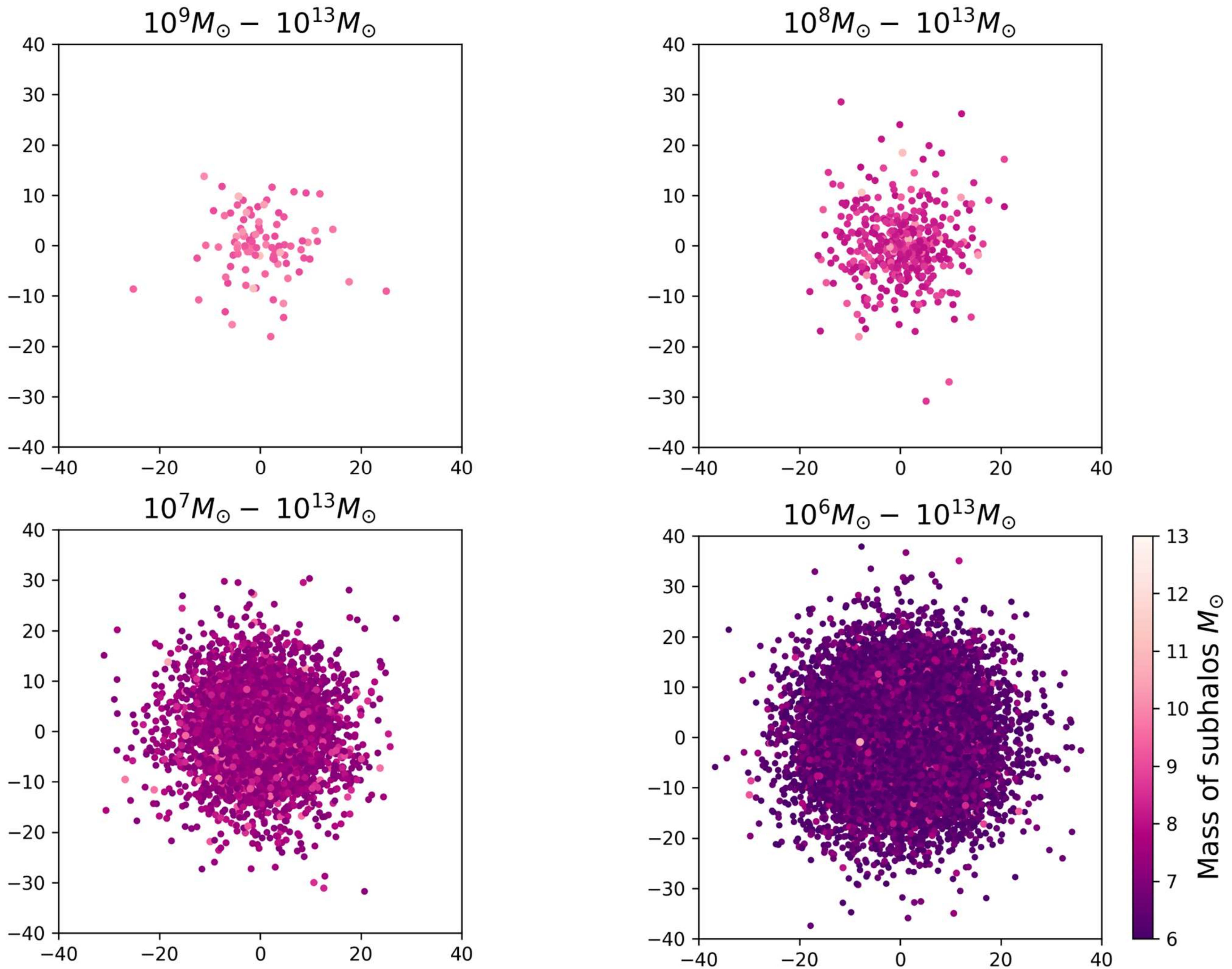


e.g. this kind of thing:-
Pacucci et al 2013

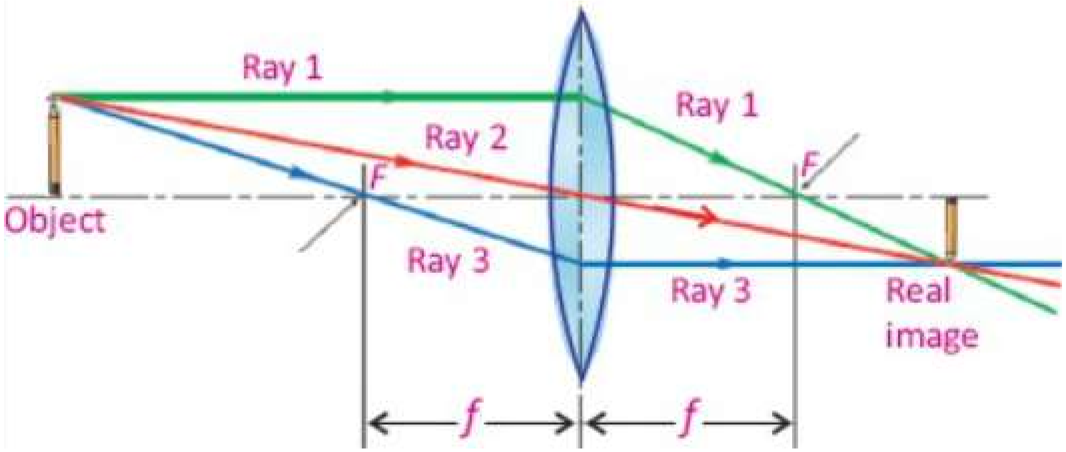
Small Subhalos can perturb stellar streams



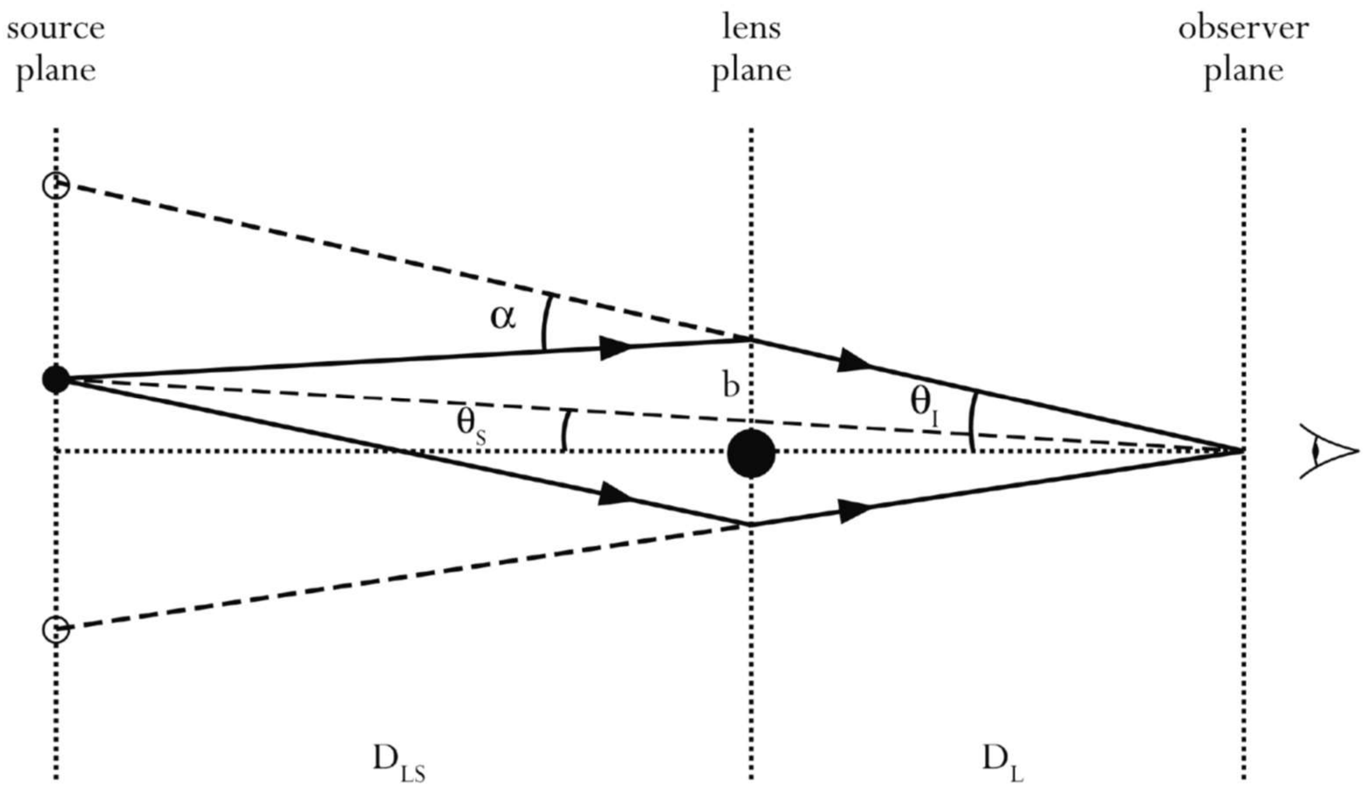
See work by Bovy, Erkal, Sanders etc
+ Bertone for possible preliminary results



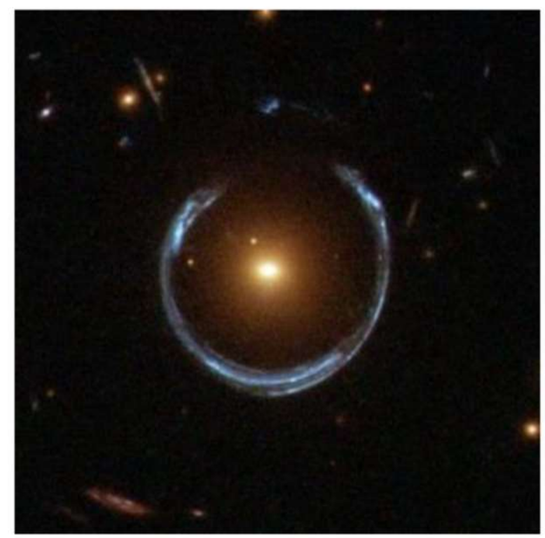
$10^9 M_\odot - 10^{13} M_\odot$
$10^8 M_\odot - 10^{13} M_\odot$
$10^7 M_\odot - 10^{13} M_\odot$
$10^6 M_\odot - 10^{13} M_\odot$
Mass of subhalos $M_\odot$

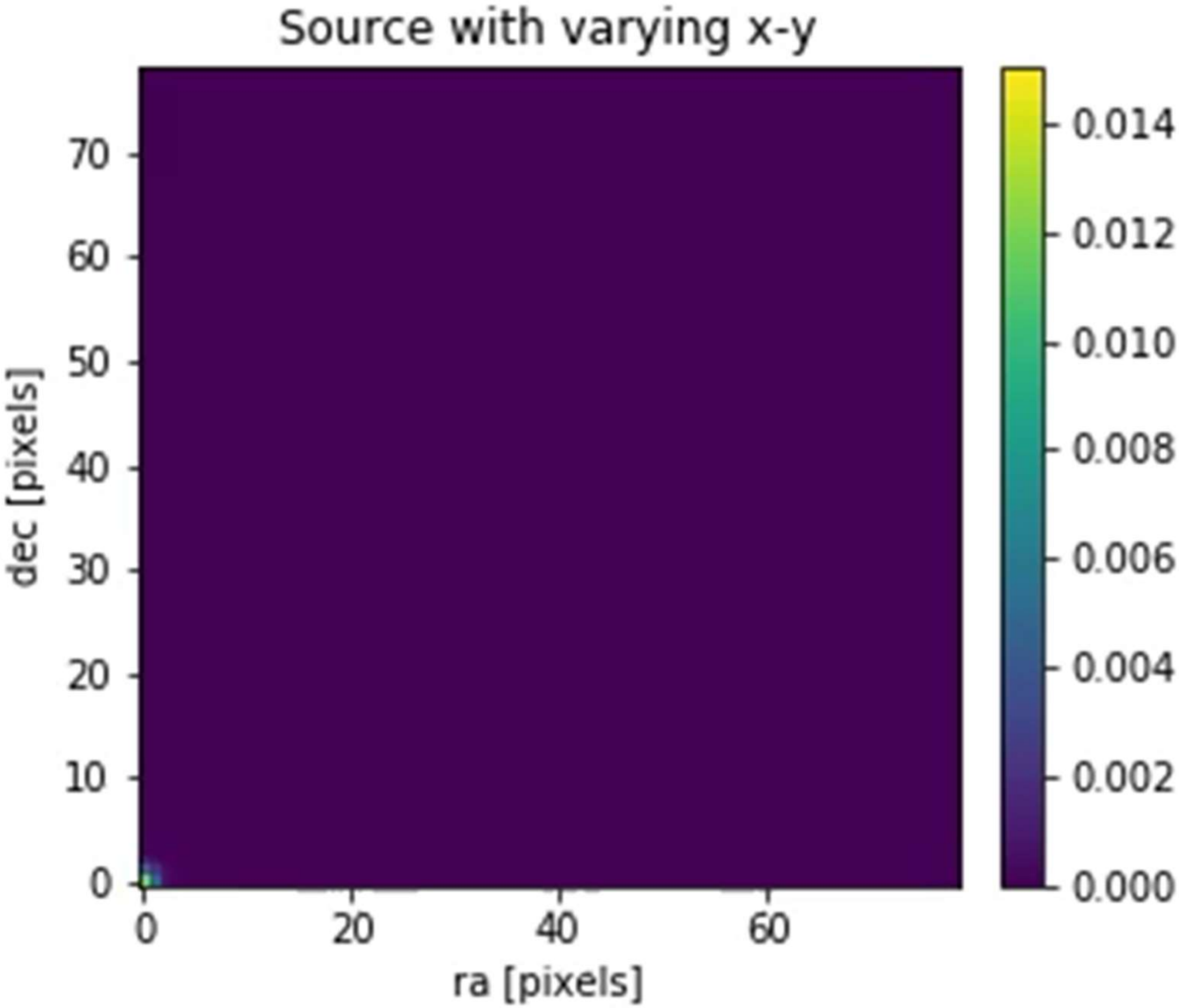


Lensing

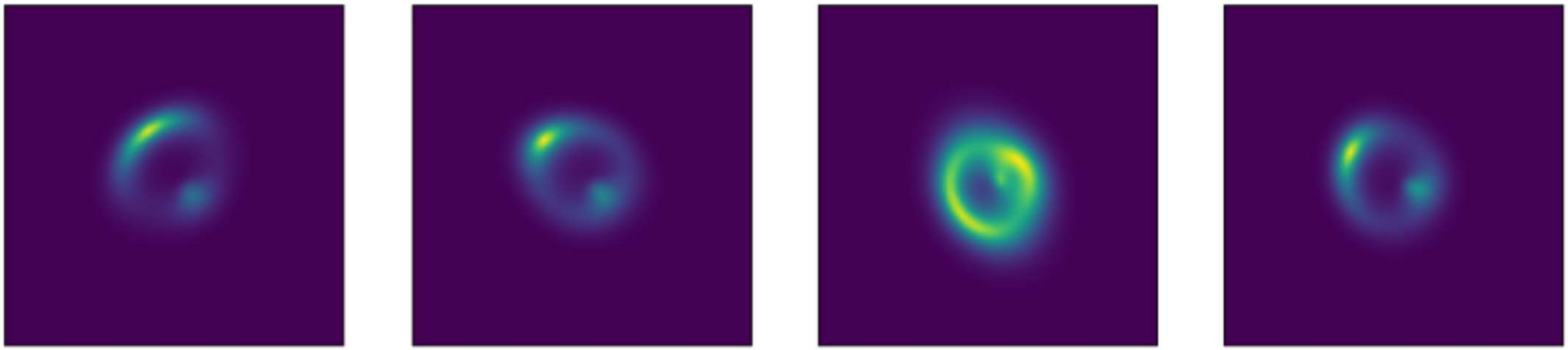


Gravitational Lensing





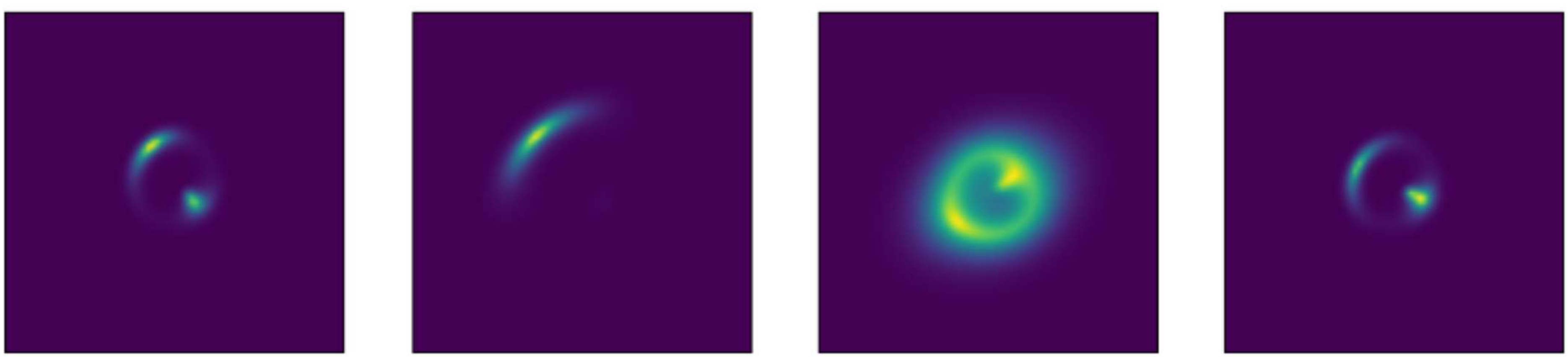
Source with varying x-y
dec [pixels]
ra [pixels]
0
10
20
30
40
50
60
70
0
20
40
60
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014



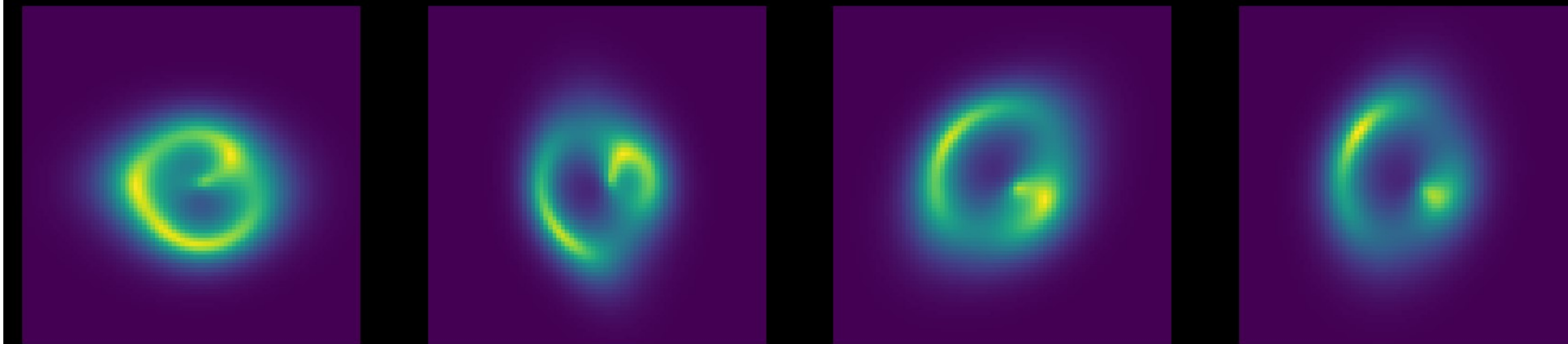
Minimum halo mass 10^9 Msun

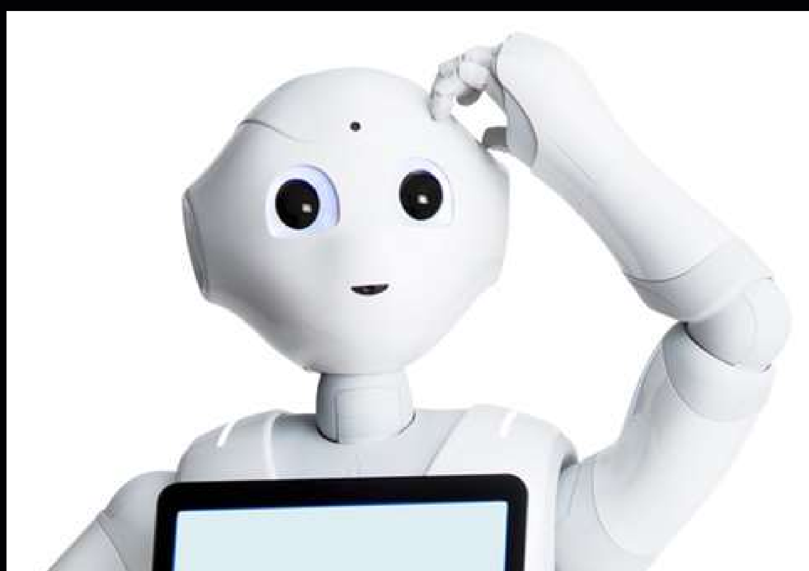
Can you tell the difference? I can't…

Minimum halo mass 10^6 Msun



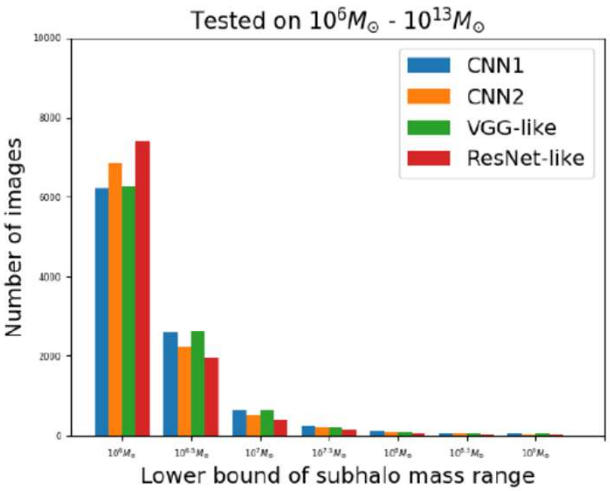
We generate lots of lensed images of galaxies.

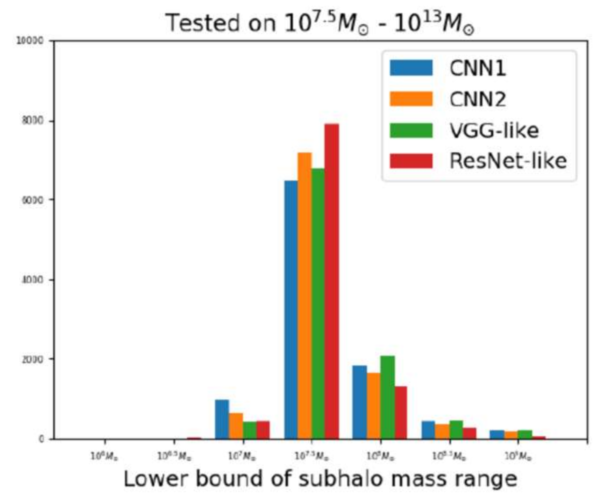


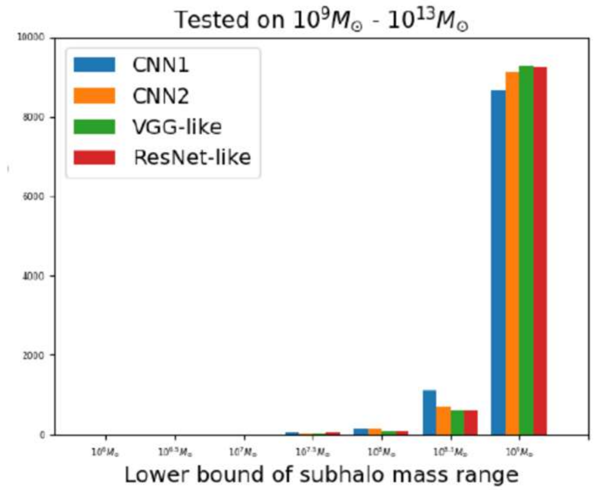


Sreedevi Varma

We then use Machine Learning to see if we can tell how small the subhalos are from the shapes of the lensing images. We can!



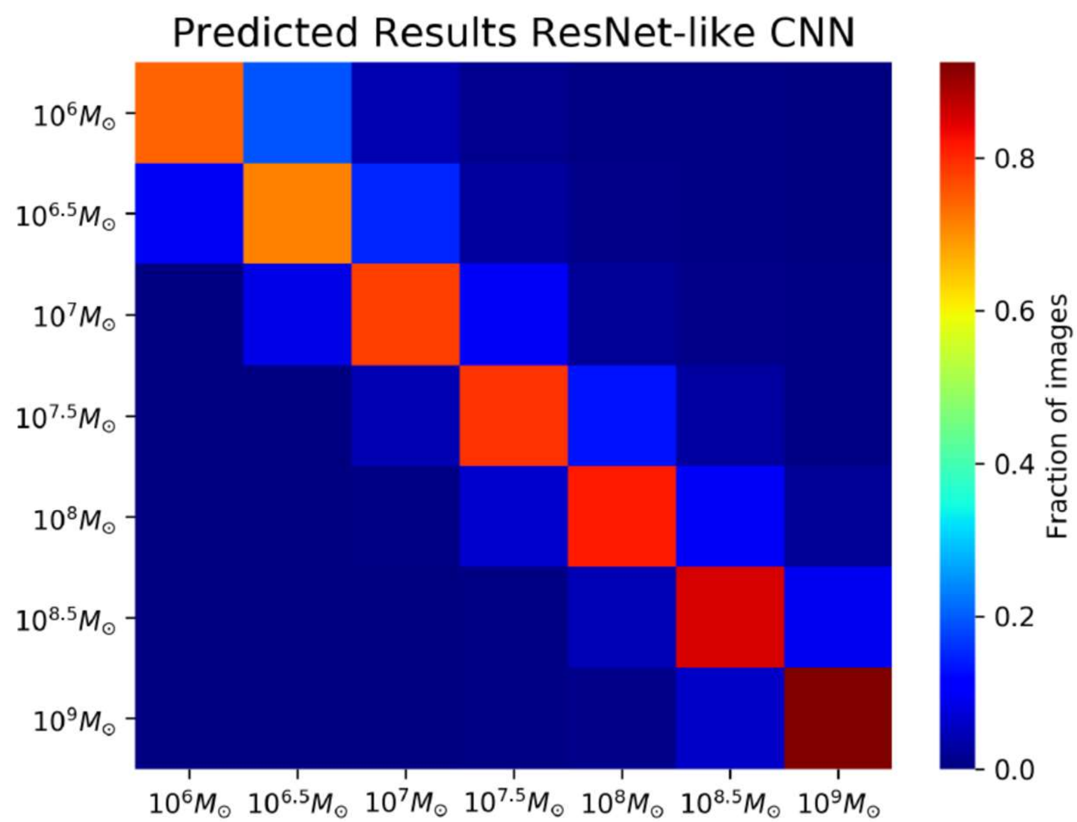




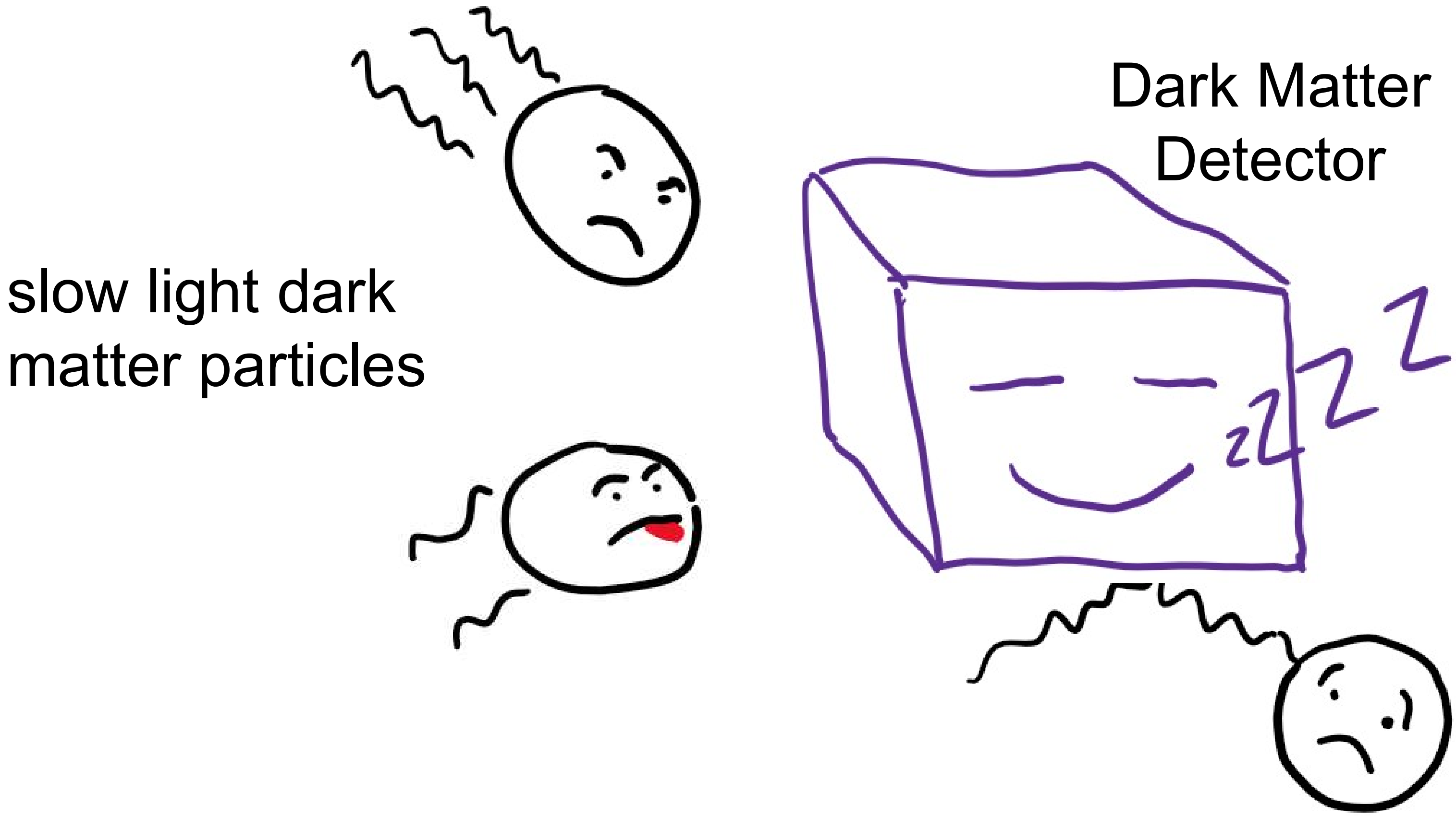
Results of the best chain seems to show we can get within half an order of magnitude to a close approximation!

We need to prove that we can do this while baryons are present… This is not as easy.

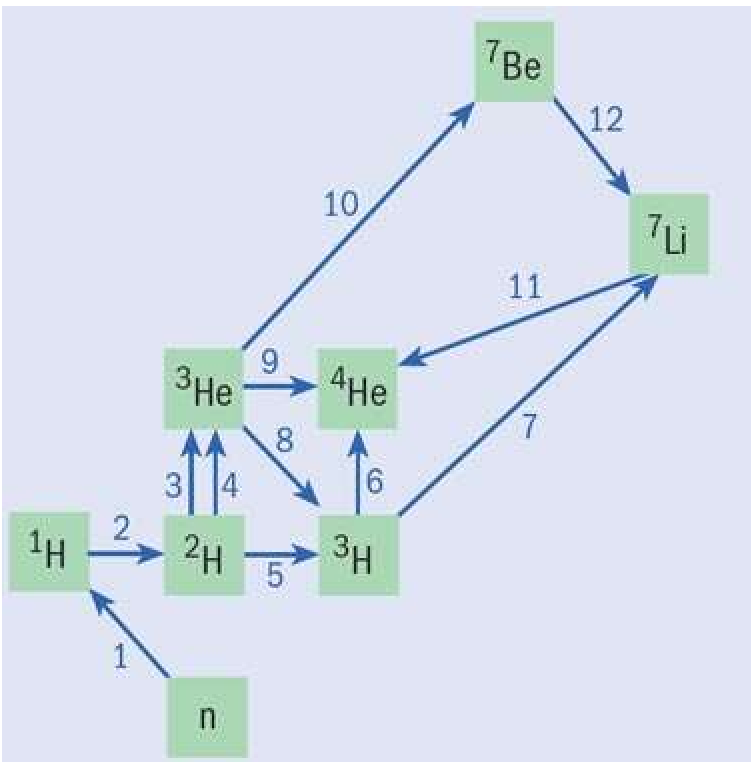
This is new work:- 2005.05353



Too light dark matter



Can still try to find dark matter in other ways



If the dark matter is too light, it can change the prediction for how much helium and deuterium is left behind after the big bang…

1910.01649

Light Dark Matter changes Evolution of photon and neutrino temperature

Neutrinophilic

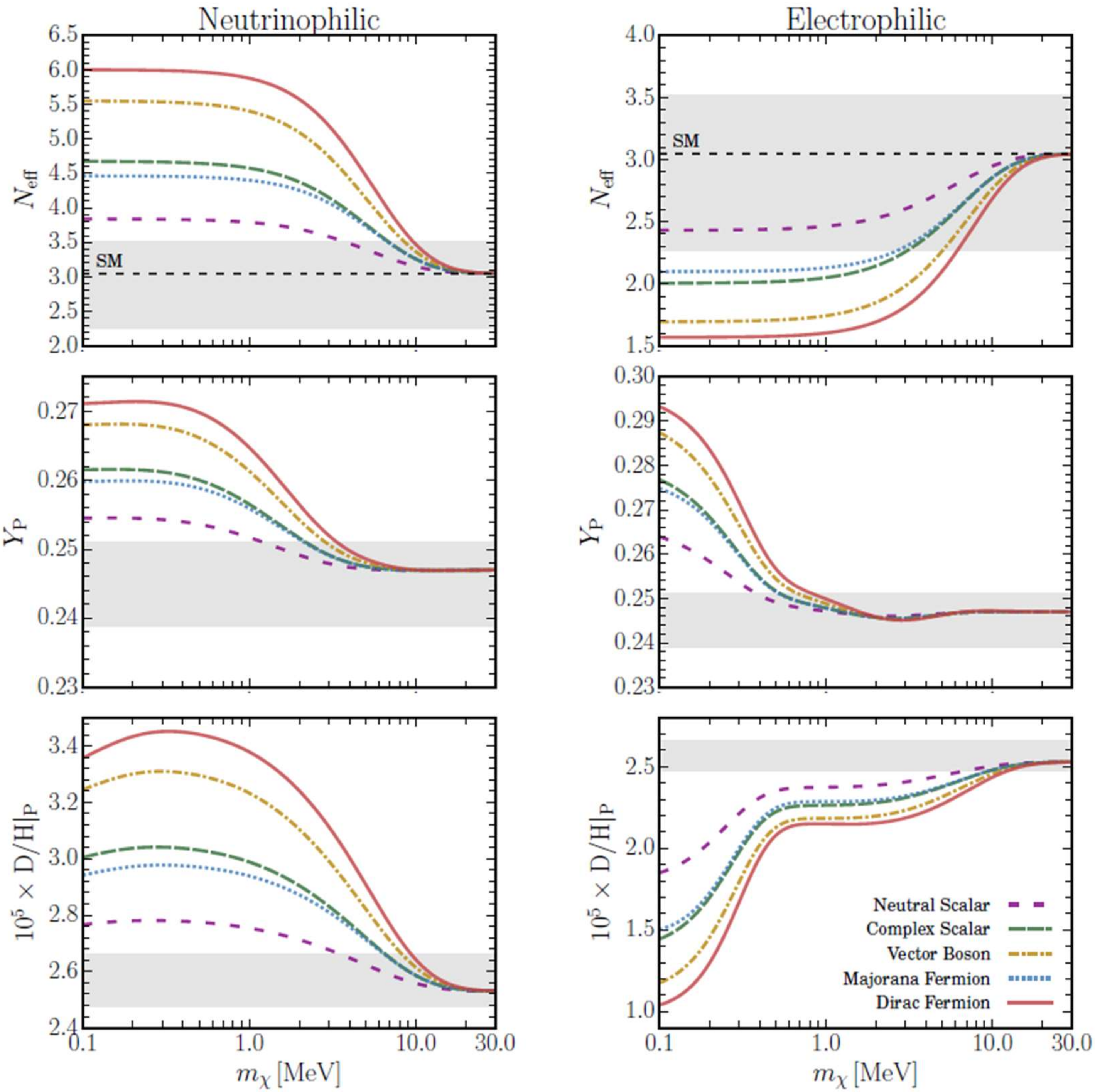
$$\begin{cases} \dfrac{dT_\nu}{dt} = -\dfrac{12H\rho_\nu + 3H(\rho_\chi + p_\chi) - 3\frac{\delta\rho_\nu}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu} + \frac{\partial\rho_\chi}{\partial T_\nu}}, \\ \dfrac{dT_\gamma}{dt} = -\dfrac{4H\rho_\gamma + 3H\,(\rho_e + p_e) + 3H\,T_\gamma\frac{dP_{\rm int}}{dT_\gamma} + 3\frac{\delta\rho_\nu}{\delta t}}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma} + T_\gamma\frac{d^2P_{\rm int}}{dT_\gamma^2}}, \end{cases}$$

Electrophilic

$$\begin{cases} \dfrac{dT_\nu}{dt} = -\dfrac{12H\rho_\nu - 3\frac{\delta\rho_\nu}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu}}, \\ \dfrac{dT_\gamma}{dt} = -\dfrac{4H\rho_\gamma + 3H\,(\rho_e + p_e) + 3H\,(\rho_\chi + p_\chi) + 3H\,T_\gamma\frac{dP_{\rm int}}{dT_\gamma} + 3\frac{\delta\rho_\nu}{\delta t}}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma} + \frac{\partial\rho_\chi}{\partial T_\gamma} + T_\gamma\frac{d^2P_{\rm int}}{dT_\gamma^2}} \end{cases}$$

$$\left.\frac{\delta\rho_\nu}{\delta t}\right|_{\rm SM} = \frac{G_F^2}{\pi^5}\left(1 - \frac{4}{3}s_W^2 + 8s_W^4\right) \times \left[32\,f_a^{\rm FD}\,\left(T_\gamma^9 - T_\nu^9\right) + 56\,f_s^{\rm FD}\,T_\gamma^4\,T_\nu^4\,\left(T_\gamma - T_\nu\right)\right]$$

$$\left.\frac{\delta\rho_\nu}{\delta t}\right|_\chi = \frac{g_\chi^2 m_\chi^5}{4\pi^4}\left(\langle\sigma v\rangle_{\chi\chi\to\bar\nu\nu}\left[T_\nu^2\,K_2^2\left[\frac{m_\chi}{T_\nu}\right] - T_\chi^2\,K_2^2\left[\frac{m_\chi}{T_\chi}\right]\right] - \langle\sigma v\rangle_{\chi\chi\to e^+e^-}\left[T_\chi^2\,K_2^2\left[\frac{m_\chi}{T_\chi}\right] - T_\gamma^2\,K_2^2\left[\frac{m_\chi}{T_\gamma}\right]\right]\right)$$



Neutrinophilic
Electrophilic
SM
$N_{\rm eff}$
$Y_{\rm P}$
$10^5 \times {\rm D/H}|_{\rm P}$
m_χ [MeV]
Neutral Scalar
Complex Scalar
Vector Boson
Majorana Fermion
Dirac Fermion

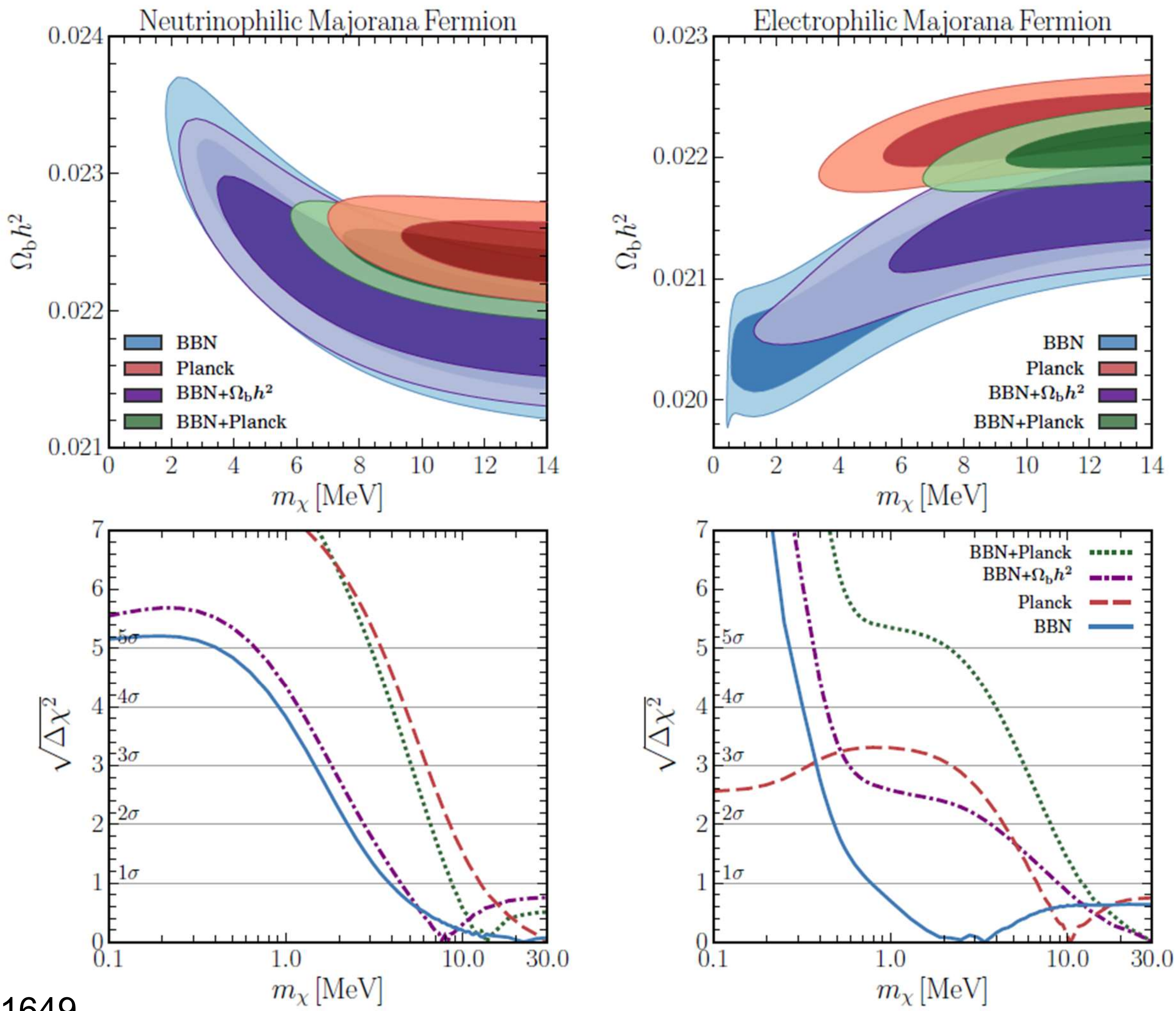
Use state-of-the-art Big Bang Nucleosynthesis code PRIMAT
arXiv:1909.12046

- accurate predictions for He & D and deuterium abundances
- up-to-date nuclear reaction rates
- finite temperature corrections
- incomplete neutrino decoupling etc.

$$\chi^2_{\rm BBN} = \frac{\left[Y_{\rm P} - Y_{\rm P}^{\rm Obs}\right]^2}{\sigma^2_{Y_{\rm P}}|^{\rm Theo} + \sigma^2_{Y_{\rm P}}|^{\rm Obs}} + \frac{\left[{\rm D/H}|_{\rm P} - {\rm D/H}|_{\rm P}^{\rm Obs}\right]^2}{\sigma^2_{\rm D/H|_P}|^{\rm Theo} + \sigma^2_{\rm D/H|_P}|^{\rm Obs}}$$

Precision Big Bang Nucleosynthesis with the New Code *PRIMAT*

Cyril Pitrou[1,2], Alain Coc[3], Jean–Philippe Uzan[1,2] and Elisabeth Vangioni[1,2]

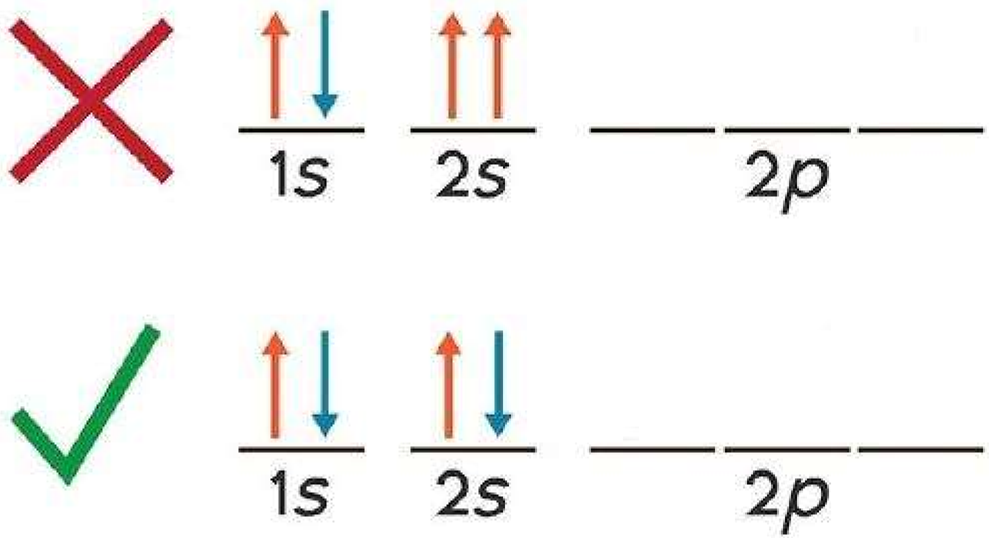


Neutrinophilic Majorana Fermion
Electrophilic Majorana Fermion
$\Omega_b h^2$
m_χ [MeV]
BBN
Planck
BBN+$\Omega_b h^2$
BBN+Planck
$\sqrt{\Delta\chi^2}$
5σ
4σ
3σ
2σ
1σ

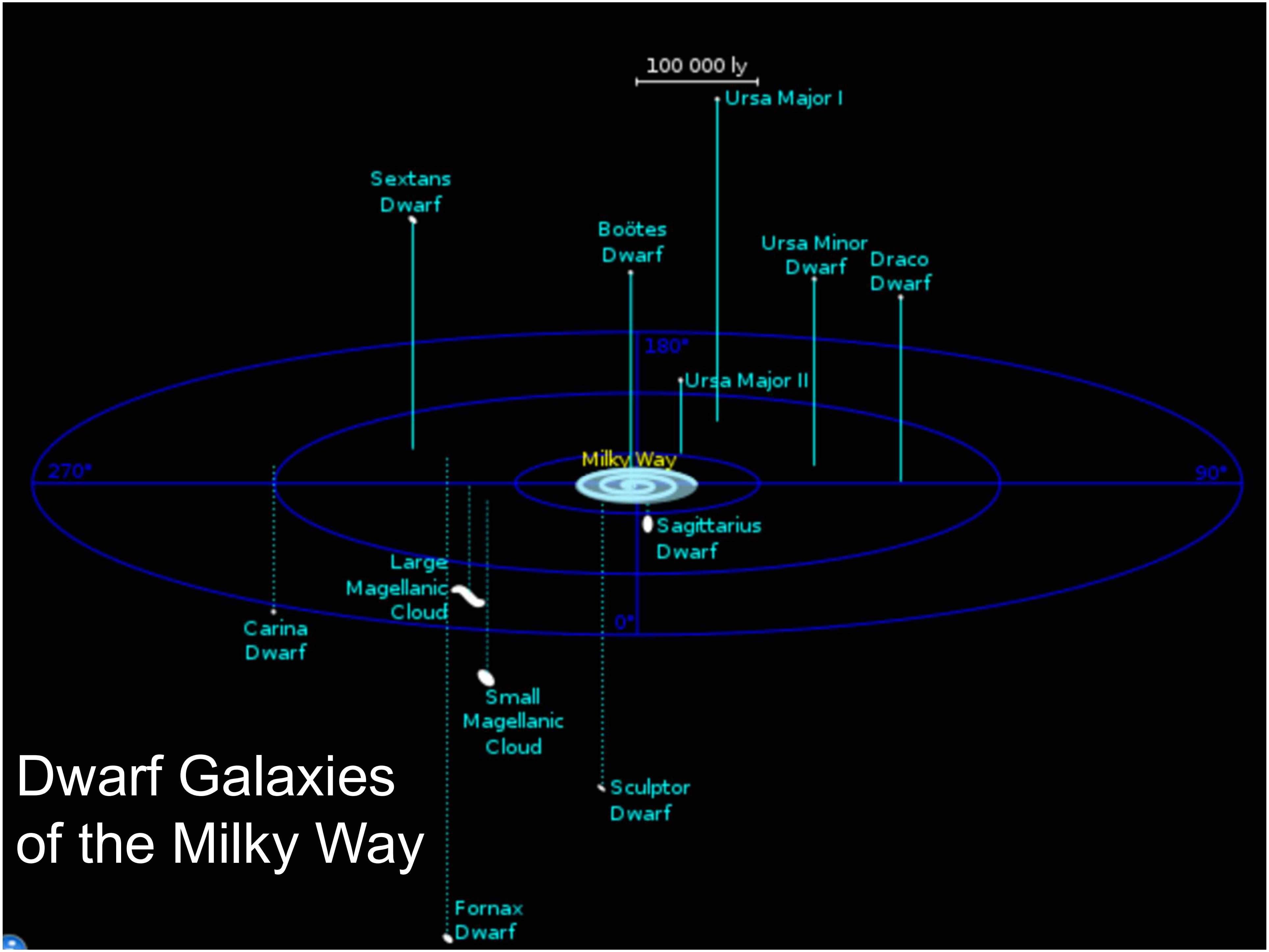
1910.01649

Light Fermionic dark Matter

can we get a constraint from the Pauli exclusion principle?



Original bound from Gunn and Tremaine in 1979 used galaxies to place a constraint on the mass of dark matter.



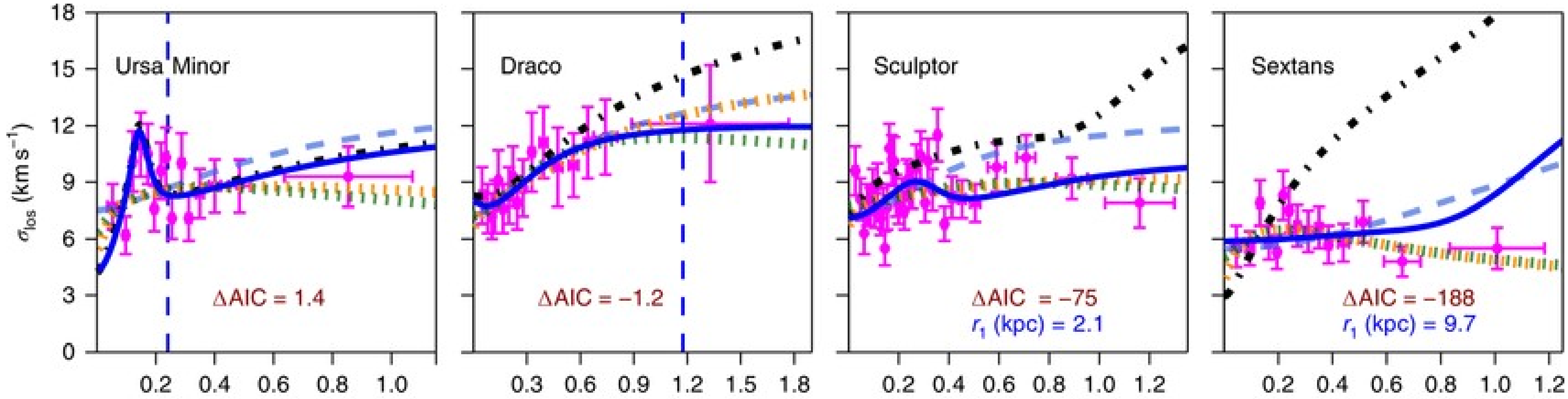
Dwarf Galaxies of the Milky Way

New Constraints on the Mass of Fermionic Dark Matter from Dwarf Spheroidal Galaxies *James Alvey, Nashwan Sabti, Victoria Tiki, Diego Blas, Kyrylo Bondarenko, Alexey Boyarsky, Miguel Escudero, Malcolm Fairbairn, Matthew Orkney and Justin I. Read*

Dwarf Galaxies heavily dominated by Dark Matter

arXiv:2010.03572

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION



Valli and Yu 2018

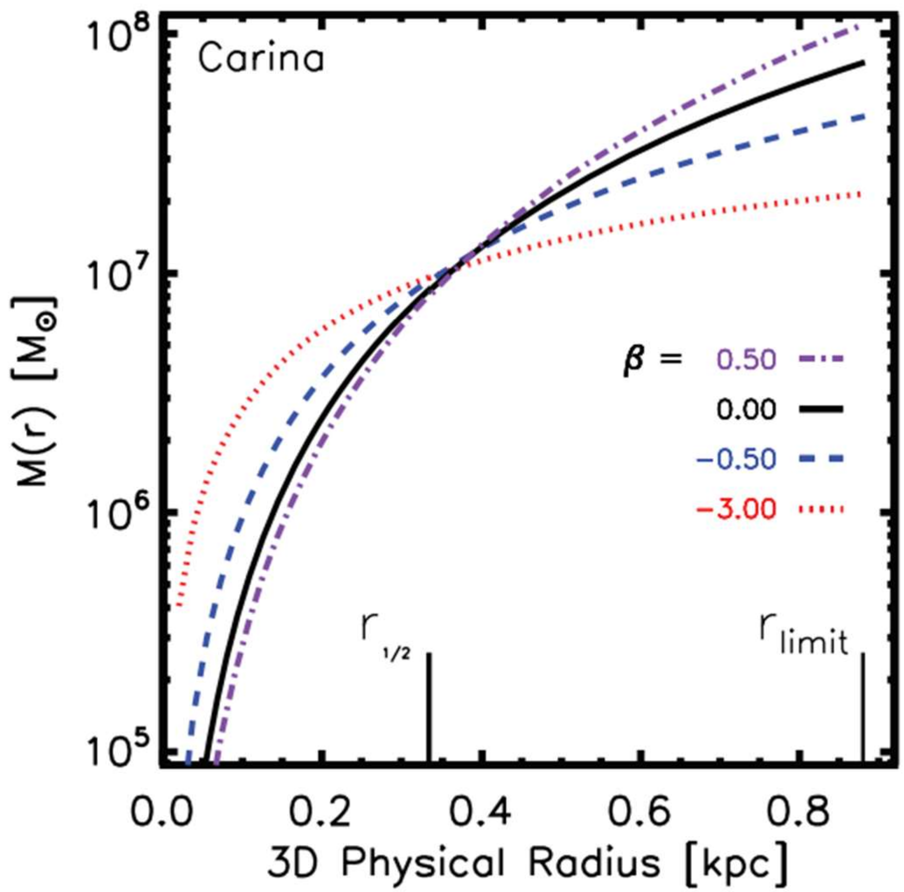
- Jeans equation:

$$\frac{1}{\nu}\frac{\partial}{\partial r}(\nu\sigma_r^2) + 2\frac{\beta(r)\sigma_r^2}{r} = -\frac{GM(r)}{r^2}\ , \qquad \beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

- Observe line-of-sight velocity and projected tracer density:

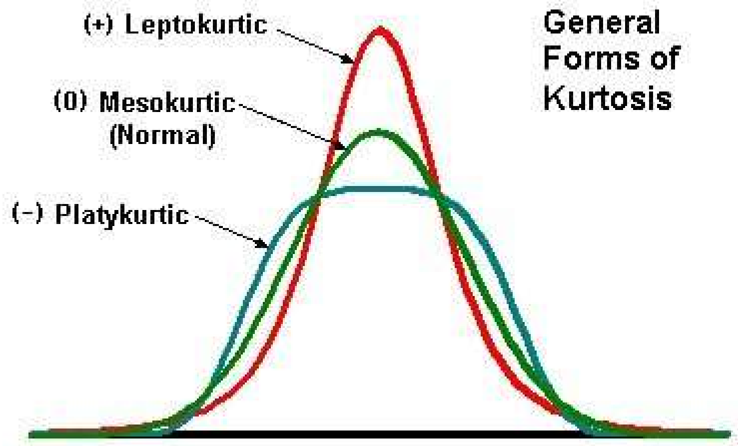
$$\sigma_{\rm LOS}^2(R) = \frac{2}{\Sigma(R)}\int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right)\nu\sigma_r^2 \frac{r\mathrm{d}r}{\sqrt{r^2 - R^2}}$$

Leads to famous “beta-degeneracy” e.g. Wolf et al 2009.



What if we include Kurtosis of LOS velocities?

Merrifield and Kent 1990
Fairbairn and Richardson 2014



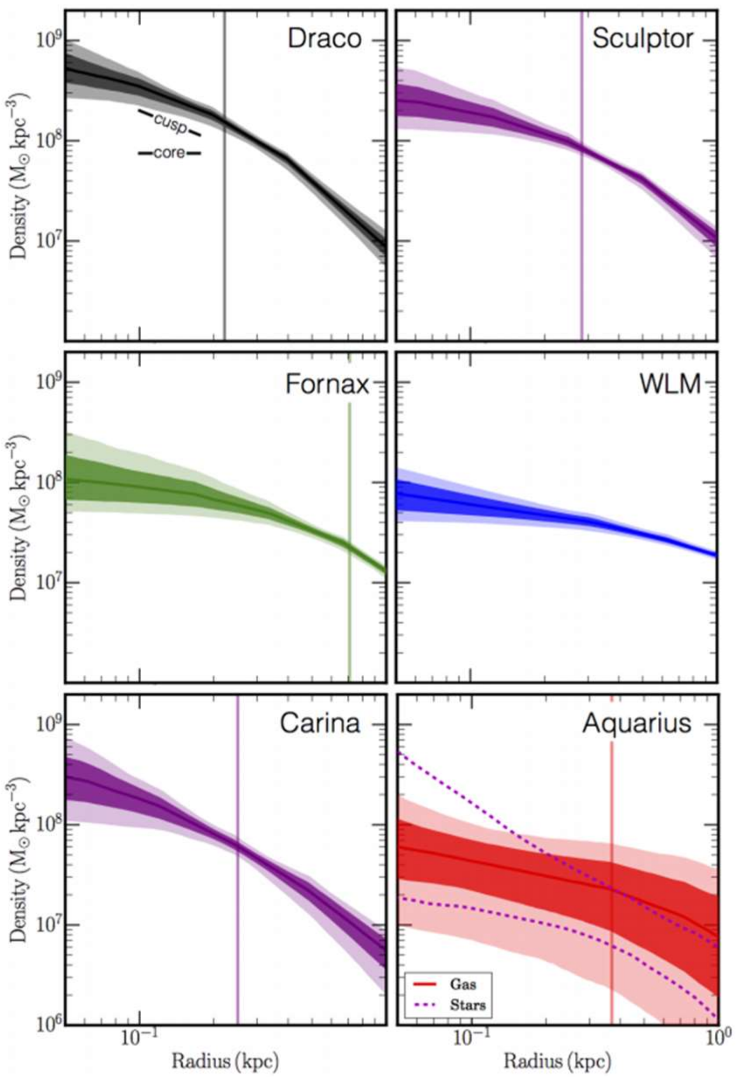
- Introduce virial shape parameters:

$$\mathrm{VSP1} = \int_0^\infty \Sigma\langle v_{\mathrm{LOS}}^4\rangle R\,\mathrm{d}R = \frac{2}{5}\int_0^\infty \nu(5-2\beta)\sigma_r^2 GMR\,\mathrm{d}R$$

$$\mathrm{VSP2} = \int_0^\infty \Sigma\langle v_{\mathrm{LOS}}^4\rangle R^3\,\mathrm{d}R = \frac{4}{35}\int_0^\infty \nu(7-6\beta)\sigma_r^2 GMR^3\,\mathrm{d}R$$

We marginalise over β using priors from simulations

Can break degeneracies and obtain good density profiles



Read et al 2018

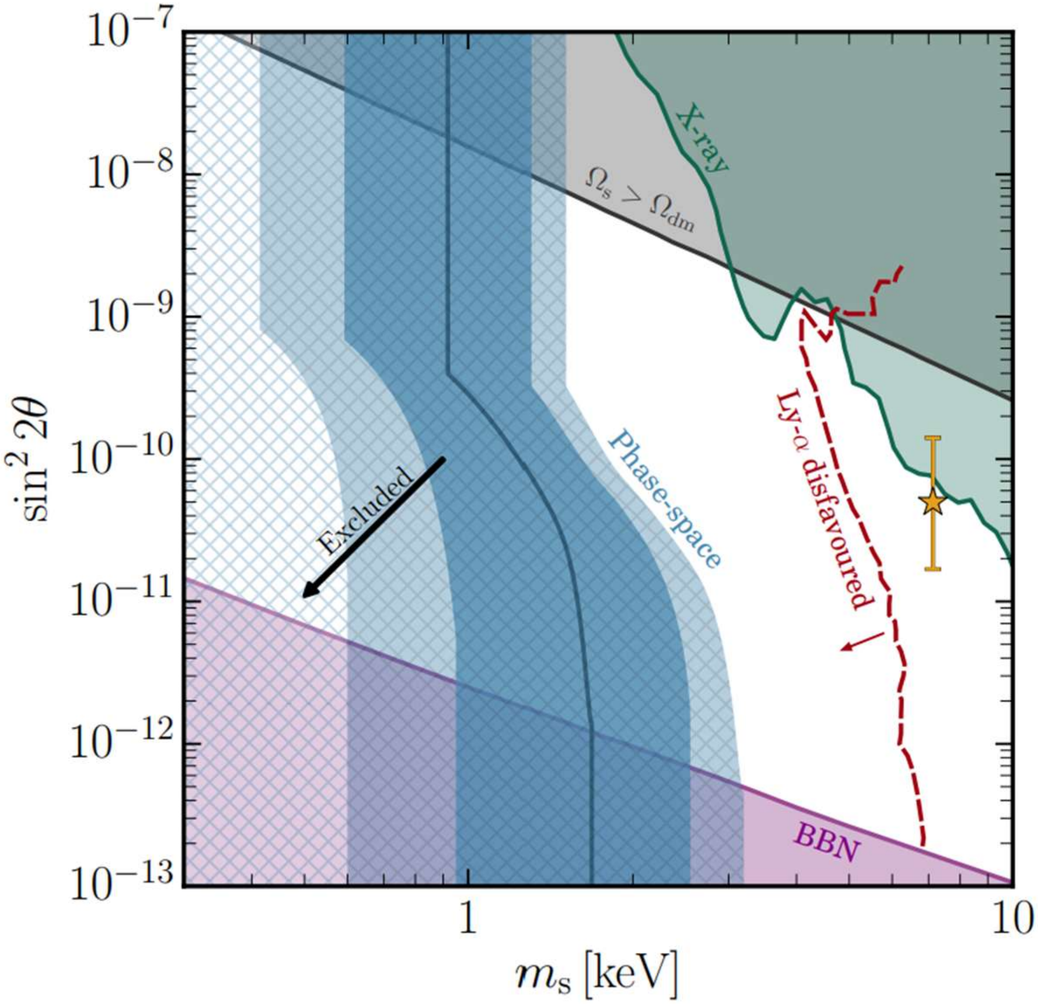
- Bounds from Pauli's principle – model independent. Fermi velocity:-

$$v_F = \left(\frac{6\pi^2\rho(r)}{gm^4}\right)^{1/3}$$

$$v_F < v_{esc} \longrightarrow m_{deg} > \left.\left(\frac{6\pi^2\rho(r)}{gv_{esc}^3(r)}\right)^{\frac{1}{4}}\right|_{r_{min}}$$

$$= 0.27^{+0.30}_{-0.14}\ \text{keV}\ (2\sigma)$$

Constraint on resonantly produced Sterile neutrino models



Uses initial phase space distribution arXiv:2010.03572

The ongoing Search for Dark Matter

- We are well into an era of using novel lensing approaches to learn more about dark matter

- Strong lensing approaches to detecting substructure with machine learning are being developed and refined

- BBN can constrain changes to thermodynamics due to light dark matter

- New techniques to study Dwarf galaxies can lead to new insights on dark matter (m>0.27 keV)

- Precision astronomical probes continue to give us more information about the dark stuff... Whatever it is or isn't…

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