Dark Matter Hunting in 2021

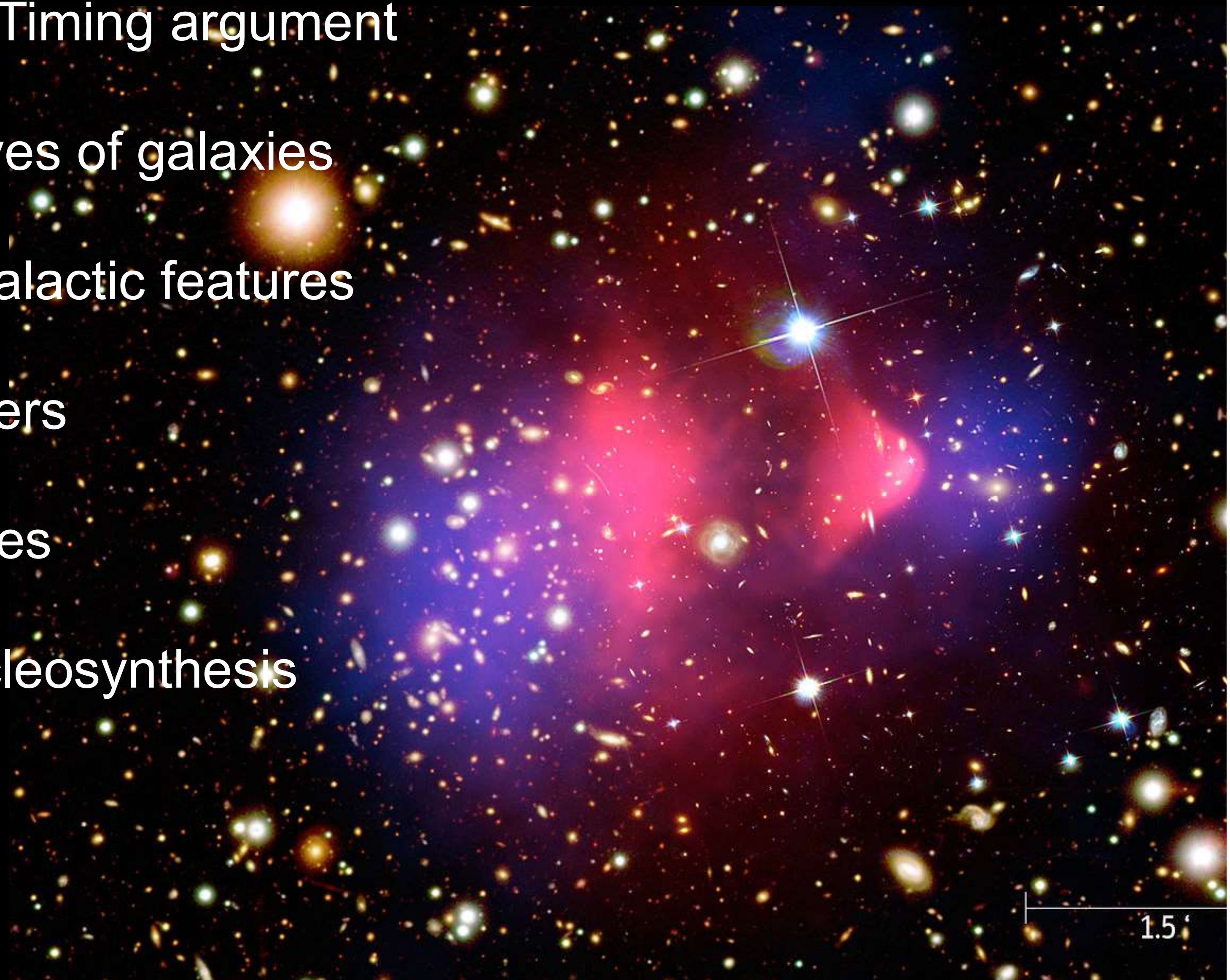
How do you look for something when you don't know what it is?

Malcolm Fairbairn

Planck 2021

Evidence for Dark Matter

- Local Group Timing argument
- Rotation curves of galaxies
- Stability of Galactic features
- Galaxy Clusters
- Dwarf Galaxies
- Big bang nucleosynthesis
- Bullet cluster
- Etc etc etc…

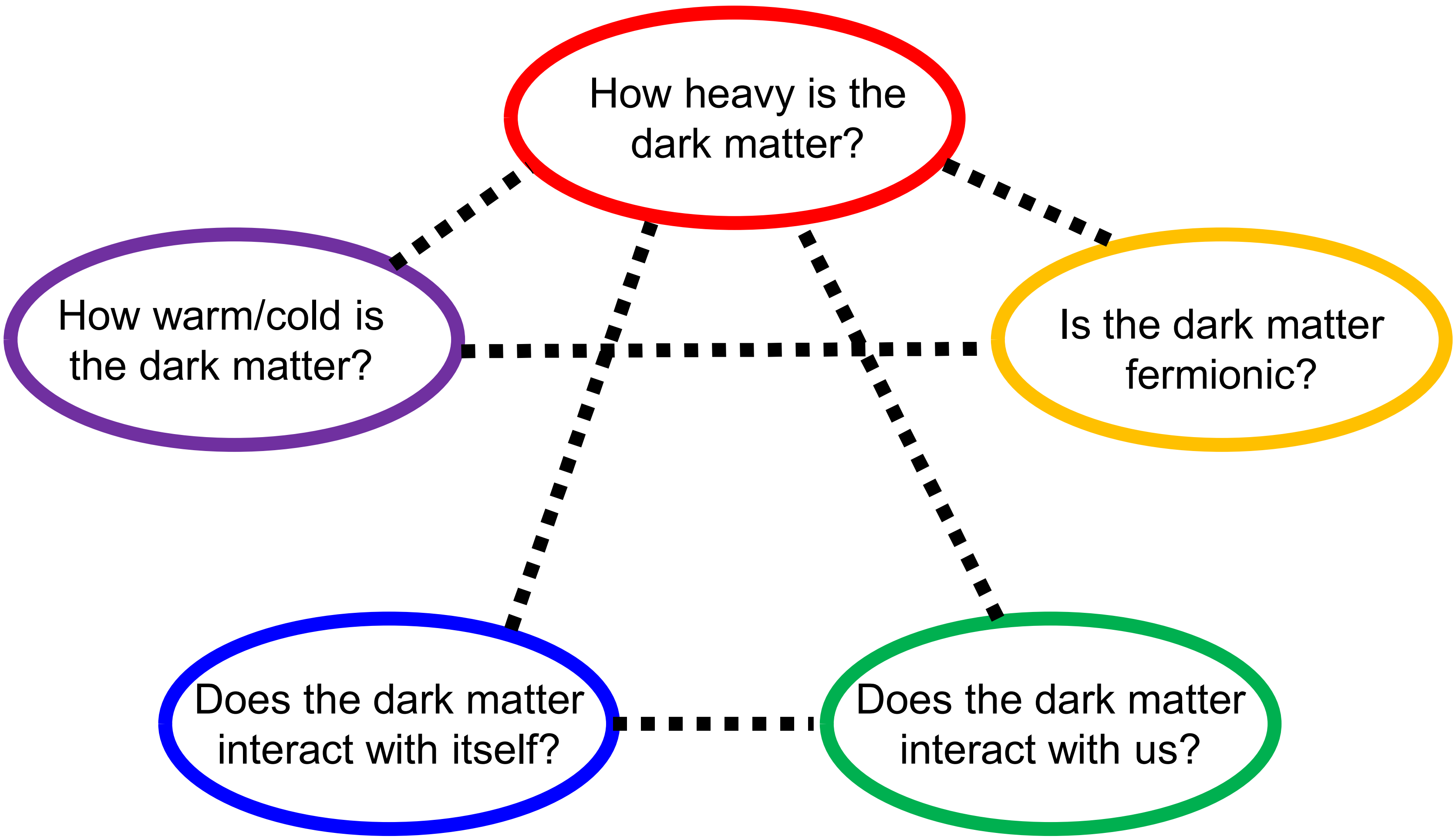



There is 6 times as much dark matter as normal matter.

No dark matter has been detected yet!

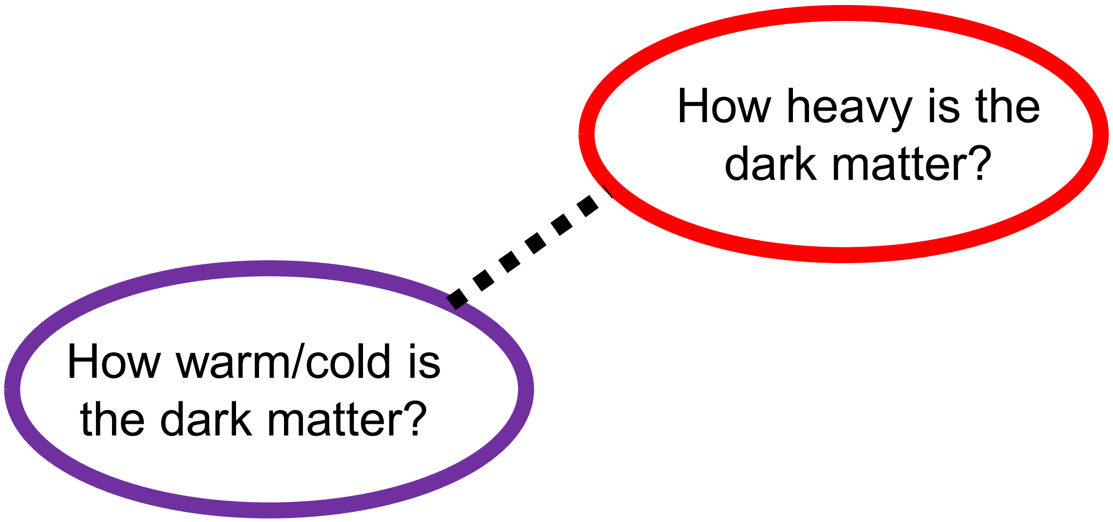
What can we find out about it without interacting with it directly?

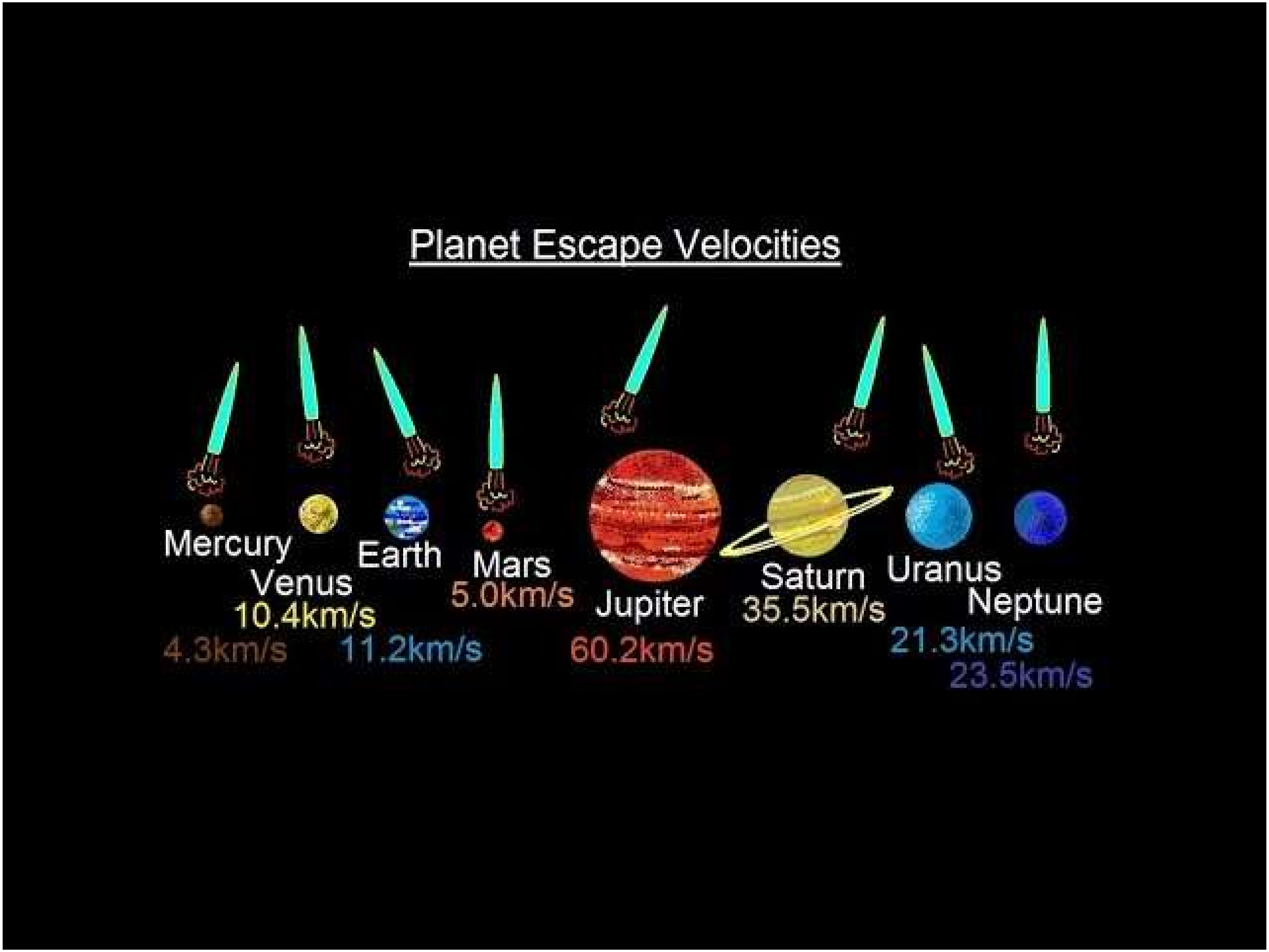
Things we can try to find out about dark matter



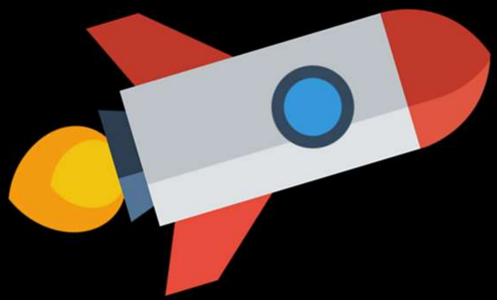
These questions are very often related to each other

Things we can try to find out about 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

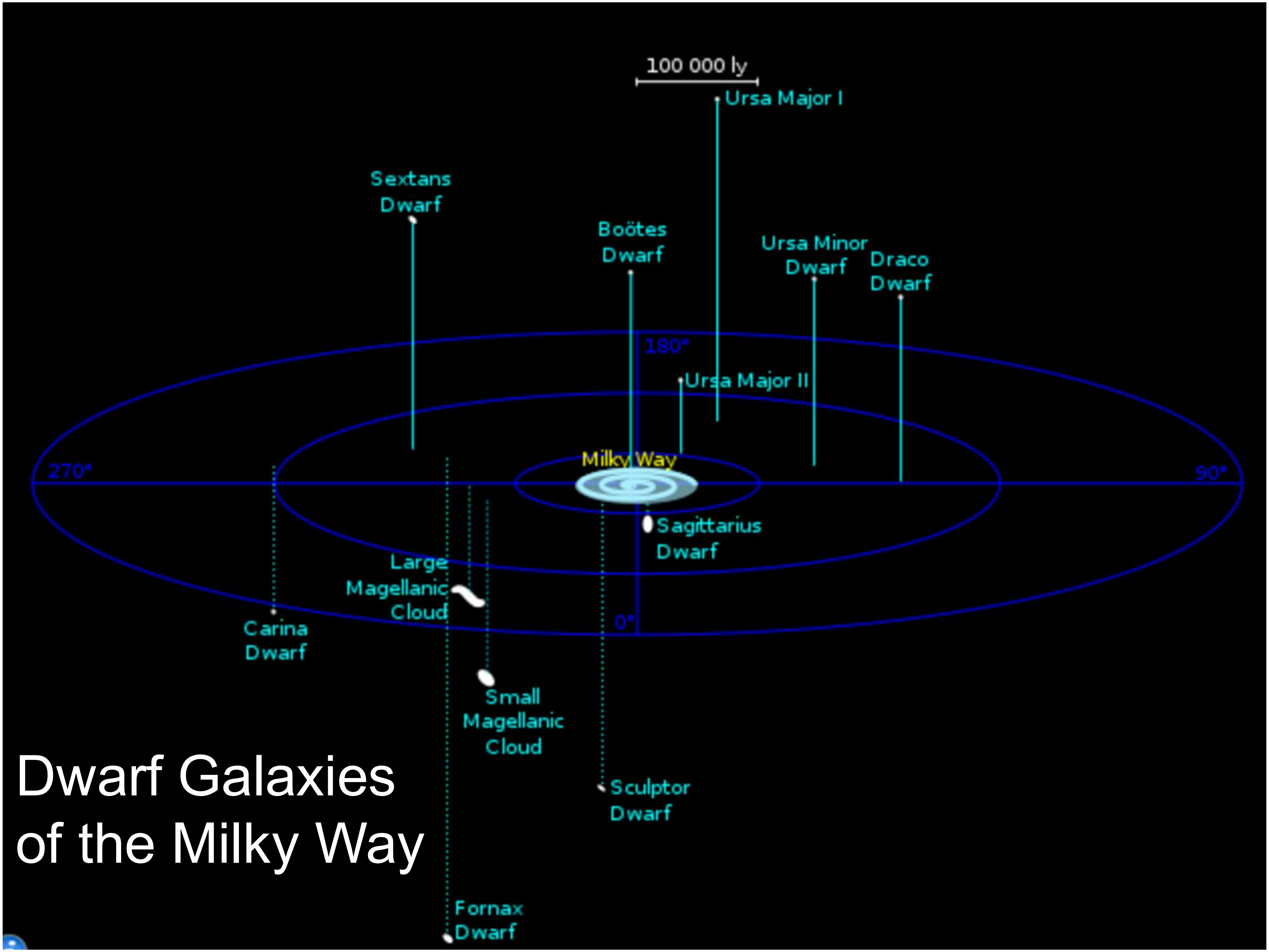
Milky Way Escape velocity



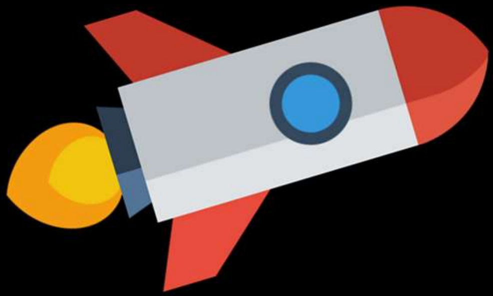
~ 500 km / s

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

Dwarf Galaxies of the Milky Way



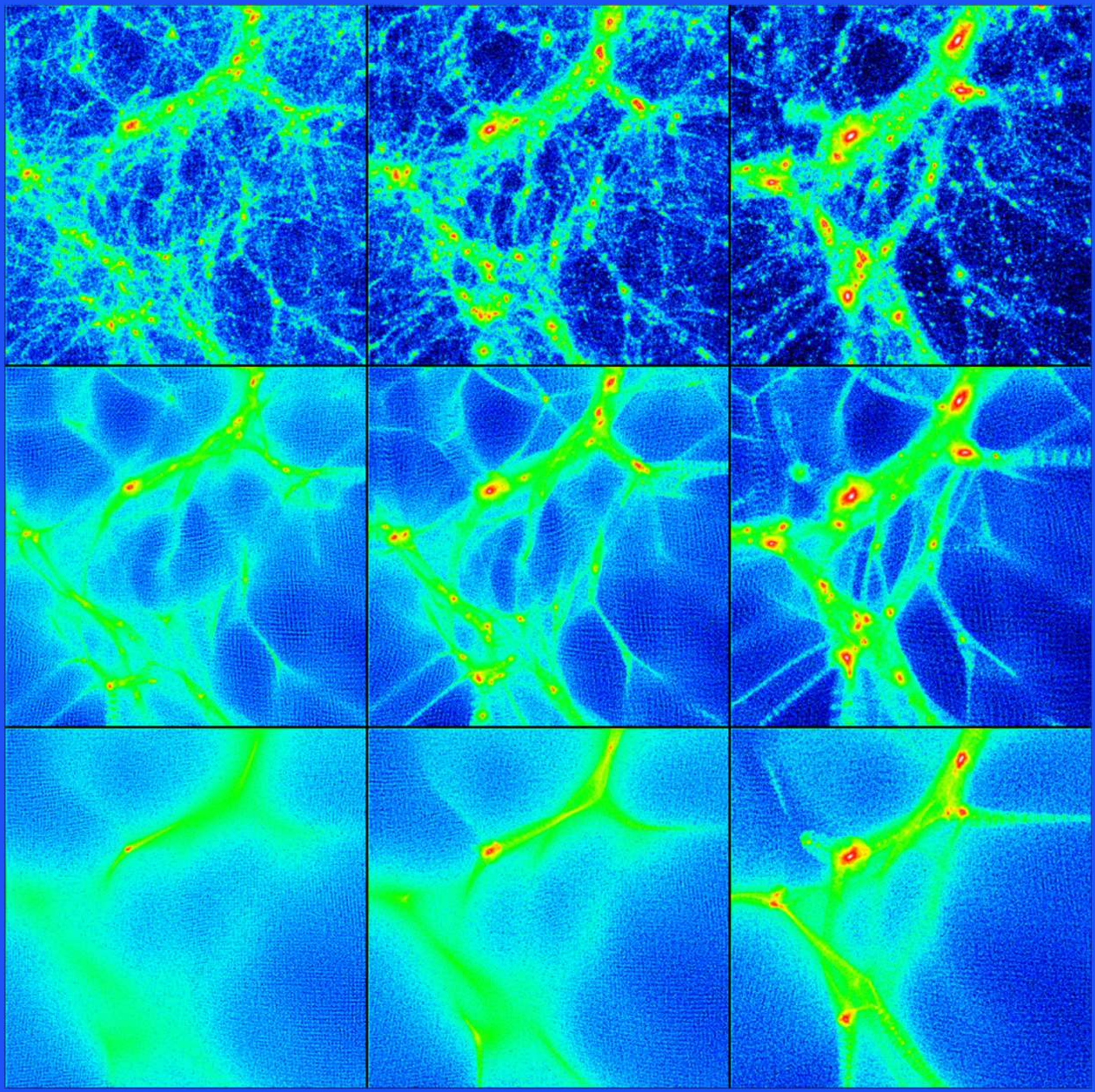
Dwarf Galaxy Escape velocity



~ 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?

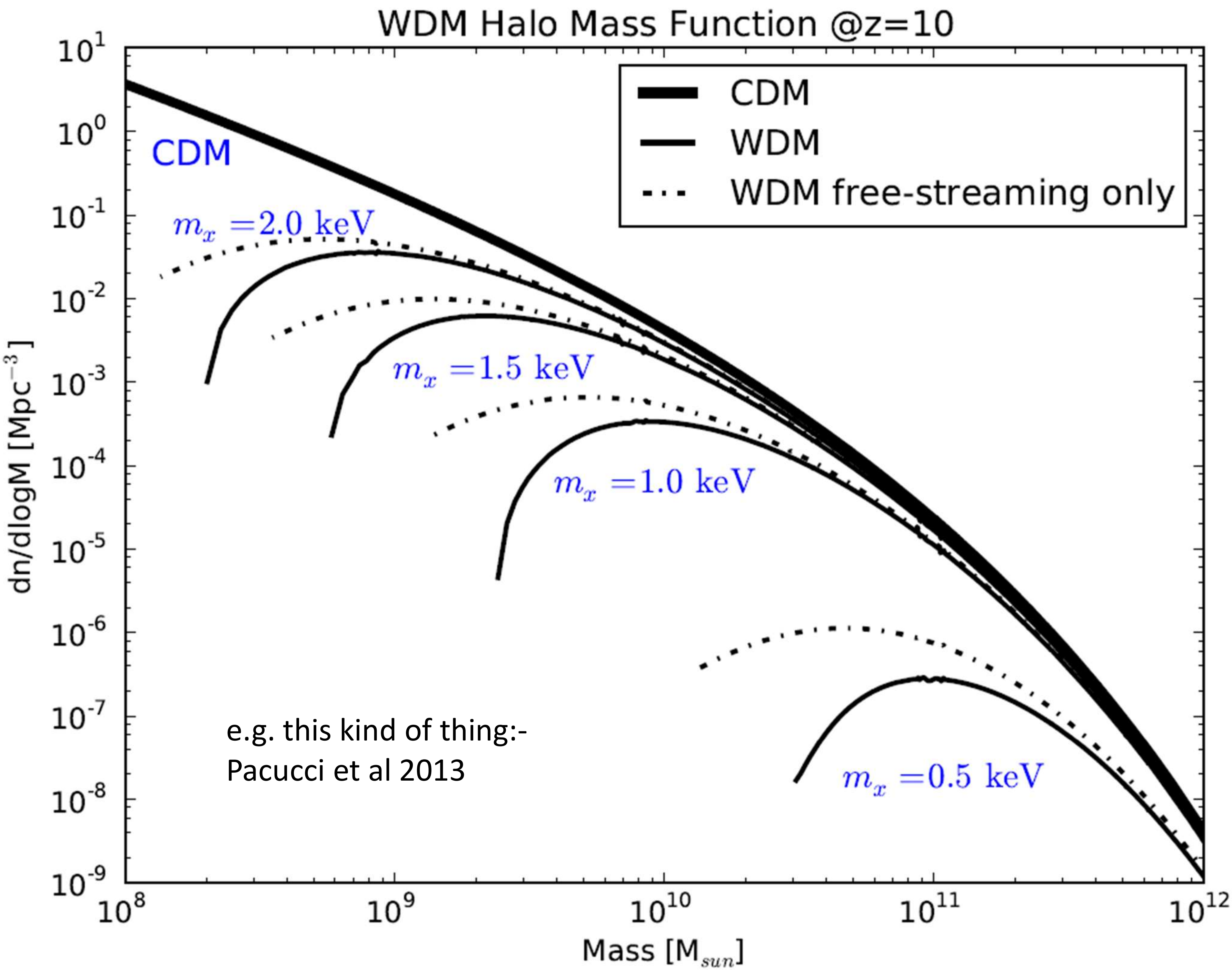


Slow moving dark matter

(computer simulations)

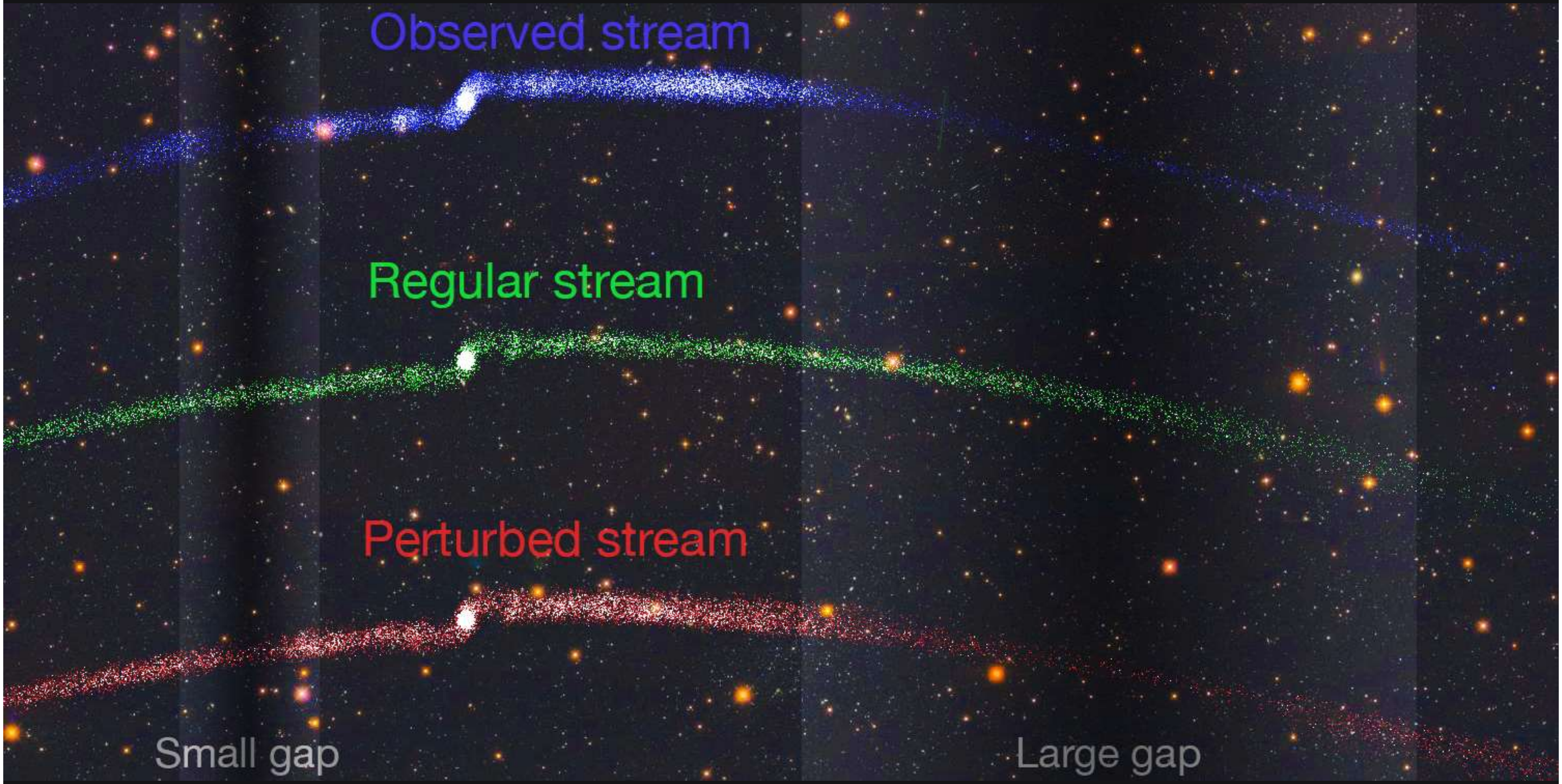
Fast moving dark matter

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

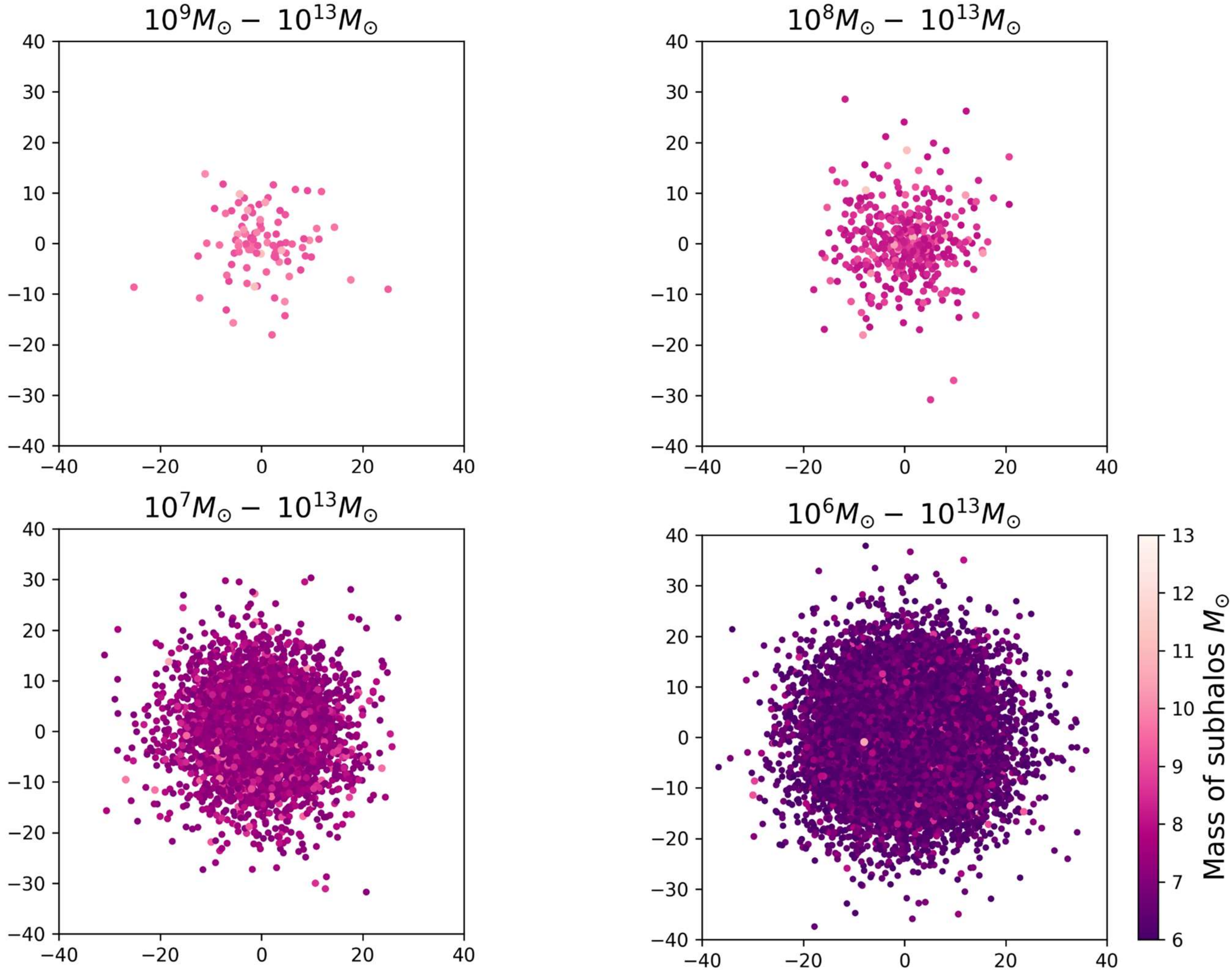


e.g. this kind of thing:-
Pacucci et al 2013

Small Subhalos can perturb stellar streams

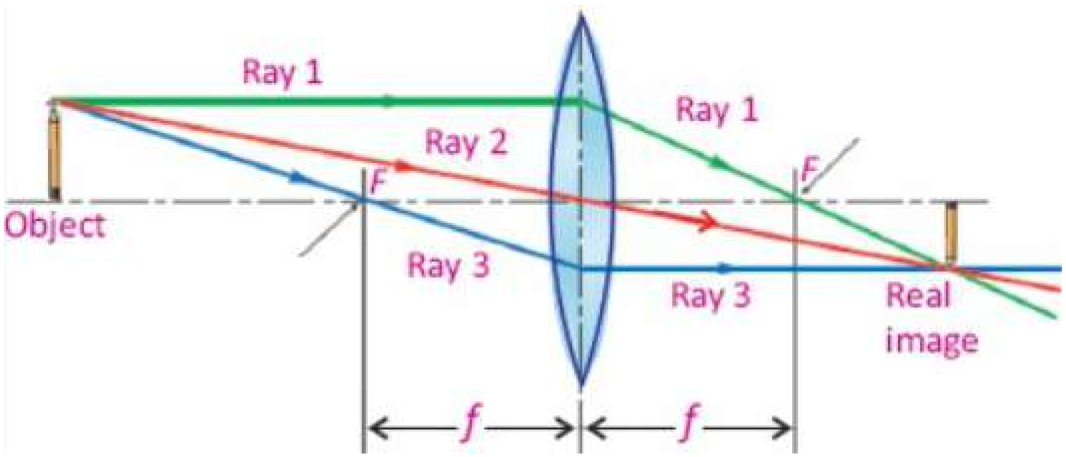


See work by Bovy, Erkal, Sanders etc
+ Bertone for possible preliminary results

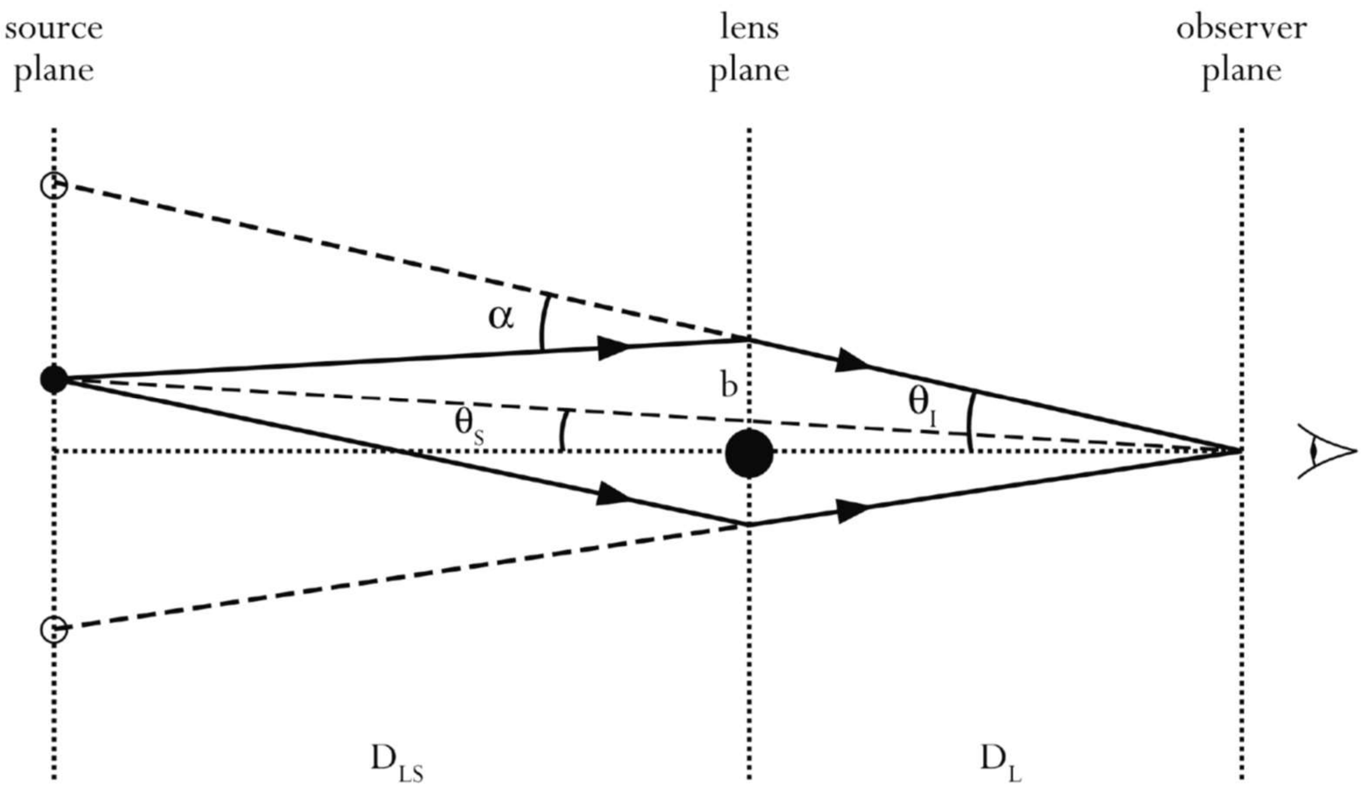


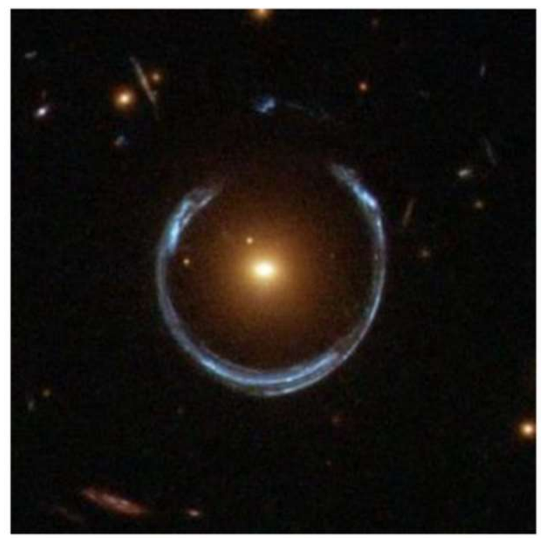
$10^9 M_\odot - 10^{13} M_\odot$
$10^8 M_\odot - 10^{13} M_\odot$
$10^7 M_\odot - 10^{13} M_\odot$
$10^6 M_\odot - 10^{13} M_\odot$
Mass of subhalos $M_\odot$

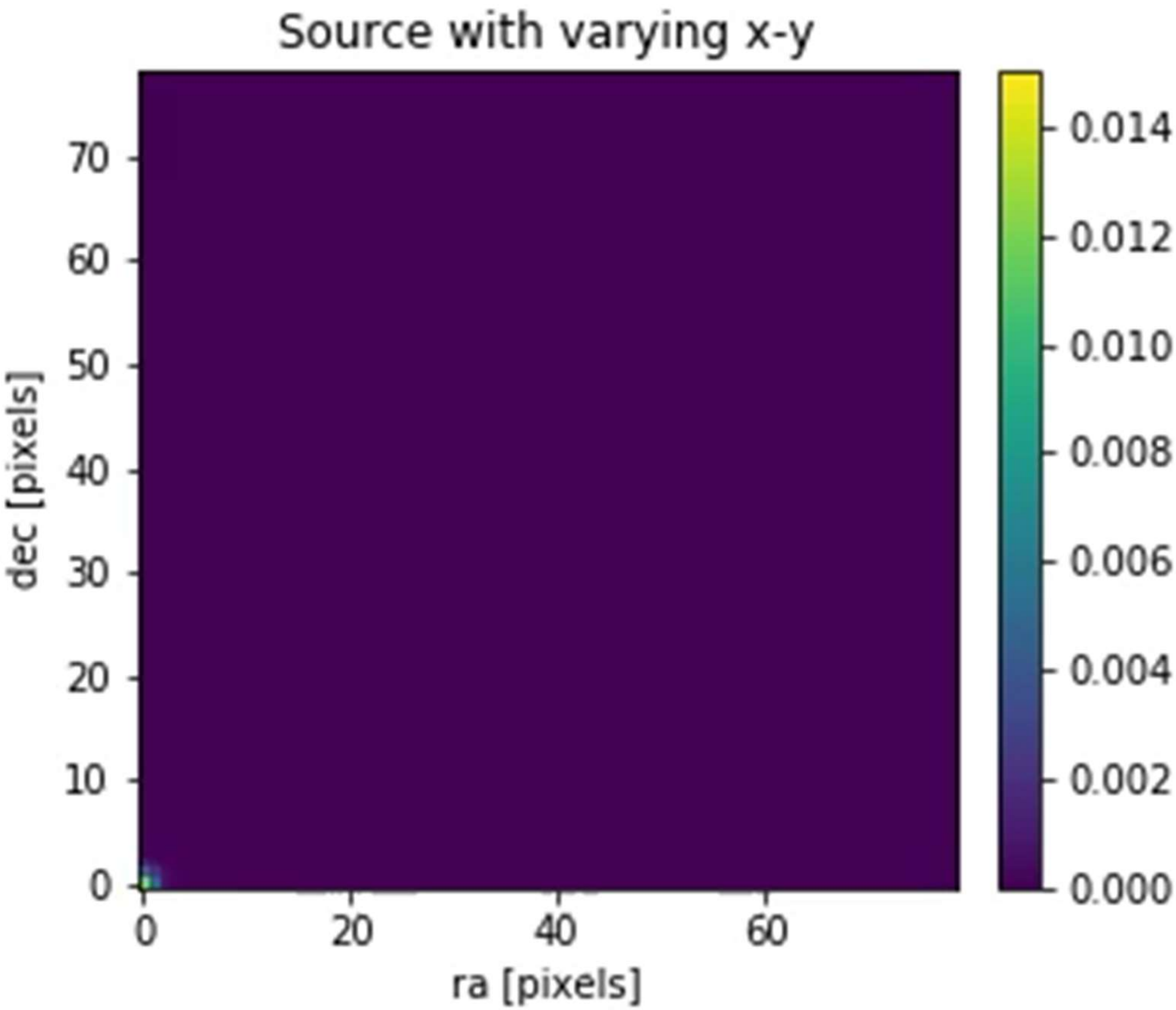
Lensing

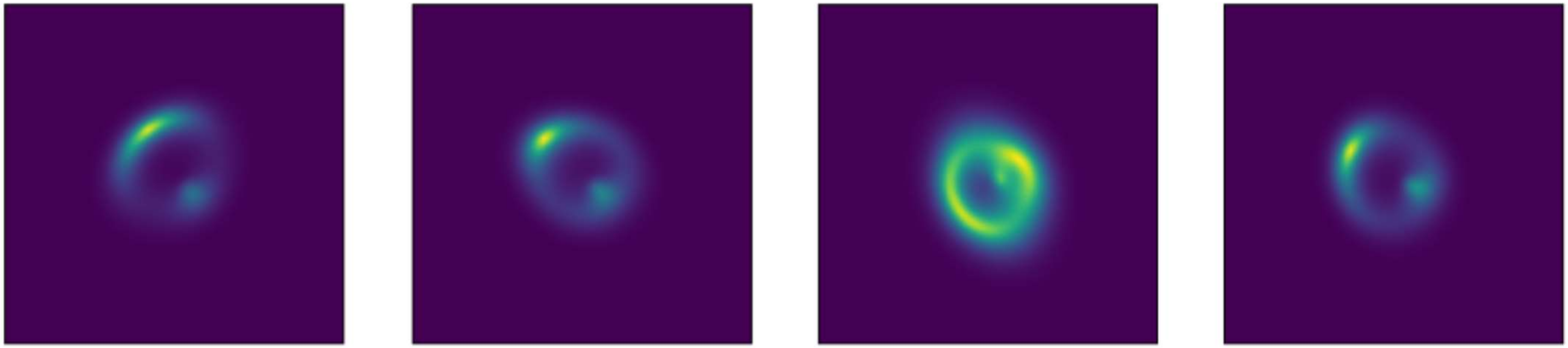


Gravitational Lensing





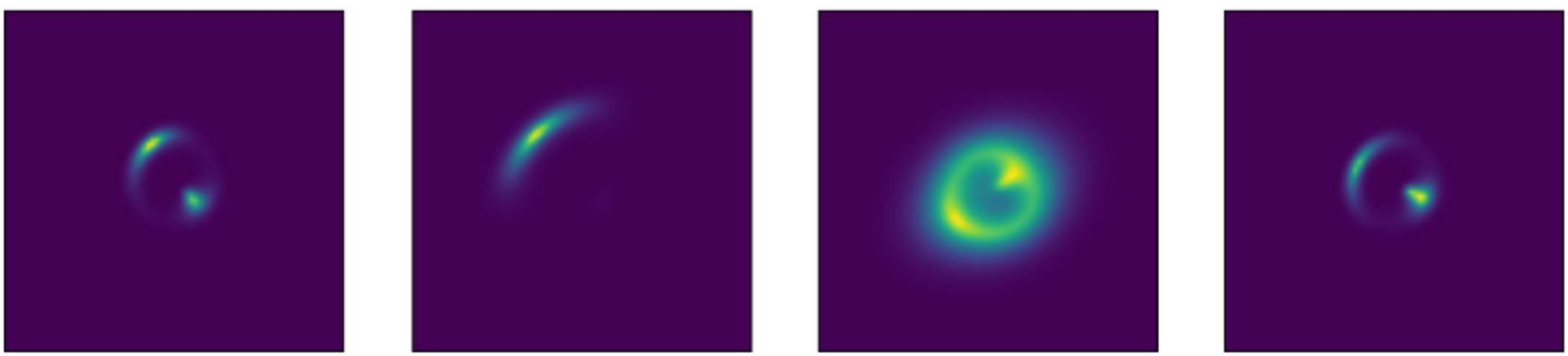

Source with varying x-y
dec [pixels]
ra [pixels]
0
10
20
30
40
50
60
70
0
20
40
60
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014



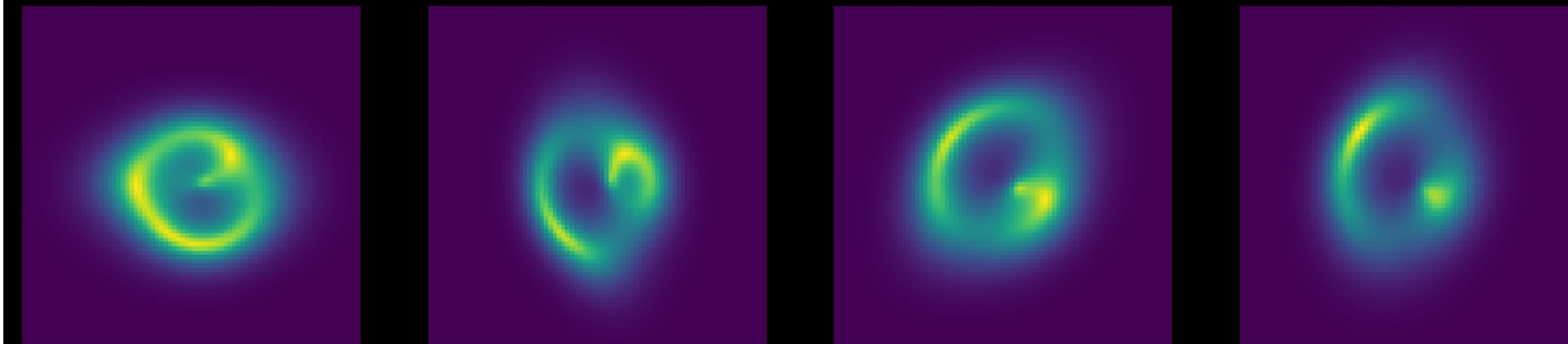
Minimum halo mass 10^9 Msun

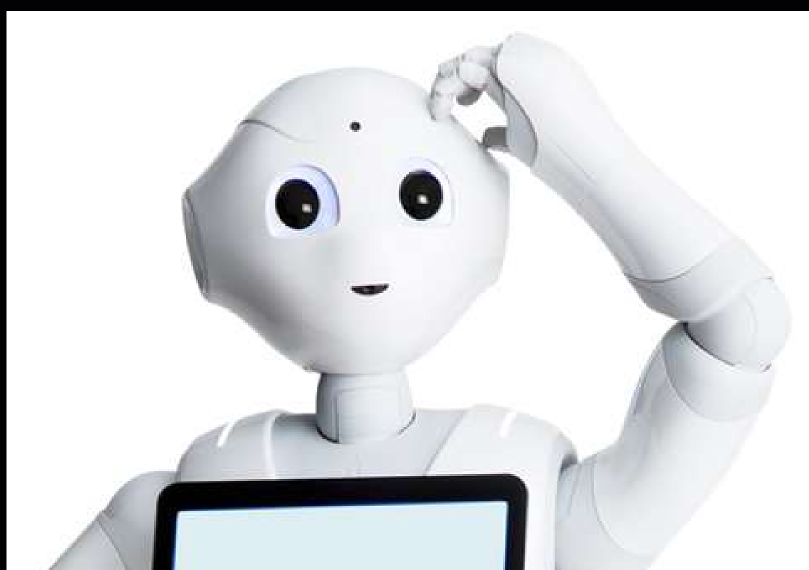
Can you tell the difference? I can't…

Minimum halo mass 10^6 Msun



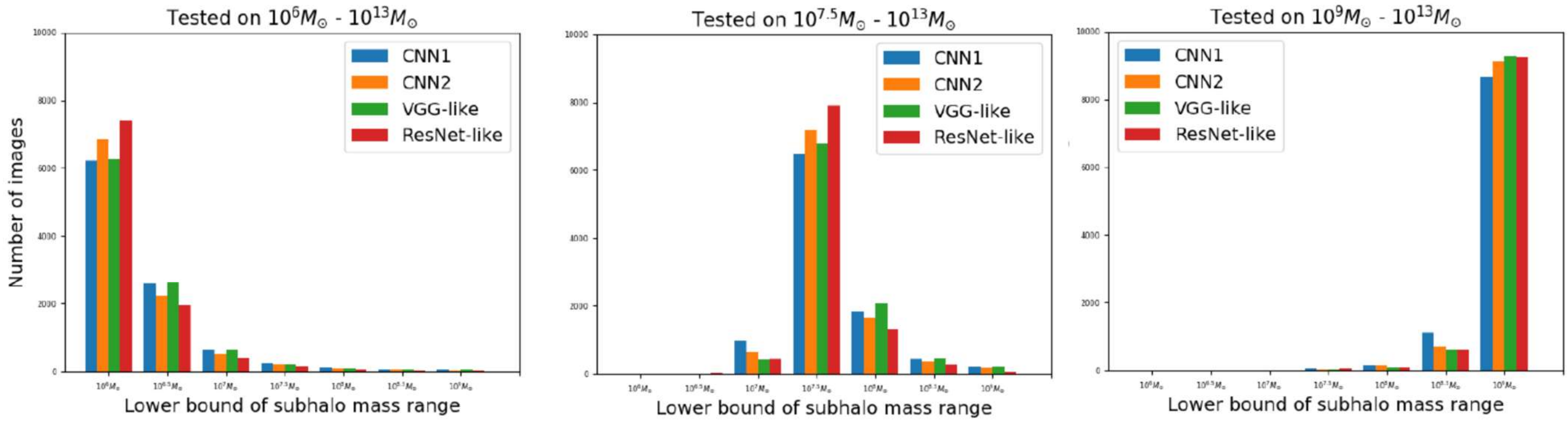
We generate lots of lensed images of galaxies.



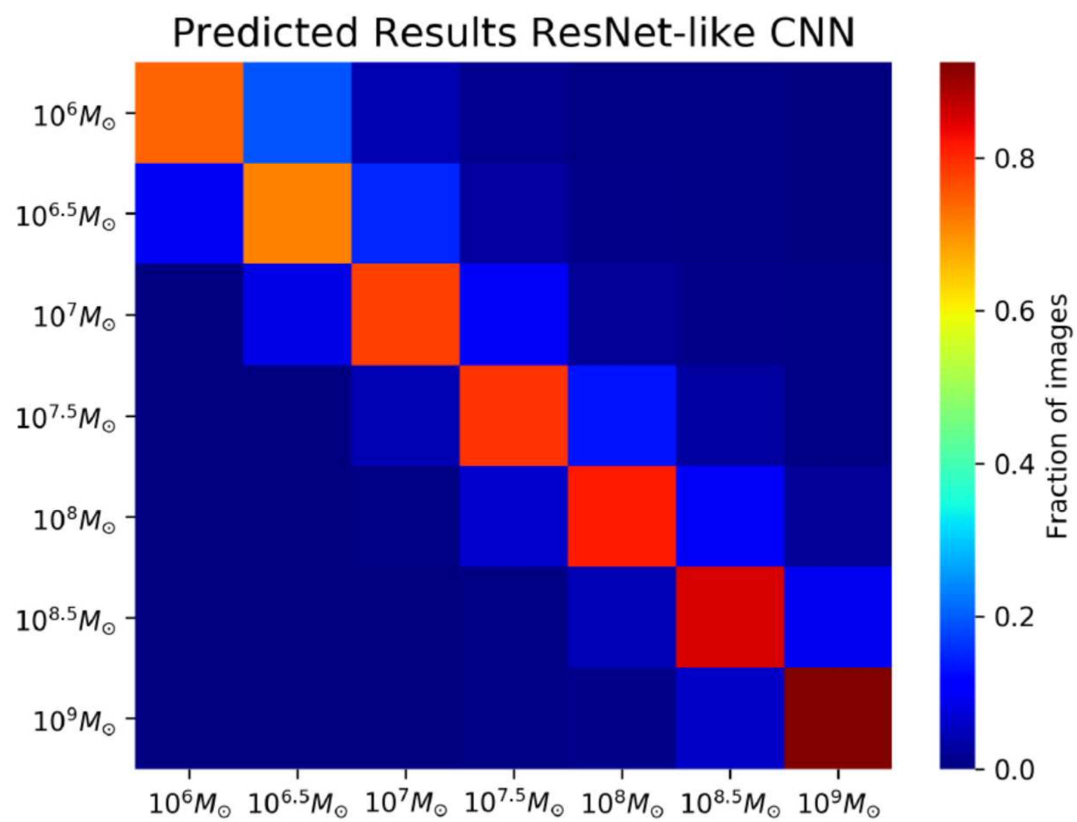


Sreedevi Varma

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!

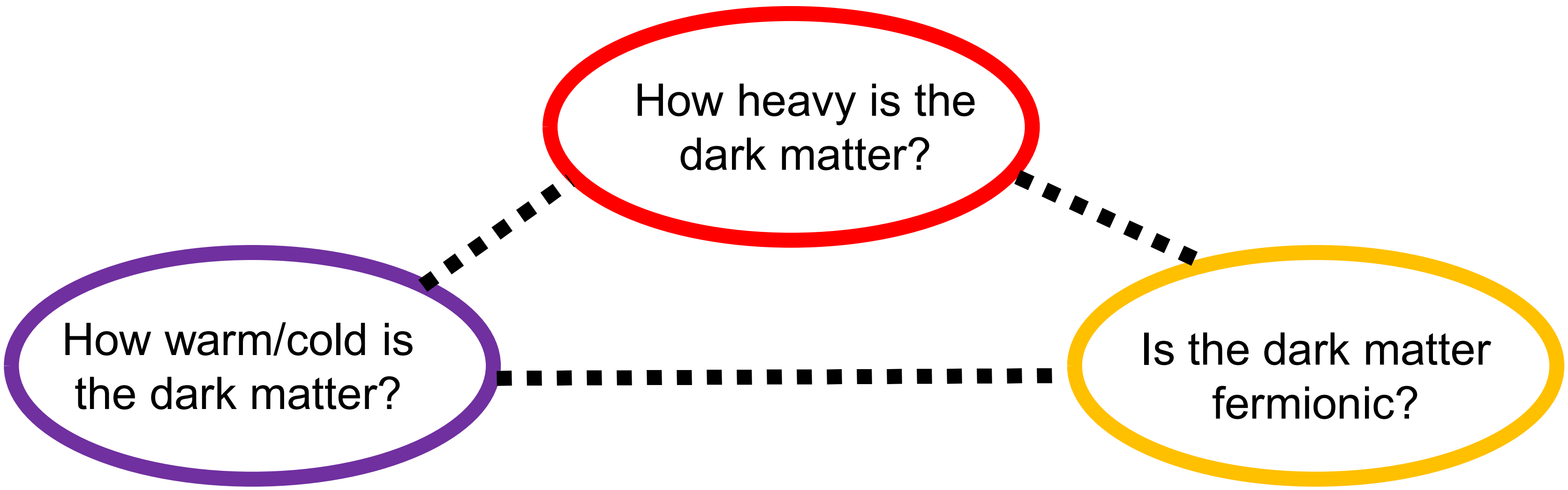


We need to prove that we can do this under more variation and while baryons are present…

This is not as easy.

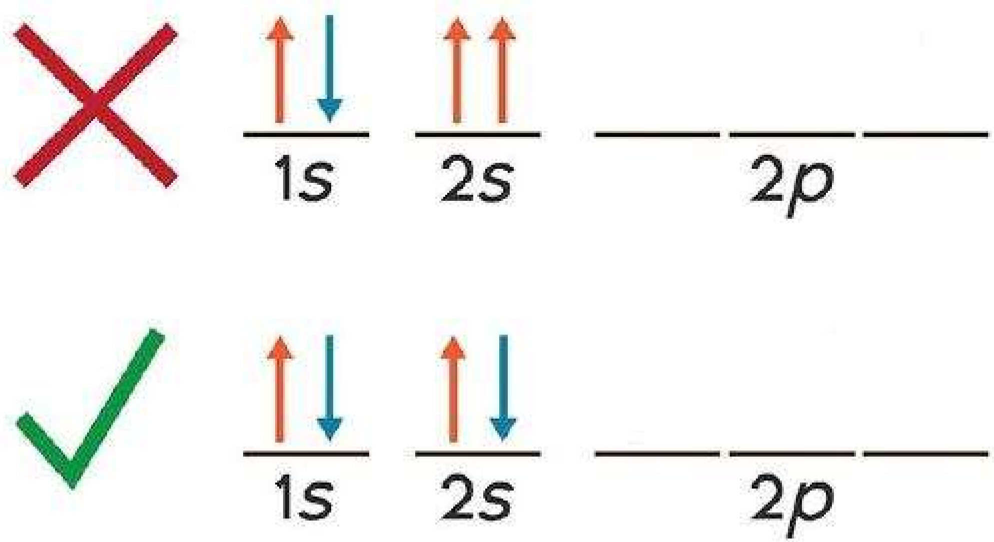
2005.05353

Things we can try to find out about dark matter



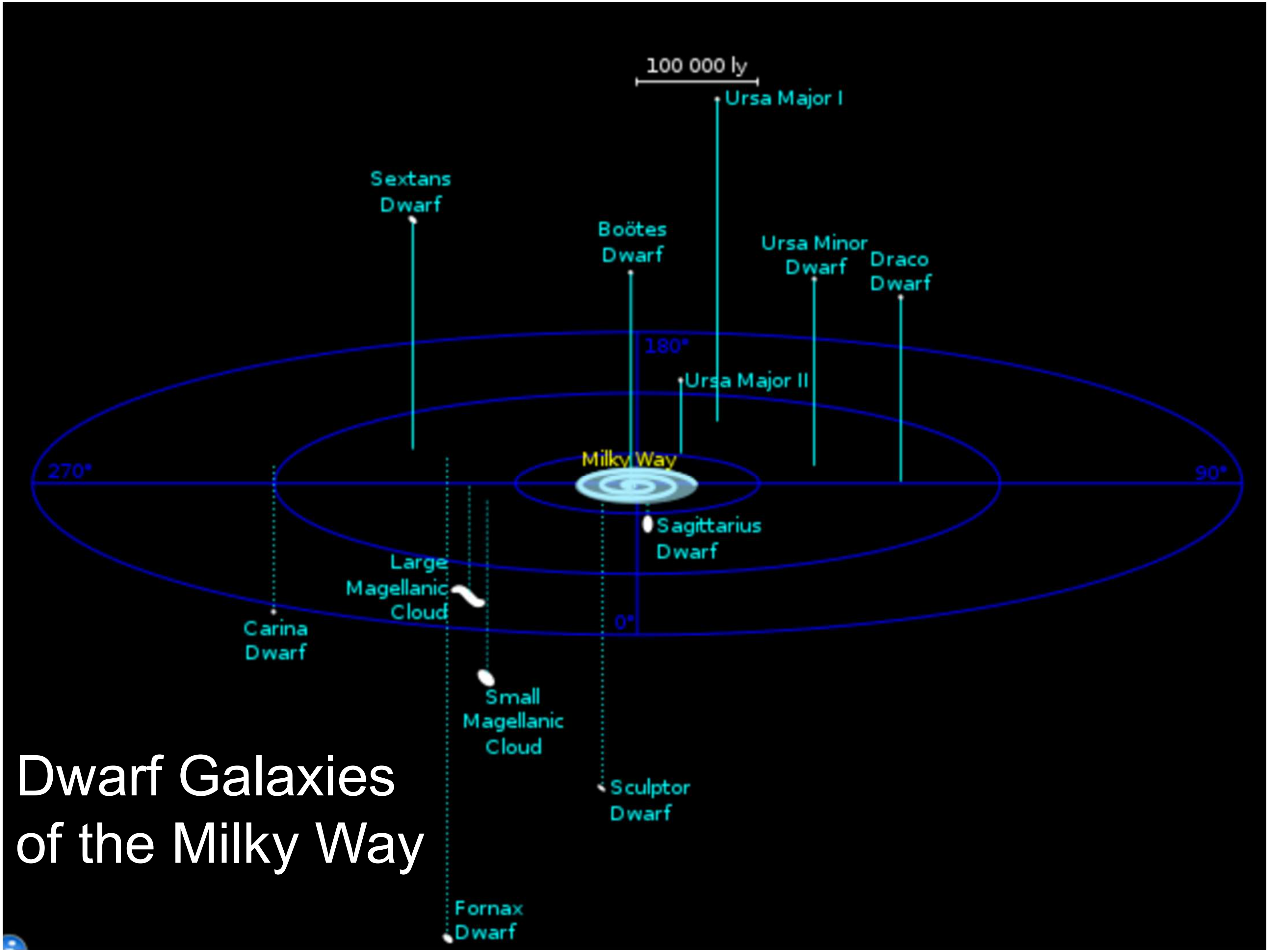
Light Fermionic dark Matter

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

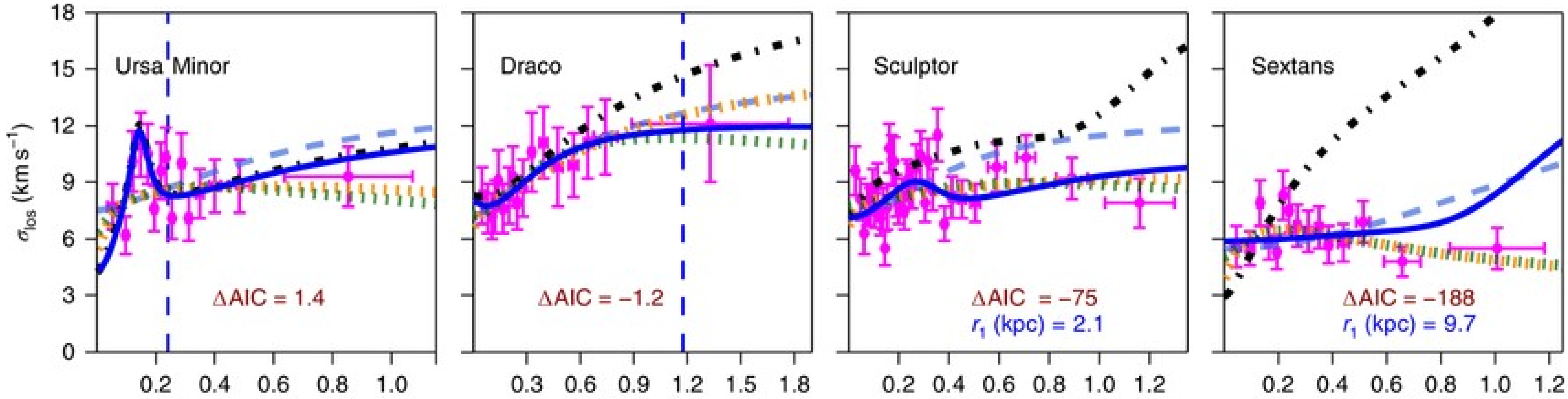


New Constraints on the Mass of Fermionic Dark Matter from Dwarf Spheroidal Galaxies *James Alvey, Nashwan Sabti, Victoria Tiki, Diego Blas, Kyrylo Bondarenko, Alexey Boyarsky, Miguel Escudero, Malcolm Fairbairn, Matthew Orkney and Justin I. Read*

Dwarf Galaxies heavily dominated by Dark Matter

arXiv:2010.03572

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION



Valli and Yu 2018

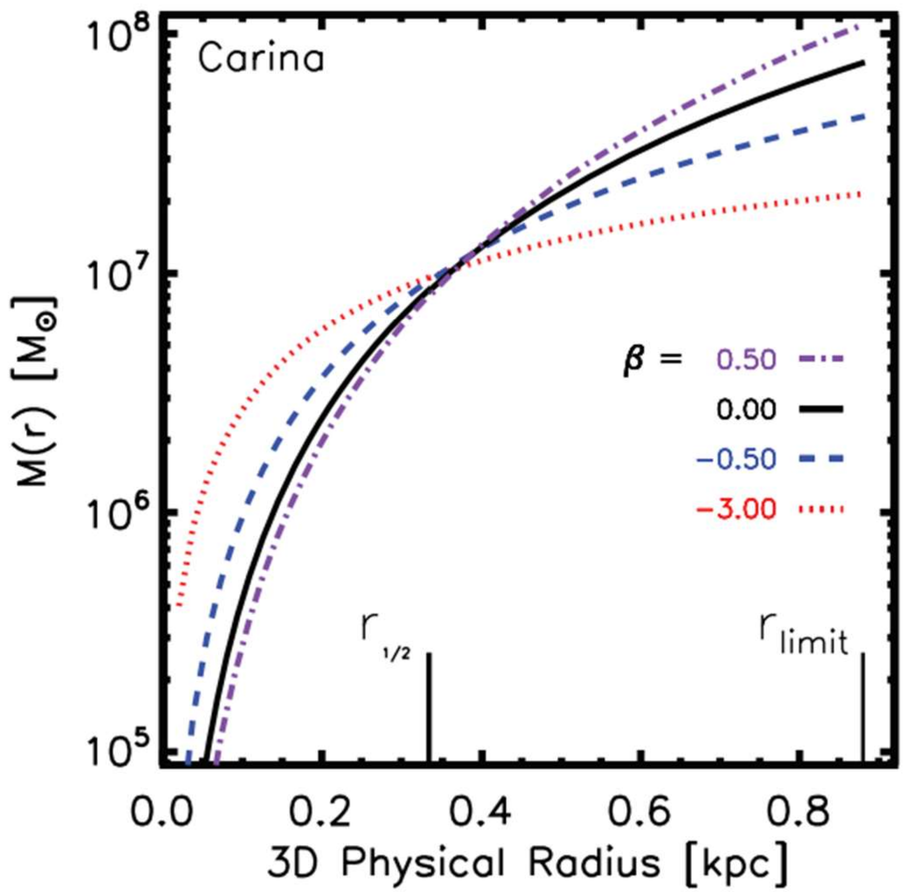
- Jeans equation:

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

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

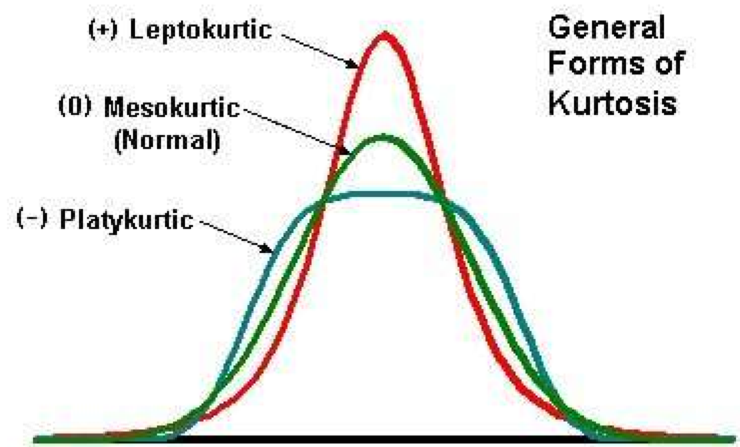
$$\sigma_{\rm LOS}^2(R) = \frac{2}{\Sigma(R)}\int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right)\nu\sigma_r^2 \frac{r\mathrm{d}r}{\sqrt{r^2 - R^2}}$$

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



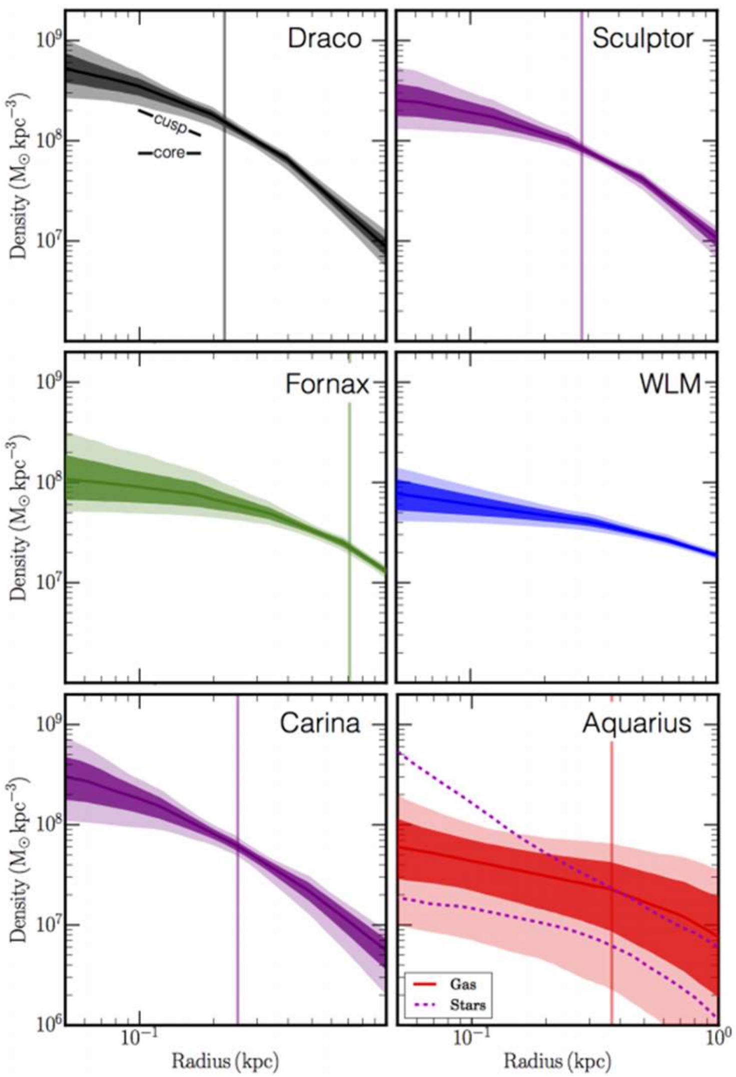
- Introduce virial shape parameters:

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

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

We marginalise over β using priors from simulations

Can break degeneracies and obtain good density profiles



Read et al 2018

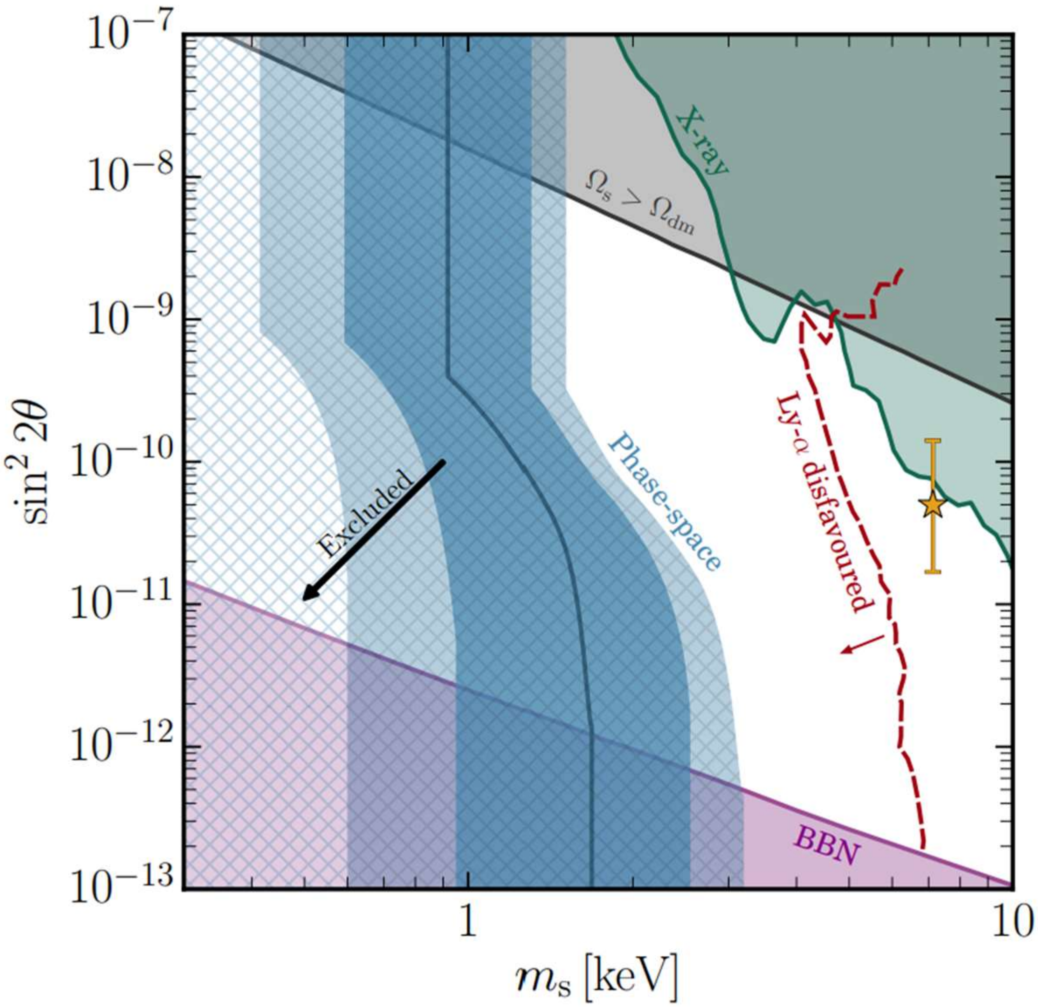
- Bounds from Pauli's principle – model independent. Fermi velocity:-

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

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

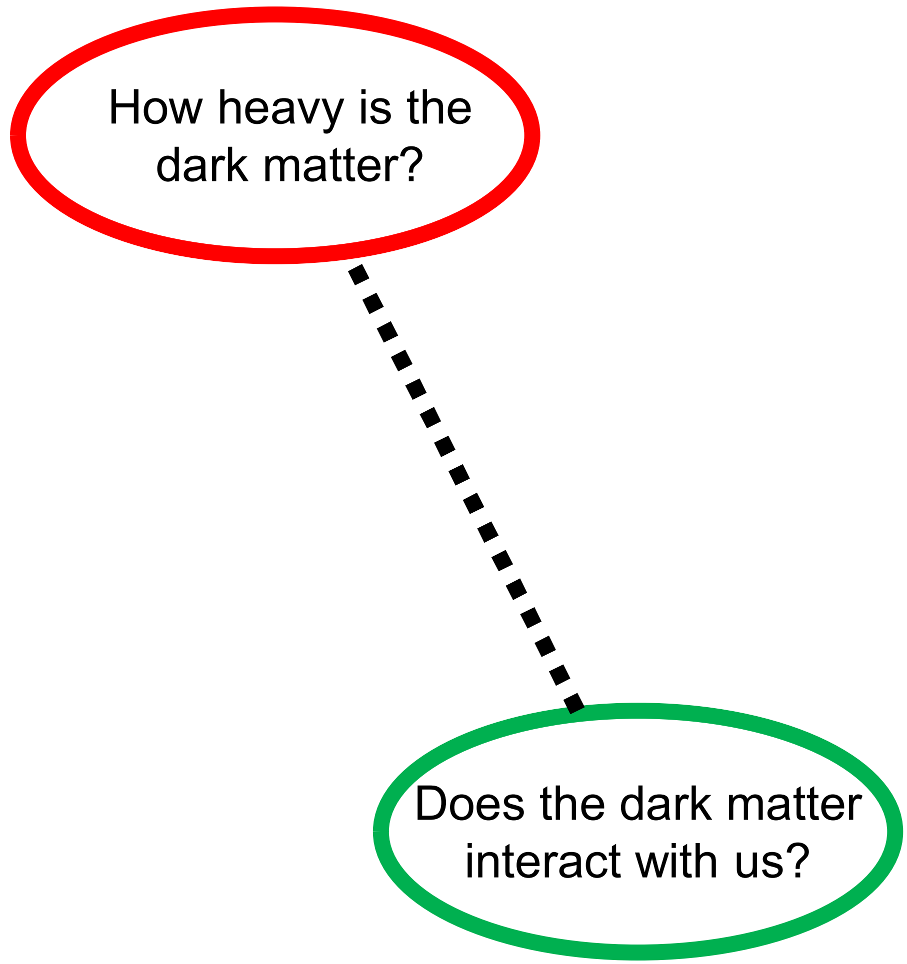
$$= 0.27^{+0.30}_{-0.14}\,\mathrm{keV}\ (2\sigma)$$

Constraint on resonantly produced Sterile neutrino models



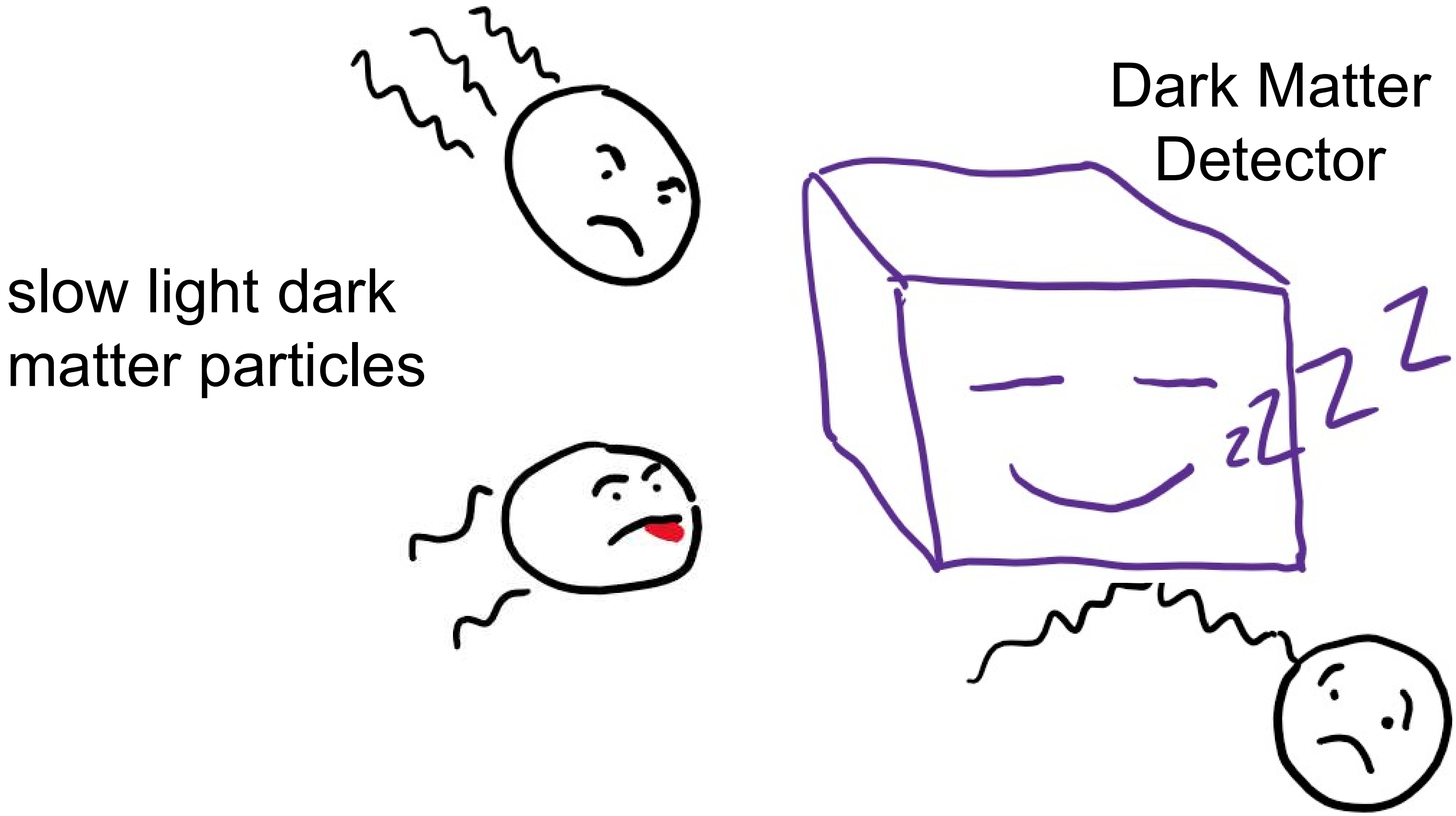
Uses initial phase space distribution arXiv:2010.03572

Things we can try to find out about dark matter

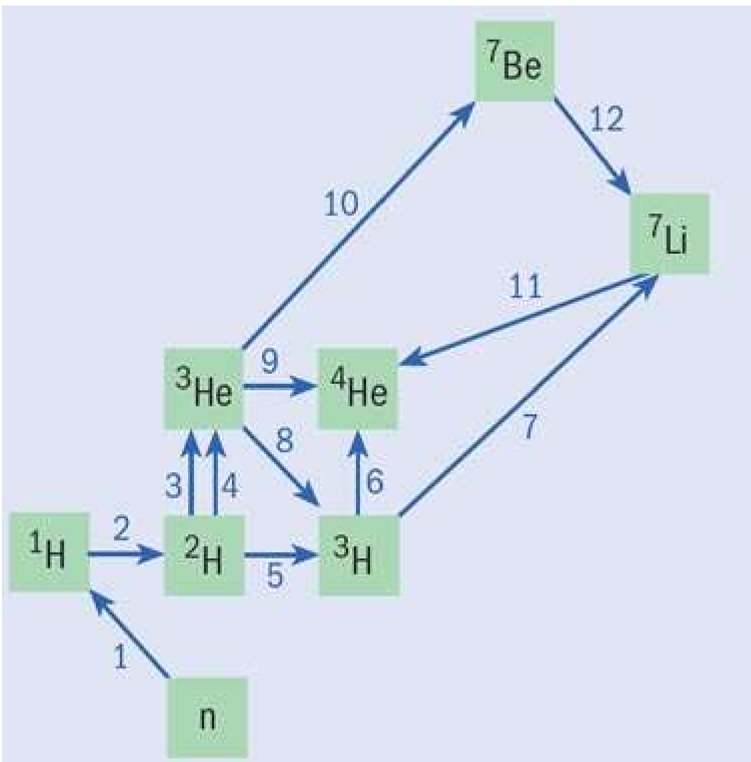


These questions are very often related to each other

Too light dark matter



If it is sufficiently light it will affect Big Bang Nucleosynthesis



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

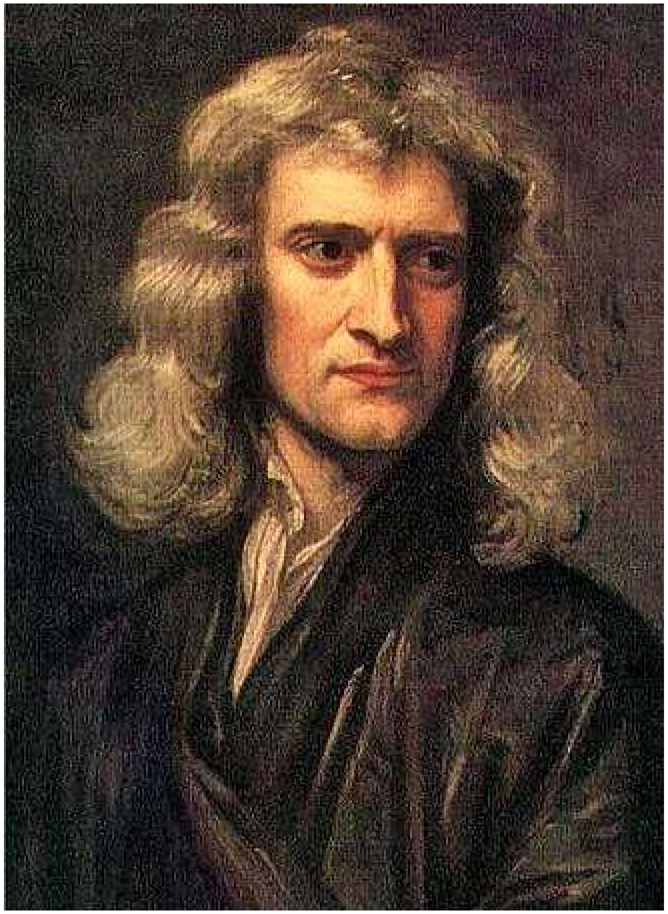
$$\begin{cases} \dfrac{dT_\nu}{dt} = -\dfrac{12H\rho_\nu + 3H(\rho_\chi + p_\chi) - 3\frac{\delta\rho_\nu}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu} + \frac{\partial\rho_\chi}{\partial T_\nu}}, \\[2ex] \dfrac{dT_\gamma}{dt} = -\dfrac{4H\rho_\gamma + 3H\,(\rho_e + p_e) + 3H\,T_\gamma\frac{dP_{\rm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

Electrophilic

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

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

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



"If I have seen further, it is by stealing other people's code off Github"
– Isaac Newton 1675.

NUDEC_BSM: Neutrino Decoupling Beyond the Standard Model

This code "NUDEC_BSM", has been developed by Miguel Escudero Abenza in order to solve for early Universe thermodynamics and neutrino decoupling following the simplified approach of ArXiv:1812.05605 [JCAP 1902 (2019) 007] and ArXiv:2001.04466 [JCAP 05 (2020) 048]. If you use this code, please, cite these references.

Precision Big Bang Nucleosynthesis with the New Code *PRIMAT*

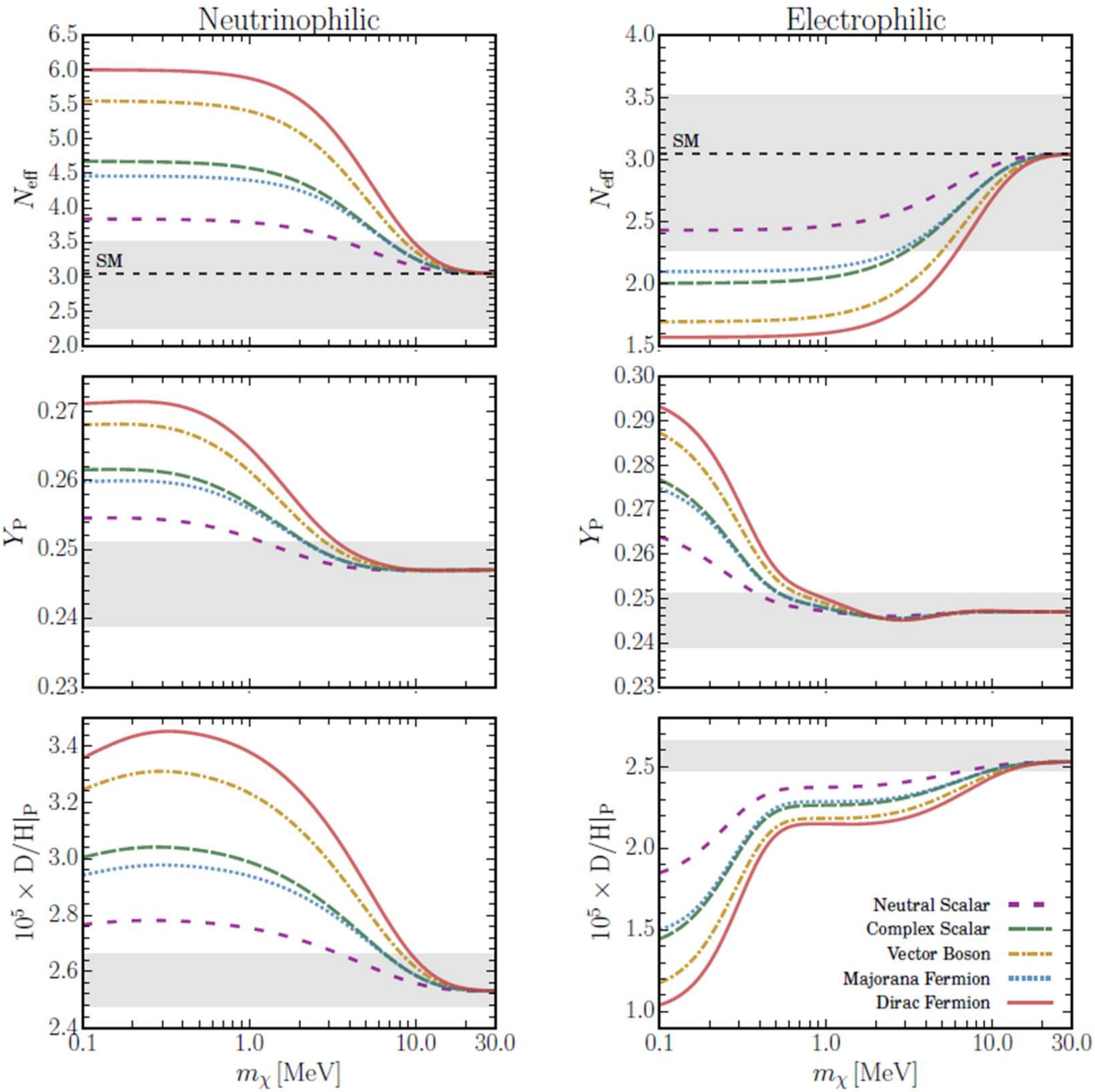
Cyril Pitrou[1,2], Alain Coc[3], Jean–Philippe Uzan[1,2] and Elisabeth Vangioni[1,2]

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

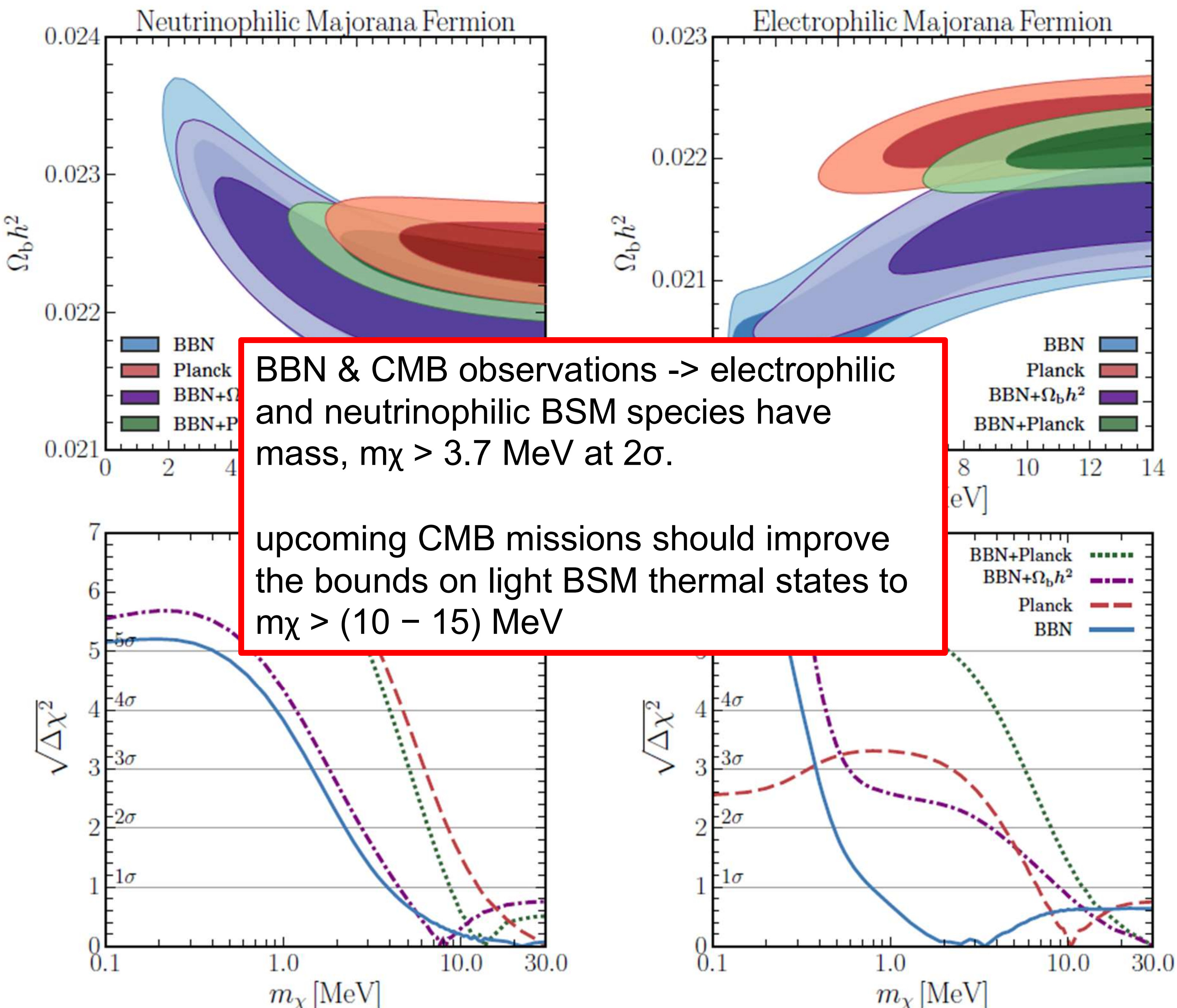
- accurate predictions for He & D and deuterium abundances
- up-to-date nuclear reaction rates
- finite temperature corrections
- incomplete neutrino decoupling etc.

Also use state of the art code “nudec” developed by Miguel Escudero in order to solve for early Universe thermodynamics and neutrino decoupling https://github.com/MiguelEA/nudec_BSM

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



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

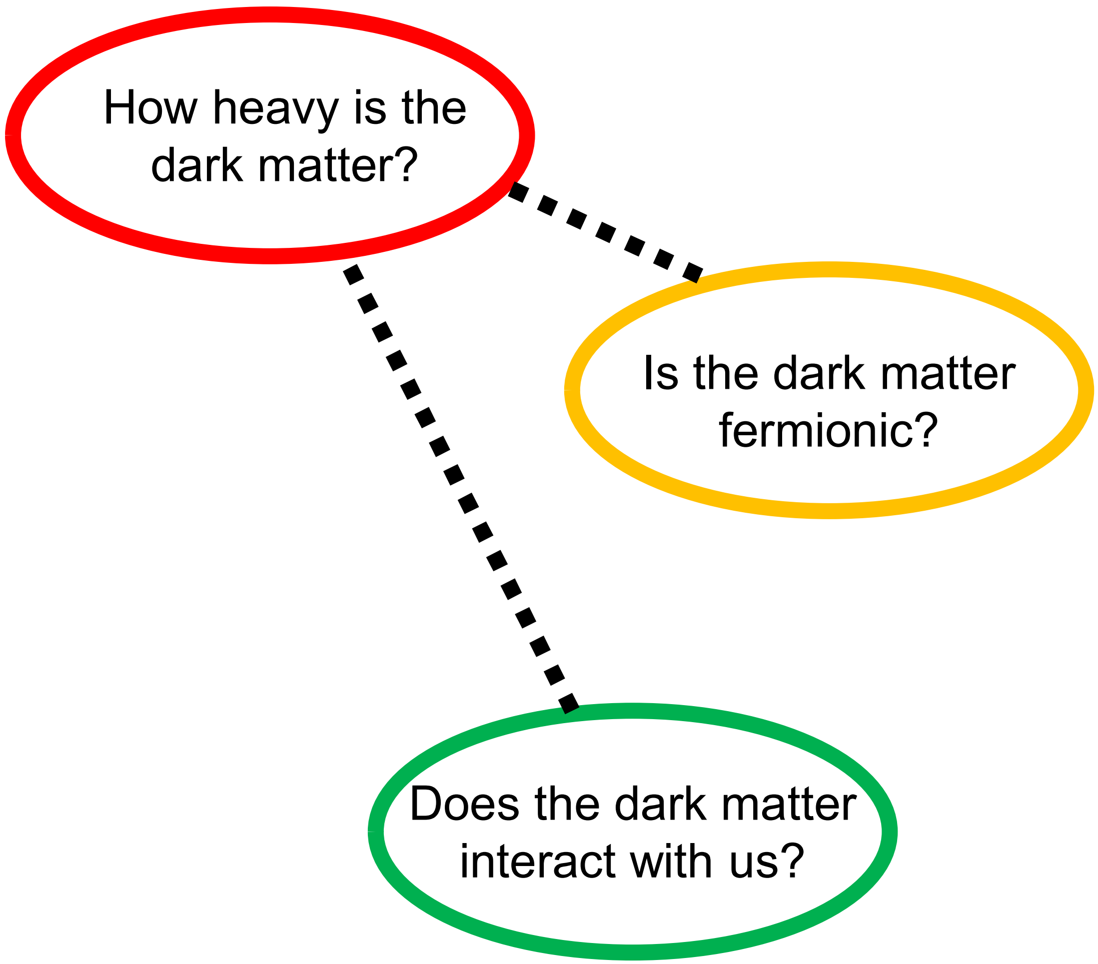


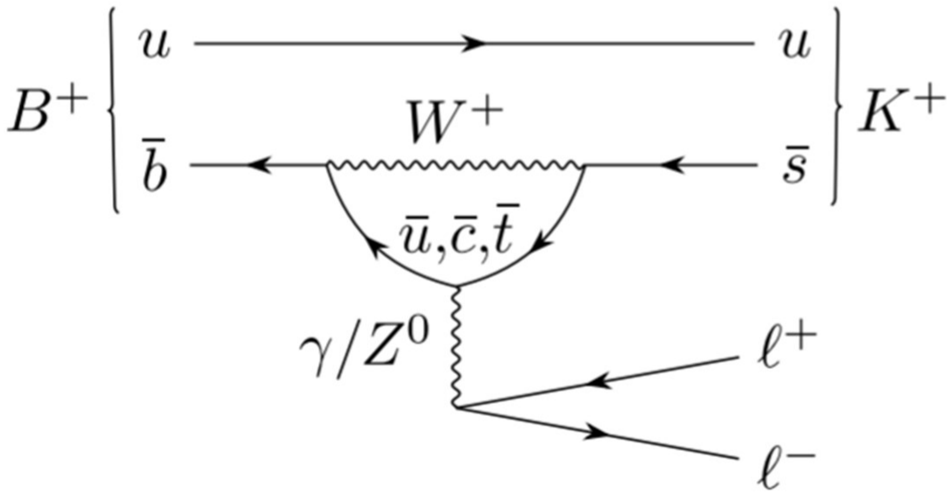
BBN & CMB observations -> electrophilic and neutrinophilic BSM species have mass, mχ > 3.7 MeV at 2σ.

upcoming CMB missions should improve the bounds on light BSM thermal states to mχ > (10 − 15) MeV

1910.01649

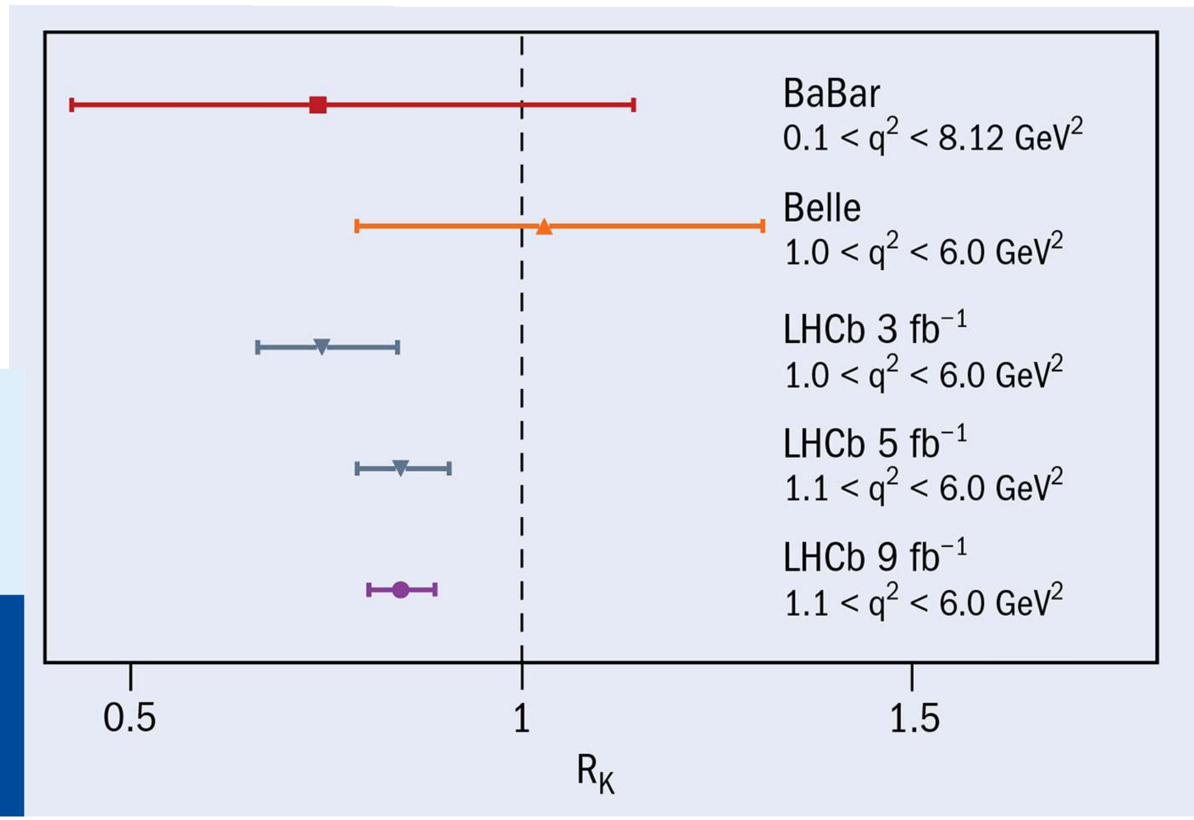
Things we can try to find out about dark matter

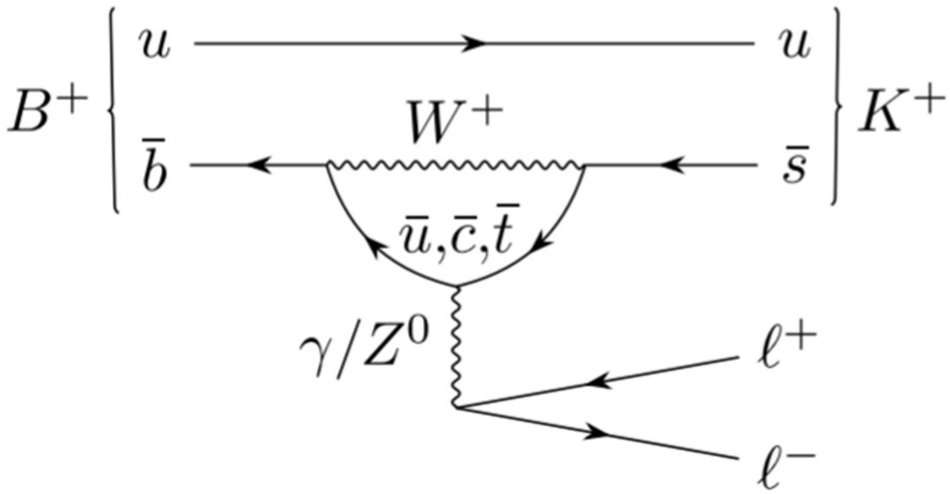




Possible observation of Lepton Universality Violation at LHCb

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)}$$



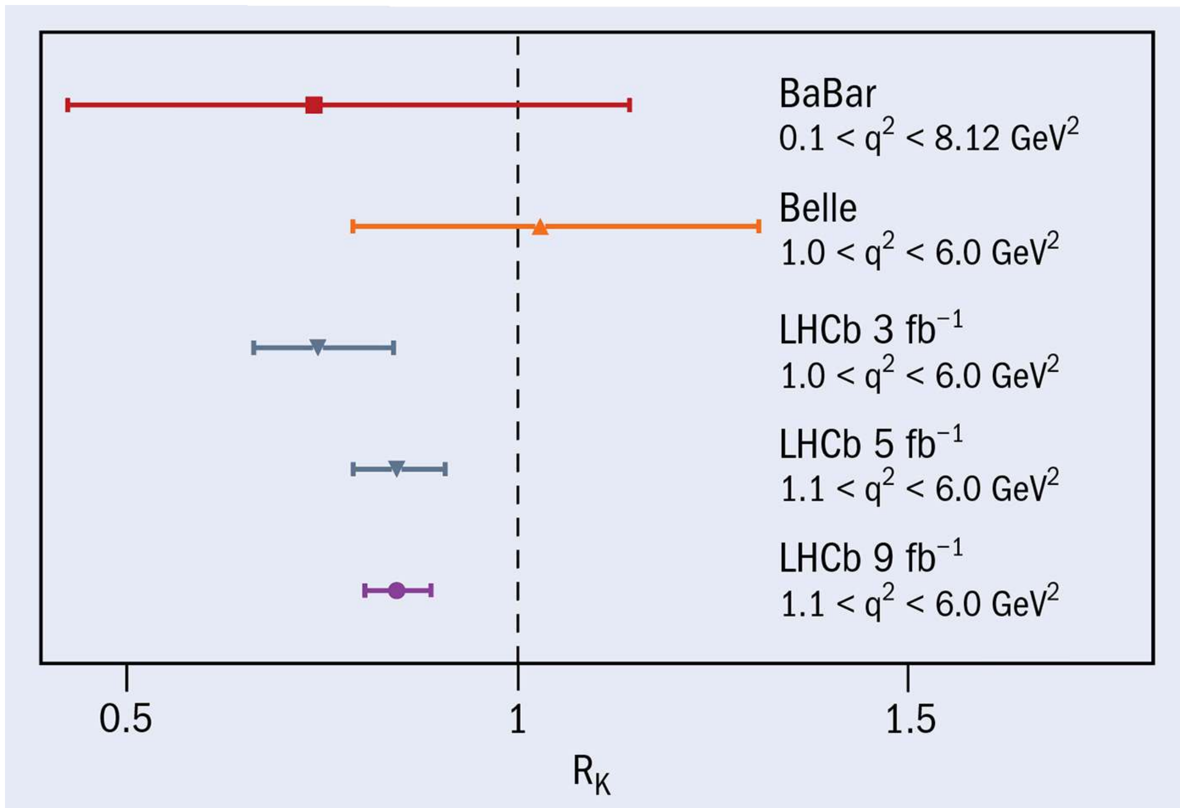


Possible observation of Lepton Universality Violation at LHCb

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)}$$

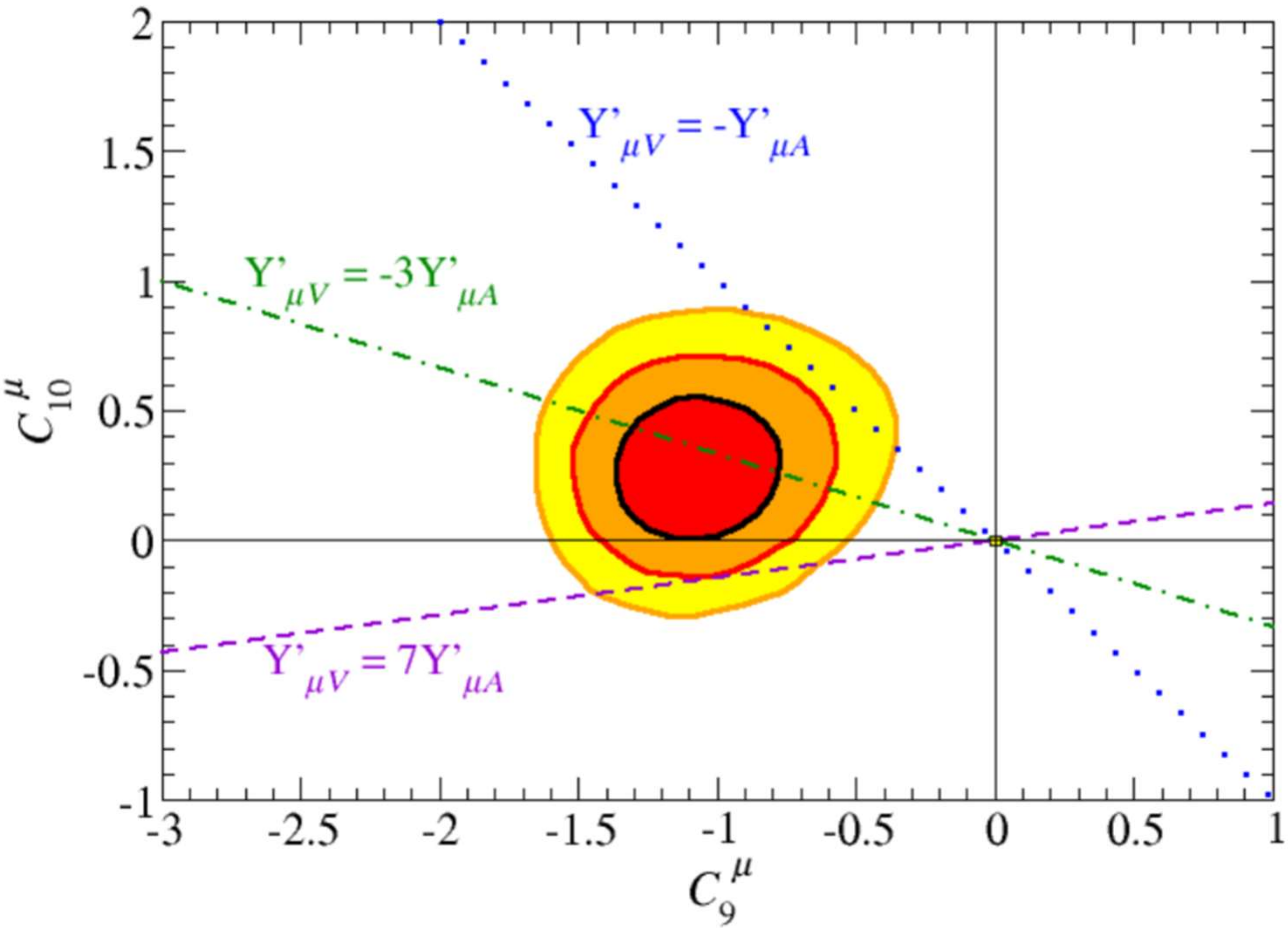
One can solve this by introducing Z' mediators which could also serve as the portal to a dark sector!

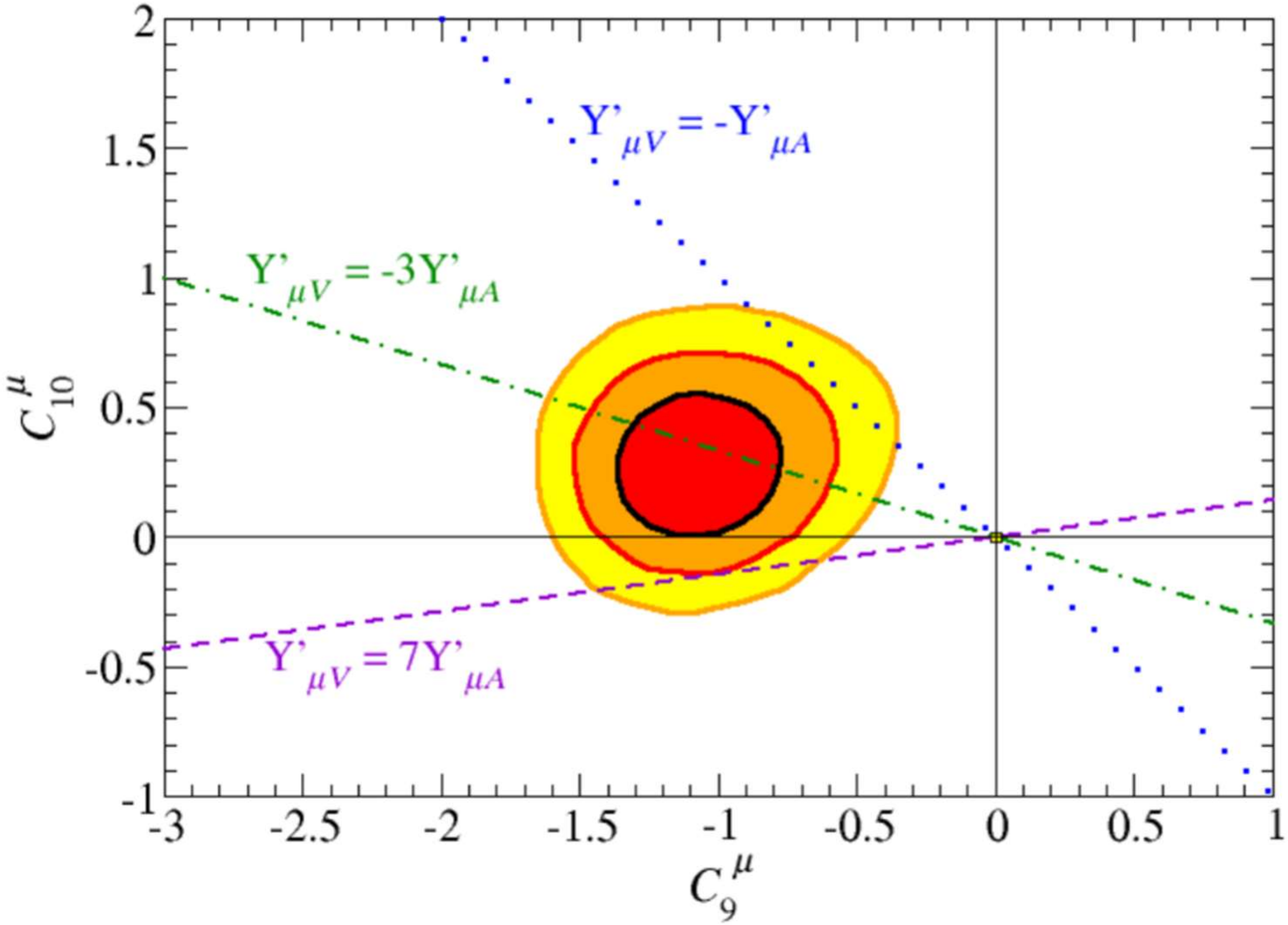
However one would ideally like such an extension of the standard model to be anomaly free…



Different data analyses lead to constraints on operators:-

$$O_9^{\mu} \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$
$$O_{10}^{\mu} \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$





1704.03850

1705.03447

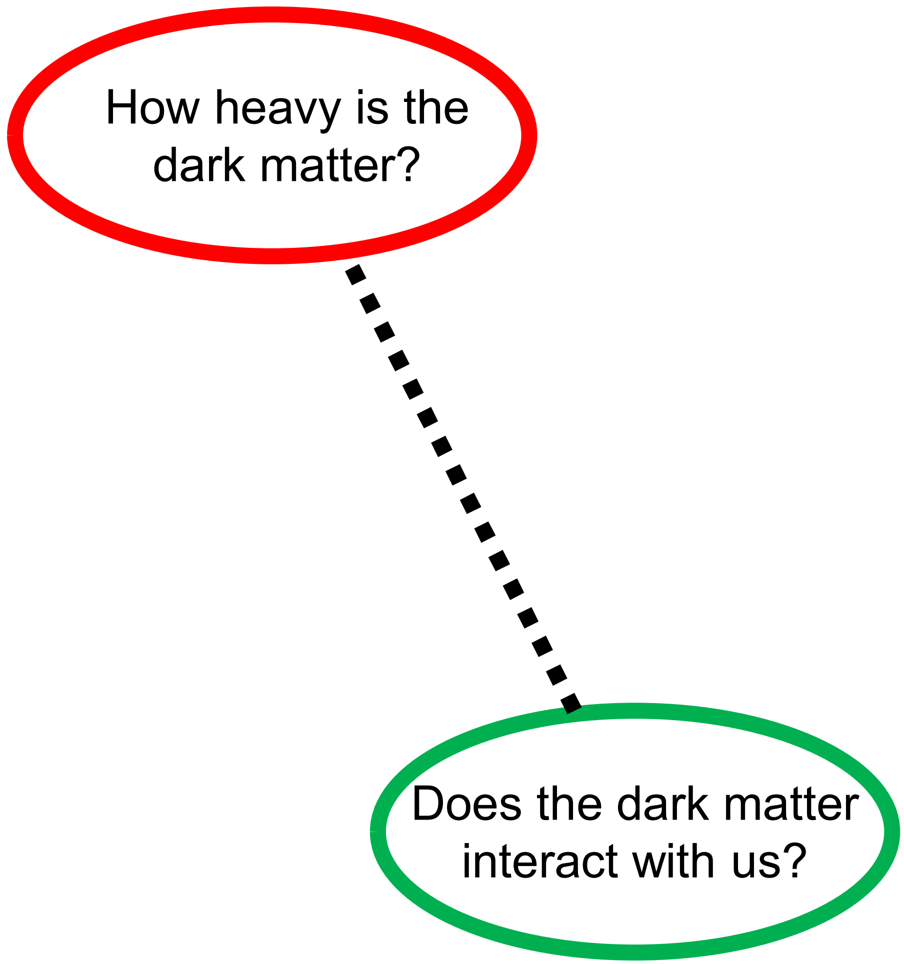
1807.02503

With
John Ellis &
Patrick Tunney

- Simplest, best fitting anomaly free models have dark matter particles with vector couplings to the mediating Z' - probably ruled out by direct detection.
- More complicated models can have dark matter with axial coupling but EW precision variables need to be carefully studied…

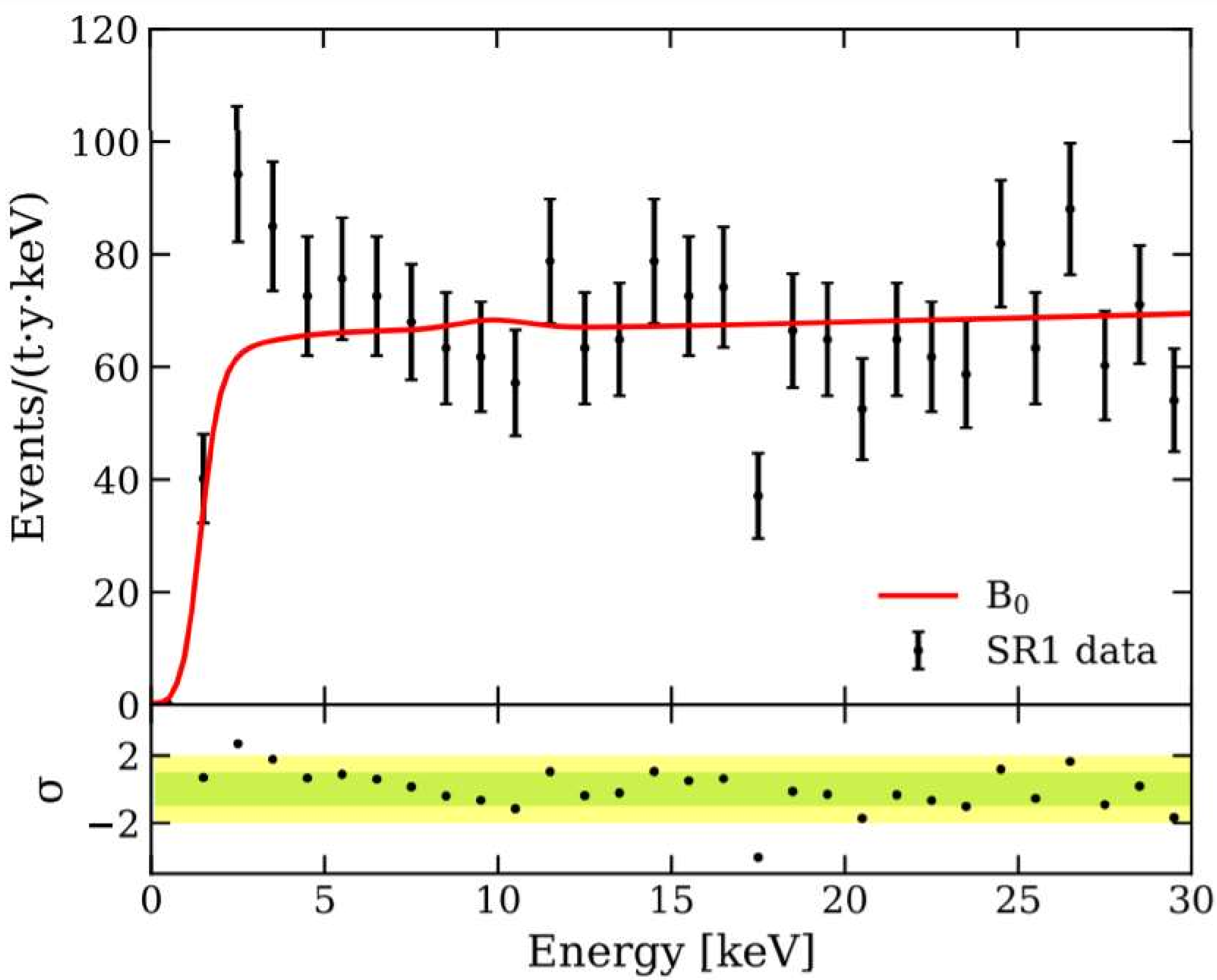
WORK IN PROGRESS……

Things we can try to find out about dark matter



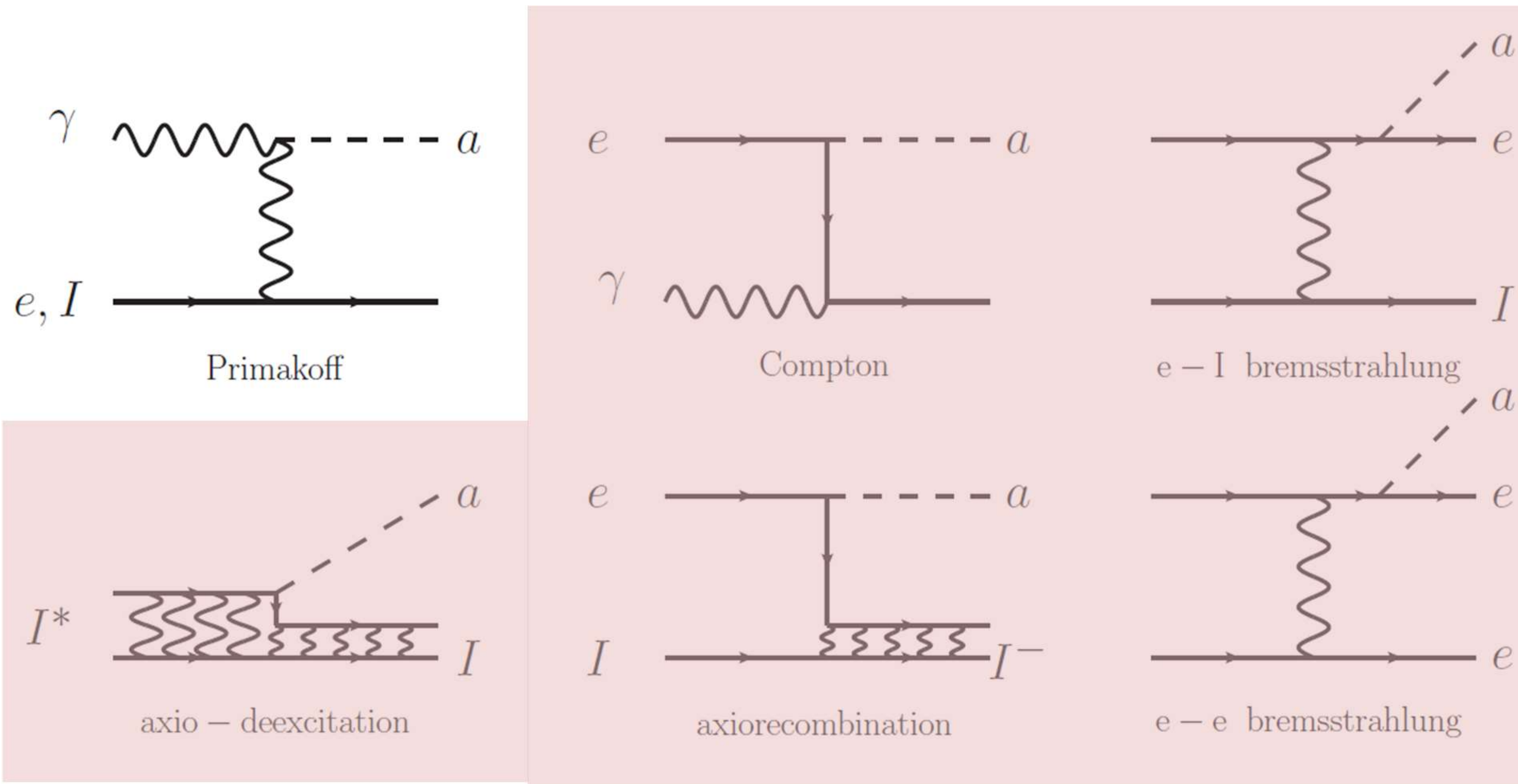
These questions are very often related to each other

June 2020, a new result from electron recoils from XENON1T collaboration arXiv: 2006.09721



The signal has an excess over the background. This could be due to new physics, but it also could be due to Tritium or Argon.

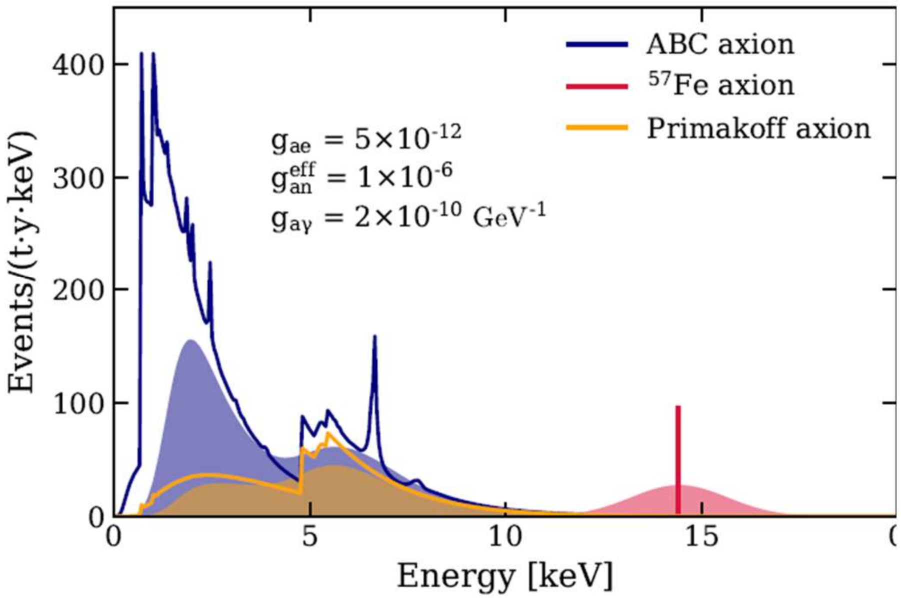
Axion production in the Sun

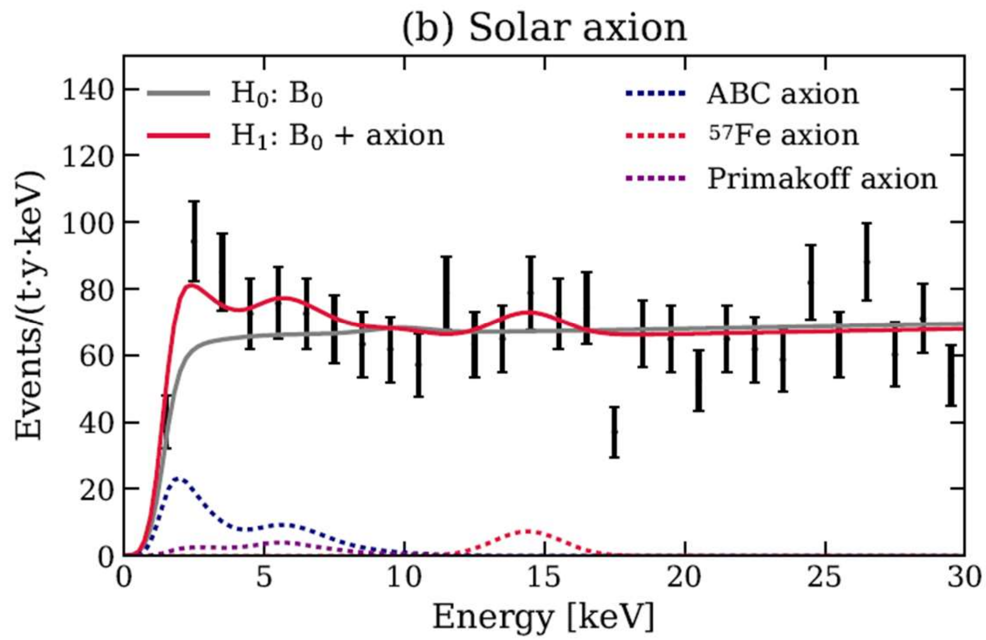


Redondo 1310.0823

ABC processes

Solar axion interpretation





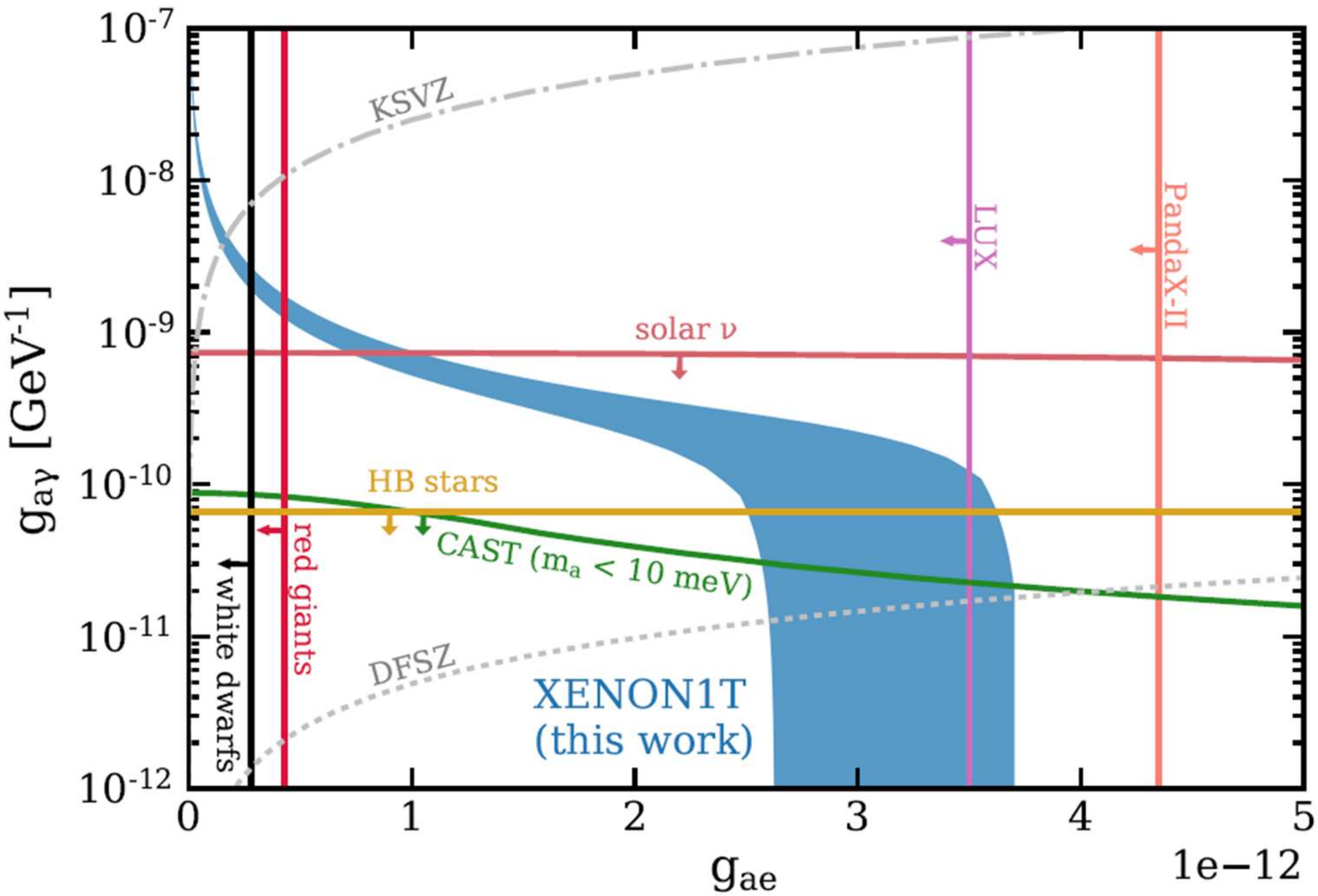
$$\Phi_a^{ABC} \propto g_{ae}^2$$

$$\Phi_a^{57\text{Fe}} = \left(\frac{k_a}{k_\gamma}\right)^3 \times 4.56 \times 10^{23} (g_{an}^{eff})^2 \ \ \mathrm{cm^{-2} s^{-1}}$$

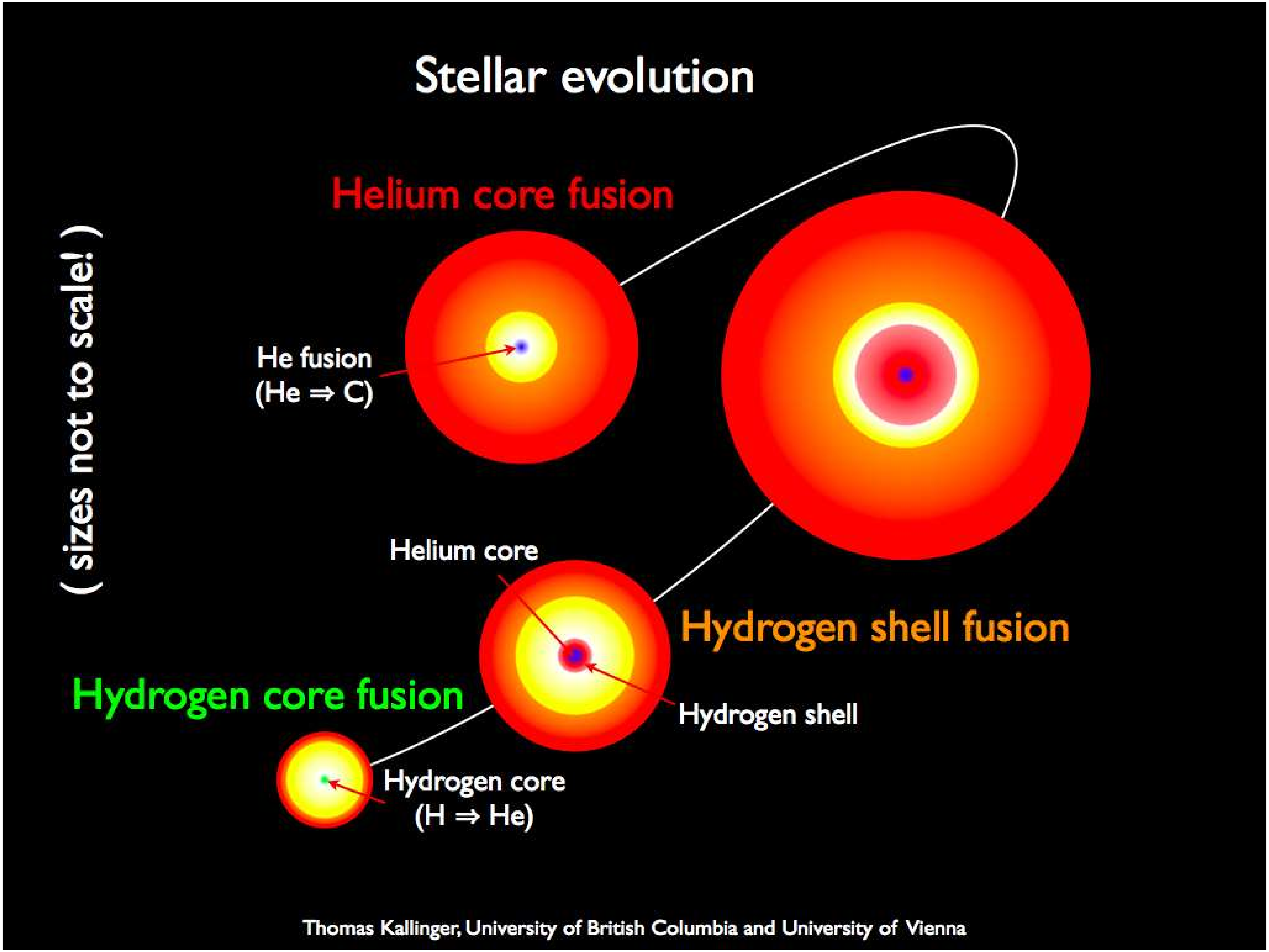
$$\frac{d\Phi_a^{Prim}}{dE_a} = \left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}}\right)^2 \left(\frac{E_a}{\mathrm{keV}}\right)^{2.481} e^{-E_a/(1.205\ \mathrm{keV})} \times 6 \times 10^{30} \ \ \mathrm{cm^{-2} s^{-1} keV^{-1}},$$

arXiv: 2006.09721

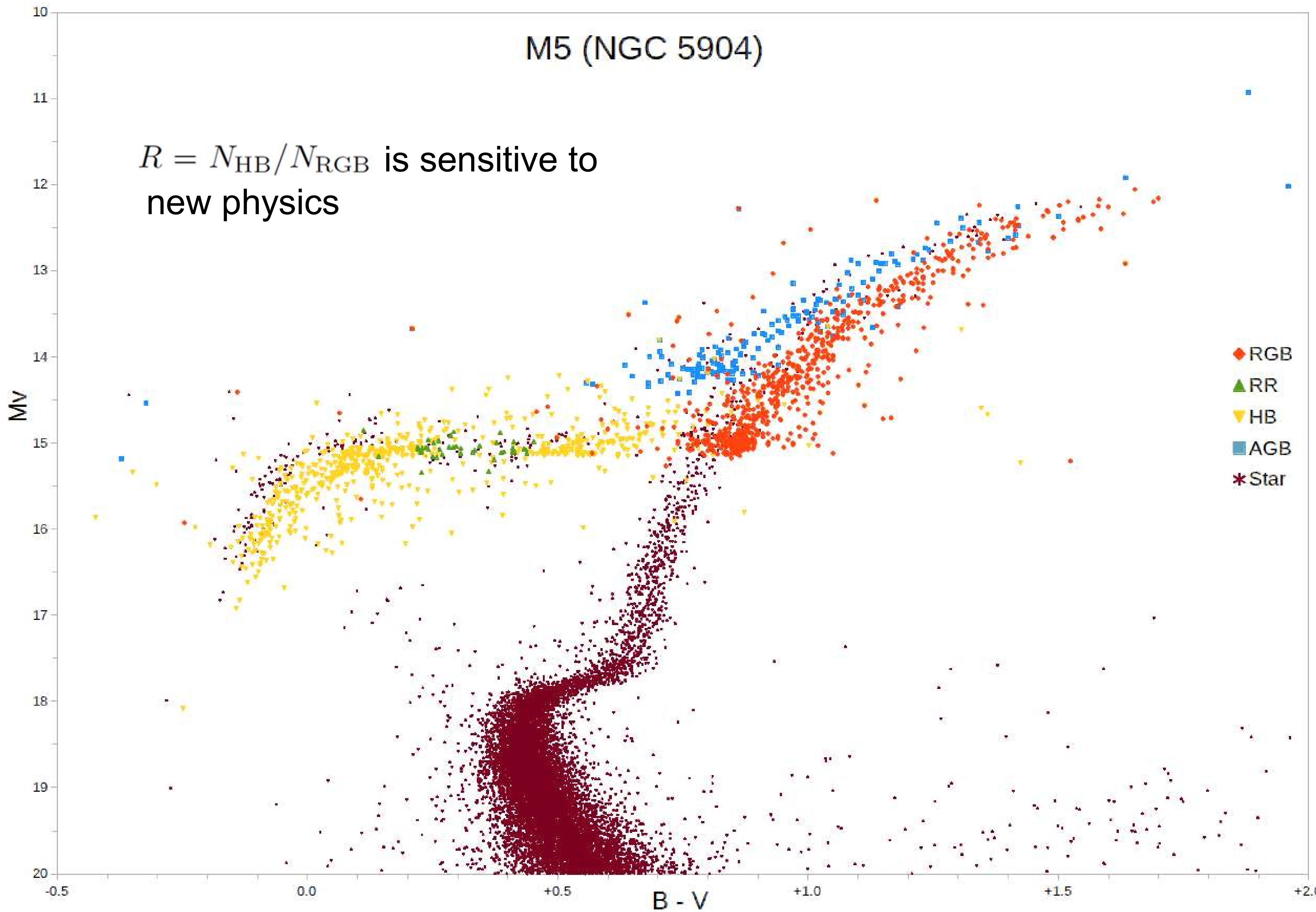
Favoured Axion Parameters to fit the excess



arXiv: 2006.09721

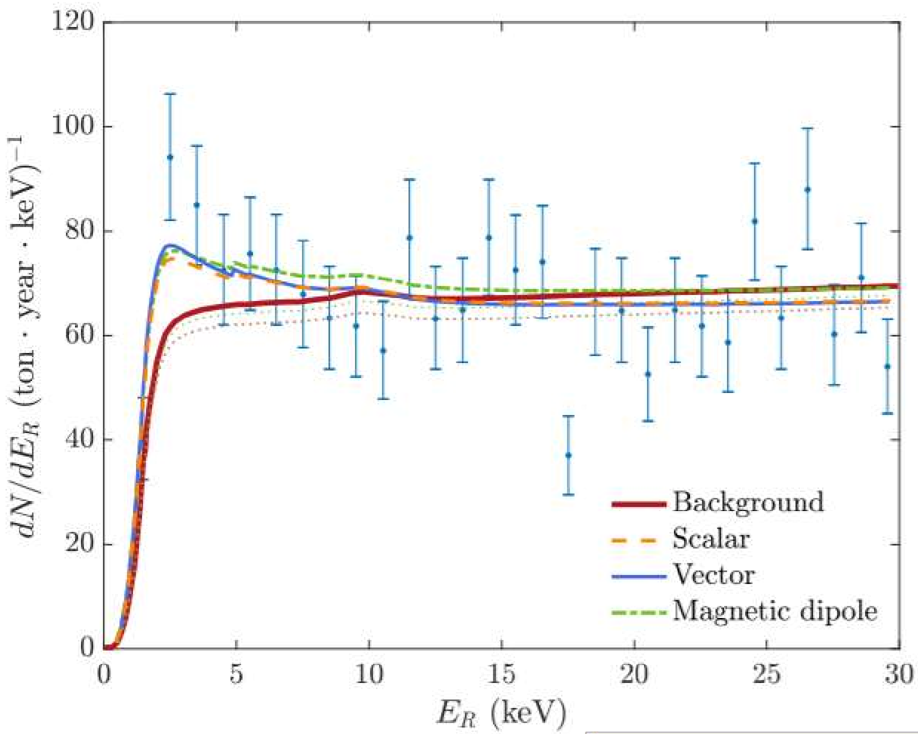

Stellar evolution
(sizes not to scale!)
Helium core fusion
He fusion
(He ⇒ C)
Helium core
Hydrogen shell fusion
Hydrogen core fusion
Hydrogen shell
Hydrogen core
(H ⇒ He)
Thomas Kallinger, University of British Columbia and University of Vienna

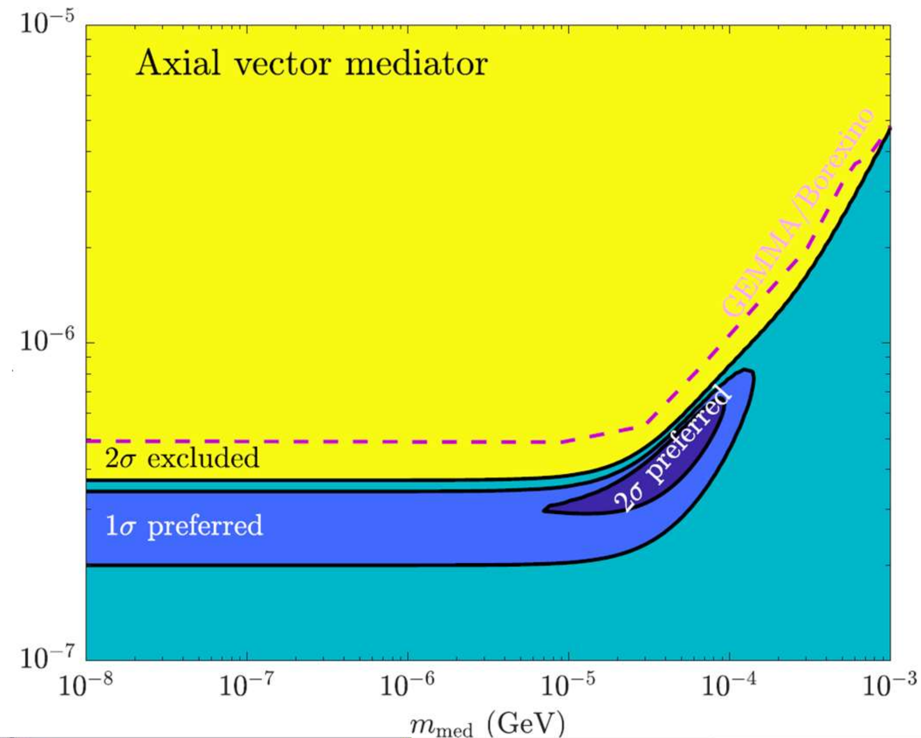

Messier 5 from
Central London

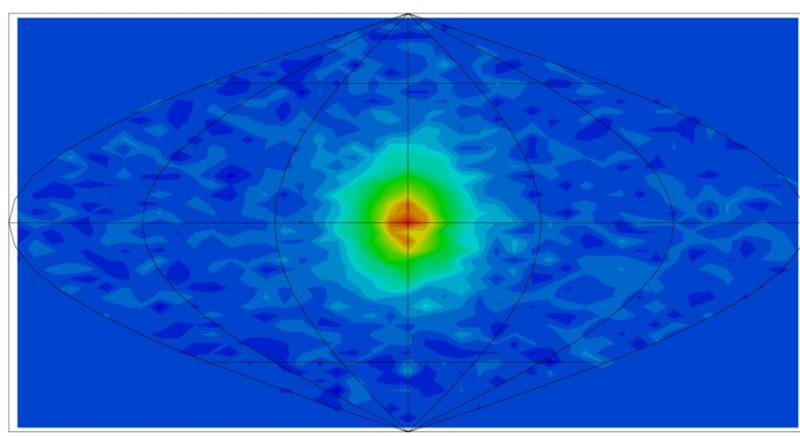


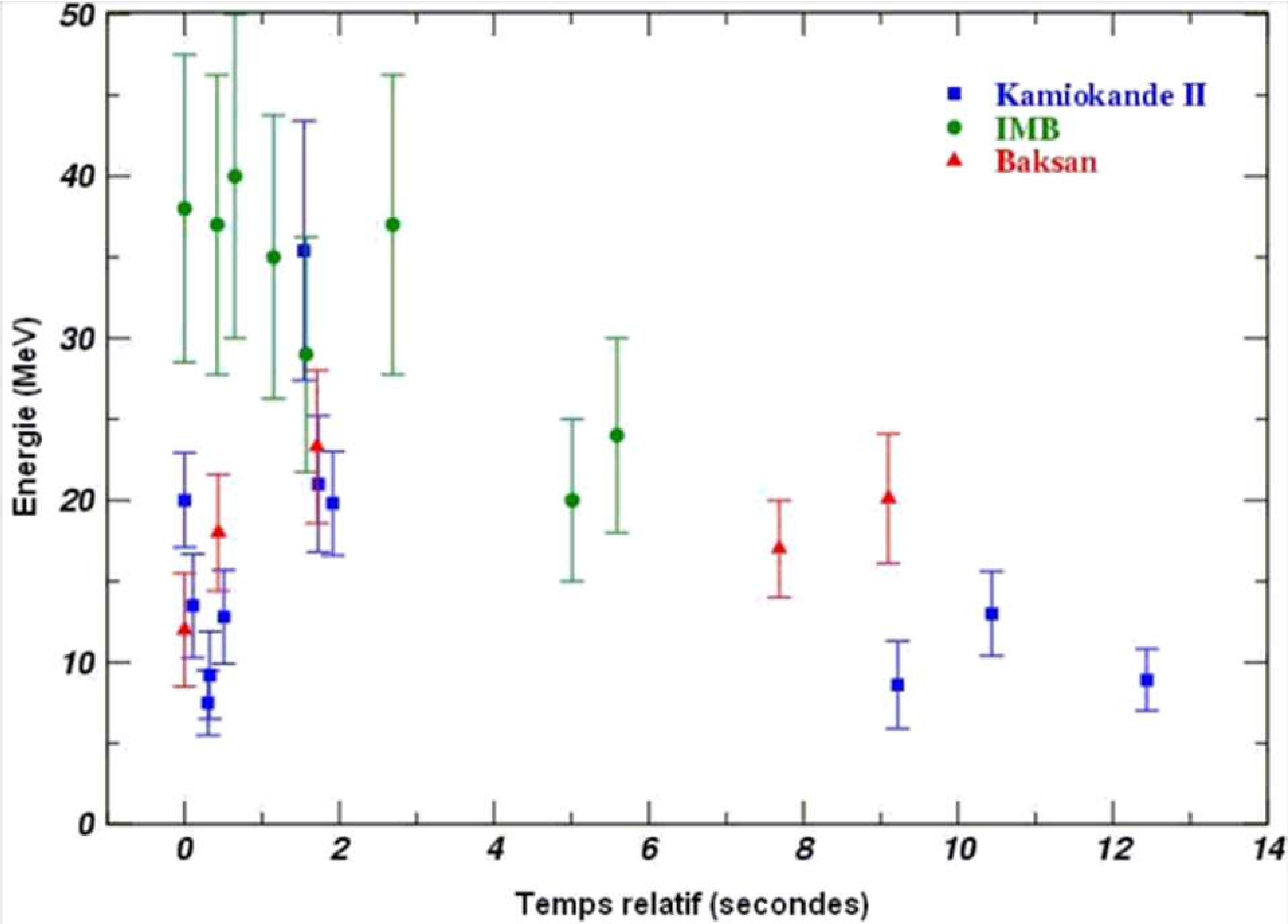
Ratio between number of HB to RGB stars sensitive to Helium and Cooling
Raffelt & Dearborn (1987)

We showed that the fit to the Xenon1T excess could be improved by various mediators between neutrinos and electrons, but this also faces difficult astrophysical constraints. arXiv:2006.11250







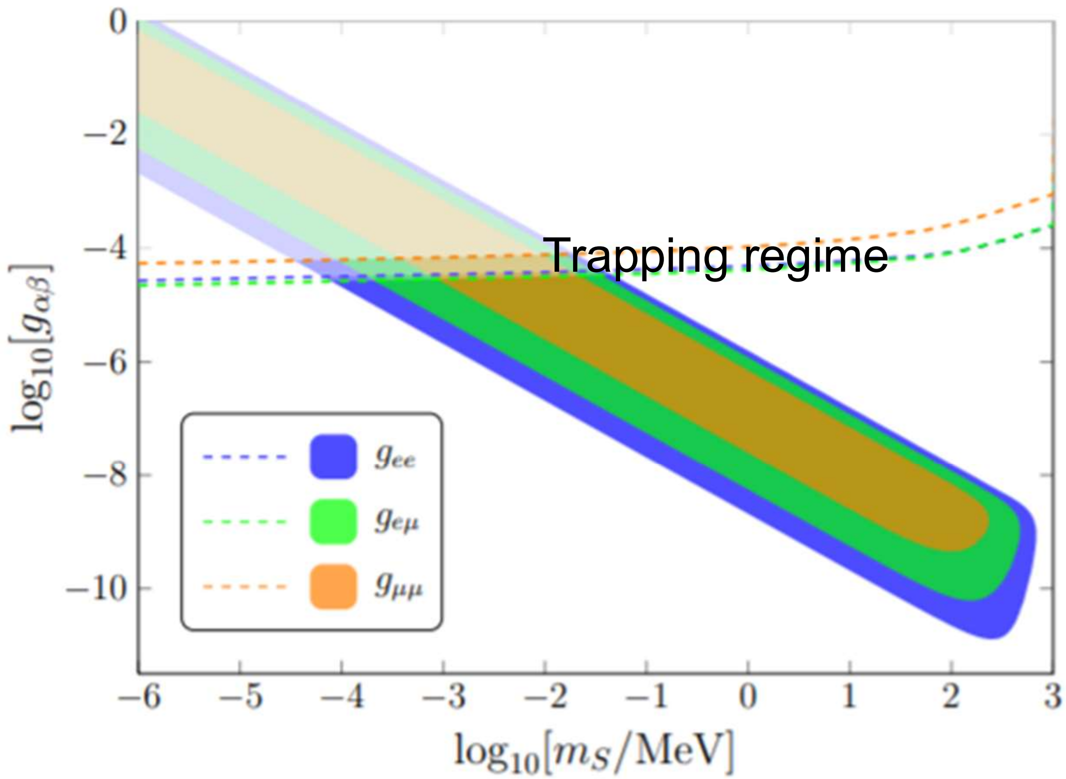


Kamiokande II
IMB
Baksan
Energie (MeV)
Temps relatif (secondes)
0
10
20
30
40
50
0
2
4
6
8
10
12
14

Constraints from SN1987A

For a massive scalar S or pseudoscalar J, the renormalizable couplings to neutrinos can be generally denoted by

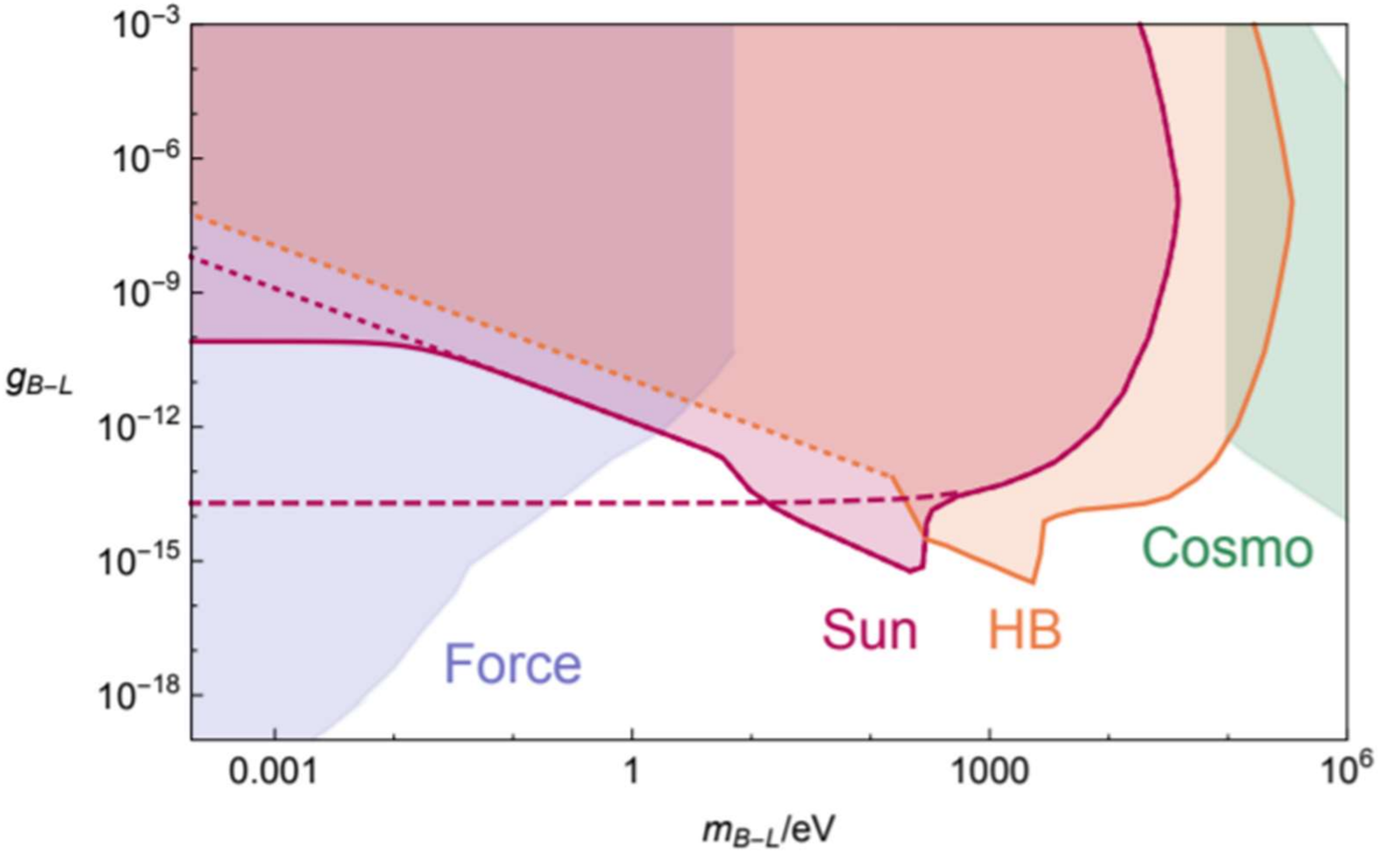
$$\mathcal{L} = \frac{1}{2} g_{\alpha\beta} S \left(\nu_\alpha^T i\sigma_2 \nu_\beta\right) + \frac{1}{2} g'_{\alpha\beta} J \left(\nu_\alpha^T \sigma_2 \nu_\beta\right) + \text{h.c.} \tag{2.1}$$



Heurtier & Zhang
1609.05882

Can also affect propagation of neutrinos from 1987a

On the other side, the coupling between electrons and vectors is also tightly constrained…



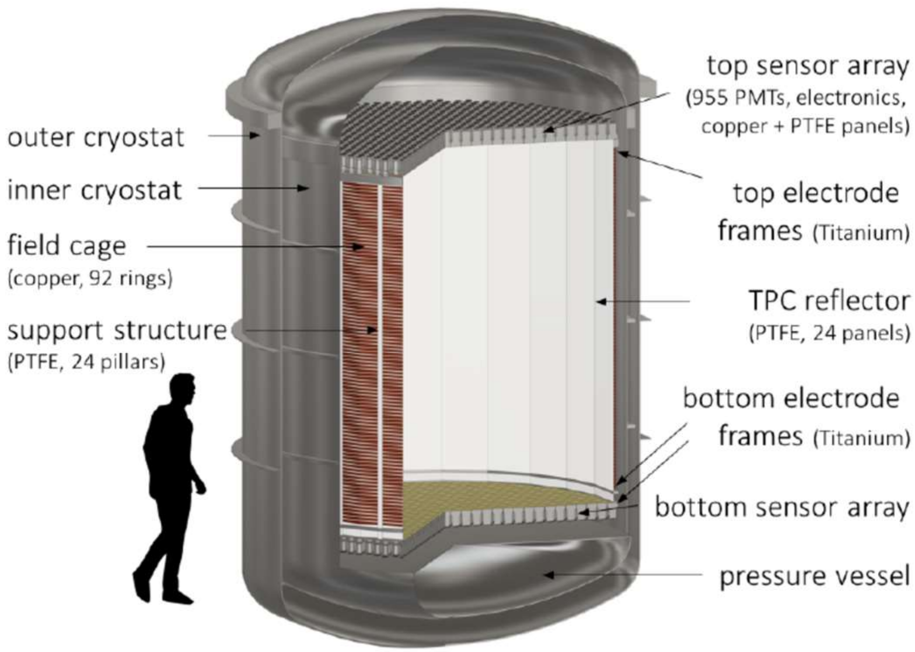
Hardy and Lasenby, 1611.05852

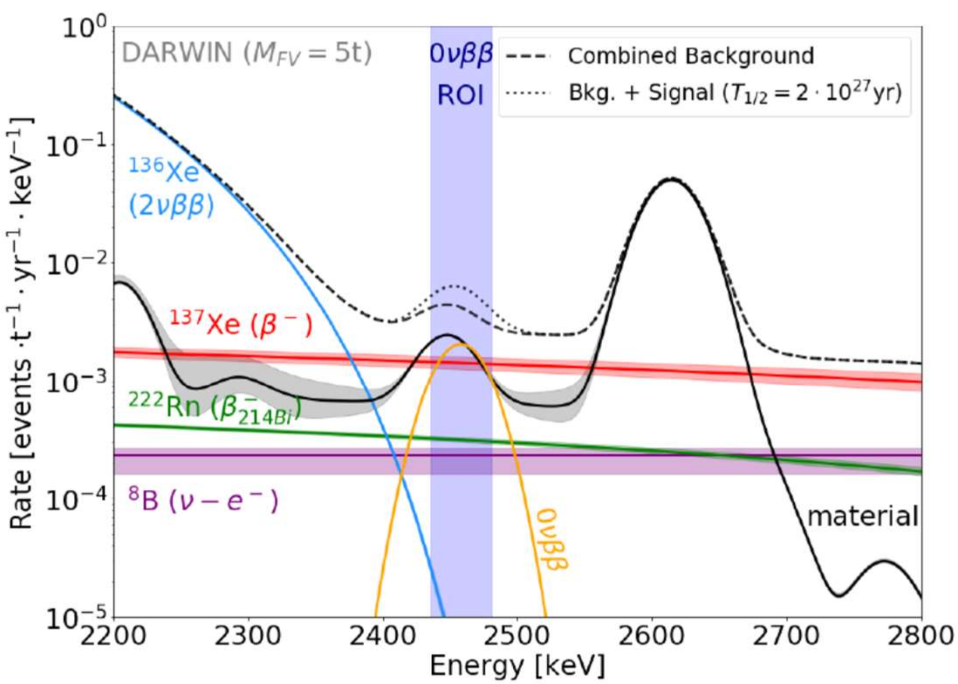
- Solar axions can’t explain the excess, because of astrophysical constraints
- This is probably also true for neutrinos with non standard interactions

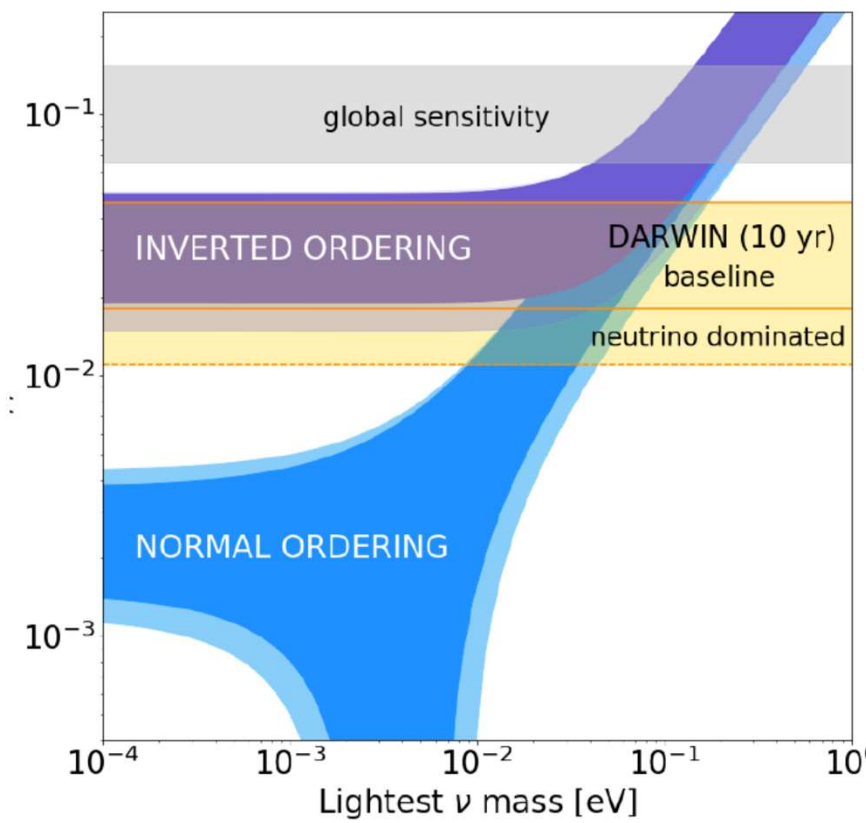
- Important point is that dark matter detectors are able to probe some aspects of the neutrino sector with precision comparable or better to some neutrino detectors!

lXenon Darwin Experiment can also search for neutrinoless double beta decay!

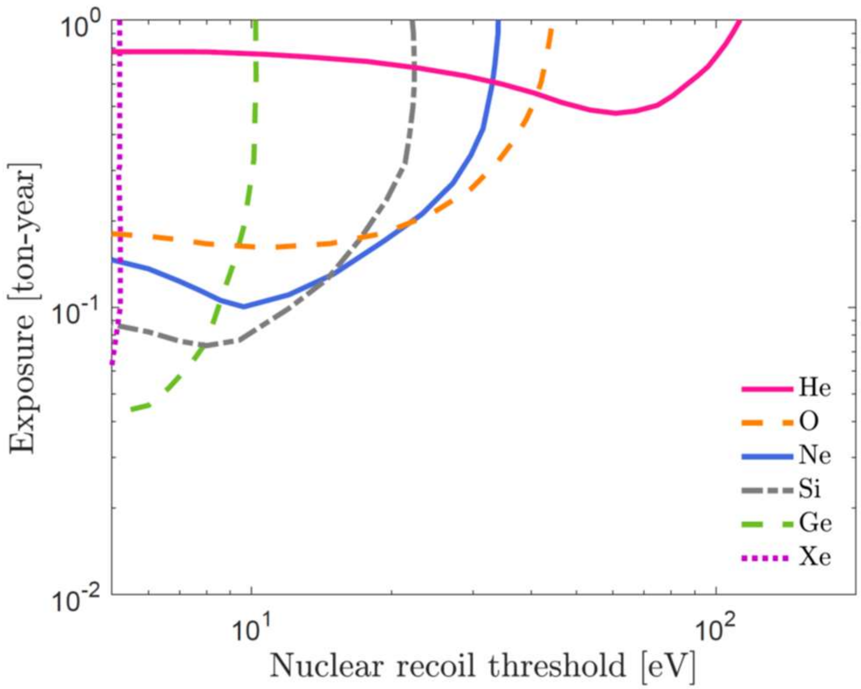
2003.13407

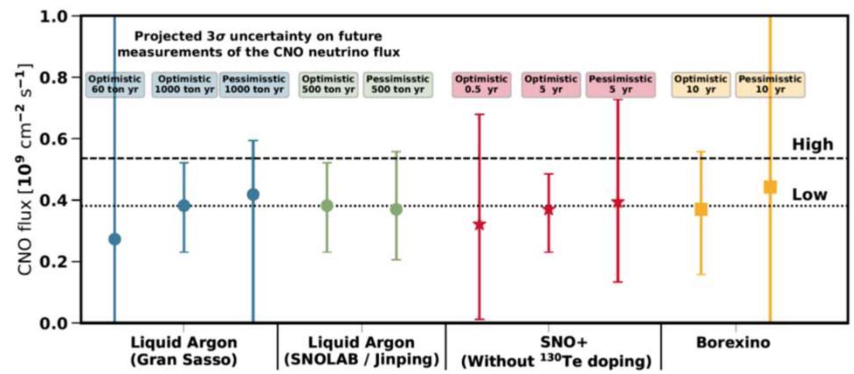






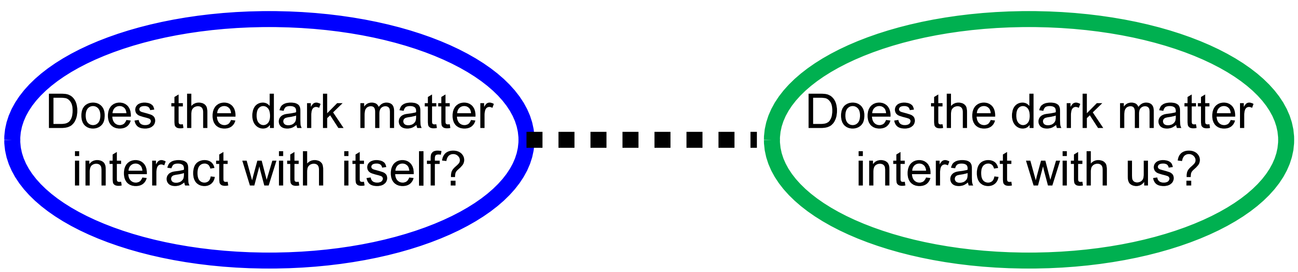
Future DM detectors can search for CNO neutrinos



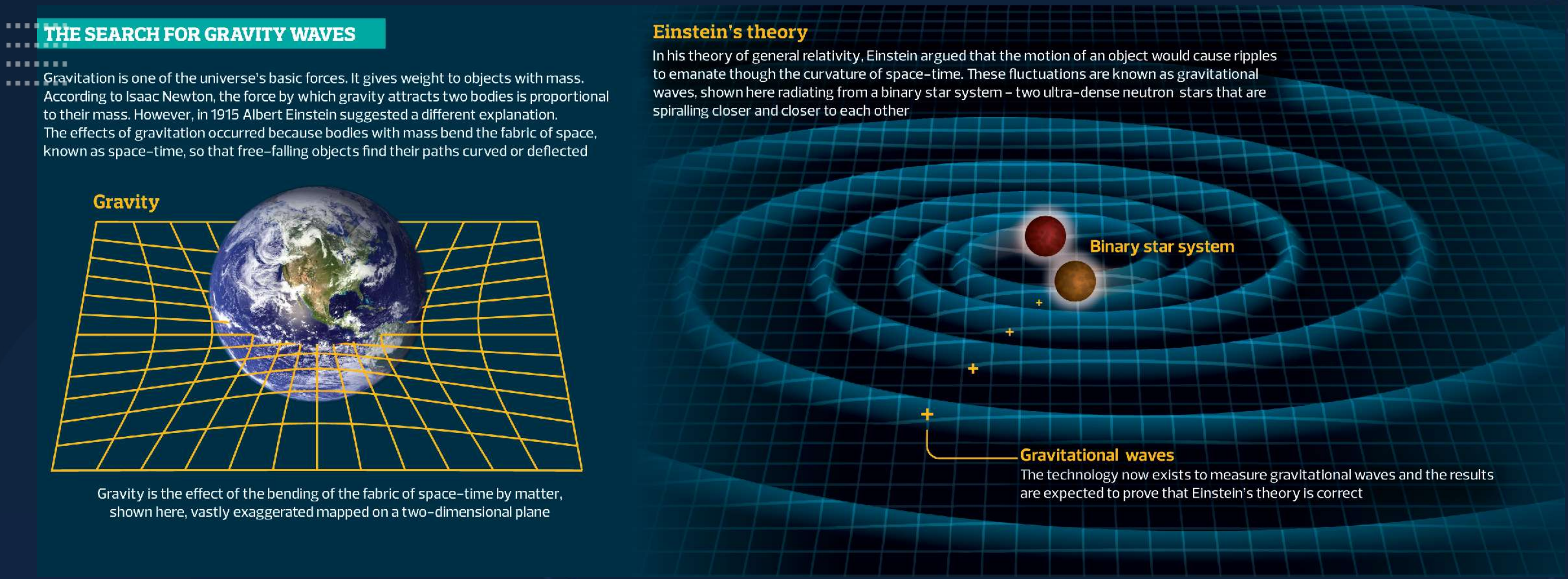


1712.06522

Things we can try to find out about dark matter



These questions are very often related to each other



Gravitational Waves are now mainstream –

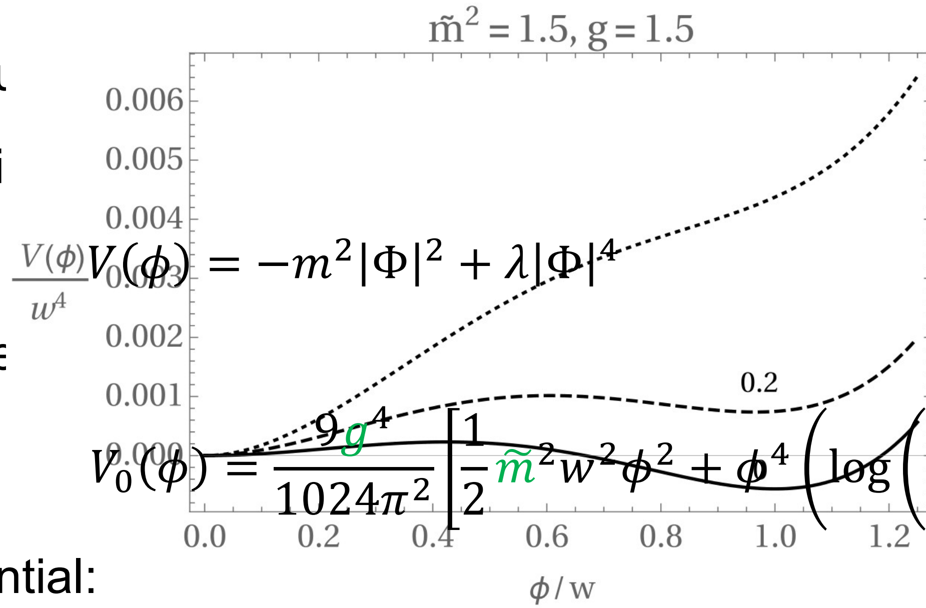
This infographic is from the UK Observer newspaper

Everything couples to Gravity!

Q. If we observe phase transitions using gravitational waves, how will we know whether they come from our sector or some dark sector?

Hearing without seeing:
Gravitational Waves from Hot and Cold Hidden Sectors
1901.11038

An example hidden sector



- SU(2) gauge grou
- Tree level potenti

$$V(\phi) = -m^2|\Phi|^2 + \lambda|\Phi|^4$$

- With 1 -loop corre

$$V_0(\phi) = \frac{9g^4}{1024\pi^2}\left[\frac{1}{2}\tilde{m}^2 w^2 \phi^2 + \phi^4\left(\log\left(\frac{\phi^2}{w^2}\right) - \frac{(2+\tilde{m}^2)}{4}\right)\right]$$

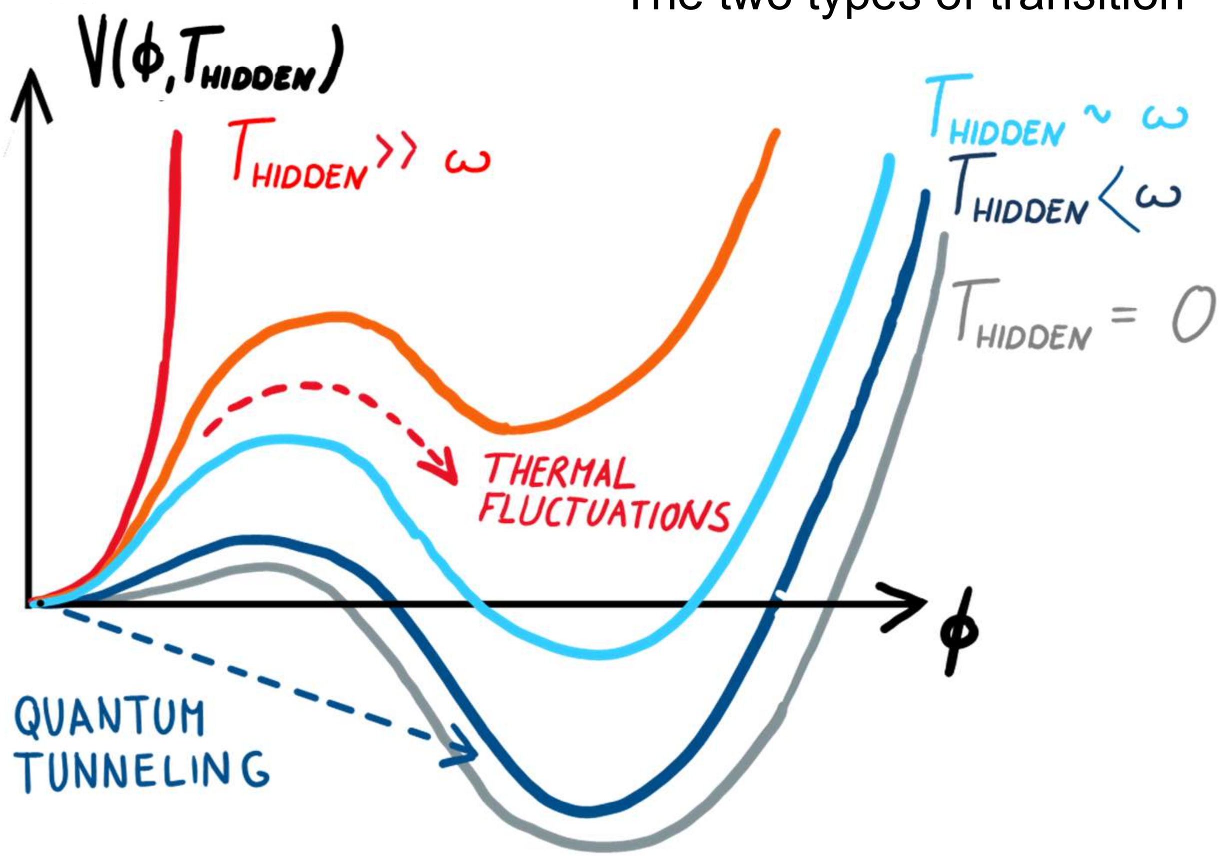
- Full thermal potential:

$$V(\phi, T_{hidden}) = V_0(\phi) + V_{T_{hidden}}(\phi, T_{hidden})$$

We consider parts of the parameter space where there is a barrier at zero temperature!

Cold hidden sectors

The two types of transition



Thermal Transition

- Happens when $\Gamma_{thermal}(t)^{\frac{1}{4}} >> H(t)$

Cold hidden sectors

The two types of transition

Thermal phase transition
$$\Gamma_3 \simeq T_{\mathrm{h}}^4 \left(\frac{S_3}{2\pi T_{\mathrm{h}}} \right)^{3/2} e^{-S_3/T_{\mathrm{h}}}$$

Tunneling Phase transition
$$\Gamma_4 \simeq w^4 \left(\frac{S_4}{2\pi} \right)^2 e^{-S_4}$$

Both temperature dependant

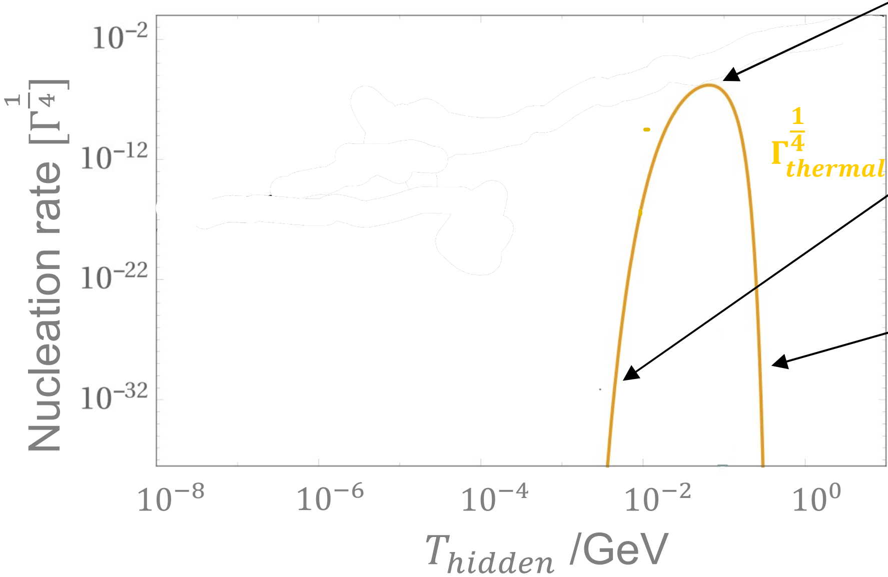
Thermal phase transition

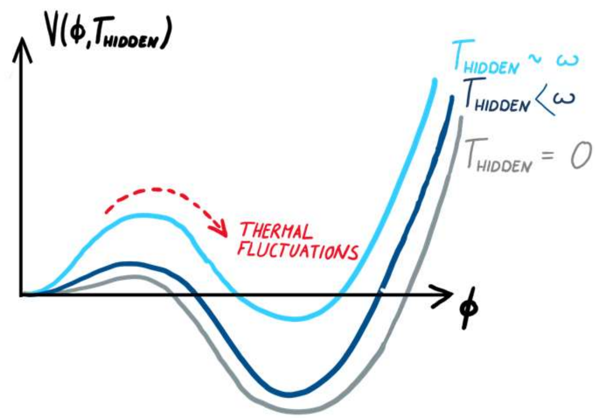
The two types of transition: concrete example

Optimal point for thermal transition

Thermal fluctuations are very small

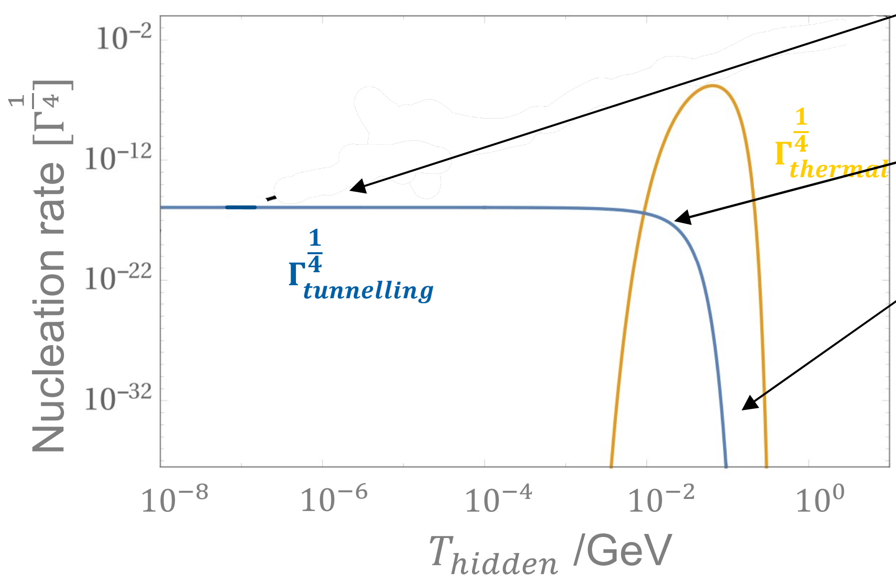
Barrier is very high





Tunnelling phase transition

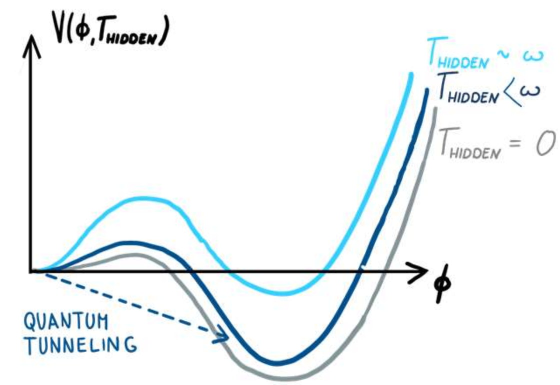
The two types of transition: concrete example



Tunnelling nucleation rate stays constant

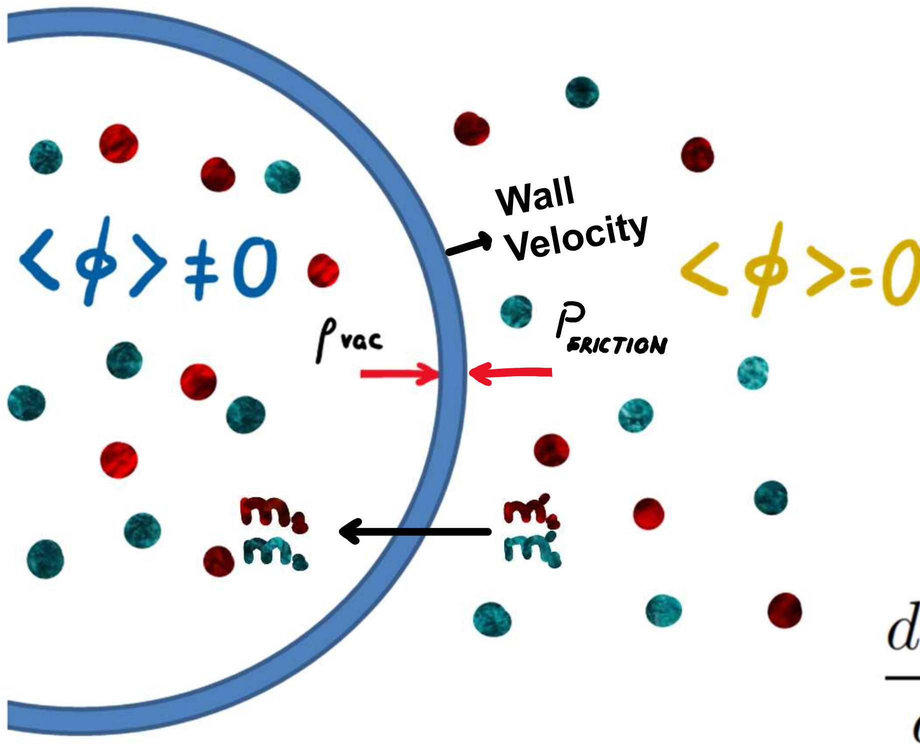
Barrier close to $T_{hidden} = 0$ form

Barrier height very high



Bubble wall dynamics

The wall velocity



- Friction set by T_{hidden}
- Friction determines wall velocity at collision
- Controls shape of GW spectrum (fraction in sound waves vs shock waves)

$$\frac{dv_{\rm w}}{dt} = \frac{1}{\sigma\gamma_{\rm w}^3}\left(\rho_{\rm vac} - P_{\rm fr}\right)$$

Ratio of temperatures between dark and visible sector

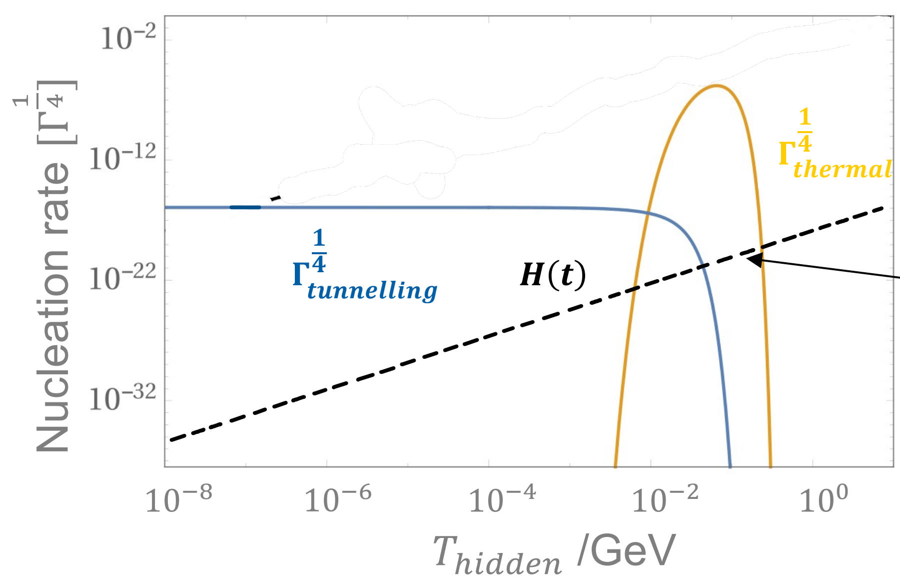
dark sector might have different temperature for a few reasons:-

- Large number of BSM degrees of freedom in visible sector
- Different reheating after inflation into visible and hidden sector
- String theory moduli decay preferentially into one sector rather than other

$$\epsilon \equiv \frac{T_{\mathrm{h}}}{T_{\mathrm{v}}}$$

Phase transitions

Case 1: $\epsilon = \frac{T_{hidden}}{T_{visible}} \approx 1$

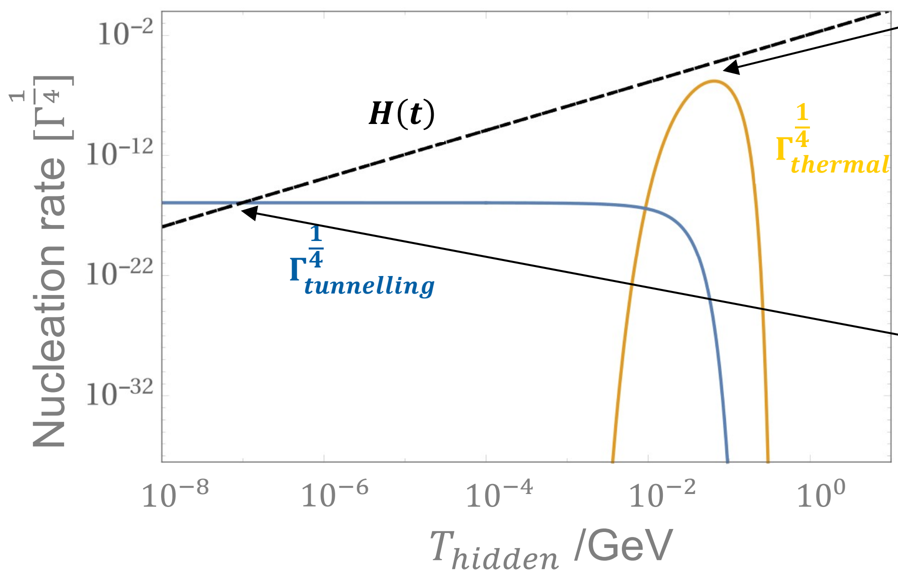


Thermal transition takes place when hidden plasma is hot

Hot plasma → High friction→ Sound wave signal

Phase transitions

Case 2: $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$



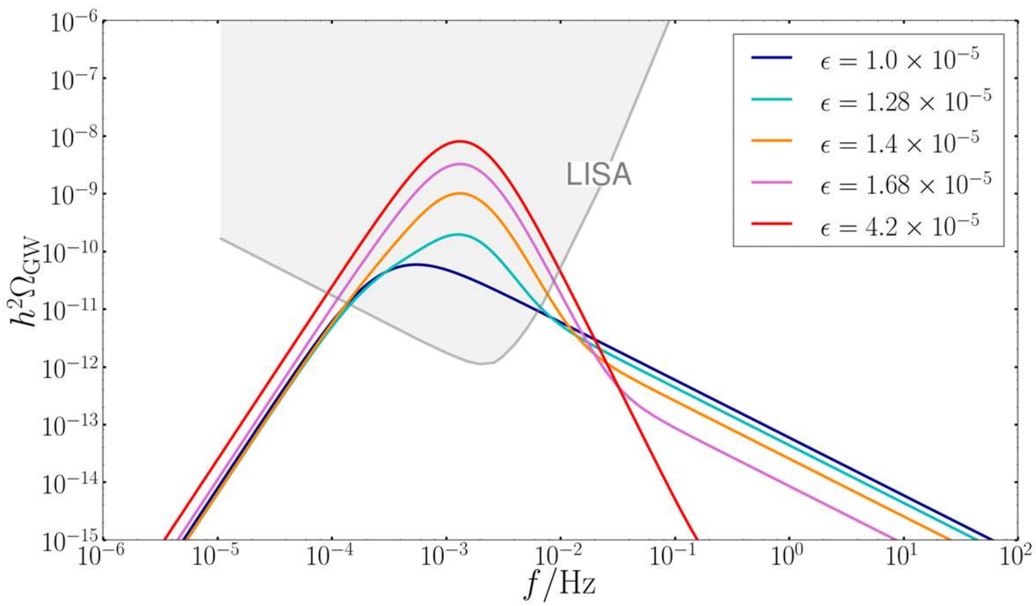
Thermal transition window missed

Tunnelling transition happens later when hidden plasma is cold

Cold plasma → Low wall friction → Bubble collision signal?

Gravitational Wave Spectrum

here **visible** temperature at transition is around TeV
Hidden sector temperature different



- Decreasing $\epsilon = \frac{T_{hidden}}{T_{visible}}$ decreases friction on bubble wall
- Sound wave → bubble collision
- Changes the shape of the gravitational wave signal

- We investigated how to distinguish between hidden and visible sector phase transitions
- Cold hidden sector could give rise to the same peak frequency as hot visible sector but with different spectrum

The ongoing Search for Dark Matter

- We are well into an era of using novel approaches to learn more about dark matter
- Astrophysical and Cosmological probes will continue to yield important information about substructure
- Anomalies at collider and direct detection experiments may one day stick and tell us something
- Gravitational Wave observations offer new perspectives on the problem
- Dark Matter is here to stay. We need more information about the dark stuff... Whatever it is or isn’t…