Dark Matter Effects on the Early Universe and Muon g-2

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Outline

- Evidence that Dark Matter exists
- Nature and mass range of Dark Matter candidates
- Searches via astrophysical, cosmological and terrestrial probes
  - hard to It is hard to look for what you do not know what it is

Discuss two examples:

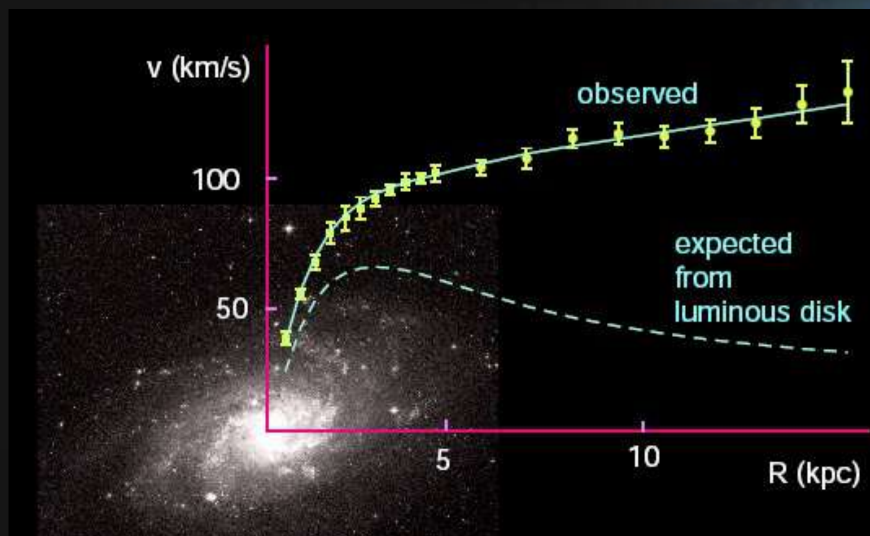
- Light Fermionic DM : cosmological probes
- possible direct detection?

- SUSY WIMP scenario with light gauginos, higgsinos and sleptons: terrestrial probes and muon g-2

Galactic and cosmological observations show there is much more matter in the Universe than what we "see"

Strong evidence for Dark Matter from its interactions with visible matter in the Milky Way

Vera Rubin



M33 rotation curve

(fig. 1)

Standard Newtonian gravity

$$v_c(r) = \sqrt{\frac{GM}{r}}$$

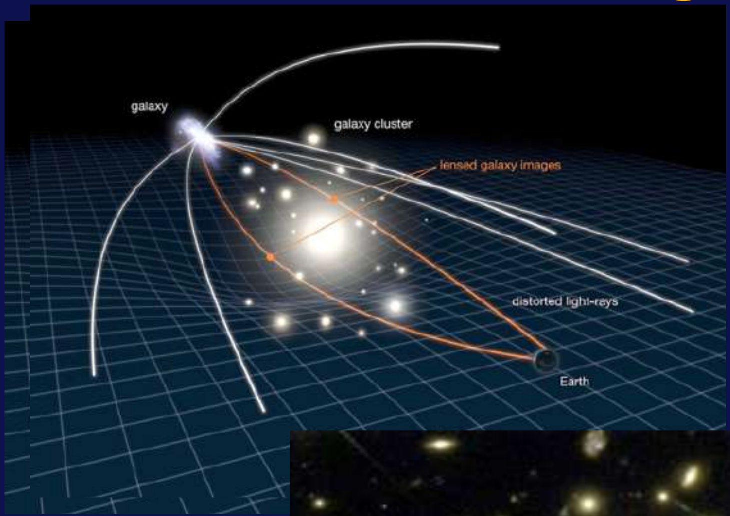
But, observations show flattening of v_c , hence

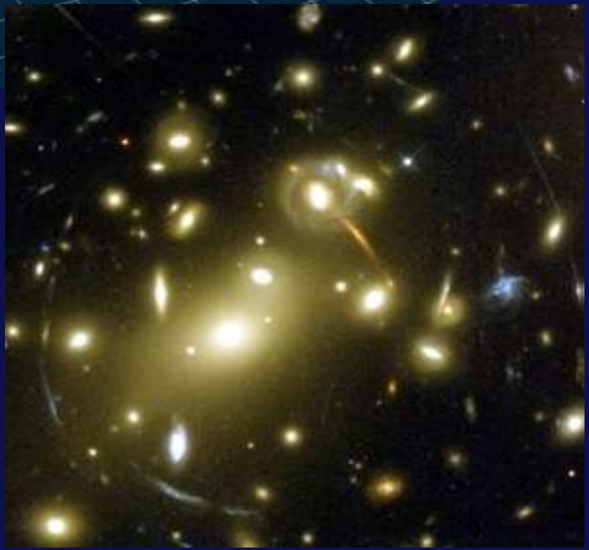
$$M(r) \propto r.$$

Something invisible is holding stars in orbit

Evidence for DM on many scales at many times

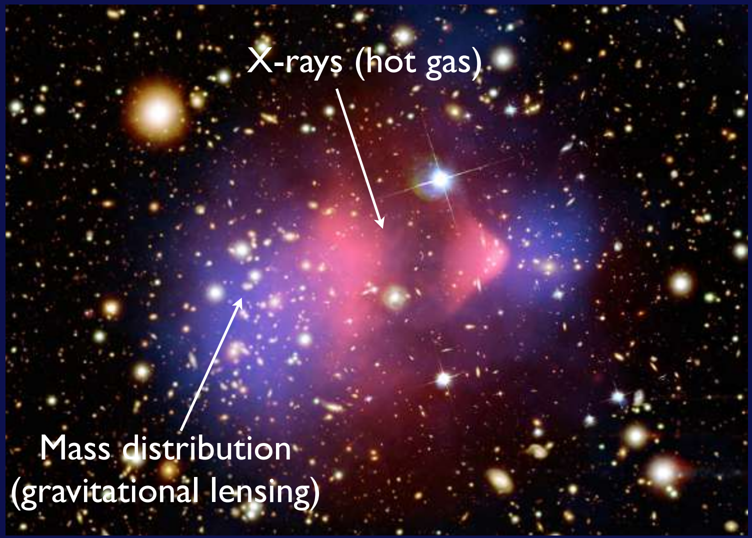
Gravitational Lensing

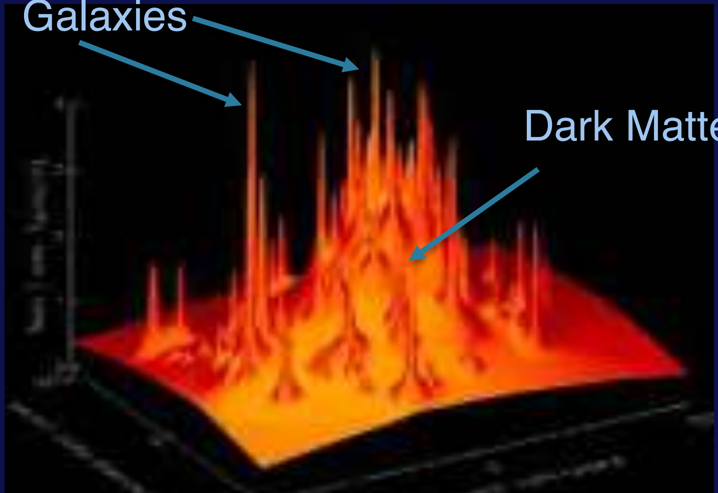




Images of distant galaxies distorted by bending of light by strong gravitational fields

Galaxy Cluster Collisions

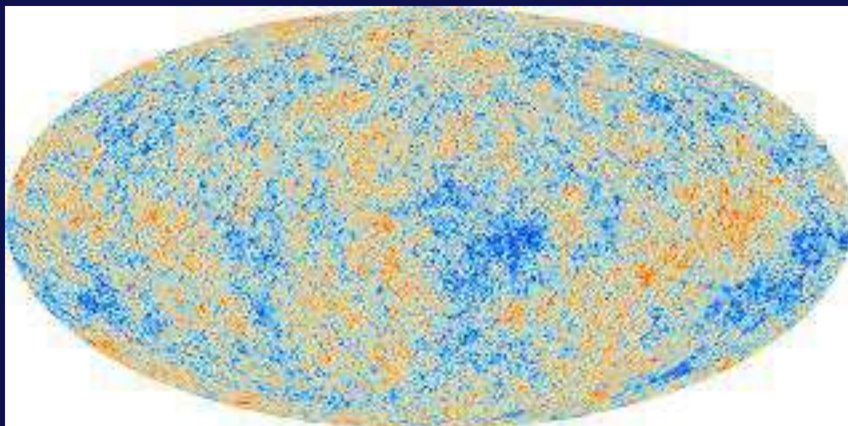




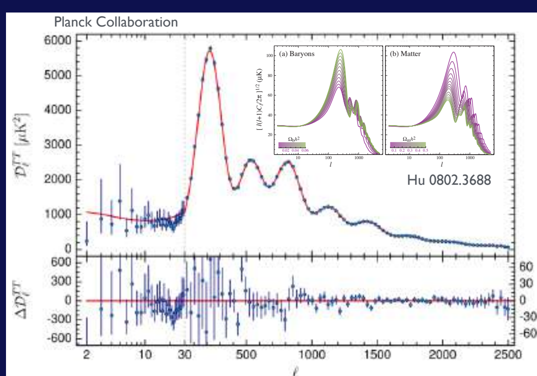
Mass distribution of cluster of galaxies inferred from gravitational lensing

Evidence for DM on many scales at many times

CMB Power Spectrum

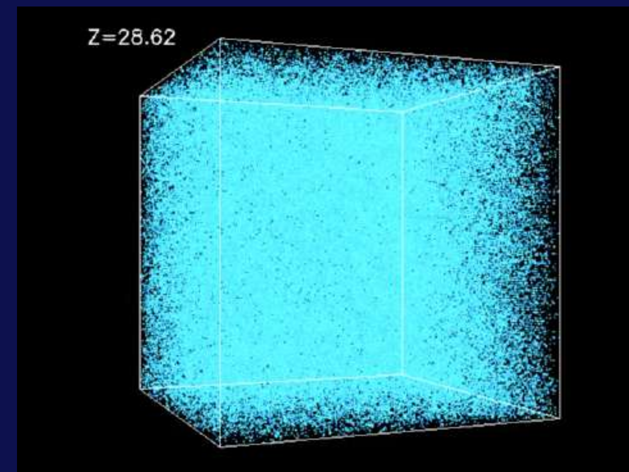


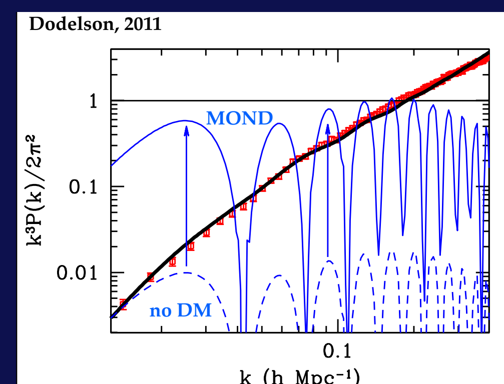
CMB temperature spectrum fluctuations at different angular scales on the sky



Constraints on the third peak yield the first direct evidence for DM at recombination.

Matter Power Spectrum

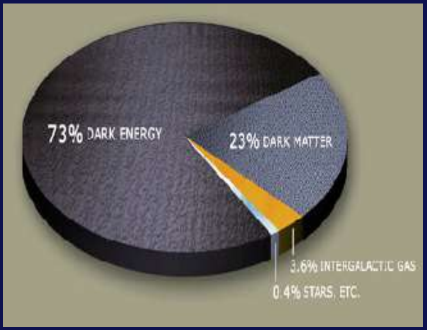




Observation & theory agree with ~ 85% pressure-less matter and 15% conventional baryonic

What do we know about Dark Matter ?

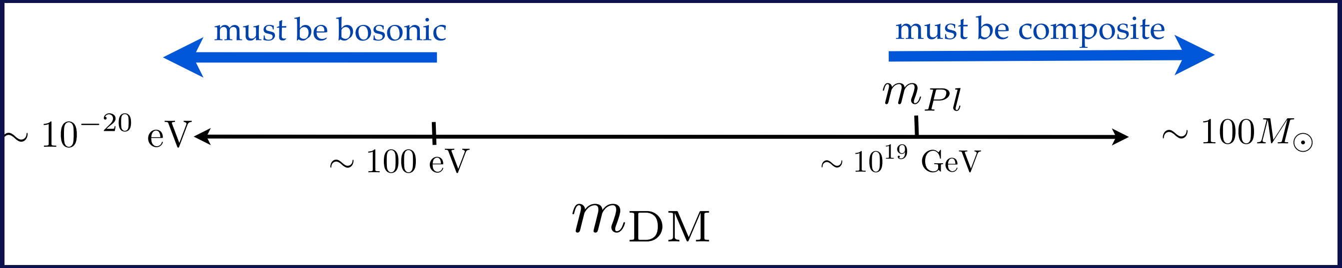
-very little -



- Couples gravitationally
- It is the most abundant form of matter
- It can be part of an extended hidden, dark sector
- It can be made of particles or compact objects

  - ultralight DM is best described as wavelike disturbances (e.g axions) -
- Its mass can be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses

Too small mass
⇒ won’t “fit”
in a galaxy!



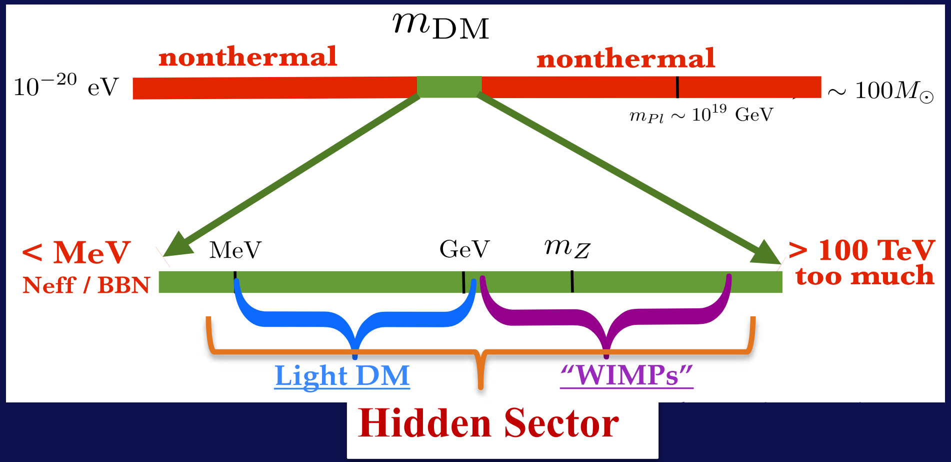
From MACHOs searches

Folding in assumptions about the evolution of the DM density in the early Universe can motivate more specific mass scales

What do we know about Dark Matter ?

- Assumptions about early Universe cosmology provides some guidance:

Thermal Equilibrium in early Universe narrows the viable mass range



- It can have weak SM charges and be part of an extended SM sector

➔ Weakly Interacting Massive Particles (WIMPs)

- It can interact indirectly with SM particles via Dark Sector mediators.

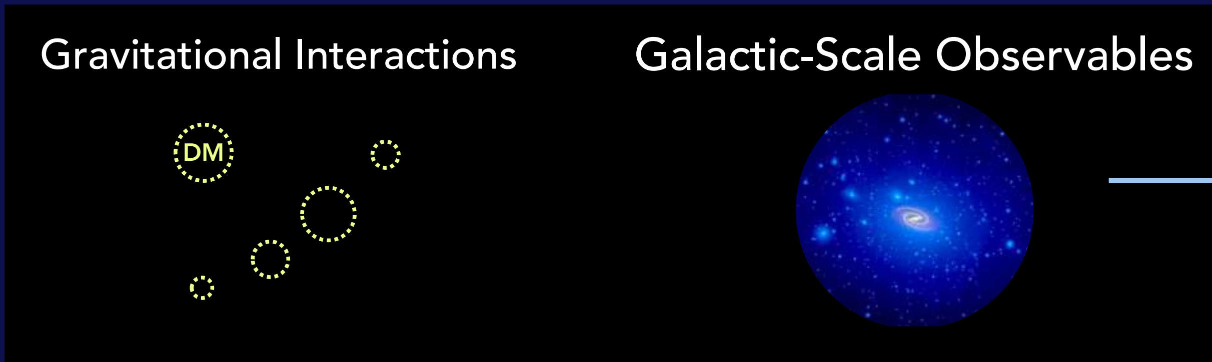
The mediators may mix with SM particles (portals) such as the Higgs boson, the photon or neutrinos or directly carry SM charges.

- It can have different type of properties with itself (e.g collisionless, self interacting)

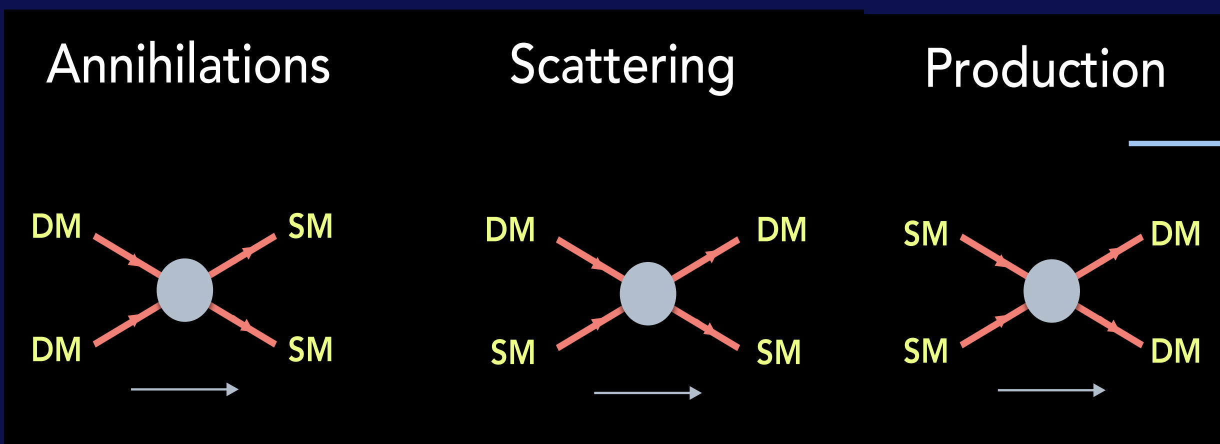
Applies to nearly all models with couplings large enough for detection (rare counter example: QCD axion DM, freeze in DM)

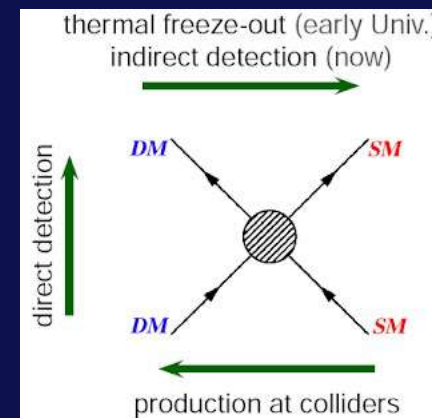
Entering a new era in the search for Dark Matter:

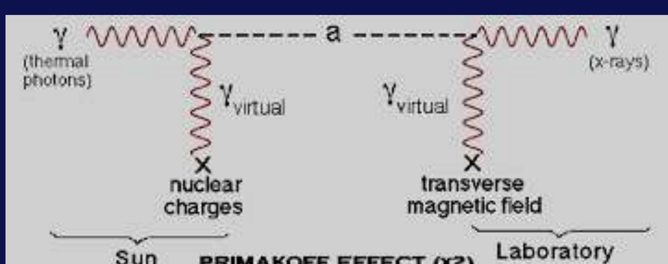
through important advancements in astrophysical, cosmological and terrestrial probes

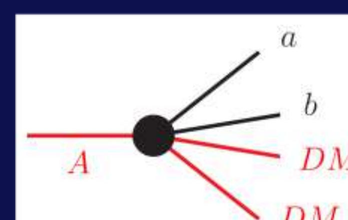


Small-Scale Structure needs to be better understood









DM produced in the decay of other, yet to be discovered particles, charged under the dark sector

The Many possible Dark Matter Solutions

Nature 562, 51 (2018)

Motivated partly by null results in weak scale DM searches and small-scale tensions that may challenge the ΛCDM predictions

Dark Matter mass ranges and nature plus thermal histories can change behavior at small-scales

($\sim$1 Mpc & mass scales smaller than $\sim 10^{11} M_\odot$)

- Cold DM (cold at all redshifts)

$$P(z) \sim 0, \rho(z) \propto \rho(z=0)(1+z)^3$$

- Baryonic physics?

- Warm DM (produced in the early universe with a Temperature)

$$P(z < z_t) \sim 0, P(z > z_t) \propto \frac{1}{3}\rho(z)$$

$$\omega = \frac{\mathcal{P}}{\rho} \qquad \rho \propto \mathrm{a}^{-\mathbf{3}(\mathbf{1}+\omega)}$$

WDM has to be cold enough for structures to form

$T \sim m_{DM} \geq 5.3$ KeV

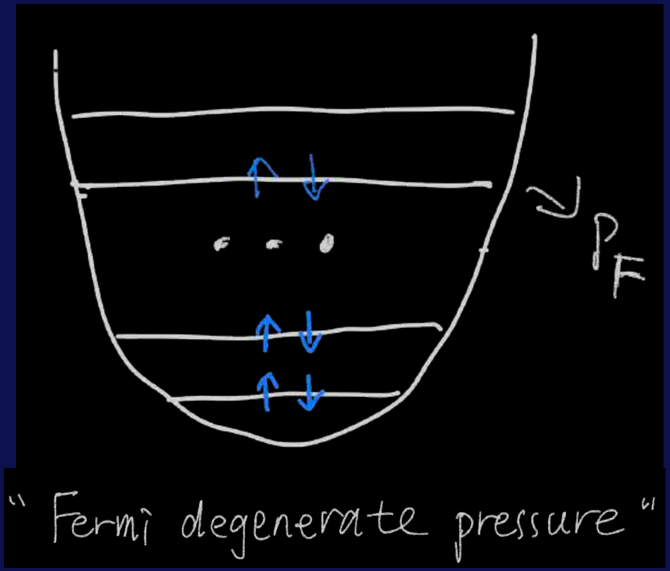
z_t Redshift of relativistic to non-relativistic transition

[V. Iršič et al, arXiv: 1702.01764]

- Mixed DM: CDM and WDM components; or other scenarios with different equation of state evolution

Cosmologically Degenerate Fermions

Fermionic DM cannot be as cold as being non-relativistic at early times



Pauli exclusion principle ➔ Fermi momentum

$$p_F = \left(\frac{6\pi^2 n_\psi}{g_\psi}\right)^{1/3}$$

Number density is higher at higher redshift

$$n_\psi(z) = n_\psi(z=0)(1+z)^3$$

Hence at some redshift, z_t, ➔ $p_F(z_t) = m_\psi$

Fermionic DM ➔ relativistic radiation at $z \geq z_t$

even in absence of Dark Sector Temperature

Assumptions:

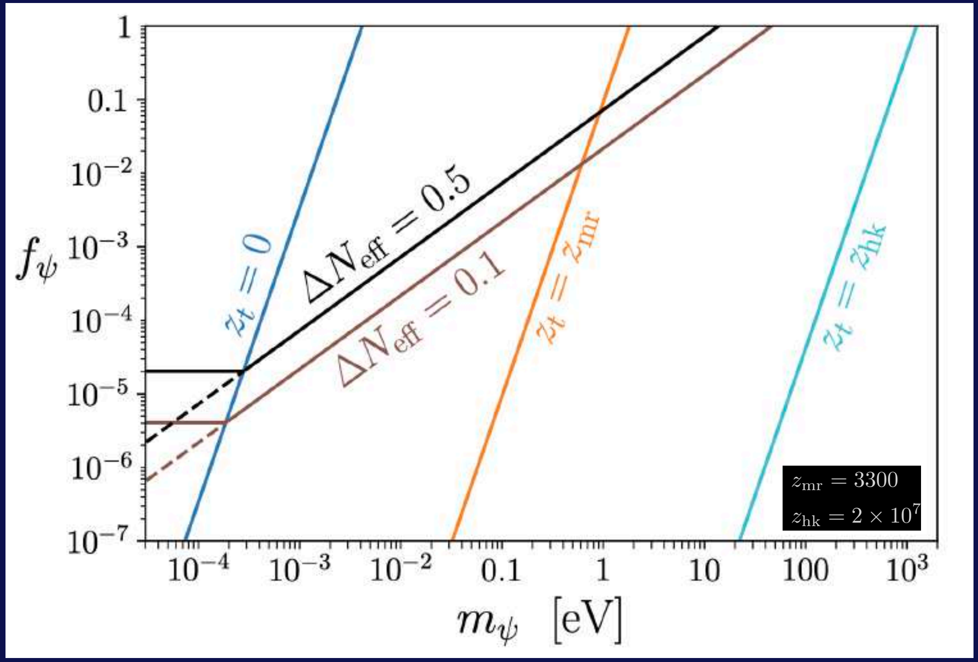
- thermally cold: kinetic energy from purely degenerate pressure
- Has a fixed comoving number since beginning of BBN until today
- Does not form bound states in high density environments

Degenerate Fermionic DM in the Early Universe

Given a present-day energy density $\rho_\psi = f_\psi\, \Omega_{DM}\, \rho_c = m_\psi\, n_\psi\, (z{=}0)\, N_f$

$$1 + z_t = \left[\frac{g_\psi N_f m_\psi^4}{6\pi^2 f_\psi \Omega_{\rm DM}\rho_c}\right]^{1/3} \simeq \frac{1500}{f_\psi^{1/3}}\left(\frac{m_\psi}{\rm eV}\right)^{4/3}$$

a fraction f_ψ of DM energy density at z = 0 (2 internal d.o.f and 1 flavor)



The energy density of ψ in its relativistic regime is characterized by its equiv. number of effective neutrinos d.o.f. ΔNeff

Need to consider that energy density in matter & radiation redshifts differently

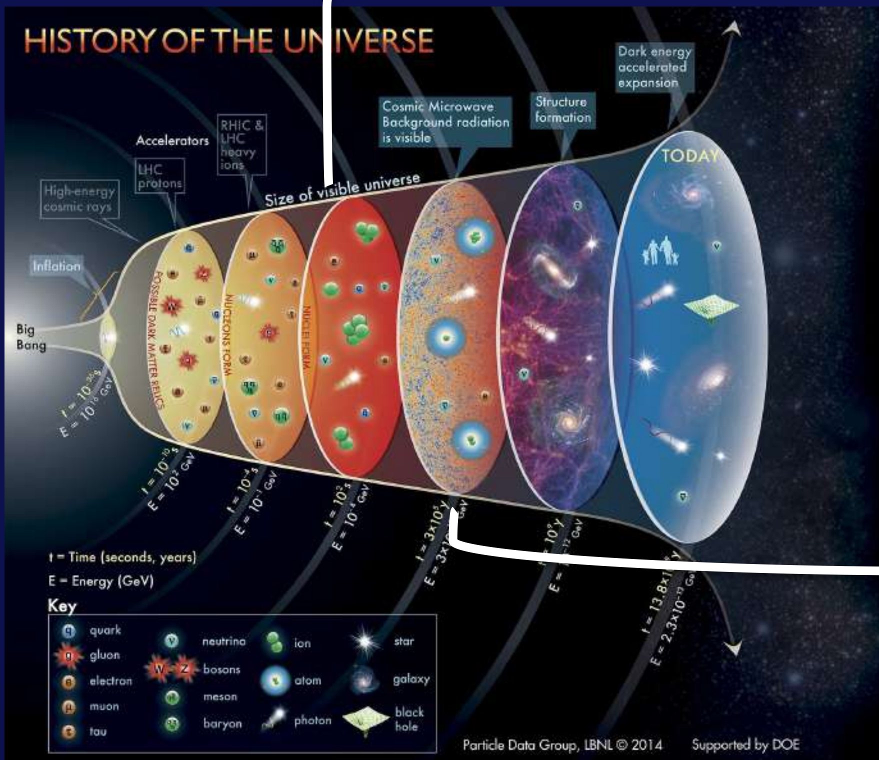
For z > zt :

$$\Delta N_{\rm eff}(m_\psi, f_\psi) = \frac{f_\psi(1+\kappa N_\nu)}{\kappa}\,\frac{1+z_{\rm mr}}{1+z_t(m_\psi, f_\psi)},$$

M.C, Coyle, Y-Y Li, McDermott, Tsai, arXiv: **2108.02785**

$N_\nu = 3.045$; k = 0.22

ΔN_{eff} constraints on light Fermionic DM



Big Bang Nucleosynthesis

constraining the number of relativistic degree of freedom at $T_f \sim \mathrm{MeV}, z \sim 10^9$

$N_{\rm eff} \nearrow, H \nearrow$

$T_f(\mathrm{neutron\ freeze-out}) \nearrow, \frac{n_n(T_f)}{n_{p^+}(T_f)} \nearrow$

current bound:

$\Delta N_{\rm eff} < 0.12$, one parameter fit

[T. -H. Yeh, et al, arXiv:2011.13874]

$\Delta N_{\rm eff} < 0.37$, joint parameter fit

[V. Mossa, et al, Nature 587, 210 (2020)]

Cosmic Microwave Background

constraining the number of relativistic degree of freedom at $T \sim 0.1\mathrm{eV}, z \sim 10^3$

$N_{eff} \nearrow, H \nearrow, f \searrow$

Current bound: $\Delta N_{\rm eff} < 0.28$, one parameter fit

[N. Aghanim, et al, arXiv:1807.06209]

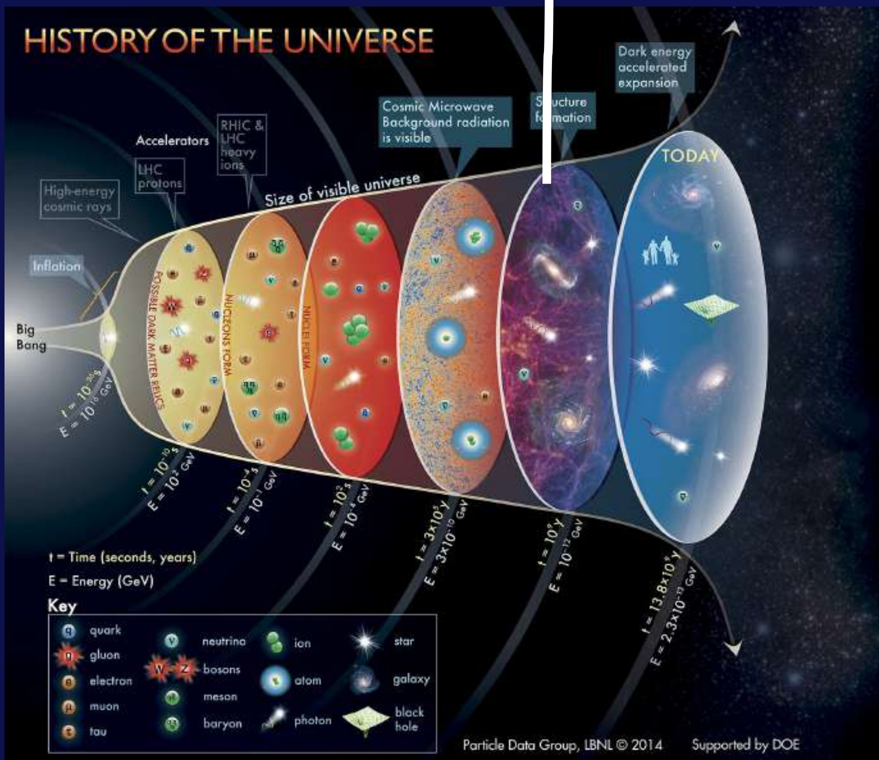
Multiparameter extensions of ΛCDM

$\Delta N_{\rm eff} < 0.5$

[N. Aghanim, et al, arXiv:1807.06209]

Structure Formation constraints on light Fermionic DM

Suppression of gravitational clustering



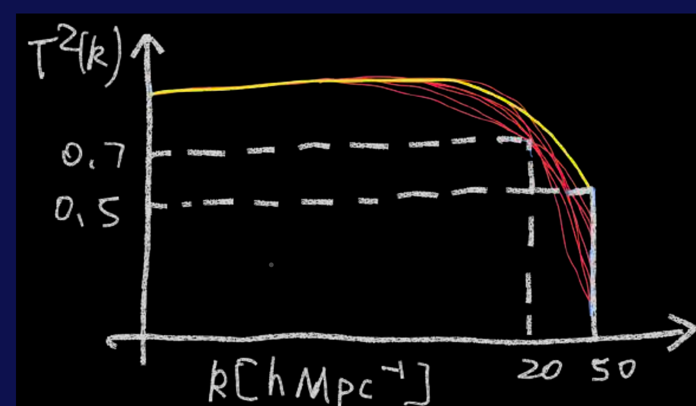
If a fraction of today's CDM remains relativistic at $z_{hk} \sim 10^7$, ($z_t < z_{hk}$) small scale clump does not occur at early times

Lyman-α forest data + counting MW satellites galaxies to determine the Sub-Halo Mass Function (SHMF)

- Calculate linear power spectrum $P_\psi(k)$ as a function of f_ψ and m_ψ
- Normalized to $P_{CDM}(k)$
- Compute transfer function $T^2(k)$ using CLASS code non-DM module

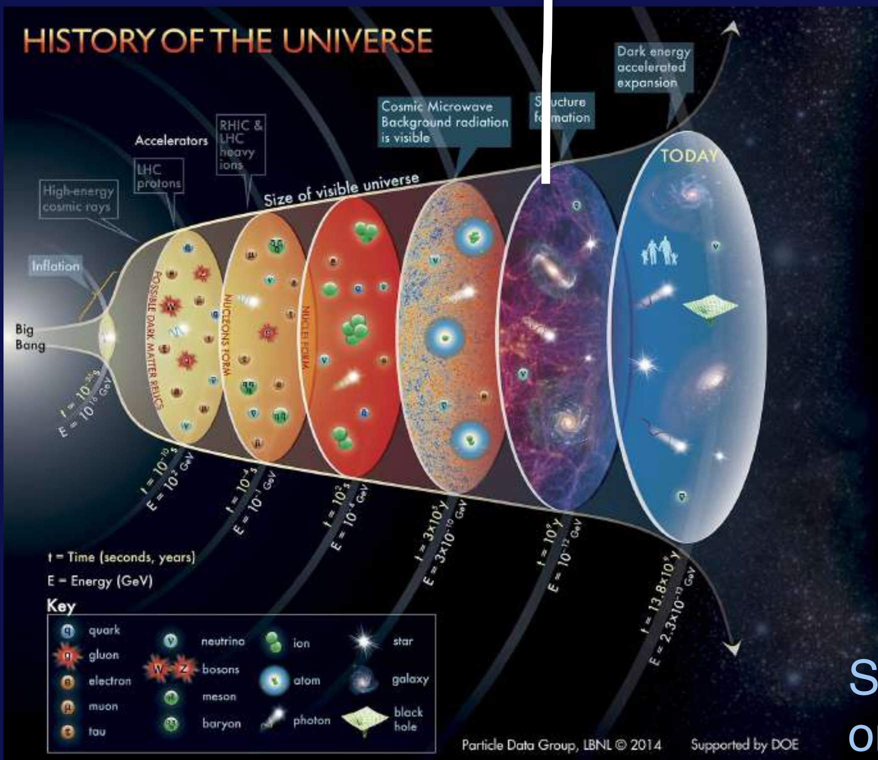
Depends on mψ, fψ and momentum distributions

$$T^2(k) = \frac{P_{\rm nCDM}(k)}{P_{\rm CDM}(k)}$$

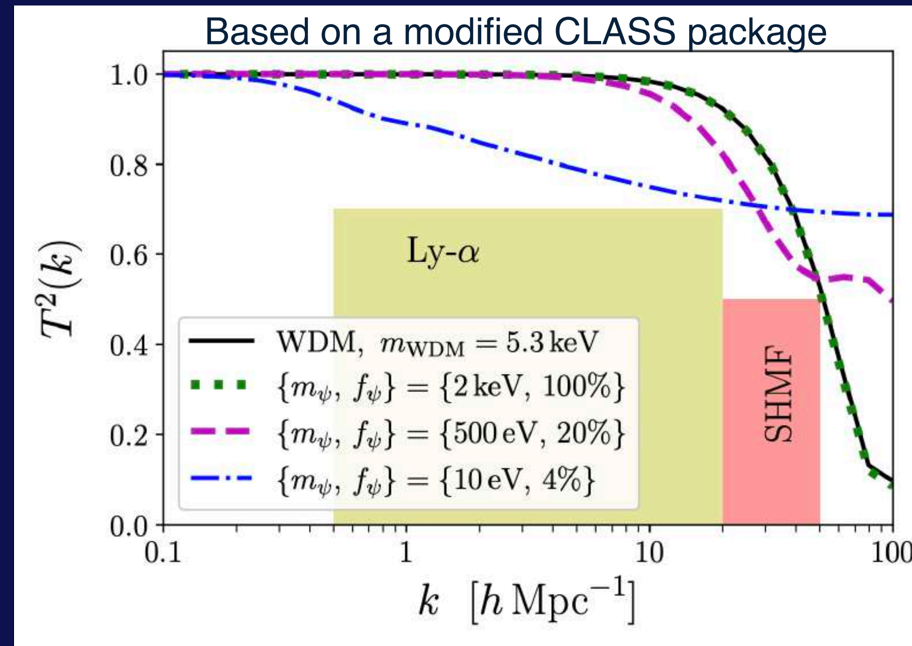


Structure Formation constraints on light Fermionic DM

Suppression of gravitational clustering



$f_\psi \ \mathrm{DF} + (1 - f_\psi)\mathrm{CDM}$



M.C, Coyle, Y-Y Li, McDermott, Tsai, arXiv: **2108.02785**

Smallest wavenumber with suppression depends on z_t ➔ lower z_t suppresses $T^2(k)$ to smaller k.

$$T^2(k) = \frac{P_{\rm nCDM}(k)}{P_{\rm CDM}(k)}$$

$$\mathrm{Ly}-\alpha : T^2(k < 20\mathrm{h/Mpc}) \geq 0.7$$

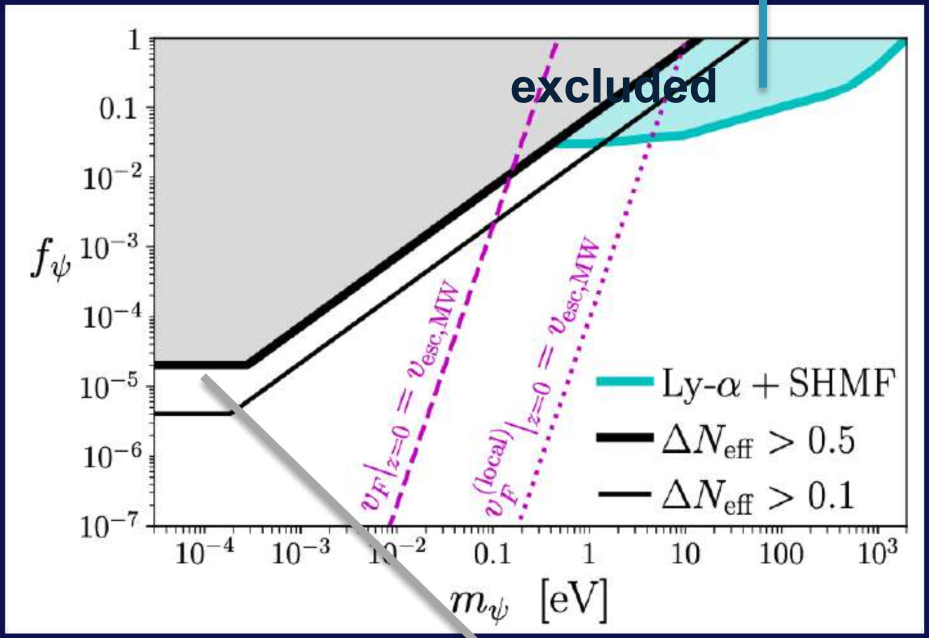
$$\mathrm{SHMF} : T^2(k < 50\mathrm{h/Mpc}) \geq 0.5$$

[R. Murgia, et al, arXiv:1704.07838]

[E. O. Nadler, et al, arXiv:2008.00022]

Light Fermionic Dark Matter parameter space

- For $f_\psi = 1$ ➔ $m_\psi \geq 2$ keV due to impacts of degeneracy pressure on structure formation in the early universe - specially from modes of size k = 50h/Mpc -
  (in comparison with m ≥ 5.3keV for WDM)
- Constrain fractions a slow as 3% for $m_\psi \lesssim 1$ eV - DF add non-negligibly to total energy density in the form of radiation during cosmic structure formation -



All results are for $T_\psi = 0$
- Kinetic energy solely from degenerate pressure

Allowing finite Dark sector temperature strengthens bounds from ΔN_{eff} and structure formation on m_ψ

$T_\psi = 0$ ➔ weakest bounds on f_ψ and m_ψ

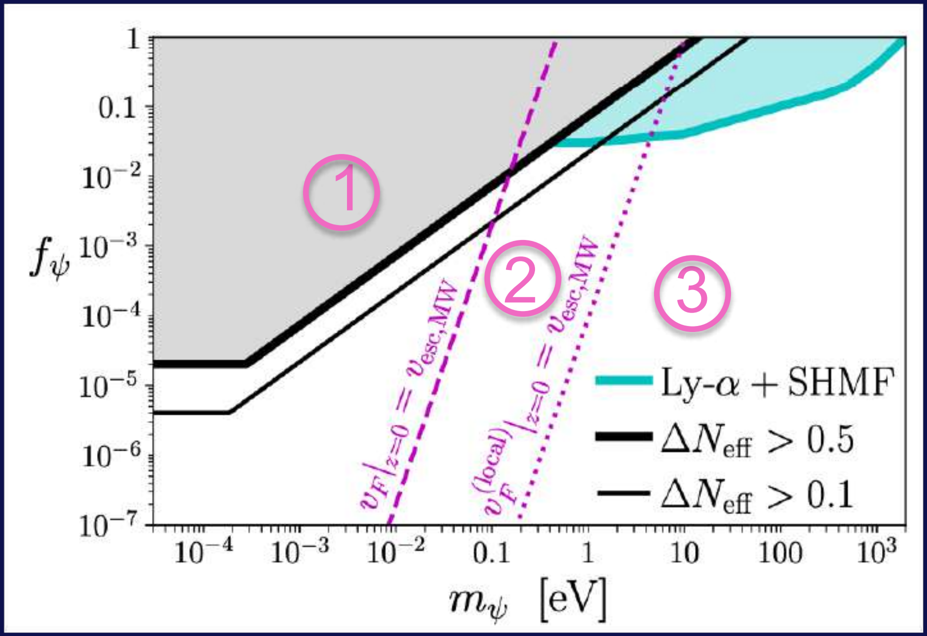
- Constrain f_ψ as small as 2 x 10^5 for $m_\psi \lesssim 0.1$ meV

M.C, Coyle, Y-Y Li, McDermott, Tsai, arXiv: **2108.02785**

Light Fermionic Dark Matter: Local Implications

Fermi velocity of degenerate fermions will modify MW DM phase space density

- Assuming $\rho_\psi = f_\psi\, \Omega_{DM}\, \rho_c$ ➔ $v_F\,(z=0) \simeq (m_\psi\,/\mathrm{eV})^{-4/3}\, f_\psi^{1/3} \times 198$ km/s
- If m_ψ light enough ➔ $v_F(z=0) > v_{esc,MW} \simeq 540$ km/s ➔ $\rho_\psi^{local} < \rho_\psi$
  particles not gravitationally bound to MW halo
- MW halo DM overdensity: $\rho_{DM}^{local} = 0.3\, f_\psi$ GeV/cm^3 $\delta_{DM} = \rho_{DM}^{local}\,/\,\rho_\psi \simeq 2 \times 10^5$



① Not accumulating: $\rho_\psi^{local} < \rho_\psi$

② **Smaller over density than CDM, or higher velocity, e.g. probed by novel material**

a) $\rho_\psi^{local} < \delta_{DM}\, \rho_\psi$ and $v_F < v_{esc,MW}$

b) some DM $v_F > v_{esc,MW}$ and can have $\rho_\psi^{local} \sim \delta_{DM}\, \rho_\psi$

③ Similar phase space distribution to that of CDM

$v_F < v_{esc,MW}$ for $\rho_\psi^{local} \sim \rho_\psi^{local,MW}$

M.C, Coyle, Y-Y Li, McDermott, Tsai, arXiv: **2108.02785**

Light Fermions cannot reach arbitrarily high density without obtaining significant kinetic energy.

The Fermi momentum can cause the DM to behave as extra radiation density in the early Universe, thereby contributing to ΔN_{eff} at BBN & CMB and it can suppress the matter power spectrum by staying relativistic until too low redshift.

Our analysis of cosmological constraints shows new regions of parameters in the fermion mass - DM fraction space
$m_\psi \geq 2$ keV for $f_\psi=1$ and f_ψ as low as 3% for $m_\psi \sim 1$ eV, reaching values as low as $f_\psi \sim 2 \times 10^{-5}$ for $m_\psi \lesssim 0.1$ meV

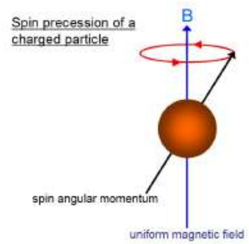
The local phase space density of DM particles can differ from the MW's virial distribution and may be suppressed for $m_\psi \lesssim 10 \text{ eV } f_\psi^{1/4}$
Close that region particles may have interesting, high-velocity distributions that may be probed in new type of experiments.

SUSY WIMPs and the Muon g-2 Anomalous Magnetic Moment

Precision Tests of QED : g-2

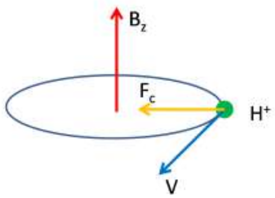
- The precession frequency of the lepton spin in a magnetic field is controlled by the so-called g-factor ($g \simeq 2$)

$$\vec{\omega}_S = -\frac{q\vec{B}}{m\gamma} - \frac{q\vec{B}}{2m}(g-2)$$



- That can be compared with the cyclotron frequency

$$\vec{\omega}_C = -\frac{q\vec{B}}{m\gamma}.$$



$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

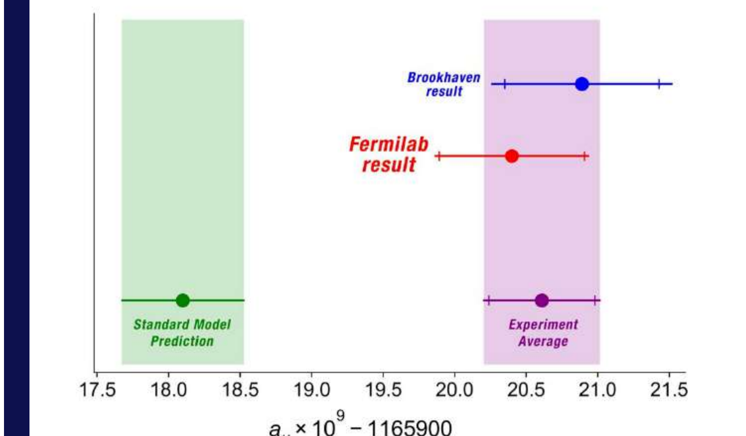
- Hence,

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{q\vec{B}}{m}\left(\frac{g-2}{2}\right)$$

- Most measurements of g-2 are based on clever ways of measuring these frequency difference in a uniform magnetic field.

Fermilab muon g-2 experiment confirms the Brookhaven result.
Deviation of 4.2 standard deviations from SM Expectations.

Observe that the g-2 errors are mainly statistical ones.



$$a_\mu^{\rm SM} = 116\ 591\ 810(43) \times 10^{-11}$$

$$a_\mu^{\rm exp} = 116\ 592\ 061(41) \times 10^{-11}$$

$$\Delta a_\mu \equiv (a_\mu^{\rm exp} - a_\mu^{\rm SM}) = (251 \pm 59) \times 10^{-11}$$

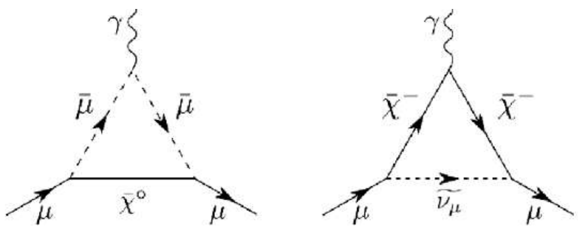
A very important result, that will be further tested in the coming years

Dominant Diagrams for g-2 in Supersymmetry

Barbieri, Maiani'82, Ellis et al'82, Grifols and Mendez'82
Moroi'95, Carena, Giudice, CW'95, Martin and Wells'00..

$$a_\mu^{\tilde{\chi}^\pm - \tilde{\nu}_\mu} \simeq \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\nu}_\mu}^2} \left[\frac{f_{\chi^\pm}\left(M_2^2/m_{\tilde{\nu}_\mu}^2\right) - f_{\chi^\pm}\left(\mu^2/m_{\tilde{\nu}_\mu}^2\right)}{M_2^2 - \mu^2} \right],$$

$$a_\mu^{\tilde{\chi}^0 - \tilde{\mu}} \simeq \frac{\alpha m_\mu^2 M_1 (\mu \tan\beta - A_\mu)}{4\pi \cos^2\theta_W \left(m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2\right)} \left[\frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_R}^2\right)}{m_{\tilde{\mu}_R}^2} - \frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_L}^2\right)}{m_{\tilde{\mu}_L}^2} \right]$$



$$f_{\chi^\pm}(x) = \frac{x^2 - 4x + 3 + 2\ln(x)}{(1-x)^3},$$

$$f_{\chi^0}(x) = \frac{x^2 - 1 - 2x\ln(x)}{(1-x)^3};$$

- If all weakly interacting supersymmetric particle masses were the same, and the gaugino masses had the same sign, then

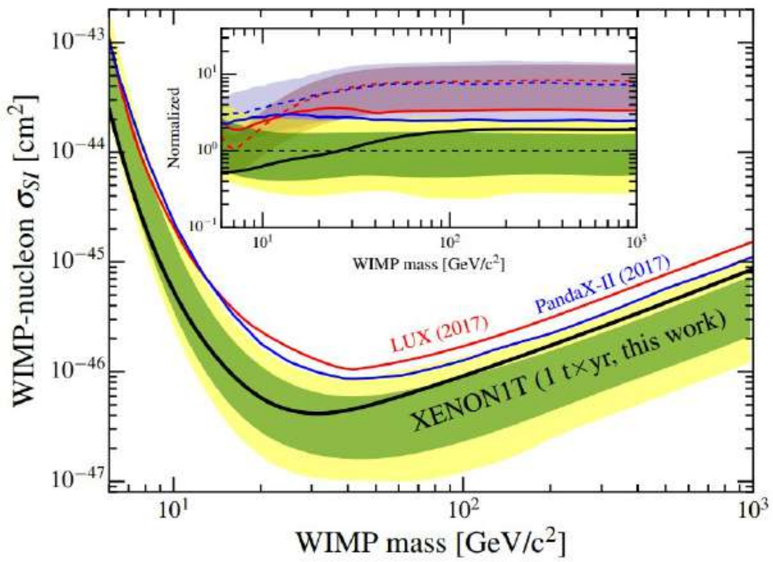
$$(\Delta a_\mu)^{\rm SUSY} \simeq 150 \times 10^{-11} \left(\frac{100 \text{ GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

- This implies that, for $\tan\beta = 10$, particle masses of order 250 GeV could explain the anomaly, while for values of $\tan\beta = 60$ (consistent with the unification of the top and bottom Yukawa) these particle masses could be of order 700 GeV.

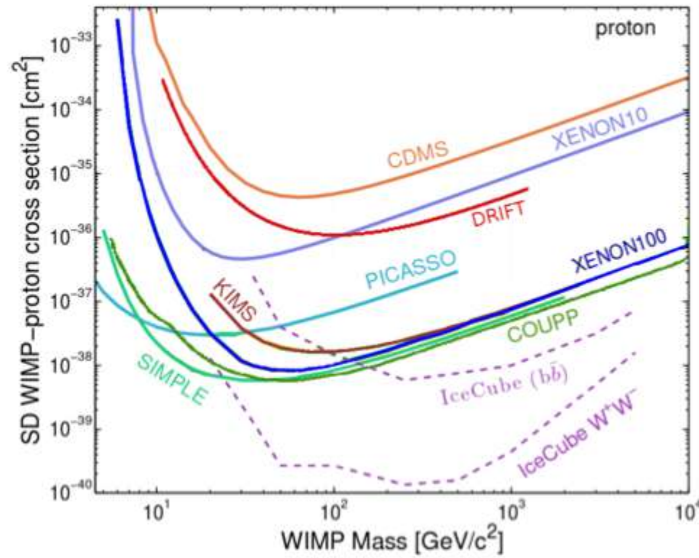
Rough Approximation

$$\Delta a_\mu \equiv (a_\mu^{\rm exp} - a_\mu^{\rm SM}) = (251 \pm 59) \times 10^{-11}$$

Dark Matter Direct Detection



Spin Independent Interactions



Spin Dependent Interactions

$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde\chi_1^0} + 2\mu/\tan\beta)\frac{1}{m_h^2} + \mu\tan\beta\frac{1}{m_H^2} + (m_{\tilde\chi_1^0} + \mu\tan\beta/2)\frac{1}{m_{\tilde Q}^2}\right]^2$$

Blind Spot :

$$2\left(m_{\tilde\chi_1^0} + 2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2} + \frac{1}{2m_{\tilde Q}^2}\right)$$

$\mu \times m_{\tilde\chi^0} < 0$

$m_{\tilde\chi^0} \simeq M_1$

$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

g-2 and Direct Detection

Reduction of the cross section in the proximity of Blind Spots may be obtained for negative values of $\mu \times M_1$
The direct detection cross sections can also be suppressed for large values of μ

g-2 has two contributions, the Bino one proportional to $\mu \times M_1$ and the other (chargino) proportional to $\mu \times M_2$

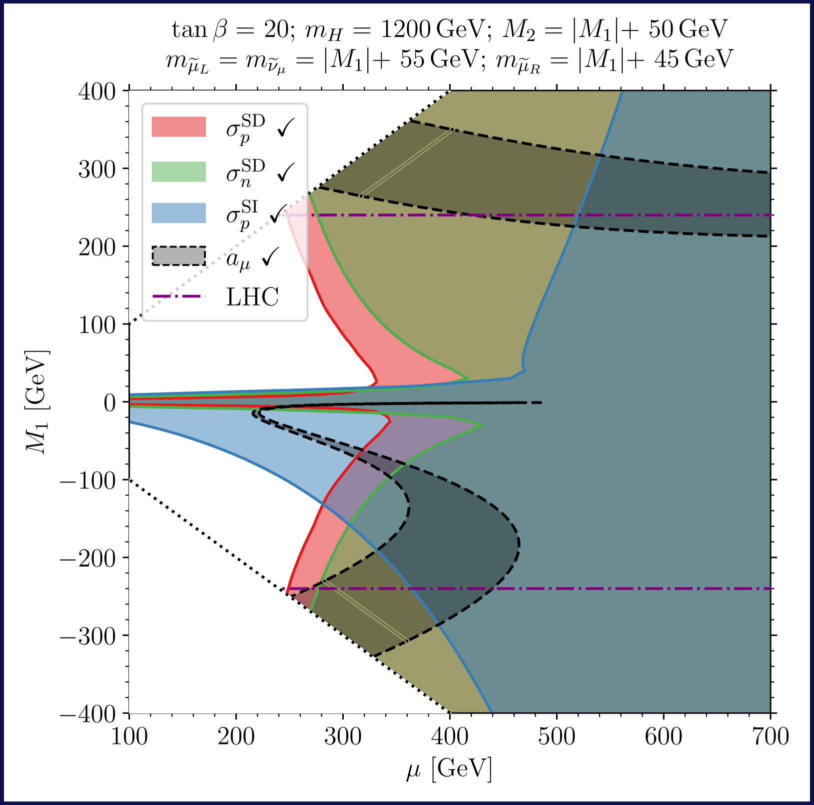
The Bino contribution to g-2 is negative at the proximity of the blind spot but becomes subdominant at smaller values of μ

The chargino contribution is the dominant one for masses of the same order and is suppressed at large μ

Since g-2 needs to be positive, compatibility between g-2 results and Direct detection may be either achieved for large values of μ or for smaller values of μ, when the relative sign of the gaugino masses is opposite.

Compatibility of Direct Detection and g-2 Constraints for a representative example of a compressed spectrum. Stau co-annihilation is assumed

Large hierarchy of values of μ between positive and negative values of the Bino mass parameter is observed.



A compressed spectrum leads to weaker bounds and to getting the DM relic density via co-annihilation.

Proximity to the blind spots or large values of μ serve to avoid the direct detection bounds.

The high luminosity LHC will further probe the presence of light weakly interacting particles and the Muon g-2 results should highly motivate these searches.

Baum, MC, Shah, Wagner, arXiv:2104.03302

The Tiny (g-2) Muon Wobble from Small-μ Supersymmetry

Benchmark Scenarios

	BMSM	BMST	BMW	BMH
M_1 [GeV]	-352	-258	-274	63
M_2 [GeV]	400	310	310	700
μ [GeV]	690	475	500	470
$M_L^{1,2}$ [GeV]	360	320	350	750
M_L^3 [GeV]	500	320	350	750
$M_R^{1,2}$ [GeV]	360	320	350	750
M_R^3 [GeV]	500	320	350	750
M_A [GeV]	2000	1800	1600	3000
$\tan\beta$	60	40	35	65

	BMSM	BMST	BMW	BMH
m_χ [GeV]	350.2	255.3	271.4	61.0 (124.9)
$m_{\tilde{\tau}_1}$ [GeV]	414.4	264.2	305.3	709.5
$m_{\tilde{\mu}_1}$ [GeV]	362.7	323.0	352.8	751.3
$m_{\tilde{\nu}_\tau}$ [GeV]	496.0	313.7	344.2	747.3
$m_{\tilde{\nu}_\mu}$ [GeV]	354.4	313.7	344.2	747.3
$m_{\chi_1^\pm}$ [GeV]	392.3	296.2	297.9	469.6
Δa_μ $[10^{-9}]$	2.10	2.89	2.35	1.93
$\Omega_{\rm DM}h^2$	0.121	0.116	0.124	0.121
$\sigma_p^{\rm SI}$ $[10^{-10}\,{\rm pb}]$	0.645	1.58	1.42	0.315
$\sigma_p^{\rm SD}$ $[10^{-6}\,{\rm pb}]$	1.03	5.11	4.23	3.01
$\sigma_n^{\rm SI}$ $[10^{-10}\,{\rm pb}]$	0.632	1.57	1.41	0.330
$\sigma_n^{\rm SD}$ $[10^{-6}\,{\rm pb}]$	0.882	4.10	3.42	2.34

Bino-like DM
co-annihilating with light sleptons (BMSM)
co- annihilating with a light stau (BMST)
co-annihilating with a Wino (BMW)
resonant s-channel annihilation via the SM-like Higgs boson (BMH)

Good prospects to probe these benchmarks at LHC and direct detection experiments

Thank You