Particle Dark Matter Direct Detection

Lecture 1

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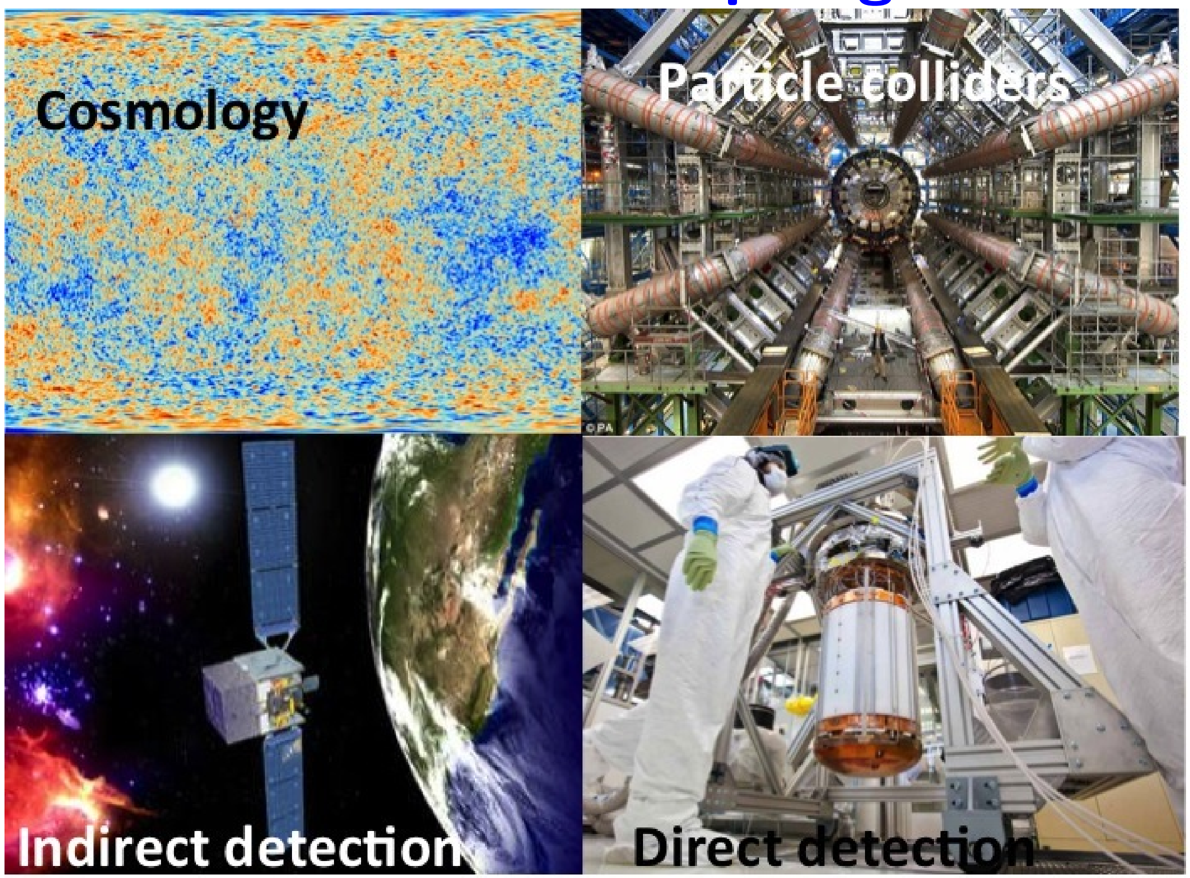
U.S. DEPARTMENT OF ENERGY | Office of Science DE-SC0009937

Theory Meets Experiments 2025, GGI, Florence, Nov 10-21 2025

The search for Dark Matter, the most abundant form of matter in the Universe, is multi-pronged involving ...



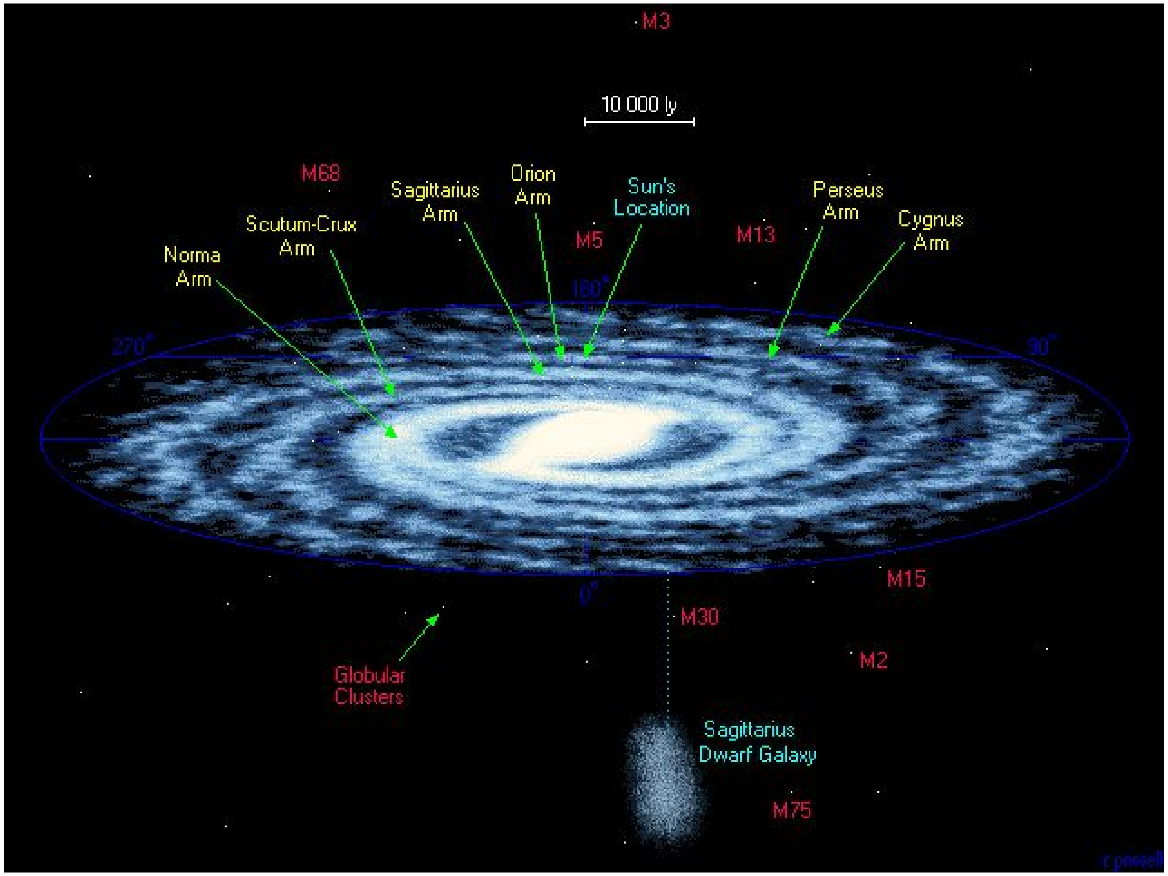
We will concentrate on Direct Detection

- Lecture 1:
  - Brief review of the observational evidence, properties and candidates for Dark Matter (DM) (PBH or particles? CDM, WDM, PIDM, DDDM, SIDM? Millicharge DM, kinetic mixing, Hidden (or Dark) Photons (HP or DP), Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, ELDERs, Axions, ALPs, WISPs, FIPs...)
  - Introduction to Direct DM Detection

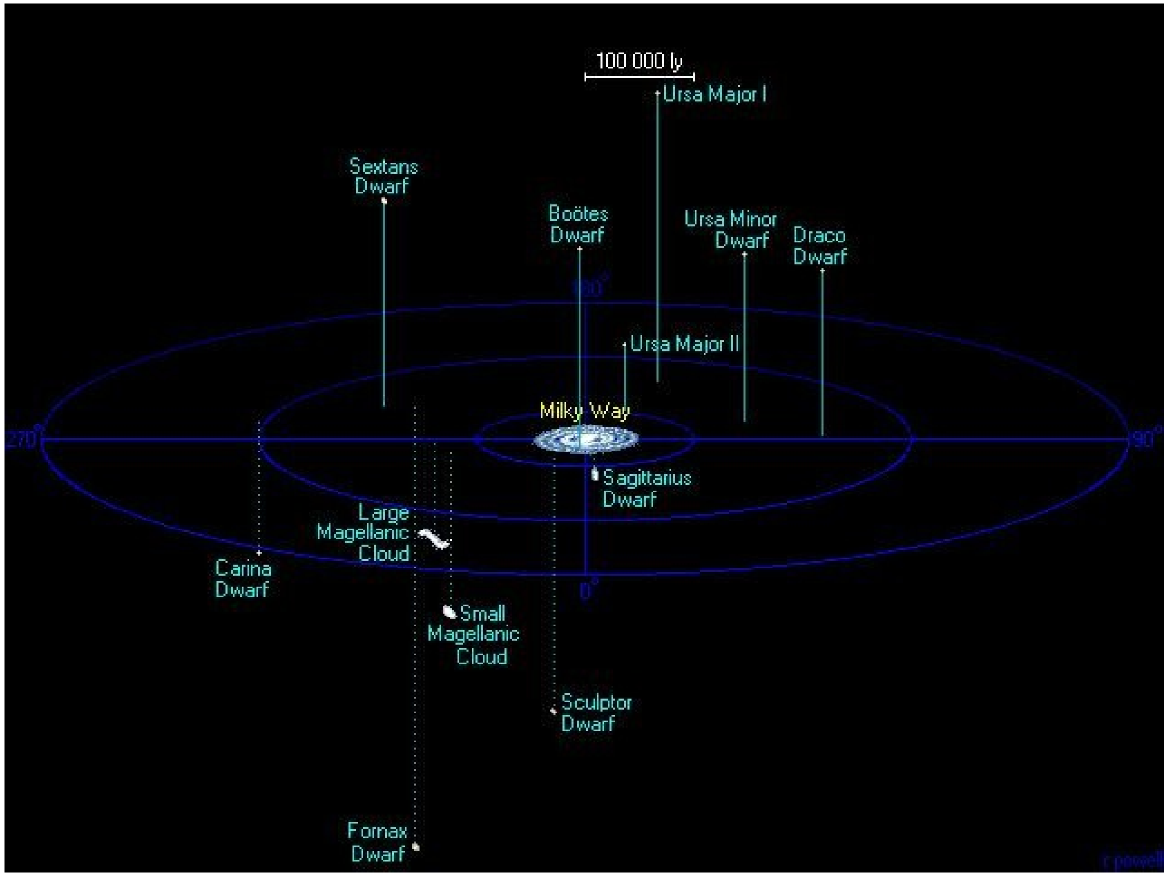
  Approximate plan for the other lectures:
- Lecture 2:
  - Non-directional Direct Detection of WIMPs
- Lecture 3:
  - Halo-Independent Data Analysis
  - Directional Direct Detection
- Lecture 4:
  - Direct Detection of Light Dark Matter

Disclaimer: idiosyncratic choice of subjects and not complete lists of citations

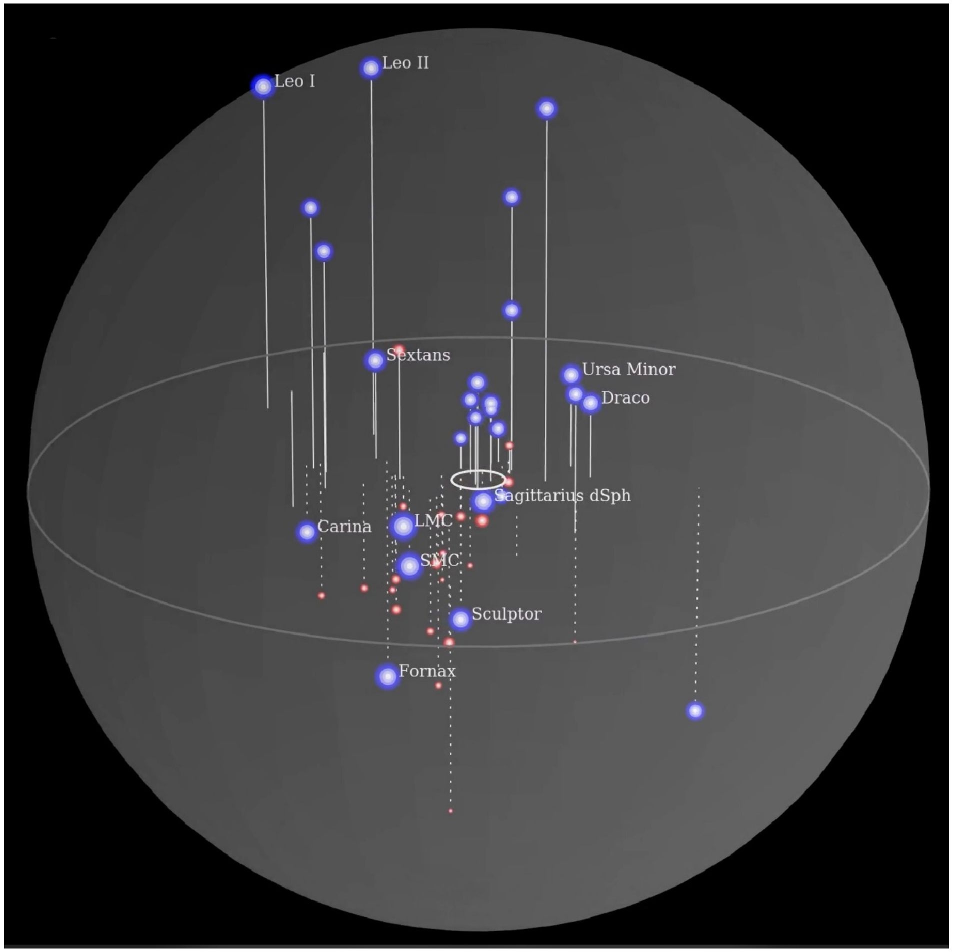
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



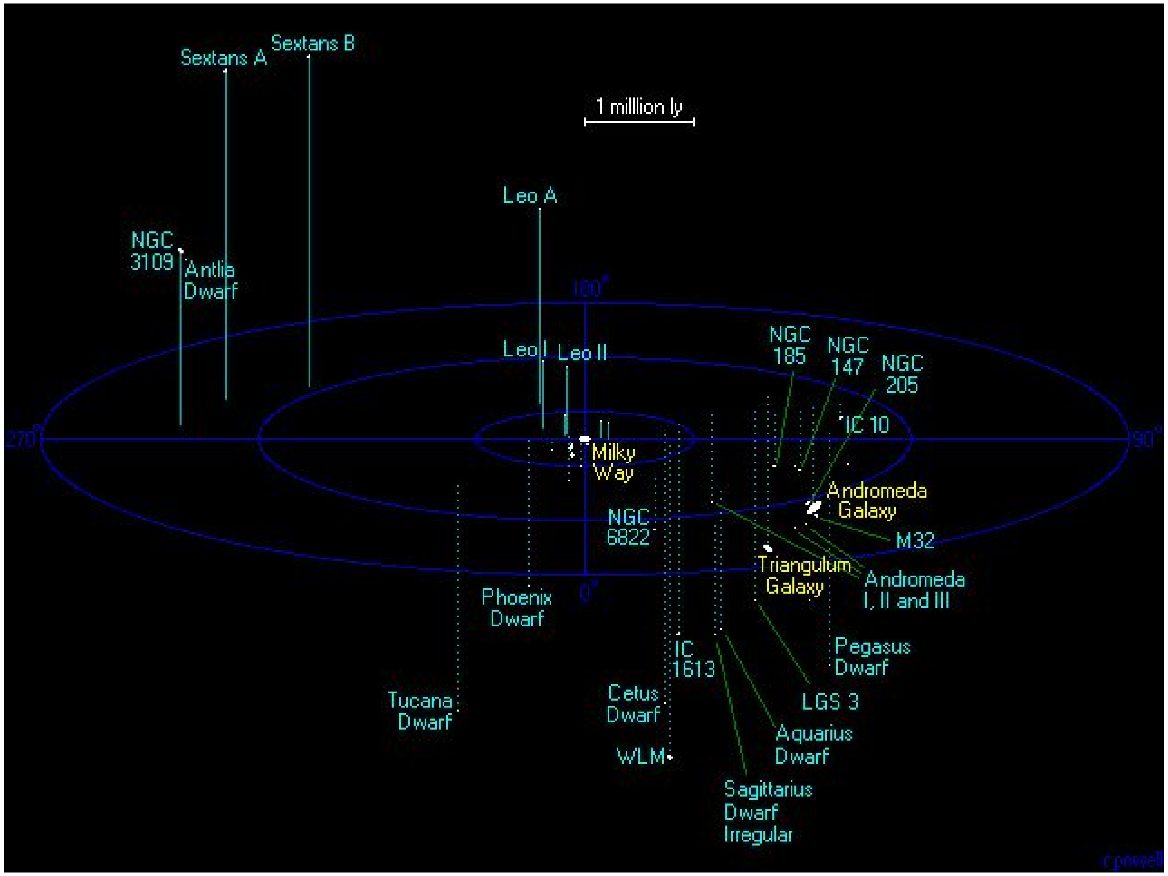
The Milky Way has many small satellite galaxies about 60 dwarf galaxies have been found so far



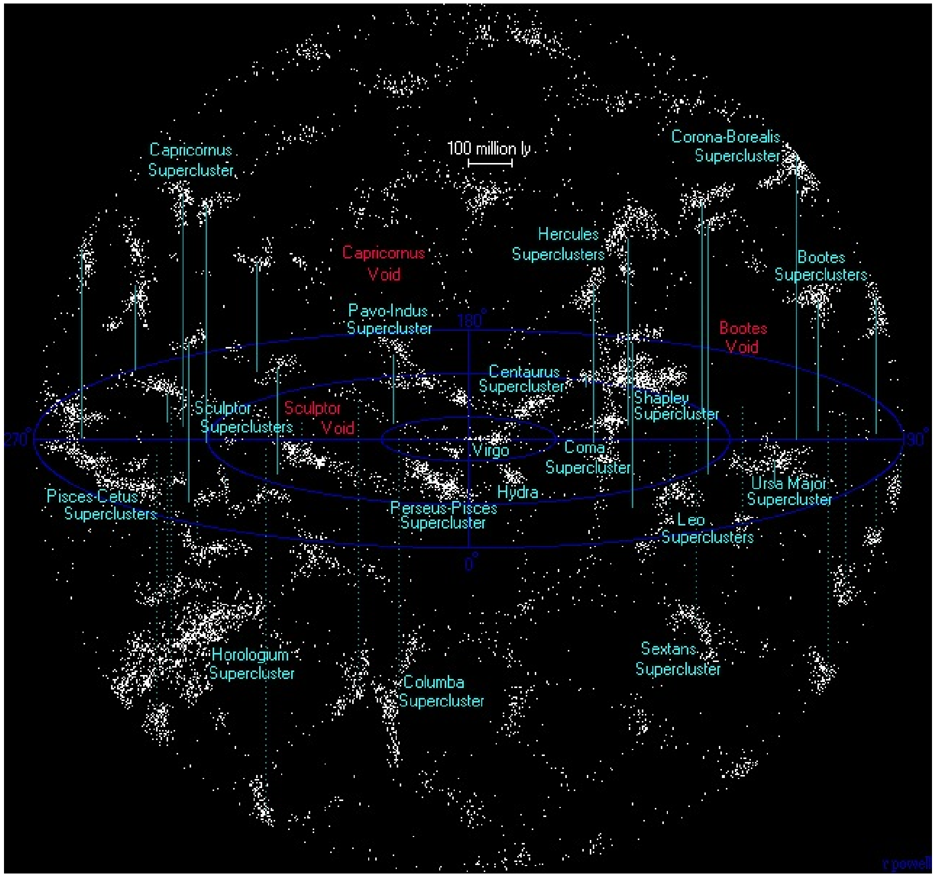
The Milky Way has many small satellite galaxies- dwarfs as of 2016 (in red DES)



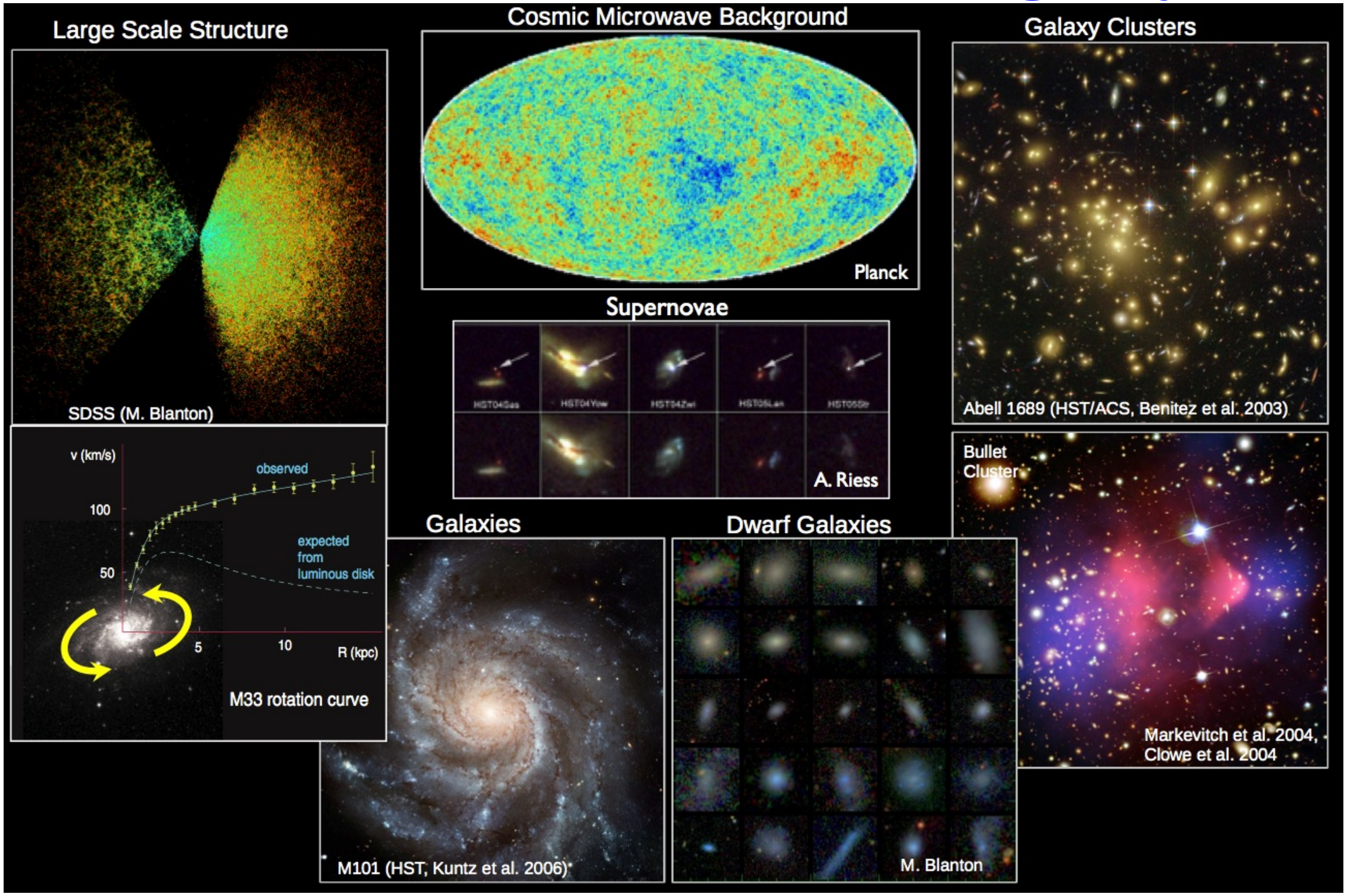
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies are the building blocks of the Universe: they come in groups, clusters, superclusters (which form "filaments, walls and voids")



DM dominates all structures from dwarf galaxy scales on



The Dark Matter problem has been with us since 1930's,

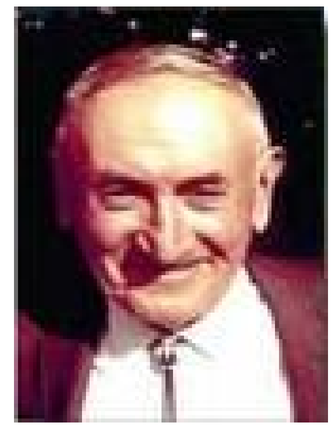
e.g. Fritz Zwicky, Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.



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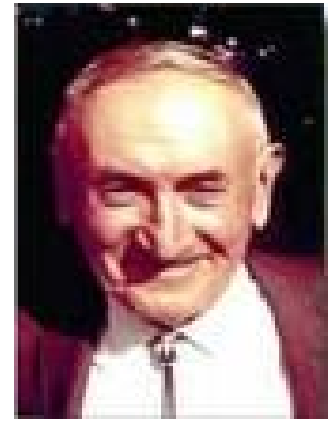
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht

Dark Matter discovered



In 1930's Fritz Zwicky found one of the first indications of the DM. Used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

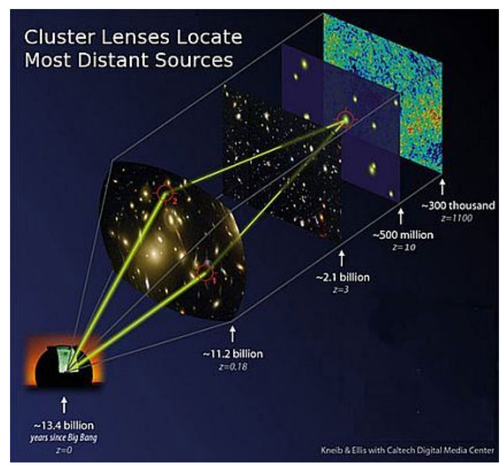
Example Virial Theorem: for planets $\dfrac{G M_{\odot} m}{r} = m v^2$

|Gravitational Potential Energy|=2×Kinetic Energy

Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there is DM.

Another later method:
gravitational lensing

depends on all the intervening mass



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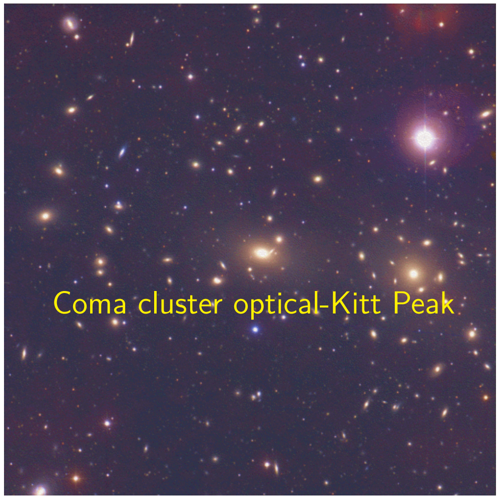
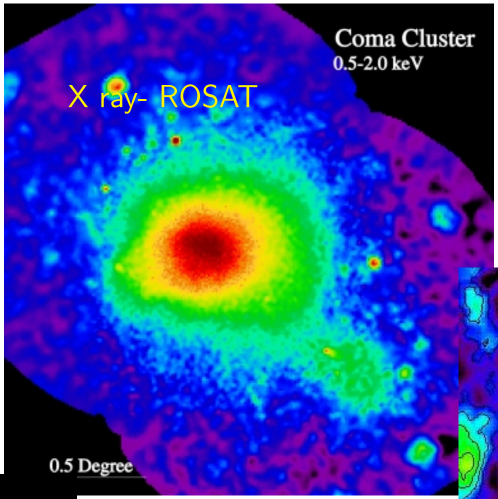
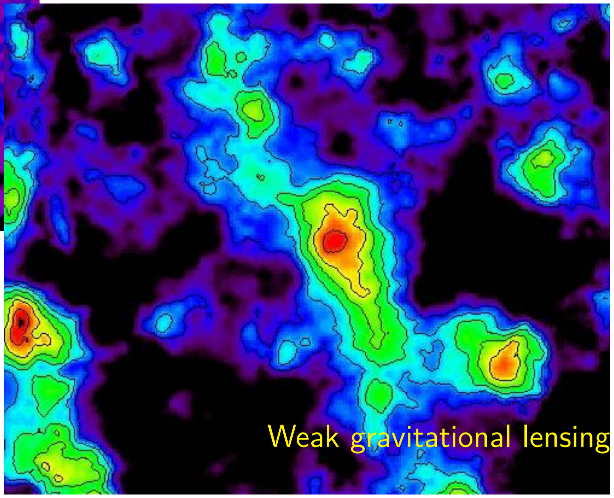
DM dominates in galaxy clusters



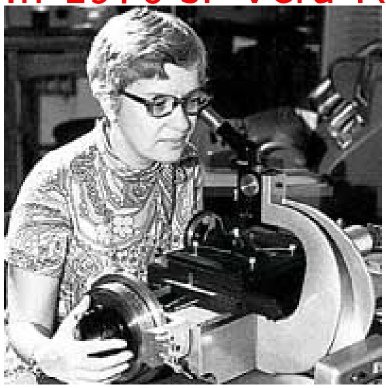


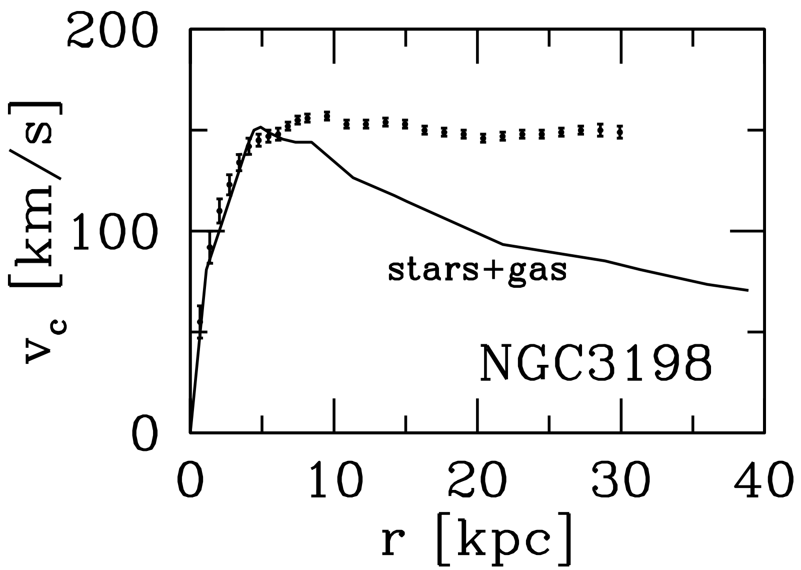
$$\frac{M}{M_{\rm vis}} \simeq 6$$



Dark Matter rediscovered

In 1970's: Vera Rubin and others found rotation curves of galaxies ARE FLAT!





$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = \text{const.} \Rightarrow M(r) \sim r$$

even where there is no light!

Dark Matter dominates in galaxies

(1 pc = 3.2 ℓy)

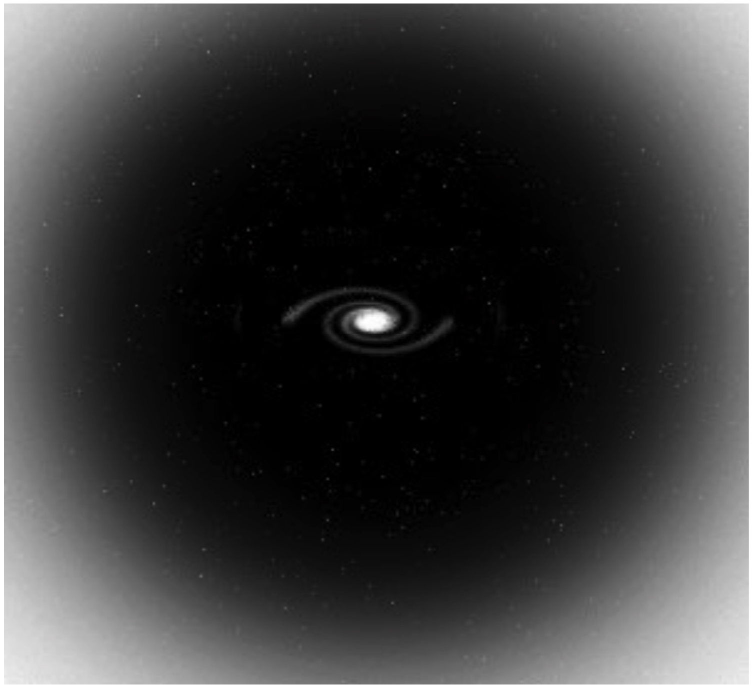
$$M = 1.6 \times 10^{11} M_\odot (r/30\ \text{kpc})$$

$$M_{\text{stars+gas}} = 0.4 \times 10^{11} M_\odot$$

$$\frac{M}{M_{\text{vis}}} > 4$$

Galaxies like ours have a Dark Halo containing about 85% the total mass

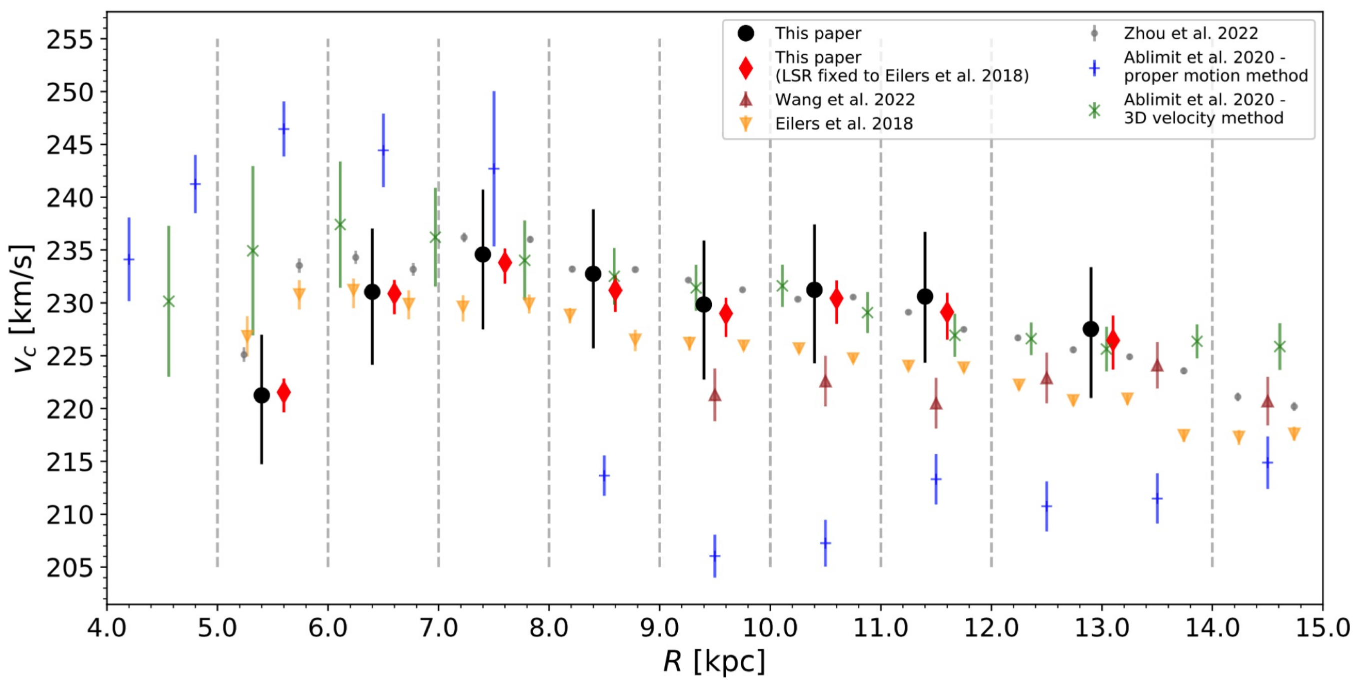
The “actual” Milky Way Artist rendition



Rotation Curve of the Milky Way Poder et al 2023

Using GaiaDR3 photometry data (ESA Gaia mission Dec 2023- March 2025- precise information of a billion stars) found $v_c(R_\odot) = 233 \pm 7$ km/s at the position of the Sun $R_\odot$= 8.277 kpc, and within 1kpc $V_{LSR} = 7 \pm 7$ km/s

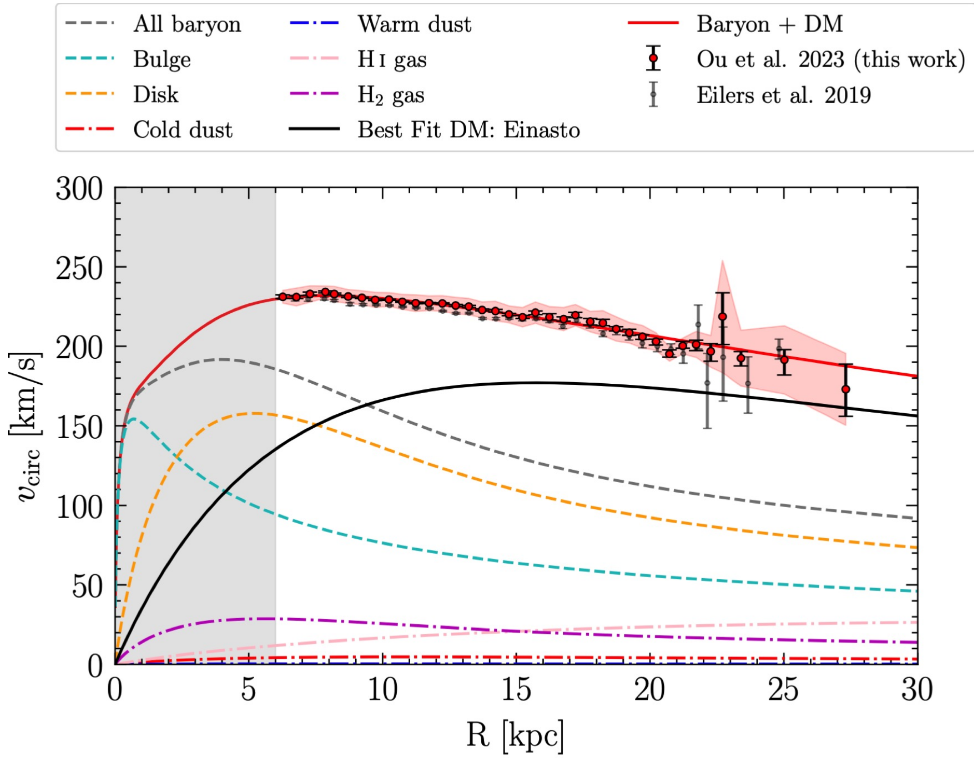
Põder, S., et al.: A&A 676, A134 (2023)

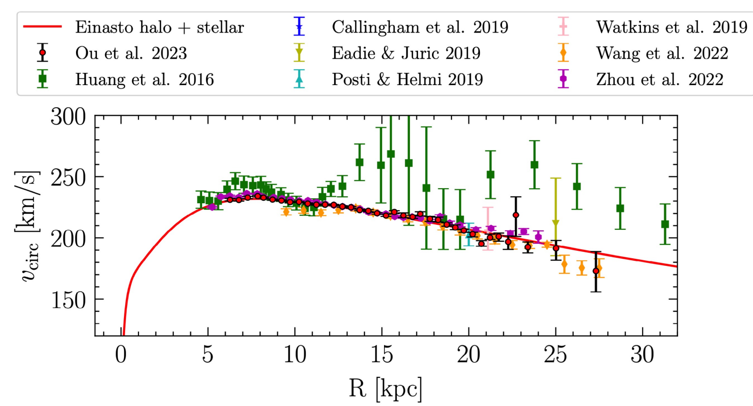


Rotation Curve of the Milky Way Ou, Eilers, Necib, Febrel 2303.1238

Out to 30 kpc- Precise parallaxes of 120,309 stars using APOGEE DR17 spectra with GaiaDR3, 2MASS, and WISE photometry data (in gray region not studied)

Position of the Sun: $R_\odot$= 8.277± 0.031 kpc GRAVITY coll 1807.09409, 1904.5721, 2004.07187, 2112.07478

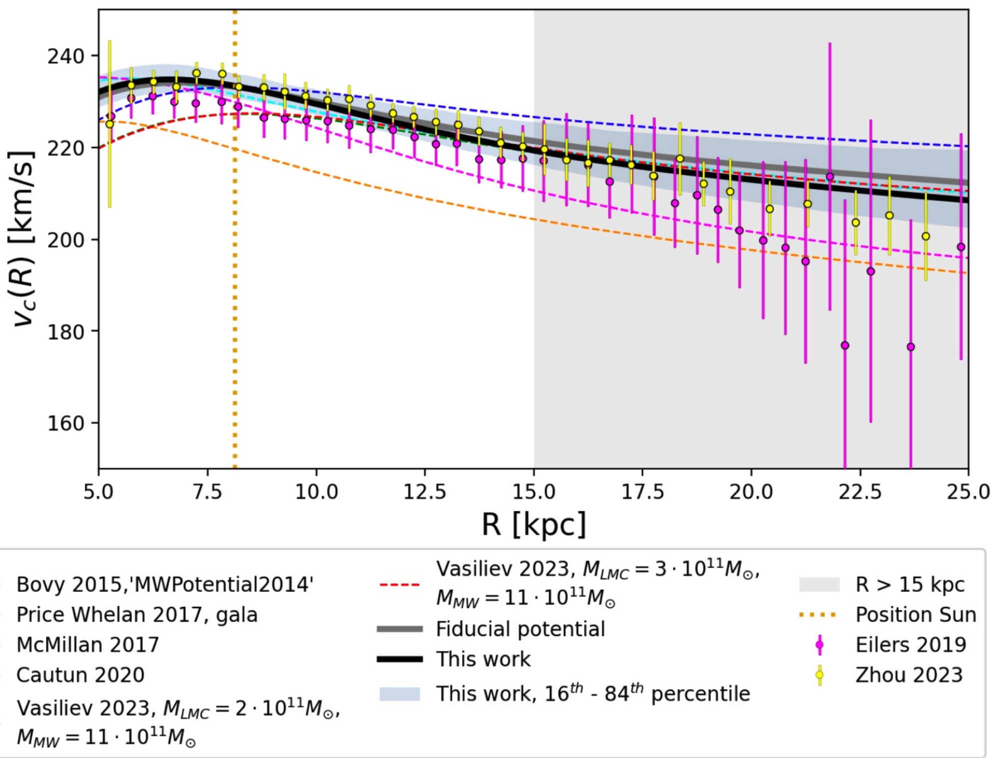




Rotation Curve of the Milky Way Woudenberg and Amina Helmi 2407.21790

Compilation using Gaia DR2 data, APOGEE, LAMOST, 2MASS and Gaia EarlyDR3

Position of the Sun taken here: $R_\odot = 8.122$ kpc



At the largest scales:

Use General Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \, (+\Lambda g_{\mu\nu})$$

To relate:

Spacetime geometry $\longleftrightarrow$ Mass-energy density

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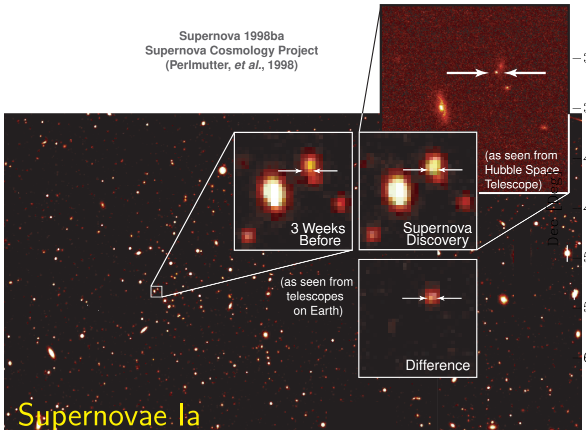
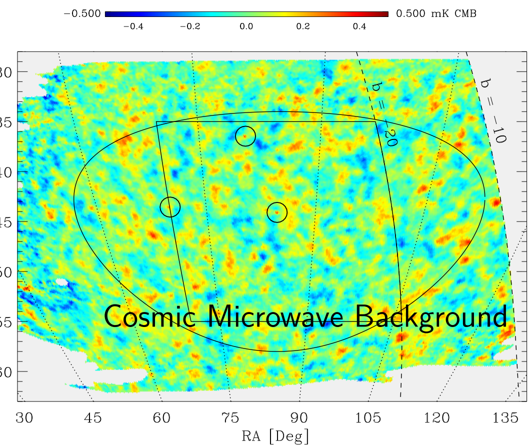
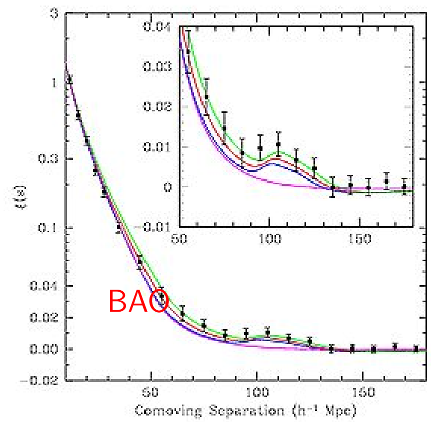
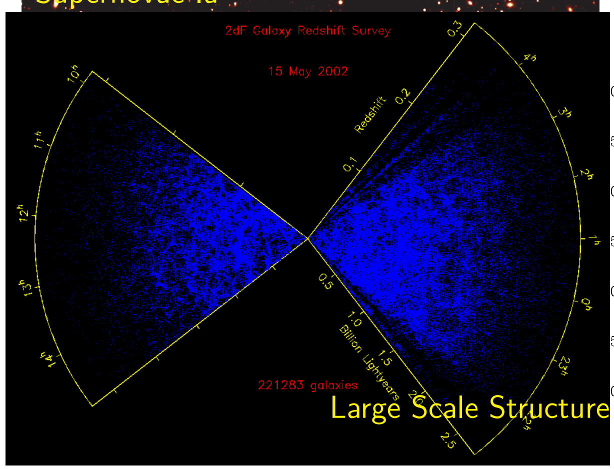
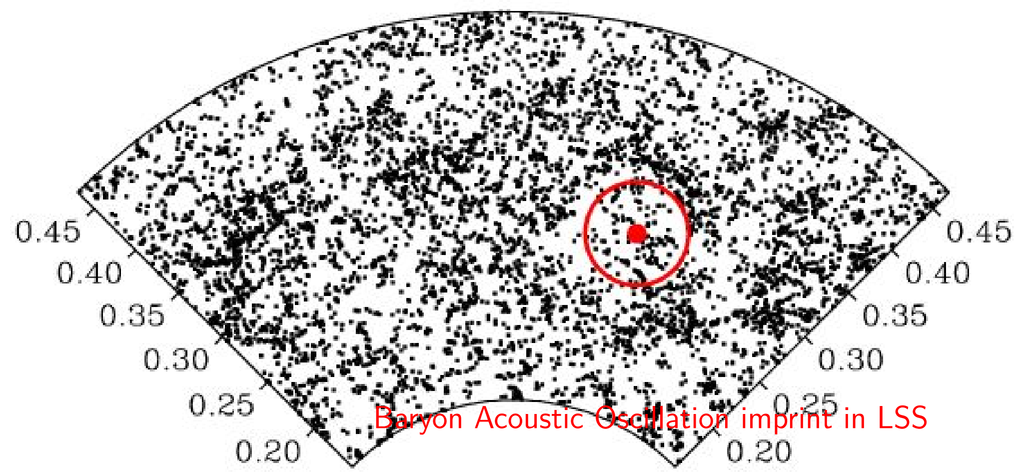
And it is data at the largest scales



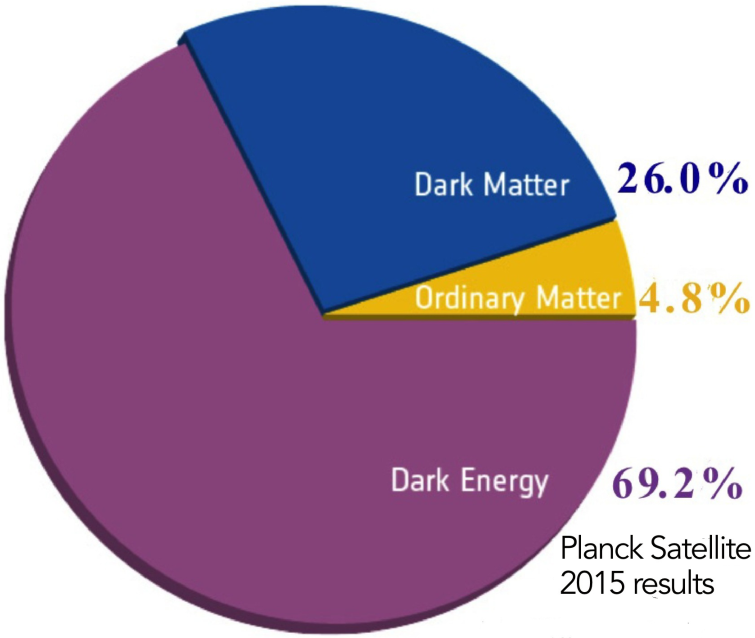


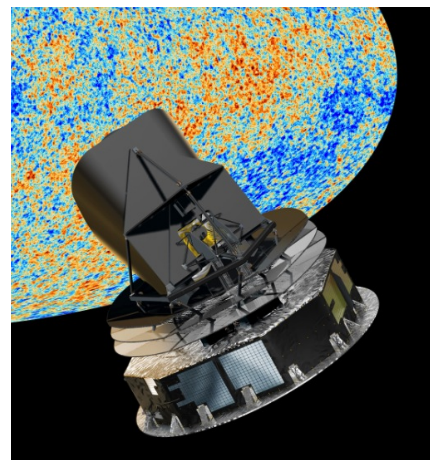






that allows us to define the “Double-Dark” model





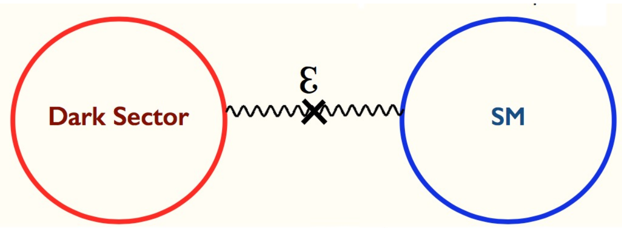
“DARK ENERGY” 69% (with repulsive gravitational interactions)
“MATTER” 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **“DARK MATTER” 26%**

DM problem since the 1930's

After 90 years, what we know about DM:

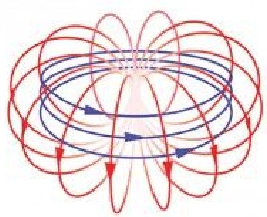
- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
  But idea always there, e.g. "Aether-Scalar-Tensor- AeST"? (Skordis, Zlosnik 2021)
- **3- DM is not observed to interact with light or other SM particles**
  but could have a very small electromagnetic coupling such as:
  — "electric or magnetic dipole DM", or "anapole DM"

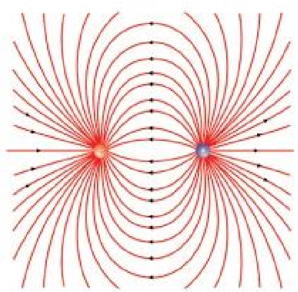
  —"Milli-Charged DM", interacting through a **Dark Photon** (DP) which has a small mixing ϵ with the photon, a "photon portal" (thus also couples to all charged particles with strength ϵQ) and could itself be the DM.

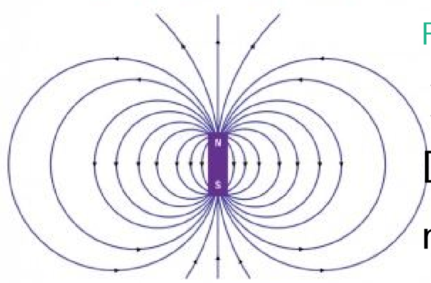


  — DM with small couplings, "portals", to other SM particles (neutrinos, the Higgs, weak gauge bosons)

Small electromagnetic couplings







Anapole moment DM (ADM) Ho-Scherrer 1211.0503

Proposed by Zel'dovich in Sov. Phys. JETP 6, 1184 (1958): breaks C and P, but preserves CP - 1st measured in 1997 (in Cesium-133 atoms) C. S. Wood et al, Science 275, 1759 (1997) P-odd, CP-even

$$\mathrm{L} \simeq \frac{g}{\Lambda^2}\bar{\psi}\gamma^{\mu}\gamma_5\psi\partial^{\nu}\mathrm{F}^{\mu\nu} \quad \rightarrow \quad \mathrm{H}_{\mathrm{Anapole}} \sim \vec{\sigma} \times \vec{\mathrm{B}}$$

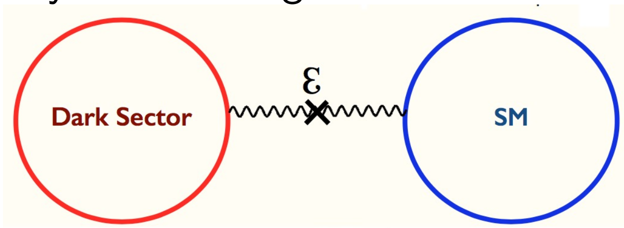
Magnetic (MDM), Electric (EDM) Dipole Moment DM Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012, many more...

$$\mathrm{L} \simeq \bar{\psi}\sigma_{\mu\nu}(d_{\mathrm{m}} + d_e\gamma_5)\psi\mathrm{F}^{\mu\nu} \rightarrow \mathrm{H}_{\mathrm{MDM}} \sim d_{\mathrm{m}}\vec{\sigma}.\vec{\mathrm{B}}, \;\; \mathrm{H}_{\mathrm{EDM}} \sim d_e\vec{\sigma}.\vec{\mathrm{E}}$$

Dipole moments are zero for Majorana fermions (although transition moments are not) and the first non-zero moment is the Anapole Moment

Can have a rich "Dark Sector" similar to visible sector, with hidden gauge interactions and flavor Foot 2004, Huh at al 2008, Pospelov, Ritz, Voloshin 2008, Arkani-Hamed et al.,2009, Kaplan et al 0909.0753 and 1105.2073. . .

"Millicharged DM" Unbroken $U_{dark}(1)$ hidden gauge symmetry that would give rise to bound states "kinetic coupling" $\epsilon F_{\mu\nu} F^{\mu\nu}_{dark}$



Diagonalized gauge boson kinetic terms: em photon $A_\mu (J^\mu_{em} + \epsilon g J^\mu_{dark})$ (g is $U_{dark}(1)$ coupling).

Holdom 1986, Burrage et al 0909.0649 Kaplan 0909.0753 1105.2073 Cline, Zuowei Liu, and Wei Xue 1201.4858

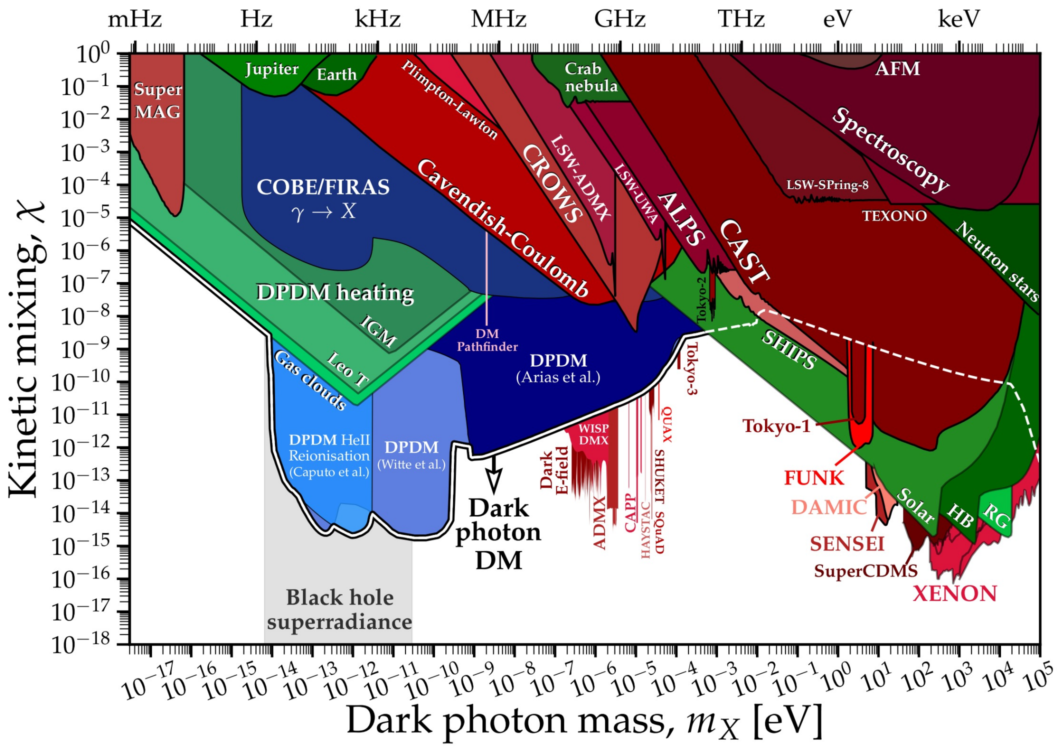
"Atomic DM" with dark analogues of p, e, H coupled to $U_{dark}(1)$ and Dark Atoms may scatter elastically or inelastically depending on the choice of parameters Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009. . .

"Dark" or "Hidden"-Photons (HP) themselves can be the DM- but "Light DM" or lighter

Pospelov, Ritz& Voloshin 0807.3279; Arias etal1201.5902

Limits on Hidden-Photons (HP) Compilation in Caputo et al 2105.04565

HP's can be very light CDM (LDM or lighter). χ is here the mixing ϵ in $\epsilon F_{\mu\nu} F^{\mu\nu}_{\rm dark}$ and m_χ is the HP mass.



After 90 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless** i.e. cannot cool by radiating as baryons do to form disks in the center of galaxies, or their extended dark halos would not exist.
  But $<$few% could be (radiating “dark photons” or other light dark particles) “Partially Interacting DM (PIDM)” and a special case of it “Double Disk DM” (DDDM)? Fan, Katz, Randall & Reece 1303.1521-1303.3271

  A Dark Disk was shown to arise in some CDM simulations (Read et al. 2008; Purcell et al. 2009; Ruchti et al. 2014) but with some dissipative DM it should be a pervasive feature of all disk galaxies- (and ”kill the dinosaurs”...?! Randall& Reece 1403.0576) GAIA data in solar neighborghood placed stringent upper limits (and are consistent with no-dark disk) (Windmark et al A&A 653, A86 (2021)) Schutz et al found DD $<$1% of DM 1711.03103

After 90 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless but ≤few% of it could be dissipative** (so dark sector)
- **5- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**
  $\sigma_{\rm self}/{\rm m} \leq 1$ cm^2/g = 2 barn/GeV = 2×10^{-24} cm^2/ GeV
  so DM could be strongly self-interacting but a Feebly Interacting Particle-FIP with the SM

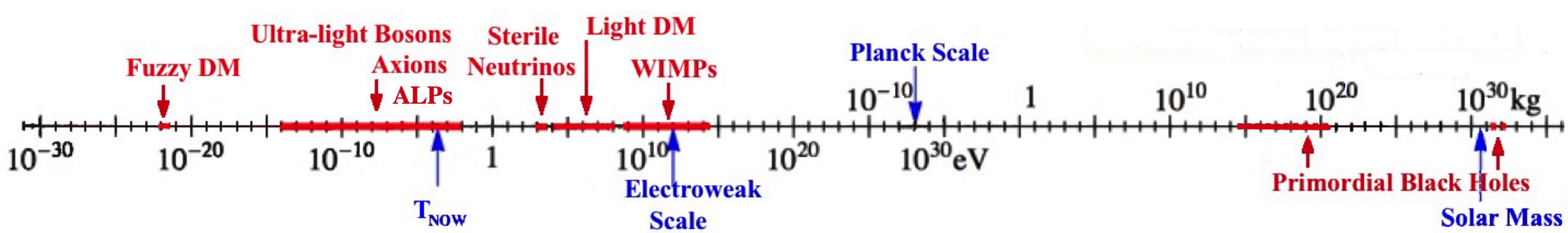
- **6- The mass of the major component of the DM has only been constrained within some 70 orders of magnitude.**

10^{-22}eV $= 10^{-31}$ GeV $\leq$ **mass** $\leq 10^{-10}M_{\odot} = 10^{41}GeV= 2 \times 10^{14}$kg

Higher end: Primordial Black Holes (PBH), in the "asteroid" mass range

Lower end: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000

(for DM particles which reached thermal equilibrium ,"Tremaine-Gunn" limit mass $\geq$ 0.2-0.7 keV - depending on boson-fermion and d.o.f. - based on maximum possible phase-space occupation number in galaxies, best from dSph's) (Tremaine-Gunn 1979; Madsen 1990, 1991, 2001; Boyarksky, Ruchayskiy and Iakubovskyi 2008; Alvey et al 2020...)

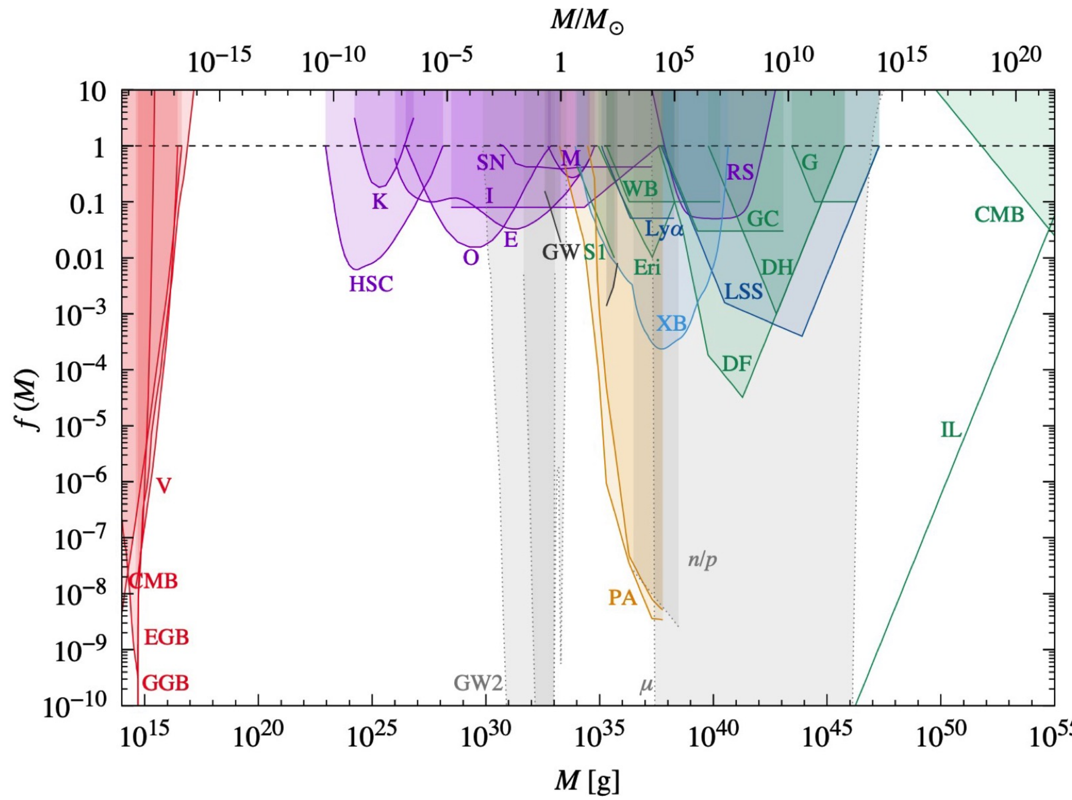


Higher end: **PBH as DM**

Compilation of bounds on the PHB/DM density fraction f for monochromatic mass function

(Carr and Kuhnel 2021, Green and Kavanagh 2020)

In the "asteroid mass" range 10^{-16} $M_\odot$ to 10^{-10} $M_\odot$ PBH could be all of the DM.



(Limits from PBH from evaporation, γ-rays- EGB: Extra Galactic Back., GGB: Galactic, V: e^+ from Voyager 1, Limits from fempto-, micro- and milli-gravitational lensing: HSC Subaru, K Kepler, M/E/O MACHO/EROS/OGLE, RS: radio sources, Limits from dynamics- WB: wide-binary disruption, Eri: star cluster survival in Eridanus II, GC: accretion in n stars there would destroy them, XR: accretion on X-ray binaries, G: galaxies tidal disruption LSS Poisson fluctuations PA: Planck CMB anisotropies Backgrounds- μ: CMB spectral distortions,GW2: 2nd order GW emission CMB: dipole, IL: incredulity limit= 1PBH / Hubble volume)

PBH as DM

PBH are hypothetical type of black hole not formed by the gravitational collapse of a large star but in the early Universe (Zel'dovich and Novikov, 1966; Hawking, 1971; Carr and Hawking, 1974) Many scenarios for PBH formation, include:

- density perturbations in the early Universe (see e.g. Carr 1975; Yokoyama 1997, Garcia -Bellido, Linde, Wands 1996; Ballesteros, Taoso 2018)

- bubble collisions Hawking, Moss, Stewart 1982, Lewicki and Vaskonen 2020

- the collapse of cosmic strings Hawking 1989

- scalar field dynamics Klopov, Malomed , Zeldovich 1985; Cotner, Kusenko 2017

- scalar long-range interactions Flores, Kusenko 2021

- collapse of domain walls Garriga, Vilenkin, Zhang 2015; Deng Garriga, Vilenkin 2016; Ferre et al 2019; Gelmini et al 2023

- collapse of vacuum bubbles in multi-field inflationary scenarios Deng, Vilenkin 2017; Kusenko et al 2020

Lower end:

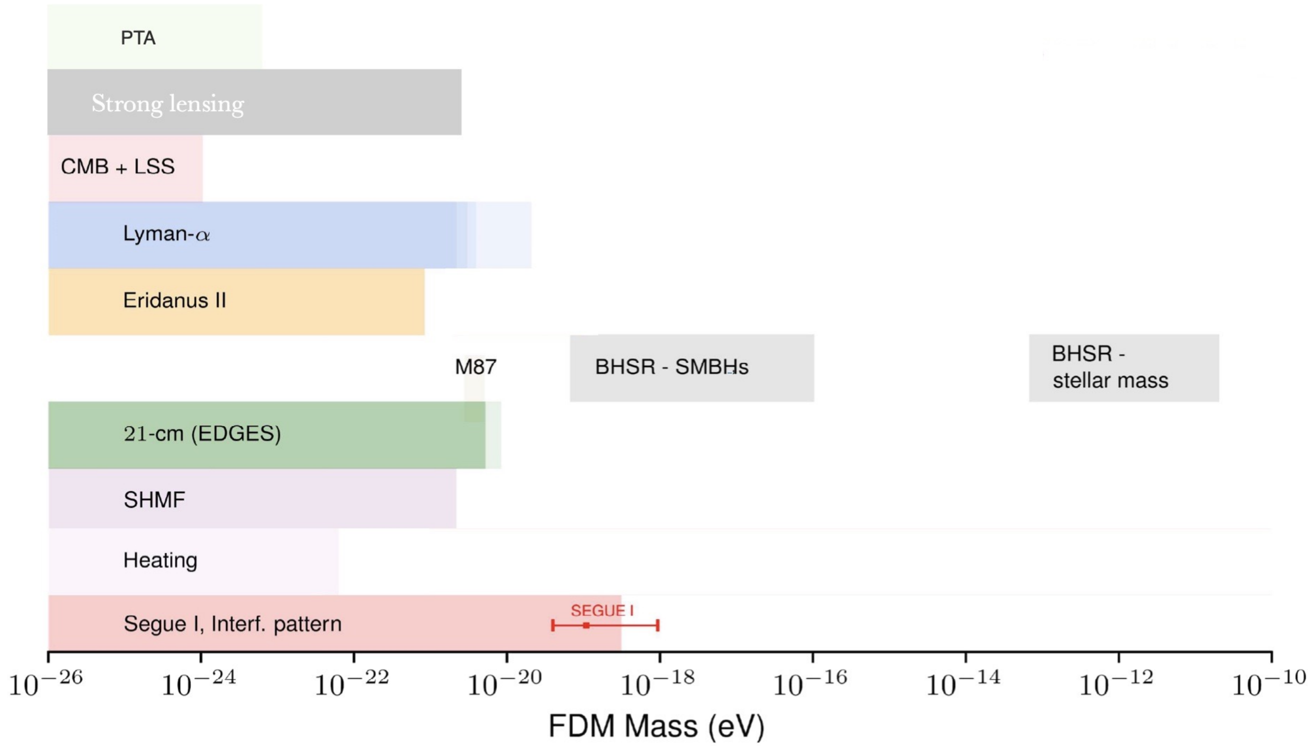
Ultra-Light Axions (ULA) or Scalar Field (SF) or Wave or Fuzzy DM

Light bosons (with $m_a \ll$ eV in our galaxy) have a very large number density so behave like a classical field or "wave-like DM" e.g. in our galaxy, $v \simeq 10^{-3}$, $\rho \simeq 0.4$ GeV/cm^3
for m=10^{-9}eV, $\lambda_{\rm deBroglie} = 2\pi/mv \simeq 10^3km(10^{-9}eV/m)$
Occupation number $N = (\rho/m)\lambda_{dB}^3 \simeq 10^{44}(10^{-9}eV/m)^4$
so $N \simeq 1$ for $m \simeq 30$eV. (Fluctuations $\sim \sqrt{N} \ll N$ negligible, so classical field.)
Instead WIMPs of $m = 10^2$ GeV, have $\lambda_{\rm dB} \simeq 10^{-16}$km, and $N = 10^{-36}$

"Fuzzy (i.e. fluffy or smeared-out) DM" $m_a \simeq 10^{-22}$ eV, $\lambda_{\rm deBroglie} \simeq$ galactic scales. At smaller scales pressure due to the uncertainty principle (quantum pressure) has several effect: forms interference patterns, balances gravity to form dense and stable soliton cores.

(First paper to consider Scalar Field DM to form galactic halos in 1983- same year when QCD axions were proposed as DM candidates: Baldeschi, Gelmini, Ruffini PLB 122 (1983) 221-224. Concluded the bosons mass should be 10^{-24} eV $< m <$10 eV)

Limits if ALL of the DM is Fuzzy DM: $m > 10^{-16}$eV (Elena Ferreira, UCLA DM 2025)

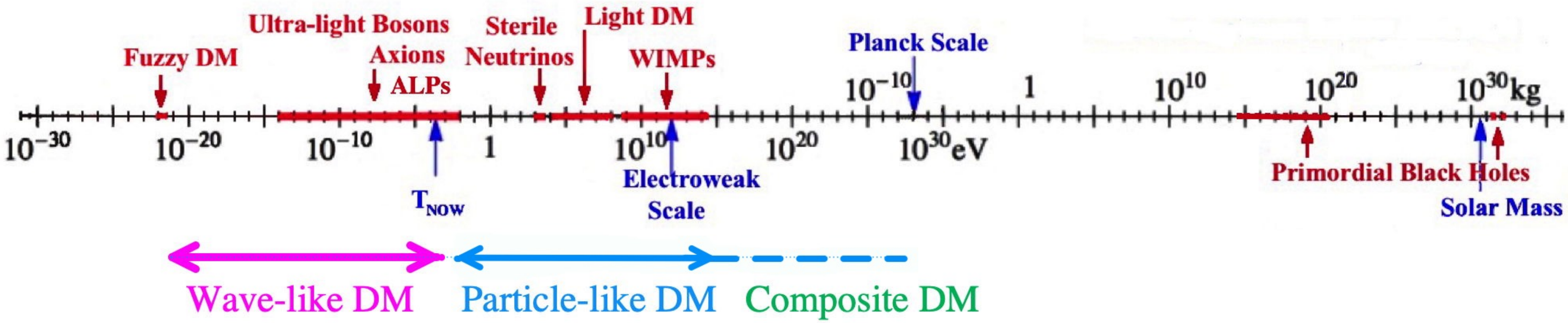


But there are still uncertainties: systematic effects, dynamics of FDM not fully understood.

And only recently, since 2020, mixed DM models FDM and CDM studied (e.g. Schwabe etal 2007.08256, Lague etal 2310.20000)

- **6- The mass of the major component of the DM has only been constrained within some 70 orders of magnitude.**

10^{-22}eV $= 10^{-31}$ GeV $\leq$ **mass** $\leq 10^{-10} M_{\odot} = 10^{41}GeV= 2 \times 10^{14}$kg



We will concentrate on Particle-like DM (Wave-like DM next week)

After 90 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but** $\leq$**few% of it could be dissipative.**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit**
- **6- Mass within some 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** i.e. either non-relativistic of becoming so when dwarf galaxy core size structures start to form, $T \simeq$ keV Distinguishing CDM-WDM-SIDM-mixedDM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

Dark Matter is “Cold” or “Warm”

Both work well at scales larger than dwarf galaxies.

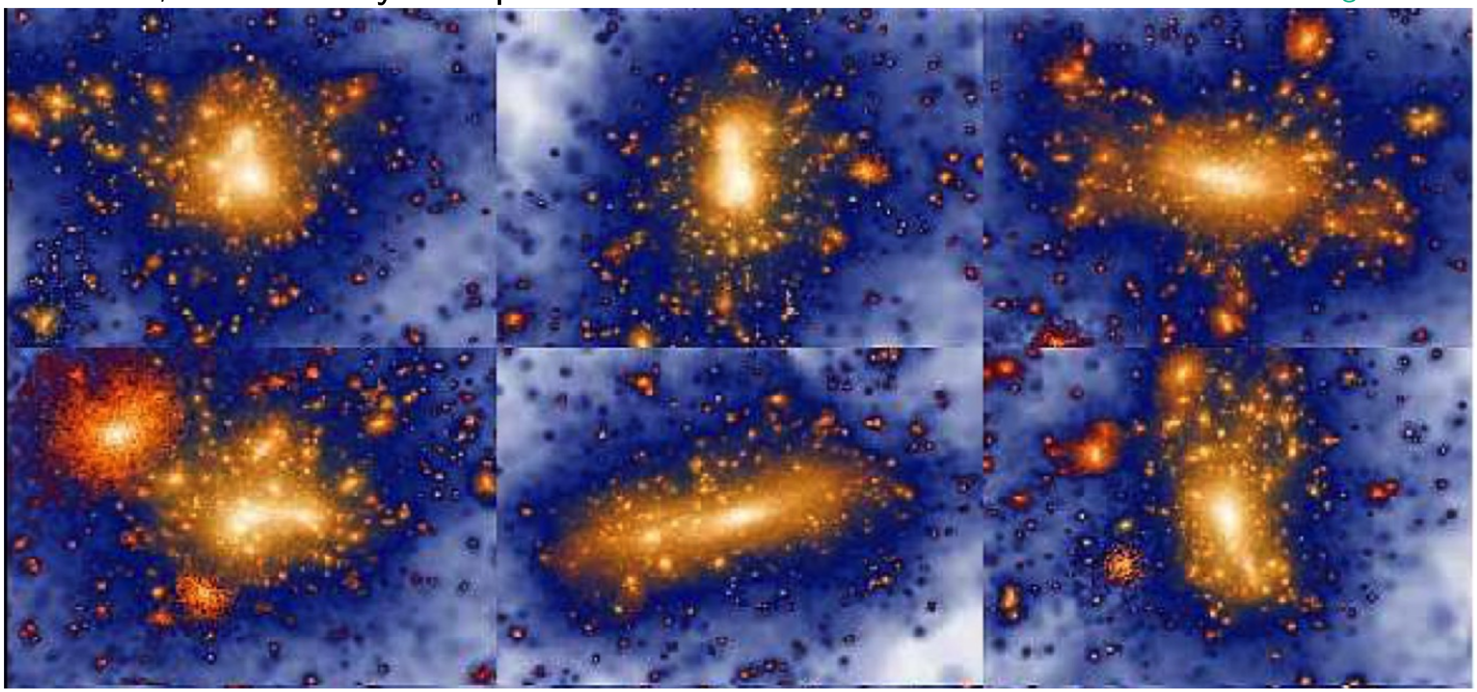
The differences are at smaller scales where observations and their interpretation are still not conclusive.

With WDM only structures of dwarf-galaxy cores size and larger survive.

With CDM structures much smaller than galaxy size survive.

With both galaxies form “bottom-up”, smaller structures merge with larger ones, some are disrupted, some may remain in the larger ones (many DM mini-haloes within galactic haloes).

Hierarchical Structure Formation Millenium-XXL DM only Simulations: many subhaloes, when tidally disrupted can leave DM substructure and streams Angulo et al 1203.3216



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- **7- The bulk of the DM is Cold or Warm** i.e. either non-relativistic of becoming so when dwarf galaxy core size structures start to form, $T \simeq$ keV
- **8**- No CDM or WDM in the SM: **particle DM requires BSM physics**

But which BSM?
The scope of DM models has changed since the 70's:

- 1980's: DM candidates were an afterthought, models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, "Little Higgs" models (electroweak hierarchy), Peccei-Quinn symmetry (strong CP problem), see-saw models (neutrino masses) - which also contain DM candidates: WIMPs, QCD axions, sterile neutrinos

- 1990's: DM candidates were mandatory in all BSM models

- Since 2000's: DM/ Dark Sector models independent of solving any SM problem
Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM- but have implications for accelerators e.g. search for light mediators, displaced vertices... Led to all types of DM and interactions, to "dark sectors" seen through **"portals"**, i.e. a small coupling to one type of SM particle (could be γ's and Z's, the Higgs boson, neutrinos), classified according to possible experimental signals....

Some members of the particle DM candidates zoo

- WIMPs "Weakly Interacting Massive Particles": have close to weak order interactions with the SM particles.

Models: Started with massive SM neutrinos in 1970's, then in 1980's to lightest particle carrying a conserved charge in most BSM UV complete models (SUSY, composite models,"Little Higgs" models, Inert Doublet models...): LSP (Lightest Supersymmetric Partner- R parity), Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3), LTP (Lightest T-odd heavy γ in Little Higgs with T-parity), LIP (Lightest Inert Particle)... in dark sectors too

Production: reach thermal equilibrium via 2 DM$\rightarrow$2 SM interactions and freeze-out, or in the decay of another WIMP (SuperWIMP scenario)

Mass: GeV to 100 TeV

- FIMPs, "Feebly Interacting Massive Particles" (or "Frozen In Massive Particles"): have interactions of order much weaker than weak, very small couplings Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442, ...

Models: moduli/modulinos of string theory compactifications with mass generated by the weak-scale SUSY breaking, right-handed sneutrino in Dirac neutrino models within weak scale SUSY (which requiere a coupling $\sim 10^{-13}$), GUT-scale-suppressed interactions, DM with small kinetic mixing coupling to the SM, DM though a Higgs portal...

Production: never reach thermal equilibrium, freeze-in as DM or freeze-in and decay to the DM

Mass: sub eV to 100's TeV (mass range of "Light DM", or WIMPs but very small couplings)

- SIMPs, "Strongly Interacting Massive Particles": Old 1990's SIMPs had strong interactions with the SM particles! Did not survive. Revived in 2014 as strongly SELF-interacting but very weakly coupled to the SM Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik *et al* 1411.3727; Choi & Lee 1505.00960; Lee&Seo 1504.00745; Bernal&Chu 1510.08527; Bernal, Garcia-Celt& Rosenfeld 1510.08063; Hochberg, Kuflik &Murayama 1512.07917.... Ho, Toma &Tsumura,1705.00592

Models: e.g. a pseudo-Nambu-Goldstone bosons of a strongly coupled confining hidden sector, with kinetic mixing with the SM (photon or Z' or Higgs portal)

Production: reach thermal equilibrium and freeze-out in the dark sector due to 3$\to$2 or 4$\to$2 DM to DM interactions- assumes kinetic equilibrium of dark and visible sectors to have the same temperature

-ELDERs,"ELastically DEcoupling Relic" type of SIMP with DM-SM elastic scattering. Kufflick, Perelstein, Lorier, Tsai 1512.04545

Mass: 100 keV - 10's MeV (they are "Light DM" LDM)

- PIMPs, "Planckian Interacting Massive Particles":
assume new physics comes only at the Planck scale M_P Garny, Sandora & Sloth 1511.03278

Models: effective couplings of DM in a hidden sector connected only with gravitational order interactions to the SM.

Production: soon after a very high T reheating inflationary period- many variations

Mass: most typical close to M_P

(Similar to GIMPs, "Gravitationally Interacting Massive Particles" in a particular Kaluza-Klein model Holthausen & Takahashi 0912.2262)

- Axions and ALPs ("Axion-Like Particles"):

The axion is the pseudo-Goldstone boson of a spontaneously broken axial U(1) global symmetry introduced by Peccei and Quinn in 1977, $U(1)_{\mathrm{PQ}}$ to solve the strong CP problem of QCD (Weinberg and Wilczek in 1978 realized the PQ model predicted an axion).

The original axion was soon rejected experimentally. So the "invisible axion" models were proposed (Kim- 1979, Shifman, Vainshtein, Zakharov (SVZ)-1980 and Dine, Fischler, Srednicki-1980 and Zhitnisky-1981 (DFSZ)

ALPs are other hypothetical pseudo-GB (among which Majorons and familons...)

Production: as a boson condensate or radiated from axion topological strings

Axion DM mass: 10^{-4} to 10^{-10} eV (for ALPs is very model dependent but light)

- WISPs, "Weakly Interacting Slim Particles (WISPs)": a combined name for axions/ALPs (spin zero) and dark (or hidden sector) photons (spin 1).

Still others:

"Dynamical DM (DDM)", dark sector with a vast number of particle species whose SM decay widths are balanced against their cosmological abundances- shorter lived has smaller densities Dienes &Thomas 2011,

"Mirror DM", from a hidden "dark" copy of the SM- could or not interact via kinetic mixing Blinnikov & Khlopov 1982, Kolb, Seckel &Turner 1985, Foot, Lew %Volkas 1991....

WIMPZILLAS, heavy particles created during reheating after inflation) Kolb, Chung & Riotto 1998,

Q-balls, non-topological solitons created as a fragmentation of a scalar condensate) Kusenko 1997, Kusenko &Shaposhnikov 1997,

Sterile neutrinos...

Direct DM searches:

Proposed byDrukier, Stodosky PRD30 (1984) 2295; Goodman-Witten PRD31 (1985) 3059

Looks for energy deposited within a detector through scattering or absorption of DM particles in the Dark Halo of the Milky Way ($v \simeq 10^{-3}$).

Detectors are sensitive to very different energies:

- Traditional experiments (since the 1980's onwards):

  - E $>$ keV's for scattering off nuclei, $\simeq E_K \simeq 10^{-6}$m reach m$>$GeV (now multi tonne)
  - E $\simeq$10^{-6}eV$\simeq$m for axion resonant absorption in cavities

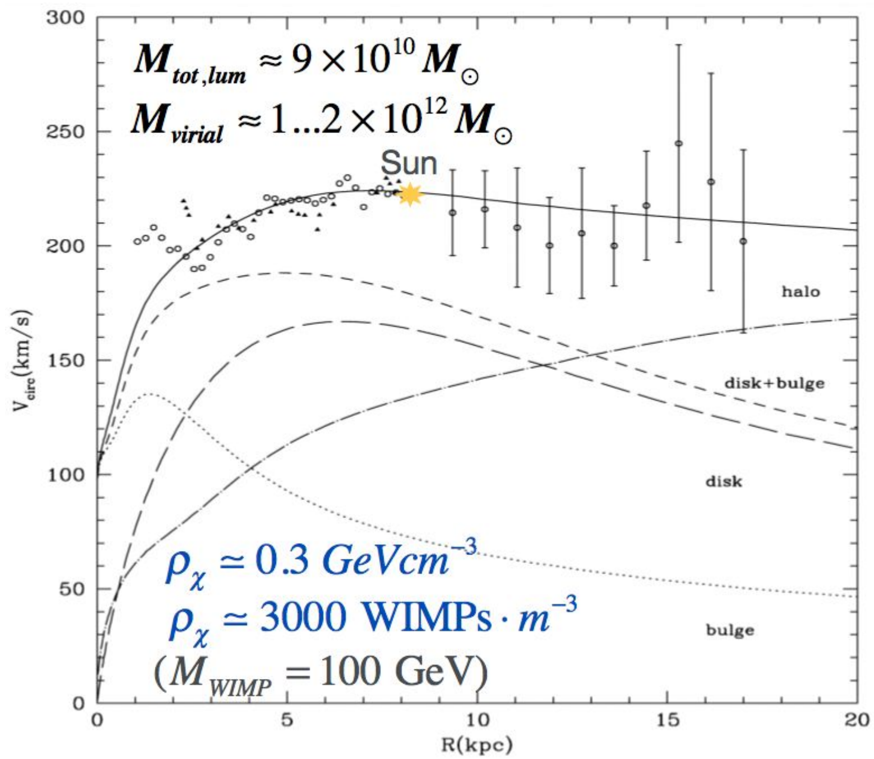
- Last 20 years driven by impressive developments in detectors, quantum sensors:

  - E$>$eV for scattering or absorption off electrons
  - E$>$meV for scattering or absorption off collective excitations
  - and even smaller...

allowing to reach Ultralight DM, where even small exposures can break new ground

Local Dark Halo
Fig. from L.Baudis; Klypin, Zhao and Somerville 2002

GAIA: $\rho_{\rm DM}$=0.32± 0.15 GeV/cm^3 Widmark et al 2021



$\simeq 10^7$(GeV/m_χ) DM particles passing through us per cm^2 per second!
a $v \simeq 10^{-3}c$ "DM wind" due to Sun's motion in the Galaxy

Local Dark Halo Measured $\rho_{\rm DM}$ by two different types of methods, global and local- table of 12 recent results Staudt, Bullock, Boylan-Kolchin, Kirkby, Wetzel, Ou 2403.04122

Global methods

	Model basis	Note	ρ / [GeV cm^{-3}]
Eilers+19 [14]	Fitting the circular speed curve		0.30 ± 0.03
deSales+19 [13]	Fitting the circular speed curve	B1	0.30 ± 0.03
		B2	0.38 ± 0.04
Nitschai+20 [15]	Anisotropic jeans modeling of disk stars		0.437 ± 0.076
Petac20 [16]	Galactic mass model with circular speed as one input	NFW	$0.357^{+0.020}_{-0.021}$
		Burkert	$0.381^{+0.020}_{-0.022}$
Benito+21 [17]	Fitting the circular speed curve		0.6 ± 0.1
Hattori+21 [18]	Galactic mass model from halo stars		0.342 ± 0.007
Ou+24 [19]	Fitting the circular speed curve		0.447 ± 0.004
Average			0.39 ± 0.10

Local methods

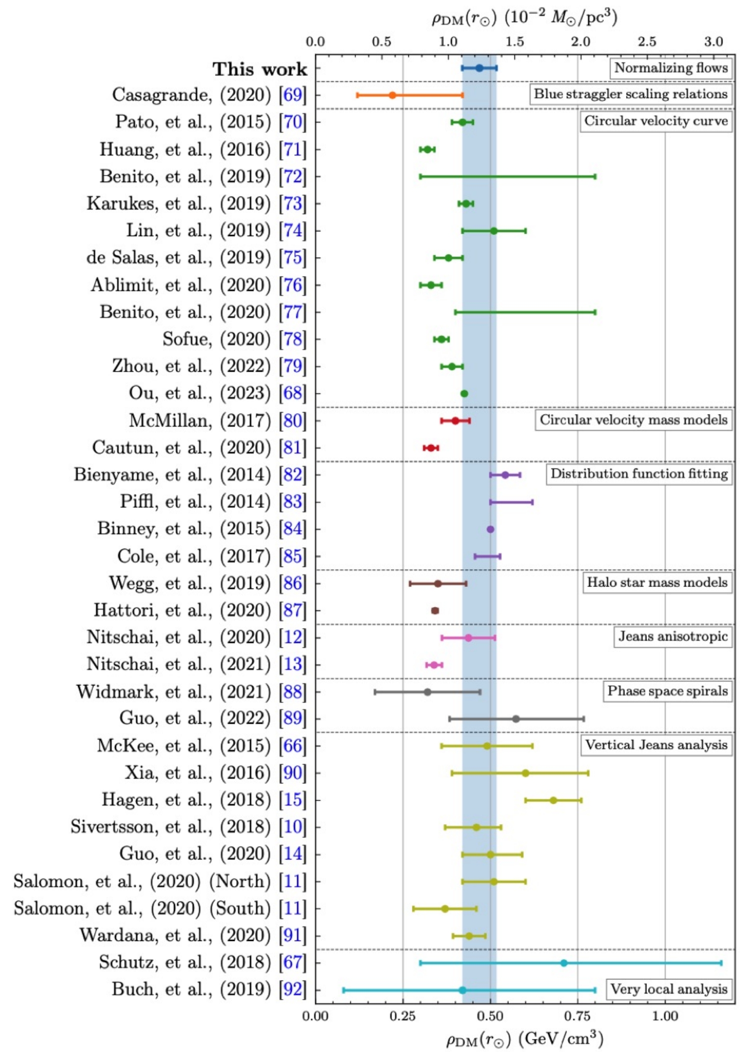
	Model basis	Note	ρ / [GeV cm^{-3}]
Sivertsson+18 [20]	Vertical kinematics		$0.46^{+0.07}_{-0.09}$
Buch+19 [21]	Very local kinematics	A stars	0.61 ± 0.38
		G stars	$0.42^{+0.38}_{-0.34}$
Guo+20 [22]	Vertical kinematics		$0.50^{+0.09}_{-0.08}$
Salomon+20 [23]	Vertical kinematics		0.37 ± 0.09
Widmark+21 [11]	Time-varying structure of the local phase-space spiral		0.32 ± 0.15
Average			0.47 ± 0.11
Average of all above			0.41 ± 0.10 GeV cm^{-3}
This paper			**0.42 ± 0.06 GeV cm^{-3}**

Local Dark Halo Blue band is

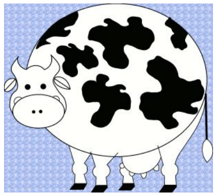
$$\rho_{\rm DM}{=}1.38{\pm}0.13{\times}10^{-2}\frac{\rm M_\odot}{pc^3}={0.47}{\pm}0.05\frac{\rm GeV}{\rm cm^3}$$

Lim, Putney, Buckley, Shih, 2305.13358- using GaiaDR3

(Useful 1 $\mathrm{M_\odot/pc^3}$= 38.47 $\mathrm{GeV/cm^3}$)



Graciela Gelmini-UCLA

Standard Halo Model (SHM) The  of halo models

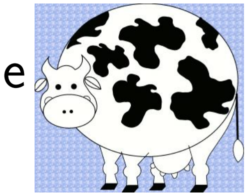
The Dark Halo is modeled as an Isothermal Sphere

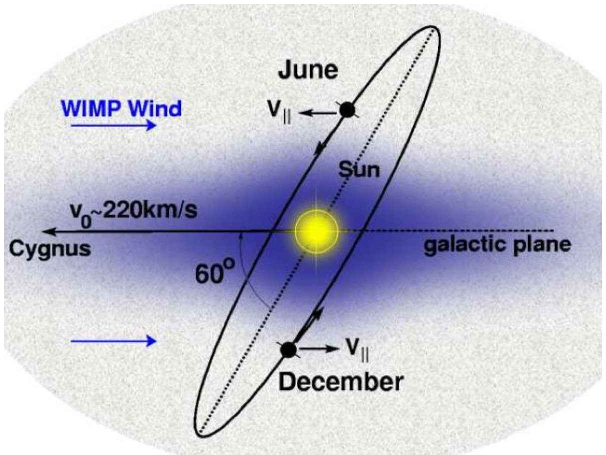
- Assumes hydrostatic equilibrium: pressure balances gravitational potential.

The rapidly changing gravitational potential of the forming Galaxy may have lead the DM particles to thermal equilibrium (Lynden-Bell's model of "Violent relaxation").

- Resulting density profile $\rho(r) \sim r^{-2}$.

- Produces flat rotation curves

Standard Halo Model (SHM) The  of halo models



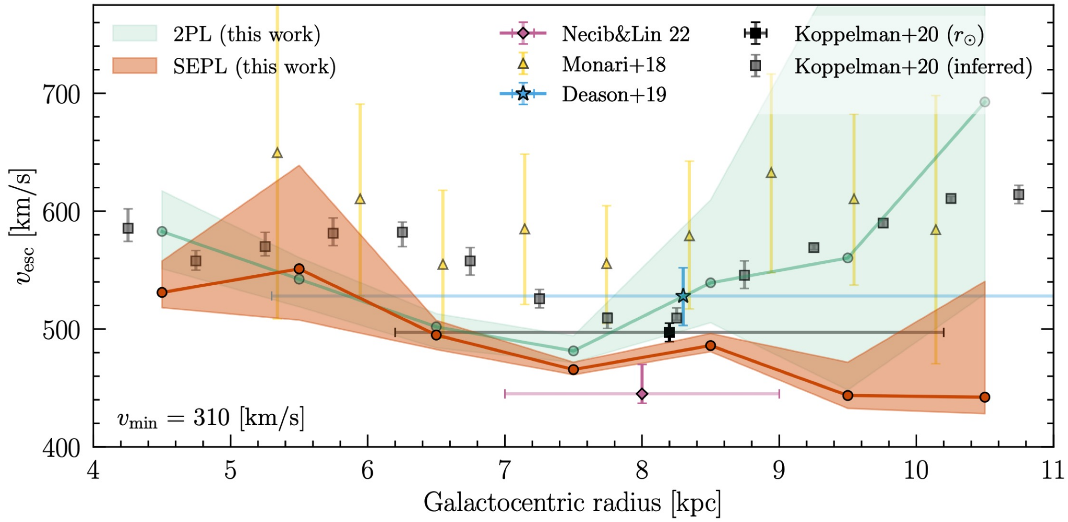
- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3 local Dark Matter density
- $f(\mathbf{v}, t)$: Maxwellian $\vec{v}$ distribution at rest with the Galaxy, so average DM velocity is $-\mathbf{v}_\odot$

$\mathbf{v}_\odot$=Sun's peculiar velocity+$\mathbf{v}_{\rm circ}$ of the Local Standard of Rest, $v_{\rm circ} \simeq$220-250 km/s,
and truncated at $v_{\rm esc} \simeq$500-650km/s

Expected annual modulation due to the max Galactic Earth velocity in early June, min. in Dec.

(Drukier, Freese, Spergel 1986)

Escape speed profile of the Milky Way GaiaDR3 data Roche, Necib, Lin, Ou, Ngyen 2402.00108



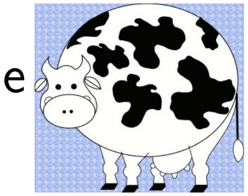
Local escape speed from the Galaxy Baxter et al. 2105.00599

Year	Reference	Survey	Data release	C.L.	$v_{\rm esc}$ interval	$v_{\rm esc}$ median
2007	[45]	RAVE	1 [68]	90 %	498 to 608 km/s	544 km/s
2014	[71]	RAVE	4 [72]	90 %	492 to 587 km/s	533 km/s
2017	[73]	SDSS	9 [74]	68 %	491 to 567 km/s	521 km/s
2018	[75]	*Gaia*	2 [50]	68 %	517 to 643 km/s	580 km/s
2019	[70]	*Gaia*	2 [50]	90 %	503 to 552 km/s	528 km/s
2019	[70]*	*Gaia*	2 [50]	90 %	548 to 612 km/s	580 km/s
2021	[76]	*Gaia*	2 [50]	68 %	477 to 502 km/s	485 km/s

Recommended conventions in 2021 by members of the DAMIC, DarkSide, DARWIN, DEAP, LZ, NEWS-G, PandaX, PICO, SBC, SENSEI, SuperCDMS, and XENON collaborations Baxter et al. 2105.00599

Tab. 1: Suggested Standard Halo Model parameters. Vectors are given as (v_r, v_ϕ, v_θ) with r pointing radially inward and ϕ in the direction of the Milky Way's rotation. Analyses insensitive to annular modulation can approximate $\vec{v}_\oplus(t)$ with Eq. 12.

Parameter	Description	Value	Reference
ρ_χ	Local dark matter density	$0.3\,\mathrm{GeV/c^2/cm^3}$	[9]
v_{esc}	Galactic escape speed	$544\,\mathrm{km/s}$	[45]
$\langle\lvert\vec{v}_\oplus\rvert\rangle$	Average galactocentric Earth speed	$29.8\,\mathrm{km/s}$	[41]
$\vec{v}_\circledast$	Solar peculiar velocity	$(11.1, 12.2, 7.3)\,\mathrm{km/s}$	[46]
$\vec{v}_0$	Local standard of rest velocity	$(0, 238, 0)\,\mathrm{km/s}$	[47, 48]

Standard Halo Model (SHM) The  of halo models

Maxwellian distribution truncated at the local Galactic escape speed $v_{\rm esc}$

$$f_{\rm h}(\vec{v},t) = \begin{cases} \dfrac{1}{N_{\rm h}(2\pi\sigma_{\rm h}^2)^{3/2}} e^{-|\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t)|^2/2\sigma_{\rm h}^2} & \text{if } |\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t)| < v_{\rm esc} = 544 \text{ km/s}, \\ 0 & \text{otherwise.} \end{cases}$$

The velocity of a WIMP relative to the Galaxy is $\vec{v}+\vec{v}_\oplus+\vec{v}_\odot$

$\vec{v}$: DM velocity relative to the Earth

$\vec{v}_\oplus(t)$: velocity of the Earth relative to the Sun (29.8 km/s tangent to orbit)

$\vec{v}_\odot = (0, v_{\rm circ}, 0) + (11.1, 12.2, 7.3)$km/s: Sun's velocity in the Galactic Rest Frame (in which halo DM is assumed to be stationary) $\simeq$ 250 km/s ($\lambda_\odot \simeq 340^\circ$, $\beta_\odot \simeq 60^\circ$ ecliptic coordinates);

$\sigma_{\rm h}$: DM velocity dispersion $= (v_{\rm circ}/\sqrt{2})$ km/s in isothermal model,

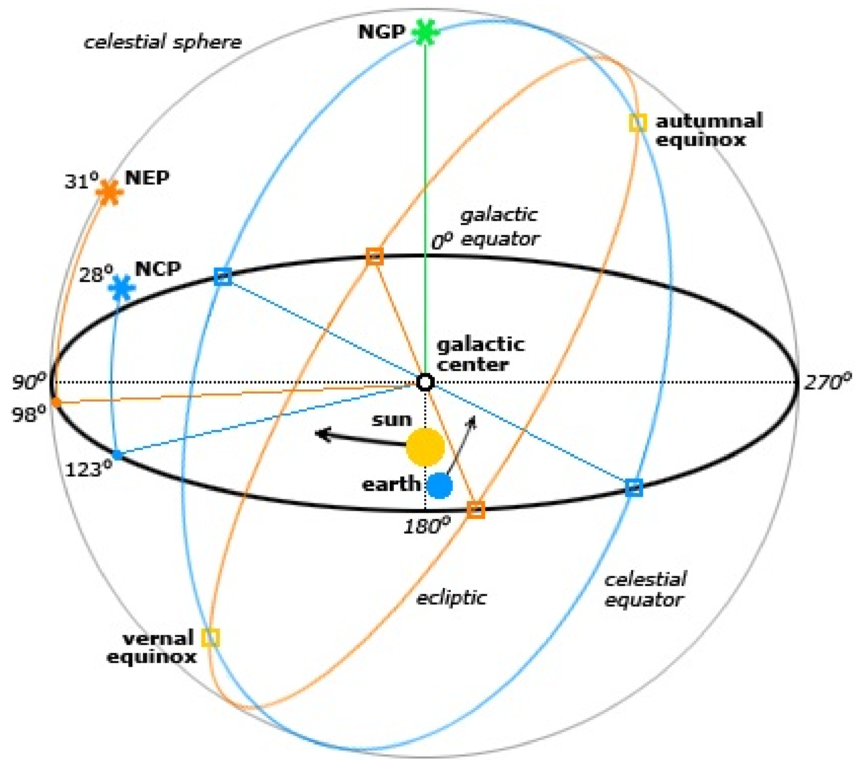
$N_{\rm h} = {\rm erf}(z/\sqrt{2}) - (2/\pi)^{1/2} z e^{-z^2/2}$, with z=$v_{\rm esc}/\sigma_{\rm h}$: normalization factor so integral is 1

With this model: maximum possible heliocentric DM velocity is $v_{\rm esc} + v_\odot = 794$ km/s.

Annual Modulation of the Rate

$|\vec{v}_\odot + \vec{v}_\oplus|$ is maximum at the beginning of June and minimum 6 months later.

$\vec{v}_\odot$ and $\vec{v}_\oplus$ are at 60^o, so $\simeq v_\oplus \cos 60^o$ sums or subtracts from $v_\odot$.



Will comment later on how good the SHM is. Let us adopt it and return to Direct Detection.