DM: an overview

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My presentation today

- Astrophysical evidence for DM:
  comments on old and new data
- LSS simulations:  DM is not hot
- CDM candidates: comments on old and new
- Search for WIMPs: indirect and direct detection
- Directional DM detection
- Alternatives to DM
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin)
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction
- Bullet cluster (Clowe+, 2006)
Wealth of evidence for DM is astrophysical!

More complex than presented usually!
Rotation curves: what is often said [incorrectly] to be expected.

Keplerian behaviour just outside the nucleus can NOT be expected.

A. Bosma (LAM)
Freeman 1970, appendix

For NGC 300 and M33, the 21-cm data give turnover points near the photometric outer edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different.

**M31 – Need for dark matter based on radio data**

![Graph showing rotation velocity versus radius for M31. Legend includes data from Babcock (1939), van de Hulst et al. (1958), Rubin & Ford (1970), and Roberts & Whitehurst (1975).]

A. Bosma
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin) Bosma (HI)
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction

- Bullet cluster (Clowe+, 2006)
Weak Lensing

Distorsion of galaxy shapes by foreground matter

without lensing

Lensing effect
Galactic forces rule dynamics Milky Way dwarf galaxies

Yang Yanbin Yunnan Sino French meeting Nov 2018

This correlation falsifies the hypothesis of neglecting the MW impact!
NGC1052-DF2: a Galaxy without DM?

Van Dokkum et al. 2018

→ Evidence for DM? (against modified gravity)
$\Lambda$CDM: Dominant theory of Structure formation and evolution

- Primordial Universe: Vacuum? Inflation?
- Tiny perturbations seed the later formation of structures
- Nearly scale-invariant Gaussian random field
  
  Bardeen, Bond, Kaiser, Szalay 1986
- Structures form by gravitational instability
- Biased galaxy formation from DM haloes
- **Matter dense regions** contract under gravity while

Many questions:

*Origins of DM? What DM?*
The Universe energy density content after Planck

Matter today ~ 32%
energy density of the Universe

85% of the matter is dark matter

% precision

Cf Planck march 2018 papers

For $\Lambda$ or DE, cf another seminar!

Wikipedia
Cosmic Web: Knots, Filaments, Sheets and Voids

From large scale structure surveys, eg, data in redshift

Voids = low density regions in space
Comparisons of LSS observations with pre-2000 N-body Simulations prefer CDM

$\Omega = 0.3$
$\Lambda = 0.7$
$H_0 = 70 \text{ km/(Mpc sec)}$
$\Sigma_8 = 0.9$

$\Omega = 0.3$
$\Lambda = 0$
$H_0 = 50 \text{ km/(Mpc sec)}$
$\Sigma_8 = 0.51$

$\Omega = 0.3$
$\Lambda = 0$
$H_0 = 70 \text{ km/(Mpc sec)}$
$\Sigma_8 = 0.85$

Collaboration VIRGO 1996
http://www.mpa-garching.mpg.de/~virgo/virgo/
<2000: Nature of DM
Hot or Cold?

CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

HDM is tightly bound by observations and LSS formation.
Nature of DM
Hot or Cold, or Warm?

CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

HDM is tightly bound by observations and LSS formation.

WDM
10 h/Mpc, keV
N-Body simulations: CDM

Preferred paradigm: CDM

Most N-Body simulations use stable CDM halos as seed for structures:

- structures evolve, merge and cluster

- Properties of CDM halos
  - cuspy density profiles,
  - Triaxial halos
  - central density depends on the mass of the halo.
Dark matter distribution—Density profiles

Universal Density Profile from N-body simulations

NFW
Navarro, Frenk, White 1996

\[
\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}
\]
~2000: Problems with CDM at small scales

Comparing data with N-body Simulations

- Galactic satellites
- cusp/core at GC
Galaxy profiles prefer core at center

CDM Simulations $\Rightarrow$ cusps
(Navarro, Frenk, White 1996):

$$\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Problems at smaller scales?

Observations favour core profile

rotation curves
Results from Trieste: analysis of high quality RCs

URC fits to RCs

PROOFS OF CORES

DDO 47


Too low number of visible Satellite galaxies

Satellite galaxies are seen in Milky Way, e.g. Sagittarius, MCs
Alternatives to CDM

- Self-Interacting Dark Matter (Spergel & Steinhardt 2000)
- Strongly Interacting Massive Particle
- Annihilating DM
- Decaying DM (eg. Zhang XM+)
- ...

- WDM: reduce the small scale power

Norma G. Sanchez, Hector J. de Vega+... Chalonge series
"Evidence" for WDM?

- "missing satellite problem",
- "cusp-core problem",
- “Too big to fail”

- mini-voids The sizes of mini-voids in the local universe: an argument in favor of a warm dark matter model? Tikhonov et al.

- HI determinations of velocity function profiles
  N-Body simulation  Comparisons with Virgo results by Arecibo Legacy (ALFALFA)
Solutions to **CDM** Problems at small scales?

- New measurements
- Better si resolution
- Additional physics in N-Body simulations (SN, AGN feedback, stellar winds...)
Einasto vs NFW

CDM Simulations ⇒ cusps rather Einasto profiles than NFW

Ma Chung Pei, Chang, P., Zhang, 2009

Figure 1. Radial profiles of the pseudo-phase-space density $\rho/\sigma^2(r)$ (upper panels) and the corresponding logarithmic slope $\frac{d\ln \rho/\sigma^2(r)}{d\ln r}$ (lower panels) obtained from the spherical Jeans equation with $\beta = 0$ for seven input halo density profiles: Einasto (solid) with $\alpha = 0.18$ (blue), 0.16 (green), and 0.12 (red), and NFW (dashed) with $\gamma = 1.5$ (blue), 1 (black), 0.75 (green), and 0.5 (red). The left panels show the behavior of $\rho/\sigma^2(r)$ over 12 orders of magnitude in $r$, while the right panels show zoom-in views of the region $0.01 \lesssim r/r_{200} \lesssim 10$, which corresponds to the range resolvable by the latest $N$-body simulations. For ease of comparison with a power-law, the light dotted straight lines indicate the critical case $\rho/\sigma^2 \propto r^{-1.9}$, and the $y$-axis in the upper right panel plots the logarithm of the ratio $\rho/\sigma^2(r)$ to $\rho/\sigma^2 \propto r^{-1.9}$. All curves are scaled to have $\rho/\sigma^2 = 1$ at $r = r_{200}$. 
More faint or dark galaxies discovered

Eg, Belokurov et al, 2010

TABLE 1
PROPERTIES OF PISCES II AND SEGUE 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pisces II</th>
<th>Segue 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec (J2000)</td>
<td>+05:57:09 ± 4</td>
<td>+19:07:02 ± 4</td>
</tr>
<tr>
<td>Galactic ℓ</td>
<td>79.21°</td>
<td>69.4°</td>
</tr>
<tr>
<td>Galactic b</td>
<td>-47.11°</td>
<td>-21.27°</td>
</tr>
<tr>
<td>r_h (Plummer)</td>
<td>1'1 ± 0'1</td>
<td>0'65 ± 0'1</td>
</tr>
<tr>
<td>θ</td>
<td>77° ± 12°</td>
<td>215° ± 20°</td>
</tr>
<tr>
<td>e</td>
<td>0.4 ± 0.1</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>(m-M)_0</td>
<td>21^m3</td>
<td>16^m1</td>
</tr>
<tr>
<td>M_{tot,V}</td>
<td>-5^m0</td>
<td>-1^m2</td>
</tr>
</tbody>
</table>

* Magnitudes are accurate to ∼ ±0^m5 and are corrected for the Galactic foreground reddening.

FIG. 4.— Color images covering 4' × 4' region centered on Segue 3 made with SDSS (left) and KPNO (right) data. SDSS image is made with g, r and i band frames. KPNO image is made with g and r band frames.
Missing satellites: **CDM** way out

- satellites do exist, but star formation suppressed (after reionization?)
- satellites orbit do not bring them to close interaction with disk, so they will not heat up the disk.
- Local Group dwarf velocity dispersion underestimated
- Galaxies may not follow dwarves

Halo substructures may be probed by
- **Lensing**
- local Milky Way structures
Nature of dark matter or astrophysics process?

REPORTS

Stellar Feedback in Dwarf Galaxy Formation
Sergey Mashchenko, James Wadsley, H. M. P. Couchman

Dwarf galaxies pose substantial challenges for cosmological models. In particular, current models predict a dark-matter density that is divergent at the center, which is in sharp contrast with observations that indicate a core of roughly constant density. Energy feedback, from supernova explosions and stellar winds, has been proposed as a major factor shaping the evolution of dwarf galaxies. We present detailed cosmological simulations with sufficient resolution both to model the relevant physical processes and to directly assess the impact of stellar feedback on observable properties of dwarf galaxies. We show that feedback drives large-scale, bulk motions of the interstellar gas, resulting in substantial gravitational potential fluctuations and a consequent reduction in the central matter density, bringing the theoretical predictions in agreement with observations.
N-Body simulations with baryons

Jing Yipeng (2005)

More recent comparisons of WDM and CDM simulations. Eg Gao+, Jing+, Guo Qi, Yepes+,
- Non-linear collapse of WDM structures

Caveat: Strong Reliance on N-body simulations might be misleading!
Some Issues

• Galaxy evolution alters DM halos and the matter power spectrum.

  Rudd, Zentner & Kravtsov, Effects of Baryons and Dissipation on the Matter Power Spectrum (2008);

  Pedrosa, Tissera, & Scannapieco, The joint evolution of baryons and dark matter halos, (2010);


• Most of the simulations (even today) are DM-only

  - DM halos extremely sensitive to the implementation of the galaxy physics in the codes.

  - DM halo morphologies and galaxy properties need resolutions: giant molecular cloud (GMC) sized regions.

But a lot of concern/work in the last years

(leading contributions from Chinese astrophysicists!)
What we know:

Comparisons of observations with N-body Simulations today prefer Non-Hot DM

Cold or Warm is a challenge for next years...
Missing satellite problem: solutions degenerated
Core/Cusp: seems not relevant to the nature of dark matter
Too big to fail problem: solutions also degenerated

Surroundings of high z galaxies hide important information of the nature of dark matter
Observations of a stringy appearance of high z galaxies will rule out CDM.

This star formation model is NOT included in any current galaxy formation models.

Many arguments against WDM should be revised. (Reionisation, Lya PS, satellites abundance …)
GAMA find “tendrils” in voids!

arxiv 1401.4064

Figure 1. A section of the G12 field with different galaxy populations shown in each panel. From left to right the populations shown are galaxies in filaments with the filament minimal spanning tree (blue and cyan respectively); galaxies in tendrils (green); galaxies in voids (red); and all three populations in their respective colours.

Thin filaments found!
WDM/CDM hydrodynamic simulations
star formation

Gao, Theuns, Springel 2014

NB: Box size: 1.5 Mpc/h
N-body simulations more recent

- The cold dark matter content of Galactic dwarf spheroidals: no cores, no failures, no problem: Fattahi, Navarro et al... 1607.06479

with APOSTLE LCDM hydro simulations with baryons

- The low abundance and insignificance of dark discs in simulated Milky Way galaxies: Schaller, Frenk et al... 1605.02770 only 1/24 has significant dark disk!

No simulation can replace measurements!
Warm or Cold DM?

- More work is necessary!
  
  Need more Baryons simulations  
  And more and better data  

CDM is not dead!
Future Measurements of DM properties with lensing

From 100 sq deg scale at CFHT to 5000 - 20000 sq deg sky surveys

KIDS  HSC

LSST  Euclid Consortium

CSS-OS

MS-DESI can provide 3D
Cosmic shear power spectra

Markovic et al. 2010 Euclid-like DE space survey + Planck:
Integral effects $\rightarrow$ better than matter power spectrum

Sensitive to $m_{WDM} < 2.5$ keV

Excluded by Ly $\alpha$?
Chinese Space Station - Optical Survey
Survey Specs

- **17500° imaging**: 255-1000nm, ≥6 filters, avg ≥25.5m (5σ, point source, AB mag);
- **17500° slitless spect**: 255-1000nm, R≥200, ≥20-21m/res;
- **400° deep imaging & spect**: at least 1m deeper.

Science

- **Cosmology**: dark energy, dark matter, gravity, large-scale structure, neutrinos, primordial non-Gaussianity...
- **AGNs**: high-z AGNs, clustering, dual AGNs, variability, UV excess, host galaxies...
- **Galaxies**: formation & evolution, mergers, high-zs, dwarfs, LSBs, near field, halos properties...
- **Milky Way**: structure, satellites, dust, extinction...
- **Stellar science**: formation, dwarfs, metal poor...
- **Solar system (high inclination)**: TNO, NEA...
- **Astrometry**: reference frame, star clusters...

Ecliptic Coord.
Deep fields will be finalized later; sim results for demo only.
## Comparison with Other Surveys

<table>
<thead>
<tr>
<th>Project</th>
<th>Site/orbit</th>
<th>Launch/Op</th>
<th>FoV</th>
<th>$R_{EE80}$</th>
<th>Num pixels</th>
<th>Area</th>
<th>Wavelength</th>
<th>Num Filters</th>
<th>Spect</th>
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<tbody>
<tr>
<td>CSS-OS</td>
<td>LEO</td>
<td>~2024</td>
<td>1.1</td>
<td>0.15</td>
<td>2.5</td>
<td>17500</td>
<td>255—1000</td>
<td>≥6</td>
<td>yes</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.074/pix</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Euclid</td>
<td>L2</td>
<td>2022</td>
<td>0.56</td>
<td>&gt;0.2</td>
<td>0.6</td>
<td>15000</td>
<td>550—920</td>
<td>1</td>
<td>no</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.55</td>
<td>pix lmt</td>
<td>0.07</td>
<td></td>
<td>1000—2000</td>
<td>3</td>
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<tr>
<td>WFIRST</td>
<td>L2</td>
<td>&gt;2025</td>
<td>0.28</td>
<td>&gt;0.2</td>
<td>0.3</td>
<td>~2000</td>
<td>927—2000</td>
<td>4</td>
<td>yes</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>LSST</td>
<td>Chile</td>
<td>2022</td>
<td>9.6</td>
<td>~0.5</td>
<td>3.2</td>
<td>18000</td>
<td>320—1050</td>
<td>6</td>
<td>no</td>
</tr>
</tbody>
</table>

$R_{EE80}$: radius encircling 80% energy

### Comparison of FWHM

<table>
<thead>
<tr>
<th></th>
<th>CSS-OS</th>
<th>HST/ACS WFC</th>
<th>Euclid</th>
<th>WFIRST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{EE50}$</td>
<td>0.1&quot;</td>
<td>0.06&quot;</td>
<td>0.13&quot;</td>
<td>0.12&quot;</td>
</tr>
<tr>
<td>$R_{EE80}$</td>
<td>0.15&quot;</td>
<td>0.12&quot;</td>
<td>~0.23&quot;</td>
<td>~0.24&quot;</td>
</tr>
</tbody>
</table>

Dynamic sims: $R_{EE80} \approx 0.13"$
Filters & Limiting Mags

<table>
<thead>
<tr>
<th>Exp.</th>
<th>NUV</th>
<th>u</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>17500°</td>
<td>2×150s</td>
<td>25.4</td>
<td>25.4</td>
<td>26.3</td>
<td>26.0</td>
<td>25.9</td>
<td>25.2</td>
</tr>
<tr>
<td>400°</td>
<td>8×250s</td>
<td>26.7</td>
<td>26.7</td>
<td>27.5</td>
<td>27.2</td>
<td>27.0</td>
<td>26.4</td>
</tr>
</tbody>
</table>

CSS-OS will improve those Euclid plots: with better photo-z and precision.
White book with Euclid people, in preparation

- Tomographic WL shear cross-power spectrum for 0.5 < z < 1.0 and 1.0 < z < 1.5 bins.
- Percentage difference [expected – measured] power spectrum: recovered to 1%.
- \( V_{\text{eff}} \approx 19 \, h^{-3} \, \text{Gpc}^3 \approx 75x \) larger than SDSS
- Redshifts 0 < z < 2
- Percentage difference [expected – measured] power spectrum: recovered to 1%.

Ref: Euclid RB arXiv:1110.3193
Baryon physics (e.g., AGN feedback) affects Matter Power Spectrum

Semboloni+ (2011)
Van Daalen+(2011)
Shale + : OWLS simulation

⇒ Consequences on WL cosmological parameters fits

Figure 1. Ratio between the power spectrum of matter fluctuations measured from the simulations with baryons and the one measured from the DMONLY simulation. The ratio for the REF simulation is shown in green, the one for the AGN simulation is shown in blue, and the one for the DBLIMFV1618 model is shown in pink. Since the simulations have been carried out using the same initial conditions, deviations of the ratio from unity are due to the differences in baryon physics.
keV WDM effect around $k=10 \, h/\text{Mpc}$
Baryon effects
different from low mass standard model
neutrino effects

Semboloni et al. 2011

Figure 14. Ratio of the AGN/DMONLY power spectra (blue line), and dark matter power spectra with $f_\nu \equiv \Omega_\nu/\Omega_m = 0.01$ and 0.05, which correspond to neutrino masses of $\sum m_\nu \sim 6.0$ and $\sum m_\nu \sim 1.2$ eV, respectively. The effect of massive neutrinos on the power spectrum is quite different from that of baryon physics, even if neutrinos are light.
What do we know about the nature of DM?

Particle: stable?
mass?
interaction cross-sections?
charge?
spin?

Constraints from non-observation in direct/indirect/LHC searches
AND
Observations in Astrophysics / Cosmology
Very different DM candidates

1. Neutrino
2. WIMPs
3. Light axions

Modified Gravity

Cold Molecular Hydrogen

SIMPs

Black holes

MACHOs

Exotica

10-1000GeV

Weakly interacting massive particles
Theories of Dark Matter

Snowmass 2013
Fashionable DM particle candidates: ultralight DM, eg, fuzzy DM

Old idea

Revival 2015-2016

- If the dark matter is composed of FDM, most observations favor a particle mass $> 10^{-22}$ eV and the most significant observational consequences occur if the mass is in the range $(1-10) \times 10^{-22}$ eV.
A case for FDM: Hui et al. 2016

- Small haloes do not form in FDM
- FDM halos central core
- FDM delays galaxy formation but its galaxy-formation history
  Still consistent with current observations

If FDM, most observations favor a particle mass in the range

\((1-10) \times 10^{-22} \text{ eV}\)

- There is tension with observations of the Lyman \(\alpha\) forest
- More sophisticated models of reionization may resolve
  this tension.
First constraints on fuzzy dark matter from Lyman-forest data and hydrodynamical simulations

Irsic, Viel, Haehnelt, Bolton, and Becker. 1703.04683
XQ-100 and HIRES/MIKE quasar spectra lower combined limits 20 to 37.5 $10^{-22}$ eV (2σ C.L.).

Light boson masses in the range (1-10) $10^{-22}$ eV are ruled out at high significance by our analysis, casting strong doubts that FDM helps solve the "small scale crisis" of the cold dark matter models.

Reionization could save FDM’
"WIMP" = "Weakly Interacting" Massive Particles

Arguments in the 1980’s:

- Need for Cold Dark Matter from Large Scale Structures
- Very good Particle physics candidate: SUSY LSP
- Weak neutrino size cross sections expected which our detectors Ge, NaI were sensitive to…
(String ) Requiem for WIMPS?

Acharya, SE, Gane, Nelson, Perry, 1604.05320, 1707.04530

Typical properties of known solutions of string/M-theory,
\[ \Rightarrow \text{LSP not stable}. \]

Most important argument: SUSY not seen yet!
Particle physics preferred DM: SUSY Neutralinos?

- A natural particle physics solution
- Stable linear combination gauginos and higgsinos (LSP)
- SUSY > 7 parameters MSSM $\rightarrow$ no predictive power
- Experimental Constraints LEP, pp, b$\rightarrow$s$\gamma$, + LHC ...

Look everywhere possible!
Direct and Indirect Detections
DID YOU DROP IT HERE?

NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!

THEN WHY ARE YOU LOOKING FOR IT HERE?

BECAUSE THE LIGHT IS BETTER HERE!

I'M LOOKING FOR MY DARK MATTER!
WIMP searches

Direct detection

Ge, Si, NaI, LXe, …

Accelerator particle production, eg, LHC

Indirect detection

ν, γ, p, e^+

+ Galactic, cluster, Universe scales…
WIMPs Indirect Detection

$\chi$ 

$\nu, \gamma, p, e^+$
Indirect Detection: Principle

Sun, Earth, Galactic center, clumps?

Accumulation + Annihilation

Possible final states: $\tau^+\tau^-$, lepton pairs, qq, WH, ZH, WW, ZZ; Hadronisation and decay

Astroparticle detectors: positrons, antiprotons, antideutons, gammas, neutrinos

Astrophysical origin of observed signals, e.g., AMS, are hard to exclude

Need discovery at accelerators!

Still hope at LHC?
Indirect Detection $e^{-}$ & $e^{+}$

eg, DAMPE, Nature Nov 29, 2017
Indirect Detection $e^-$ & $e^+$

DM or pulsar?  (Yuan et al., 1711.10989)

Log scale
WIMP searches: Direct detection

• Principle: (Goodman and Witten, 1985, Drukier and Stodolsky 1984)

Elastic scattering of galactic DM off detector nuclei

Nuclear recoils of a few keV

Ge, Si, NaI, LXe, …
WIMP searches: Direct detection

- Principle: (Goodman and Witten, 1985, Drukier and Stodolsky 1984)

Elastic scattering of galactic DM off detector nuclei

Nuclear recoils of a few keV

- Exponential recoil energy distribution

\[
\frac{dR}{dE} = \frac{R_o}{E_{or}} e^{-E_R/E_{or}}
\]

event rate per unit mass

total event rate (point like nucleus)

recoil energy

incident energy

kinematic factor

\[
= 4M_\chi M_N/(M_\chi + M_N)^2
\]

- Rates: Weak interactions or smaller

Ge, Si, NaI, LXe, …
Differential rate for WIMP elastic scattering

\[ \frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{v_{\text{min}}}^{v_{\text{max}}} dv f(v) v \frac{d\sigma}{dE_R} \]

\[ v_{\text{min}} = \sqrt{\frac{m_N E_{\text{th}}}{2 m_r^2}}, \quad v_{\text{max}} = v_{\text{esc}} \]

\[ f(v) dv = 4\pi \left( \frac{3}{2\pi \bar{v}^2} \right)^{3/2} v^2 \exp \left( -\frac{3v^2}{2\bar{v}^2} \right) dv, \bar{v} \approx 270 \text{ km/s} \]

\[ E_R = \frac{m_r^2 v^2 (1 - \cos \vartheta)}{m_N} \]

\[ \frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{\text{max}}} F^2(E_R), \quad \sigma_0 = \frac{1 + m_W / m_p}{1 + m_W / m_N} A^2 \sigma_{\text{scalar}} ^{nucleon} \]
Direct detection: Interaction rates

Depend on several parameters

- **Astrophysical hypothesis:** model of DM in Galaxy (SMMG)
  \[ \rho_{\text{DM}}, f(v) \]

- **Nuclear form factors** \( F^2 \) important for heavy nuclei

- **Detector response** Quenching factors, resolutions, thresholds,....

- **Particle physics** Nature of WIMP and cross-sections

\[ \sigma_\chi \]

- **Coherent**
  - Spin Independent (SI)
  - eg, Dirac \( \nu \)

- **Axial**
  - Spin Dependent (SD)
  - eg, Majorana \( \nu \)

Neutralinos are a linear combination of higgsinos and gauginos

with cross-sections \(< 0.1 \sigma_\nu\)
Usual assumptions of DM distribution in our Galaxy

Usual assumptions:

$\rho_{DM} = 0.3 \text{ GeV/cm}^3$, $\beta = 10^{-3}$,
Maxwellian distribution of velocities, $v_{rms} = 270 \text{ km/s}$

« Simplified Model » of Matter in our Galaxy: SMMG

Used for most comparisons…

But is it the reality? Clumps? Corotation?
Galactic scale N-body simulations with Baryons

Ling+ 2009 Dark Matter Direct Detection Signals inferred from a Cosmological N-body Simulation with Baryons

➔ 2 DM populations: halo DM + disk DM
➔ only measurements can tell

Figure 5: Velocity distributions of dark matter particles ($N_{\text{ring}} = 2,662$) in a ring $7 < R < 9$ kpc, $|z| < 1$ kpc around the galactic plane.
a) Radial velocity $v_r$, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
b) Tangential velocity $v_t$, with a double Gaussian fit. $f$ indicates the fraction of each component.
c) Velocity across the galactic plane $v_z$, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
d) Velocity module, with Maxwellian (red) and a generalized Maxwellian (green) fit (cfr. Eq. (2.2)). $\mu$, $\sigma$ (both in km/s) and $K$ stand for the mean, the standard deviation and the Kurtosis parameter of the distribution. The goodness of fit is indicated by the value of the $\chi^2$ vs. the number of degrees of freedom (dof).
Some numbers ... 

A galaxy like the Milky Way or Andromeda has a total visible mass of about $6 \times 10^{10}$ $M_{\odot}$.

- rotation velocity is $\sim 220$ km/sec
- radius about $\sim 30$ kpc

Newton:

$$v_{\text{rot}} = \sqrt{\frac{GM}{R}} \Rightarrow M = \frac{v_{\text{rot}}^2 R}{G}$$

$\Rightarrow$ total mass: $3.3 \times 10^{11}$ $M_{\odot}$

$\Rightarrow \Rightarrow \sim 5$ times more dark mass than visible

Local density: (0.3- 0.4 GeV/cm$^3$)

$0.0159 \pm 0.0047 \pm 0.0057$ $M_{\odot}/$pc$^3$, LAMOST (China). 0.7GeV/cm$^3$

1 $M_{\odot} = 2$. E30 kg, 1pc=3.0857E16 m, 1$M_{\odot}/$pc$^3$= 6.8 E-8 kg/cm$^3$

1kg = 5.625 * $10^{26}$ GeV/c$^2$
Analysis of Gaia results

second release april 2018: high-precision positions, velocities, and distances for 1.3 billion stars

1) GD-1 stream from Gaia ➔ a new level of precision in simulating a stream-dark-matter encounter (A. Bonaca et al., 2019).

Need a clump of \(10^7\)Mo!

2) Lisanti et al 2019: 2 non disk populations of stars:
   i) Old, isotropic velocity distributions
   ii) Young, large radial velocities from merger 7 billion years ago!

Each should have its own DM population!!!
WIMP direct detection schemes with and w/o background rejection

Elastic scattering off nuclei

Ionization

Scintillation

Liquid Xe

NaI, CaF$_2$, LXe, ...

Ge, Si

Al$_2$O$_3$, LiF, ...

Phonons

mixed detections

WIMP

WIMP

WIMP

WIMP target

• He 3 detector
• Superconducting granules
• Freon aerogel

CaWO$_4$, BGO, ...
Present limits: Spin Independent coupling

From Ji Xiangdong, Dec 2016
Present Spin Dependent Exclusion plots

90% C.L. of PICO-2L plotted along with limits from PICO-60
COUPP-4: light blue region,
PICASSO: dark blue,
sIMPLE: thin green,
XENON100: orange,
IceCube: dashed and solid pink,
SuperK: dashed and solid black
CMS: dashed orange

Best results are not direct and need assumptions!

IceCube and SuperK:
- dashed lines: annihilation to W pairs
- solid lines: annihilation to b quarks.

Comparable limits ANTARES, Baikal and Baksan neutrino telescopes

CMS/ATLAS limit: monojet search with effective field theory
Direct detection Situation

![Graph showing WIMP-nucleon cross section versus WIMP mass with various detection experiments and neutrino scattering events labeled including CoGeNT (2012), CDMS Si (2013), DAMA, CRESST (2014), SIMPLE (2012), COUPP (2012), ZEPLIN-III (2012), CDMS II Ge (2009), Xenon100 (2012), LUX (2013), and neutrino scattering events such as $^7$Be Neutrinos and $^8$B Neutrinos.]}
Great mountain coverage
Chinese Underground Laboratory in Jinping
CJPL

Road and Tunnel

July 1, 2009
TAUP09@Rome
CDEX: reaching best present Ge limits in 5 years!

10 kg crystal

Y.Qian et al., arxiv 1404.4946

Cosmogenics Ge-68 has 270.8 days half-life!
CDEX stages

- DM detection w/ Ge prepared since 2003 and started in 2005 in Y2L (5g);
- CDEX-1: Development of PPC Ge detector, bkg understanding, since 2011;
- CDEX-10: Performances of Ge array detector immersed in LN$_2$, since 2016;
- CDEX-10X: Home-made Ge detector and Ge crystal growth;

Direct detection of low-mass WIMPs w/ Ge detector at CJPL.
CDEX 2016 Results

• >500 days run, ~336 d·kg dataset;
• Energy threshold: 475 eVee;
• Bulk/Surface disc. to cut events with slow rise-time and partial charge collection;
• K/L X-rays from Cosmogenic nuclides to trace crystal history;

• SI sensitivity improved;
• SD best below 6 GeV then;

PRD93, 092003, 2016
CDEX 2018 Results

- Detector upgraded w/ lower JEFT noise and material bkg;
- Run 3.3 years, totally 737.1 kg·d exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/c².

<table>
<thead>
<tr>
<th>Detector</th>
<th>FWHM of pulser</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDEX-1A</td>
<td>130 eVee</td>
</tr>
<tr>
<td>CDEX-1B</td>
<td>80 eVee</td>
</tr>
</tbody>
</table>
CDEX-10

- Array detectors: 3 strings with 3 det. each, ~10kg total;
- Direct immersion in LN$_2$;
- Prototype system for future hundred-kg to ton scale experiment
  - Light/radio-purer LN$_2$ replacing heavy shield i.e. Pb/Cu;
  - Arraying technology to scalable capability;
CDEX-10 first results

- First results from 102.8 kg·day exposure with $E_{th} = 160$ eV;
- Bkg level: 2 cpkkd at 2-4 keV;
- New SI limit on 4-5 GeV/c$^2$.
CDEX-10X (T1)

- Commercial Ge crystal + stainless steel canister;
- T1 detector: 500g Ge(φ50×50mm) + CMOS ASIC preAmp;
- Works, and Performance expected;
- Going on to improve bkg, low-noise electronics...
Bare HPGe in LN2

- Vacuum chamber, structure materials, not conducive to further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;
- Develop bare HPGe detectors immersed into LN$_2$!
- Immerse the detector into liquid nitrogen for about 8 hours, we got a stable leakage current $\sim$10 pA for 1000V bias voltage.

Bare HPGe detectors

Bare HPGe in LN$_2$

PPC: $\phi$50mm x 50mm, Depleted voltage: $\sim$800V
CMOS ASIC Front end electronics

- Light DM search $\rightarrow$ low noise/threshold (low capacity, etc)
- Very close to Ge detectors $\rightarrow$ low bkg(radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC $\sim$26e(<200eV) w/ 4$\mu$s shaping time, mainly from 1/f noise ($\sim$21e);

Noise components analysis

![Noise components graph](image)
Planned developments

• New detectors cooperated with commercial companies
  • 3kg from BSI, 2kg from ORTEC, planning 5kg from CANBERRA/ORTEC;
  • Particular control of detector fabrication process above ground;

• Home-made detectors
  • Improve T1 w/ low bkg material and low noise electronics;
  • Set up underground fabrication and testing facility;

Detector production: 45 days +
Ground transportation: 60 days +
Underground cooling: 180 days →

Cosmogenic bkg: 0.03 cp kkd (sim.)
Pandax: inauguration
end march 2014 – results 2016

Ton scale liquid Xenon two phase (liquid and gas) TPC
Project lead by SJTU

No events found in the DM search region!
PandaX WIMP direct detection

- **PandaX-I**: 2009-2014
- **PandaX-II**: 2014-2018
  - 60 cm x 60 cm dual-phase xenon TPC
  - 580 kg LXe in sensitive volume
- Dual-phase xenon detectors:
  - Large monolithic target
  - 3D reconstruction and fiducialization
  - Good ER/NR rejection
  - Calorimeter capable of seeing a couple of photons/electrons

Dark matter: nuclear recoil (NR)

\[
\frac{S_2}{S_1}
\]

\[\text{Drift time} \rightarrow \text{S2}\]

\[
\text{(S2/S1)}_{NR} \ll \text{(S2/S1)}_{ER}
\]

\[
\frac{S_1}{S_2}
\]

\[\text{Drift time} \rightarrow \text{S1}\]

\[
\text{(S1/S2)}_{ER} \ll \text{(S1/S2)}_{NR}
\]

\[
\frac{S_1}{S_2}
\]

\[\text{Drift time} \rightarrow \text{S2}\]

\[
\text{(S2/S1)}_{NR} \ll \text{(S2/S1)}_{ER}
\]
Highlights of PandaX-II Results

- 33 ton-day: spin independent search, **PRL 117, 121303 (2016)**
- 33 ton-day: spin dependent search, **PRL 118, 071301 (2017)**
- 27 ton-day: inelastic scattering search, **PRD 96, 102007 (2017)**
- 27 ton-day: Axion and ALP search, **PRL 119, 181806 (2017)**
- 54 ton-day: spin independent search, **PRL 119, 181302 (2017)**
- 54 ton-day: light mediator search, **PRL 121, 021304 (2018)**
- 54 ton-day: general EFT and spin-dependent search, **PLB 792, 193 (2019)**
CJPL-I

- CJPL-I
- Volume: 4000 m³
- 1 main hall (6.5x6.5x42m)
From CJPL-I to CJPL-II

• CJPL-I to CJPL-II
  • Volume: 4000 m³ to 300,000 m³;
  • 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  • Additional pit for next-generation CDEX;

[Diagram of CJPL-II layout]
Why a Directional Dark Matter detector?
WIMP searches: Direct detection

- **Principle**: Goodman and Witten, 1985; Drukier and Stodolsky 1984

Elastic scattering of galactic DM off detector nuclei $M_\chi$ $M_N$

Nuclear recoils of a few keV

- Exponential recoil energy distribution

\[
\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} \text{ (kinematic factor)}
\]

\[
R = \frac{4M_\chi M_N}{(M_\chi + M_N)^2}
\]

event rate per unit mass
recoil energy
total event rate (point like nucleus)
incident energy

- **Rates**: Weak interactions or smaller

- Need of signatures for identifying galactic origin
  - Annual modulation with MASSIVE detectors
  - Directionality: low pressure TPC?
  - Dependence on nucleus
Why a Directional Dark Matter detector?

Need signatures:

1) A signal in different detectors with different nuclei
2) Show the Galactic origin

All experiments not in competition but complementary!
Expected signal from Galactic WIMPs

Dark matter Halo
= gaz of WIMPs

Solar System’s orbit

Galactic coordinates

Cygnus Constellation (l = 90°, b = 0°)

After collision

WIMP signal detected

J. Billard et al., PLB 2010
J. Billard et al., arXiv:1110.6079
Proof of discovery: Signal pointing toward the Cygnus constellation

Blind likelihood analysis in order to establish the galactic origin of the signal:

\[ \mathcal{L}(\ell, b, m_\chi, \lambda) \]

Strong correlation possible with the direction of the Cygnus Constellation even with a large background contamination.
Angular resolution < 20deg: R&D studies for requirements

- Measurable track length
- Measurable directionality
- Head-tail separation
- Ion/electron separation
- Quenching factor
- Reconstruction of initial recoil angle
- ...
An old idea: Dark matter detection with hydrogen proportional counters

G. Gerbier, J. Rich, M. Spiro, C. Tao
Nuclear Physics B - Proceedings Supplements
Volume 13, February 1990, Pages 207-208

Problems: - technical: low pressure, short track length expected
- Is DM Cold? N-body simulations issues

⇒ Astrophysics
Special gaz mixture

- 70% CF$_4$ + 28% CHF$_3$ + 2% iC$_4$H$_{10}$

- Reduces electron drift velocity

- Operating at low pressure
MIMAC strategy

- **Cathode**
- **Grid**
- **Anode**

Sampling at 50 MHz
- T=60 ns
- T=40 ns
- T=20 ns
- T=0 ns

**Flash Signal**

**3D Track Signal**

Micromegas 10x10 cm², designed by IRFU-Saclay (France)
MIMAC-bi-chamber module prototype

Diagram showing the schematic of the MIMAC-bi-chamber module prototype. Key components include:
- Buffer volume (1 bar)
- Circulation
- O₂, H₂O filter
- Pressure regulator
- Pump
- Flow controller

The diagram illustrates the gas mixture used:
- 70% CF₄ + 28% CHF₃ + 2% C₄H₁₀ @ 50 mbar

Dimensions of the module:
- 256 µm
- 10.8 cm
- 25 cm

Other components include:
- 12 µm cathode
- Grid
- X, Y strips
- Electronic board
- X-ray generator

The gas mixture is designed for optimal performance in the MIMAC-bi-chamber module prototype.
MIMAC Bi-chamber

- Energy
- 3D track

2 x (10.8 x 10.8 x 25 cm³)
9 keV ion track in Mimac prototype

FIG. 4. Example of an ion track in ZX and ZY projection using barycenter representation (left), triggered wires and 2D fits (middle) and 3D (right) for an ion of kinetic energy of 9.32 keV.
Specially developed keV ion beams

LHI facility in Grenoble

COMIMAC – a portable ion source
Quenching factor measurement facility

Our targets: $^{19}$F, H, He,...
Directional experiments around the world

DMTPC (WIPP)

DRIFT (Boulby)

Emulsions (Gran Sasso)

MIMAC (Modane)

NEWAGE (Kamioka)

Running in an Underground Laboratory
**MIMAC:** the only experiment that has shown 3D reconstructed tracks

**Fluorine 6.3 keV (~2 keVee)**

**Fluorine 26.3 keV (~9 keVee)**
Angular resolution: better than required 20deg!
Summary for MIMAC R&D

i) A new directional detector of nuclear recoils at low energies has been developed giving a lot of flexibility on targets, pressure, energy range…

ii) Ionization quenching factor measurements have been determined experimentally and they can be checked in-situ.

iii) MIMAC bi-chamber module has been installed at Modane Underground Laboratory in June 2012. An upgraded versions in June 2013 and June 2014 and it shows an excellent gain stability. For the first time the 3D nuclear recoil tracks from Rn progeny have been observed.

iv) Angular resolution and directional studies of 3D tracks are now possible with COMIMAC and the angular resolution aim of less than 10 deg has been shown down to 8 keV.
Comparison data - simulation

Need to be understood!

Large discrepancy!!
Molecular effect?
MIMAC 1m³ in preparation

Figure 5. The preliminary mechanical design of the demonstrator of MIMAC -1m³.

Fully funded
(< 1 Meuros including manpower)

Installation in 2020-2021 in LSM
Towards an international DMDD?

Initiative led by Neil Spooner with Japanese, Italian, Australian, US, Chinese, French, +...

MIMAC-based technology? only detector which has shown < 10 keV tracks

- Low radioactivity issues
- Which underground lab(s)? One or many?
Alternatives to Gaseous detectors

eg DAMIC DM detection with CCD

- Low energy threshold of a few tens of eV
- High spatial resolution

**Figure 5:** Candidate β decay sequence found in data. The first cluster had 114.5 keV of energy. A second cluster, with energy 328.0 keV, was observed in an image taken 35 days later. Both tracks appear to originate from the same point (yellow star) in the CCD x-y plane.

**Figure 6:** Cross section exclusion limit at 90% CL for the DAMIC 2014 results (solid black) compared to DAMIC 2012 (dashed black) [9], CRESST 2014 (solid green) [18], CDMSlite 2013 (solid red) [17].
SRIM simulations

Couturier et al. 1607.08157

Figure 1. Development of the tracks of recoils with the maximum kinetic energy induced by a 1000 GeV/c^2 WIMP. From left to right: \(^{16}\text{O}\) of 29 keV in ZnWO\(_4\), \(^{12}\text{C}\) of 22 keV in Emulsion, \(^{19}\text{F}\) of 34 keV in the TPC gas mix. (SRIM simulations)

For solids, need submicron resolutions!
WIMP DM searches

- No convincing signal to date!
- Exclusion/discovery plots are interpretation dependent!
- Once a signal is found (ie $\sigma > 5$ statistics)
  but also confirmed by different signatures!

- Direct Detection: floor from solar neutrino scattering
- Indirect Detection: many signals -
  Cannot exclude easily conventional astrophysics solutions

- Beware of assumptions for absolute exclusions!!!
Axion DM

- Some types can be found in existing WIMP detectors
- More connexion to advanced technology?
**Axion DM and advanced technology**

NIST JILA, U. Chicago, and Fermilab

Use Fock states to stimulate emission from DM axions into cavity photons

Use qubits to load individual quanta into detection RF cavity

Resulting large N Fock state is a quantum superposition of all possible oscillation phases

Enhanced response to all possible signal phases

---

Konrad Lehnert (NIST JILA), David Schuster (U. Chicago), Aaron Chou (FNAL)
What is DM?

not understood yet!

the next Graal of physics!
DM: most fundamental problem in Physics today?

- Do gravitational waves exist? After A-LIGO Gravitational astronomy!
- Dark Energy: maybe cosmological constant
- Dark Matter: is there DM? and what is its Nature?

Future DM Astronomy?
Dark Matter: What do we really know?

DM: - particles that does not emit observable radiation
    - interacts gravitationally…
    - non baryonic

DM: we know it exists!
But not much more... Need more data!!!

Or do we even really know it exists?
Alternatives to DM?

Not so many models any more, but still...

some are still doubting:

eg http://www.astro.uni-bonn.de/~pavel/kroupa_SciLogs.html
Famaey & Mc Gaugh

- **MOND** - Milgrom /TEVES-Beckenstein needs neutrinos to explain Bullet Cluster...

- **MOG**: Moffat and collaborators
  Scalar-Tensor-Vector Model of gravity: “few parameters can explain away DE and DM”.

- **GR with torsion**
Milgrom MOdified Newtonian Dynamics (MOND) for flat Galaxy rotation curves

modification of Newton’s law at very weak accelerations,

\[ \mu(a/a_0) = \frac{M G}{r^2} = a_N \quad \text{where} \quad \mu(x)=1, \ x \gg 1 \]
\[ =x, \ x \ll 1 \]

\[ a_0 \sim 1.2 \text{ A/s}^2 \]
**MOND** = phenomenological model

- Violates equivalence principle
- Violates conservation of momentum
- Violates Lorentz invariance
- Violates Cosmological Principle
- .....

**Bekenstein astro-ph/0403604**, a coherent scalar-tensor theory?

**TEVES** a tensor-vector theory

- Fits all rotation curves with 1 parameter variable: galaxy M/L
- Predicts Tully Fisher Mass-rotation (R. Sanders) M prop v^4
- Fits CMB without CDM  S. Mc Gaugh

Effective theory?

Excludes it? or More interesting?
N-body simulations with no DM?

- Modified gravity f(R) simulations often have DM
- MOND/TeVes (Zhao Hongsheng, N-Mody, … )
  Status?
- Torsion model, etc…?
Universe with Torsion

- Extension to GR:
  in simplest CARTAN model:
  (eg, Schucker and Tilquin, 2012)
  Lambda/DE still needed but... DM reduced (to zero?)

- Difficulties with many extensions
  eg Gauss theorem not valid, pathologies...
Summary: What do we know about DM?

- Astrophysical observations
  - existence of non baryonic Dark Matter
- N-Body simulations and Observations of LSS
  - existence of not-hot DM?

Many problems with CDM simulations can be solved with 

$O(1\text{keV})$ WDM or Baryon physics?

- More work on baryonic N-body simulations needed!

Need to find DM in accelerators and DD/ID experiments!
A mysterious Dark Universe!

What we know is only 4-5% of the energy density of the Universe.

We now measure with precision the extent of our ignorance!
Thank you