Cosmology
Lecture 2

Andrea De Simone
• **LECTURE 1:**

The Universe around us. Dynamics. Energy Budget.

The Standard Model of Cosmology: the 3 pillars (Expansion, Nucleosynthesis, CMB).

• **LECTURE 2:**

Dark Energy.
Dark Matter as a thermal relic. Searches for WIMPs.

• **LECTURE 3:**

Shortcomings of Big Bang cosmology. Inflation. Baryogenesis
• LECTURE 1:

The Universe around us. Dynamics. Energy Budget.

The Standard Model of Cosmology:
the 3 pillars (Expansion, Nucleosynthesis, CMB)

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Shortcomings of Big Bang cosmology. Inflation. Baryogenesis
2 main sets of evidences for Dark Energy:

1. **energy budget:**

   fit to CMB anisotropy map provides many cosmological parameters:
   \[ \Omega_{\text{tot}} \sim 1.0, \quad \Omega_{\text{matter}} \sim 0.3, \quad \Omega_{\text{radiation}} \sim 0.0 \quad \Rightarrow \quad \Omega_{\Lambda} \sim 0.7 \]

2. **distant SuperNovae (SN)**
   (1998-Pelmlutter, Schmidt, Riess - Nobel prize 2011)
Dark Energy

luminosity distance \[ d_L = (1 + z)r(z) \]

depends on \( \Omega_{\text{matter}}, \Omega_\Lambda, \Omega_{\text{radiation}}, \Omega_k \)

absolute \((M)\) and apparent \((m)\) magnitude are related to distance:
\[ m - M = 5 \log \left( \frac{d_L}{10\text{pc}} \right) + K \]

SN are ‘standard candles’ (known absolute magnitude).

Measure \( m \) \rightarrow measure \( d_L \) \rightarrow measure \( \Omega_{\text{matter}}, \Omega_\Lambda \)

new form of energy with negative pressure \((w<0)\)

results consistent with cosmological constant
(vacuum energy with \( w=-1 \))
so WHAT IS DARK ENERGY?

\( \Omega_\Lambda \simeq 0.7 \implies \rho_\Lambda \simeq (\text{meV})^4 \)

New physics at the meV scale?

Some form of energy density which stays constant as the Universe expands:

\[ \rho_\Lambda \propto a^{-3(1+w)} \sim \text{const.} \]

at what scales do we expect new physics? \( M_{\text{weak}} \sim \text{TeV}, M_{\text{Planck}} \sim 10^{22} \text{ GeV} \)

\[ \rho_\Lambda \sim 10^{-123} M_{\text{Planck}}^4 \]

\[ \rho_\Lambda \sim 10^{-60} M_{\text{weak}}^4 \]

the “WRONGEST” estimate of particle physics
(and biggest hierarchy problem...)

SO WHAT?
- maybe anthropic principle (we could only live in universes with small \( \Lambda \))
- maybe quantum gravity...
Evidences for Dark Matter

Energy budget of the Universe

\[ \Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_c} \quad \rho_c \equiv \frac{3H^2}{8\pi G_N} \approx 1.05 \times 10^{-5}h^2 \text{ GeV cm}^{-3} \]

\[ h \equiv \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}} \approx 0.67 \]

\[ \Omega_{\text{DM}}h^2 = \frac{\rho_{\text{DM}}}{\rho_c/h^2} = 0.1196 \pm 0.0031 \] (Planck Coll.)

Observational Evidences for Dark Matter:

- Galaxy clusters
- Galaxies
- Cosmology (CMB and Large Scale Structure formation)

Firmly established, but only gravitational interactions are probed
F. Zwicky (1933) measured proper motion of galaxies in Coma cluster (~1000 galaxies within radius ~ 1 Mpc)

**Virial Theorem:** \[ \langle V \rangle + 2 \langle K \rangle = 0 \]

\[ \langle V \rangle = -\frac{N^2}{2} G_N \frac{\langle m^2 \rangle}{R} \]  
average potential en. due to \( N^2/2 \) pairs of galaxies

\[ \langle K \rangle = N \frac{\langle m v^2 \rangle}{2} \]  
average kinetic en. due to \( N \) galaxies

Total mass \[ M = N \langle m \rangle \sim \frac{2R \langle v^2 \rangle}{G_N} \]  
\( \Rightarrow \) \[ \frac{M}{L} \sim 300h \frac{M_\odot}{L_\odot} \]

"should this be true, this surprising result would show that dark matter is of much greater density than luminous matter"

Most of the matter is NOT LUMINOUS
- X-ray observations

most ordinary mass in clusters is hot gas, emitting X-rays
Pressure is due to electrons: \( P(r) = n_e(r)T_e(r) \)

Law of hydrostatic equilibrium:

\[
dP = -dm \frac{\text{accel}}{\text{Area}} = - \rho_b(R) \frac{dV}{\text{Area}} \frac{G_N M(R)}{R^2} = - \rho_b(R) \frac{G_N M(R)}{R^2} dR
\]

where

\[
M(R) = 4\pi \int_0^R \rho(r) r^2 dr
\]

\[
\rho_b(r) = \mu n_e(r) m_b
\]

from temperature maps

from X-ray luminosity and spatial distributions

EXTRACT THE MASS

More matter than just baryons!
- Gravitational Lensing

General Relativity at work!

Abell NGC 2218

- “Bullet” Cluster

Two colliding clusters of galaxies
Rotation curves

\[ v(R) = \sqrt{\frac{G_N M(R)}{R}} , \quad M(R) = 4\pi \int_0^R \rho(r) r^2 \, dr \]

Expectation: \( v(r) \propto R^{-1/2} \) at large \( R \)

Observations: \( v(r) \approx \text{const.} \) at large \( R \)

More matter than visible! and distributed differently (in the halo)

\[ M_{DM} \propto R \quad \text{requires} \quad \rho_{DM} \propto \frac{1}{r^2} \]
Recall that CMB temperature maps give accurate information about cosmological parameters ($H_0$, $\Omega_{tot}$, $\Omega_B$ etc...) (see 1st lecture)

Different DM types give different scenarios:

- Hot DM \text{ "top-down": large structures fragment into smaller pieces.}
- Cold DM \text{ "bottom-up": smaller objects merge into bigger structures hierarchically.}

Cosmological observations (CMB and galaxy observations) + numerical simulations \textit{exclude} HDM.
Problems of Cold DM (?)

“cusp-core problem”

Numerical simulations predict “cuspy” density profiles $\rho \sim r^{-1 \div -1.5}$ (small r)

Observations favor more constant densities

“missing satellite problem”

Numerical simulations predict large number (100-1000) of sub-haloes

Only $\sim 10$ observed

NOT CLEAR SITUATION

Some propose Wark Dark Matter

It may simply be that Numerical Simulations are not accurate enough (baryons not included) and small sub-haloes are invisible.
explanation of flat rotation curves with modification of gravity (rather than DM)?

**MOND (MOdified Newtonian Dynamics)**

$$\frac{G_N M(R)m}{R^2} = \begin{cases} \frac{ma}{R^2} & (a > a_*) \\ \frac{ma^2}{a_*} & (a < a_*) \end{cases}$$

(critical acceleration $a_* \sim 10^{-11} \text{ m/s}^2$)

$$v(R) = \begin{cases} \left[\frac{G_N M(R)}{R}\right]^{1/2} & \text{(Newton)} \\ \left[\frac{G_N M(R)a_*}{a^*}\right]^{1/4} & \text{(MOND)} \end{cases}$$

**MOND IS FALSE!**

1. evidence for DM is much more than rotation curves

2. bullet cluster contradicts MOND

3. some galaxies do not have a flat rotation curve
Key Properties of Particle DM

- **stable** (or with lifetime at least longer than the age of the Universe)
- no electric charge, no color charge
- non-collisional
- not hot
- DM is in a **fluid limit** (not a collection of discrete compact objects)

MAssive Compact Halo Objects (MACHOs) are astrophysical objects with macroscopic mass (large planets or small dead stars).

MACHOs searches exclude (using gravitational lensing)

\[ 10^{-7} M_\odot \lesssim M \lesssim 10 M_\odot \]

A small window for **primordial black holes** still open

\[ 10^{-13} M_\odot \lesssim M \lesssim 10^{-7} M_\odot \]
• **DM is classical (non-relativistic) today**

confined on galactic scales \(\sim 1 \text{ kpc}\), with densities \(\sim 1 \text{ GeV cm}^{-3}\) and velocities \(\sim 100 \text{ km/s}\).

For **bosons**: De Broglie wavelength \(\lambda = h/p\) must be less than 1 kpc

\[
m \gtrsim \frac{h}{1\text{ kpc} \cdot v} \approx \frac{2\pi}{\frac{1}{3} 10^{-3} c} \frac{1}{3 \cdot 10^{21} \text{ cm}} (2 \cdot 10^{-14} \text{ cm} \cdot \text{GeV}) \approx 10^{-22} \text{ eV}
\]

\((v=100 \text{ km/s})\)

For **fermions**: DM quantum occupation number must be <1 (Pauli)

\[
\frac{\rho(r_\odot)}{m} \lambda^3 \lesssim 1 \implies \rho(r_\odot) \lesssim \frac{m}{\lambda^3} \implies m \gtrsim \left[ \frac{h^3 \rho(r_\odot)}{v^3} \right]^{1/4} \approx 1 \text{ keV}
\]

(Gunn-Tremaine bound)

\((\rho(r_\odot) = 0.4 \text{ GeV cm}^{-3} \approx (0.04 \text{ eV})^4)\)
Candidates for Dark Matter

(an incomplete list)

**WIMP**
- neutralino
- minimal DM
- heavy neutrino
- inert Higgs doublet
- LKP
- LTP
- ...

**non-WIMP**
- axion
- gravitino
- sterile neutrino
- techni-baryon, topological defects
- primordial black holes
- ...

**WIMP** = Weakly Interacting Massive Particle
(or... the “Holy Grail” of DM physics)
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**WIMP** = Weakly Interacting Massive Particle
(or... the “Holy Grail” of DM physics)
Assume:

- X is stable
- X is in thermal eq. at $T >> m_X$

**QUALITATIVE ANALYSIS**

- initially, in thermal equilibrium
  \[ \chi \chi \leftrightarrow \text{SM SM} \]

- Universe **cools**, less and less X
  \[ \chi \chi \xrightarrow{\nabla} \text{SM SM} \]

- Universe **expands**, reaction slows down and X abundance “freezes out” of the expansion
  \[ \chi \chi \nrightarrow \text{SM SM} \]
**Back-of-the-envelope**

when annihilation rate becomes smaller than expansion, $X$ decouples from the plasma

$$\Gamma \lesssim H \quad \iff \quad \langle n_X \sigma \rangle \lesssim T^2/M_P$$

number density of $X$ remains $\sim$ constant

$$\frac{n_X}{n_\gamma} \sim \frac{T^2/(M_P \sigma)}{T^3} \sim \frac{1}{M_P \sigma T} \sim \frac{1}{M_P \sigma m_X}$$

the energy density of $X$ today (wrt photons) is:

$$\frac{\rho_X}{\rho_\gamma} \sim \frac{m_X}{T_0} \frac{n_X}{n_\gamma} \sim \frac{1}{M_P \sigma T_0}$$

- independent of mass of $X$
- inversely proportional to cross section (the weakest wins!)
MORE PRECISELY

freeze-out temperature when

\[ n \sigma v = H \]

i.e. \( (n \sigma)_{T_f} = H(T_f) \)

where \( n = n_\chi = g_\chi \left( \frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} \)

\( H(T_f) \simeq 1.66 \sqrt{g_*} \frac{T_f^2}{M_P} \equiv \frac{T_f^2}{M_P^*} \)

\[ T_f \simeq \frac{m_\chi}{\ln \left( \frac{g_\chi m_\chi M_P^* \sigma}{(2\pi)^{3/2}} \right)} \]

typically \( T_f \sim m_\chi/20 - m_\chi/30 \)

number density after freeze-out \( n_\chi(T_f) = \frac{T_f^2}{M_P^* \sigma v} \)

is ~ constant until today, up to a redshift dilution \( n_\chi(T_0) = \left( \frac{T_0}{T_f} \right)^3 n_\chi(T_f) \propto \frac{1}{T_f} \propto \frac{1}{m_\chi} \)

so energy density of \( X \) (\( n_\chi \) * \( m_\chi \)) today does not depend on \( m_\chi \)! (actually, \( T_f \) contains \( m_\chi \))

\[ \Omega_\chi h^2 = \frac{(n_\chi(T_0)m_\chi)}{\rho_c/\hbar^2} = \ldots \simeq 0.1 \frac{3 \times 10^{-26} \text{cm}^3/\text{sec}}{\sigma v} \simeq 0.1 \frac{1 \text{ pb}}{\sigma v} \]

typical weak-scale interactions provide thermal relic with the “right” relic abundance
(REMARKABLE COINCIDENCE, a.k.a. “WIMP MIRACLE”)
neutrinos freeze-out while relativistic (hot relics)

number density after freeze-out does not depend on mass

\[ n_\nu(T_f) = n_\nu^{eq}(T_f) \sim T_f^3 \]

\[ \rho_\nu(T_0) = \left( \frac{T_0}{T_f} \right)^3 n_\nu(T_f) m_\nu \propto m_\nu \quad \Rightarrow \quad \Omega_\nu h^2 \propto \sum m_\nu \]

Require neutrinos do not “over-close” the Universe \( \Omega_\nu < 1 \)

\[ \sum m_\nu < \mathcal{O}(10) \text{eV} \]

Cosmology tells us something non-trivial on particle physics!
WHY WIMPS ARE SO NICE?

- WIMP “miracle”
- SUSY (?), neutralino in primis
- link with BSM physics with new particles at weak scale
- multi-sided searches (LHC, direct detection, indirect detection) are possible
**INDIRECT DETECTION**

DM DM → $e^+ e^-$, ...

**DIRECT DETECTION**

DM Nucleus → DM Nucleus

**COLLIDER**

$p p \rightarrow$ DM + X

*(in LHC we trust...)*
**Direct Detection**

**DD:** looking for the scattering of galactic halo DM on heavy nuclei in underground labs.

DM Nucleus $\rightarrow$ DM Nucleus

C.o.m. recoil momentum (momentum transfer):

$$|\vec{q}|^2 = 2\mu_X^2 v^2 (1 - \cos \theta), \quad \mu_X = m_X M_A / (m_X + M_A)$$

Recoil energy imprinted on nucleus:

$$E_R = \frac{|\vec{q}|^2}{2M_A}$$

$$E_R^{\text{max}} = 2\frac{\mu_X^2 v^2}{M_A}$$

Ex: $^{131}\text{Xe}$, $m_X=100$ GeV

$$E_R^{\text{max}} = 2 \left( \frac{v}{200 \text{ km/s}} \right)^2 \left( \frac{2}{3} \cdot 10^{-3} \right)^2 \frac{100^2 \cdot 131}{231^2} 10^6 \text{ keV} \approx 22 \text{ keV} \left( \frac{v}{200 \text{ km/s}} \right)^2$$
Direct Detection

\[
\frac{\text{# events}}{\text{time}} = \text{(\# targets)} \times (\text{WIMP flux on Earth}) \times (\text{cross section})
\]

\[
= N_T \left( \frac{\rho_\oplus v}{M_\chi} \right) \sigma_{\chi A}
\]

\[
\leq \frac{1 \text{ event}}{\text{yr}} \times \frac{M_T}{A} \times \frac{\sigma}{10^{-39} \text{cm}^2} \times \frac{\rho_\oplus}{0.3 \text{ GeVcm}^{-3}} \times \frac{v}{200 \text{ km/s}} \times \frac{100 \text{ GeV}}{m_\chi}.
\]

spectrum of events per recoil energies

\[
\frac{dR}{dE_R} = N_T \frac{\rho_\oplus}{m_\chi} \int_{|\vec{v}| > v_{min}} d^3v |\vec{v}| f(\vec{v}, t) \frac{d\sigma_{\chi A}}{dE_R}
\]

\[
v_{min} = \sqrt{\frac{M_A E_{th}^R}{2 \mu_{\chi A}^2}}
\]

minimal DM velocity to transfer \(E_{th}\) to nucleus
Direct Detection

total event rate

\[ R \propto \frac{\lambda \mu^2_{\chi A}}{m_\chi} < R_{\text{observed}} \]

experimental bound on total number of observed events \[ \lambda < \lambda_{\text{bound}} \propto \frac{m_\chi}{\mu^2_{\chi A}} \sim \begin{cases} m_\chi^{-1} & (m_\chi \ll m_A) \\ m_\chi & (m_\chi \gg m_A) \end{cases} \]

maximal exclusion power for \[ m_\chi \simeq m_A \]
- some experiments (DAMA, CRESST, CoGeNT) see positive hints/signals

**DAMA/Libra (NaI)**

8σ observation of annual modulation

2-4 keV

![Graph showing residuals vs. time](image)

<table>
<thead>
<tr>
<th>Energy Interval</th>
<th>Target Mass</th>
<th>Residuals (cpd/kg/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4 keV</td>
<td>0.29 ton yr</td>
<td>DAMA/NaI = 0.0215 ± 0.0026</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAMA/LIBRA = 0.0176 ± 0.0020</td>
</tr>
</tbody>
</table>

- some other (Xenon, LUX, CDMS-Ge) see no signal

**puzzling situation**: maybe it is telling us something about the WIMP-nuclei interactions or the structure of the DM halo
vector interactions mediated by Z-boson $\sigma \sim \alpha_w^2 m_p^2/M_Z^4 \approx 10^{-39}\text{cm}^2$

already excluded

ATTENTION: plot not complete!
Indirect Detection

\[ \text{DM DM} \rightarrow e^+ e^-, \ldots \]

\[ e^+, \bar{p} \quad \text{AMS-02, Pamela, Fermi, HESS} \]

\[ \gamma \quad \text{ATIC, Fermi} \]

\[ \nu \quad \text{IceCube, Antares, Km3Net} \]

\[ \bar{d} \quad \text{GAPS, AMS-02} \]
Indirect Detection

DM annihilation in galactic halo/center

$$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$$

Primary channels

$$\ell^+, q, W^+, Z, \gamma, \ldots$$

SM evolution

$$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$$

Stable species

Astrophysical propagation

$$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$$

Fluxes at detection
Indirect Detection

model for DM interactions
\( (\mathcal{L}) \)

radiation/hadronization/decay
\( (\text{QCD, QED, EW}) \)

DM annihilations in galactic halo/center

\( e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots \)

primary channels
\( \ell^-, \bar{q}, W^-, Z, \gamma, \ldots \)

\( \ell^+, q, W^+, Z, \gamma, \ldots \)

stable species

particle physics

astrophysical propagation

fluxes at detection

A. De Simone
Astrophysics.
Galactic center: bigger signal, bigger bkg
Dwarf Galaxies (DM dominated): smaller signal, smaller bkg

\[ \rho(r) = \begin{cases} 
\rho_s \left[ (1 + r/r_s)(1 + (r/r_s)^2) \right]^{-1}, & r_s = 12.67 \text{ kpc}, \quad \rho_s = 0.712 \text{ GeV/cm}^3, \quad \text{(Burkert)} \\
\rho_s \exp \left[ -\frac{2}{0.17} \left( \frac{r}{r_s} \right)^{0.17} - 1 \right], & r_s = 28.44 \text{ kpc}, \quad \rho_s = 0.033 \text{ GeV/cm}^3, \quad \text{(Einasto)} \\
\rho_s (r_s/r) \left( 1 + r/r_s \right)^{-2}, & r_s = 24.42 \text{ kpc}, \quad \rho_s = 0.184 \text{ GeV/cm}^3, \quad \text{(NFW)} 
\end{cases} \]
Indirect Detection

**ATLAS**

- 2 × (Fermi-LAT dSphs (χχ)\^{}_{\text{Majorana}} \to \text{u}\bar{\text{u}}, 4 years)
- 2 × (HESS 2011 (χχ)\^{}_{\text{Majorana}} \to \text{qq}, Einasto profile)
- 2 × (HESS 2011 (χχ)\^{}_{\text{Majorana}} \to \text{qq}, NFW profile)
- D5: χ\^{}_{\gamma} \gamma \text{q} \to (χχ)\^{}_{\text{Majorana}}
- D8: χ\^{}_{\gamma} \gamma \text{q} \to (χχ)\^{}_{\text{Dirac}}

- truncated, coupling = 1
- truncated, max coupling
- thermal relic

- Fermi-Lat telescope

LHC

WIMP mass m\^{}_{\chi} [GeV]

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Collider Searches (in LHC we trust...)

\[ pp \rightarrow \text{DM} + X \]

Some trivial considerations:

- Dark Matter in a collider is like a neutrino (missing \( E_T \))

- if stabilized by a \( Z_2 \) symmetry \( \rightarrow \) DM produced in pairs

- Difficult search, unless correlating missing \( E_T \) with other handles

  - jets/photons from initial state radiation?
  - displaced vertices?
  - accompanying particles?

- Need new ideas!
More complete/ more parameters

Complete Models

lots of parameters...

MSSM, Composite Higgs, Extra-Dim...

pMSSM scan

Figure 9: Comparisons of the models surviving or being excluded by the various searches in the LSP mass-scaled SI cross section plane as discussed in the text. The SI XENON1T line is shown as a guide to the eye.
many jets (+ leptons) + MET
Complete Models

More complete/
more parameters

Effective Theories

less complete/
less parameters
✓ constrain **DM-quarks** interactions and translate into limits on **DM-nucleon** cross-section

✓ complementary/competitive with direct detection

✓ no astrophysical uncertainties

---

**Figure** Dark matter production in association with a single jet in a hadron collider. This is shown in figure also demonstrates how the monojet/Mono-Photon channel can be used to constrain DM-quarks interactions and translate into limits on DM-nucleon cross-section, complementary/competitive with direct detection, and with no astrophysical uncertainties.
Effective low-energy description

\[ M_Z \approx 1 \text{ TeV} \]

EFT OK

LHC can access regions beyond the validity of the eff. description

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

\[
\frac{1}{\Lambda^2} (\bar{\chi} \Gamma^A \chi)(\bar{q} \Gamma_A q)
\]

need to use EFT carefully and consistently
• the momentum transfer in the relevant process must be \( Q_{\text{tr}} \ll M_{\text{med}} \)

\[
\begin{align*}
\frac{1}{Q_{\text{tr}}^2 - M_{\text{med}}^2} &= -\frac{1}{M_{\text{med}}^2} \left[ 1 + \frac{Q_{\text{tr}}^2}{M_{\text{med}}^2} + \mathcal{O} \left( \frac{Q_{\text{tr}}^4}{M_{\text{med}}^4} \right) \right] \\
\end{align*}
\]

• \( Q_{\text{tr}}/M_{\text{med}} \) measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones

• Usually, lowest order is OK. Not a problem for direct/indirect searches. Situation is different @ LHC.
use only “selected” events with small enough momentum transfer

- after truncation: theoretically robust limits

- still relevant at low DM masses

The “money plots”
$\sqrt{s} = 14$ TeV

**EFT Discovery Potential**

$L = 25$ fb$^{-1}$

- **ATLAS Simulation Preliminary**
  - $\sqrt{s} = 14$ TeV, $\int L dt = 25$ fb$^{-1}$
  - $D_5$, $m_\chi = 50$ GeV
  - $\pi < \sqrt{\theta_{SM}^2 \theta_{DM}^2} < 4\pi$
  - $5\sigma$ discovery, $3\sigma$ evidence

- 5% systematic

$L = 300$ fb$^{-1}$

- **ATLAS Simulation Preliminary**
  - $\sqrt{s} = 14$ TeV, $\int L dt = 300$ fb$^{-1}$
  - $D_5$, $m_\chi = 50$ GeV
  - $\pi < \sqrt{\theta_{SM}^2 \theta_{DM}^2} < 4\pi$
  - $5\sigma$ discovery, $3\sigma$ evidence

- 5% systematic, 1% systematic

$L = 3000$ fb$^{-1}$ (HL-LHC)

- **ATLAS Simulation Preliminary**
  - $\sqrt{s} = 14$ TeV, $\int L dt = 3000$ fb$^{-1}$
  - $D_5$, $m_\chi = 50$ GeV
  - $\pi < \sqrt{\theta_{SM}^2 \theta_{DM}^2} < 4\pi$
  - $5\sigma$ discovery, $3\sigma$ evidence

- 5% systematic

EFT validity assumed

**Effective Operator**

$(\bar{\chi} \gamma^\mu \chi)(\bar{q} \gamma_\mu q)$

$m_{DM} = 50$ GeV

*Note: The figure includes simulation results and data points for different integrated luminosities, with additional details on the discovery potential and EFT validity assumptions.*
**Way Out?**

**Complete Models**
- More complete/
  more parameters

**Effective Theories**
- limited validity
- not entirely model-independent
  (still rather general...)

less complete/
less parameters
Complete Models

Simplified Models

Effective Theories

More complete/
more parameters

less complete/
less parameters

Other?
... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM

>> just another parametrization of unknown high energy physics <<

- ☑ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet
- ☑ theoretically consistent, no worries about EFT, widths, etc.

- ❌ 1 or 2 more parameters (g’s)
• Dark Energy is a big question mark (maybe quantum gravity...)

• Dark Matter looks more \textit{bread-and-butter} particle physics

• WIMPs are the Holy Grail of Dark Matter physics

• direct/indirect/collider searches for WIMPs

• ... and if WIMPs are not found in the next \textasciitilde5 years ??