Search for Dark Matter

森井政宏

ATLAS EXPERIMENT

HARVARD UNIVERSITY
Department of Physics

LUX

東京大学物理学教室コロキウム

Evidence for Dark Matter

Overwhelming evidences for Dark Matter from astronomy

Observed motions of stars and galaxies

- Rotational curves in galaxies
- Velocity dispersions in galaxy clusters

Mass distribution measured with gravitational lensing

- Cluster mass-light ratios from strong lensing
- Cluster mass maps in clusters from weak lensing
- Smoking gun: Separation of visible and dark matters in colliding clusters

Bullet cluster

Lambda-CDM Universe

Observation has improved dramatically in the last decade

- Cosmic Microwave Background anisotropy (WMAP/Planck)
- Accelerating expansion of the Universe (Type-1a SNe)
- Large-Scale Structure (2dFGRS, SDSS)
- Light-element abundances & Big-bang nucleosynthesis

Data support a universe with a positive cosmological constant Λ and Cold Dark Matter — ΛCDM model

Ω_{baryon}	0.0456 ± 0.0015	Ordinary Matter
Ω_{CDM}	0.228 ± 0.013	Cold Dark Matter
Ω_{Λ}	0.726 ± 0.015	Dark Energy
Ω_{total}	1.005 ± 0.006	Flat Universe

WMAP, Astrophys. J. Suppl. **180** (2009) 225-245

What We Know about Dark Matter

Dark Matter must be there

- ~23% of the energy of the Universe

Near the Solar System

- Local density: ~0.3 GeV/cm^3
  - Give or take a factor of 2
- Velocity: assumed to be Maxwell-Boltzmann with σ_v ~ 230 km/s
  - Simplest model, but not necessarily true

Dark Matter is not part of the Standard Model

- Non-baryonic
- No electromagnetic interactions
- Stable
- Cold: non-relativistic in early Universe to create the LSS

Electroweak Puzzle

In Particle Physics, O(100 GeV) is a special energy scale

- Masses of W and Z bosons, top quark, and Higgs boson

… for no apparent reason

Higgs mass = 125 GeV is particularly problematic

- Only spin-0 particle in the Standard Model
- Quantum (loop) correction to the Higgs mass is O(10^{16} GeV)
- Why is it so "light"? — Known as the "weak hierarchy problem"

Many proposed solutions

- Supersymmetry — Cancel loop corrections between two sets of similar particles that differ only by spin ½
- Extra Dimensions — Additional space dimensions at short distances
- Little Higgs — New global symmetry broken at 1–10 TeV

… the list goes on

WIMP Dark Matter

Theories of new physics predict new particles in O(100 GeV)

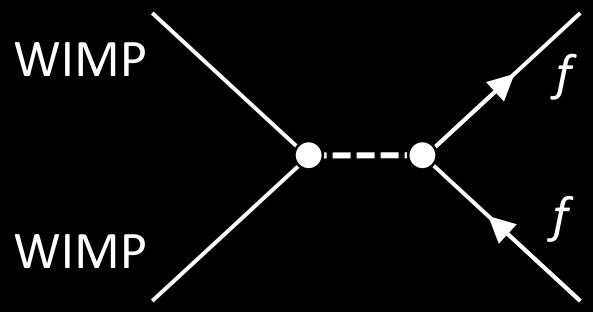
- We haven't discovered any

Symmetry in the theory protects the lightest new particle

Theory	Symmetry	Stable new particle
Supersymmetry	R parity	Lightest Supersymmetric Particle
Little Higgs	T parity	Lightest T-odd Particle
Universal Extra Dimension	KK parity	Lightest Kaluza-Klein Particle

WIMP = weakly-interacting massive particle

- Can be produced or destroyed only in pairs
- Good candidate for Dark Matter



If they were produced at the Big Bang
how many would have survived to today?

WIMP Relic Density

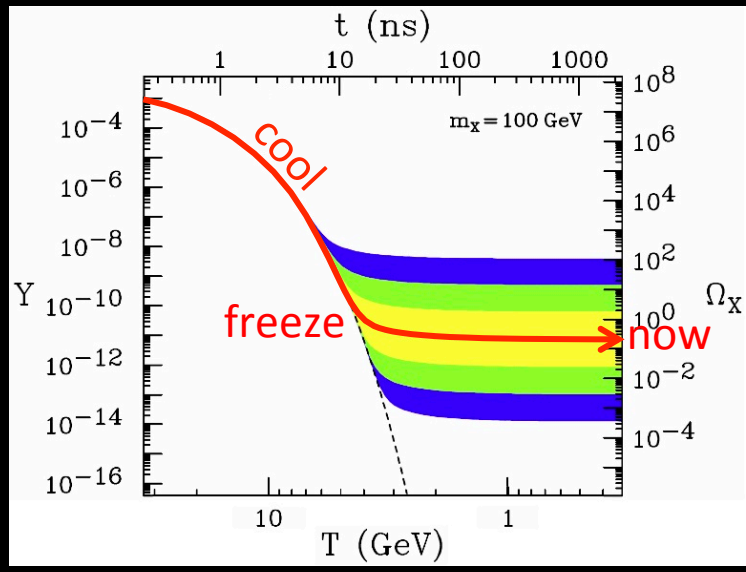
WIMPs were in thermal equilibrium with ordinary particles after inflation

- As the Universe cools, their density drops as

$$n_\chi \propto \exp\left(-\frac{T}{m_\chi}\right)$$

- This goes on until the WIMP annihilation rate becomes smaller than the expansion rate, i.e.,

$$\Gamma_A = \frac{n_\chi}{\langle \sigma_A v \rangle} < H$$



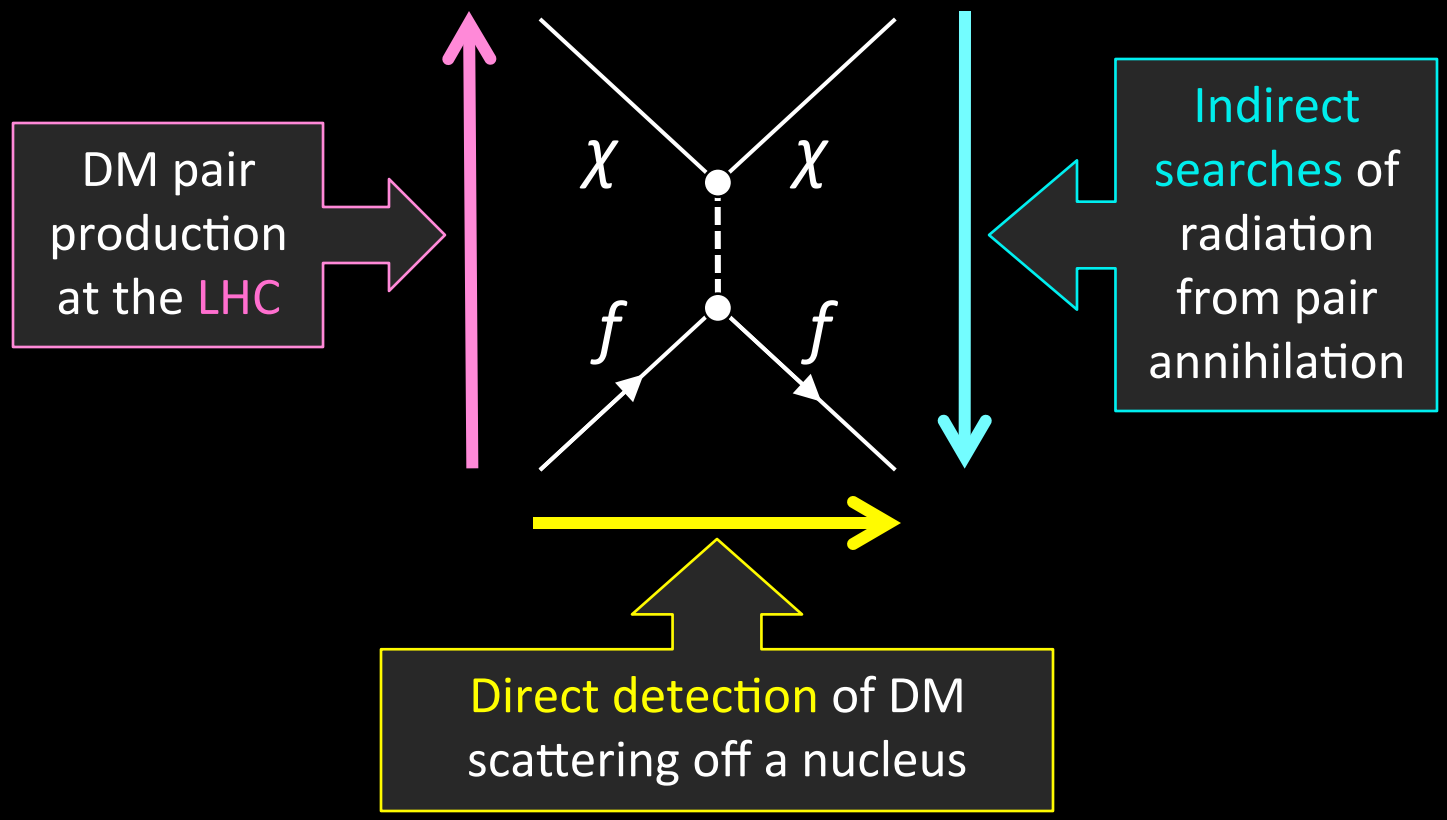
Feng, arXiv:1003.0904 [astro-ph.CO]

- The WIMPs freeze out with the relic density $\Omega_\chi \propto \frac{1}{\langle \sigma_A v \rangle} \approx \frac{m_\chi^2}{g_\chi^4}$

m_χ = 100 GeV and $g_\chi = g_{EW}$ → observed Dark Matter density

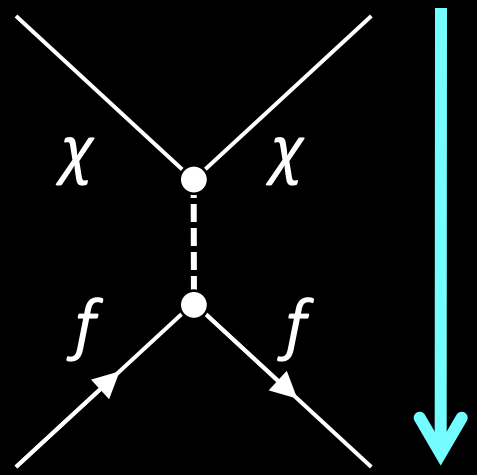
Dark Matter Hunting

Going beyond gravity, three ways to detect Dark Matter



Indirect DM Searches

Indirect searches look for radiations (photon, positron, anti-proton) from Dark Matter pair annihilation in space



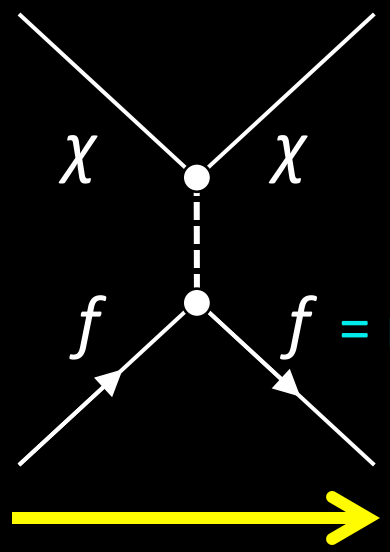
Same process determines the DM relic density

Uncertainties come from astronomy

- Annihilation rate depends on (local DM density)^2
  - Focus on the Galactic center, Solar core
- Background sources are poorly understood
  - Are there local sources of energetic radiations, e.g., pulsars?

Direct DM Detection

Direct detection experiments wait for cosmic Dark Matter scattering off nuclei in their detector



= nucleus (e.g. Xe, Ge, Ar)

Elastic scattering cross-section $\sigma(N\chi \rightarrow N\chi)$ is related to the DM relic density — but it's model-dependent

Uncertainty in the DM abundance and velocity distribution

- Assume 0.3 GeV/cm^3 and Maxwell-Boltzman with r.m.s. 230 km/s

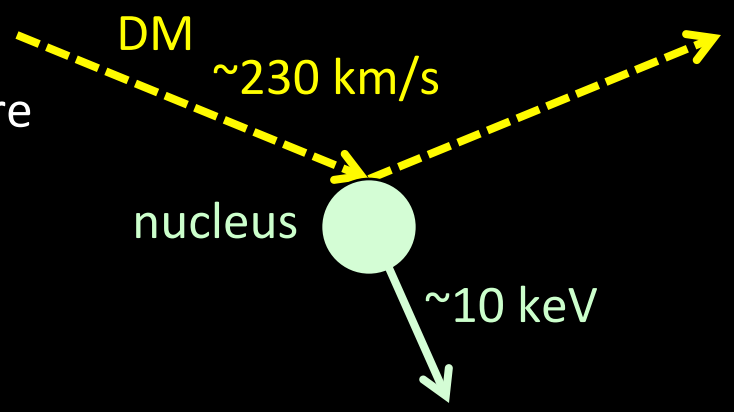
Experimental Challenges

Signal is elastic $\chi N \rightarrow \chi N$ with small recoil energy E_N ~10 keV

- Signatures: scintillation, ionization, heat (phonons)

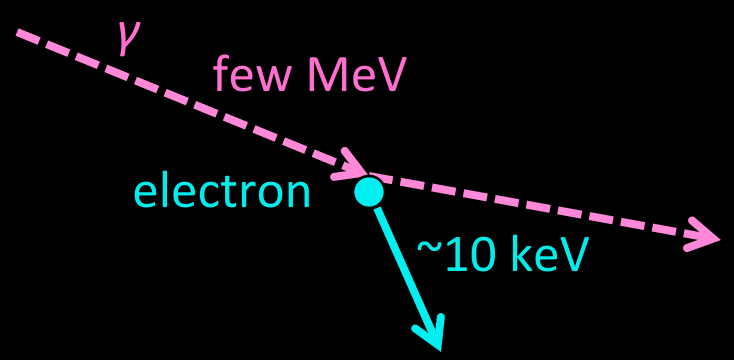
Background sources:

- γ rays from radioactivity
  - Recoils electrons → Different signature
- Neutrons generated by cosmic rays
  - Recoils nuclei → Same signature



To combat the backgrounds

- Detector must be able to distinguish nuclear vs. electron recoils
- Remove radioisotopes from the detector
- Go deep underground to avoid background created by cosmic rays



Target Material

WIMP-nucleus cross section ∝ A^2

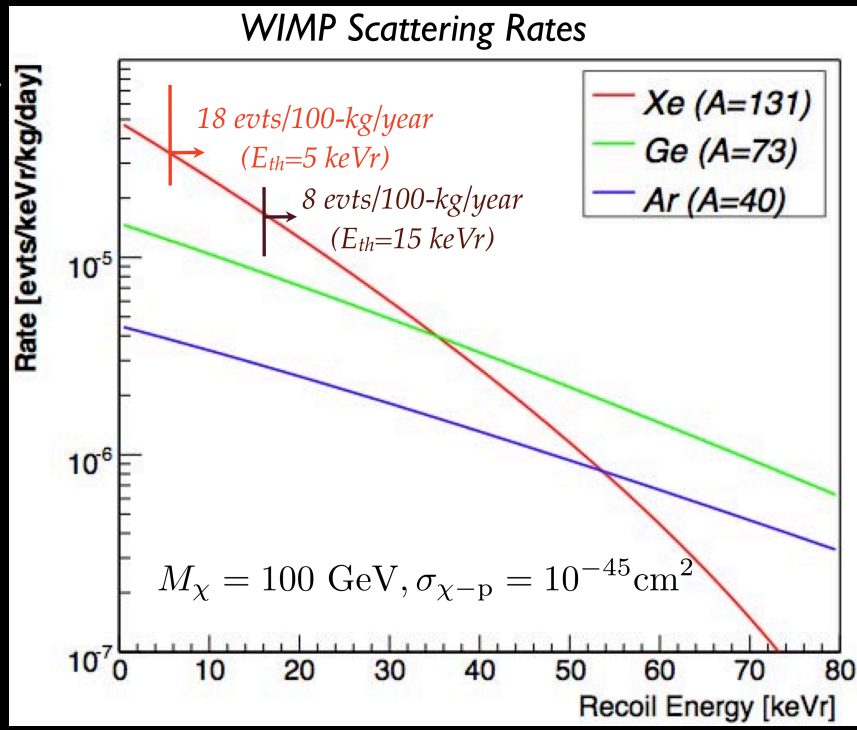
- WIMP scatters off *A* nucleons coherently because wavelength ≥ nuclear radius

➔ Xe > Ge > Ar

- NB: This is true only for spin-independent interactions

Recoil energy becomes small if WIMP is lighter than the nucleus

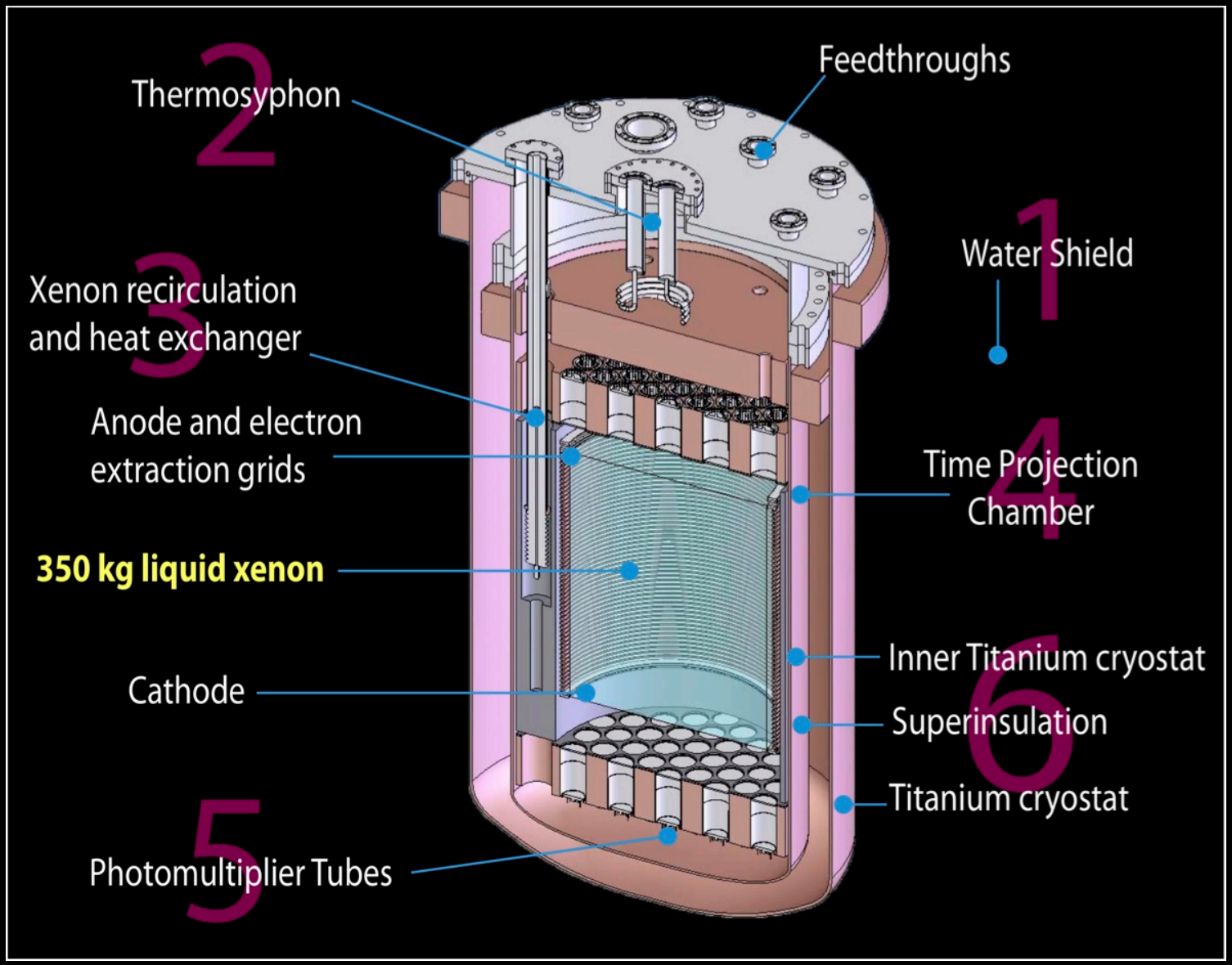
➔ Xe < Ge < Ar



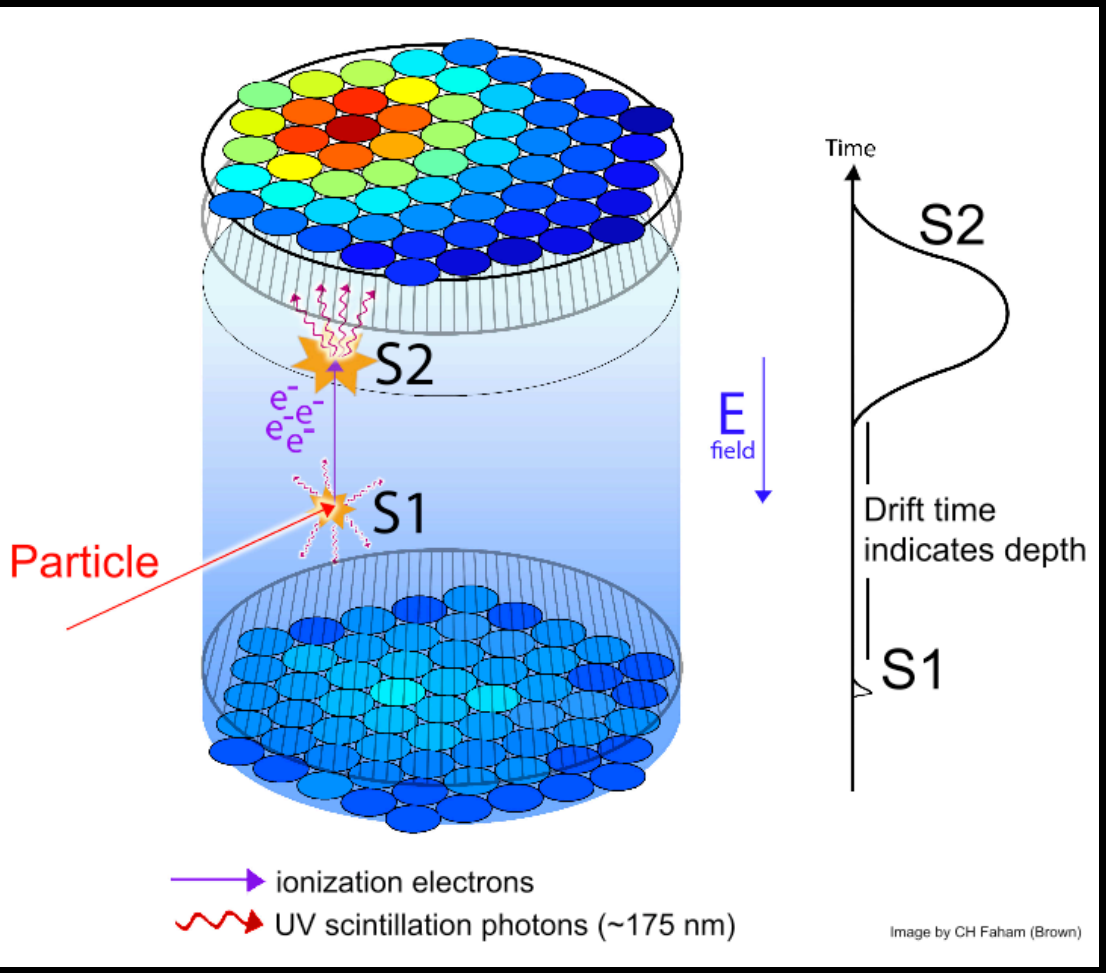
Difference in background rejection

- Different techniques for suppressing electron recoils
- NB: Ar contains 1 Bq/kg of radioactive ^{39}Ar

LUX Experiment



Two-Phase Xe Detector



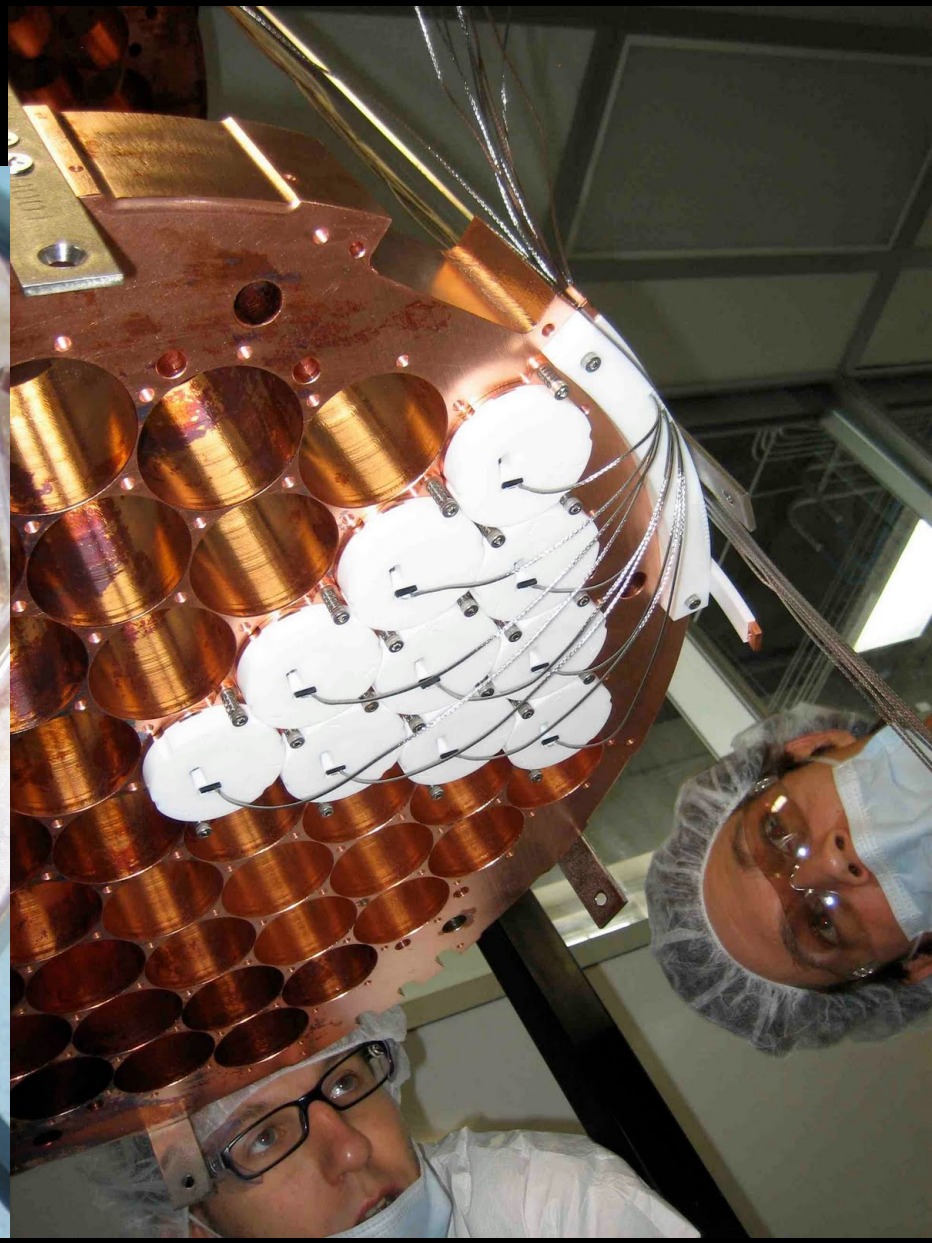
PMTs collect prompt (S1) and proportional (S2) light

- S1-S2 delay → Drift length
- S2 light pattern → Horizontal location

S2/S1 ratio distinguishes between electron and nuclear recoils

- Nuclear recoils have higher ionization density → higher recombination probability → higher S1 yield

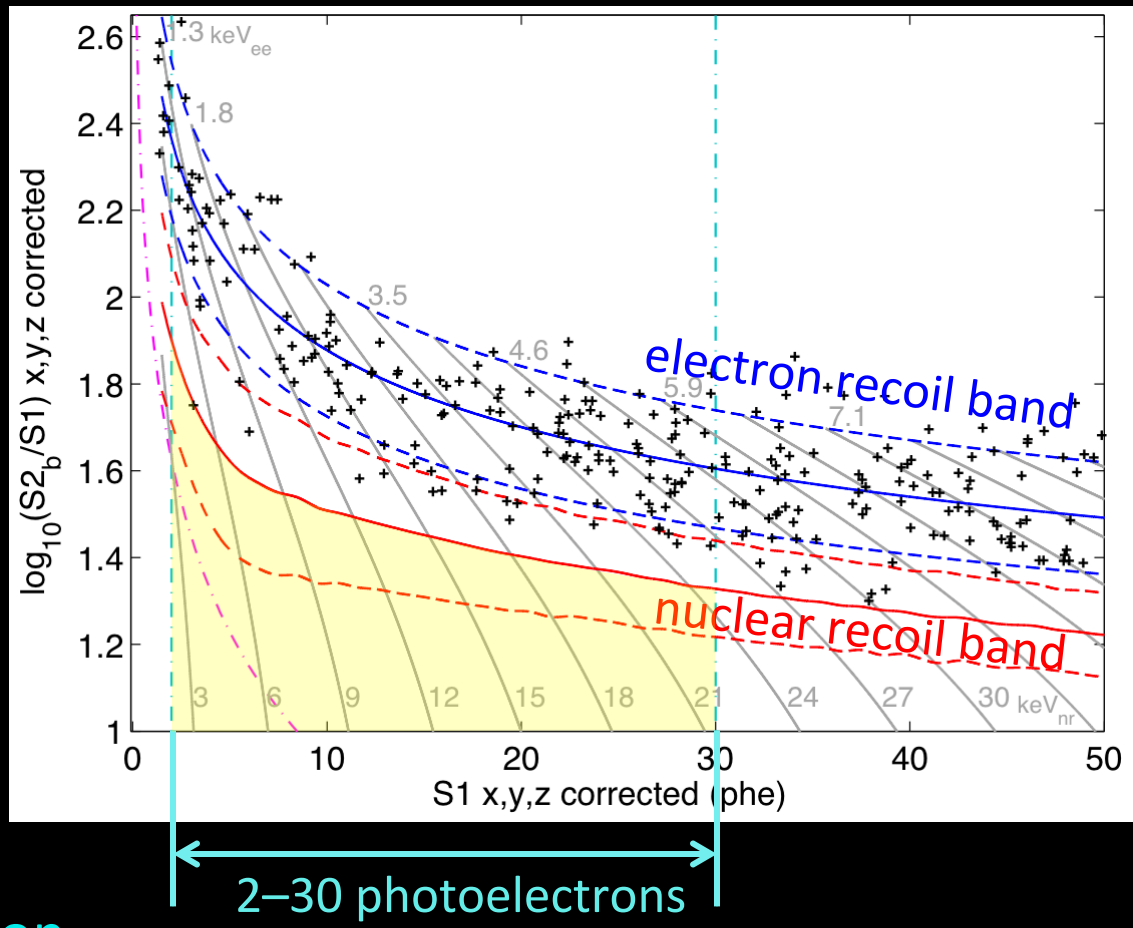
PMT Installation



LUX First Result

LUX, Phys. Rev. Lett. 112, 091303 (2014)

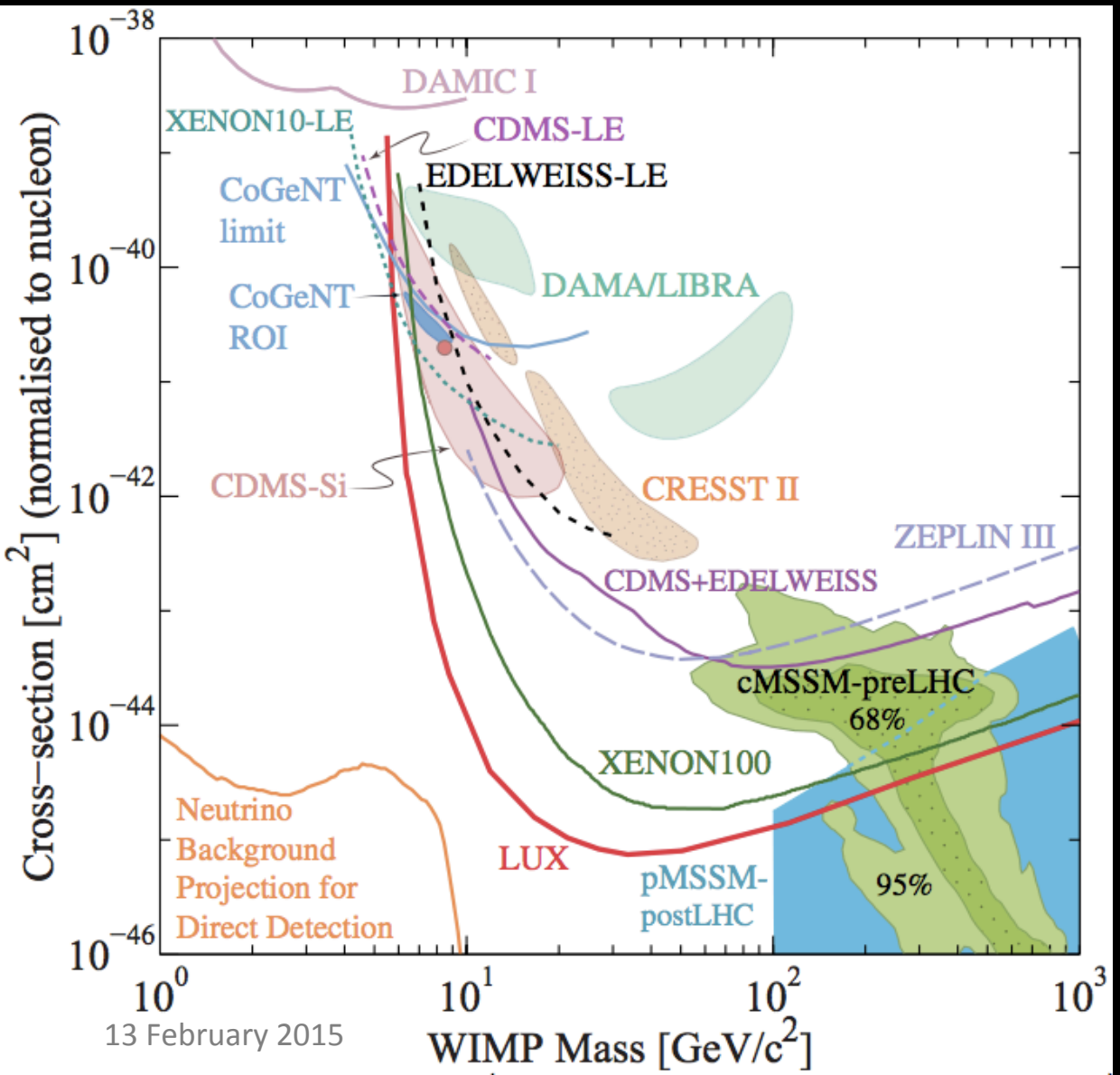
- 118 kg × 85.3 days
- 0 observed events below the mean S2/S1 for nuclear recoil
- Expected background from electron recoil is 0.64 ± 0.16 events
- Detection threshold is 4.3 keV for nuclear recoil



Set upper limit on the WIMP-nucleon cross section

- $< 7.6 \times 10^{-46}$ cm^2 (90% CL) for M_{WIMP} = 33 GeV

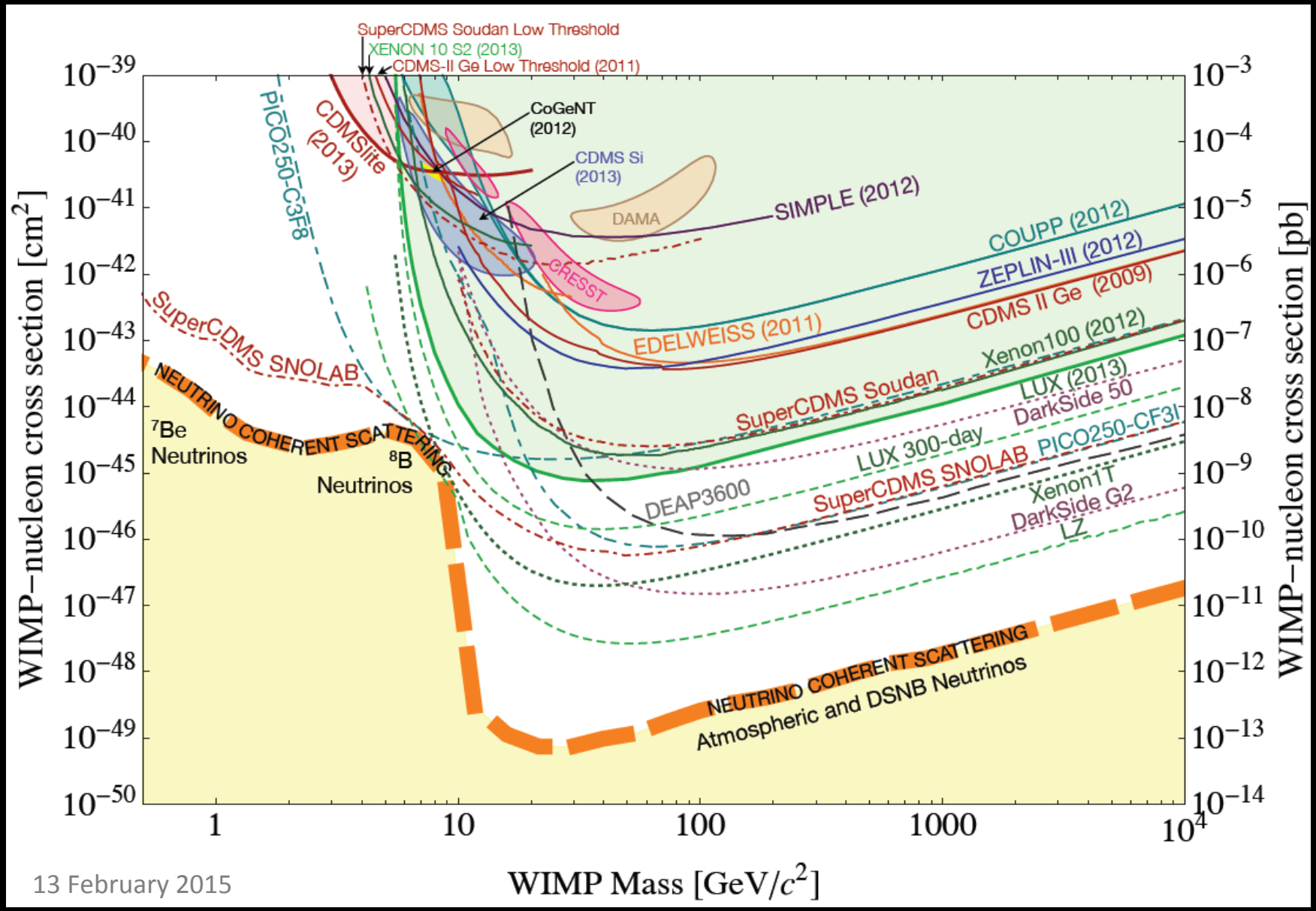
Direct Detection Limits



Limits on the spin-independent WIMP-nucleon cross section are ~10^{-45} cm^2 for 10–100 GeV WIMPs

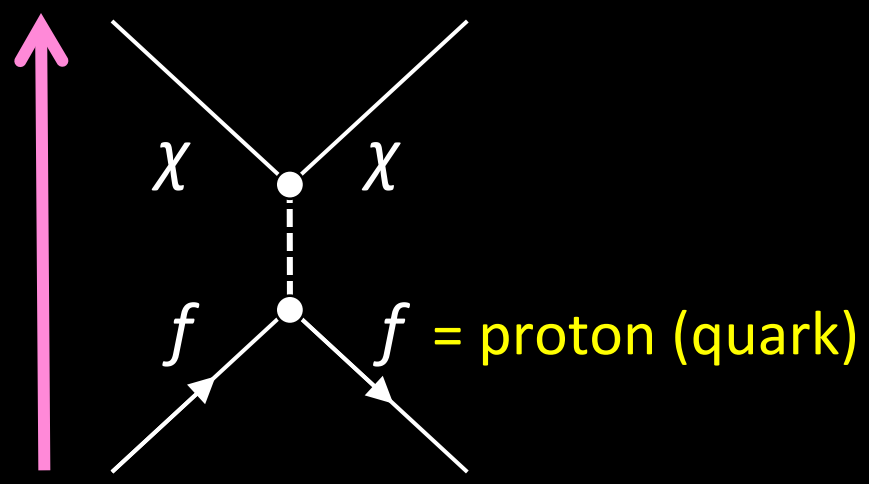
- XENON100 Phys. Rev. Lett. 109, 181301 (2012)
- LUX Phys. Rev. Lett. 112, 091303 (2014)

Direct Detection Landscape



DM Searches at the LHC

LHC can pair-produce WIMPs in proton-proton collisions



Production cross-section $\sigma(pp \to \chi\chi)$ is related to the DM relic density — but it's model-dependent

- Differently from $\sigma(N\chi \to N\chi)$

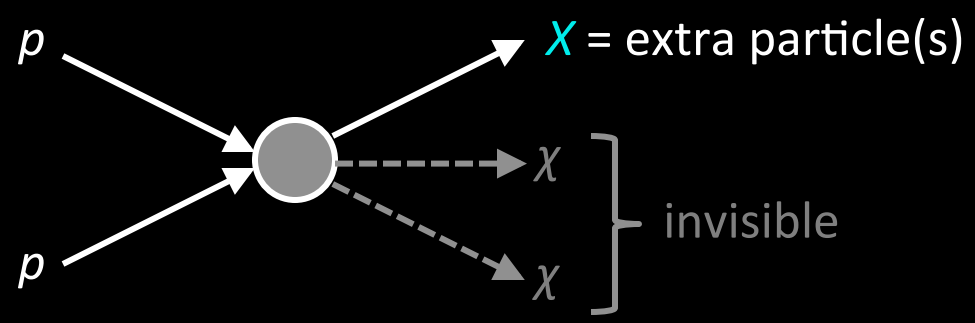
Final state with two WIMPs is invisible to the experiment

- How do we record and count such events?

Dark Matter Search at the LHC

$pp \rightarrow \chi\chi$ is undetectable

- We need ≥1 extra particles produced with the WIMPs



Signal event contains only *X*

- We call it "mono-*X*" with *X* = jet, photon, Higgs, *W*, *Z*, etc.

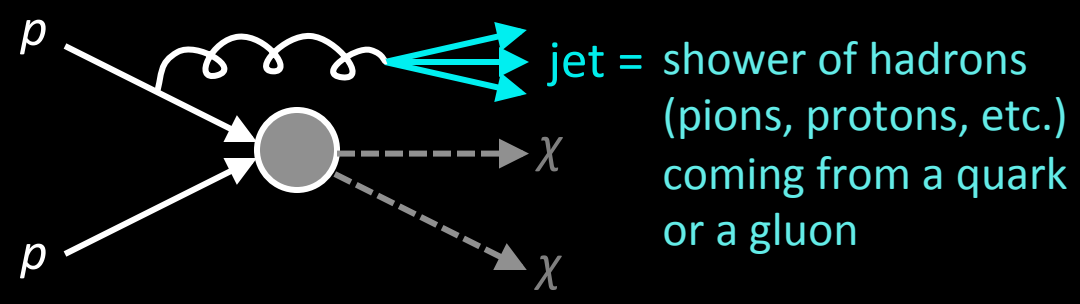
Net momentum of the outgoing particles seems to violate momentum conservation

- Momentum imbalance in the plane perpendicular to the proton beams = missing transverse momentum = "MET"

Mono-*X* Searches

Production cross-section $\sigma(pp \rightarrow \chi\chi X)$ is more model-dependent than $\sigma(pp \rightarrow \chi\chi)$

- Special case: X = QCD jet radiated from an incoming proton

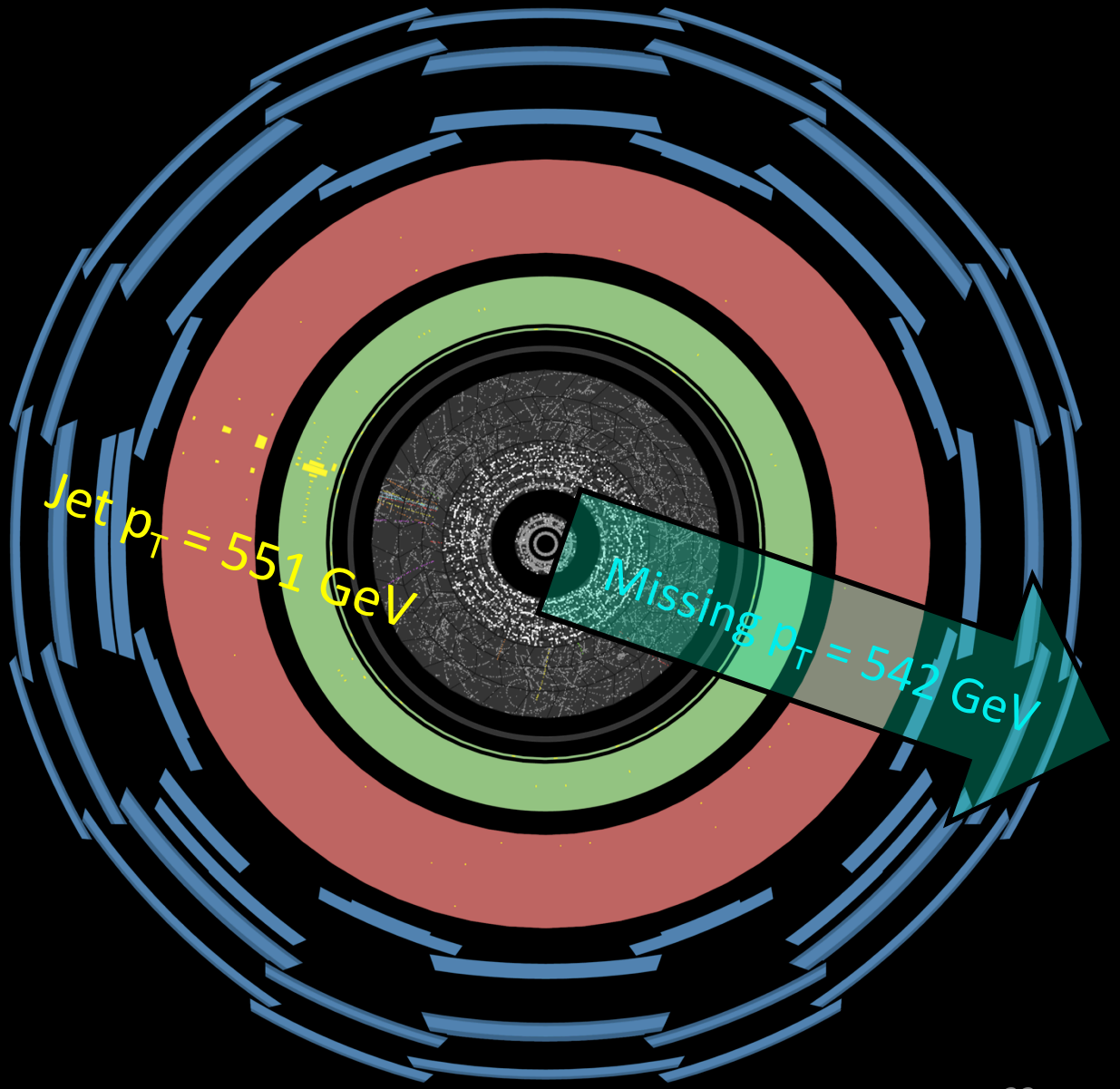


For most models of DM production, "mono-jet" gives the highest sensitivity among "mono-*X*" signatures

- Others (mono-photon, mono-Higgs, mono-*W*, mono-*Z*) can be more sensitive for specific theoretical models
- Interpretation can get messy

Mono-Jet Event in ATLAS

Highest p_T mono-jet event recorded by ATLAS at 7 TeV



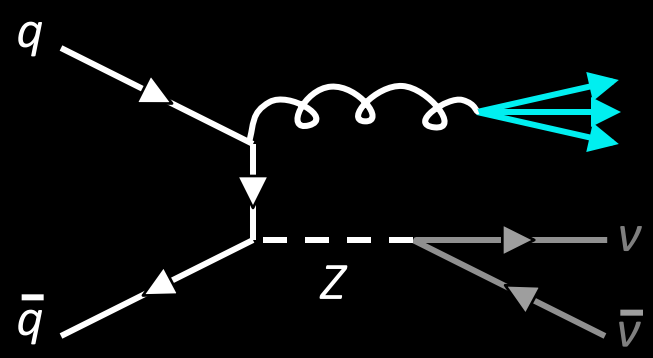
ATLAS Collab.
JHEP 1304 (2013) 075

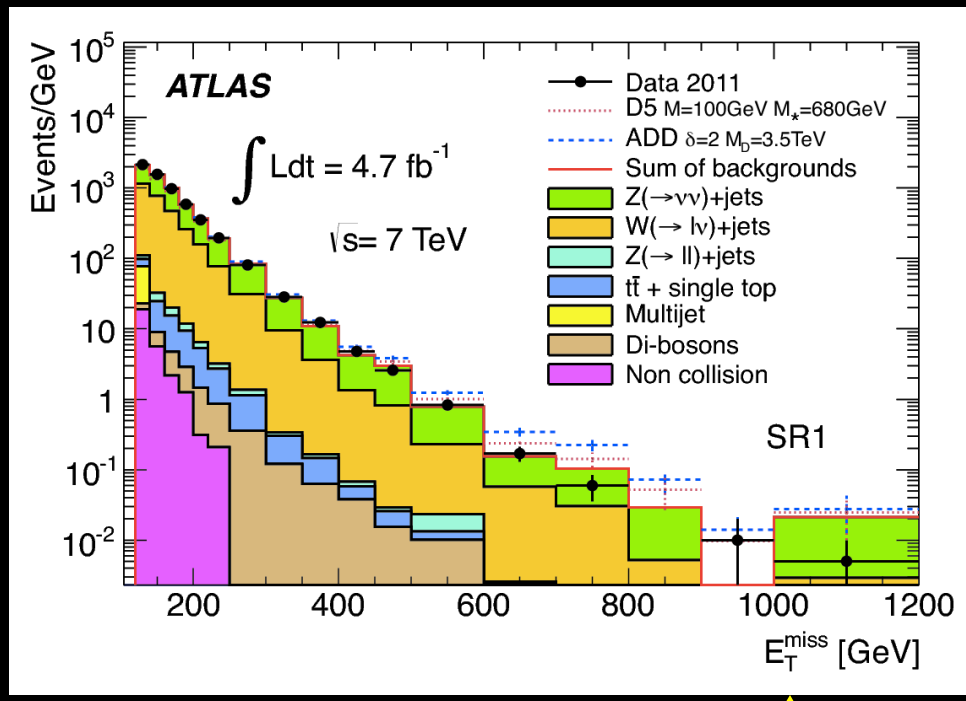
Background

ATLAS mono-jet 7 TeV, JHEP 04 (2013) 075

Dominant backgrounds are

- $Z\ (\rightarrow \nu\nu)$ + jets
- $W\ (\rightarrow \ell\nu)$ + jets





They are irreducible ➔ Estimate the rates and subtract

- Select Z or W + jets events where the Z or W decayed visibly

Look for an excess at large MET

Interpretation

LHC measures $\sigma(pp \rightarrow \chi\chi X)$

- How does it relate to the relic DM abundance?
- How does it compare against direct-detection experiments?

Both questions require theoretical assumptions

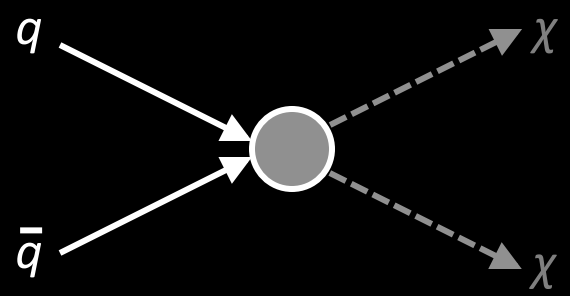
- What kind of WIMP is it? (mass, spin, parity)
- How does the WIMP interact?

Approach #1: Test theoretical models one-by-one

- Ex 1) Assume SUSY and constrain the model parameters
- Ex 2) Assume Large Extra Dimension [Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B 429 (1998) 263] and set limits on the mass scale for different number of extra dimensions
- Ex 3) … repeat for other models …

Interpretation

Approach #2: Effective Field Theory (EFT)



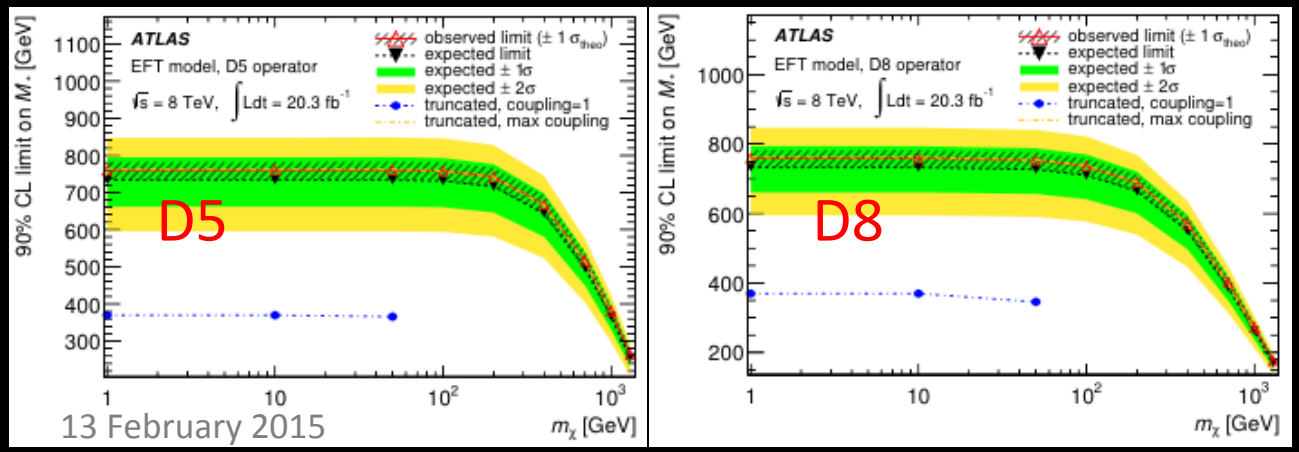
New physics at very high energy scale is integrated out (in the "dot")

- Write down all possible terms of the interaction
  - 14 terms if the WIMP is a Dirac fermion
  - Interaction strength is set by the scale M_*

Goodman et al., PRD 82 (2010) 116010

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

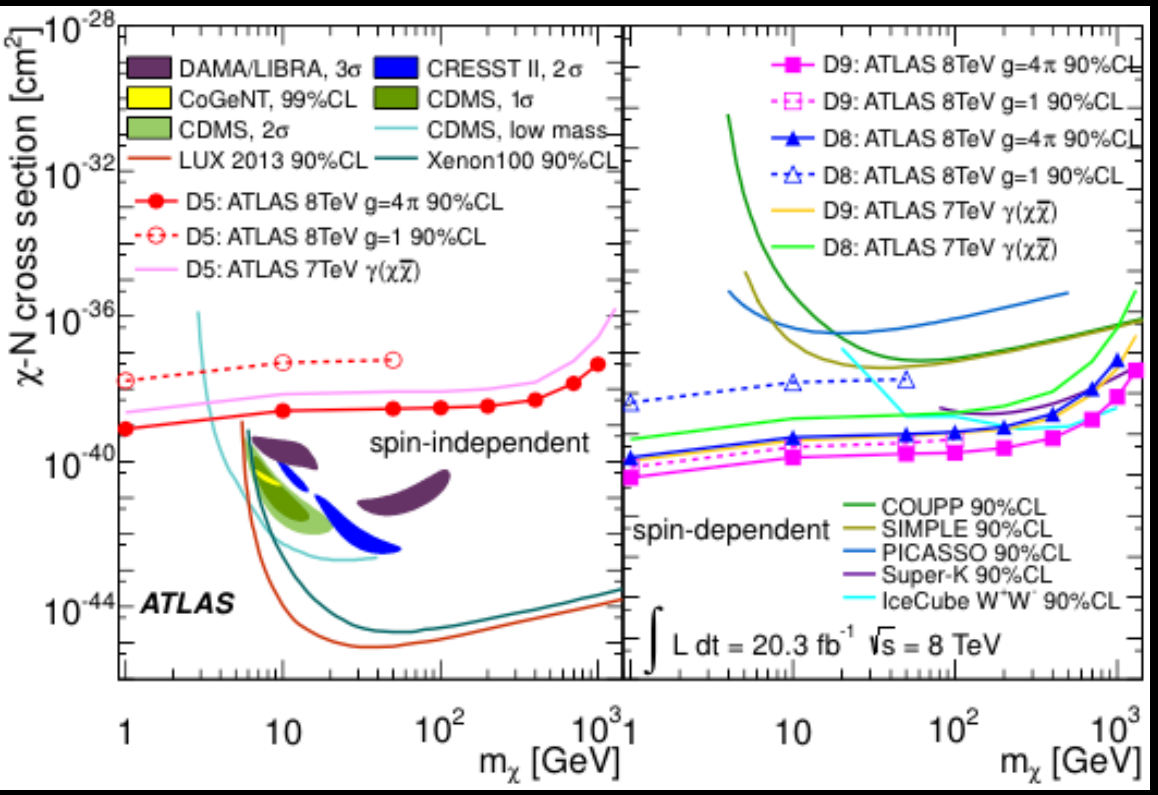
ATLAS mono-photon 8 TeV, arXiv:1411.1559



Direct-Detection vs. LHC

Caution: comparisons are strongly model-dependent

- Ex) EFT results from ATLAS mono-photon 8 TeV [arXiv:1411.1559]



Generally speaking,

- Direct-detection is more sensitive for heavy (> 10 GeV) WIMPs with spin-independent interactions
- LHC is more sensitive to light WIMPs, and to spin-dependent interactions

Summary and Prospect

Dark Matter ← convergence of astronomy and particle physics

- Evidences point to WIMPs waiting to be discovered

Direct-detection experiments search for Dark Matter in elastic $\chi N \rightarrow \chi N$ scattering

- Sensitive to >10 GeV WIMPs down to $\sigma_{\chi N} \approx 10^{-45}$ cm^2
- Next-generation experiments will push into the region favored by SUSY

LHC searches for Dark Matter in $pp \rightarrow \chi\chi + X$ production

- Sensitive to broader WIMP masses and spin-dependent interactions
- LHC Run 2 will improve the sensitivity very soon

Interpretation of results are often model-dependent

- Careful with plots that are valid only for particular form of interactions

Next 10 years will be exciting for Dark Matter

References

Direct detection experiments

- XENON100, arXiv:1207.5988, Phys. Rev. Lett. 109 (2012) 181301
- LUX, arXiv:1310.8214, Phys. Rev. Lett. 112 (2014) 091303
- SuperCDMS, arXiv:1402.7137, Phys. Rev. Lett. 112 (2014) 241302

ATLAS mono-X results

- X = photon, 8 TeV, arXiv:1411.1559, submitted to Phys. Rev. D
- X = heavy quark, 8 TeV, arXiv:1410.4031, submitted to Eur. Phys. J. C
- X = $Z \rightarrow \ell\ell$, 8 TeV, arXiv:1404.0051, Phys. Rev. D 90 (2014) 012004
- X = W or $Z \rightarrow qq$, 8 TeV, arXiv:1309.4017, Phys. Rev. Lett. 112 (2014) 041802
- X = jet, 7 TeV, arXiv:1210.4491, JHEP 04 (2013) 075

New Physics — Where?

From the labs — Unexplained experimental data

- Ex: nuclear β decays violate energy conservation → neutrinos
- Much of the 20th-century particle physics was driven by data
- Today: all HEP data are consistent with the Standard Model

From imagination — Quest for consistency/symmetry/beauty

- Ex: equivalence principle → general relativity
- Few of the many brilliant ideas succeed
- Today: too many ideas to fit on this slide

From the sky

- Ex: matter-dominant universe → CP violation
- Particle physics and astronomy must agree on the observable universe
- Today: Dark Matter and Dark Energy

What is Dark Matter Made Of?

Neutrino

- SM neutrinos are too light
- Heavy sterile neutrino?

WIMP

- ~100 GeV mass particles with Weak interactions

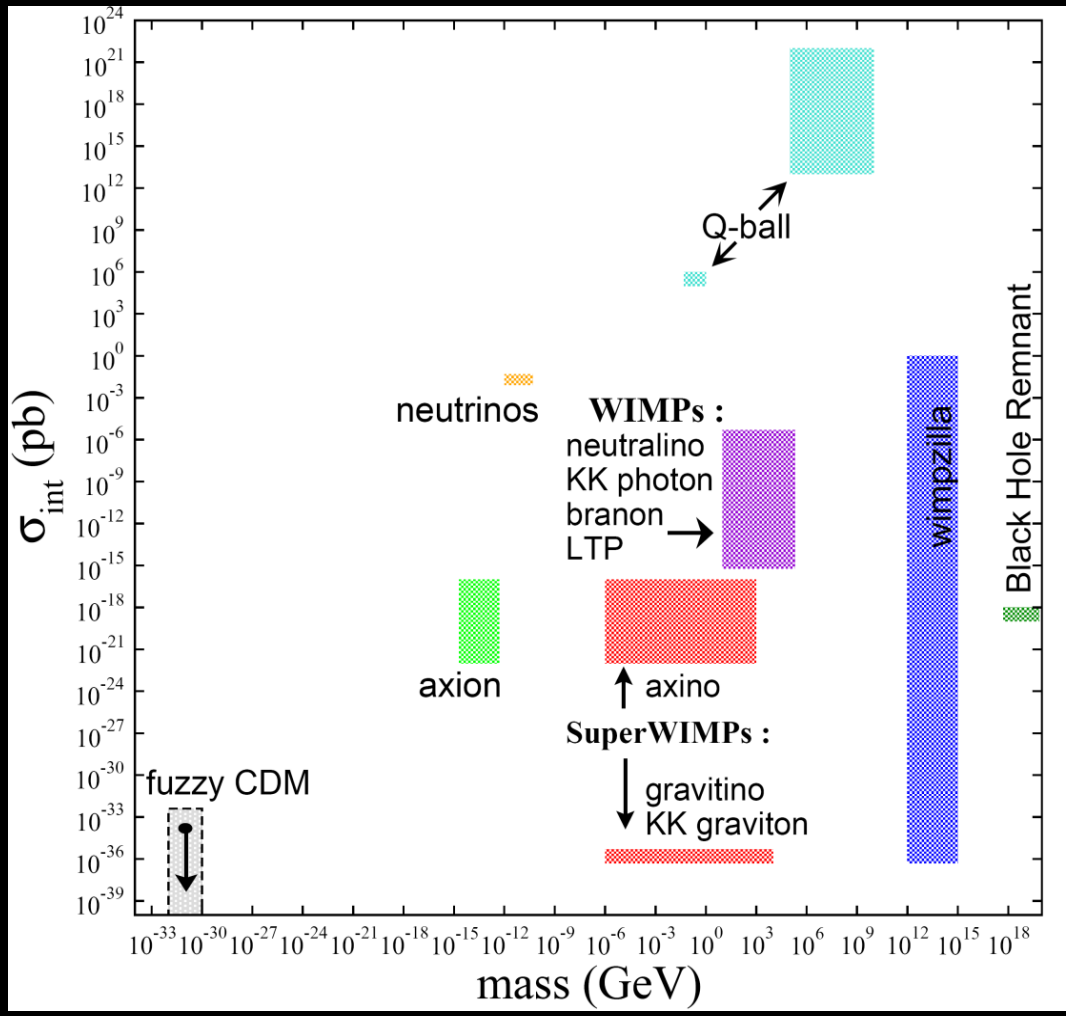
Axion

- Cold even with small masses

SuperWIMP

- Weaker-than-EW interactions
- Axino, gravitino, KK gravitons

Many many others ...



HEPAP/AAAC DMSAG Subpanel (2007)

Other Searches at the LHC

Many searches for heavy new particles that decay to Dark Matter

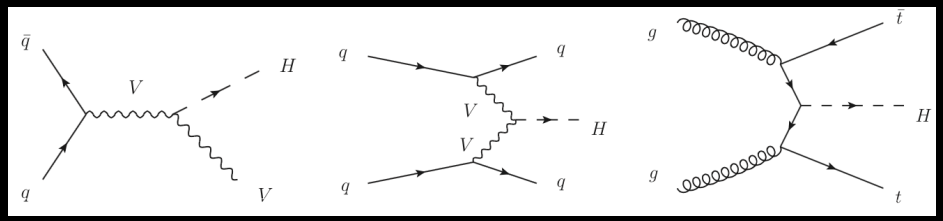
- SUSY, Little Higgs, Extra Dimensions …
- Typical signature includes MET due to escaping WIMPs

Signal rate depends on the nature and the mass of the heavy particle

- Interpretation as a "DM Search" is complicated

Suppose Higgs is the only connection between the Standard Model and Dark Matter

- Search for decays of Higgs → DM
- Higgs produced with other particles: ZH, qqH, ttH



Combine ATLAS + CMS

- BR(H → invisible) < 0.40

[Zhou et al., arXiv:1408.0011]

Interpret within the Higgs-portal model

- Strong limit on fermion DM, but highly specific to the model