Experimental Searches for Dark Matter

Masahiro Morii

HARVARD UNIVERSITY
Department of Physics

ATLAS EXPERIMENT

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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}	0.048 ± 0.001	Ordinary Matter
Ω_{CDM}	0.257 ± 0.006	Cold Dark Matter
Ω_{Λ}	0.694 ± 0.007	Dark Energy
Ω_{total}	1.000 ± 0.005	Flat Universe

Planck, Astronomy & Astrophysics **594**, A13 (2016)

What We Know about Dark Matter

Dark Matter must be there

- ~26% 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 $\sigma_v \sim 230$ km/s
  - Simplest model, but not necessarily true

Dark Matter is not part of the Standard Model

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

On the Particle Physics Side…

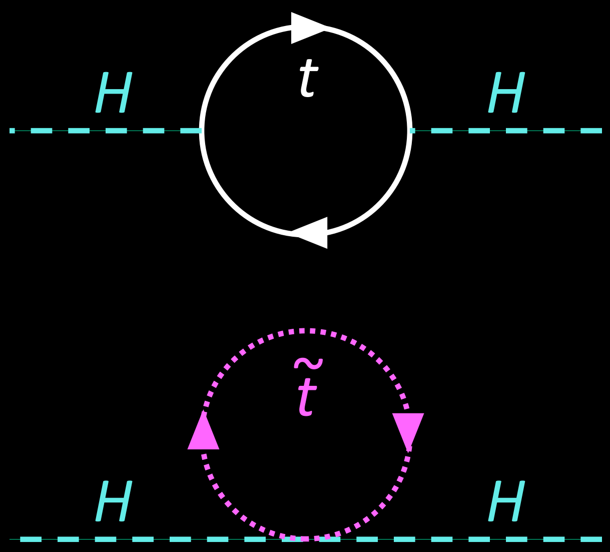
Higgs discovered (2012) with m_H = 125 GeV

- 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 SM particle and its super-partner 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)

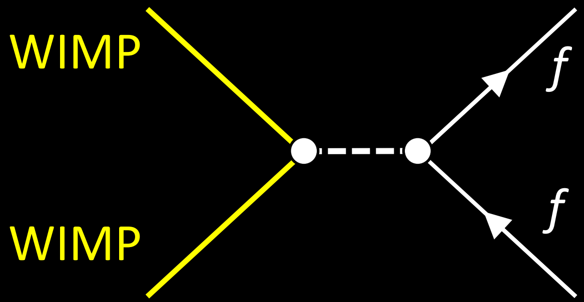
- We haven't discovered any ☹

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



Would there be enough WIMPs around us?

WIMP Relic Density

WIMPs were in thermal equilibrium with ordinary particles after inflation

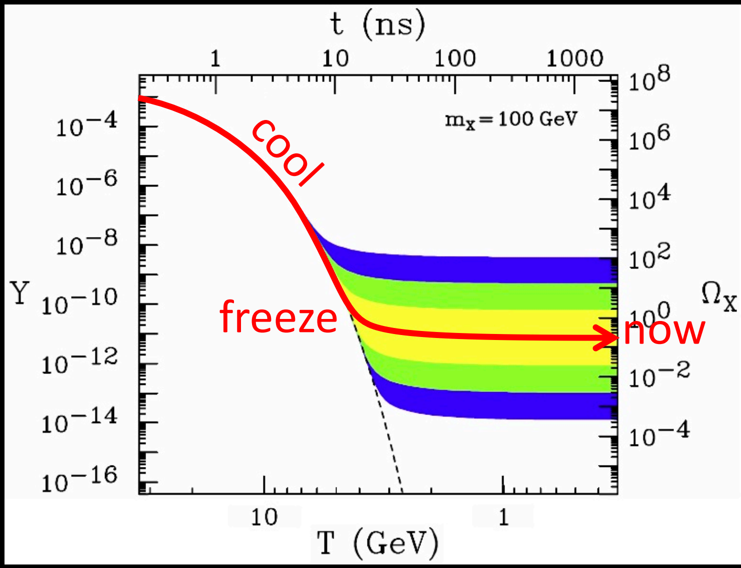
- As the Universe cools, their density drops as

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

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

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

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

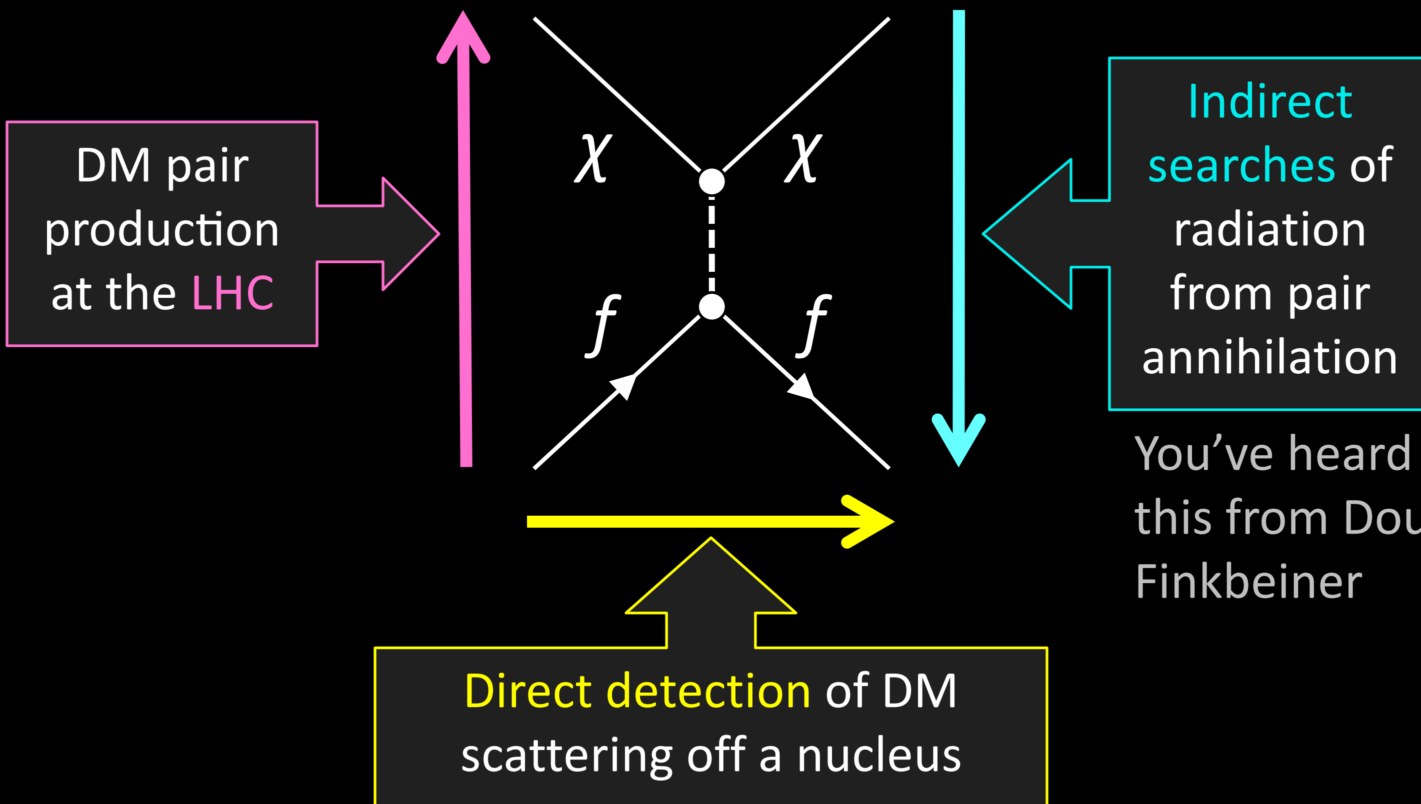


Feng, arXiv:1003.0904 [astro-ph.CO]

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

Dark Matter Hunting

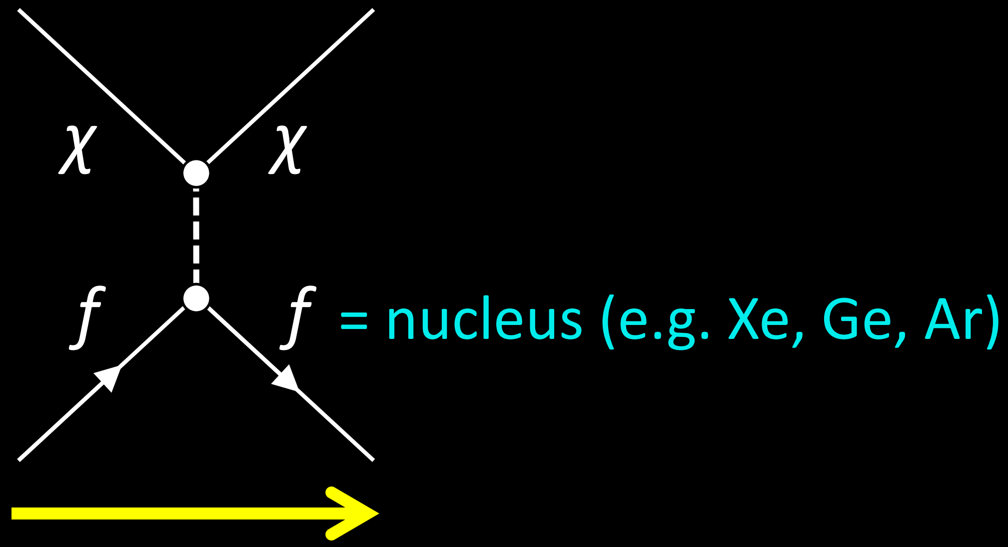
Going beyond gravity, three ways to detect Dark Matter



You've heard about this from Doug Finkbeiner

Direct DM Detection

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

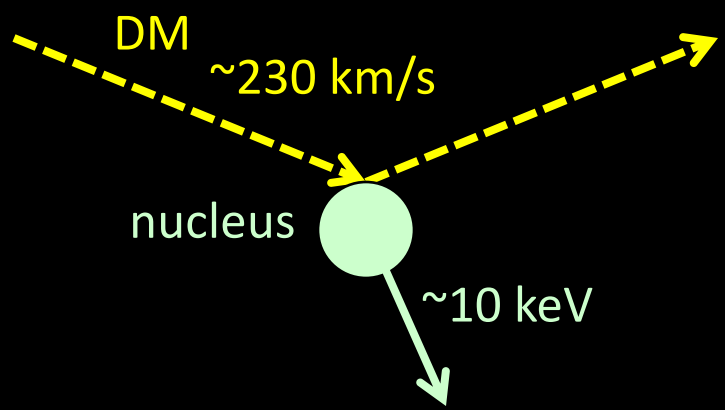


Elastic scattering cross-section $\sigma(N\chi \to N\chi)$ is related to the DM relic density — but it's model-dependent

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



Direct DM detection experiment must

- detect elastic $\chi N \rightarrow \chi N$ with small recoil energy E_N ~ 10 keV
- be scalable to > 100 kg

Few good choices

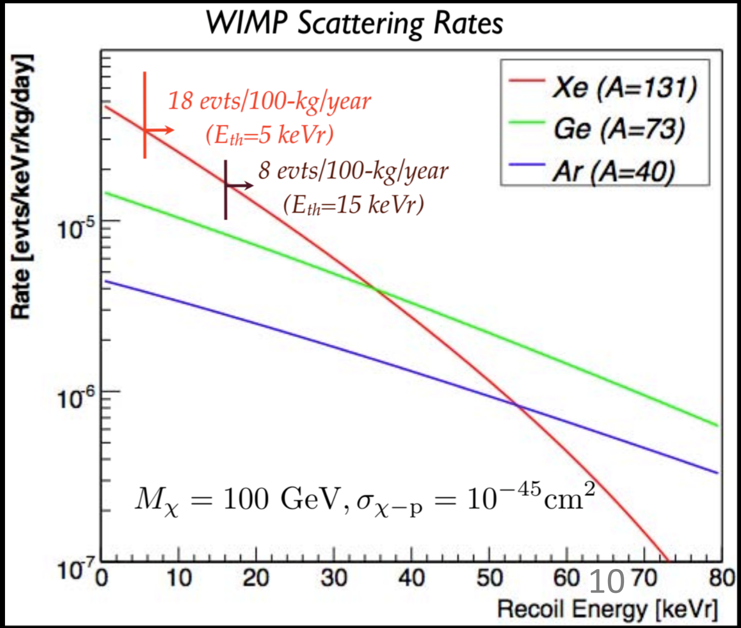
- Noble liquid — ionization and scintillation
- Cryogenic semiconductor — ionization and heat (phonons)

WIMP-nucleus cross section $\propto A^2$

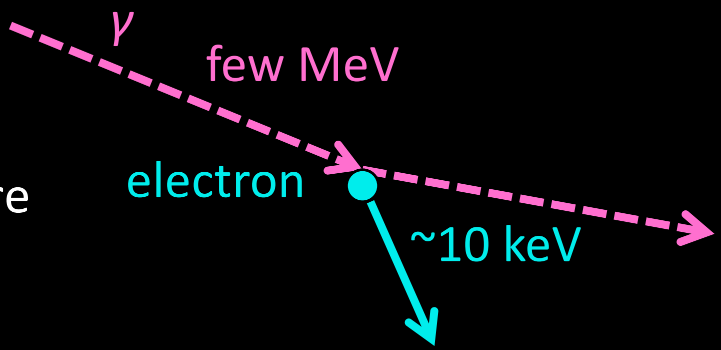
➔ Xe > Ge > Ar > Si

E_N becomes small if WIMP is lighter than the nucleus

➔ Xe < Ge < Ar < Si



Background



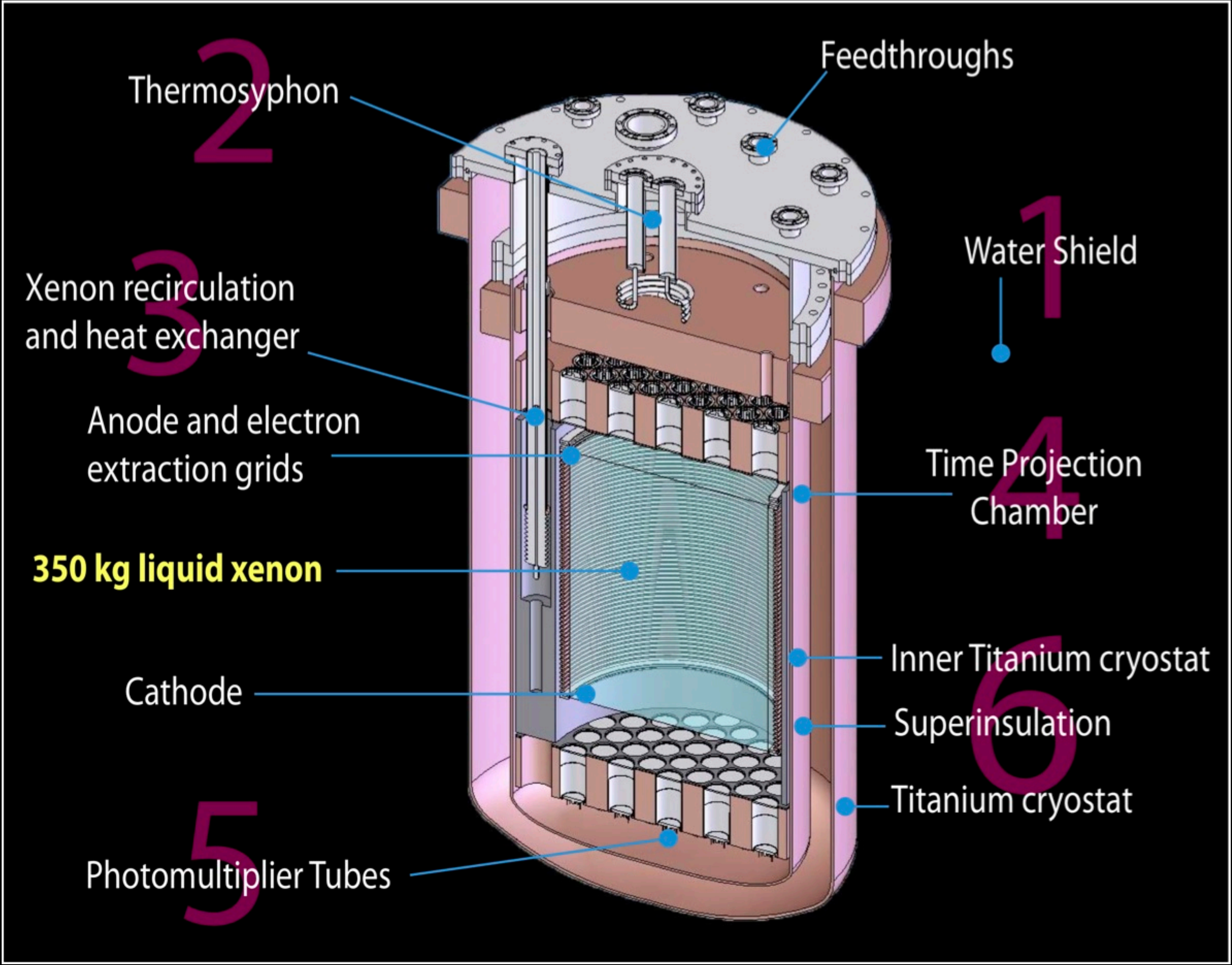
Background sources:

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

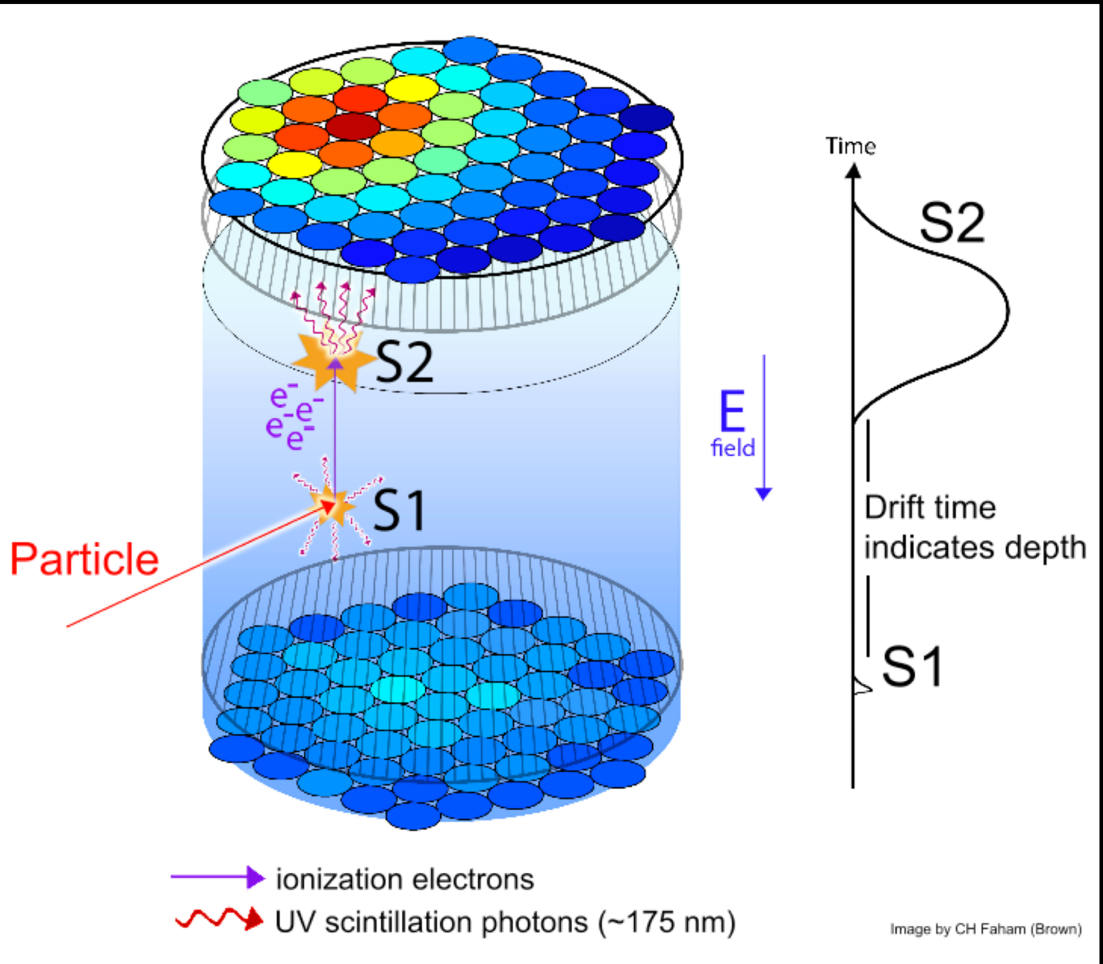
To combat the backgrounds

- Go deep underground → Avoid cosmogenic neutrons
- Eliminate radioisotopes (U, Th, Rn) from the detector
- Determine the $\chi N \to \chi N$ scattering location in the detector
  → Reject surface events
- Distinguish nuclear vs. electron recoils

Liquid-Xe Experiment (ex: LUX)



Two-Phase Xe Detector



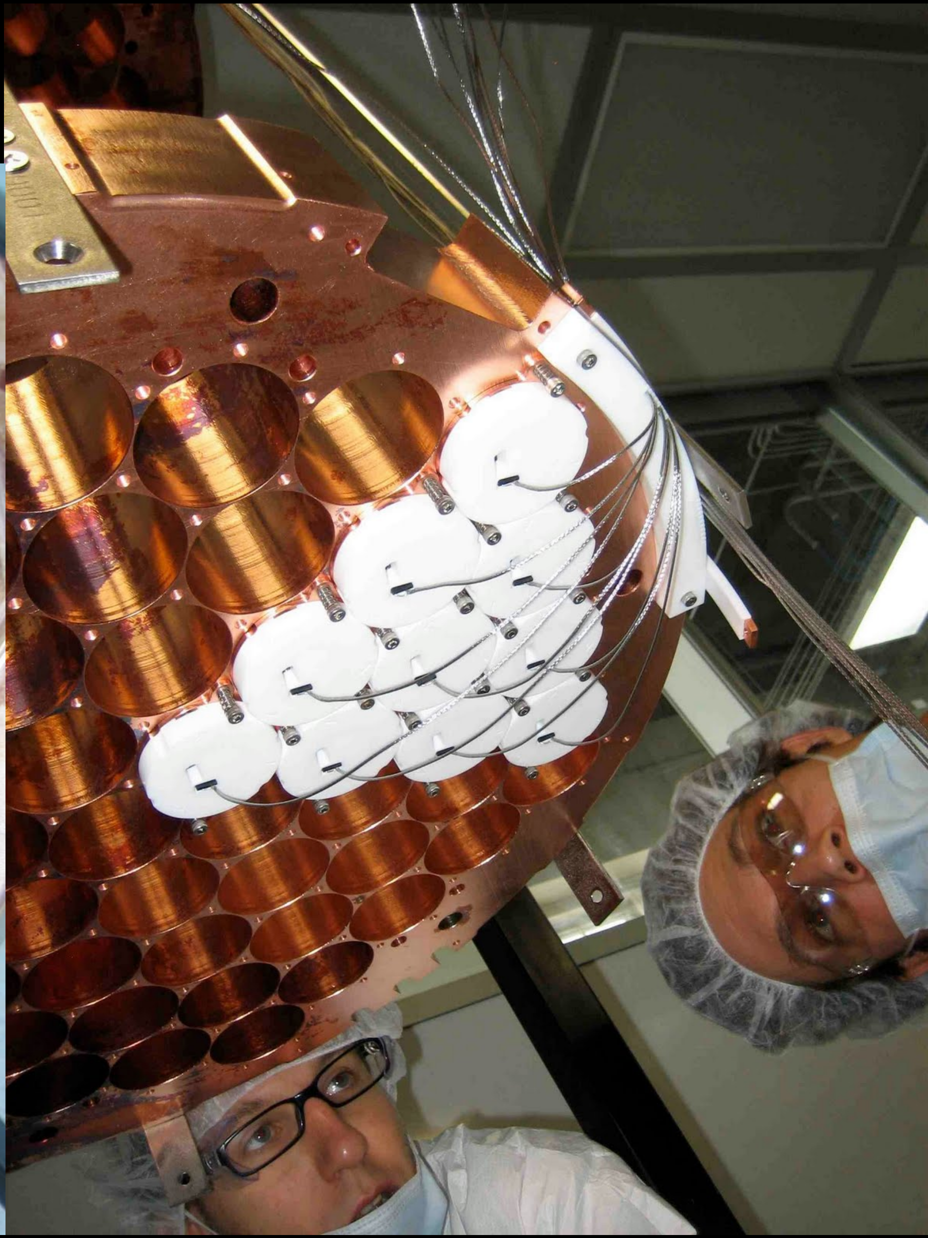
PMTs collect prompt (S1) and proportional (S2) light

- 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

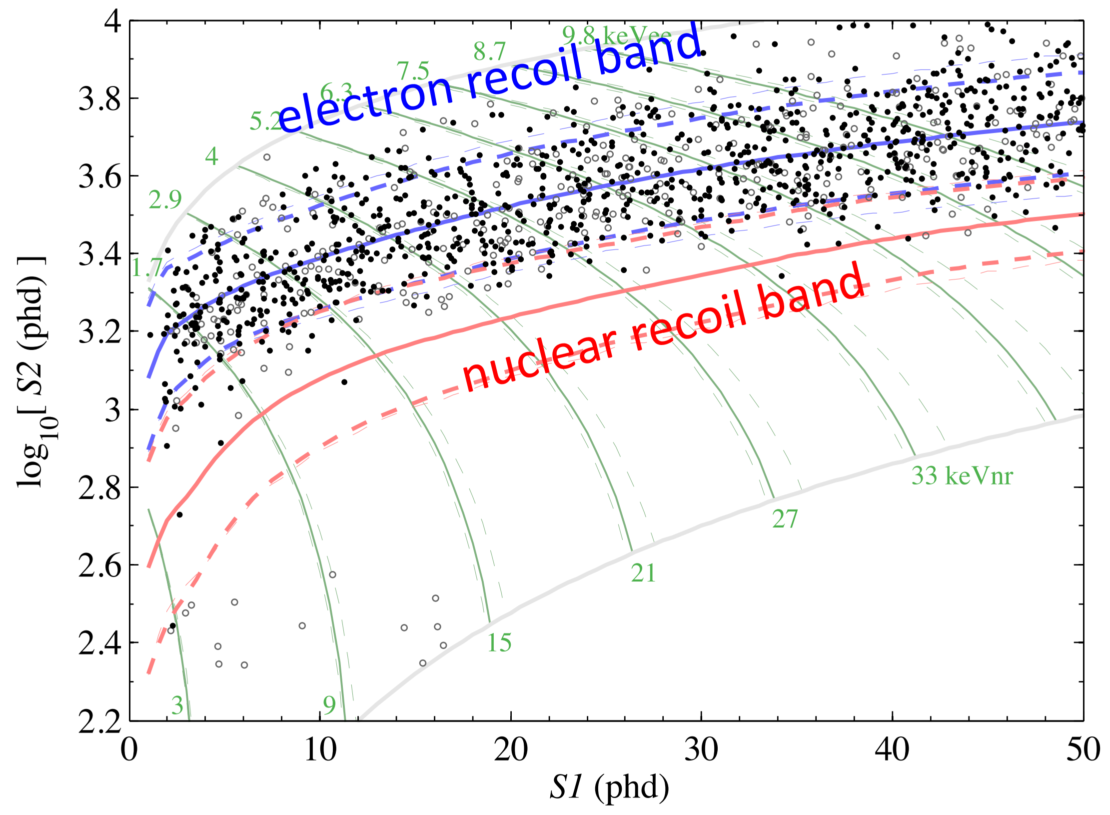


LUX Full Data Result

LUX, Phys. Rev. Lett. 118, 021303 (2017)

101 kg × 332 days of data on the S2-vs-S1 plane →

- ~1200 events in the electron recoil band
  → γ and β background
- ~10 PTFE-surface radon background events
- No evidence of WIMP recoil events in the nuclear recoil band



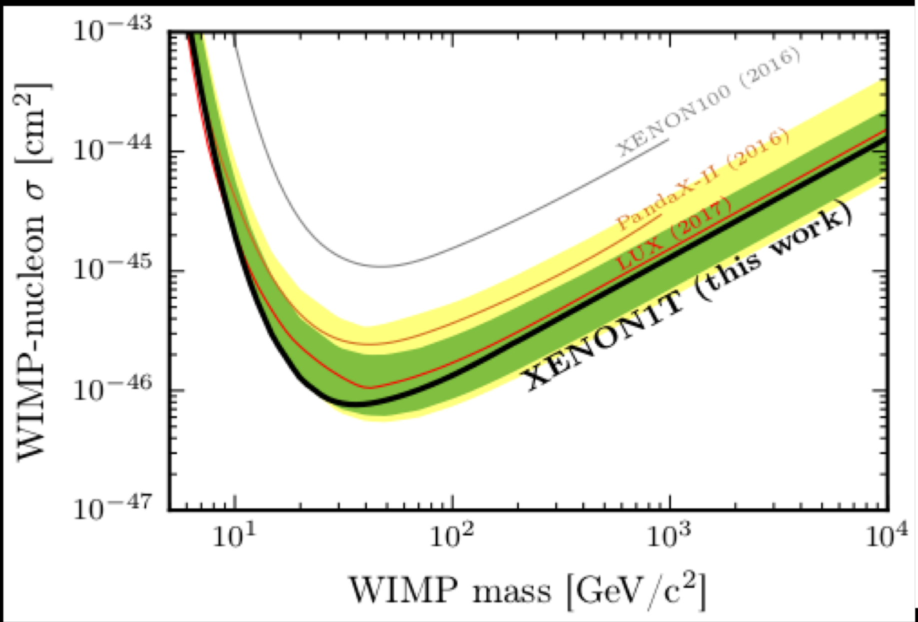
Set upper limit on the WIMP-nucleon cross section

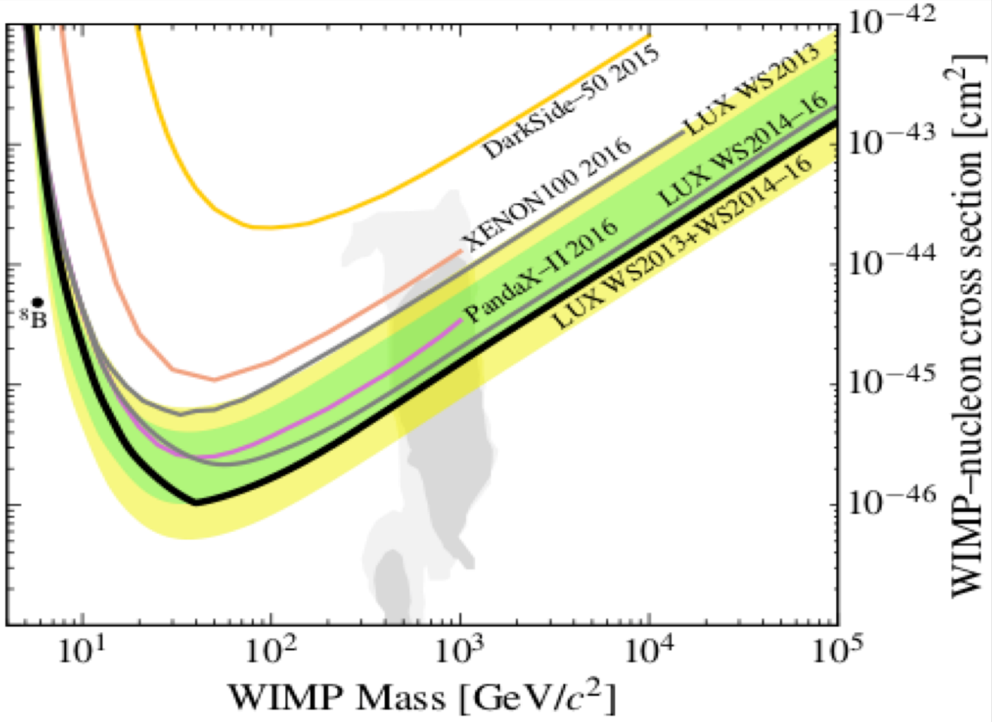
Direct Detection Limits

Limits on the spin-independent WIMP-nucleon cross section are ~10^{-46} cm^2 for 20–100 GeV WIMPs

LUX, Phys. Rev. Lett. 118, 021303 (2017)

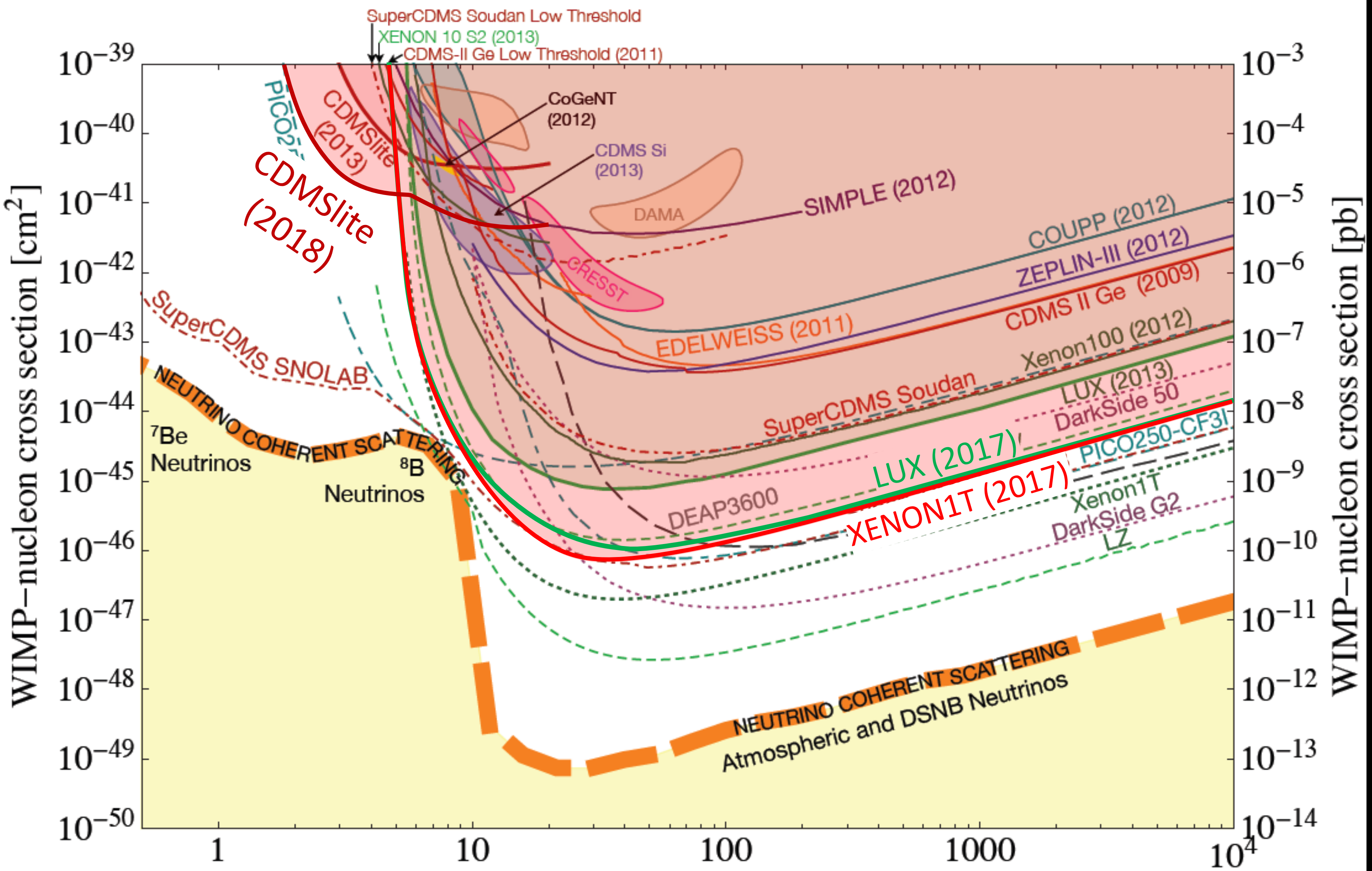
XENON1T, Phys. Rev. Lett. 119, 181301 (2017)





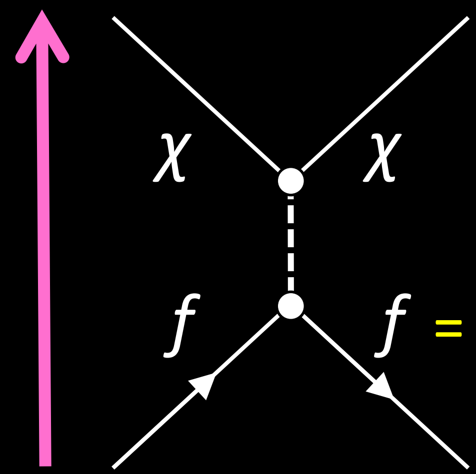
- Coming soon: XENON1T will present their 1 ton*year result on May 28

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 $\sigma(N\chi \to N\chi)$

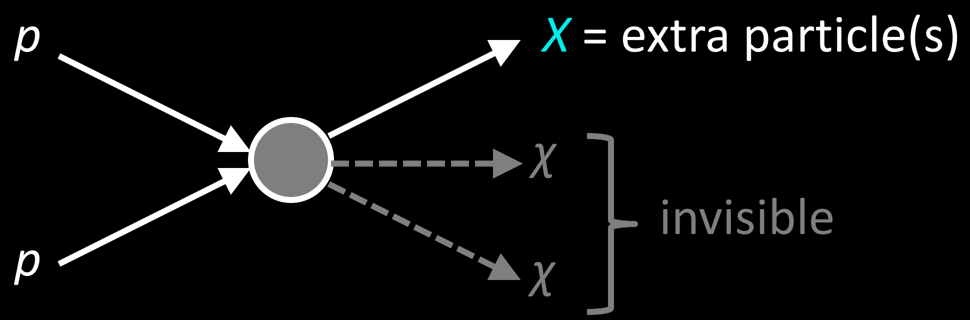
Final state with two WIMPs is invisible to the experiment

- 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.

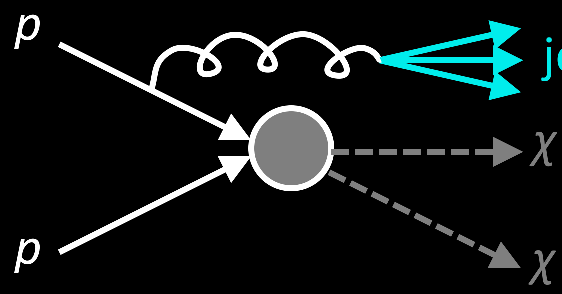
Net momentum of the outgoing particles seems to violate momentum conservation

- 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



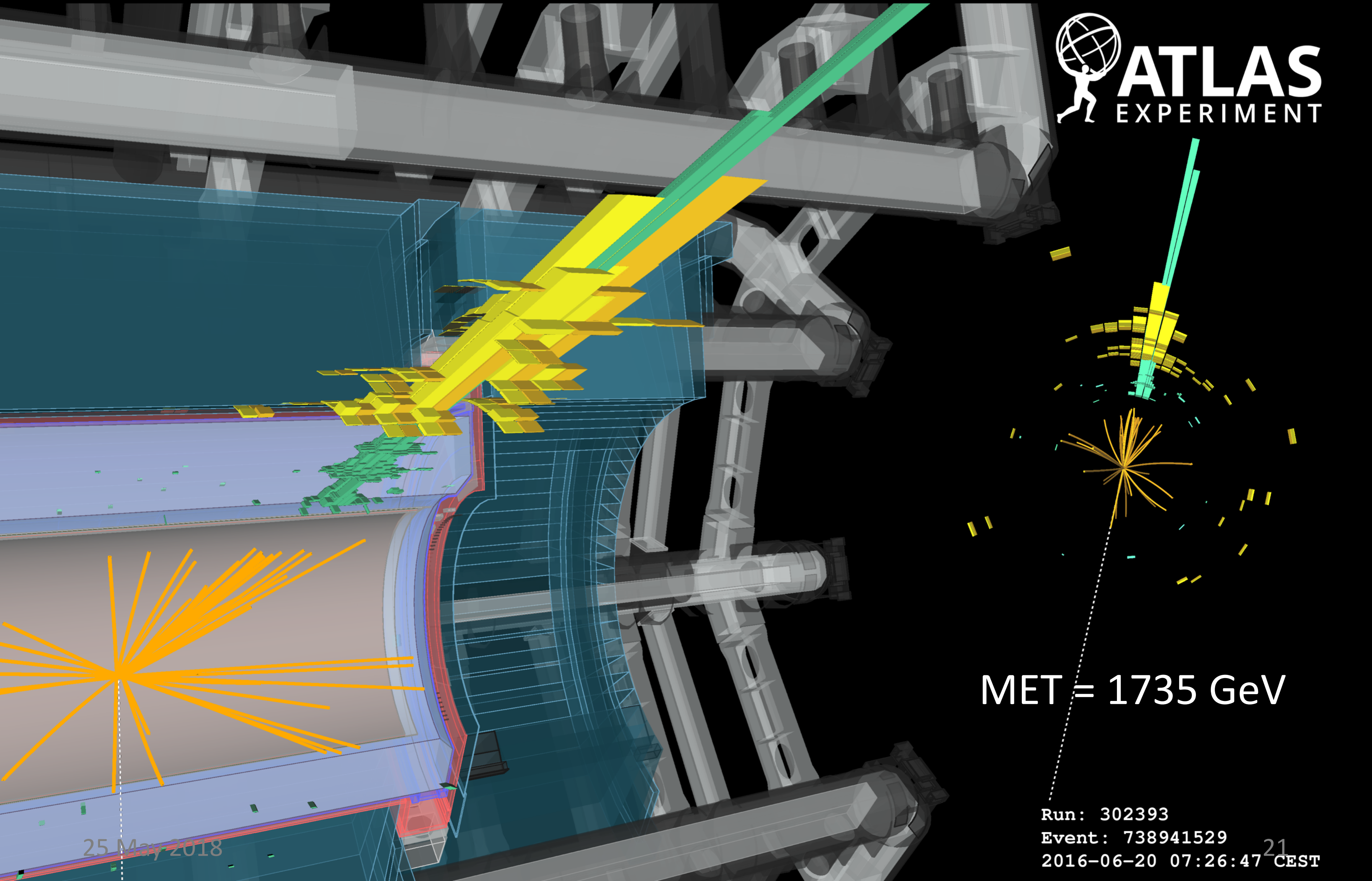
jet = shower of hadrons (pions, protons, etc.) coming from a quark or a gluon

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

ATLAS-CONF-2017-060

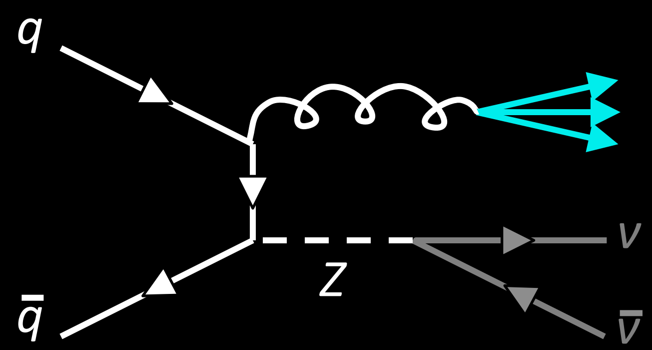


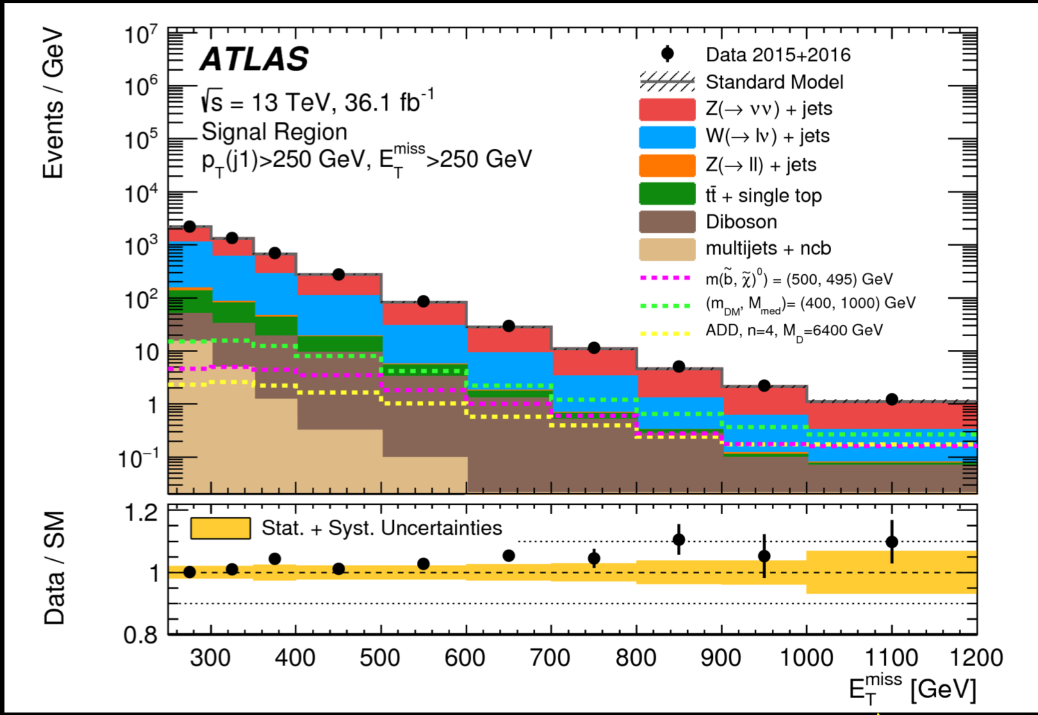
Background

ATLAS JHEP 01 (2018) 126

Dominant backgrounds are

- $Z\,(\to \nu\nu)$ + jets
- $W\,(\to \ell\nu)$ + 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?

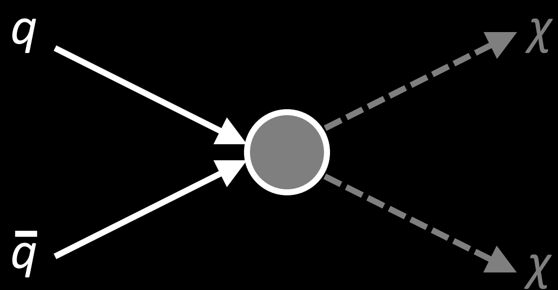
Approach #1: Test theoretical models one-by-one

- 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

Goodman et al., PRD 82 (2010) 116010

Approach #2: Effective Field Theory (EFT)

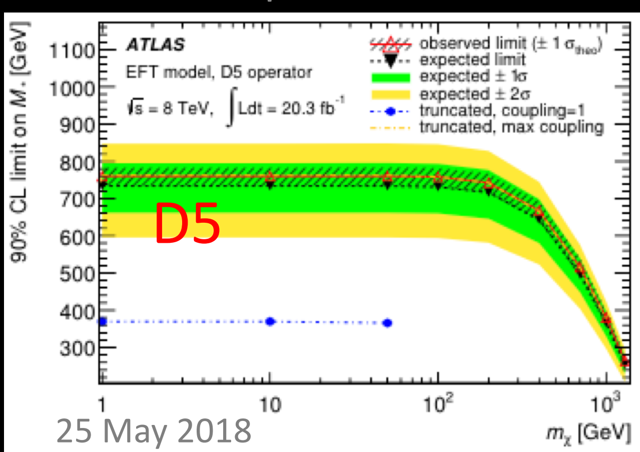


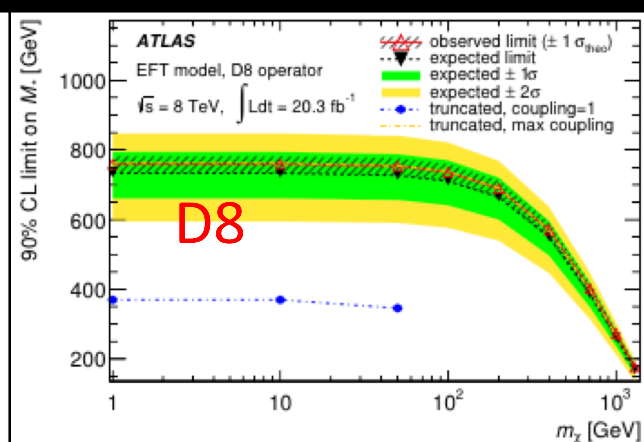
New physics at very high energy scale is integrated out (in the “dot”)

- 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_*

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



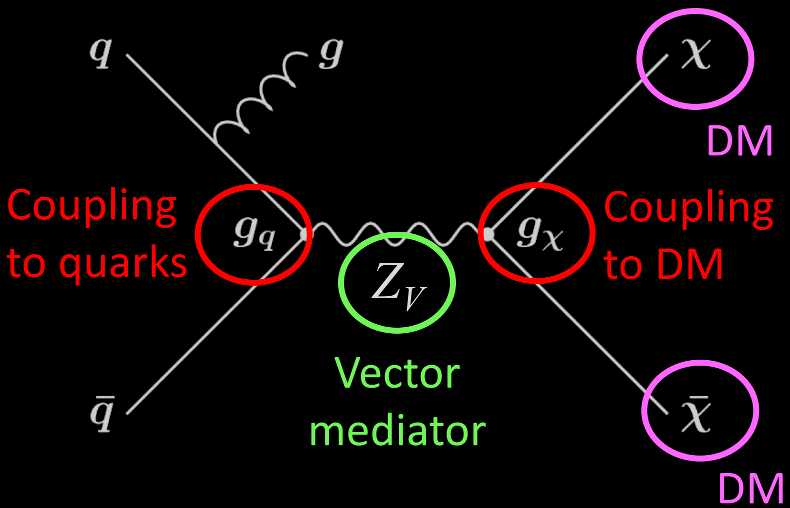


Interpretation

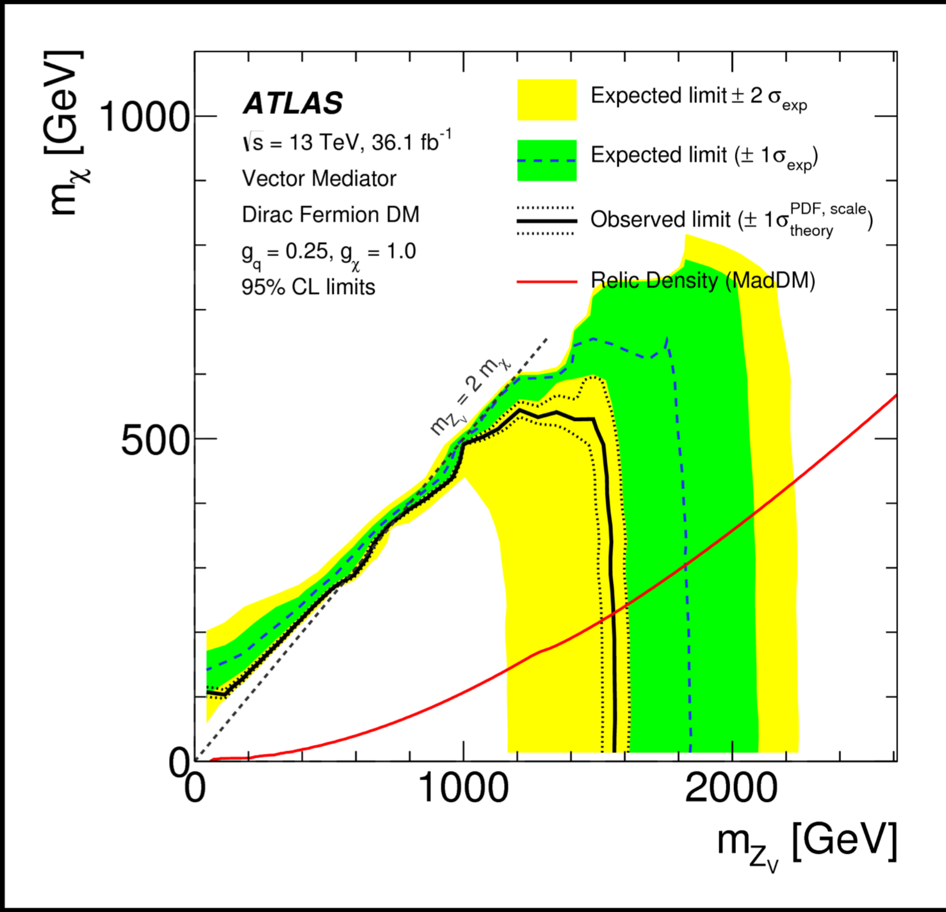
ATLAS JHEP 01 (2018) 126

Approach #3: Simplified Models

- Consider generic diagrams with a few free variables, e.g.:



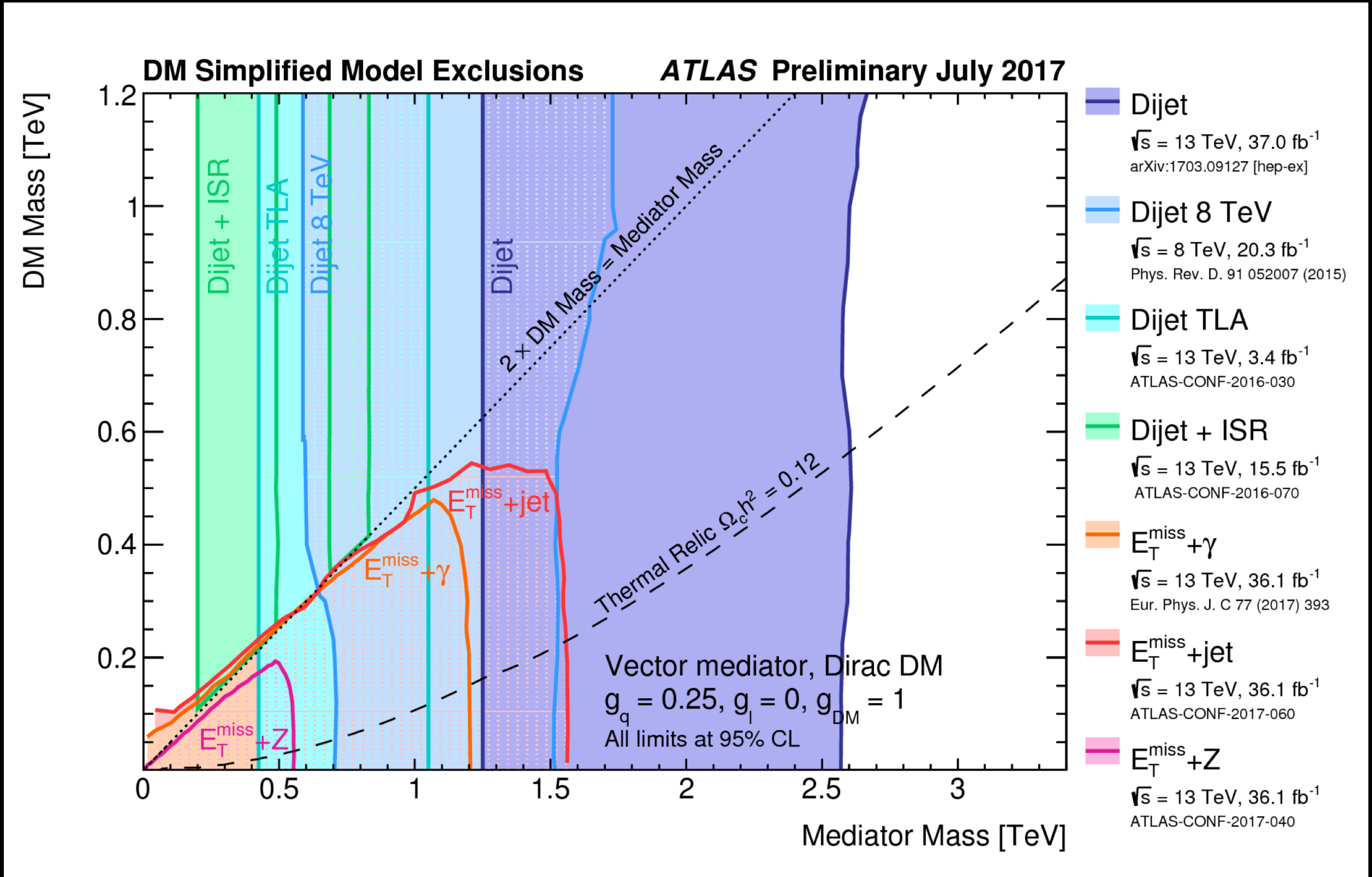
- Constrain DM mass, mediator mass, and coupling constants



Combining LHC Searches

LHC searches depend heavily on the mediator mass/couplings

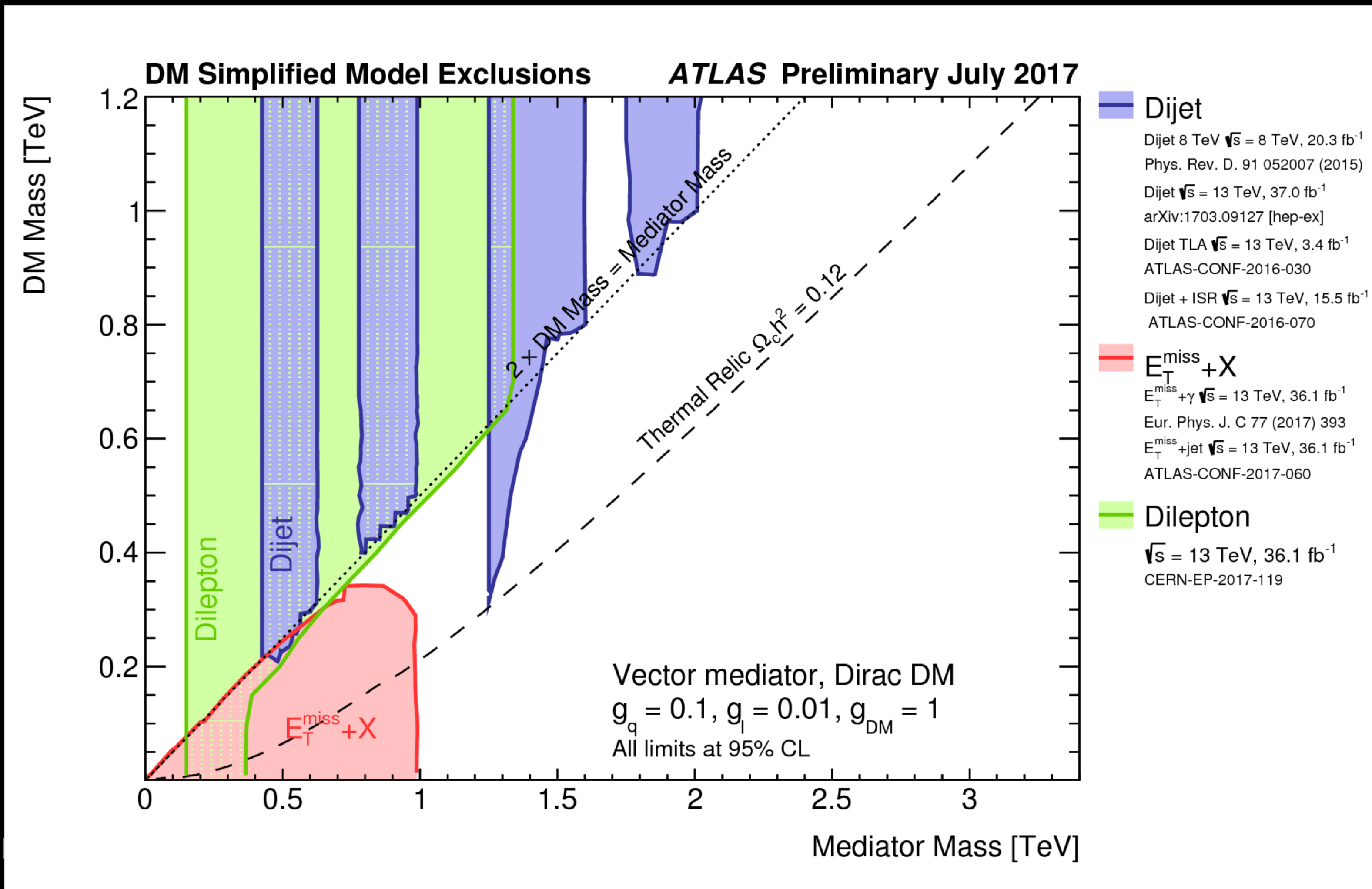
- If it couples strongly to quarks/leptons, it would be found as a resonance



Combining LHC Searches

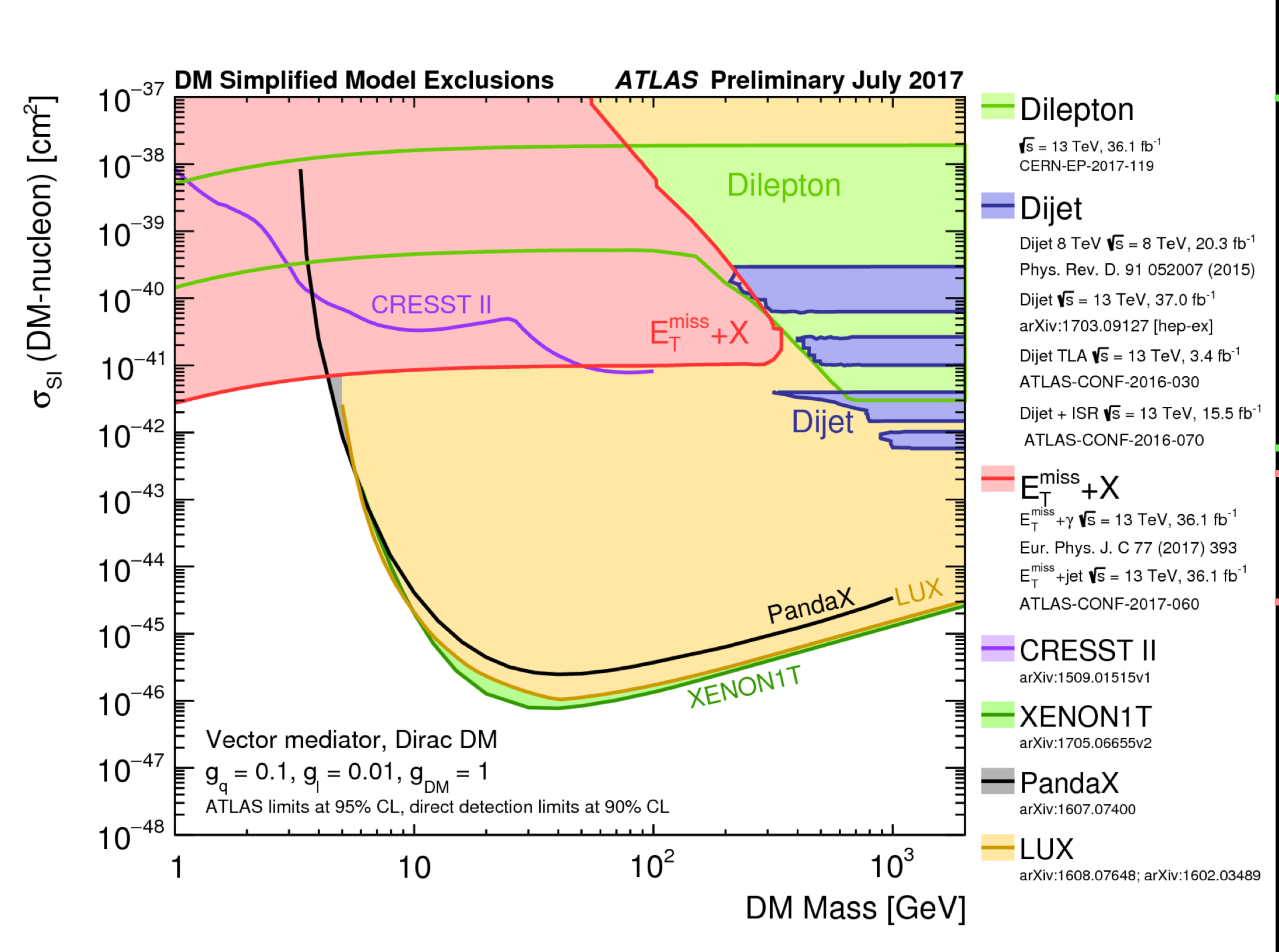
LHC searches depend heavily on the mediator mass/couplings

- Very different picture if the mediator couples mostly to DM



Direct-Detection vs. LHC

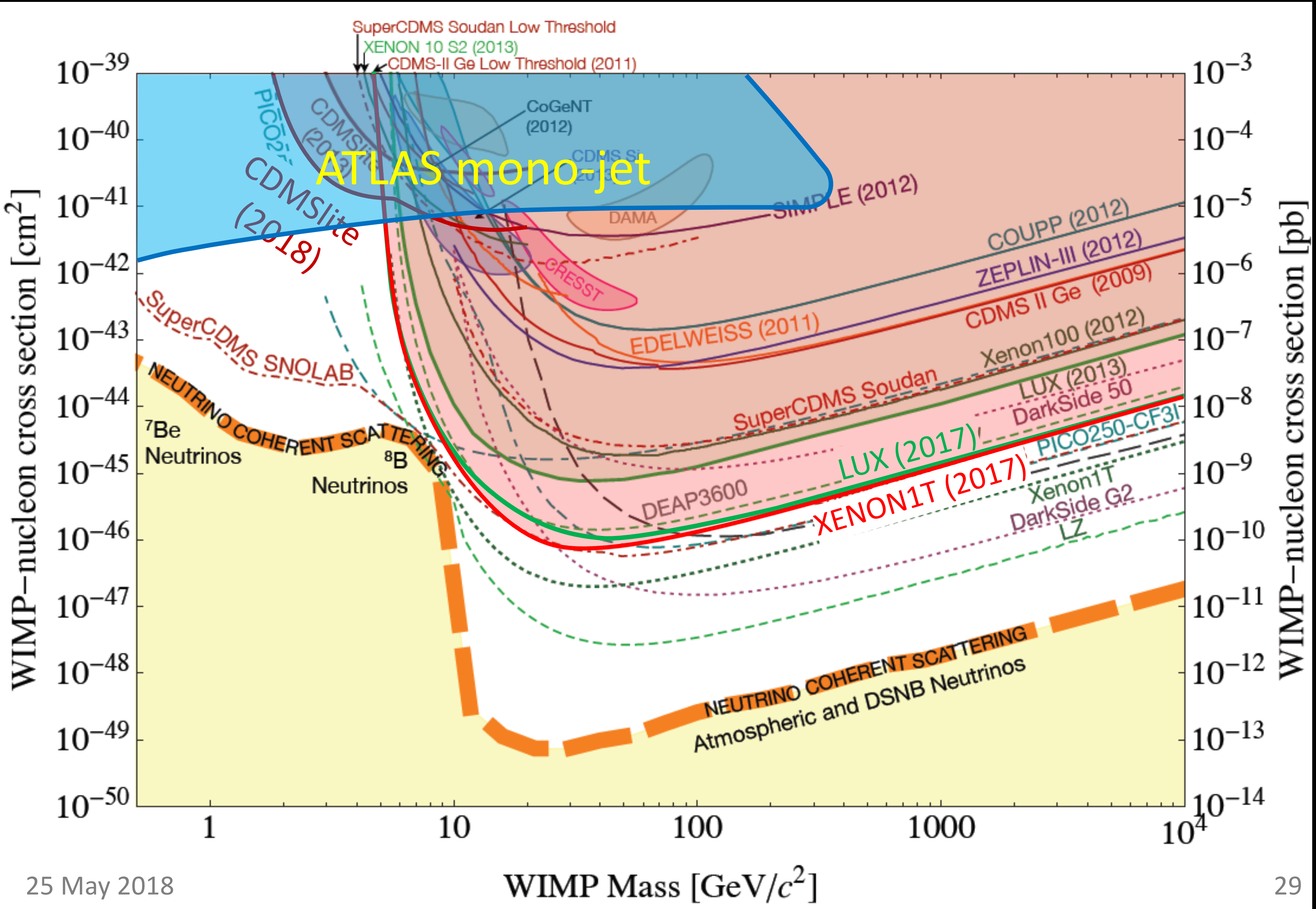
Caution: comparisons are strongly model-dependent



Very sensitive to couplings

~10^{-41} cm^2 for relatively light DM

Landscape with LHC



Summary and Prospect

Dark Matter ← convergence of astronomy and particle physics

- Evidences point to WIMPs waiting to be discovered

Direct-detection expts. search for DM in $\chi N \rightarrow \chi N$ scattering

- Sensitive to >10 GeV WIMPs down to $\sigma_{\chi N} \approx 10^{-46}$ cm^2

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

- Sensitive to <100 GeV WIMPs down to $\sigma_{\chi N} \approx 10^{-41}$ cm^2

Interpretation of results are often model-dependent

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

Next 10 years will bring:

- Large liquid-Xe expts. → 1000x sensitivity for high-mass WIMPs
- LHC searches for low-mass WIMPs with 10–100x data
- New direct-detection expts. optimized for low-mass WIMPs and spin-dependent couplings

References

Direct detection experiments

- XENON1T, arXiv:1705.06655, Phys. Rev. Lett. 119, 181301 (2017)
- LUX, arXiv:1608.07648, Phys. Rev. Lett. 118, 021303 (2017)
- PandaX-II, arXiv:1607.07400, Phys. Rev. Lett. 117, 121303 (2016)

ATLAS mono-X results with data from 2015–16 @ 13 TeV

- X = jet, arXiv:1711.03301, JHEP 01 (2018) 126
- X = photon, arXiv:1704.03848, Eur. Phys. J. C 77 (2017) 393
- X = heavy quark, arXiv:1710.11412, Eur. Phys. J. C 78 (2018) 18
- X = $Z \rightarrow \ell\ell$, arXiv:1708.09624, Phys. Lett. B 776 (2017) 318
- X = $H \rightarrow bb$, arXiv:1707.01302, Phys. Rev. Lett. 119 (2017) 181804
- X = $H \rightarrow \gamma\gamma$, arXiv:1706.03948, Phys. Rev. D (2017) 112004