Imperial College
London

Search for Dark Matter at the LHC

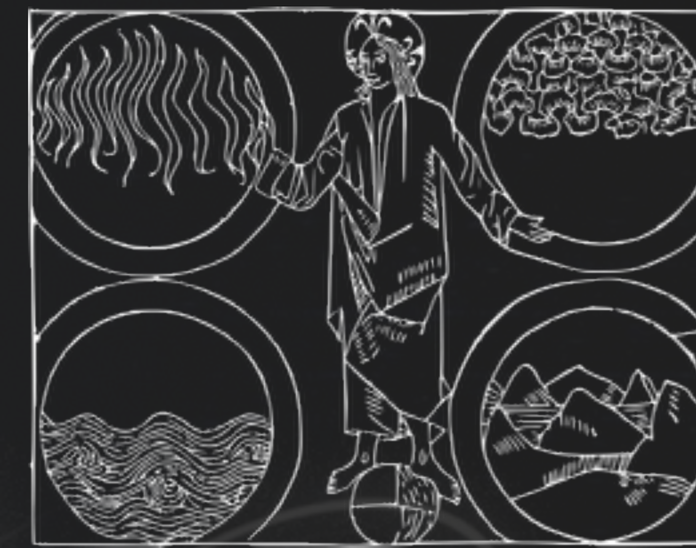
Björn Penning
Imperial College London

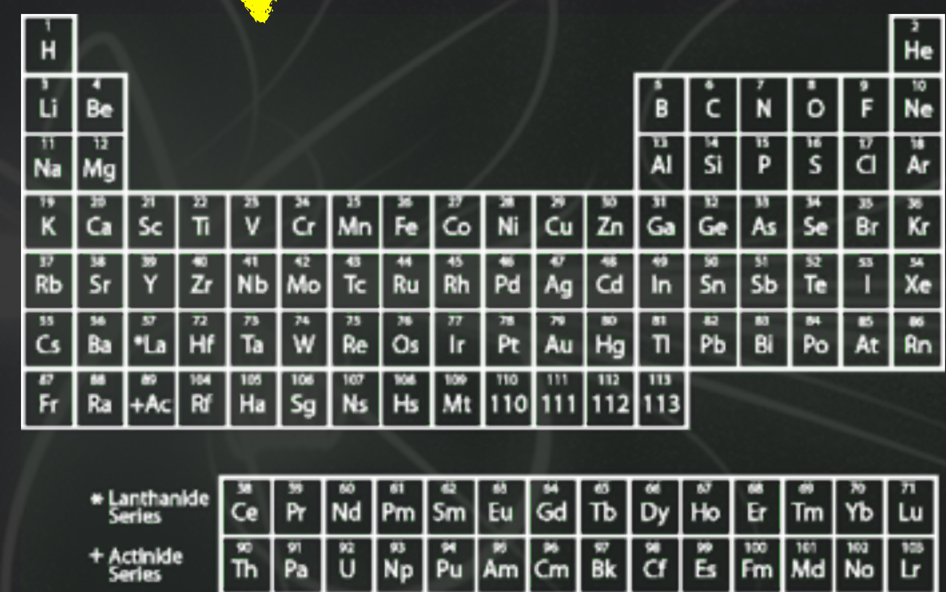
July 23, 2015

- What is DM and how do we search for it?
- Traditional DM searches at Colliders
- A novel idea: DM searches with heavy quarks
- An outlook

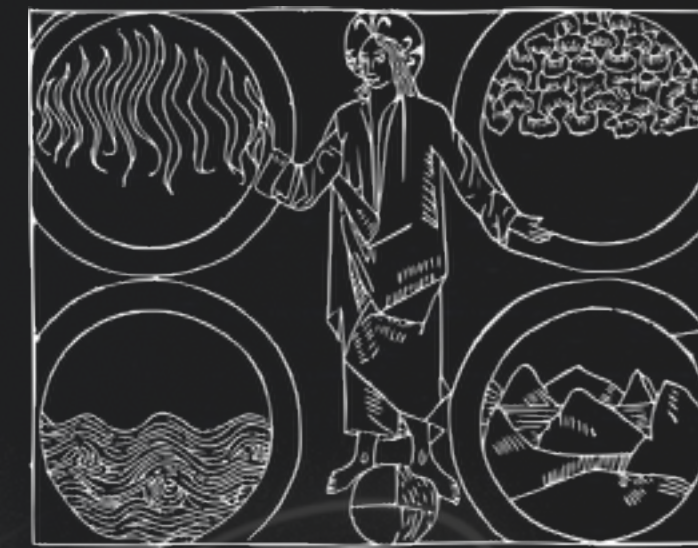
- Hundreds of years of science have given us a good understanding of the structure of matter

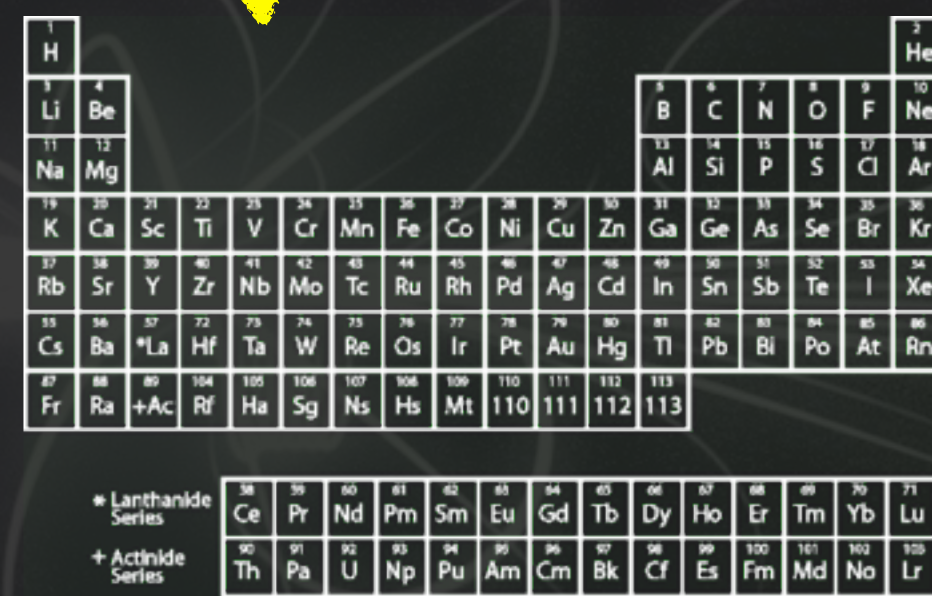
- **Hundreds of years of science** have given us a **good understanding of the structure of matter**

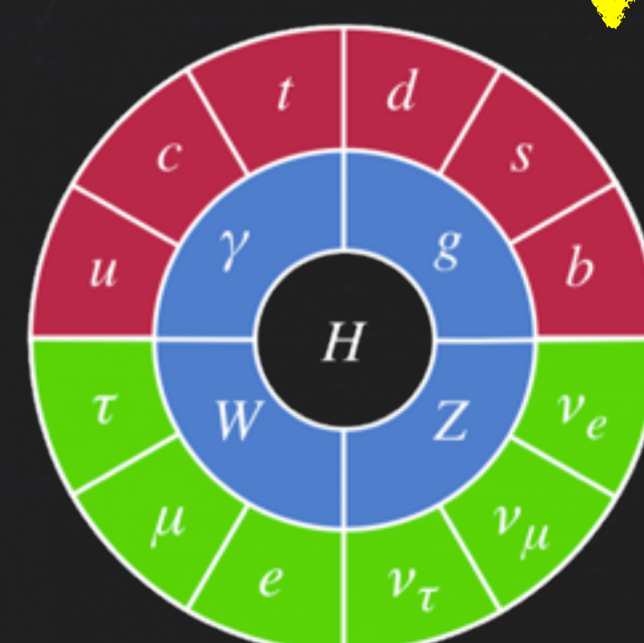




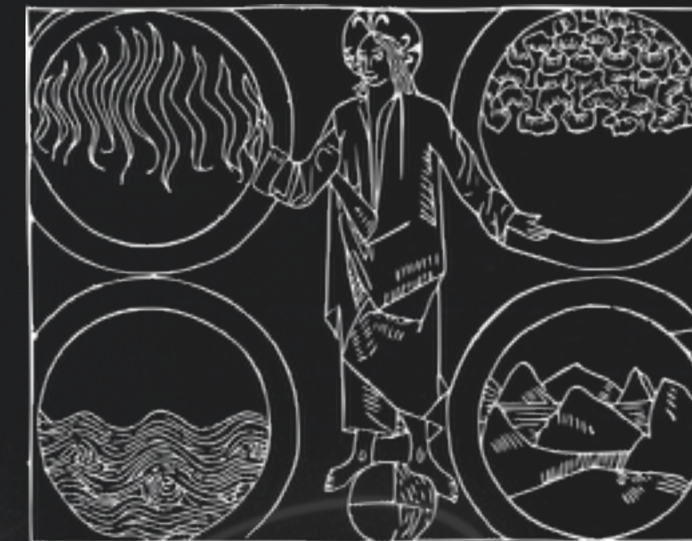
- **Hundreds of years of science** have given us a **good understanding of the structure of matter**
- The discovery of the **Higgs boson** completed the **Standard Model**

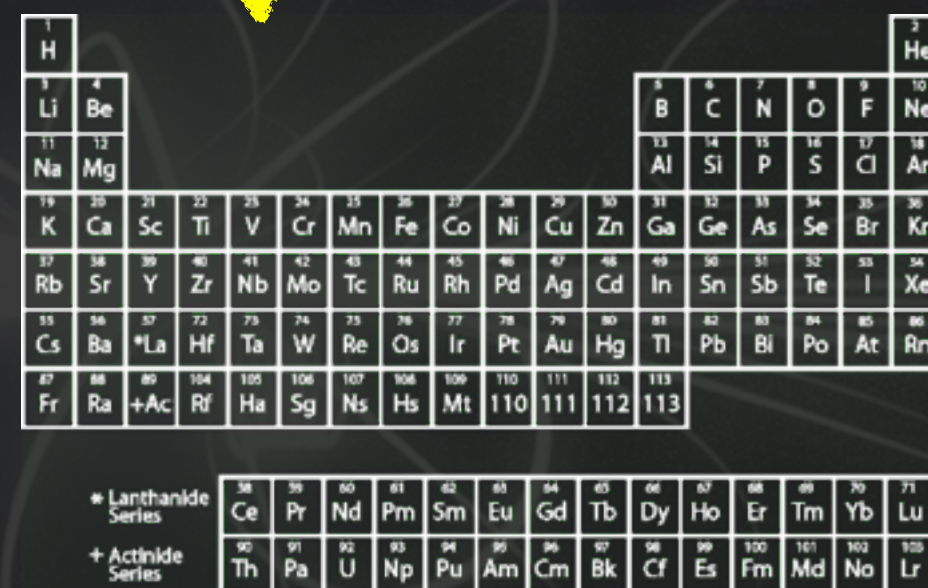


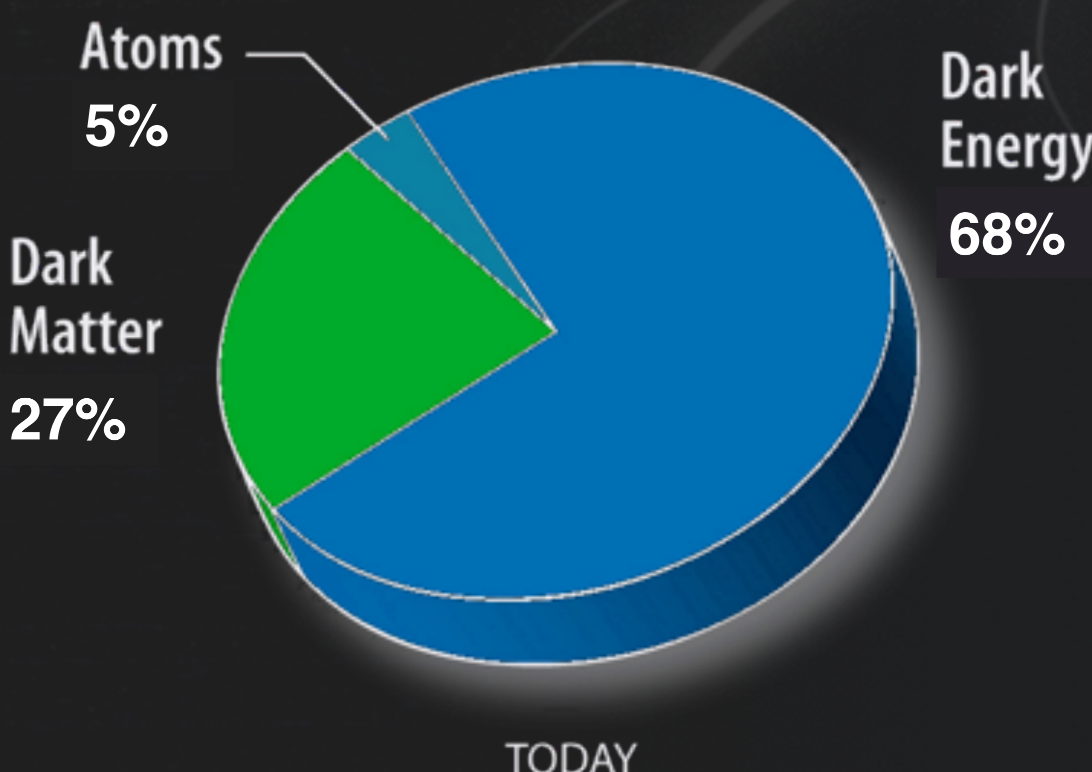




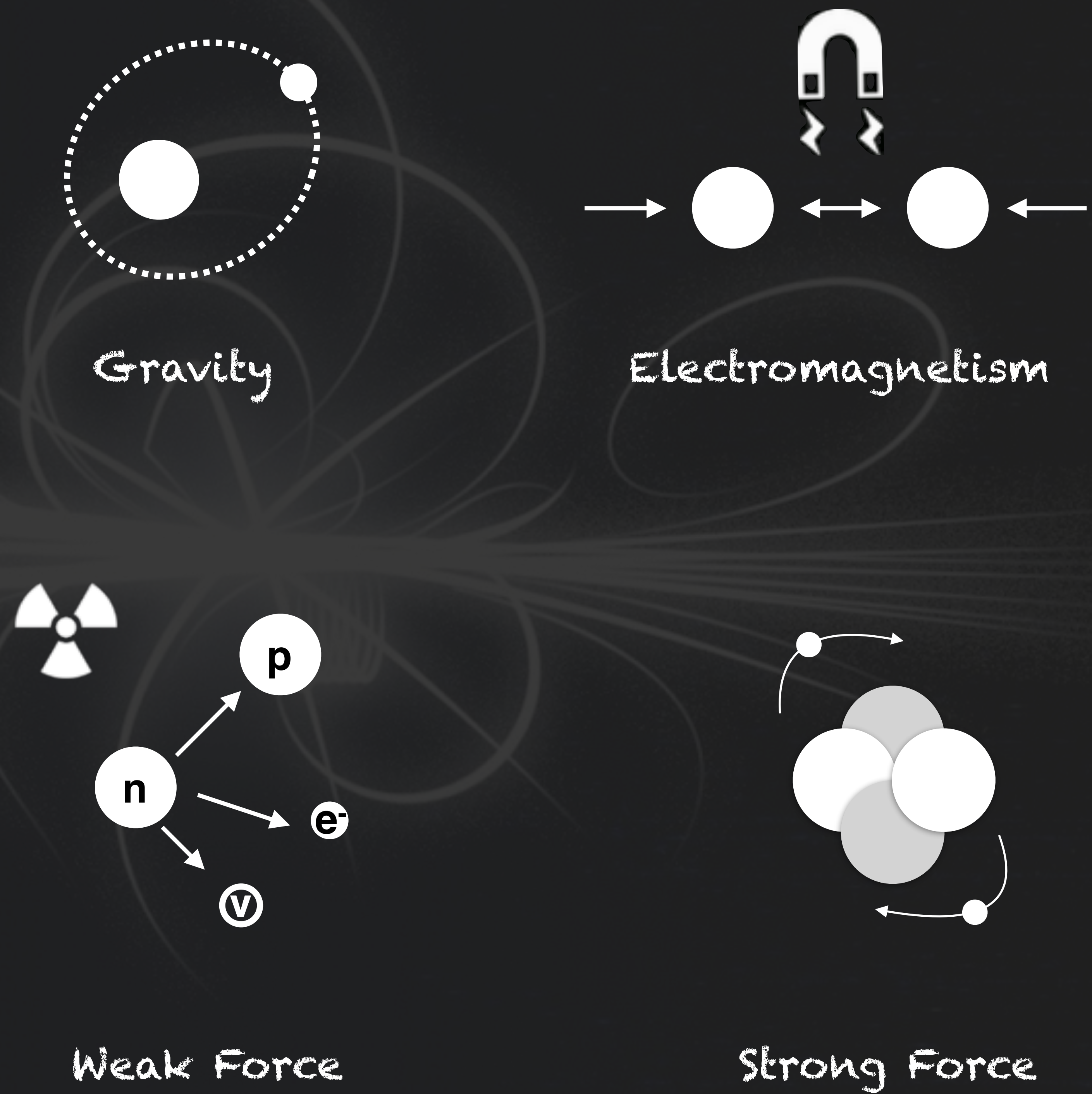
- **Hundreds of years of science** have given us a **good understanding of the structure of matter**
- The discovery of the **Higgs boson** completed the **Standard Model**
- However, this is just the **tip of the iceberg**



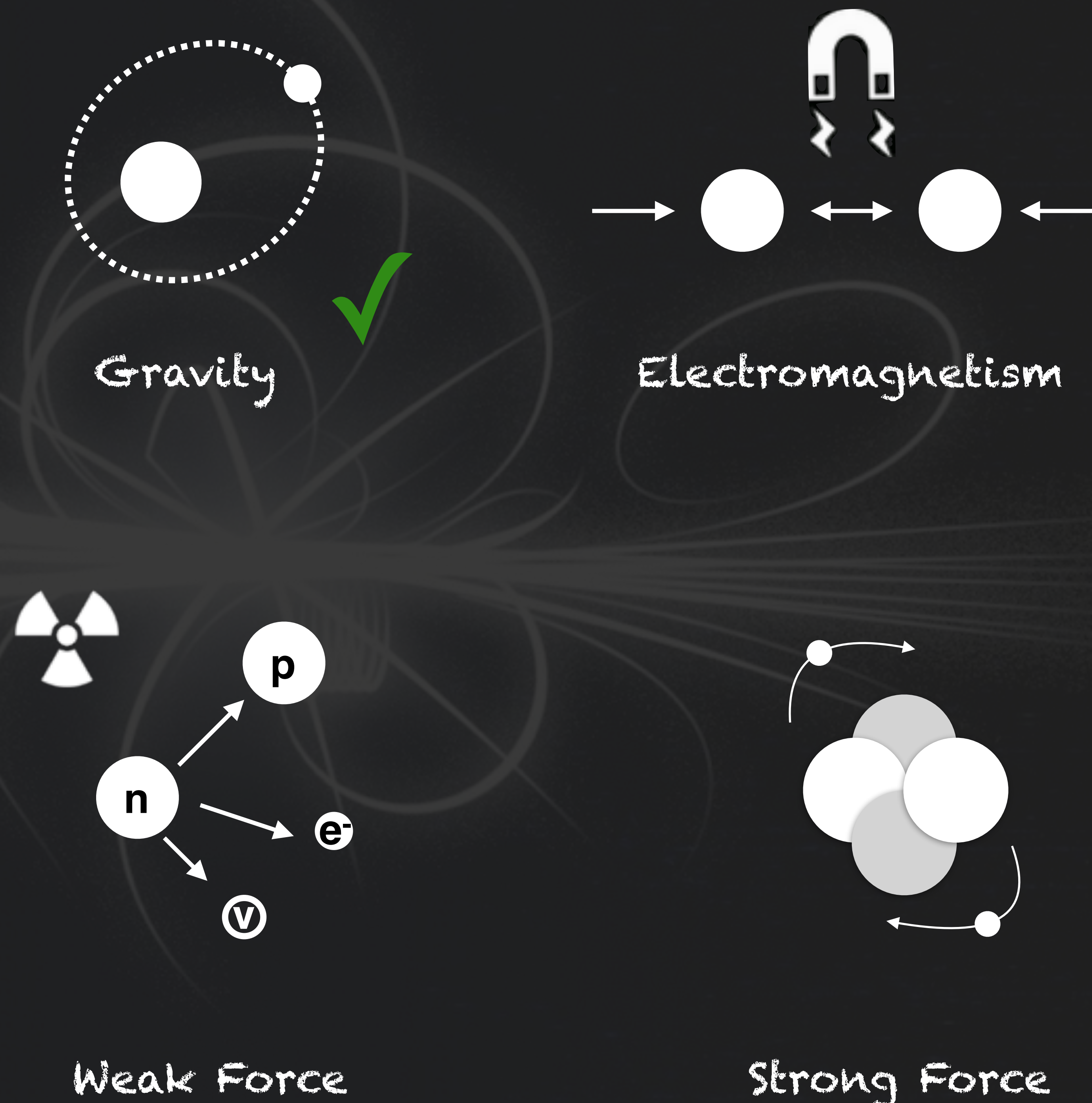




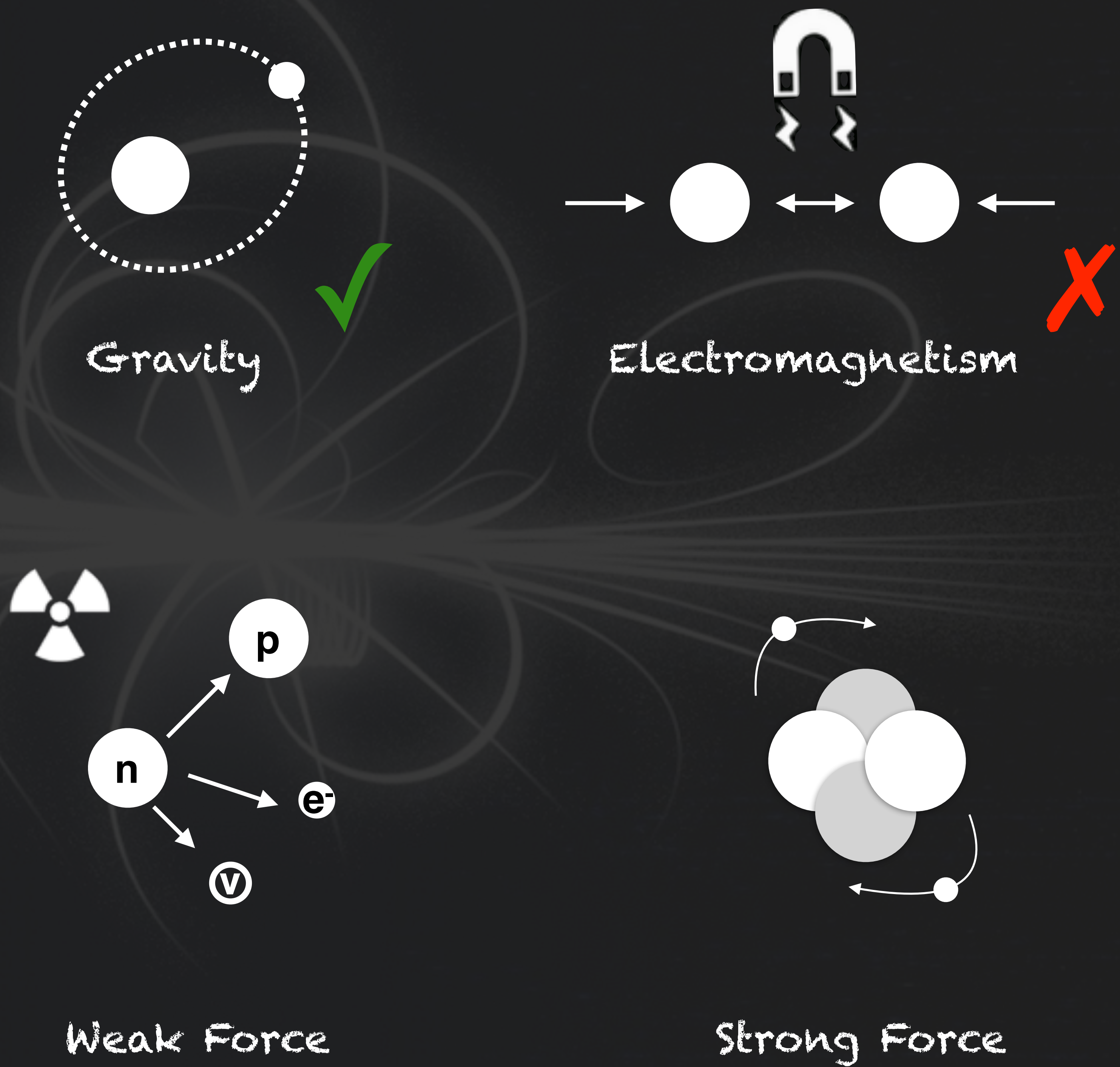
- We know of **four fundamental interactions**



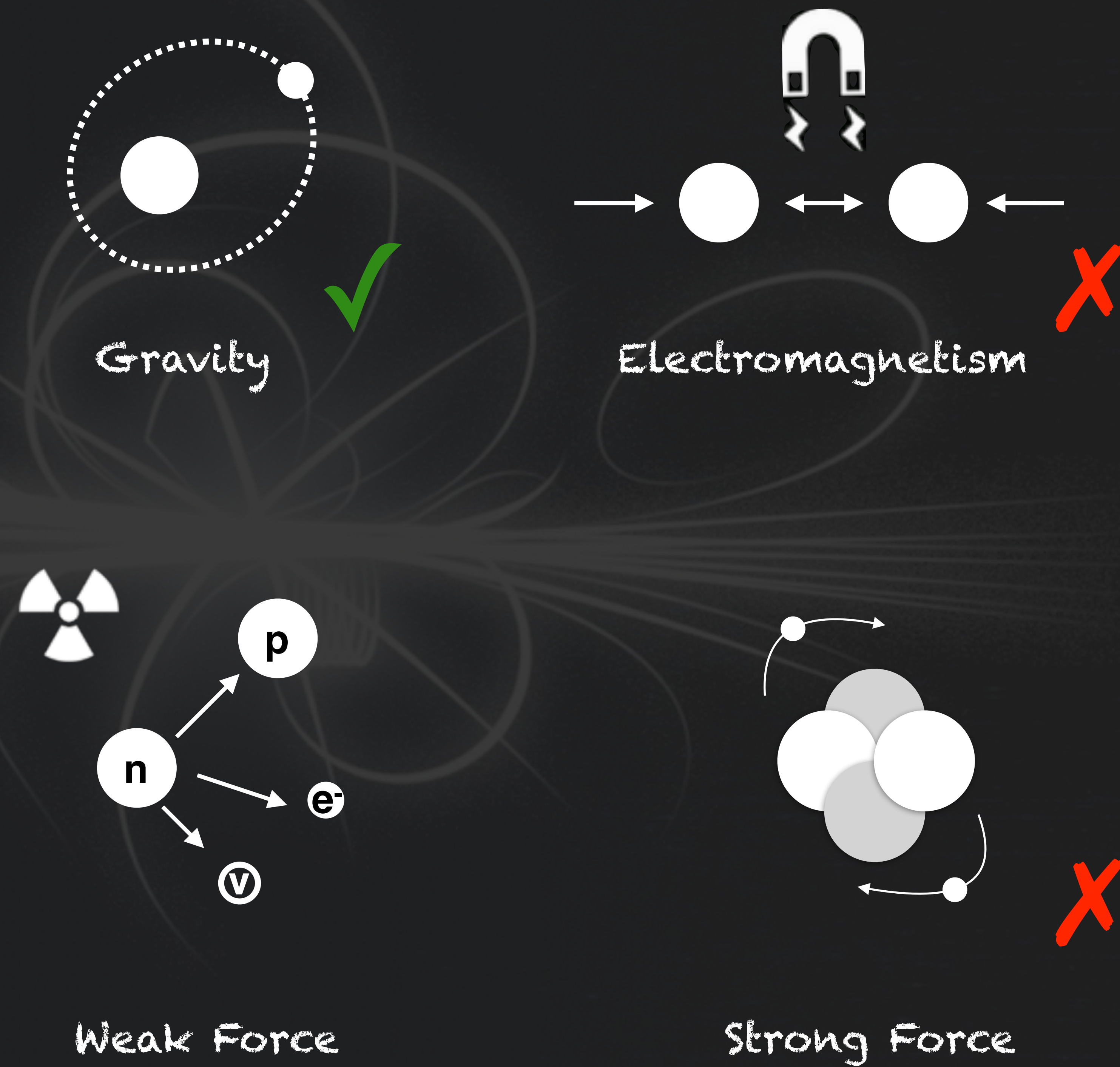
- We know of four fundamental interactions
- Dark Matter does
    - interact gravitationally



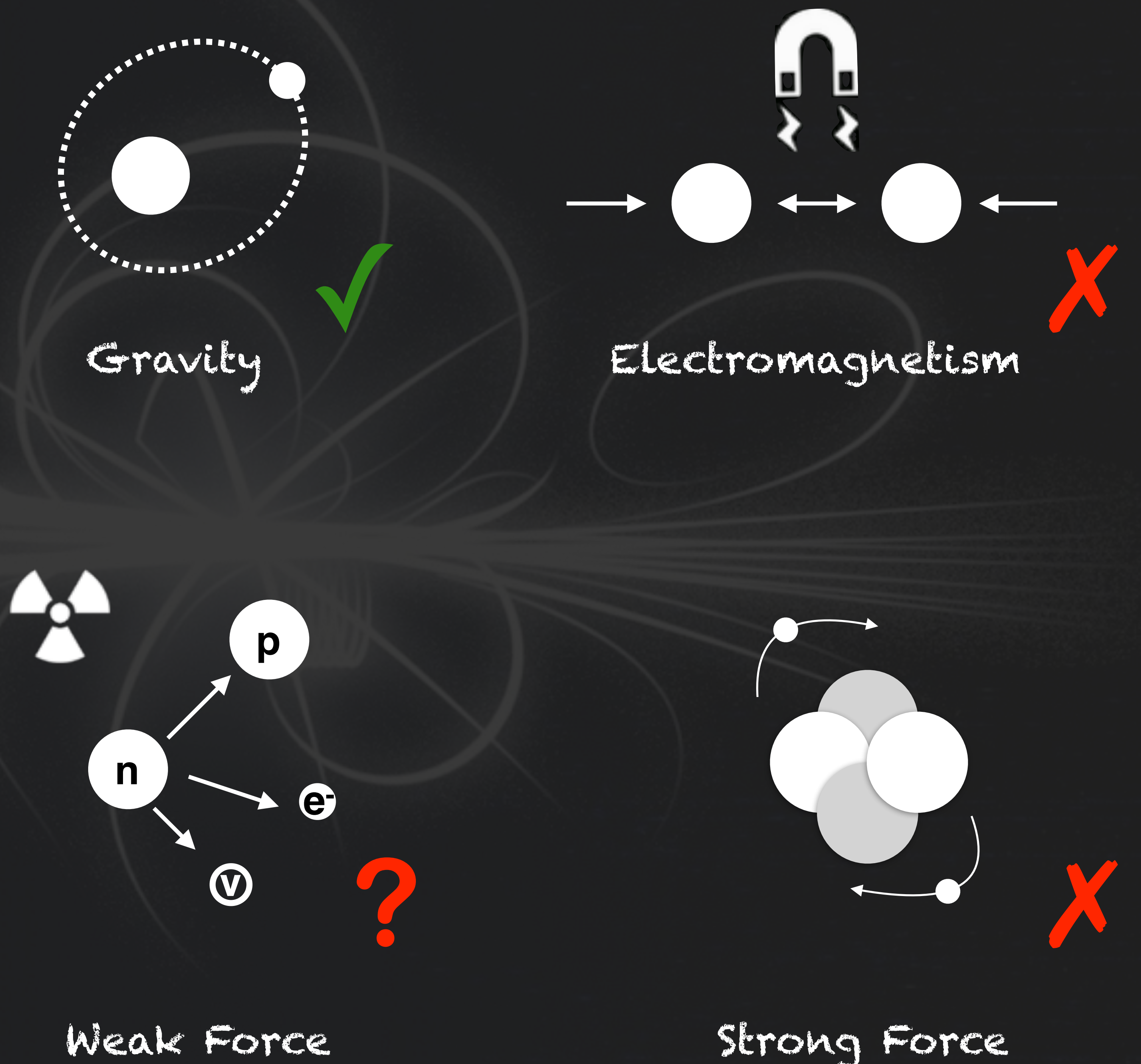
- We know of four fundamental interactions
- Dark Matter does
    - interact gravitationally
    - not have any electromagnetic interaction



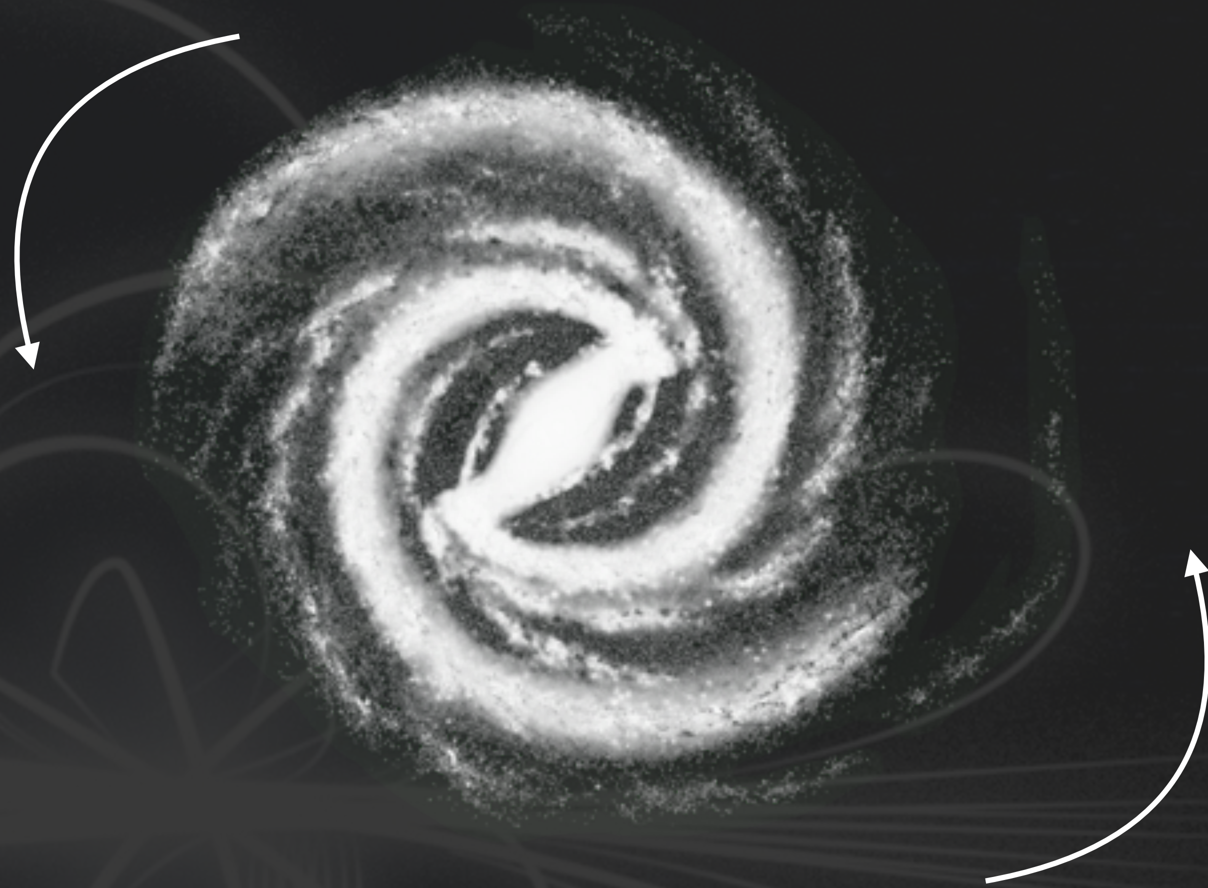
- We know of **four fundamental interactions**
- **Dark Matter does**
    - interact **gravitationally**
    - not have any **electromagnetic interaction**
    - not interact via the **strong force** (not a baryon)

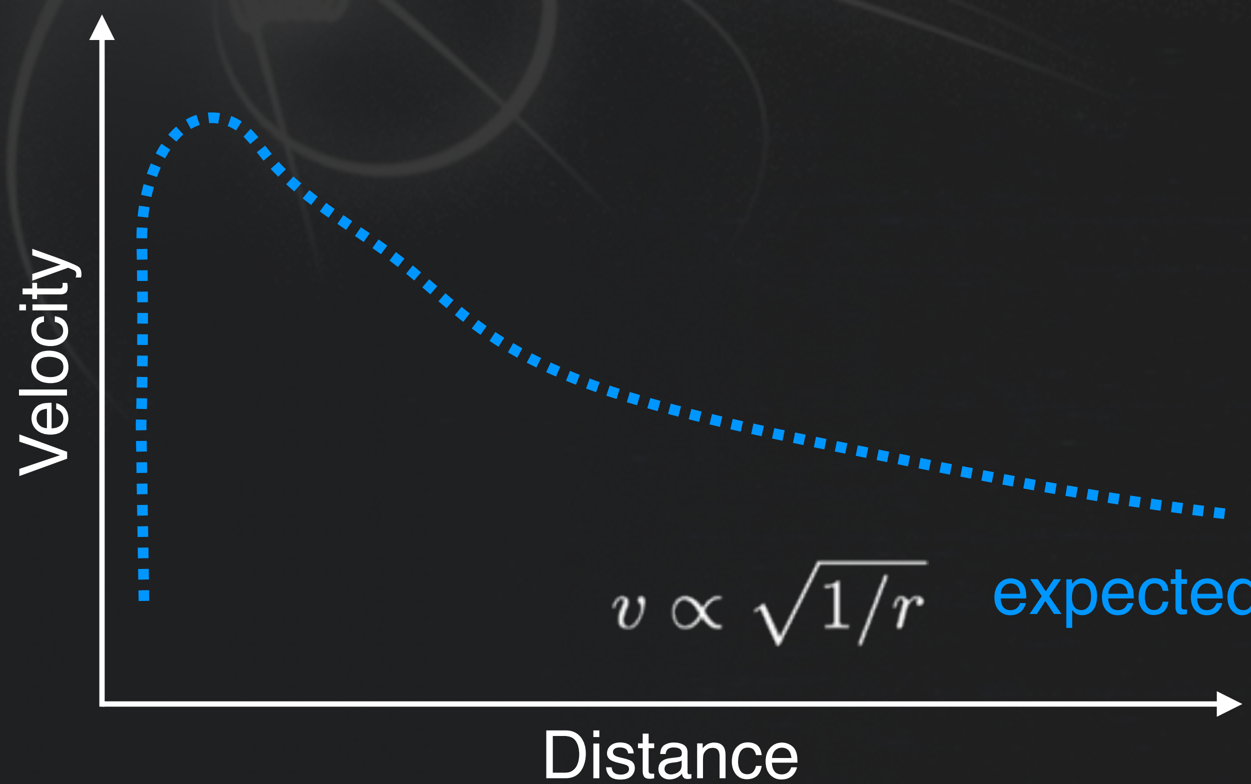


- We know of four fundamental interactions
- Dark Matter does
    - interact gravitationally
    - not have any electromagnetic interaction
    - not interact via the strong force (not a baryon)
    - perhaps interact via the weak force but it is not the neutrino

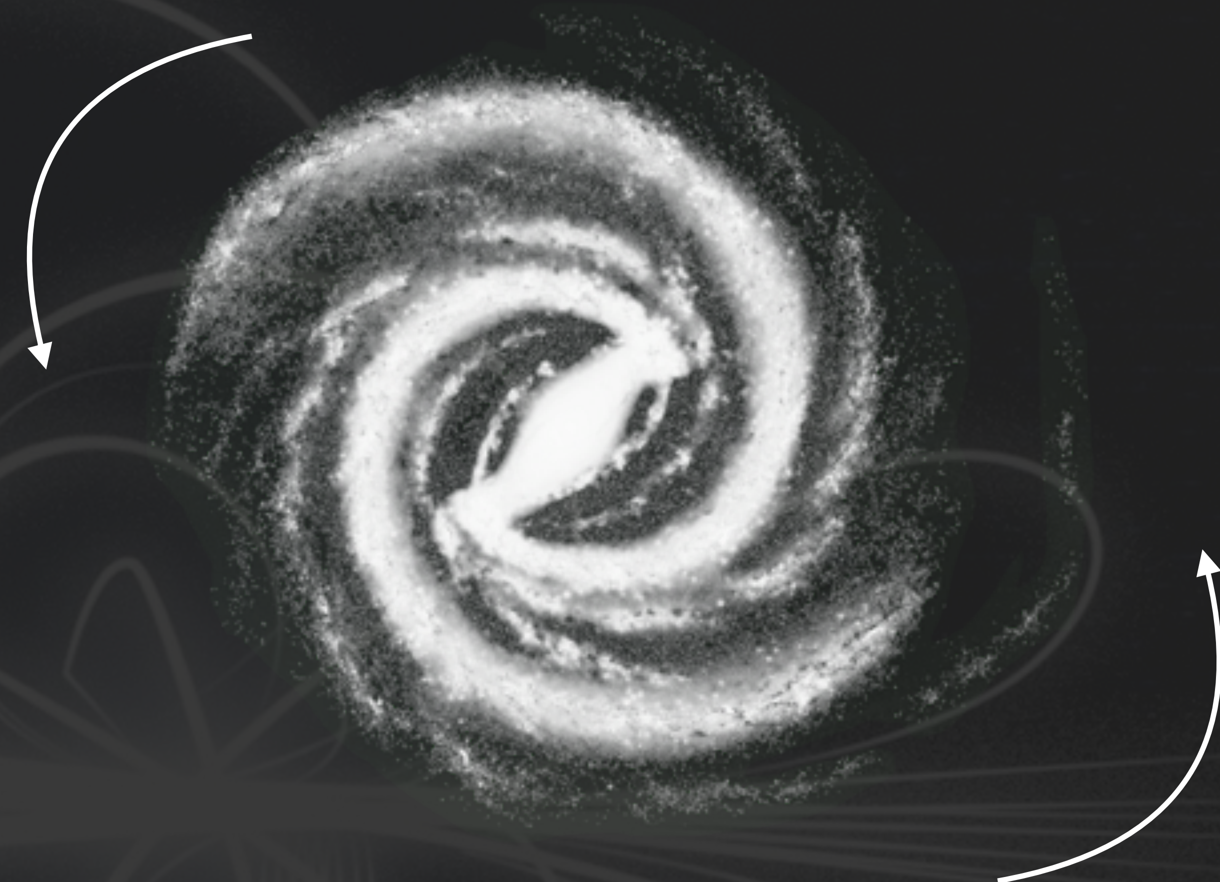


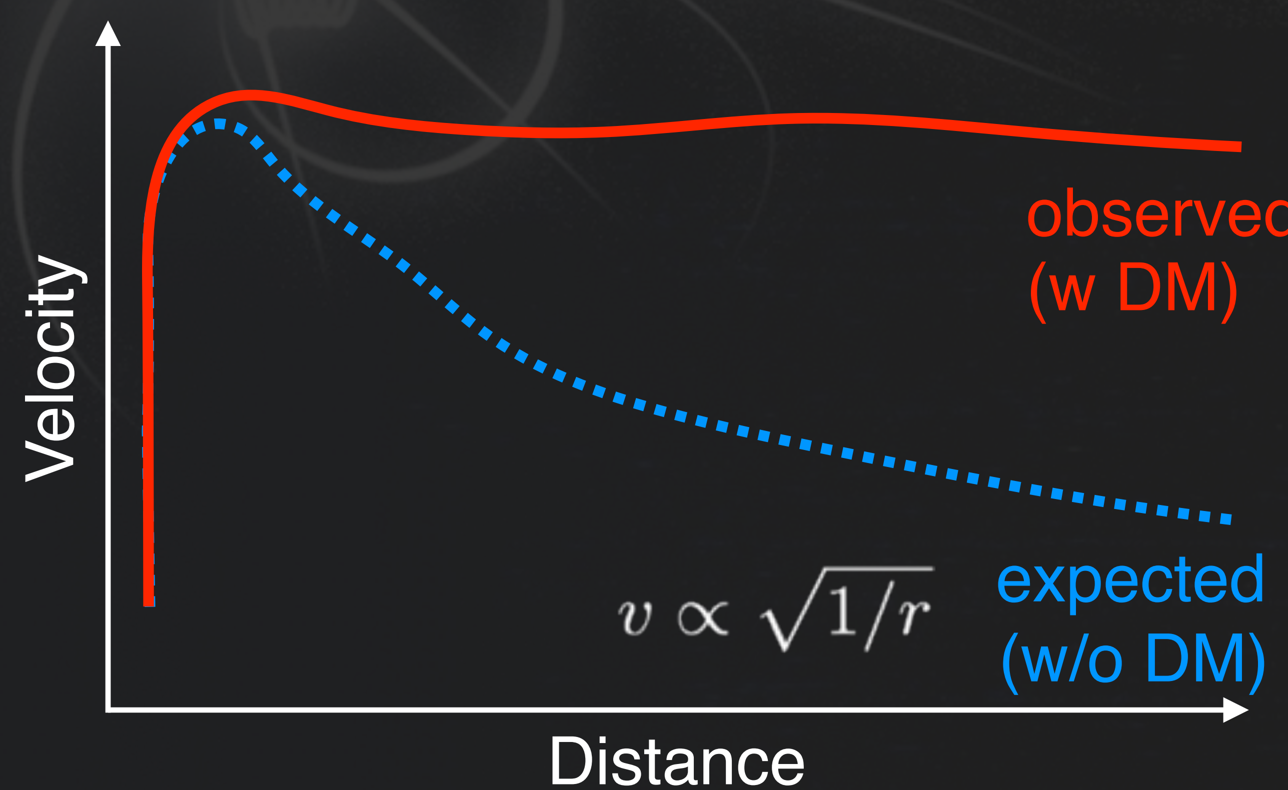
- **Galaxies rotate faster** than they should according to the luminous matter we see



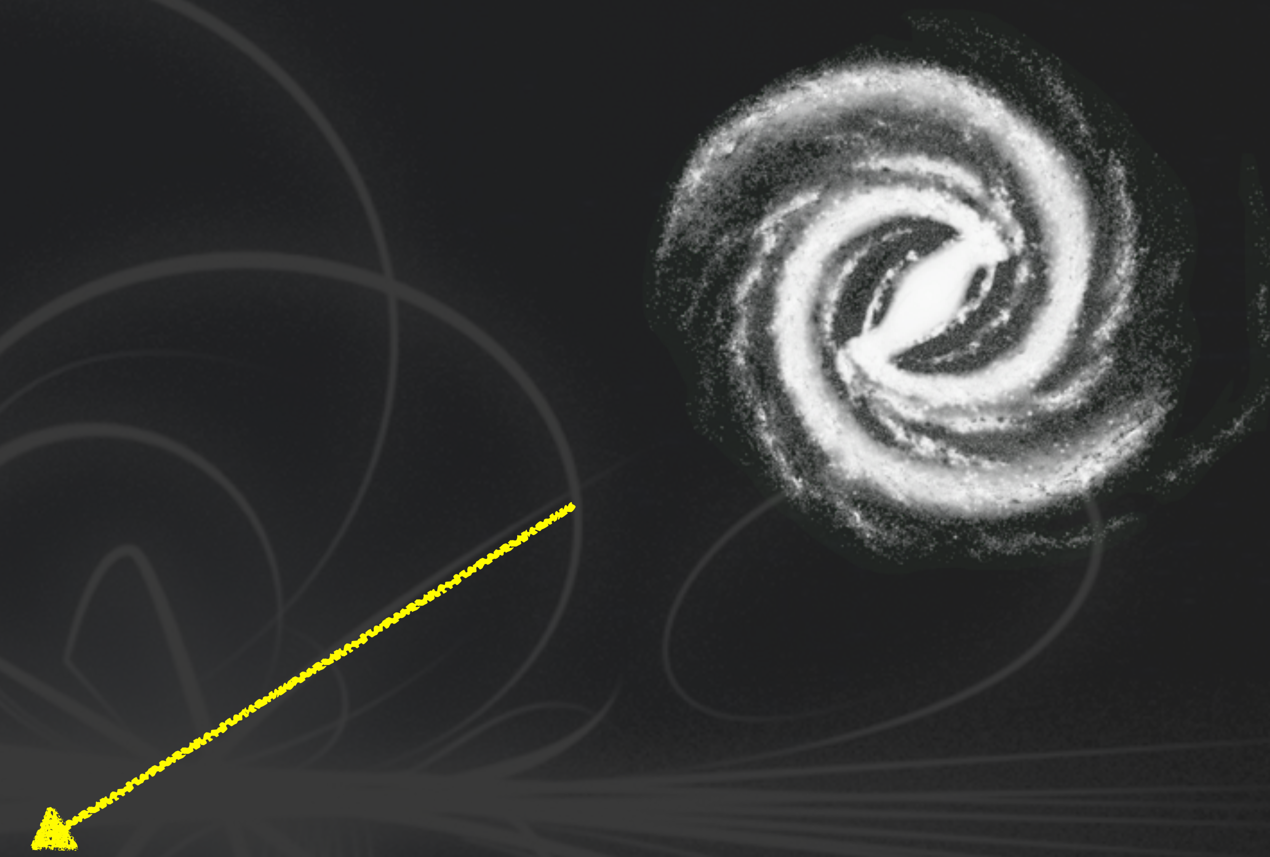


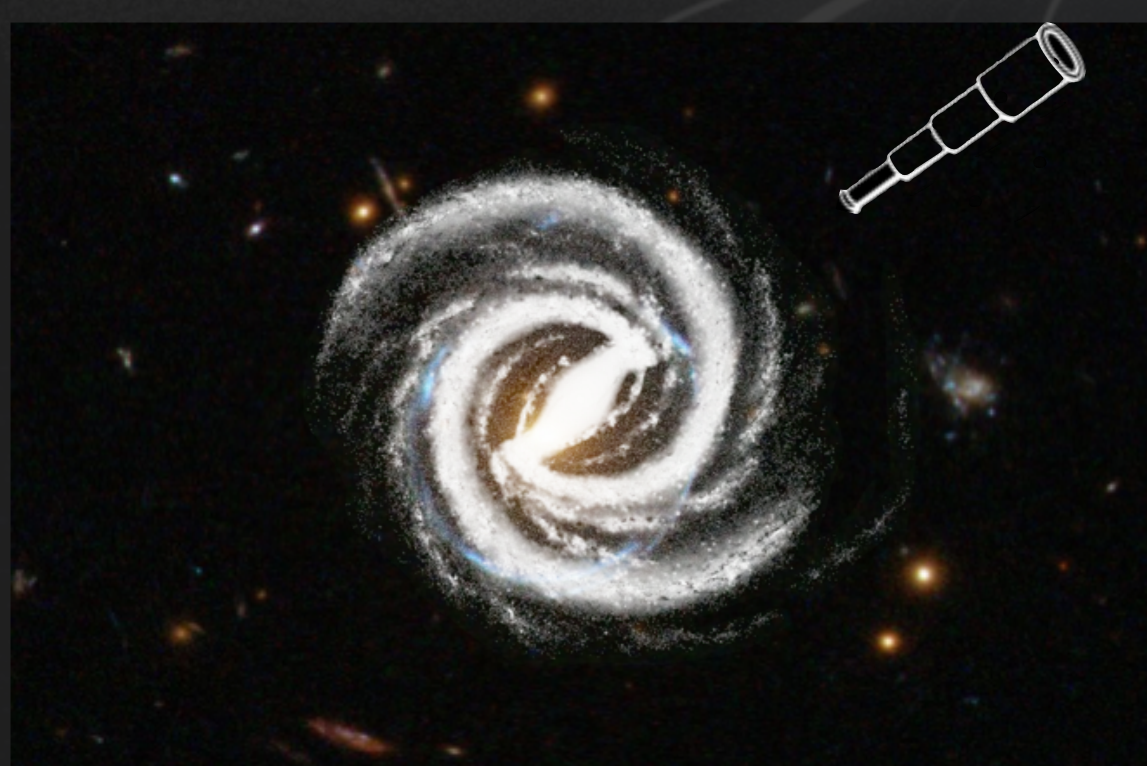
- **Galaxies rotate faster** than they should according to the luminous matter we see





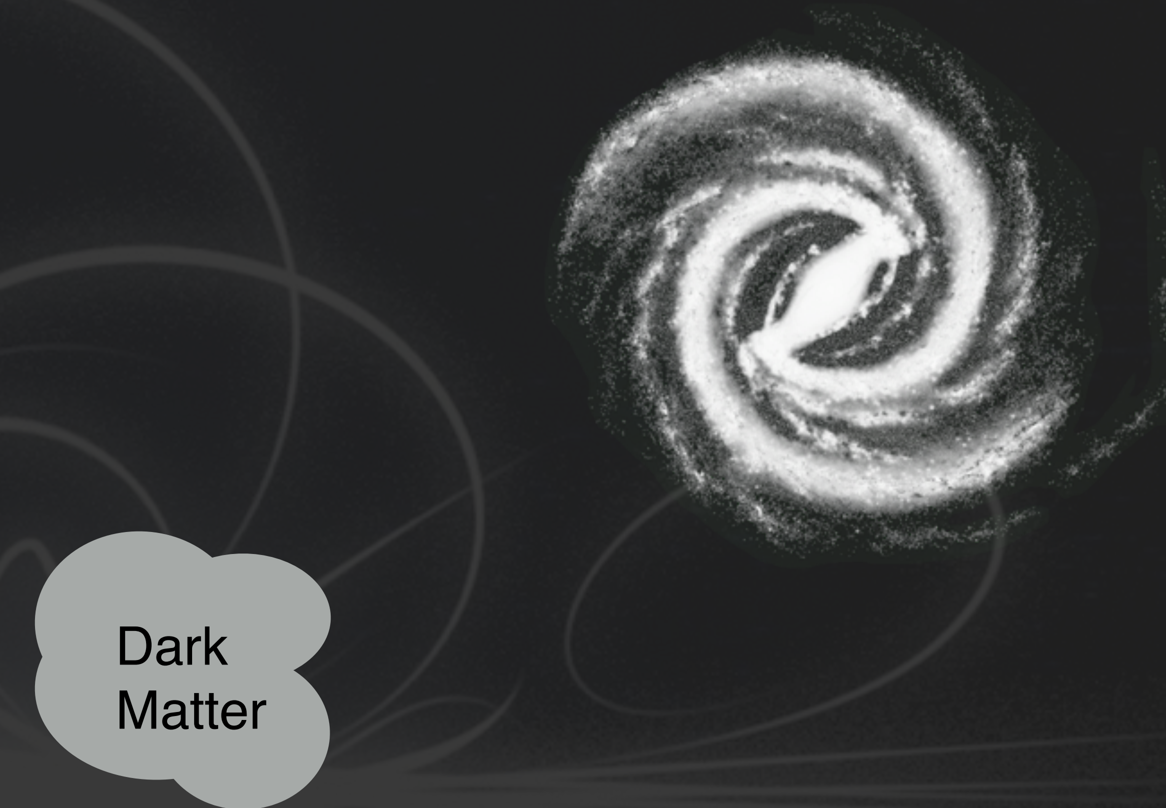
- We also see its effect in **Gravitational Lensing**

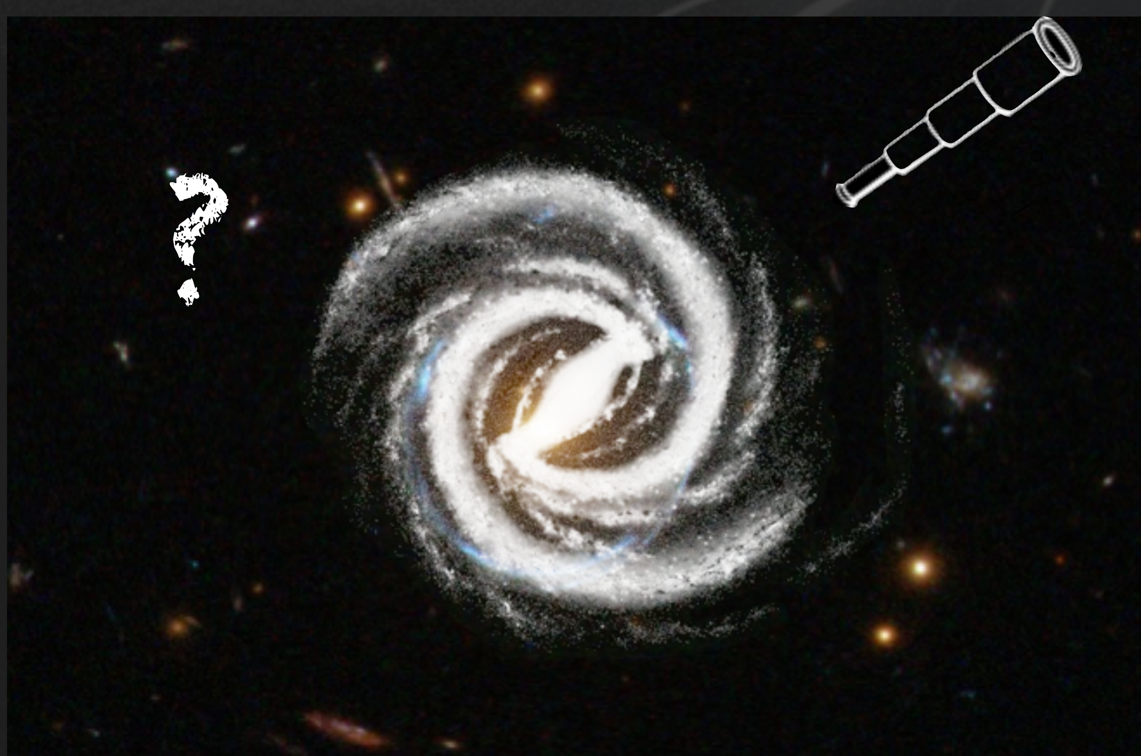




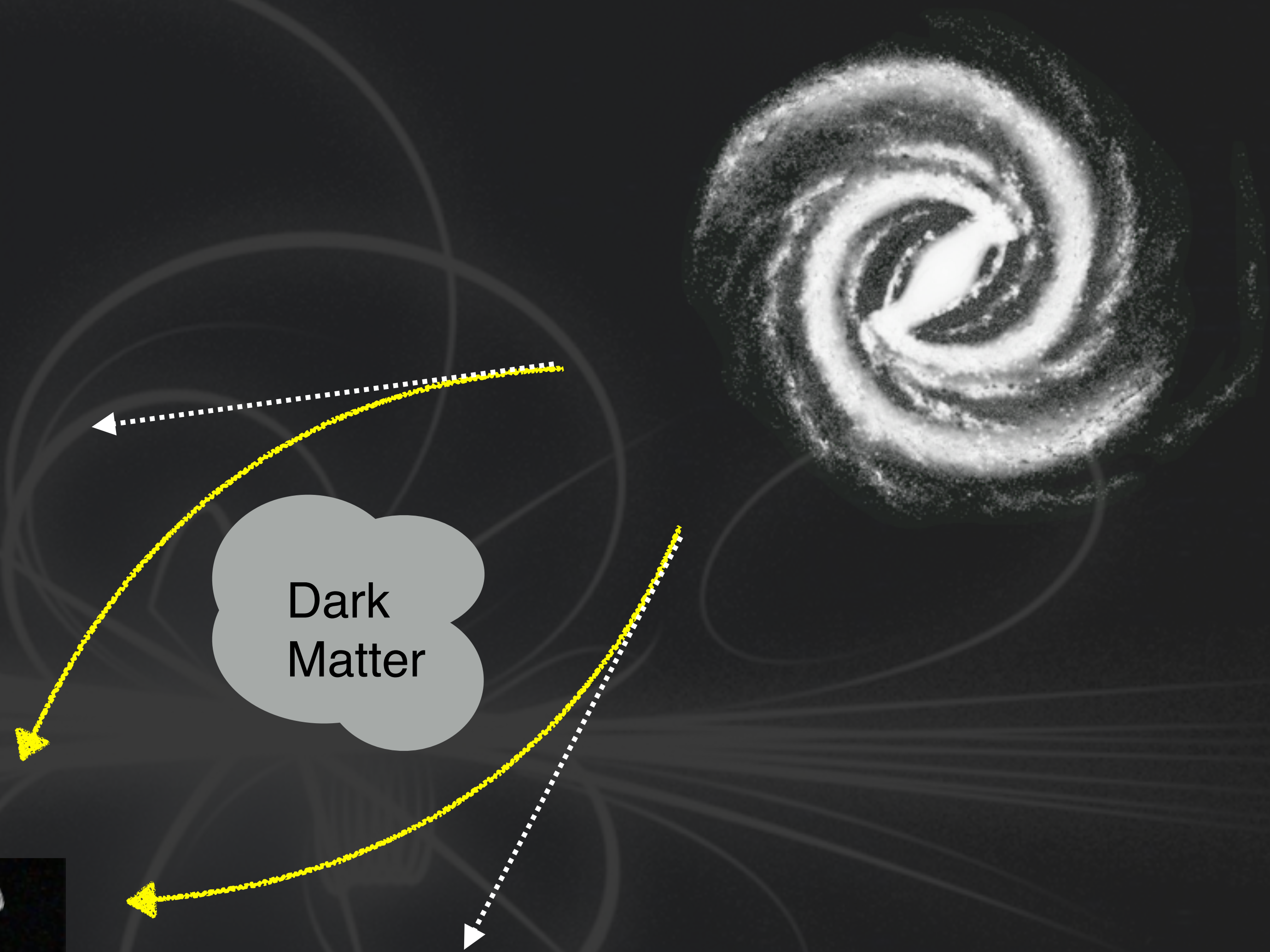
Imperial College London

- We also see its effect in **Gravitational Lensing**
- **Light is bent by a gravitational** potential and we see **multiple images** of the same object



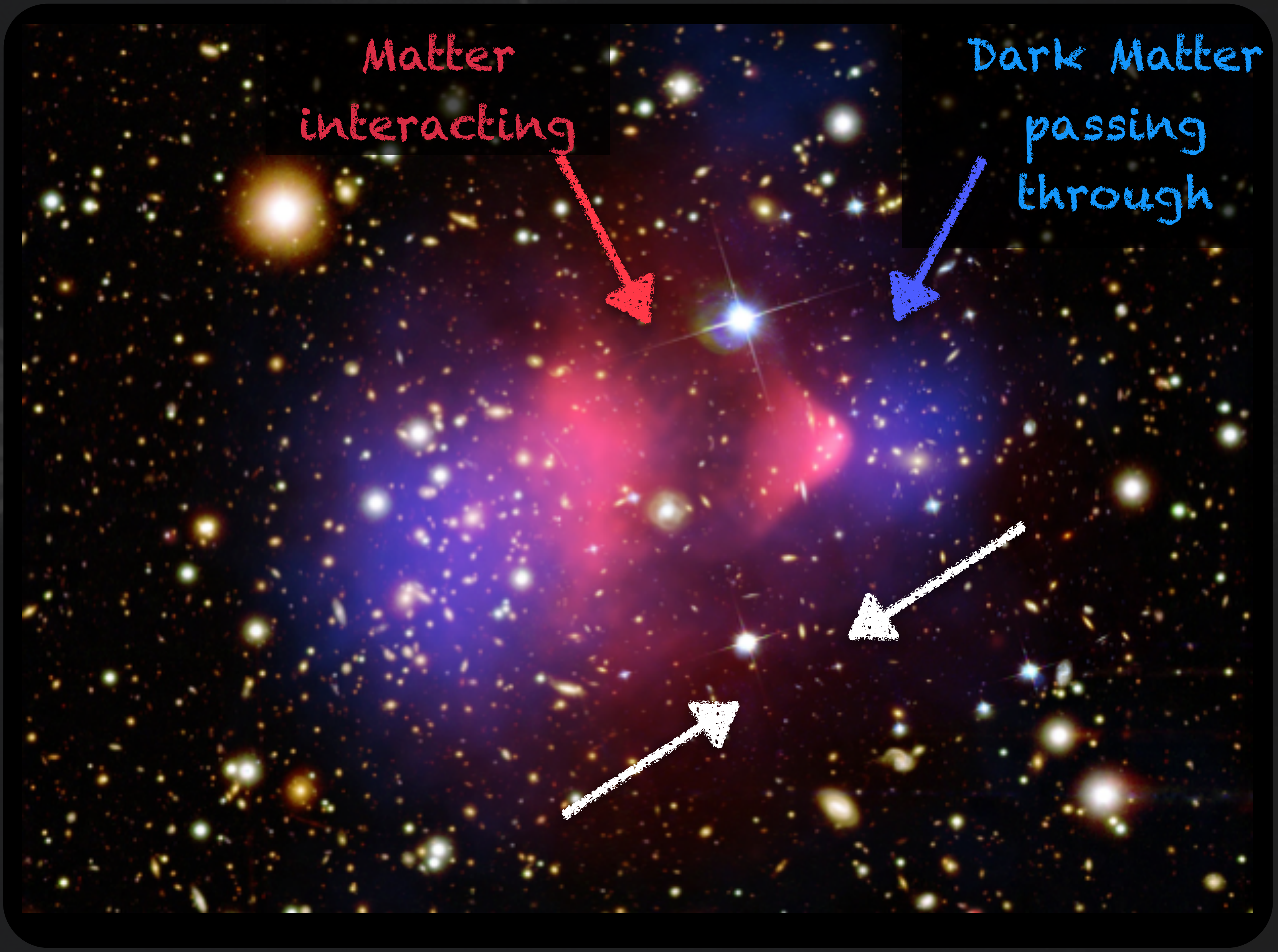


- We also see its effect in Gravitational Lensing
- Light is bent by a gravitational potential and we see multiple images of the same object

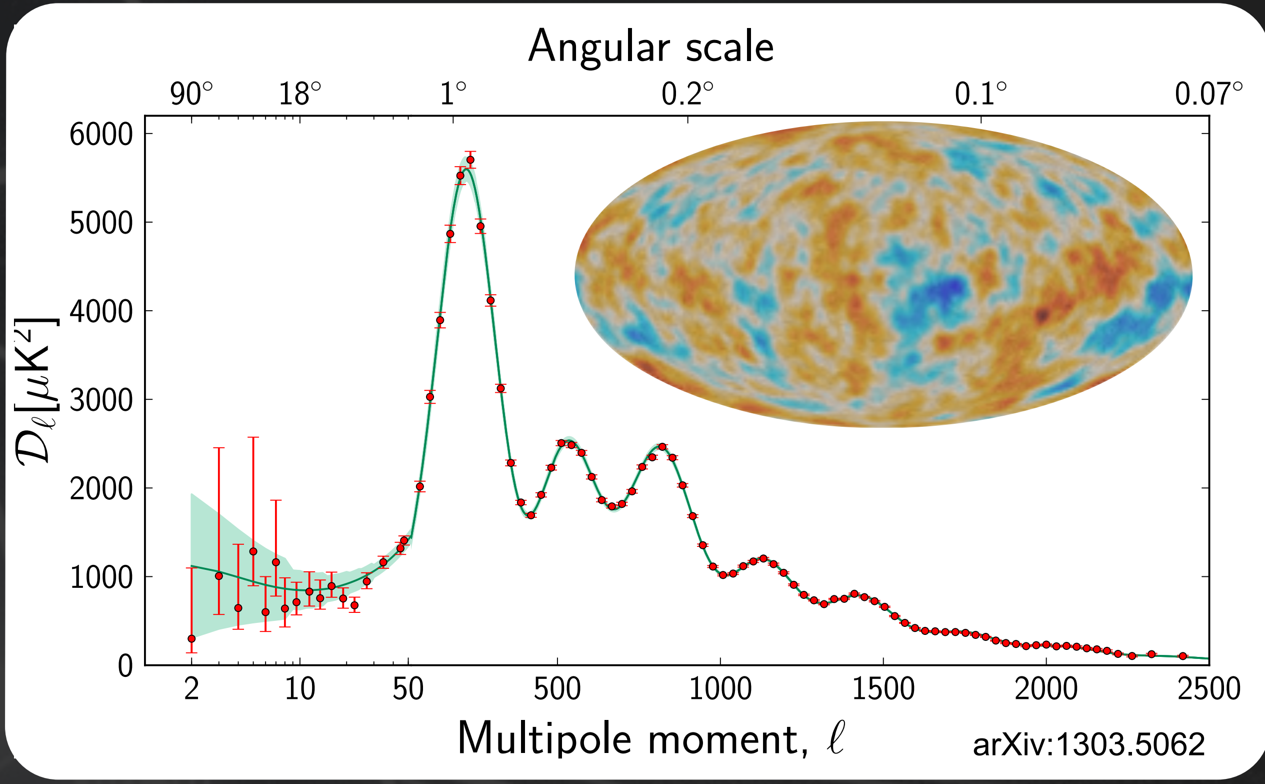


- This is why we call it 'Dark Matter' - we don't see it but it feels gravitation like other matter

- Also more direct evidence
- E.g. in the 'Bullet Cluster' we see the remnants of two galaxy clusters colliding
- This collision leads to interactions in normal matter but Dark Matter passes through



- Dark Matter (DM) **firmly established signal of new physics**
- **Many more independent observations:**
  - **Anisotropy** of CMB (WMAP), **large-scale structure** (galaxy surveys), Type Ia **supernovae** survey, hot **gas**



- DM likely to be '**non-baryonic cold dark matter**'
- Global fit of cosmological parameters, **ΛCDM:**

$\rightarrow \Omega_\Lambda \approx 0.68, \ \Omega_{DM} \approx 0.27, \ \Omega_b \approx 0.05$

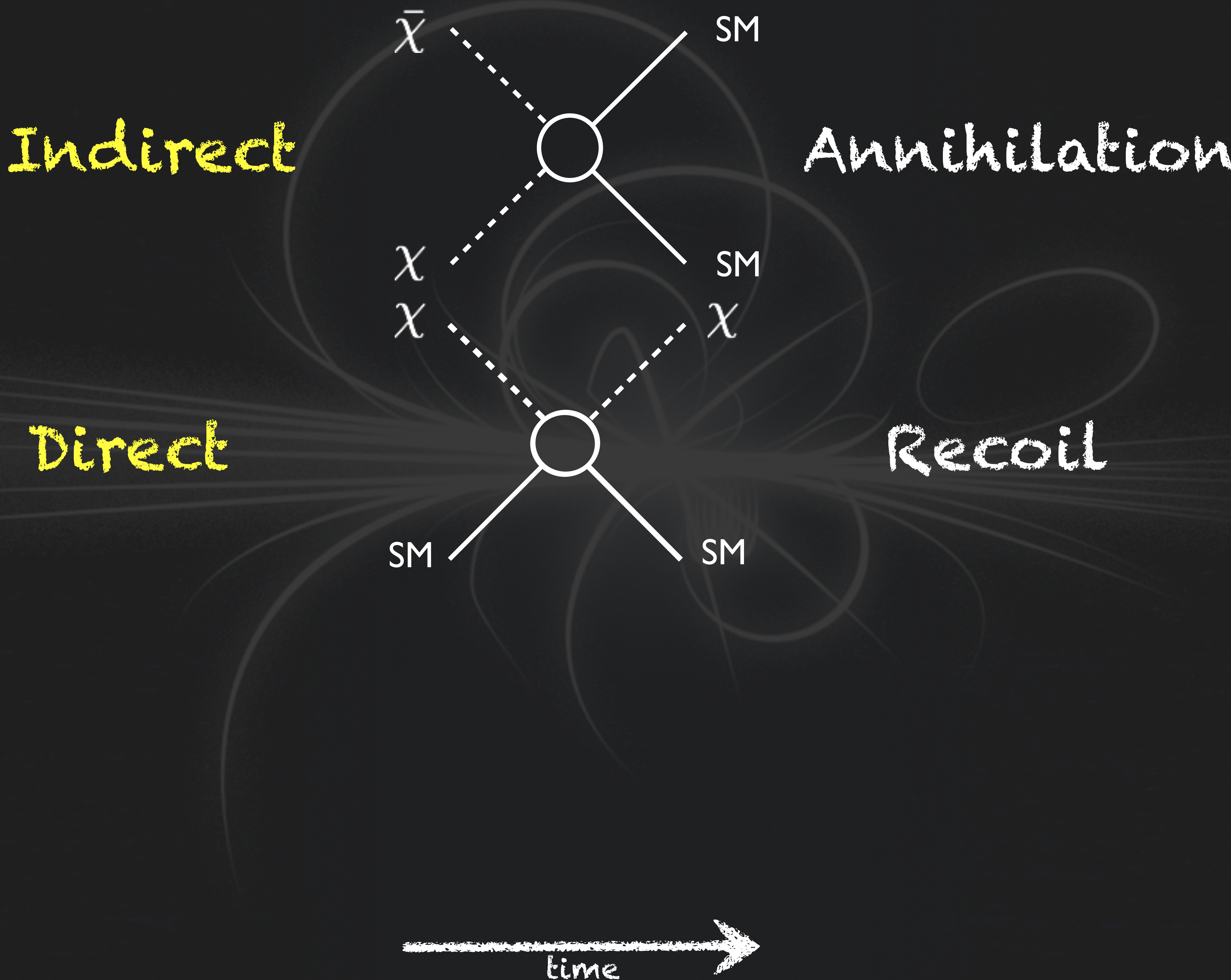
Detecting Dark Matter

Indirect

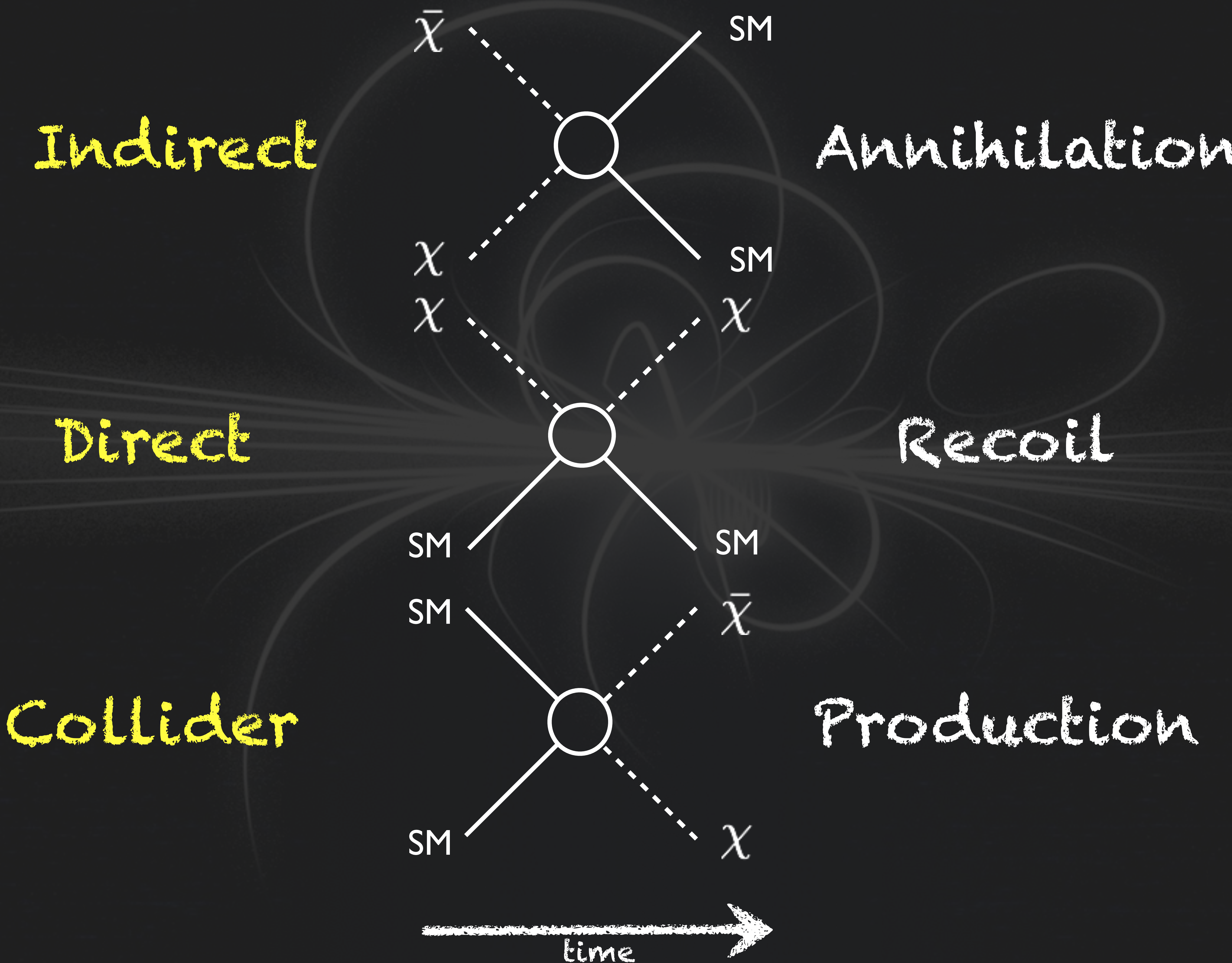
Annihilation

time

Detecting Dark Matter



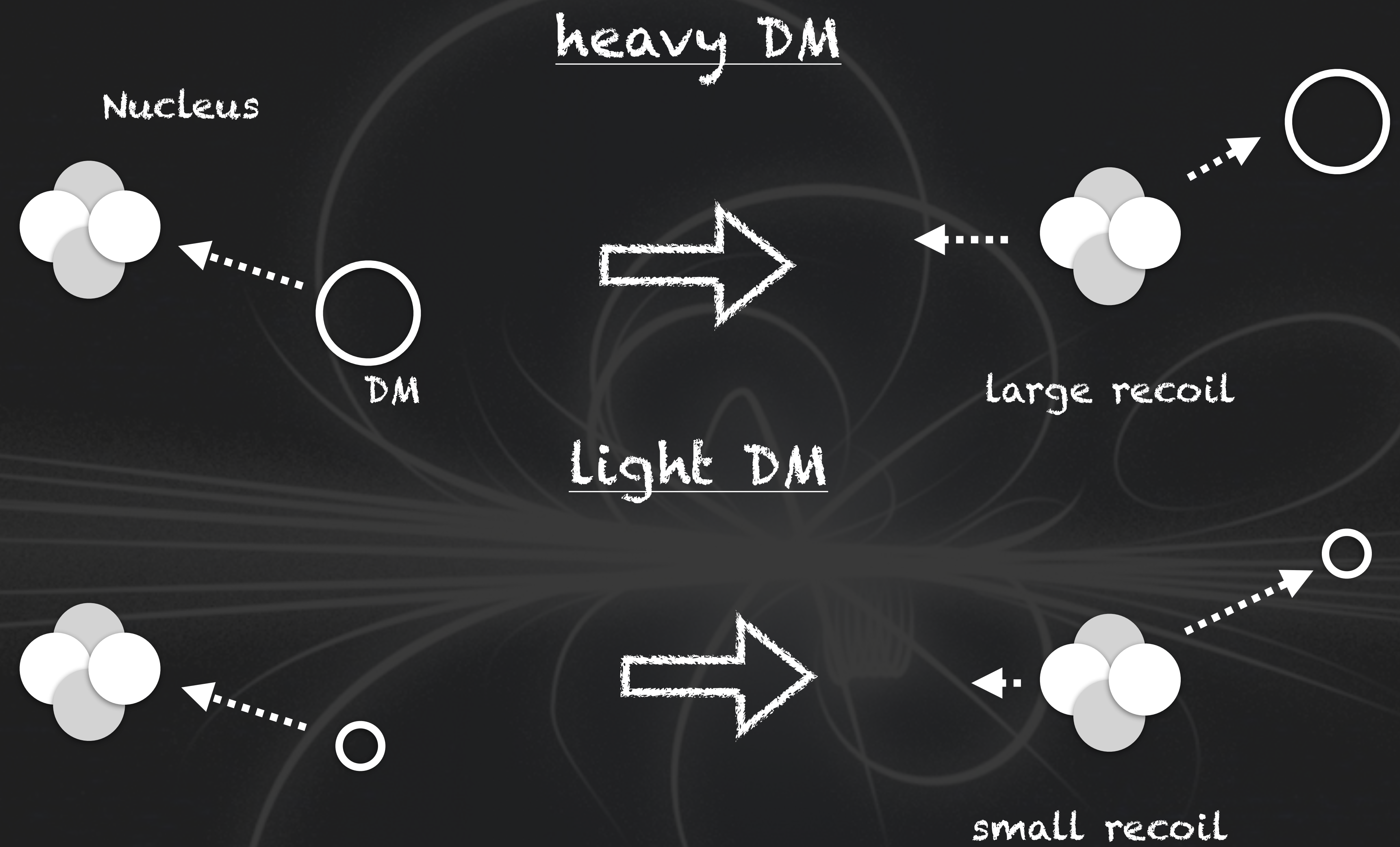
Detecting Dark Matter



Direct Detection

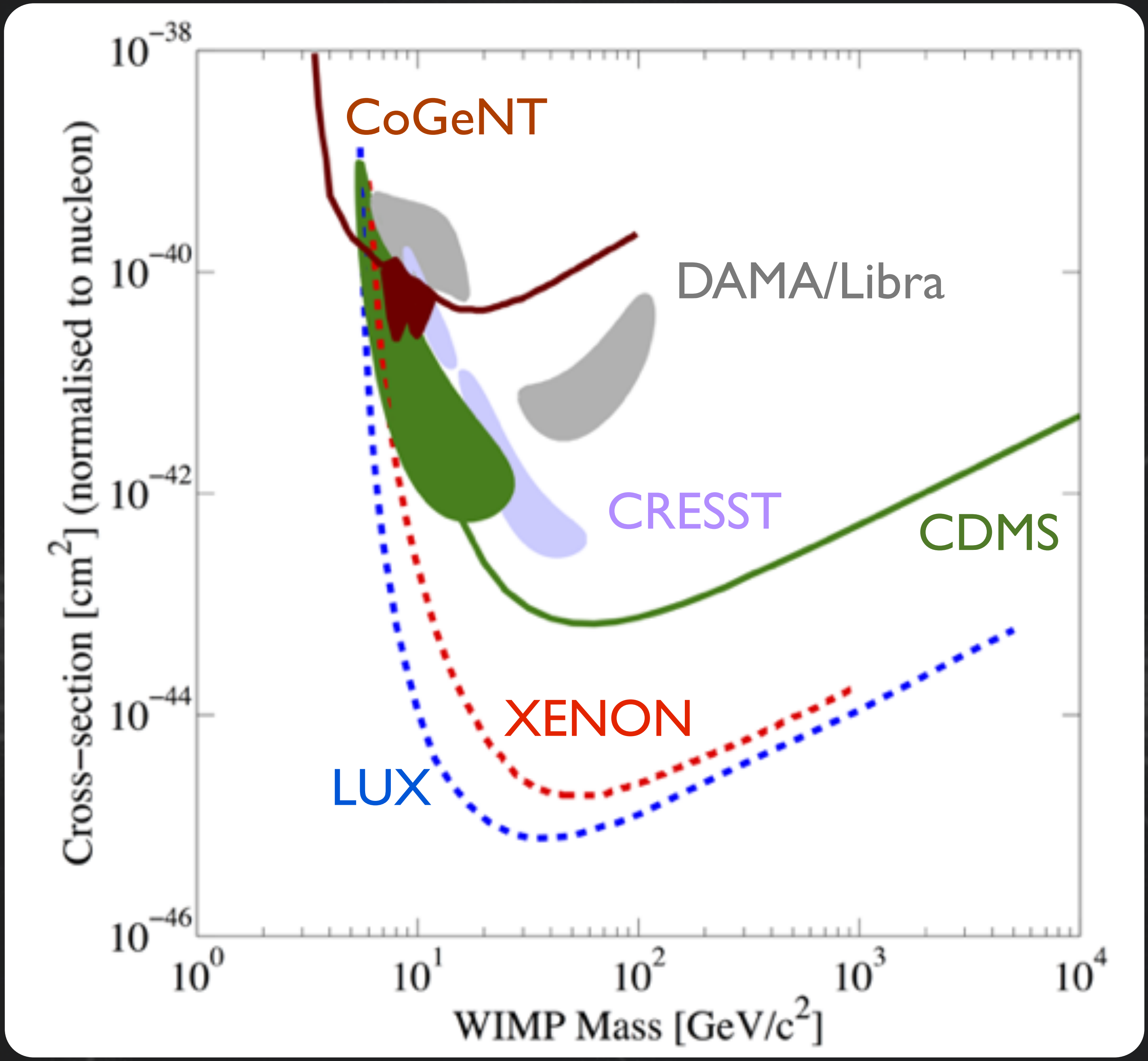
- Underground dark matter searches look for nuclear recoil
- Very active field: Variety of detection channels & techniques, spin dependencies
- Momentum transfer crucial

Direct Detection



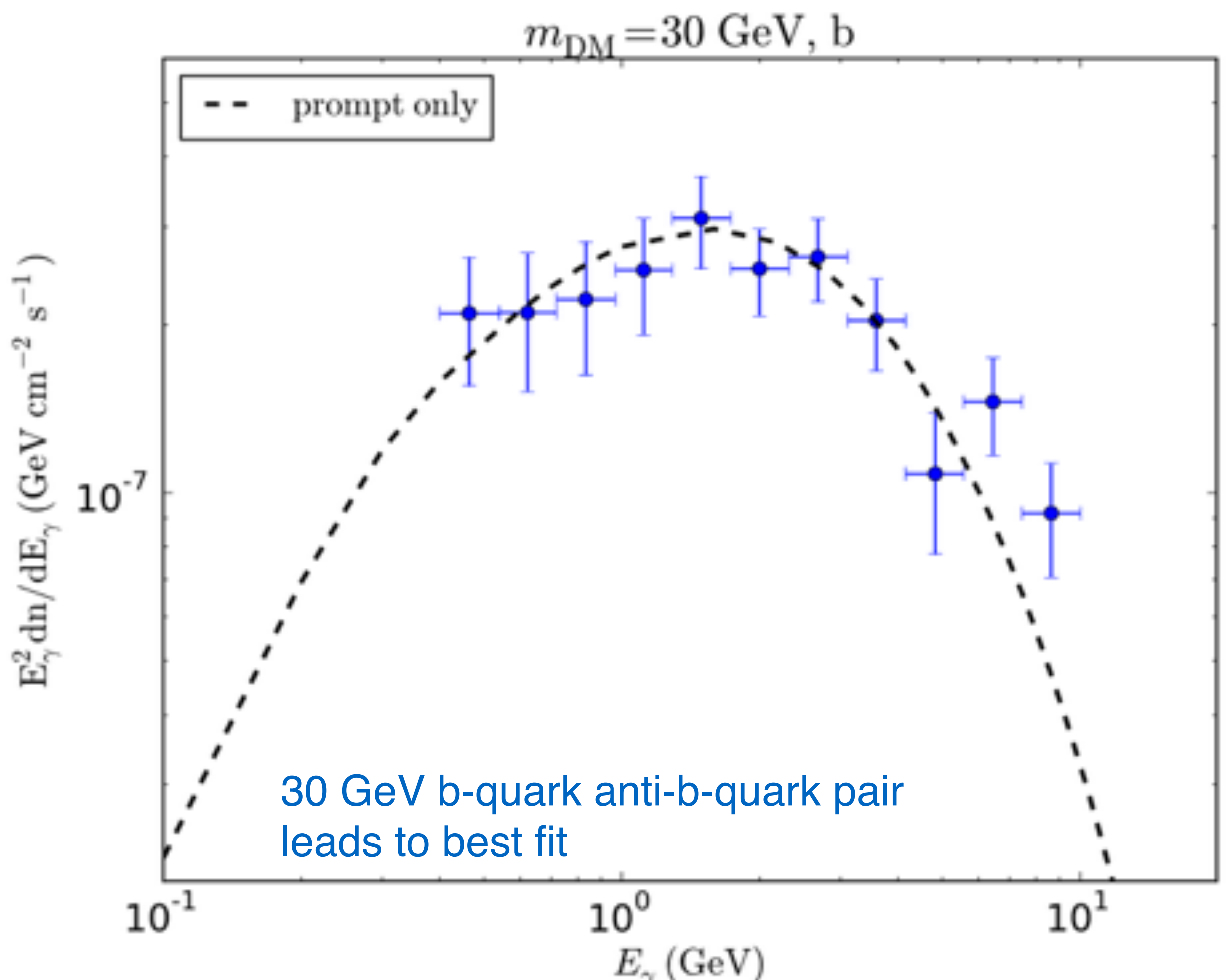
- Underground dark matter searches look for nuclear recoil
- Very active field: Variety of detection channels & techniques, spin dependencies
- Momentum transfer crucial

Direct Detection

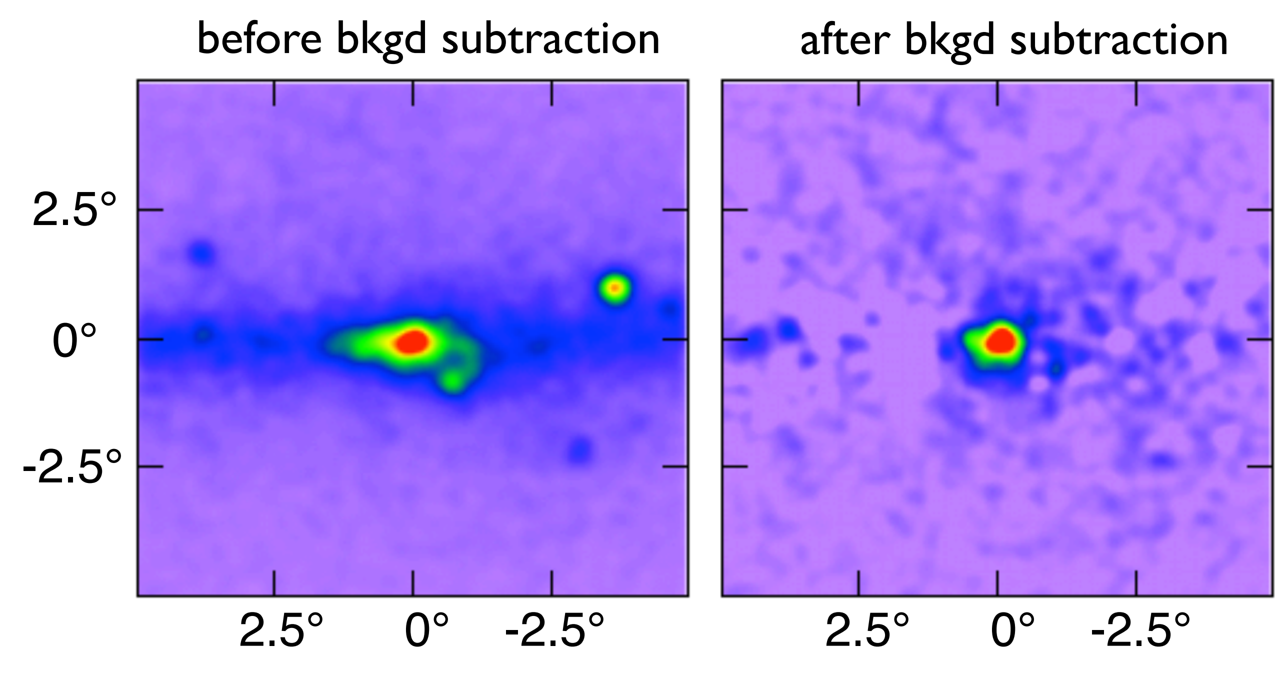


- **Underground dark matter** searches look for **nuclear recoil**
- Very **active field:** LUX, Zeplin, Xenon, CDMS, COUPP…
- **Momentum transfer crucial**

Indirect Detection



arXiv:1403.1987



Potential signal from annihilating DM

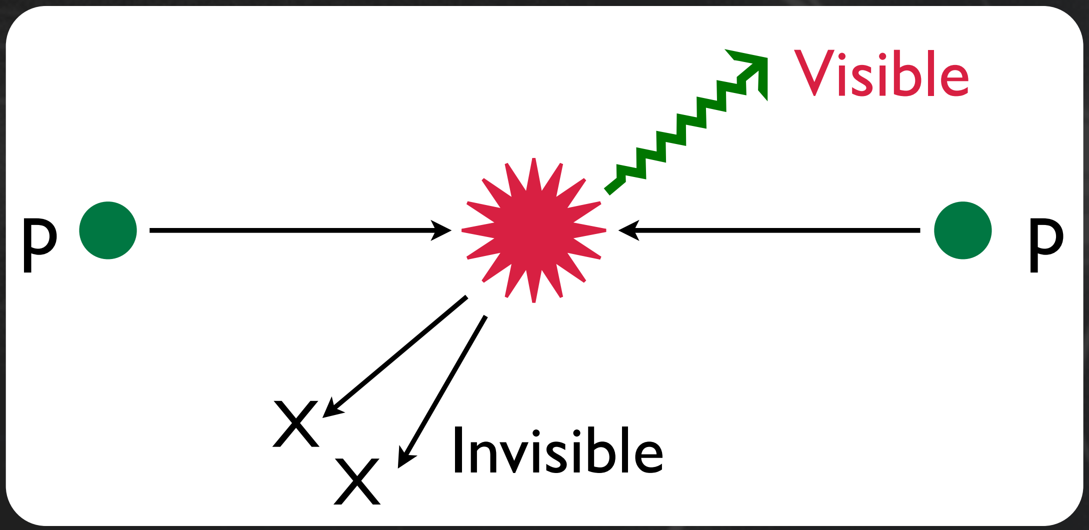
arXiv:1402.6703

- Galactic center (GC) **excess in γ-rays between 0.1 and 10 GeV** in Fermi data
  - Fermi-LAT collaboration 2009, Hooper & Linden 2011, Gordon & Macias 2013, Abazajian et al. 2014, Daylan et al. 2014, Fermi-NASA Symposium 11/14
- **Spherically symmetric** within < 10° × 10° around the **Galactic Center**
- Subtract known sources and use Fermi models for diffuse emission
- Background modeling debated, **DM interpretation** possible

Collider Production at the LHC

Collider DM searches

- DM ‘non-baryonic cold dark matter’ → ‘WIMP Miracle’ → BSM physics
- Properties of low mass DM
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed → Effective Field Theory (EFT)



Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

spin-independent spin-dependent

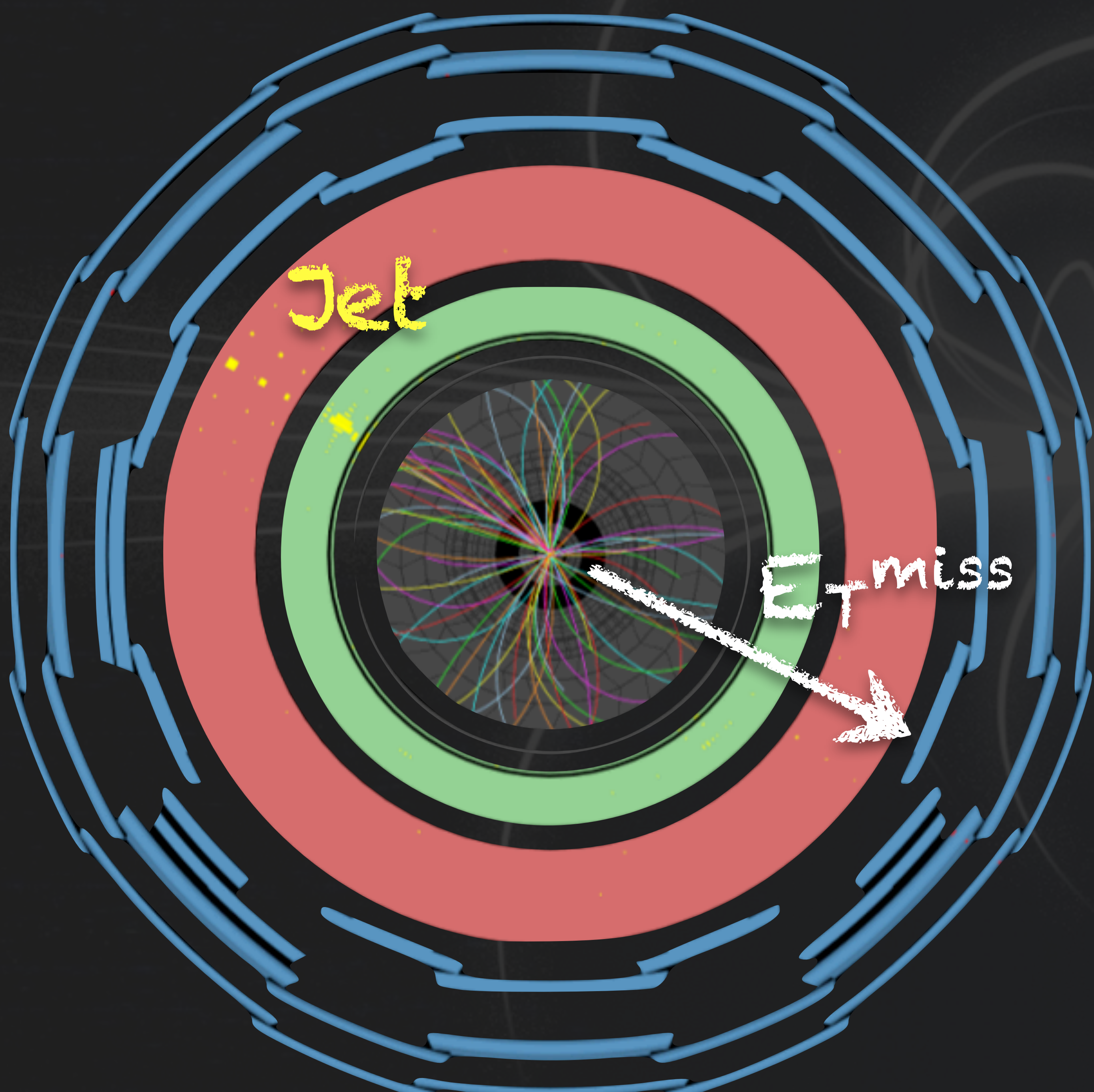
Ref: arxiv:1008.1783v2

- Collider signature: mono-’X’
- Lead and involved in several of these searches
- Sensitive to spin-dependent and independent dark matter and low masses

Example of Present Searches

- Mono-jet
- Mono-photon

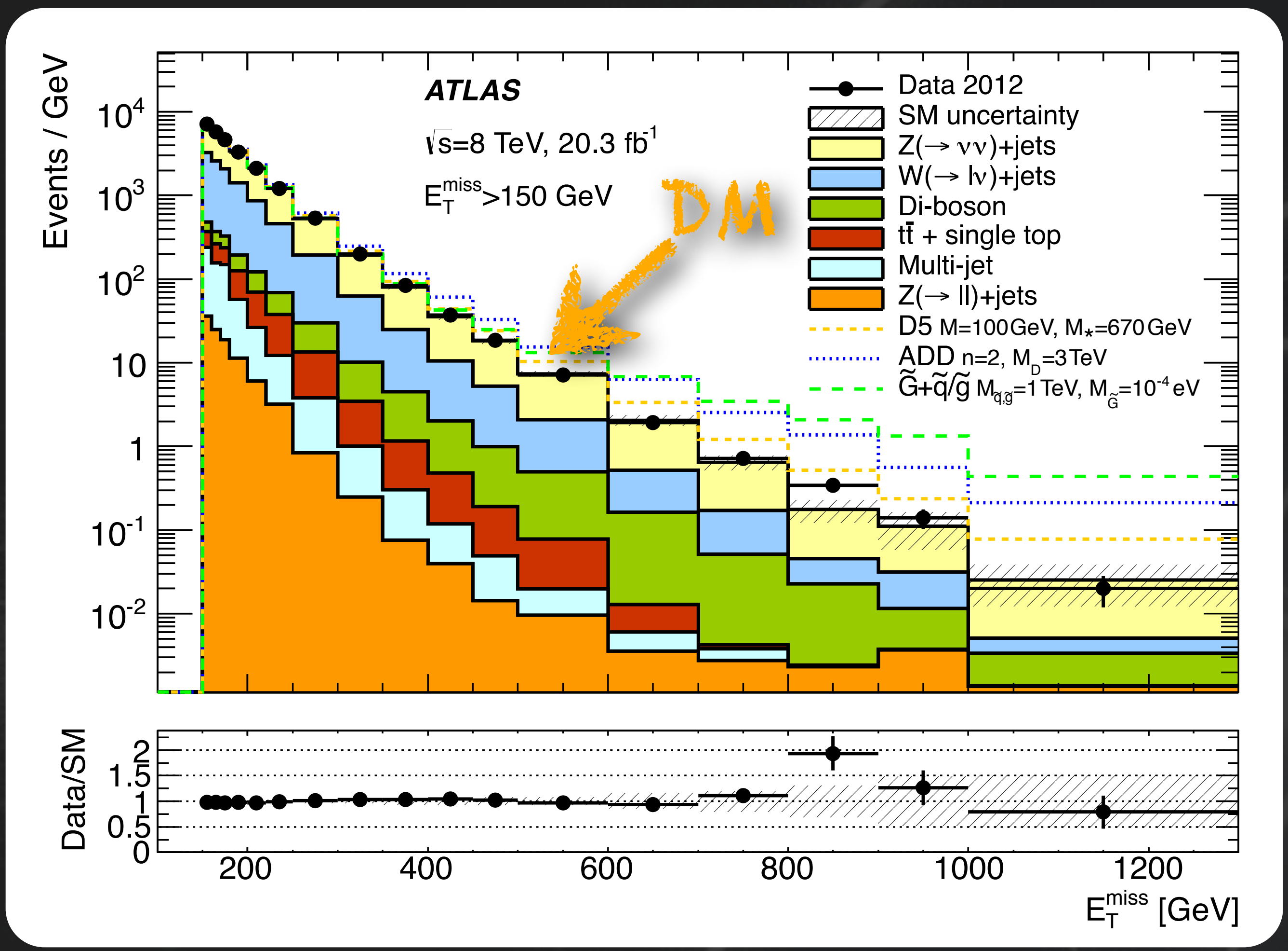
Mono-jet/Mono-photon



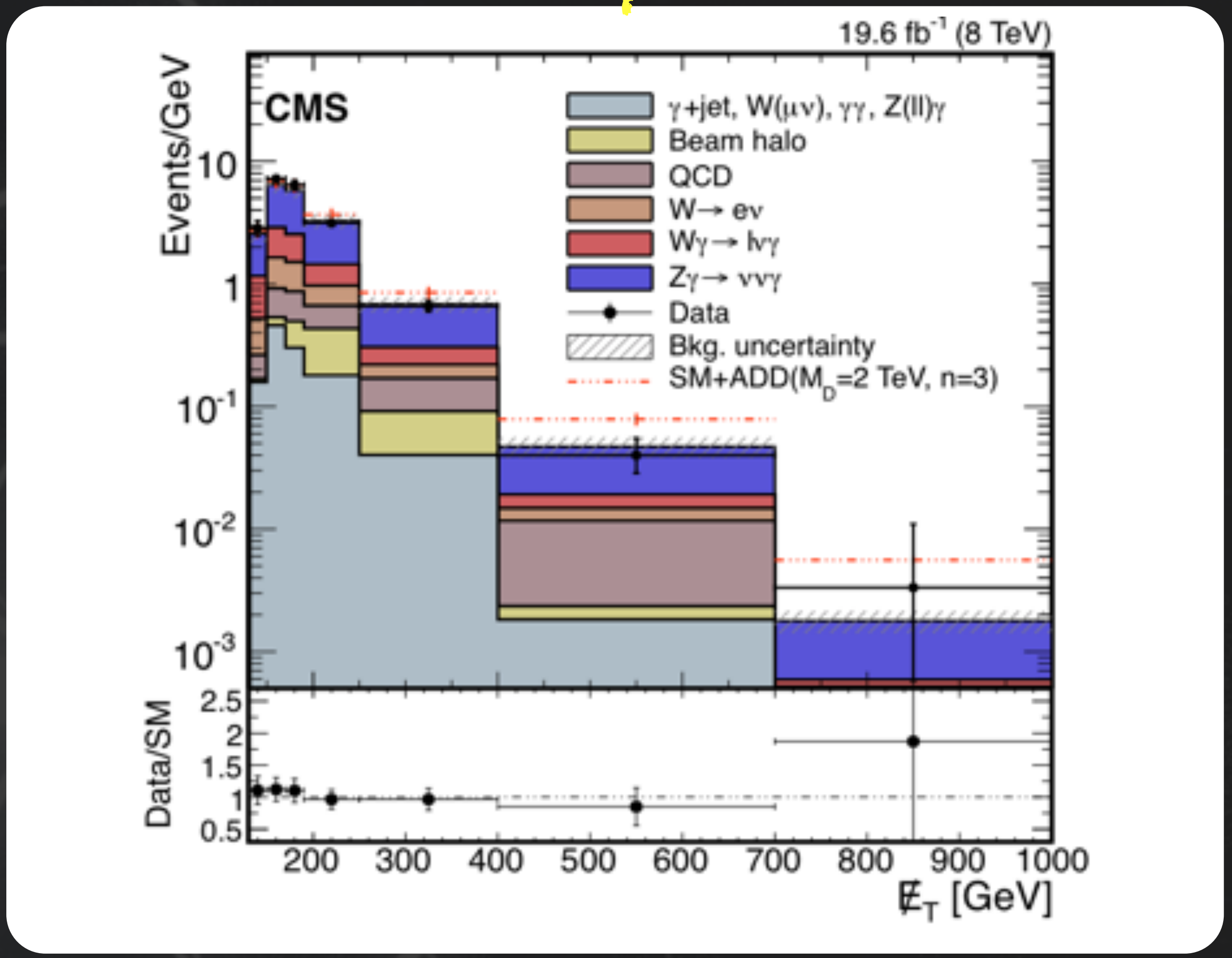
- E_T^{miss} trigger
- Monojet (8 TeV, 20.3 fb-1)
  - E_T^{miss} , $p_T(j)$ > 150, 250,..,400,..900 GeV
  - 1 or 2 jets (anti-k_T, R=0.4, p_T>30 GeV)
  - $|\Delta\varphi(E_T^{miss}, j_2)|>0.5$
- Monophoton (8 TeV, 19.6 fb^{-1}):
  - E_T^{miss} , $p_T(\gamma)$>140 GeV,
  - N_{jet} < 2 (anti-k_T, R=0.5, p_T>30 GeV)
  - $\Delta\varphi$ (γ, E_T^{miss}) >2,
  - (X^2, $\Delta\varphi$ (jet, E_T^{miss}) >0.4)

Mono-jet/Mono-photon

mono-jet



mono-photon

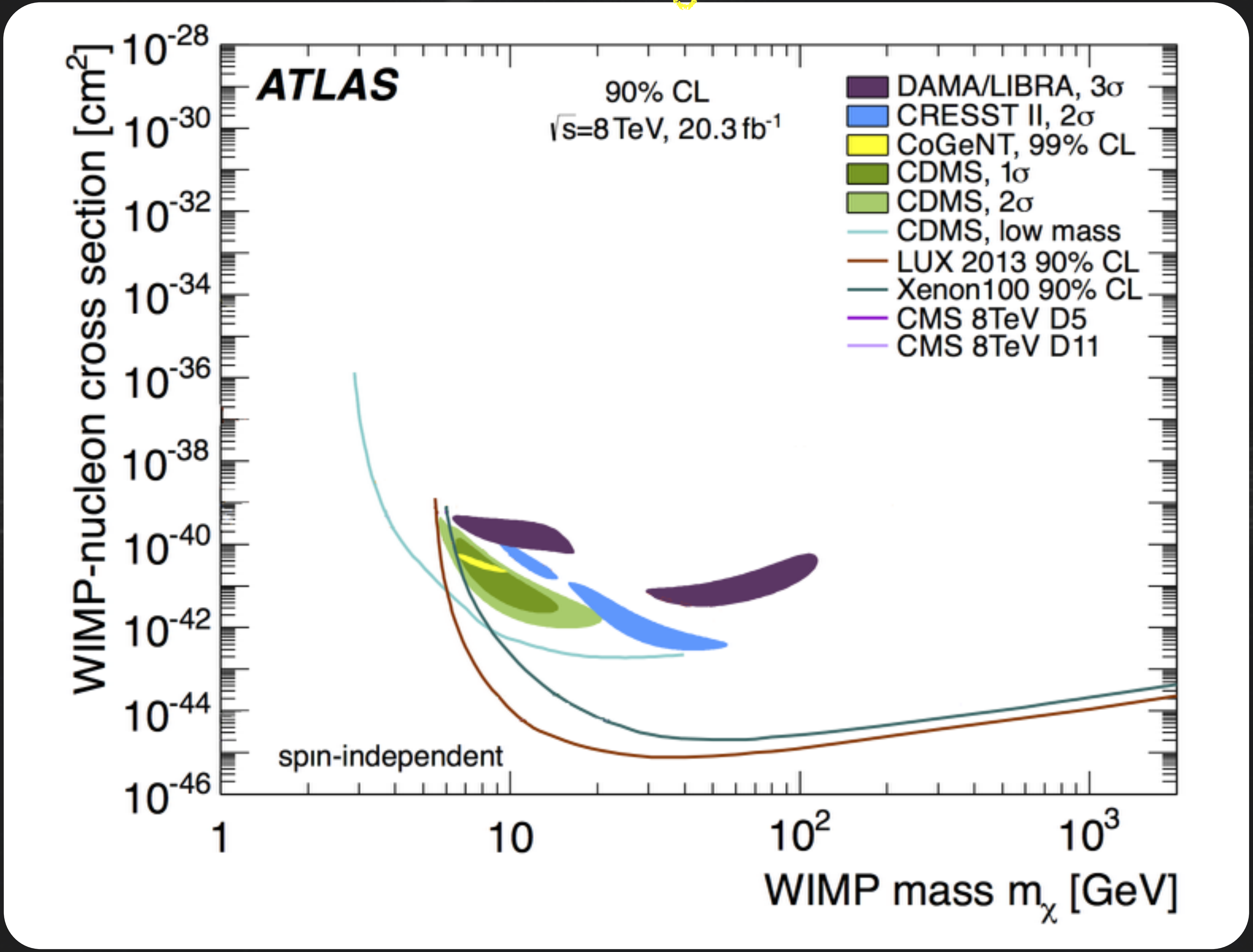


- **Example**: vector couplings (orange line)
  - other limits also re-interpreted
- **Expected and observed number of events agree**

→ Place upper limits on the visible cross section

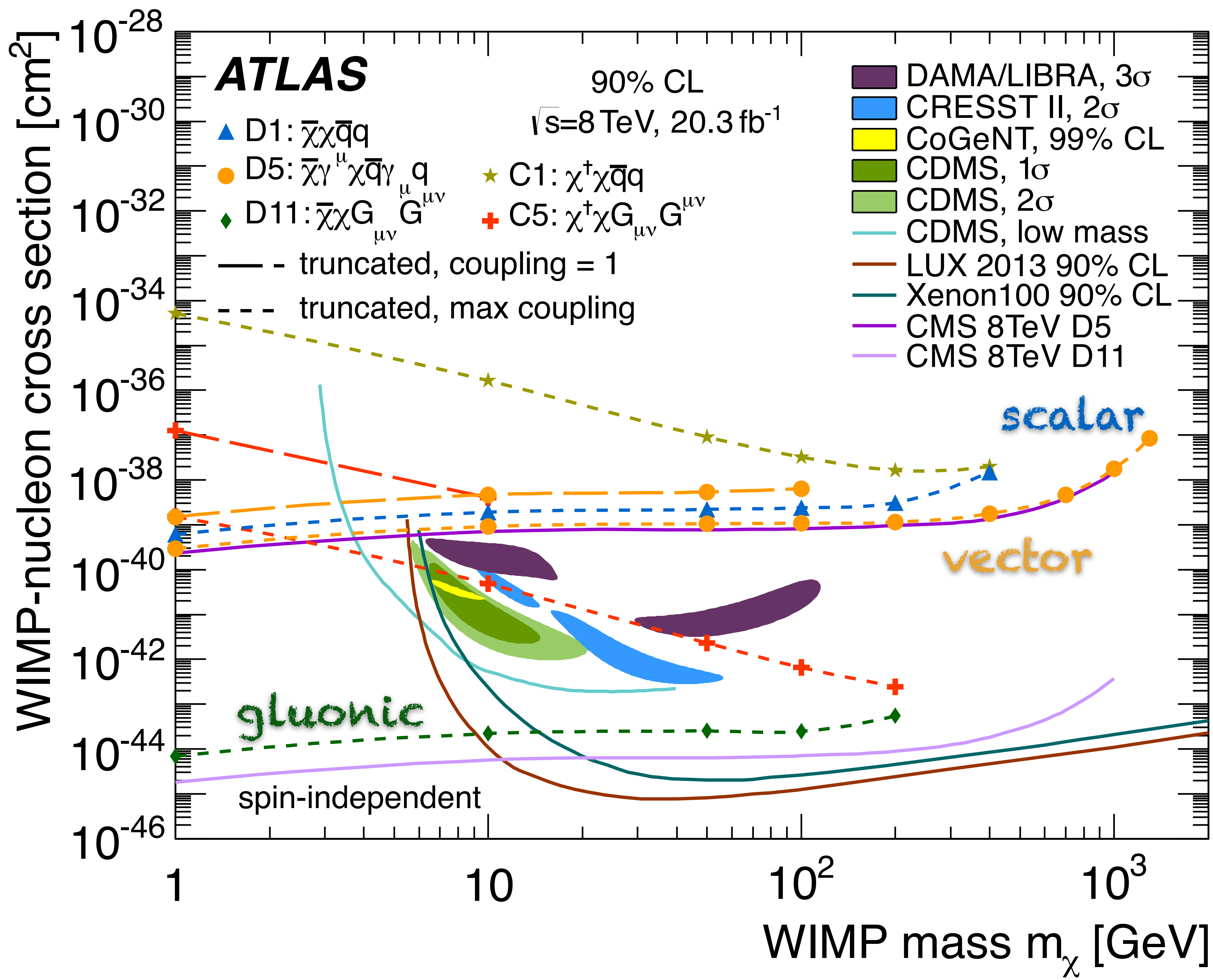
Mono-jet/Mono-photon

mono-jet



Mono-jet/Mono-photon

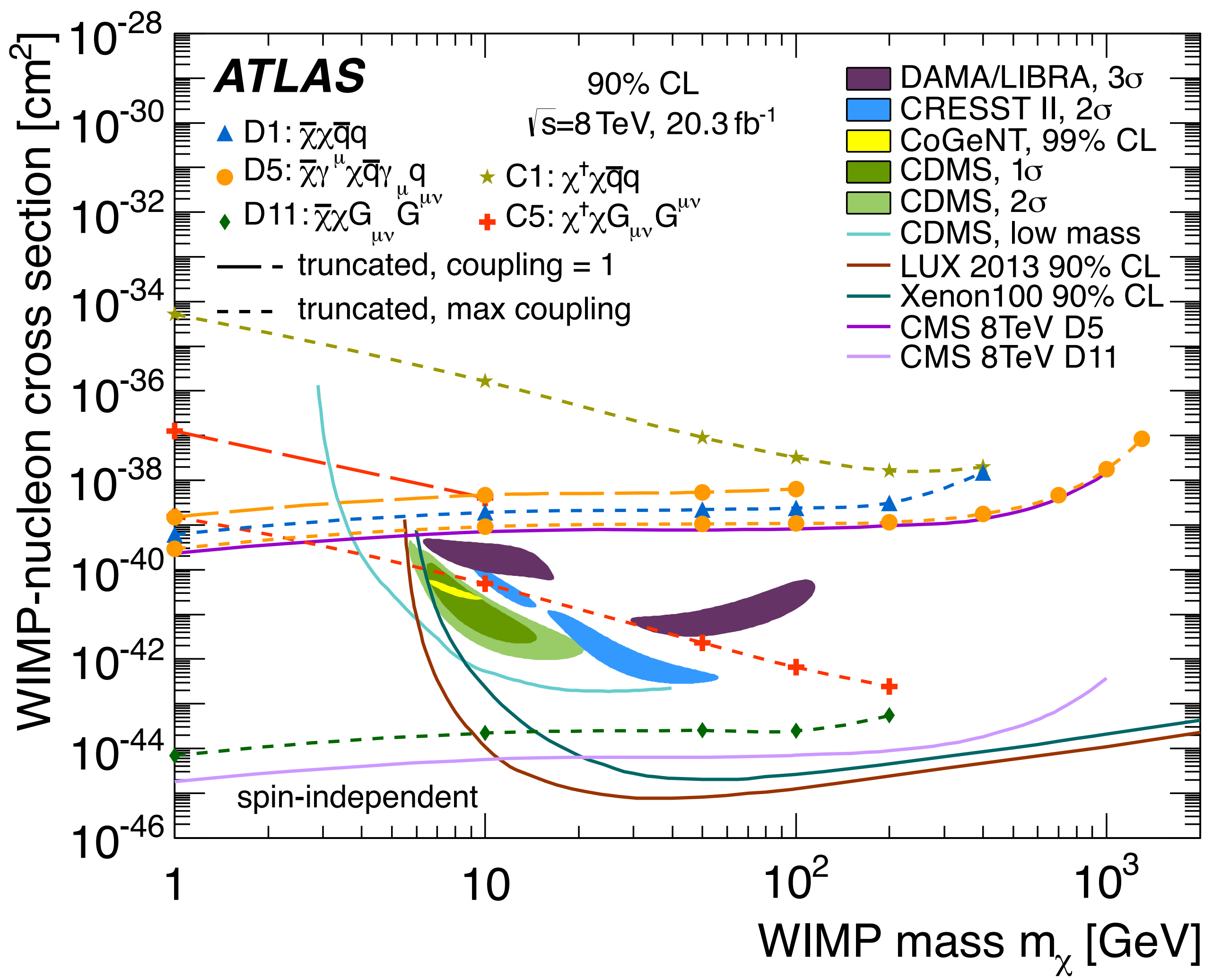
mono-jet



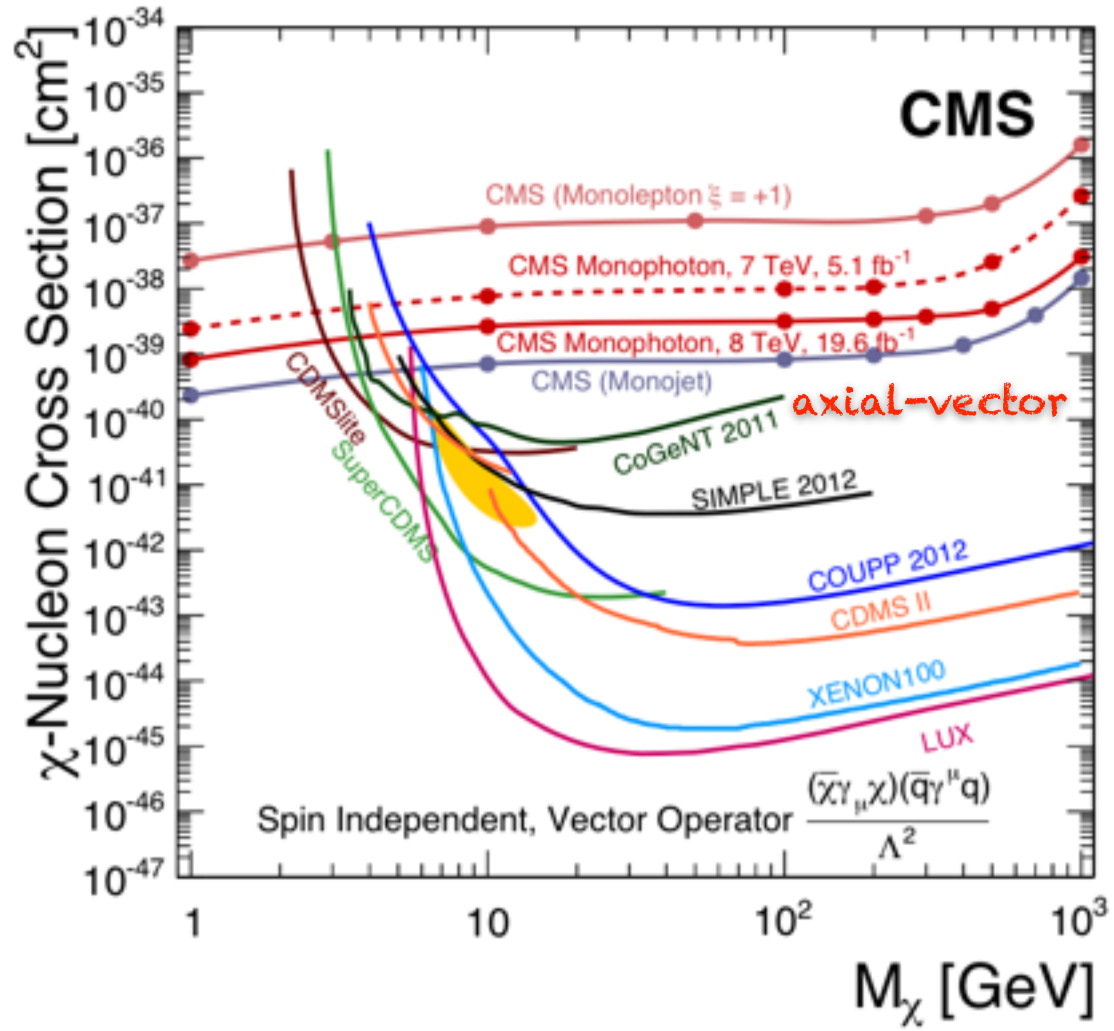
1109.4398v1, Fox et al.

Mono-jet/Mono-photon

mono-jet



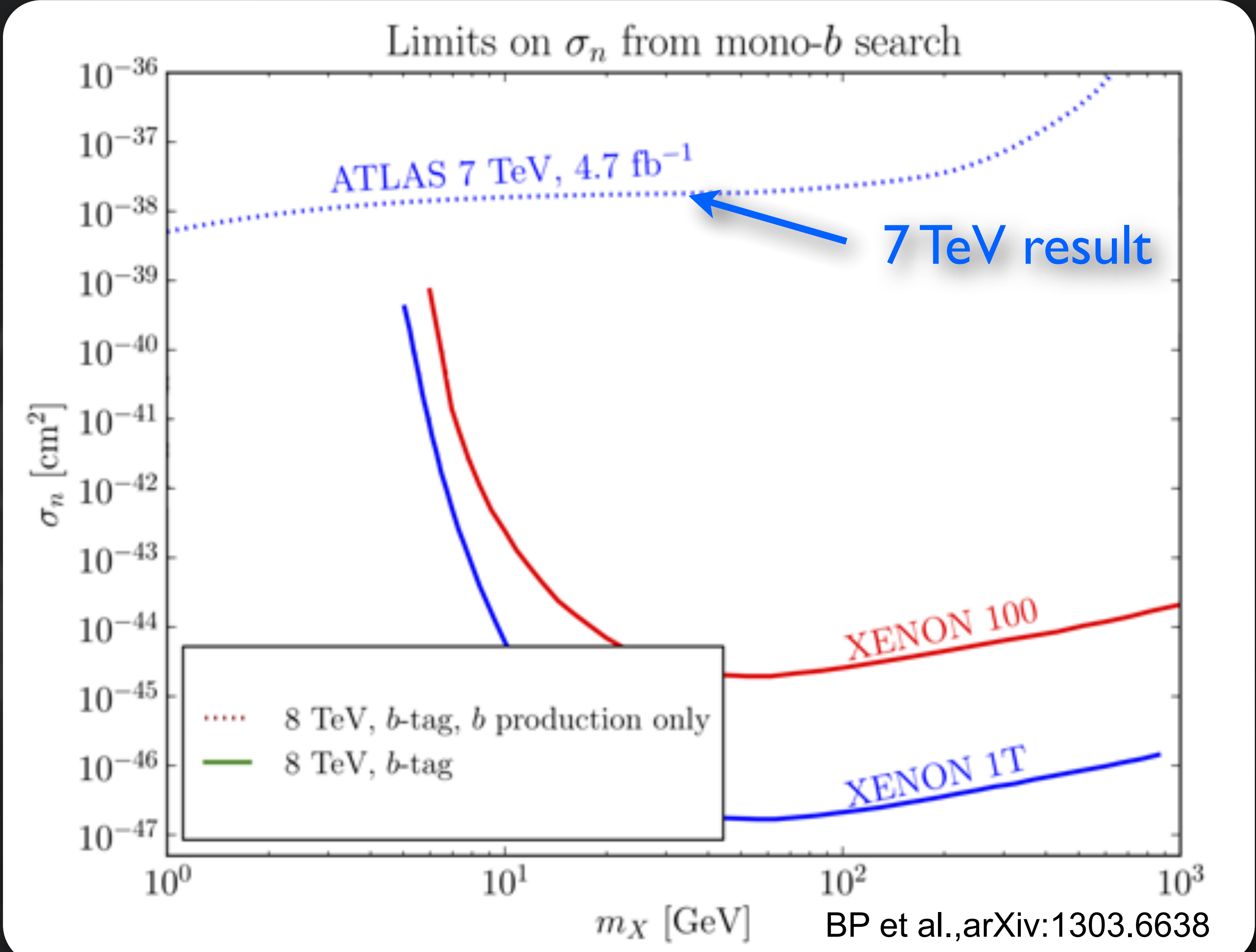
mono-photon



- Cross sections for mono-photon suppressed by ratio of strong and electromagnetic fine structure constants as well as a color factor
- Relative size of excesses in mono-photon vs. mono-jets is sensitive to whether the operator involves up or down quarks
- Some operators (e.g. gg) won’t produce mono-photon signals

A novel idea: heavy quark searches

Initial sensitivity studies

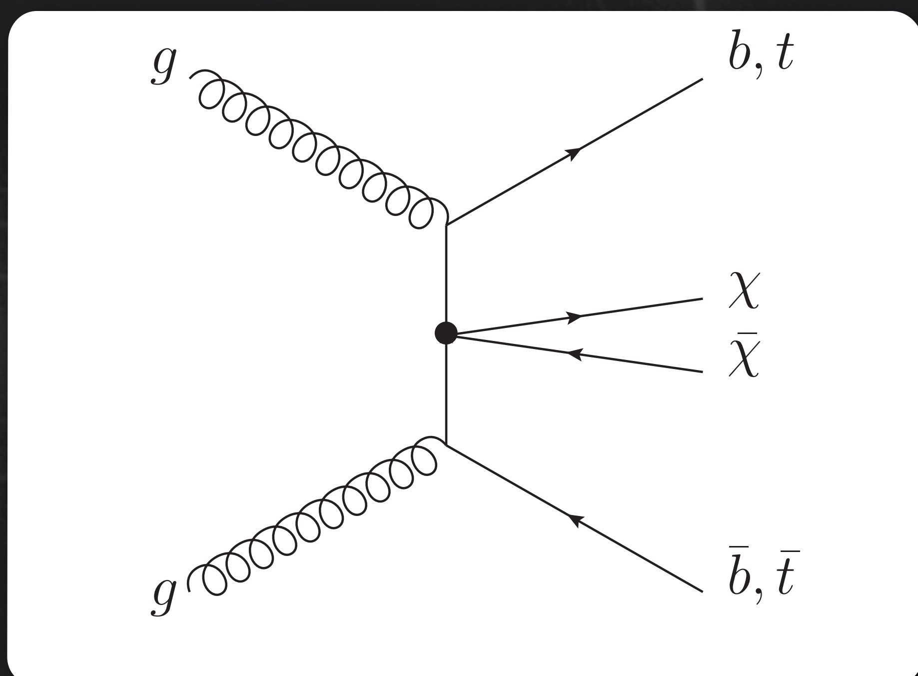


BP et al.,arXiv:1303.6638

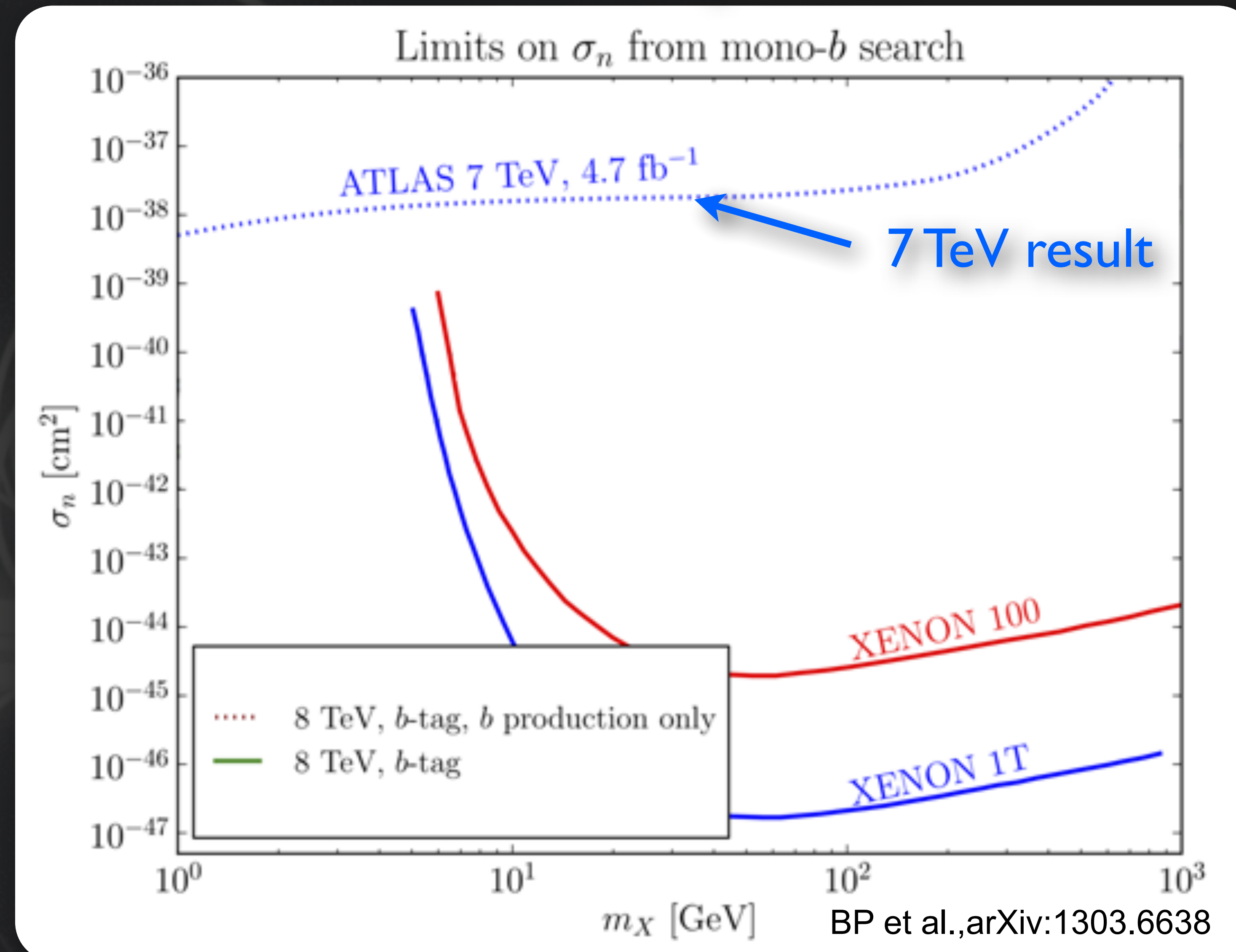
- Monojet provide most powerful LHC DM limits currently
  - Mono-photon & mono-W/Z probe more specific coupling
- Typically light flavor jets, narrow kinematic regions
- Heavy flavor jets:
  - Third generation coupling enhanced for given couplings $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
  - Access more inclusive final states
  - Experience as b-ID convener, WH and Wbb measurements

A novel idea: heavy quark searches

$$bg \to \chi\bar{\chi} + b$$
$$gg \to \chi\bar{\chi} + b\bar{b}$$
$$gg \to \chi\bar{\chi} + t\bar{t}$$



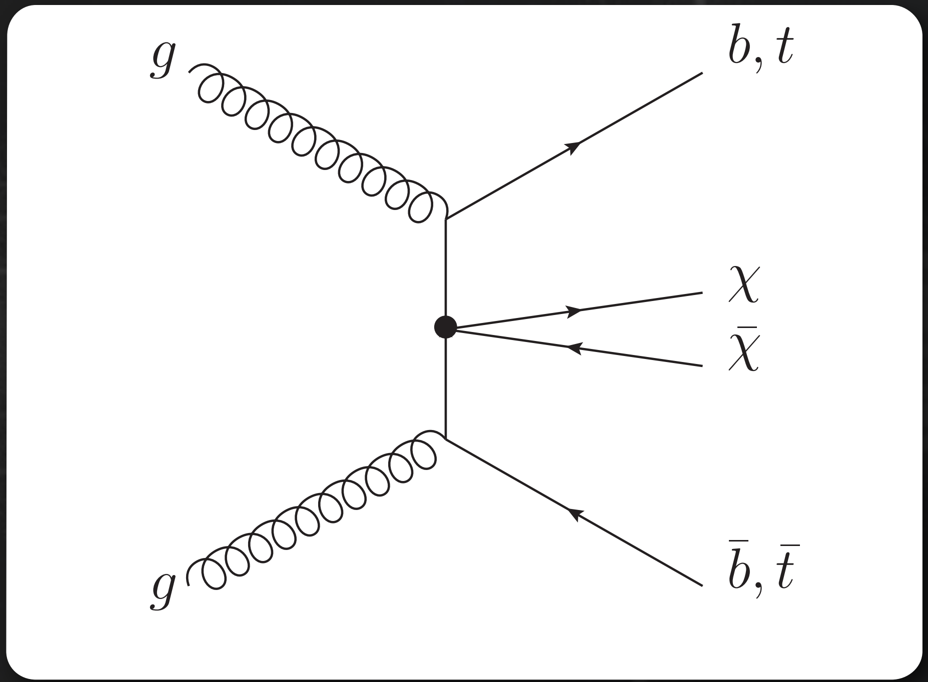
Initial sensitivity studies



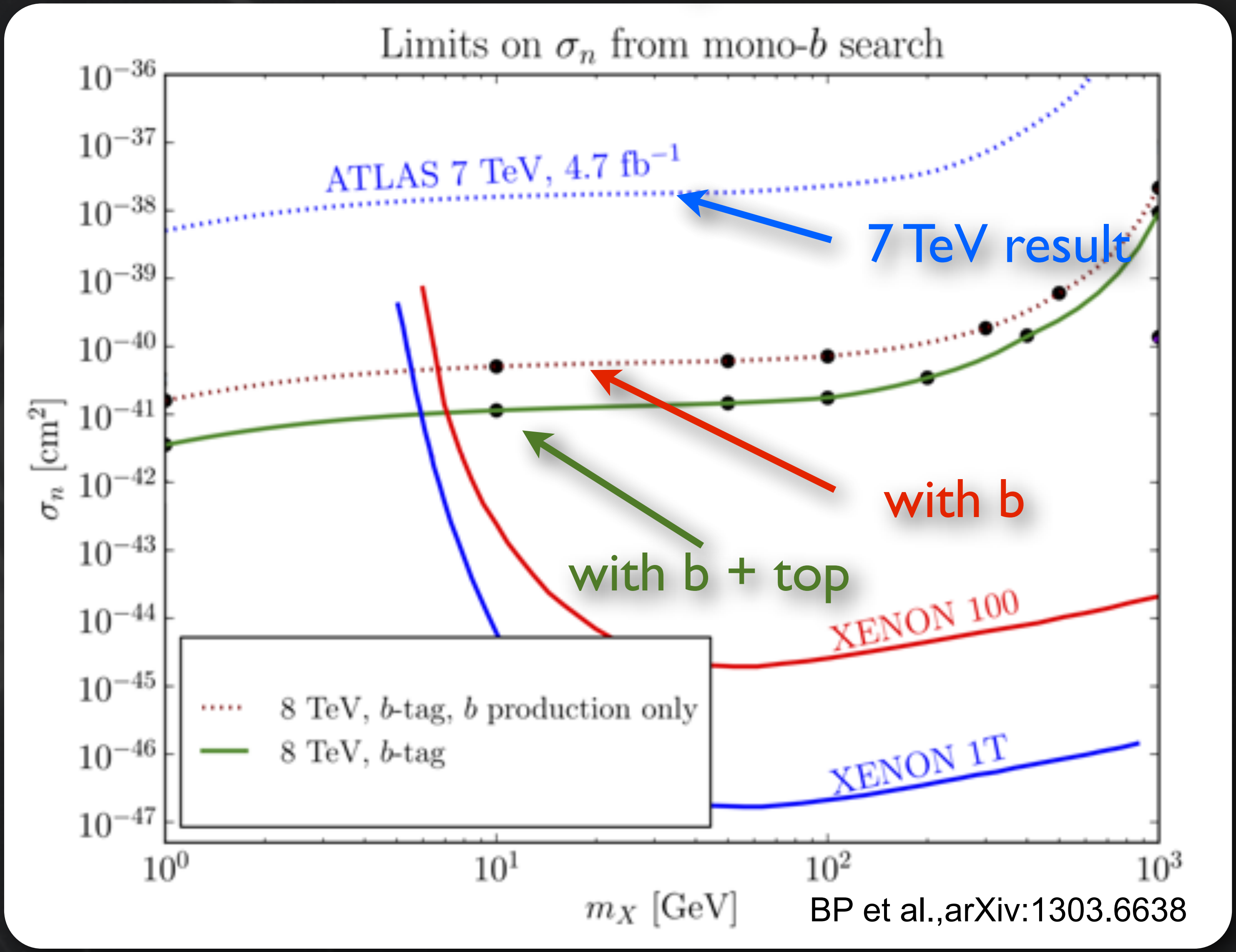
- **Collaborating with theorist I** extended approach guided by **interdisciplinary results**
- **Testing coupling of new operators to mass**
- **Extended mono-X** approach to complex topologies: **DM+b(b), DM+tt**

A novel idea: heavy quark searches

$$bg \to \chi\bar{\chi} + b$$
$$gg \to \chi\bar{\chi} + b\bar{b}$$
$$gg \to \chi\bar{\chi} + t\bar{t}$$

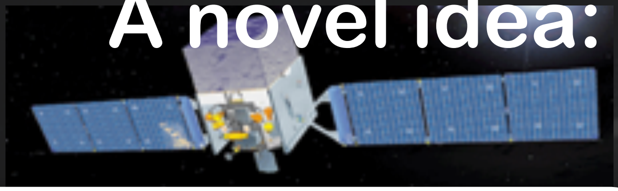


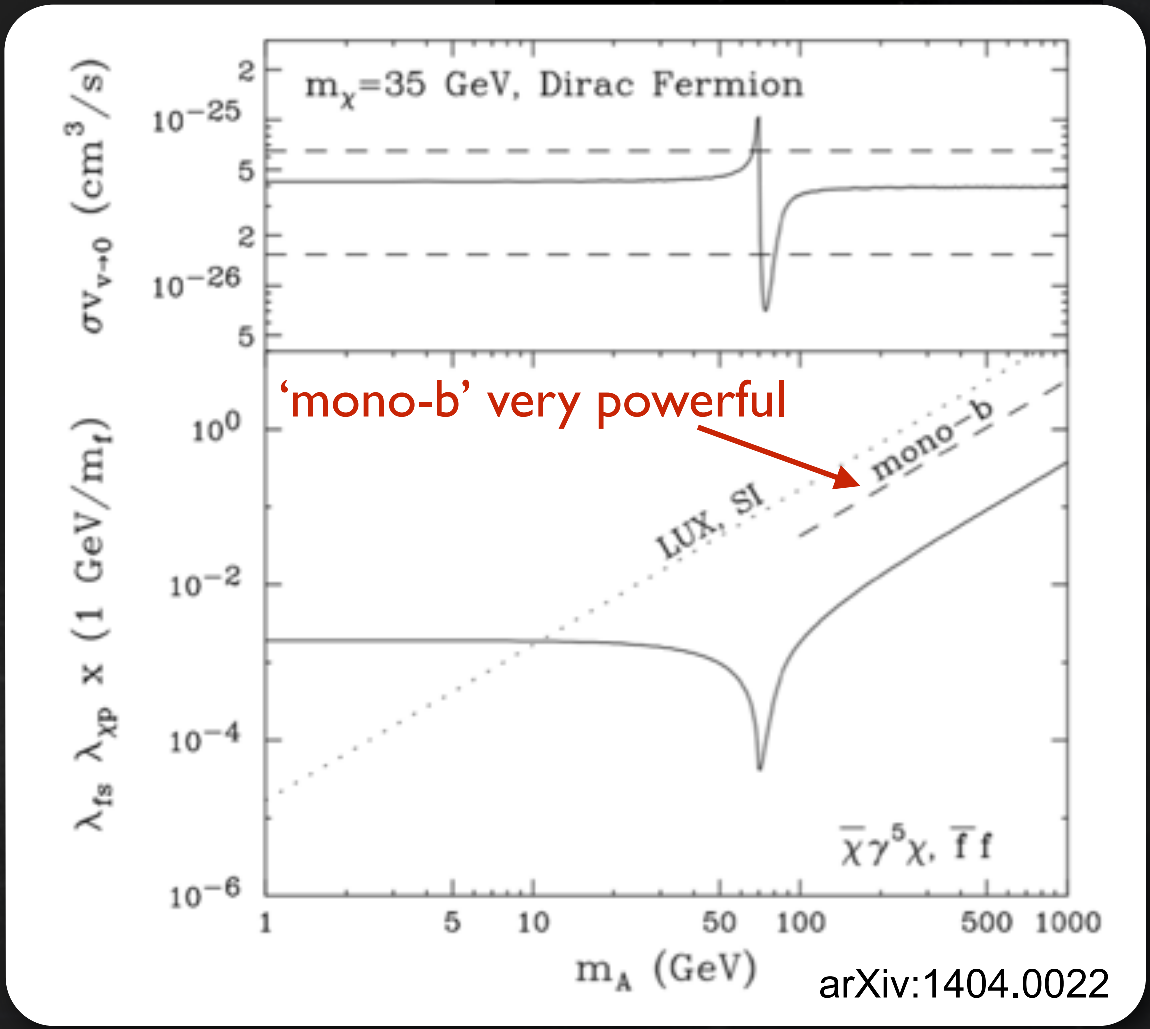
Initial sensitivity studies

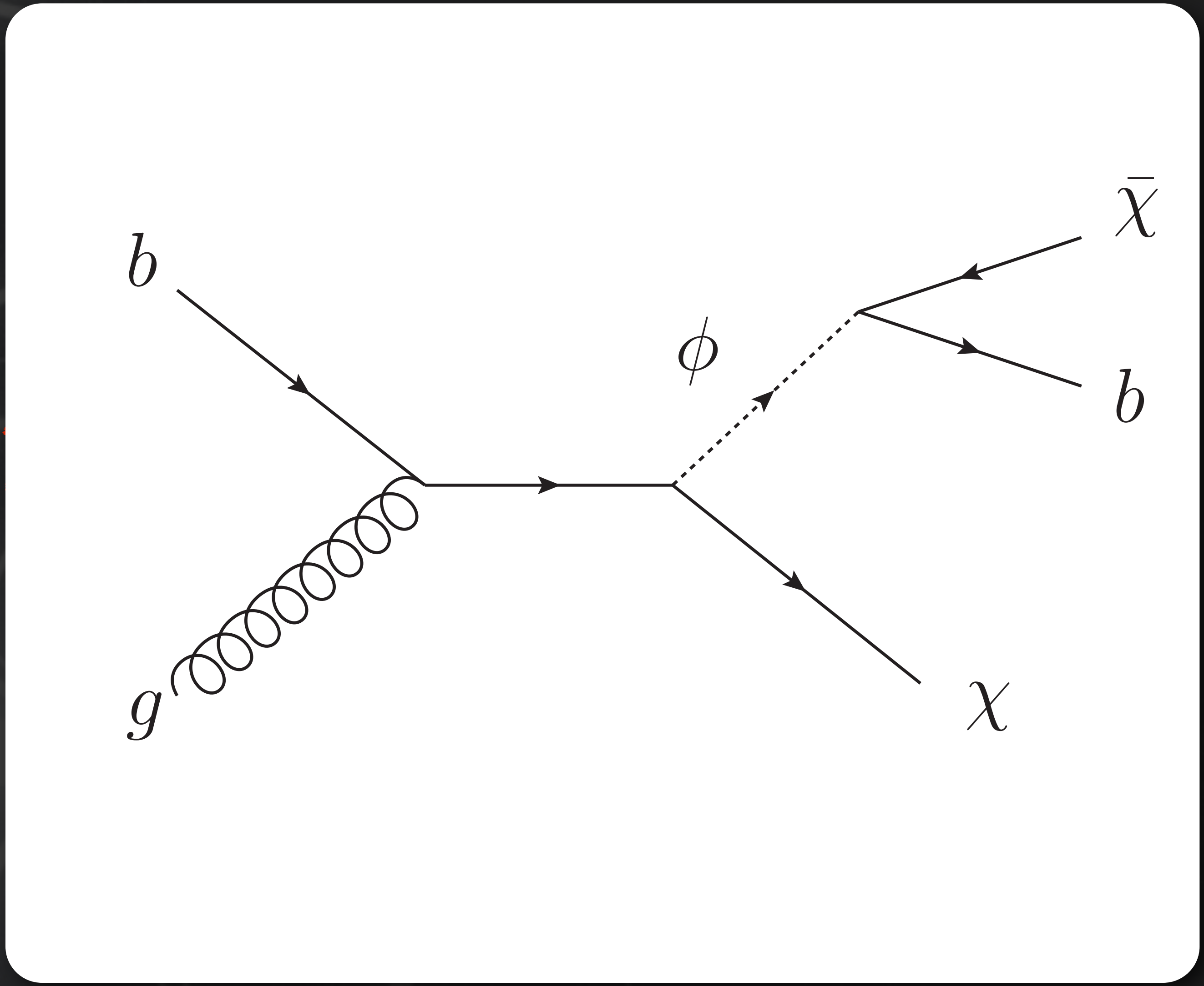


- **Collaborating with theorist** I extended approach guided by **interdisciplinary results**
- **Testing coupling of new operators to mass**
- **Extended mono-X** approach to complex topologies: **DM+b(b), DM+tt**

A novel idea: heavy quark searches







- **Collaborating with theorist** I extended approach guided by **interdisciplinary results**
- **Testing coupling of new operators to mass**
- **Extended mono-X** approach to complex topologies: **DM+b(b), DM+tt**
- Address **EFT validity constrains** and first search **using simplified limits**

Berlin, Hooper, McDermott, arXiv: 1404.0022

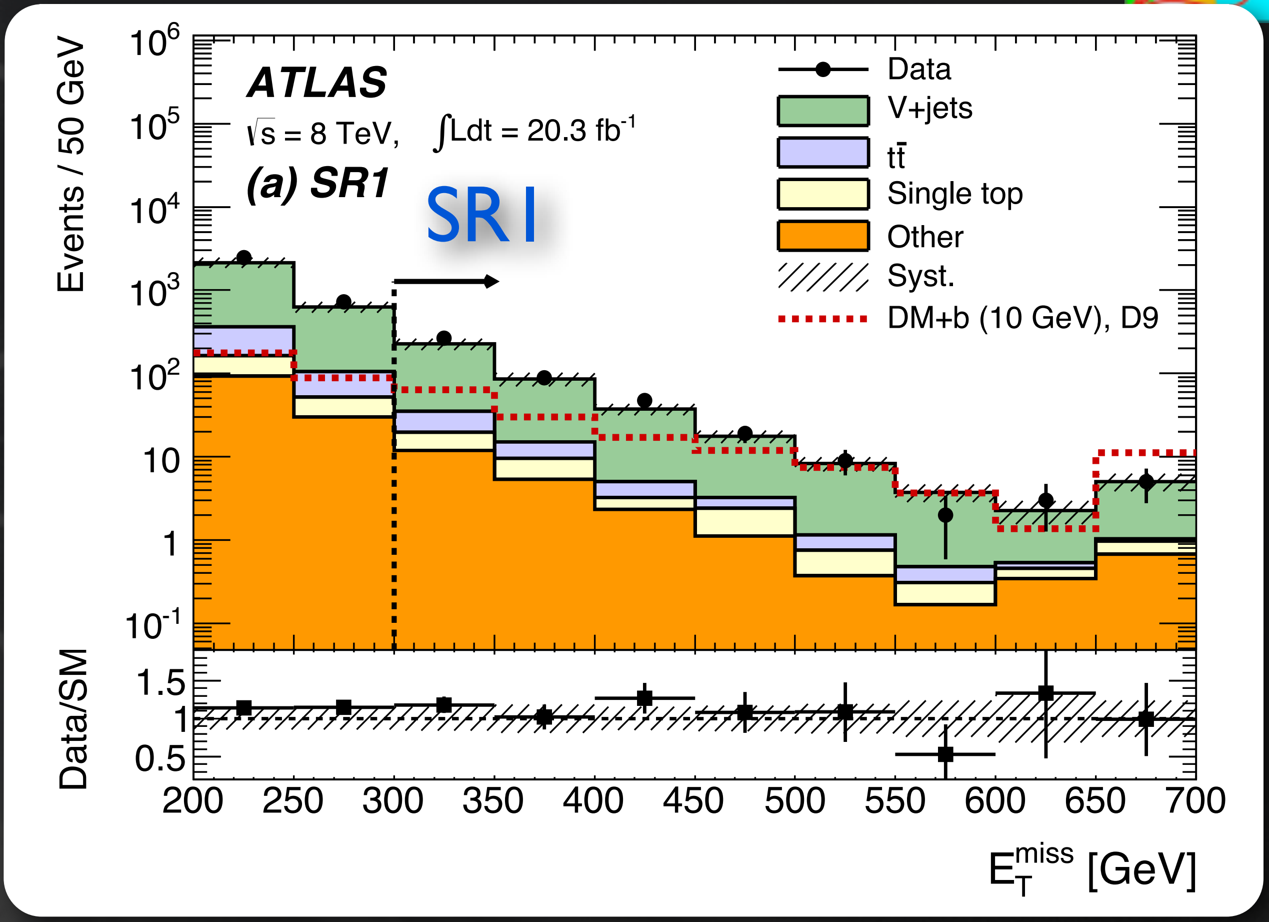
Imperial College London

DM+heavy quark analysis

- 4 Signal regions based on
  - E_T^{miss} - momentum carried by invisible particle
  - b-jet - decay of non-stable particle

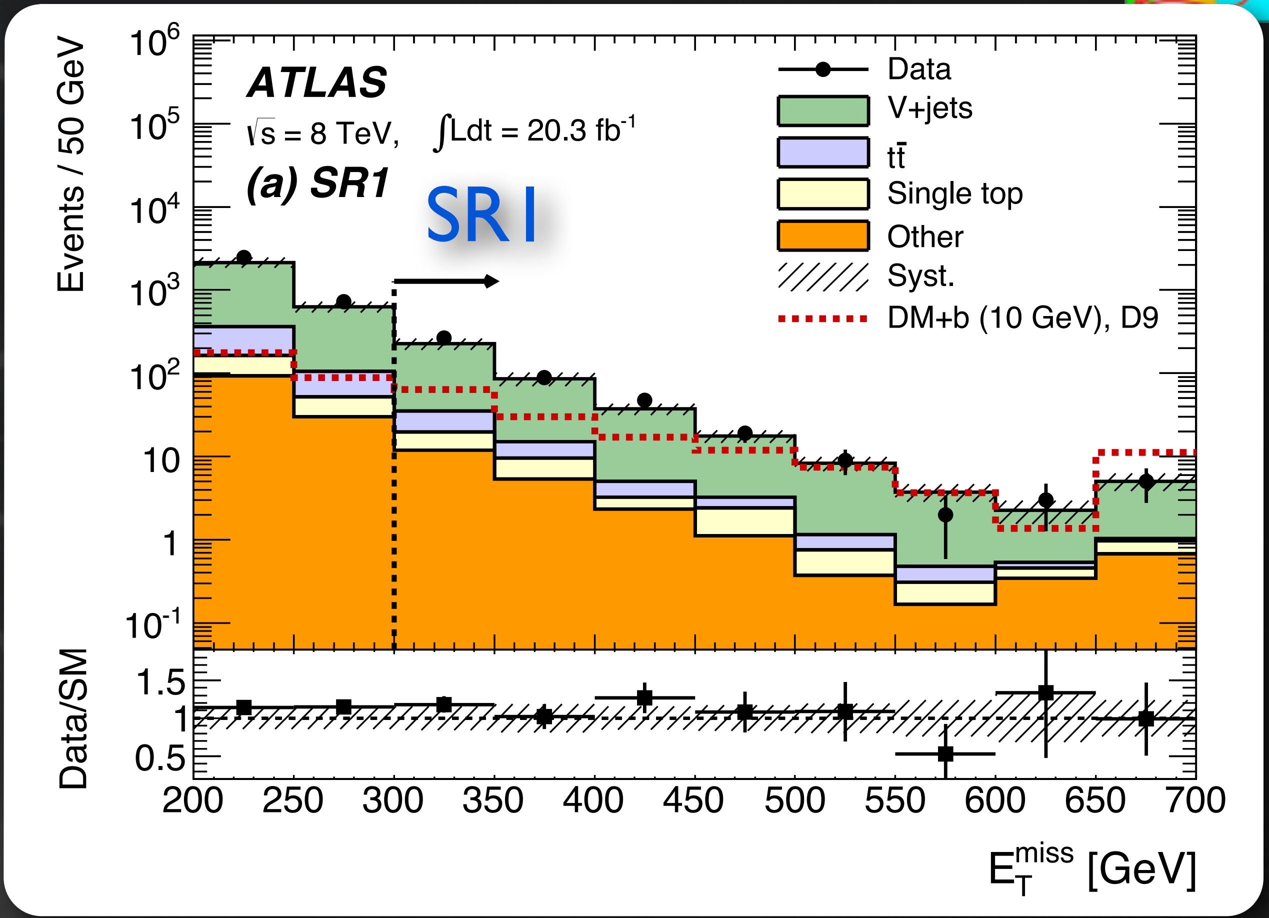
DM+heavy quark analysis

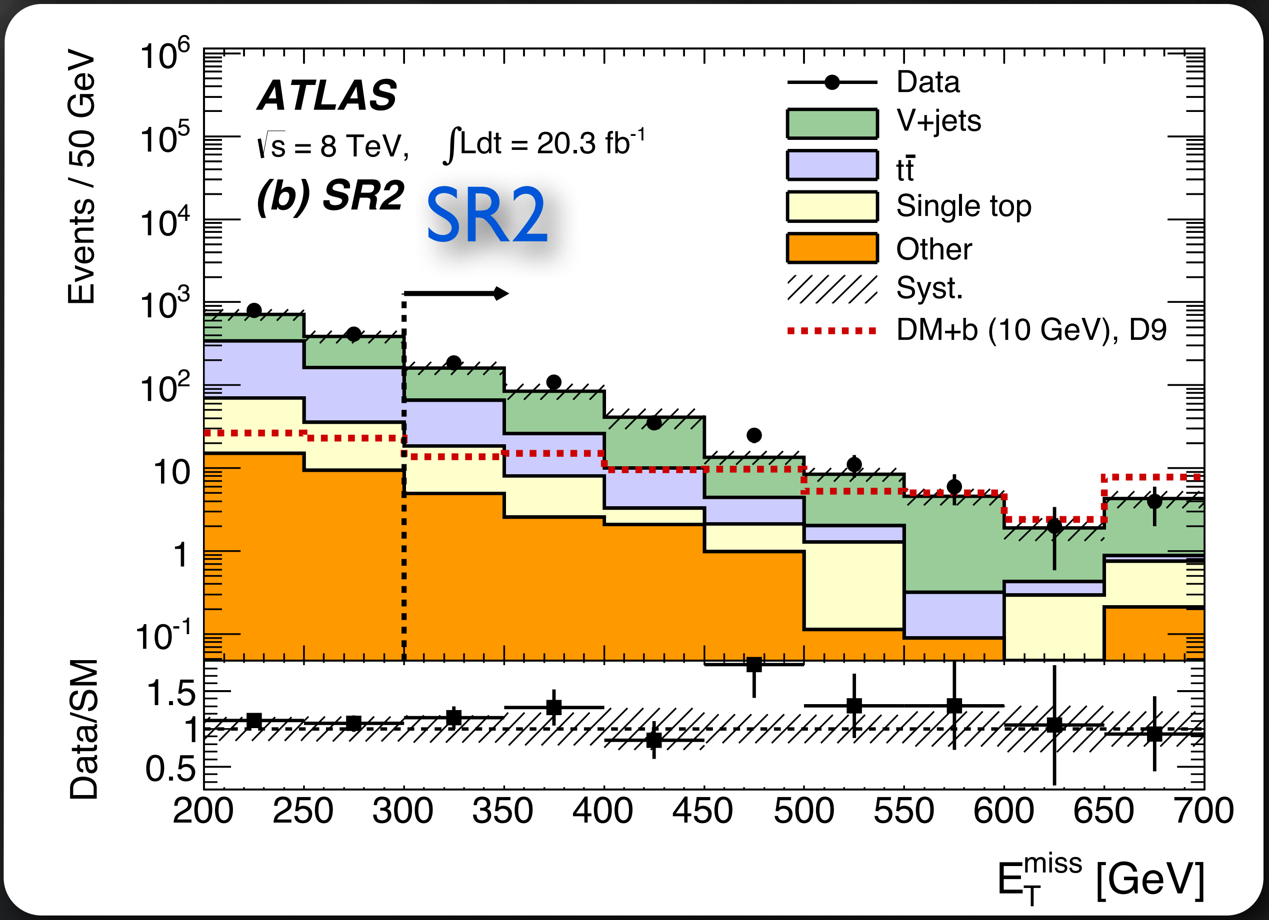
- **4 Signal regions** based on
  - E_T^{miss} - momentum carried by invisible particle
  - b-jet - decay of non-stable particle
- **DM+b**:
  - E_T^{miss}>300 GeV, p_T(b)>100 GeV
  - SR1: n_{jet}=1,2



DM+heavy quark analysis

- **4 Signal regions** based on
  - E_T^{miss} - momentum carried by invisible particle
  - b-jet - decay of non-stable particle
- **DM+b**:
  - E_T^{miss}>300 GeV, p_T(b)>100 GeV
  - **SR1**: n_{jet}=1,2
  - **SR2**: n_{jet}=3,4

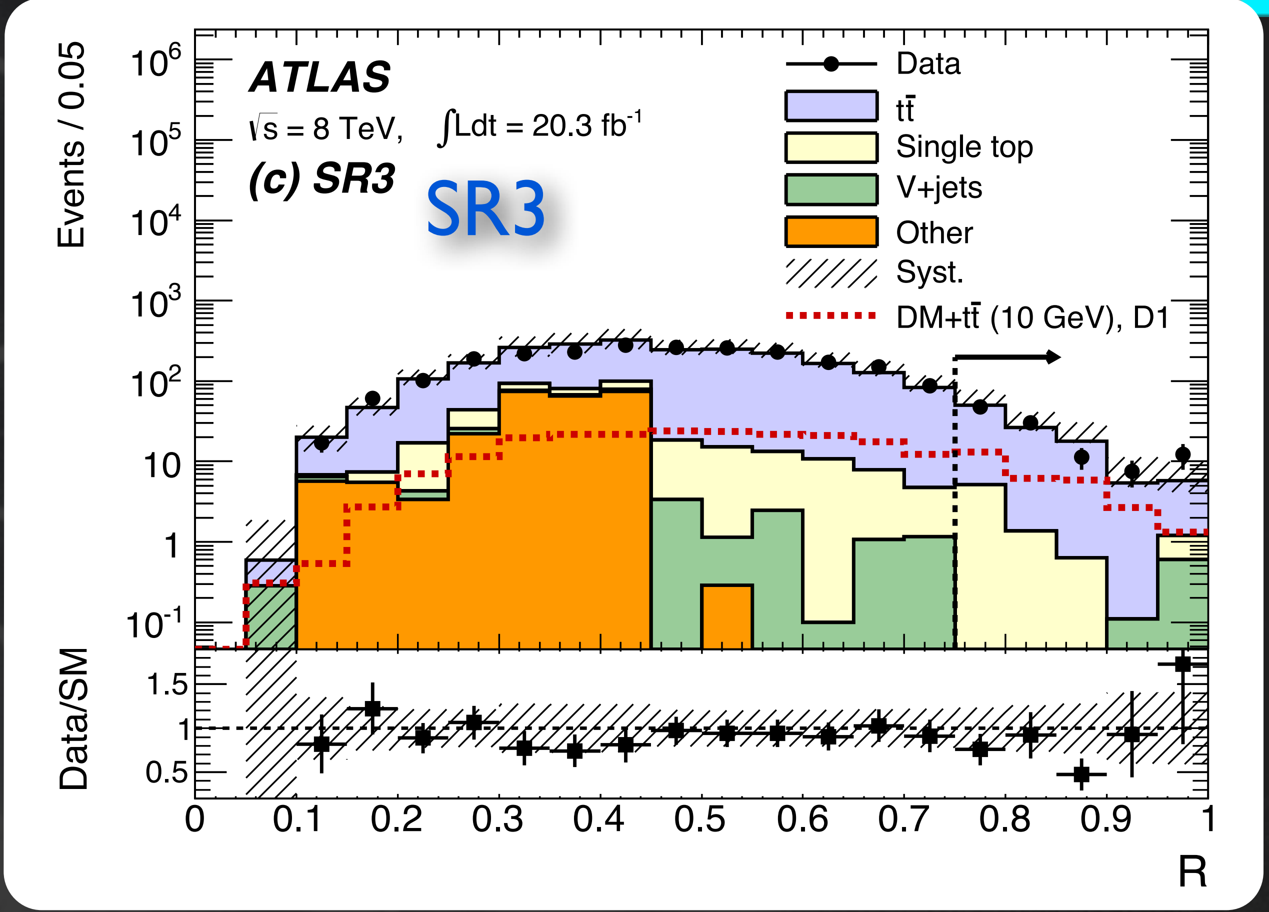


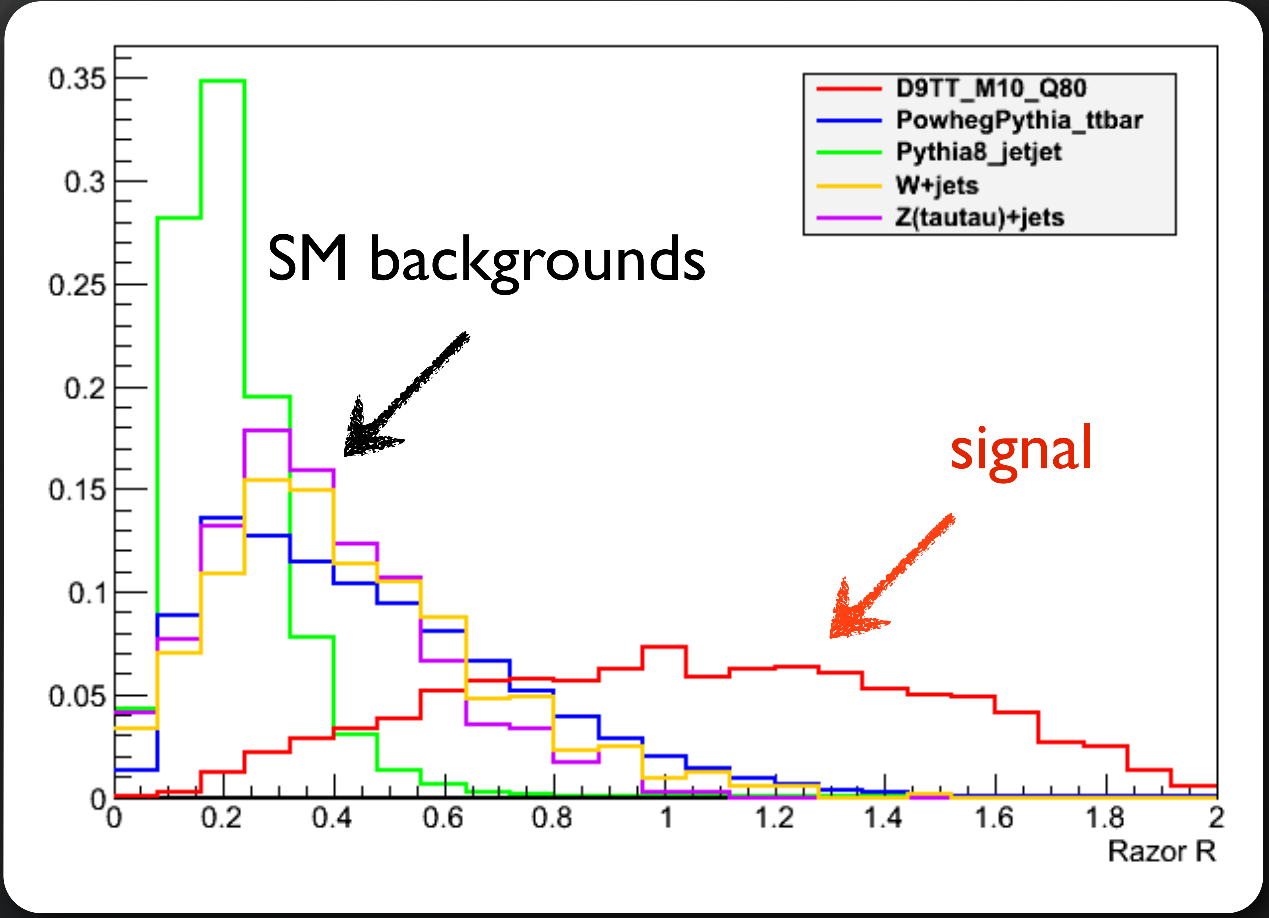


Imperial College London

DM+heavy quark analysis

- **4 Signal regions** based on
  - E_T^{miss} - momentum carried by invisible particle
  - **b-jet** - decay of non-stable particle
- **DM+b:**
  - E_T^{miss}>300 GeV, p_T(b)>100 GeV
  - **SR1**: n_{jet}=1,2
  - **SR2**: n_{jet}=3,4
- **DM+tt:**
  - **SR3:** had (n_{jet}>4), Razor

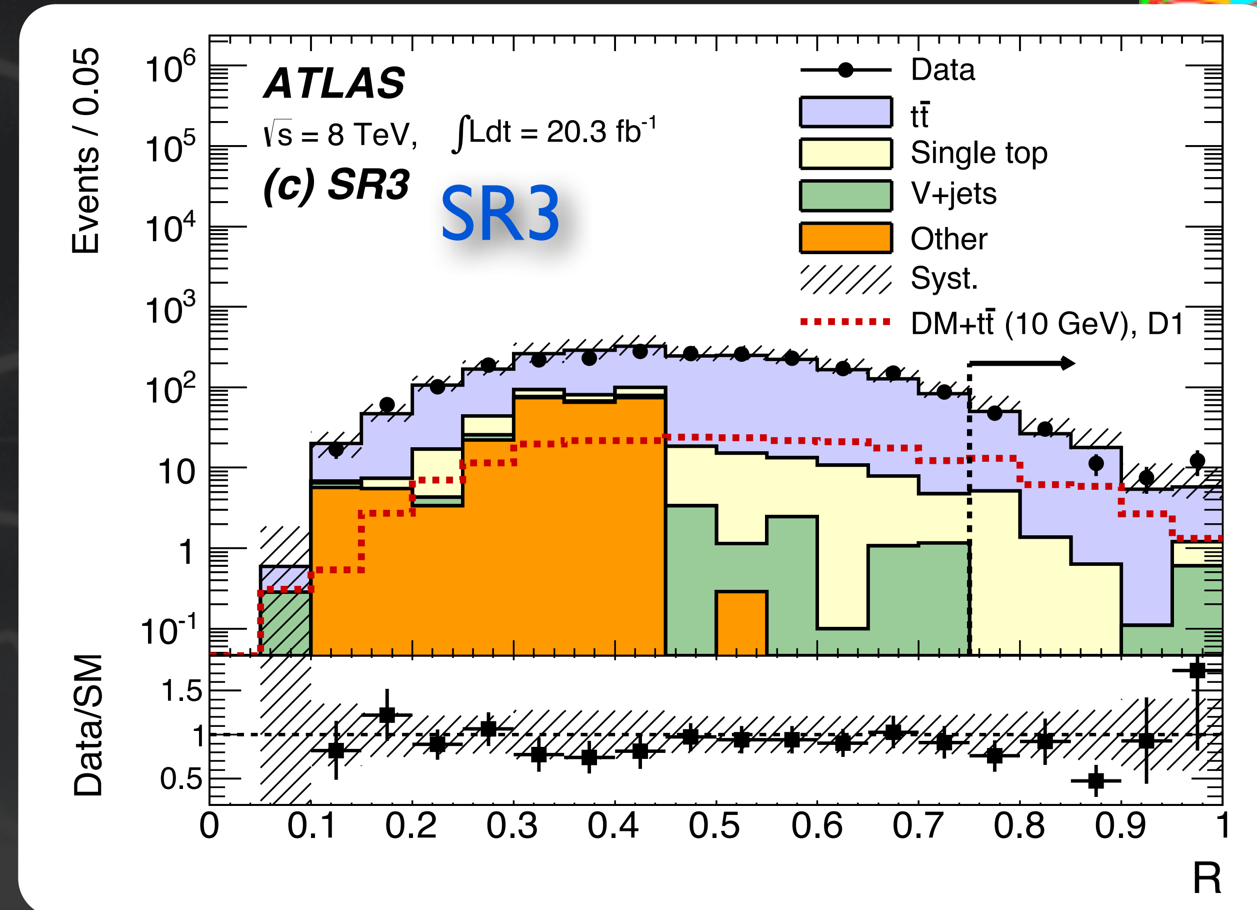


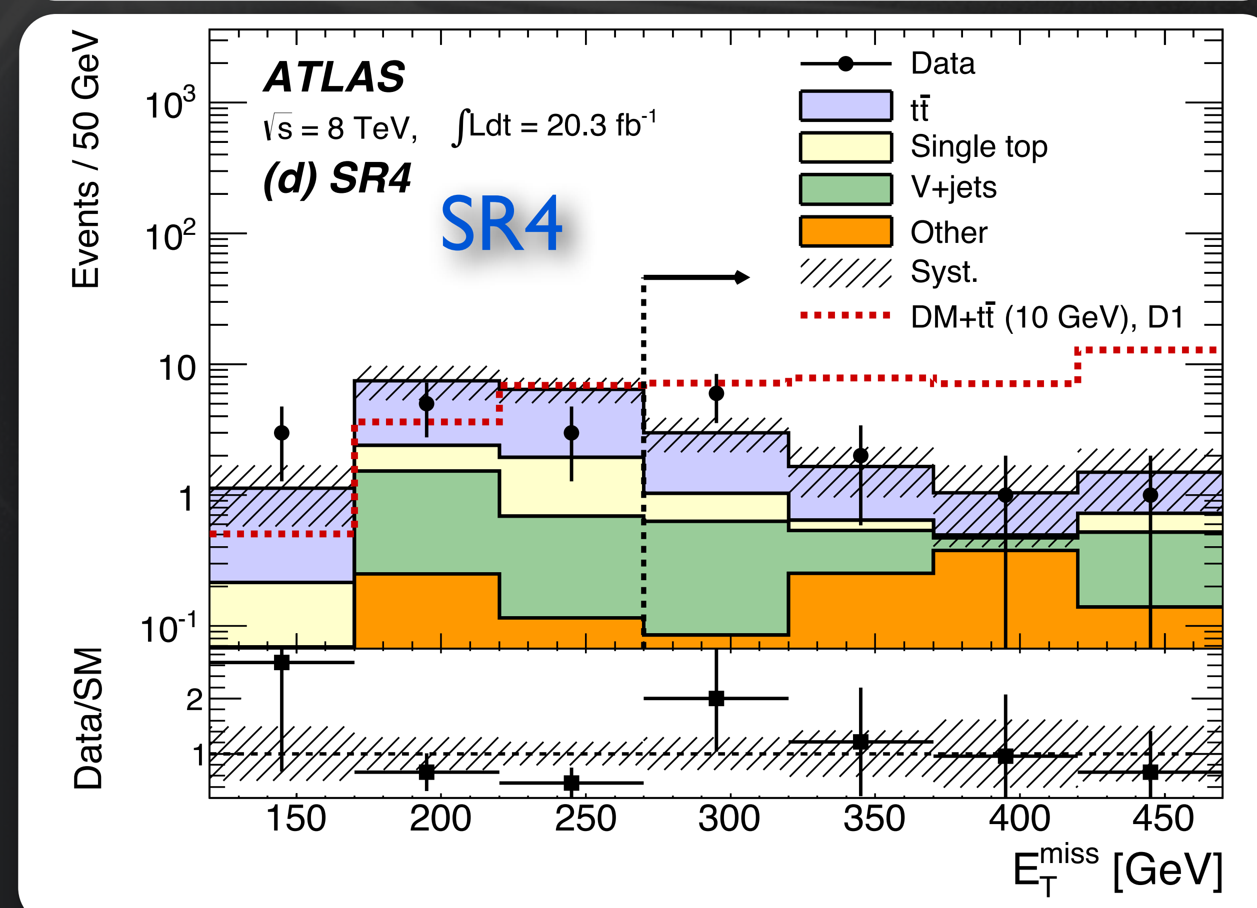


Imperial College London

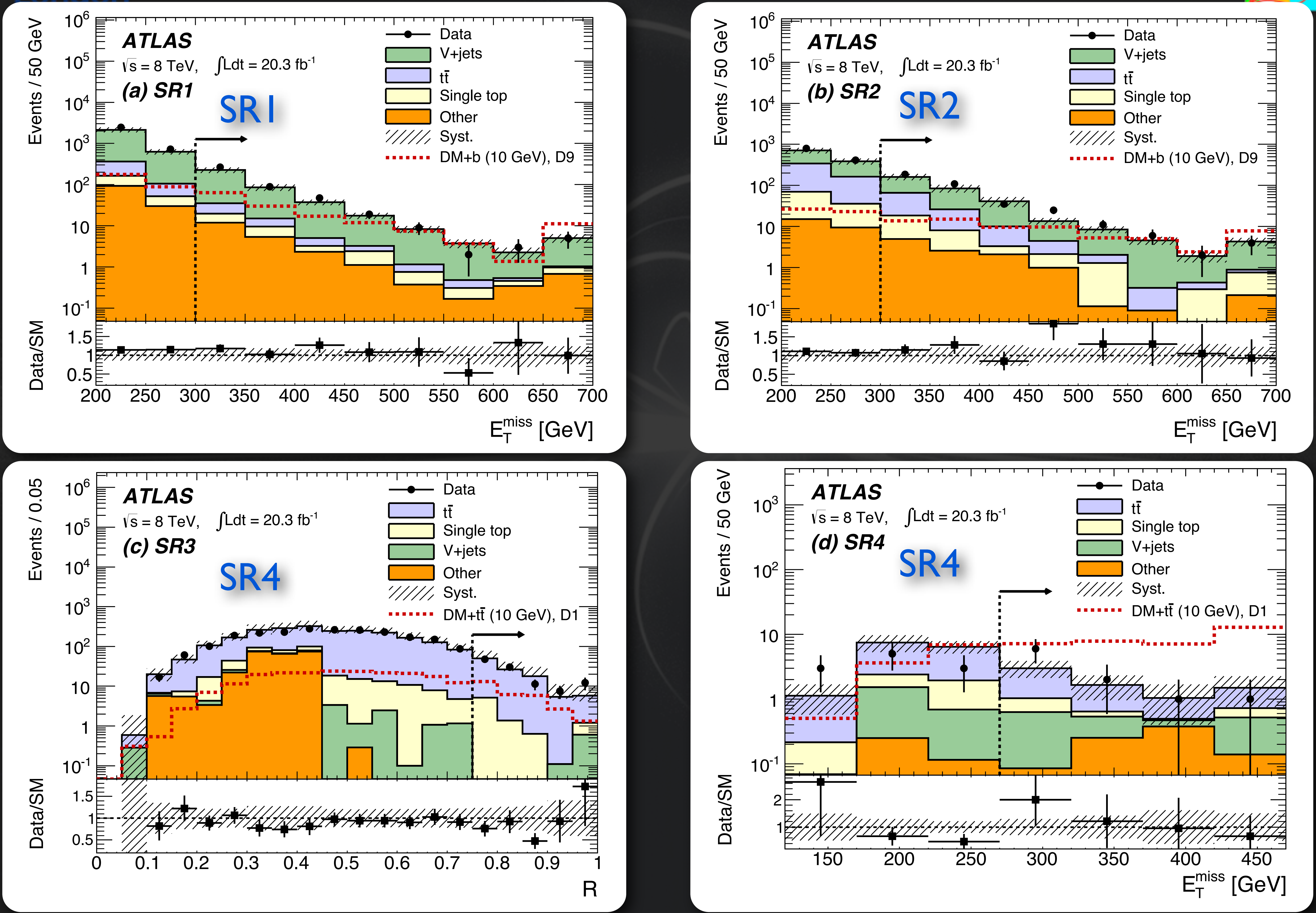
DM+heavy quark analysis

- **4 Signal regions** based on
  - E_T^{miss} - momentum carried by invisible particle
  - b-jet - decay of non-stable particle
- **DM+b:**
  - E_T^{miss}>300 GeV, p_T(b)>100 GeV
  - SR1: n_{jet}=1,2
  - SR2: n_{jet}=3,4
- **DM+tt:**
  - SR3: had (n_{jet}>4), Razor
  - SR4: lep+jet, E_T^{miss}>270, angular variables

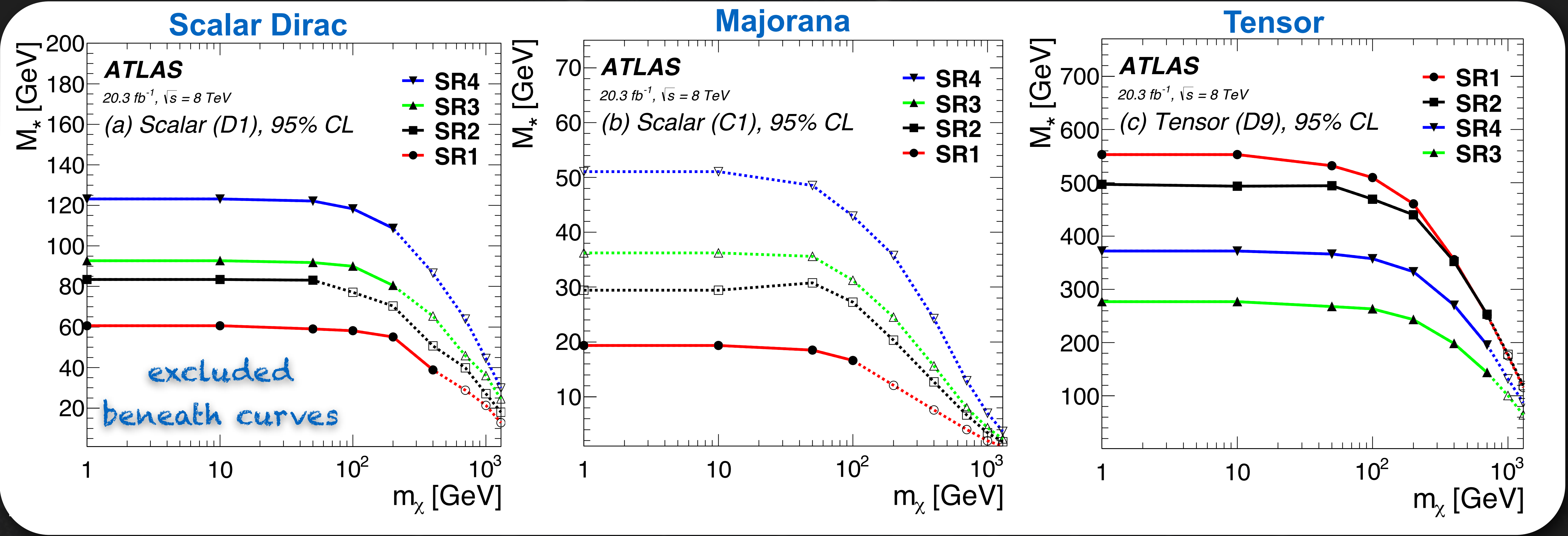




DM+heavy quark analysis

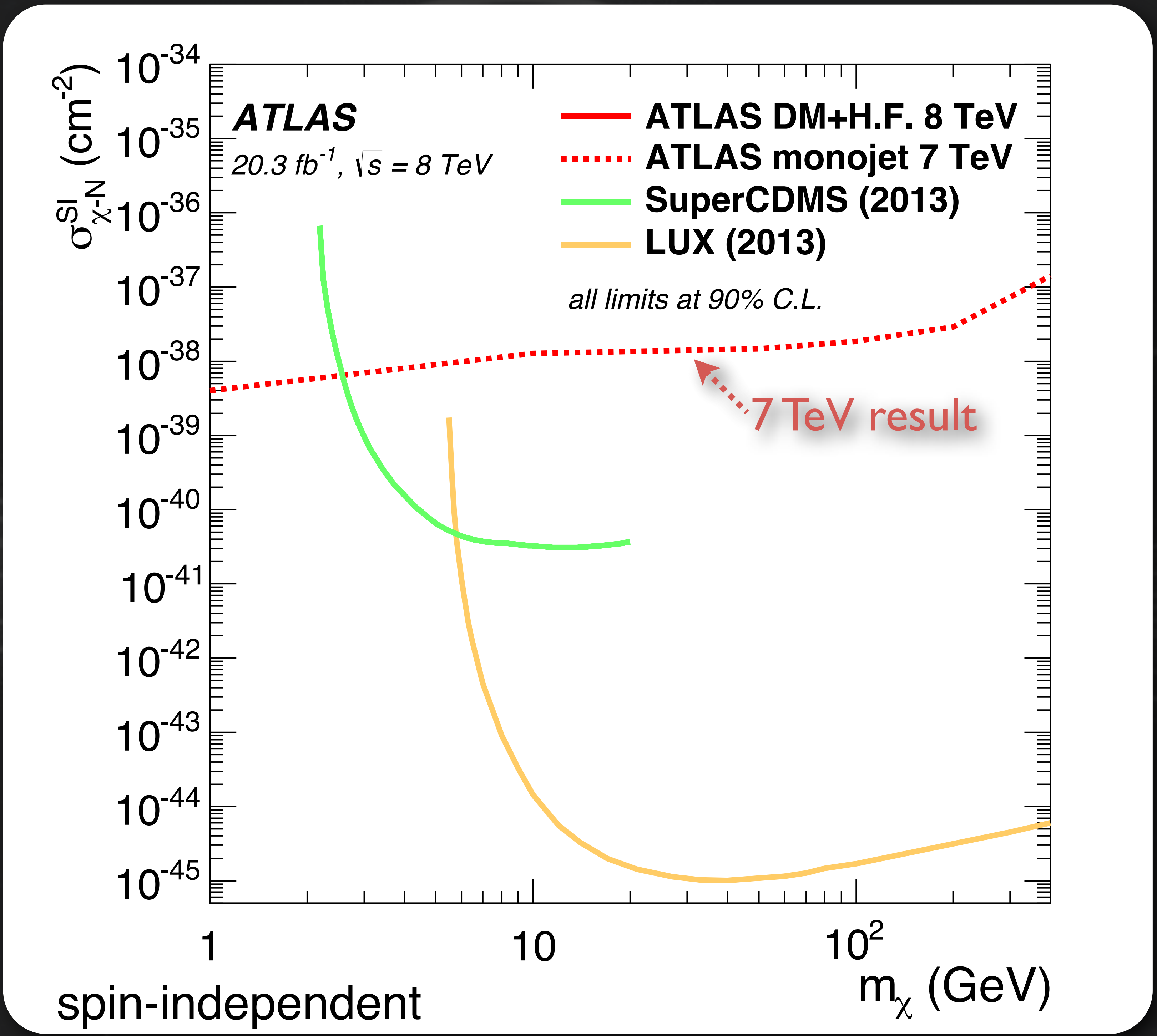


DM+heavy quark analysis

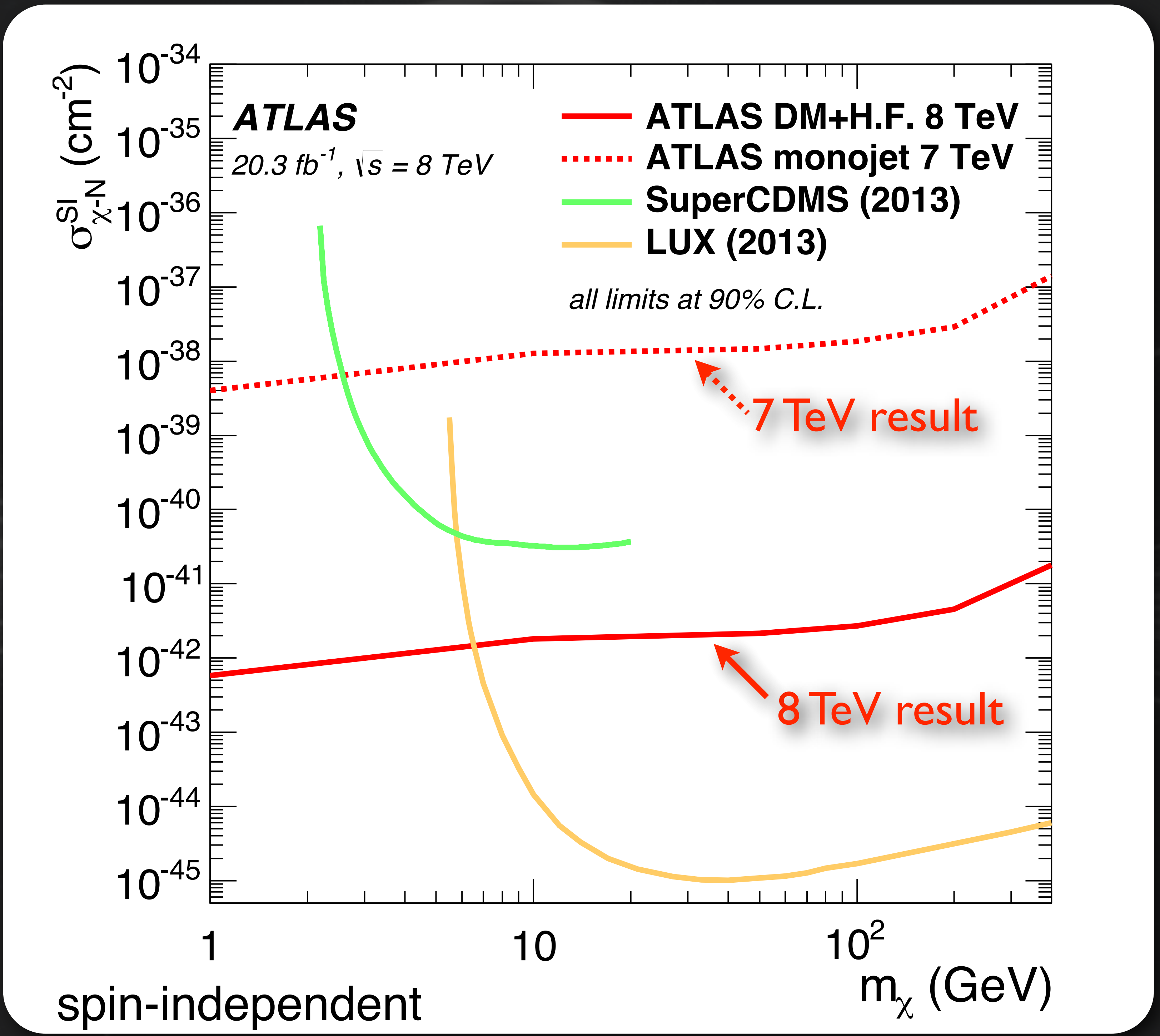


- Characterize strength of interaction by limit on M*
- **Improve scalar operator (D1)**, first limits on **tensor coupling (D9) with heavy quarks, only valid constraints on C1**
- Only present m_χ points where **$m(\chi\chi)<Q_{TR}$,** e.g. $Q_{\mathrm{TR}} < \sqrt{\frac{4\pi M_*^3}{m_q}}$

Comparison to direct searches

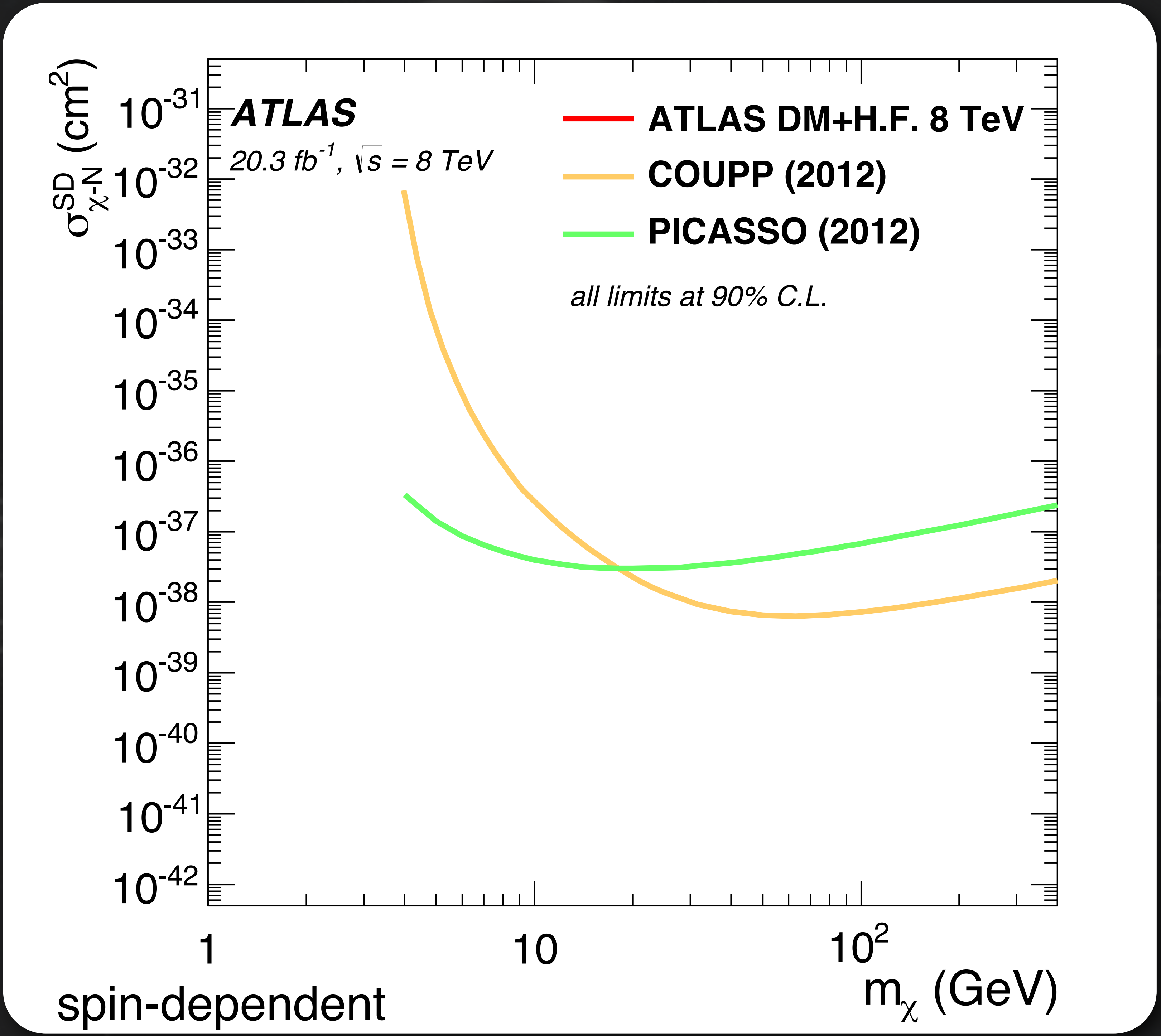


Comparison to direct searches

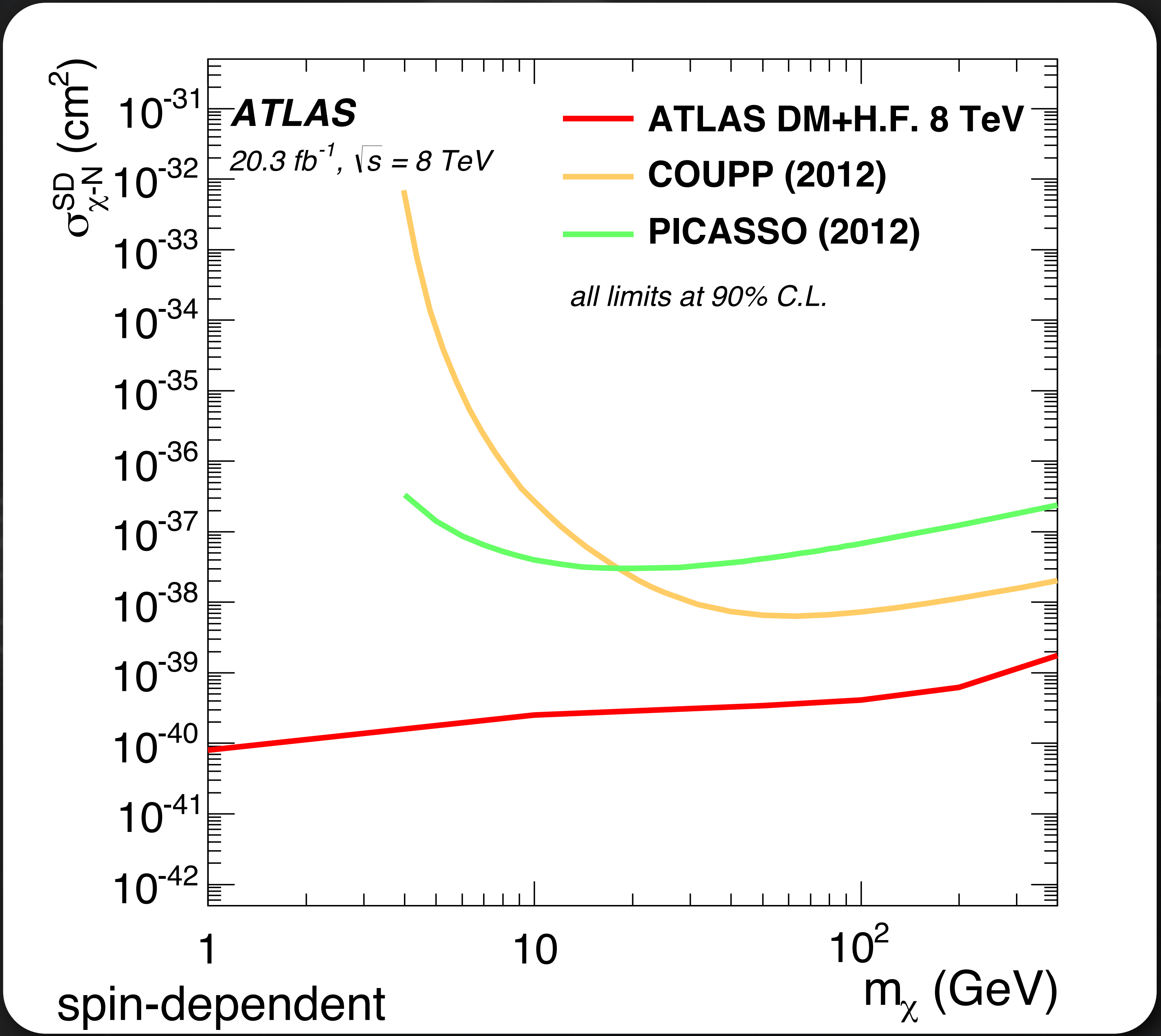


- Setting **world leading limits** on scalar operators
- Improving **existing collider limits by three orders of magnitude**

Comparison to direct searches

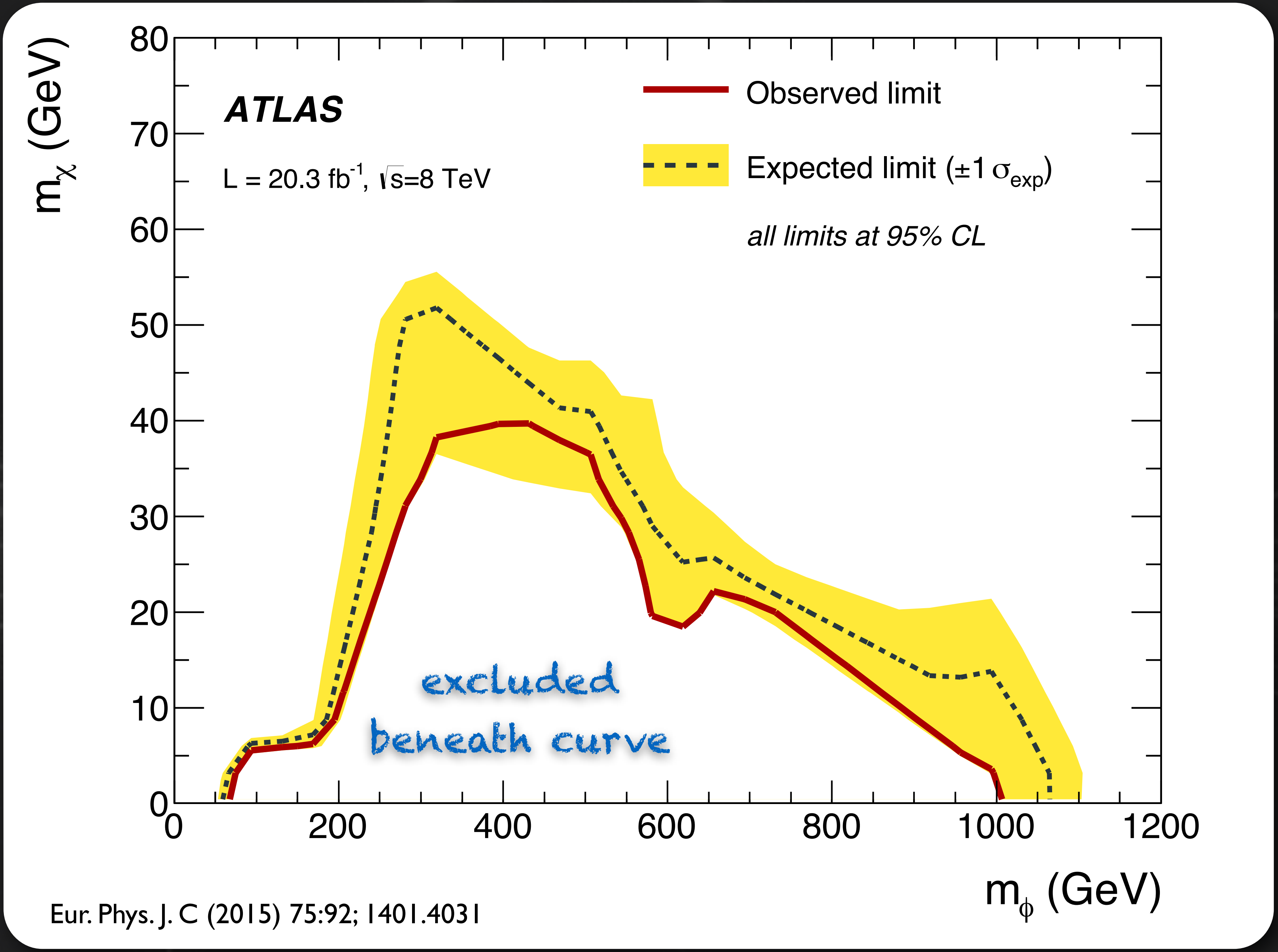


Comparison to direct searches



- **Performing very well** over wide mass range

Sensitivity to GC excess



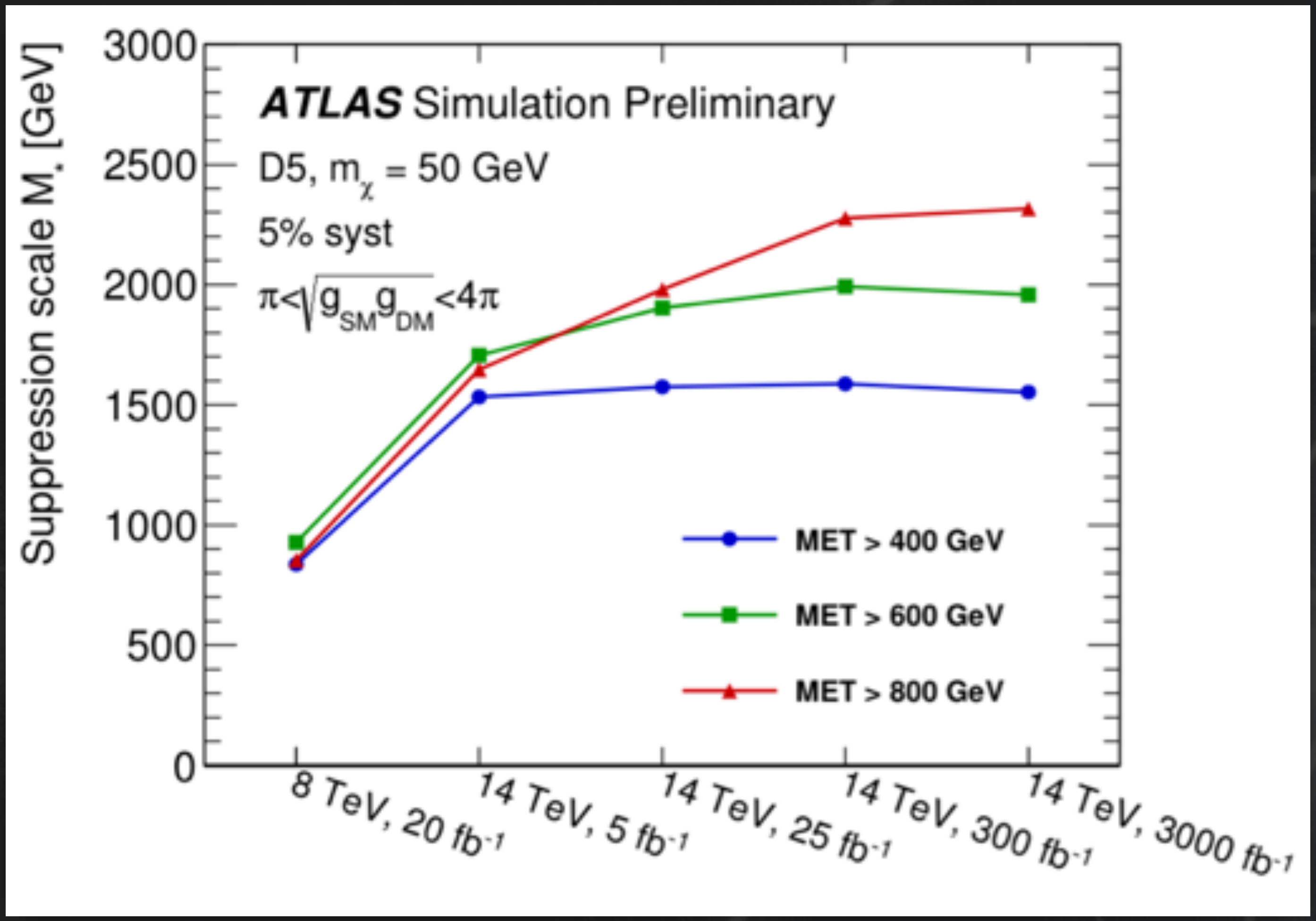
- **First collider limits** on **possible source of Fermi-LAT annihilation signal** (m_{DM} ~ 35 GeV).
- **First results using simplified model**, excluding **mediators from m_φ=300-500 GeV**

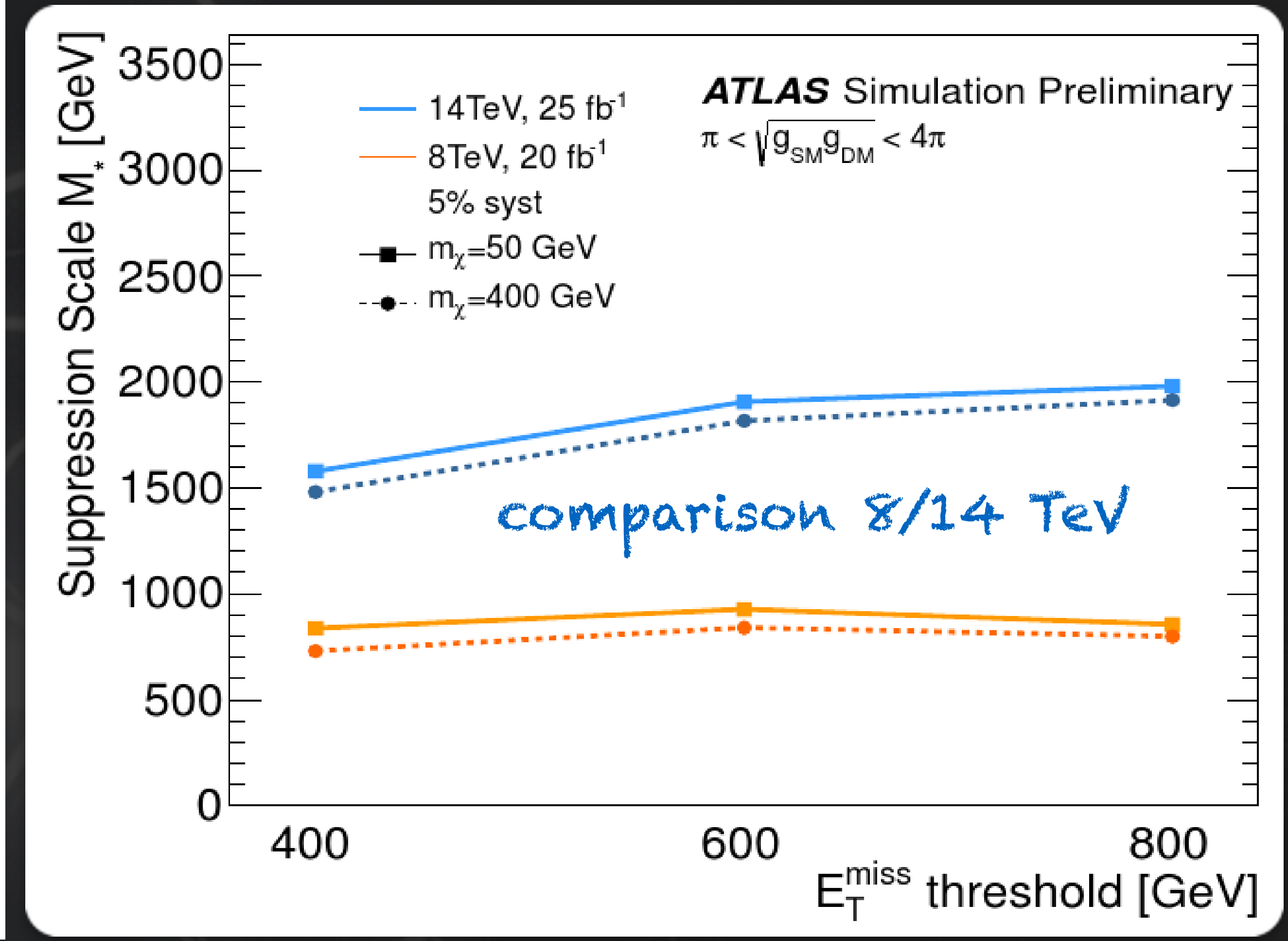
Outlook

- Projections for EFT and simplified models
- Collaboration with Theory
- Hardware improvements

EFT projections

ATLAS-PHYS-PUB-2014-007



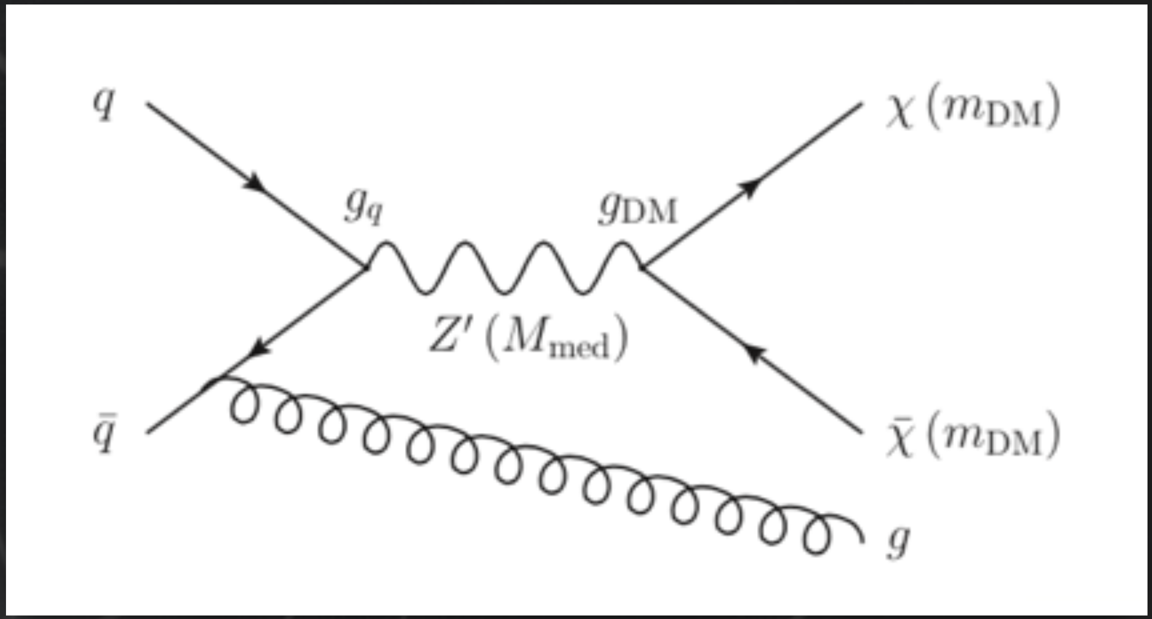


- **Limits in M* improve by x2 from 8→14 TeV** with about same amount of data.
- For **high luminosities** assume **improved performance** and **systematics**
  - Factor of two improvement
- The usual validity concerns apply but deferred here (details in reference)

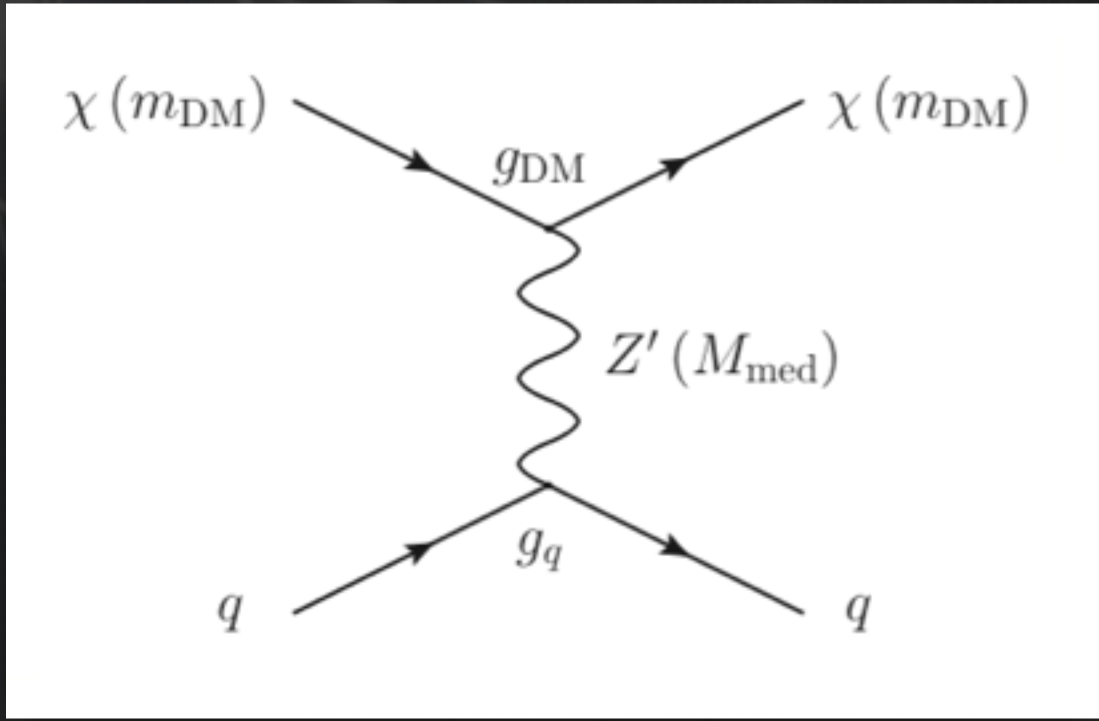
Simplified model projections

arXiv:1407.8257
Buchmueller et al

- Moving to simplified models for more realistic picture
- Also (vector-) axial models
- Minimal Simplified DM framework (MSDM), probe m_{DM}, m_{Med}, g_{DM}, g_q
- Monojet searches interpreted
  - optimized E_T^{miss} requirement
- Reproduce well existing collider constraints
- Compared to direct searches



Collider

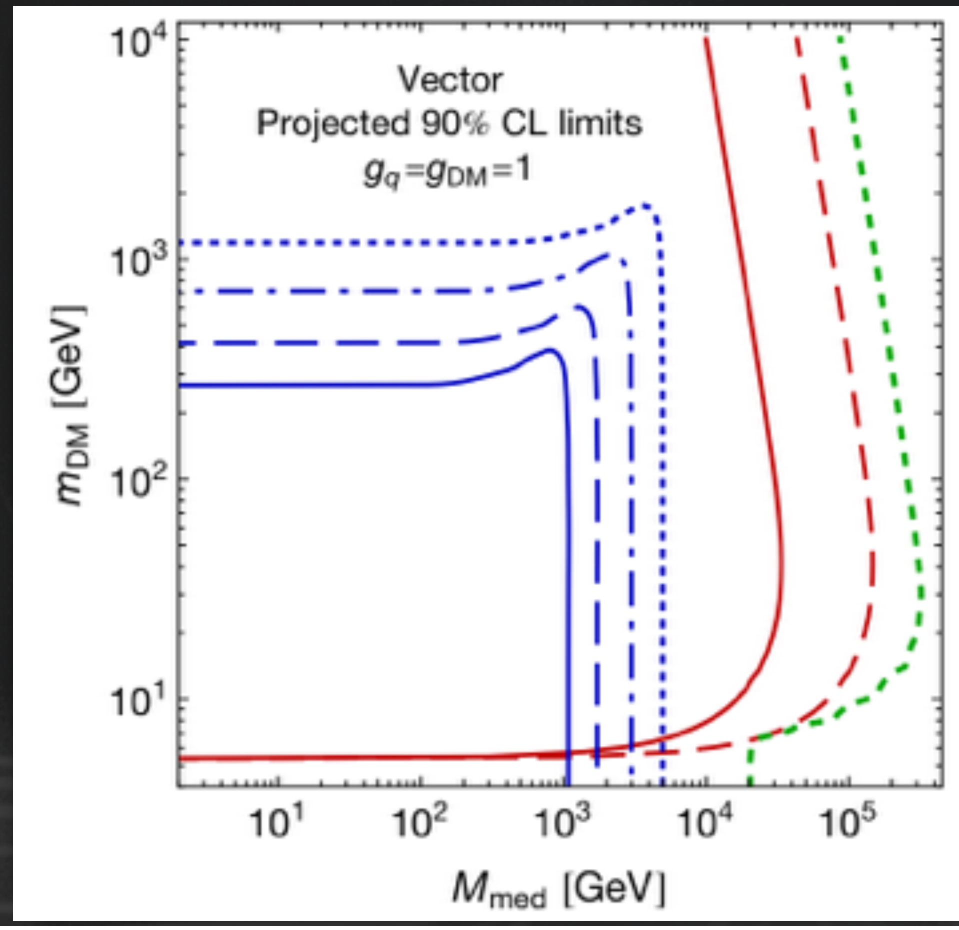


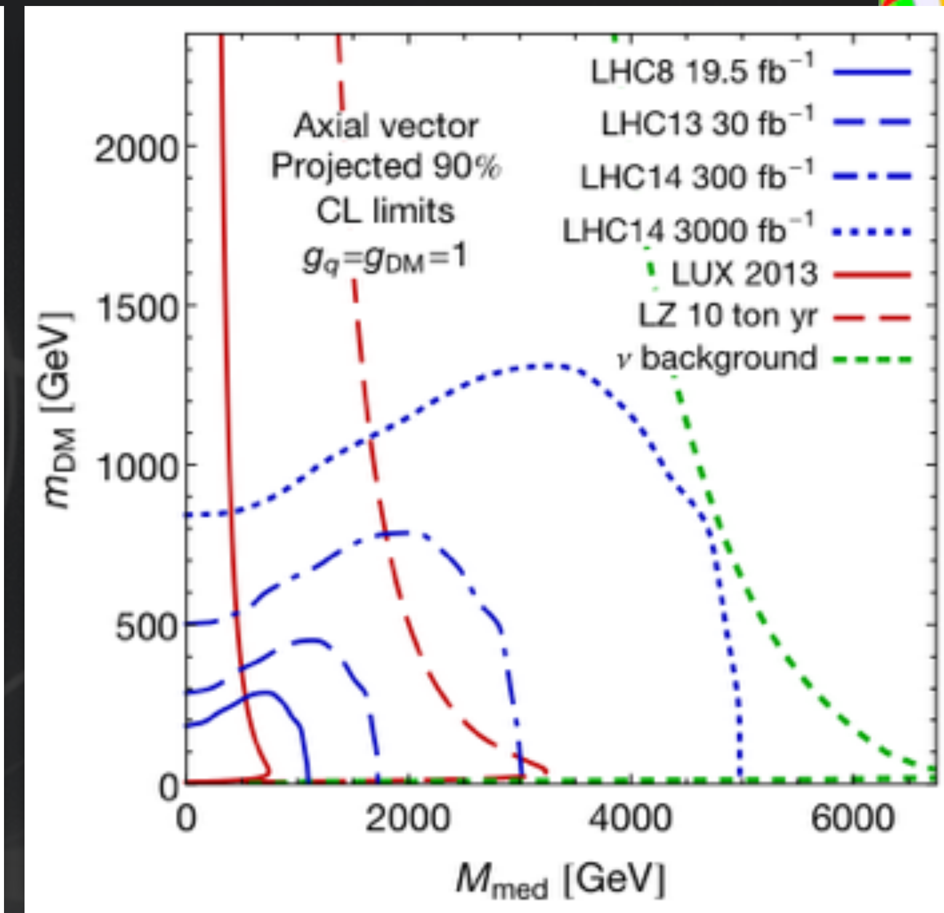
Direct Detection

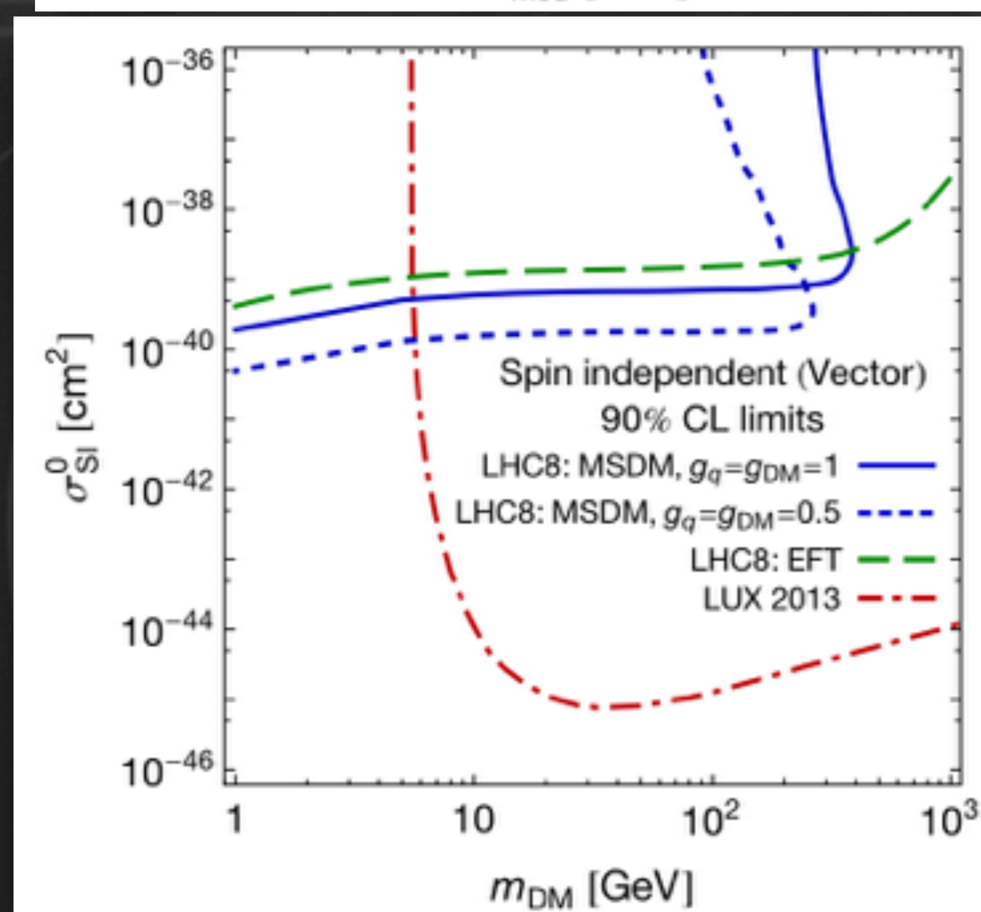
Simplified model projections

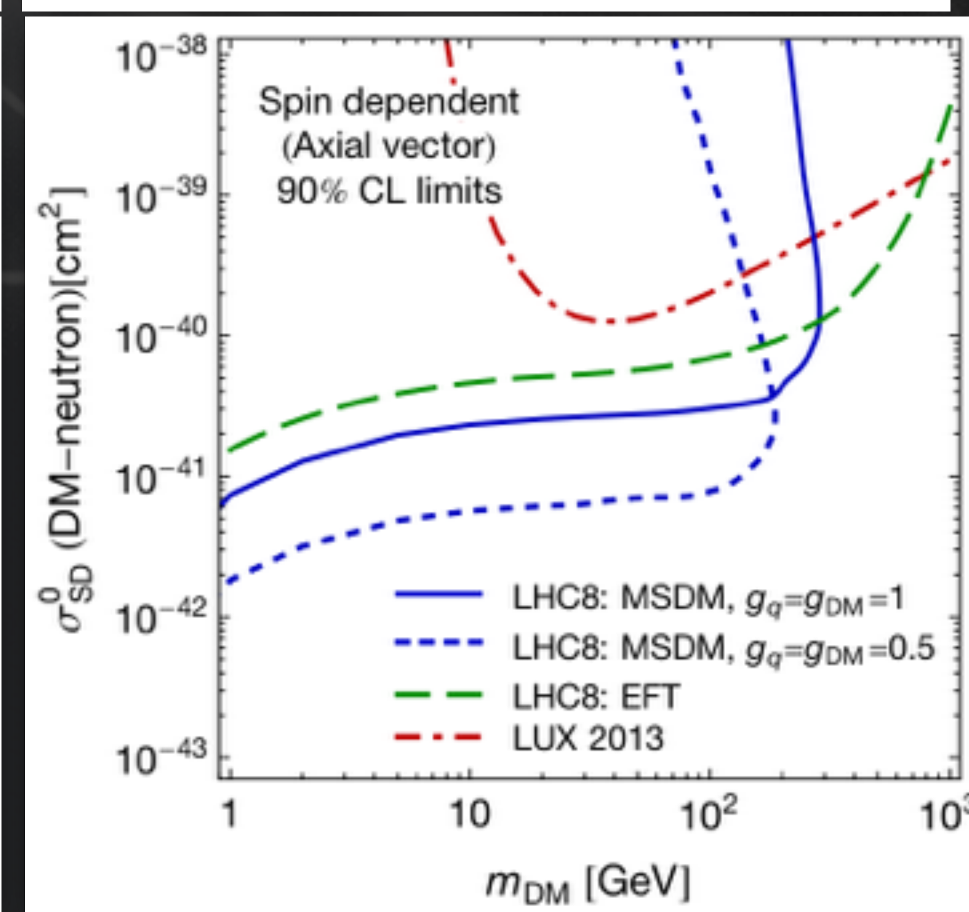
arXiv:1407.8257
Buchmueller et al

- **HL-LHC** reaches **impressive sensitivity**
- Future runs/ collider **may go beyond the neutrino floor** for certain models



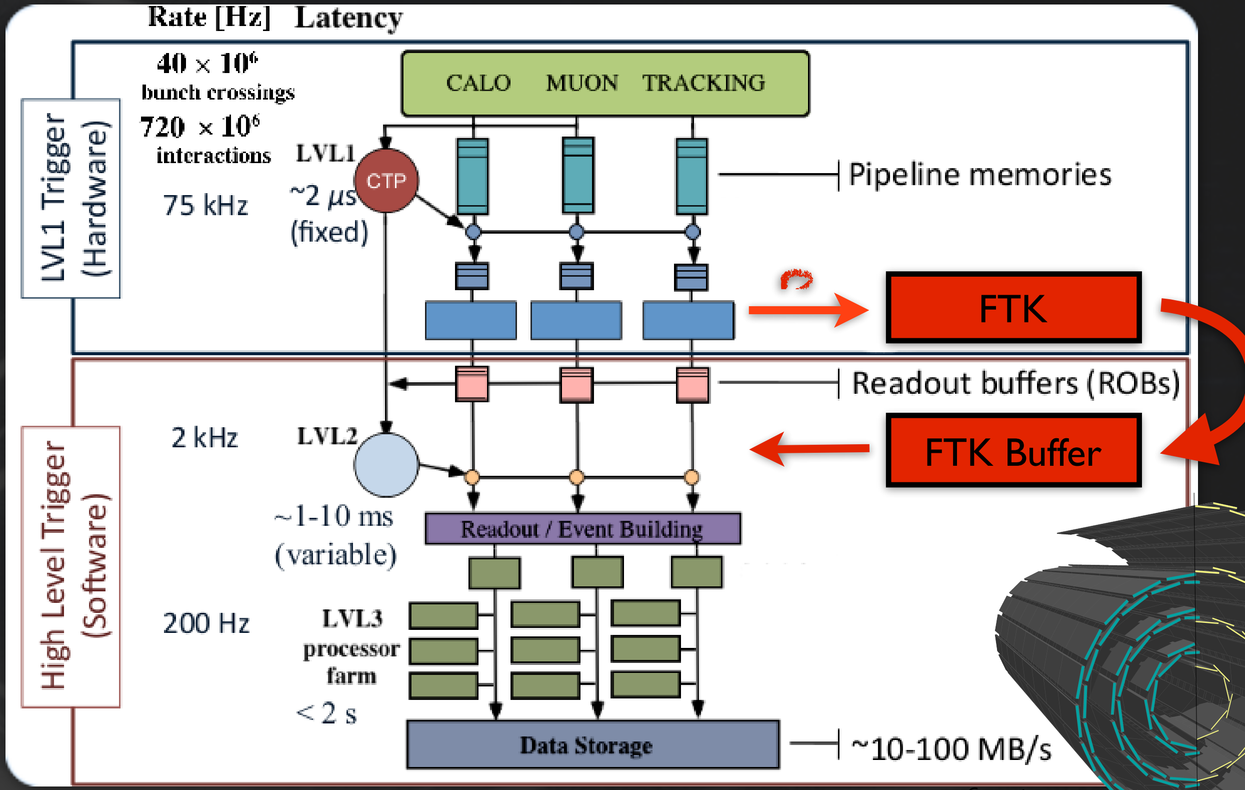


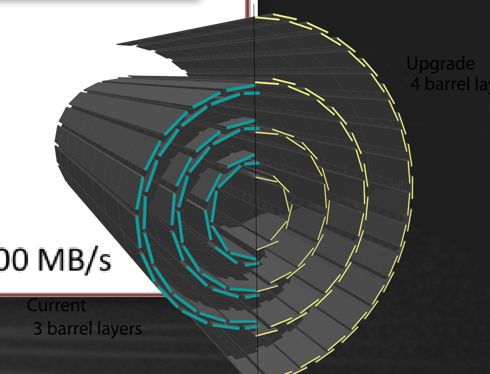


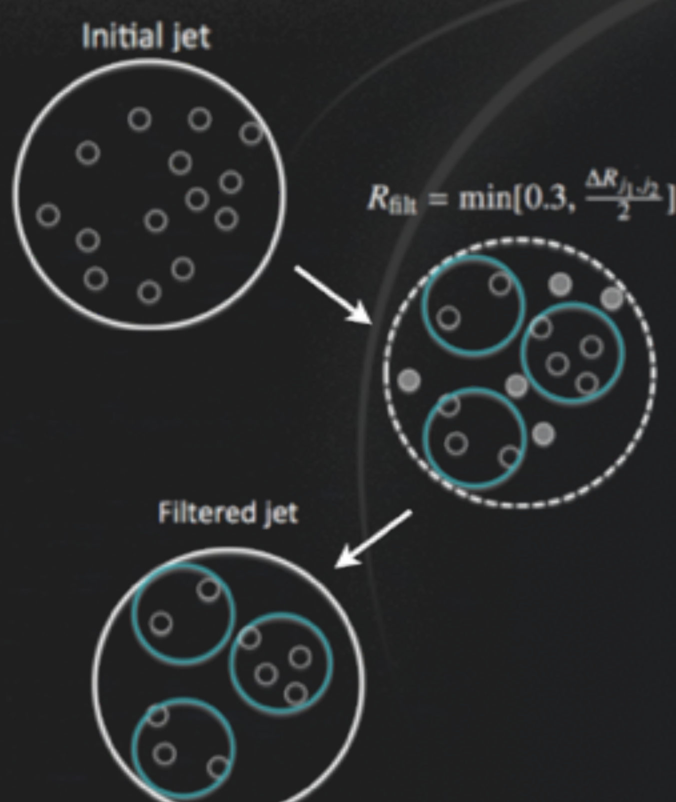


Analysis and experimental improvements

1. Perform timely **14 TeV measurements** to **either discover DM** or set **stringent bounds** with **inter-disciplinary impact**
2. Perform **precision measurements** to measure **new particle** or **further enhance sensitivity** (DM or e.g. Z+t production)
3. Strongly involved in **upgrade projects** to maintain and improve sensitivity in future runs





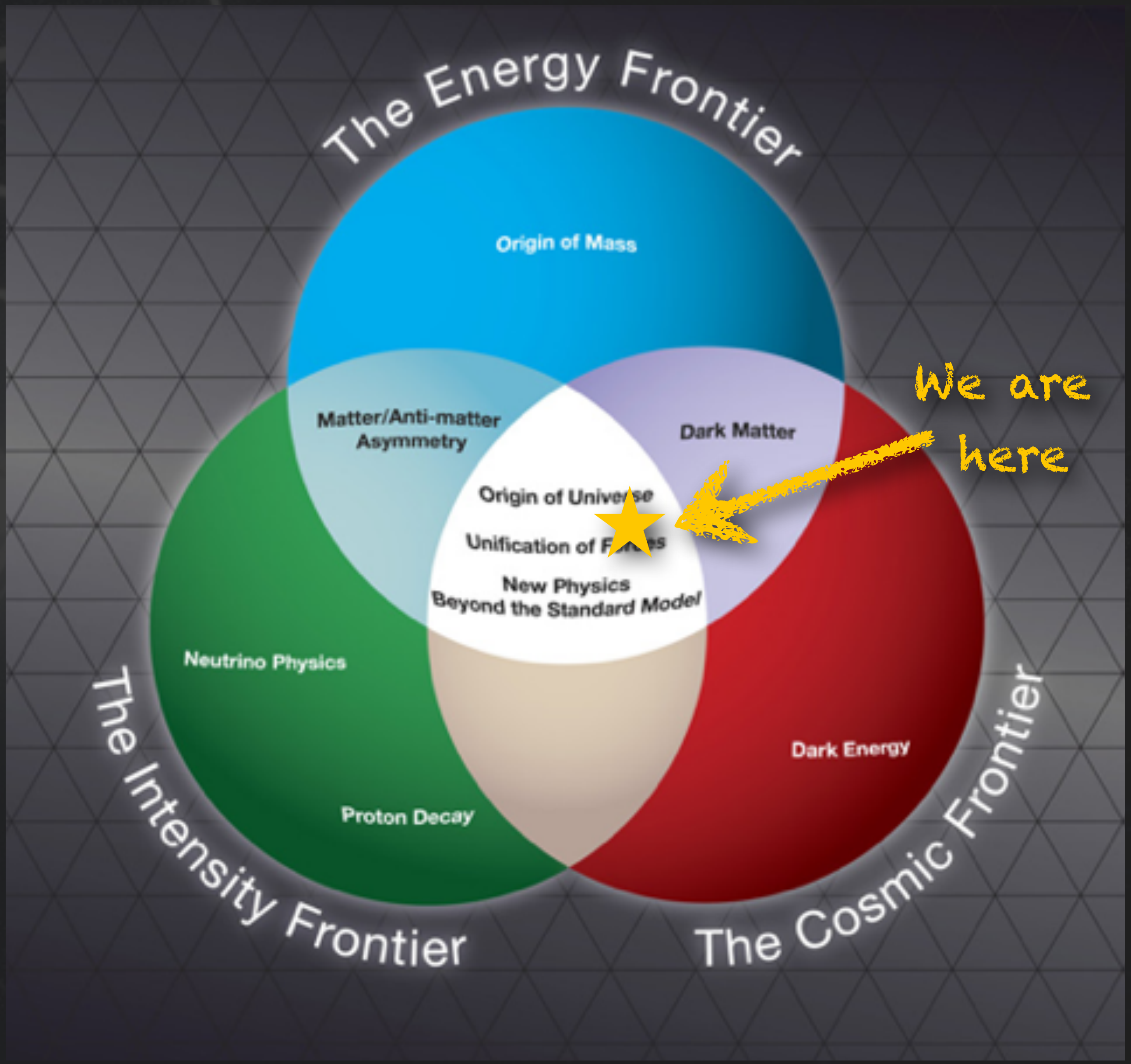


- Taking advantage of **new experimental techniques available**
- **Tracker upgrade:**
  - **Track Trigger**
  - **b-jet triggering**
  - Enhanced sensitivity for **low mass final state**
- Sophisticated **jet algorithms**:
  - Jet substructure
  - high p_T **b-tagging / q-g-tagging**

Theory Collaboration

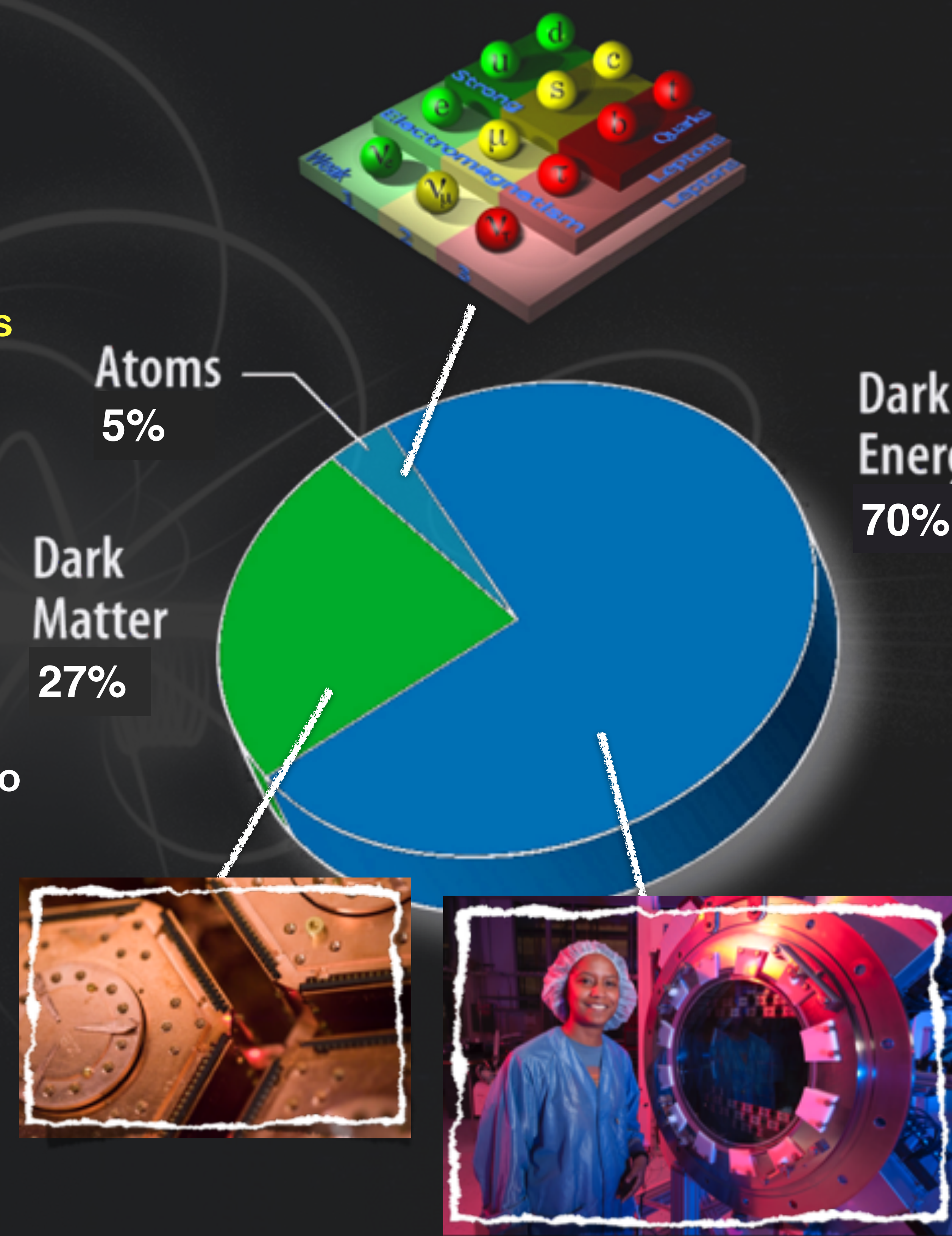
- Large parts of the program presented developed with L. Wang, T. Lin, T. Tait, R. Kolb, P. Fox, D. Hooper, C. McGabe
- Based on inter-disciplinary results
- However, theory collaboration far from done:
    - Extrapolate to leptons, ‘mono-H‘ and weak bosons (✔)
    - Higher order corrections (✔)
    - Advanced kinematic variables ✔
    - Simplified models (✔)
    - Validity of EFT approach ✔
    - Better presentation of results, combination ✔
- DM Forum

- **DM searches** at collider **just started**
- **Collider searches will have great impact**
  - **Essentially** new field at the LHC
  - Results **complementary** to **other WIMP searches**
  - Better **sensitivity at low masses**
- DM searches **truly interdisciplinary field**
  - Collaborate with theory, direct and indirect searches
  - DM will have to be discovered in several areas to be truly confirmed
- **Just the beginning, many channels not yet explored:** leptonic, VBF, mono-top, higher energies,(more) simplified models
- Improve **experimental tools** (improved b-tagging, triggering, jet substructure, upgrade)



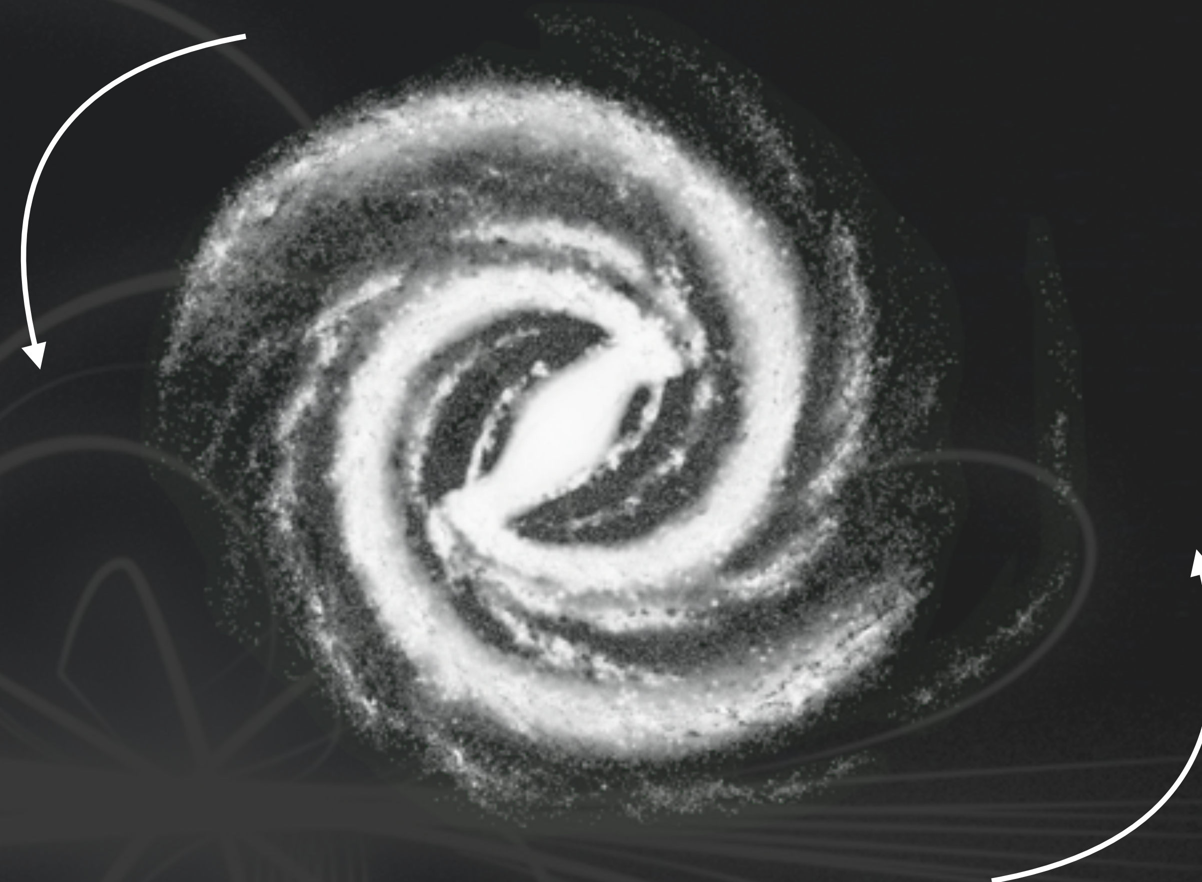
Imperial College London

- DM searches at collider just started
- Collider searches will have great impact
  - Essentially new field at the LHC
  - Results complementary to other WIMP searches
  - Better sensitivity at low masses
- DM searches truly interdisciplinary field
  - Collaborate with theory, direct and indirect searches
  - DM will have to be discovered in several areas to be truly confirmed
- Just the beginning, many channels not yet explored: leptonic, VBF, mono-top, higher energies,(more) simplified models
- Improve experimental tools (improved b-tagging, triggering, jet substructure, upgrade)



Backup

- **Galaxies rotate faster** than they should according to the luminous matter we see

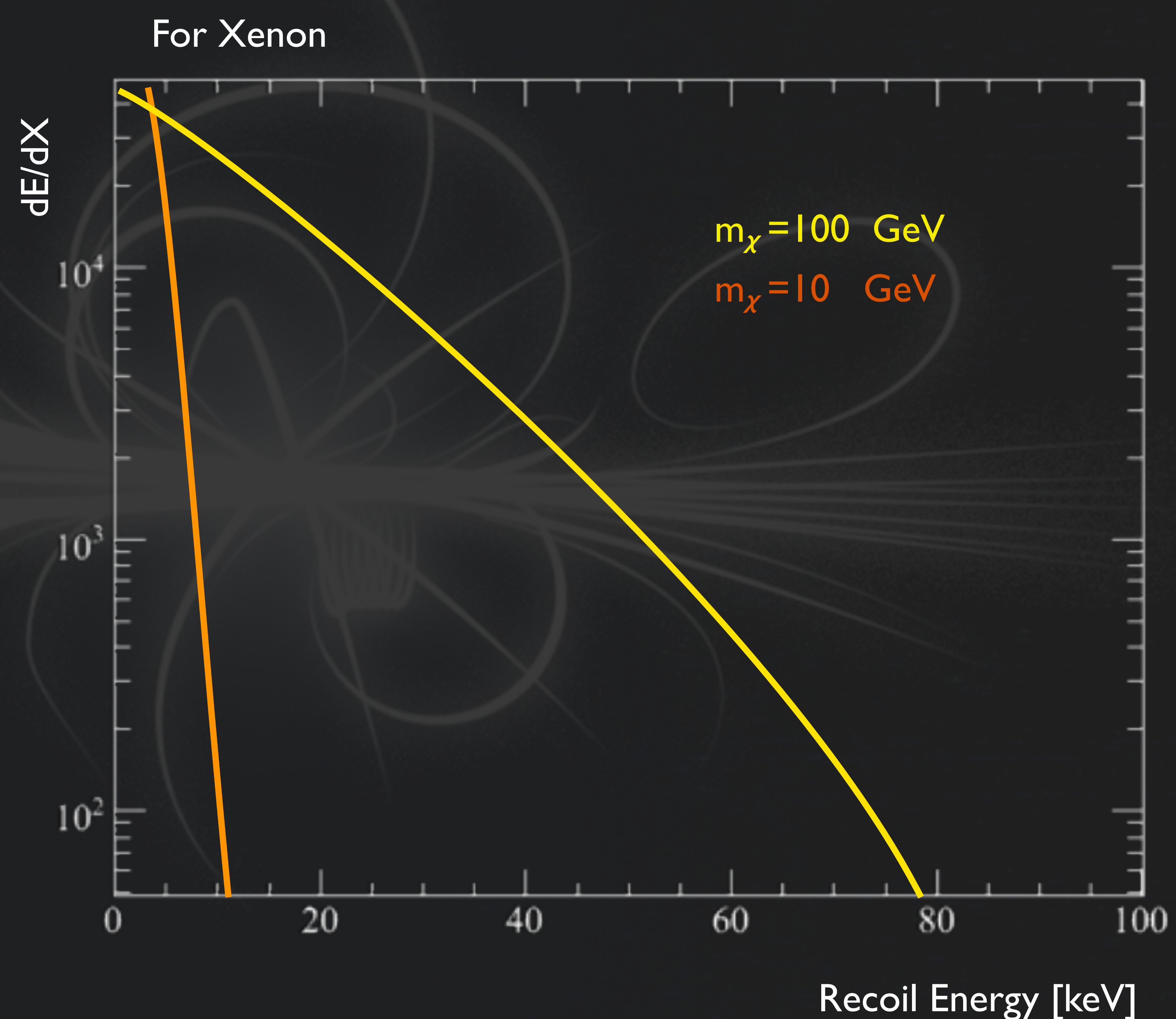


$$F_{\text{centripetal}} = F_{\text{gravitational}}$$

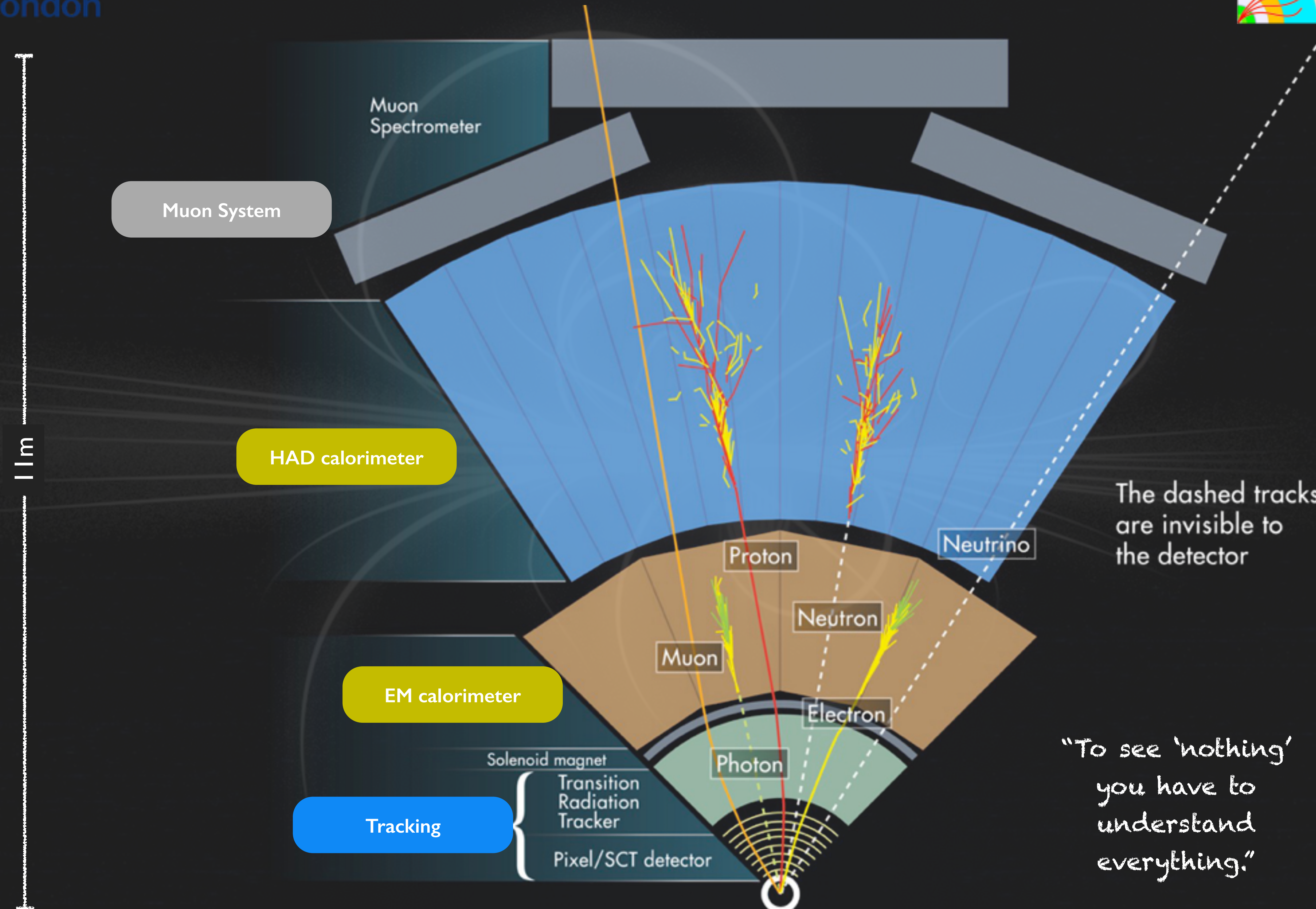
$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$v^2 = \frac{GM}{r^2} \Rightarrow v \propto \sqrt{1/r}$$

- **Underground dark matter** searches look for **nuclear recoil**
- Very **active field**
- Wide variety of **detection channels & techniques**
- **Momentum transfer crucial**
- **Spin-dependent / independent** DM
  - DM may interact with spin of target nucleon



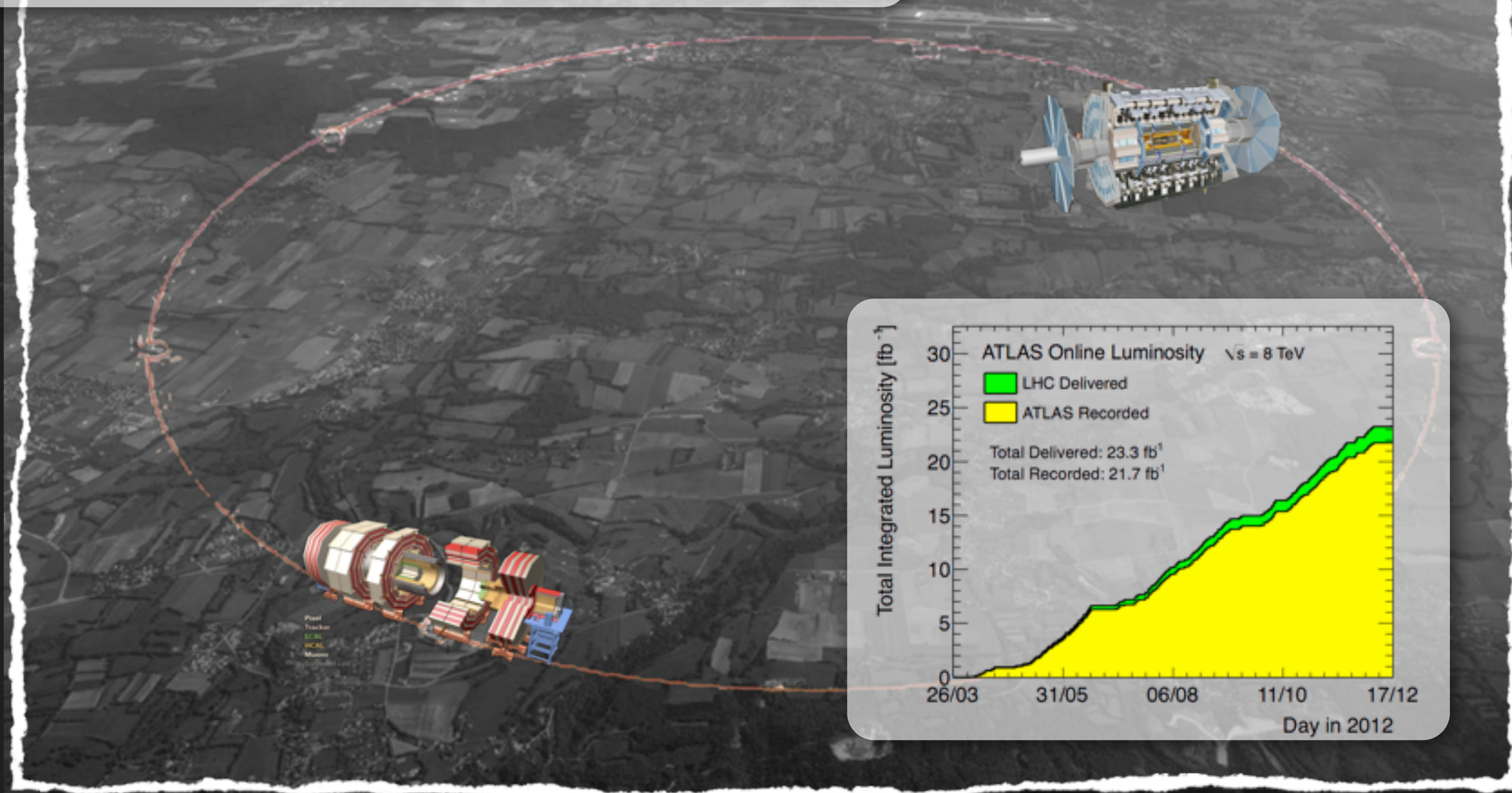
Imperial College London

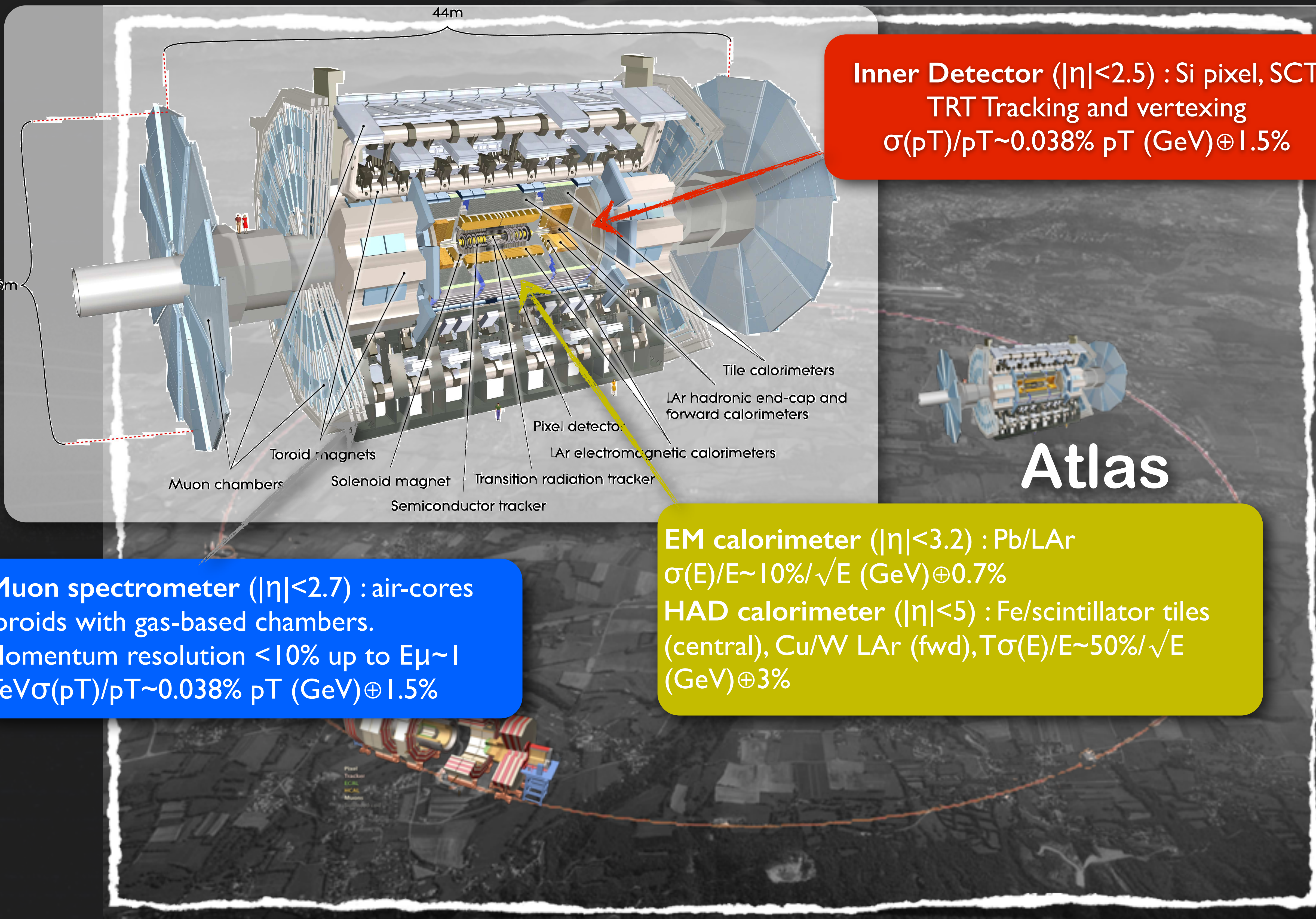


The dashed tracks are invisible to the detector

"To see 'nothing' you have to understand everything."

	2011/12	Design
Energy	7 / 8TeV	14 TeV
Bunch Spacing	50ns	25(50)ns
Luminosity	$3.6/8\times10^{33}$	10^{34} $cm^{-2}s^{-1}$
Pile-Up	~20/40	~50(100)





Inner Detector (|η|<2.5) : Si pixel, SCT, TRT Tracking and vertexing
$\sigma(p_T)/p_T \sim 0.038\%\ p_T\ (\text{GeV}) \oplus 1.5\%$

EM calorimeter (|η|<3.2) : Pb/LAr
$\sigma(E)/E \sim 10\%/\sqrt{E}\ (\text{GeV}) \oplus 0.7\%$
HAD calorimeter (|η|<5) : Fe/scintillator tiles (central), Cu/W LAr (fwd), T$\sigma(E)/E \sim 50\%/\sqrt{E}\ (\text{GeV}) \oplus 3\%$

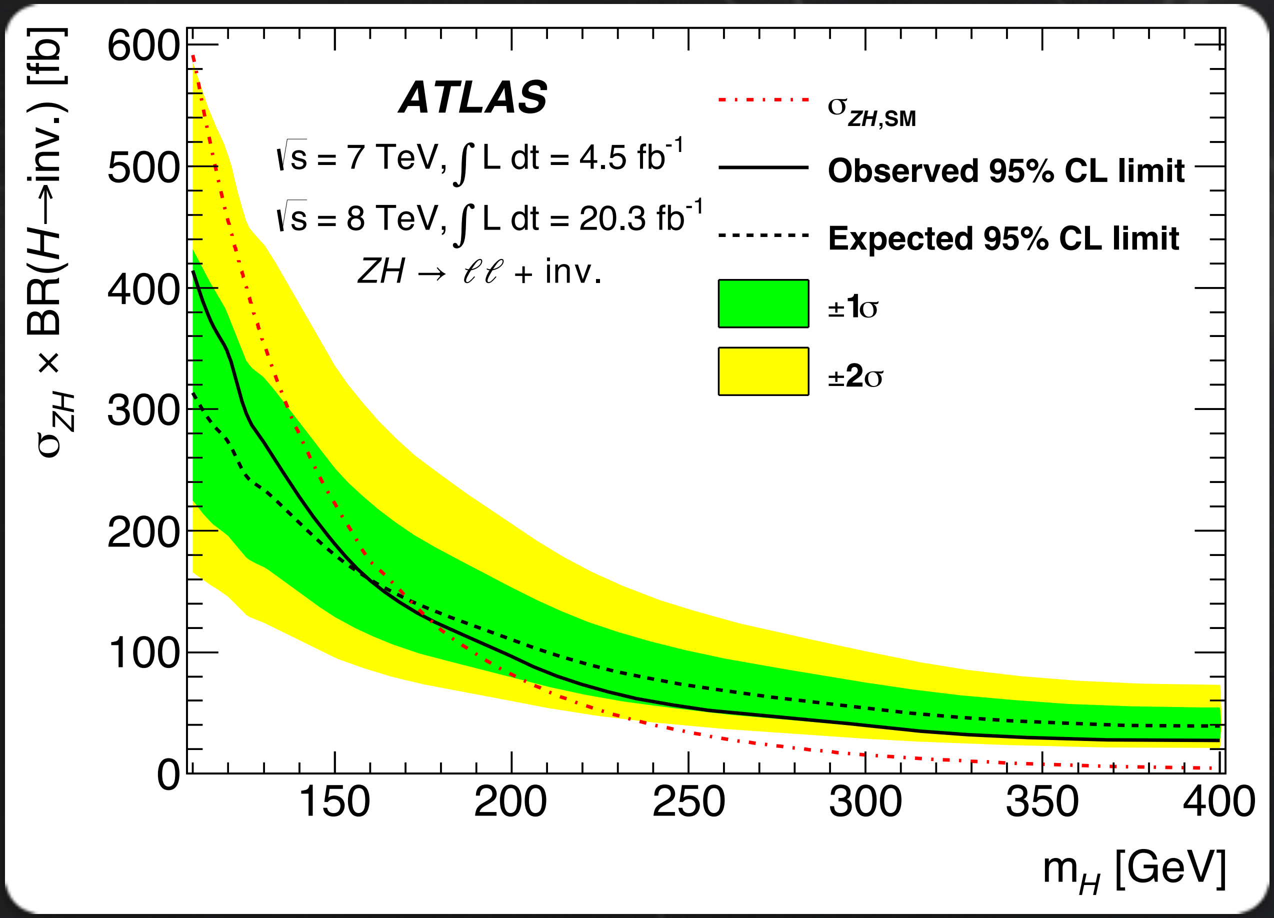
Muon spectrometer (|η|<2.7) : air-cores toroids with gas-based chambers.
Momentum resolution <10% up to Eμ~1 TeV$\sigma(p_T)/p_T \sim 0.038\%\ p_T\ (\text{GeV}) \oplus 1.5\%$

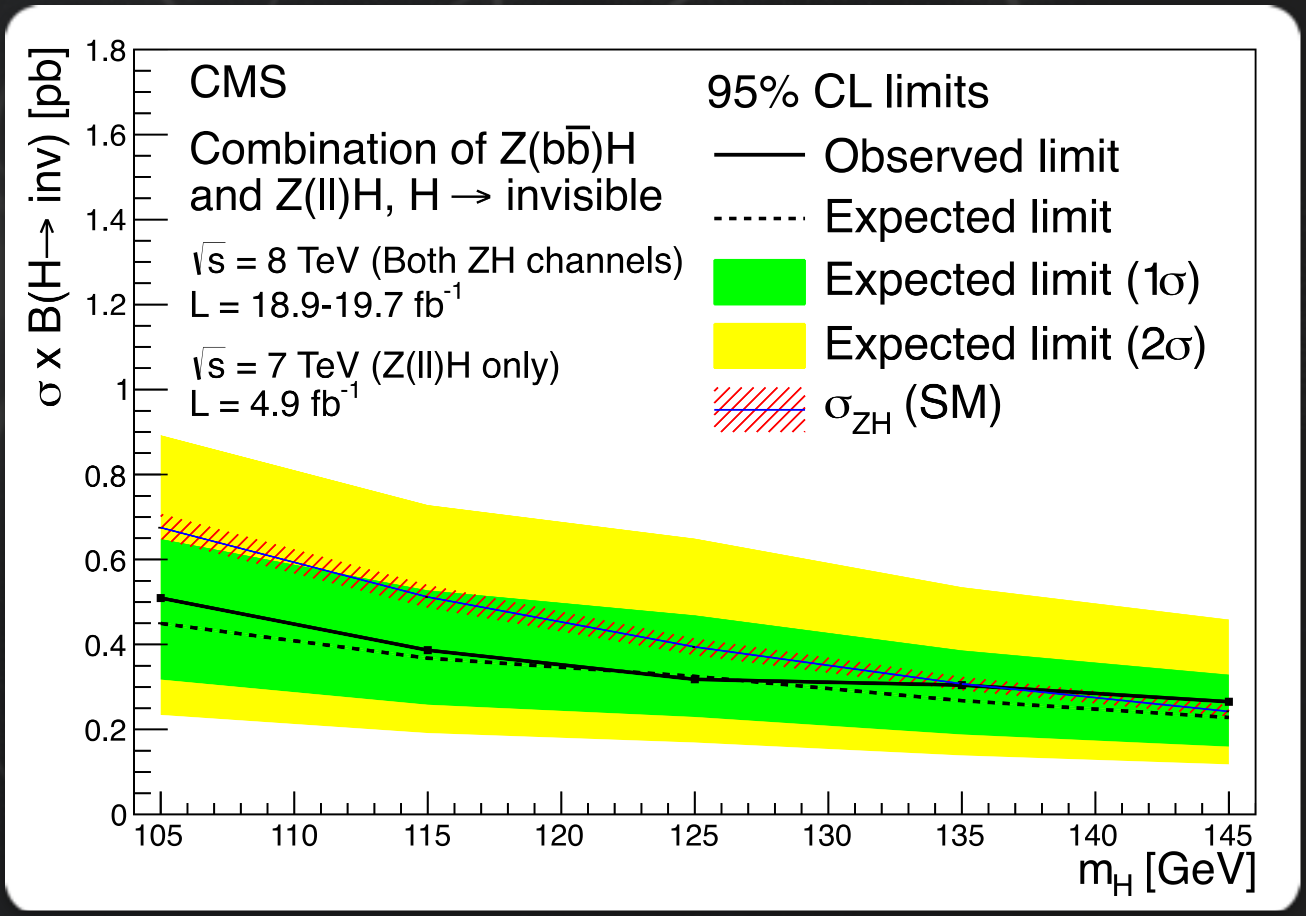
Imperial College London

DM+Higgs

arXiv:1402.3244 (ATLAS)
arXiv:1404.1344 (CMS)

- Analysis based on **associated ZH** production
- **SM cross section predictions for m_H=125 GeV**
- **Upper limits** on σ x BR(H→inv) as function of m_H





BR(H → inv) < 0.75 (0.62) obs (exp) @m_H = 125 GeV.

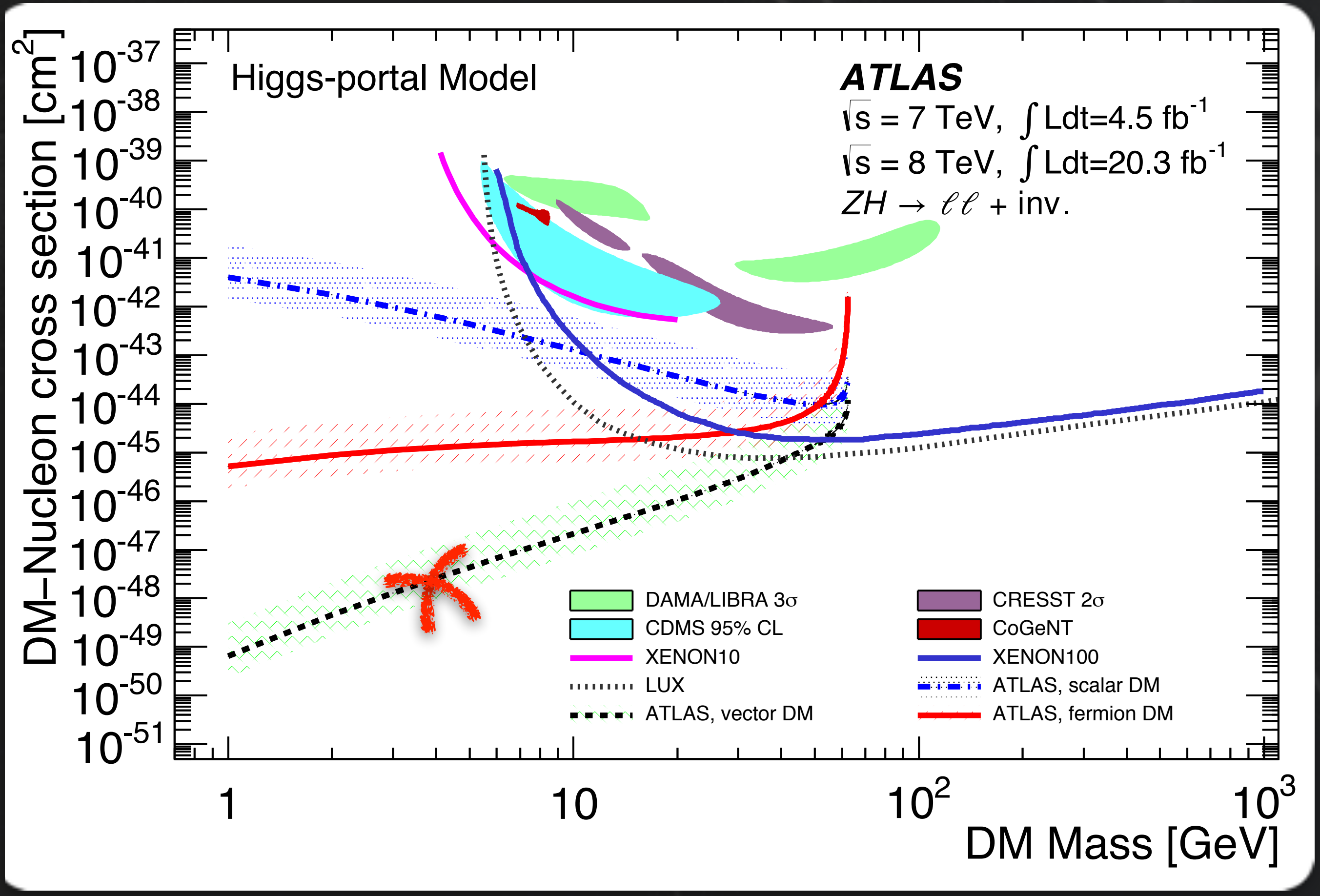
BR(H → inv) < 0.58 (0.44) obs (exp) @m_H = 125 GeV.

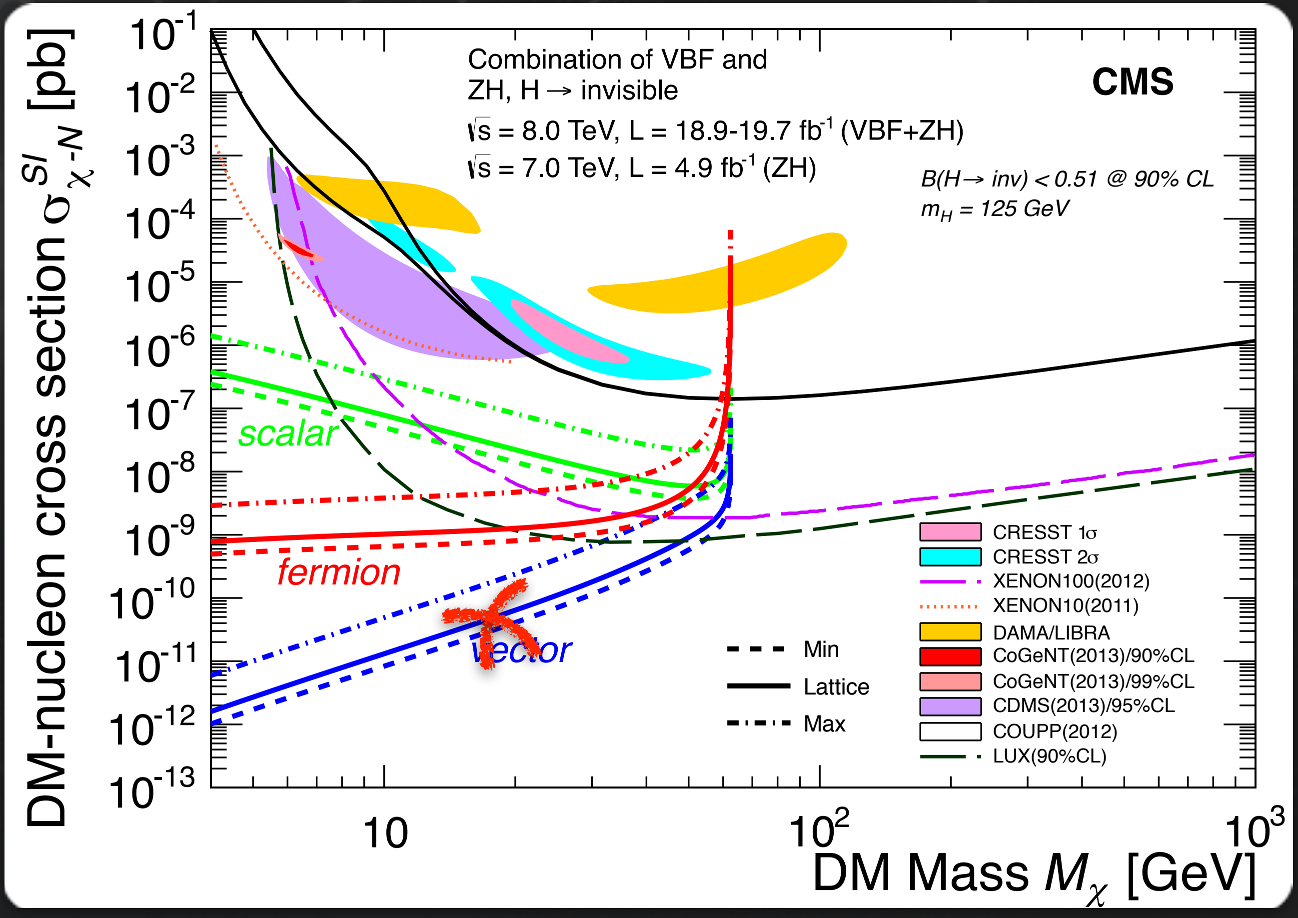
Imperial College London

DM+Higgs

arXiv:1402.3244 (ATLAS)
arXiv:1404.1344 (CMS)

- Analysis based on **associated ZH** production
- **SM cross section predictions for m_H=125 GeV**
- **Upper limits** on σ x BR(H→inv) as function of m_H



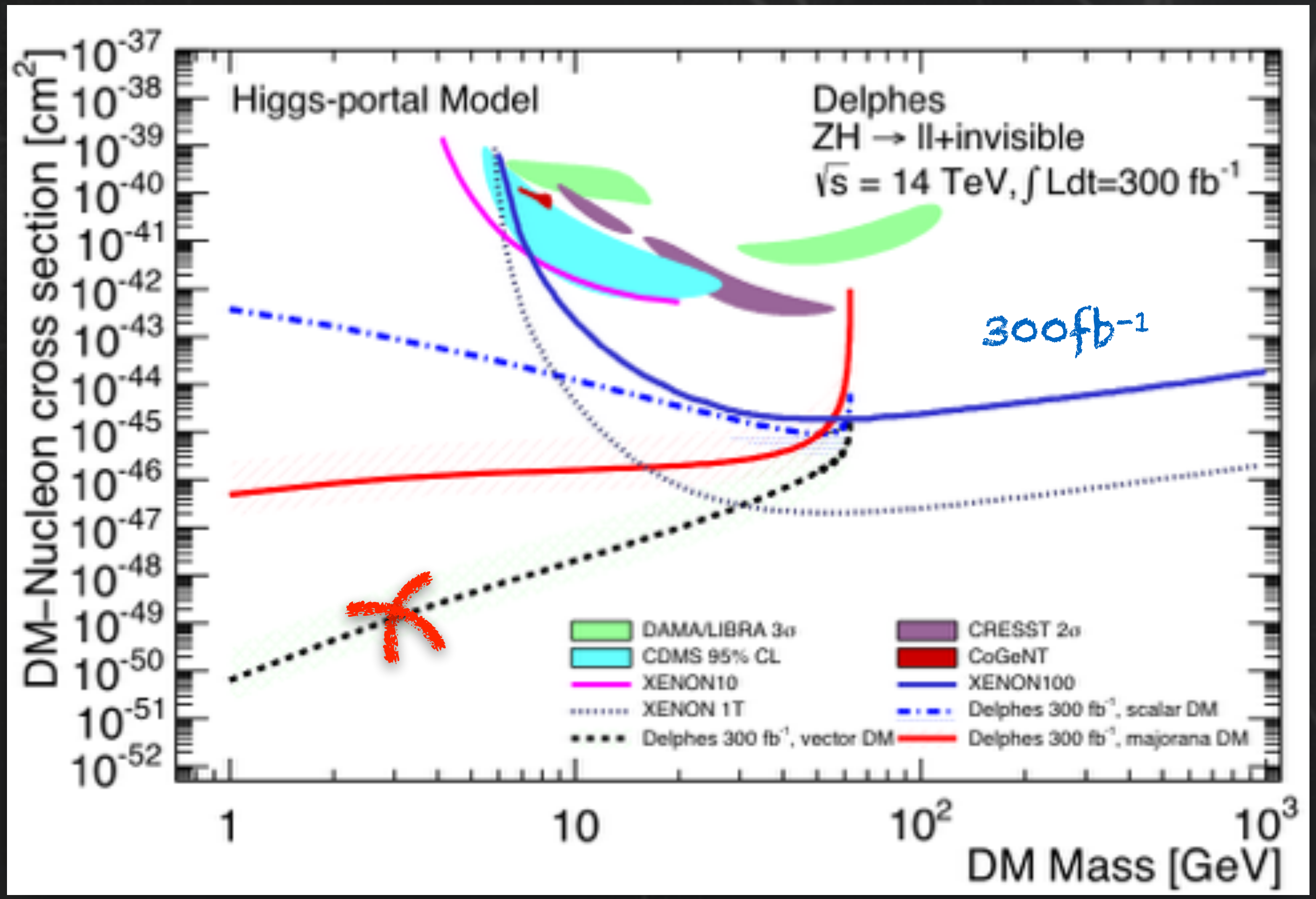


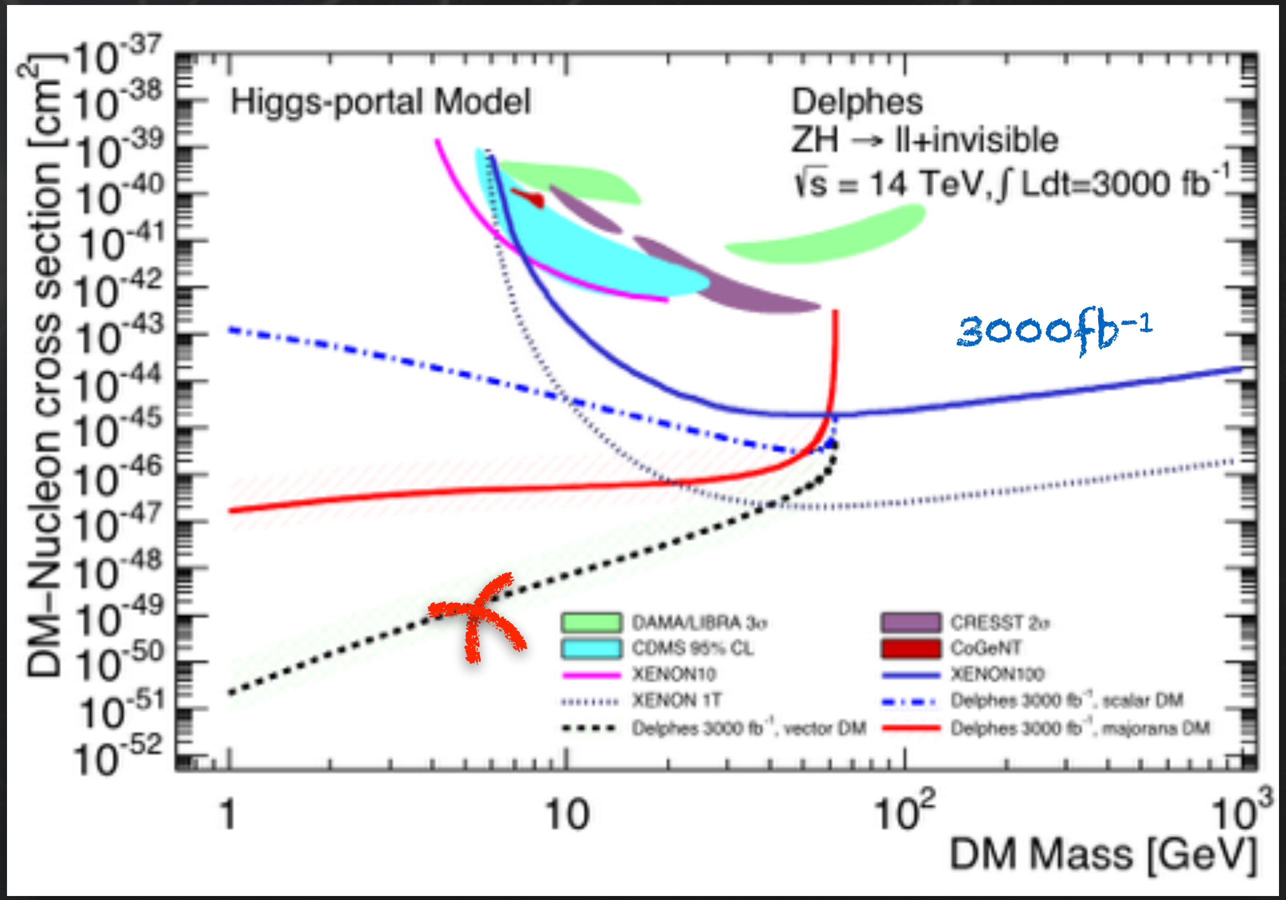
Limits for scalar (fermion) DM:
~ 10^{-41} (10^{-45})cm^2

DM+Higgs

arXiv:1309.7925
H. Okawa, J. Kunkle, E. Lipeles

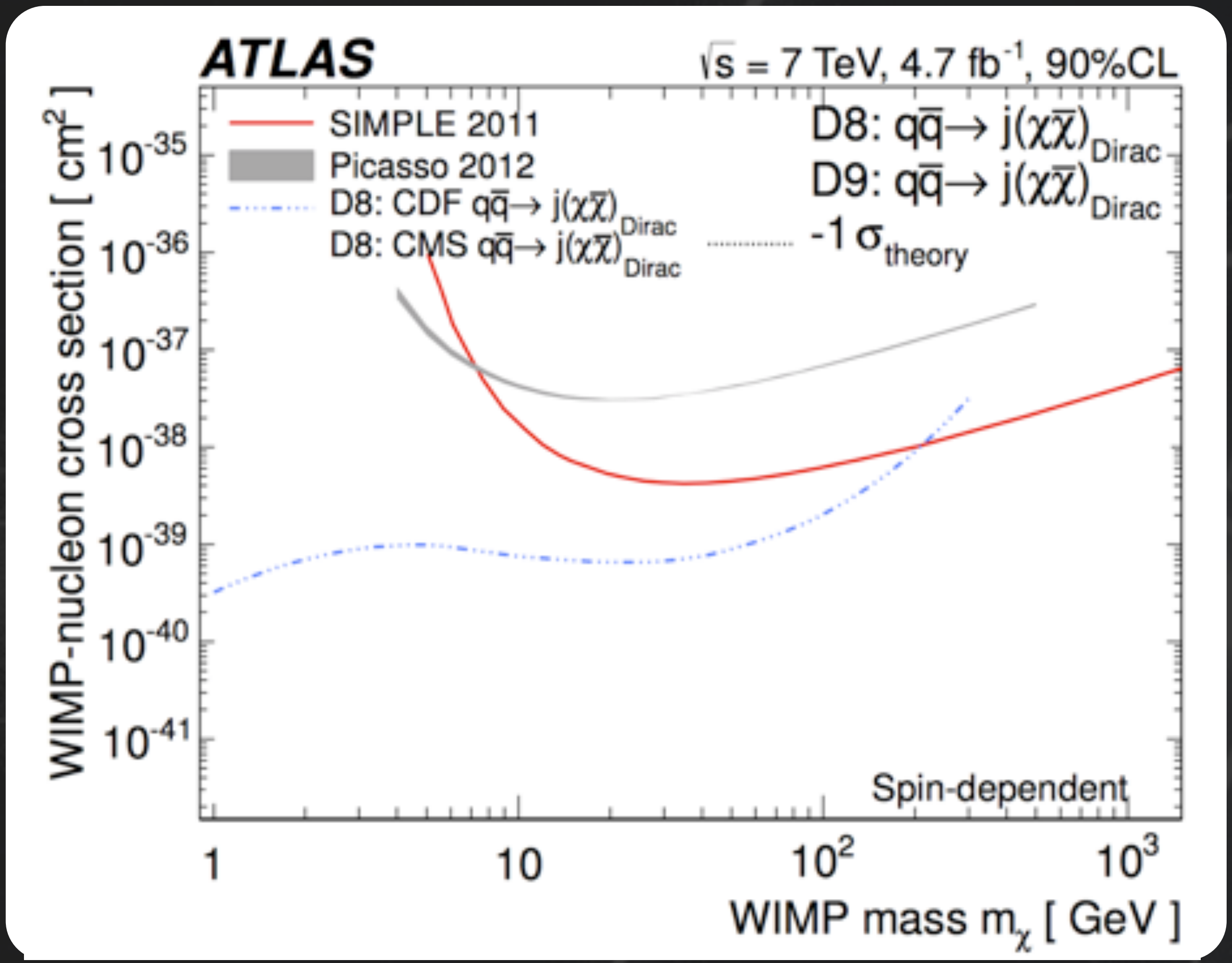
- Analysis based on **associated ZH** production
- **SM cross section predictions for m_H=125 GeV**
- **Upper limits** on σ x BR(H→inv) as function of m_H



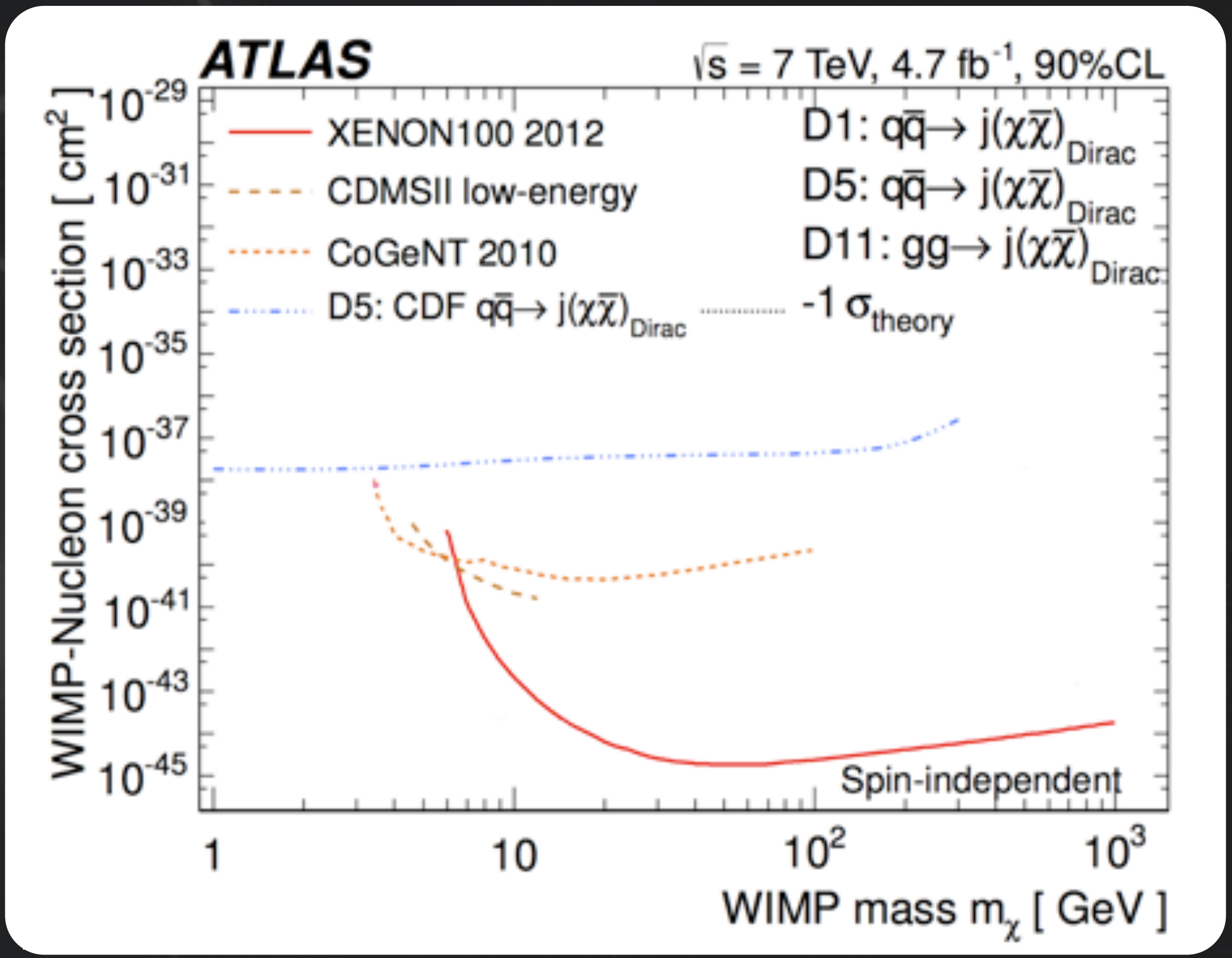


Improvements by two orders of magnitude!

spin-dependent



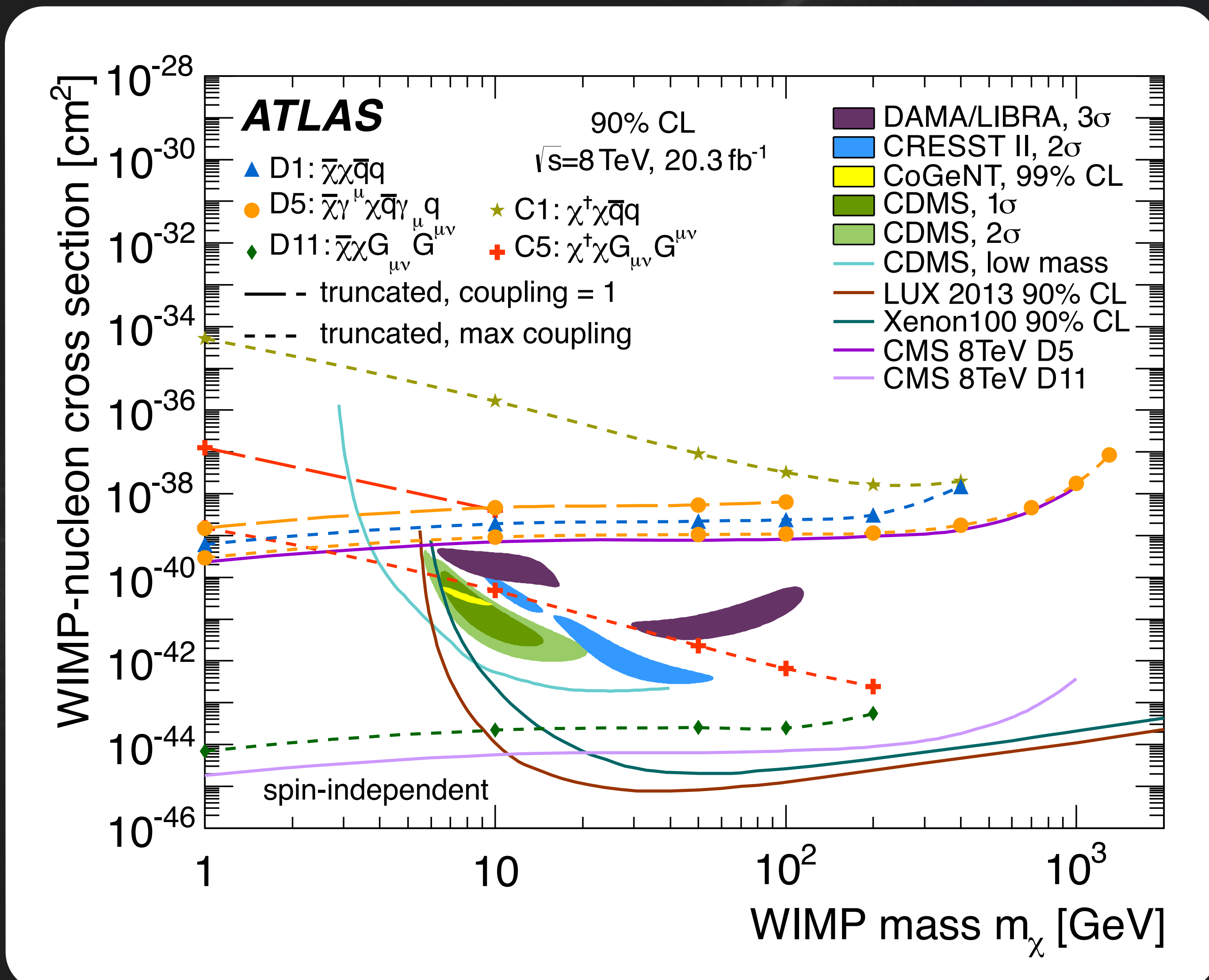
spin-independent



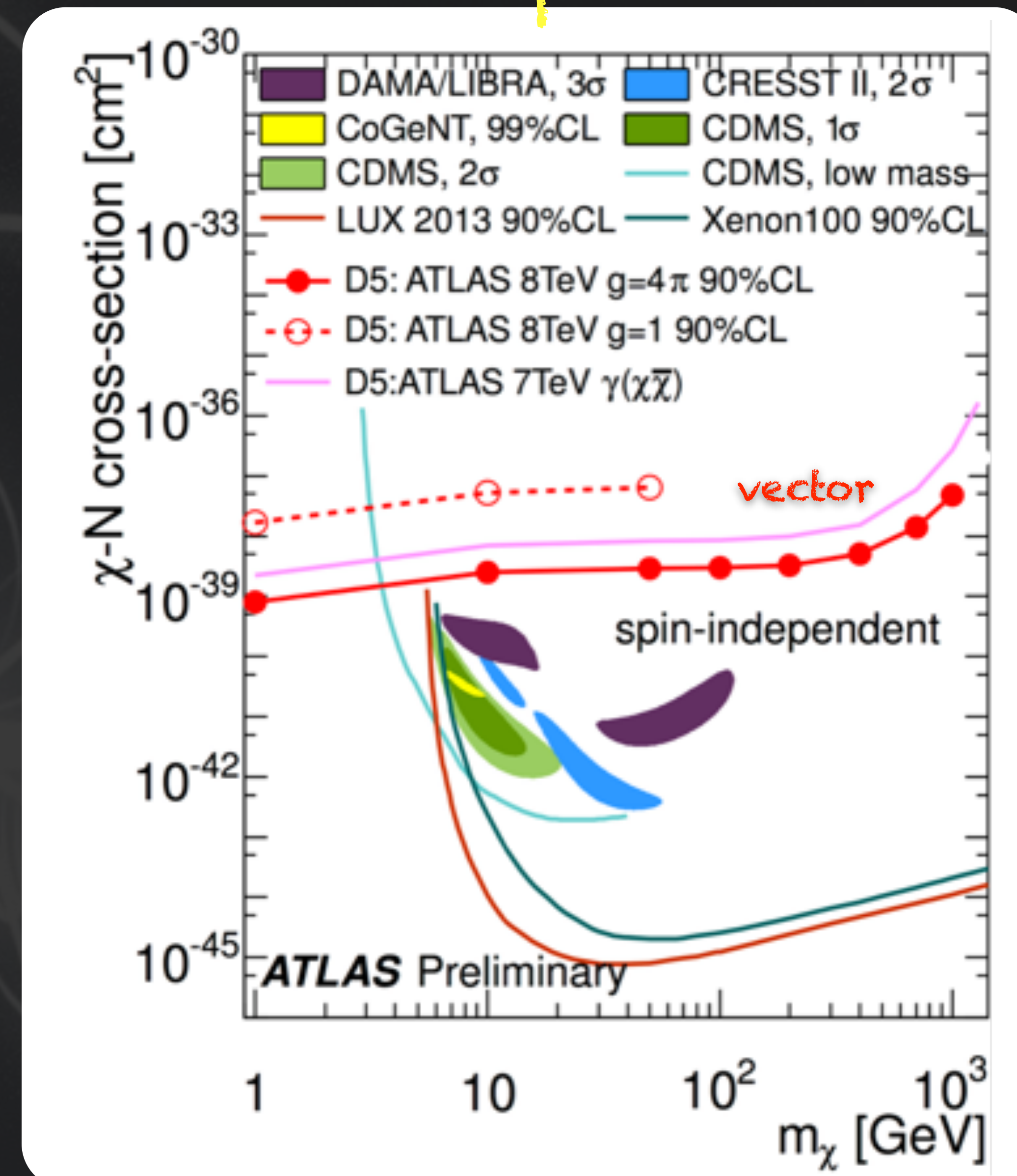
- **Spin-Dependent** (SIMPLE, Picasso)
  Atlas limits stronger for axial vector (D8) and tensor (D9) couplings
- **Spin-Independent** (XENON100, CDMSII, CoGent)
  Atlas limits stronger for scalar (D1) and vector (D5) at low m_χ

Imperial College London

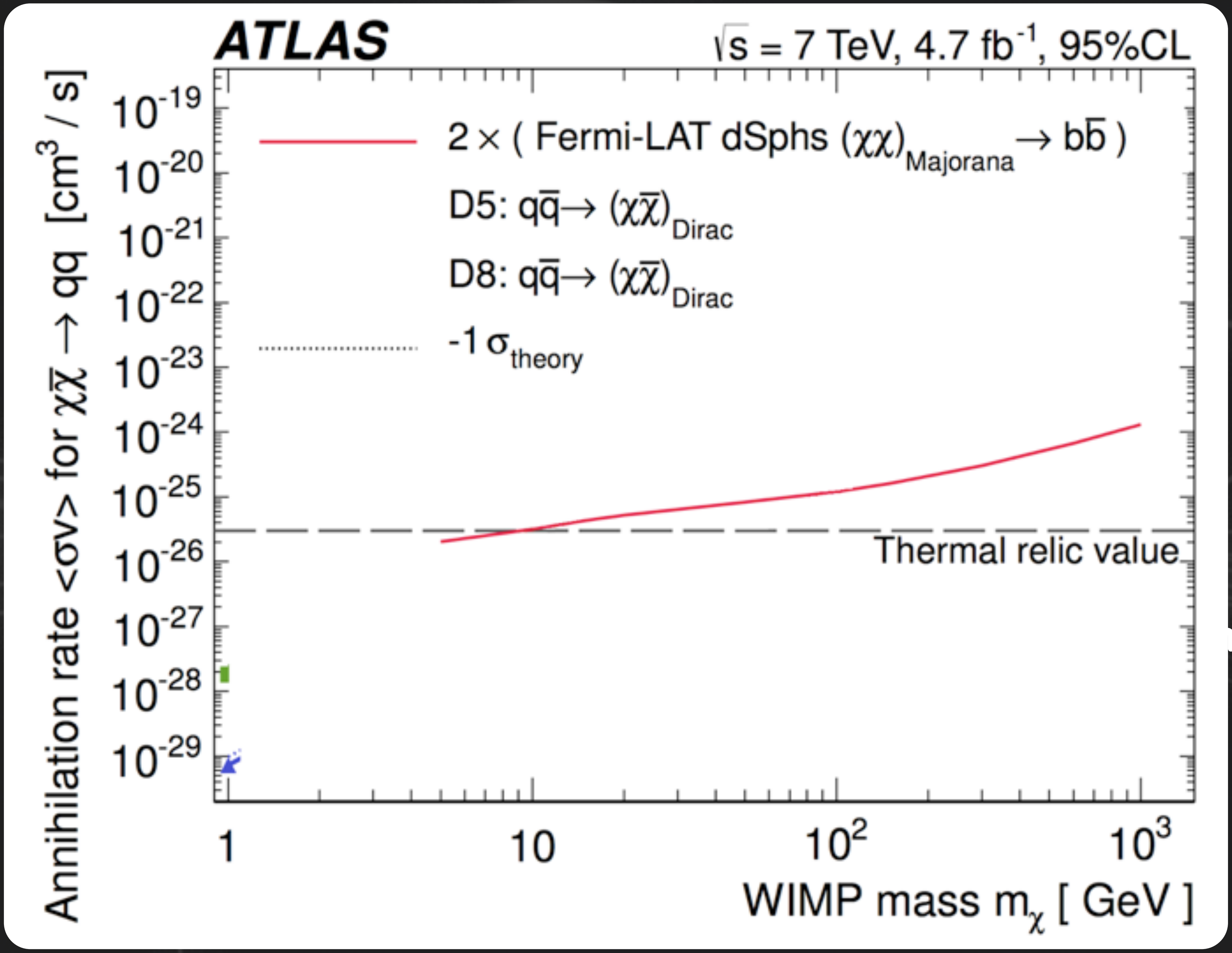
mono-jet



mono-photon

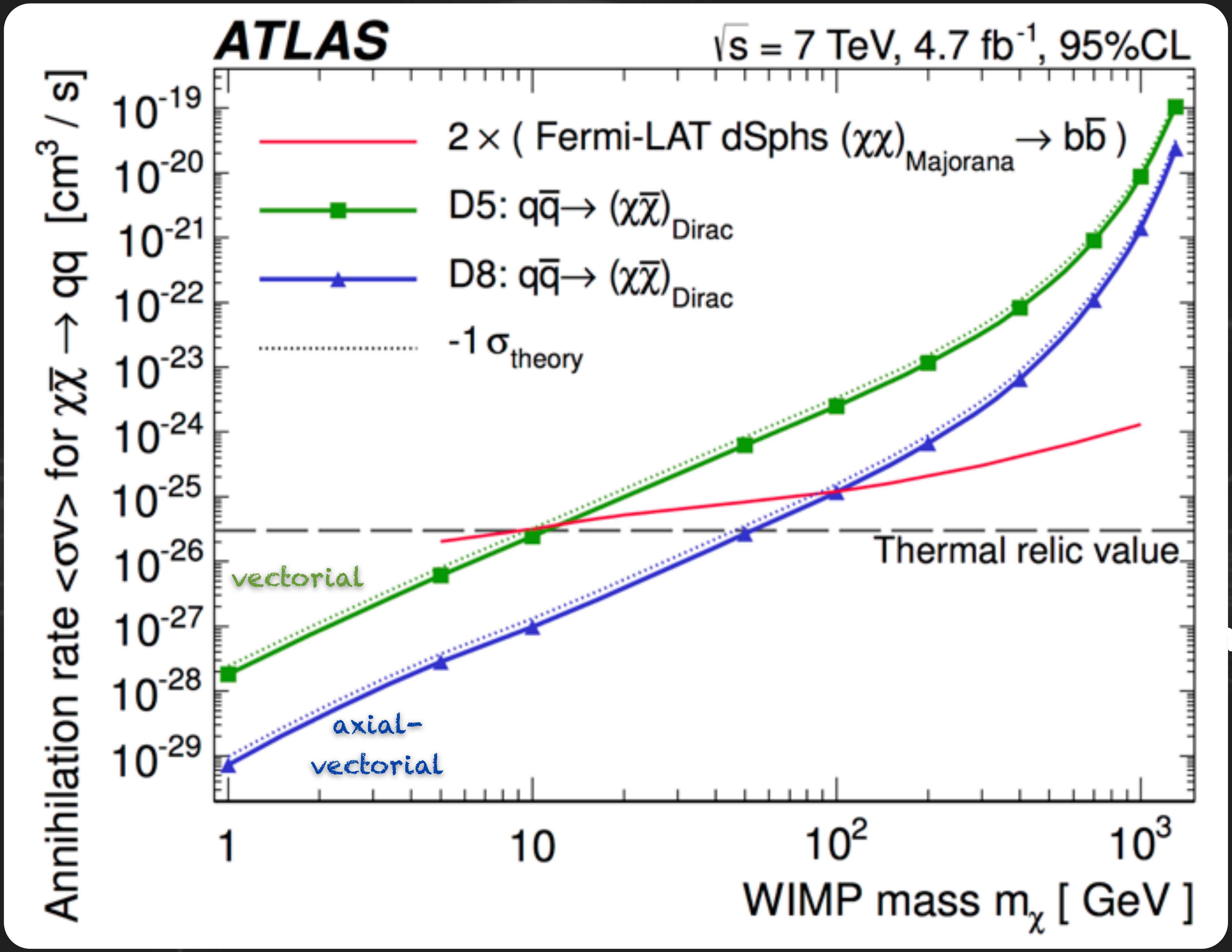


- **ATLAS results**



- nma

- **Comparing to annihilations from galactic high energy gamma ray observations by FERMI LAT**

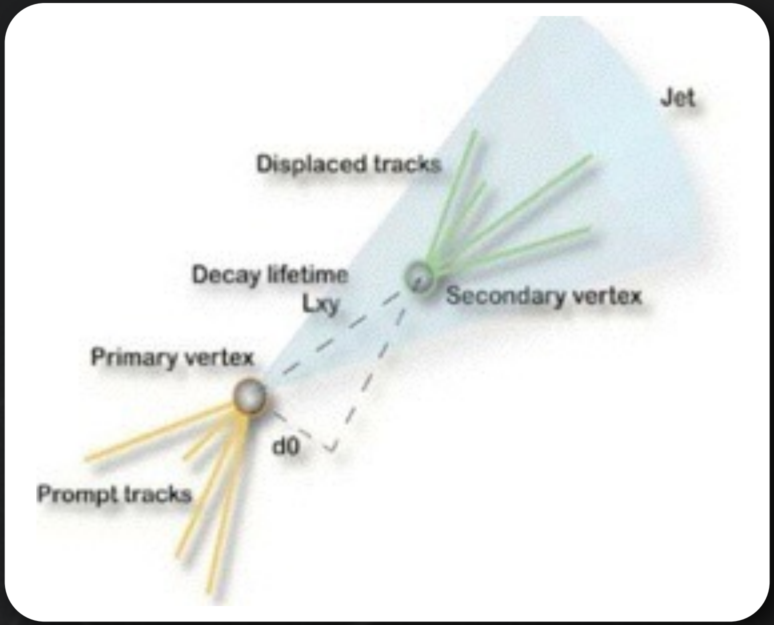


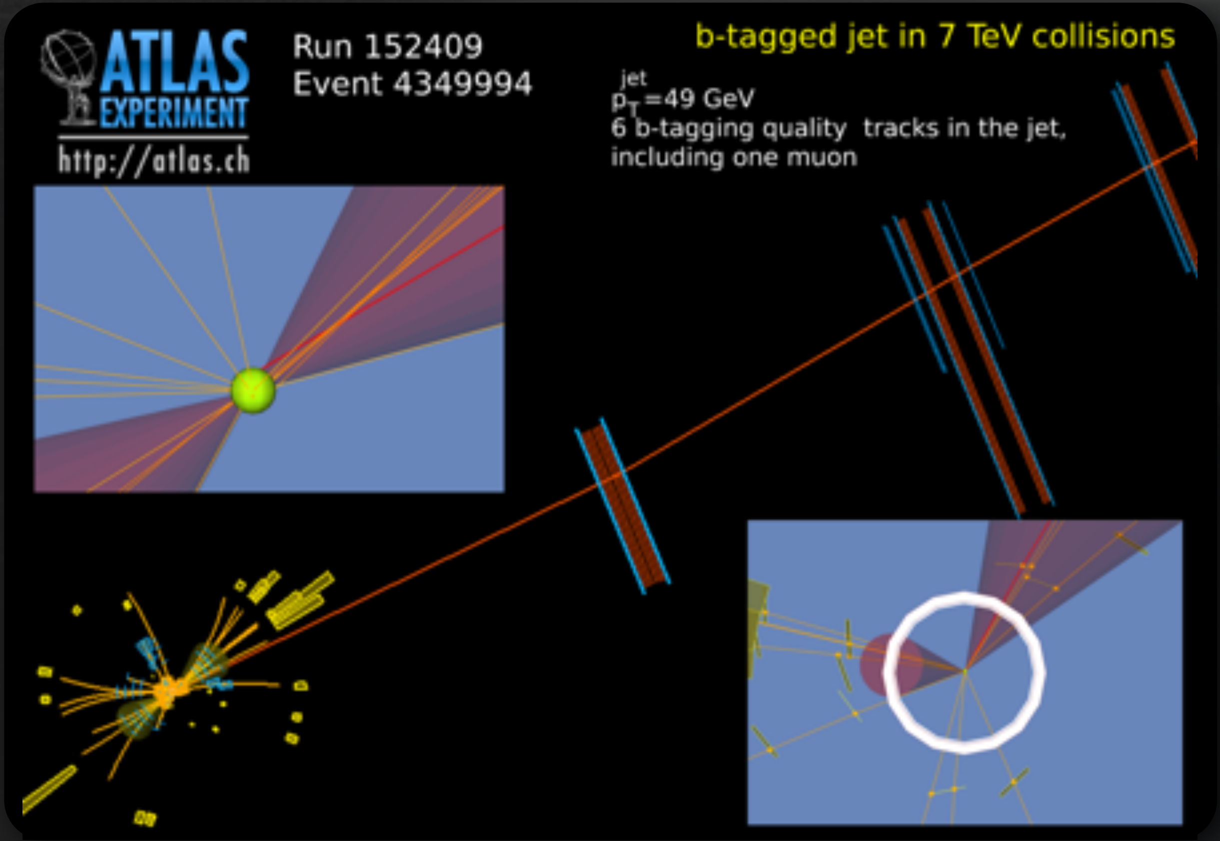
- ...mma

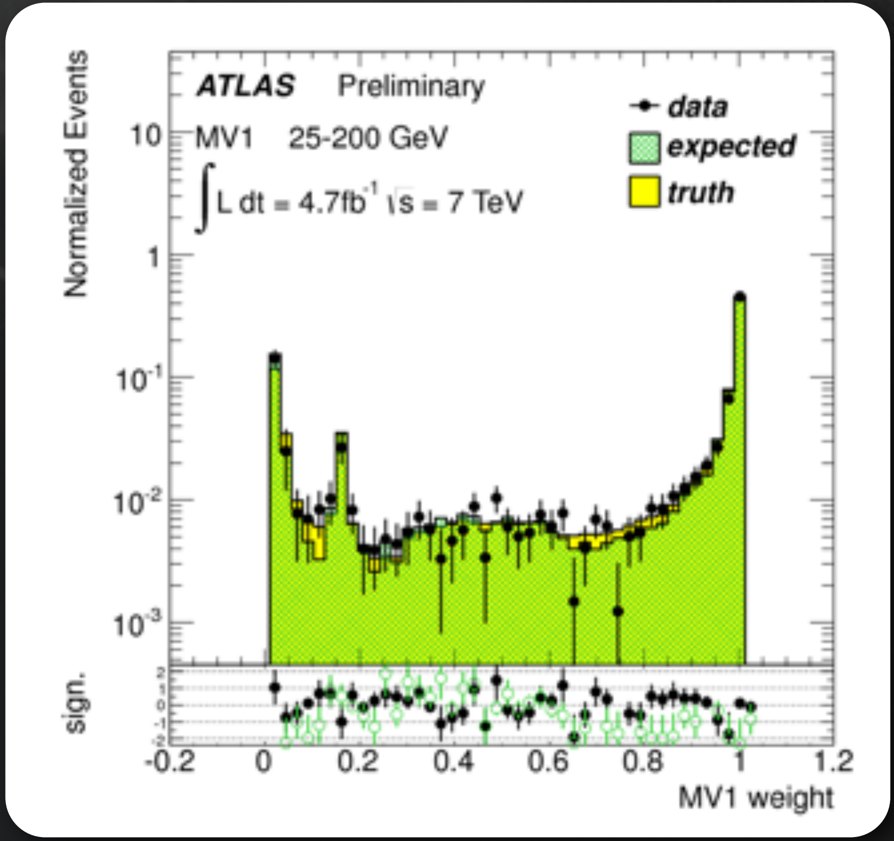
- Comparing to annihilations from galactic high energy gamma ray observations by **FERMI LAT**

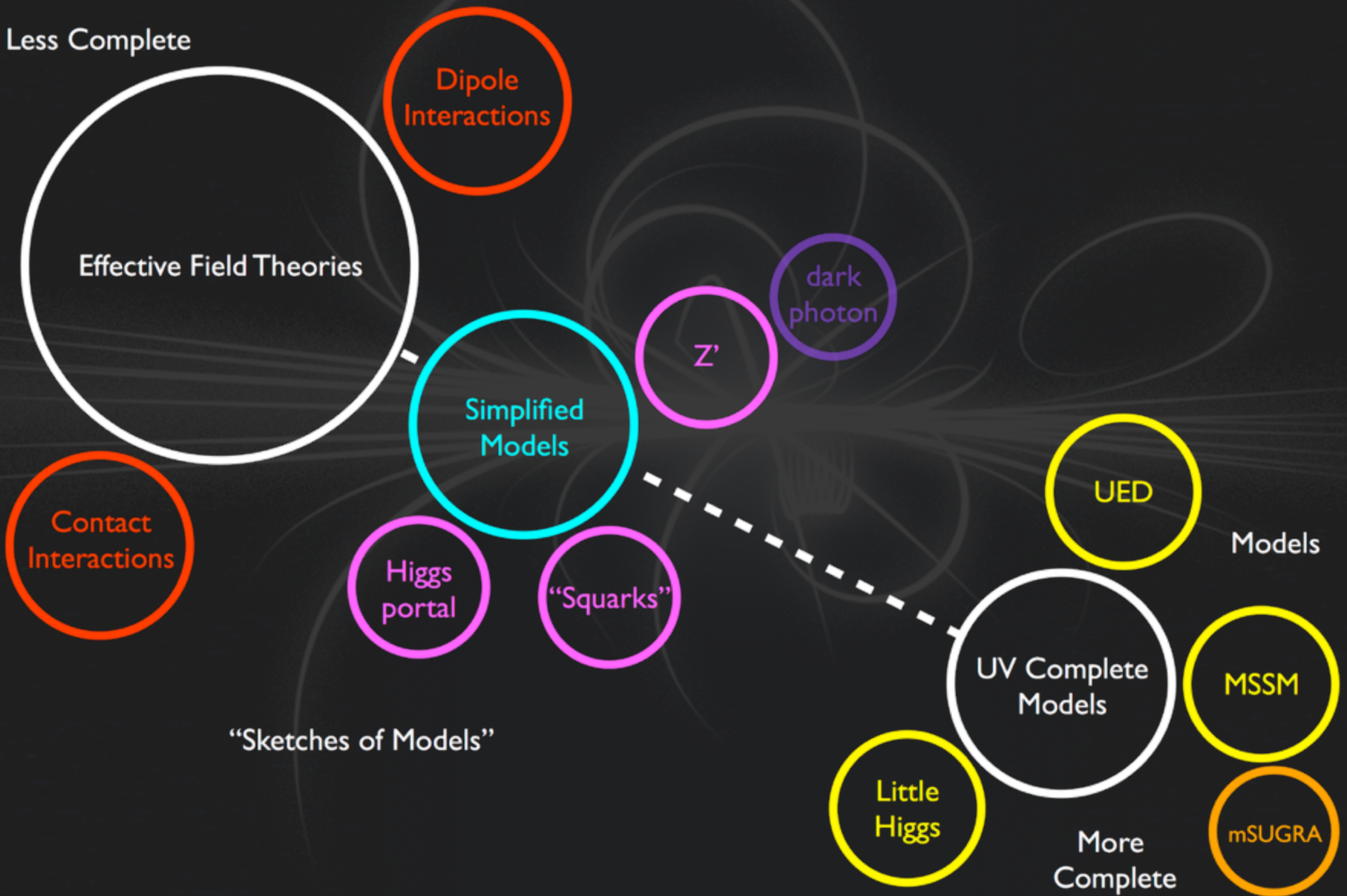
1109.4398v1, Fox et al.

- Long life-time of b/c-hadrons → displaced vertex
- ATLAS uses multivariate method, exploiting information of displaced vertex, track impact and PV association probability
- Typically 50-60% efficient for 0.5-1.5% fake rate

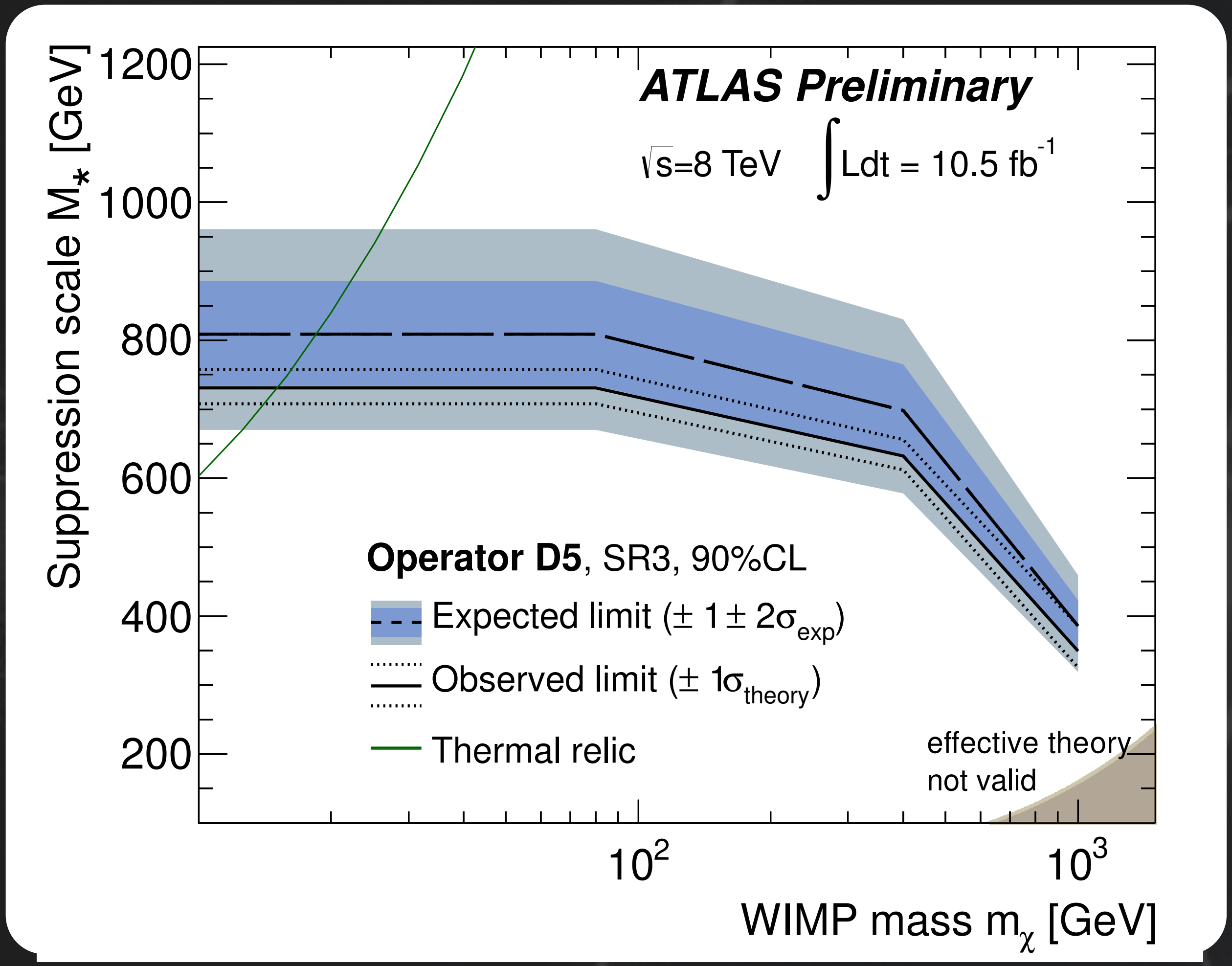







Less Complete
Dipole
Interactions
Effective Field Theories
dark
photon
Z'
Simplified
Models
UED
Models
Contact
Interactions
Higgs
portal
"Squarks"
UV Complete
Models
MSSM
"Sketches of Models"
Little
Higgs
More
Complete
mSUGRA

- **Lower limits** at 90% C.L. on the suppression scale of M* set for different operators (arXiv:1008.1783v2, Goodman et al.)



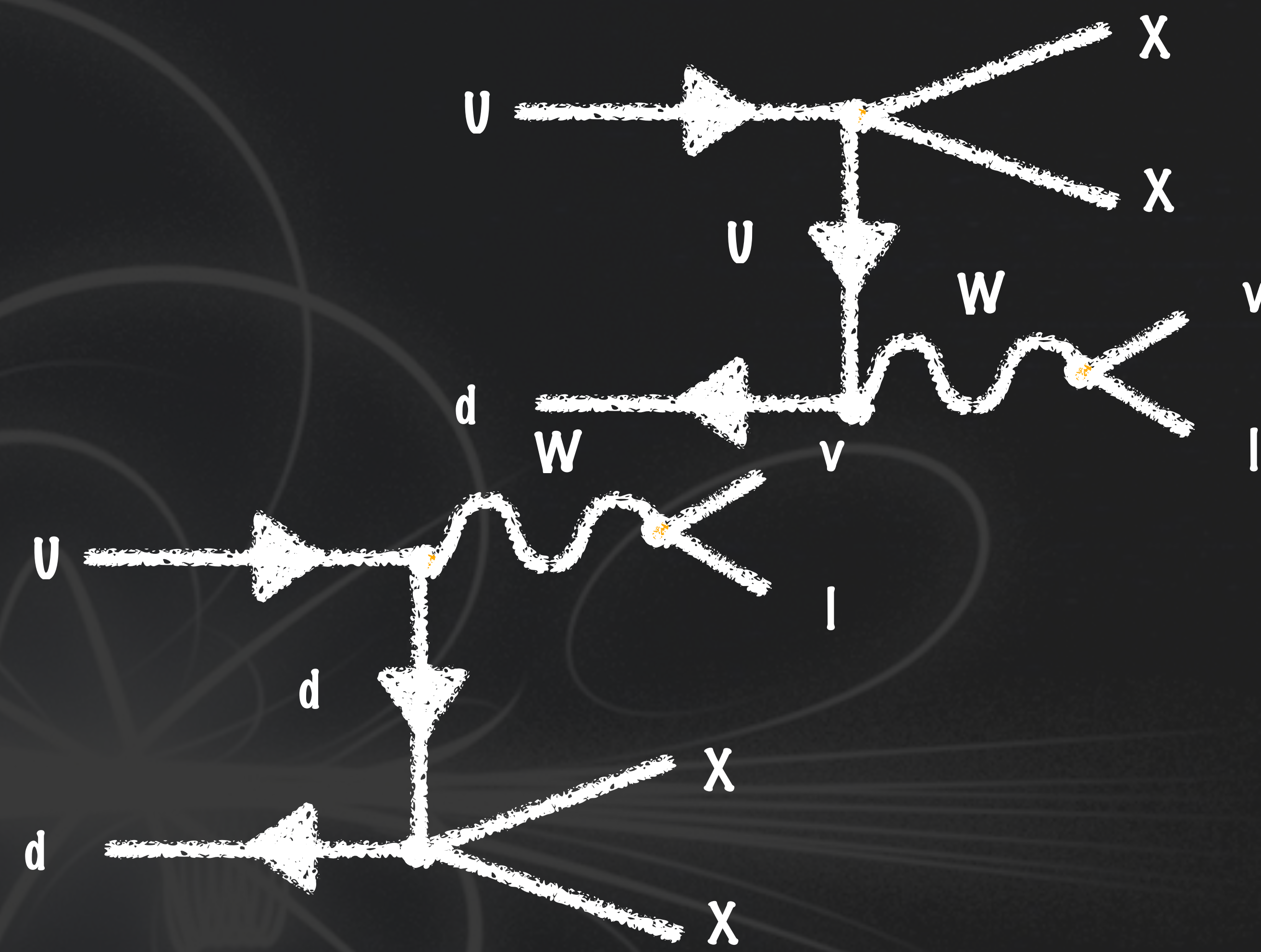
characterize strength of interaction

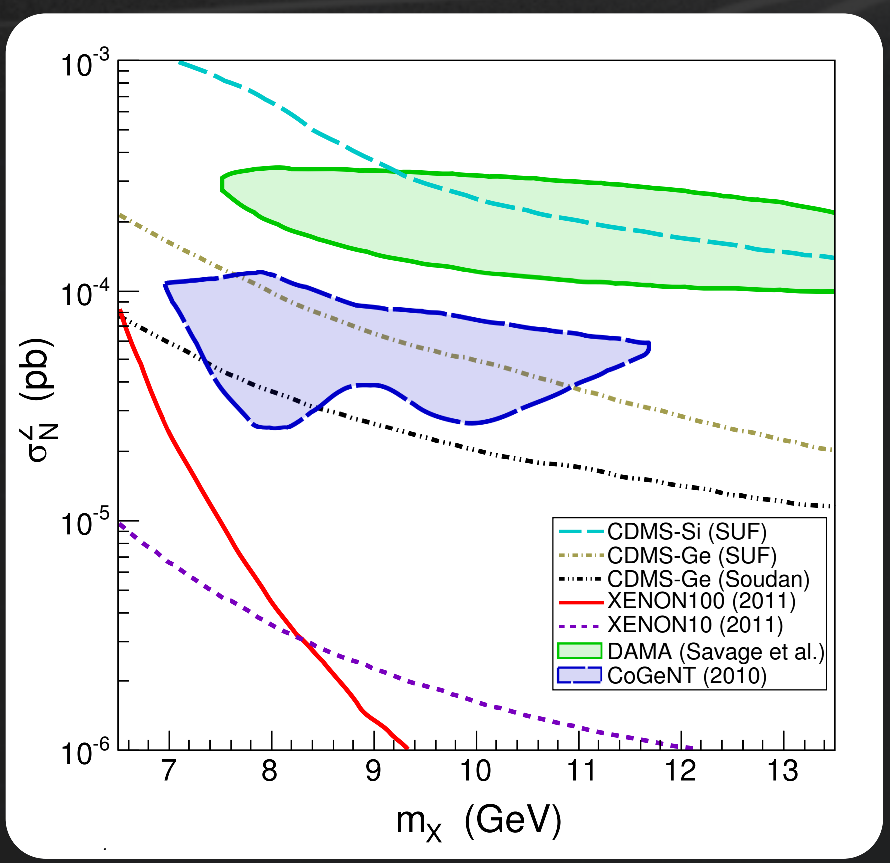
$$M_* \sim M/\sqrt{g1g2}$$

$$M > 2m_\chi$$

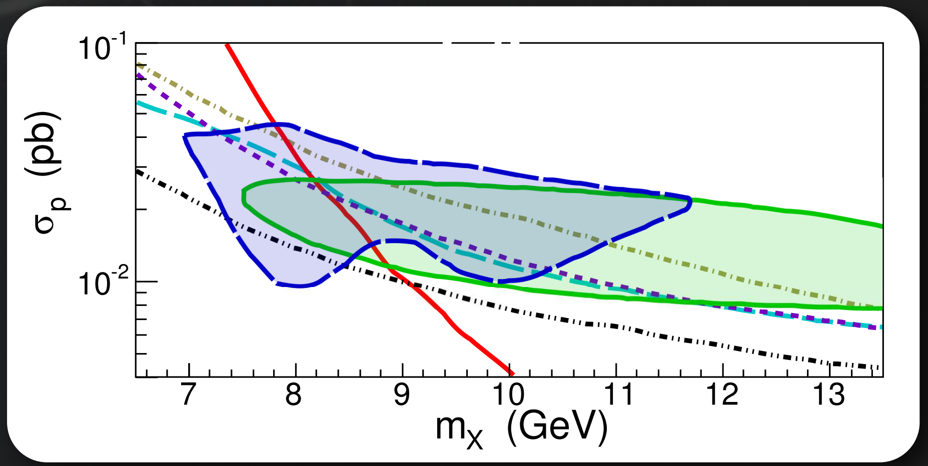
- Distinct acceptances for **scalar, vector, axial-vector** quark-quark to WIMP-WIMP interaction, and a gluon-gluon to WIMP-WIMP (D1, D5, D9, D11) operators.
- Above the **thermal relic line** additional coupling have to exist

- Mono-W small rate for same couplings up/down-type quarks
- W boson emission may become dominan for opposite sign couplings
- f_n/f_p = ratio of proton/neutron coupling
- For $-0.72 < f_n/f_p < -0.66$ DAMA- and CoGeNT, and XENON are consistent





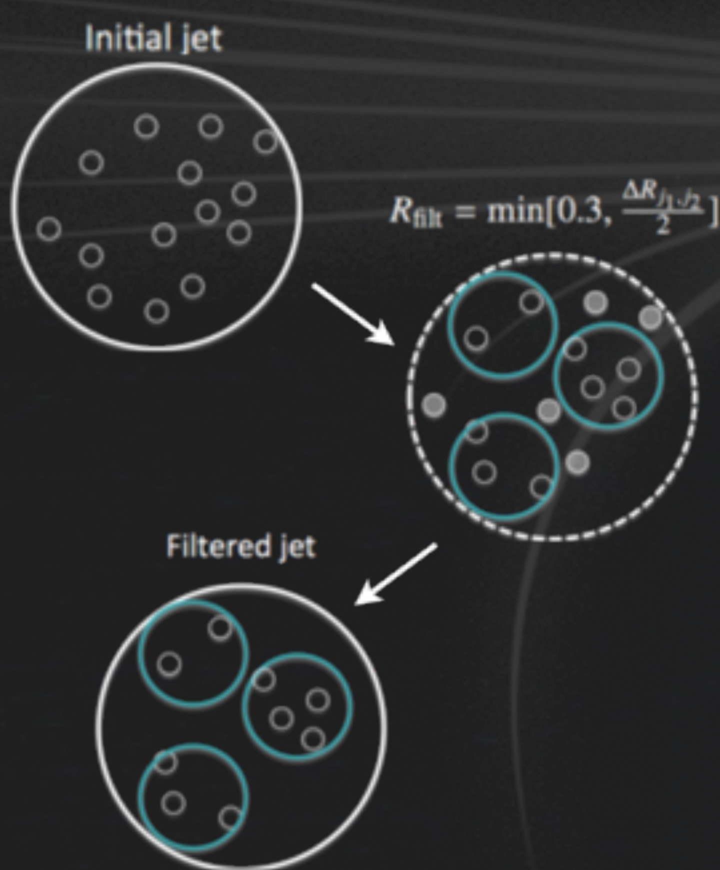
f_n/f_p



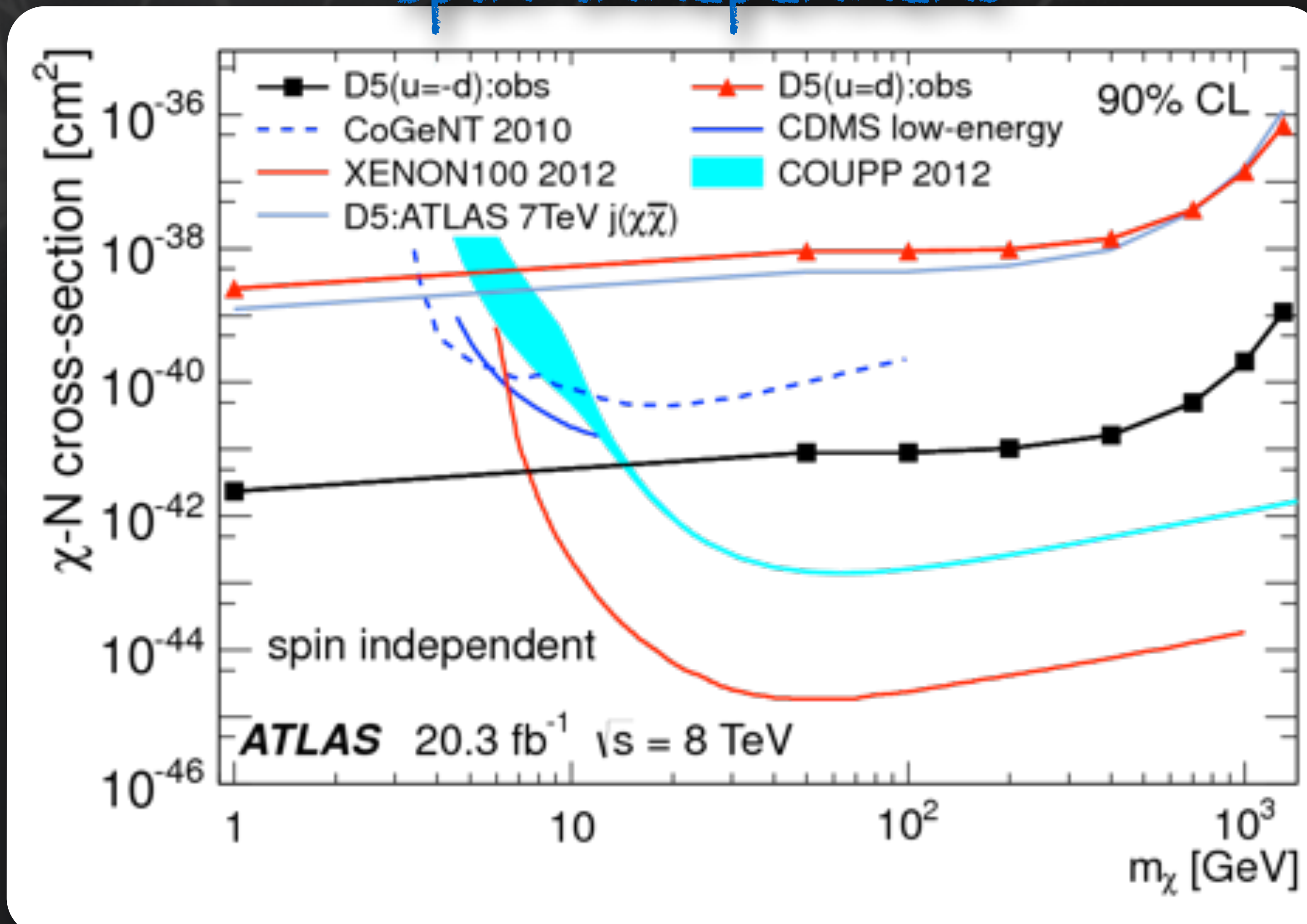
Y. Bai, T. Tait; arXiv:1208.4361
Feng et al.; arXiv:1102.4331

Imperial College London

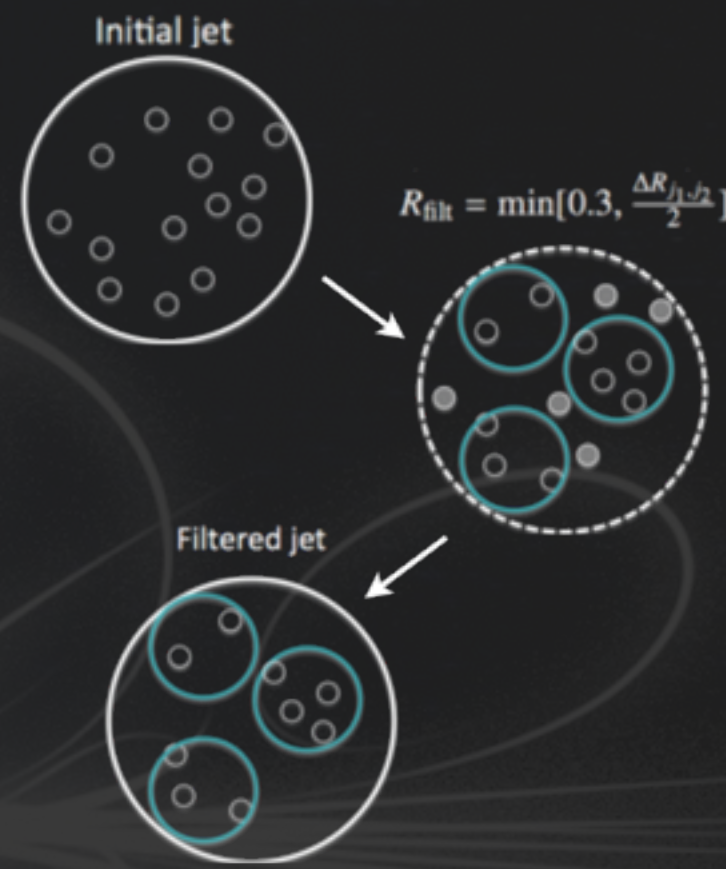
- **Jets boosted**, reconstructed as single large radius jet
- Using '**Cambridge-Aachen**' algorithm for jet reconstruction

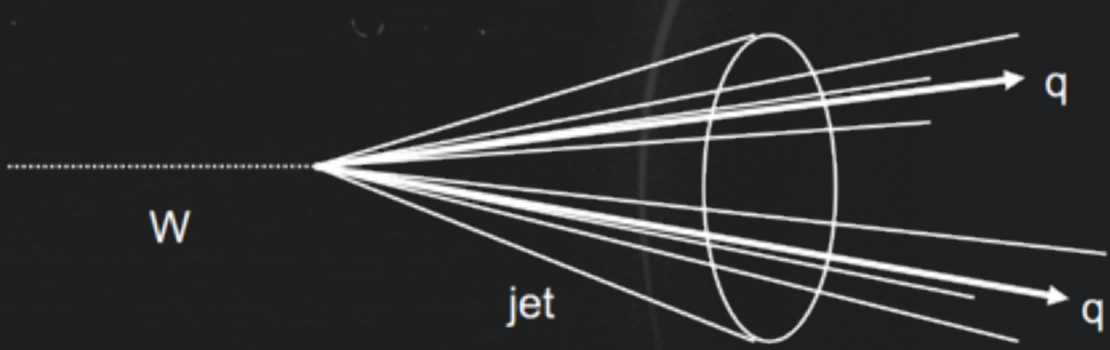


spin-independent

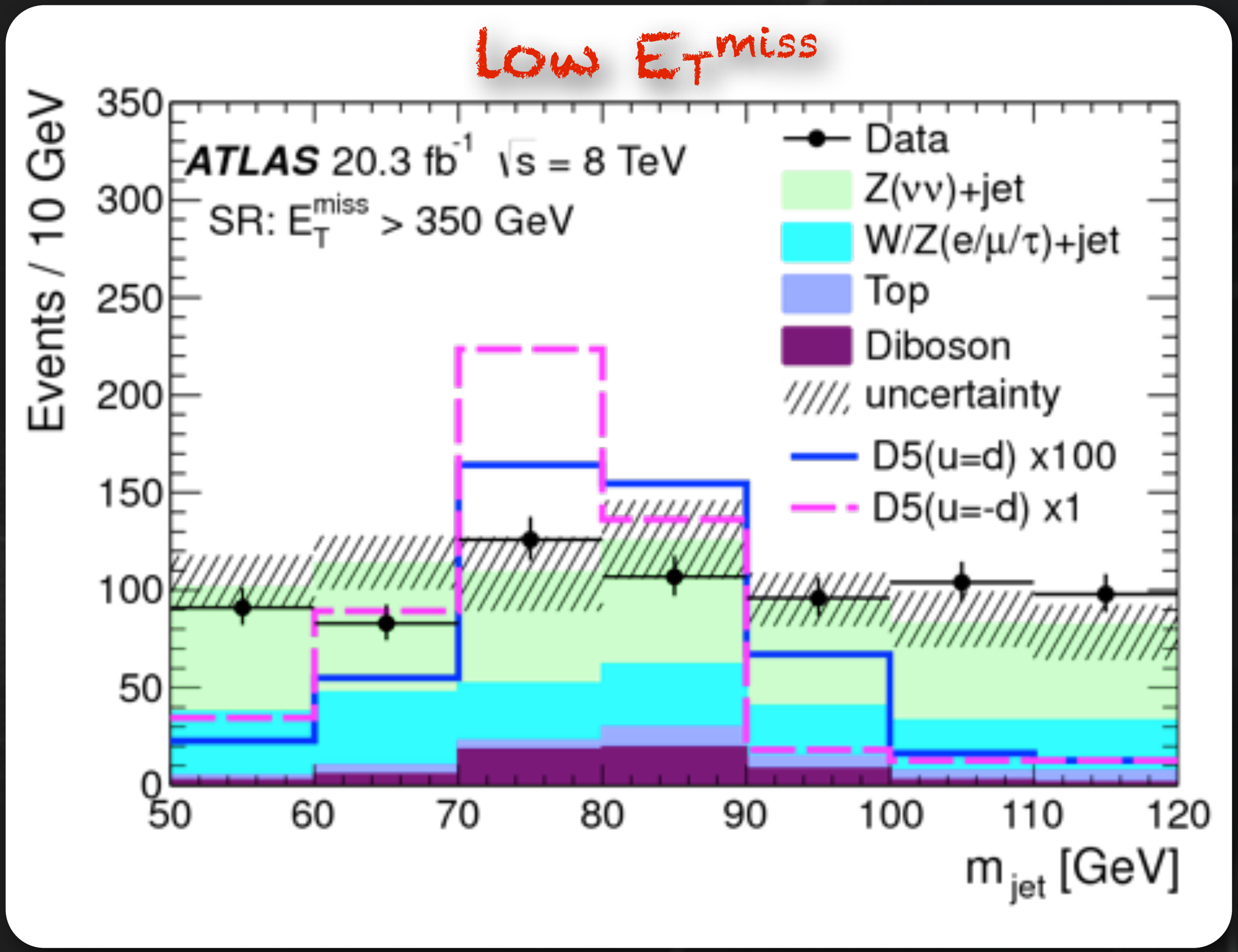


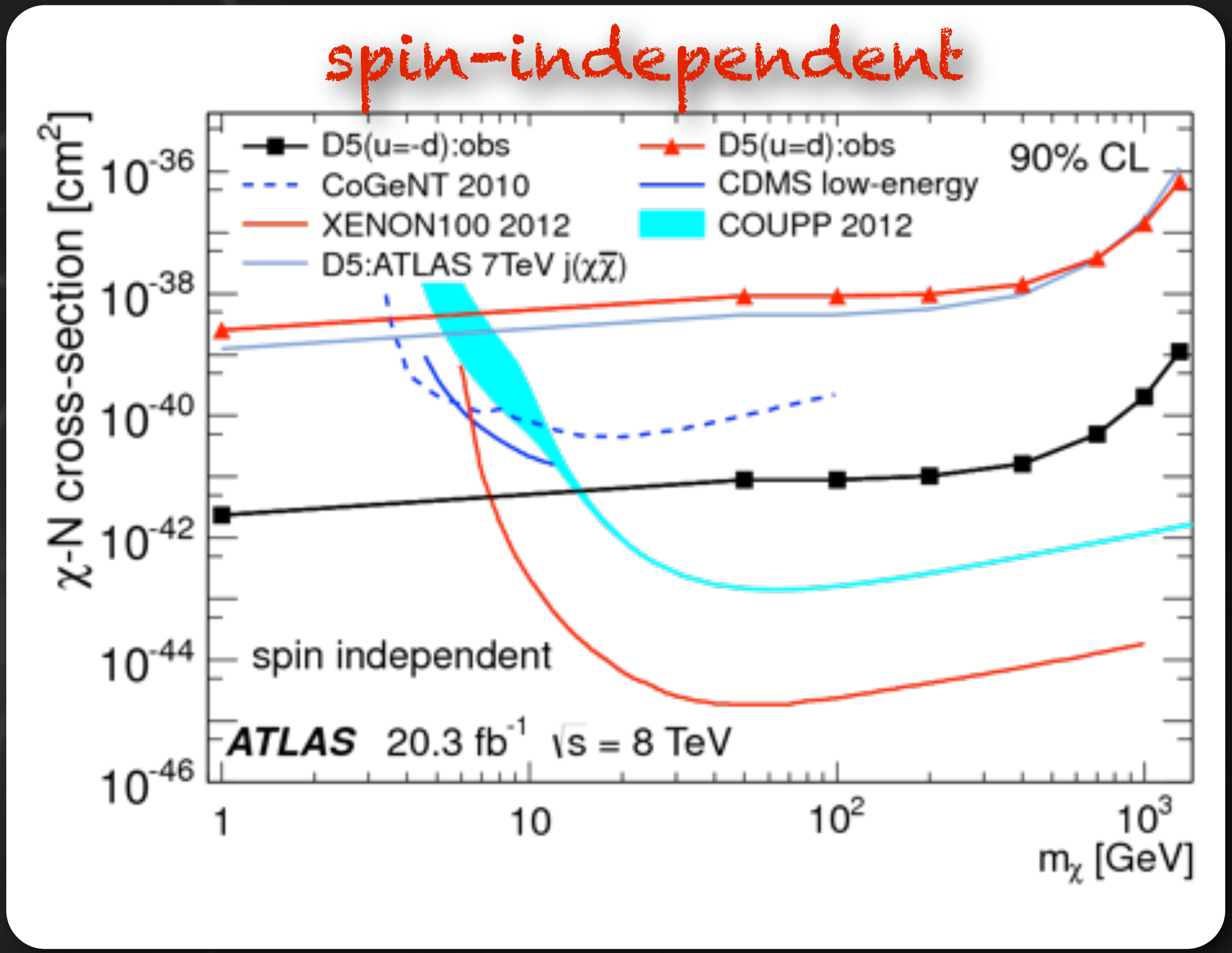
- **Jets boosted**, reconstructed as single large radius jet
- Using '**Cambridge-Aachen**' algorithm for jet reconstruction
  - p_T>250 GeV, $|\eta|$<1.2
  - 50 GeV < M_{jets}< 120 GeV
  - $\sqrt{(y)}$<0.4, where $\sqrt{(y)}$<min(p_T^1, p_T^2) ΔR1,2 / M_{jets} (balancing of two leading subjets)





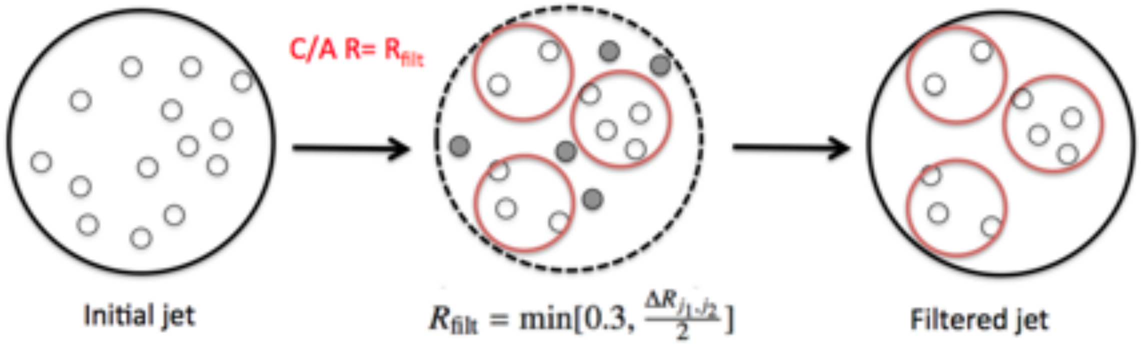
- **Further selections**:
  - <=1 regular jet
  - separated from large radius jet and E_T^{miss}
  - Signal Regions: E_T^{miss}> 350, 500 GeV





- Unfortunately no excess over SM found
- Converting into limits on WIMP-Nucleon scattering cross section
- Spin independent limits improve by three orders of magnitude if up/down have opposite sign

- For highly boosted objects objects, decay products have narrow dR distribution
- To recover efficiency & resolution:
  - Use a single large R Cambridge/Aachen jet encompassing all decay products
  - Revert last step of clustering and look for two low mass, symmetric sub-jets
  - Recluster constituents of sub-jets, keep 3 hardest new sub-jets
- Process greatly improves jet mass measurement, QCD separation



arXiv:1306.4945