University of BRISTOL

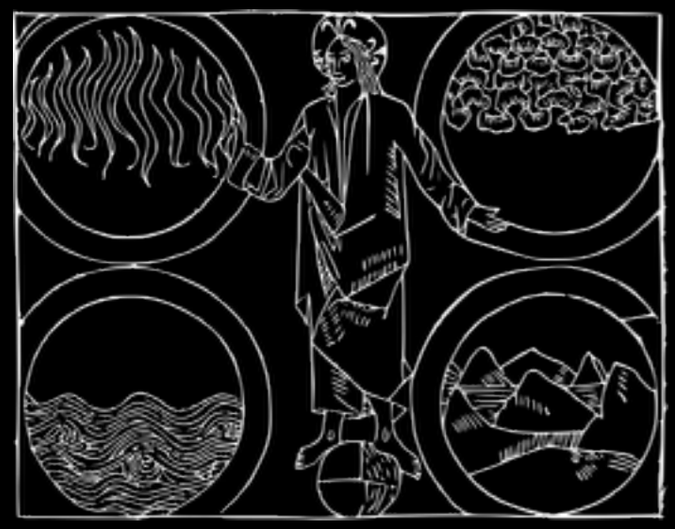
# Connections & Future

Bjoern Penning

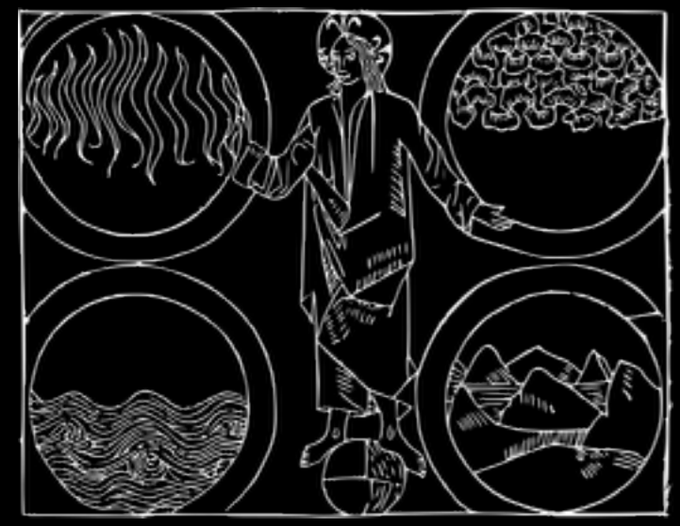
University of BRISTOL

- Reminder: What is Dark Matter not?
- Reminder: How to search for Dark Matter
- Combination and near future
- Axion Experiments
- Future ideas

University of BRISTOL

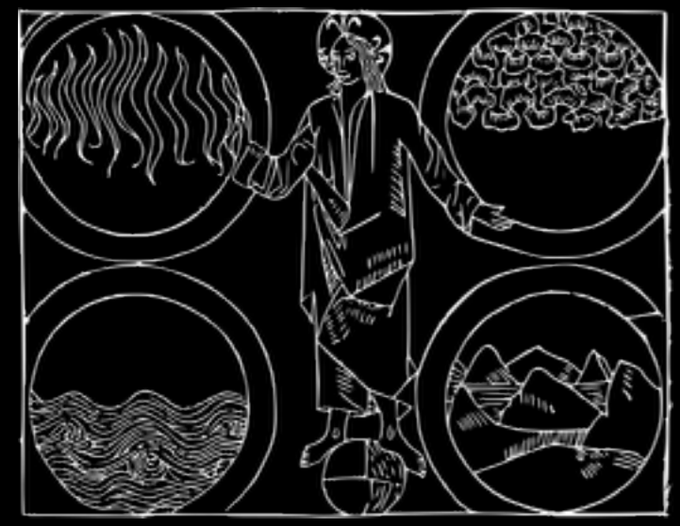


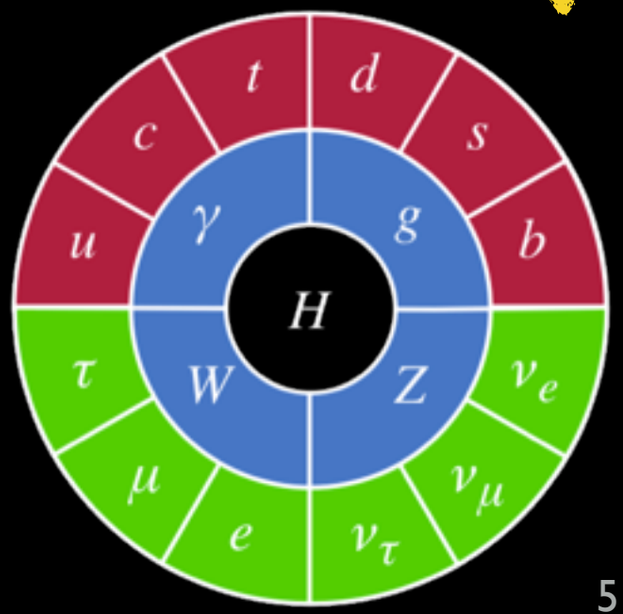
- It took a few hundred years



- It took a few hundred years

- With the discovery of the Higgs boson the Standard Model has been completed

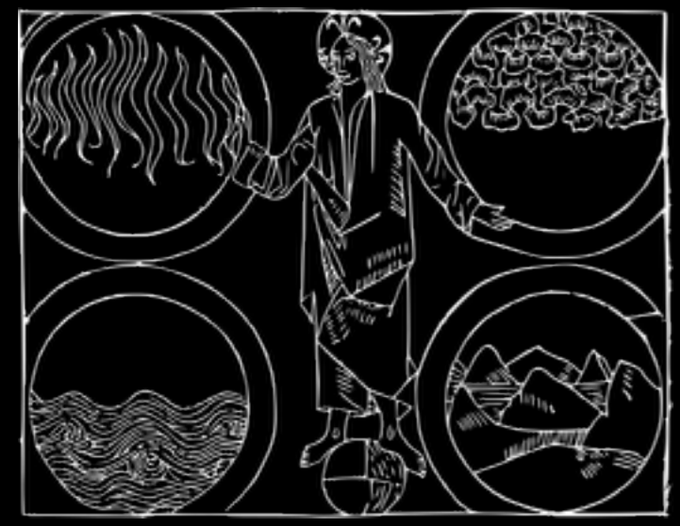


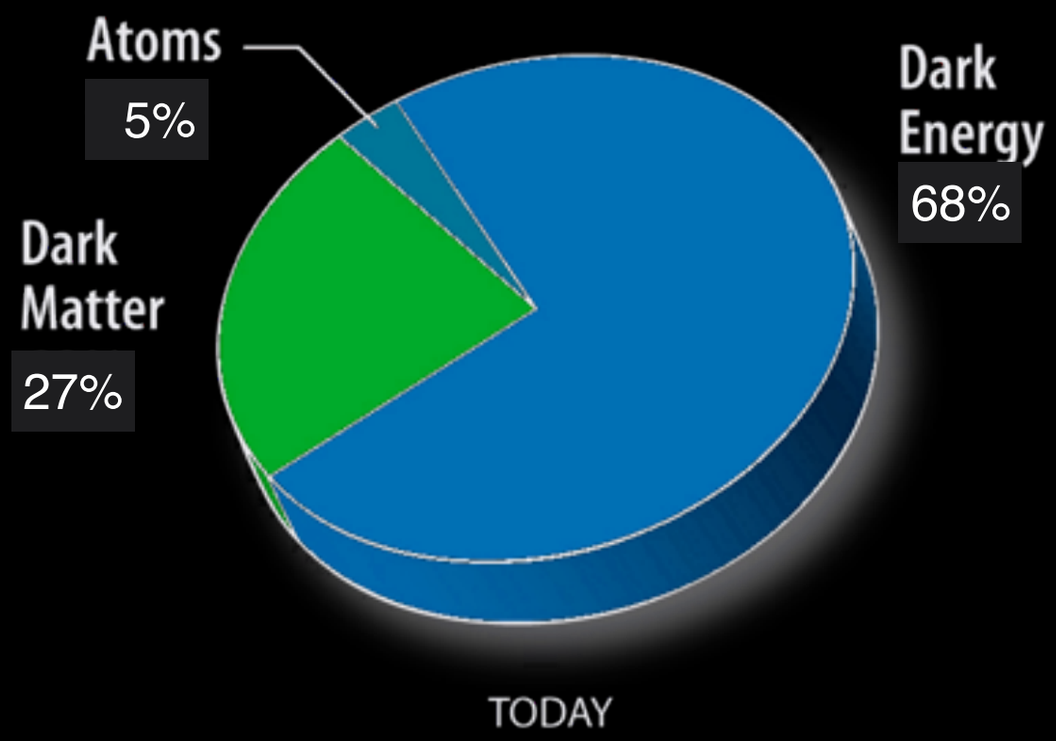


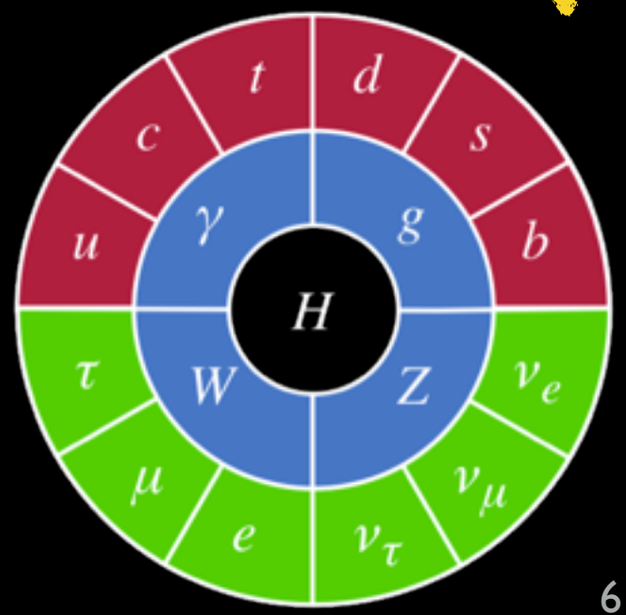
- It took a few hundred years

- With the discovery of the Higgs boson the Standard Model has been completed

- However, this is just the tip of the iceberg

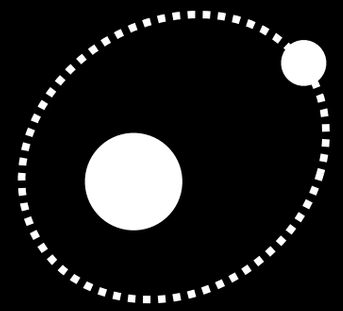




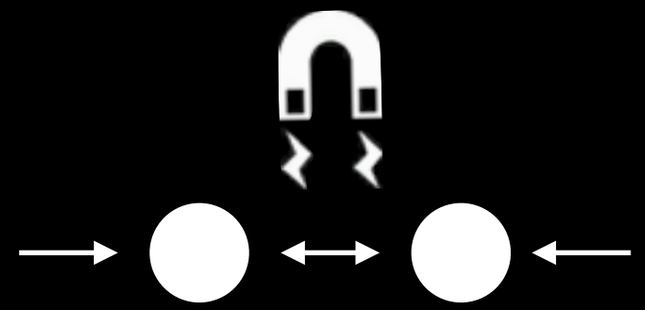



# What is DM?

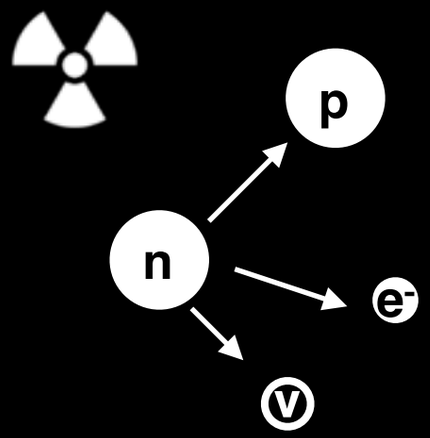
- We know of four fundamental interactions
- Dark Matter does



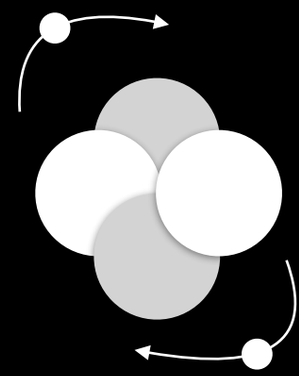
Gravity



Electromagnetism



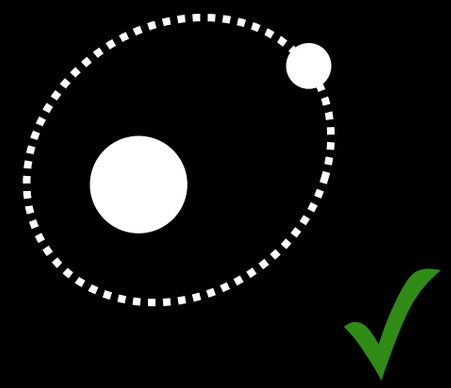

Weak Force

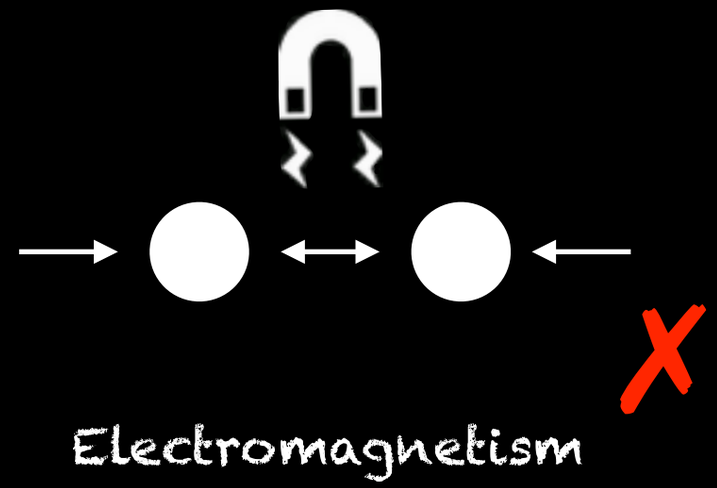


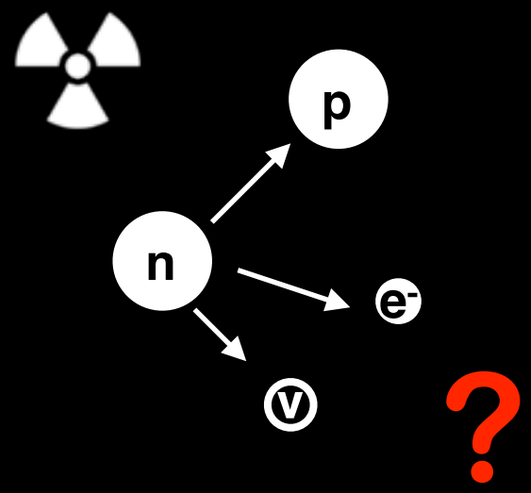
Strong Force

# What is DM?

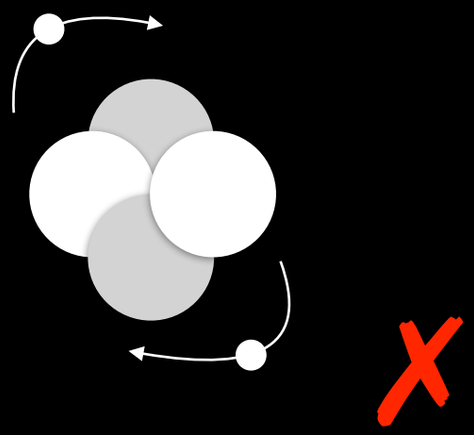
- We know of four fundamental interactions
- Dark Matter does
  - interact gravitationally
  - not have any electromagnetic interaction
  - not interact via the strong force (not a baryon)
  - perhaps interact via the weak force but it is not the neutrino



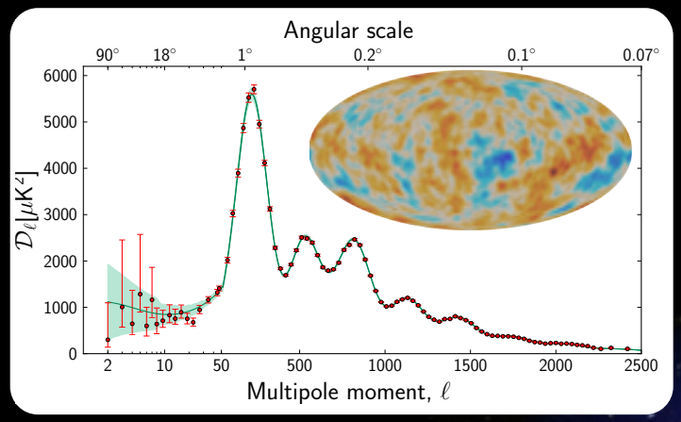




Weak Force

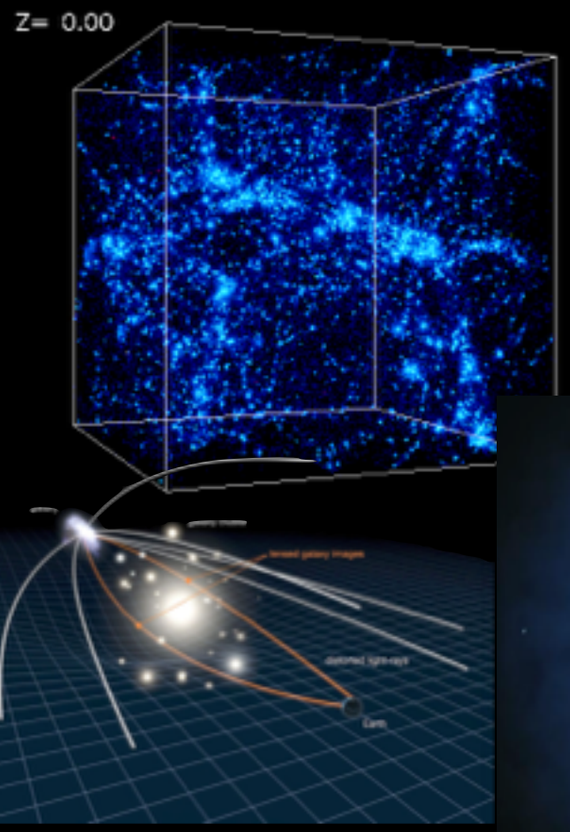


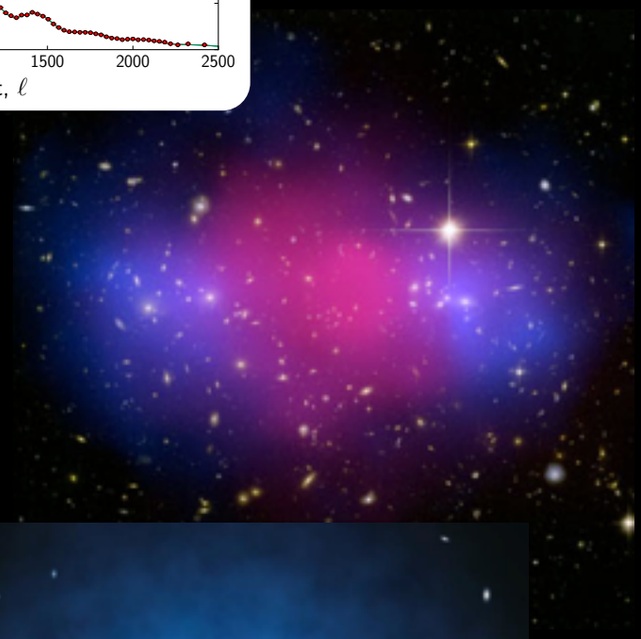
Strong Force

# What is DM?



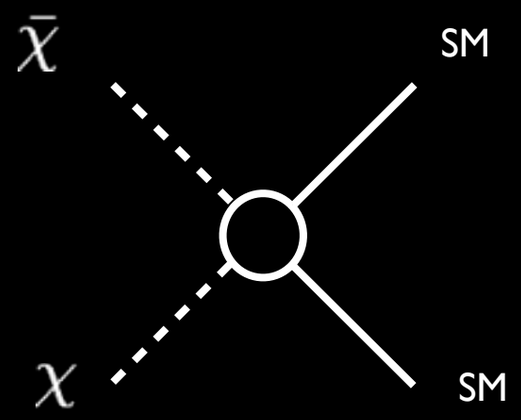

- Dark matter is a hugely successful theory to explain plenty of observations
- It is the one theory that can successfully simulate and reproduce the universe on all scales:
  - Galaxy rotation curves
  - Galaxy clustering
  - Cluster collision
  - Large-scale structures
  - CMB fluctuations
  - Gravitational lensing



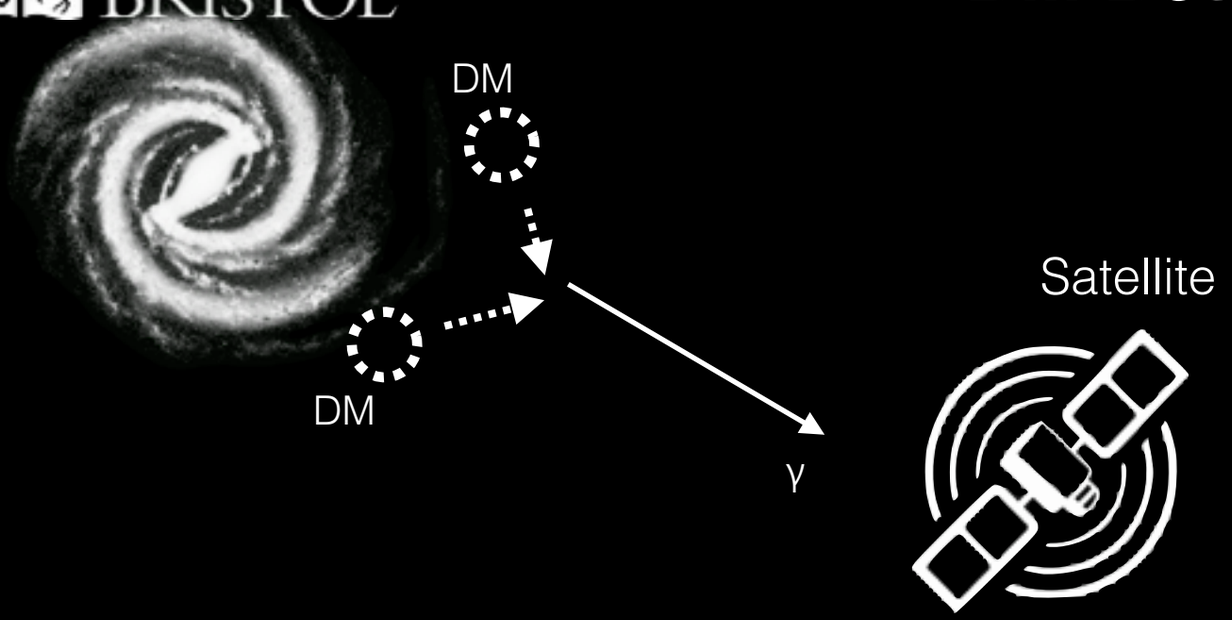



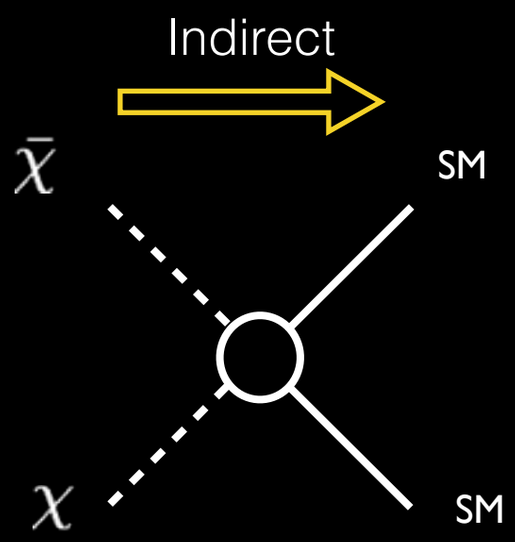
- Global fit of cosmological parameters, ΛCDM:
  → $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$

# DM Detection



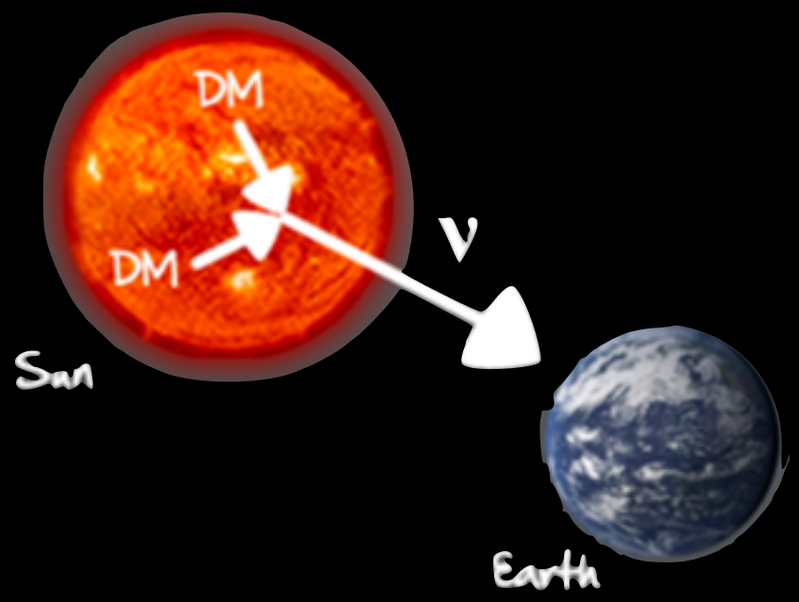
# DM Detection





# DM Detection

- DM annihilates in halo and create cosmic rays (AMS, Pamela)
- Excesses observed (positron high mass, antiproton low mass )
- Not pointing to sources

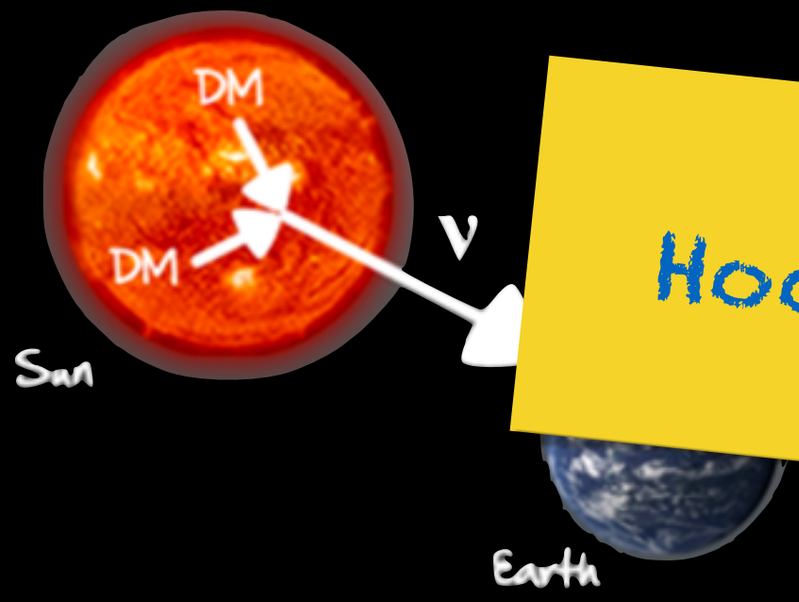



- DM annihilates in sun and creates neutrino detected on Earth (IceCube)
- Sensitivity approaching viable models

- DM annihilates in dwarf galaxies/GC creating continuous or line photon spectrum (Fermi-LAT)
- Interesting excess observed
- Bright future: HESS2, HAWC, CTA, GAMMA- 400…

# DM Detection

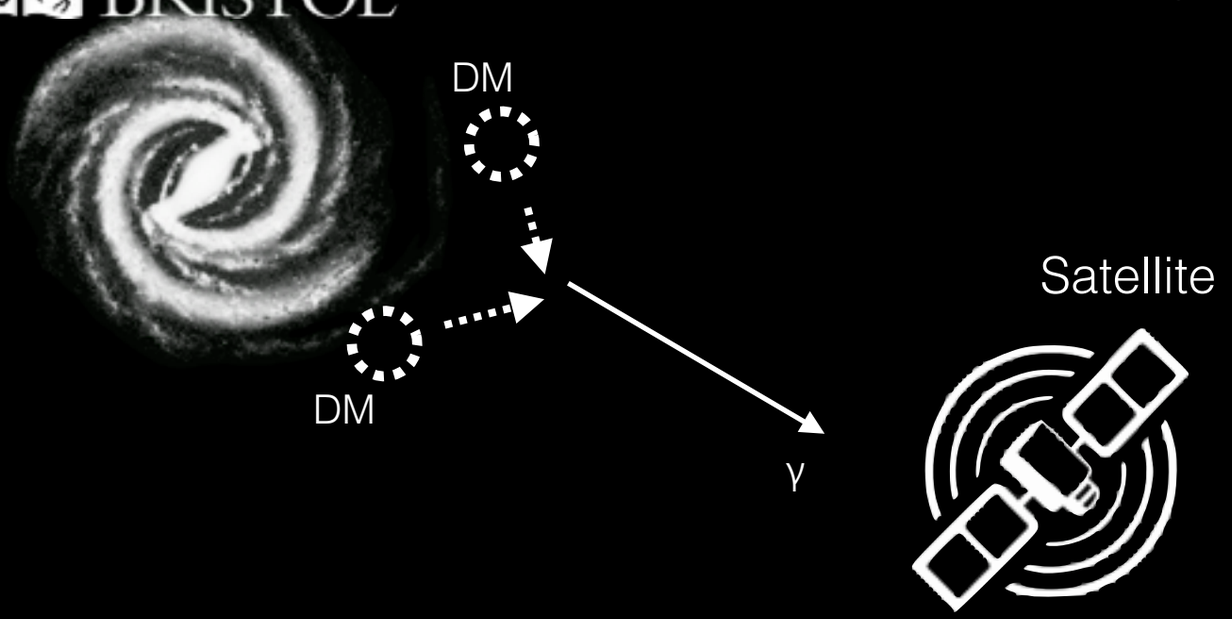
- DM annihilates in halo and create cosmic rays (AMS, Pamela)
- Excesses observed (positron high mass, antiproton low mass )
- Not pointing to sources

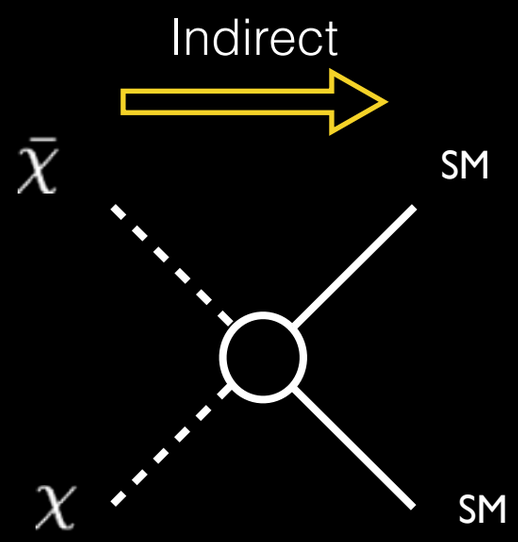



Hooman, Sergio

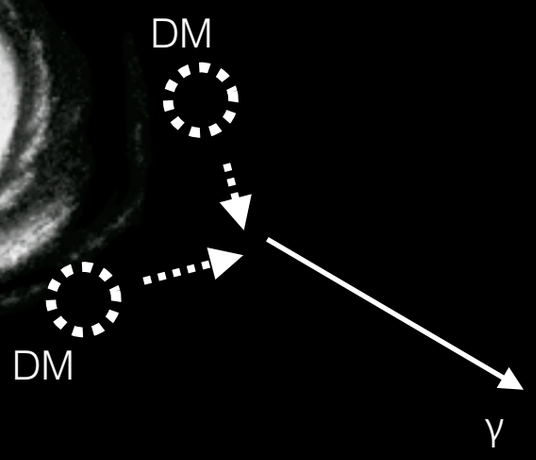
- DM annihilates in dwarf galaxies/GC creating continuous or line photon spectrum (Fermi-LAT)
- Interesting excess observed
- Bright future: HESS2, HAWC, CTA, GAMMA- 400…

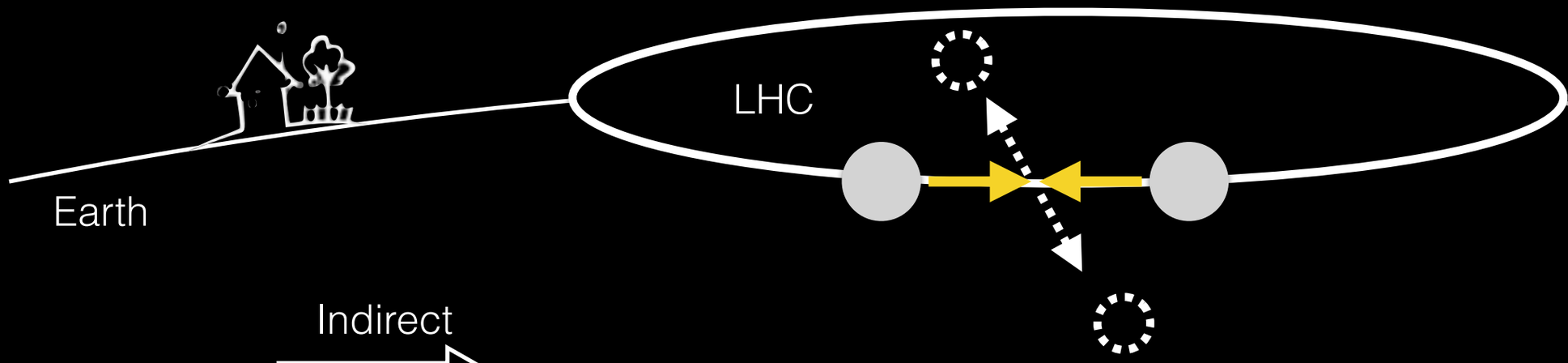
# DM Detection

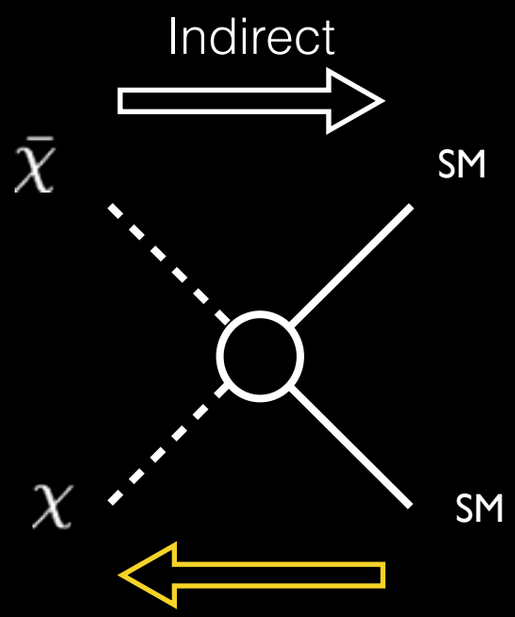




# DM Detection





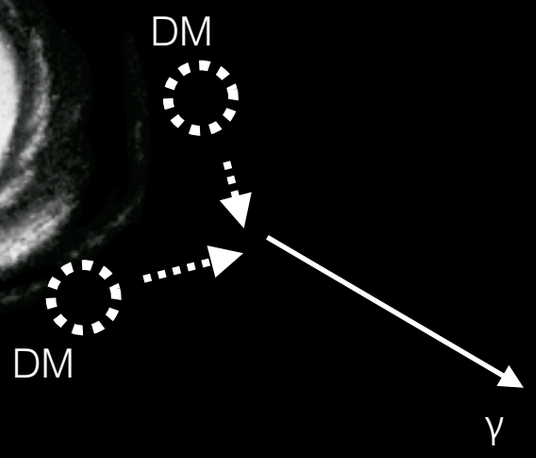
# DM Detection

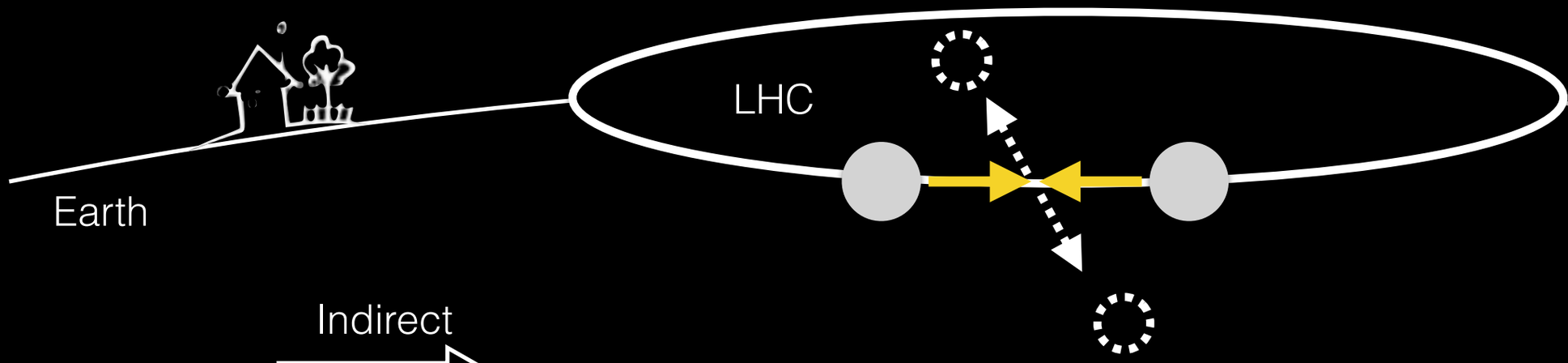
- DM relic density predicts DM candidates accessible at collider experiments
- Only type of experiment possibly can create DM laboratory
- Independent systematic uncertainties and performance compared to other searches
- DM has to be kinematically accessible: ~1-1000GeV

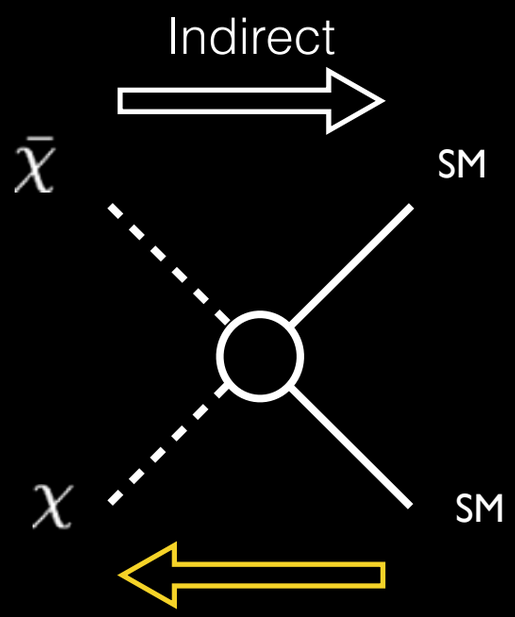
# DM Detection

- DM relic density predicts DM candidates accessible at collider experiments
- Only type of experiment that possibly can create DM in the laboratory
- Independent systematic uncertainties and performance compared to other searches
- DM has to be kinematically accessible: ~1-1000GeV

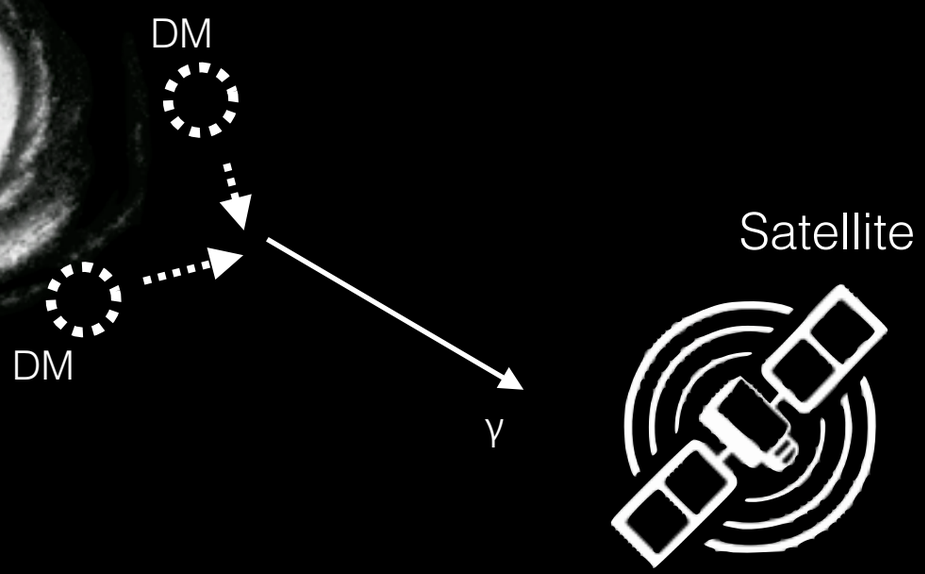
# DM Detection

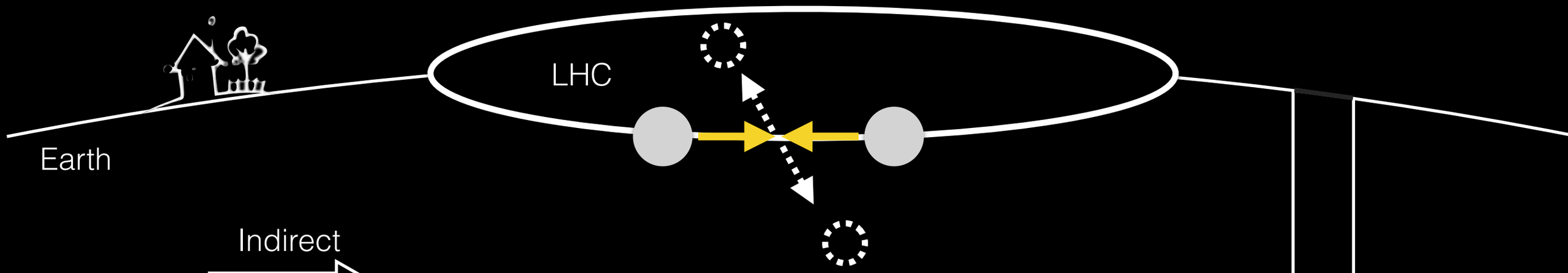


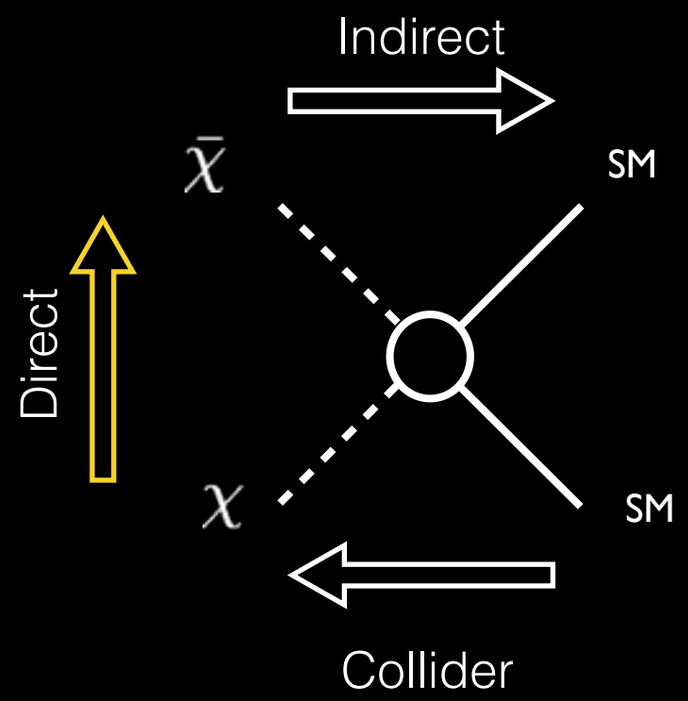


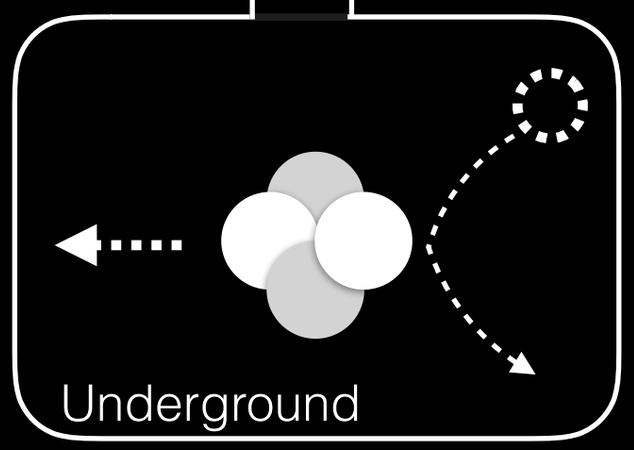



# DM Detection



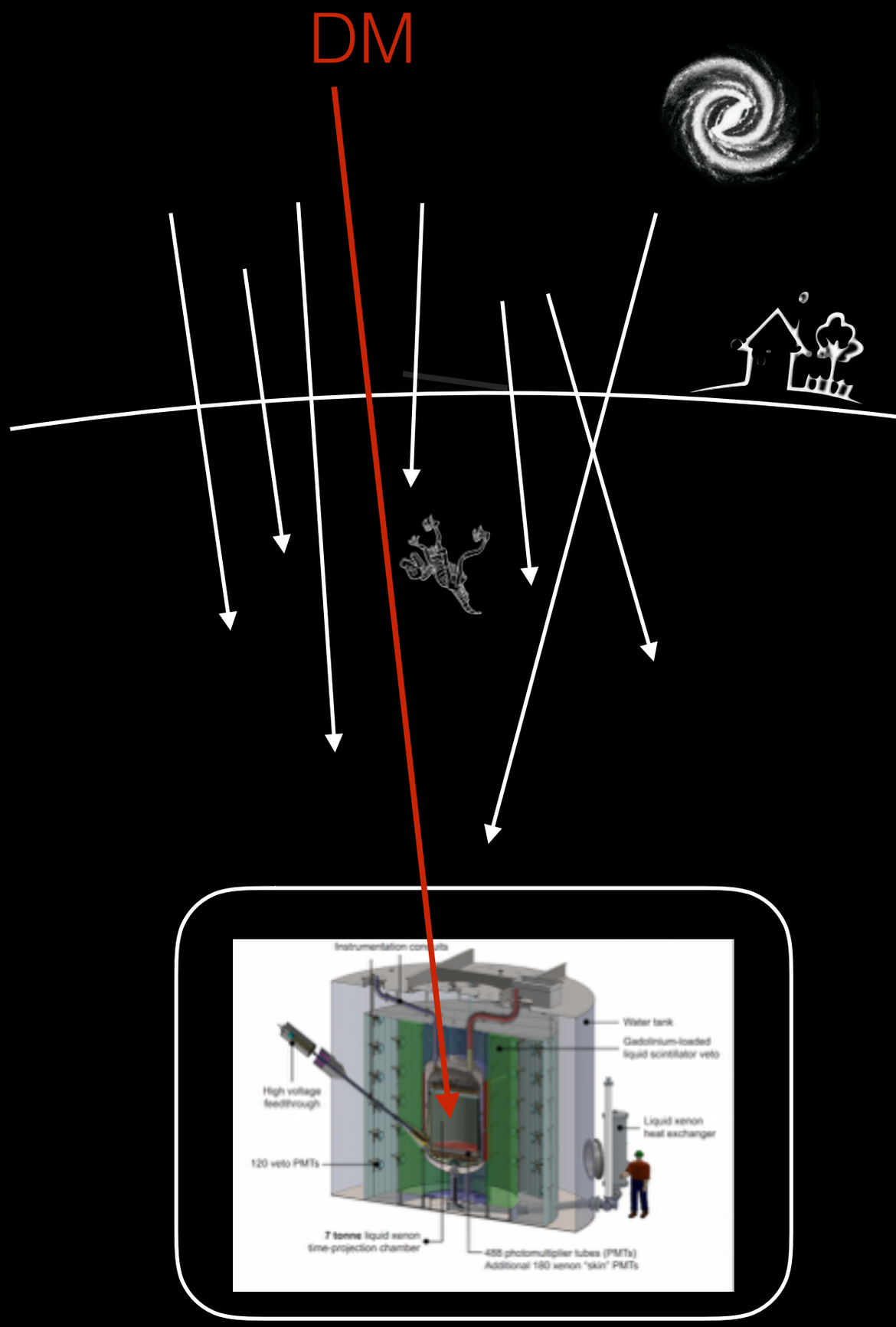



# DM Detection

- Detect DM as our solar system passes through the galactic halo
  - $v \sim 10^{-3}$ c
  - Kinetic energy ~ 100 keV
- Detected by recoils off ultra - sensitive detectors placed deep underground
- Roughly 1 interaction per kg per year
- Very stringent cleanliness and background rejection requirements
- Variety of detection methods and targets



# Direct Detection

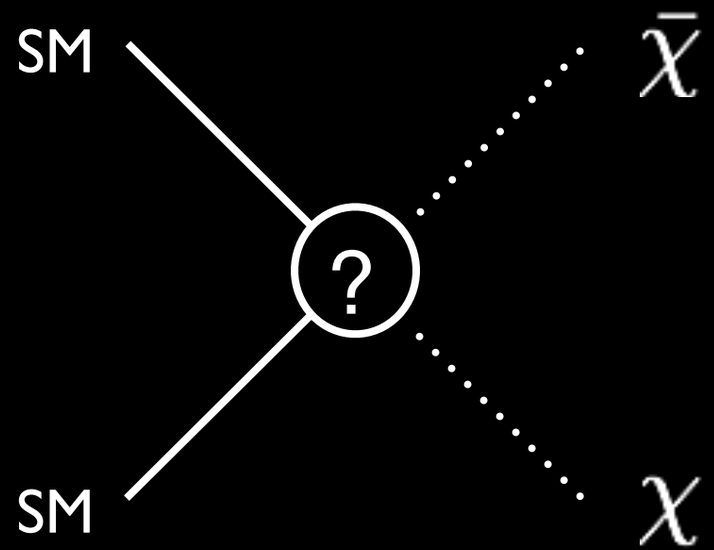
- Momentum transfer crucial,
- Low mass difficult (as opposed to collider)

University of BRISTOL

# How do we connect and learn from all three fields?

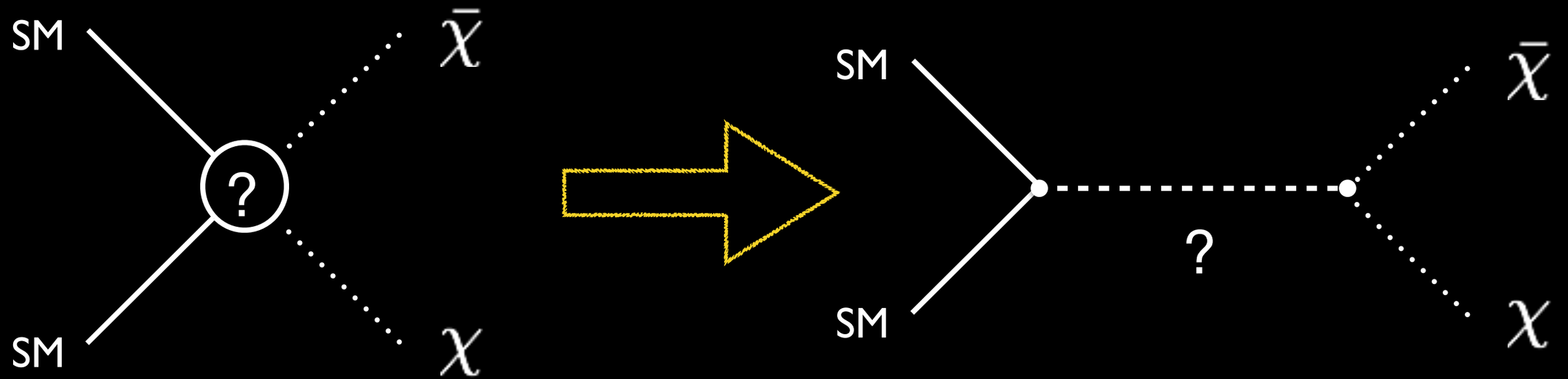
# Parameterizing Dark Matter

- In a real life we need some mediator between the ‘dark World’ and the known Universe



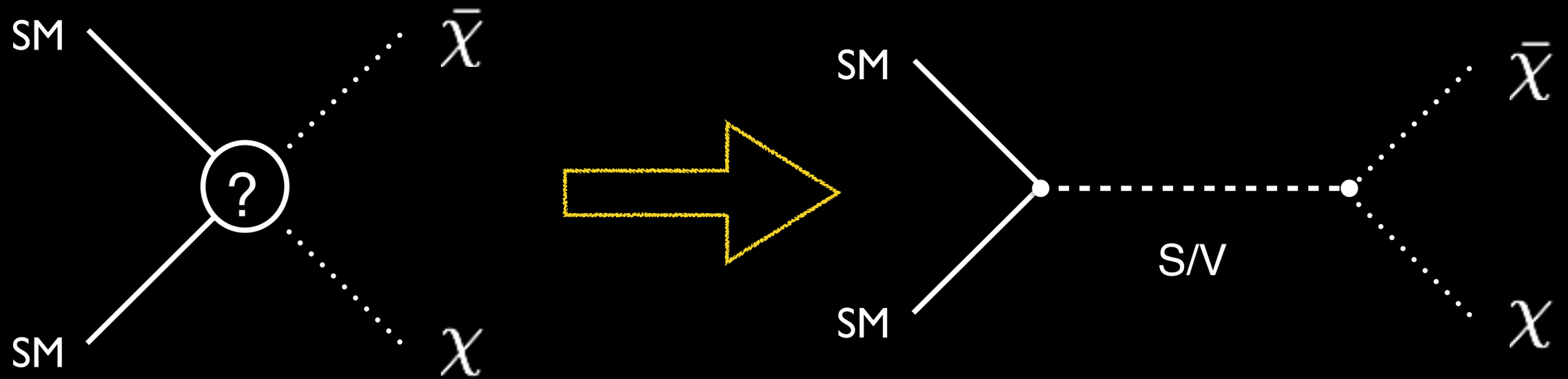
# Parameterizing Dark Matter

- In a real life we need some mediator between the ‘dark World’ and the known Universe



# Parameterizing Dark Matter

- In a real life we need some mediator between the ‘dark World’ and the known Universe




- Leads to known interactions
  - scalar ($\psi\psi$),
  - pseudo scalar ($\bar{\psi}\gamma^5\psi$),
  - vector $\bar{\psi}\gamma^\mu\psi$,
  - axial-vector ($\bar{\psi}\gamma^\mu\gamma^5\psi$)
- Interesting kinematics and experimental sensitivities

# Parameterizing Dark Matter

EWK style (equal to leptons)

## Vector

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

Besides very low DM masses DD wins clearly over collider

## Axial-Vector

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

mass based (Yukawa)

## Scalar

$$g_{\mathrm{DM}} S \bar{\chi} \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

## Pseudo-Scalar

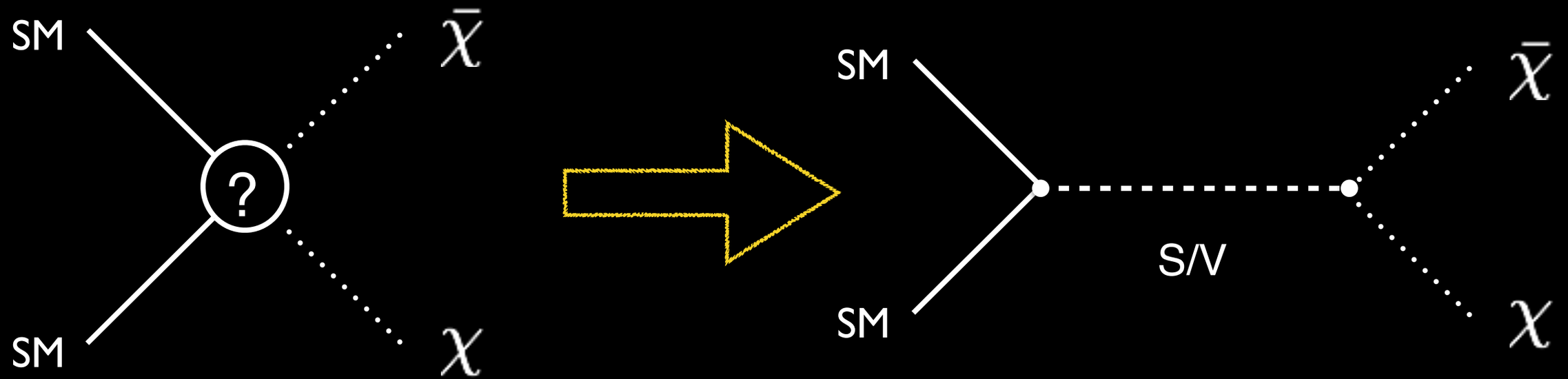
$$g_{\mathrm{DM}} P \bar{\chi} \gamma^5 \chi$$

No limits from DD (only from ID). Collider provides limits similar to scalar couplings

DM can only b discovered by combining these approaches

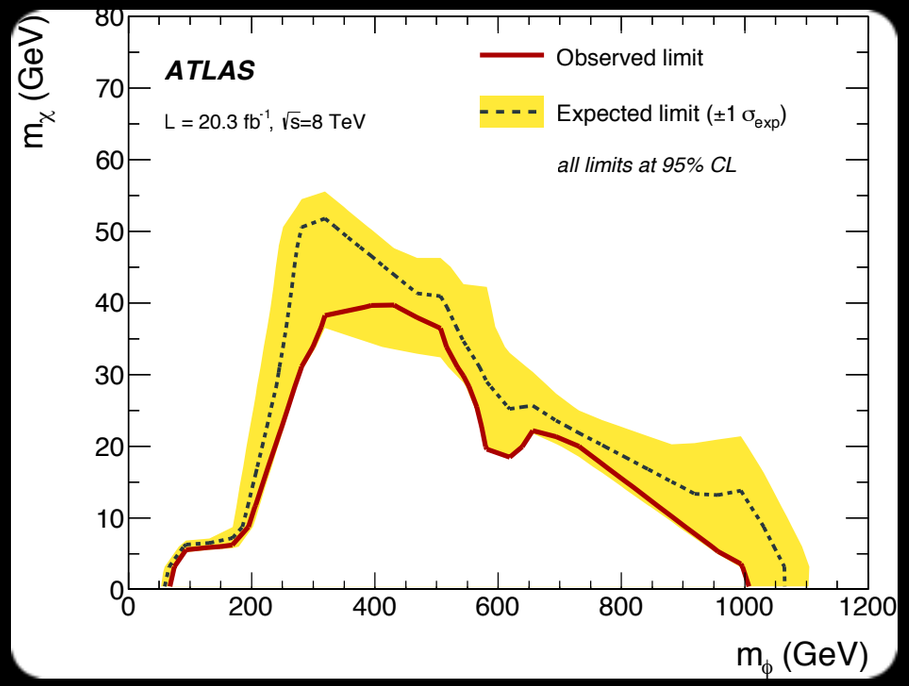
# Parameterizing Dark Matter

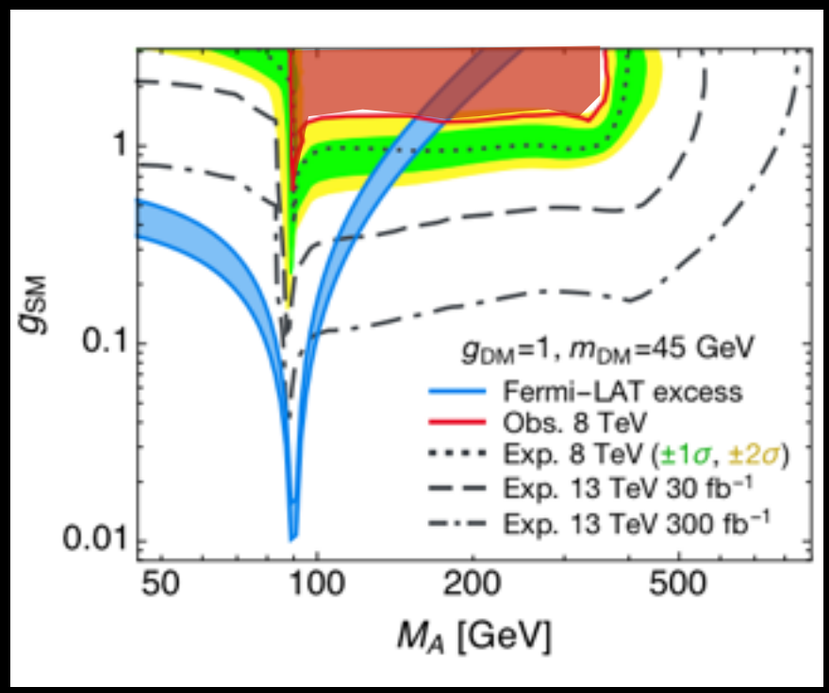
- In a real life we need some mediator between the ‘dark World’ and the known Universe

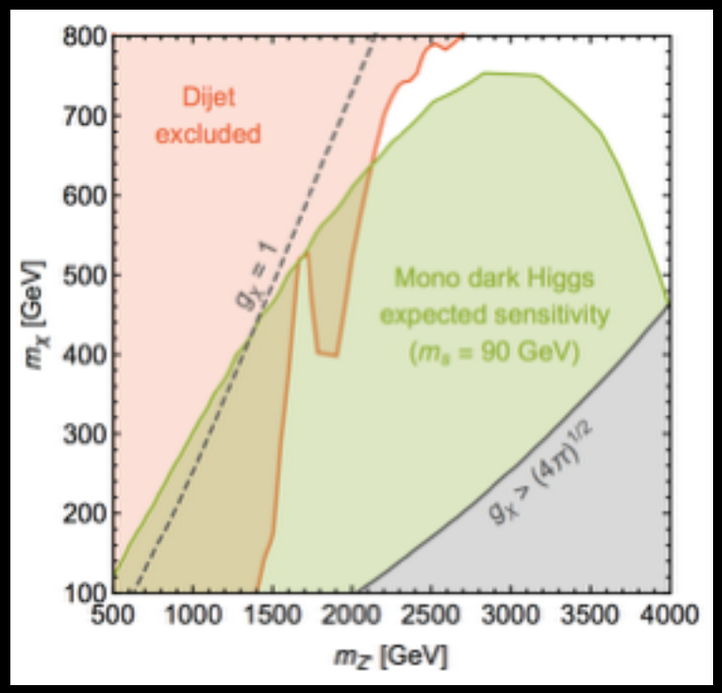



- Discovery of DM will be discovery of two particles
  - dark matter itself
  - the dark mediator
- More appropriate to interpret results in terms of $m_{DM}$ and $m_{Med}$

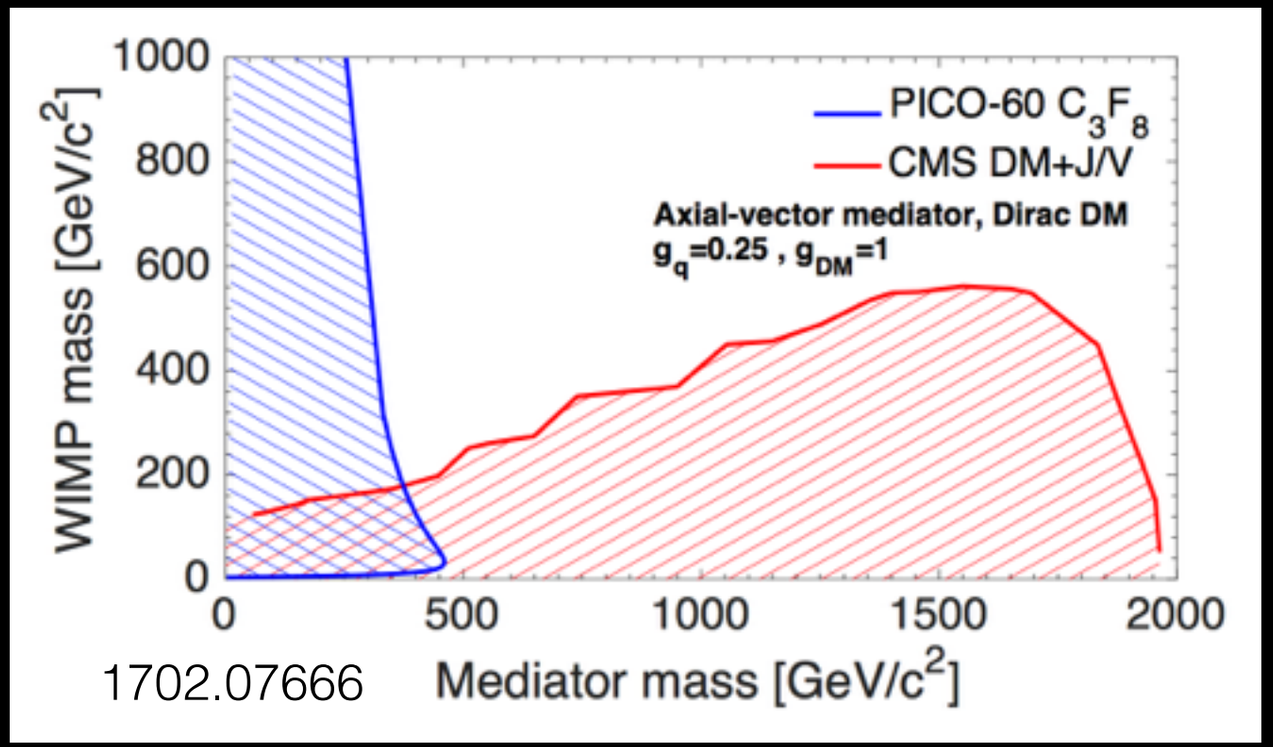
# Interplay



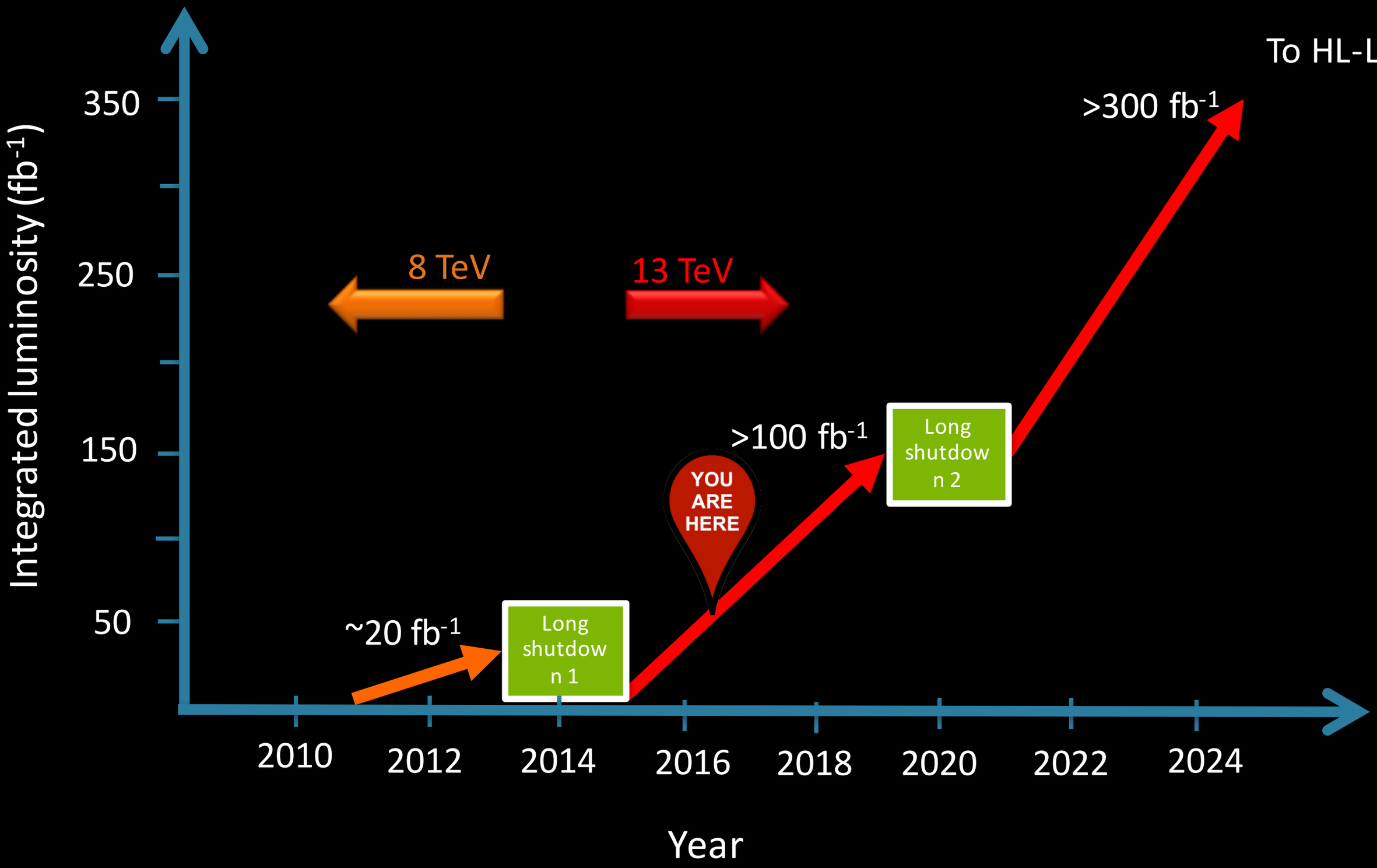

- Continue to provide viable models and identify unexplored phase space
- Provide original ideas across experimental approaches & provide leadership



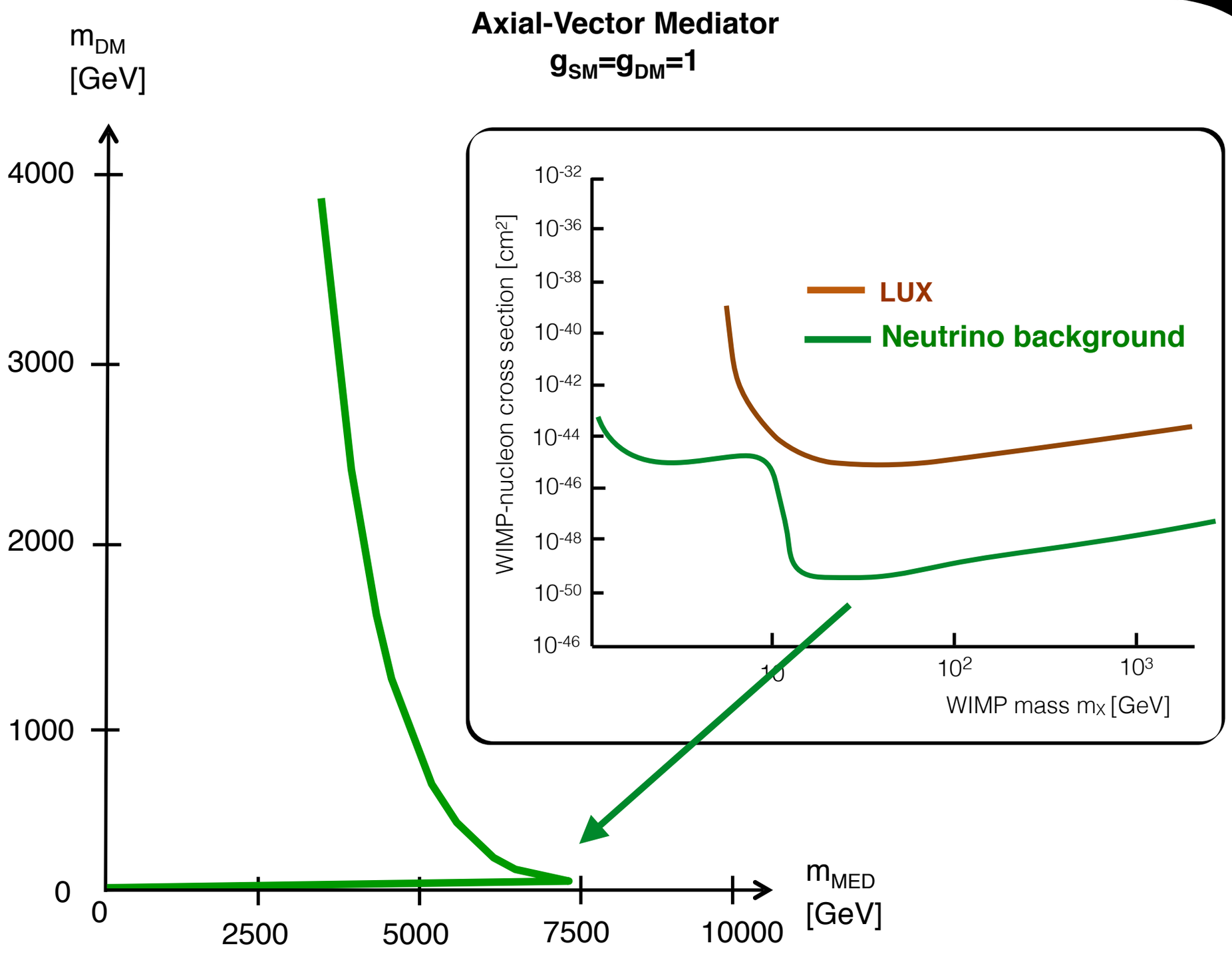
University of BRISTOL

# The (near) future

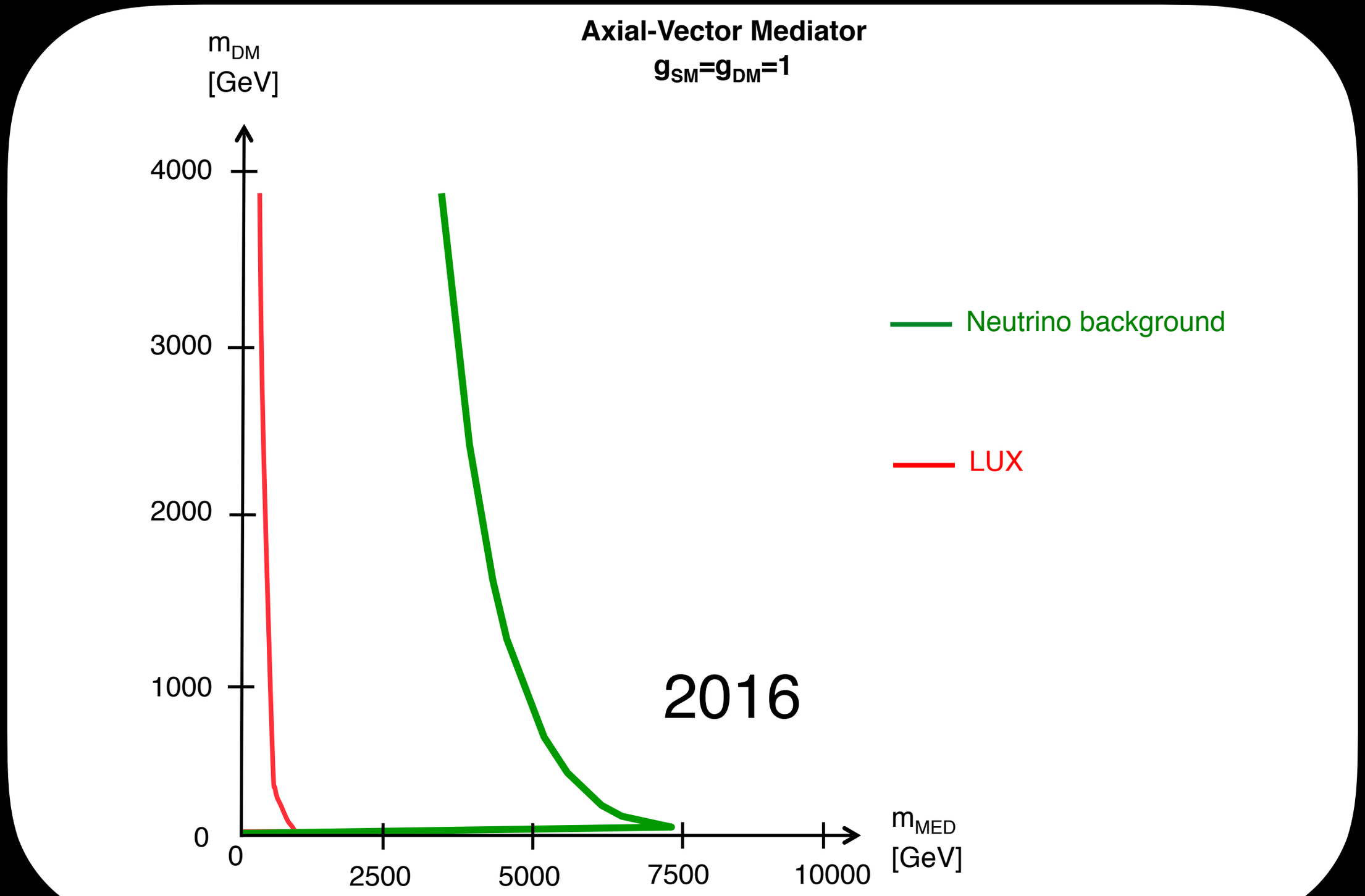
# Outlook


Integrated luminosity (fb-1)
350
250
150
50
8 TeV
13 TeV
To HL-LHC
>300 fb-1
>100 fb-1
~20 fb-1
Long shutdown n 1
Long shutdown n 2
YOU ARE HERE
2010
2012
2014
2016
2018
2020
2022
2024
Year

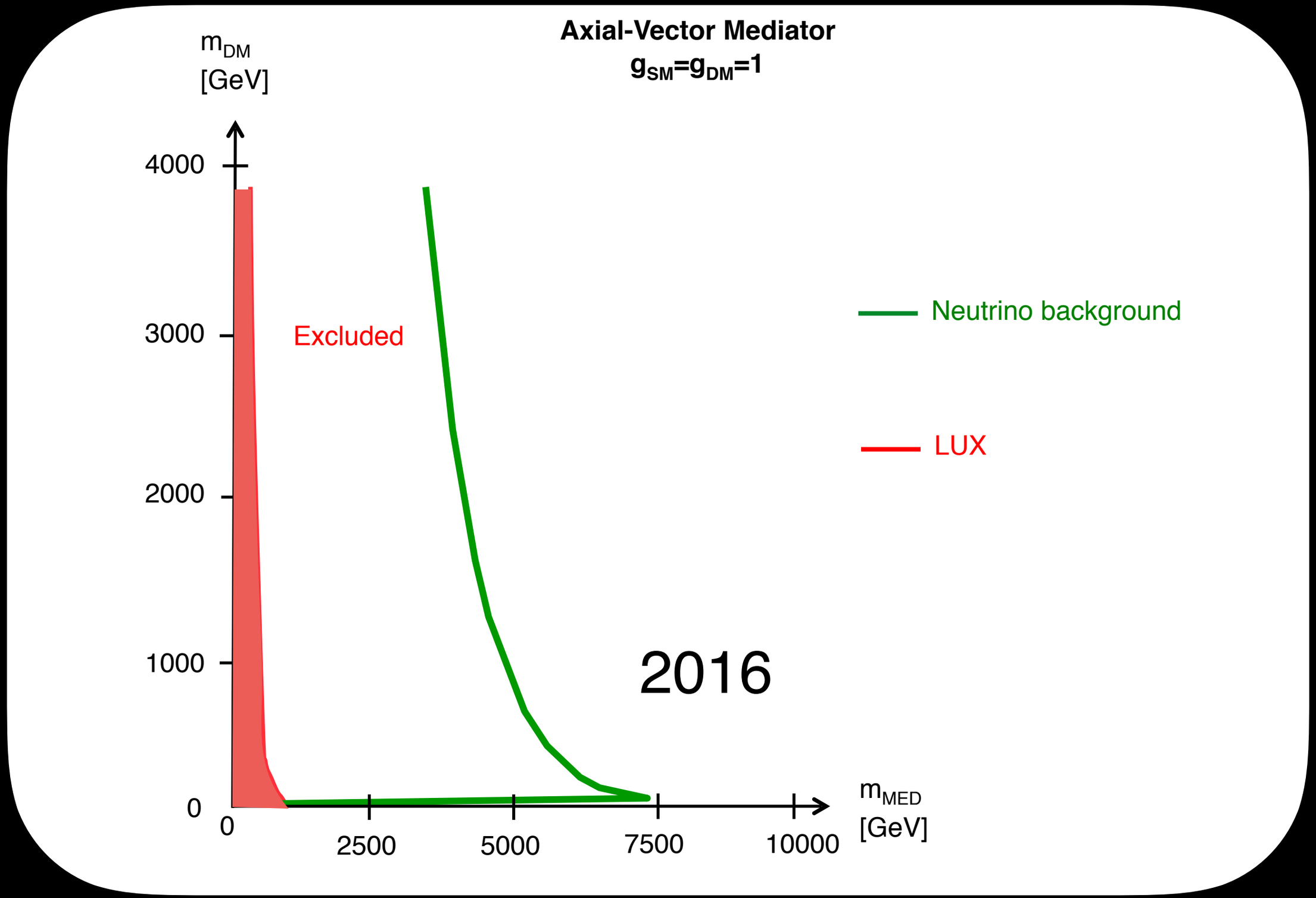
# The Path to Discovery



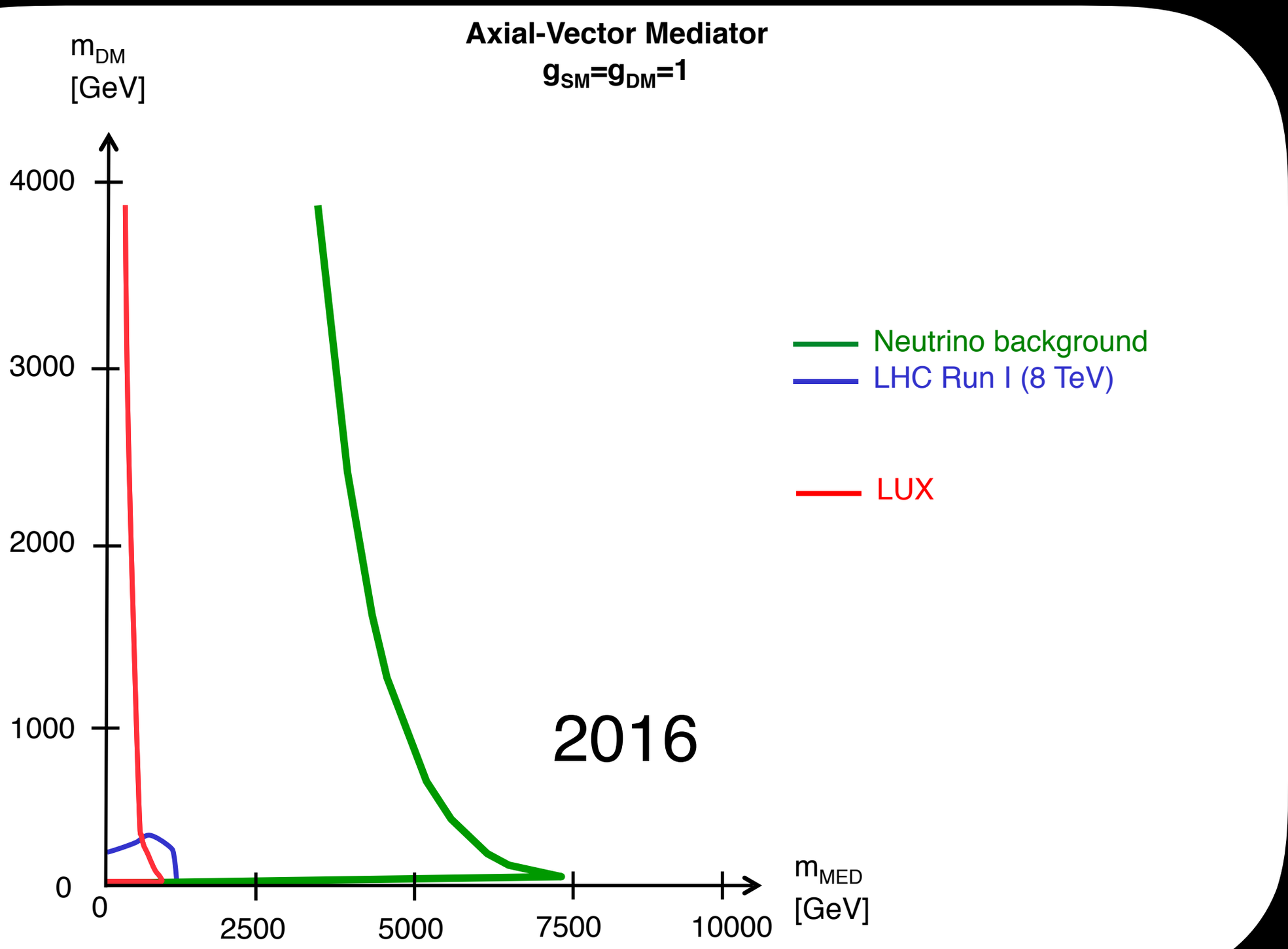
# The Path to Discovery



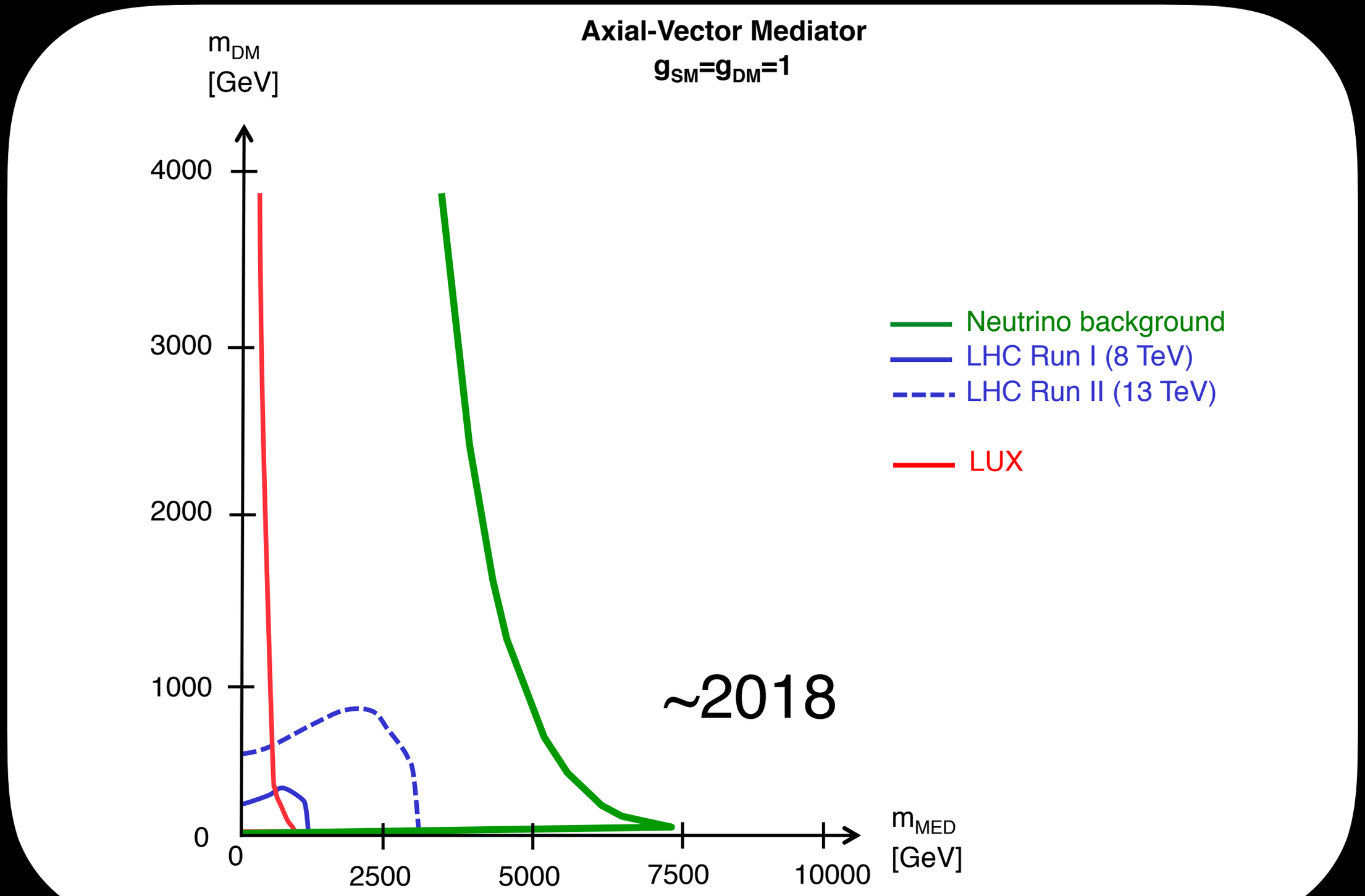
# The Path to Discovery



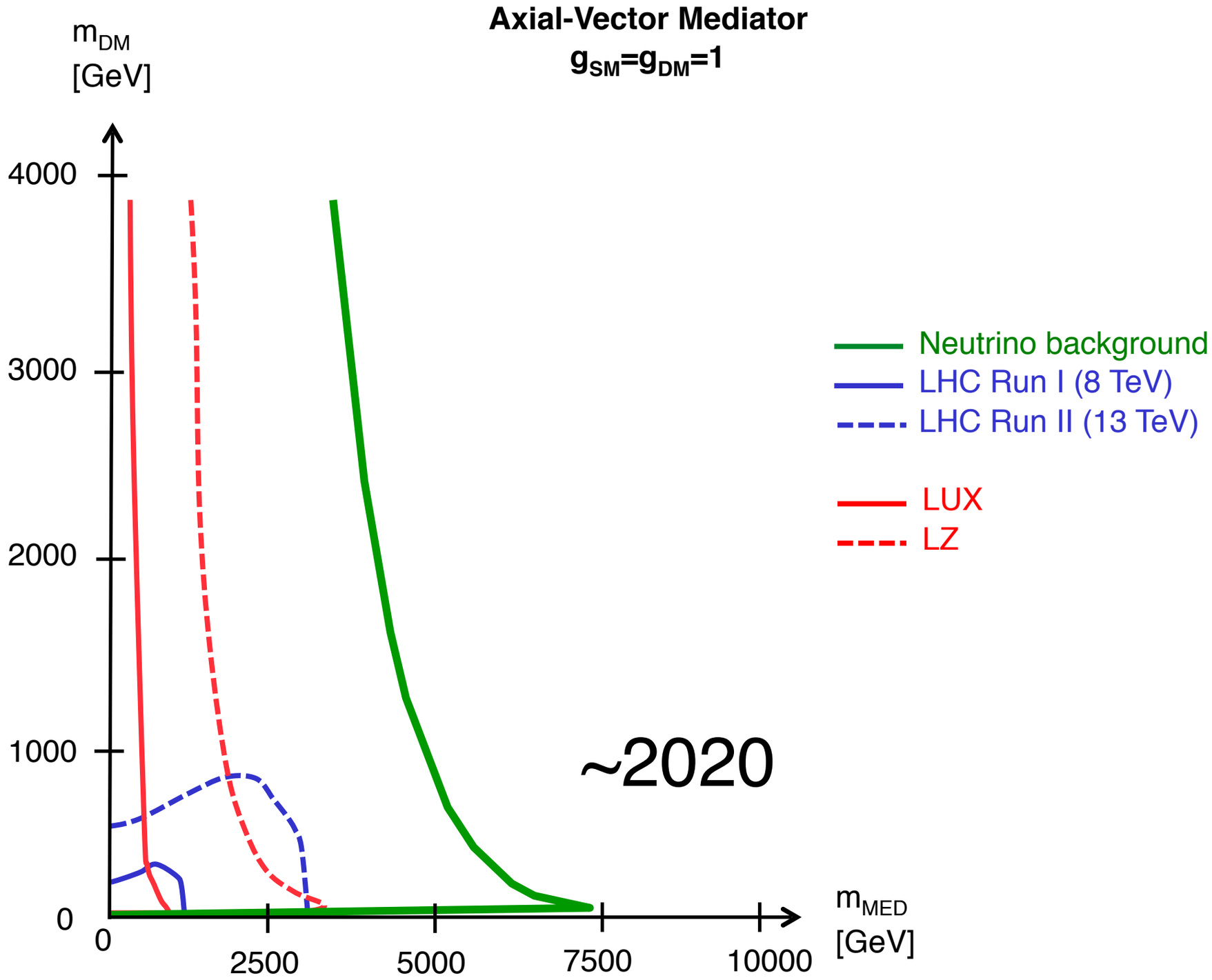
# The Path to Discovery



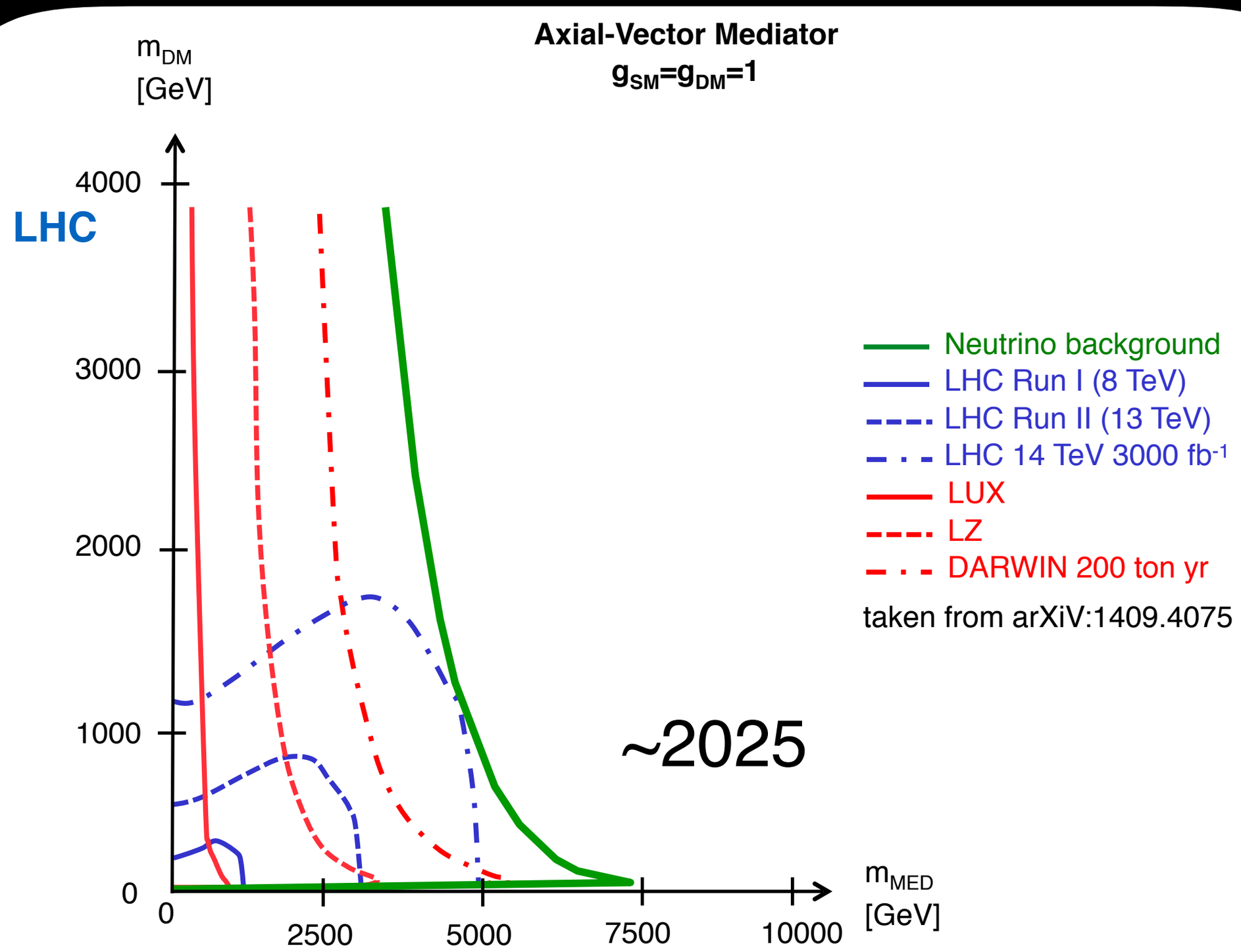
# The Path to Discovery



# The Path to Discovery

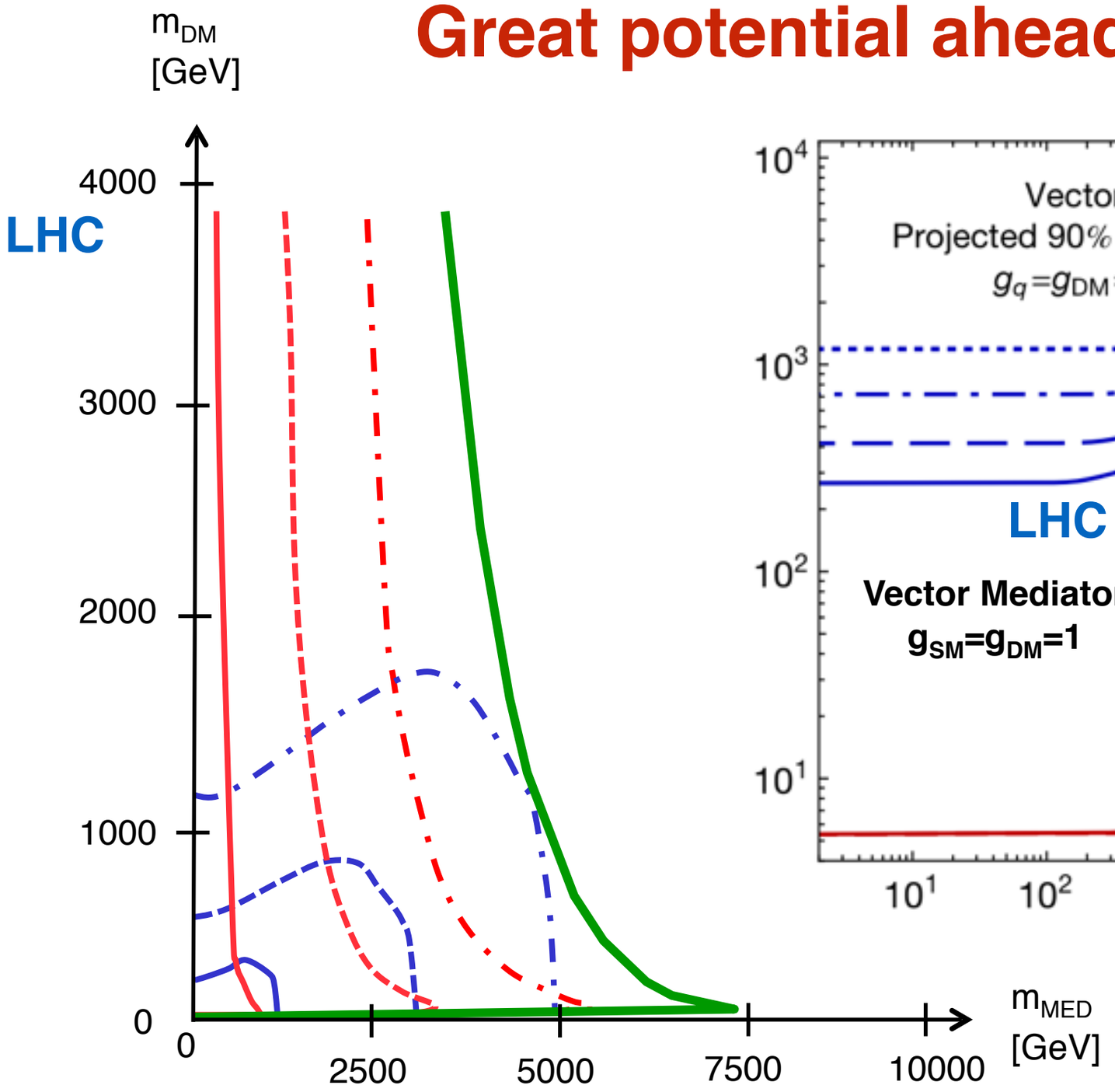


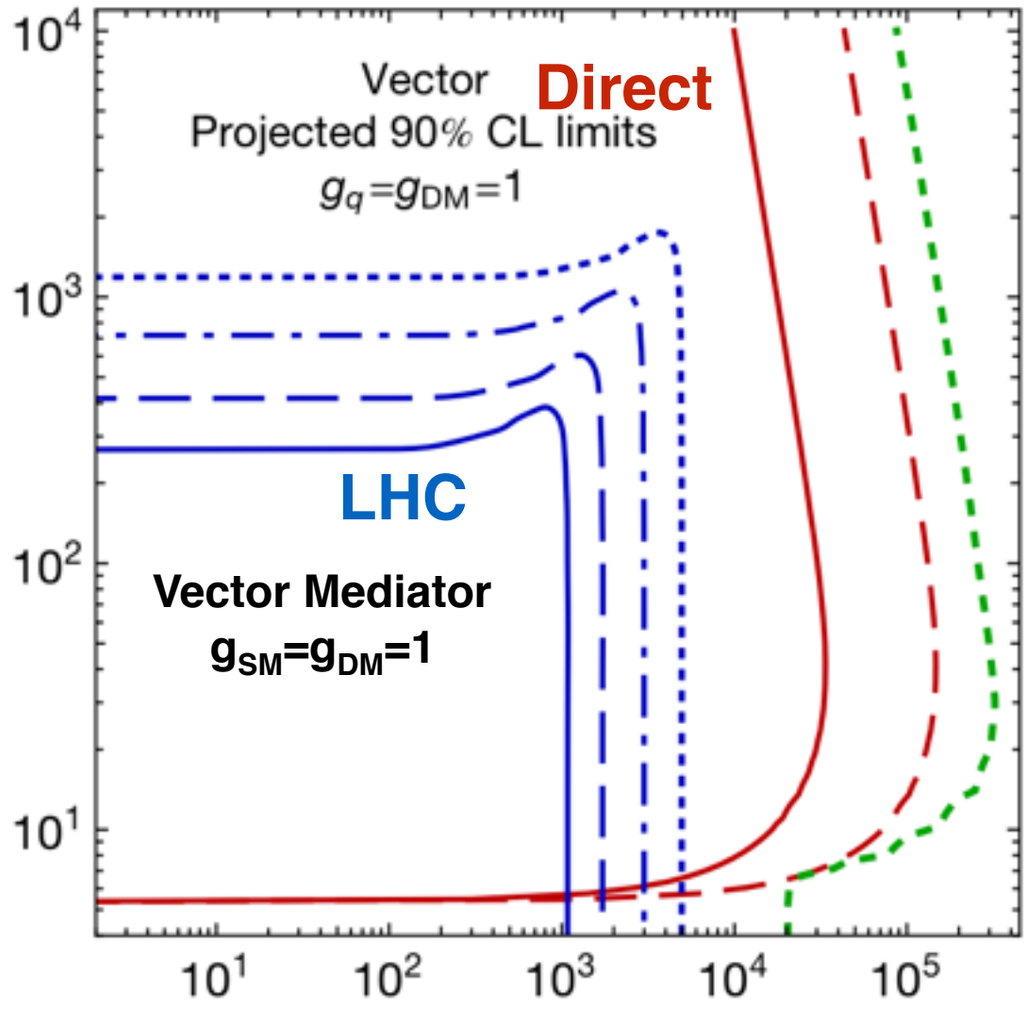
# The Path to Discovery



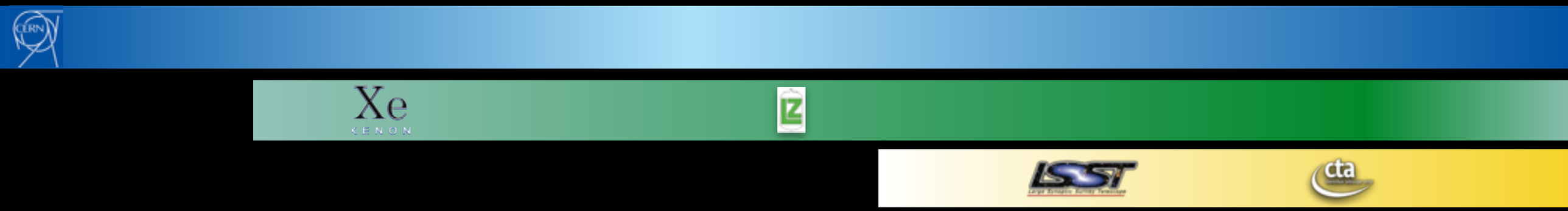
# The Path to Discovery

## Great potential ahead



# Timeline




- Panda-X
- Xenons 1T

- Xenon1T large exposure
- LZ assembly

- LZ starting, XenonNT construction/starting

- 2nd Gen large exposures, towards 3rd Gen

## LHC

- New signatures (boosted objects , scalar DM,VBF). Long lived particles etc

- LHC: Upgrade, Full dataset paper, combinations, towards RunIII

- LHC Run III starts, aiming for HL-LHC

## Astro

- Indirect Searches with AMS, IceCube, DES and Fermi collect further data, yielding greater sensitivity

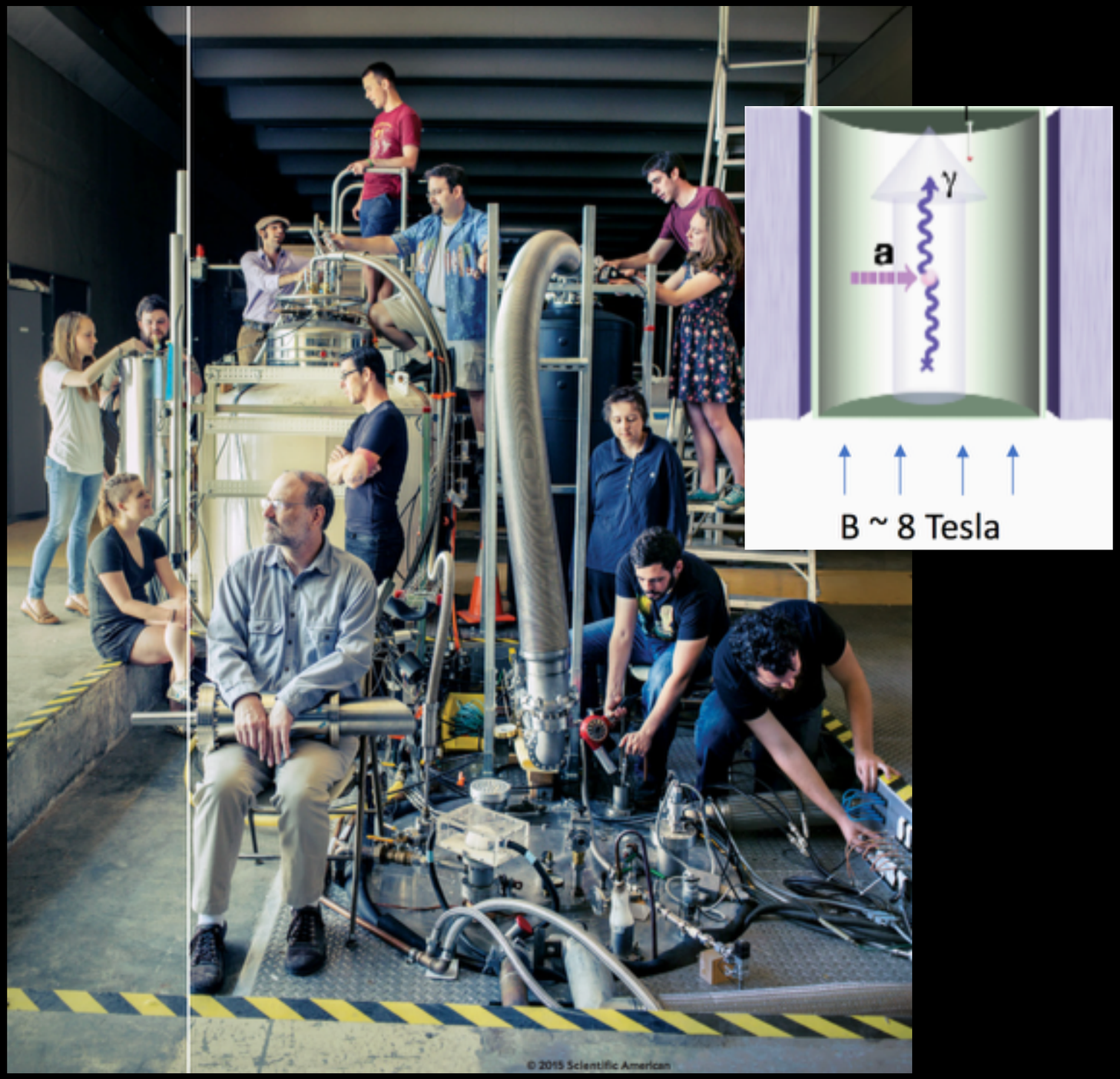
- New dwarf discoveries by LSST, Galactic Center by Fermi, GAIA and other sattelites

- CTA, next gen radio surveys (MeerKAT, SKA)

University of BRISTOL

# Future Ideas in Dark Matter

# ADMX Experiment

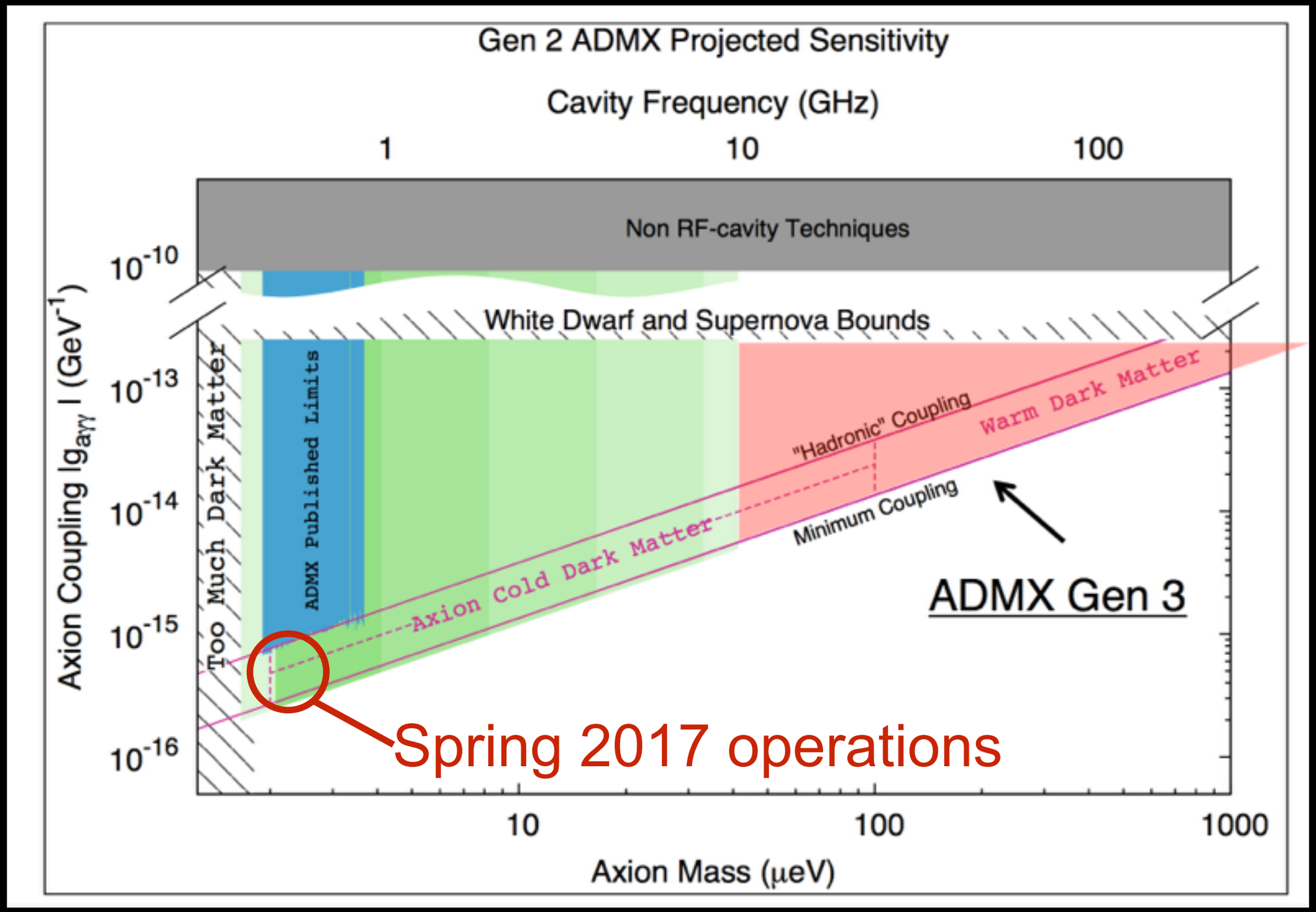






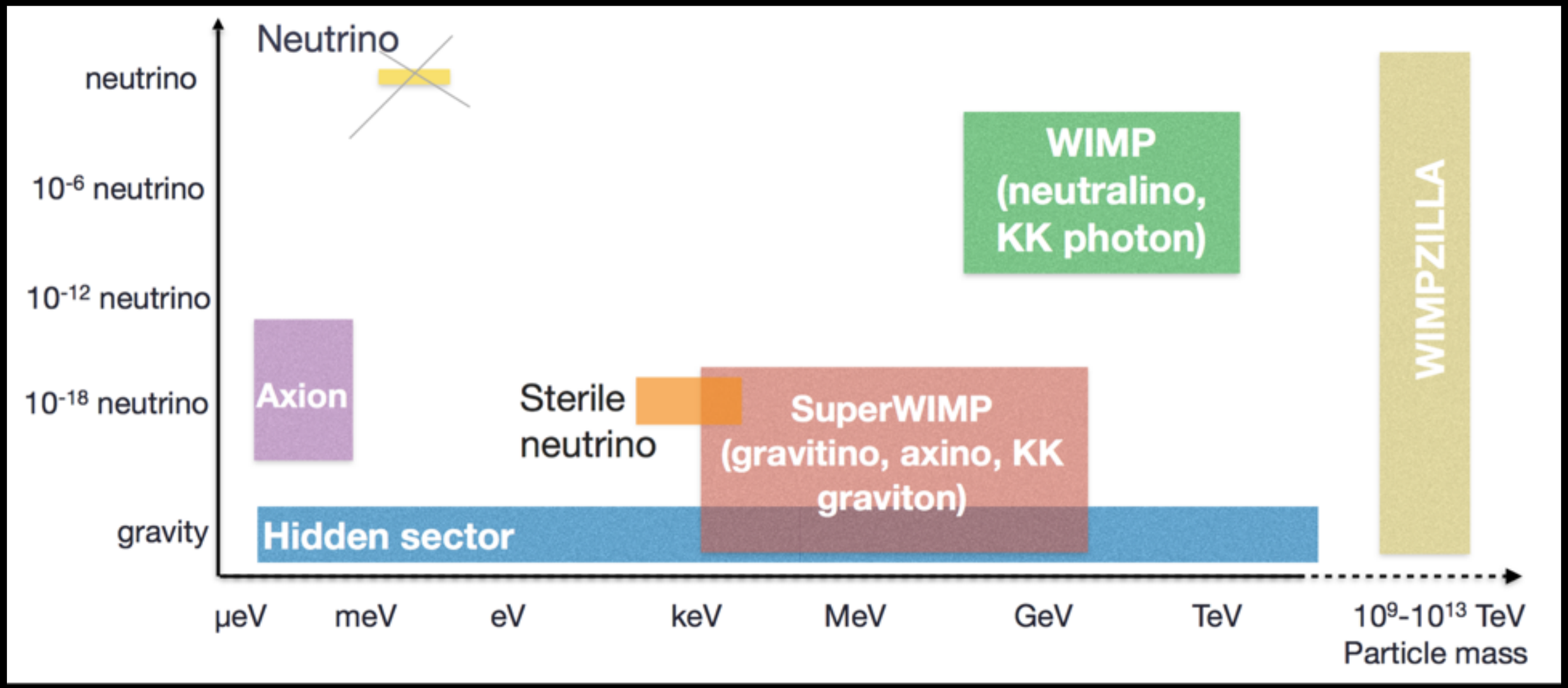
- ADMX - another 2nd gen dark matter experiment
- Axions convert to microwave photons (GHz)
- Targets the entire 1-10 GHz region over 6 years
- If the QCD axion with a mass in that region makes up most of the local dark matter density, ADMX has a very good chance of fining it

# ADMX Experiment



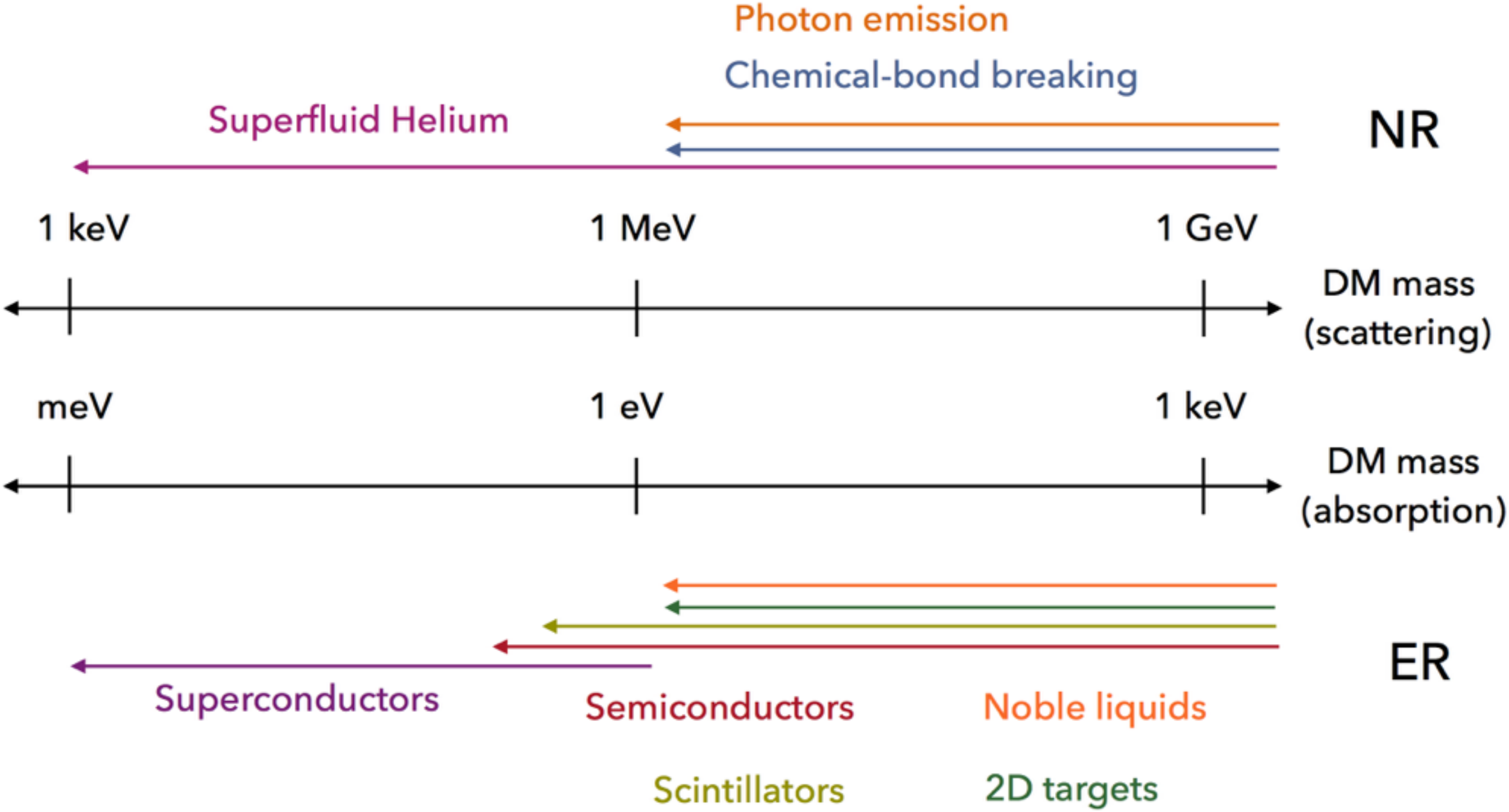

- OPerating at since January 2017
- ADMX G2 will cover much of the plausible axion mass range
- At ~660 MHz and scanning upwards, discovery can happen any day

# Going beyond



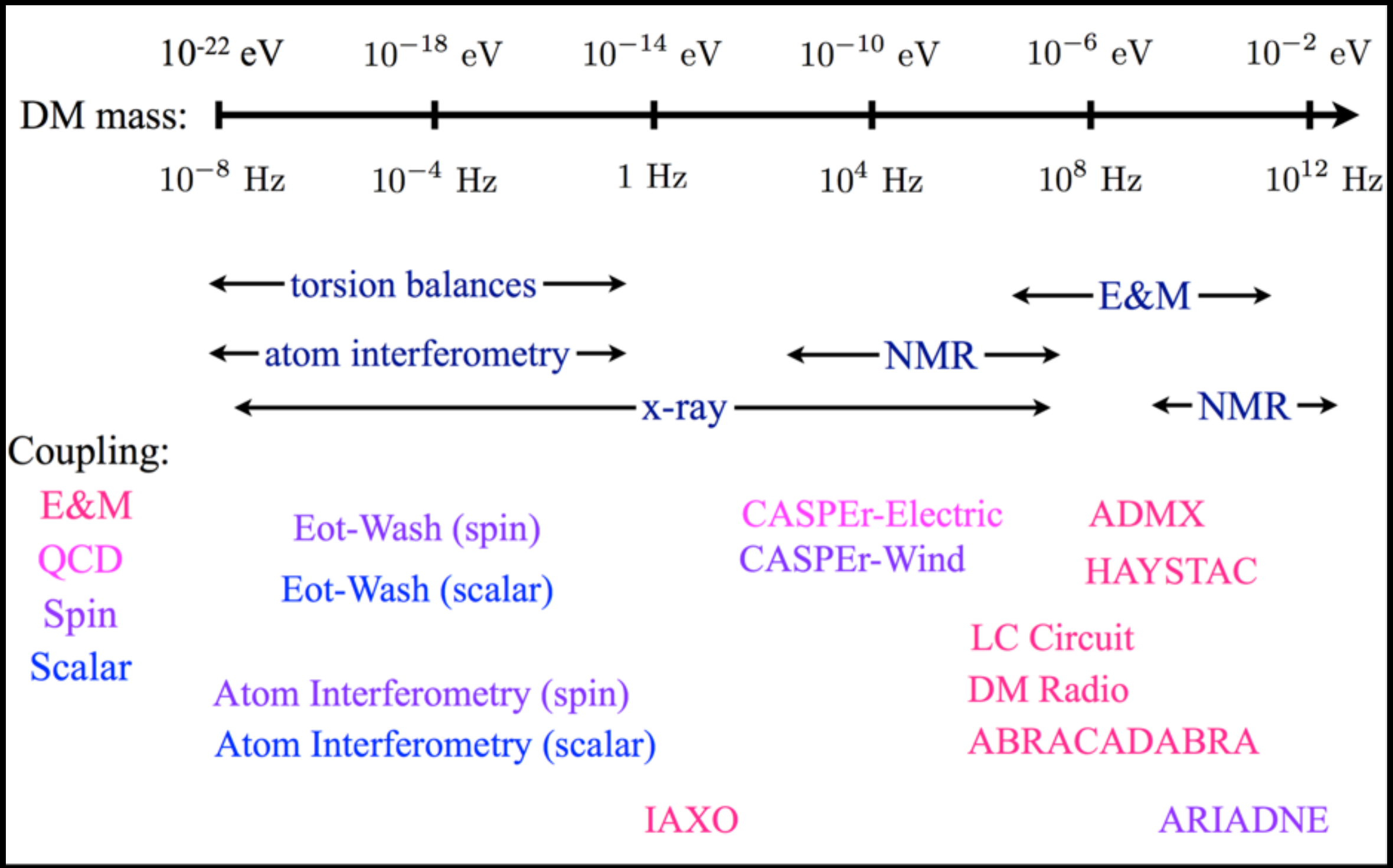

The mass and cross section span many orders of magnitude

# New Ideas for WIMP detection




Explosion of new ideas over last few years

# New Idea for Axion/Dark Photons

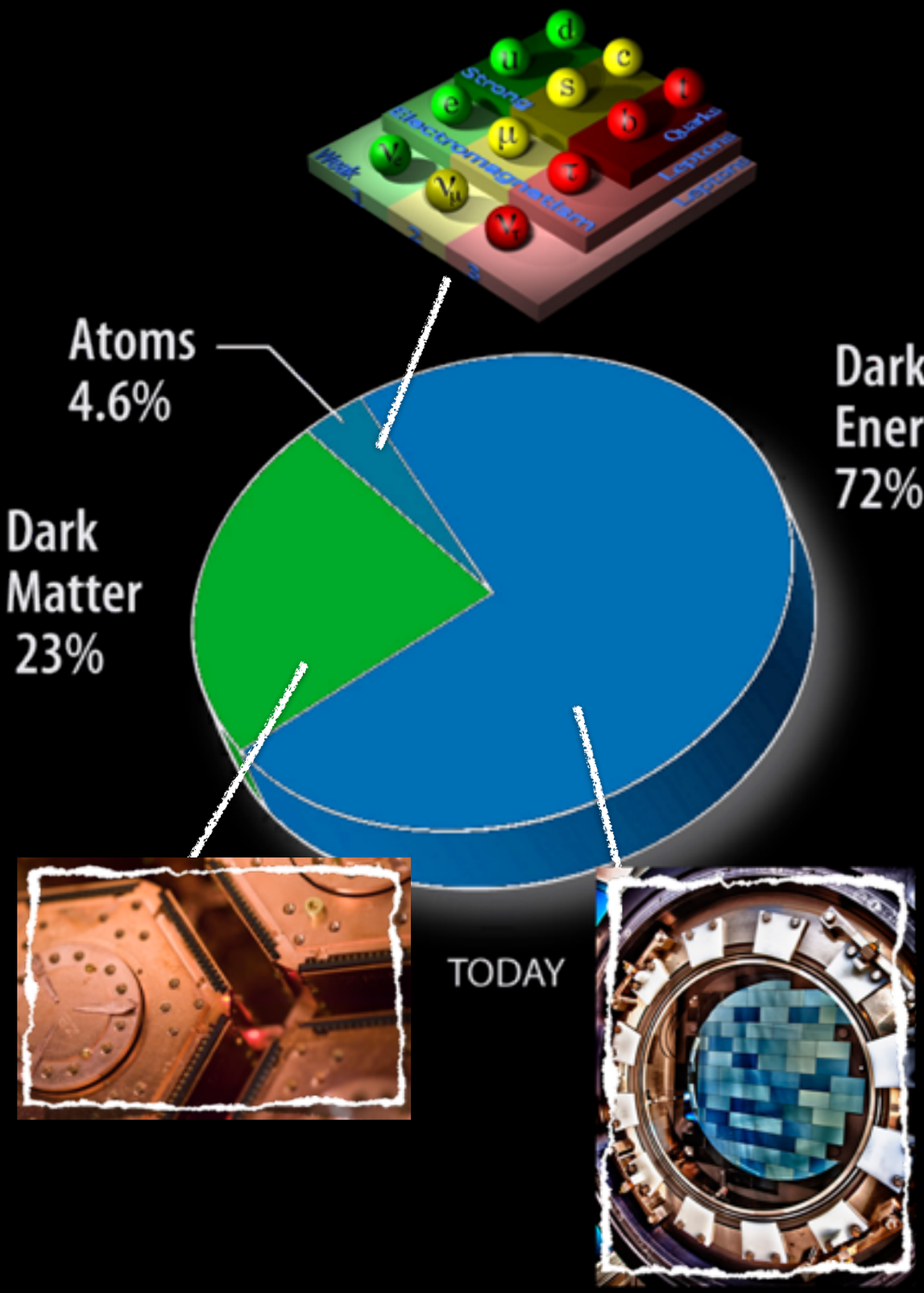


| EXP | target material | readout | science | budget | timescale |
|---|---|---|---|---|---|
| scintillating bubble chambers | Xe, Ar, $C_2F_6$<br>H20 | light<br>heat (bubble) | GeV WIMPS | $200K | 10 kg Xenon 2 yr program to test with coherent scattering CENNS |
| CYGNUS HD-10 | SF6<br>4He | charge cloud tomography, directional sensitivity | GeV WIMPS | R&D $250k<br>1 m3 ~ $450k<br>10 m3 ~ $3M | R&D 1 yr<br>1 m3 : 2yr<br>10 m3: 2ry |
| DAMIC | Si | charge | GeV WIMPS | $3M | start 2019-2020 the construction<br>R&D going now |
| news-G | H. He | charge | GeV WIMPS | | installing 140 cm sphere at SNOLAB in 2018 |
| liquid xenon TPC | Xe | charge only | sub-GeV DM - ER | $3M | 1 yr design<br>1 yr deploy 10kg @surf<br>1 yr commision and run |
| SENSEI | Si | charge | sub-GeV DM - ER | $1.2M | 2 yrs to build the 100g experiment starting (could start now) |
| Dopped germanium with internal amplification | Ge semiconductor | charge 0.1 eV (nuclear) | sub-GeV DM - ER | R&D 600k<br>10 kg —> 1.5M<br>100kg —> 10M | R&D +3yr |
| 2d graphere<br>Ptolomey-G3 | graphene cube | charge(G-FET)<br>(300 B channel count @ 1 kHz | sub-GeV DM - ER | $200k needed for wafer fab for demonstrator (1e4 cm2) | 1 yr fab 1 yr data<br>ready for the "generation 1" |
| single photon detector with TES readout | GaAs(Si) | light | sub-GeV DM - ER | R&D 200k<br>project 600k | R&D 1eV thr<br>the project would on on SuperCDMS 2020 |
| NaI/ScI cooled crystals | NaI/ScI | light | sub-GeV DM - ER | R&D - $250k<br>projecy $100k | R&D - 3 yr<br>project 2020 w/TES |
| superconducting AL cube | Al superconductor | TES<br><br>meV energy resolution. | sub-GeV DM - ER | | +10 yr science program |
| LHe detector | He | phonon | sub-GeV DM - NR | 3M | 2018 R&D<br>2020 final design<br>2022 start data taking |
| field ionization helium | He | phonon | sub-GeV DM - NR | R&D $725k | R&D 3 years |
| color centers | crystals (example: CaF) | light | sub-GeV DM - NR | | R&D going on now |
| bubble chambers<br>PICO | wide range of target nuclei. This is what makes then unique. | heat (bubbles) | spin dependent | lowest cost per ton of any target mass<br>pico-500 - ~$3M | just finished pico-60<br>pico40L in Fy17 (funded)<br>pico 500 coming |
| emulsions (news-dm) | high position resolutions nuclear emulsions (silver bromide crystals + I C O N H S) | imaging with optical microscopes, and validation of candidates with X-ray microscope | beat neutrino floor | — | R&D phase complete.<br>Technical test to confirm negligible background running now. |

Preliminary

# Summary

- DM is out there and will transform our understanding of the universe
- LHC is running, DD, and indirect detection are improving rapidly – the field is being transformed now
- DM has to be discovered in several fields to be confirmed and measured
- Not necessarily imply vanilla dark matter: SuperWIMPs, WIMPless DM may be warm,….
- In the best of all worlds: Multiple discoveries (direct detection, the LHC, indirect detection) & constraints of the DM properties & DM astronomy
- If no discovery: “ultimate” WIMP DM detectors might at least be able to disprove the WIMP hypotheses (still valuable)
- Plethora of new ideas and experiments



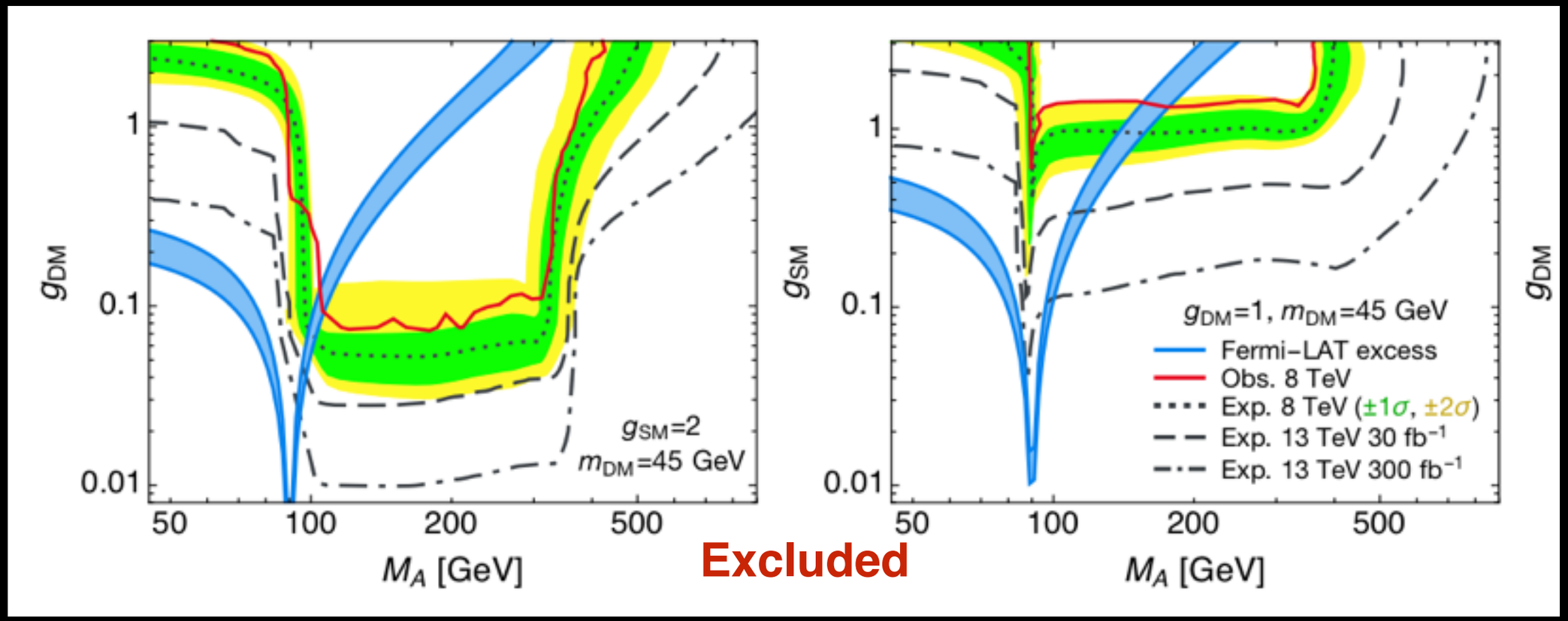
University of BRISTOL

# Backup

# E.g.: Constraining Fermi-LAT

arXiv:1505.07826

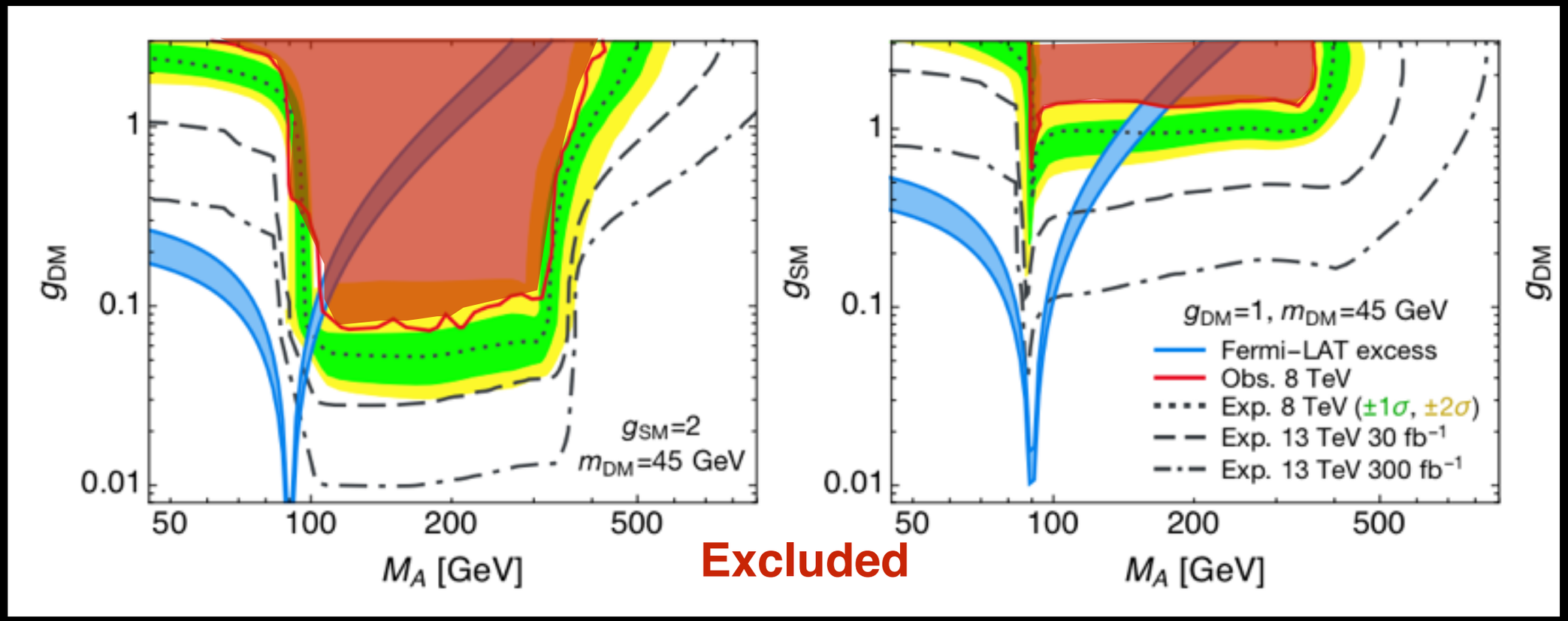
- Testing Fermi-LAT excess and inclusive analyses using collider data
- Inclusive search has significantly better expected sensitivity



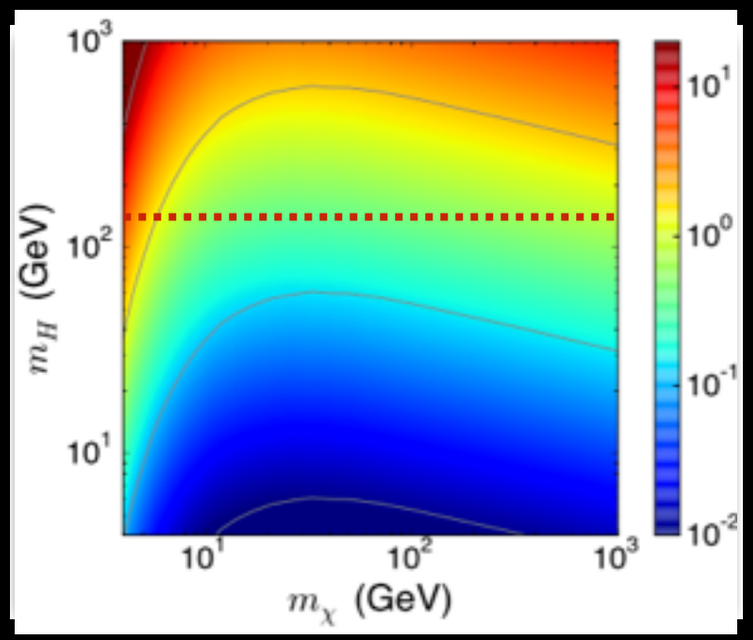
# E.g.: Constraining Fermi-LAT

arXiv:1505.07826

- Testing Fermi-LAT excess and inclusive analyses using collider data
- Inclusive search has significantly better expected sensitivity
- Excluding already part of the phase space
- More 13 TeV data will be very exciting

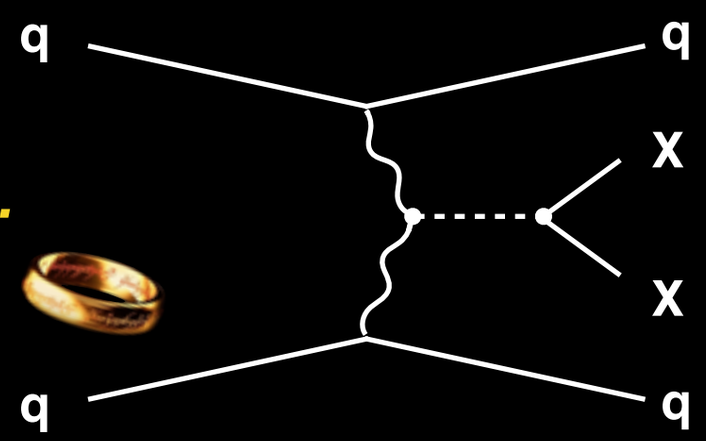


# Interplay

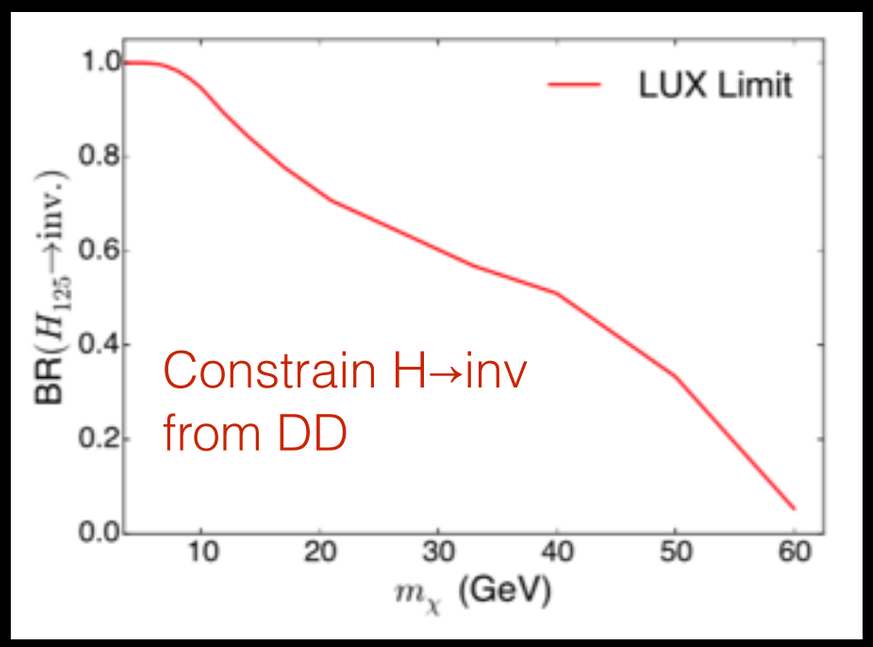



Derive constraints from astrophysical measurements

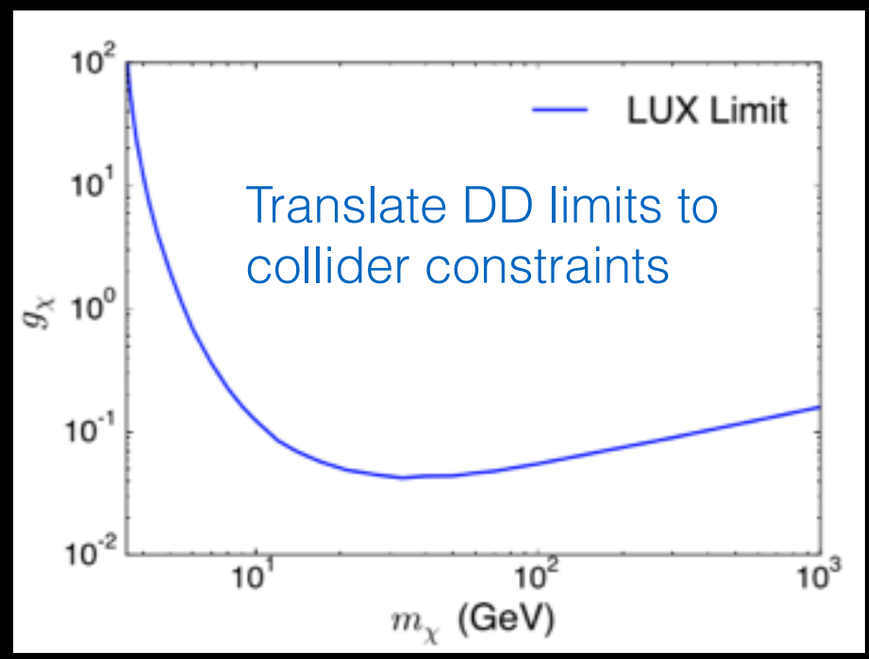
*One model…*




*… to rule them all.*

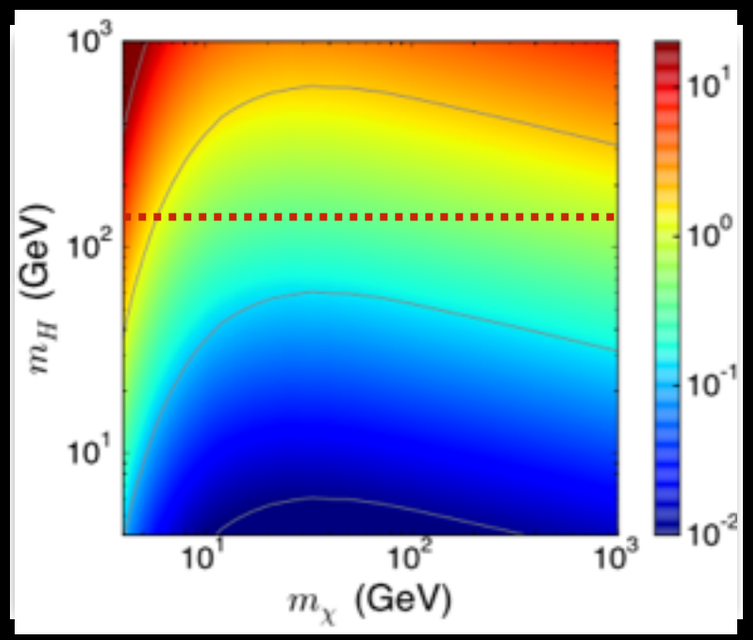



Constrain H→inv from DD



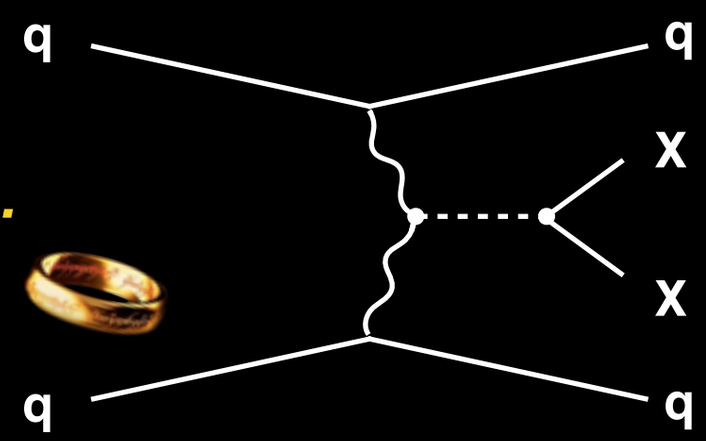

Translate DD limits to collider constraints

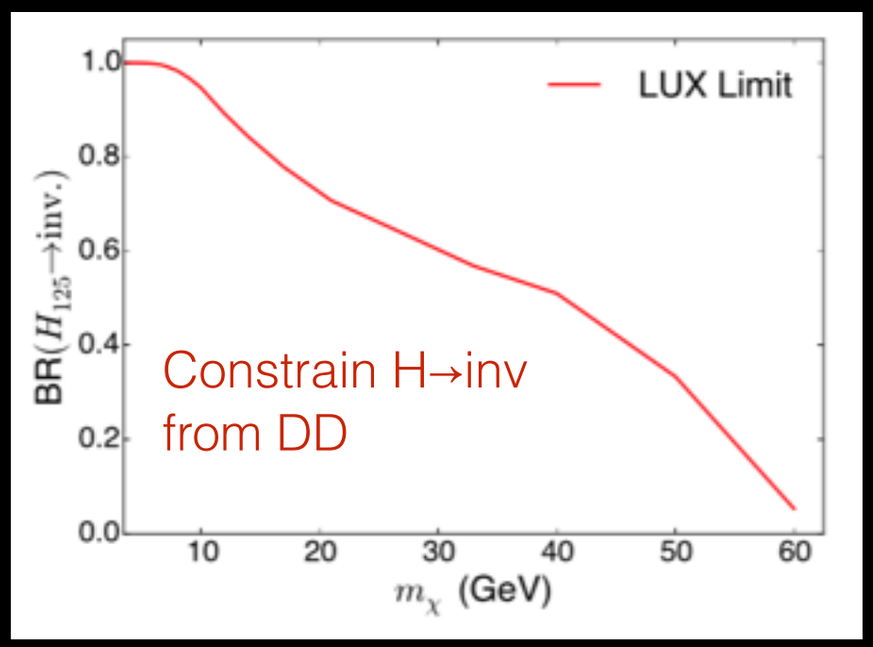
# Interplay




Derive constraints from astrophysical measurements

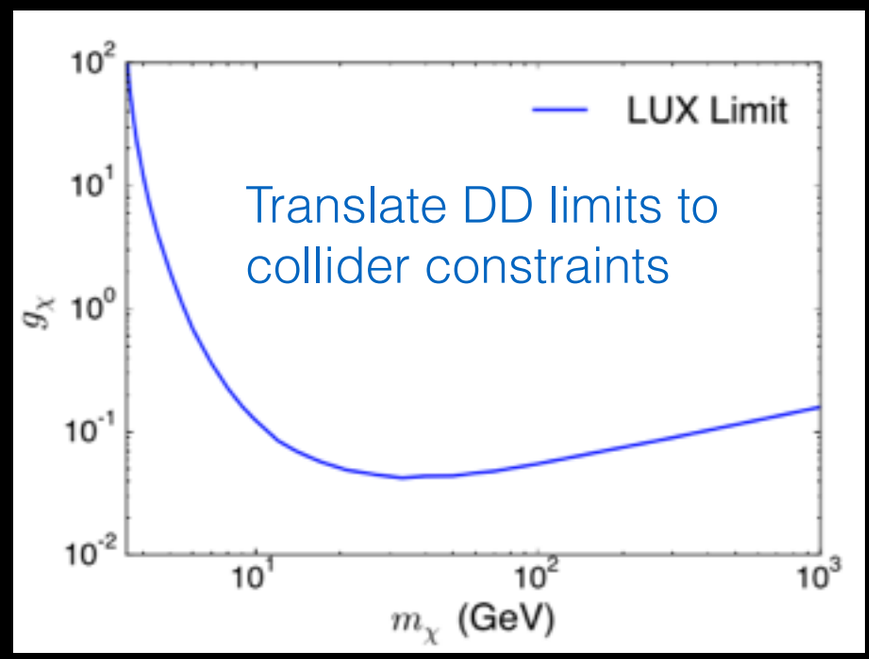
*One model…*  *to rule them all.*




Constrain H→inv from DD

These connection are of uttermost importance to be ‘DM Hunter’




Translate DD limits to collider constraints