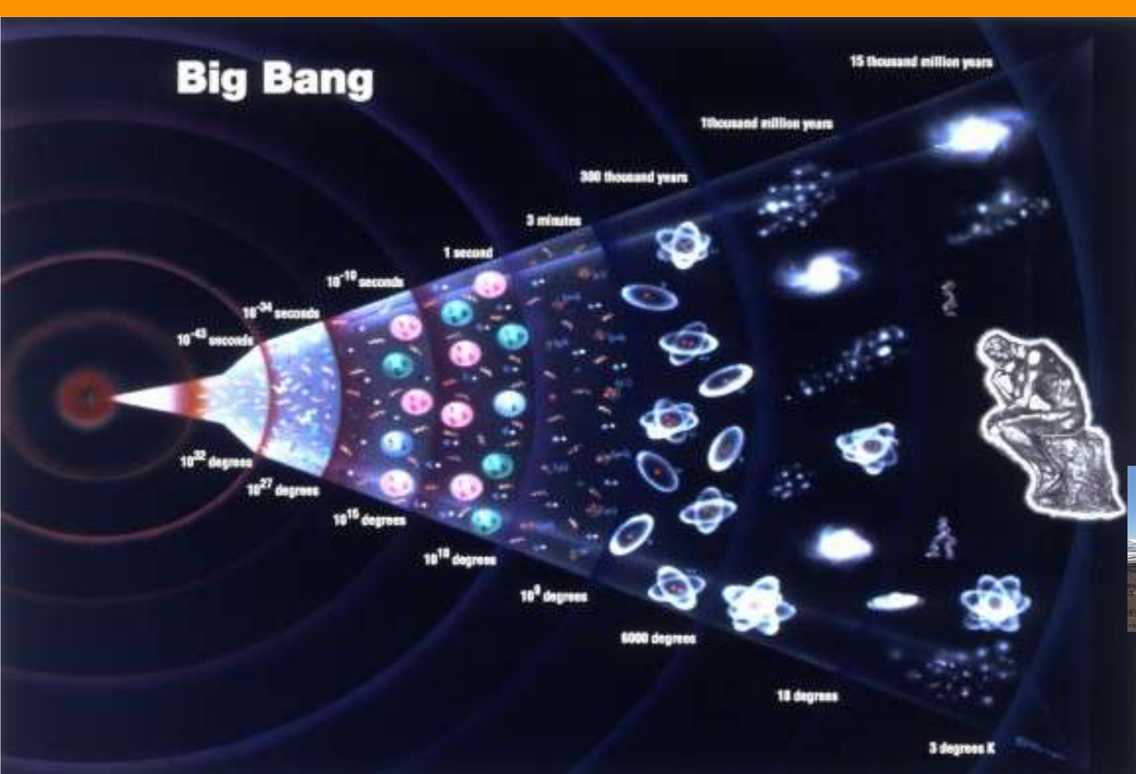
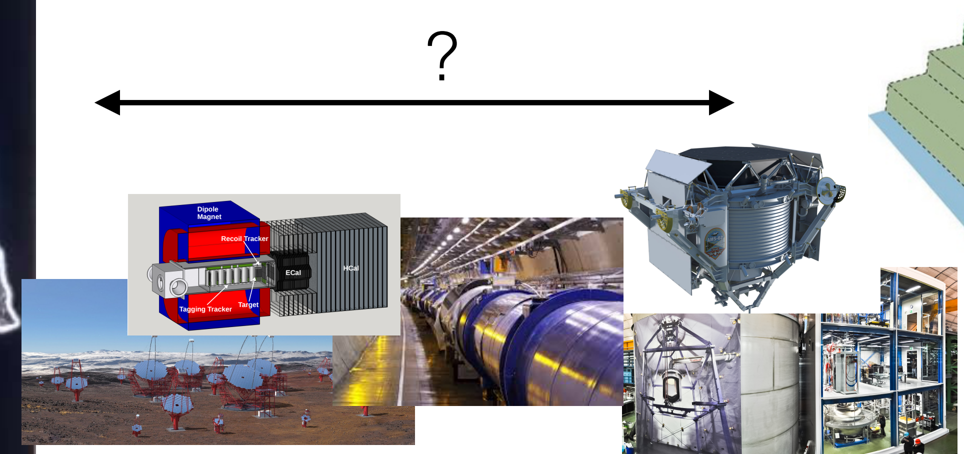
Dark Matter
(from a particle physicists point of view)

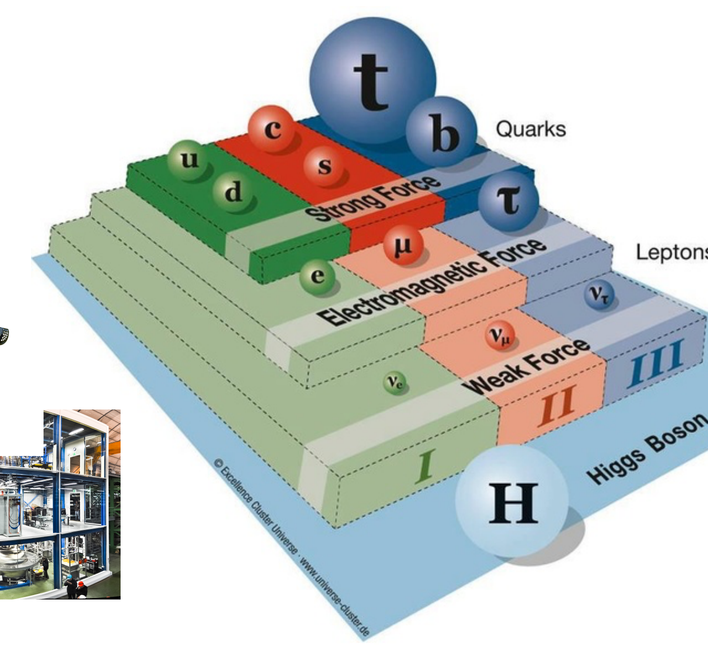
VT 2020

Ruth Pöttgen

25 February 2020

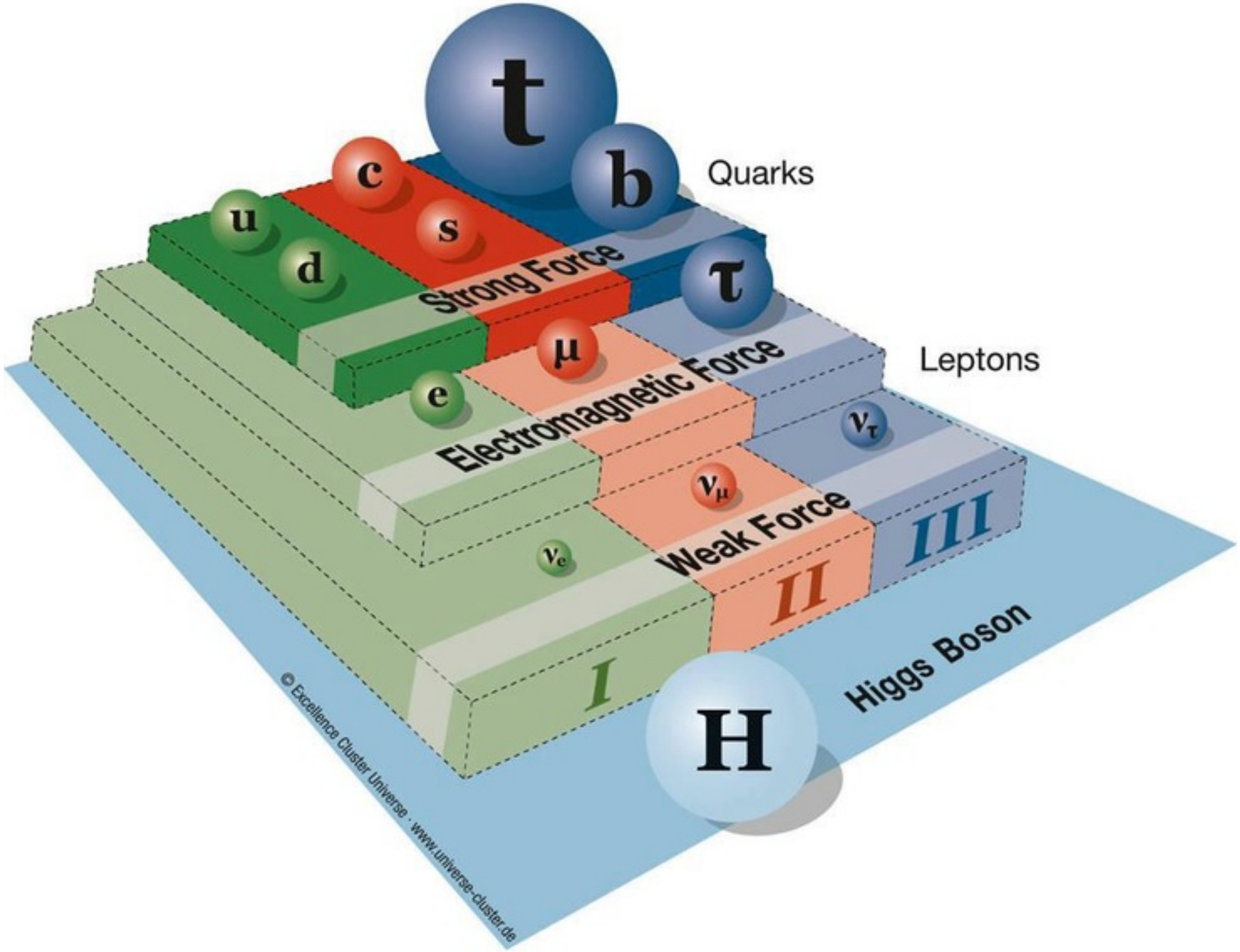






In particle physics

- two main questions:
  - what are things (matter) made of?
    - **fundamentally!**
  - how do fundamental particles **interact**?



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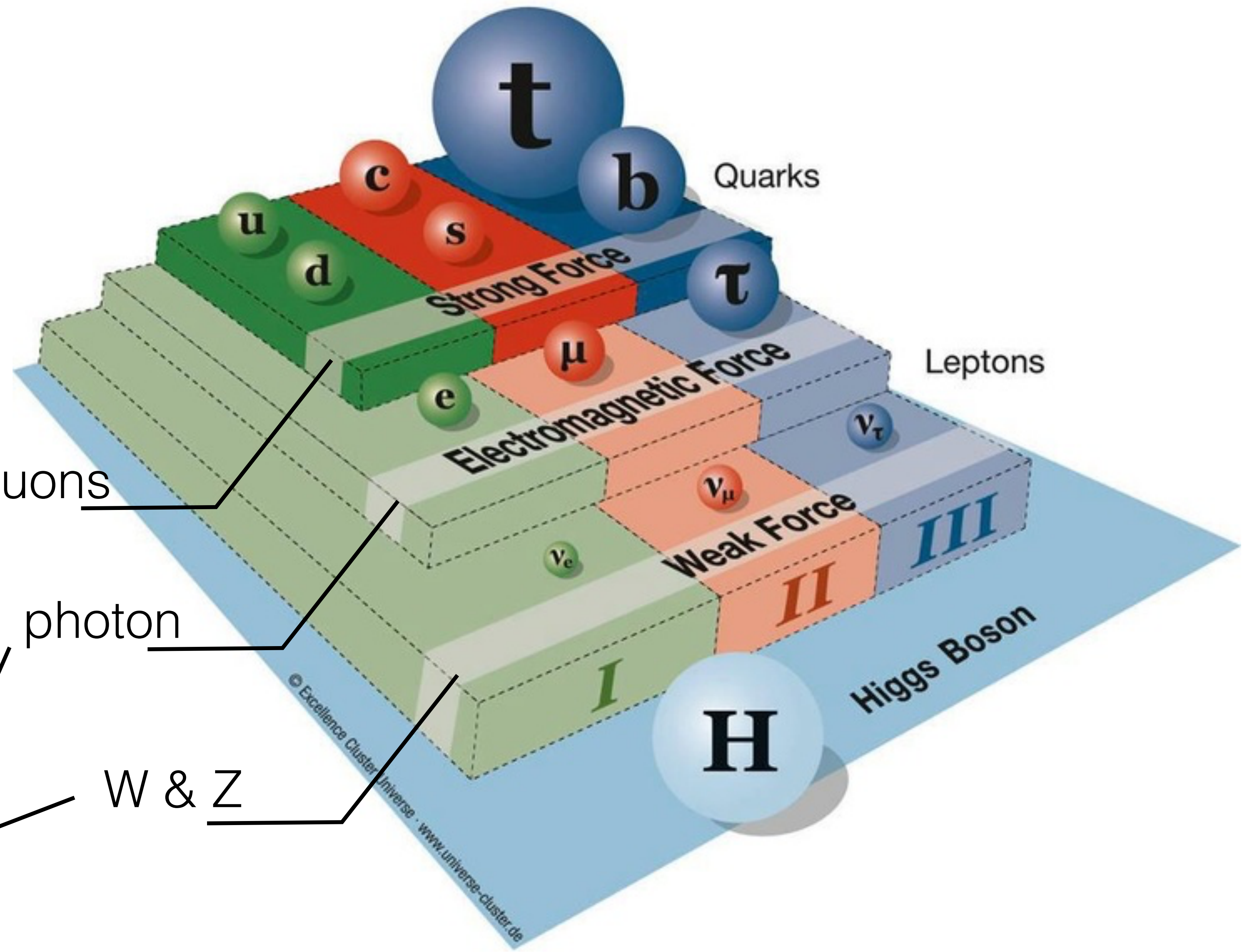


gluons

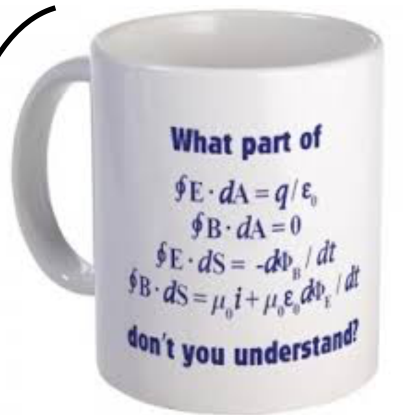
photon

W & Z

force carriers

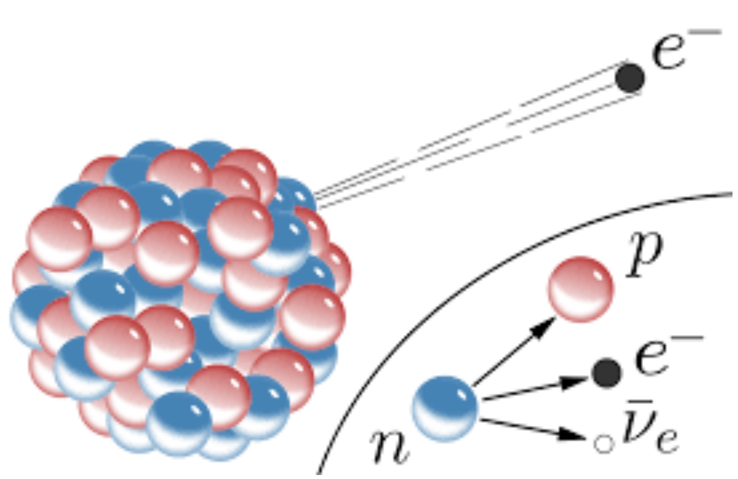
electro-weak

electromagnetic

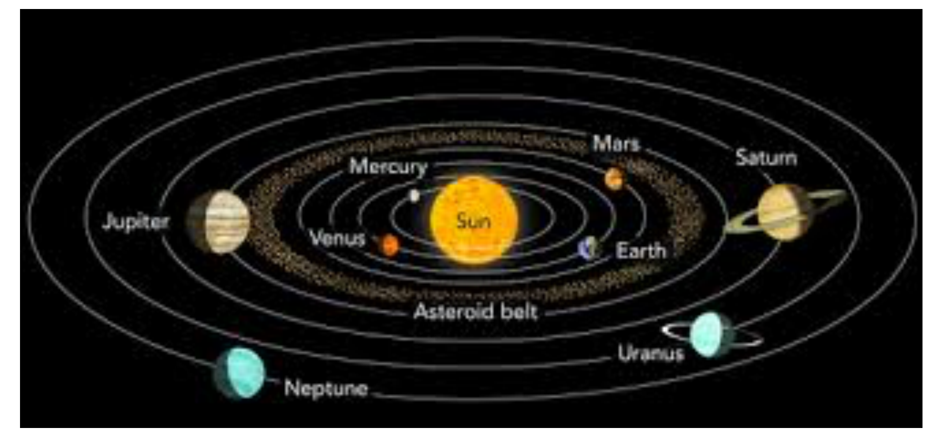


(Maxwell)

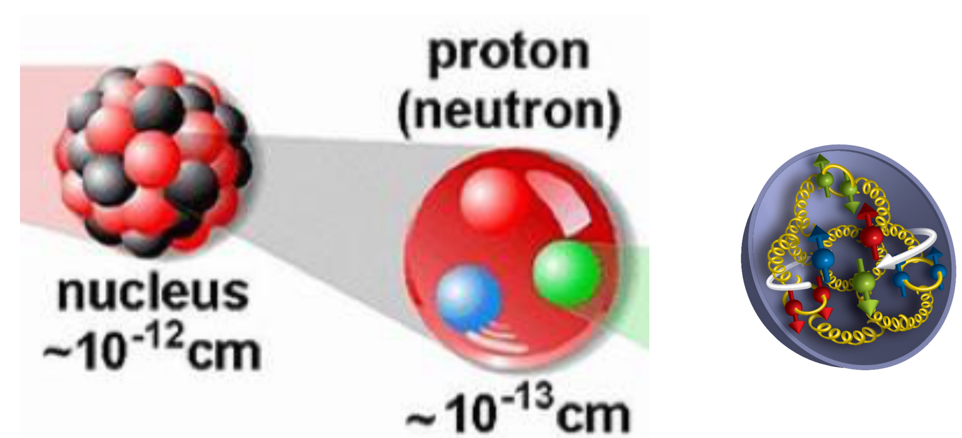
weak



gravity



strong



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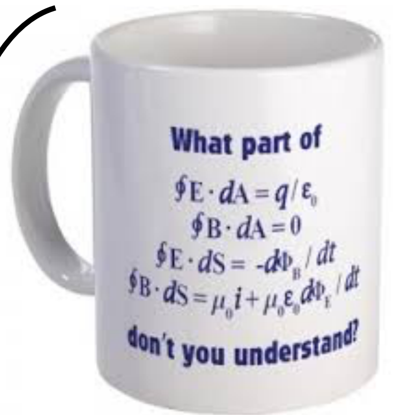

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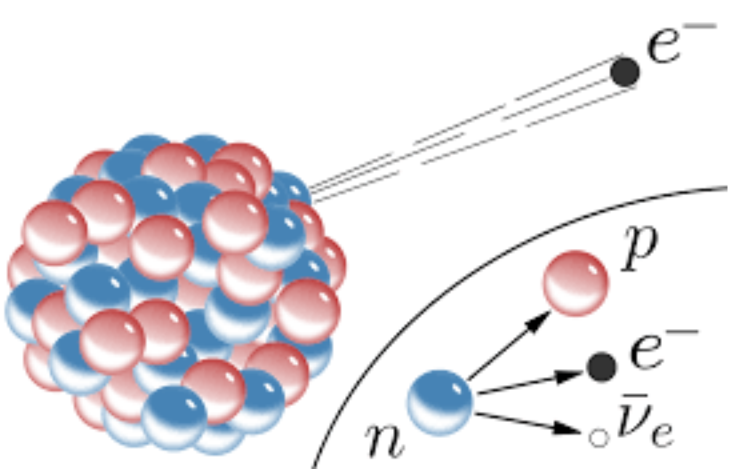

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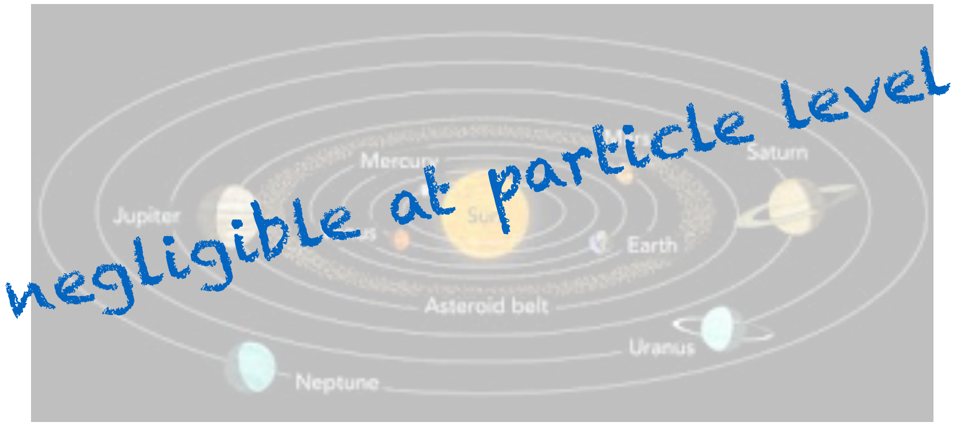
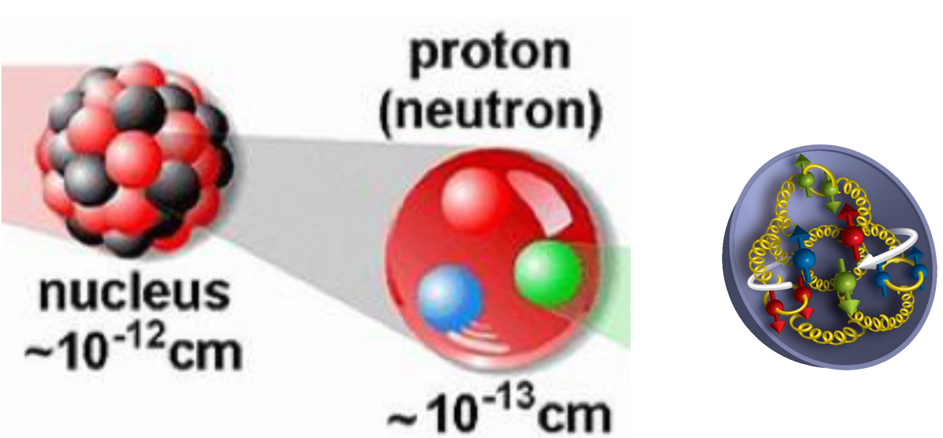
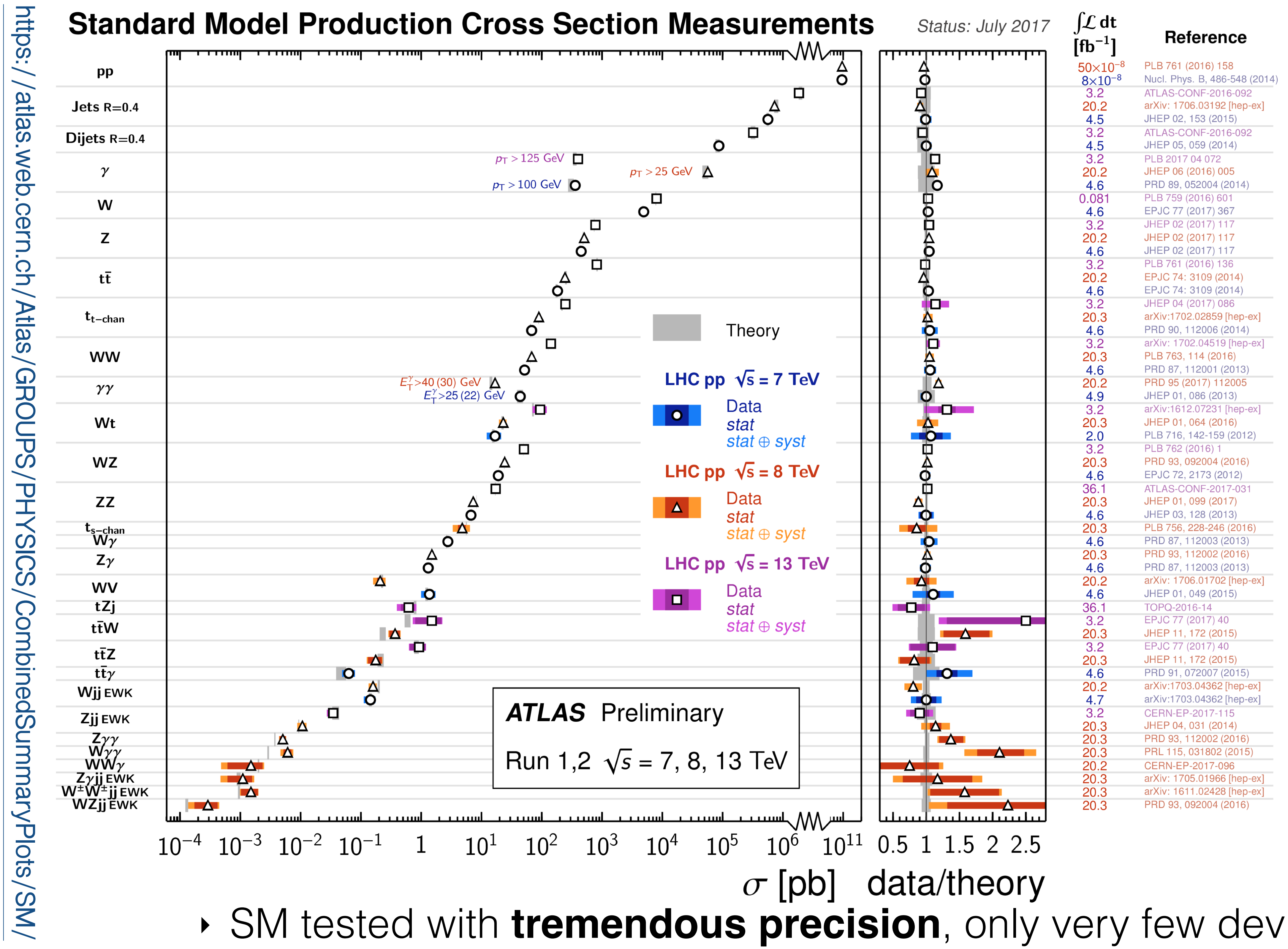


negligible at particle level

strong



Standard Model Measurements



- SM tested with **tremendous precision**, only very few deviations

so, are we all done here?

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Let's think big

Let’s think big

Let's think big

- the Universe

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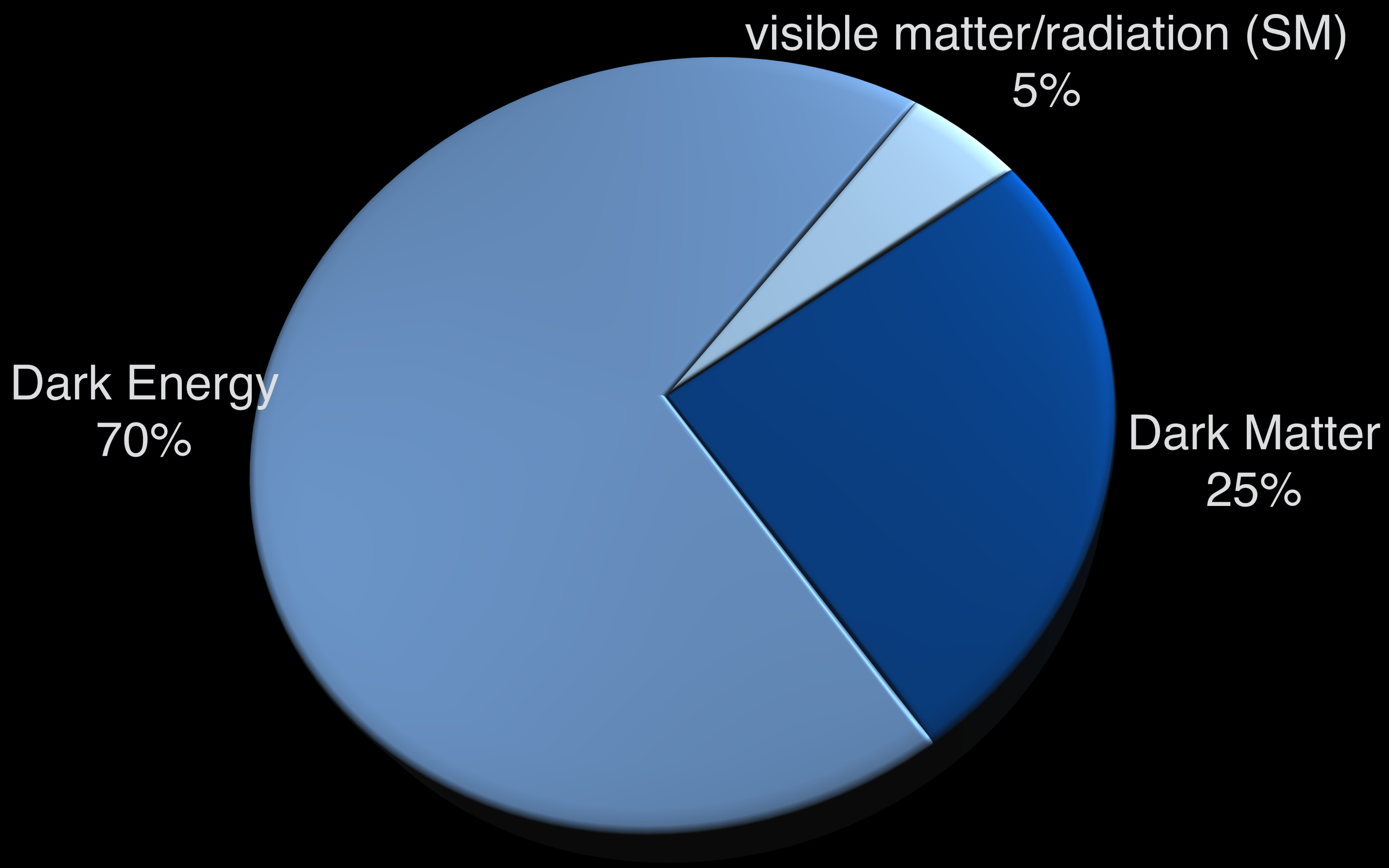
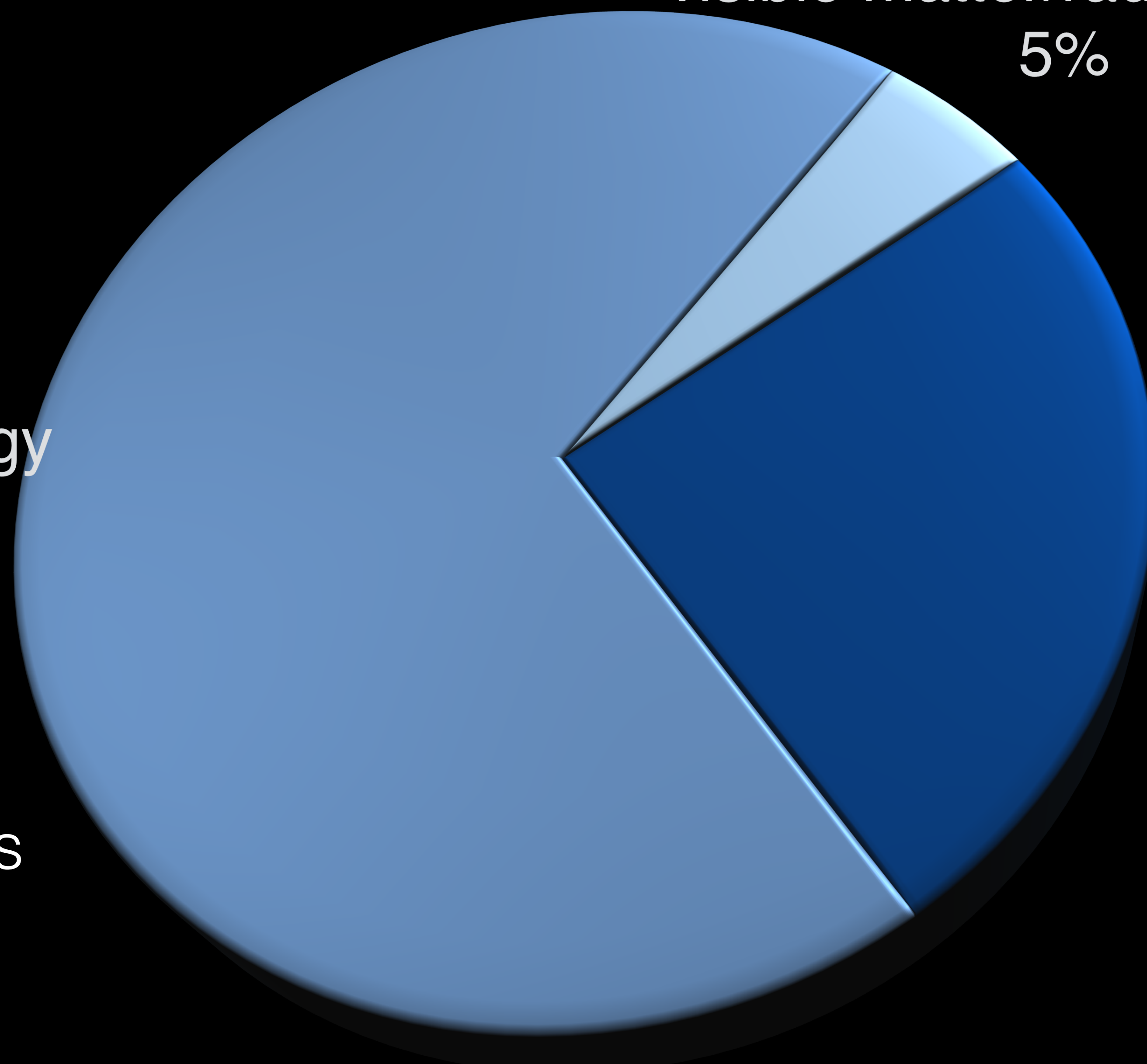
- the Universe



Let's think big

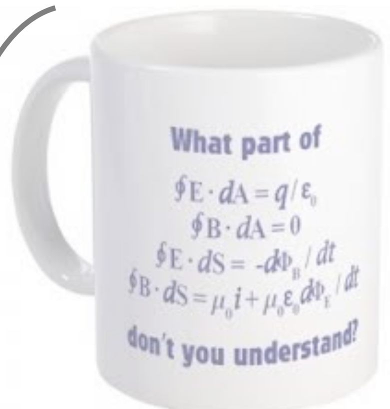
- the Universe



- that's all we know!
- we are not going to talk more about this
- remainder of this lecture

How do we know Dark Matter is there?

electromagnetic



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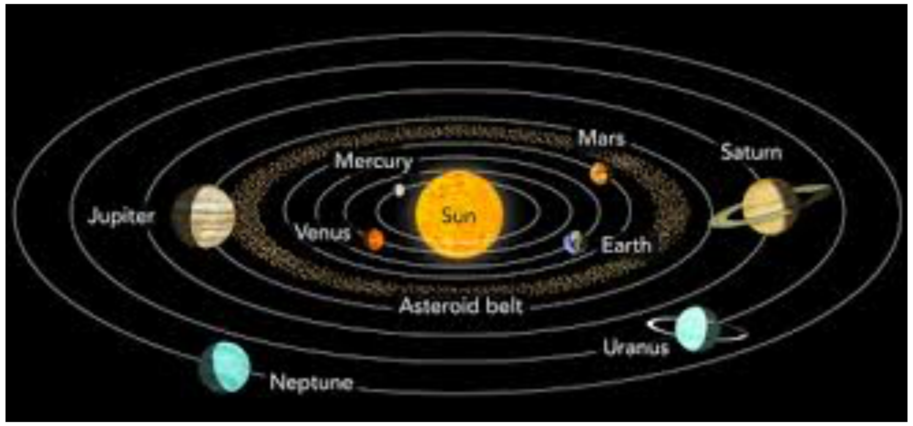
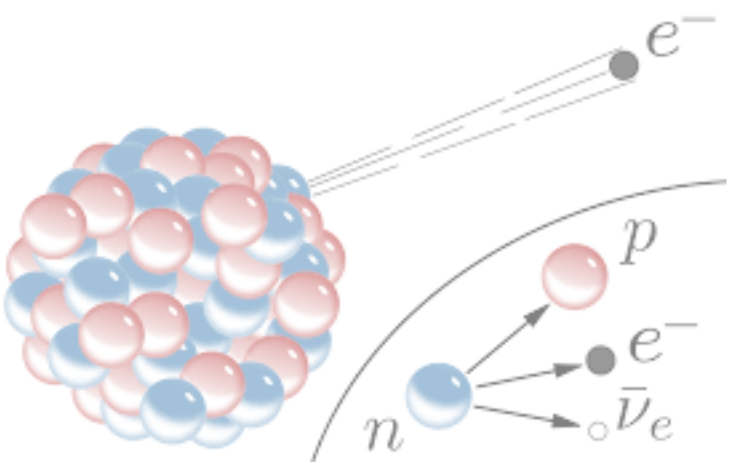
gravity

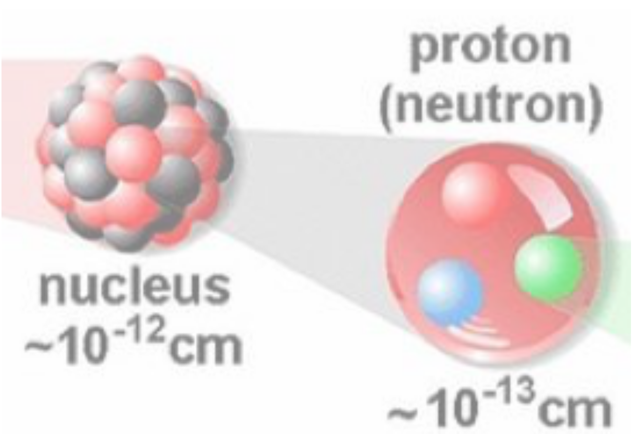


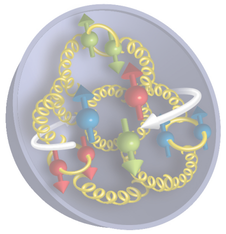
electro-weak

weak



strong





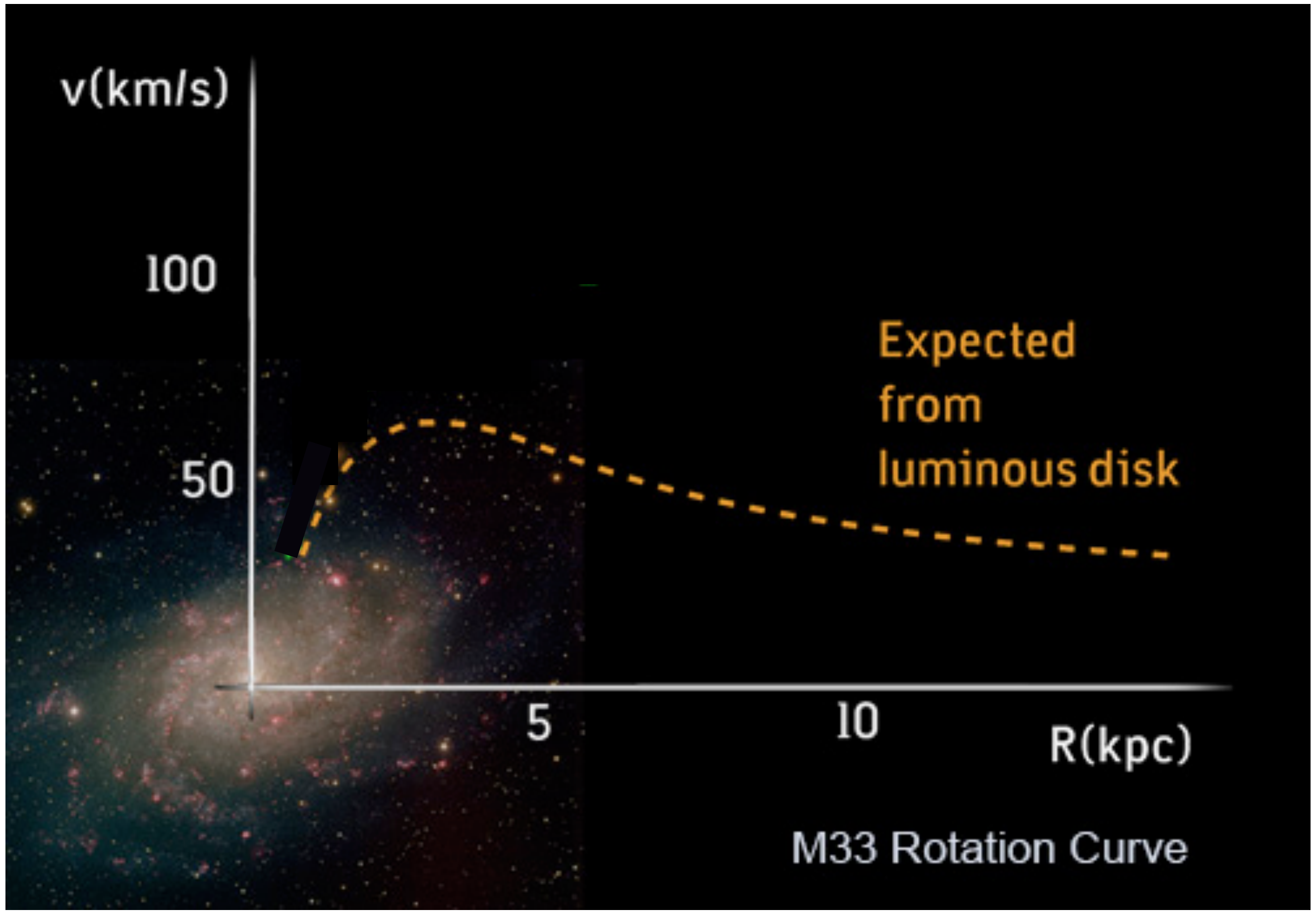
A bit of Newton

stars in a galaxy orbit the galactic centre

from Newton:

$$mv^2/r = GmM/r^2$$

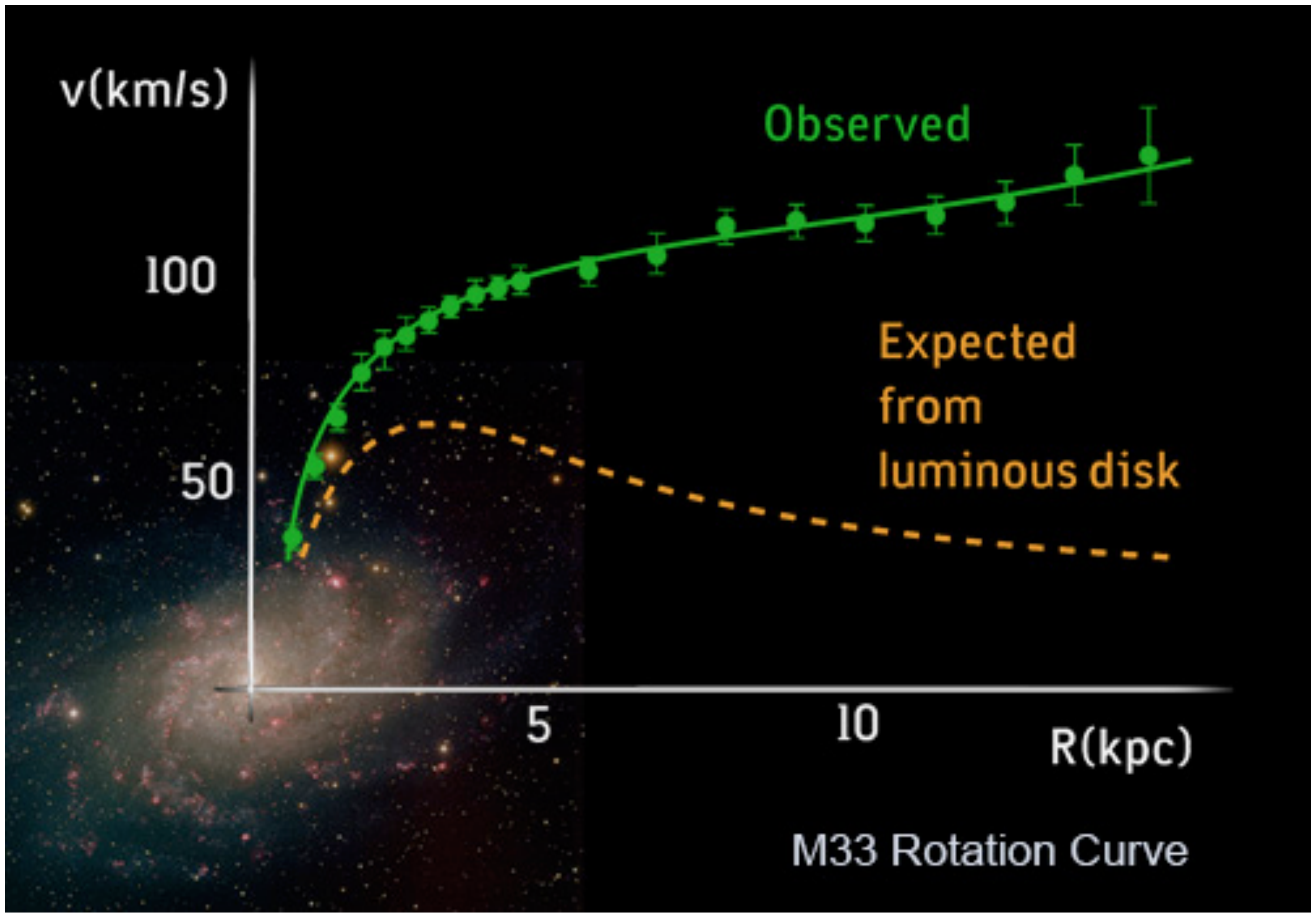
$$v = \sqrt{(GM/r)} \sim 1/\sqrt{r}$$



http://www.spitzer.caltech.edu/images/1074-ssc2003-06d1-Infrared-Spiral-Galaxy-Messier-81

level of single galaxies

what's actually observed:



http://www.learner.org/courses/physics/unit/text.html?unit=10&secNum=2

first mentioned by

Knut Lundmark in 1930

(see this presentation from April 2015)

Über die Bestimmung der Entfernungen, Dimensionen, Massen und Dichtigkeiten für die nächstgelegenen anagalaktischen Sternsysteme.

Von Knut Lundmark.

Tabelle 4.

Objekt	Verhältnis: Leuchtende + dunkle Materie / Leuchtende Materie	Mittlere Zahl der Sterne für Lichtjahre³
Messier 81	100 : 1 (?)	0.20 (?)
N. G. C. 4594	30 : 1	0.042
Andromedanebel	20 : 1	0.006
Messier 51	10 : 1	0.012
Milchstraßensystem	10 : 1	0.08
Messier 33	6 : 1	0.026

"more mass than light"

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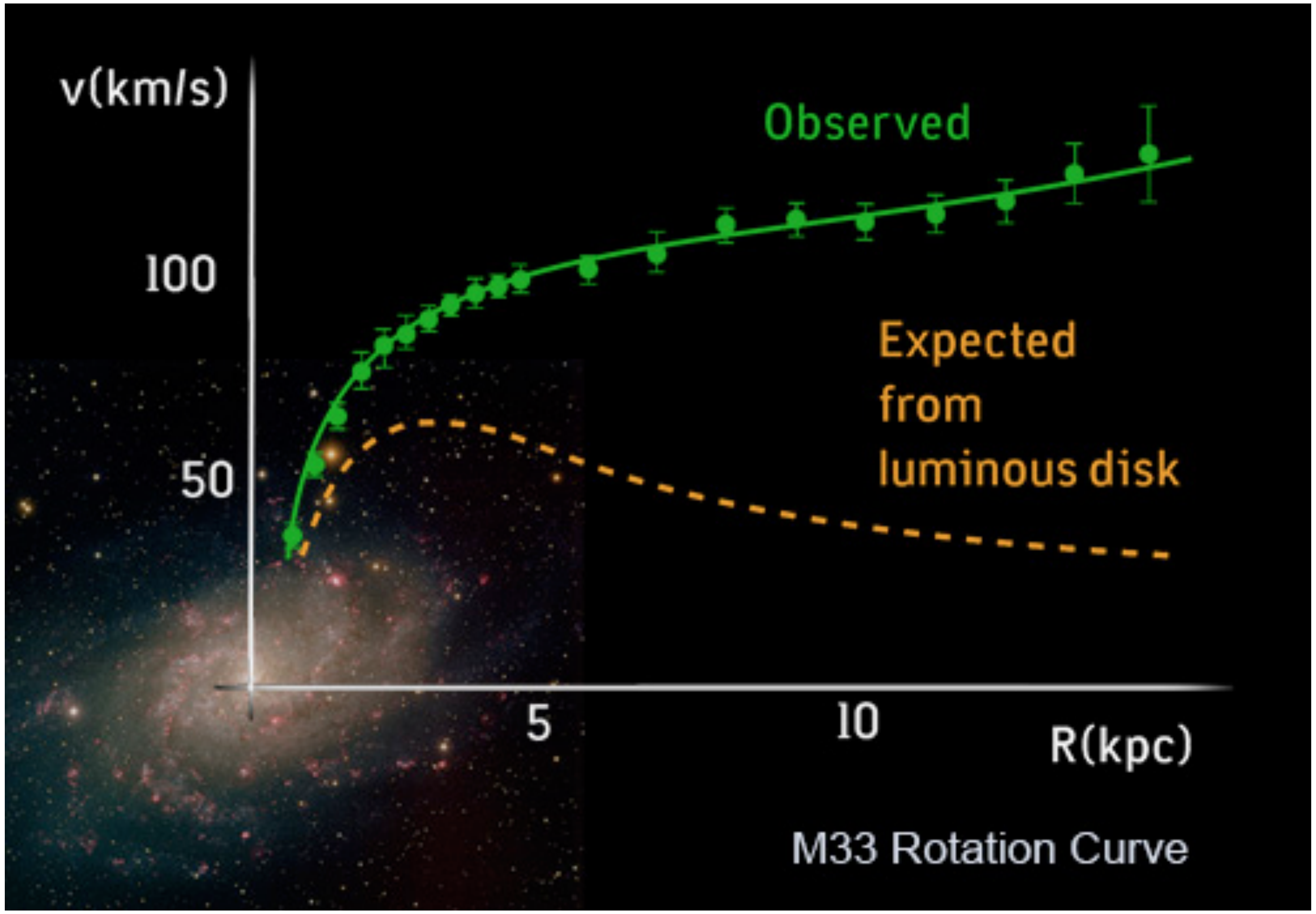
Rotation Curves

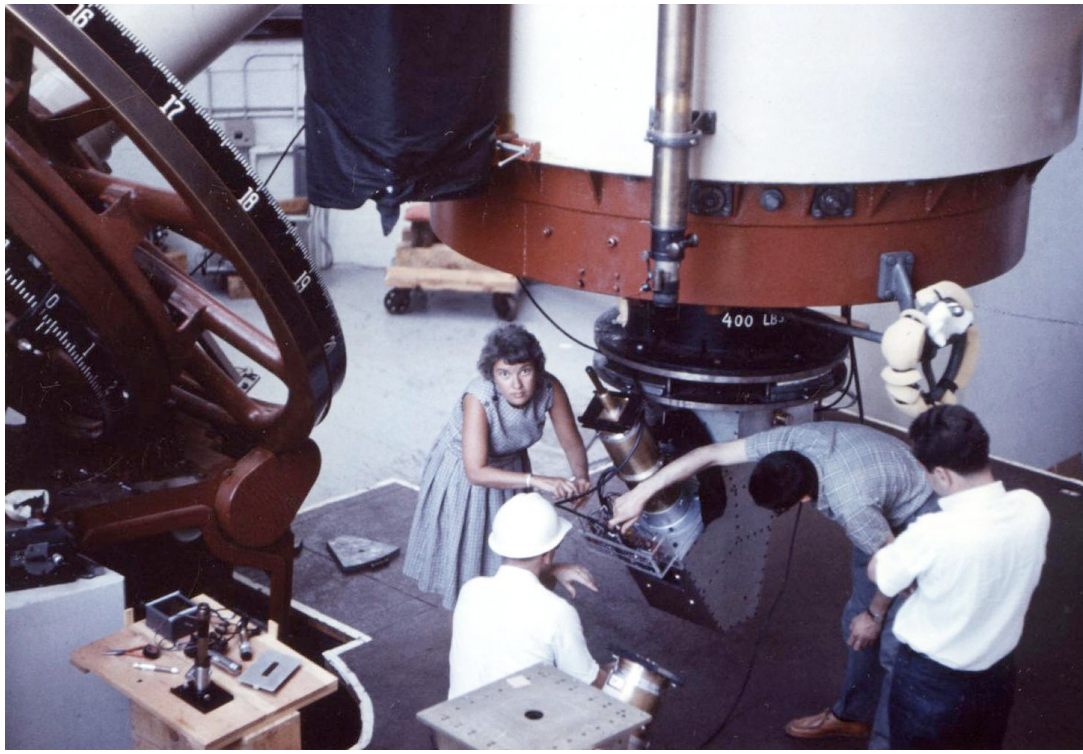
level of single galaxies

what's actually observed:



http://www.learner.org/courses/physics/unit/text.html?unit=10&secNum=2

https://news.nationalgeographic.com/2016/12/vera-rubin-dark-matter-galaxy-rotation-nobel-science/



Vera Rubin in the 1970s observed this effect in more than 200 galaxies!

"more mass than light"

Velocity Distribution in Galaxy Cluster

level of cluster of galaxies

http://earthsky.org/clusters-nebulae-galaxies/the-coma-berenices-galaxy-cluster

often claimed to have been the first to use the term “Dark Matter”: Fritz Zwicky in 1933

https://writescience.wordpress.com/tag/fritz-zwicky/

measured velocity distribution of galaxies in Coma cluster

applied virial theorem to infer total mass of the cluster

K = 1/2 |U| (for a system in equilibirum)

compared this to total light output of the cluster

found that there was much more mass (=matter) than the light output suggested (today: factor of 10)

=> **dark matter**

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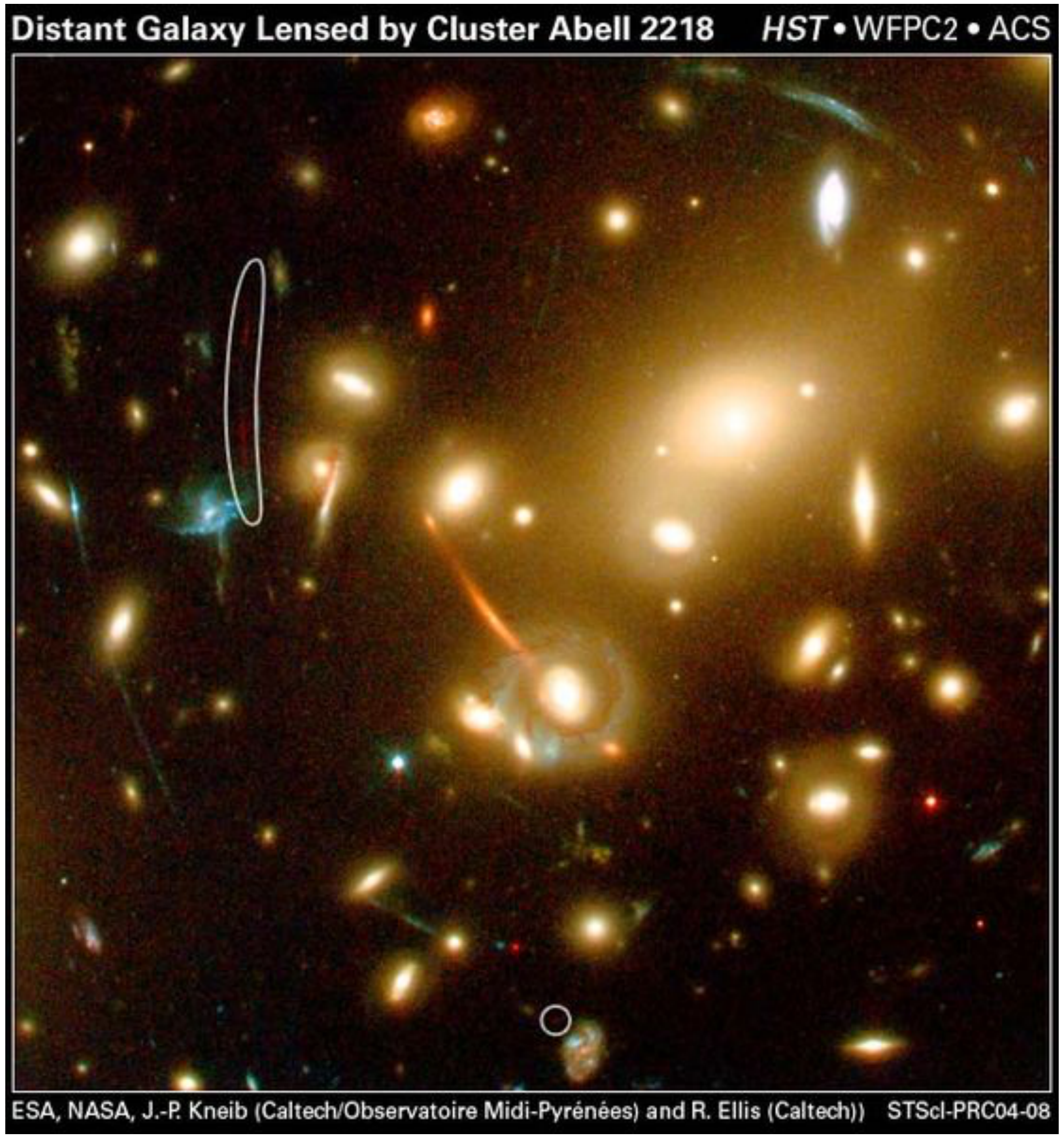
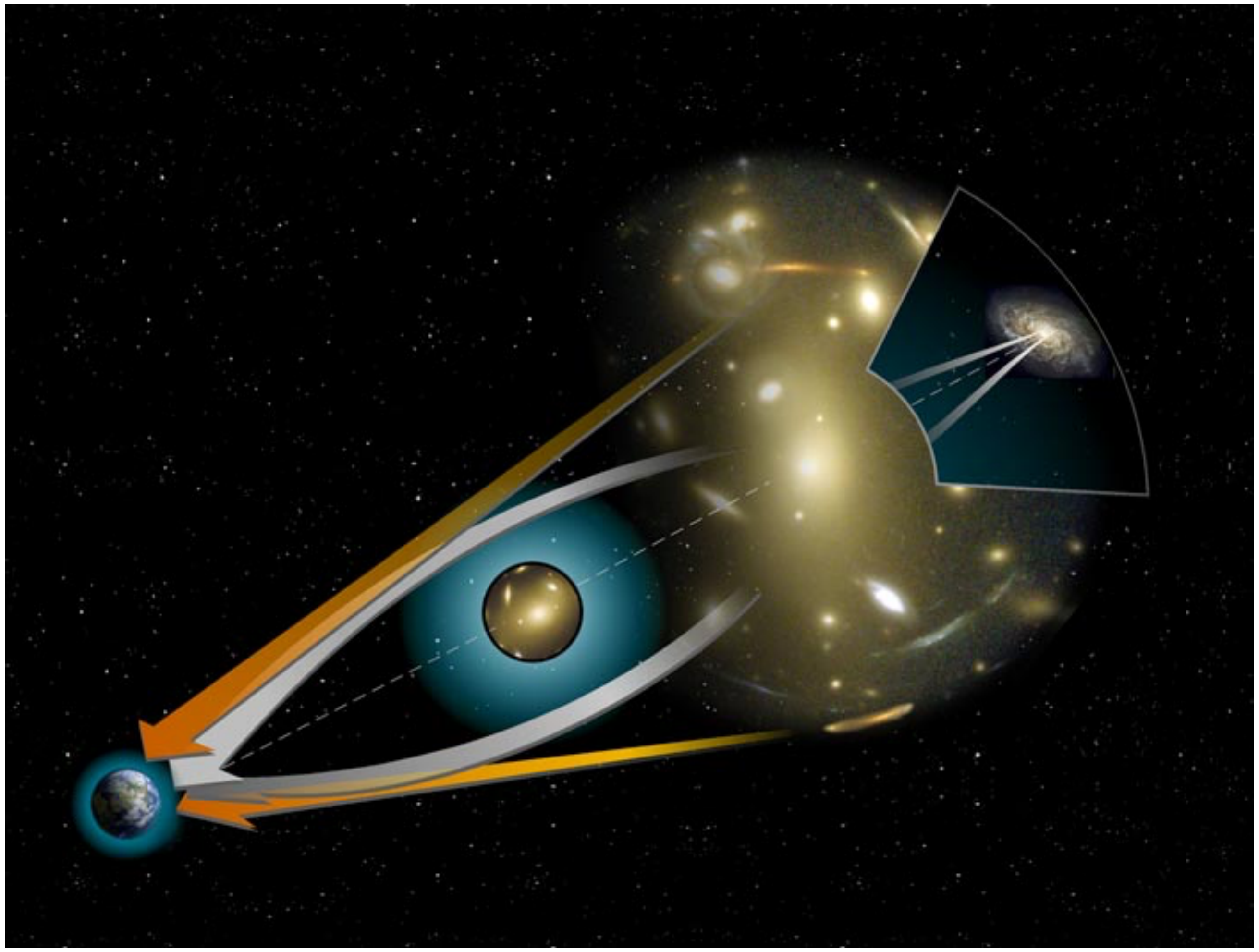
level of galaxy clusters

"mass bends light" (general relativity)





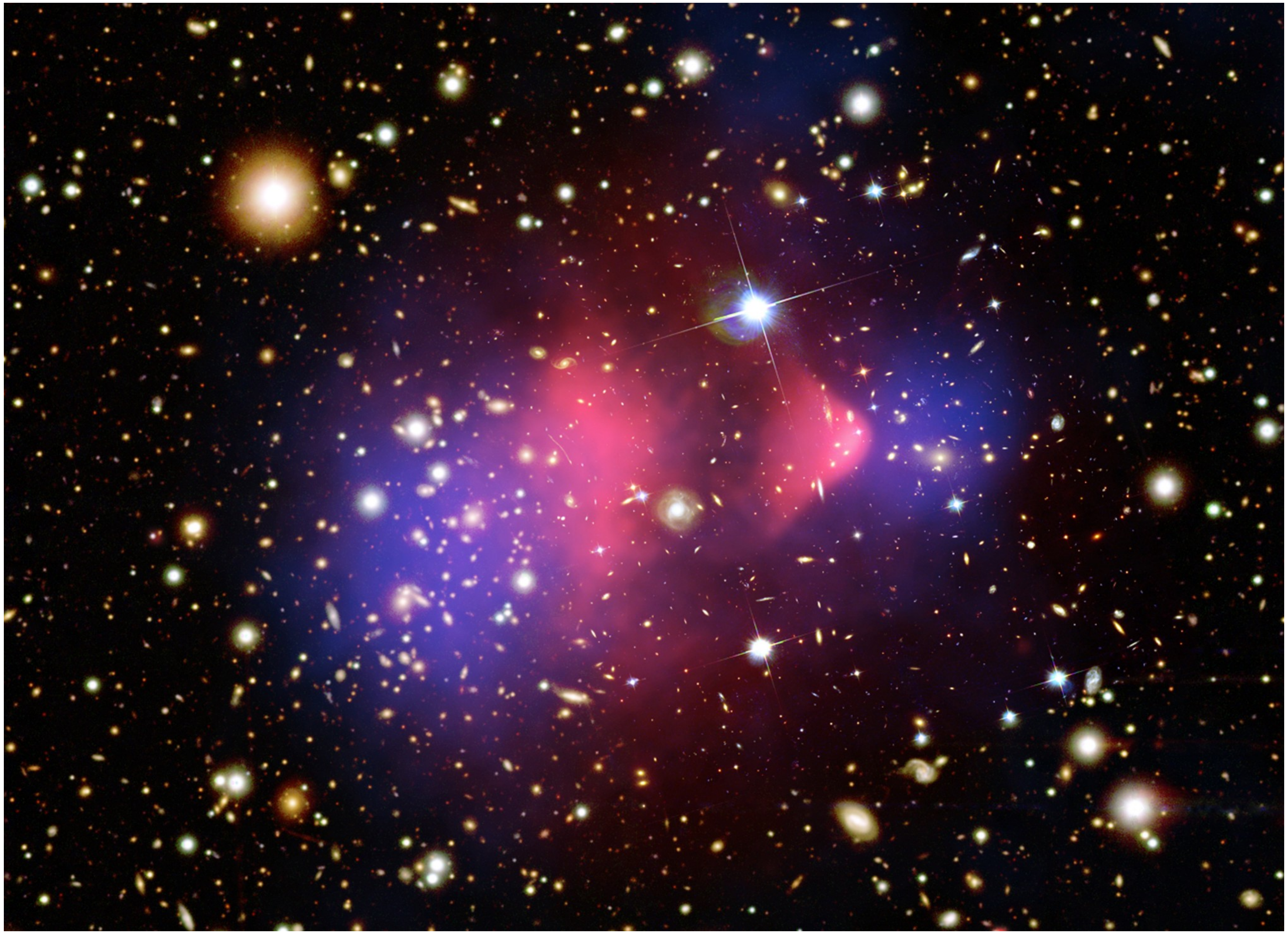
http://scienceblogs.com/startswithabang/2011/04/20/how-gravitational-lensing-show/

again, we see more bending than visible mass can account for

Bullet Cluster

remnant of collision of two galaxy clusters

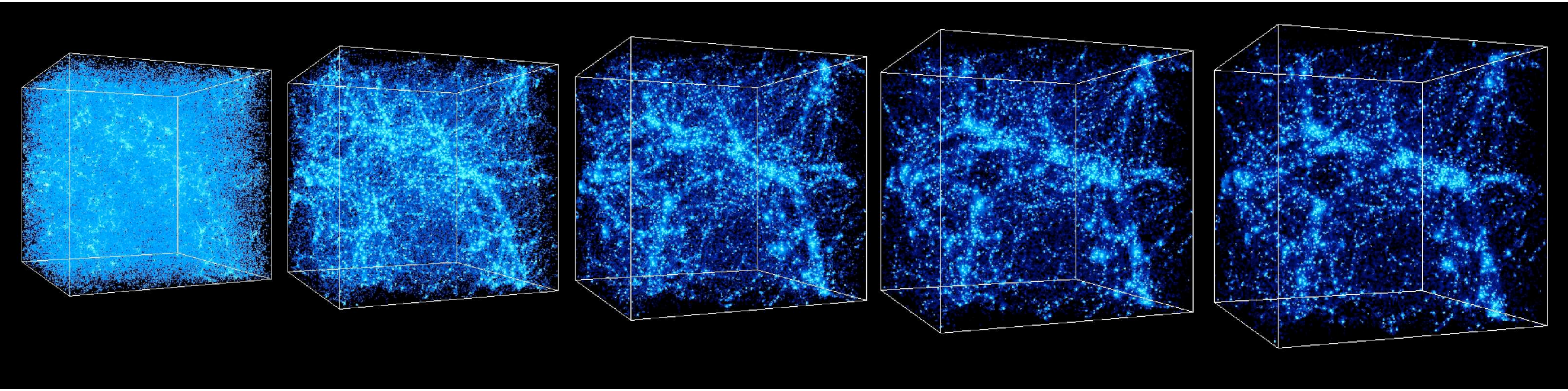
animation



https://svs.gsfc.nasa.gov/30094

centre of gravity ≠ centre of visible mass level of the entire Universe

http://cosmicweb.uchicago.edu/filaments.html



simulation

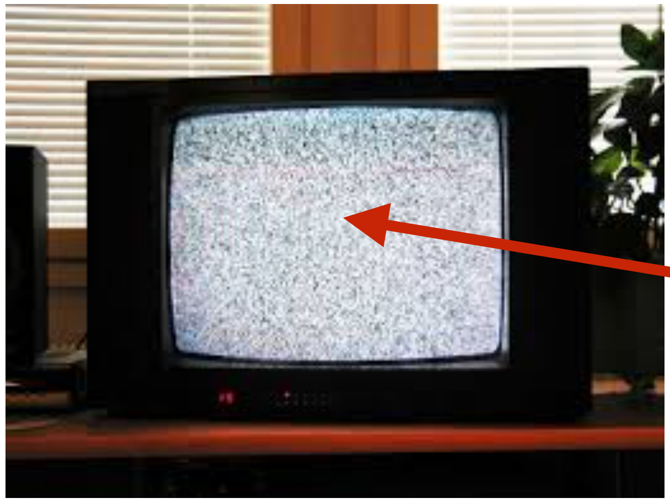
simulations fail miserably to produce the observed structures in models that do not include Dark Matter

example: *age of galaxies*:
galaxy formation starts earlier in presence of DM, which can explain existence of very old galaxies that shouldn't be there otherwise

need the **additional mass** for sufficient "clumping"

Cosmic Microwave Background

- up to ~400 000 years after Big Bang: Universe opaque (photons can't travel far)
  - "too hot to shine"
- cooled and became transparent ("recombination" of e and nuclei to atoms)
- photons from this time have been travelling through space to us and can be detected => "afterglow of the big bang"
- discovered by accident by radio astronomers Penzias and Wilson
  - they thought it to be noise from pigeon dung
- evidence that Big Bang theory is correct
  - Nobel Prize 1978



a few % of this is CMB

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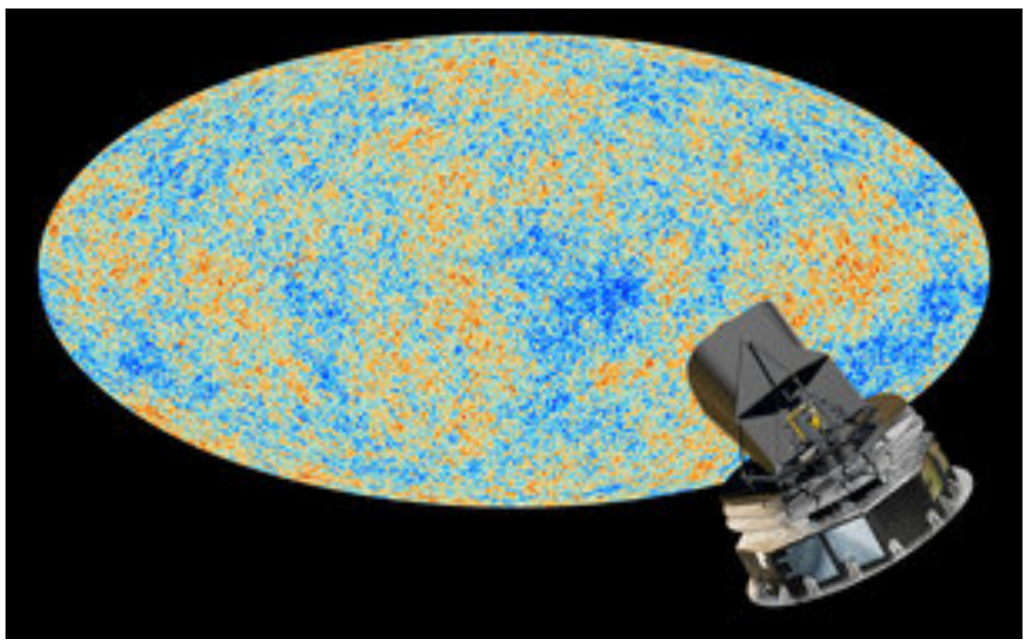
How do we know how much DM there is?

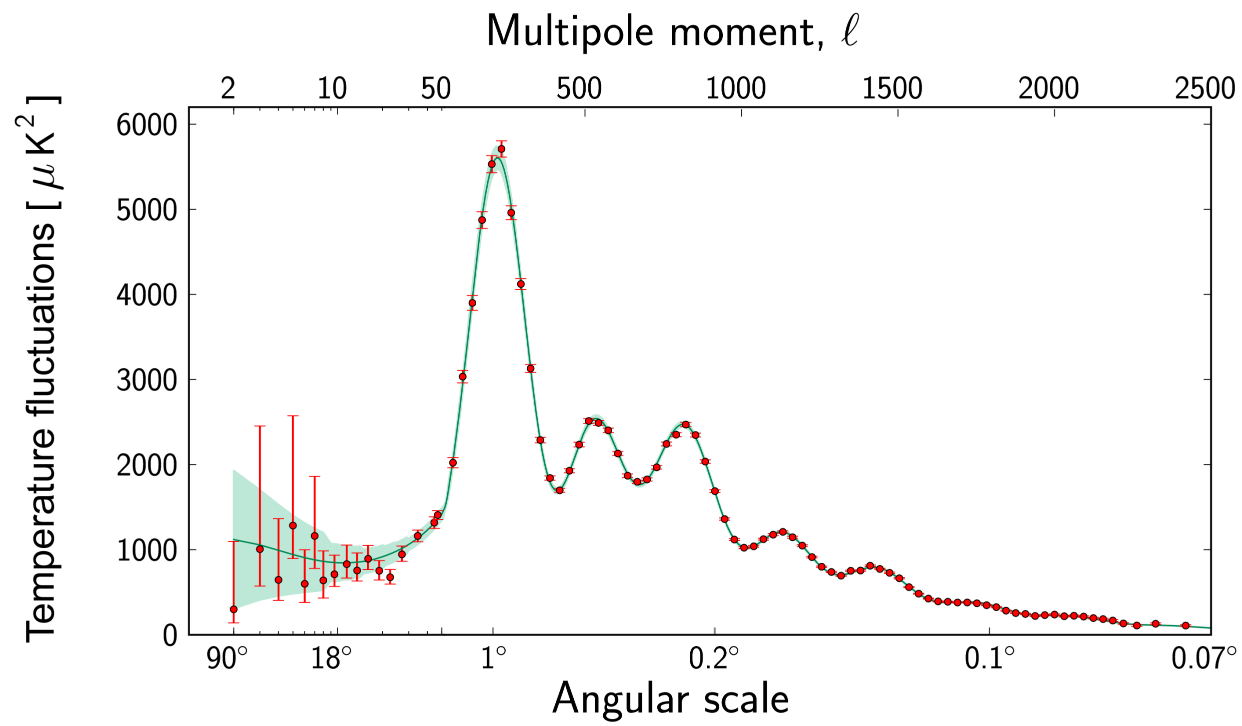
level of the entire Universe ESA **PLANCK** mission

tiny temperature fluctuations (anisotropies) in CMB

http://www.esa.int/Our_Activities/Space_Science/Planck_overview



a different way of looking at it



cosmological parameters can be estimated from best fit to observation

position/height of peaks contains information about composition of the Universe

Nobel Prize 2019 for J. Peebles

one of them is the **amount** of Dark Matter, called “**relic density**”

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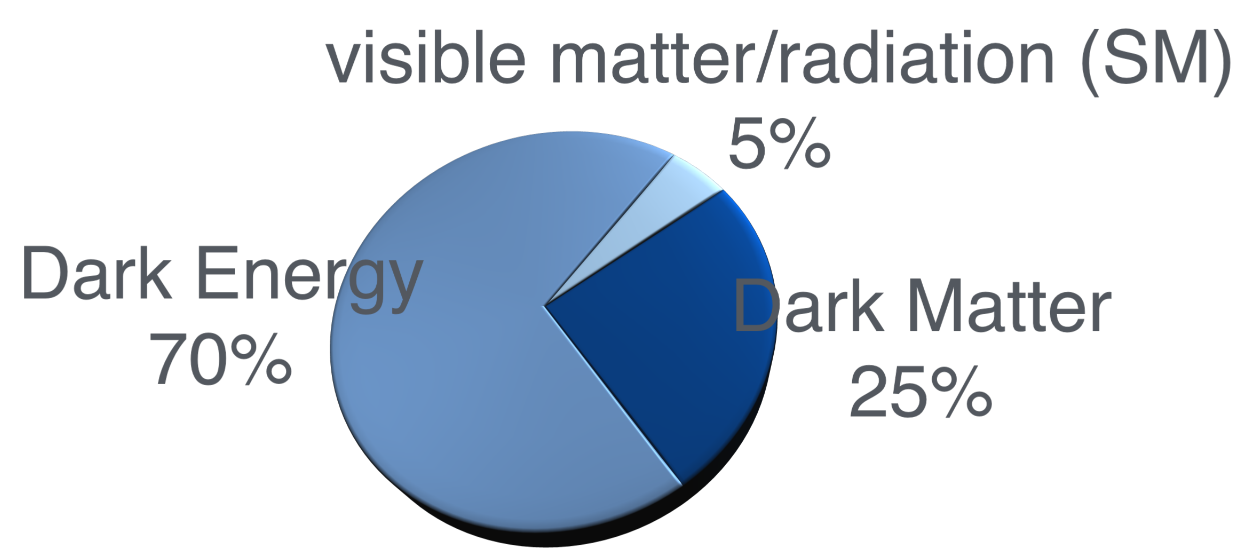
Summary up to here

There are **numerous observations** on largely different cosmological scales that all indicate that there is **more matter in the Universe than what we can see**.

This additional (dark) matter is widely accepted to be the most convincing, **consistent explanation** of all of these phenomena.

Thanks to PLANCK (and similar measurements before) we know that it is about **five times as abundant** as normal matter.

In other words, we have close to no clue what **>80% of the matter in our Universe** is, even though we've known for almost 100 years that it is there.



What do we know?

Dark Matter Properties

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dark!

—> doesn't interact with photons

—> **electrically neutral**

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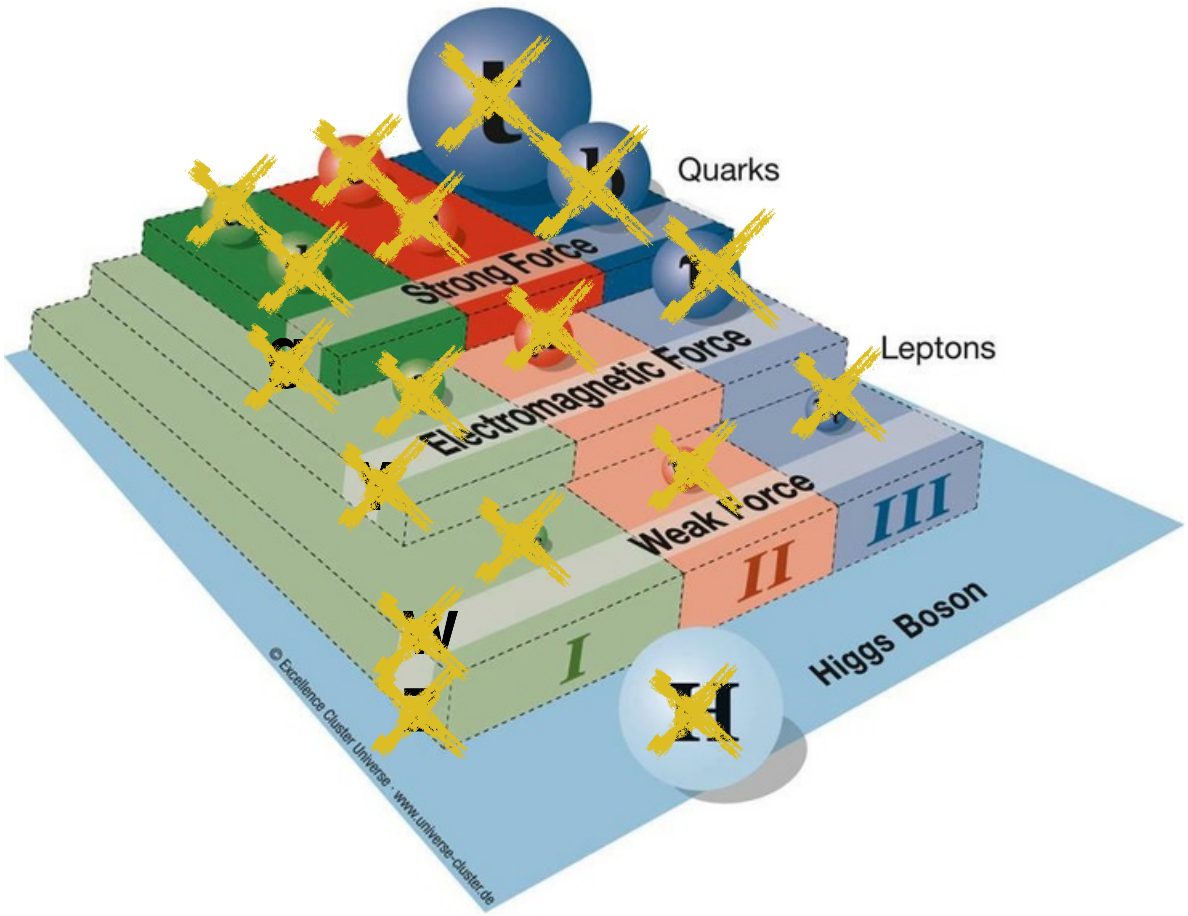

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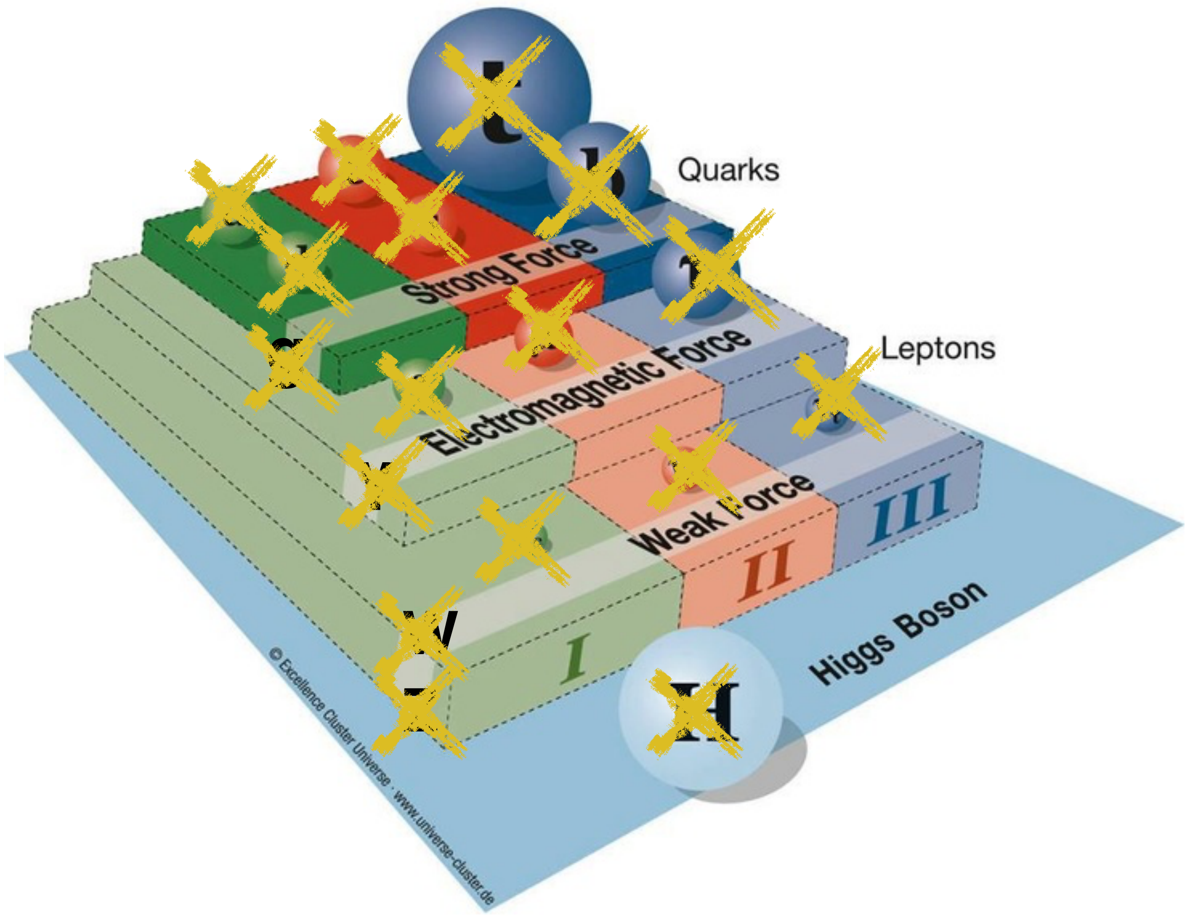

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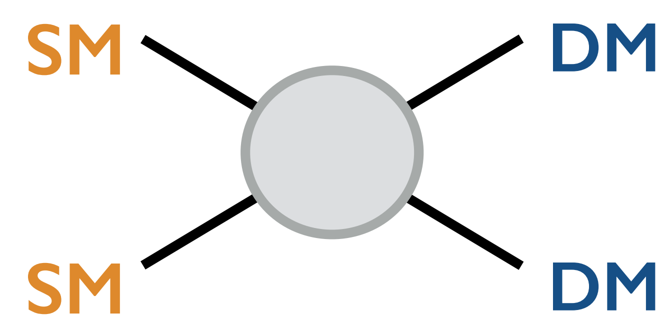
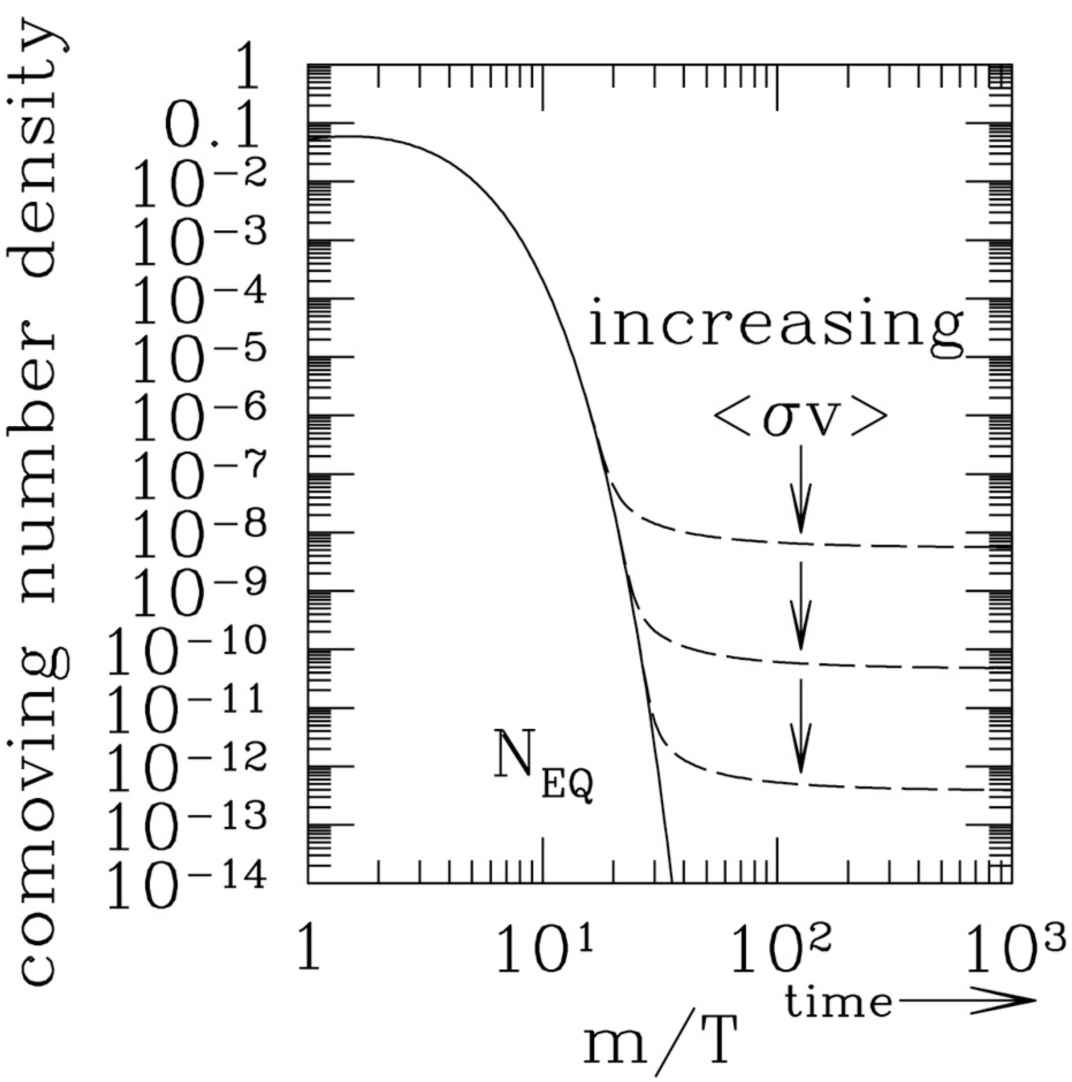
what can it be?

Relic abundance

- equilibrium in the early Universe
- creation and annihilation of DM particles at the same rate

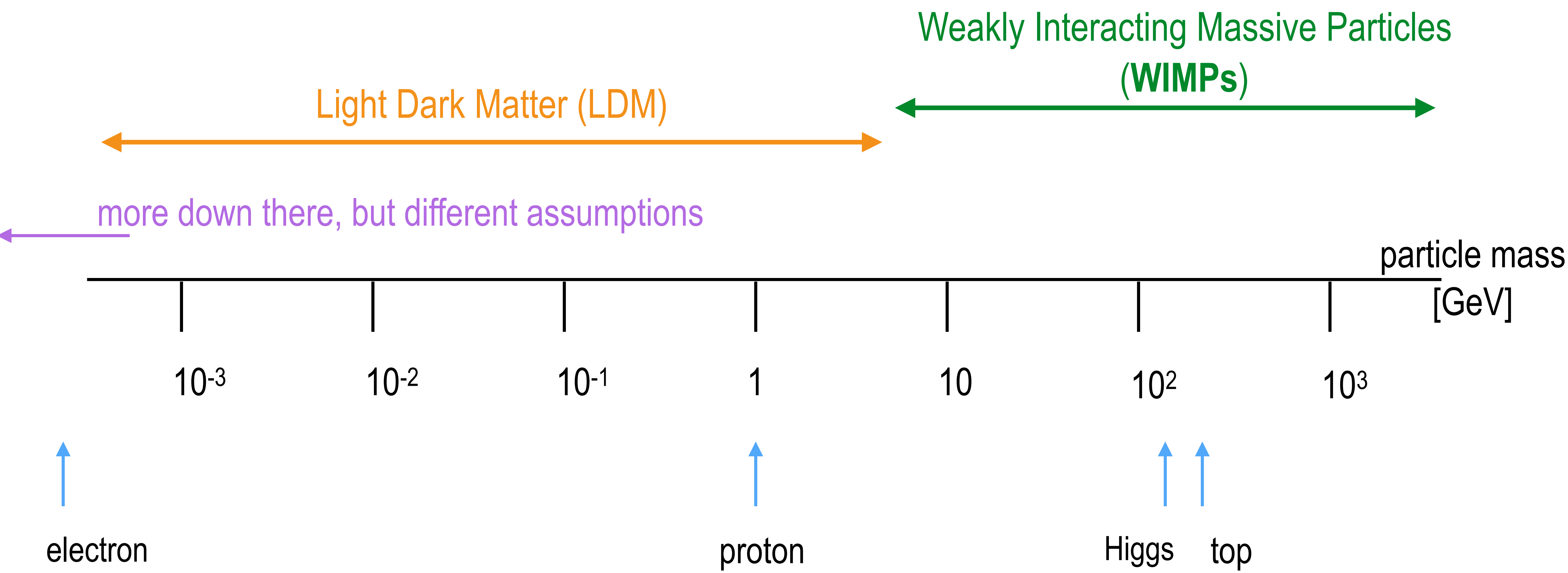




- Universe expanded & cooled
- interaction rate became “too low"
- amount of DM remained stable or “frozen" —> *freeze-out*
- the weaker the interaction, the more DM remained
  - "survival of the weak"
- *relic abundance* depends on interaction **cross section** and **mass** of particles

Dark Matter Particle Masses

- measurement of DM amount (PLANCK) defines possible mass range
  - under certain, well motivated assumptions



- there are many other ideas, but I focus on these because this is what we work on in Lund

Weakly Interacting Massive Particles

- **special combination** of mass and interaction strength yielding “correct" amount of Dark Matter:
  - interaction strength typical for weak interaction (SM)
  - masses in a range where we might expect new particles

    (based on theories that set out to address other problems of the SM, like SUSY)

    - "*WIMP miracle*"
      - without having to cook up some involved theory, these Dark Matter candidates just happen to be in a range that is…

        … pointed to by several extensions of the SM

        … experimentally well accessible

WIMPs have been the **prime DM candidate** for decades

Light Dark Matter

- WIMPs cannot be lighter than a few GeV
  (otherwise amount of DM doesn't come out right)

- How do we get light Dark Matter?
  - need to add **a new mediator particle**
    - modifies interactions such that relic abundance can still be obtained
    - this particle is called a **Dark Photon**
      - similar to SM photon,
        but mass is not 0

decay of Dark Photon **into DM** is the **new** kid on the block

Other Options

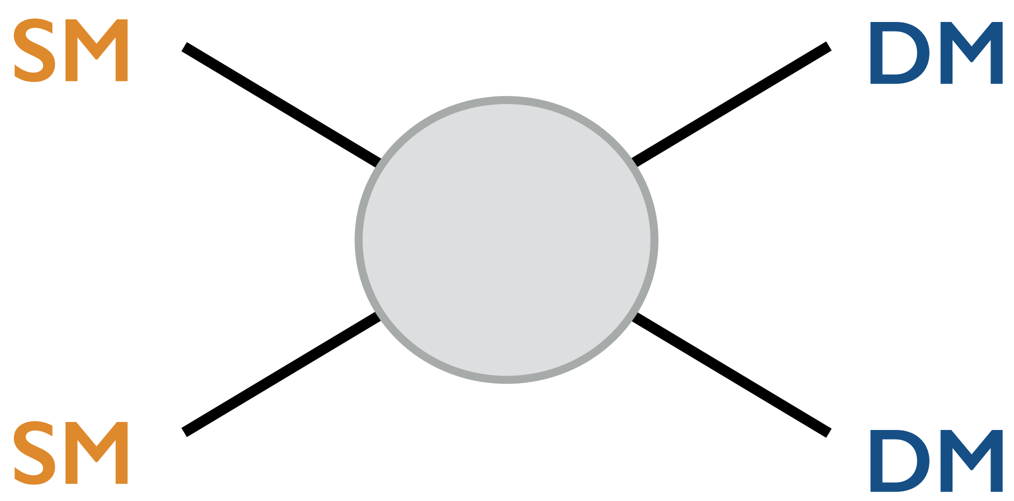
- other candidates typically have **different production mechanisms** and fall in **different mass ranges**

- **axions**
  - postulated to solve *strong CP problem* (the fact that there appears to be exactly no CP violation in the strong interaction for no reason)
  - extremely light: μeV - meV

- **sterile neutrinos**
  - interacts even more feebly than usual (“active") neutrinos
  - mixes with active neutrinos
  - masses of order keV

- plenty of others…

Let's start conventional - WIMPS



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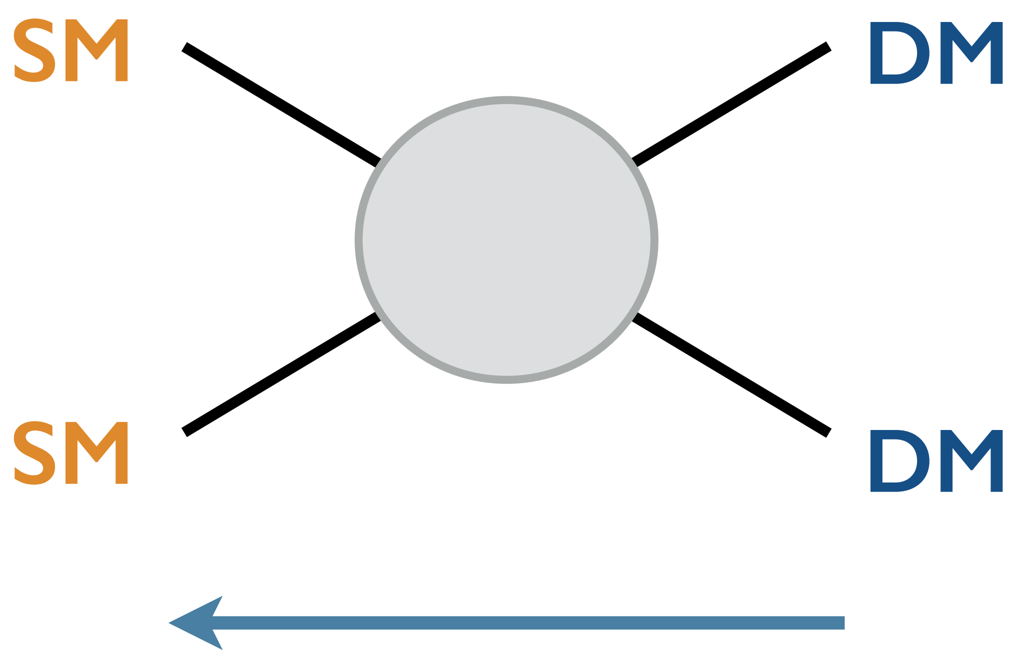

indirect

detect annihilation products

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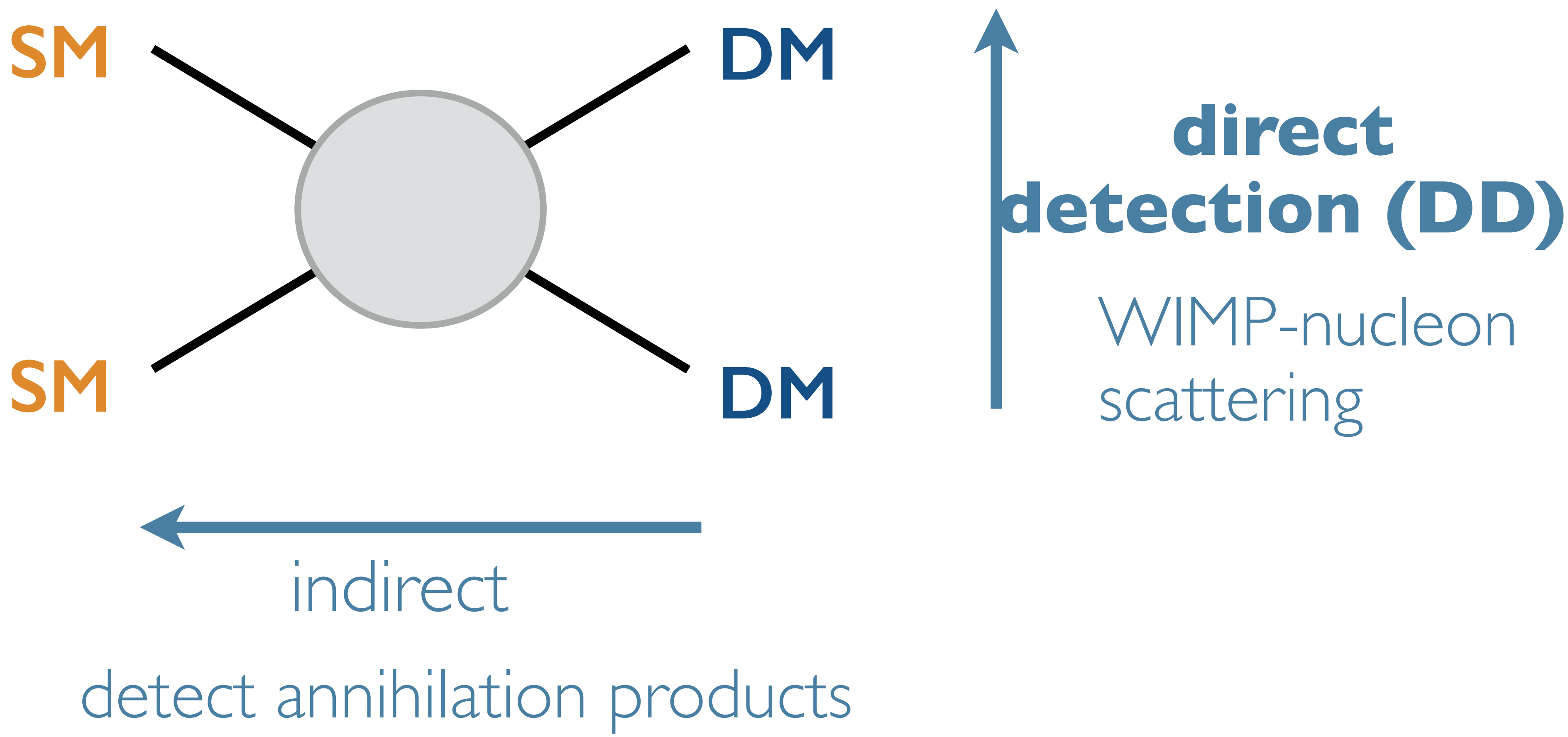
Let's start conventional - WIMPS



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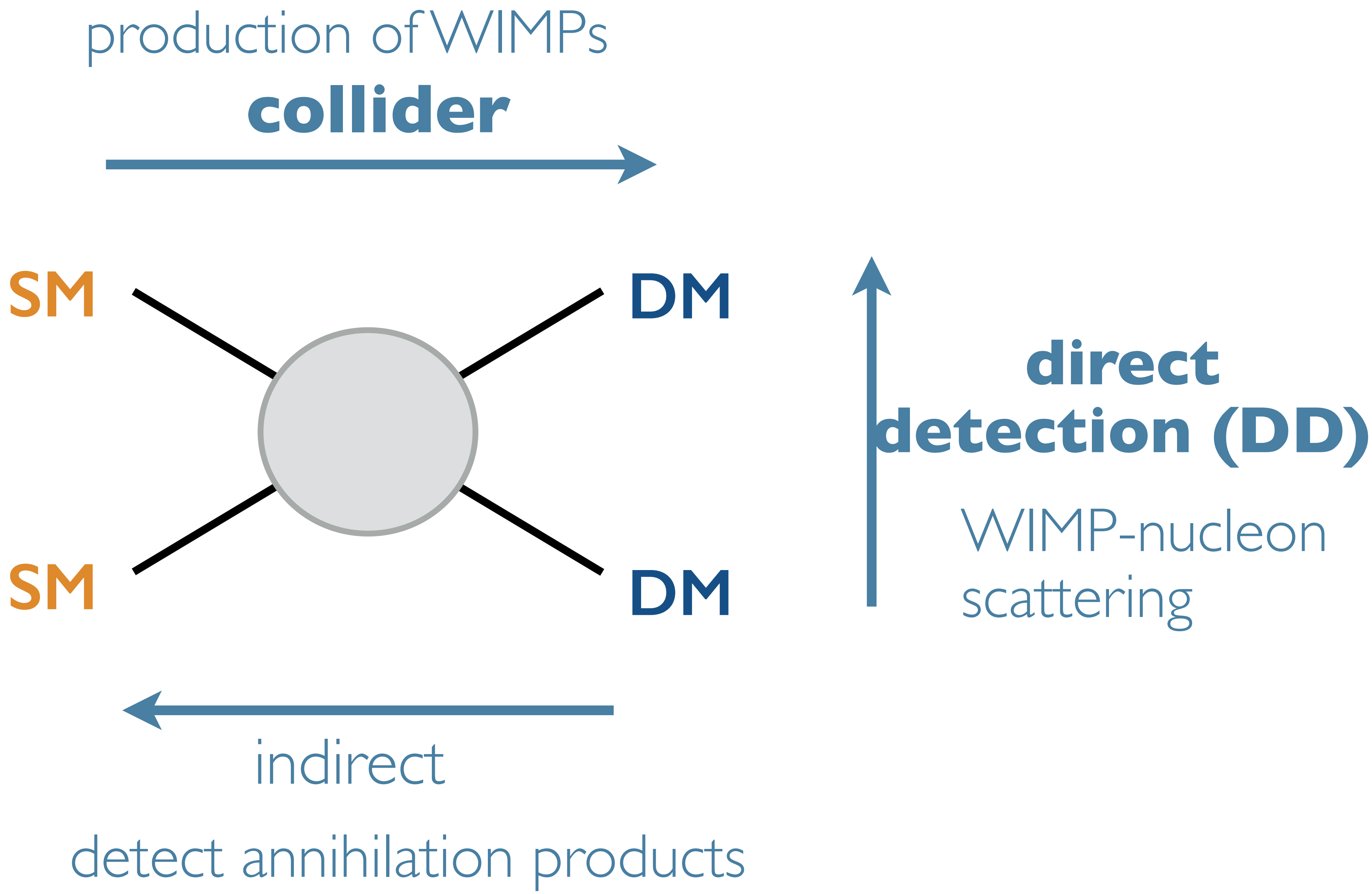

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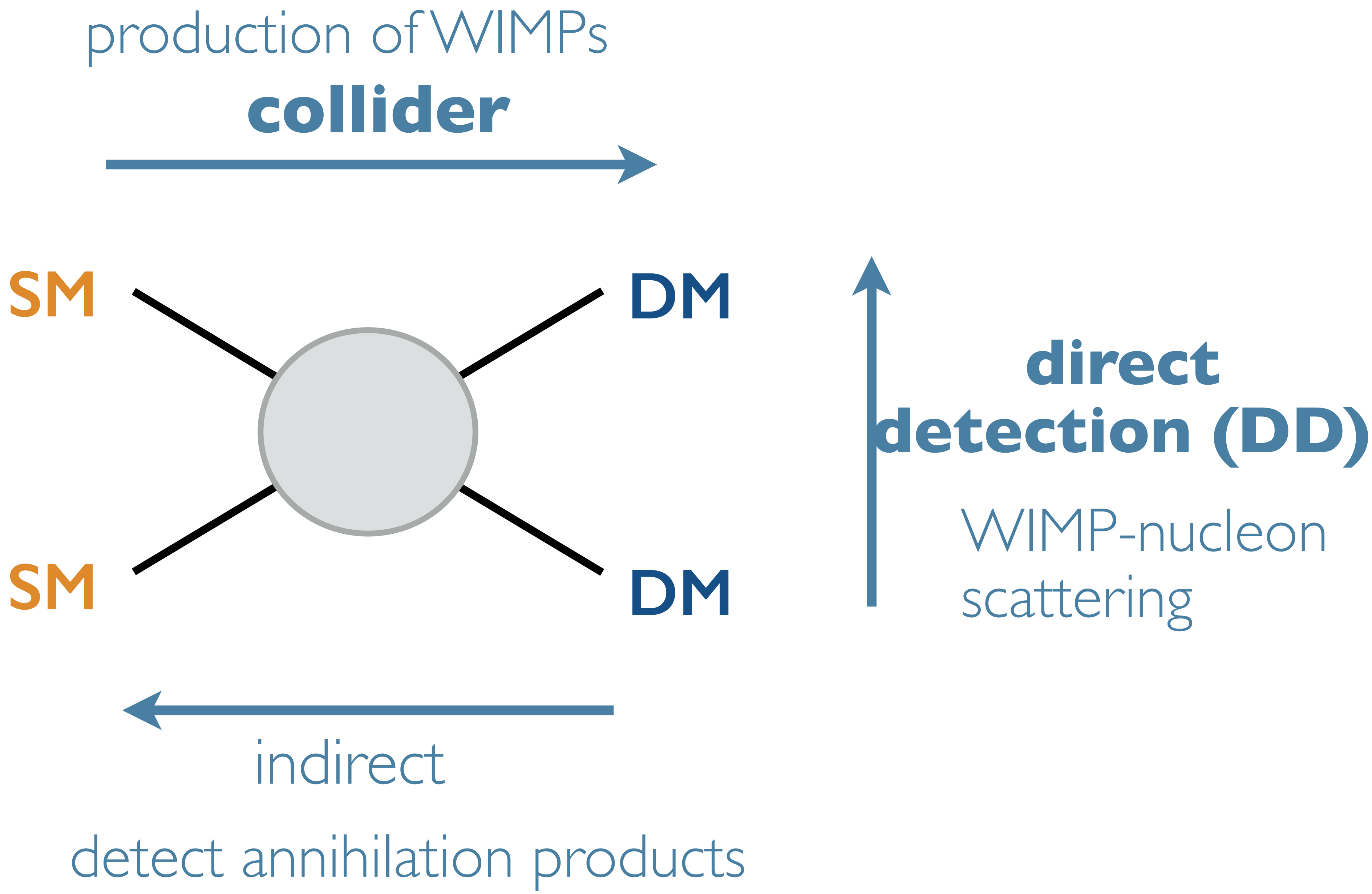
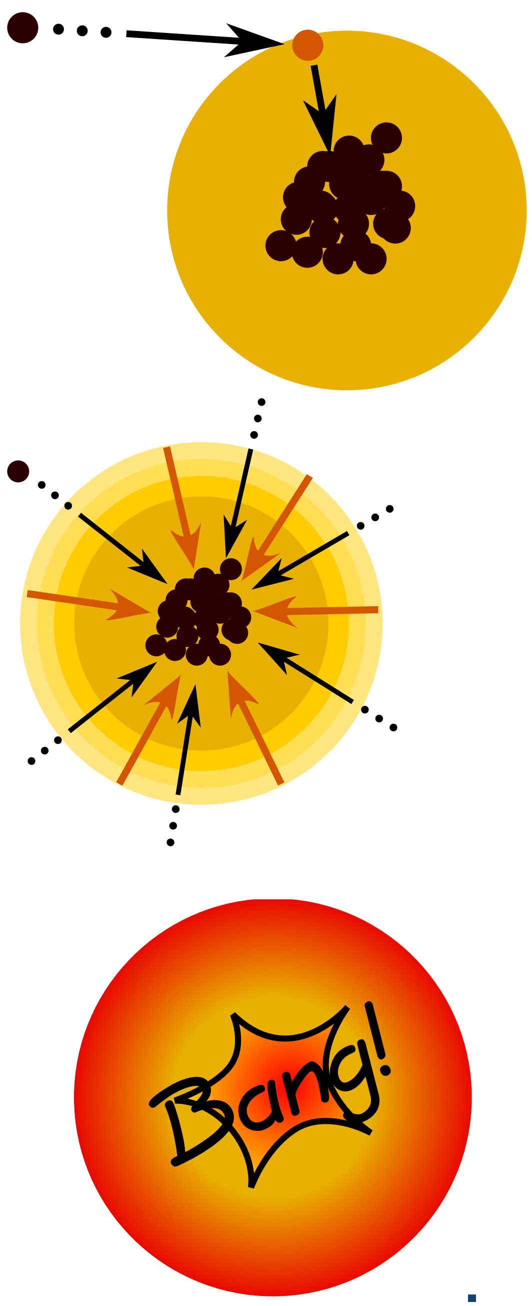


- each would merit their own lecture, of course

Indirect Detection

- look for SM products of DM annihilation
- from direction of heavy objects, where WIMPs can accumulate, e.g. sun



http://astro.ic.ac.uk/sites/default/files/PS_UKHEP15.pdf

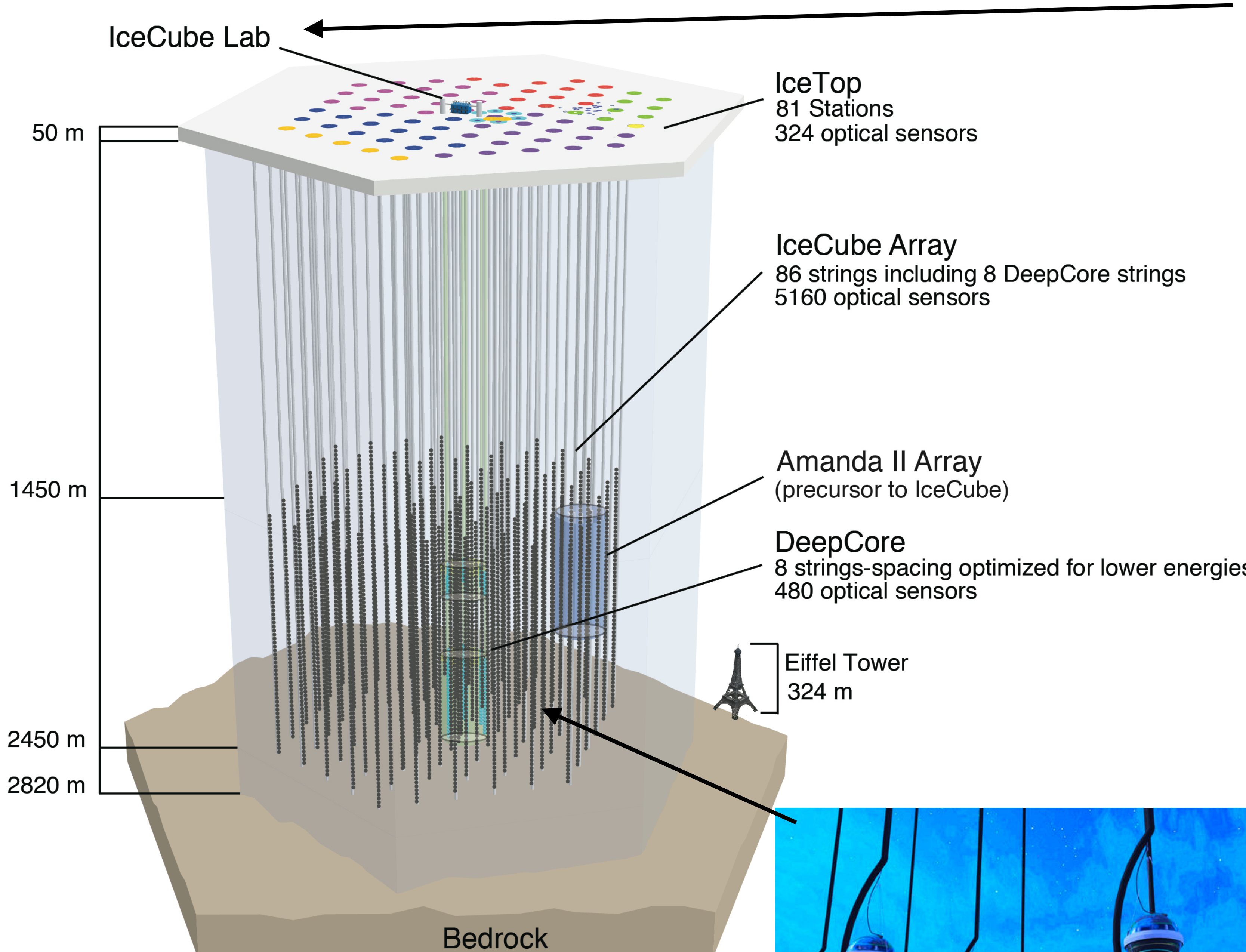
- what comes out can be
  photons,
  neutrinos,
  e^+/e^-,
  W^+/W^-,
  proton/anti-proton…

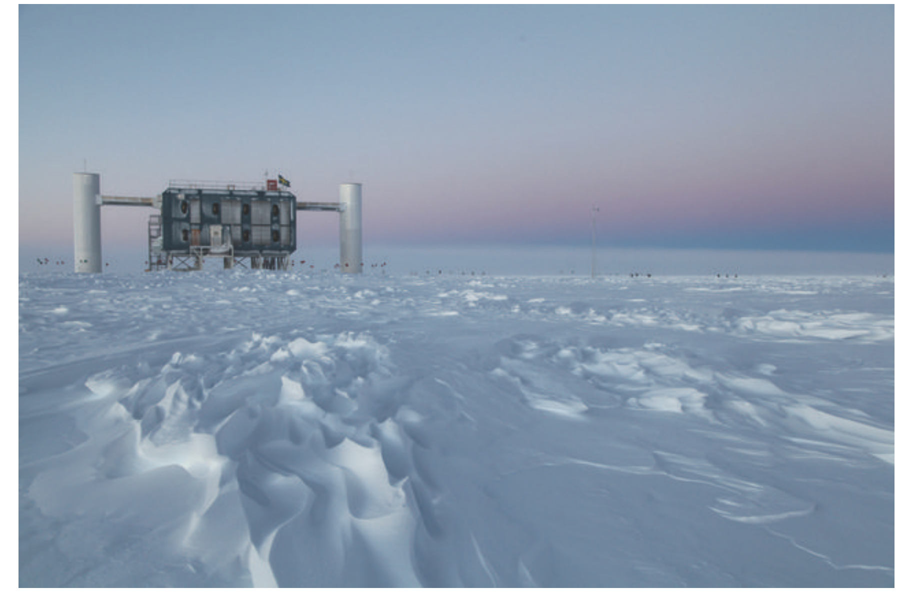
- various experiments looking for one or several of these

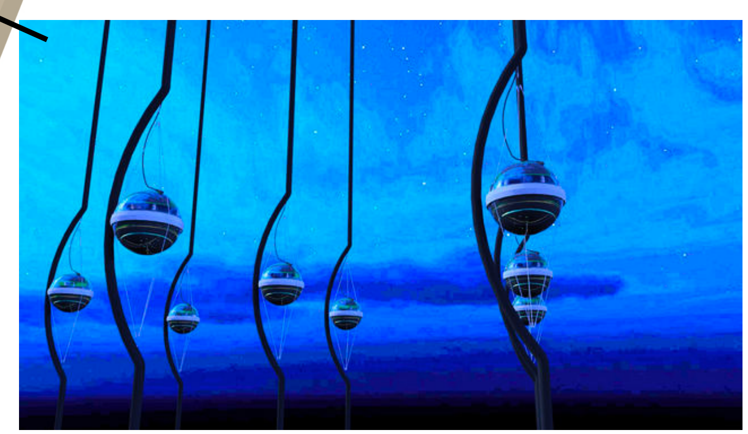
- usually needs some "extreme" location, e.g. South Pole, desert, space…

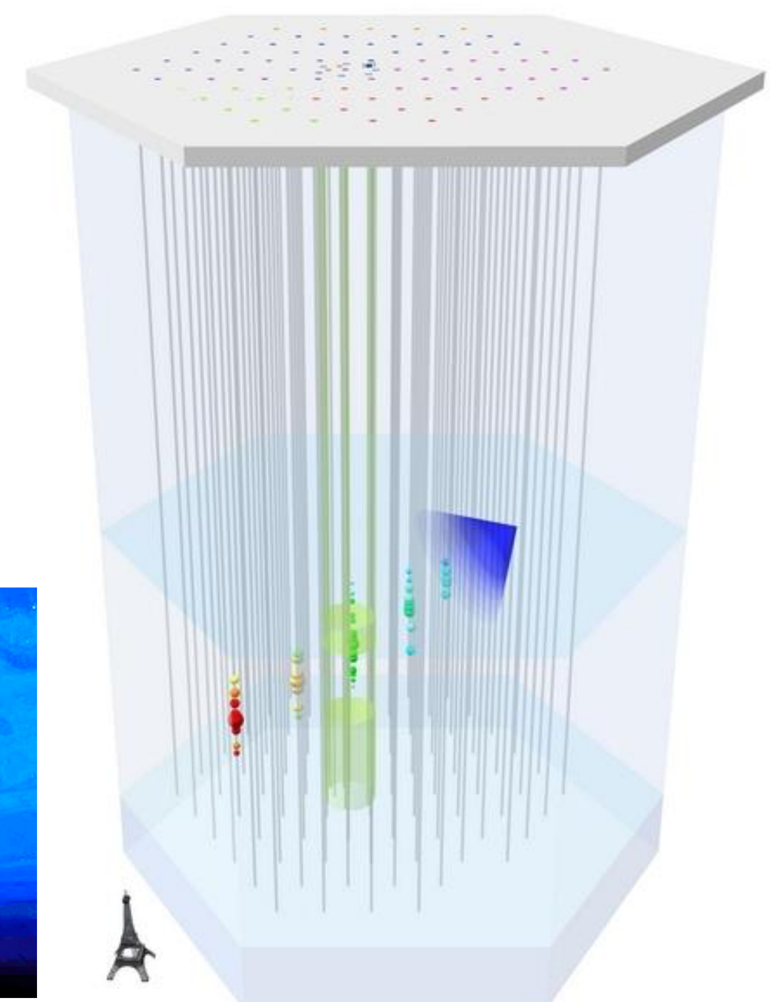
Indirect Detection – Example: IceCube

- neutrino detector at the South Pole







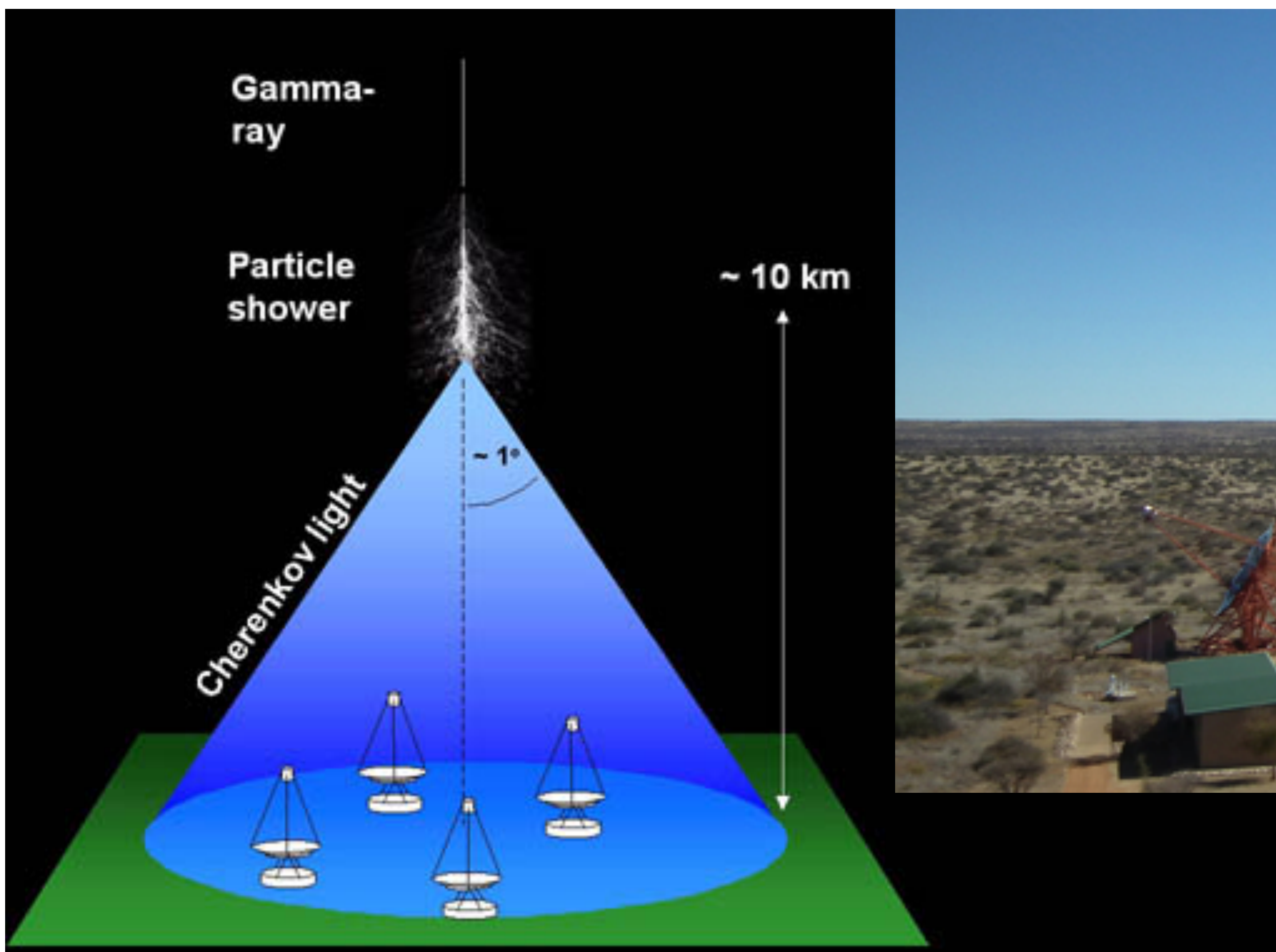


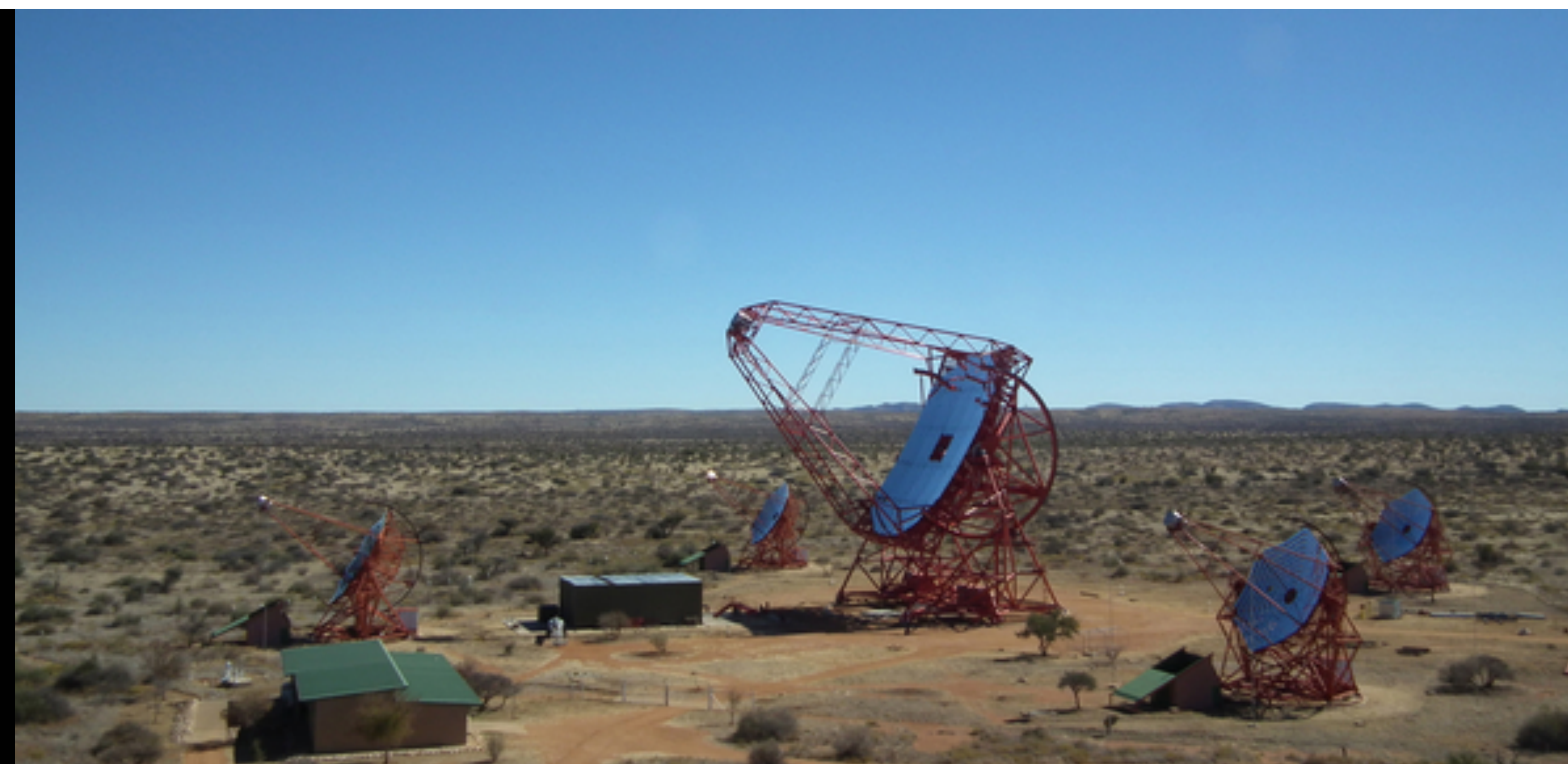
http://icecube.wisc.edu

Indirect Detection – Example: HESS

https://www.mpi-hd.mpg.de/hfm/HESS/

- H.E.S.S. - High Energy Stereoscopic System
  - astrophysics of very high energy gamma-rays (up to O(10TeV))
- look for **line in the gamma ray spectrum** ($E=m_{DM}$) from the galactic centre
- Cherenkov light from secondary particles produced in atmosphere
- TeV photon —> ~100 photons / m^2 on ground





- H.E.S.S. site in Namibia

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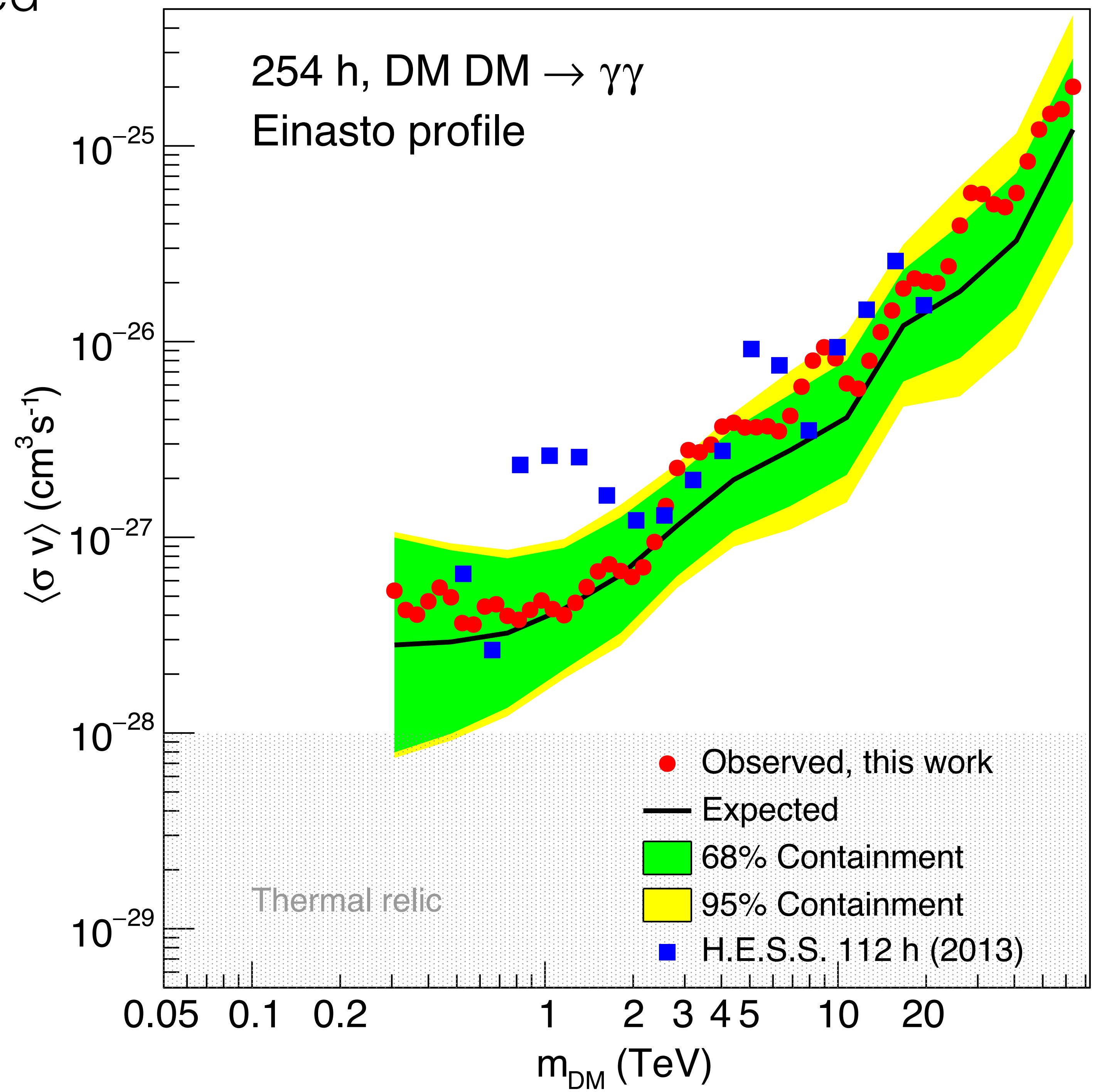
Indirect Detection – Example: HESS

- recent result [[Phys. Rev. Lett. 120, 201101 (2018)]]
  - no signal observed



Indirect Detection – Example: HESS

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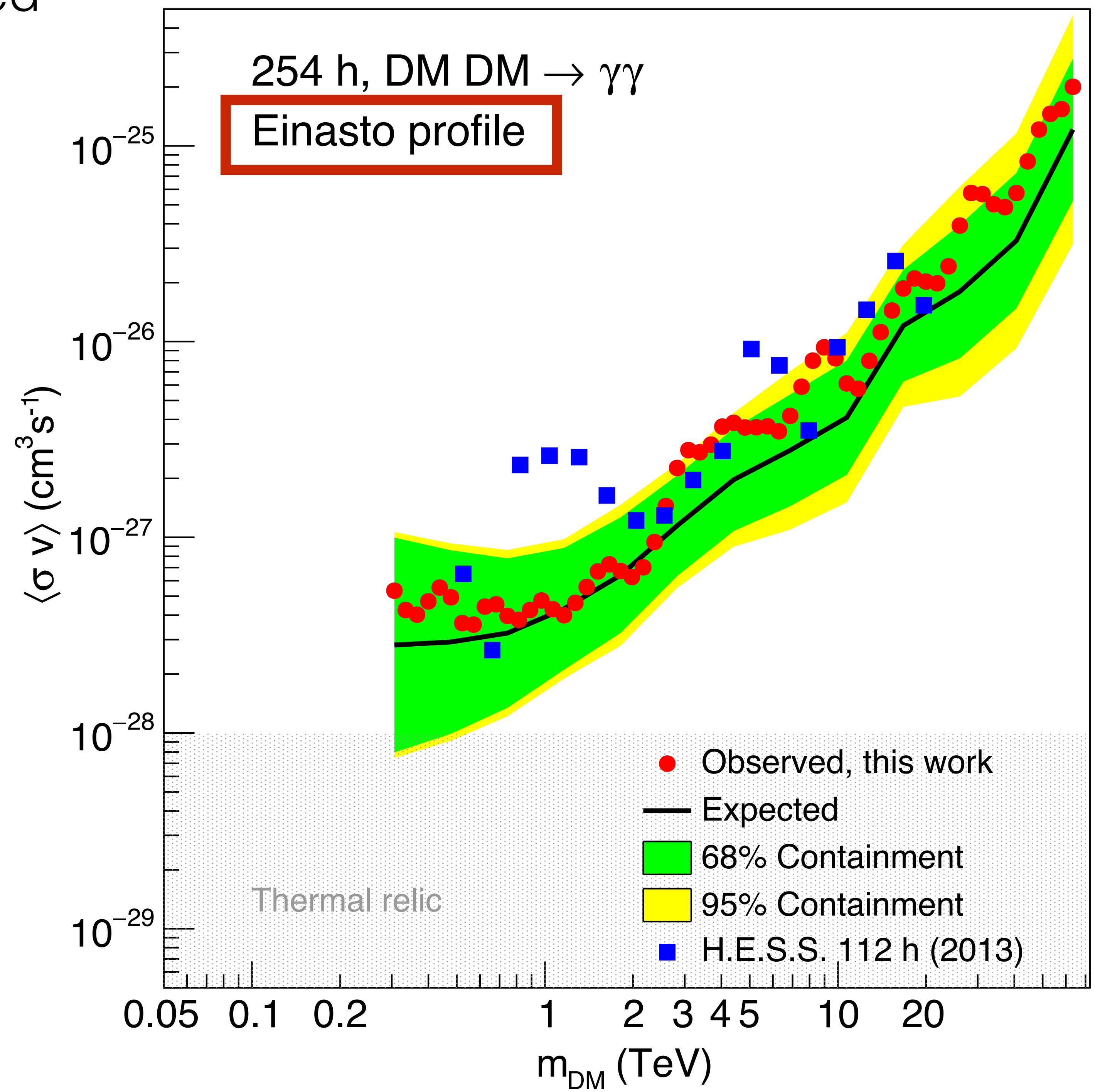

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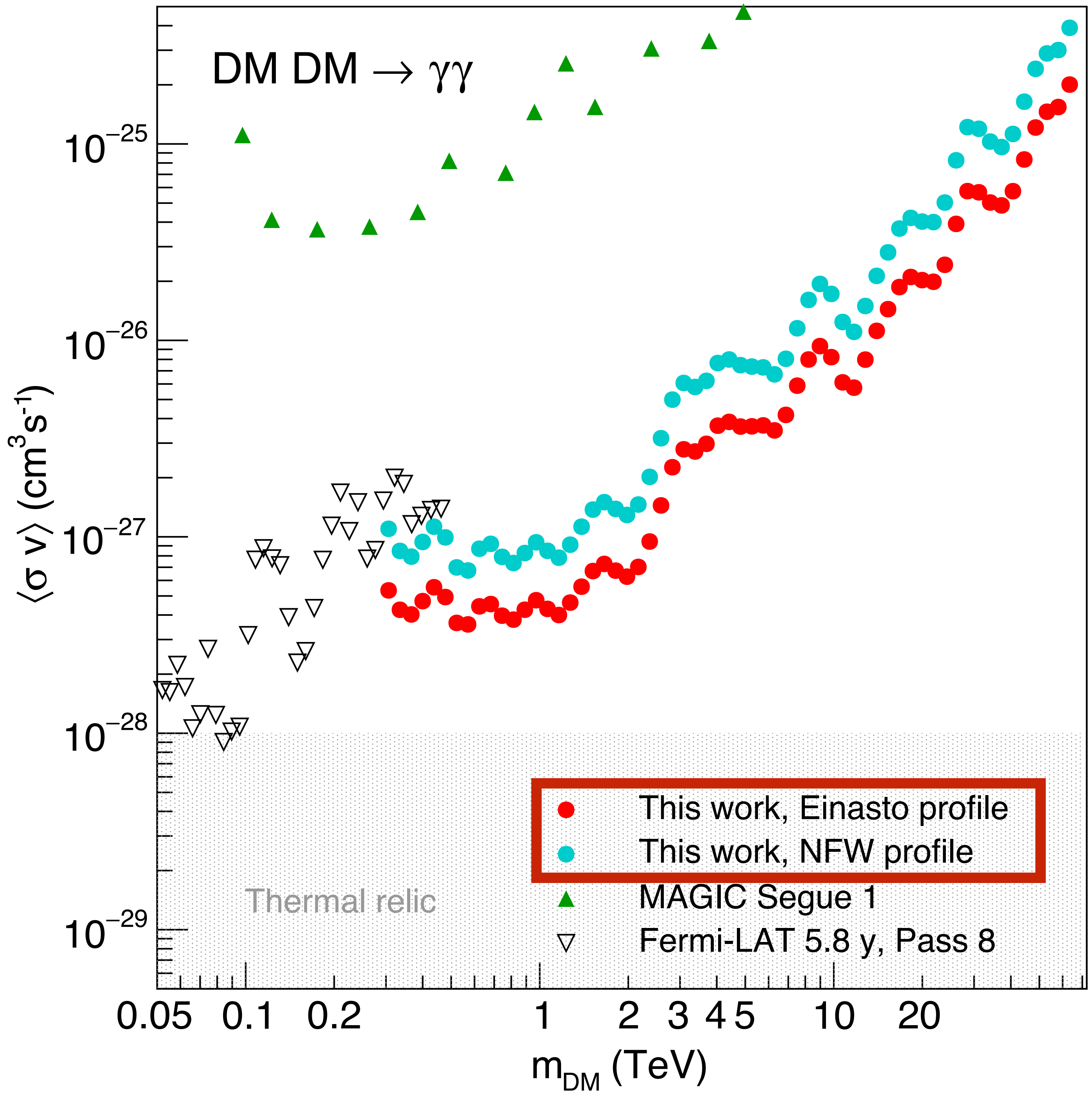

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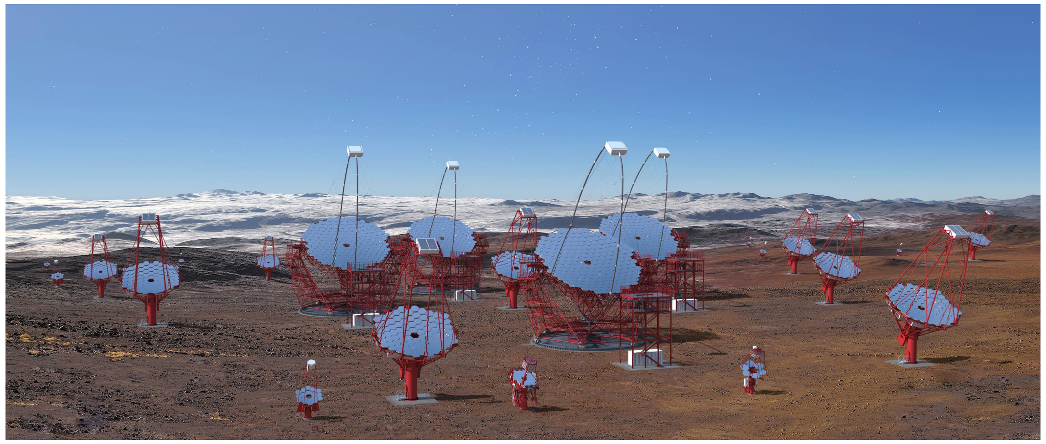
Indirect Detection – Next:CTA

- Cherenkov Telescope Array (CTA)
  https://www.cta-observatory.org

  - >100 telescopes, two sites
    (Northern and Southern hemisphere)

    - La Palma

    - Chile

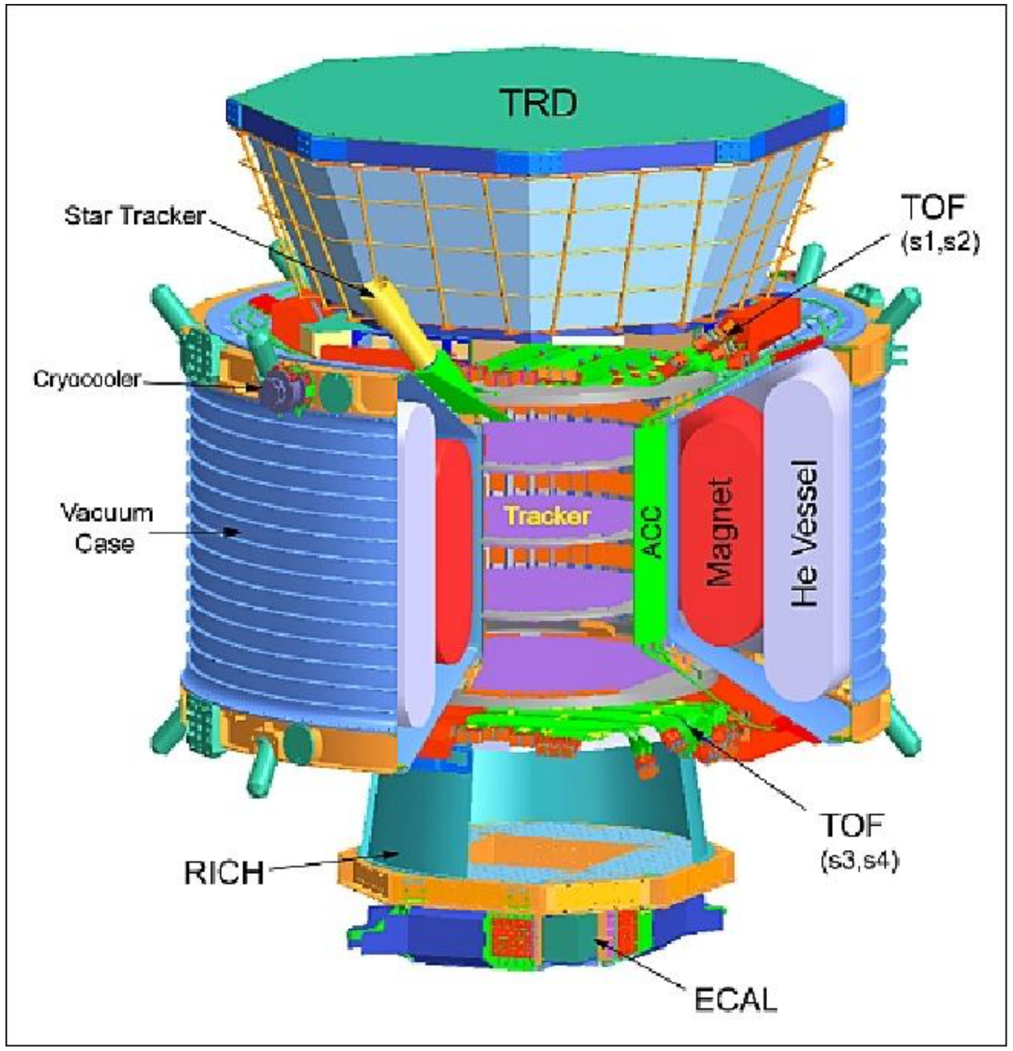


- host agreement signed in Dec 2018
  link

Indirect Detection – Example: AMS

http://www.ams02.org

- Alpha Magnetic Spectrometer on ISS
  - large magnet system to measure charge of particles —> distinguish particles and anti-particles
  - several sub-systems for particle identification, energy/velocity measurements…



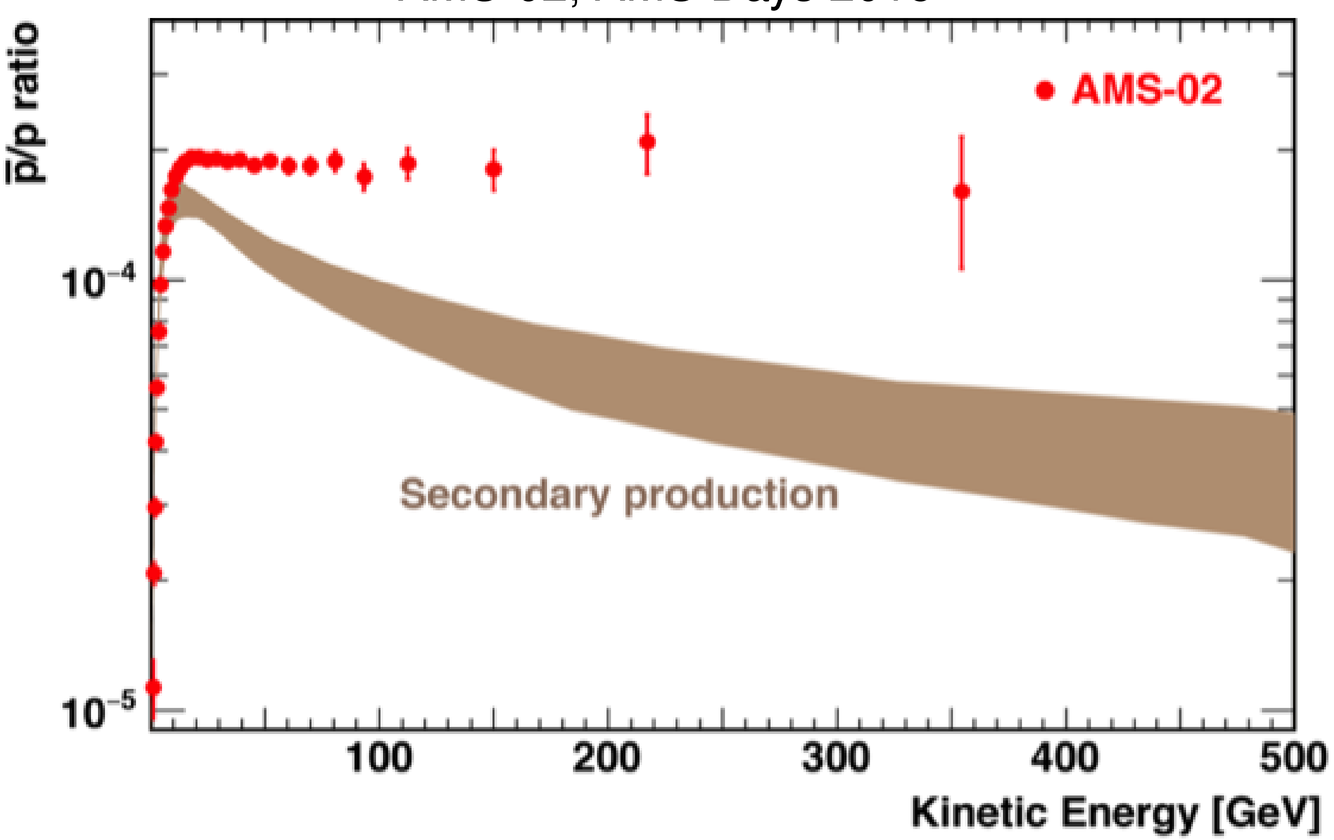
https://eoportal.org/web/eoportal/satellite-missions/content/-/article/iss-utilisation-ams

- studies the composition and flux of cosmic rays outside the Earth's atmosphere

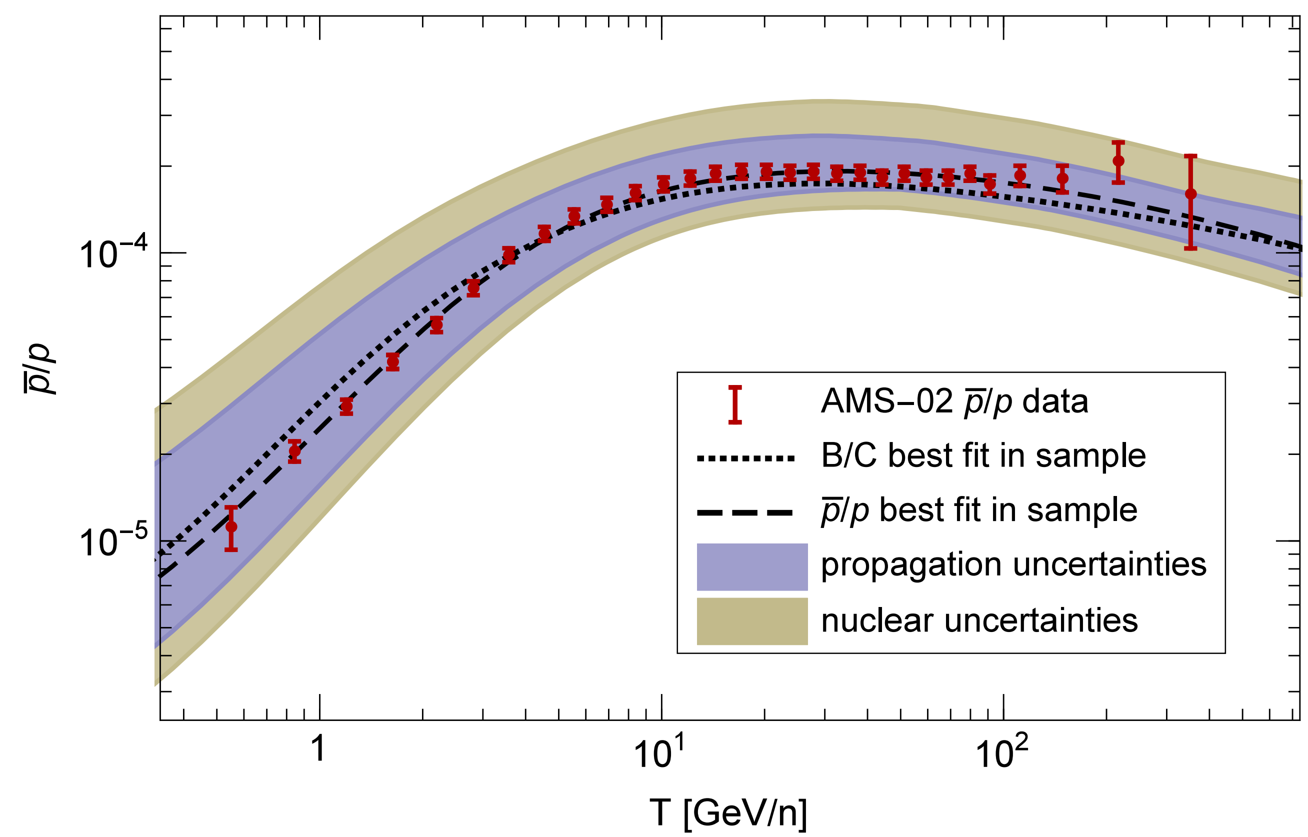
Indirect Detection – Interpretation

- example from AMS
- interpretation can be difficult

AMS-02, AMS Days 2015



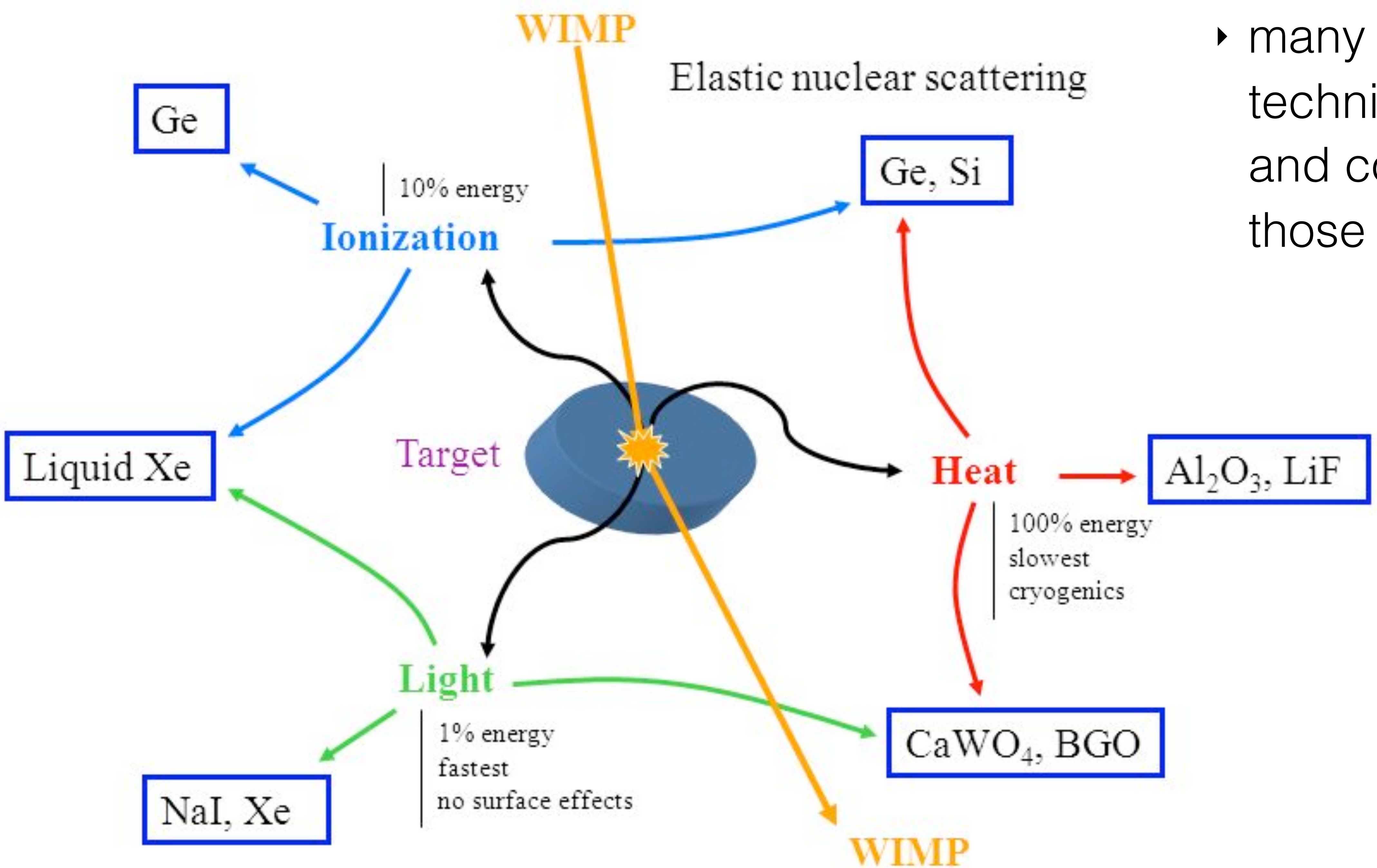
Kappl et al, arXiv:1506.04145



- often not straight forward to exclude astrophysical sources for effects seen
- discovery somewhat difficult

Direct Detection Techniques

- general principle: detect elastic scattering of WIMPs in a detector
- deep underground to shield from backgrounds from cosmic rays

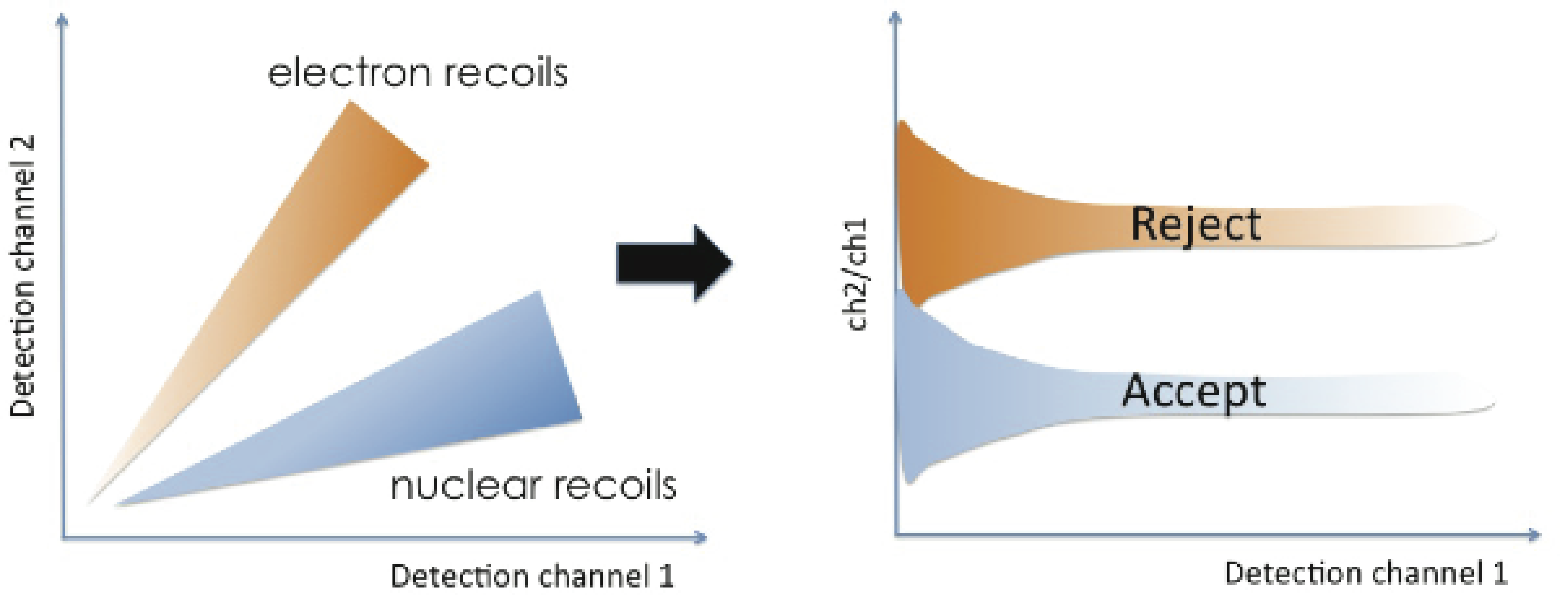


- many different techniques/materials and combination of those

http://slideplayer.com/slide/10386524/

Direct Detection Techniques

- advantage of dual signal use:
  exploit correlation to increase signal/background separation



Direct Detection - Example: Liquid Xenon

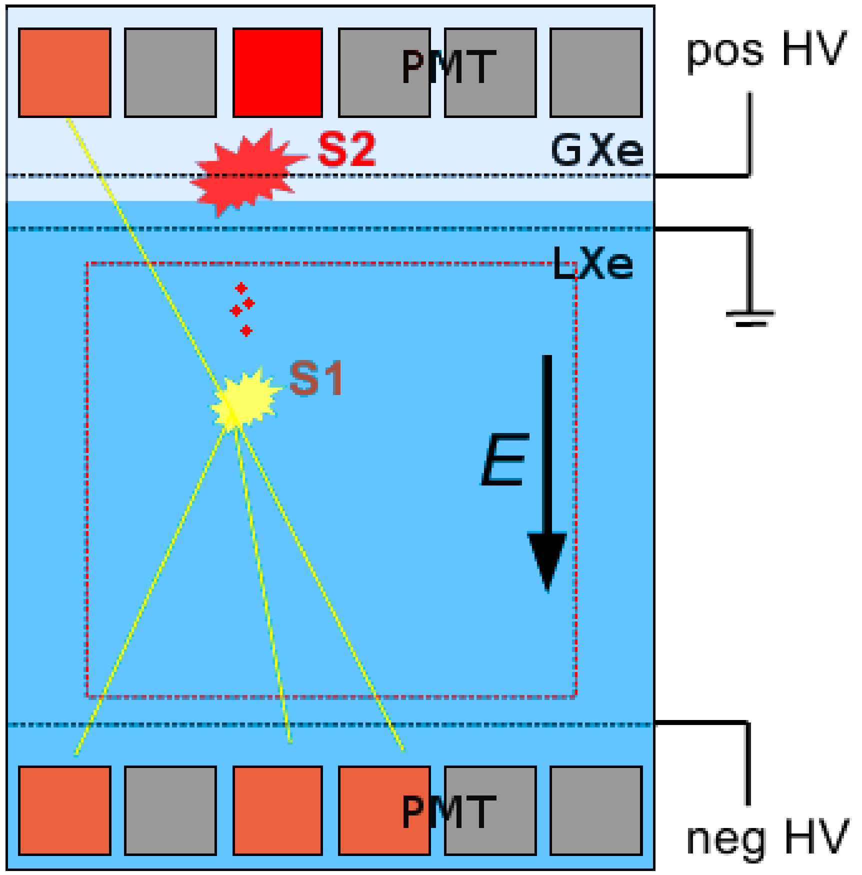
- example: Xenon(1T)
  http://www.xenon1t.org

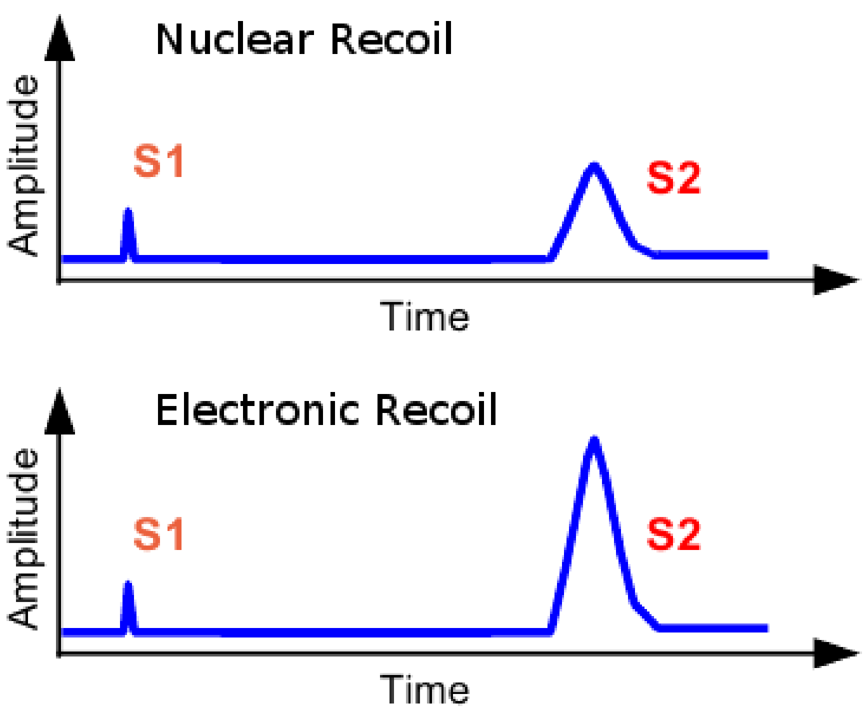
https://indico.fnal.gov/event/9942/session/2/material/slides/0?contribId=36

- below 1400m of rock

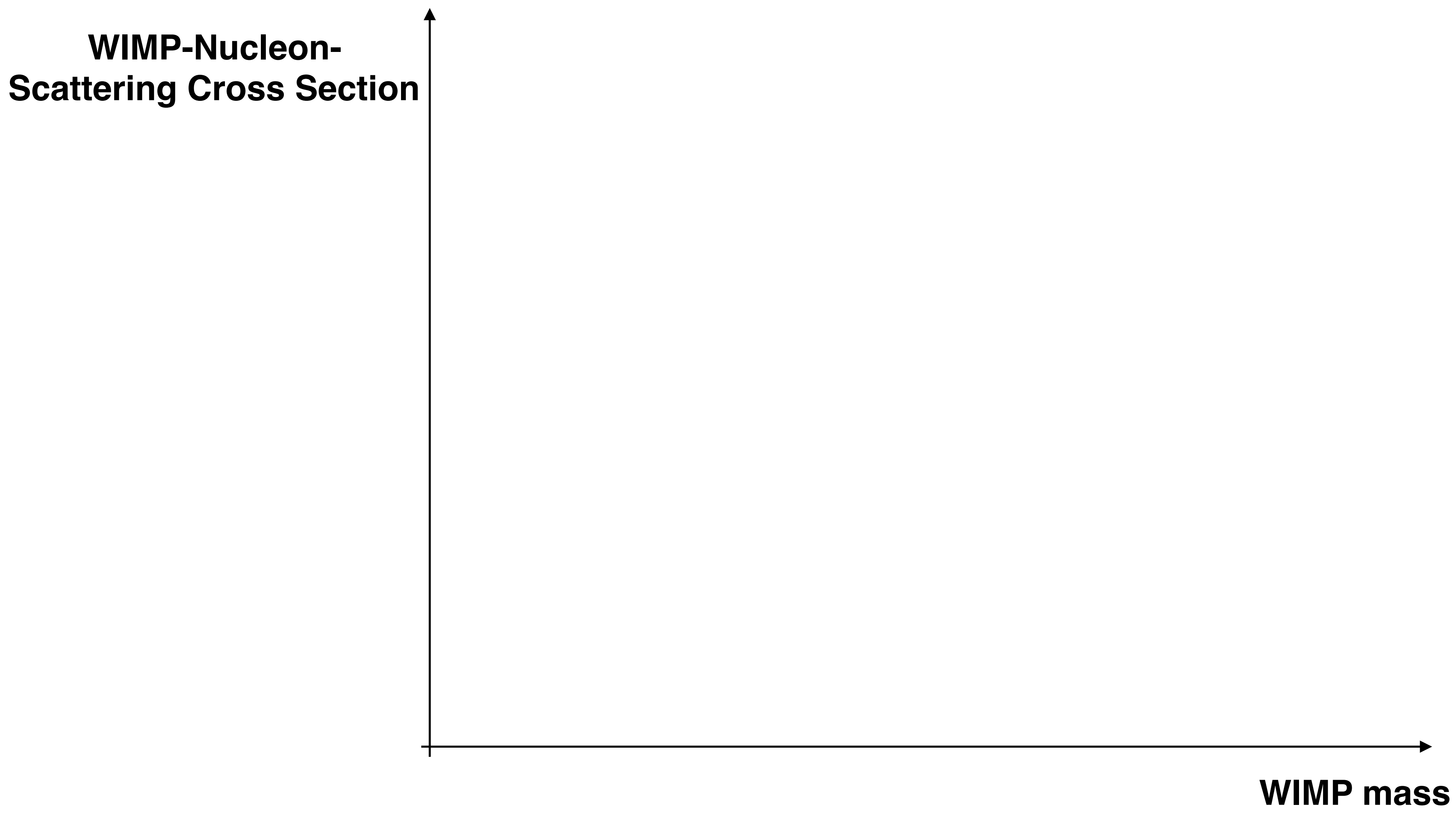
- uses both ionisation & scintillation

https://arxiv.org/abs/1405.7600





Presentation of Results



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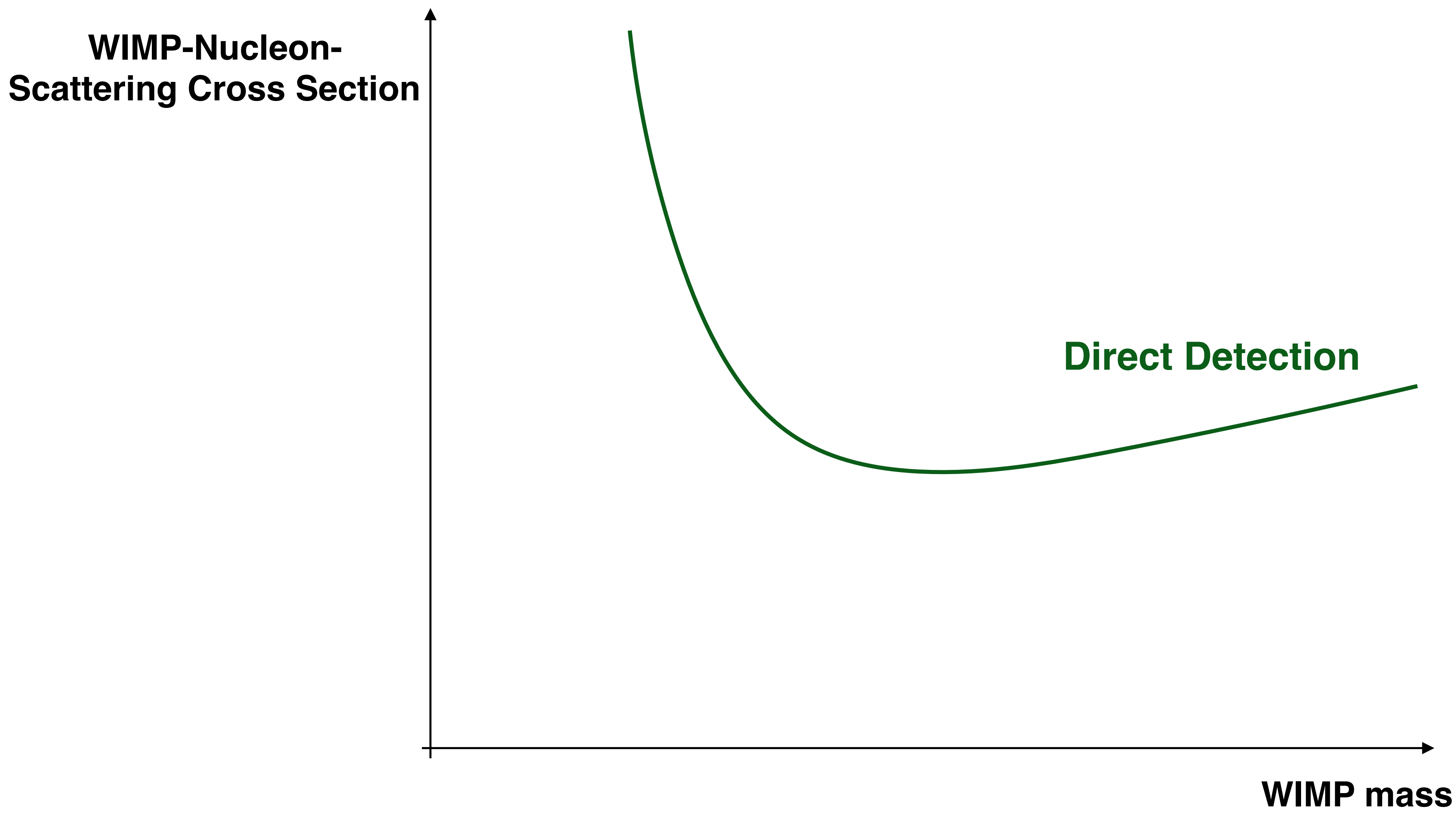
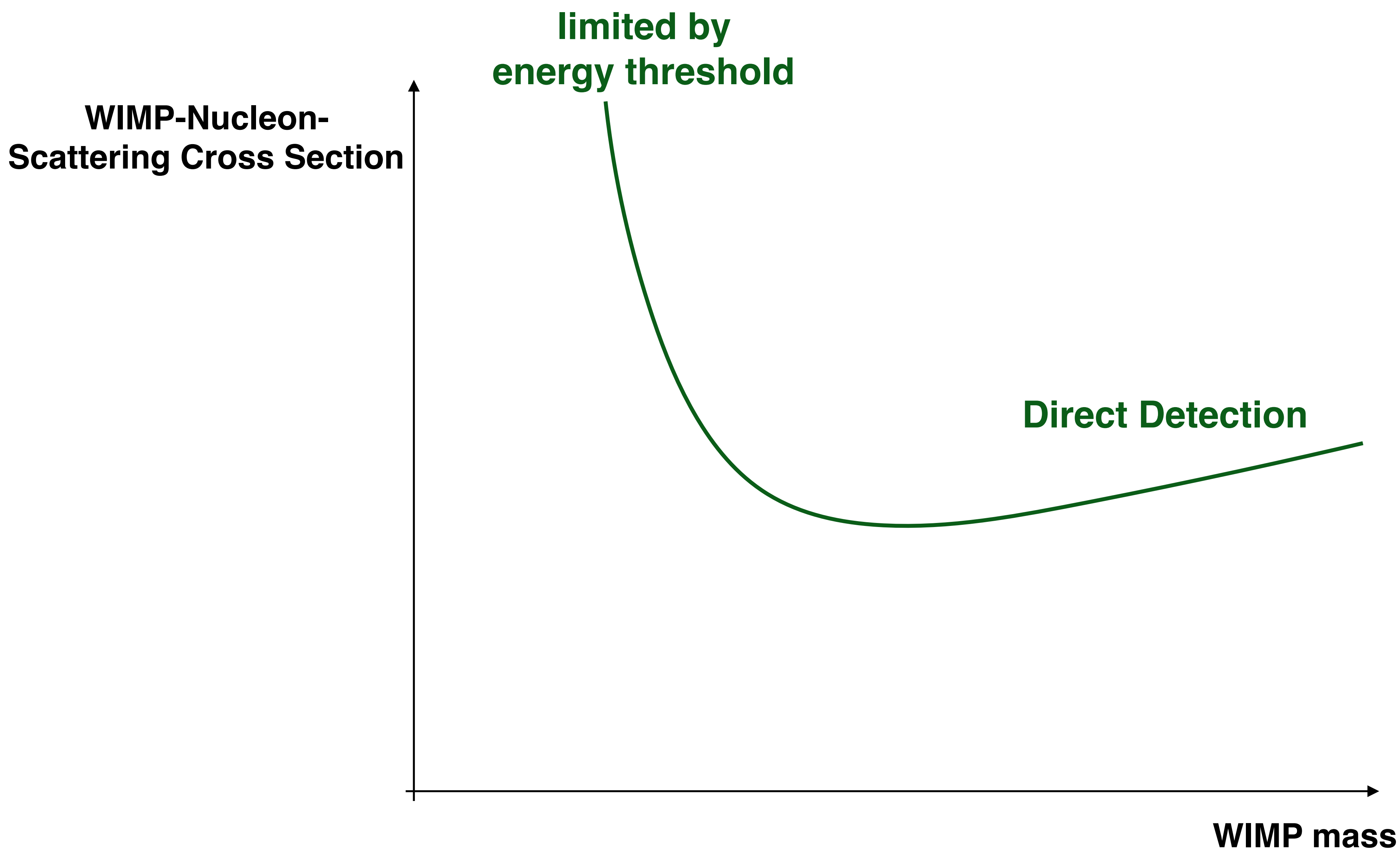
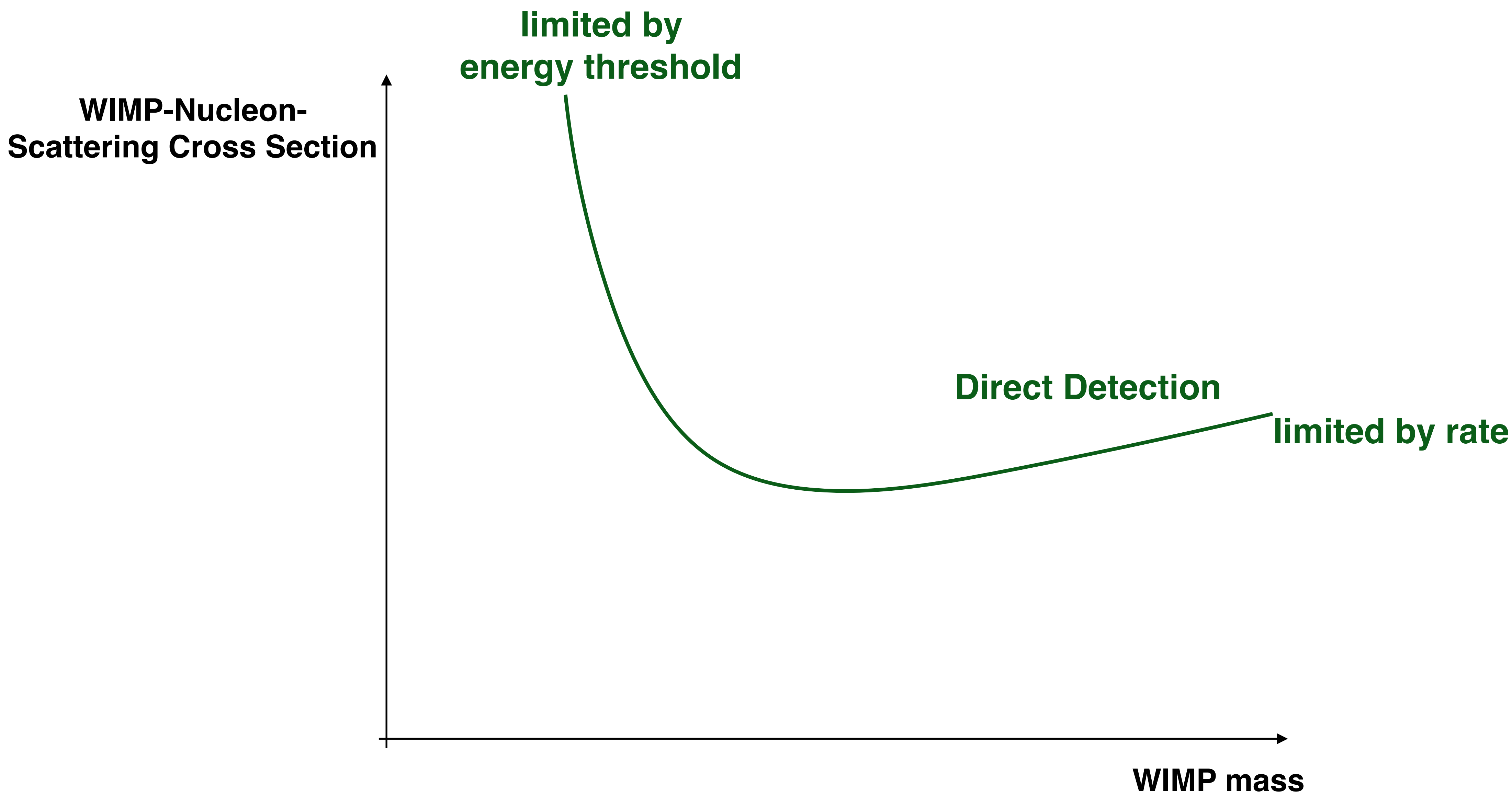
Presentation of Results



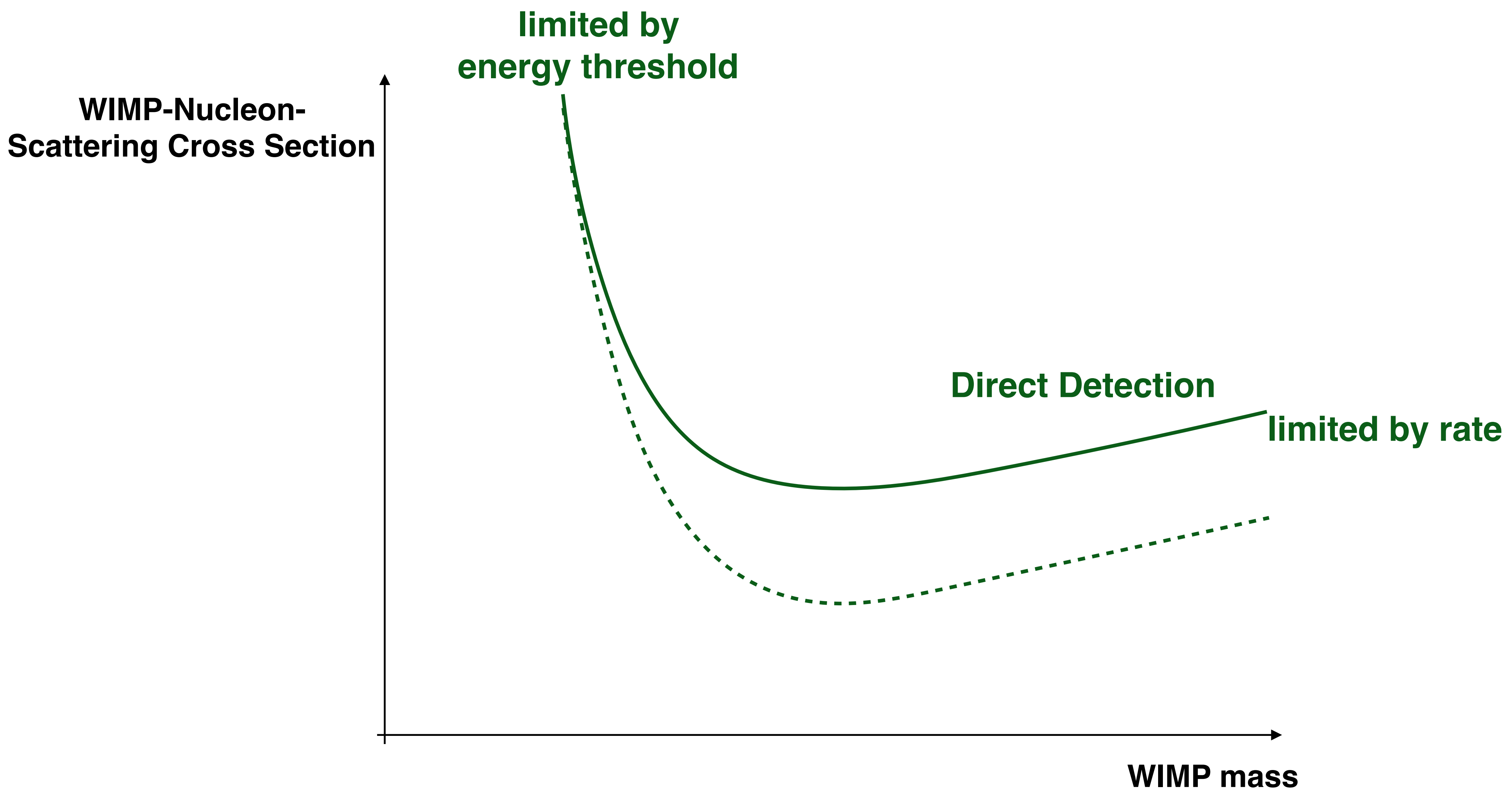
Presentation of Results



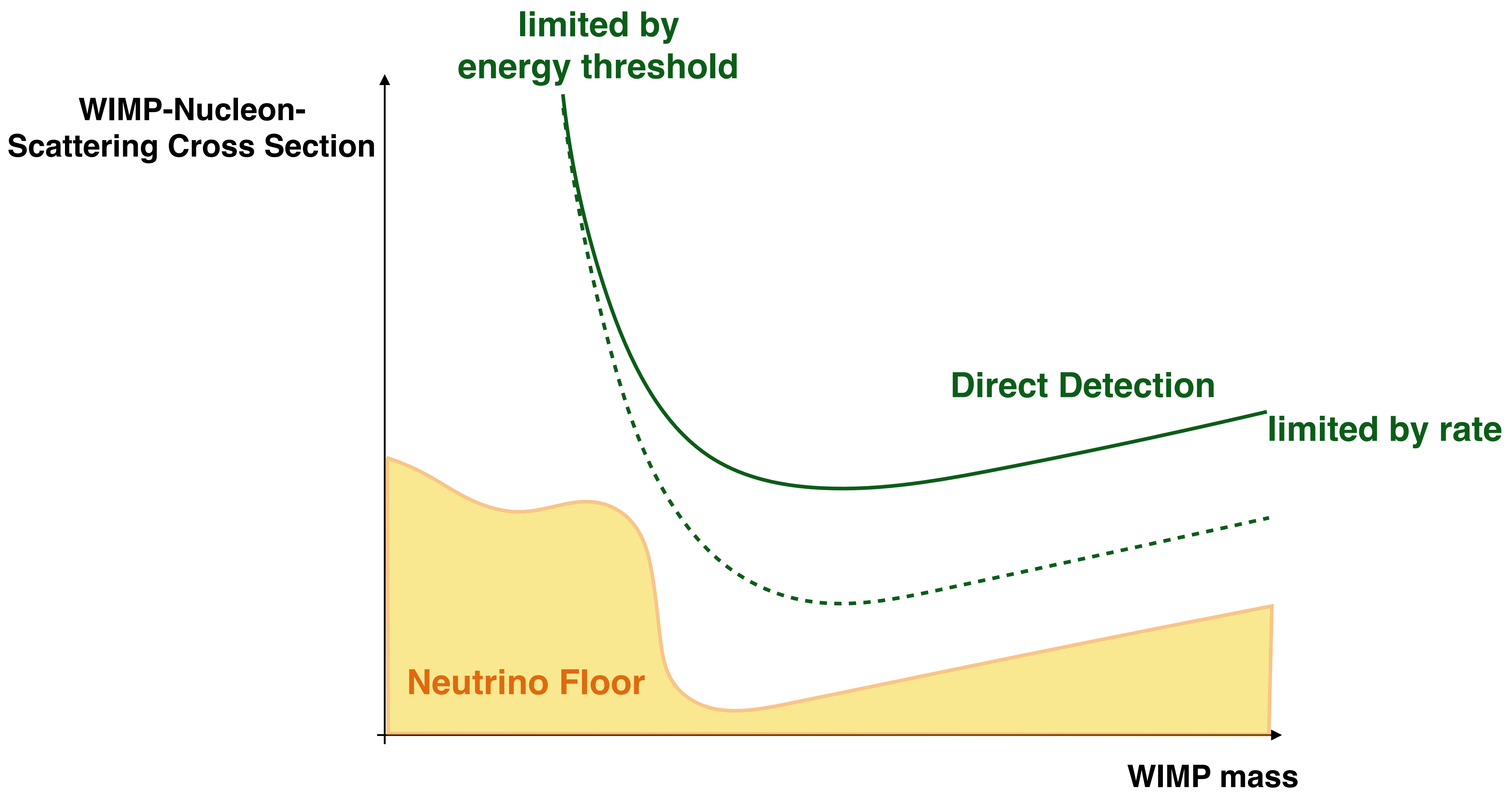
Presentation of Results



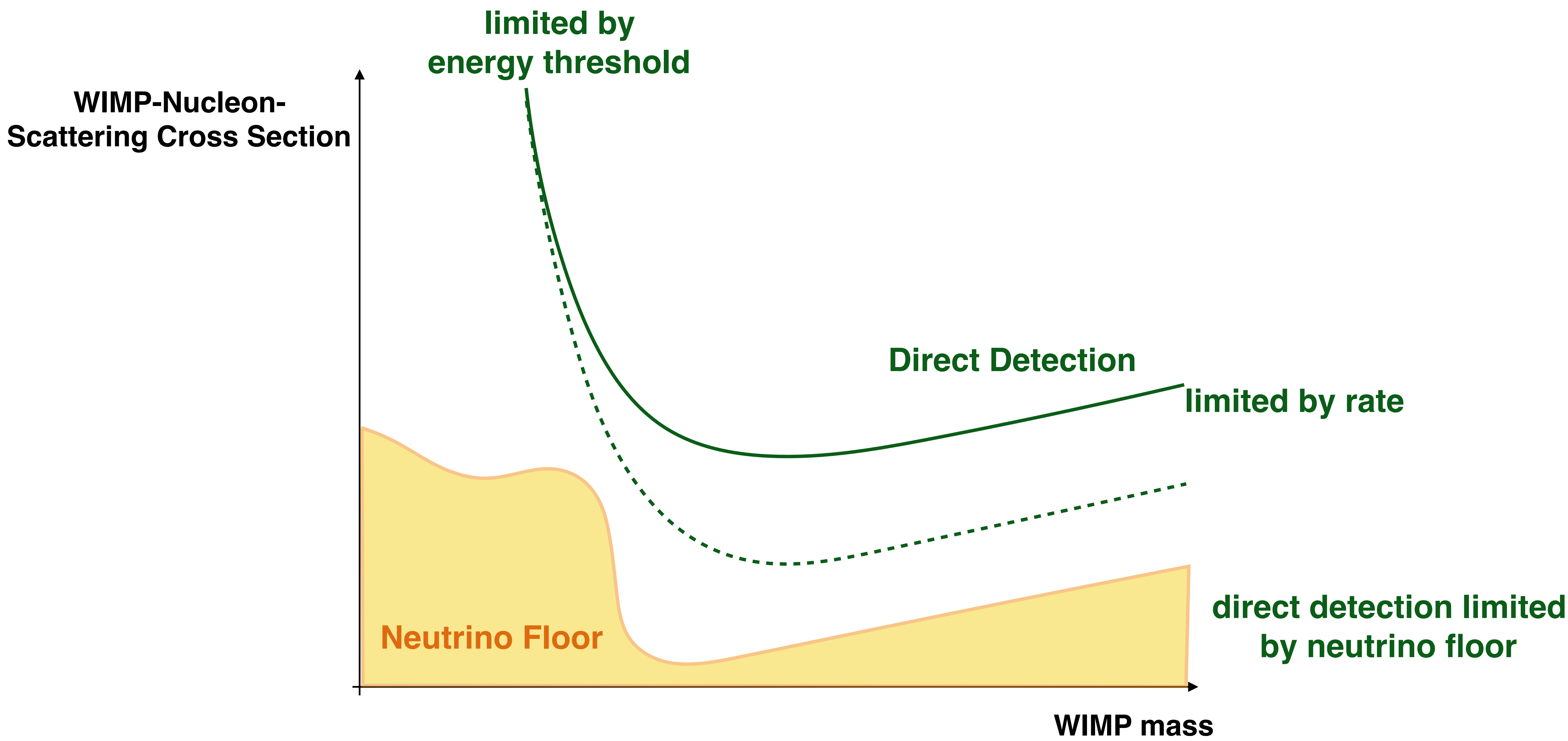
Presentation of Results



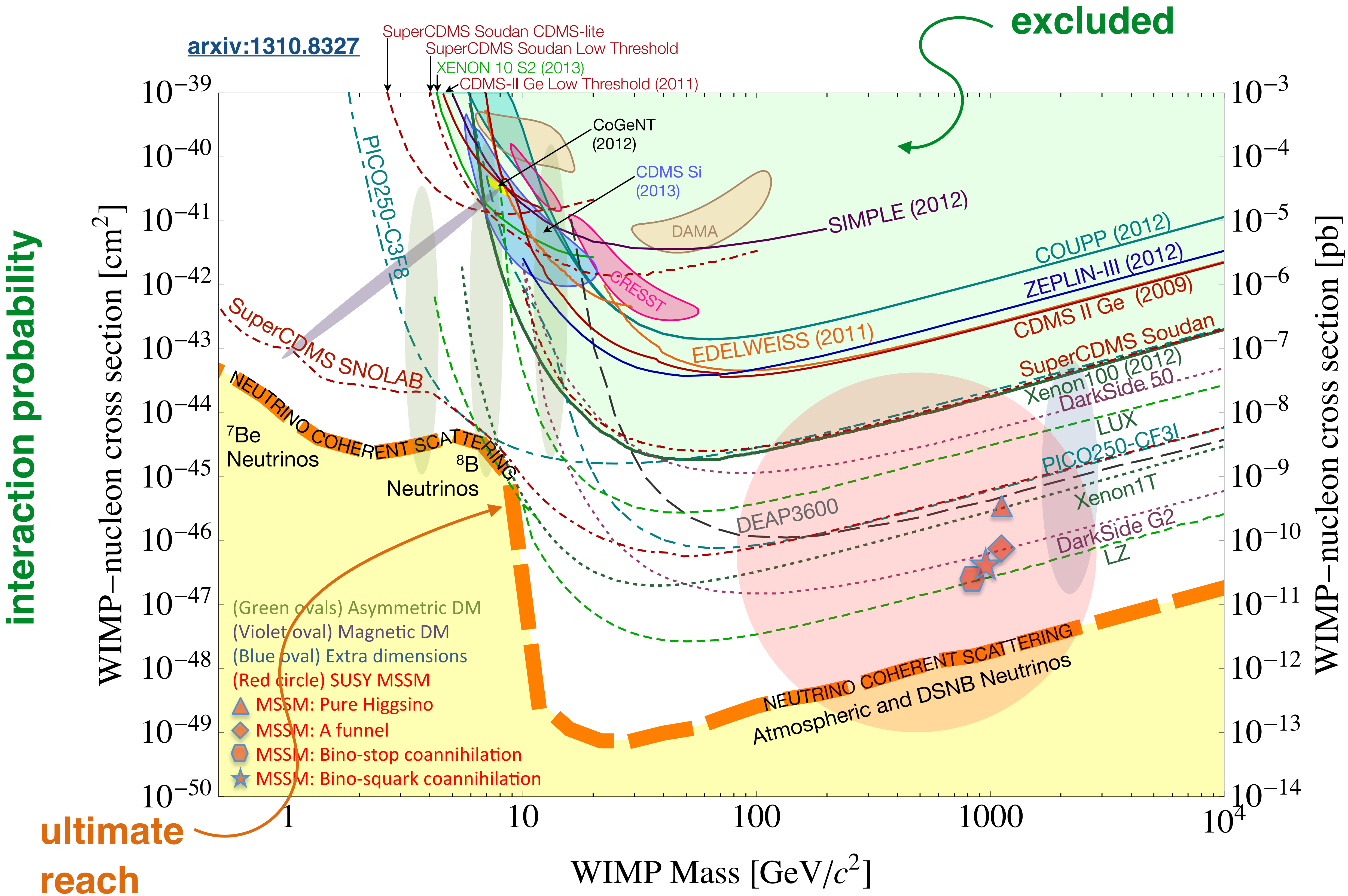
Presentation of Results



Presentation of Results



Real Life

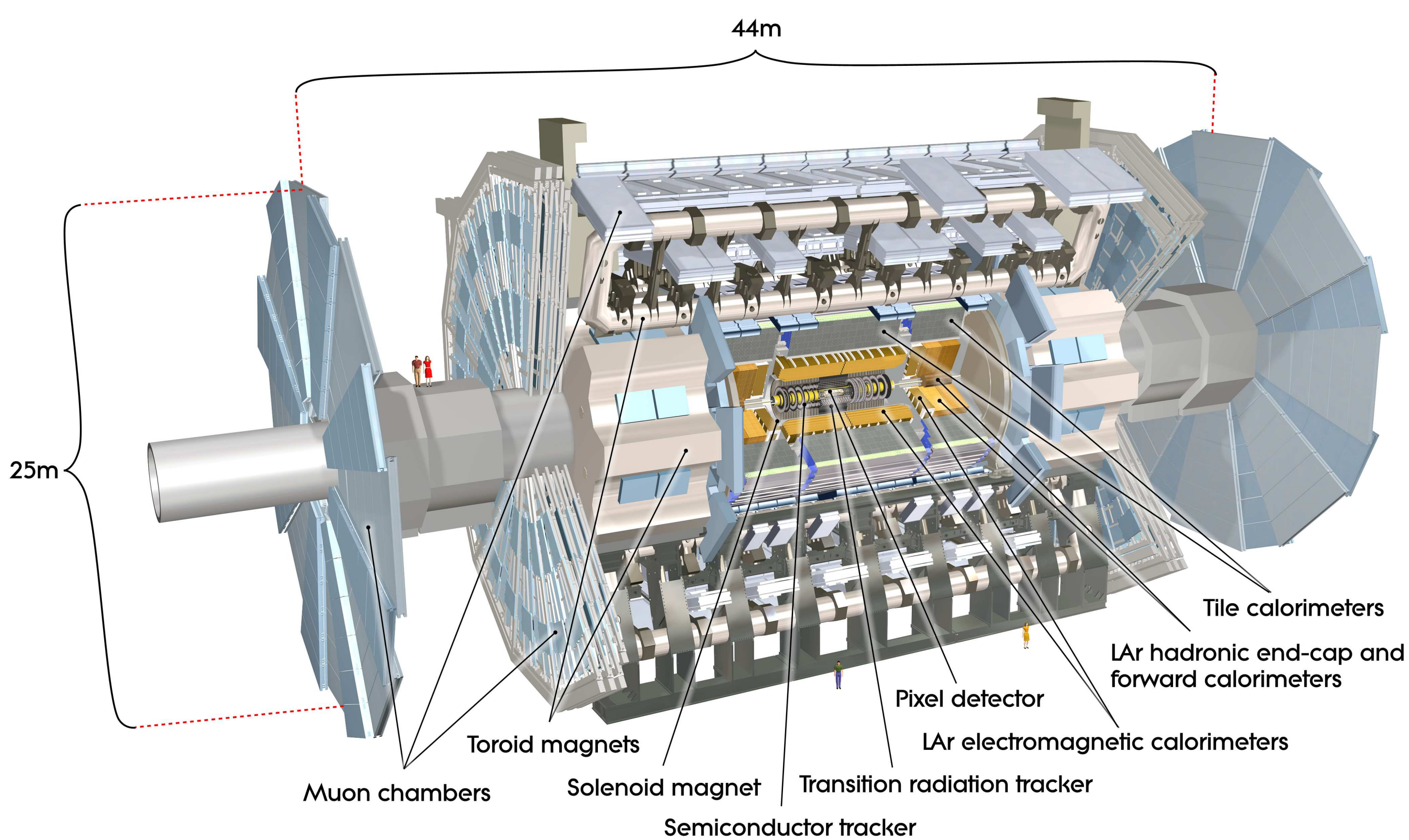


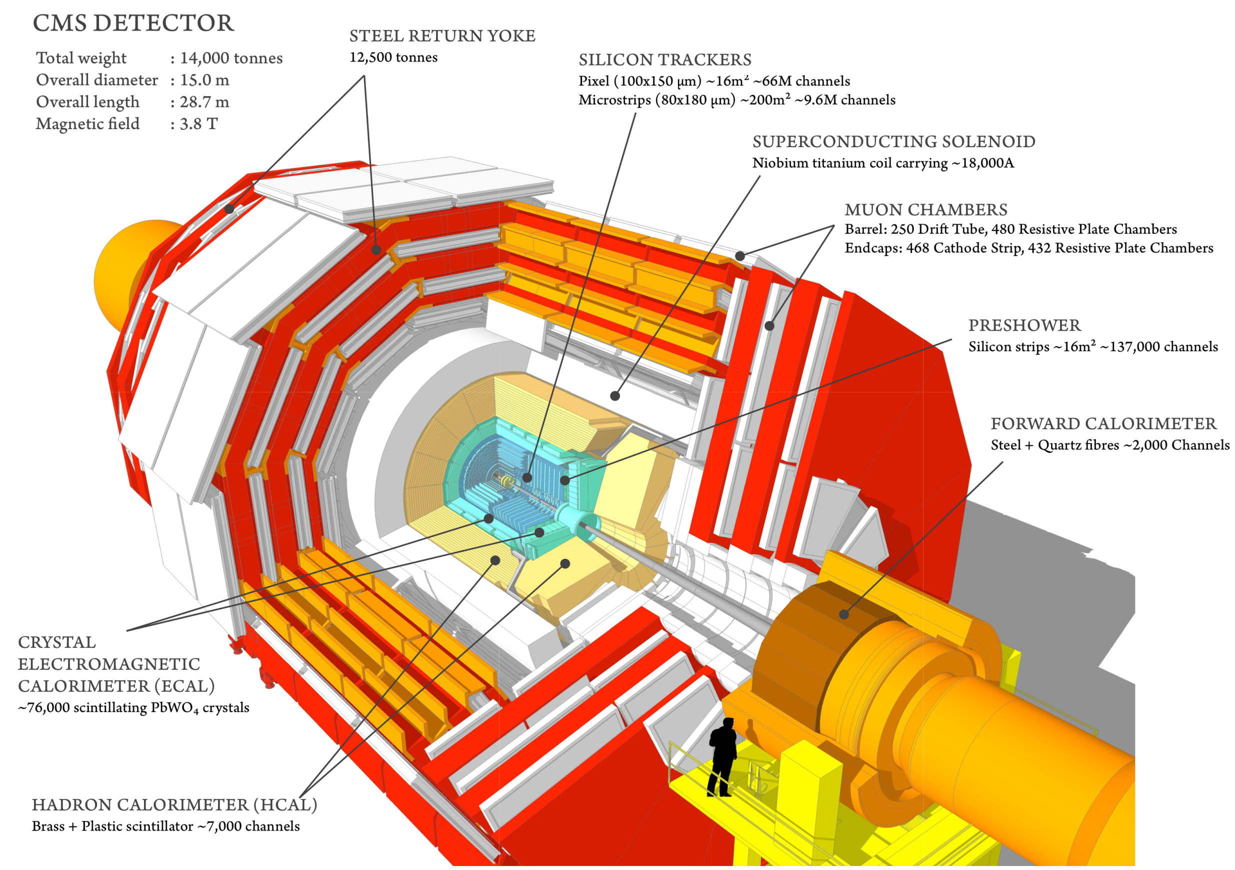
arxiv:1310.8327
excluded
interaction probability
ultimate reach
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4

Collider-based Searches

i.e. LHC

- ATLAS, CMS — *general purpose* experiments
  - designed to study a lot of different questions



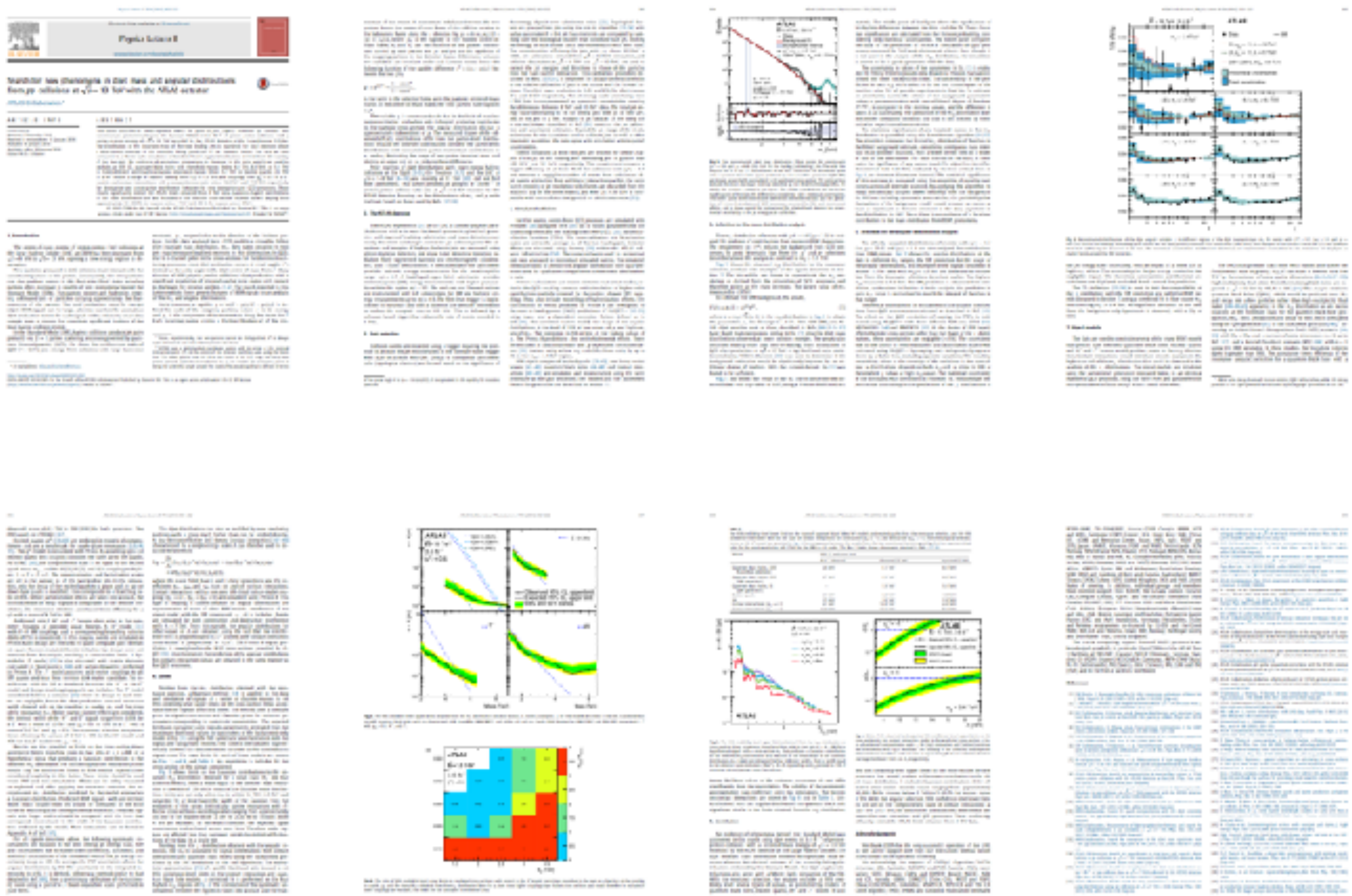


- LHCb, ALICE: more specialised

ATLAS Collaboration

- ~5000 scientists from 180 institutes in 38 countries

An ATLAS scientific paper (made in Lund)



(from Caterina Doglioni)

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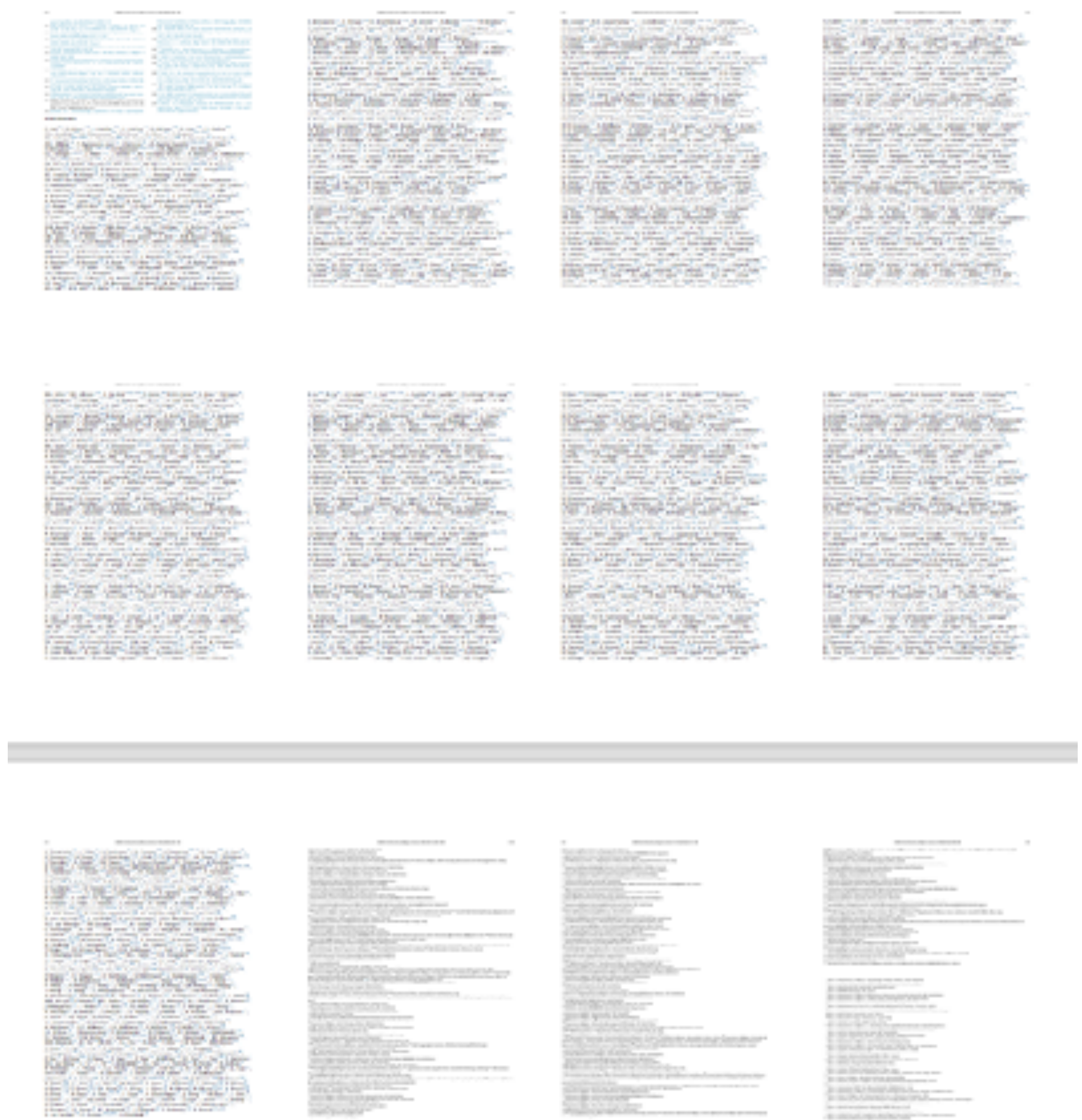
The author-list of an ATLAS paper



(from Caterina Doglioni)

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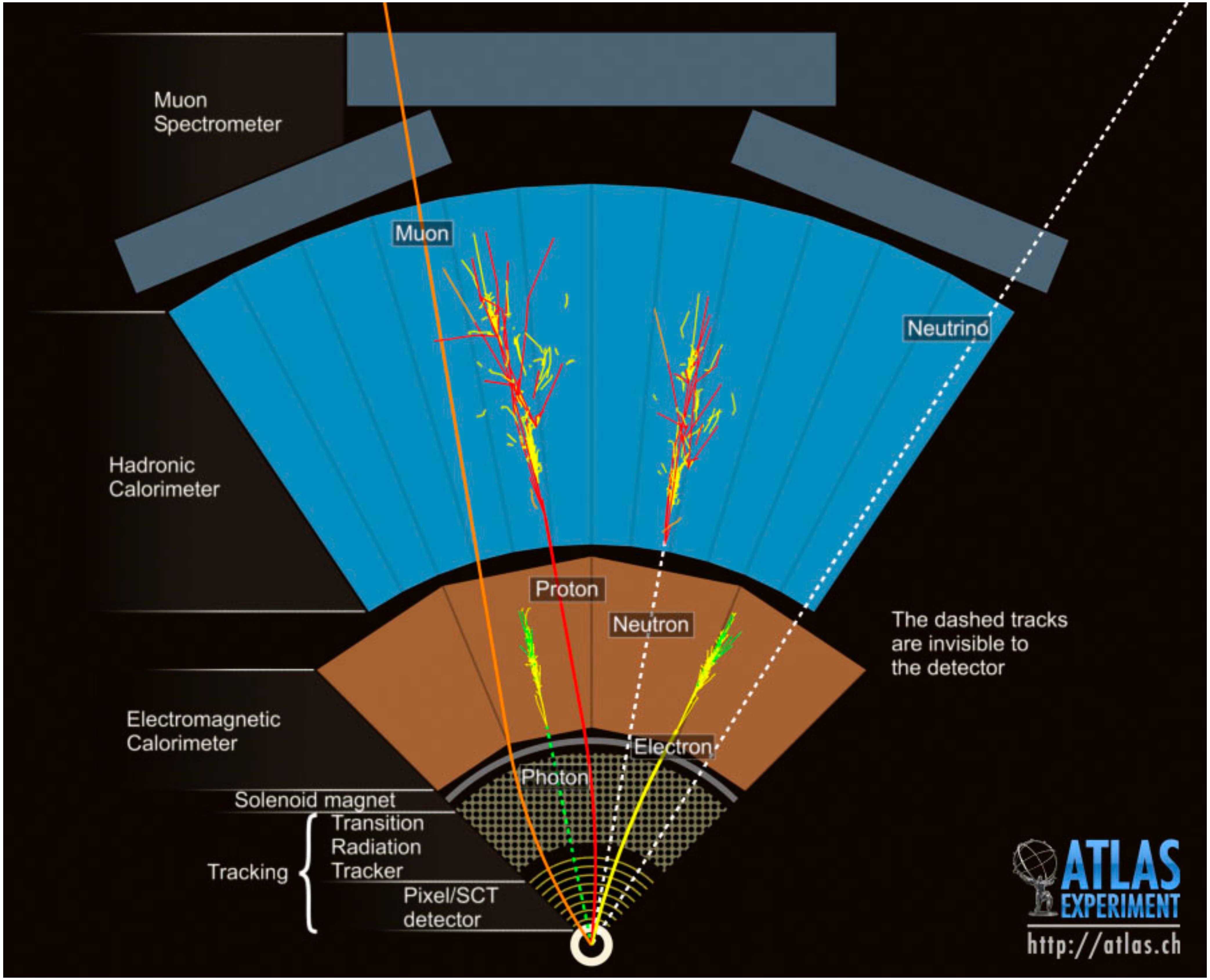
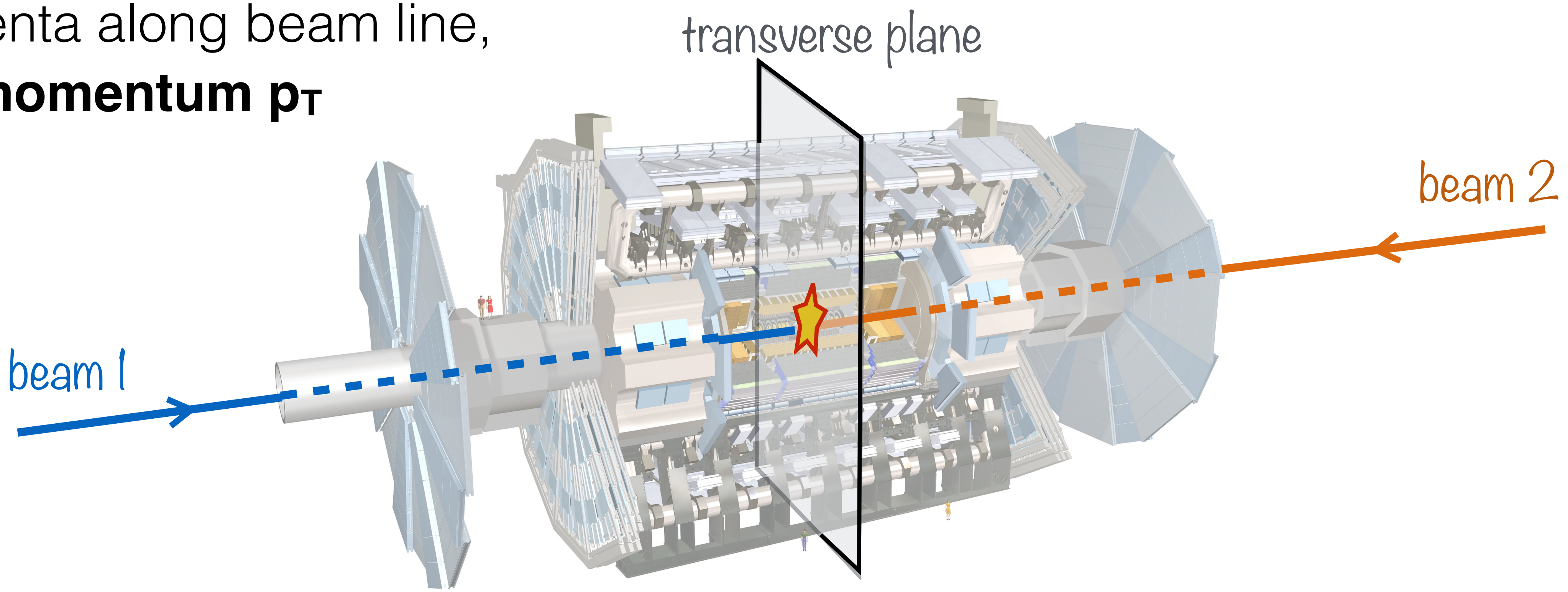
Particles in ATLAS



Seeing the invisible

- initially: all momenta along beam line, **no transverse momentum p_T**



- vector sum of transverse momenta after collision has to **sum up to 0**!

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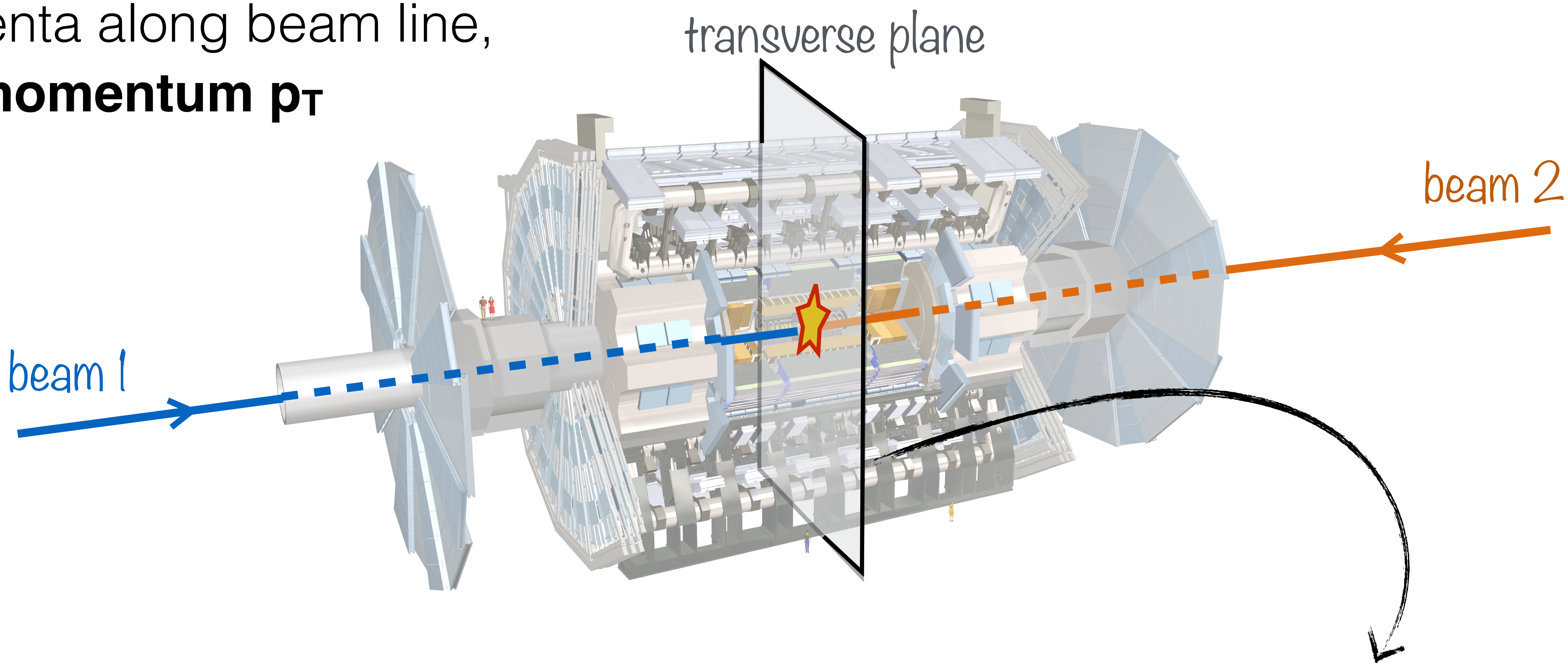

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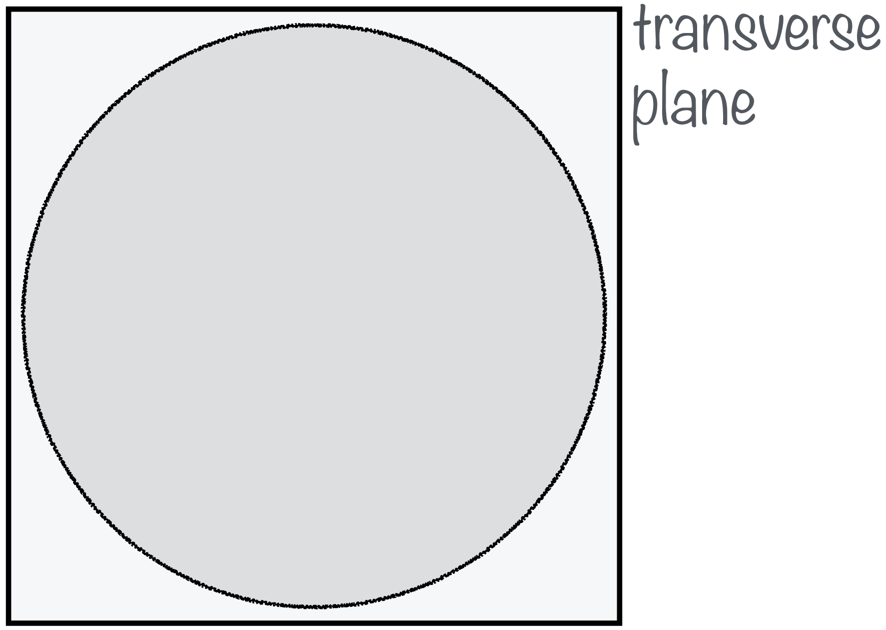

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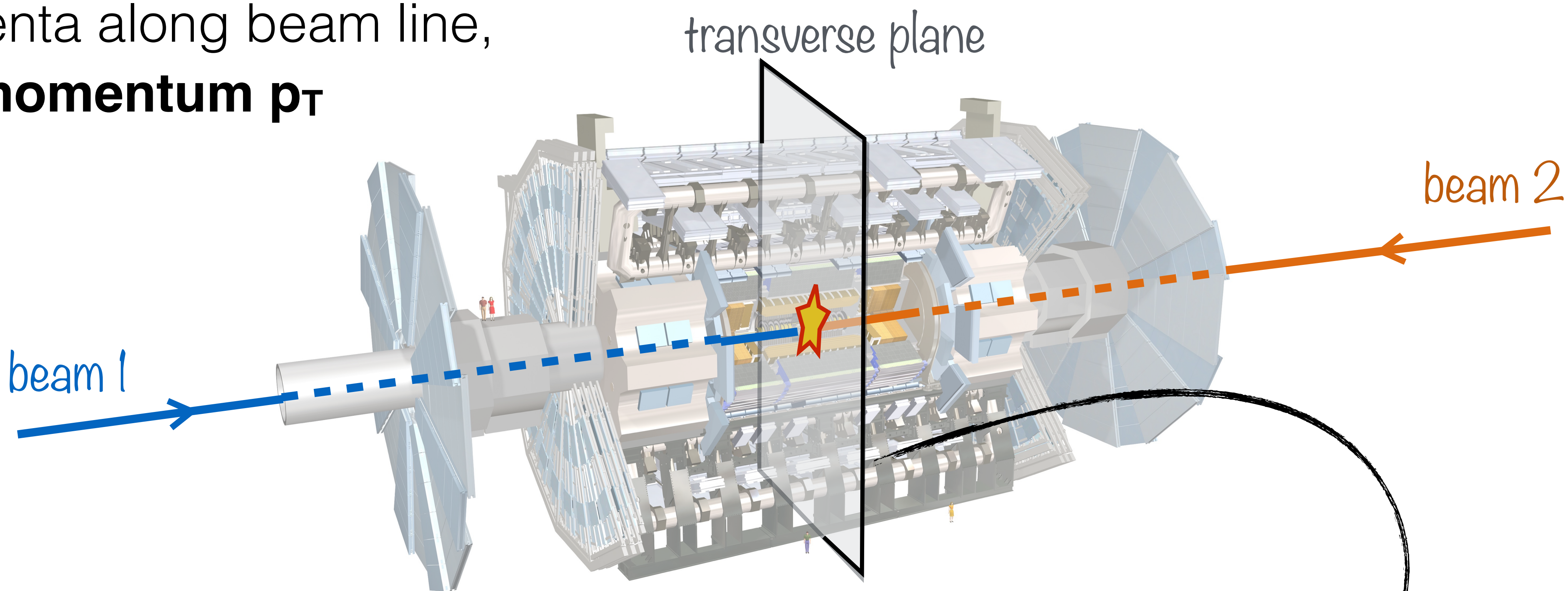

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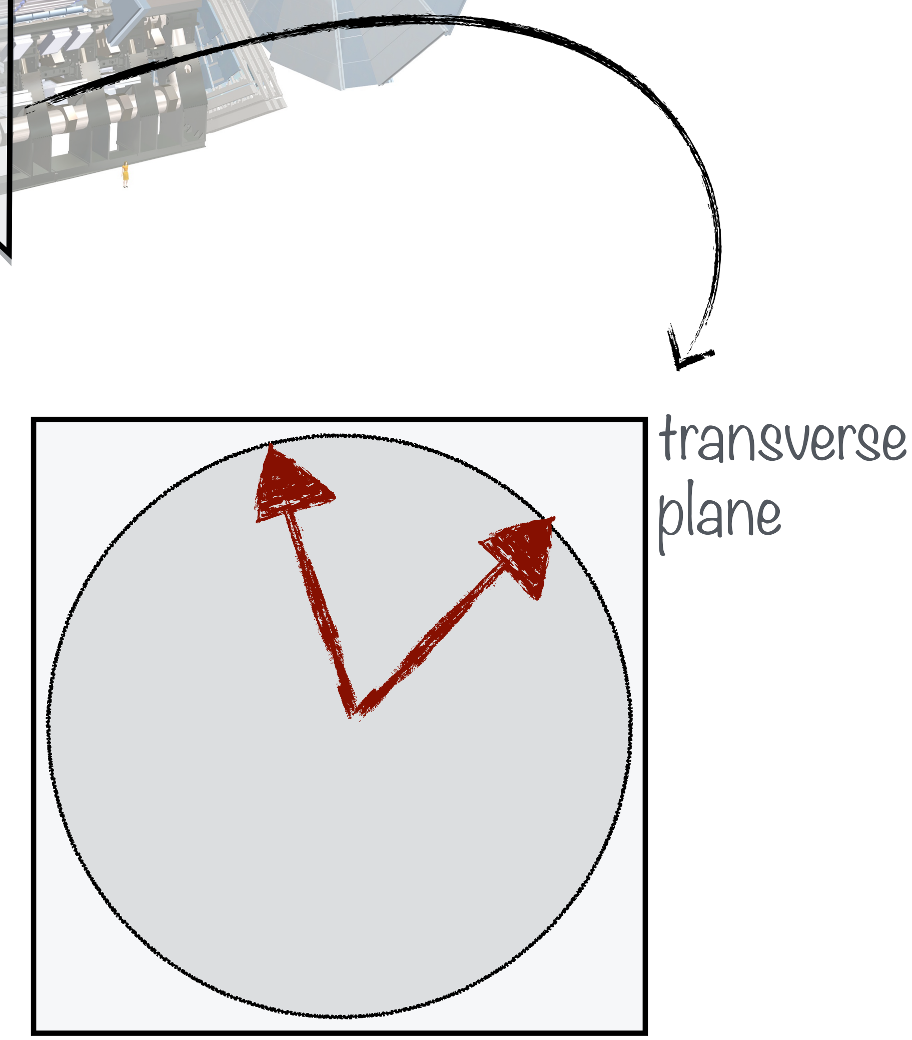

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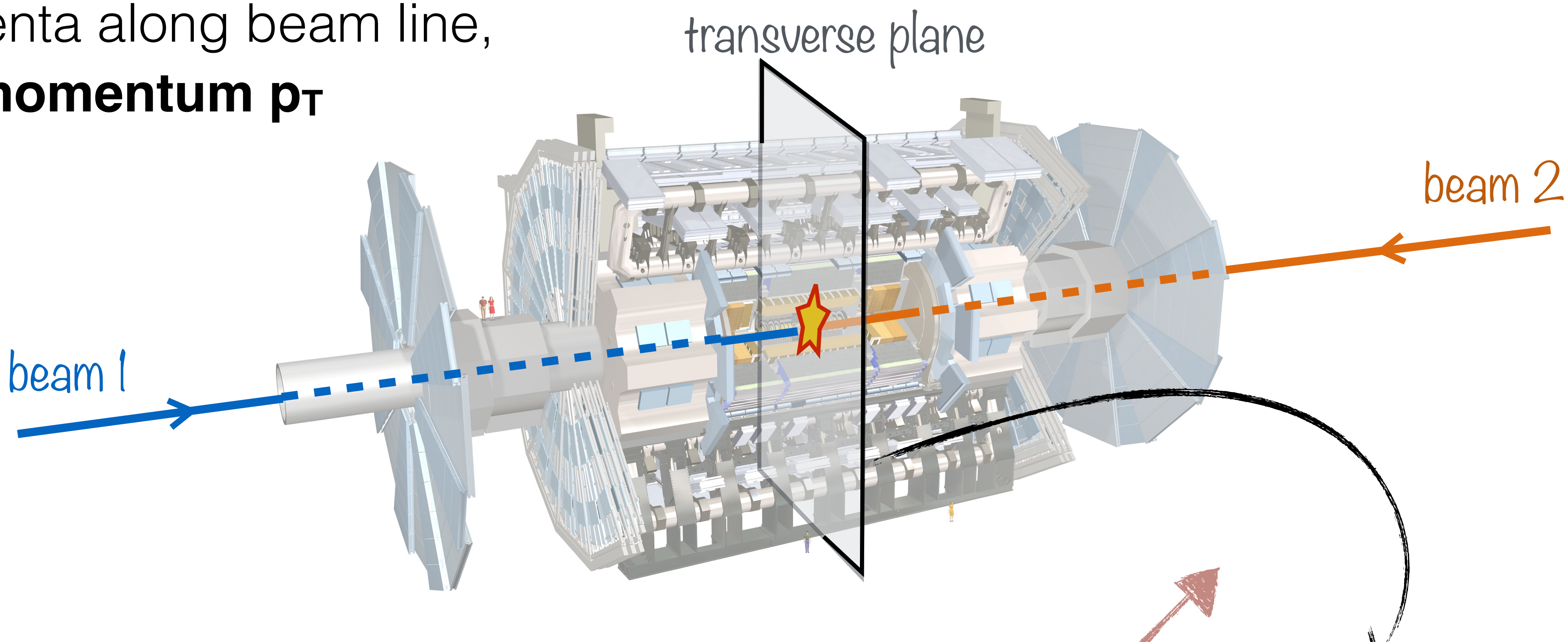

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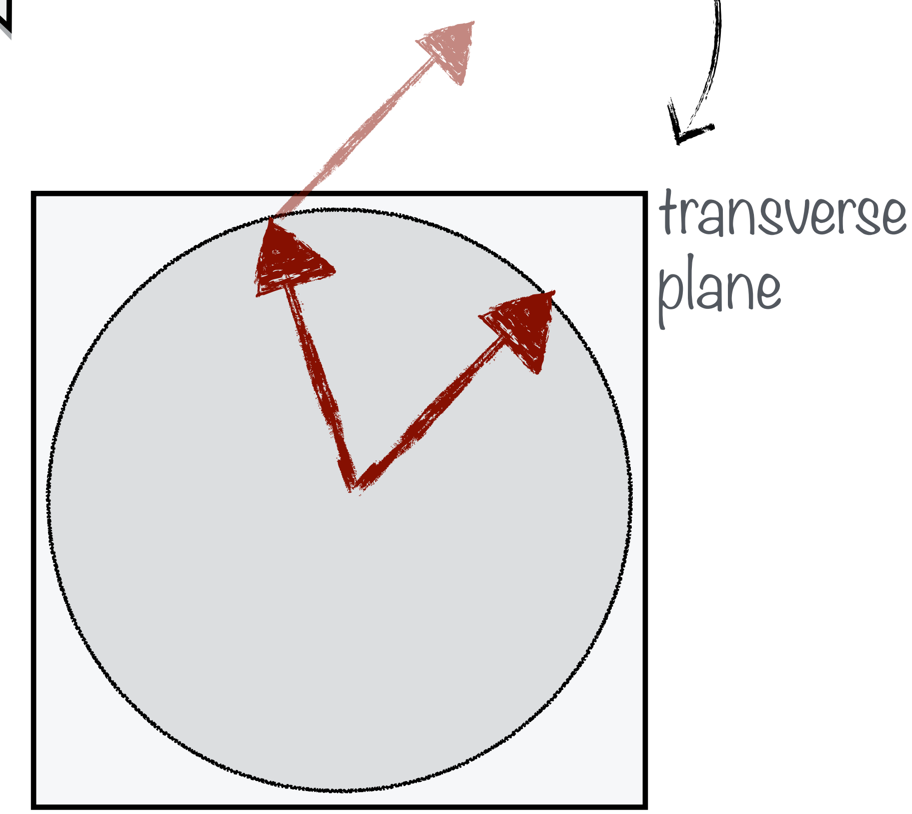

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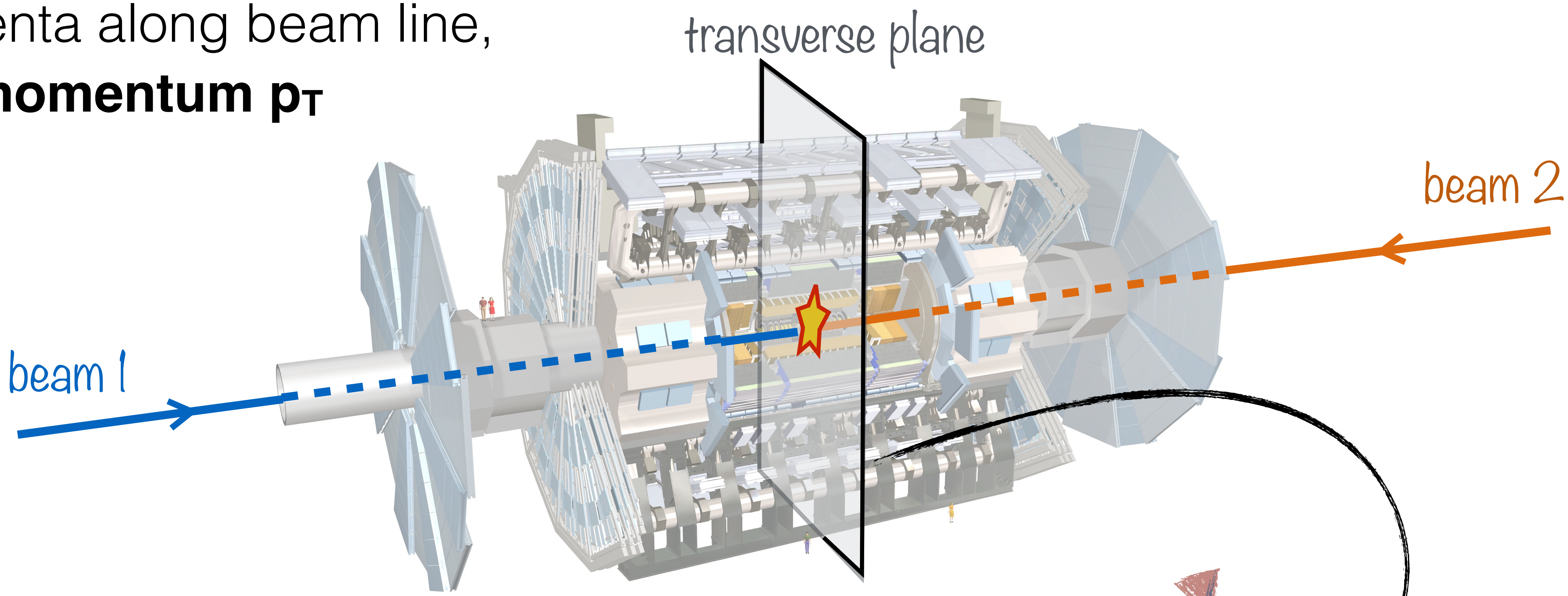

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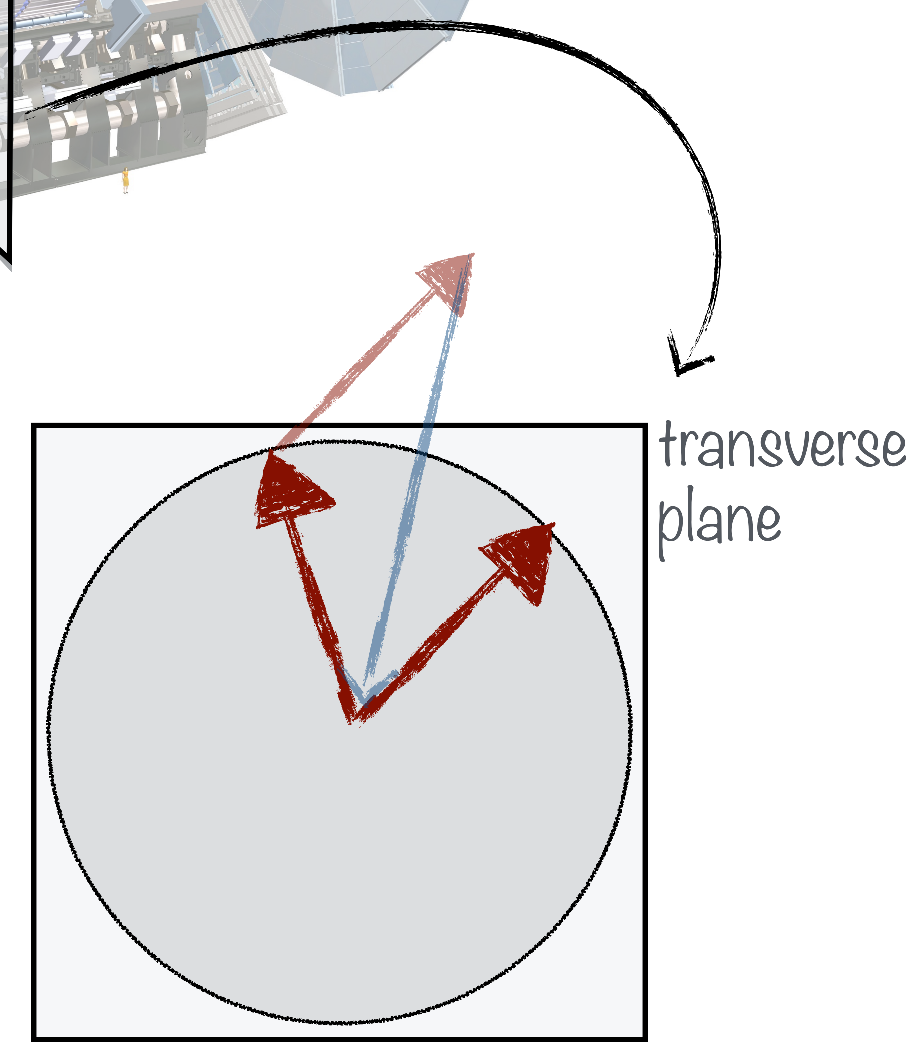

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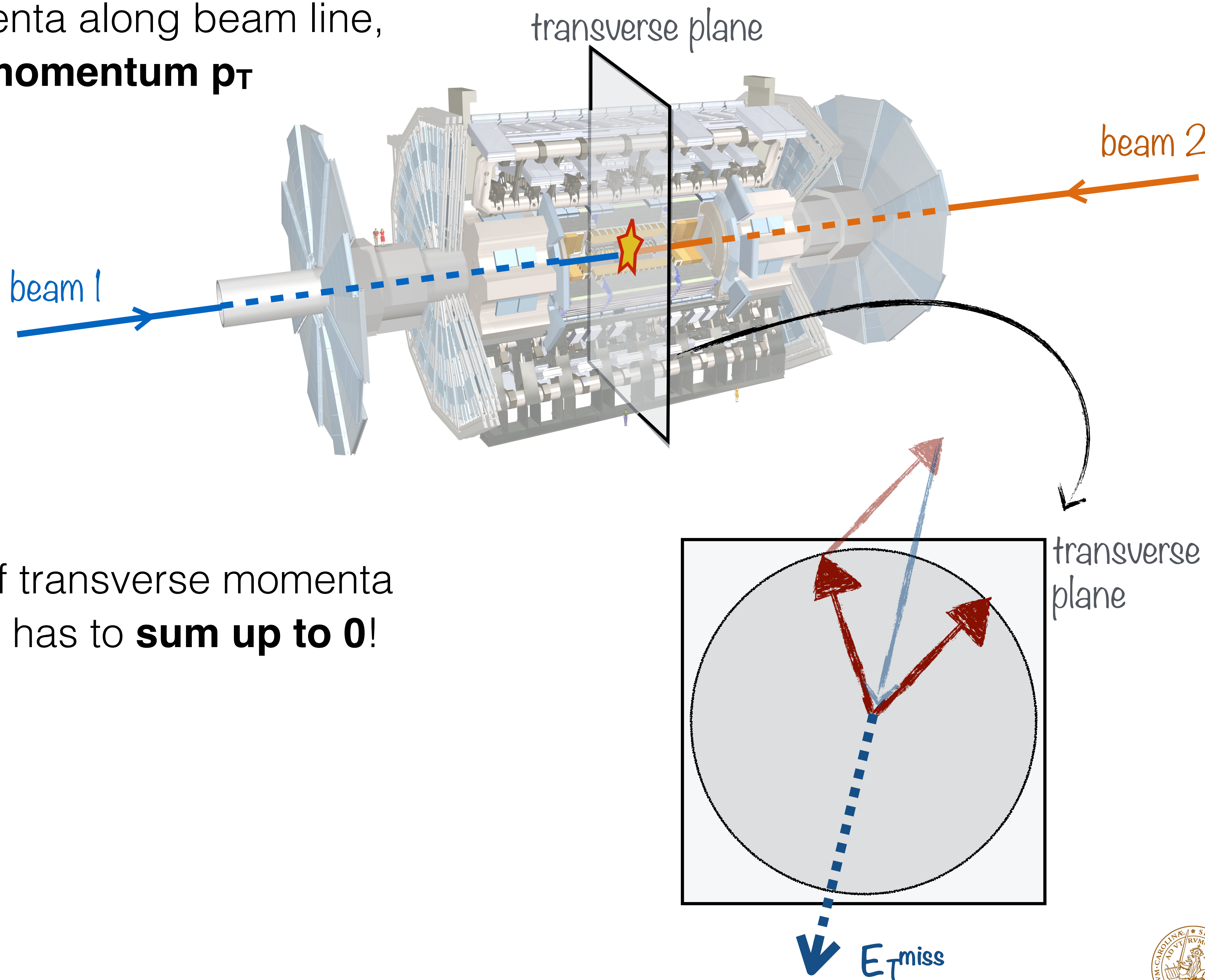

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Seeing the invisible

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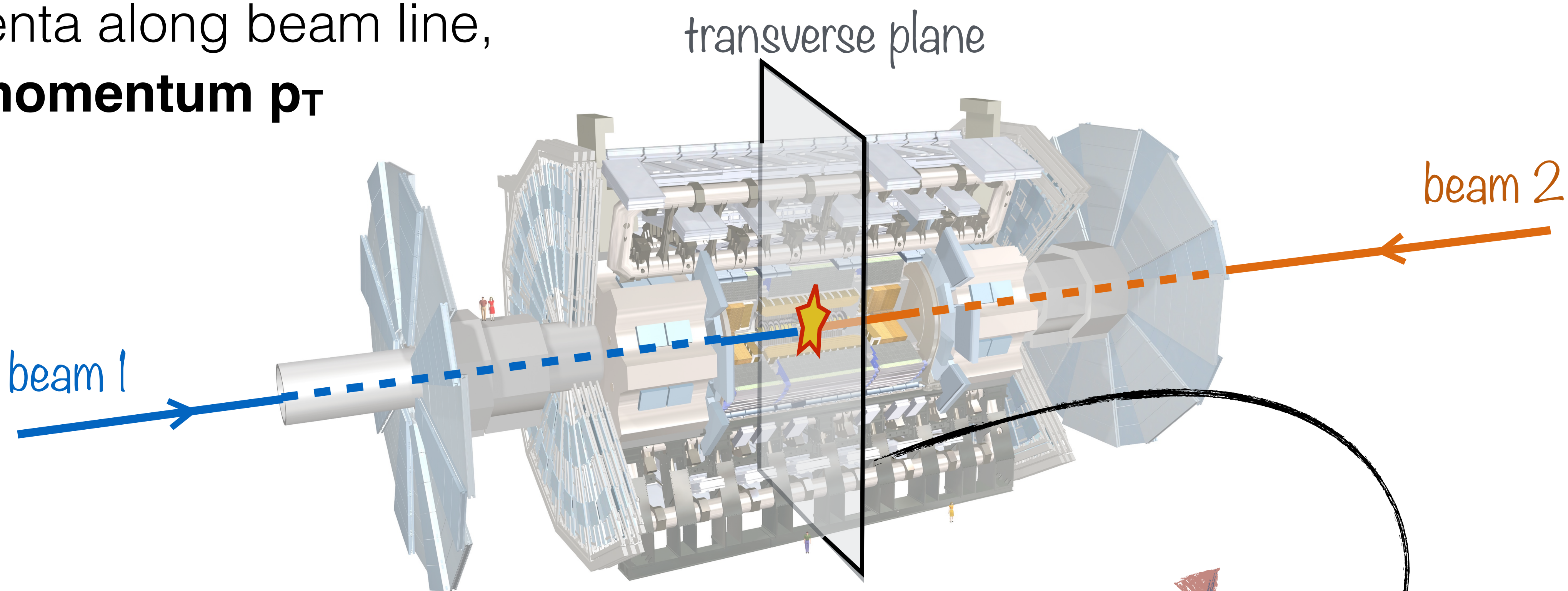

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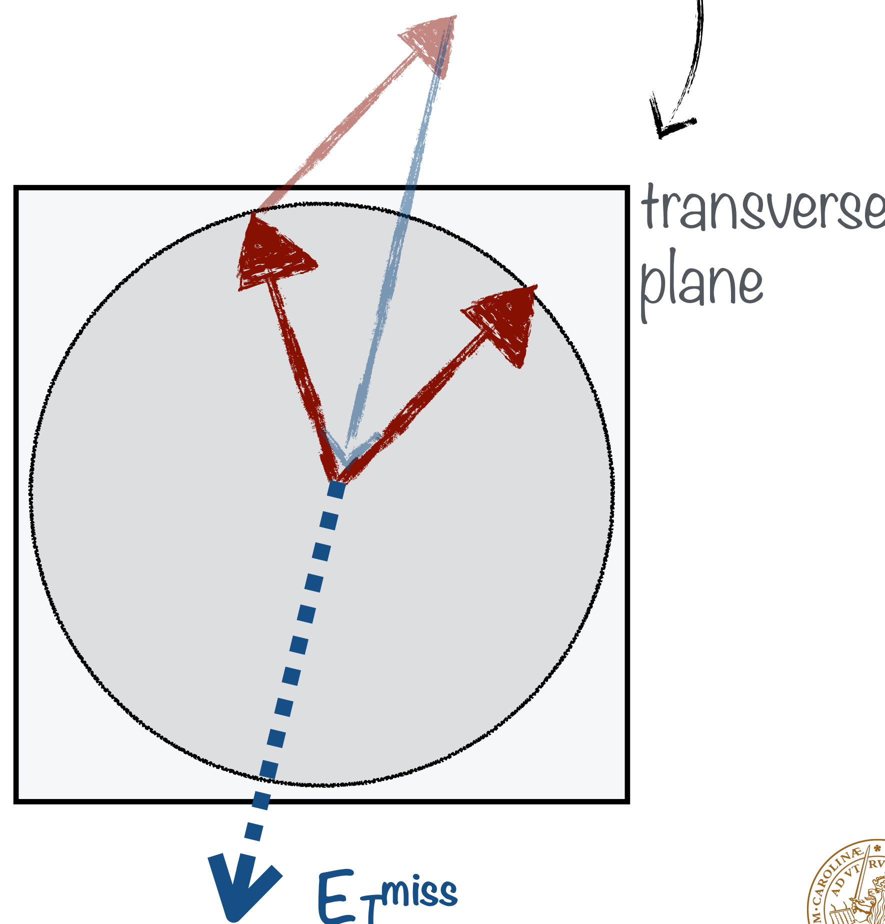

- infer that some "invisible" particle(s) have escaped detection

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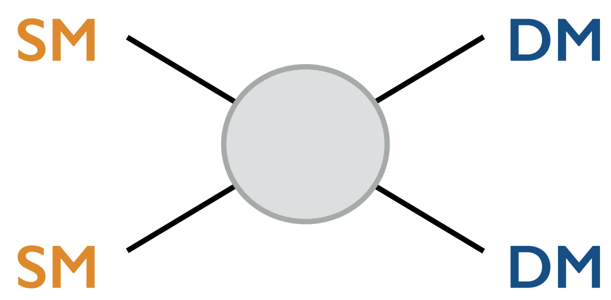
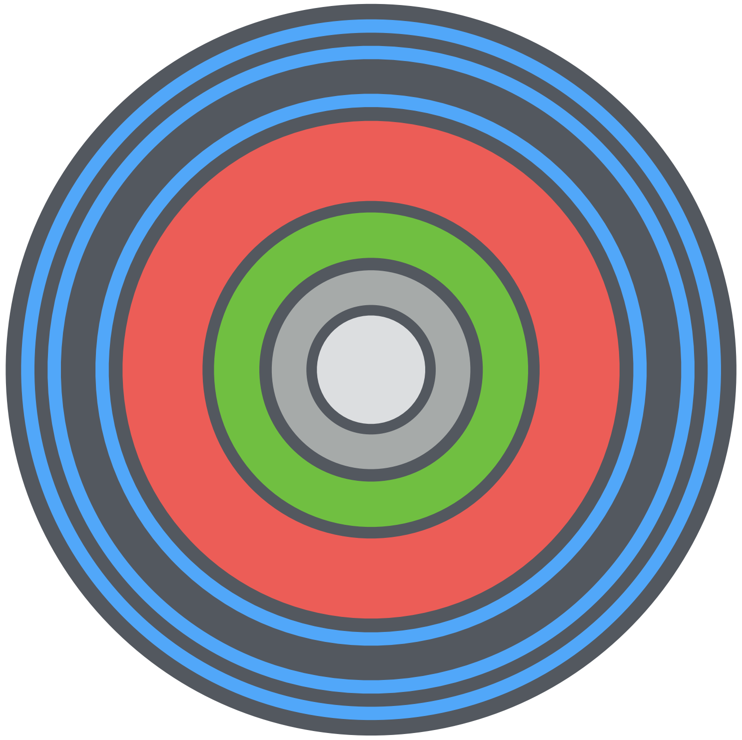
"Invisible Signatures"

- most of the searches for Dark Matter at colliders use **missing energy**
- to see anything, there must be something else in the event!





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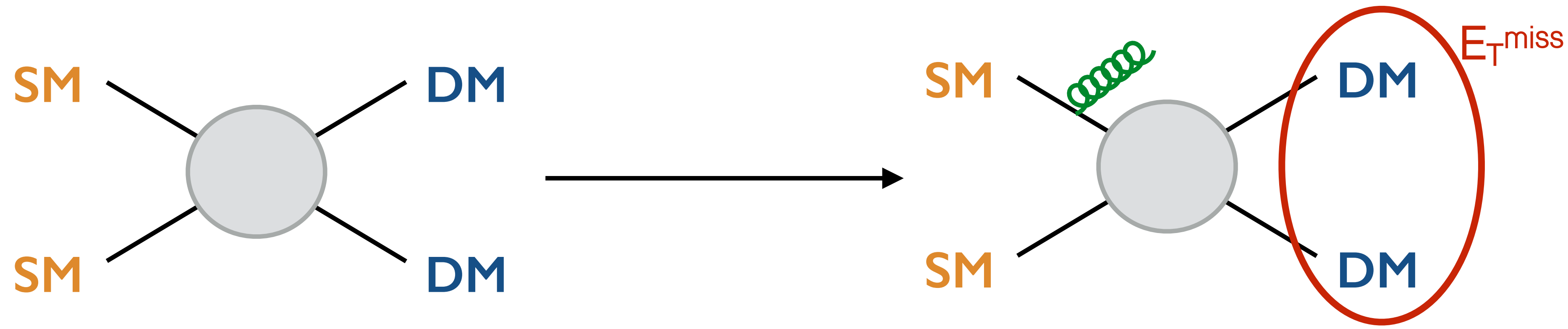

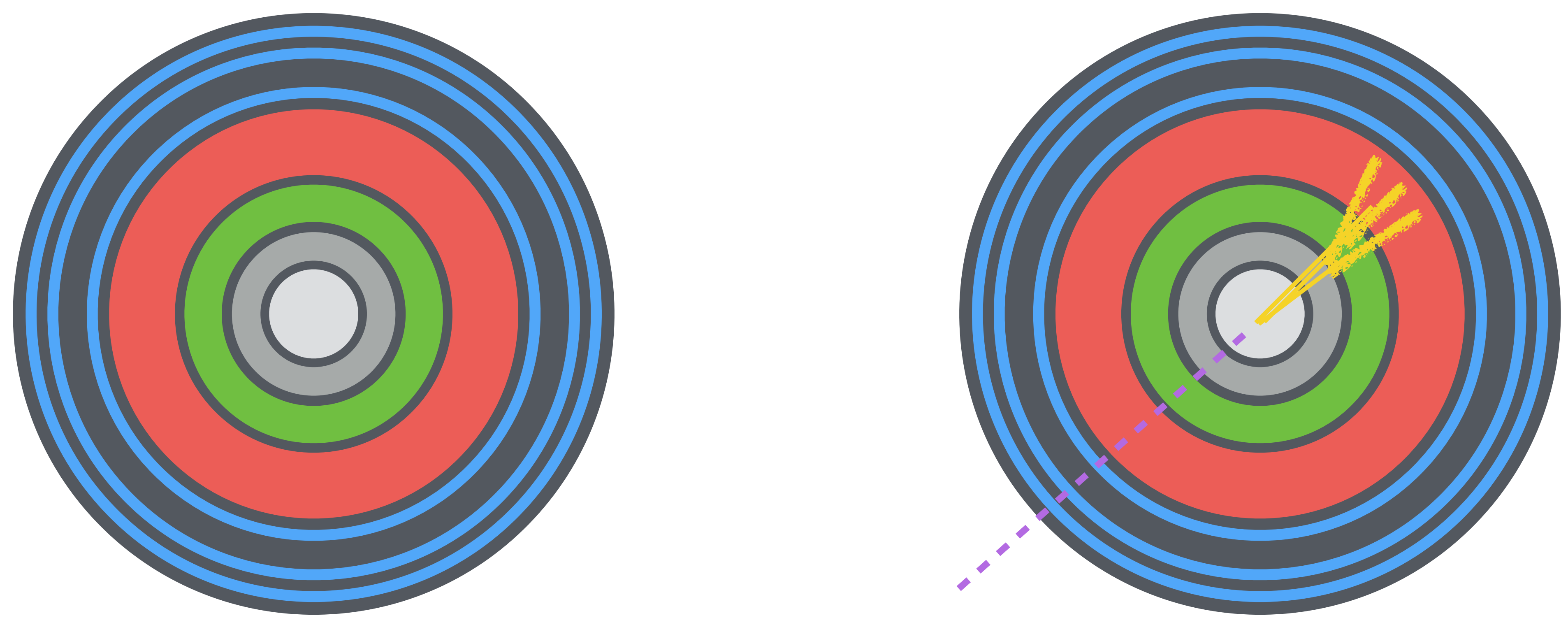

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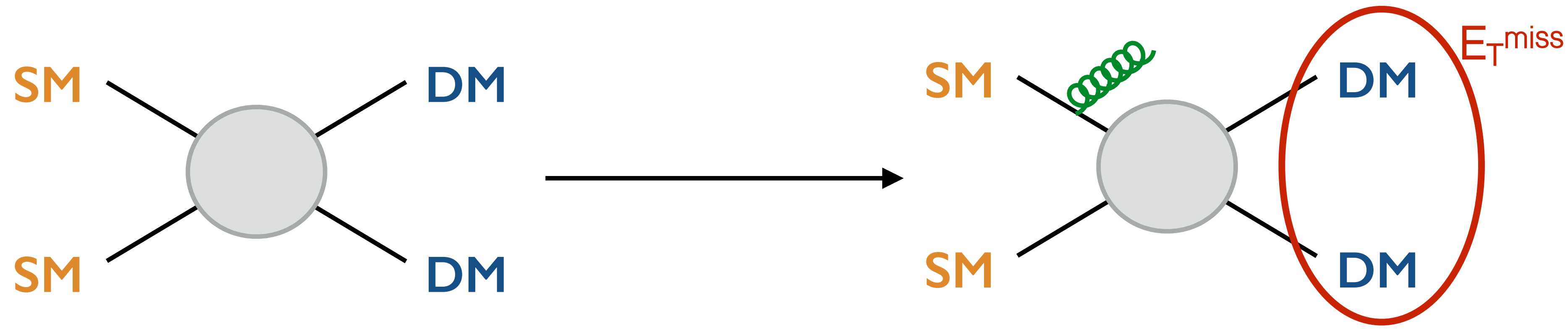
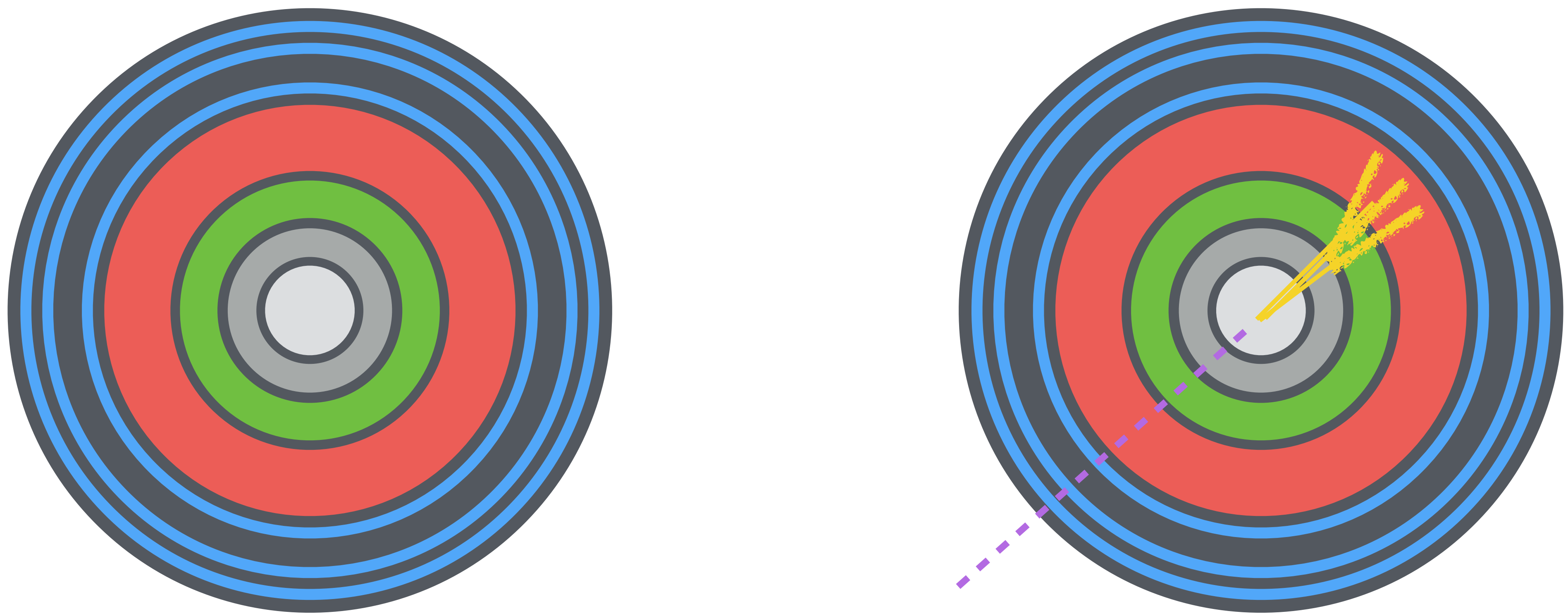
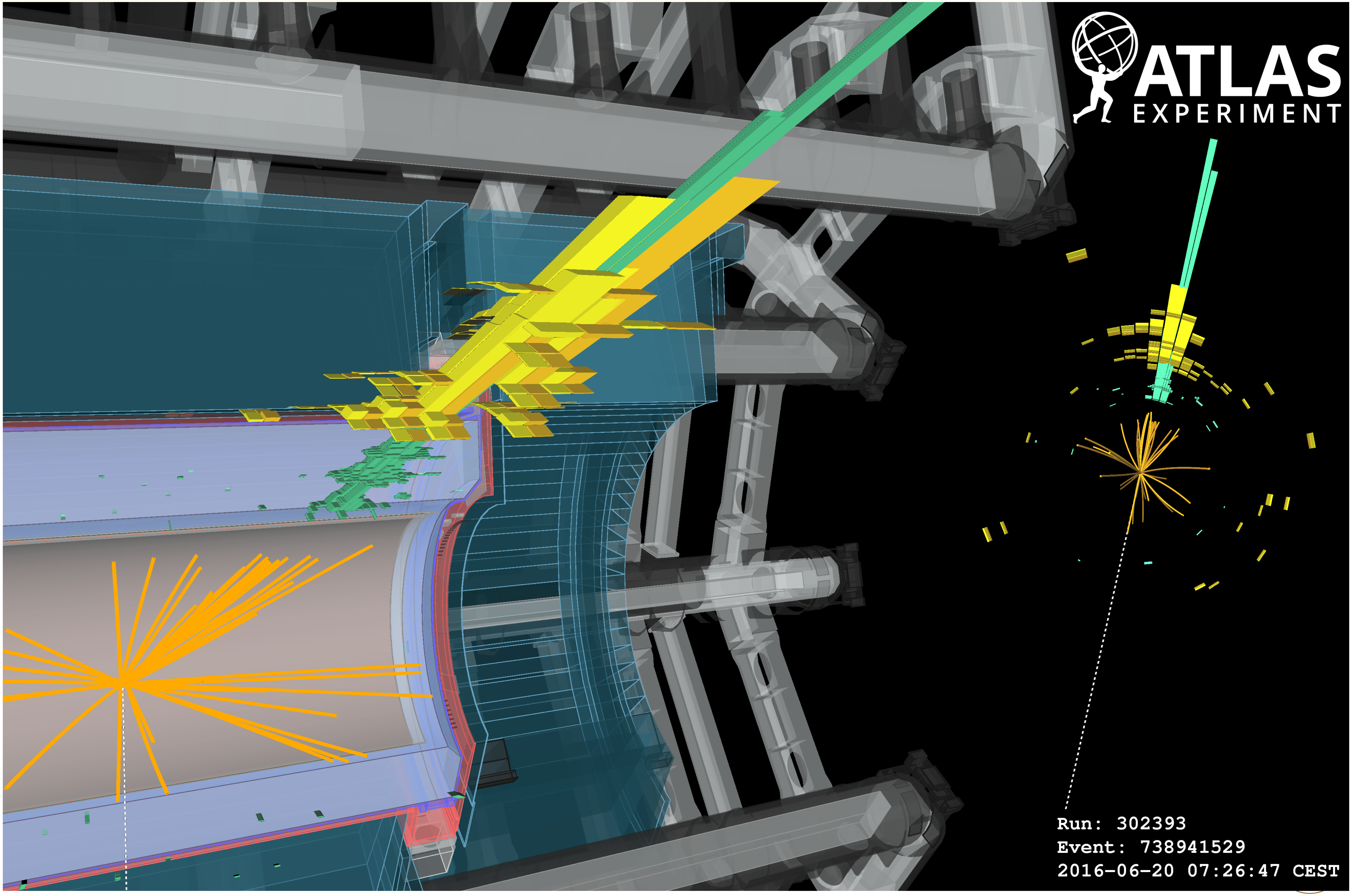




- can be really anything, a photon, W, Z, Higgs…

A jet+invisible event

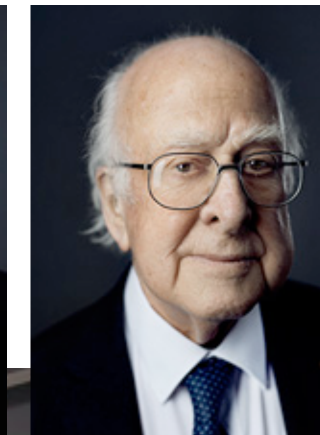


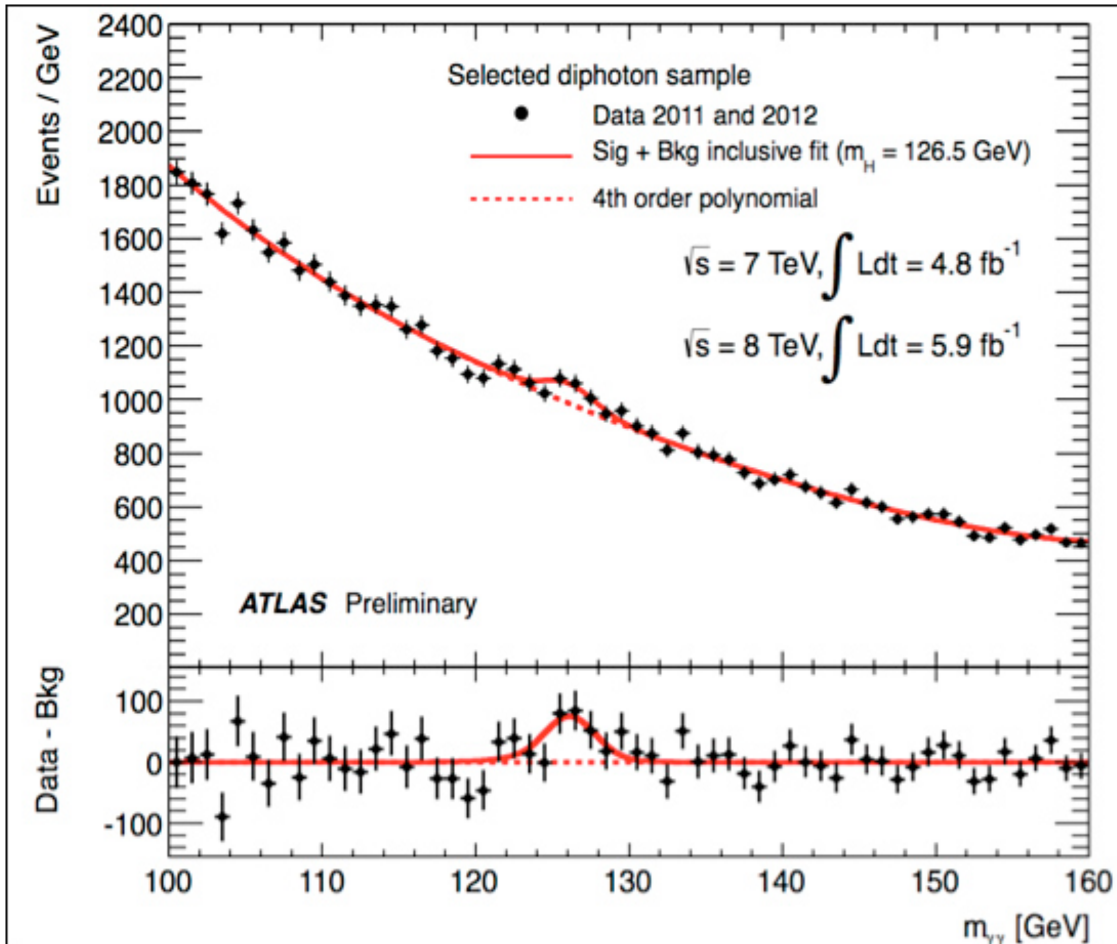
final missing piece of the SM

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

July 4, 2012

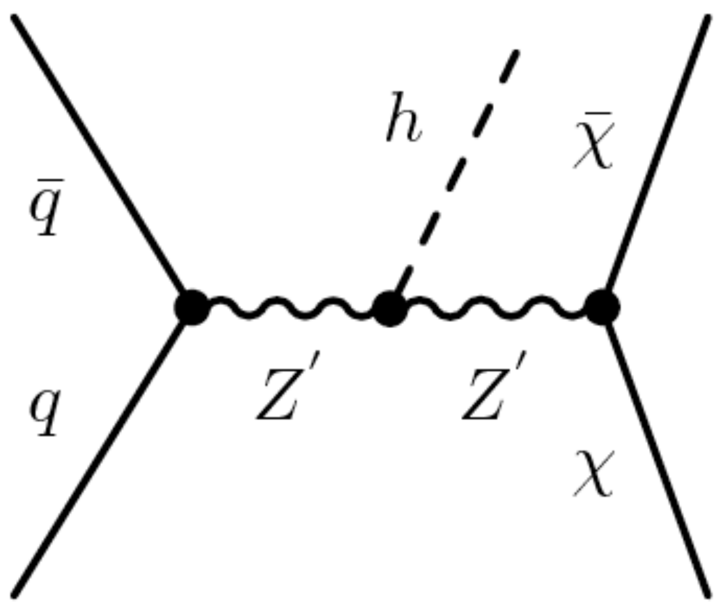
animations

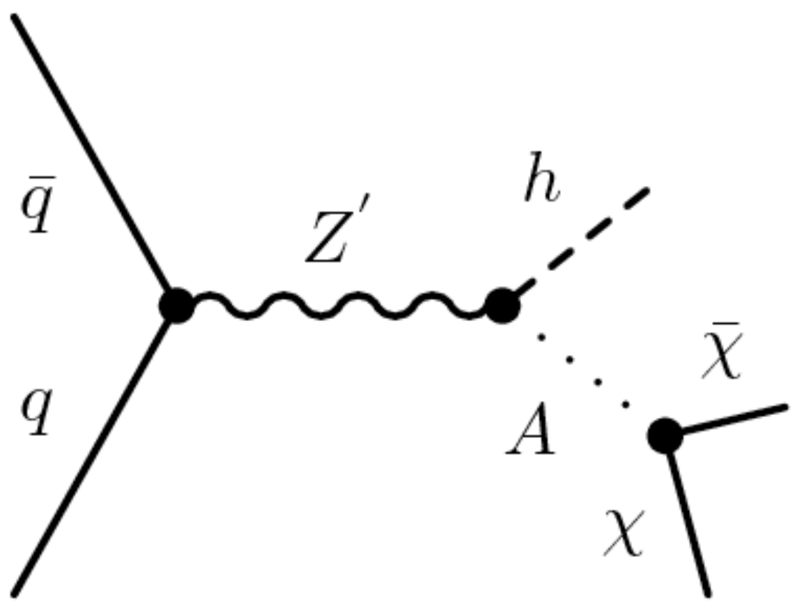




Example: Higgs+E_T^{miss}

- discovery of a Higgs boson opens **new possibilities** to look for Dark Matter!
- different theoretical models than for other something+E_T^{miss} searches
  - Higgs couples to mass, so will not simply be emitted from initial state partons
- some examples:

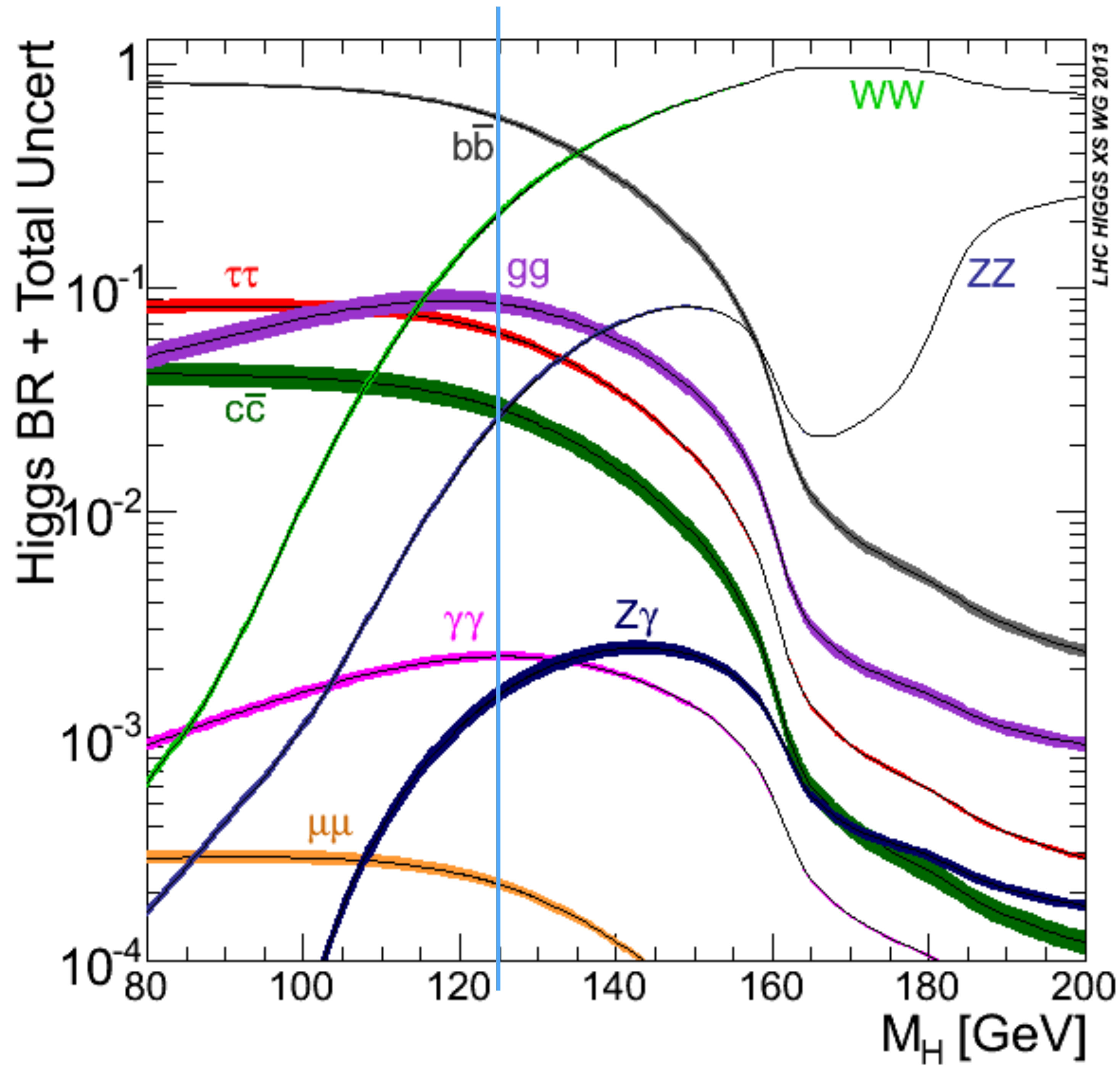




- final state: Higgs + DM
  - but Higgs not stable!

Example: Higgs+E_T^{miss}

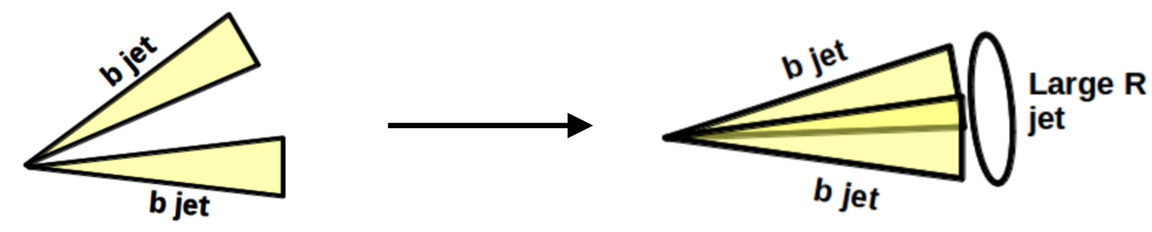
- where to start?
- decay into bb most common:



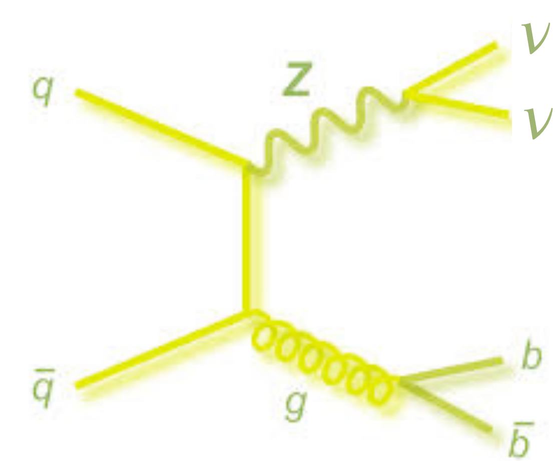
- need to be able to identify jets originating from b-quarks (**b-jets**)
  - luckily, we are (and we call it *b-tagging*)

Higgs(bb)+E_T^{miss} in a nutshell

- look for collision events that have
  - large amount of E_T^{miss}
  - 2 b-tagged jets **or** 1 big jet made of 2 b-jets
    - high E_T^{miss}: H is "boosted"
      —> b-jets *merge* into one



  - nothing else (no electron, muons…)

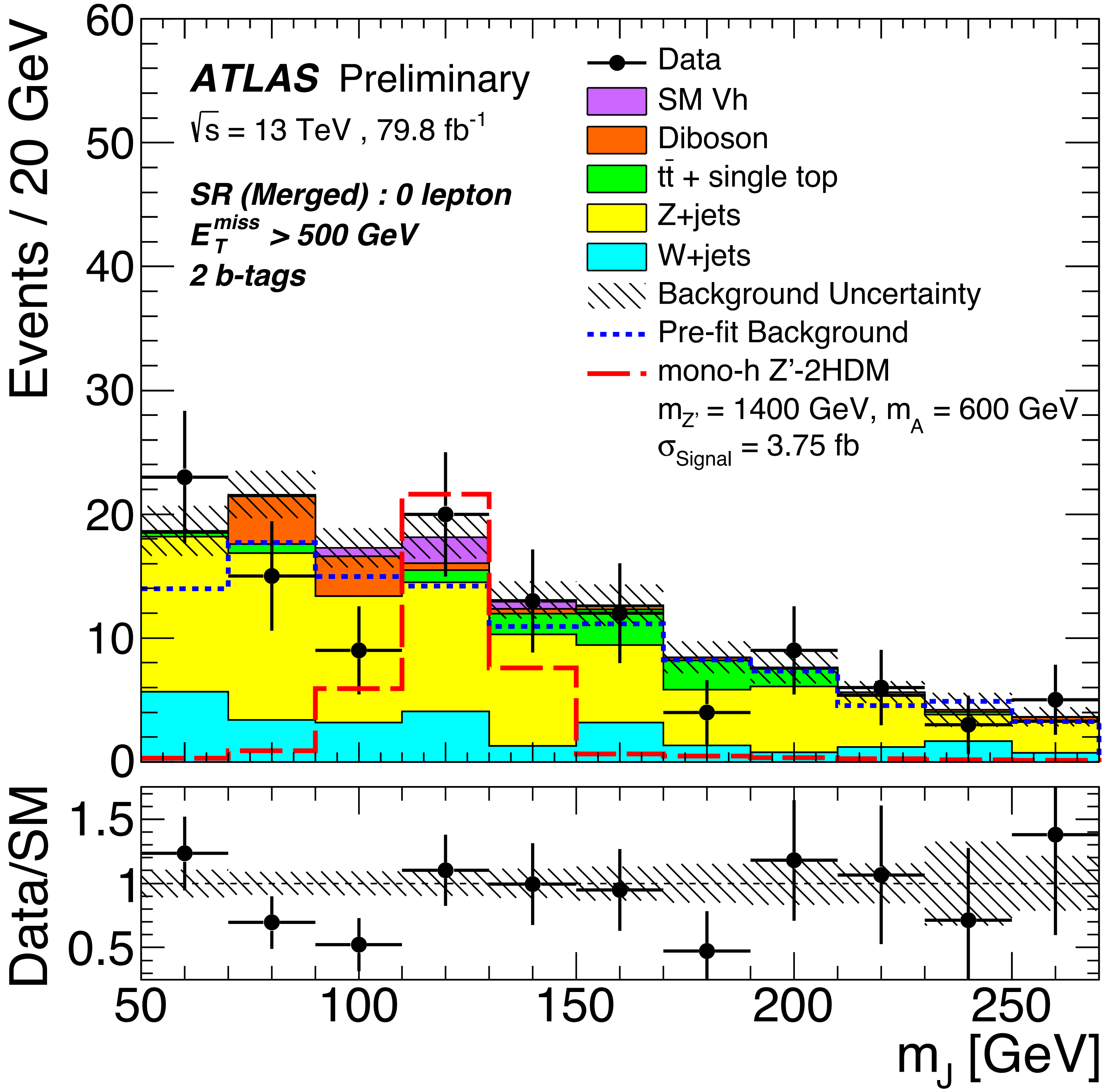


- important **background**:
  production of Z boson together with (b-)jets,
  with Z—>$\nu\nu$ => E_T^{miss}
  - to estimate this and other backgrounds: use **control samples**
    - events that have characteristics of a given background process
    - improves confidence in and precision of background simulations

- **statistical evaluation**:
  fit of background prediction to observed data, quantify the agreement

Higgs(bb)+E_T^{miss} – The Signal Region

- large amount of information in such plots



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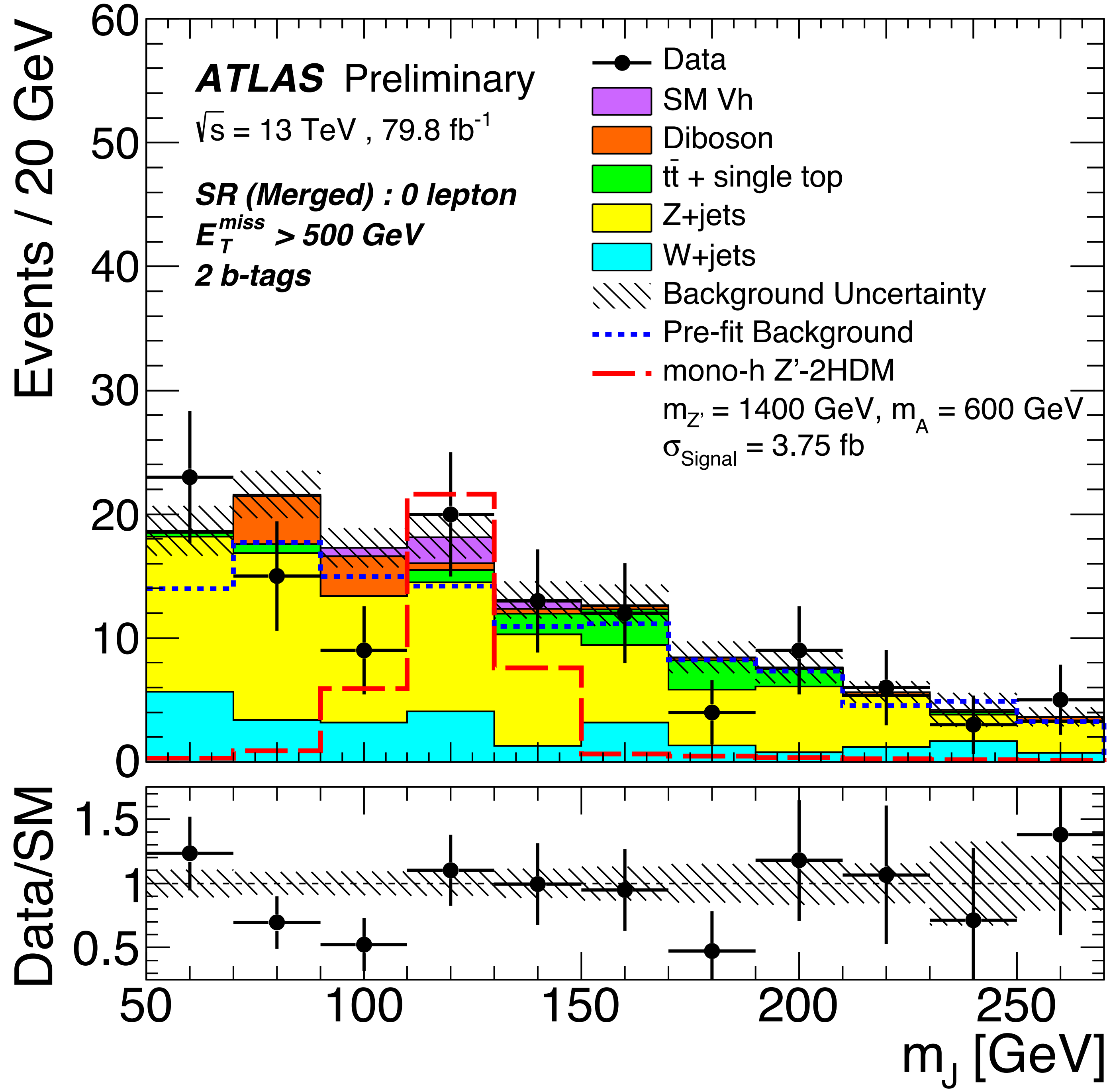
Higgs(bb)+E_T^{miss} – The Signal Region

- large amount of information in such plots



- no signal observed

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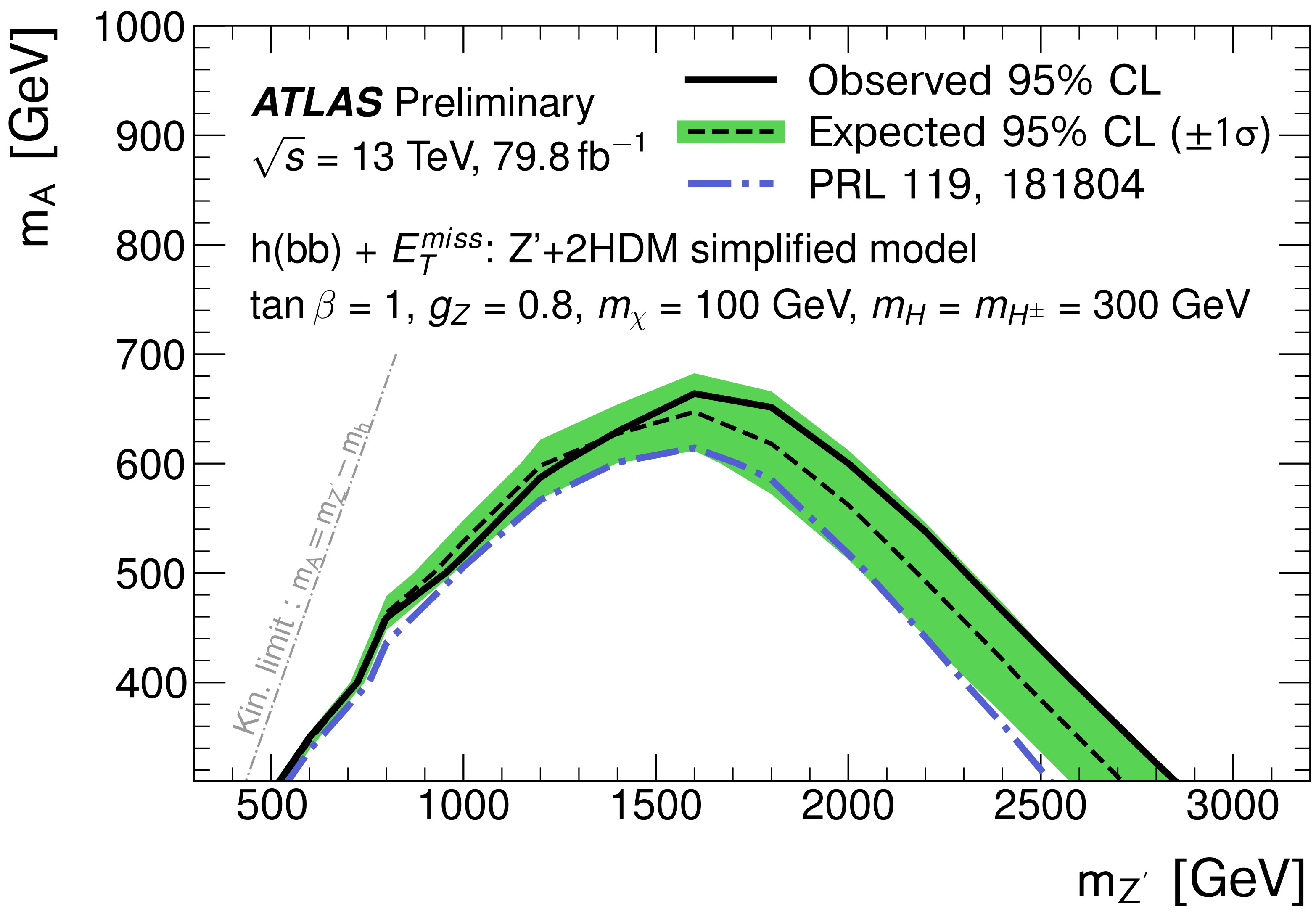
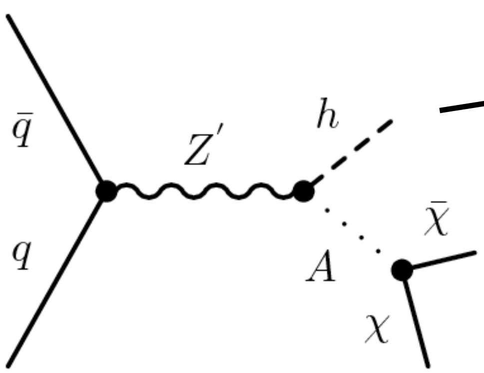
Higgs(bb)+E_T^{miss} – The Outcome

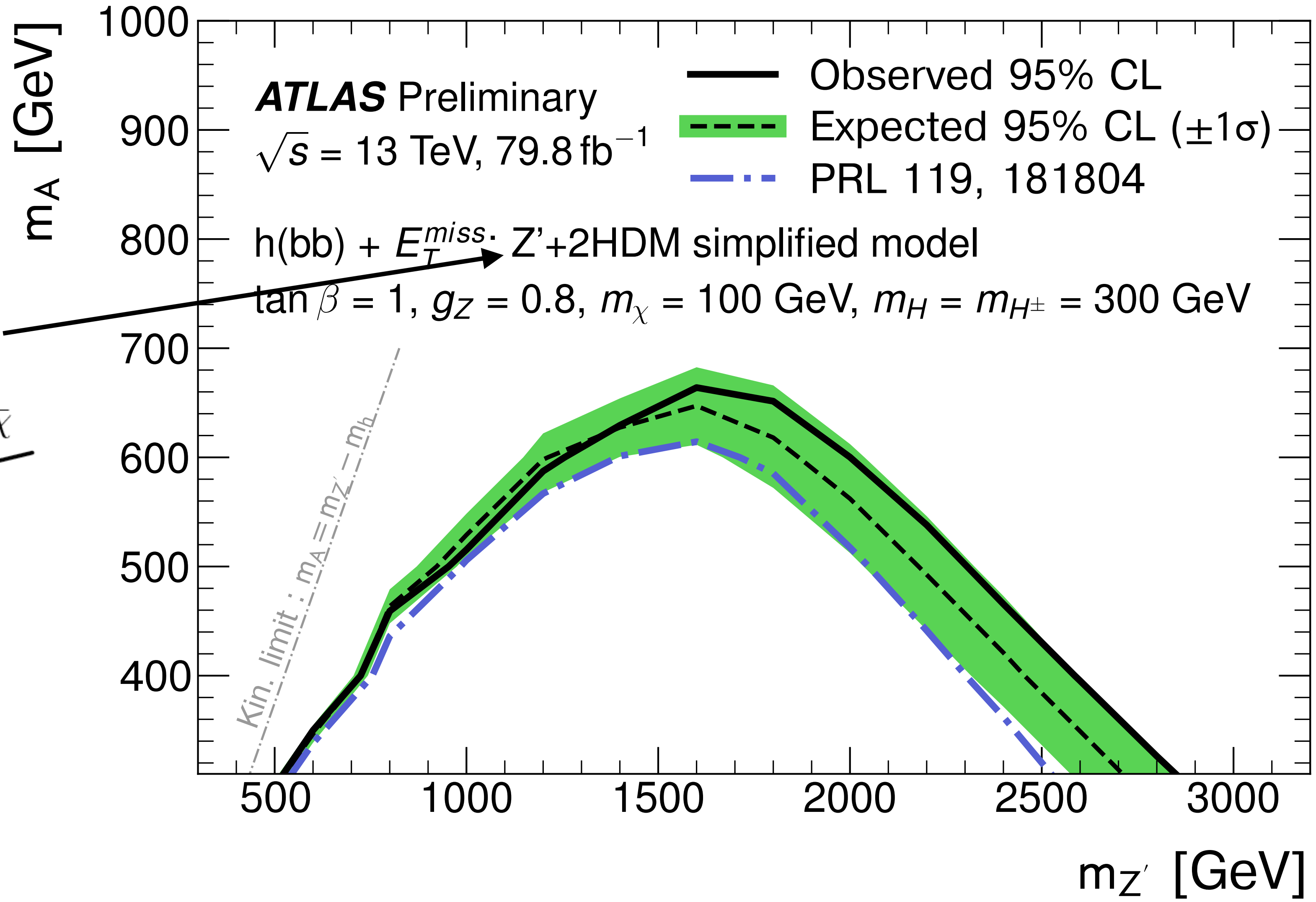
- a typical result plot: exclusion bounds ("limits")



Higgs(bb)+E_T^{miss} – The Outcome

- a typical result plot: exclusion bounds ("limits")





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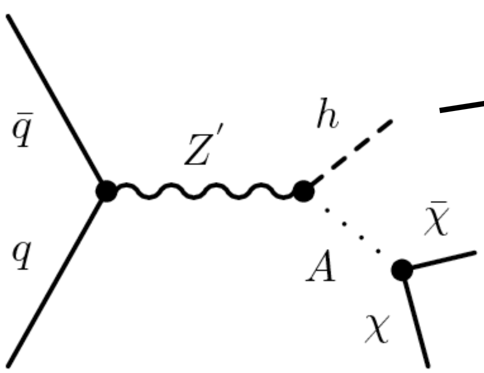
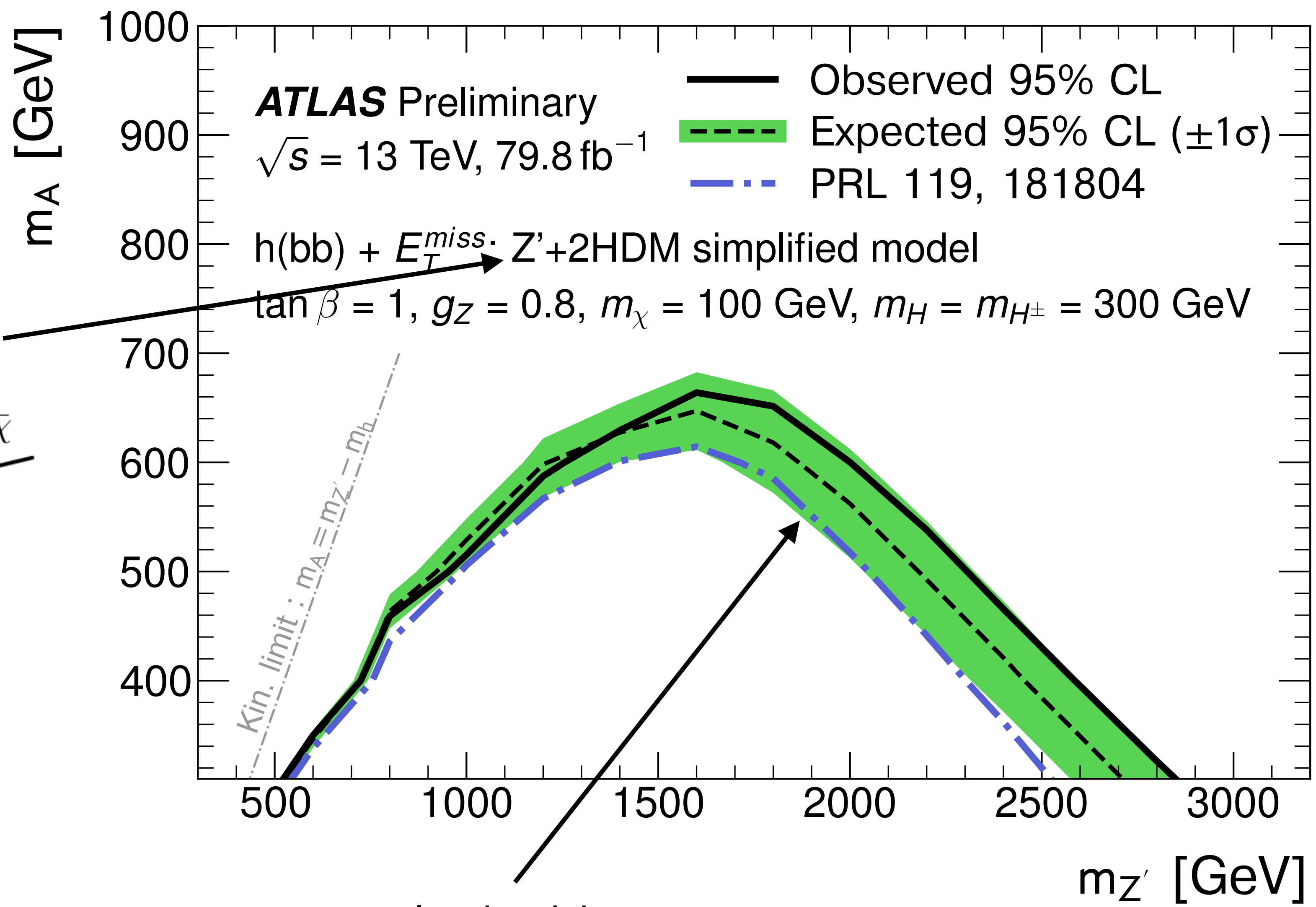
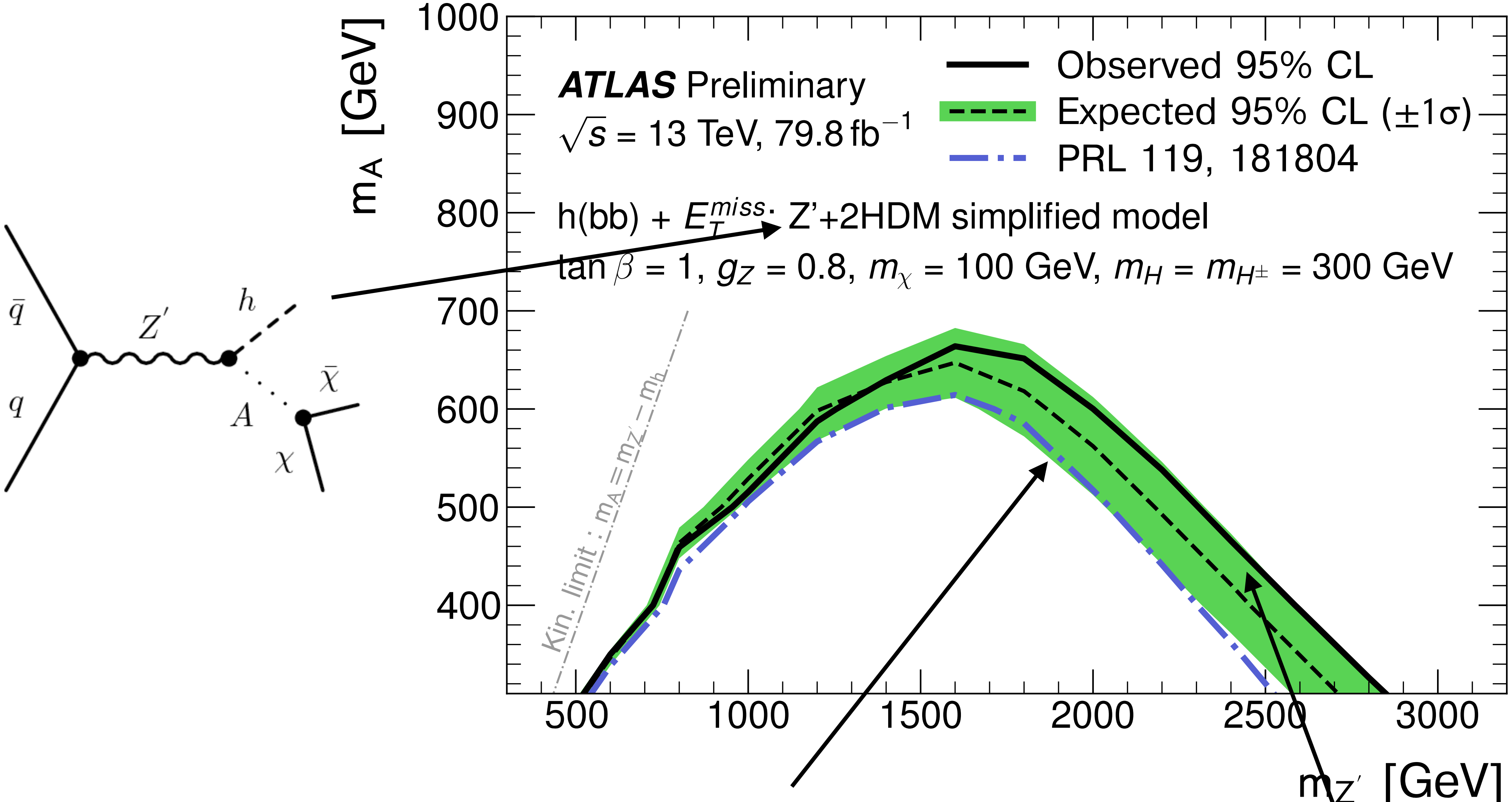




excluded by
2015/16 data

Higgs(bb)+E_T^{miss} – The Outcome

- a typical result plot: exclusion bounds ("limits")



excluded by
2015/16 data

excluded by
2015/16/17 data

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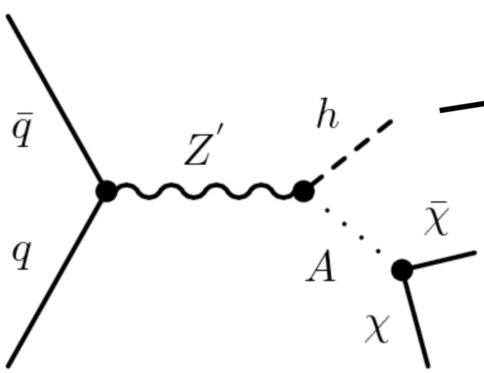
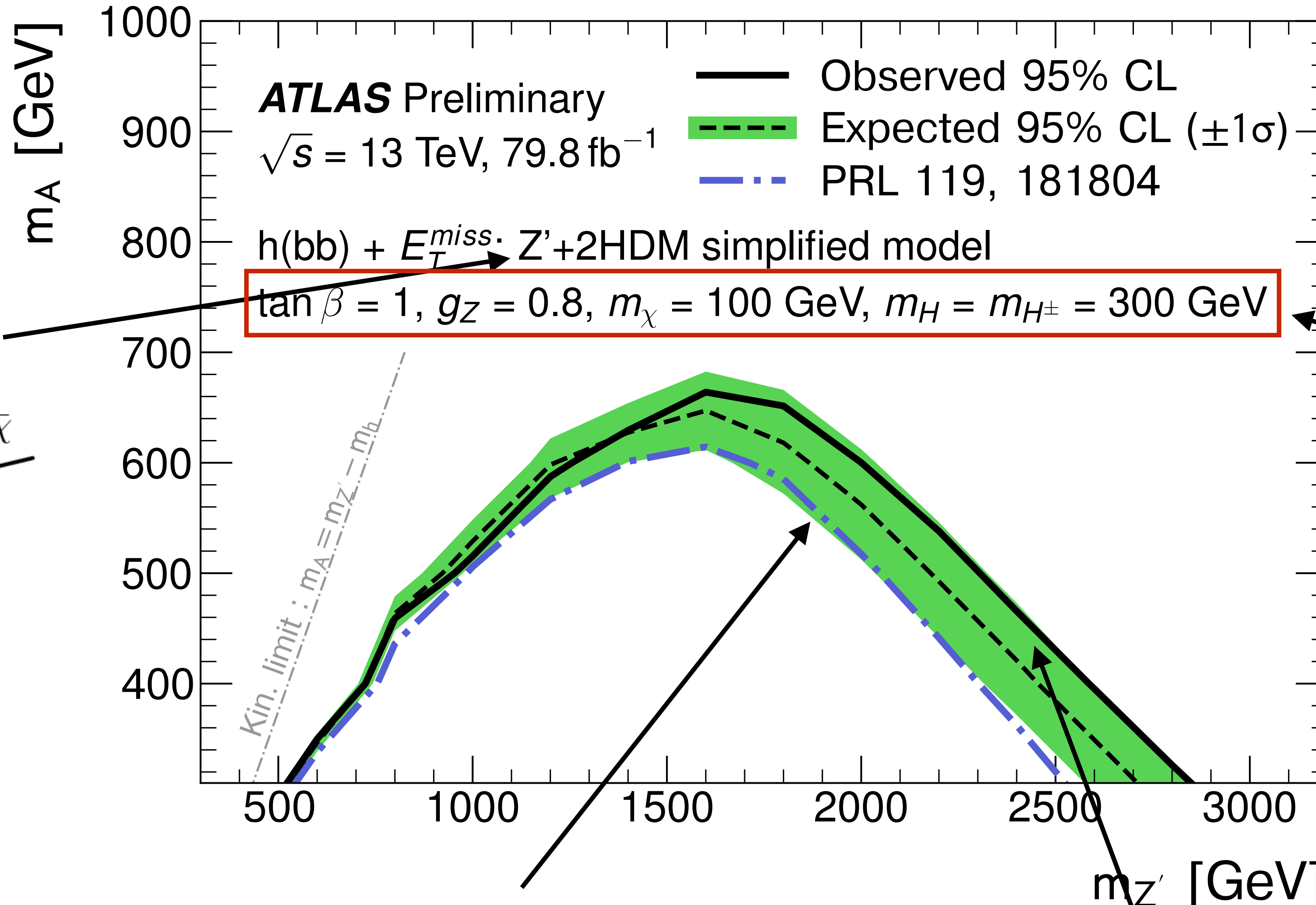
Higgs(bb)+E_T^{miss} – The Outcome

- a typical result plot: exclusion bounds ("limits")





conclusions (exclusion) made in terms of $m_{Z'}$, m_A only valid for these assumptions about the other model parameters

excluded by 2015/16 data

excluded by 2015/16/17 data

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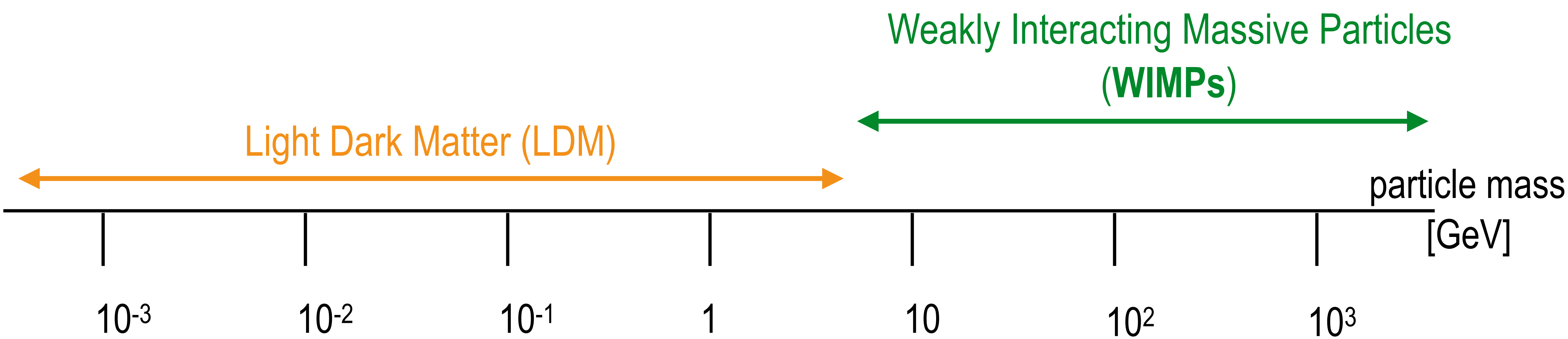
Accelerator-based Search

Light Dark Matter

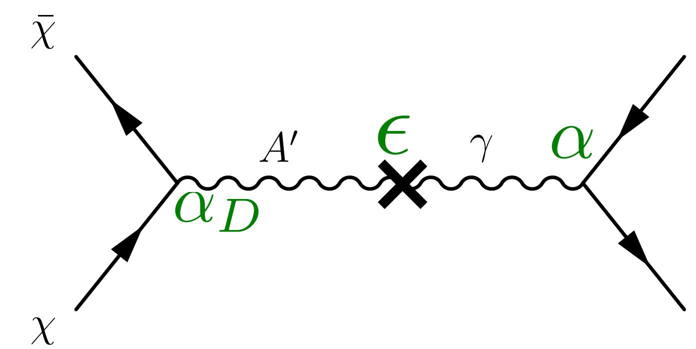
- so, we have a lot of experiments searching for **WIMPs**, but **no observation**
- should start **looking elsewhere** —> lighter DM particles
- **thermal relic** —> mass constraint & minimum annihilation cross section
  - WIMP too light —> annihilation inefficient —> overproduction of DM
    - Lee-Weinberg bound: m_χ > some GeV



- this isn't really LHC realm anymore
  - take a different approach

How to evade the Lee-Weinberg bound

- new, light mediator —> additional annihilation channels
  - avoids overproduction of DM



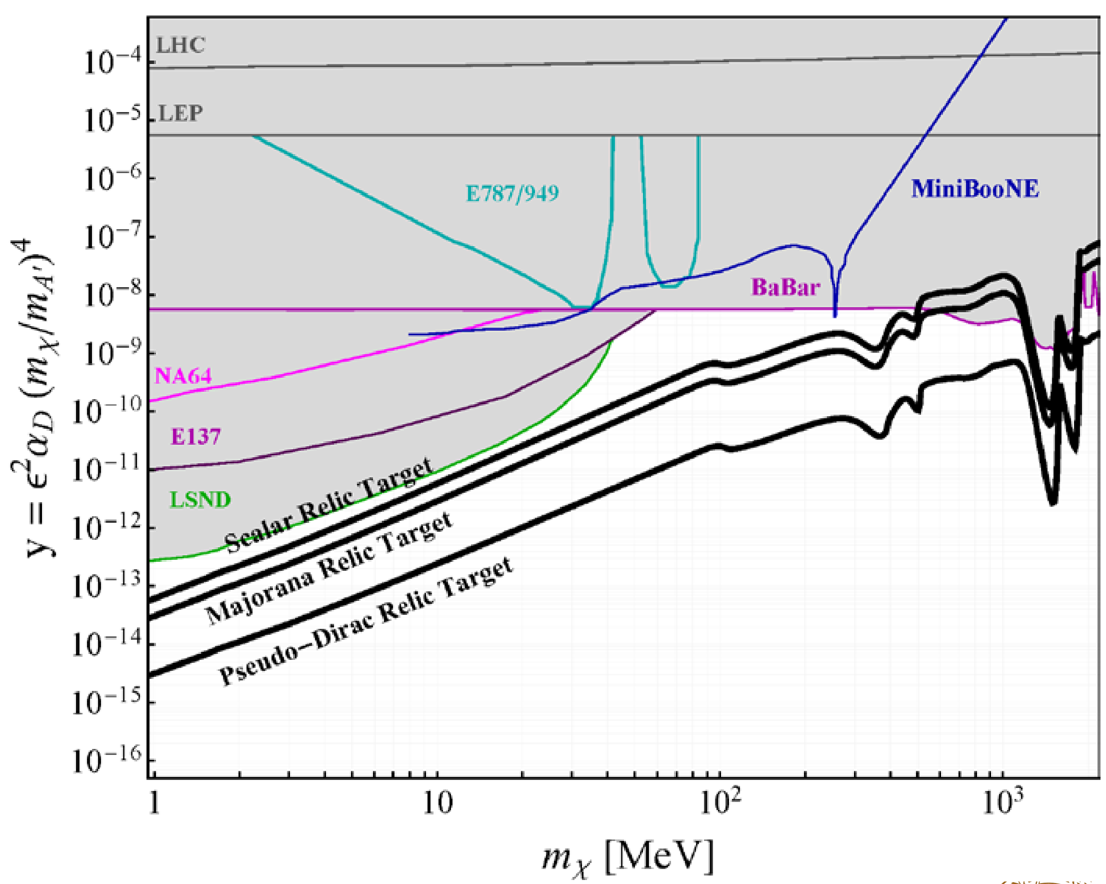
- representative model:

Dark Photon, A'

- mixes with SM photon (ε) —> interaction between SM and "dark sector"
- $m_{A'} > 2m_\chi$: **invisible** decay into DM
- annihilation cross section ~ y * m_χ^{-2}

$$y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$$

- *'thermal targets'* in y-mass-plane

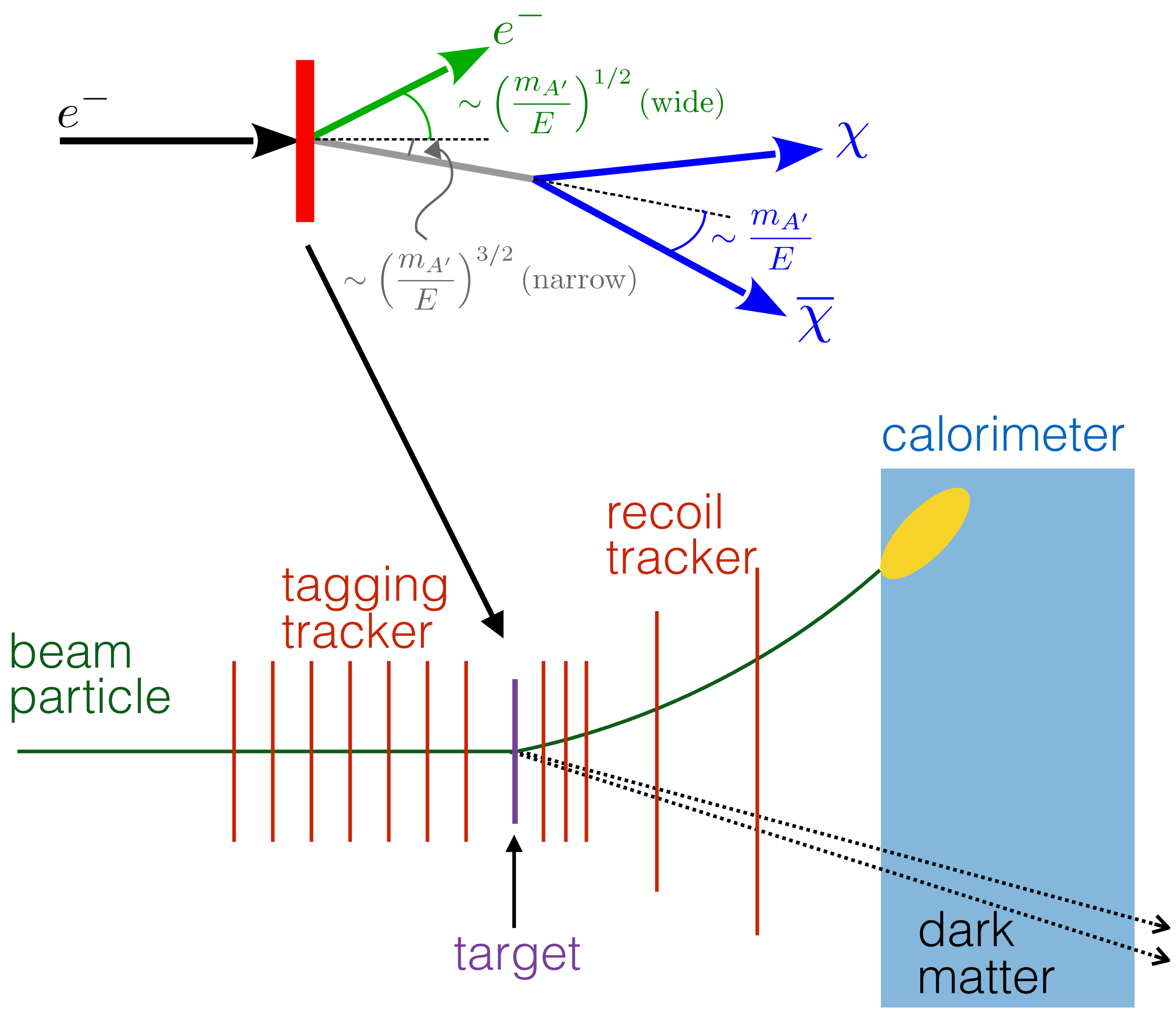


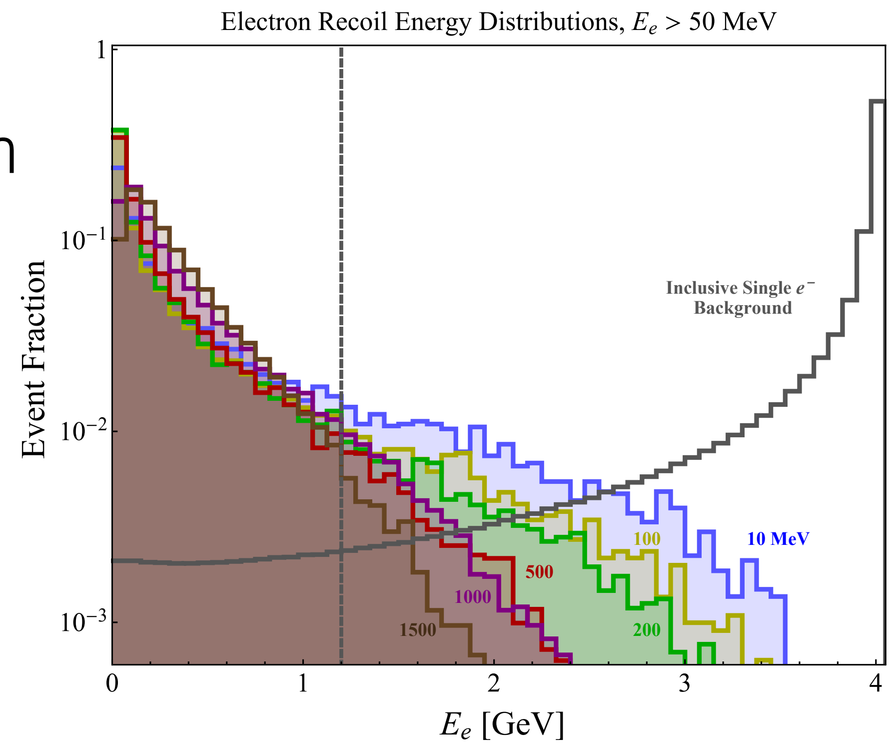
How to look for this?

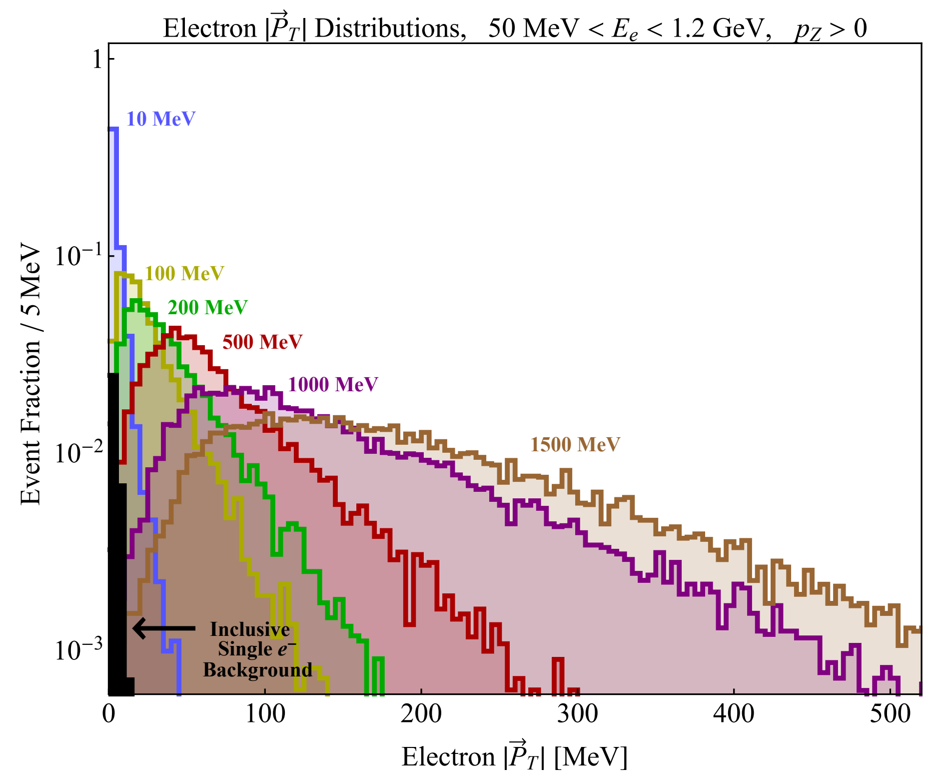
- as said, not LHC…
- instead: **fixed-target missing momentum experiment**

Why missing momentum?

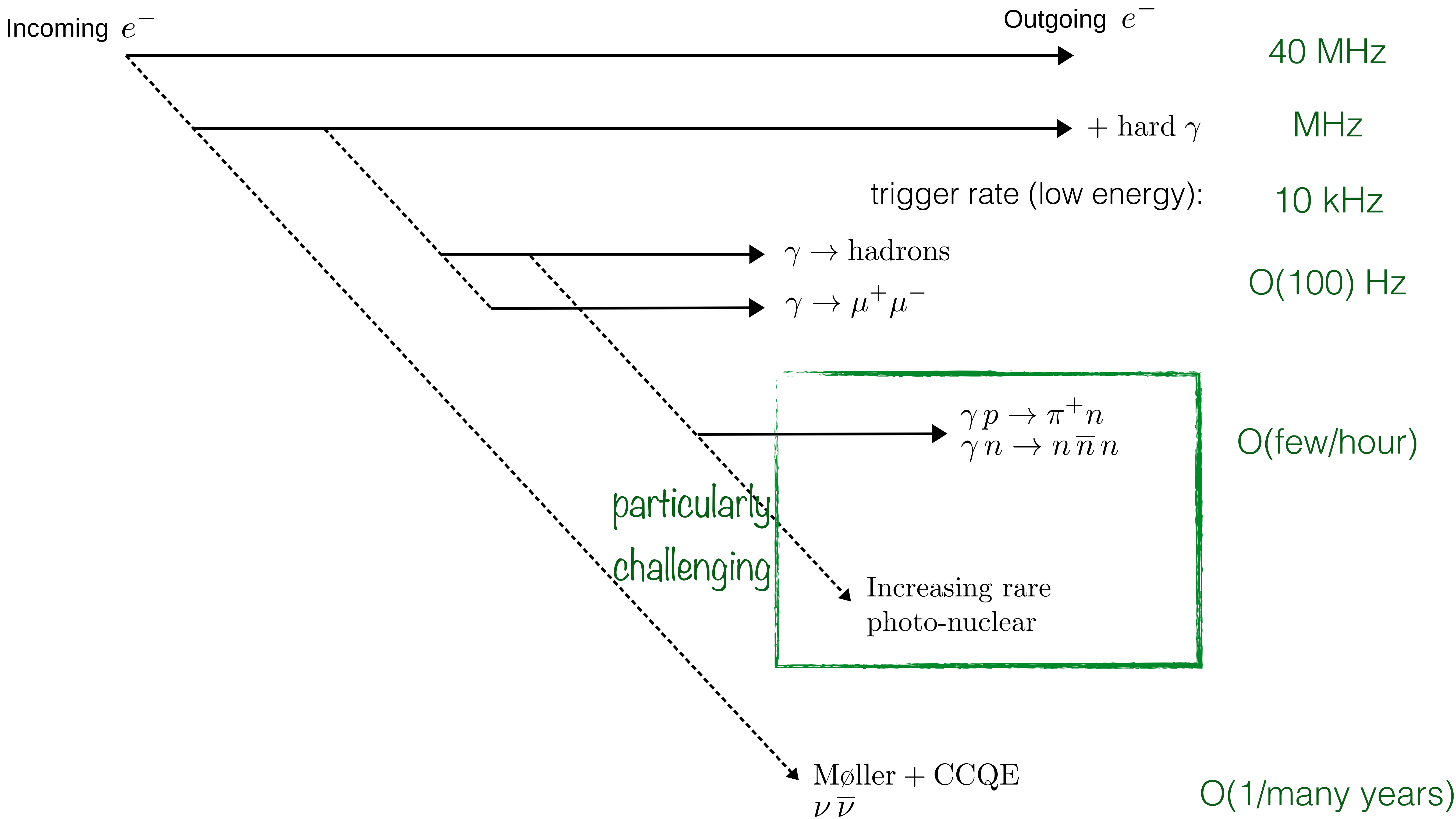
- due to mass of mediator, kinematics distinctly different from SM bremsstrahlung
  - mediator carries most of the energy
    —> soft recoil electron, large missing momentum
  - recoil electron gets transverse 'kick'
    —> large missing transverse momentum



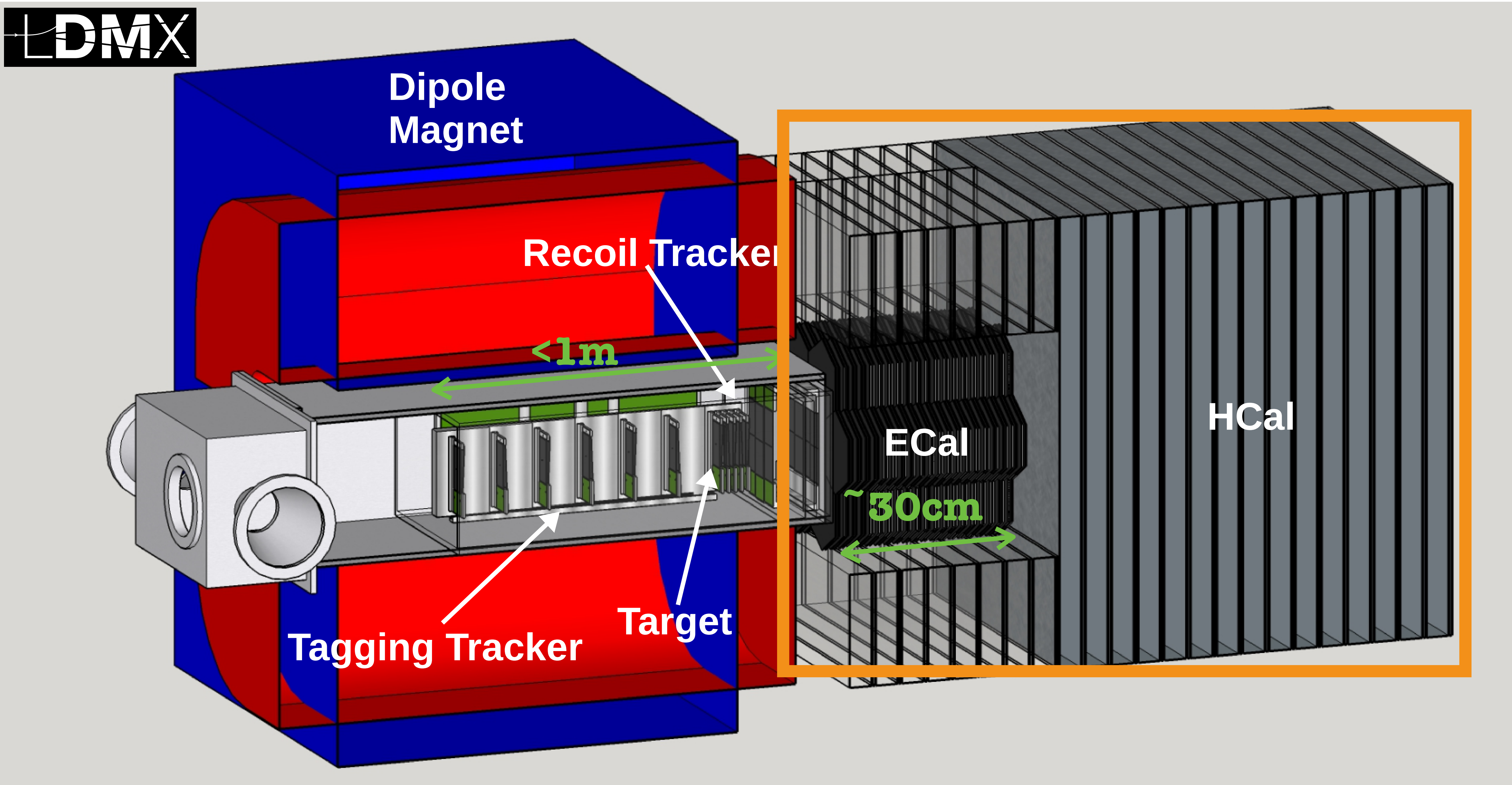




Challenge: Backgrounds!



Light Dar Matter eXperiment



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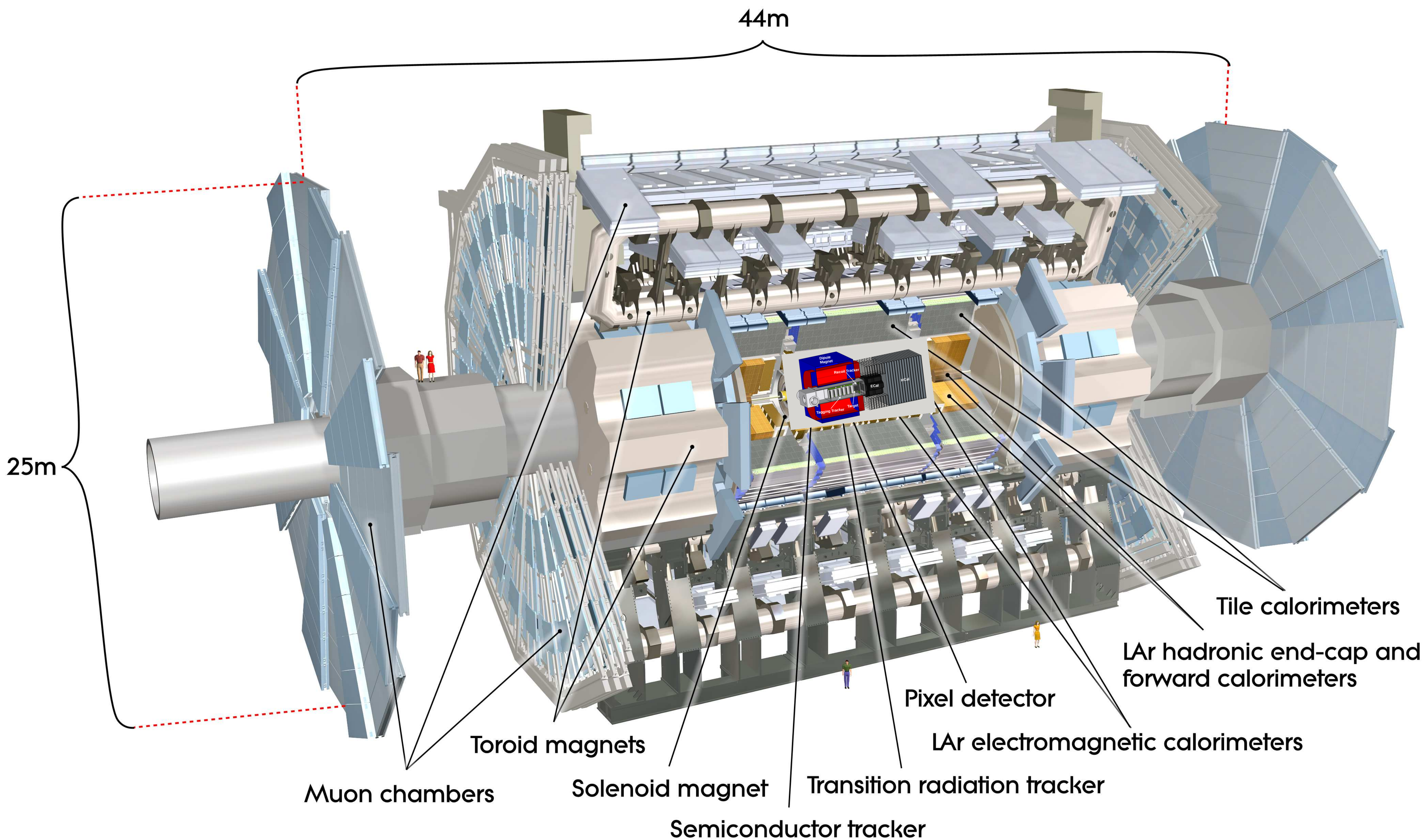
LDMX is a small experiment

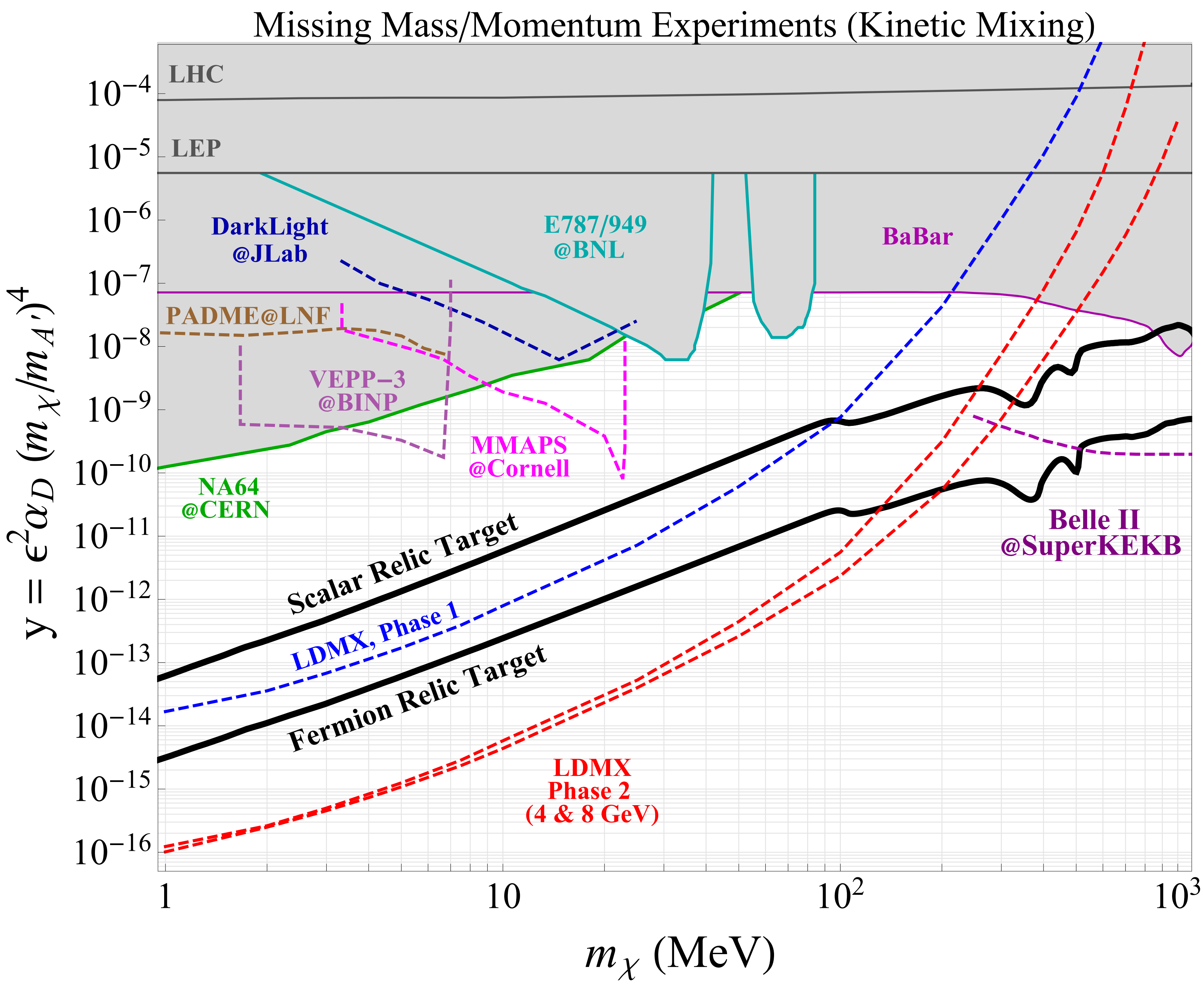


LDMX

- very young experiment, still in planning phase
- will run at beam energies of 4 - 20 GeV (<< LHC)
  - either at SLAC (California) or CERN
- detector components re-use methods from other experiments in unique combination —> unparalleled sensitivity
- main challenge: need extremely high background rejection to be able to pick out the very rare signal events
- several detector components being optimised to provide very high veto power for different kinds of backgrounds

  - **extremely exciting new project!**

- LDMX will have better reach than any other experiment



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Summary

- Dark Matter one of the hottest topics in particle physics
  - **+** : we know it must be there
  - **-** : we haven't found anything where we thought it should be
- many different ways to look for Dark Matter, still lots to explore
- WIMPs still are the most popular candidates,
  but other options are moving into focus as well
- CERN experiments still have much more data to analyse
- new experiments like LDMX cover new ground

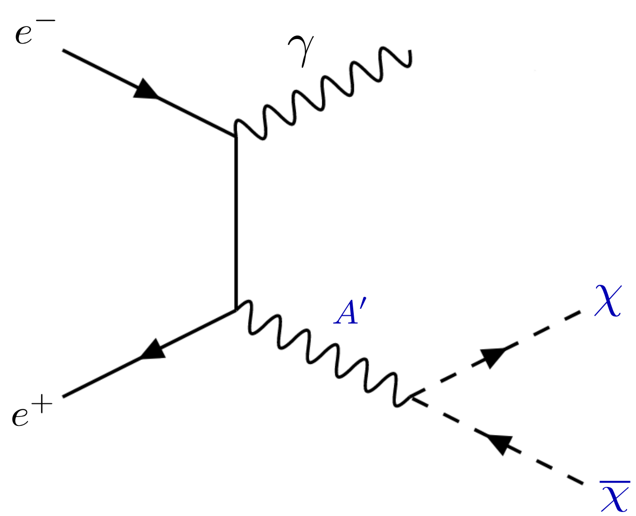
  - **very exciting times! :)**

Additional Material

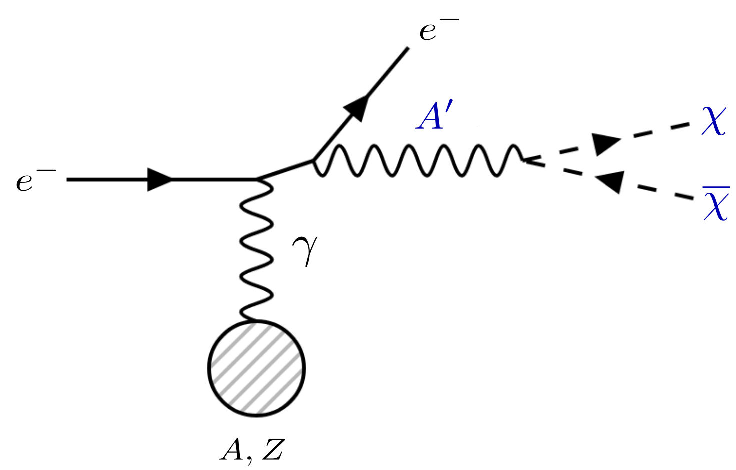
Why fixed-target?

- maximise DM yield (**production** & detection **efficiency**)

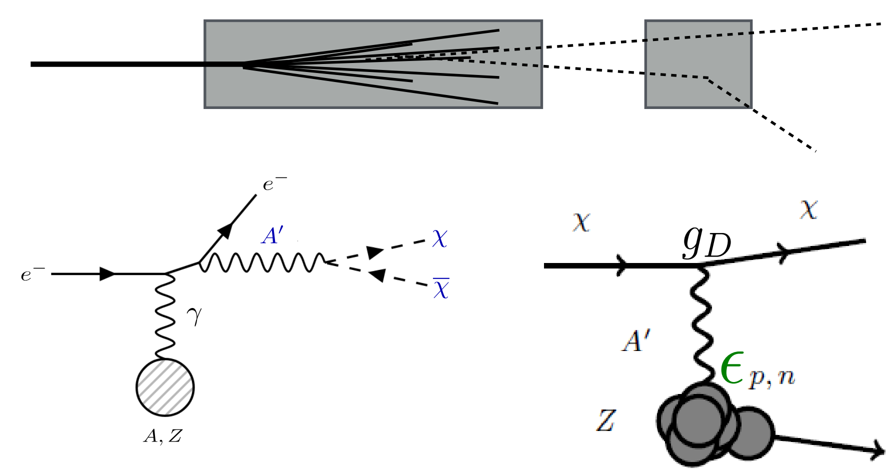
- collider
  ($m_{A'} << E_{cm}$)



- fixed target
  dark bremsstrahlung



- beam-dump



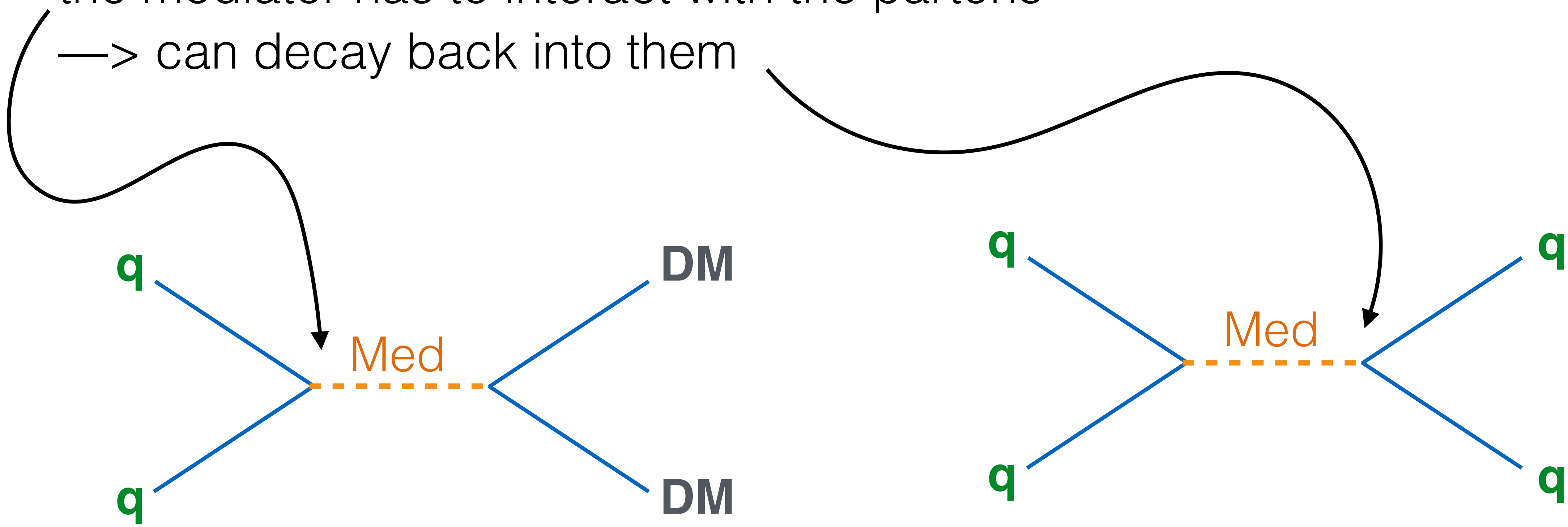
$$\sigma_{\text{coll}} \propto \frac{\varepsilon^2}{E_{\text{cm}}^2} \quad << \quad \sigma_{\text{FT}} \propto \frac{Z^2\varepsilon^2}{m_{A'}^2}$$

$$\frac{\sigma_{\text{FT}}}{\sigma_{\text{coll}}} \propto Z^2\left(\frac{E_{\text{cm}}}{m_{A'}}\right)^2 \quad >> 1$$

$$N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2 \quad >> \quad N \propto \varepsilon^4$$

Visible Signatures (Indirect)

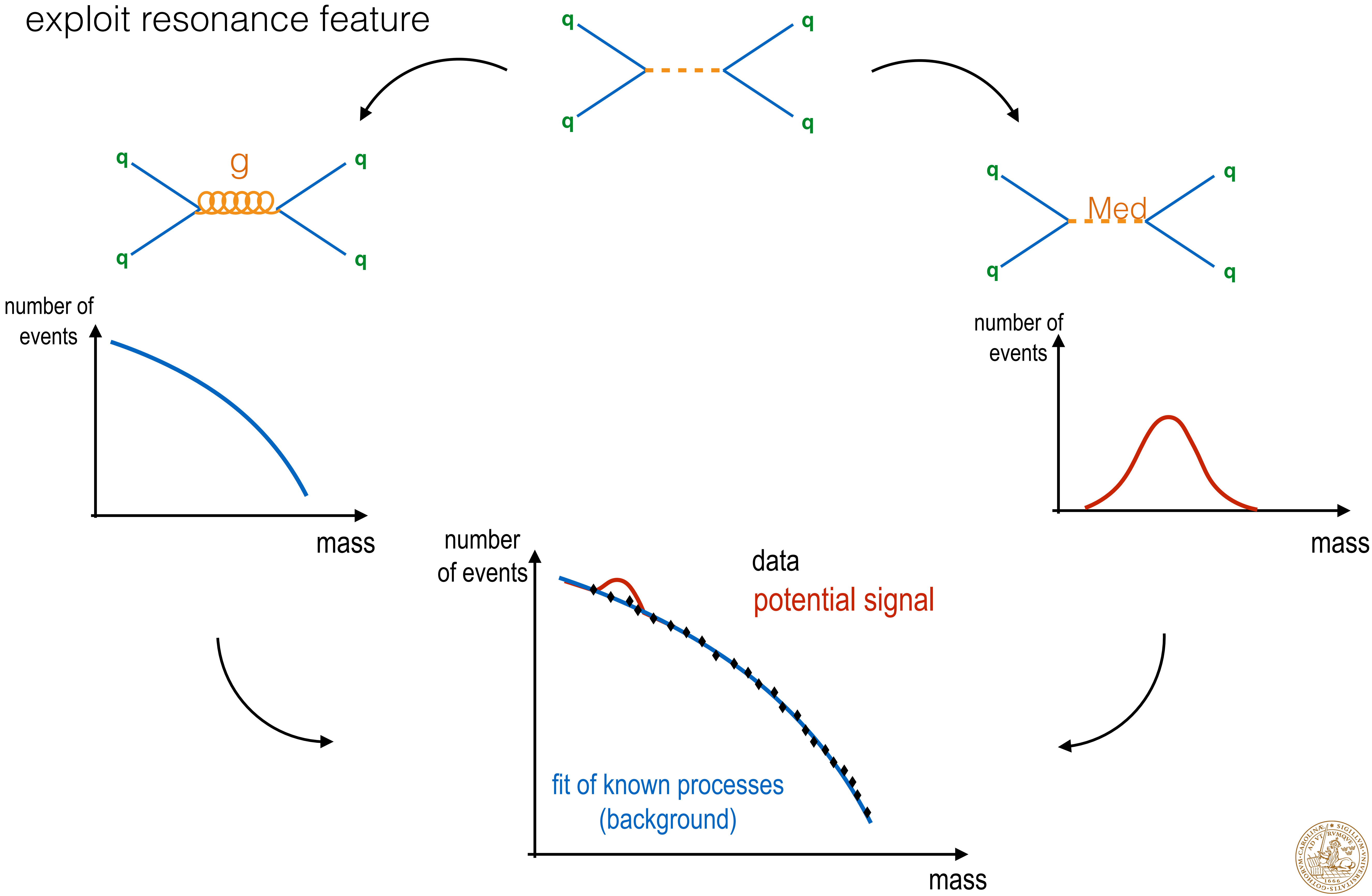
- another approach: look for the **mediator**!
  - Dark Matter has to interact in order to be produced
    —> there must be a mediator
  - the mediator has to interact with the partons
    —> can decay back into them



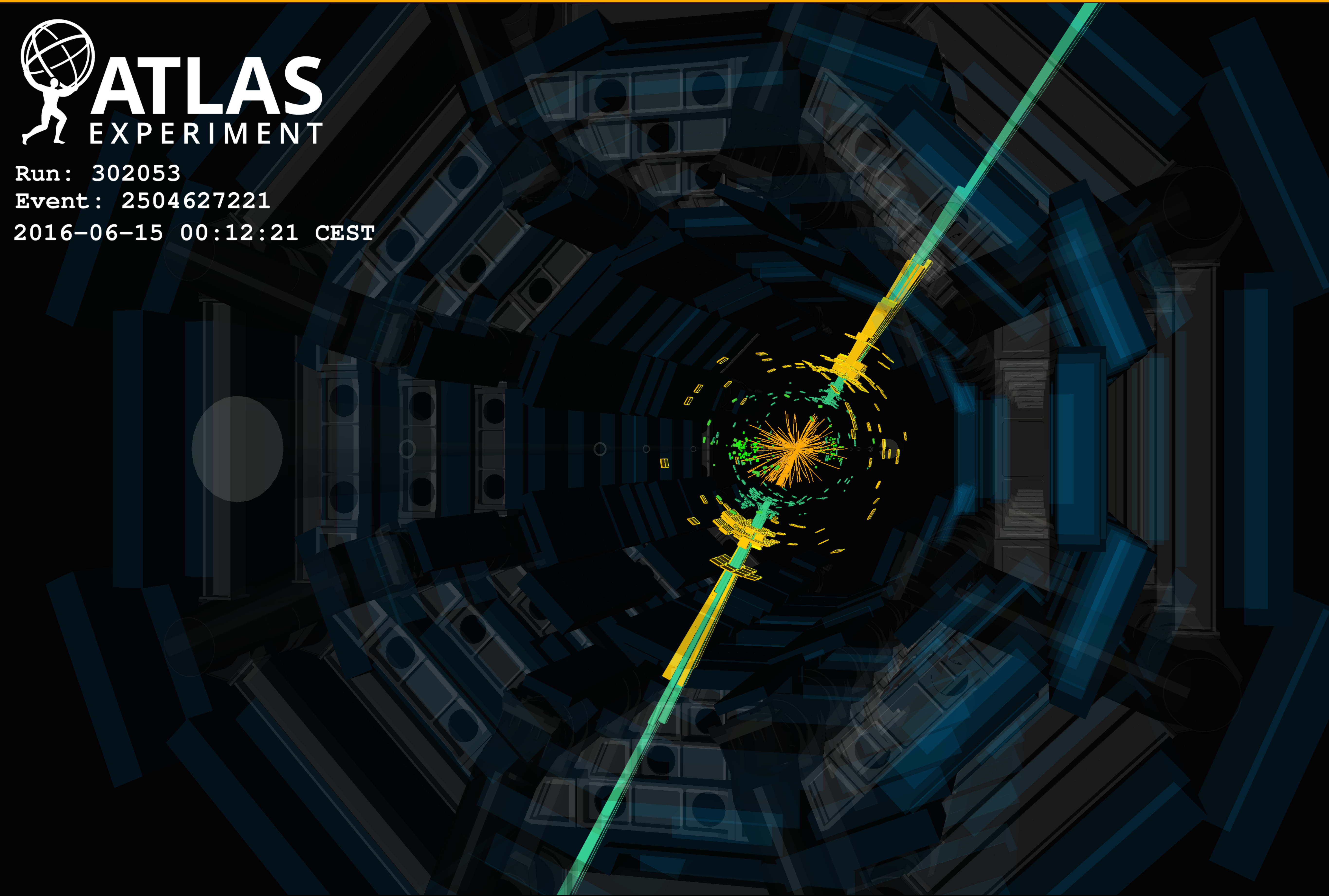
- not looking for a signature of the actual Dark Matter

Di-Jet Events

- exploit resonance feature

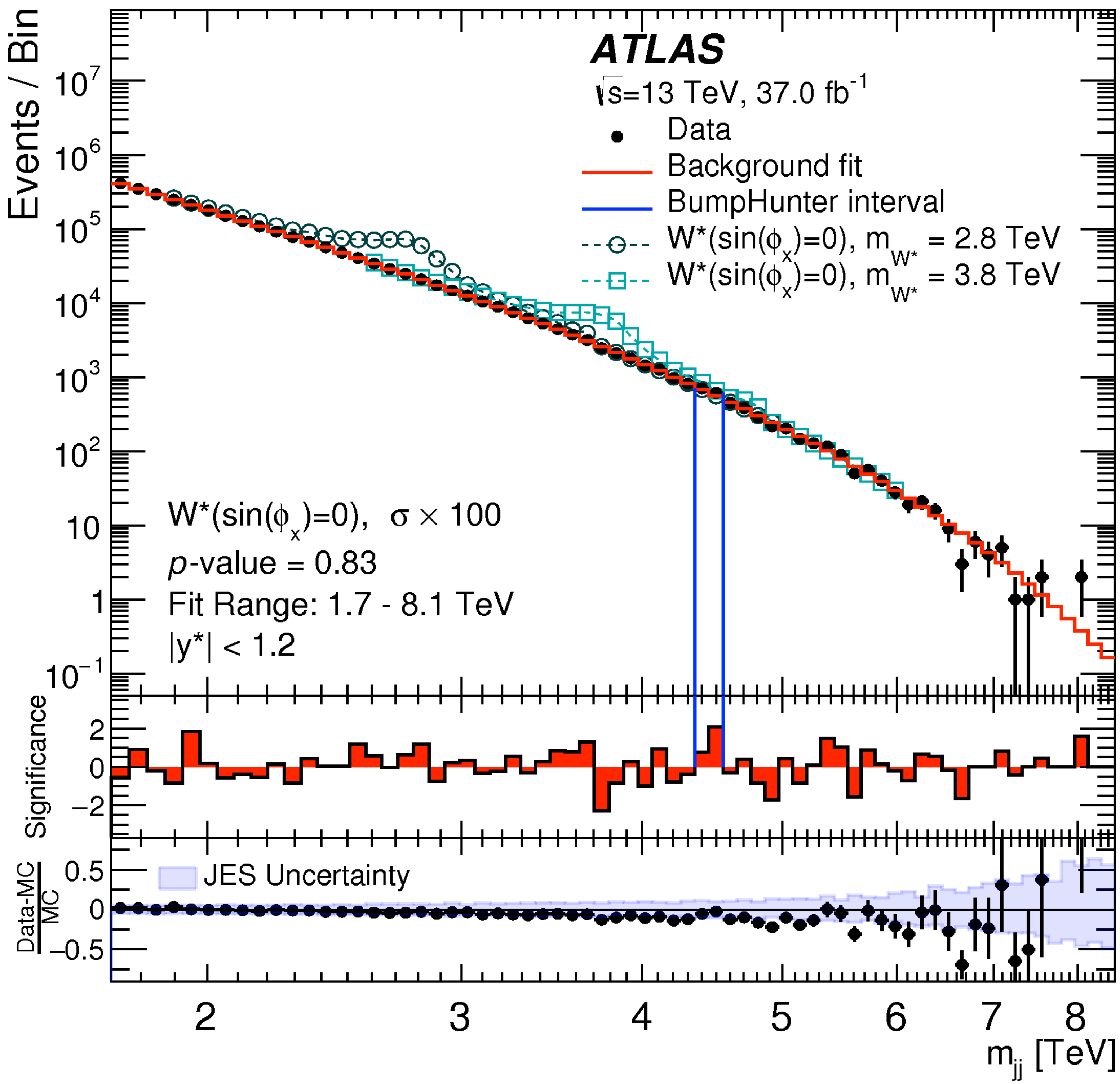


A beautiful di-jet event



Mediator Searches

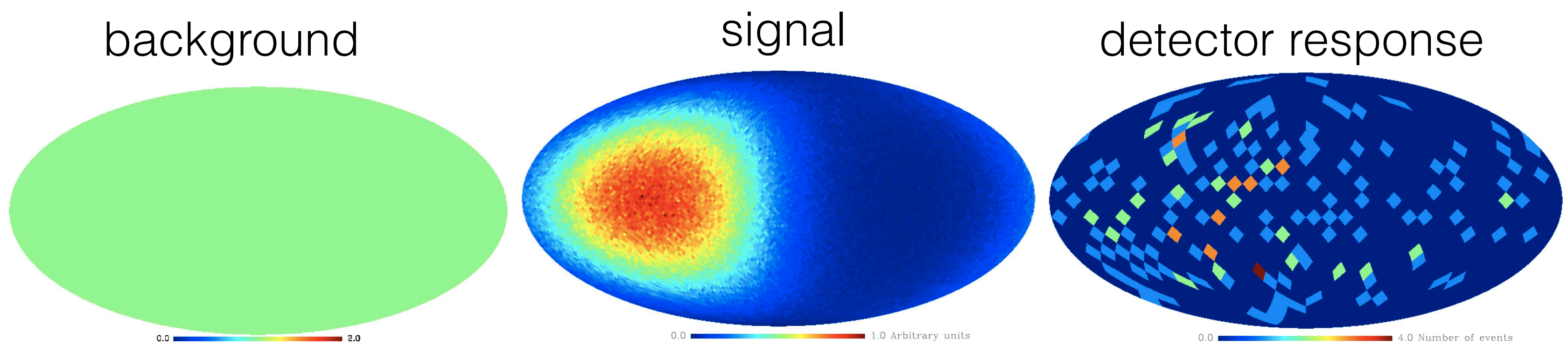
- from a real publication https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/



- no clear signal seen so far (but we keep looking! much more data still to be analysed!)

Directional Direct Detection

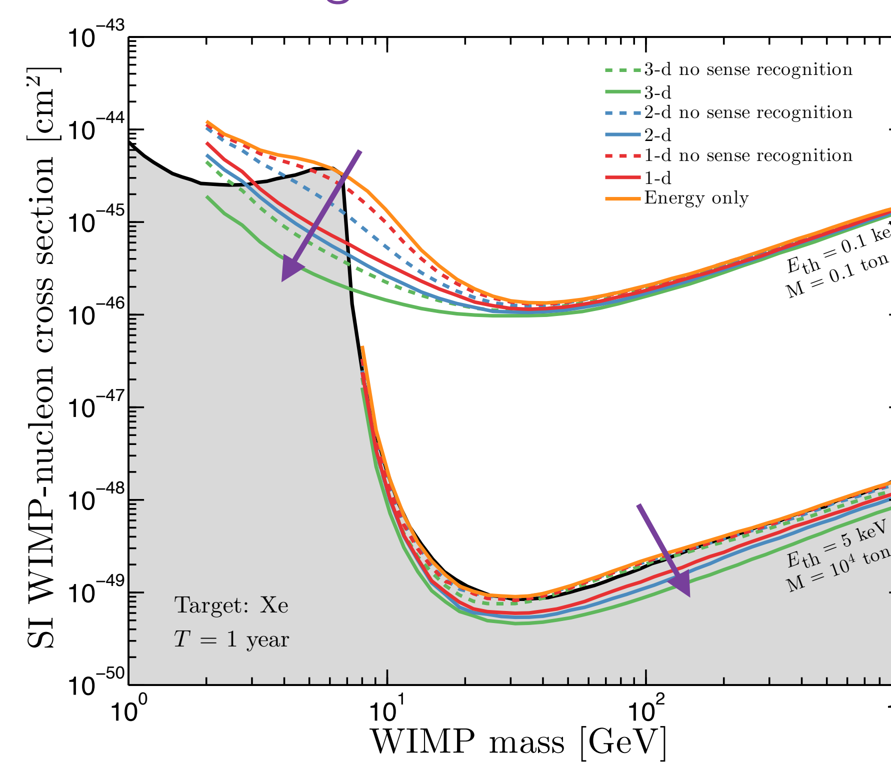
- direct detection uses only **energy** of recoiling nucleus
- using **recoil direction** in addition: powerful **background removal tool**



arxiv:1304.2255

- **DM** looks distinctly **different** from other things (background)!
    - details depend on theory parameters
        - **distinguish** between theories
- could go beyond “ultimate reach"
    - also important in case of **no signal**

adding directional information



arxiv:1602.03781

- **very active area!**

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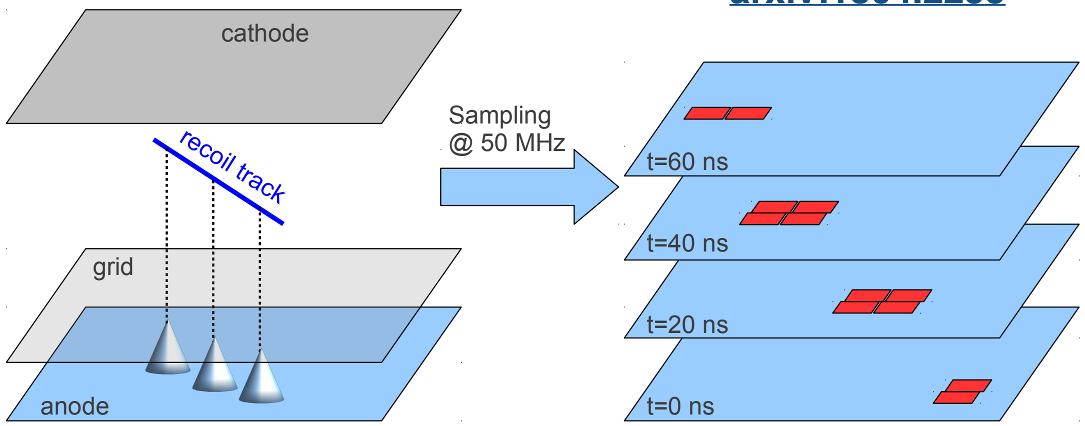
Directional Direct Detection

- various techniques being explored
- most mature: low-pressure *time projection chambers* (TPCs)
  - measure two coordinates, get the third one from drift time of charge signal
- coming years: can we built large scale detectors?
  - important to get high enough rate
- example: **MIMAC**
  - specific gas mixture to slow electrons
  - reconstruction of 3rd spatial component

arxiv:1304.2255

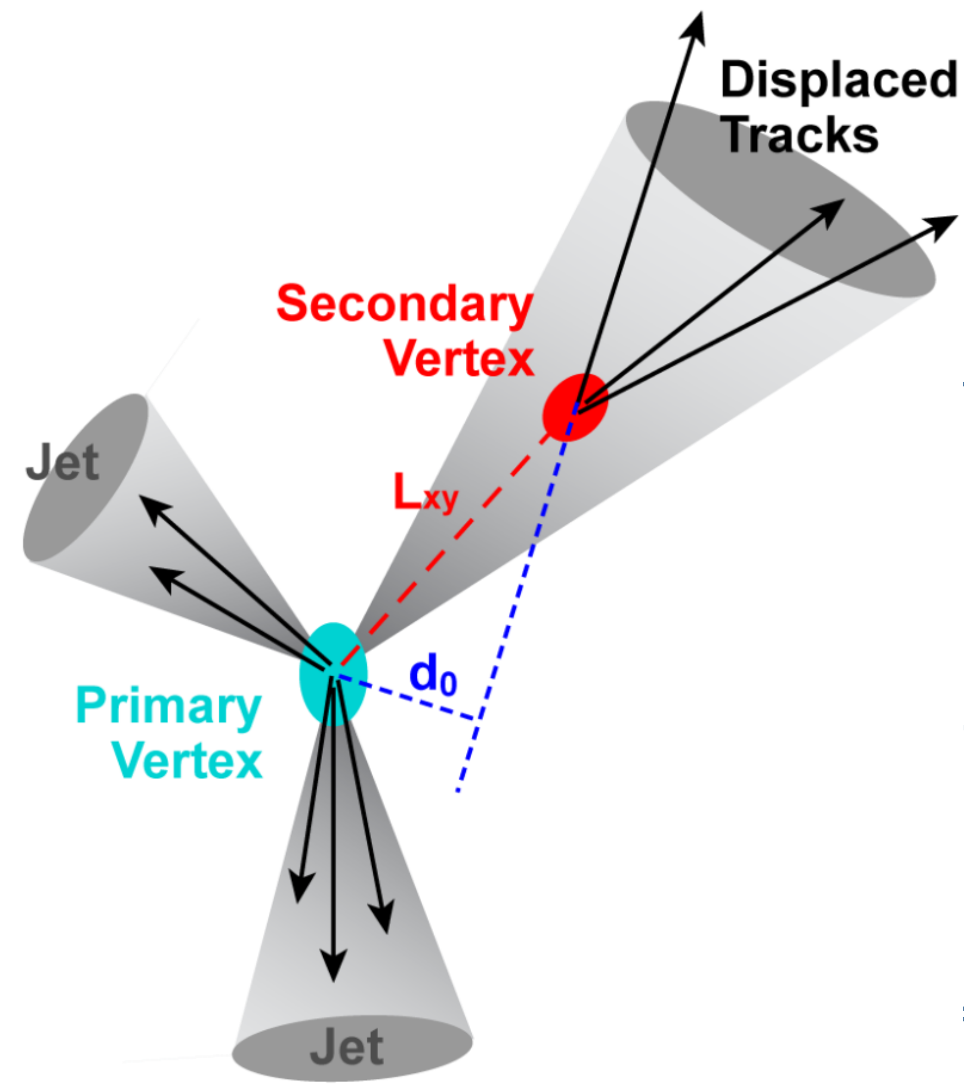


  - currently 5.8l prototype taking data
  - next step: $1m^3$ demonstrator towards $50m^3$ TPC

- **very active research area!**

Identifying b-quarks

- quarks generally produce **jets** (spray of particles) in the detector
  - maaaaany jets produced at a hadron collider
- need to find jets that originate from a b-quark (*b-tagging*) —> **b-jet**
- in jets, hadrons are formed, b-jets will contain **B-hadrons** (contain b-quarks)
  - B-hadrons have “visible" lifetimes
    - their “late" decay leads to **secondary vertex**
      - resolved with excellent tracking resolution
    - rather involved techniques using several variables at the same time used to distinguish b-jets from jets from lighter quarks



https://amva4newphysics.wordpress.com/2016/01/04/b-tagging-101/