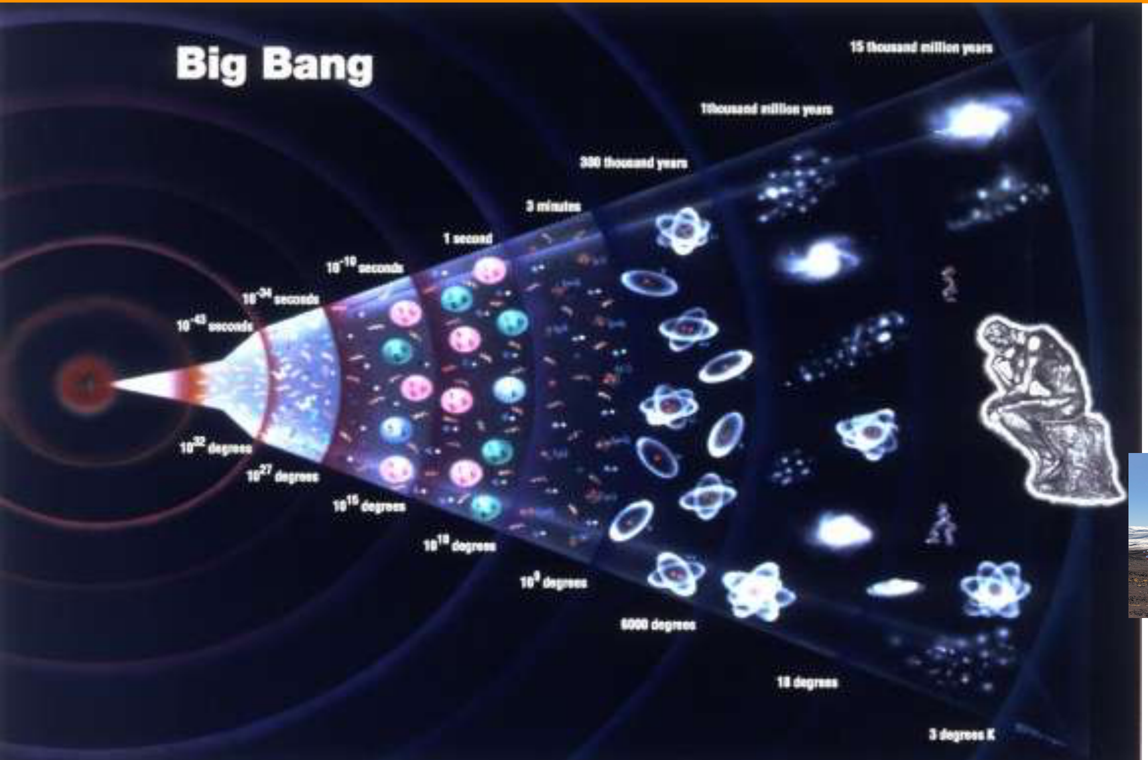
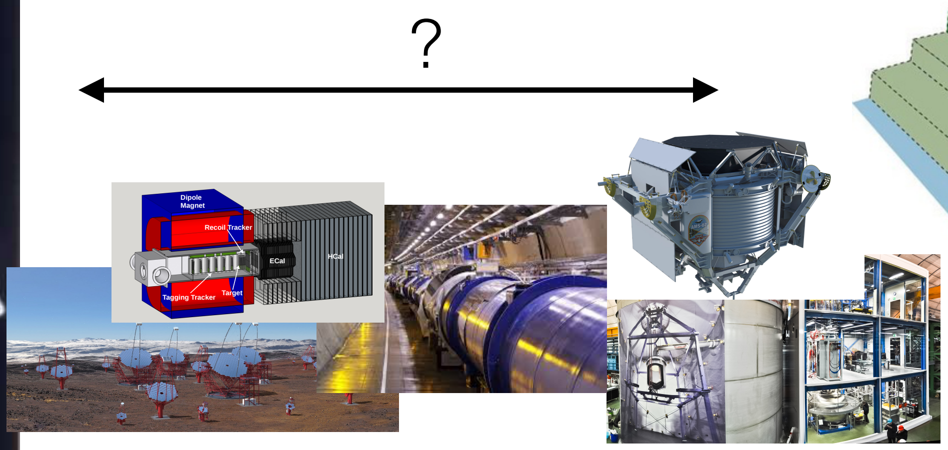
Dark Matter
(from a particle physicists point of view)

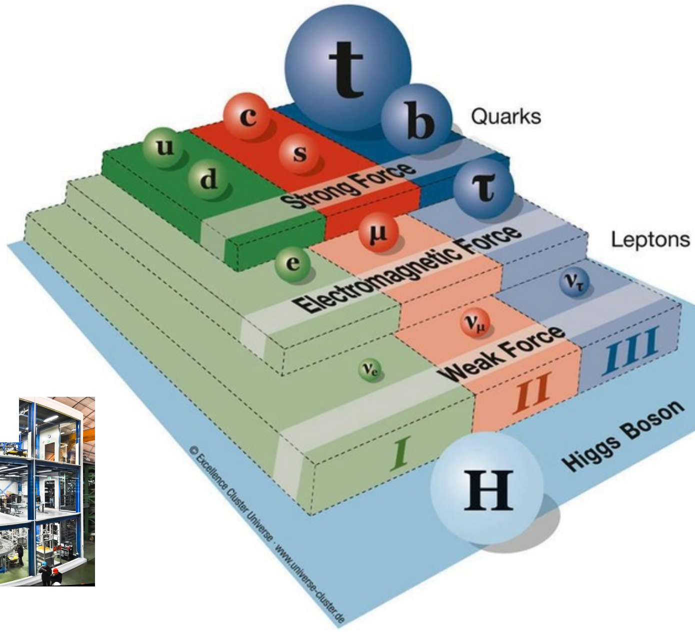
VT 2018

Ruth Pöttgen

22 February 2018







What is particle physics?

- two main questions:
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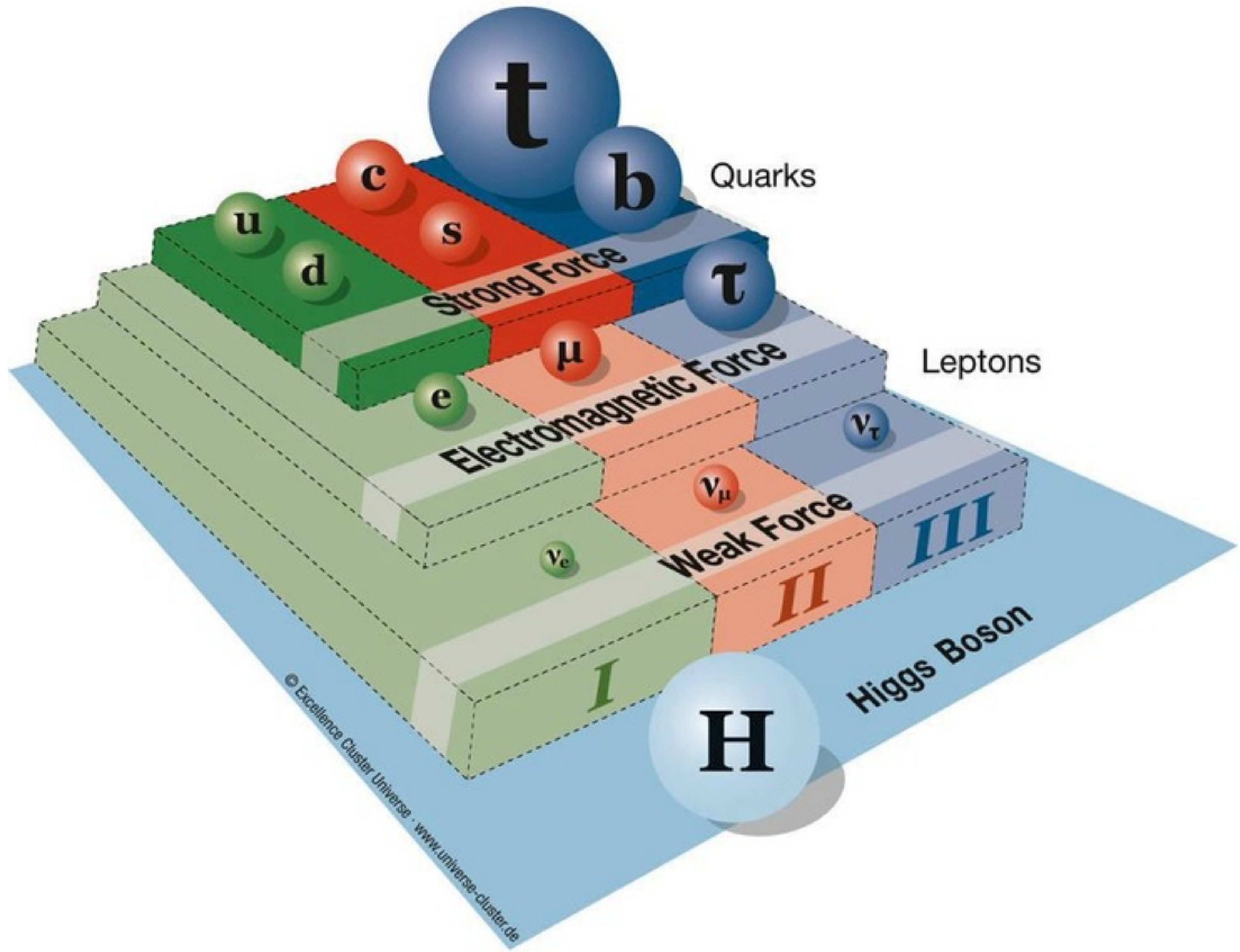
    - **fundamentally!**
  - how do fundamental particles **interact**?



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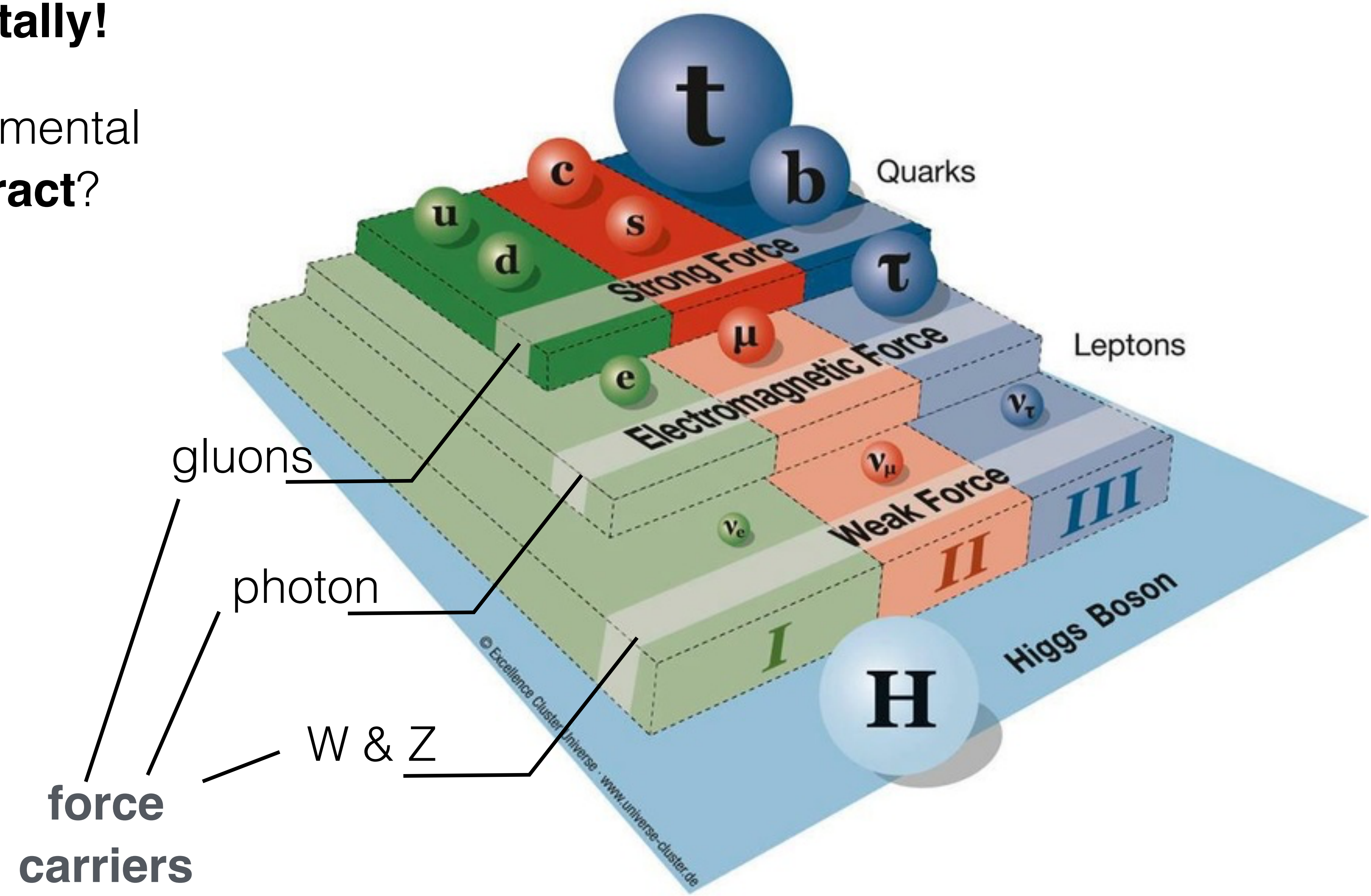
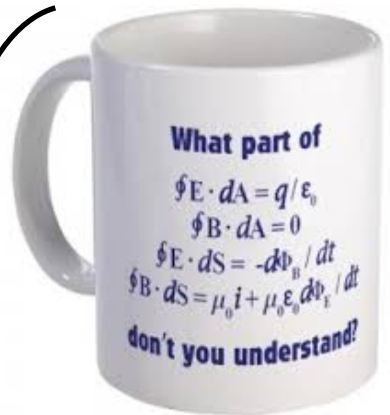


FFF: Four Fundamental Forces

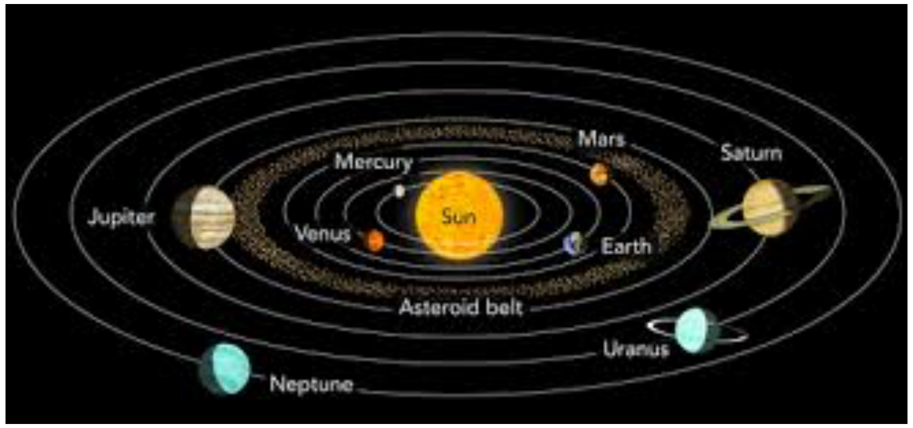
electro-weak

electromagnetic

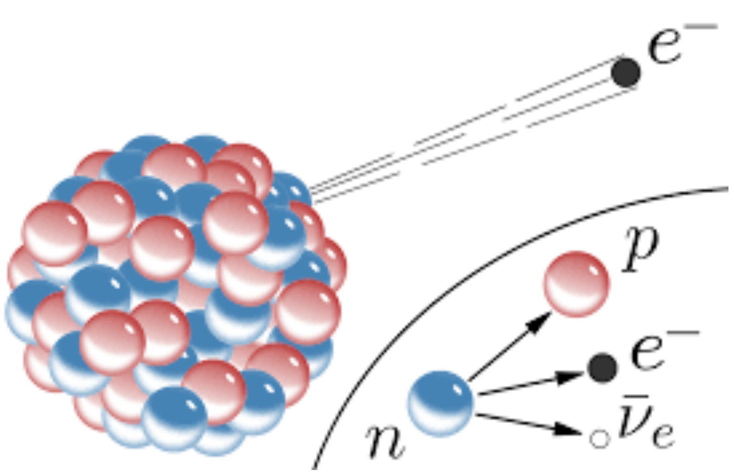


(Maxwell)

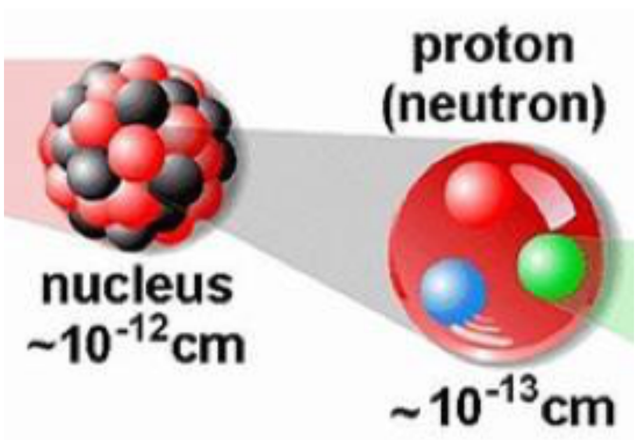
gravity

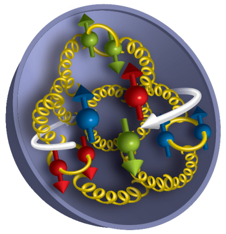


weak



strong





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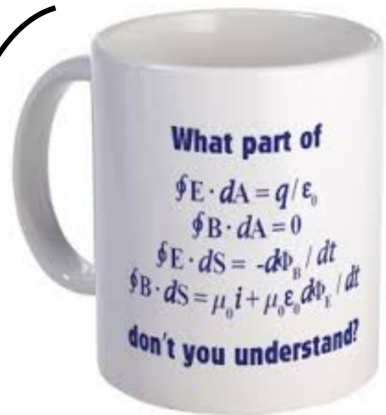

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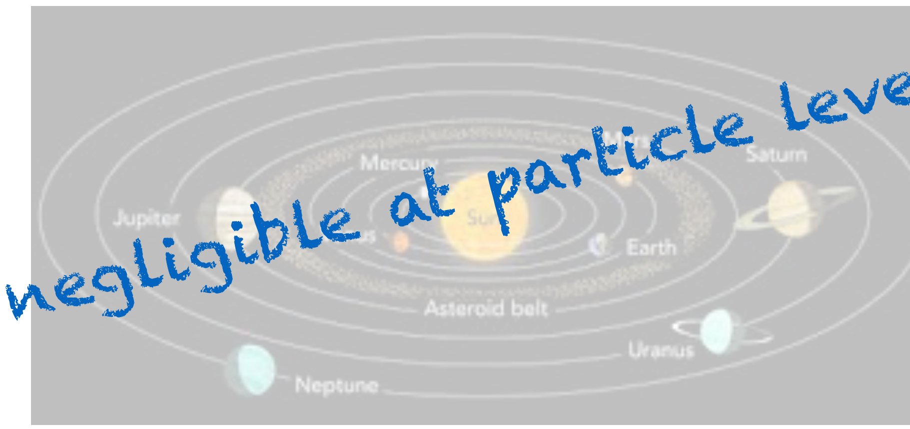
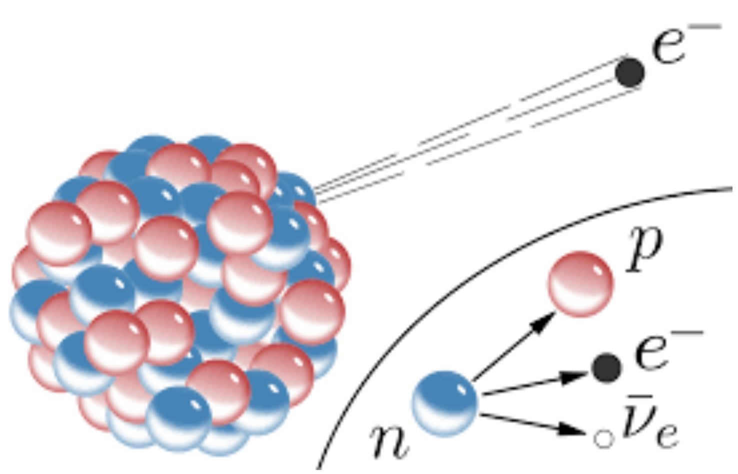


negligible at particle level

weak



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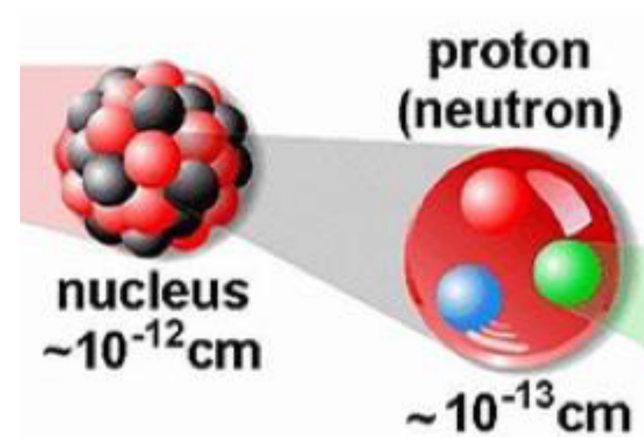
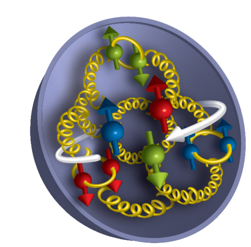
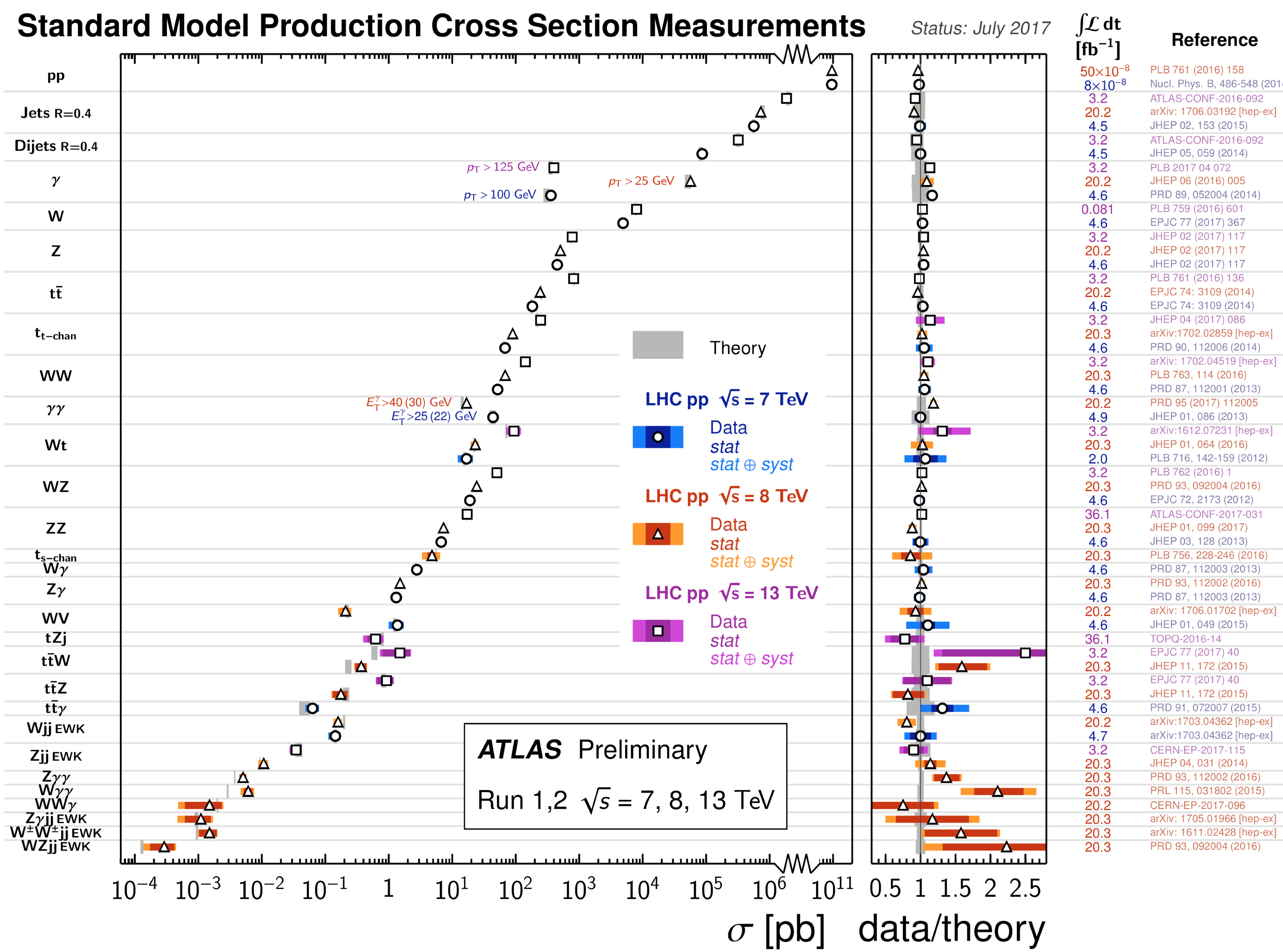




Standard Model Measurements

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/



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

so, are we all done here?

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Let's think big

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- the Universe

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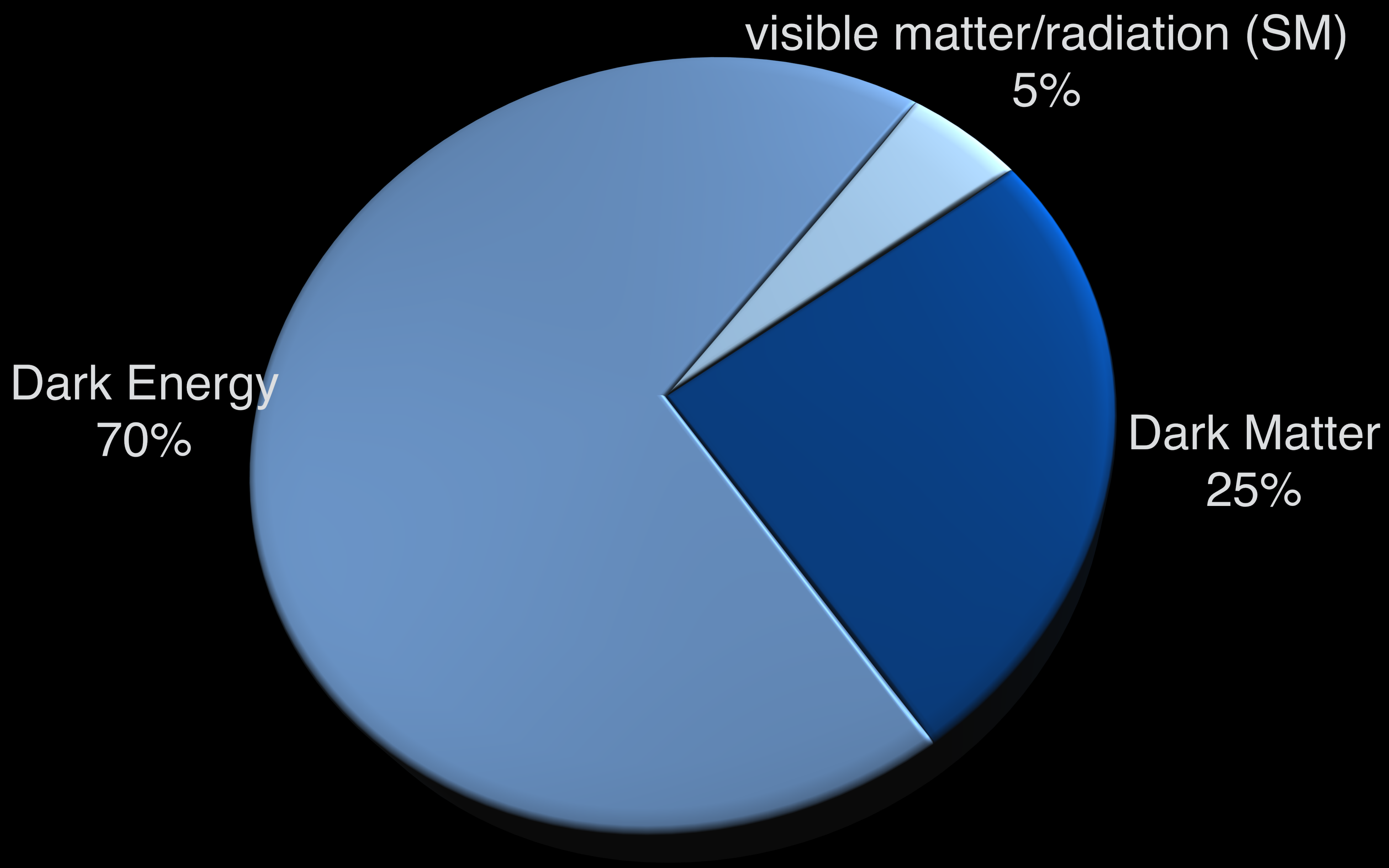
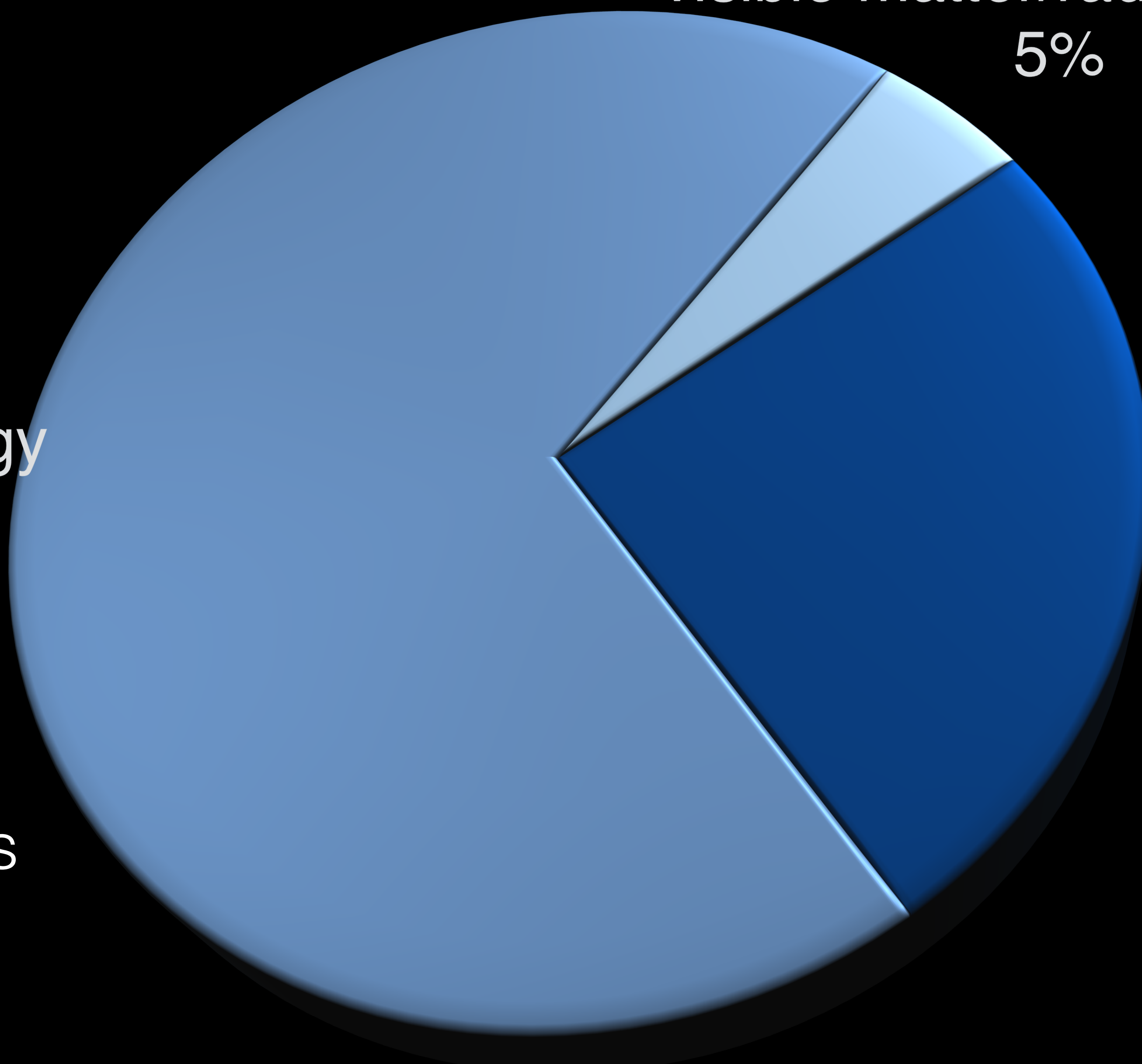


Let's think big

- 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?

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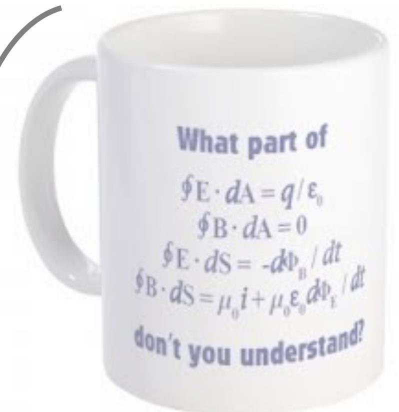
electromagnetic



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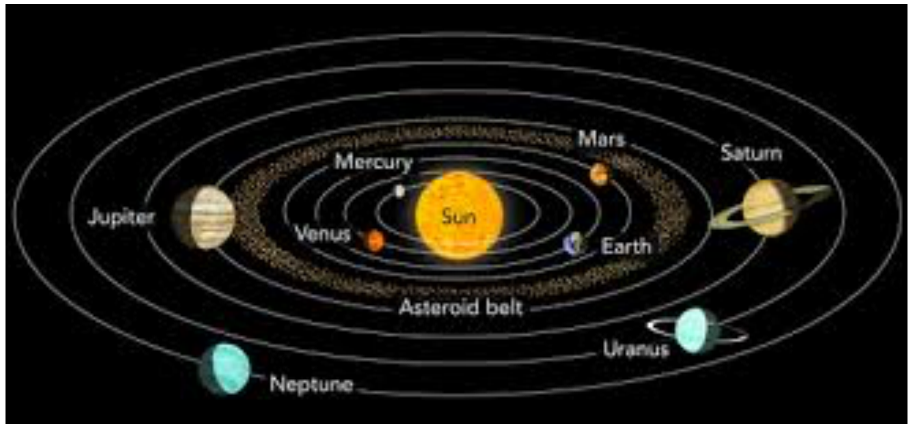

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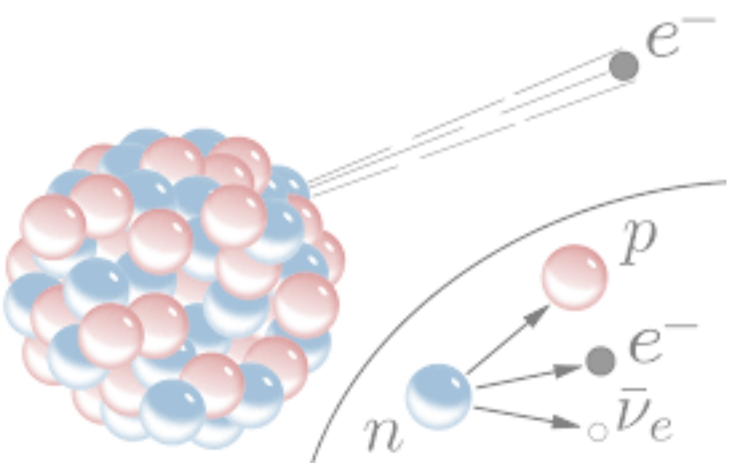

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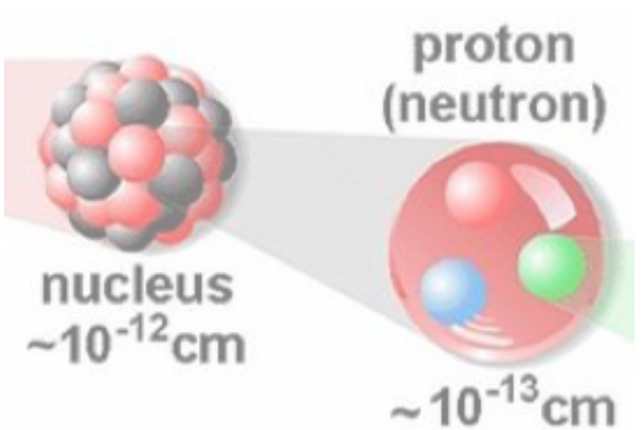
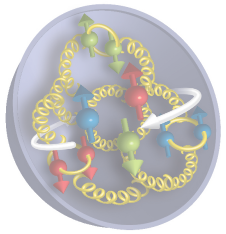




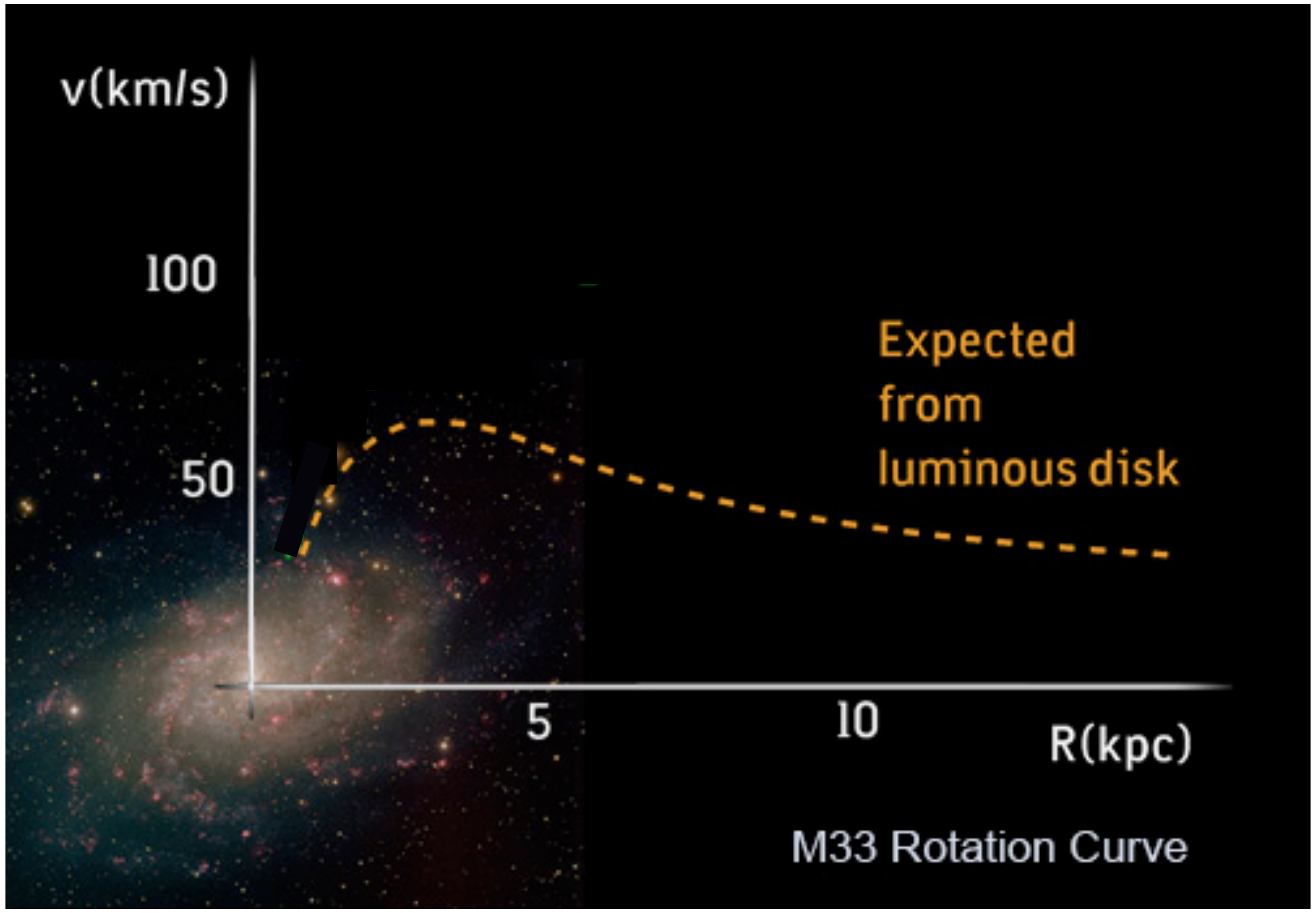
A bit of Newton

stars in a galaxy orbit the galactic centre

from Newton:

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

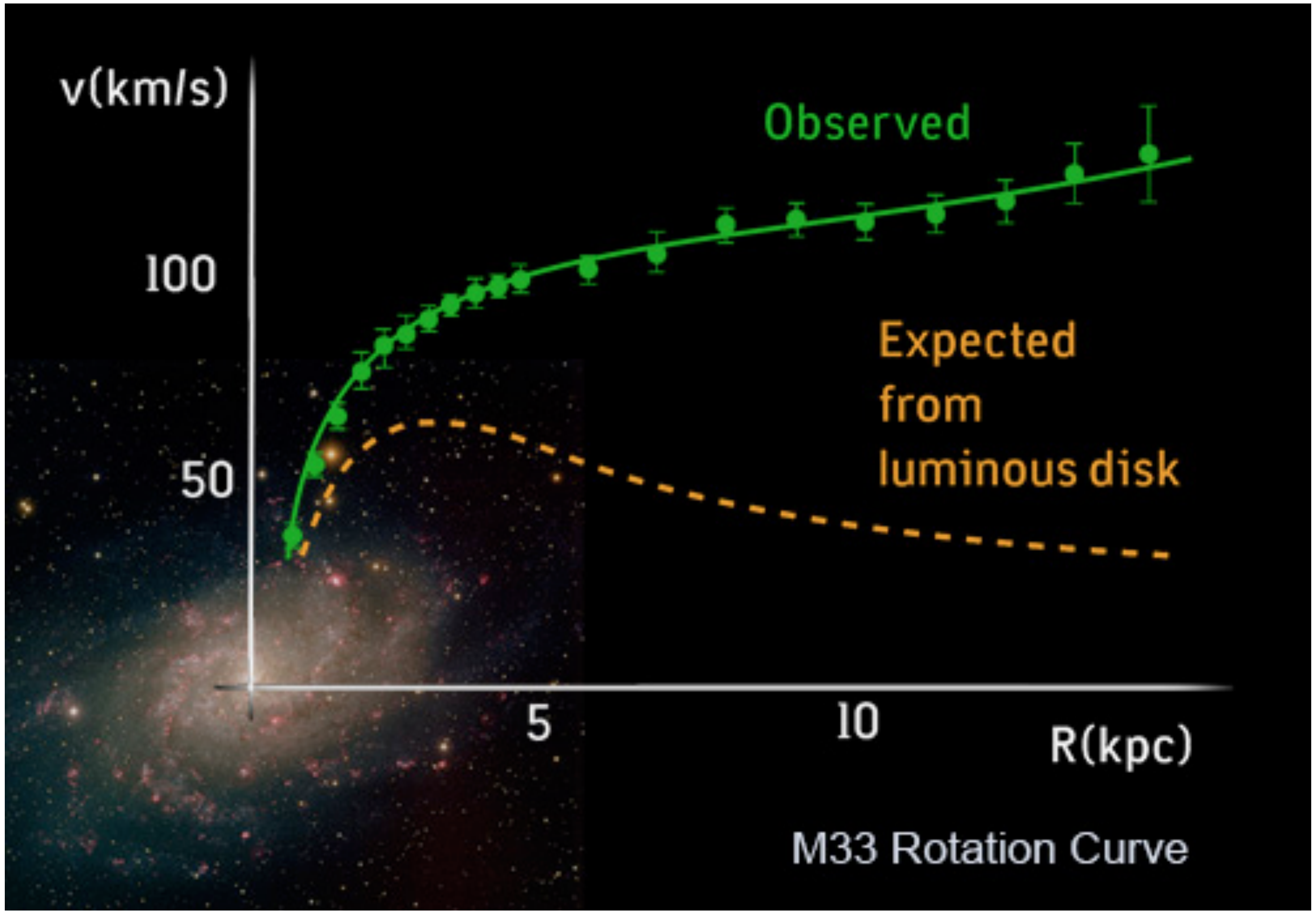
$$v = \sqrt{(GM/r)} \sim 1/\sqrt{r}$$



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

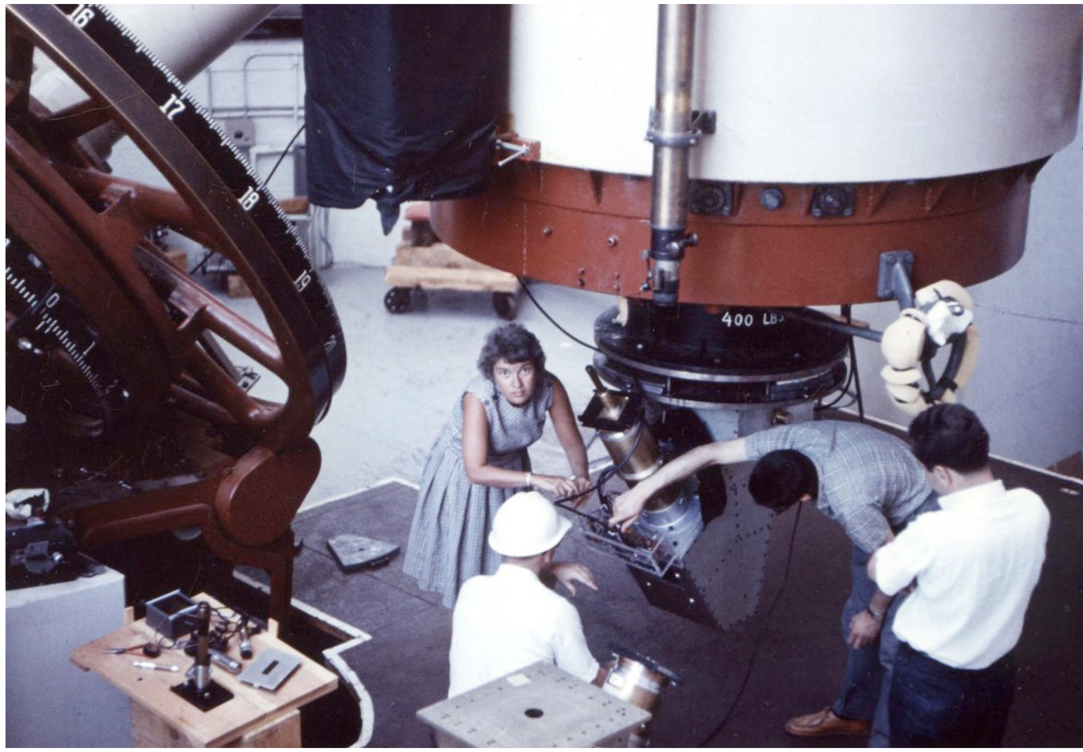
level of single galaxies

what's actually observed:



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

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"

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Velocity Distribution in Galaxy Cluster

level of cluster of galaxies

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

one of the first to coin 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

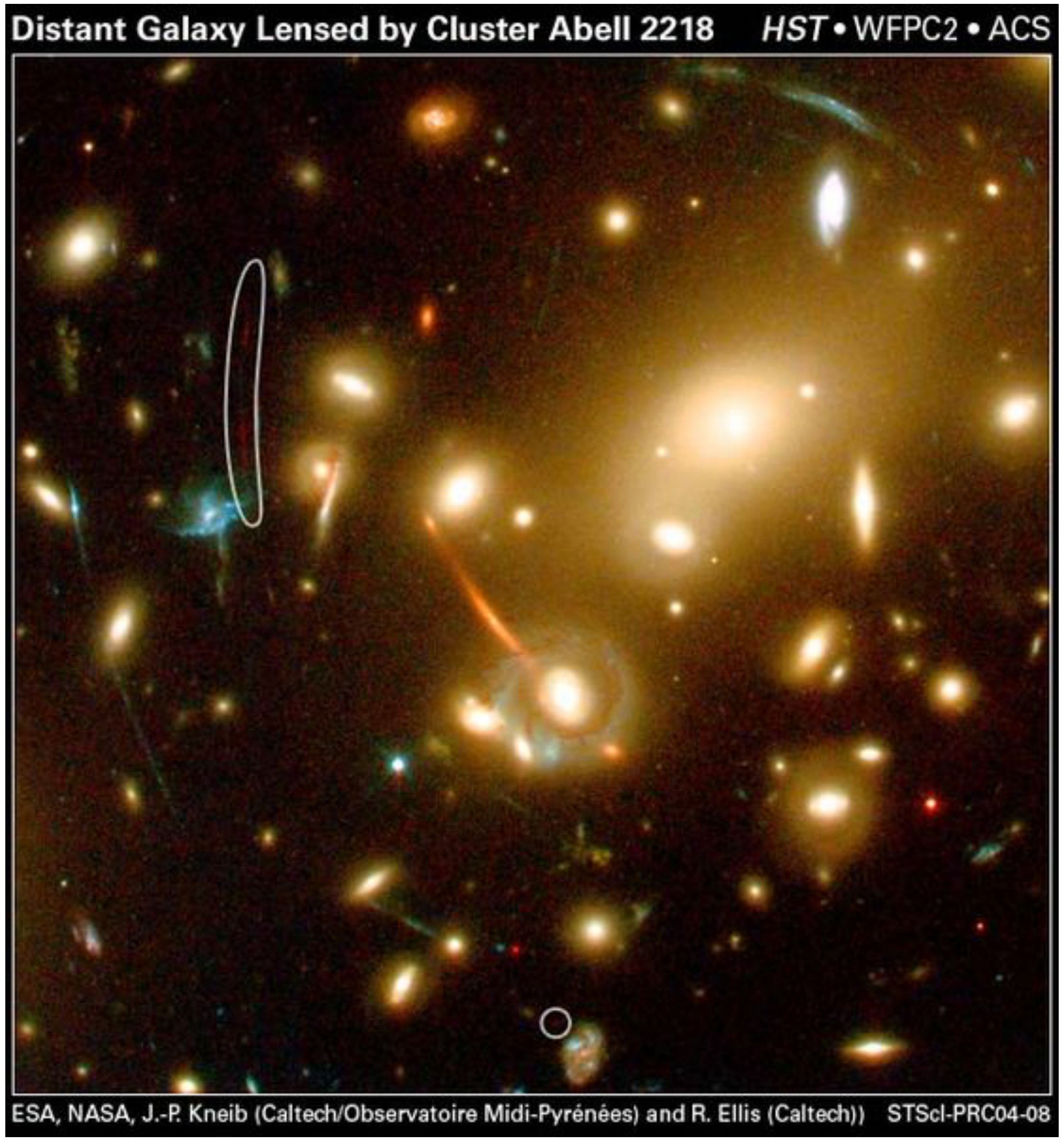
found that there was much more mass (=matter) than the light output suggested (today: factor of 10)

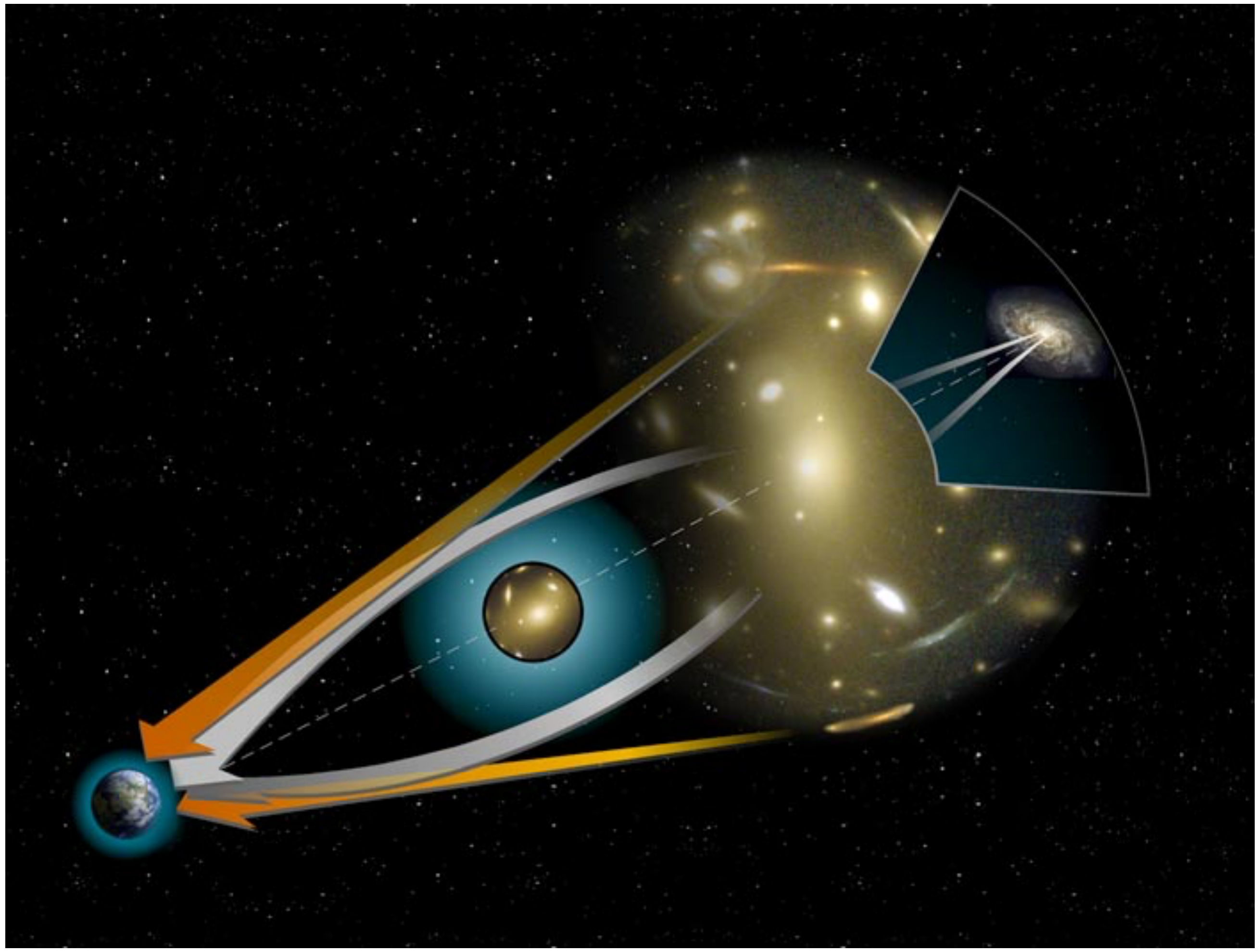
=> **dark matter**

Gravitational Lensing

level of galaxy clusters

"mass bends light" (general relativity)





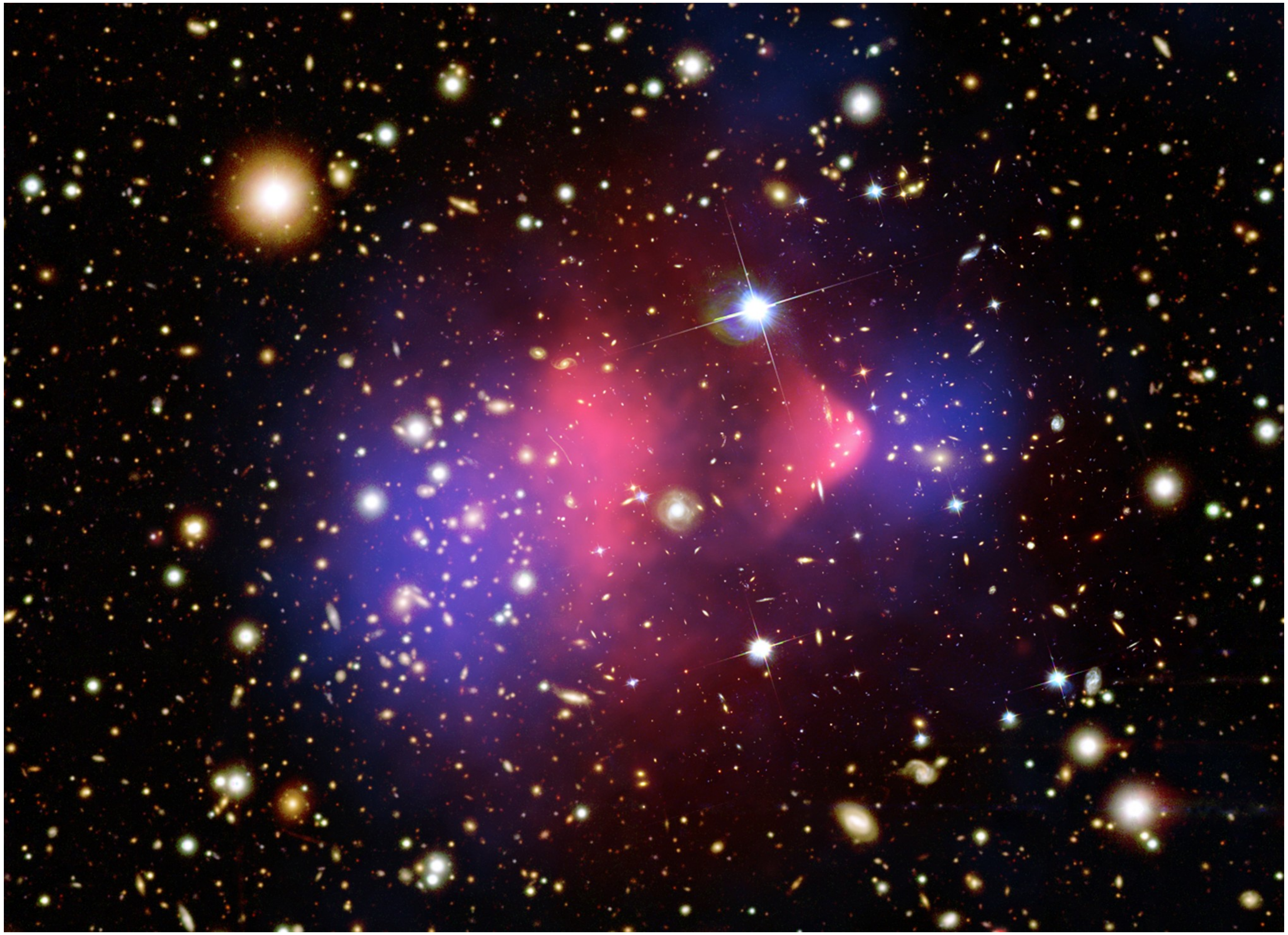
http://scienceblogs.com/startswithabang/2011/04/20/how-gravitational-lensing-show/

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

Bullet Cluster

remnant of collision of two galaxy clusters

animation

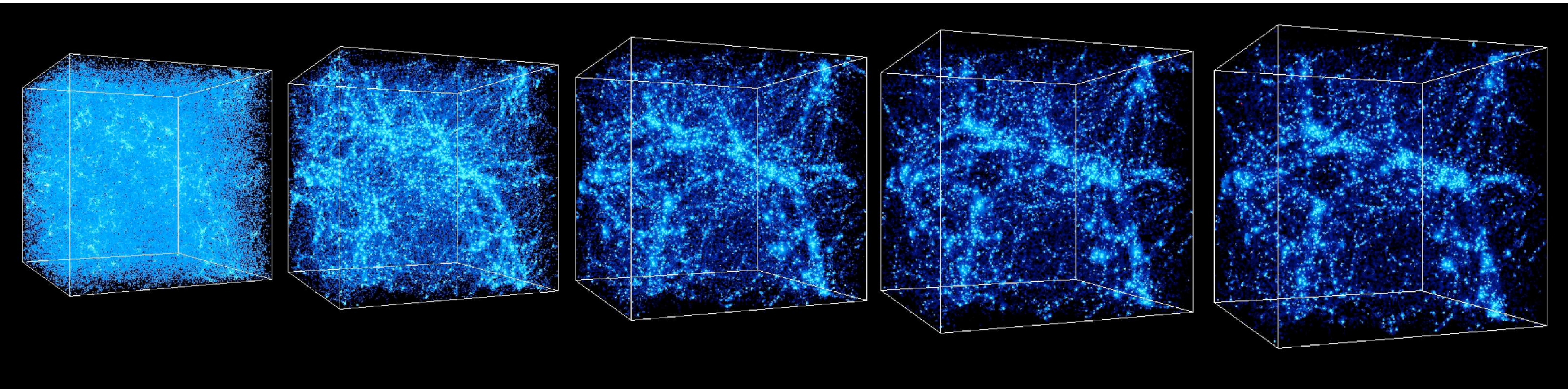


https://svs.gsfc.nasa.gov/30094

centre of gravity ≠ centre of visible mass

level of the entire Universe

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



simulation

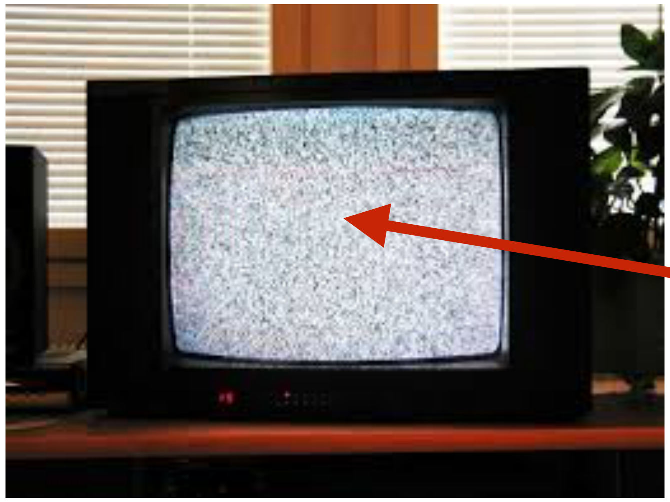
simulations fail miserably to produce the observed structures in models that do not include Dark Matter

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 Band: 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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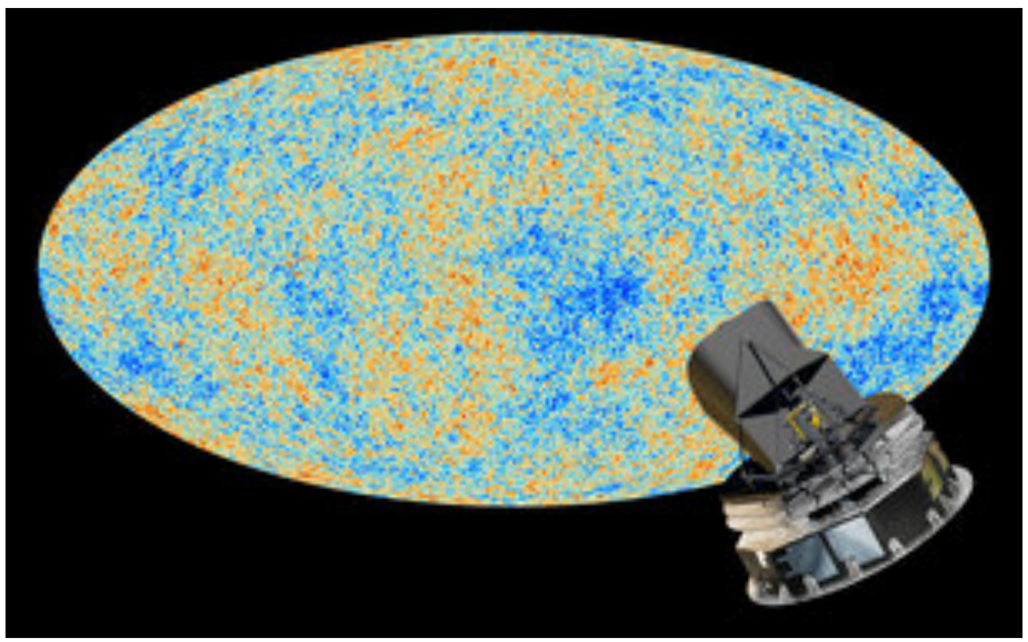
How do we know how much DM there is?

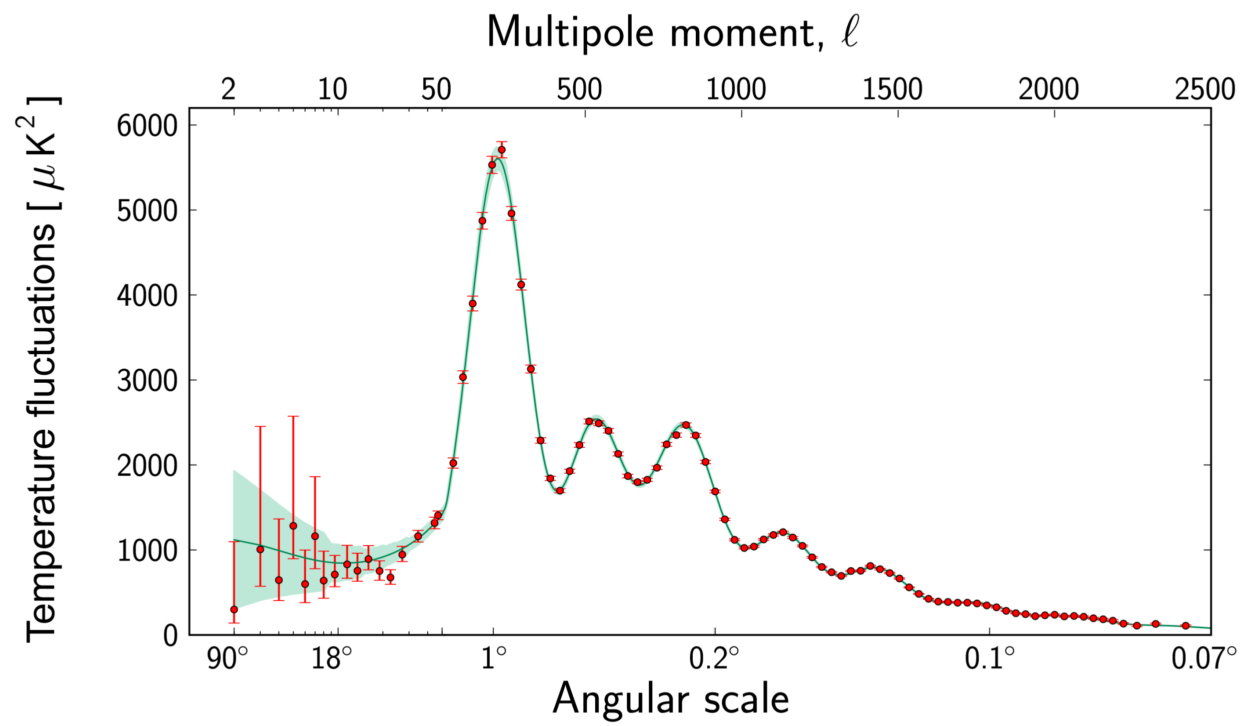
level of the entire Universe ESA **PLANCK** mission

tiny temperature fluctuations (anisotropies) in CMB

a different way of looking at it

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





cosmological parameters can be estimated from best fit to observation

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

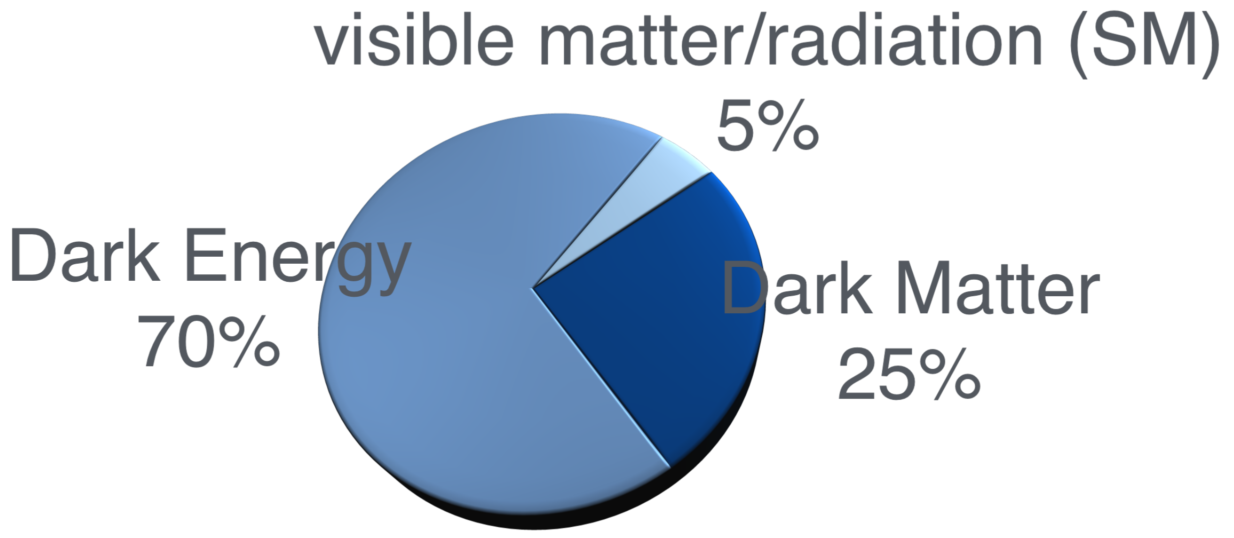
Summary up to here

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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—> doesn't interact with photons
—> **electrically neutral**

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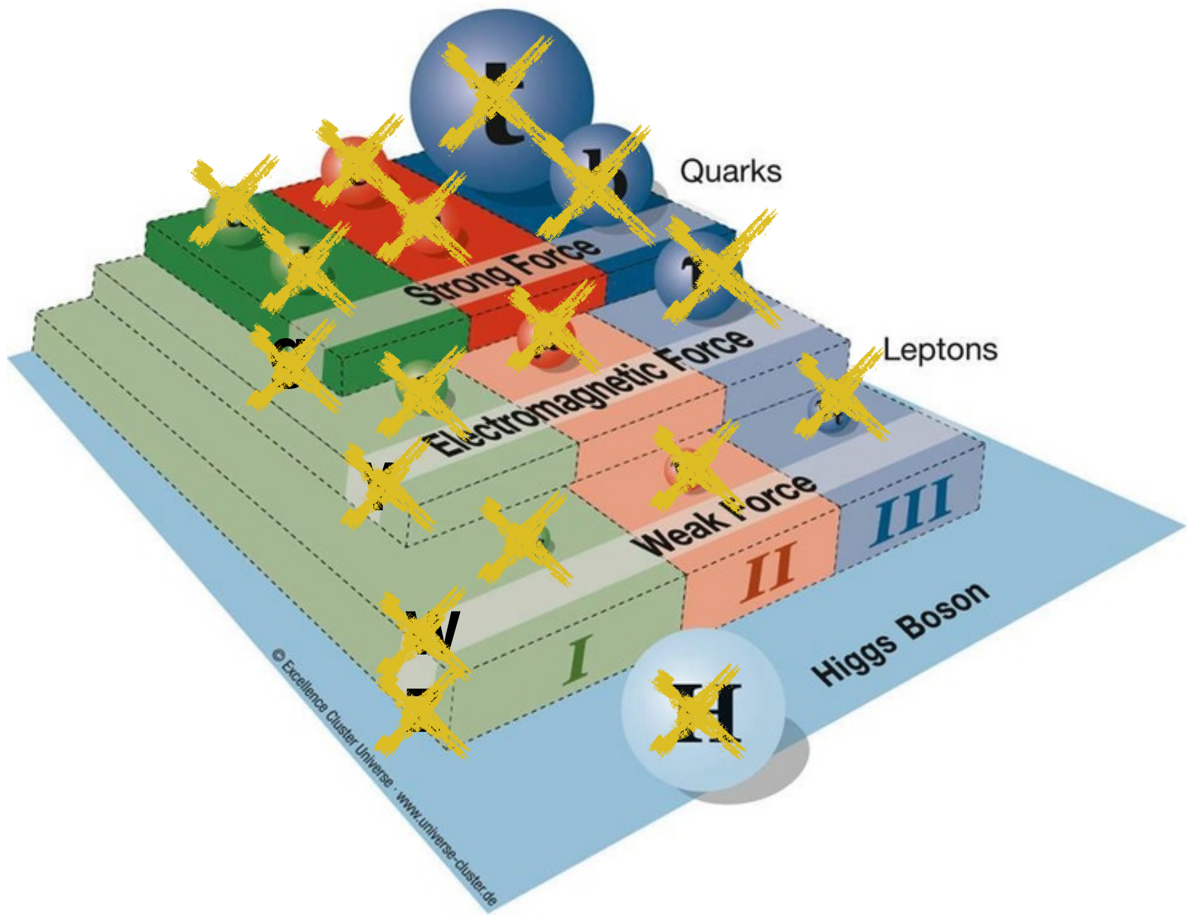

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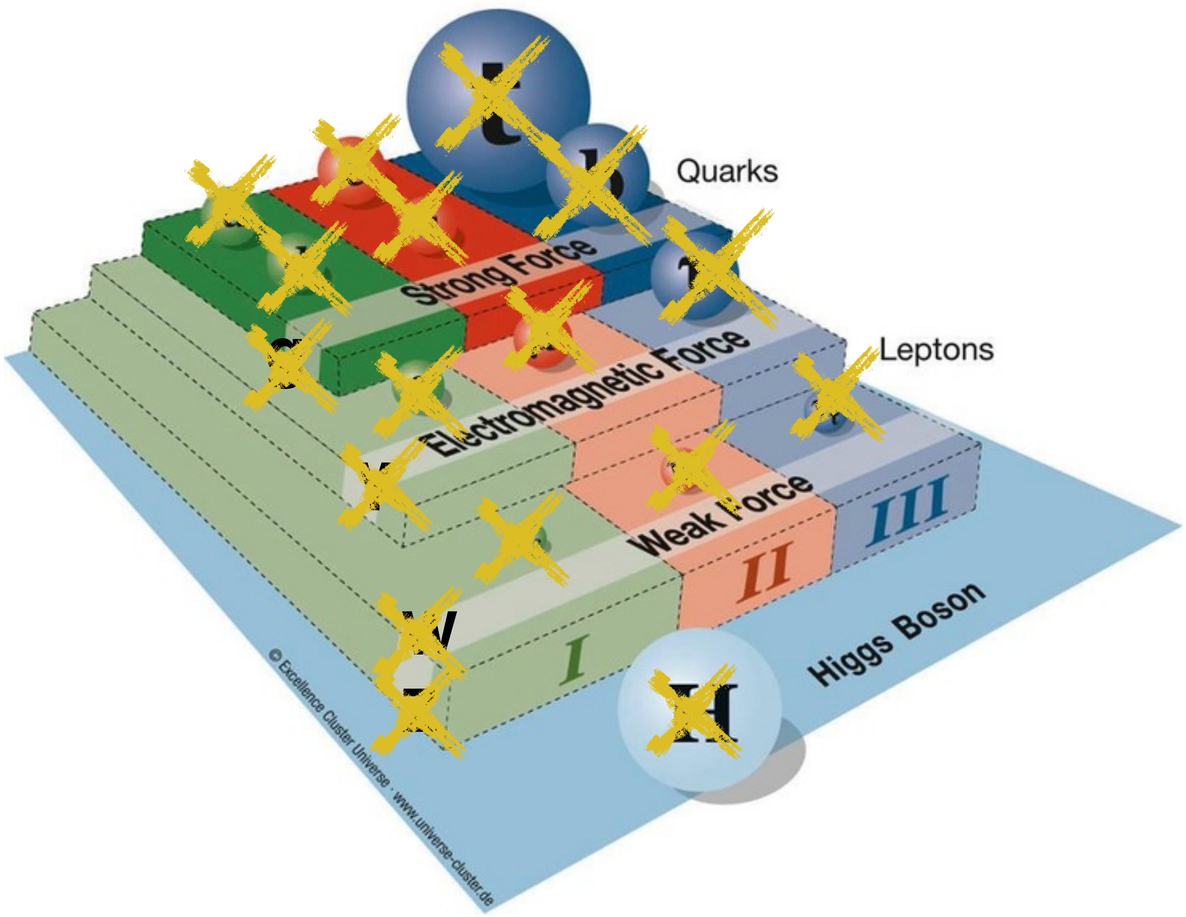

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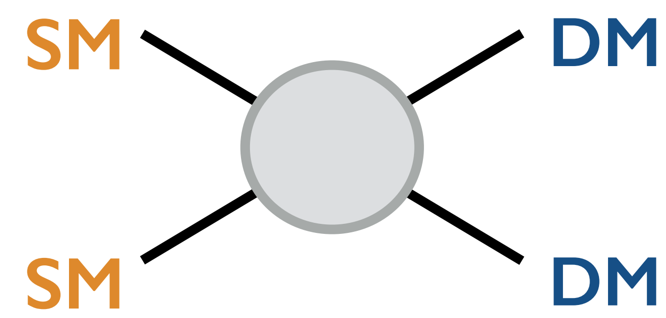
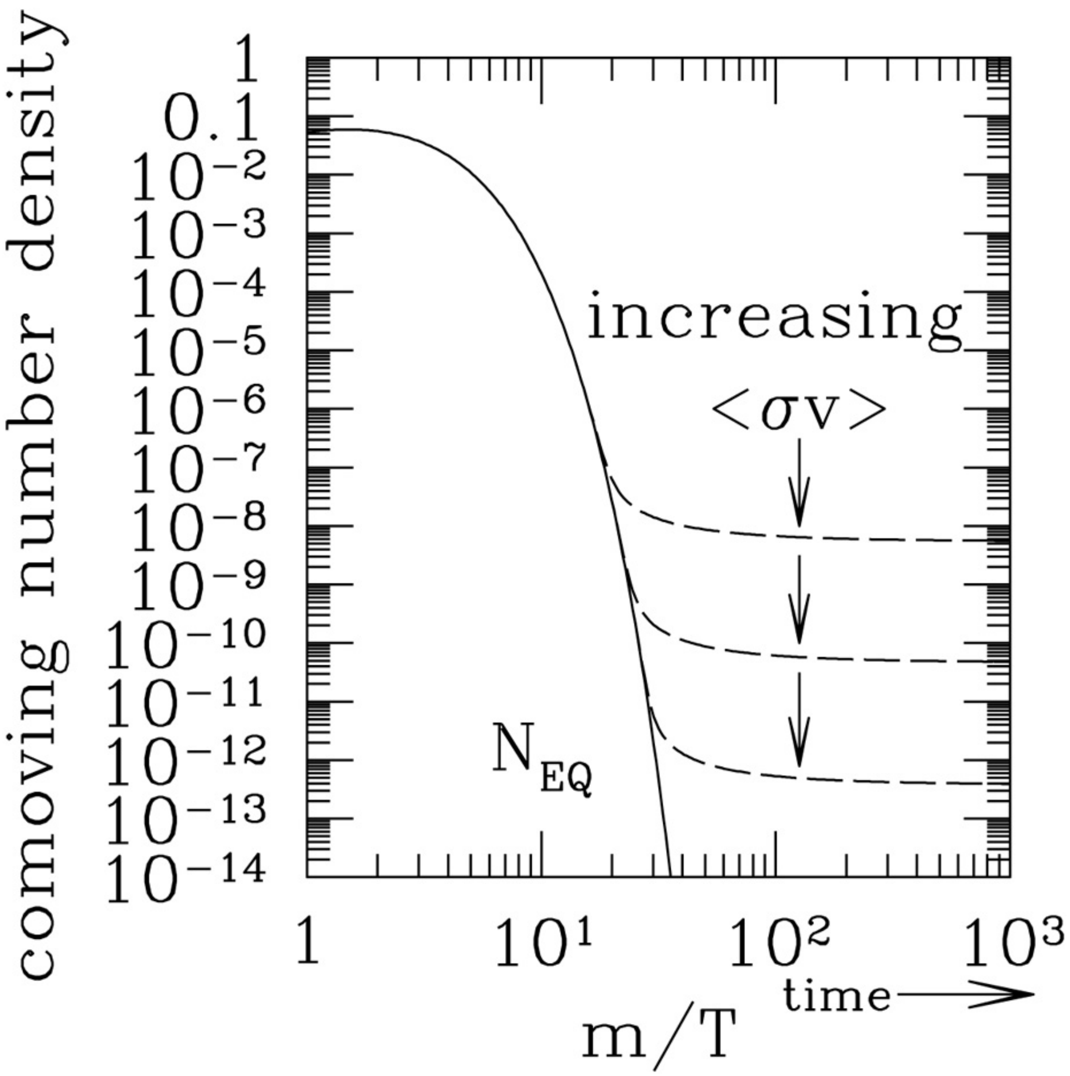
what can it be?

Relic abundance

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

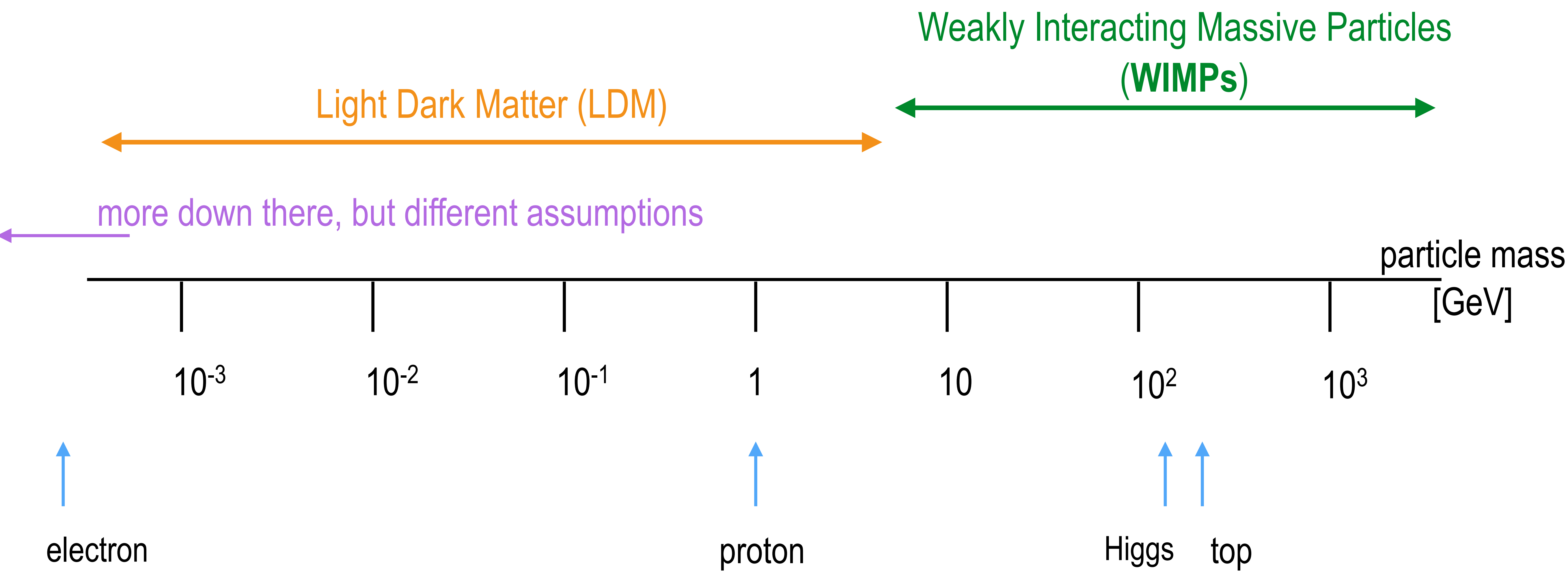




- Universe expanded & cooled
- interaction rate became “too low"
- amount of DM remained stable or “frozen" —> *freeze-out*
- the weaker the interaction, the more DM remained
  - "survival of the weak"
- *relic abundance* depends on interaction **cross section** and **mass** of particles

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…

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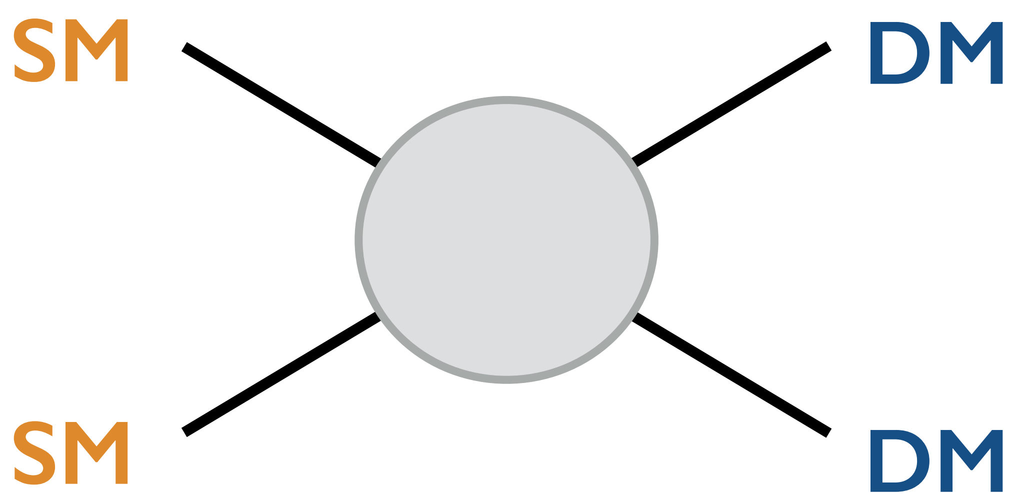
Let's start conventional - WIMPS



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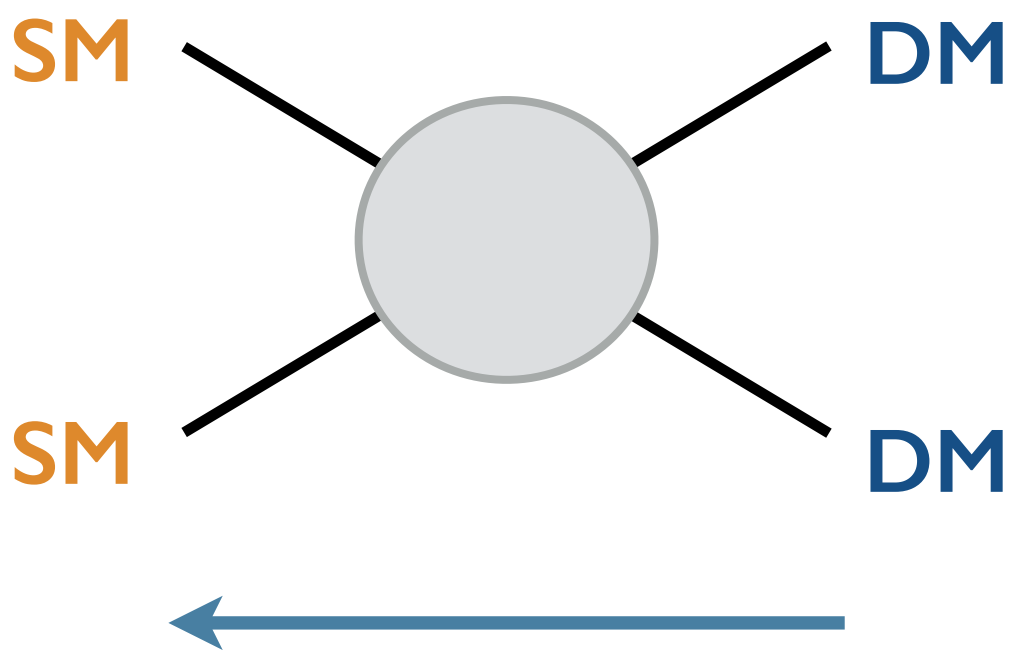
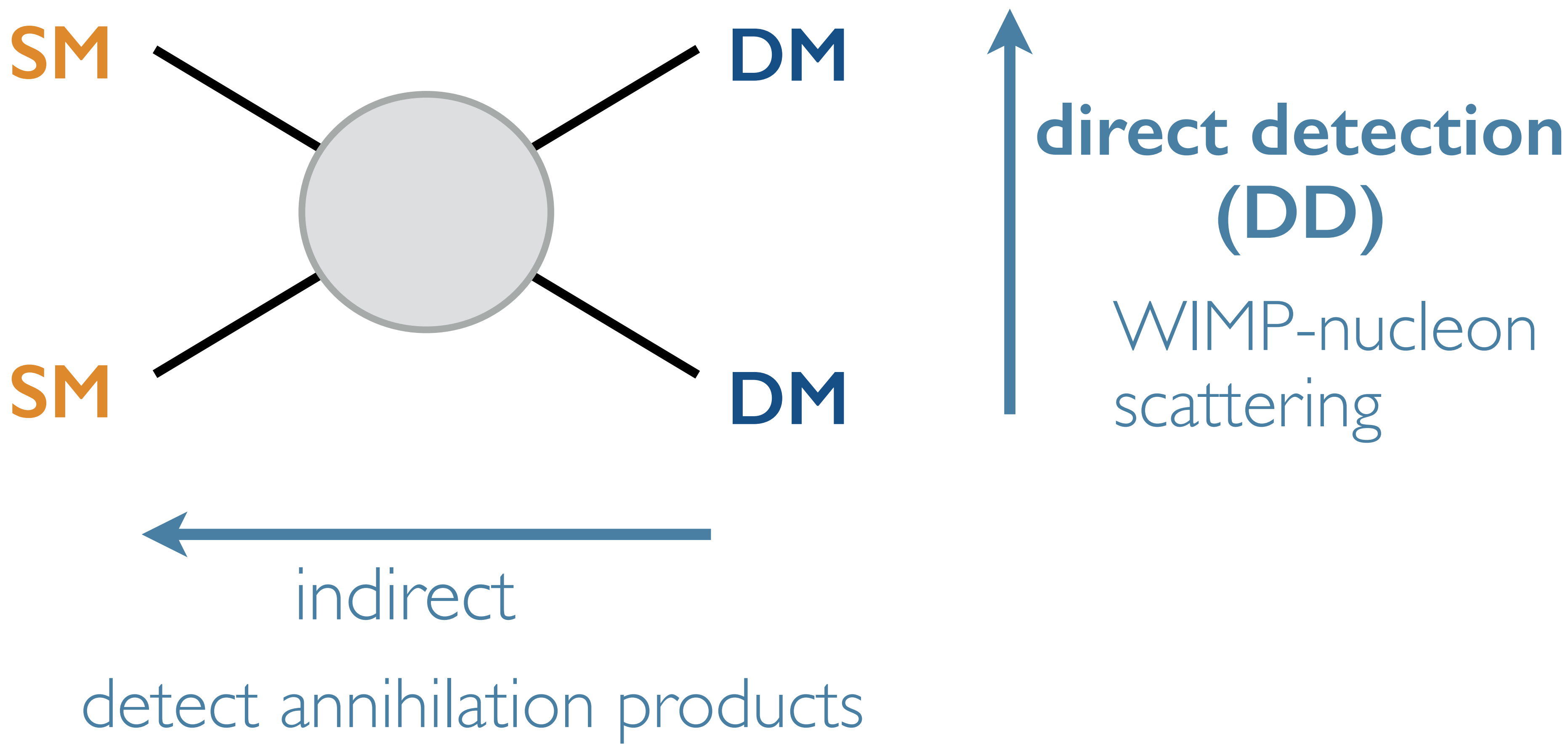


indirect

detect annihilation products

Let's start conventional - WIMPS



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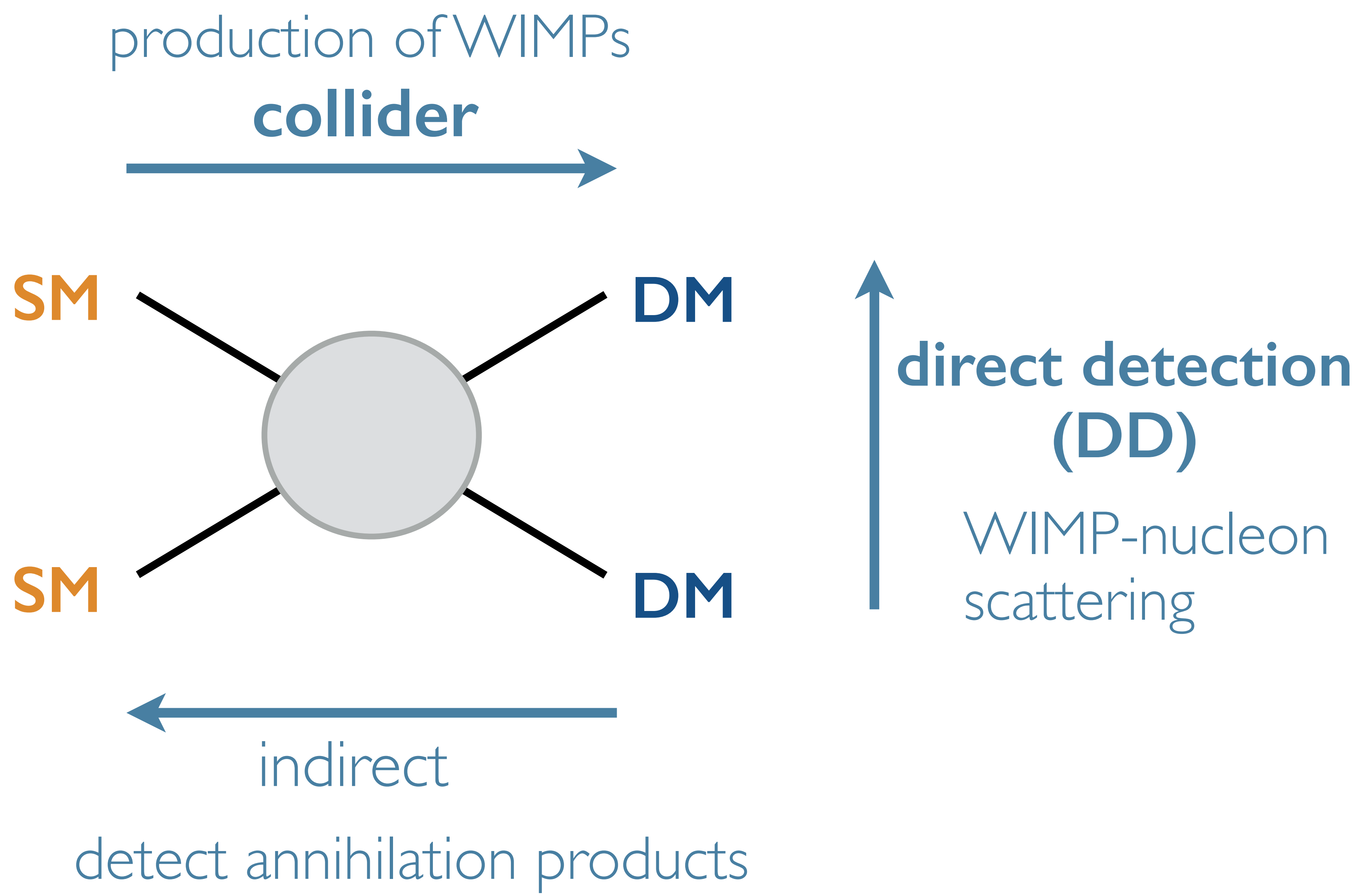

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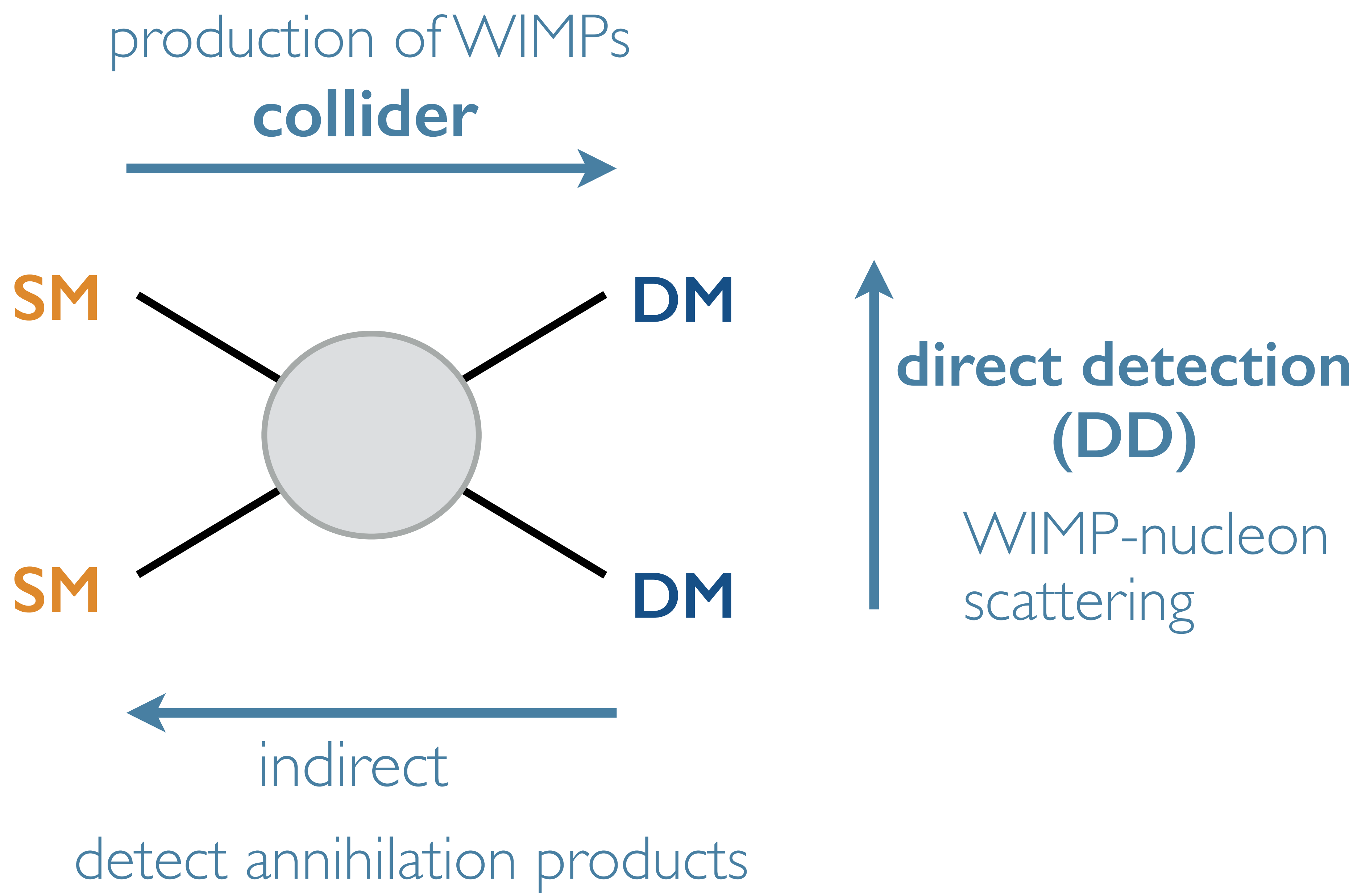

- each would merit their own lecture, of course

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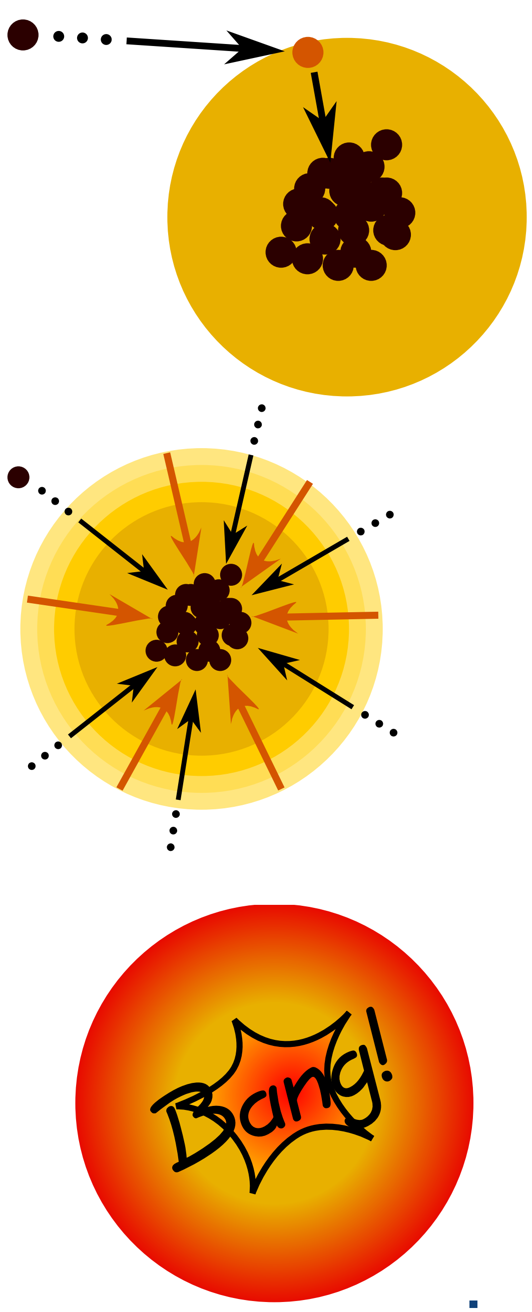
Indirect Detection

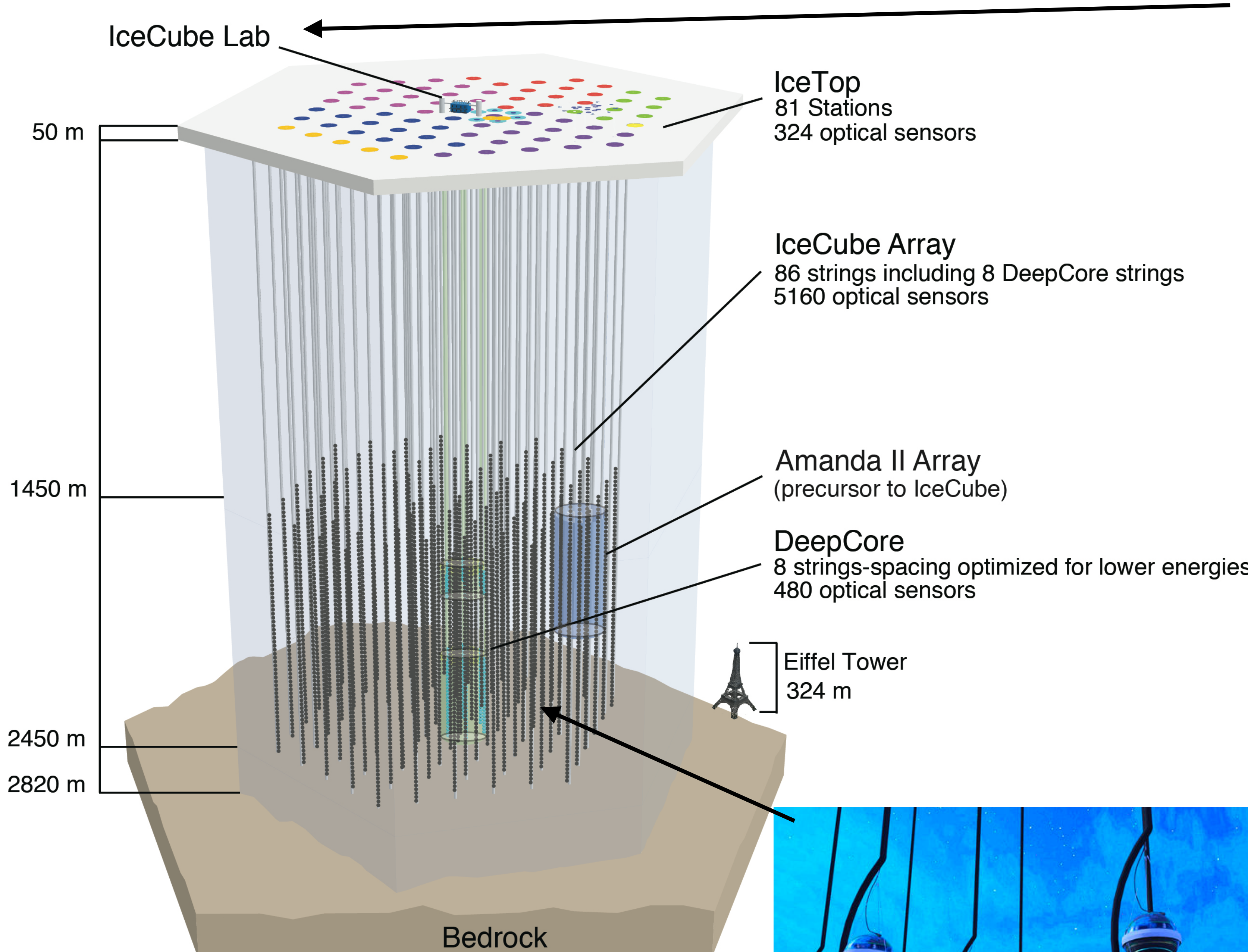
- look for SM products of DM annihilation
- from direction of heavy objects, where WIMPs can accumulate, e.g. sun

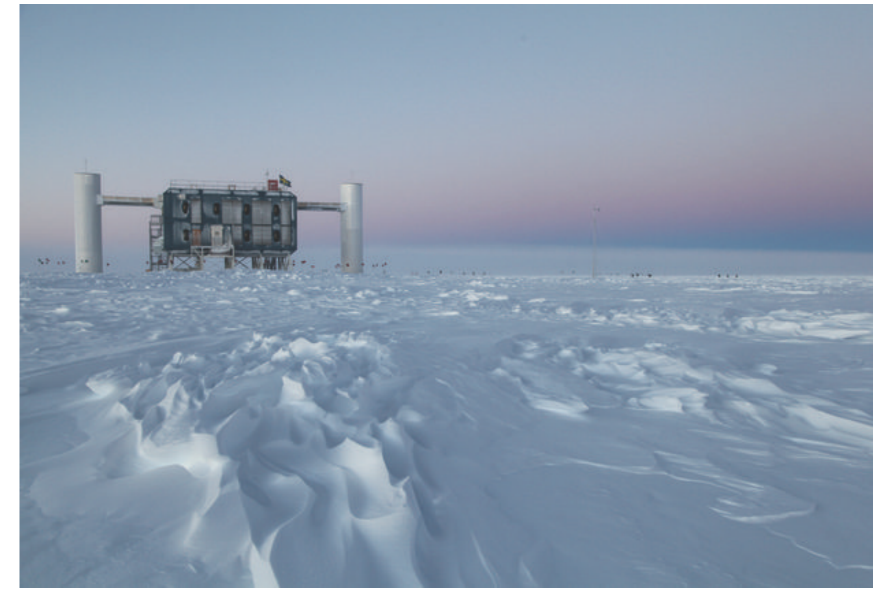


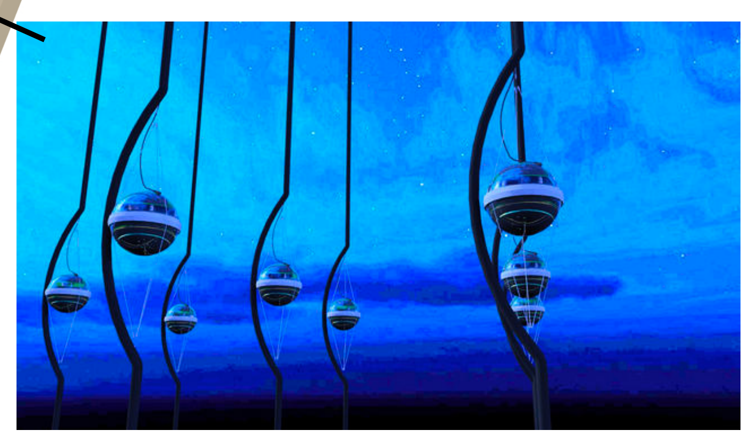
http://astro.ic.ac.uk/sites/default/files/PS_UKHEP15.pdf

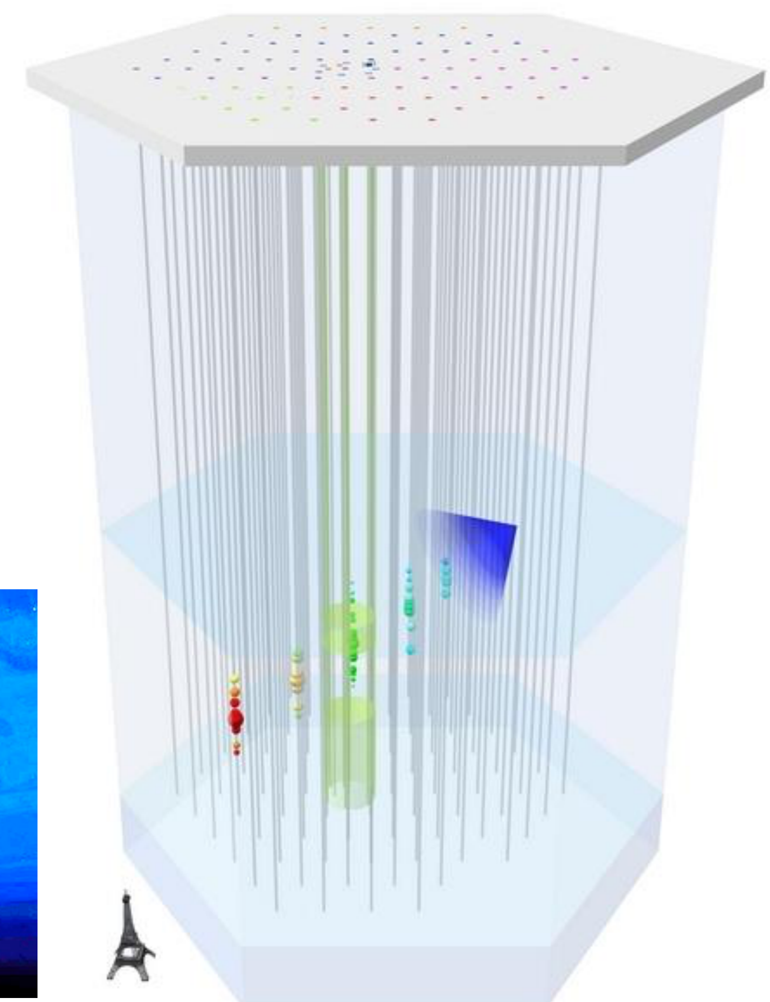
- what comes out can be
  photons,
  neutrinos,
  e^+/e^-,
  W^+/W^-,
  proton/anti-proton…
- various experiments looking for one or several of these
- usually needs some "extreme" location, e.g. South Pole, desert, space…

- neutrino detector at the South Pole







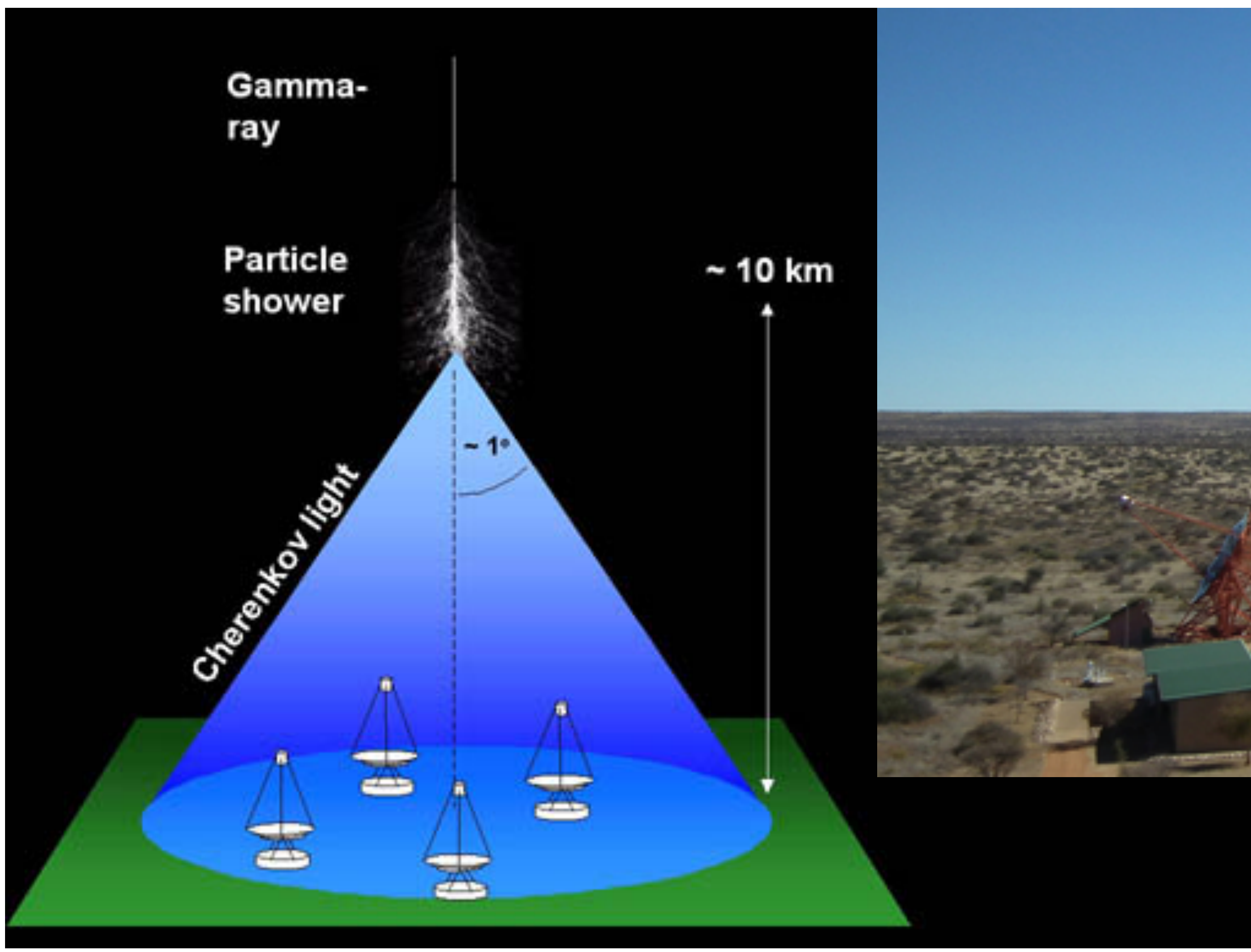


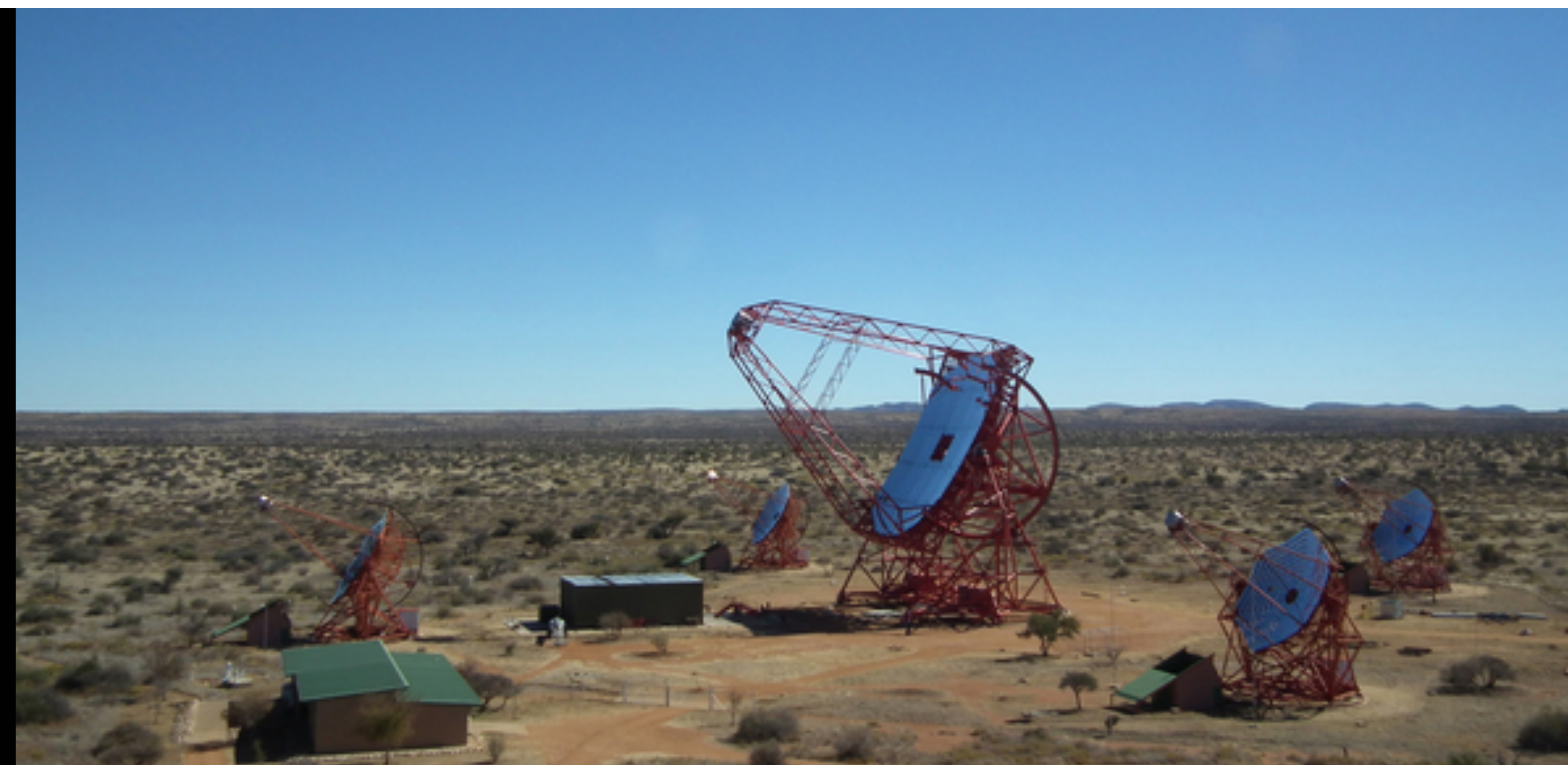
http://icecube.wisc.edu

Indirect Detection – Example: HESS/CTA

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 / m² on ground





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

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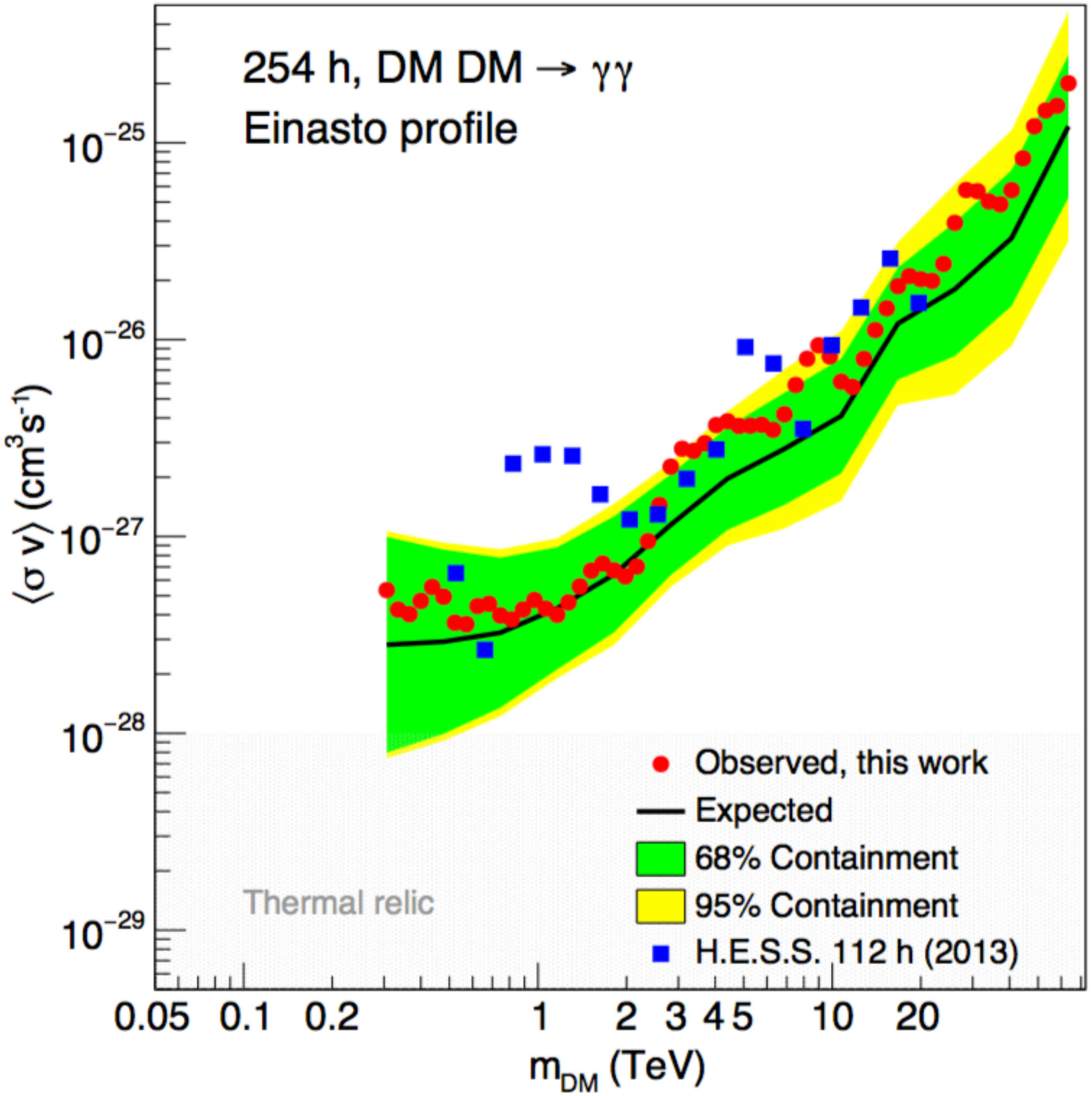
- latest result (Feb 2018, not even published yet)
  - no signal observed

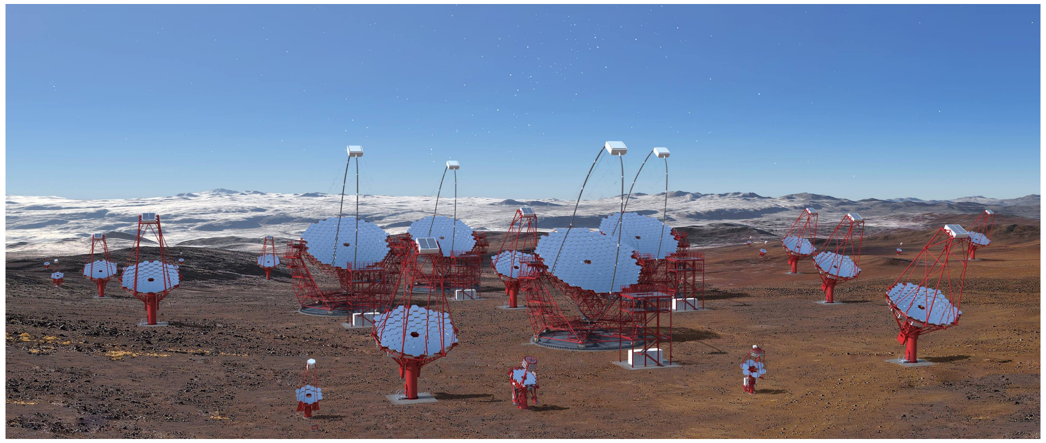


https://www.mpi-hd.mpg.de/hfm/HESS/

https://www.cta-observatory.org

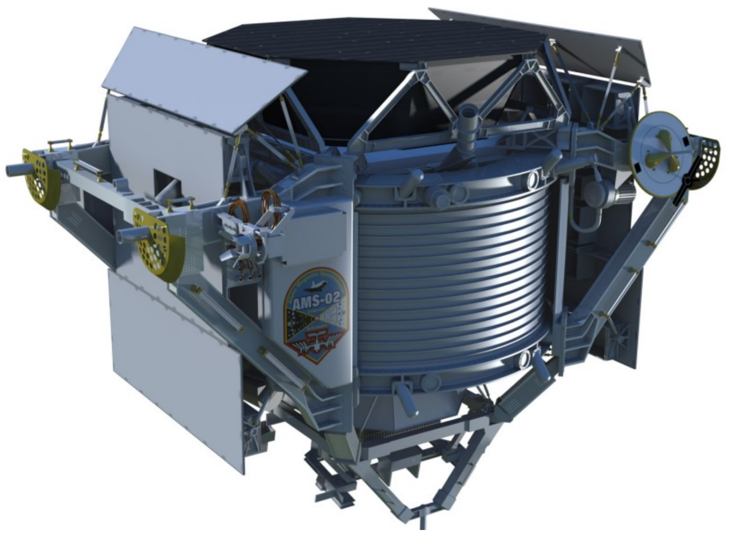
- next: Cherenkov Telescope Array (CTA)
  - >100 telescopes, two sites (Northern and Southern hemisphere)
    - La Palma

    - Chile

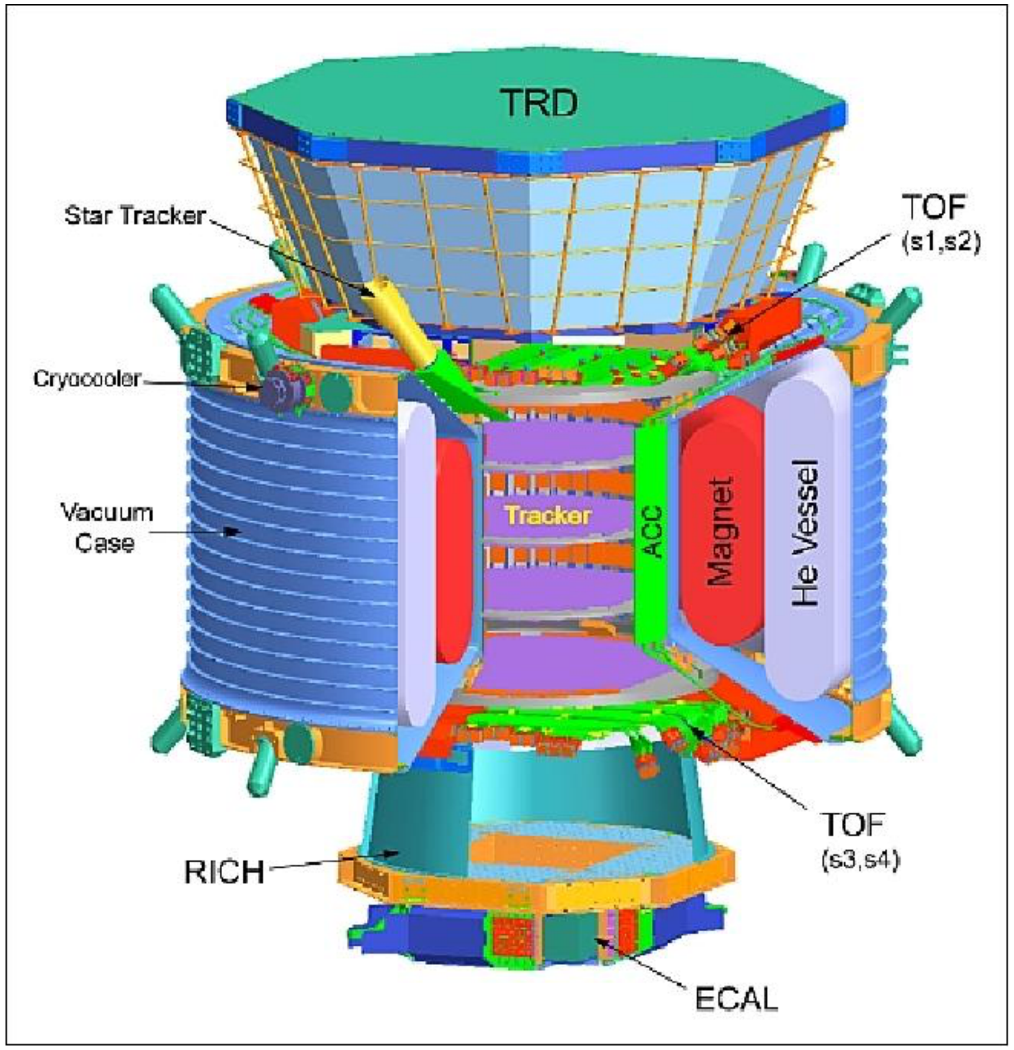


Indirect Detection – Example: AMS

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…



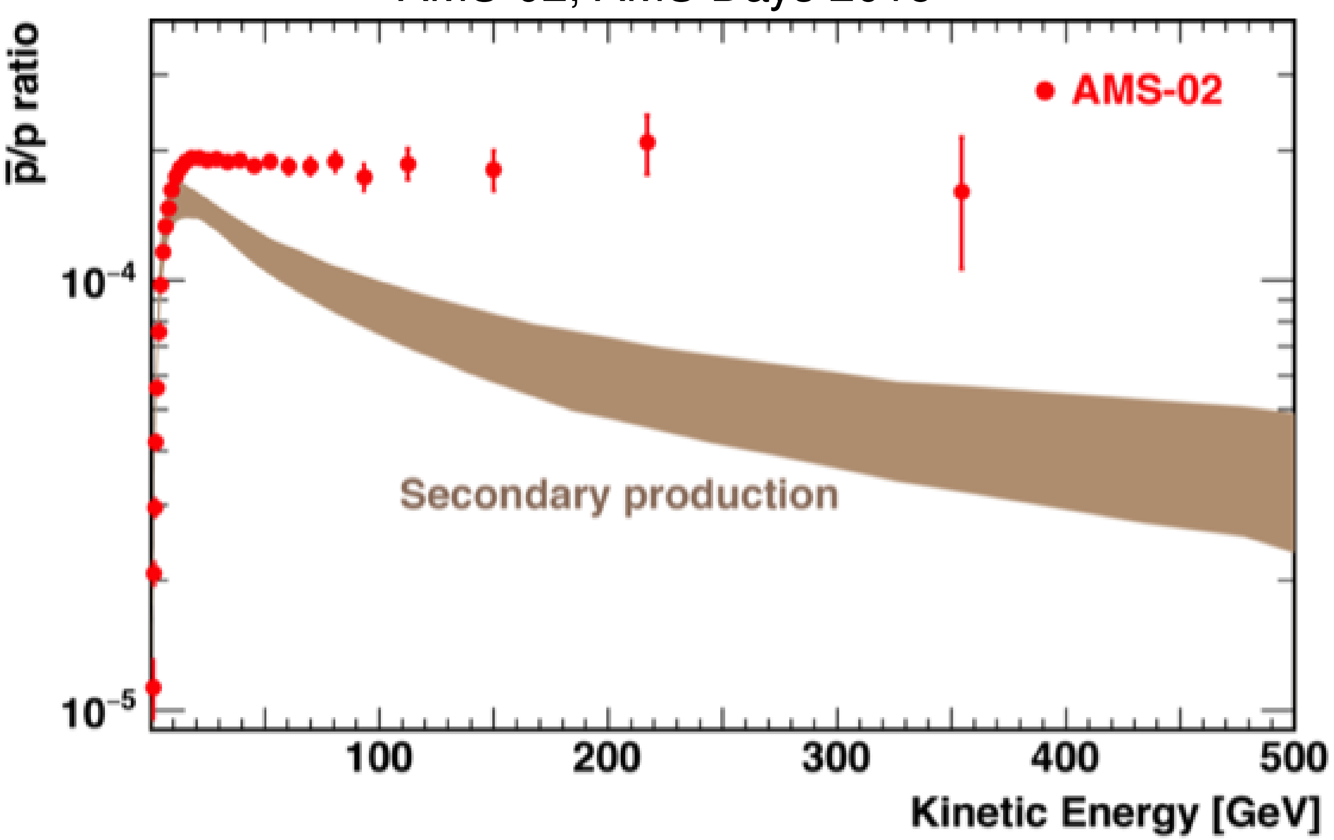
https://eoportal.org/web/eoportal/satellite-missions/content/-/article/iss-utilisation-ams

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

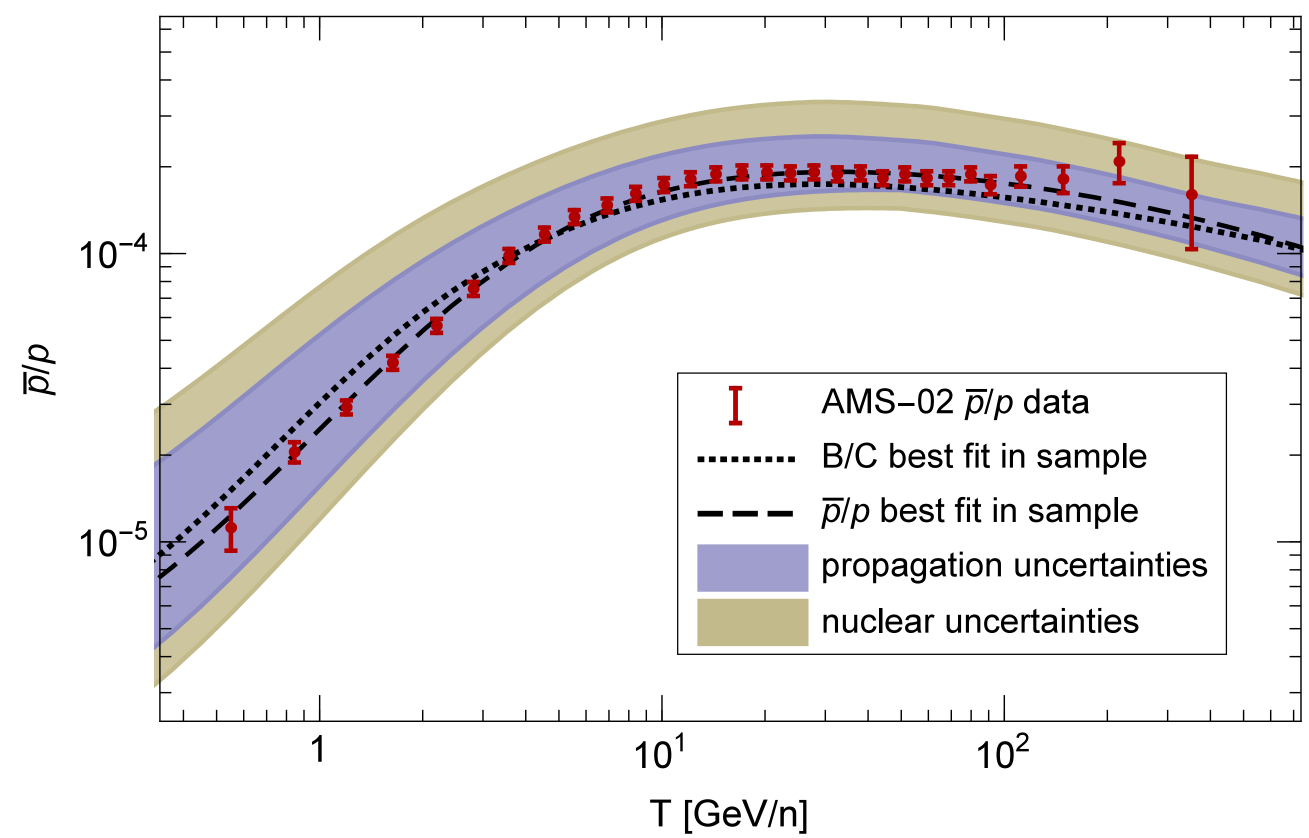
Indirect Detection – Interpretation

- 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

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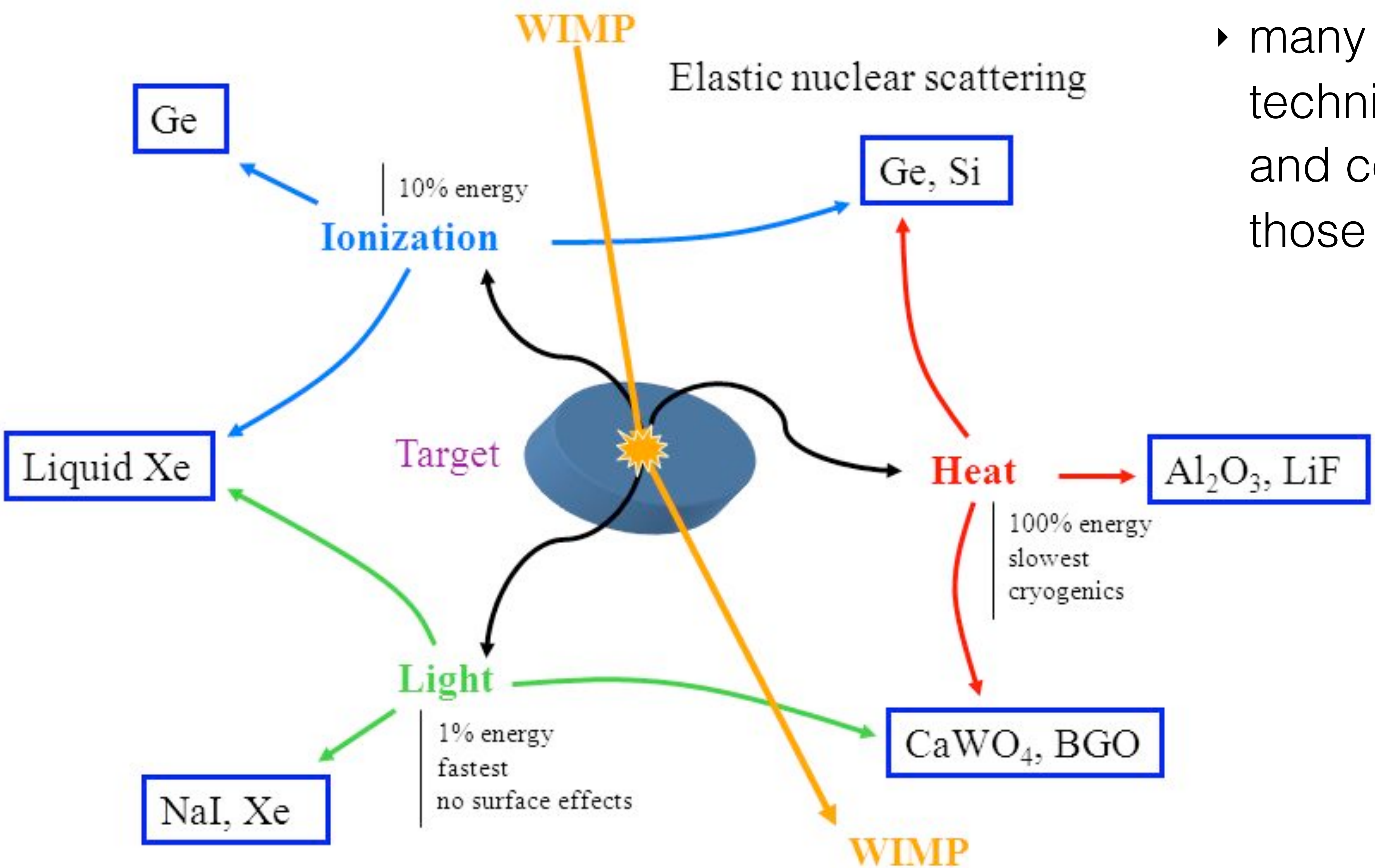
Direct Detection Techniques

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

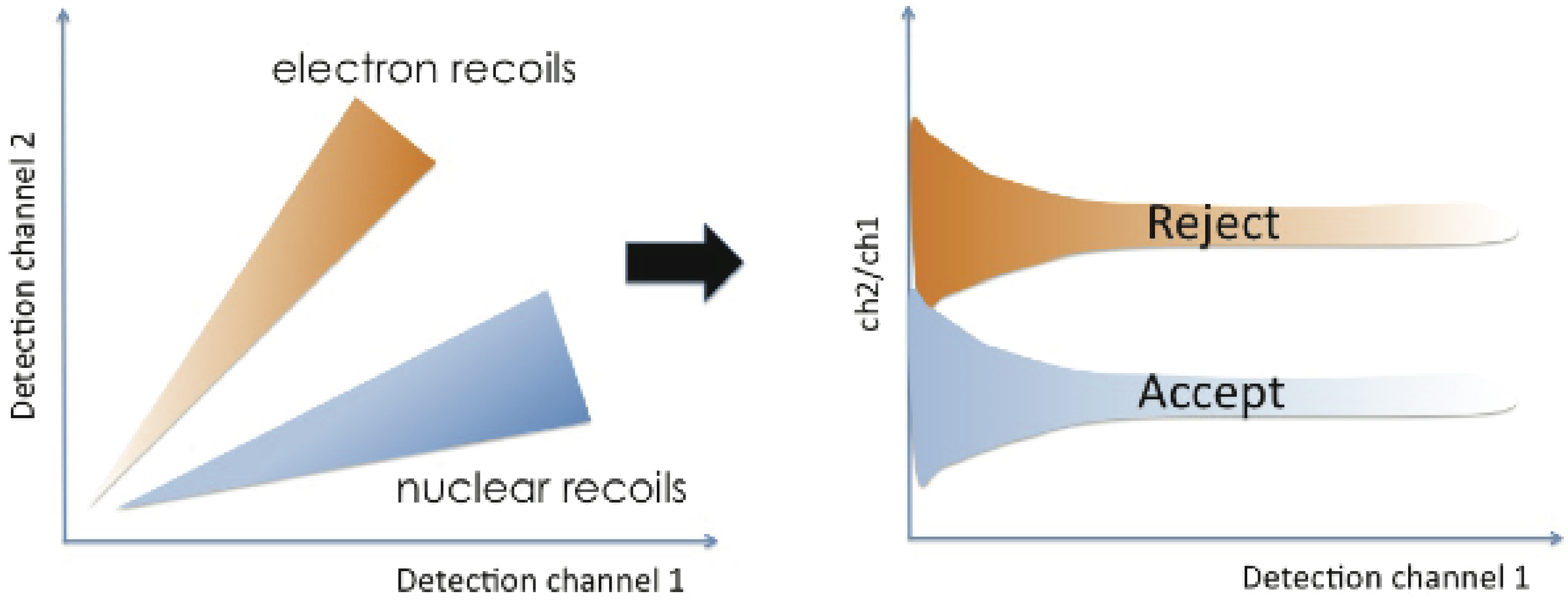


- many different techniques/materials and combination of those

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

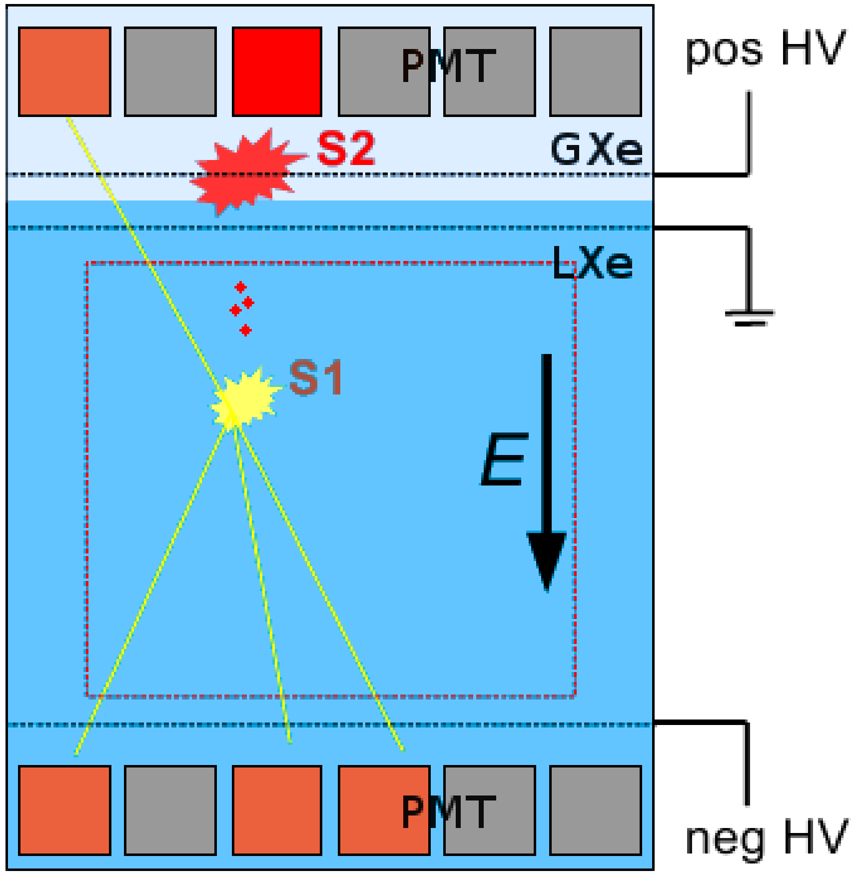
- example: Xenon(1T)
  http://www.xenon1t.org

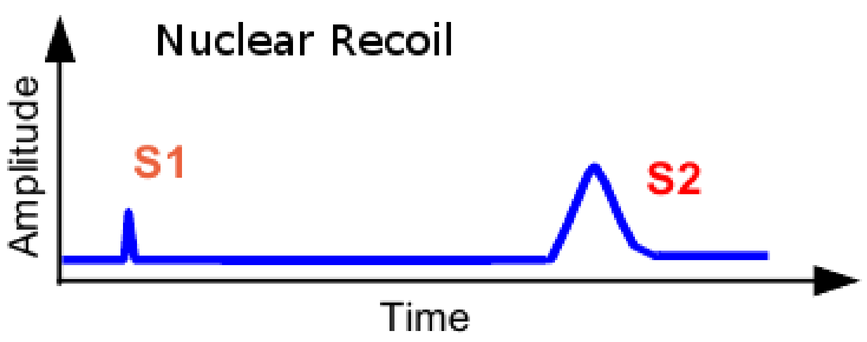
https://indico.fnal.gov/event/9942/session/2/material/slides/0?contribId=36

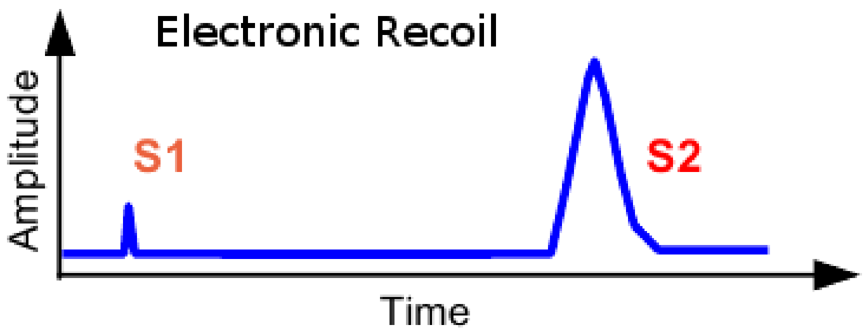
- below 1400m of rock

- uses both ionisation & scintillation

https://arxiv.org/abs/1405.7600







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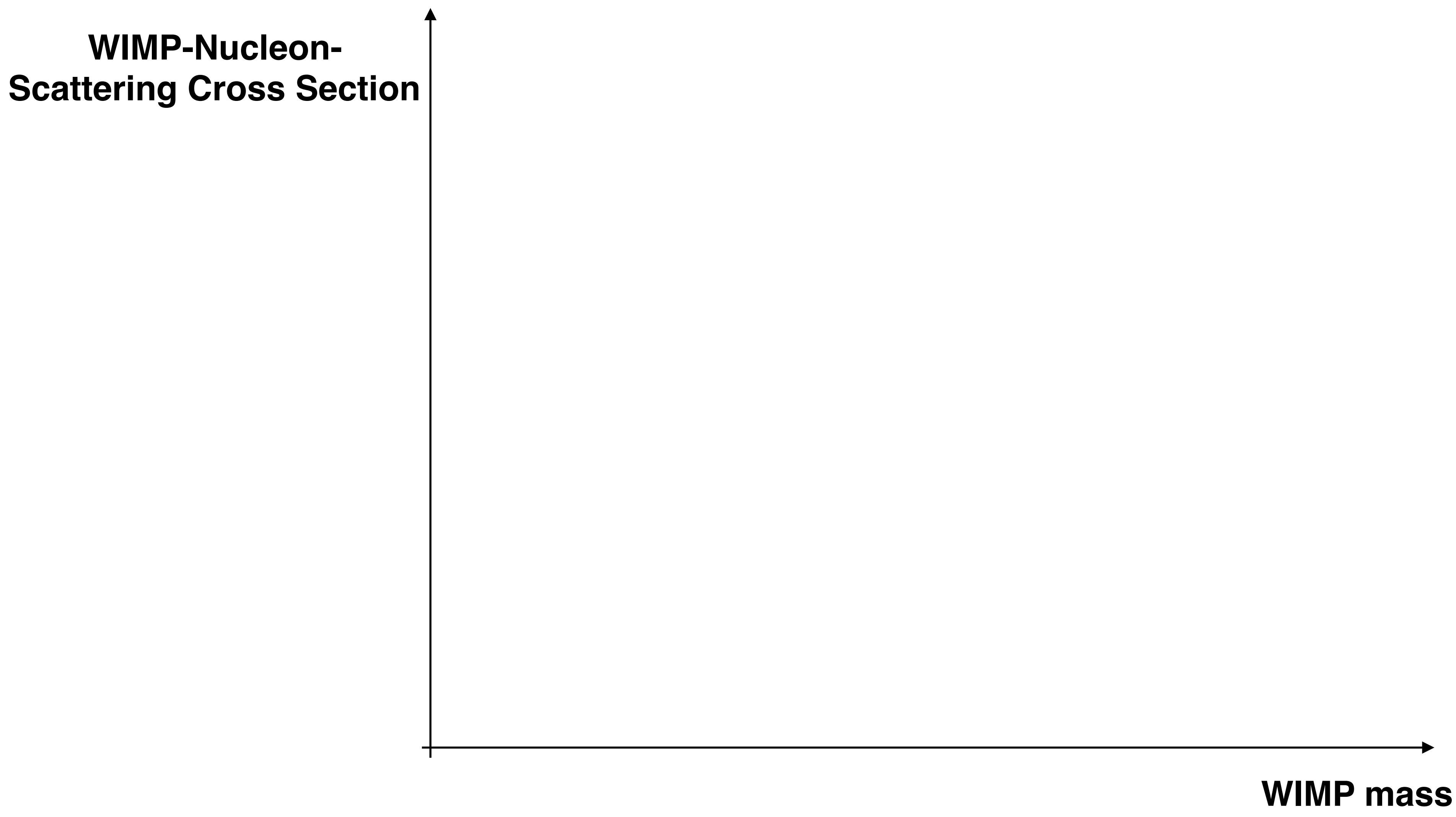
Presentation of Results



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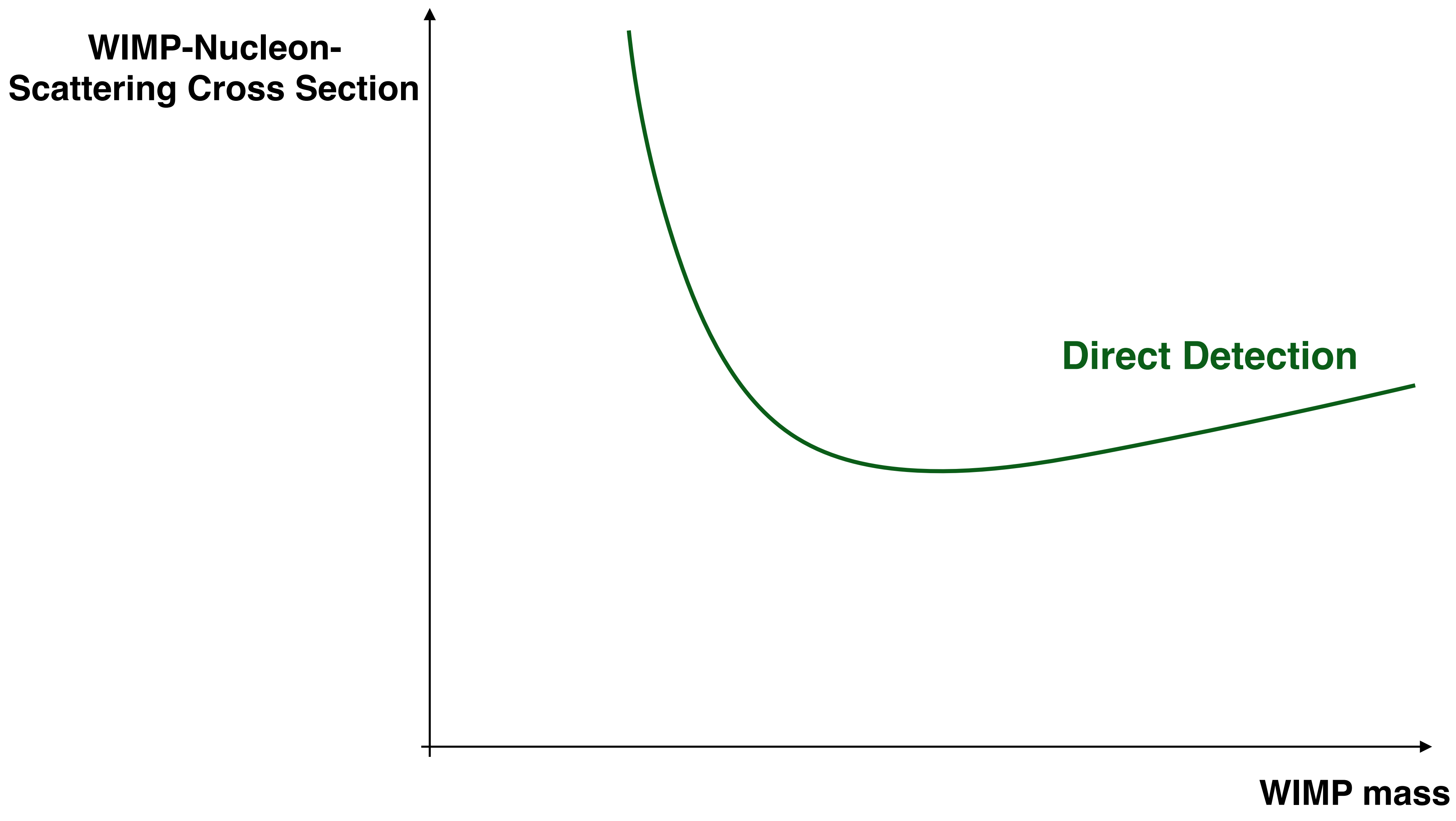

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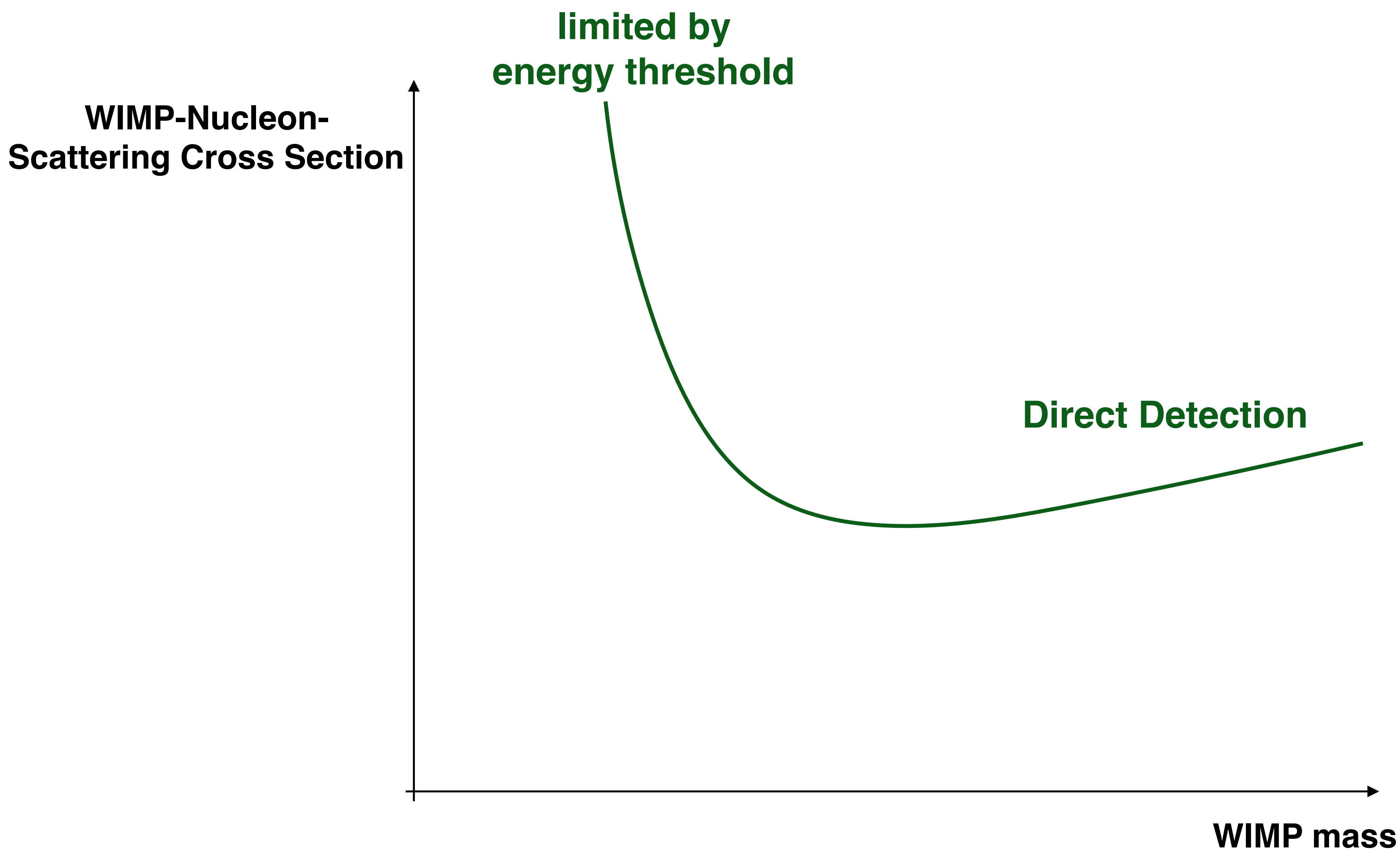

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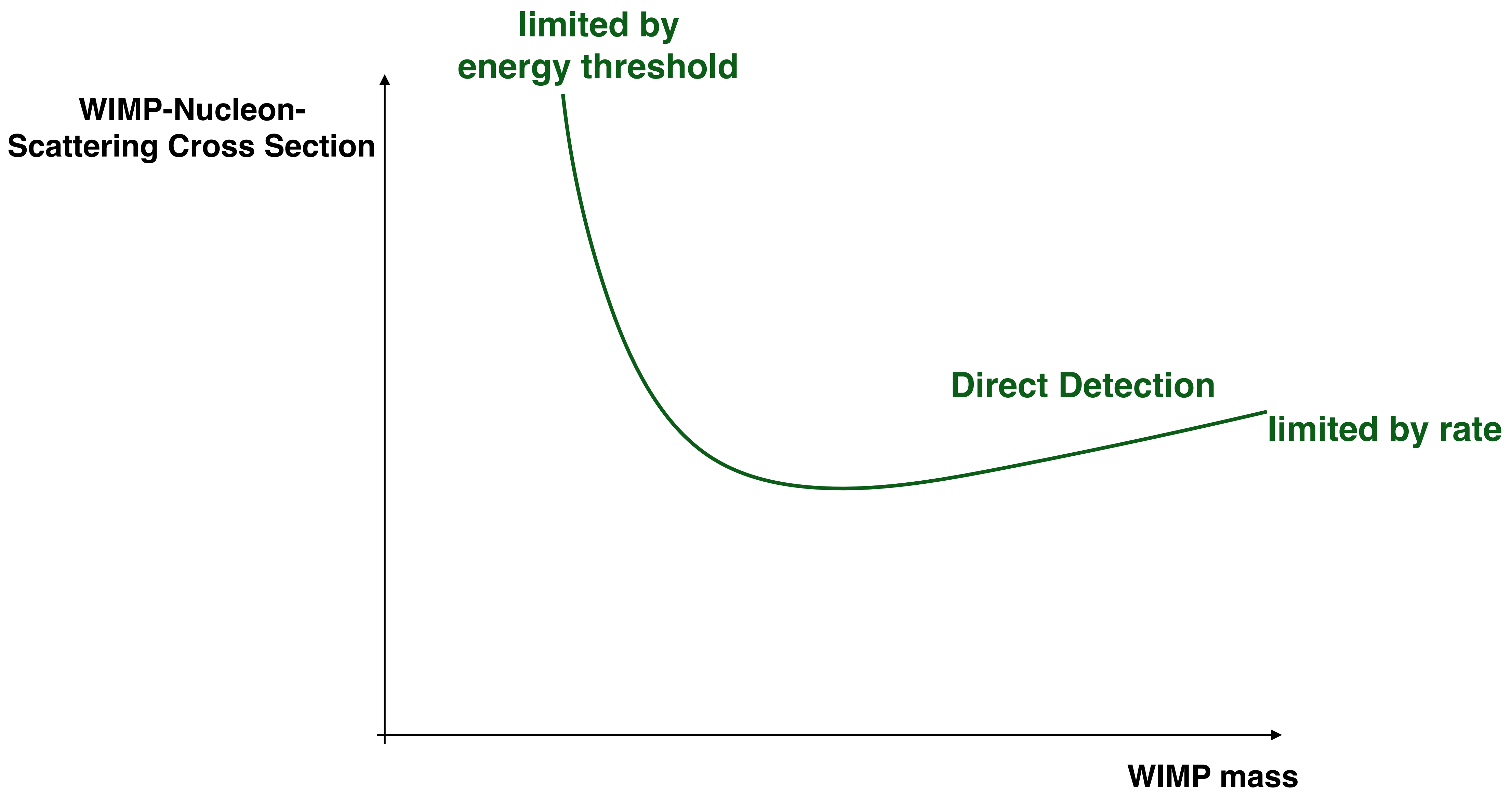

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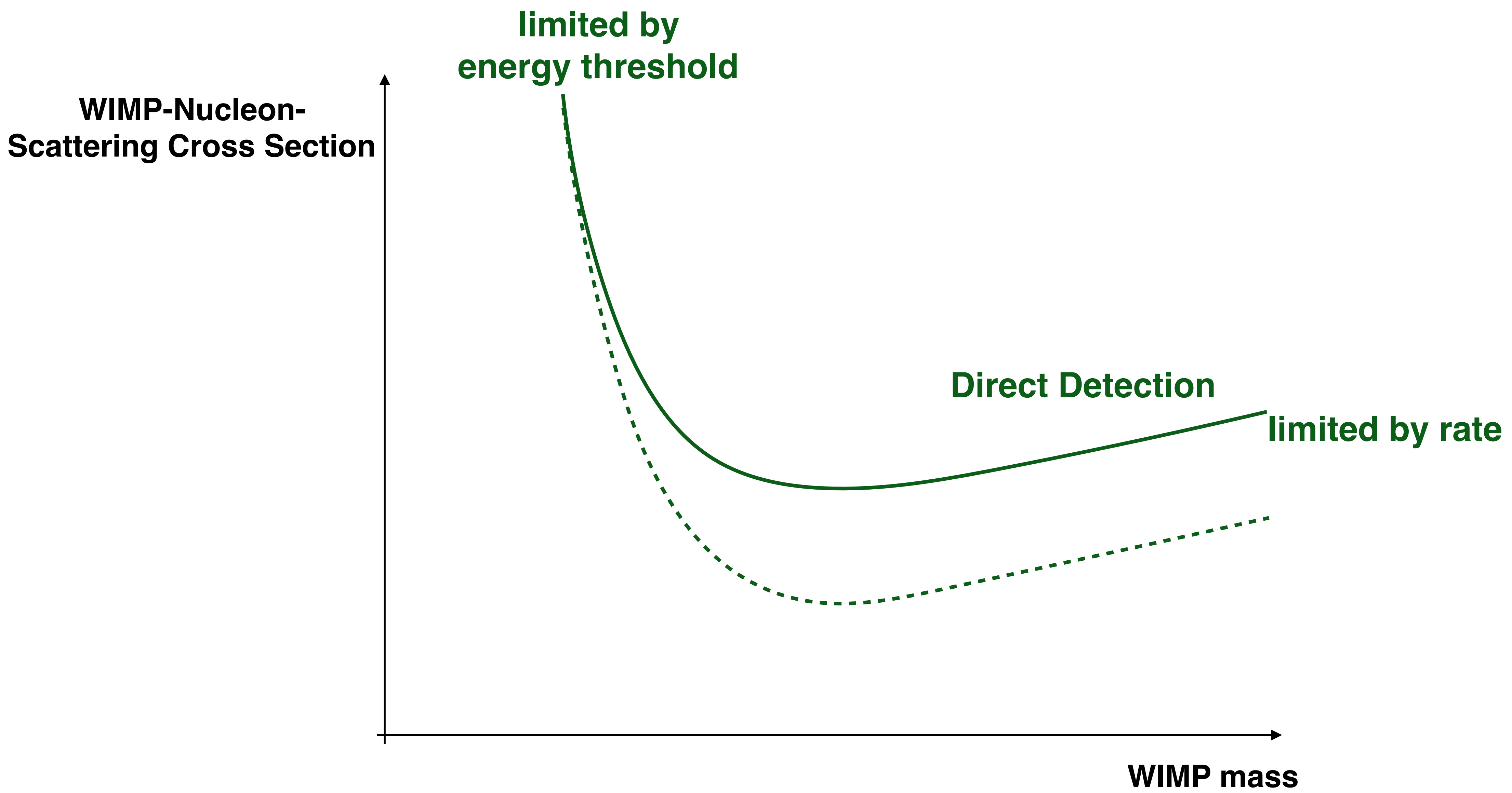

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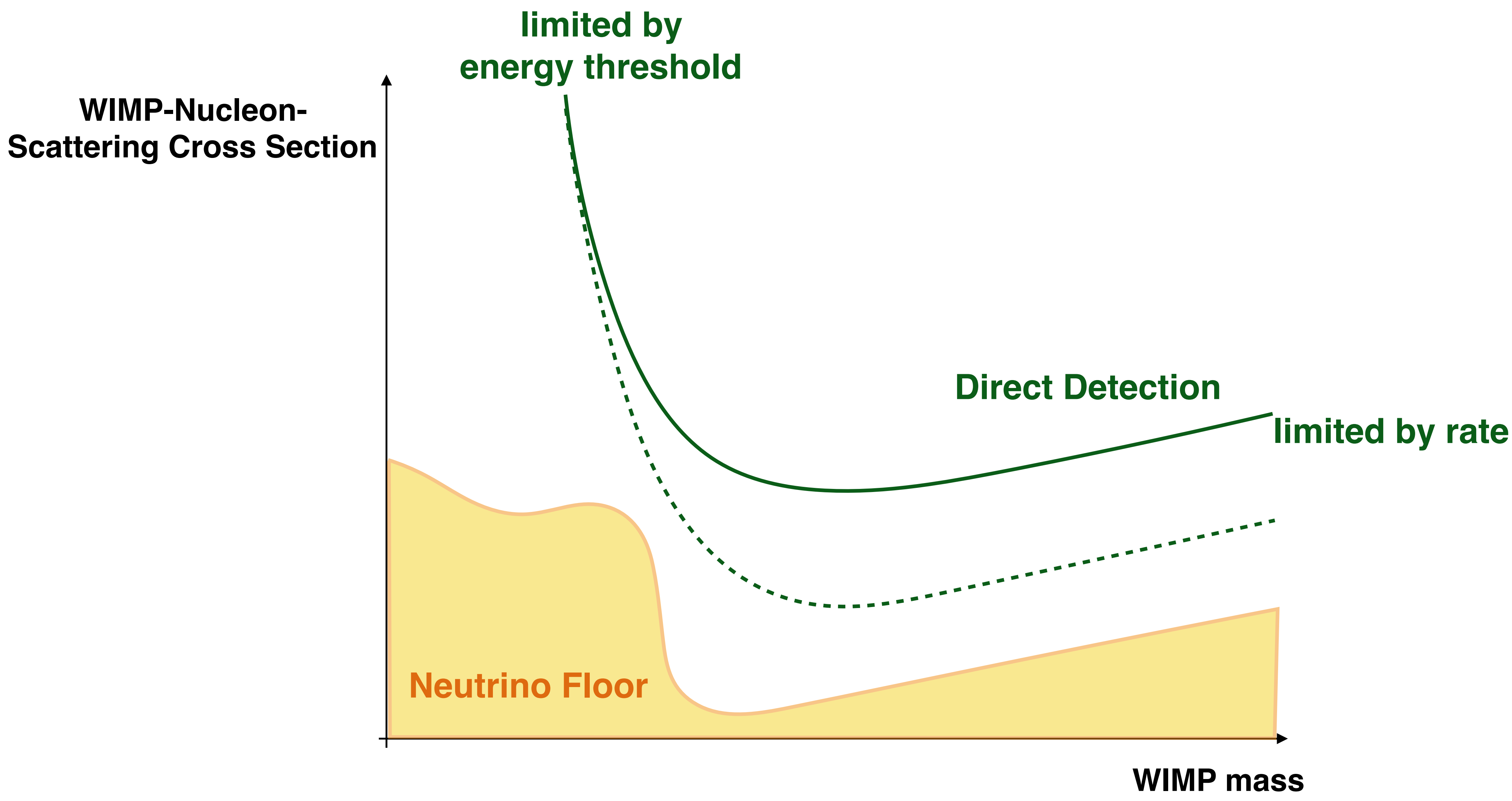

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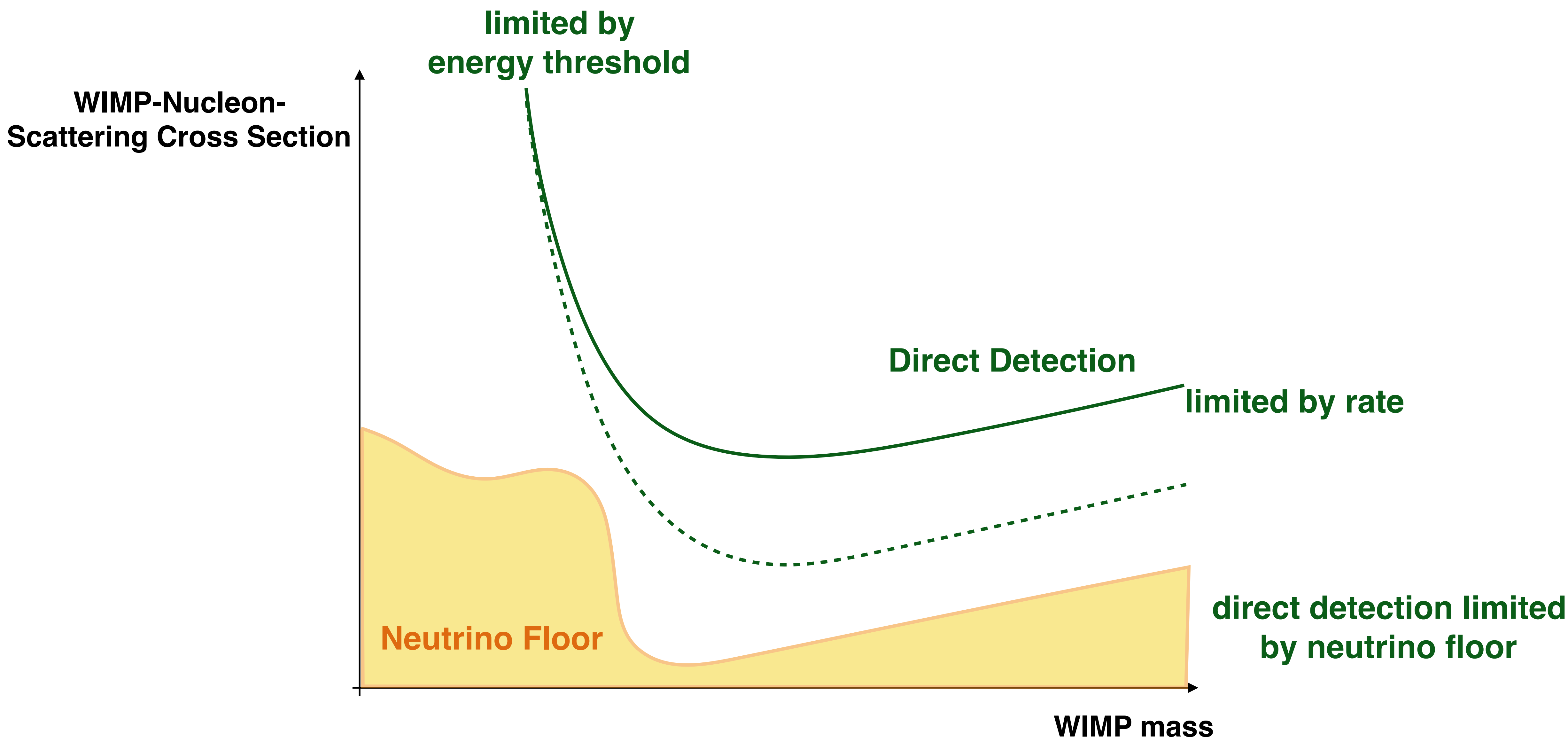
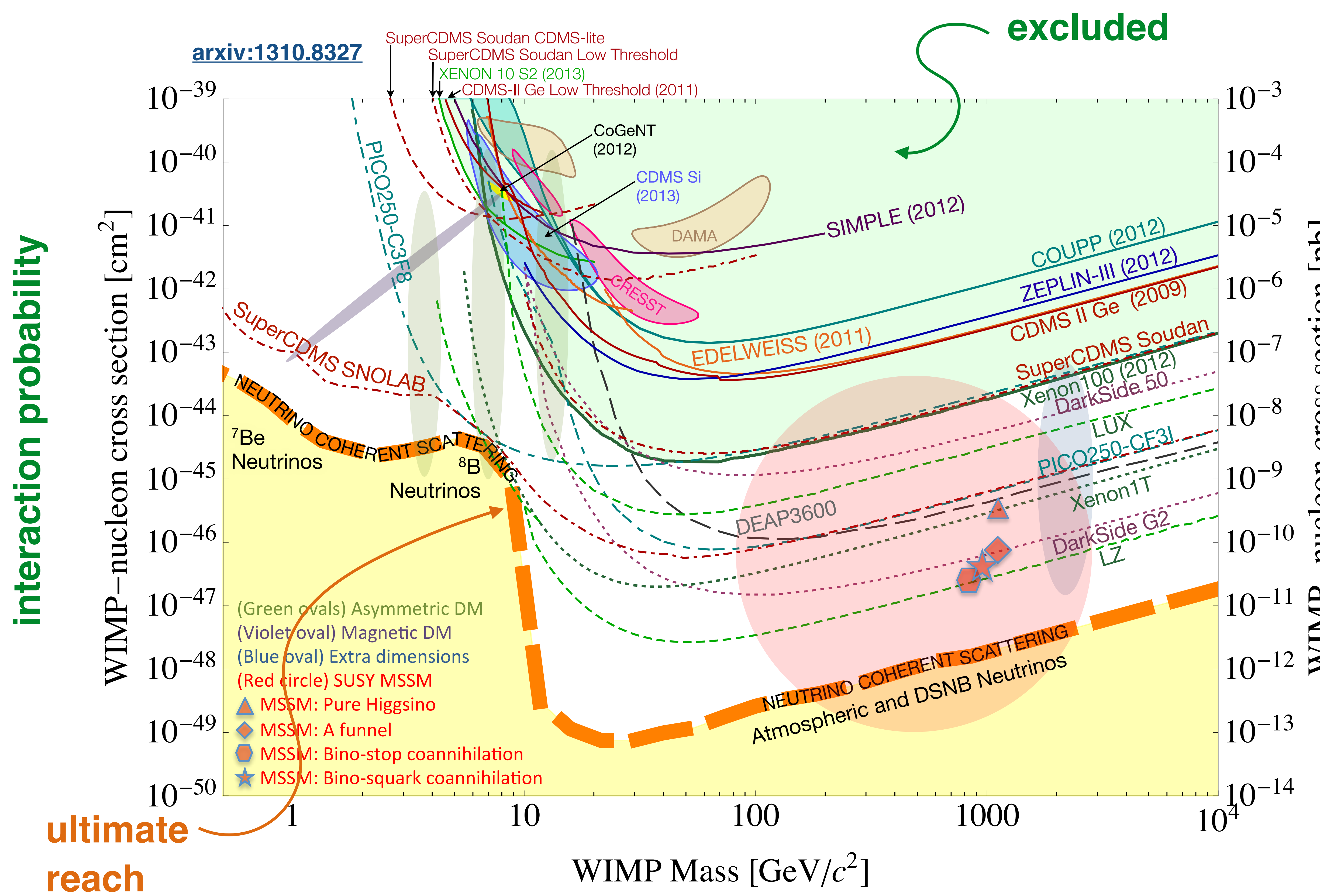


Real Life



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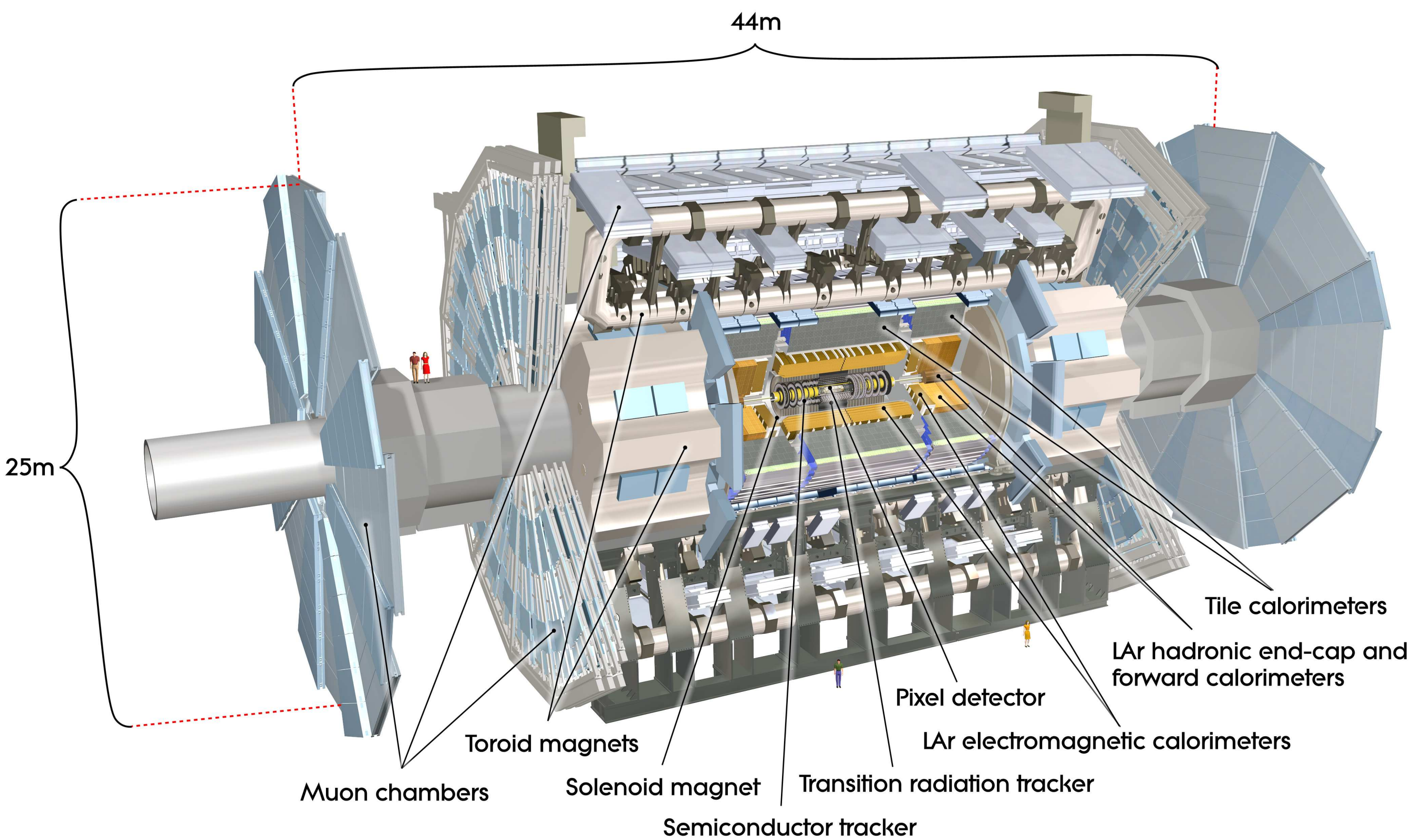
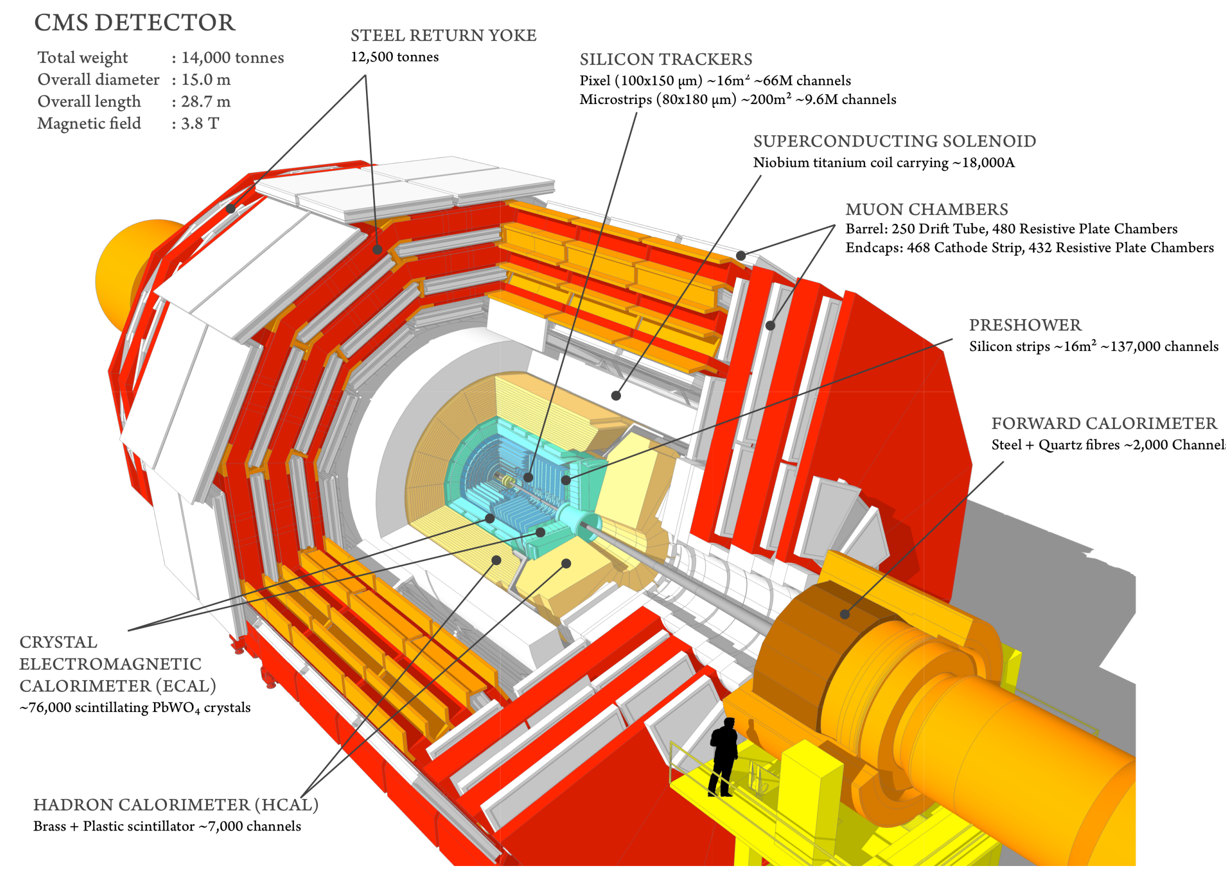
Collider-based Searches

i.e. LHC

Collider Searches - LHC Experiments

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





- LHCb, ALICE: more specialised

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ATLAS Collaboration

- ~5000 scientists from 180 institutes in 38 countries

An ATLAS scientific paper (made in Lund)

(from Caterina Doglioni)

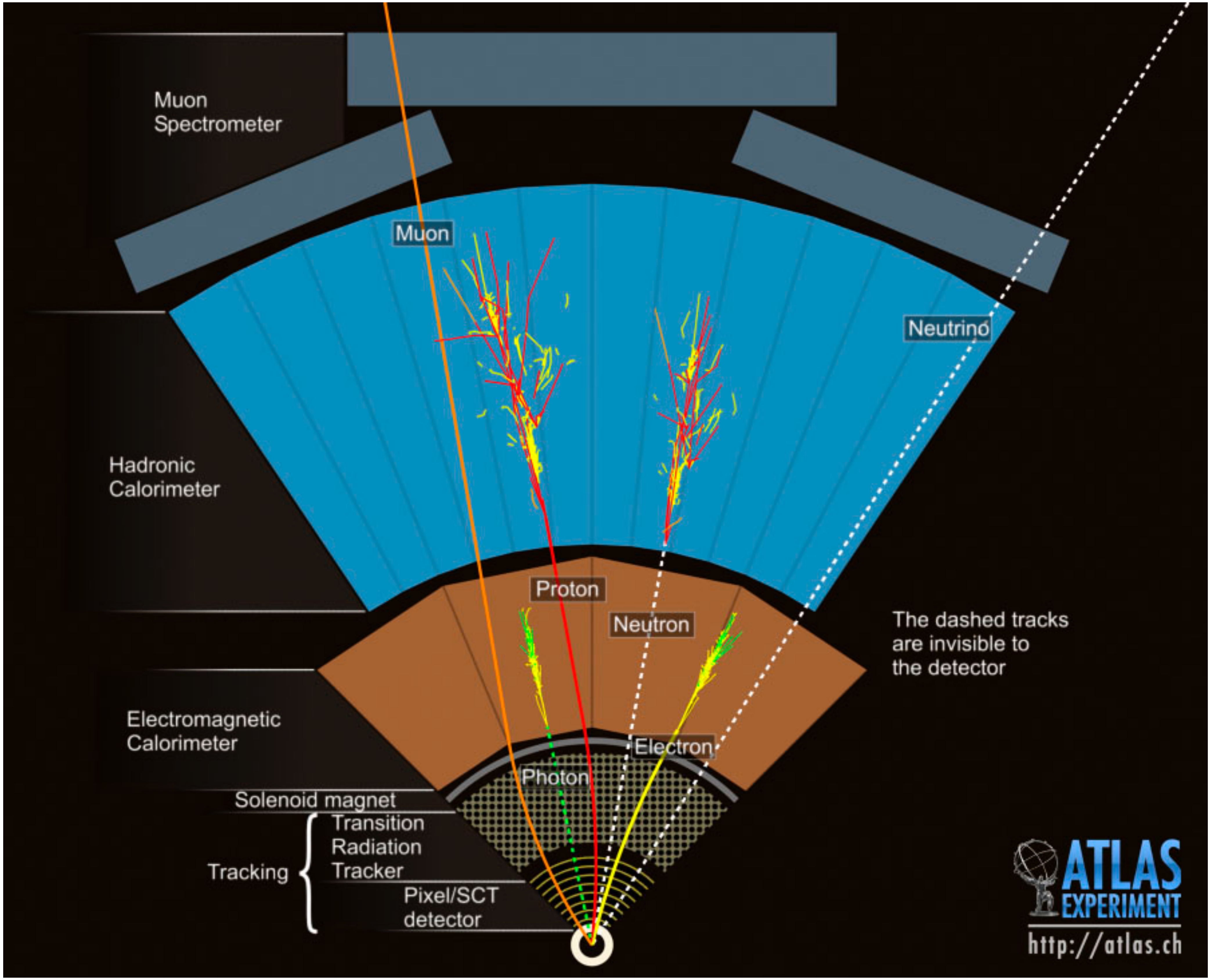
ATLAS Collaboration

- ~5000 scientists from 180 institutes in 38 countries

The author-list of an ATLAS paper

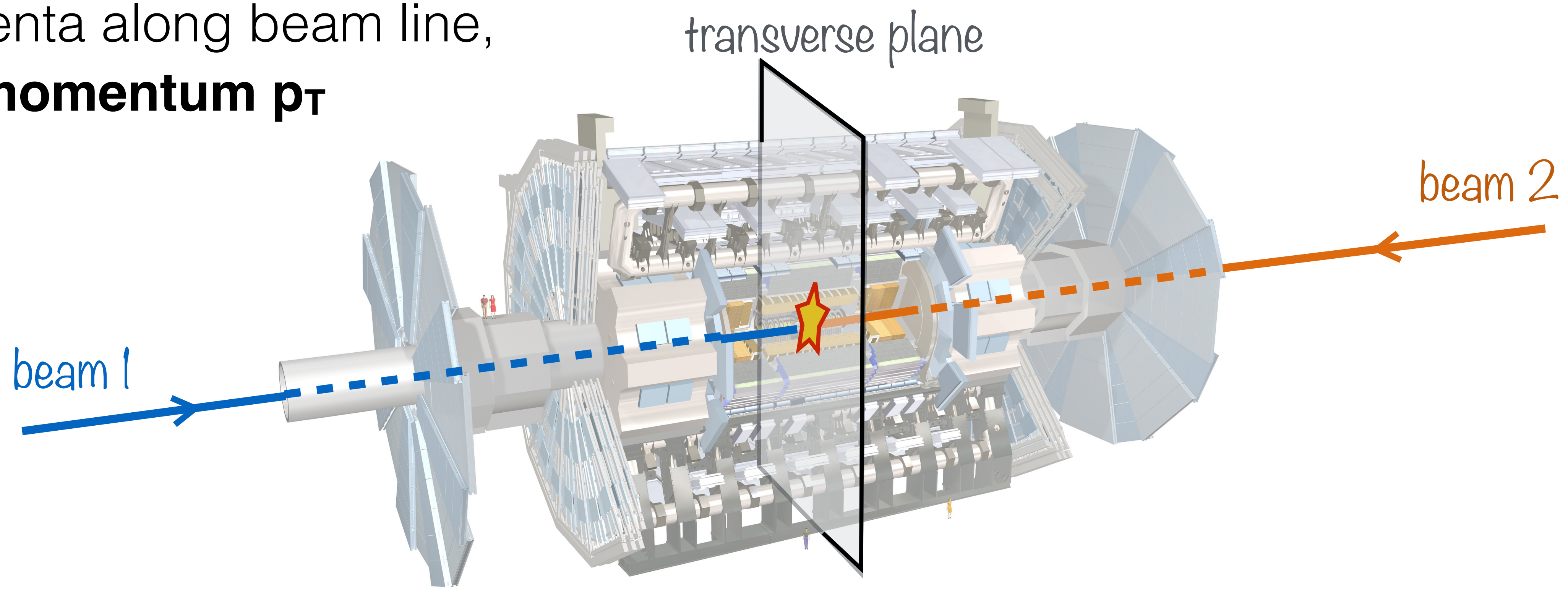
(from Caterina Doglioni)

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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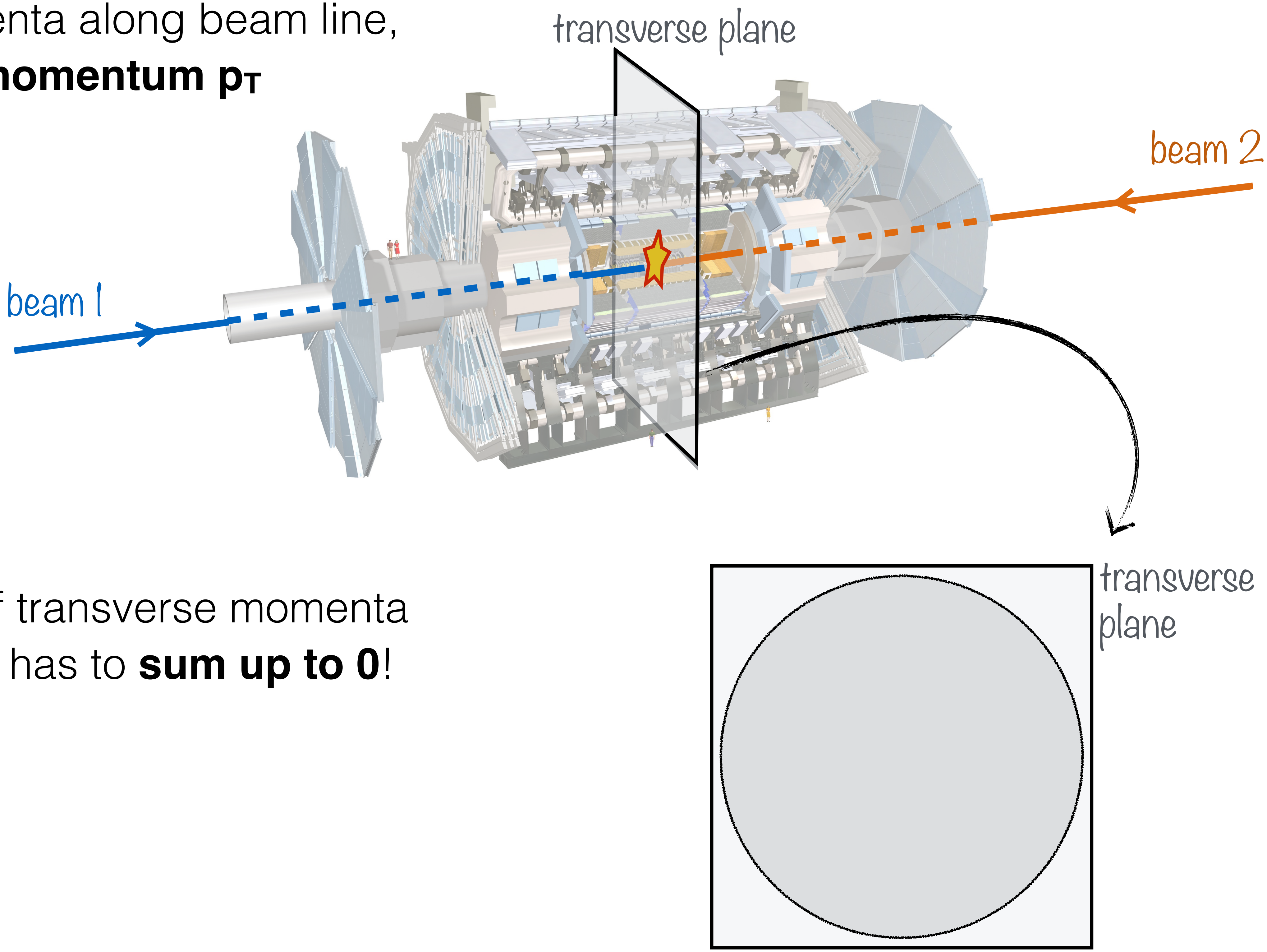

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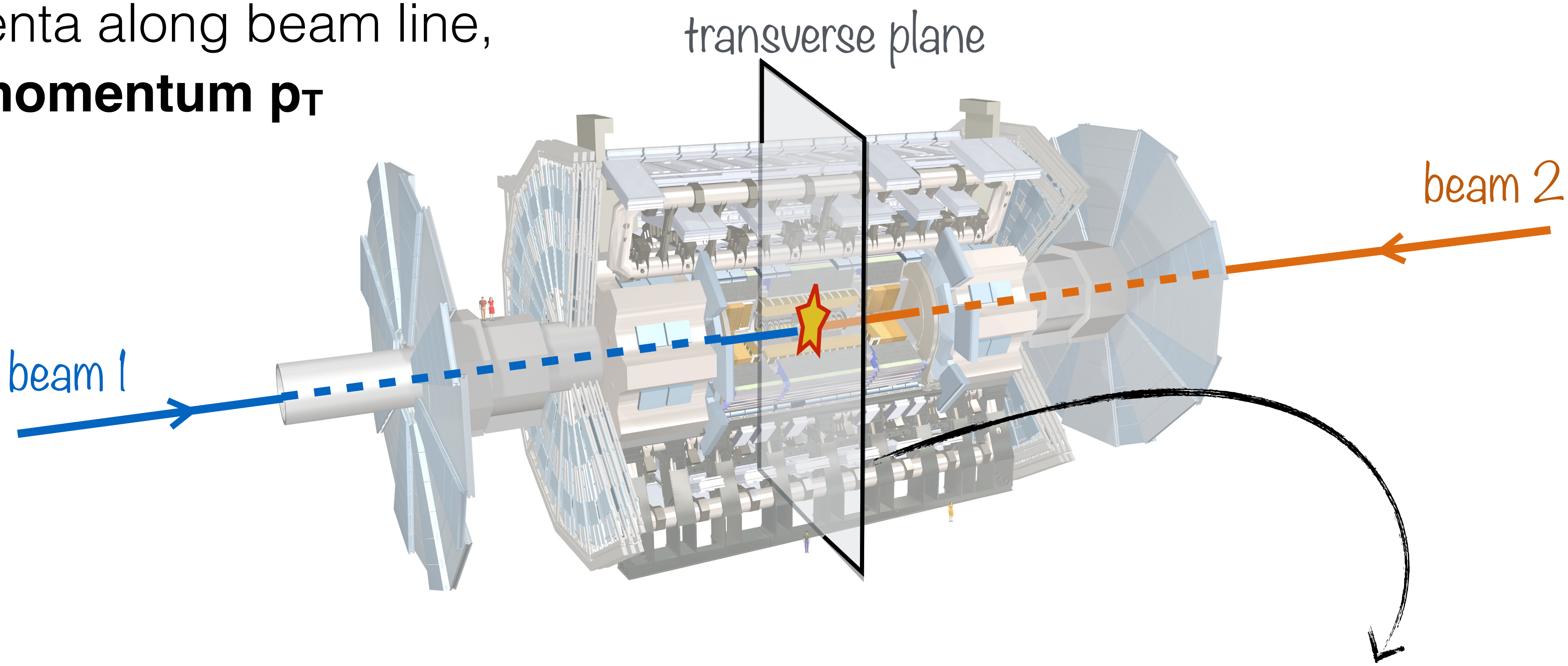

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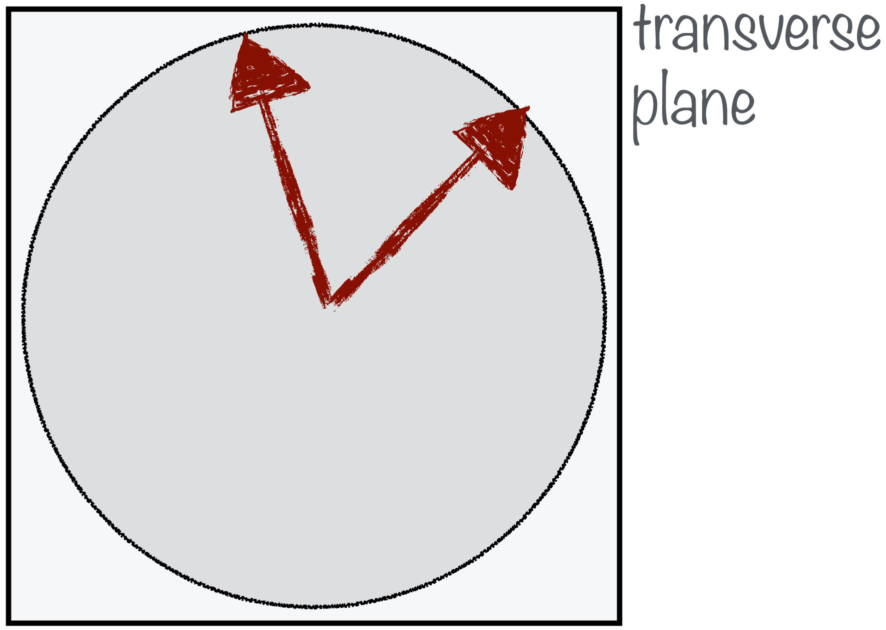

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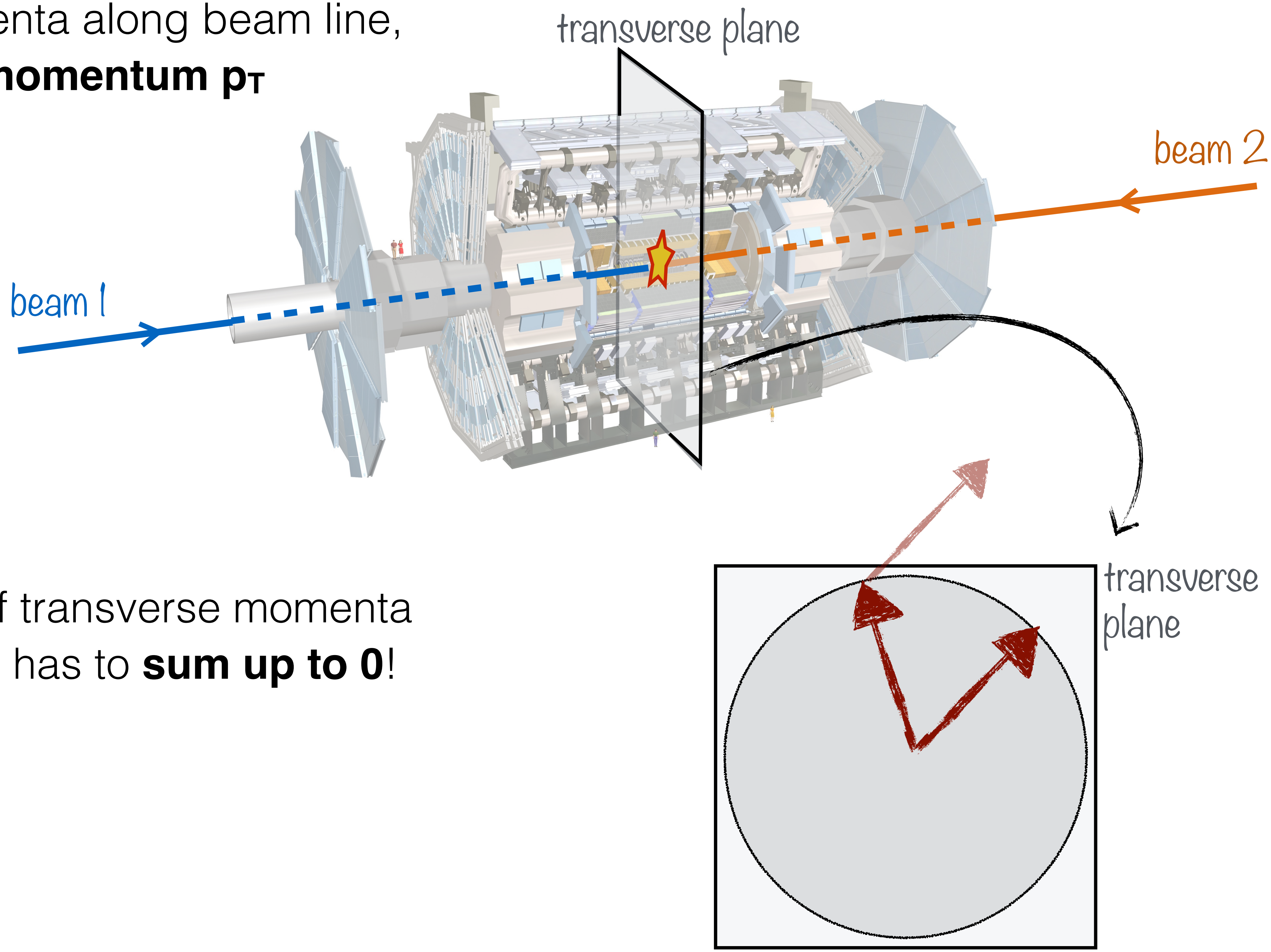

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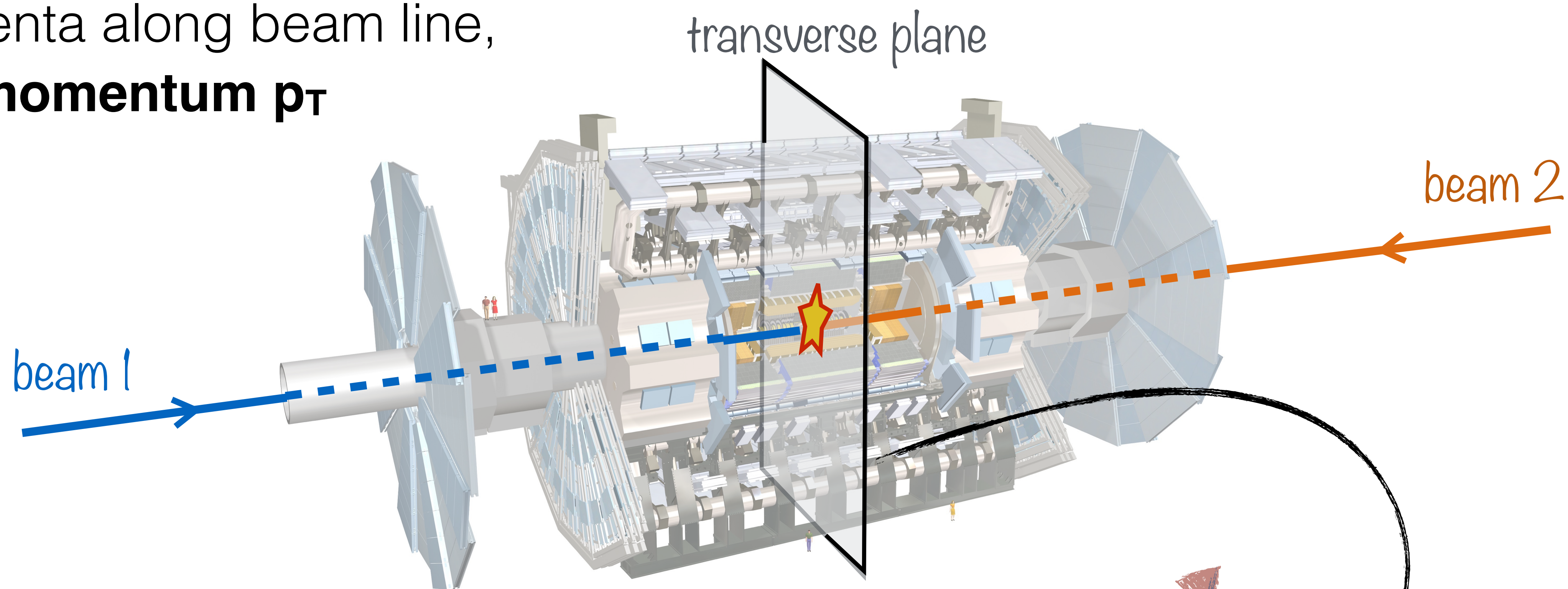

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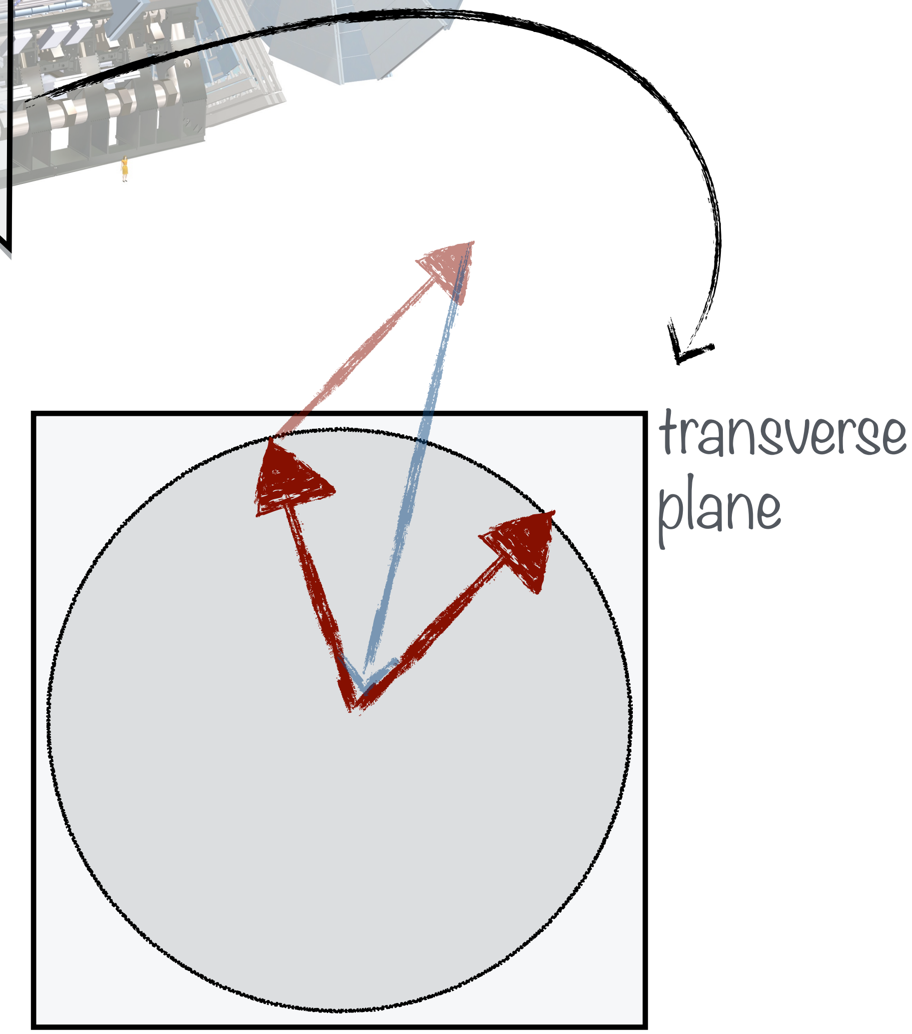

Seeing the invisible

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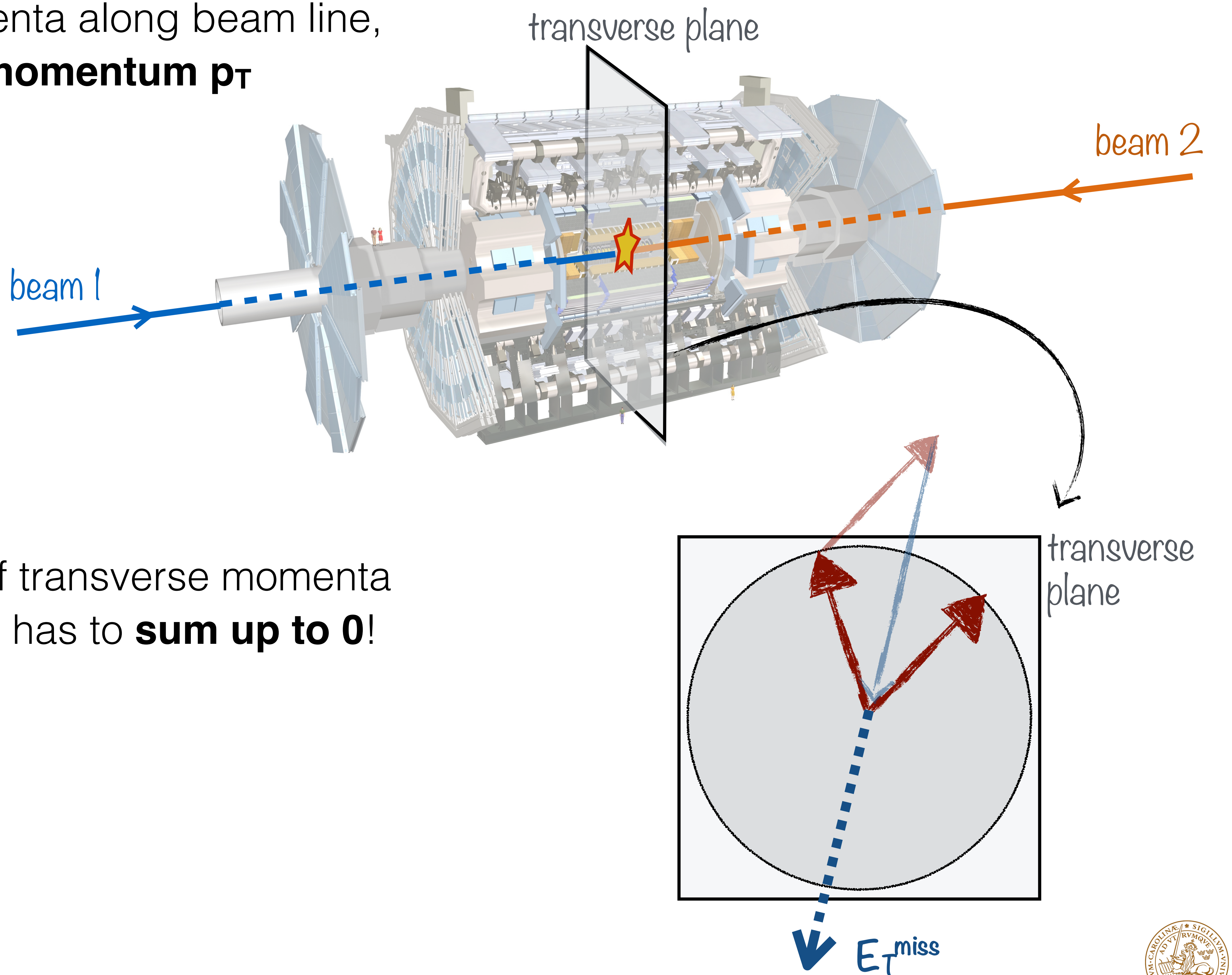

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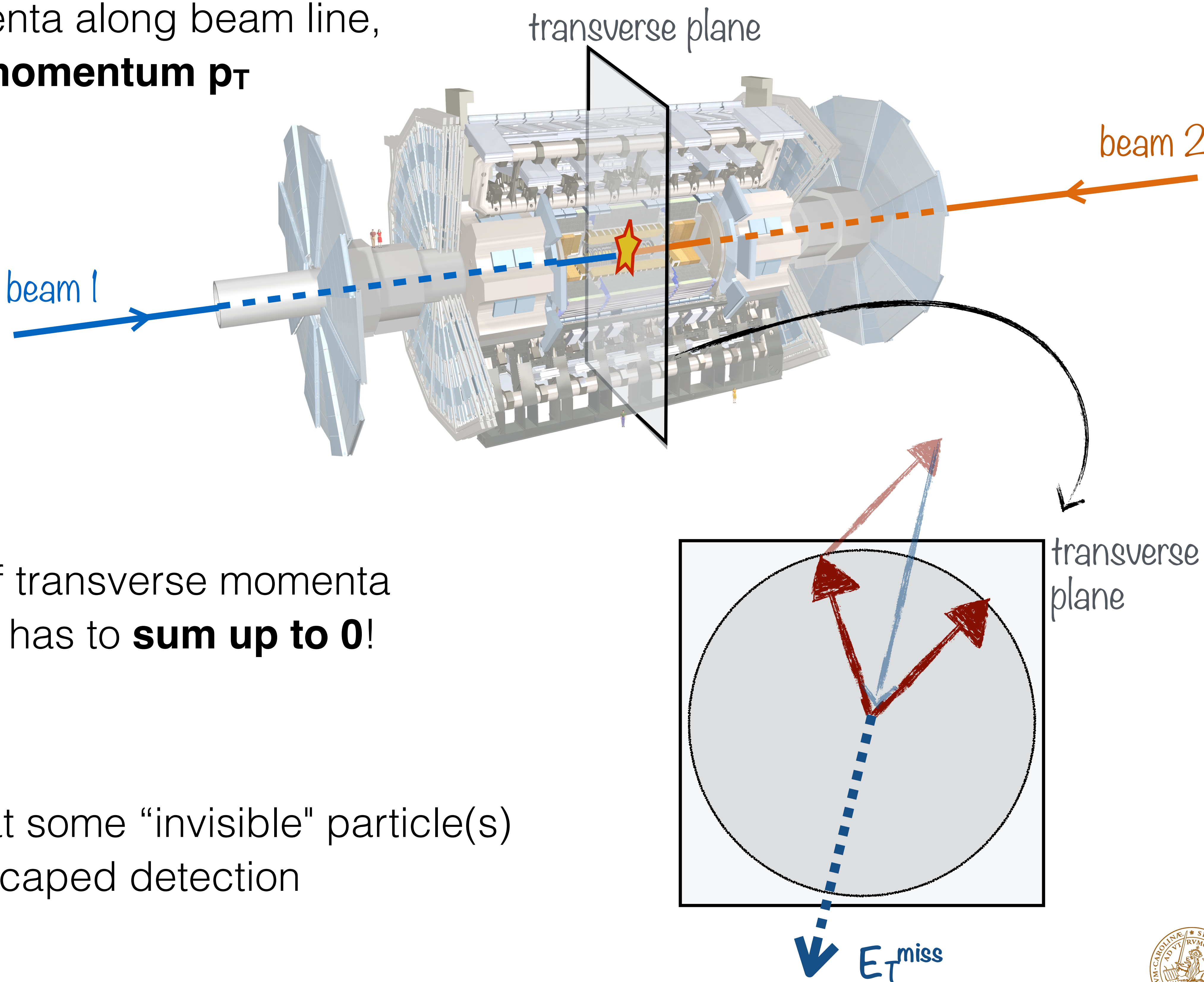
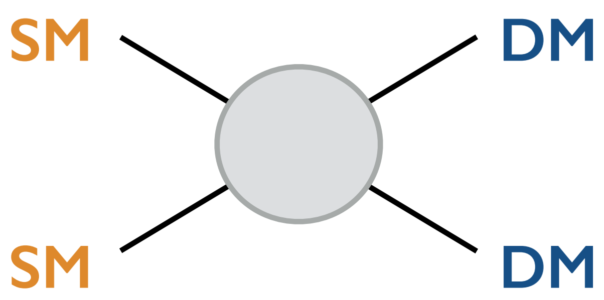
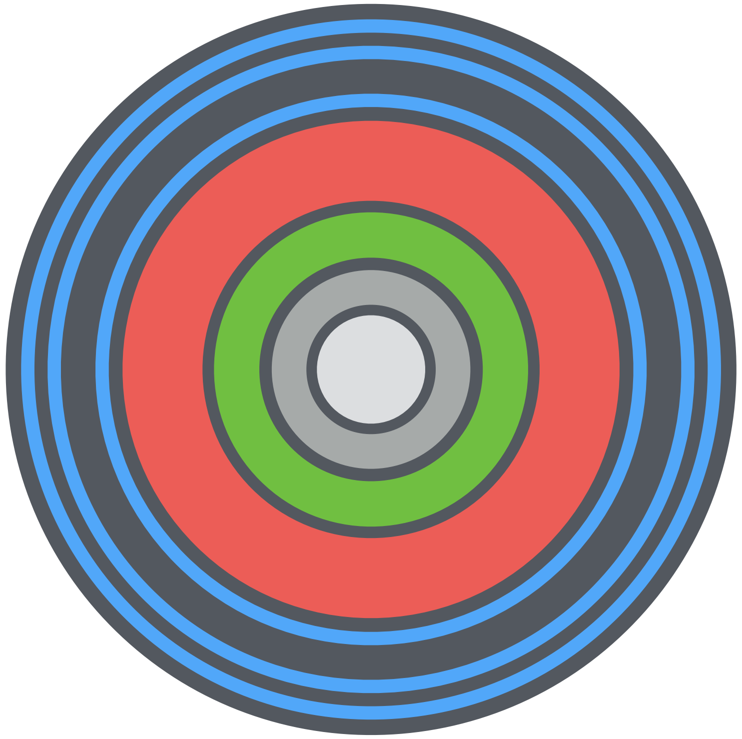


- vector sum of transverse momenta after collision has to **sum up to 0**!
  - infer that some "invisible" particle(s) have escaped detection

"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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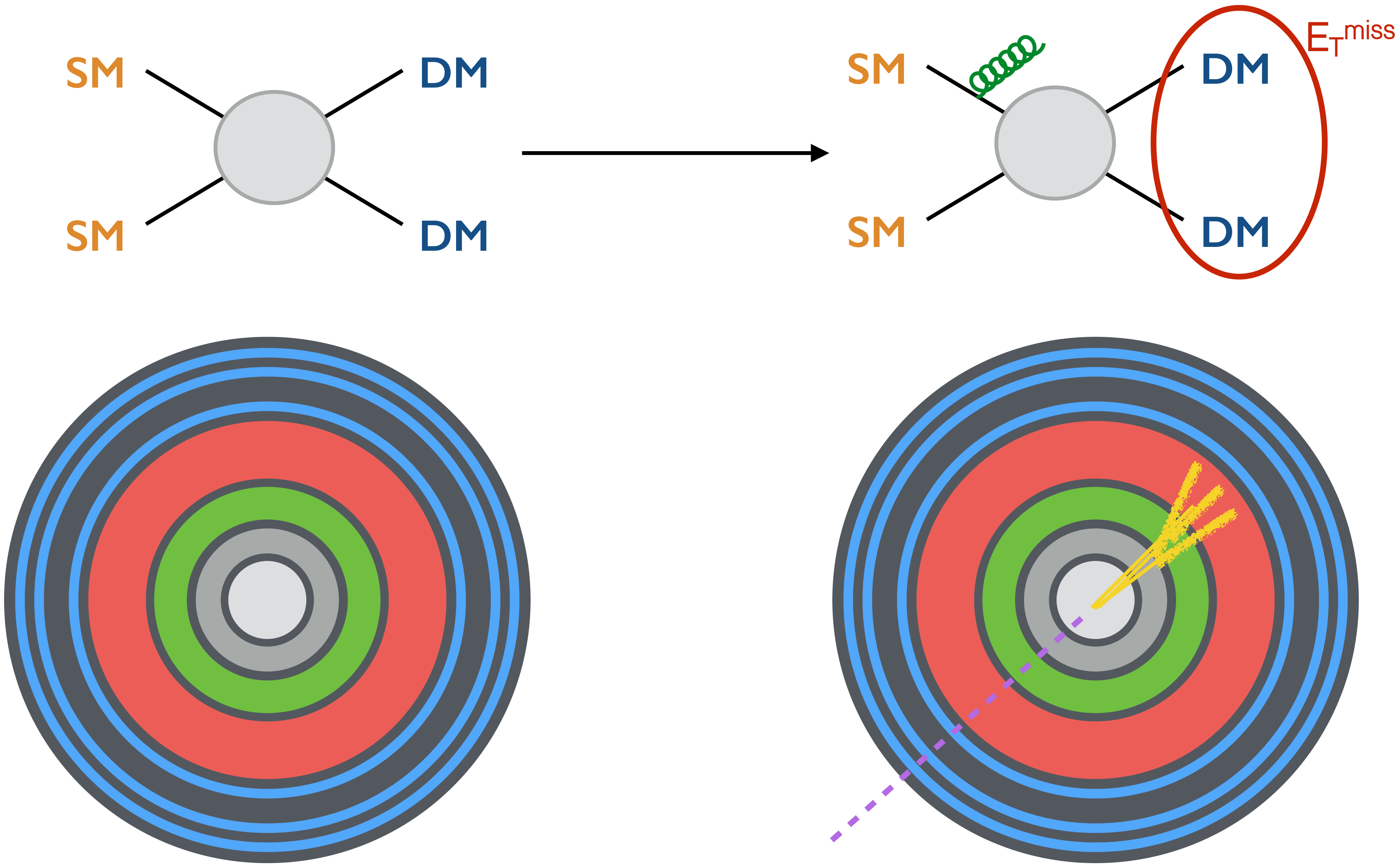

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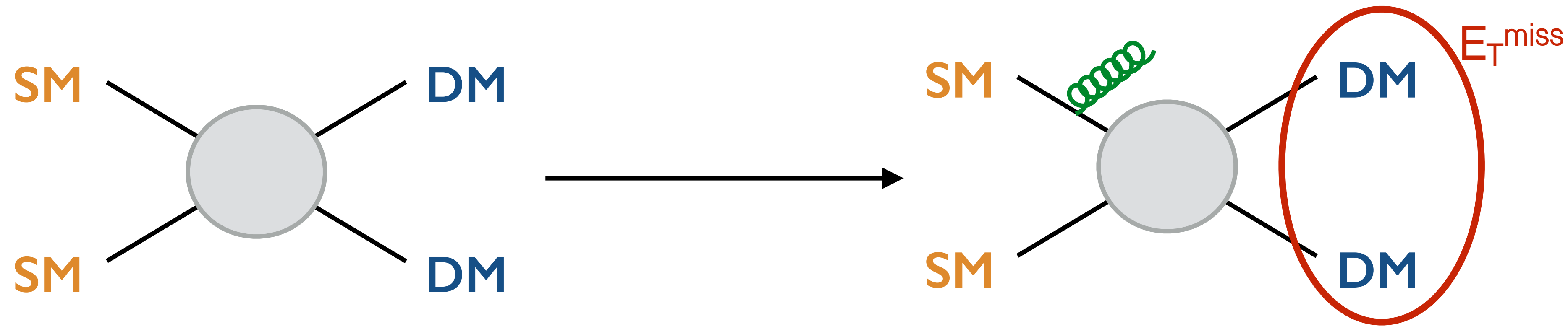
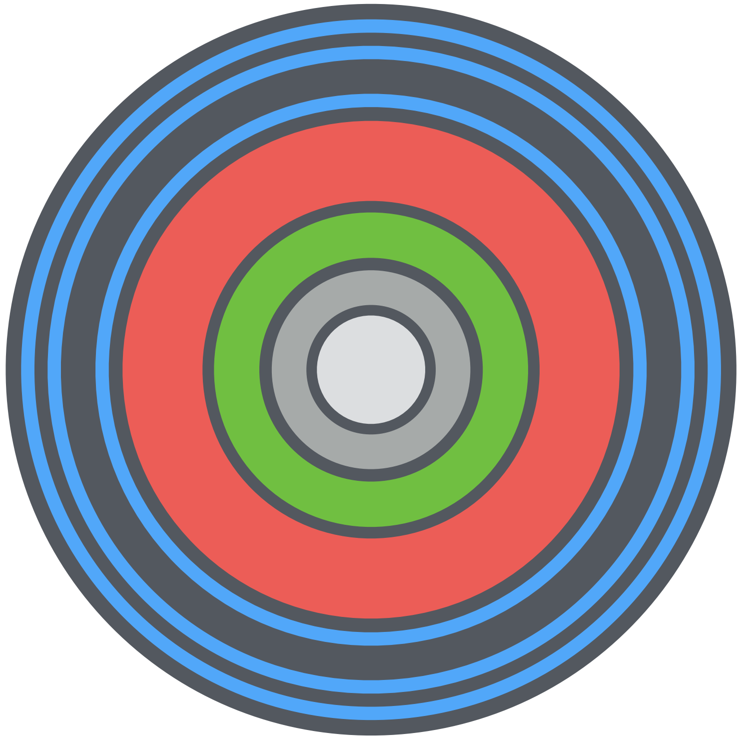
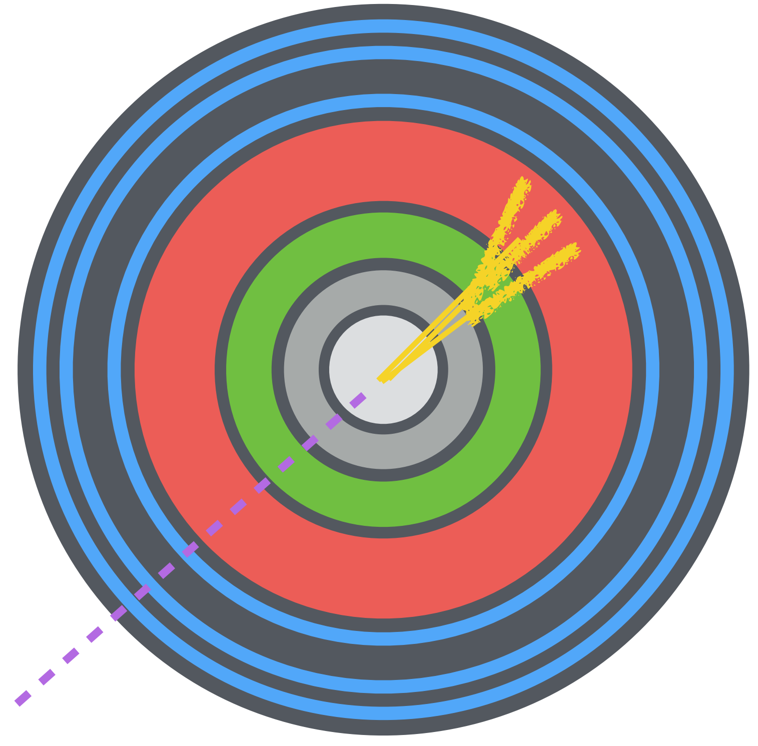
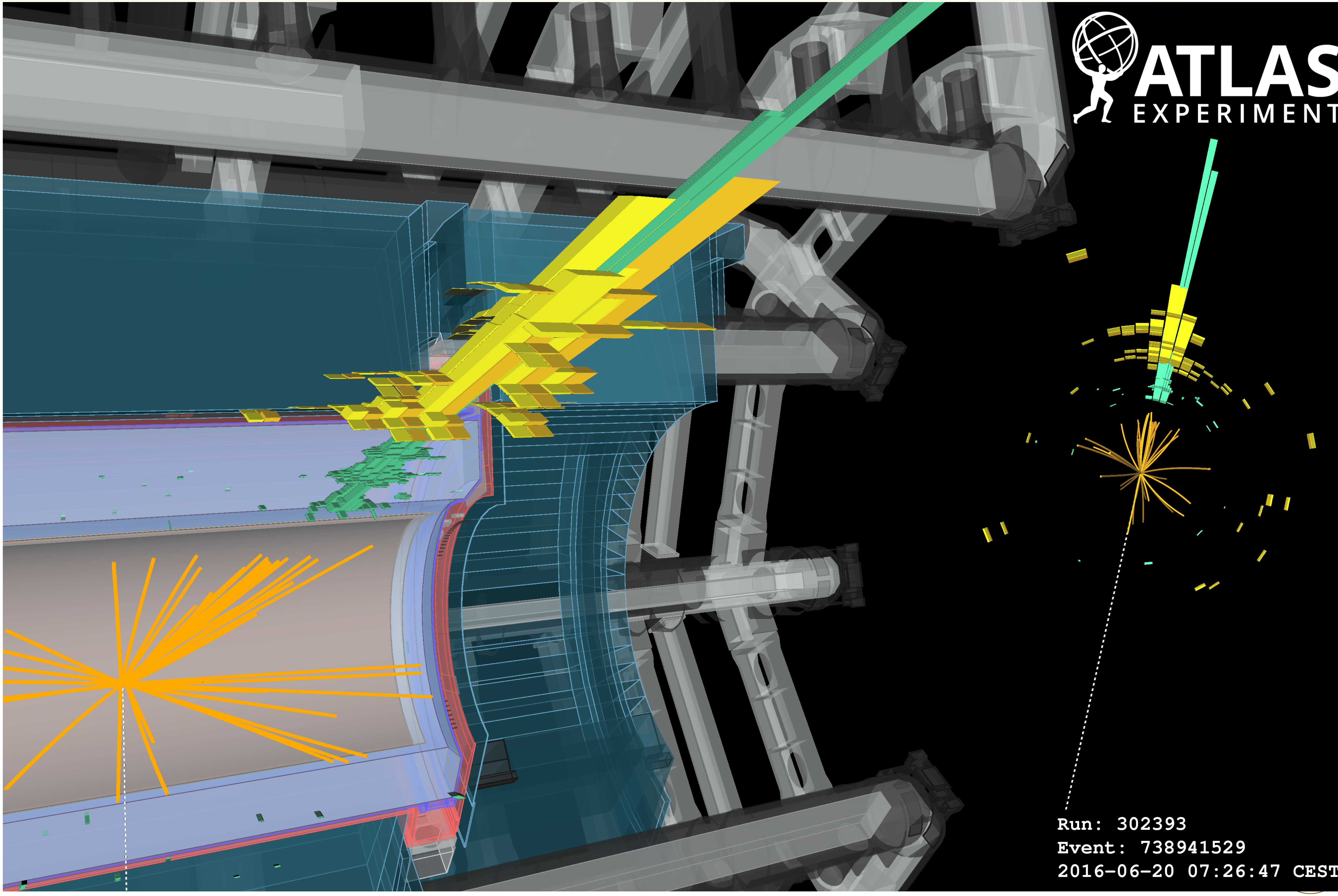




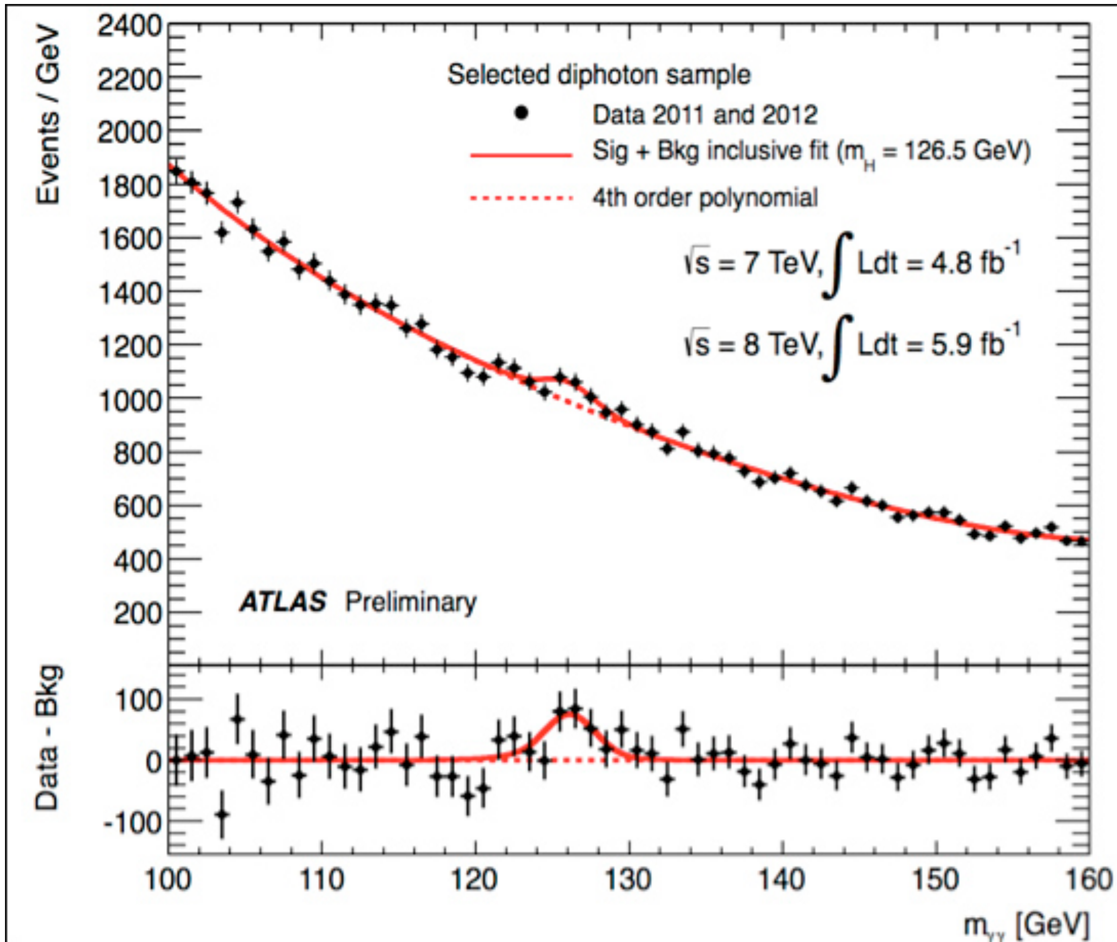


- can be really anything, a photon, W, Z, Higgs…

A jet+invisible event



final missing piece of the SM

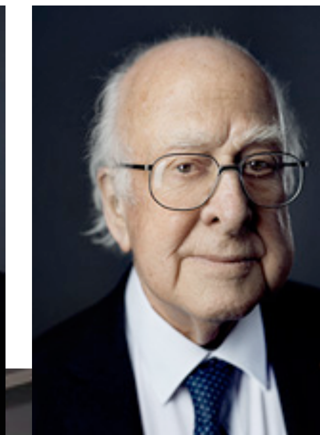


July 4, 2012

animations

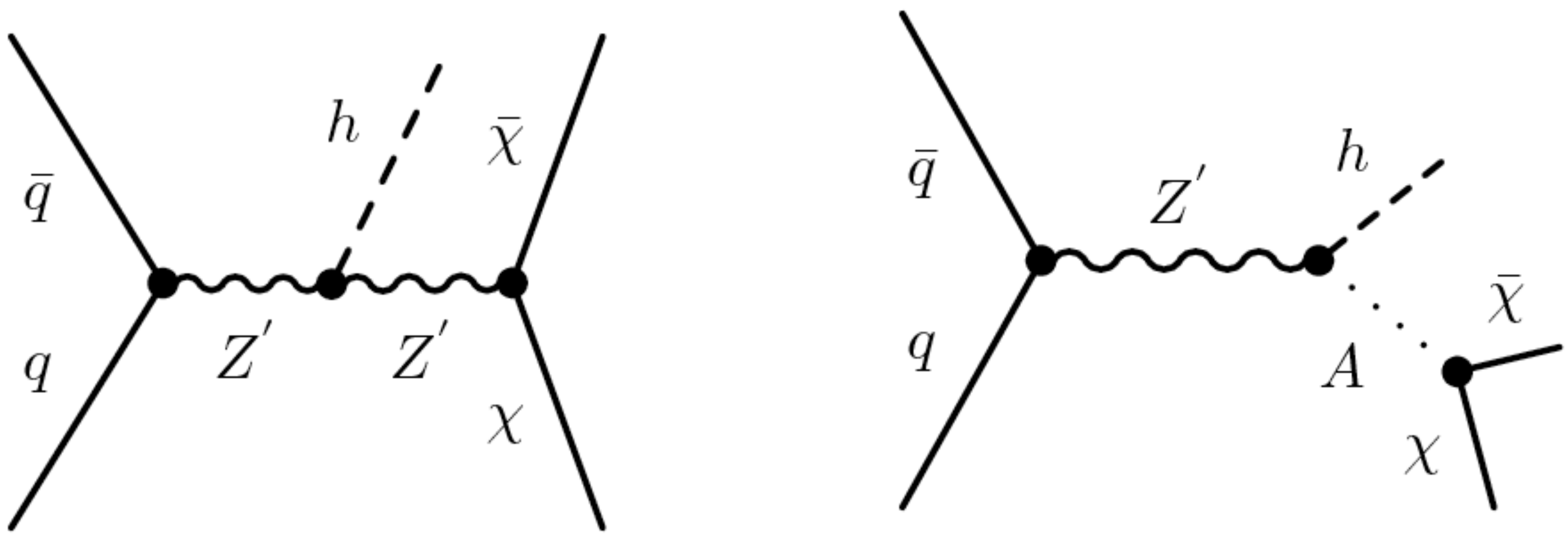
The Nobel Prize in Physics 2013

François Englert, Peter Higgs



Example: Higgs+E_T^{miss}

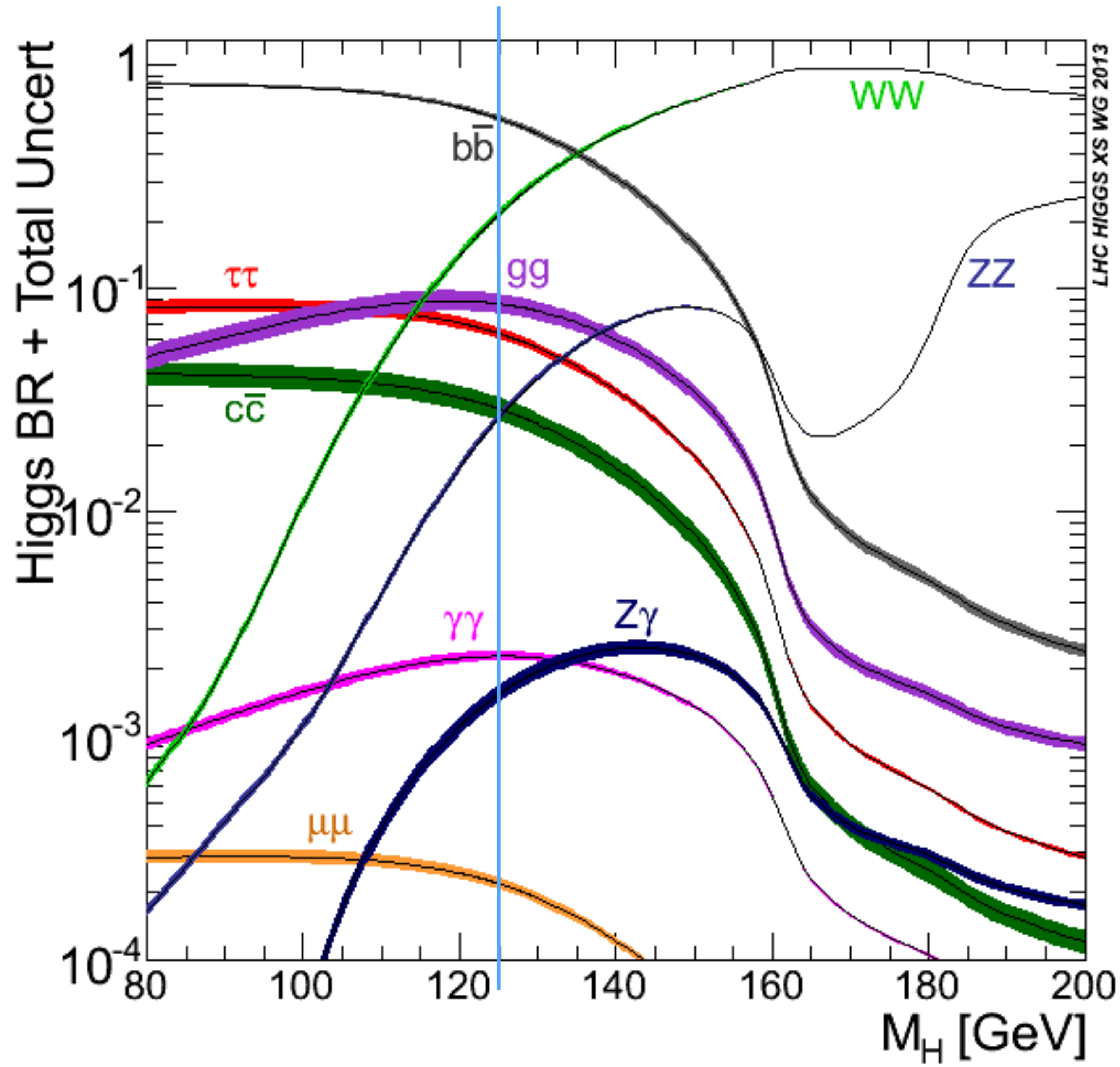
- discovery of a Higgs boson opens **new possibilities** to look for Dark Matter!
- different theoretical models than for other something+E_T^{miss} searches
  - Higgs couples to mass, so will not simply be emitted from initial state partons
- some examples:



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

Example: Higgs+E_T^{miss}

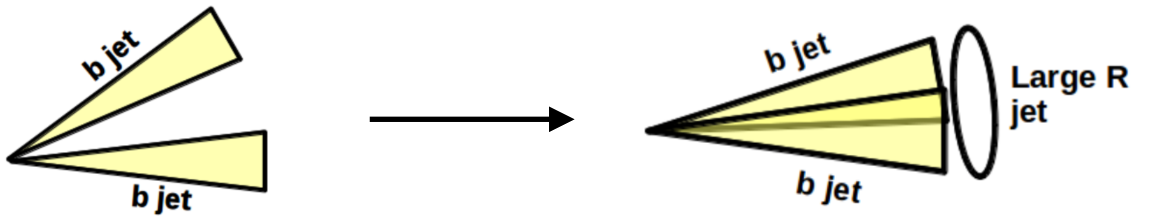
- where to start?
- decay into bb most common:



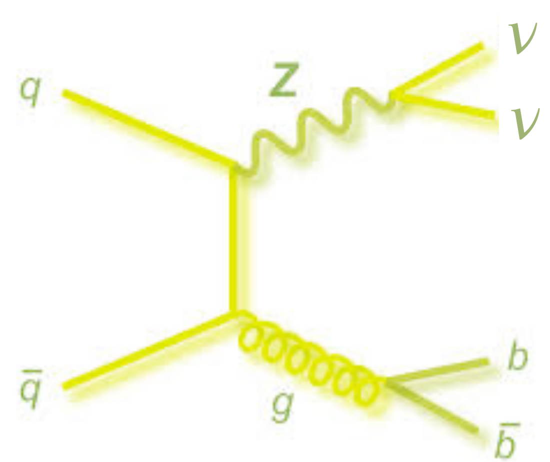
- need to be able to identify jets originating from b-quarks (**b-jets**)
  - luckily, we are (and we call it *b-tagging*)

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…)

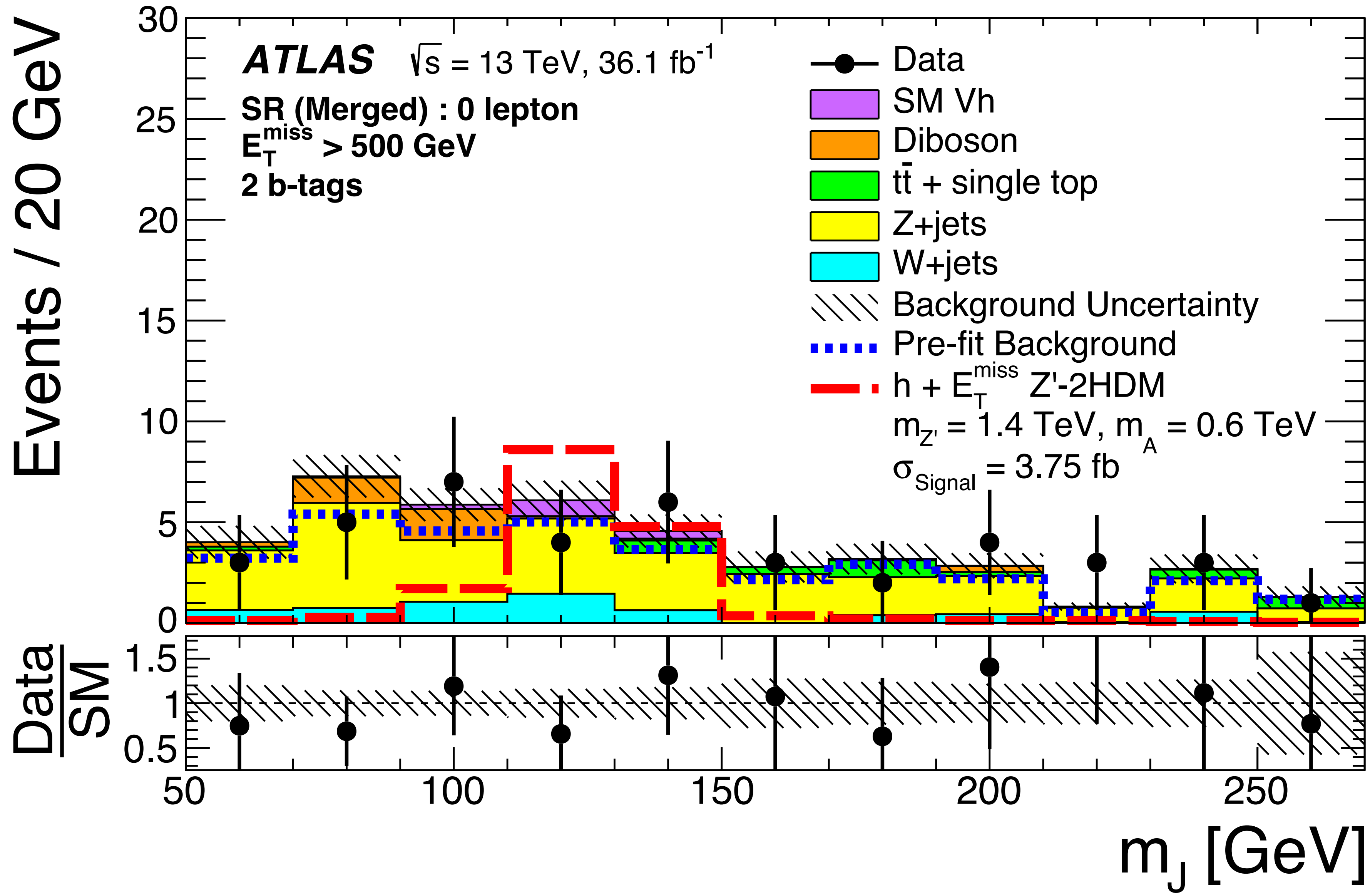


- important **background**:
  production of Z boson together with (b-)jets,
  with Z—>$\nu\nu$ => E_T^{miss}
  - to estimate this and other backgrounds: use **control samples**
    - events that have characteristics of a given background process
    - improves confidence in and precision of background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



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

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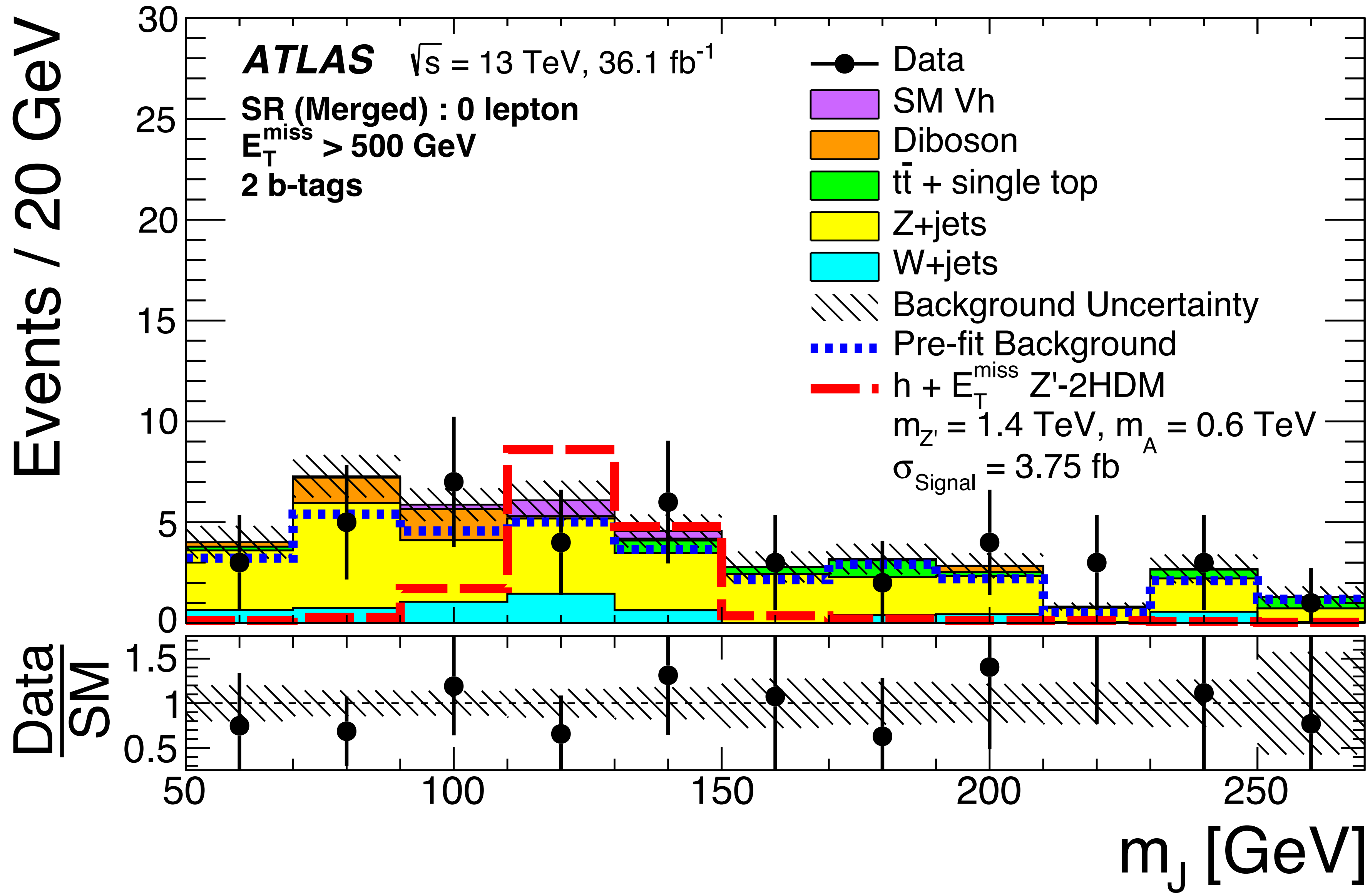
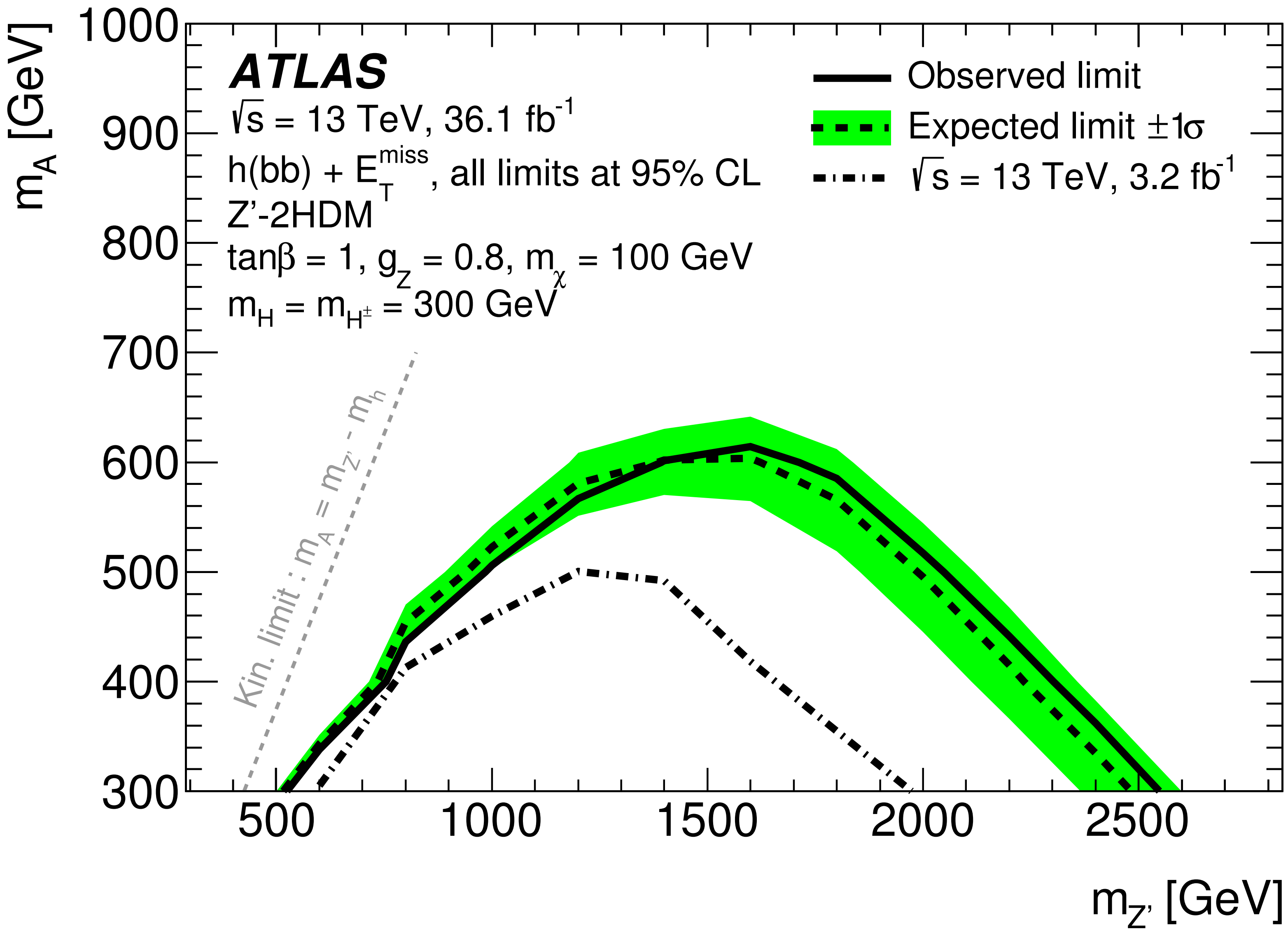


- no signal observed!

Higgs(bb)+E_T^{miss} – The Outcome

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



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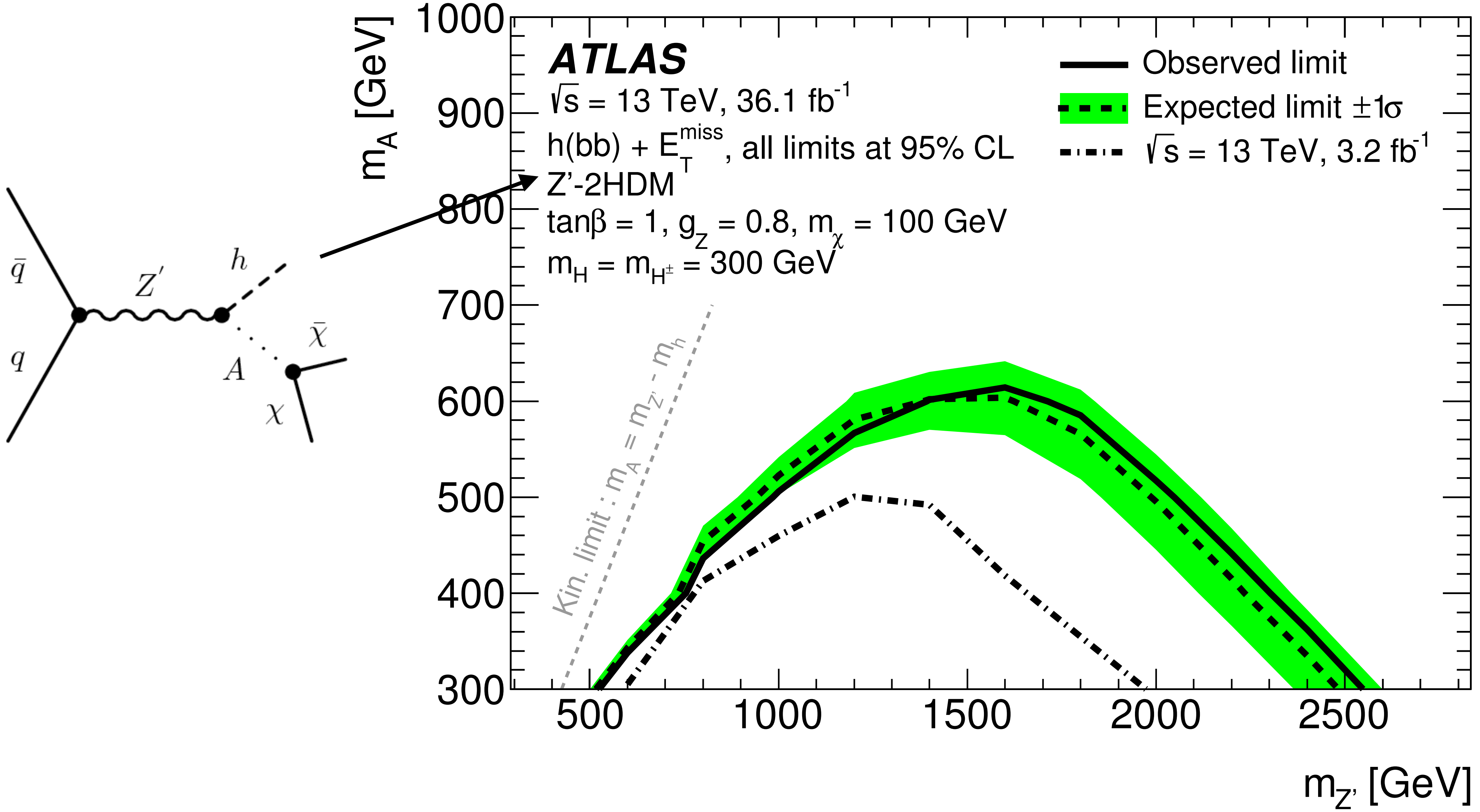

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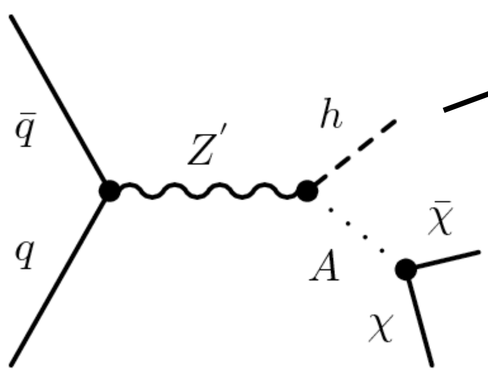

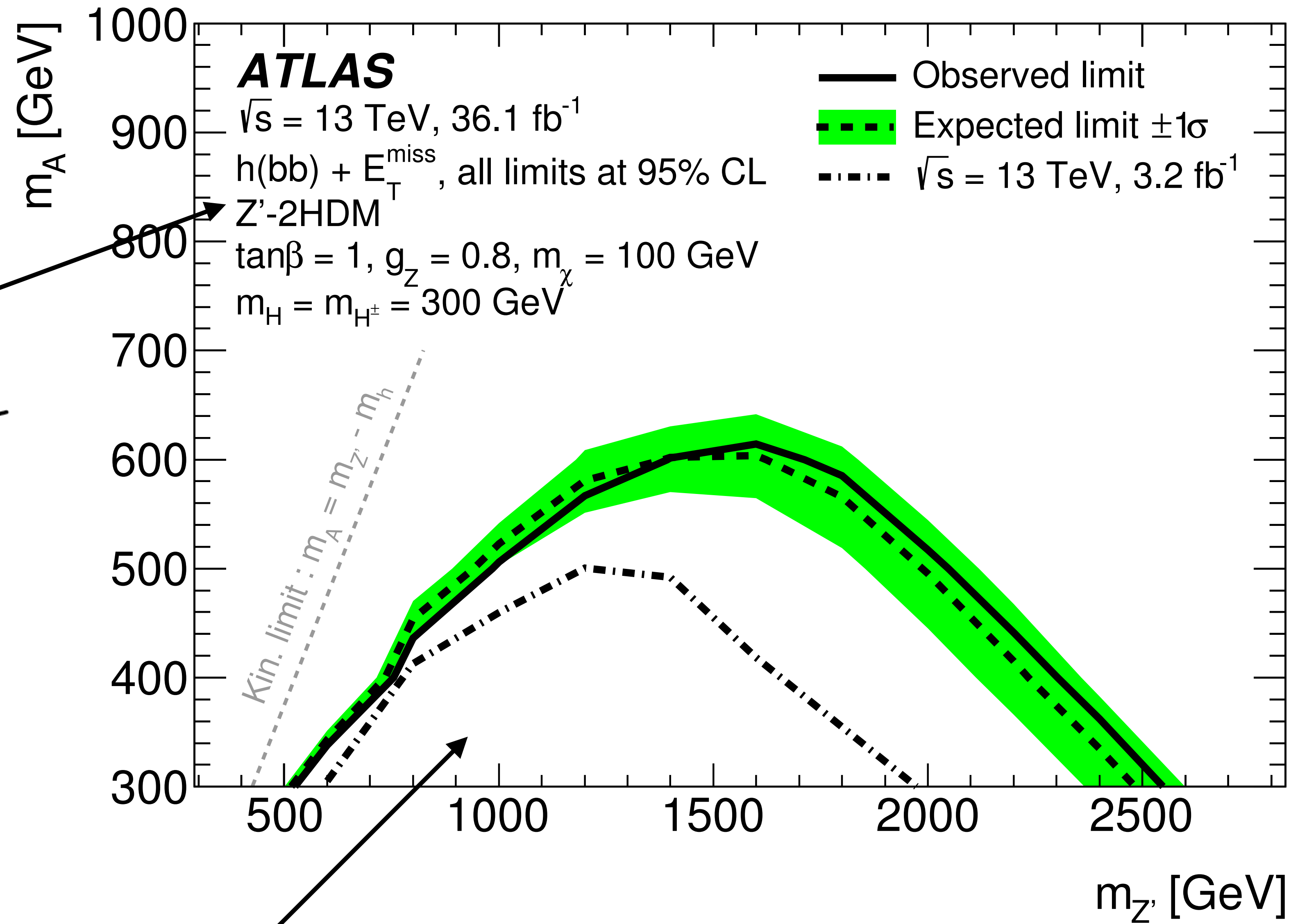

excluded by
2015 data

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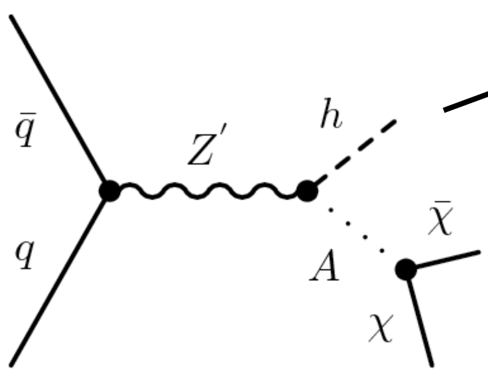
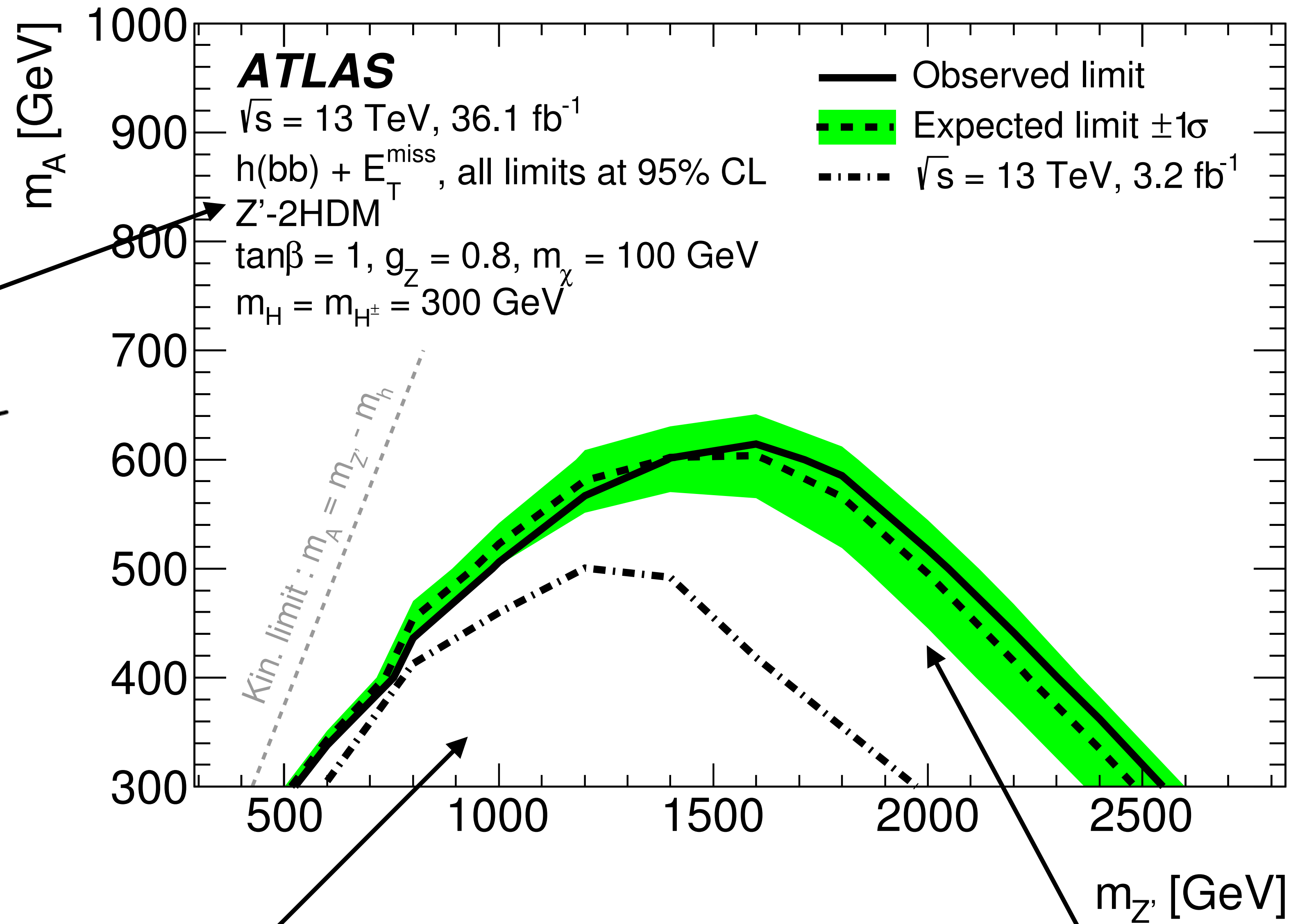
- a typical result plot: exclusion bounds ("limits")





excluded by 2015 data

excluded by 2015+2016 data

Higgs(bb)+E_T^{miss} – The Outcome

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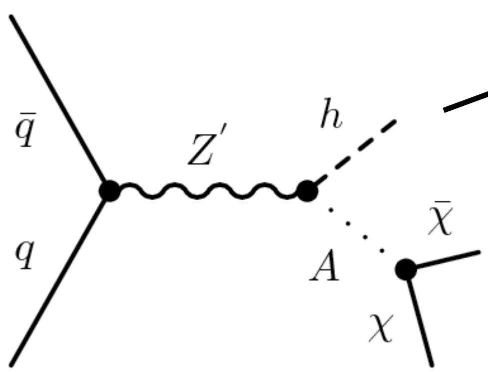
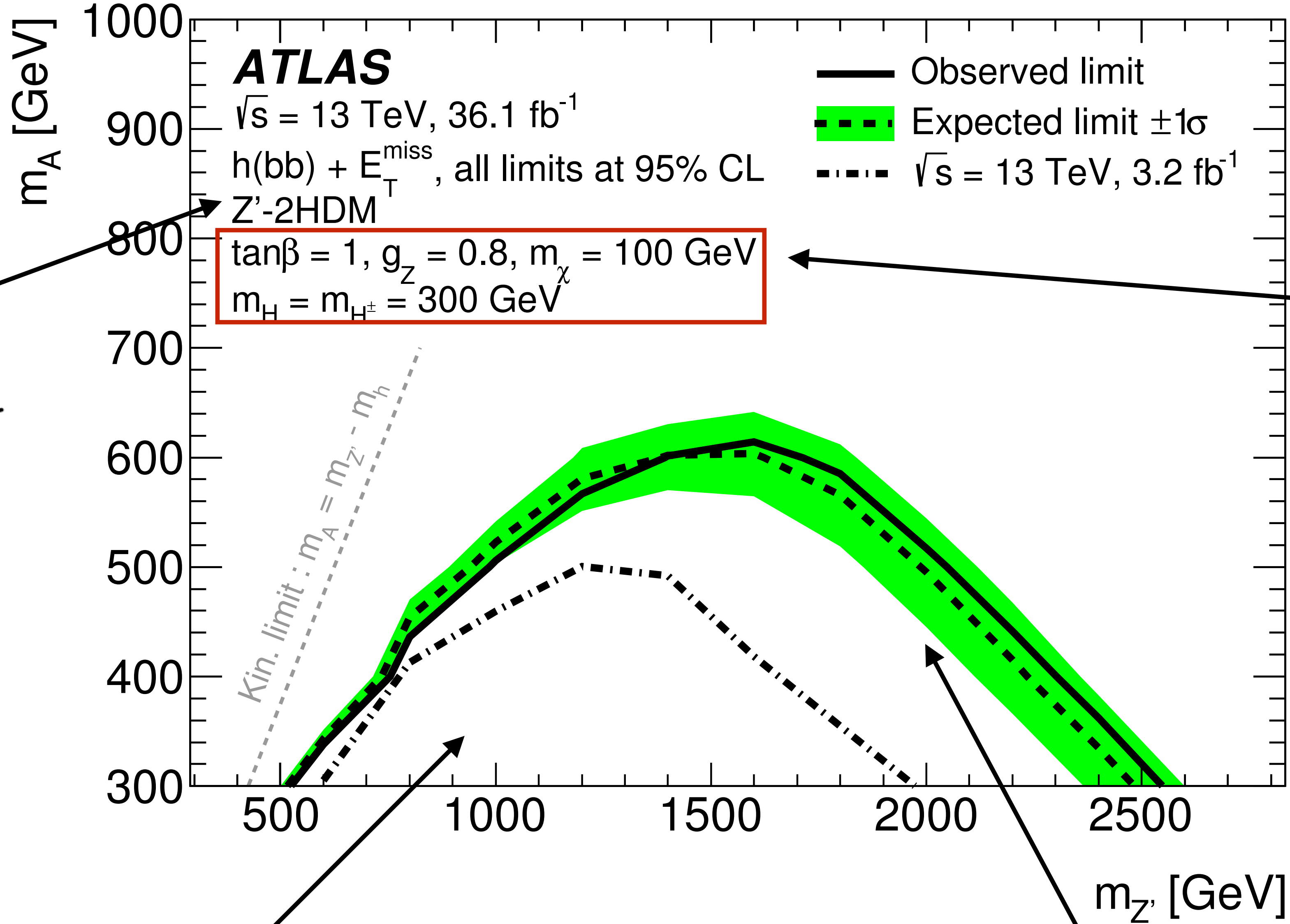




conclusions (exclusion) made in terms of $m_{Z'}$, m_A only valid for these assumptions about the other model parameters

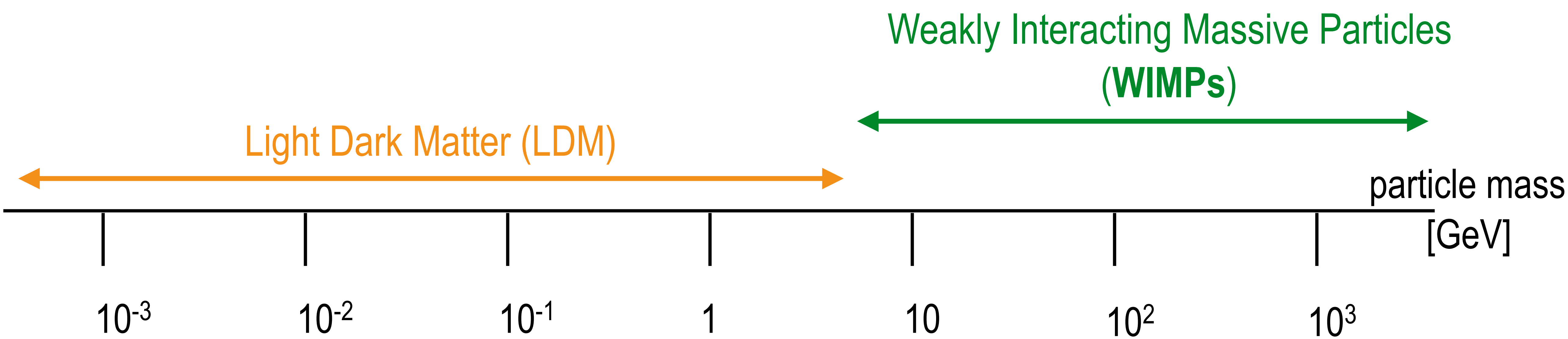
excluded by 2015 data

excluded by 2015+2016 data

Accelerator-based Search

Light Dark Matter

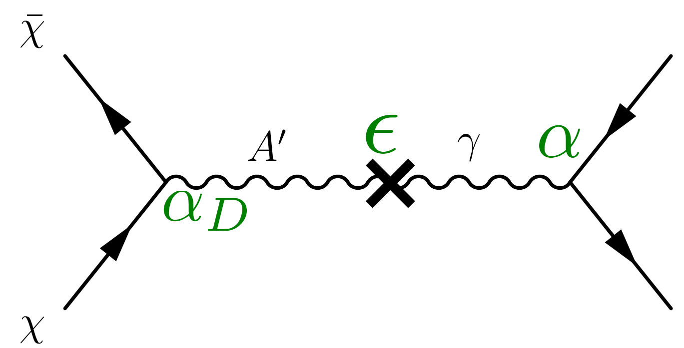
- so, we have a lot of experiments searching for **WIMPs**, but **no observation**
- should start **looking elsewhere** —> lighter DM particles
- **thermal relic** —> mass constraint & minimum annihilation cross section
  - WIMP too light —> annihilation inefficient —> overproduction of DM
    - Lee-Weinberg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



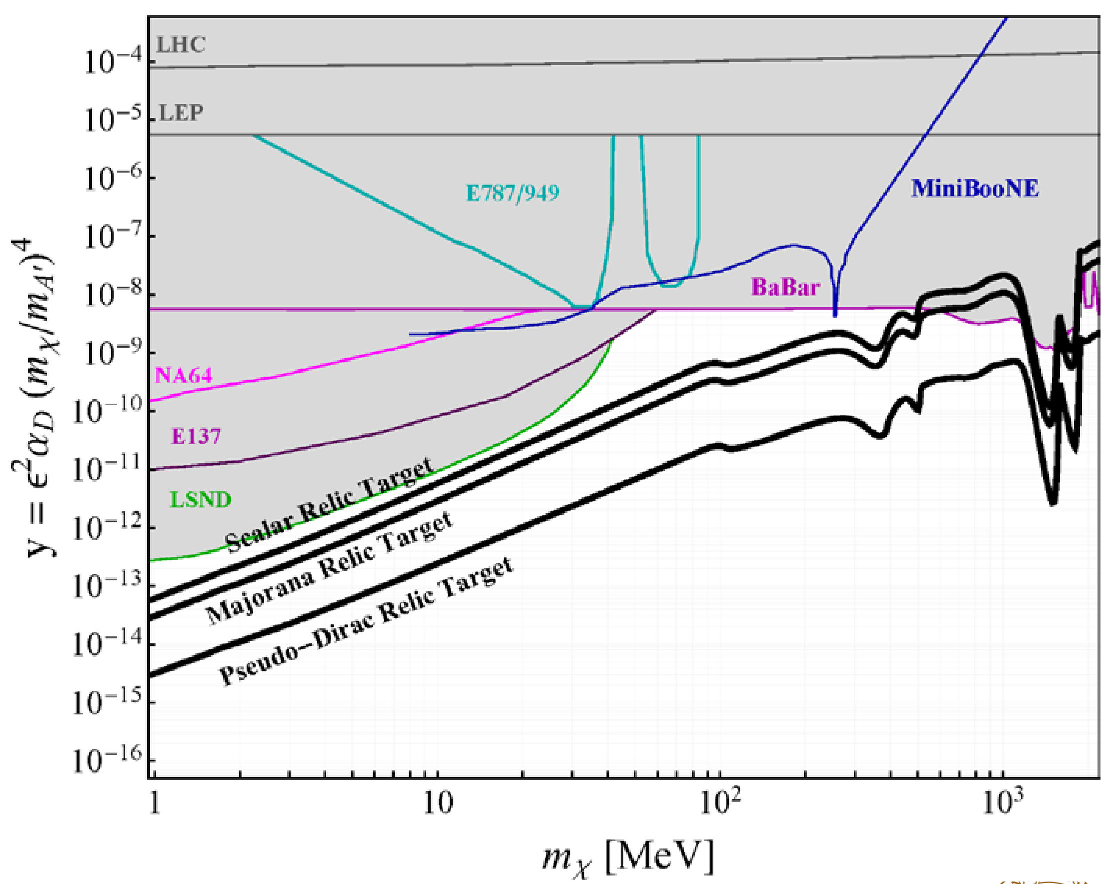
- representative model:

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



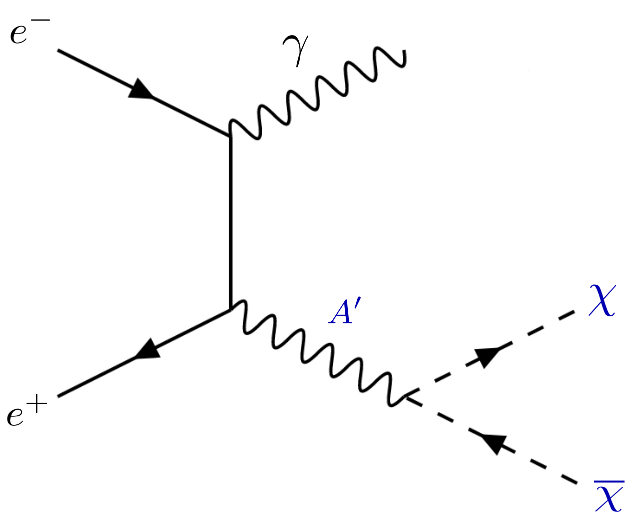
How to look for this?

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

Why fixed-target?

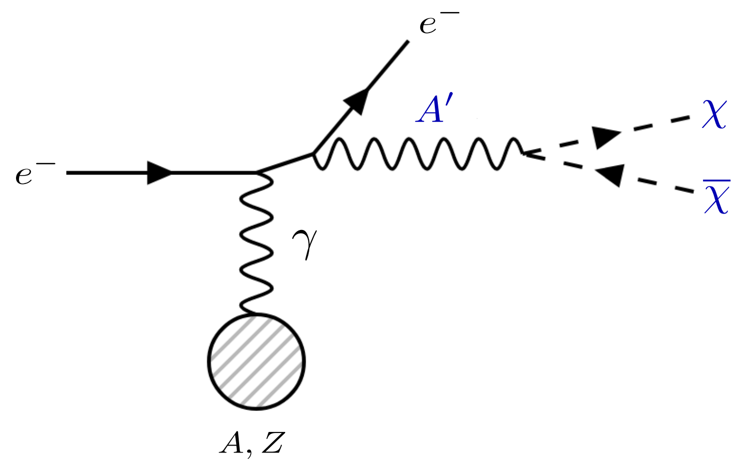
- maximise DM yield (**production** & detection **efficiency**)

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

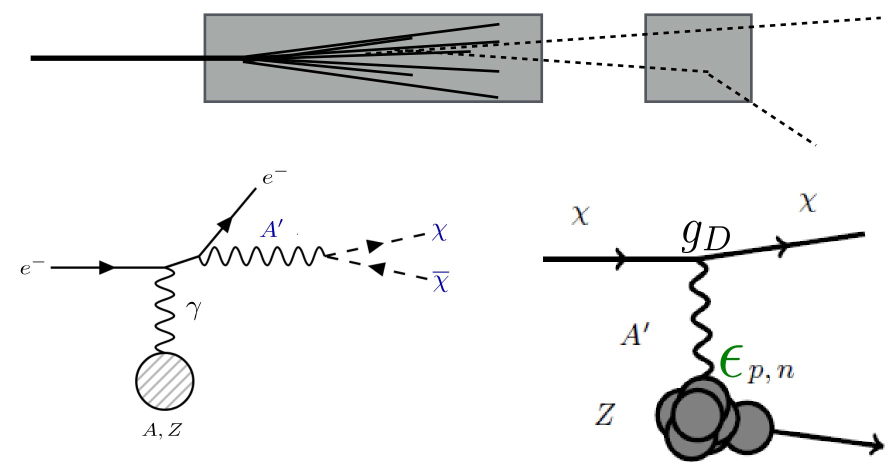


- fixed target

dark bremsstrahlung



- beam-dump



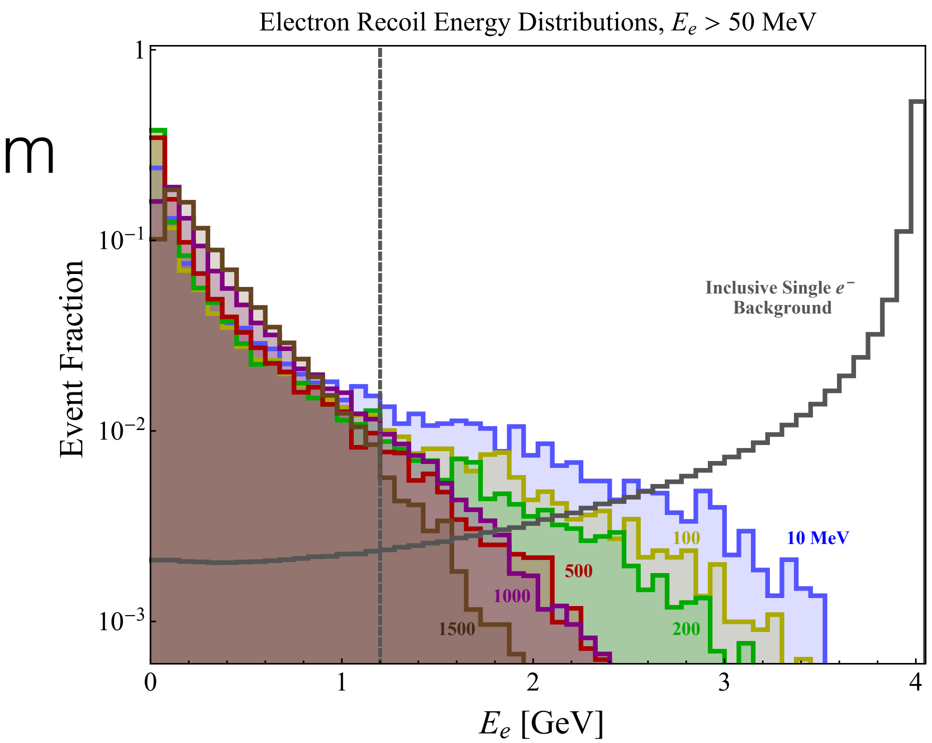
$$\sigma_{\text{coll}} \propto \frac{\varepsilon^2}{E_{\text{cm}}^2} \quad << \quad \sigma_{\text{FT}} \propto \frac{Z^2\varepsilon^2}{m_{\text{A'}}^2}$$

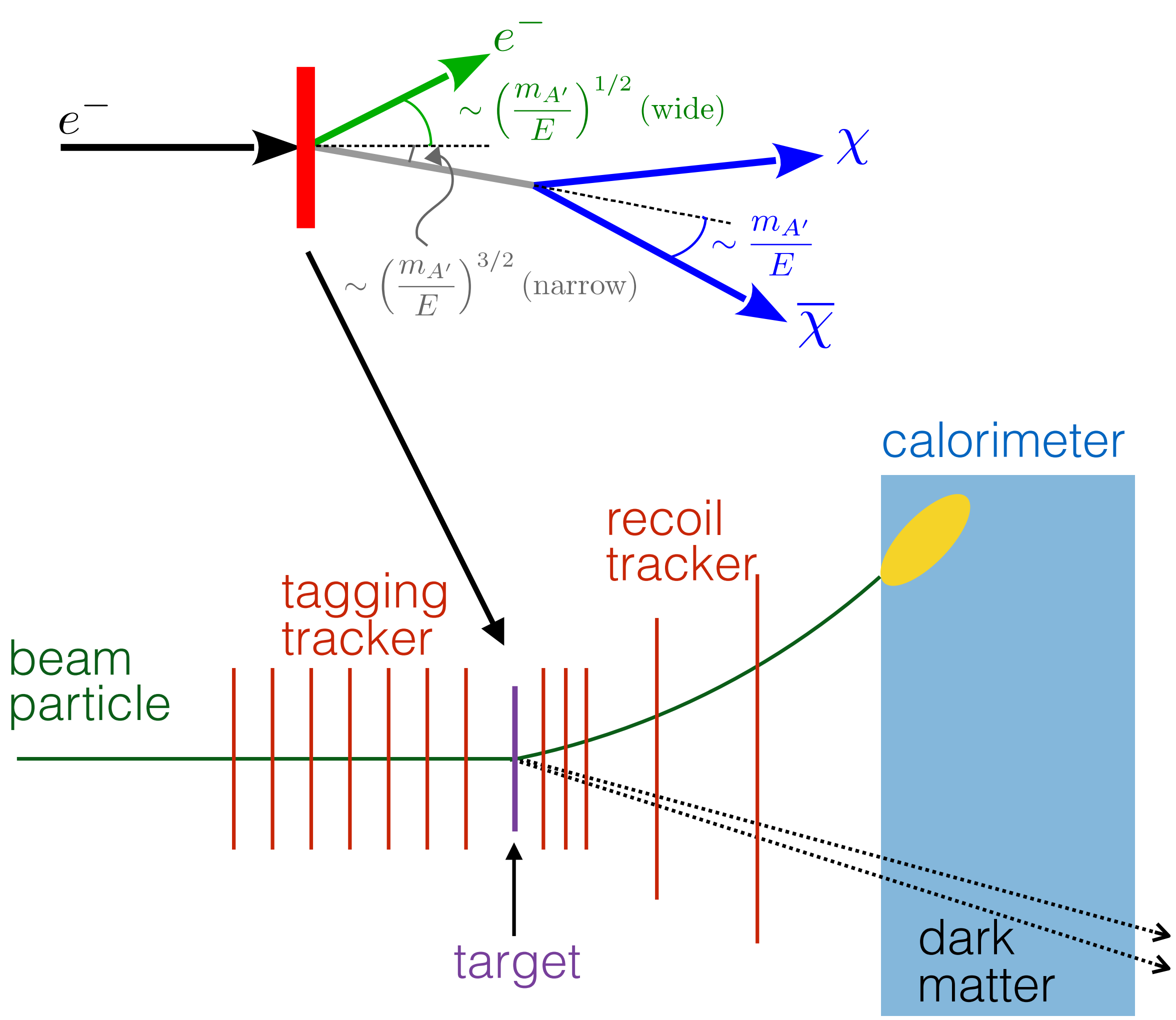
$$\frac{\sigma_{\text{FT}}}{\sigma_{\text{coll}}} \propto Z^2 \left(\frac{E_{\text{cm}}}{m_{\text{A'}}}\right)^2 \quad >> 1$$

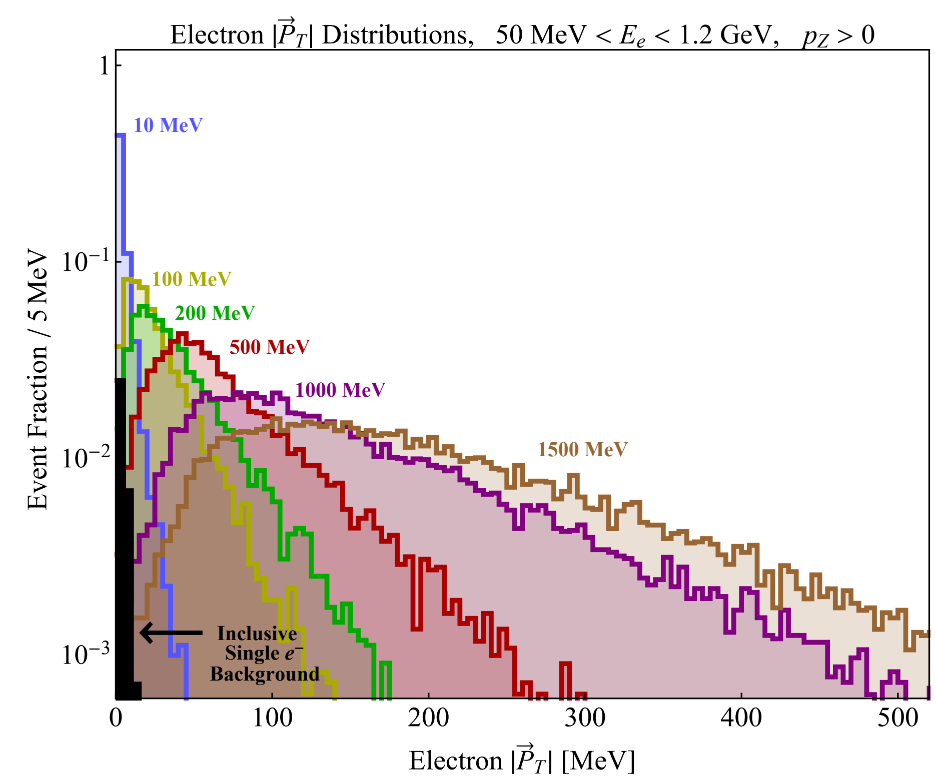
$$N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2 \quad >> \quad N \propto \varepsilon^4$$

Why missing momentum?

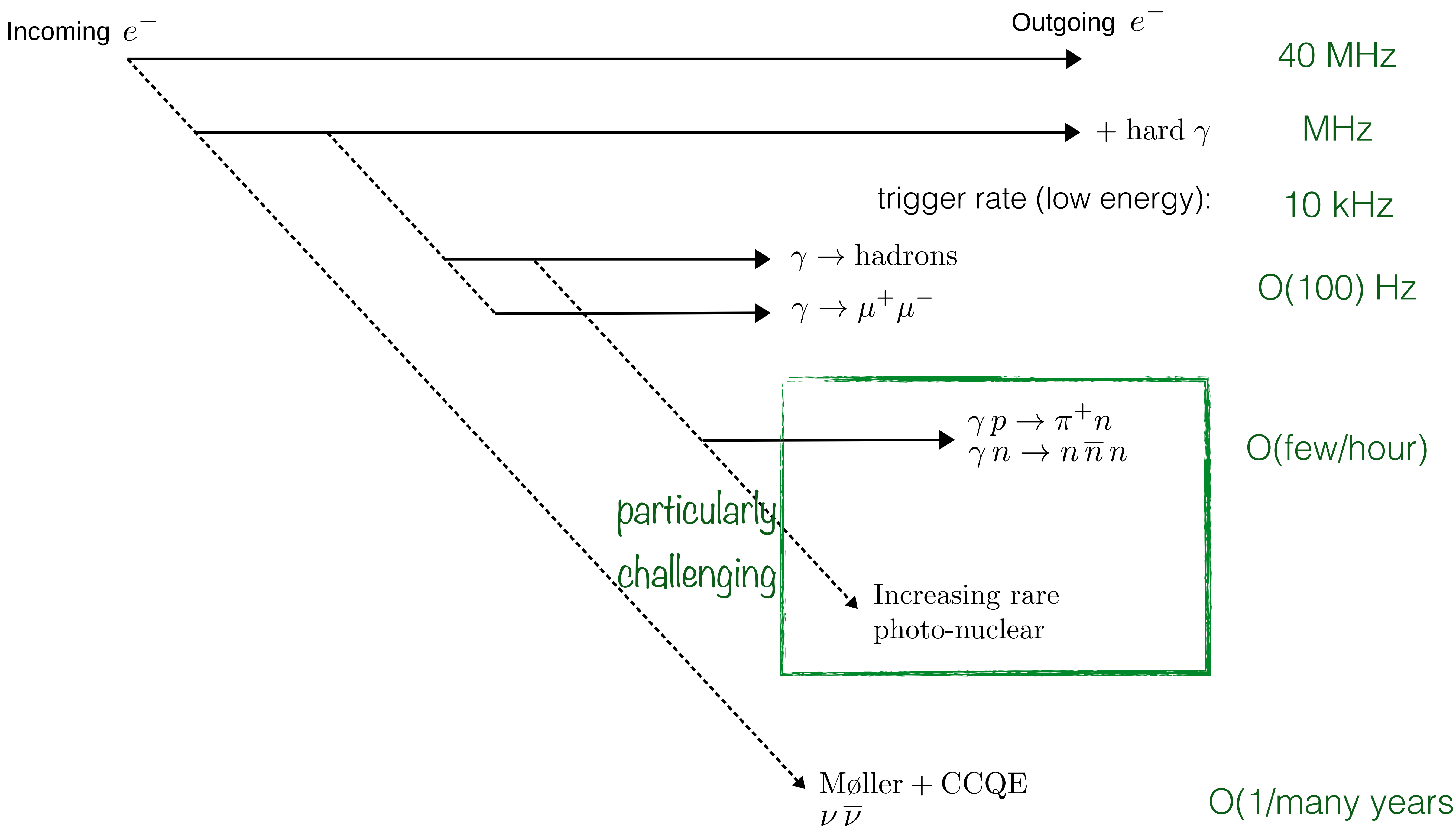
- due to mass of mediator, kinematics distinctly different from SM bremsstrahlung
  - mediator carries most of the energy
    —> soft recoil electron, large missing momentum
  - recoil electron gets transverse 'kick'
    —> large missing transverse momentum







Challenge: Backgrounds!



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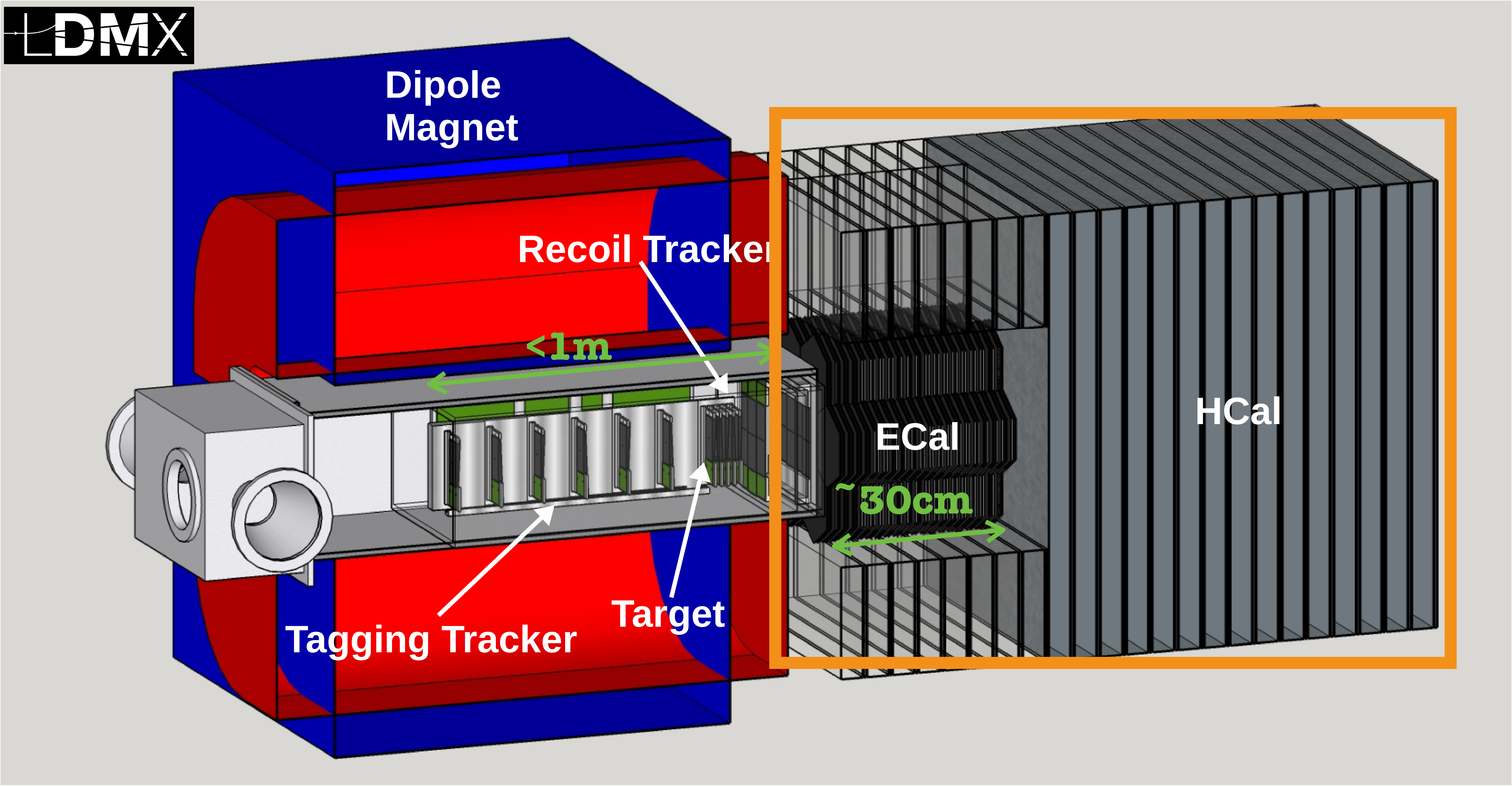
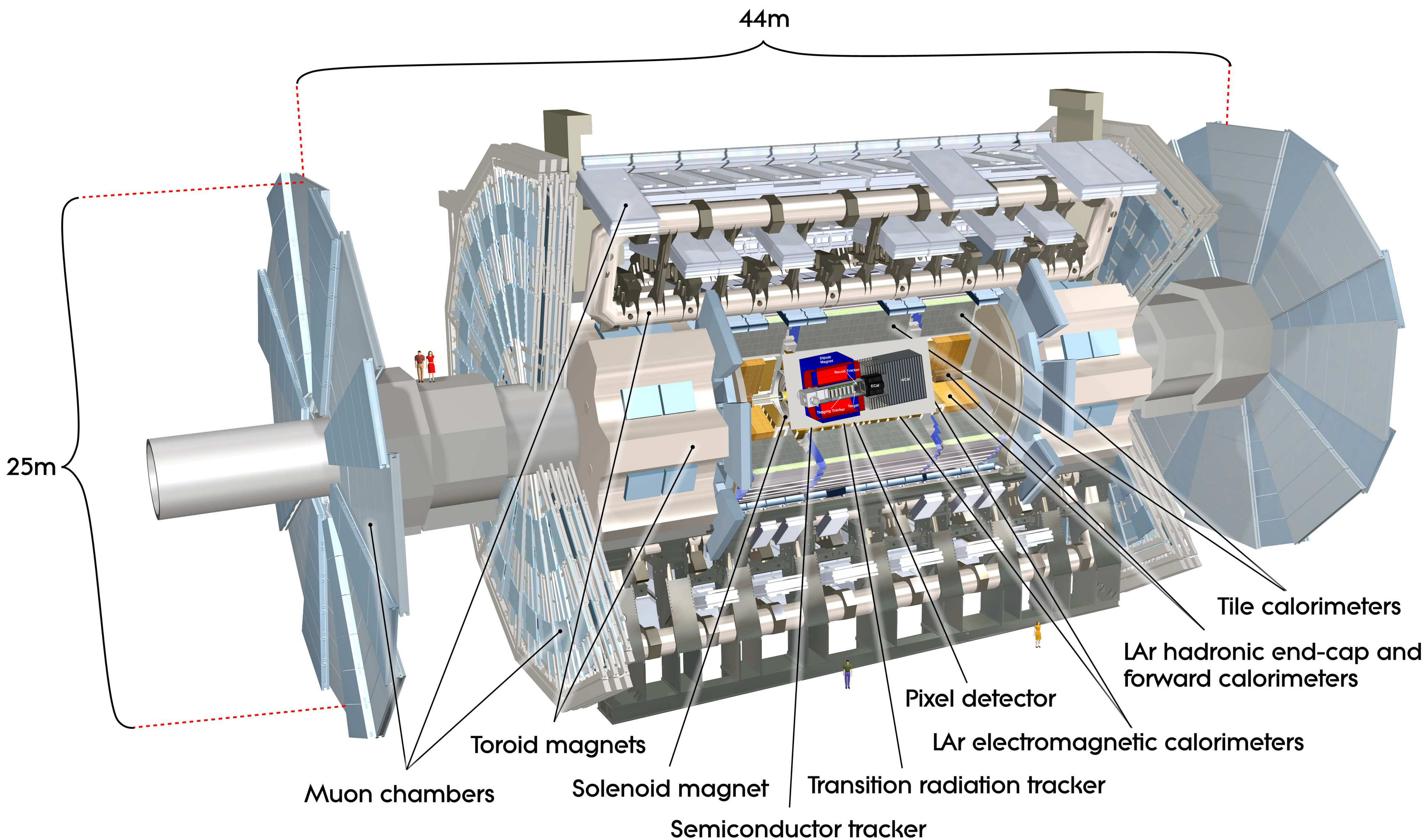
Light Dar Matter eXperiment



Caltech · Fermilab · SLAC National Accelerator Laboratory · UCSB University of California Santa Barbara · University of Minnesota · University of California Santa Cruz · Lunds Universitet

LDMX is a small experiment

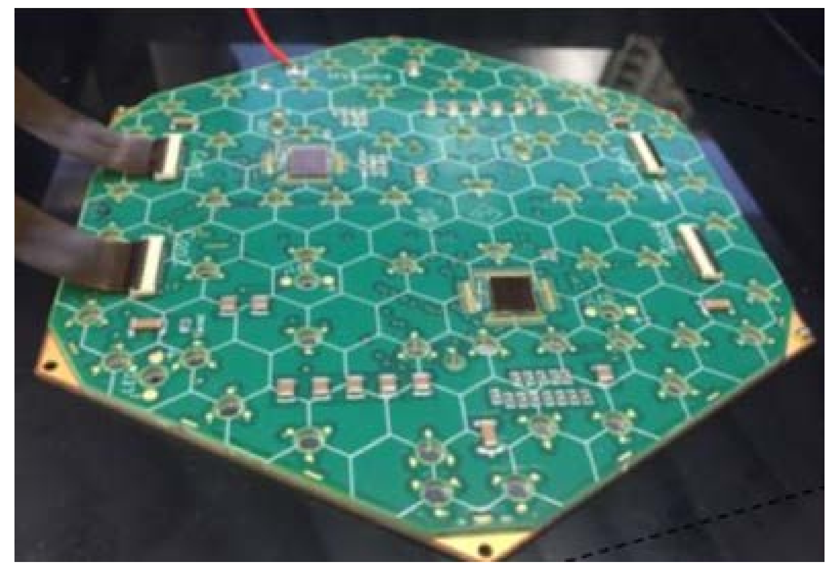


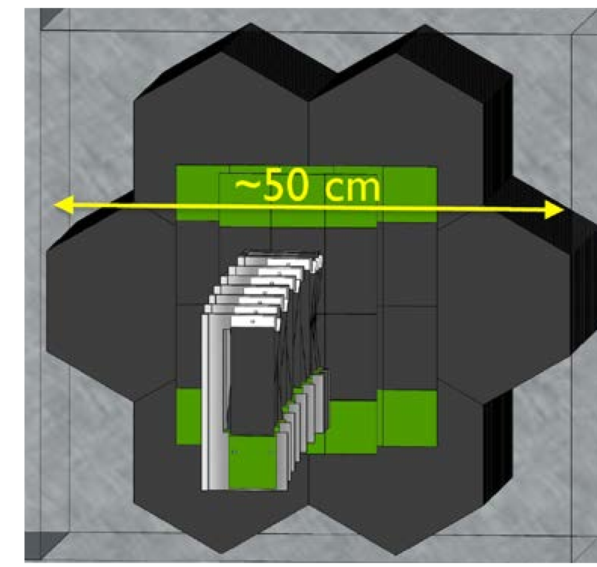
Electromagnetic Calorimeter (Ecal)

- to achieve **large number of electrons** on target (10^{14}-10^{16}): **high-rate beam** (1e/few ns)

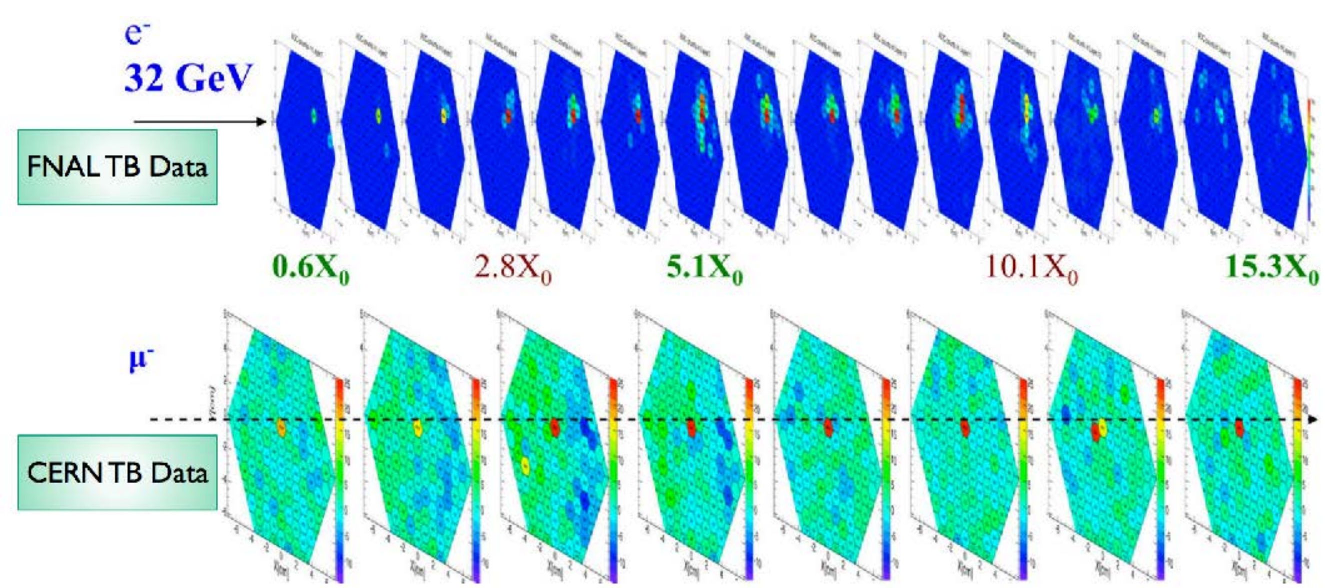
- ECal shopping list:
  - fast
  - radiation hard
  - dense
  - high-granularity
  - deep (containment)

very similar to forward SiW sampling calorimeter for CMS@HL-LHC → design based on this





- in LDMX:
  - 40 radiation lengths deep
  - 30 layers, 7 modules each
  - central modules with higher granularity (up to 1000 channels)
    - challenging for readout h/w
    - high granularity allows 'tracking' —> important tool in background reduction



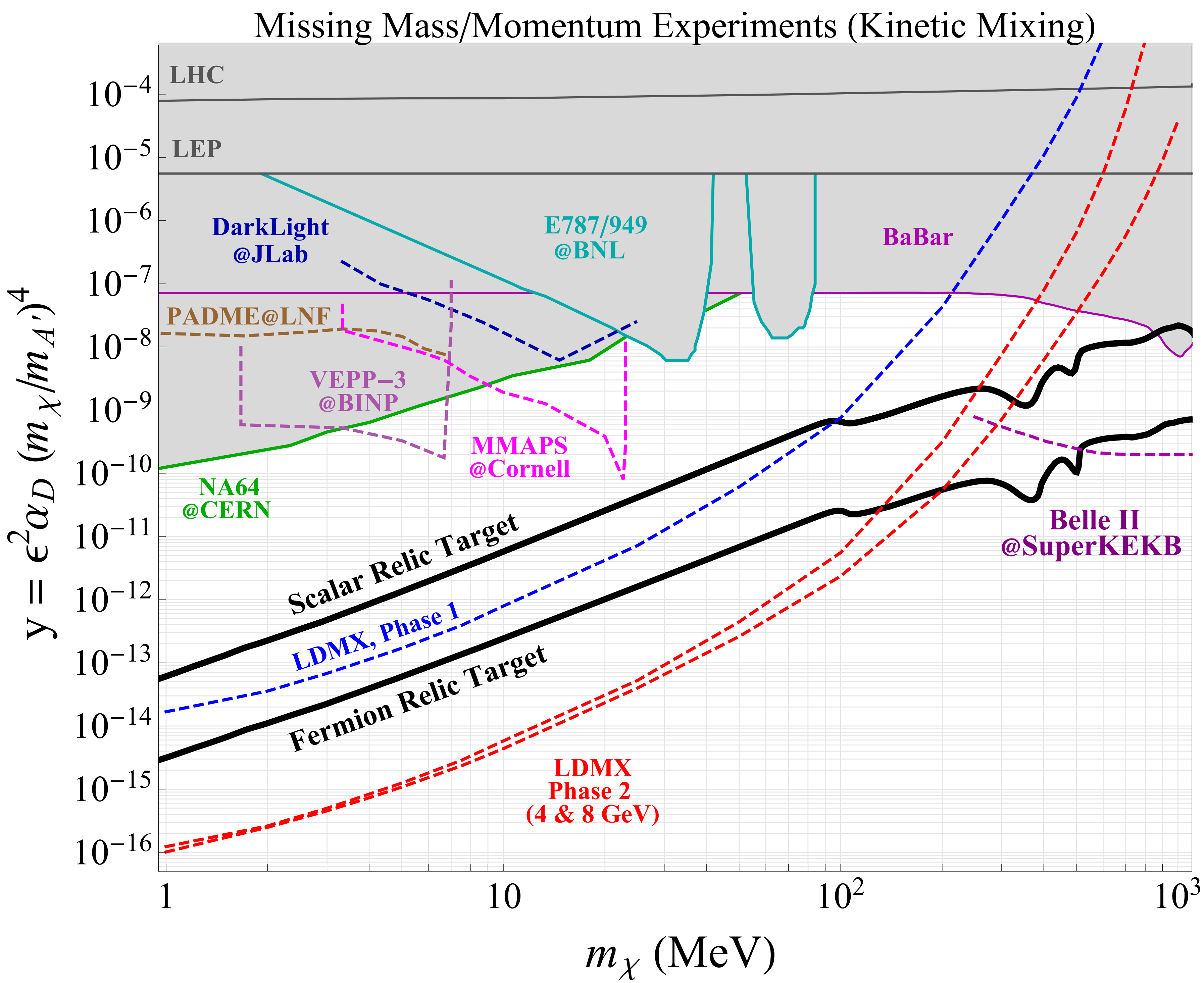
LDMX

- 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!**

Sensitivity

- LDMX will have better reach than any other experiment



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Summary

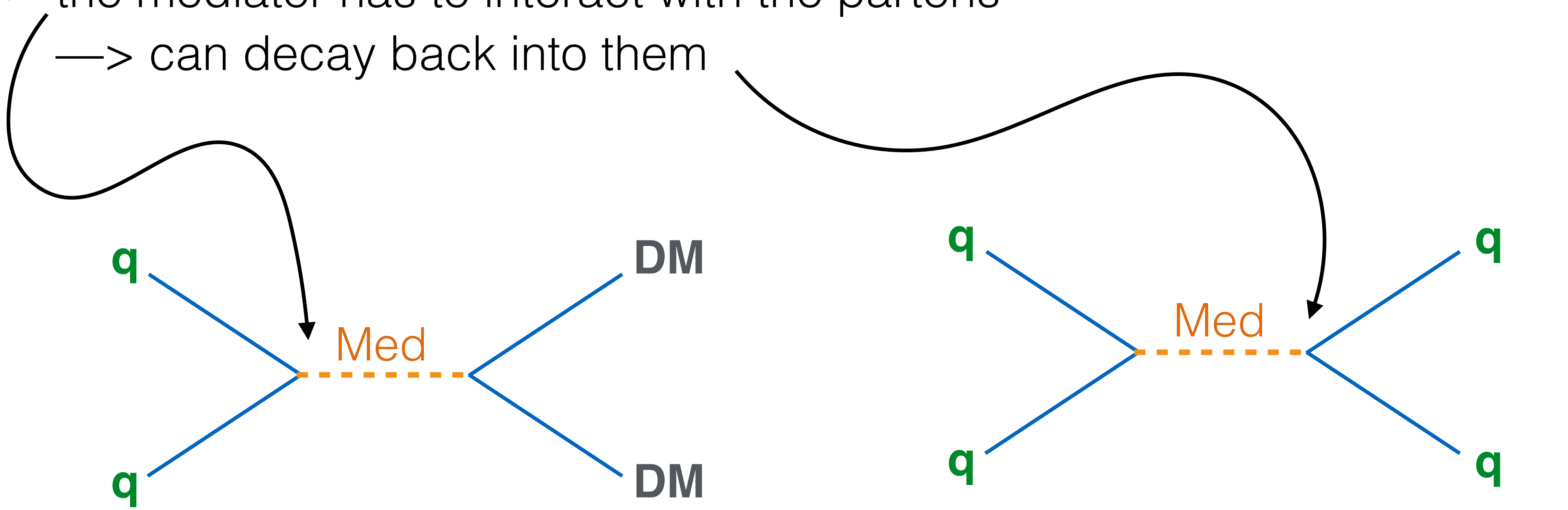
- Dark Matter one of the hottest topics in particle physics
  - **+** : we know it must be there
  - **-** : we haven't found anything where we thought it should be
- many different ways to look for Dark Matter, still lots to explore
- WIMPs still are the most popular candidates,
  but other options 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

Visible Signatures (Indirect)

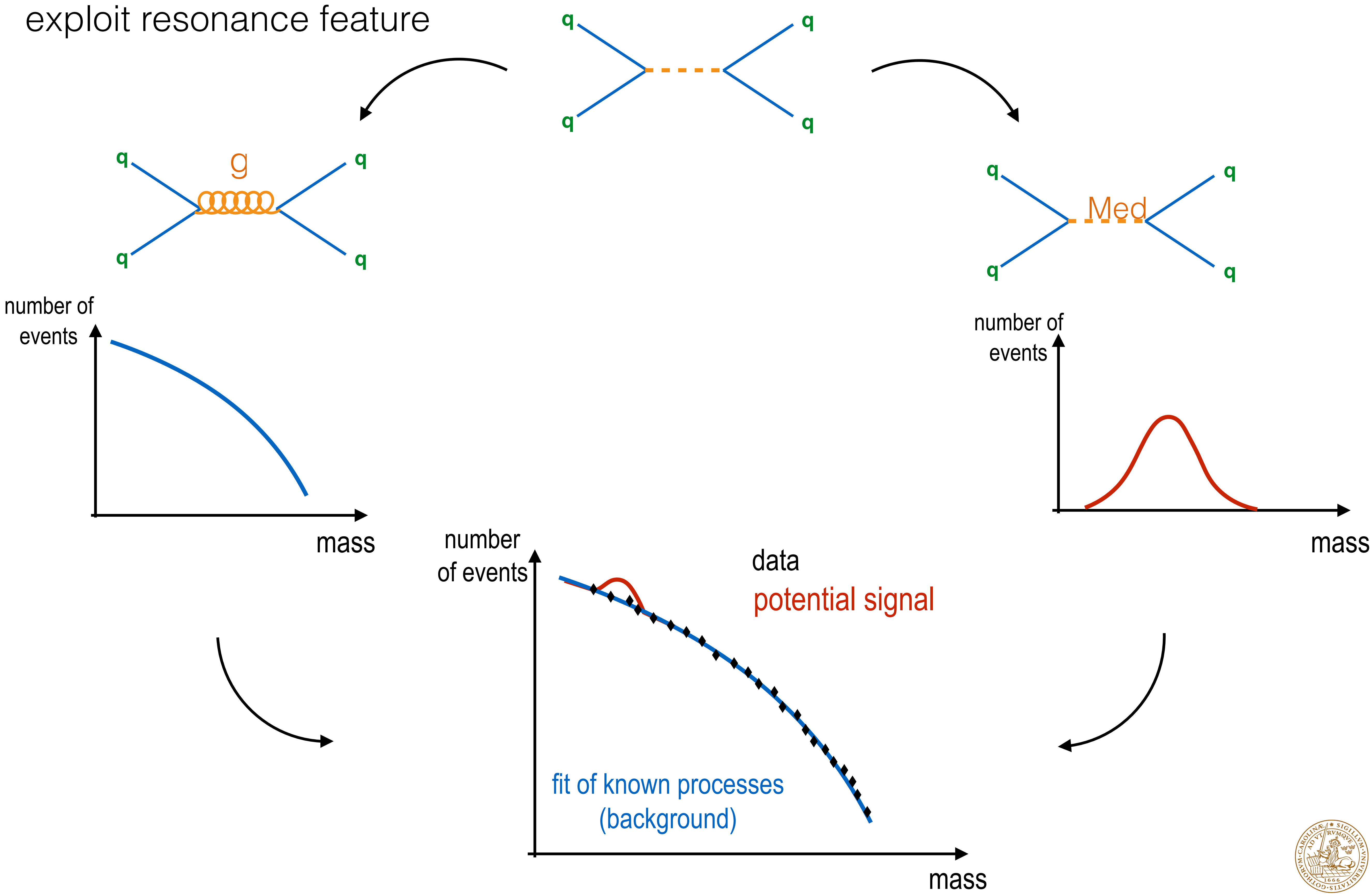
- another approach: look for the **mediator**!
  - Dark Matter has to interact in order to be produced
    —> there must be a mediator
  - the mediator has to interact with the partons
    —> can decay back into them



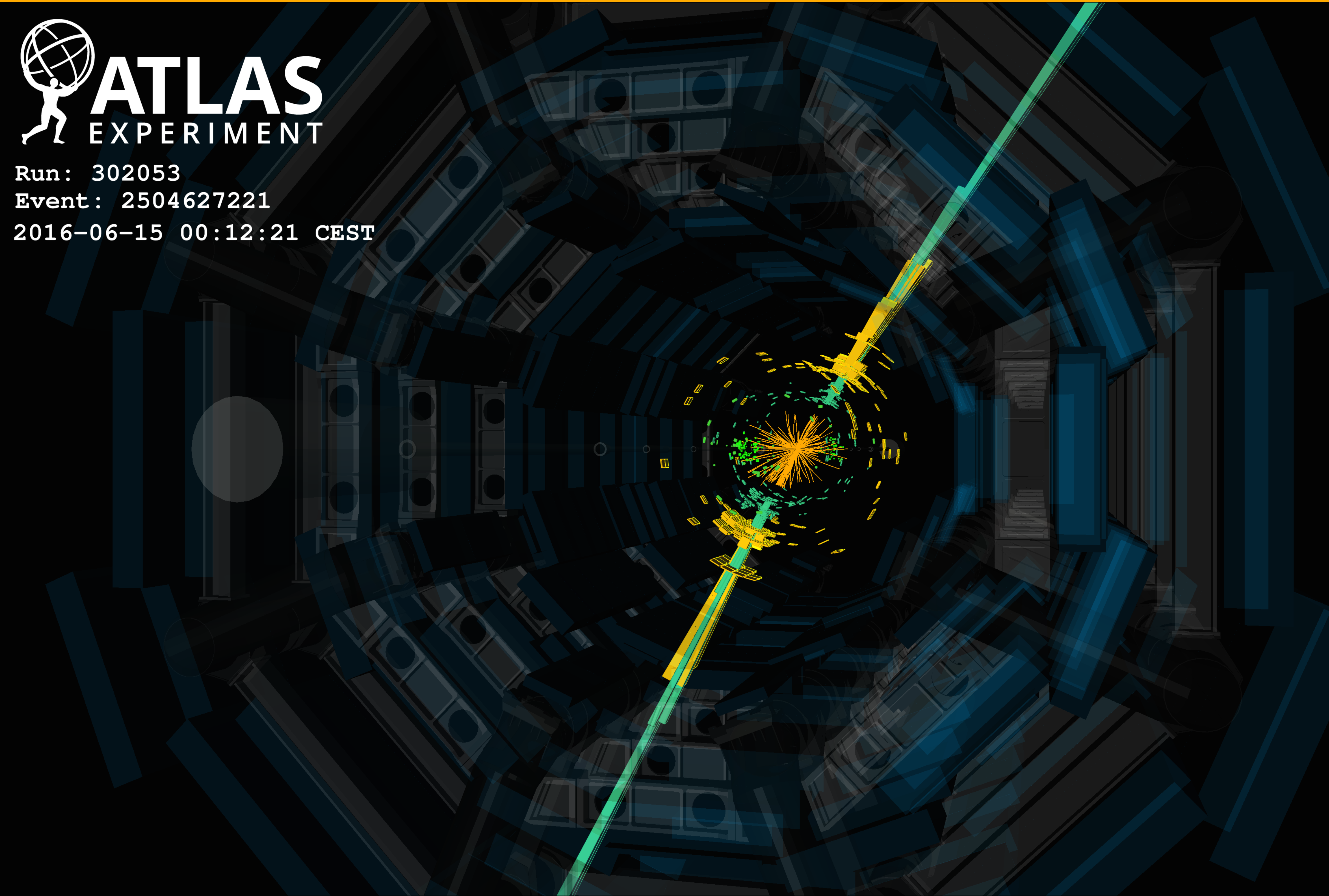
- not looking for a signature of the actual Dark Matter

Di-Jet Events

- exploit resonance feature

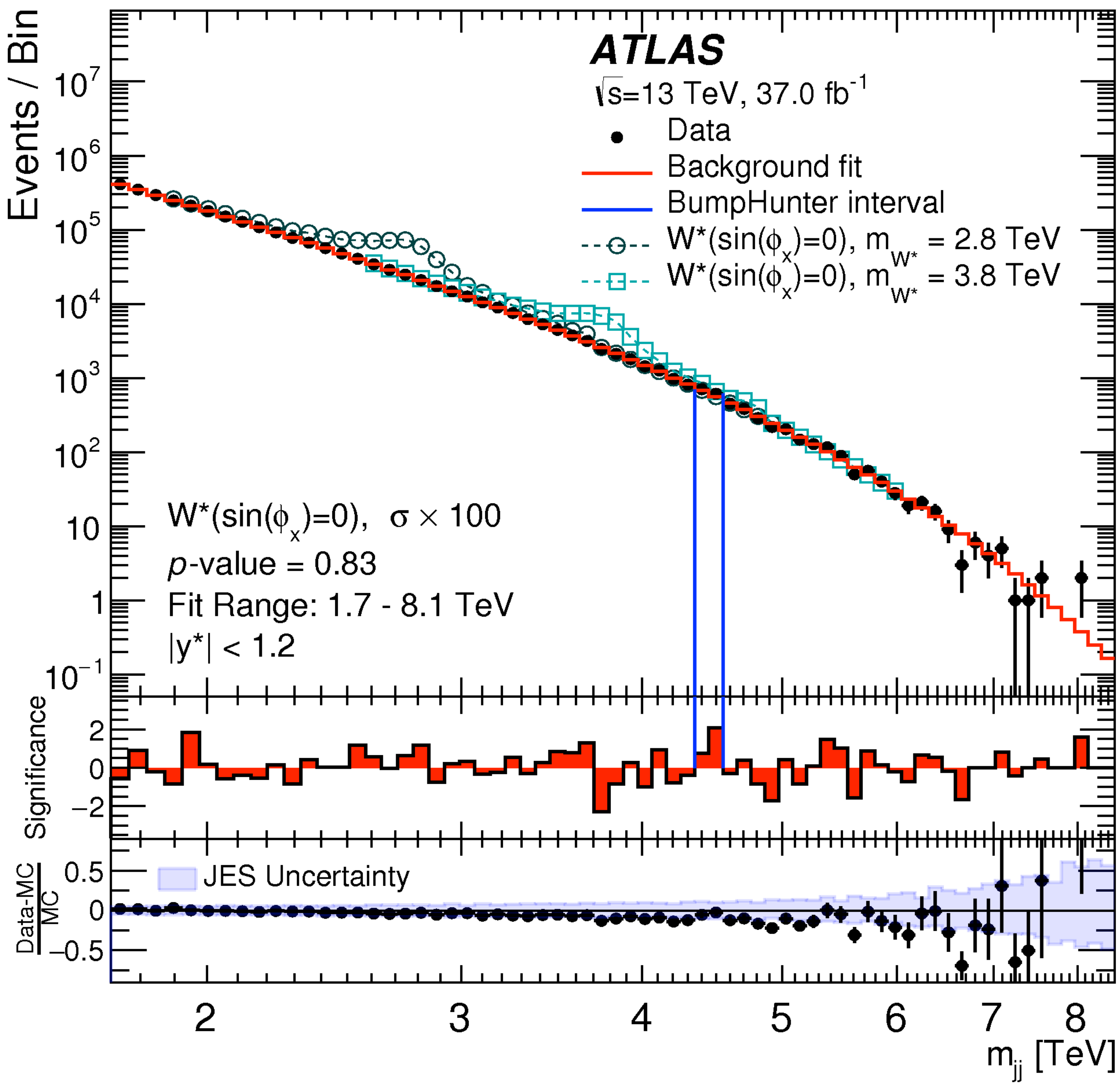


A beautiful di-jet event



Mediator Searches

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



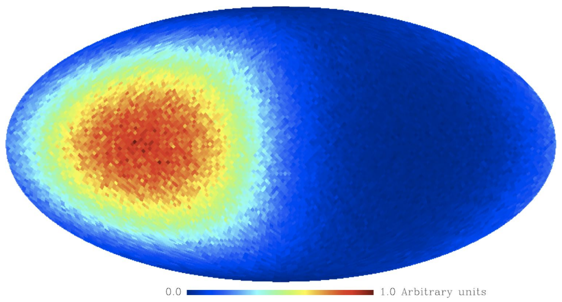
- no clear signal seen so far (but we keep looking! much more data still to be analysed!)

Directional Direct Detection

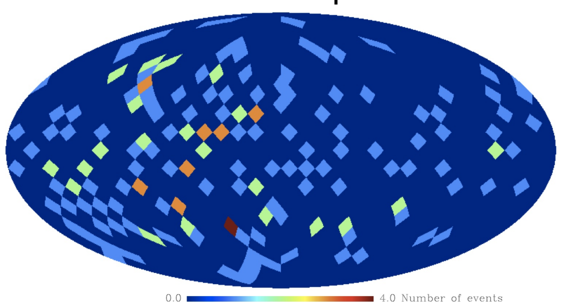
- direct detection uses only **energy** of recoiling nucleus
- using **recoil direction** in addition: powerful **background removal tool**

background

signal



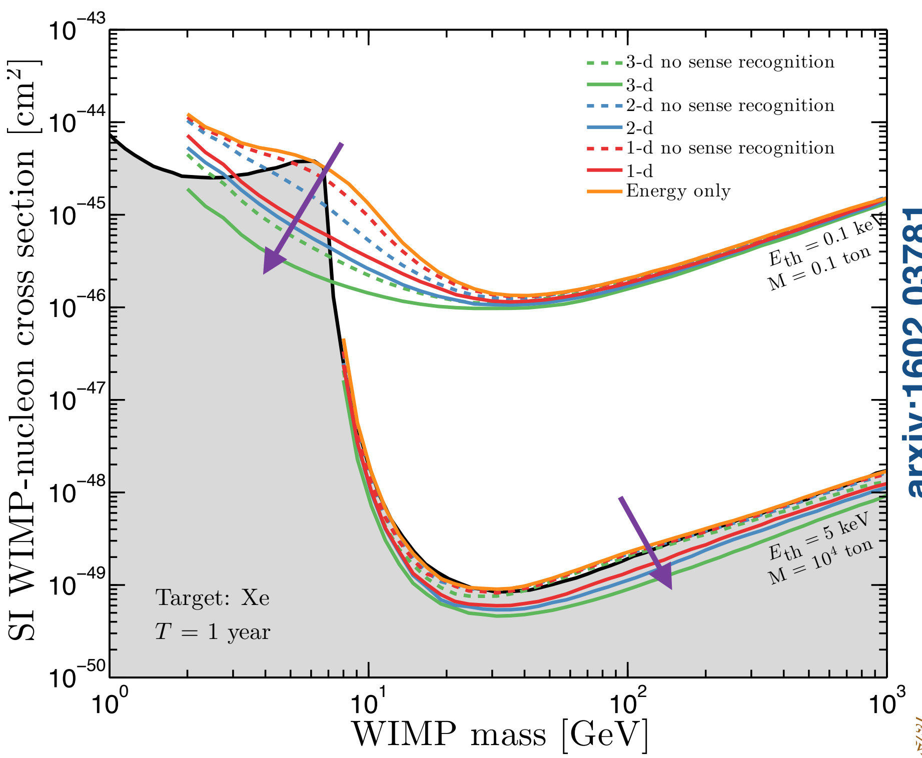
detector response



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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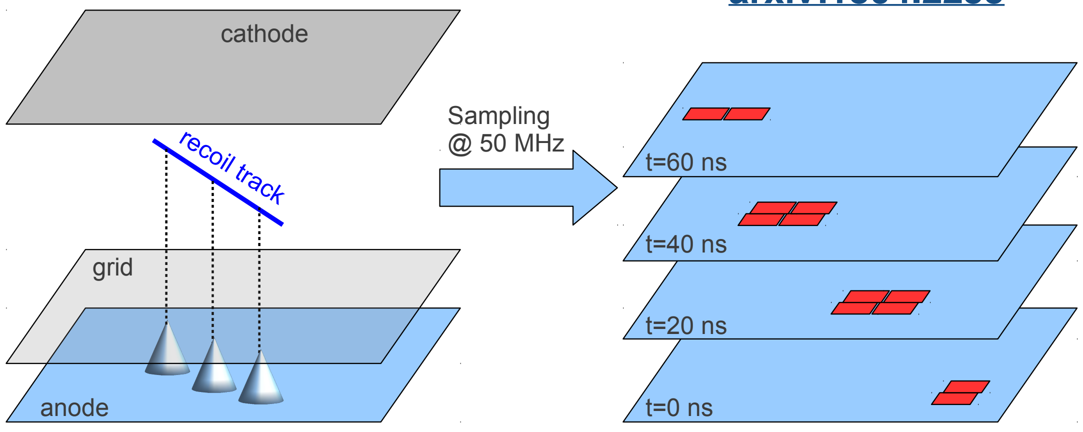
Directional Direct Detection

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

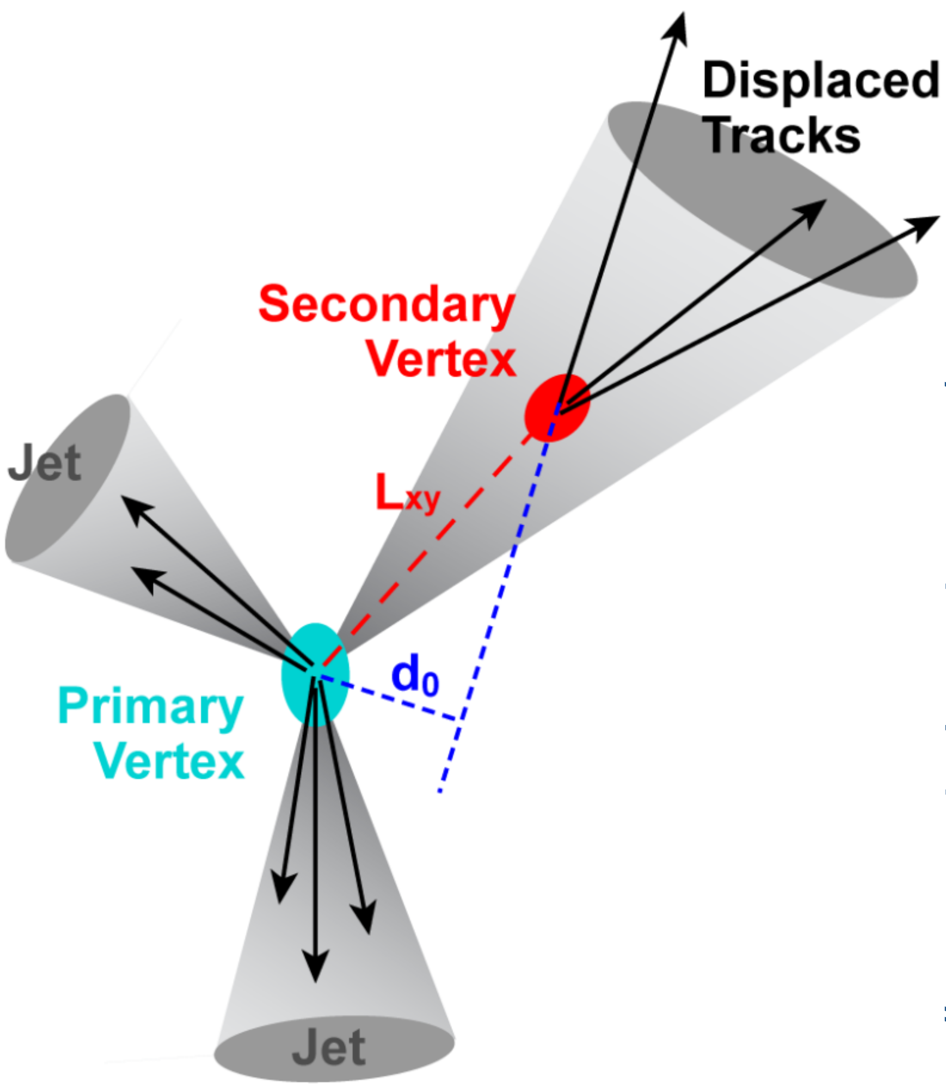
arxiv:1304.2255



- **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/