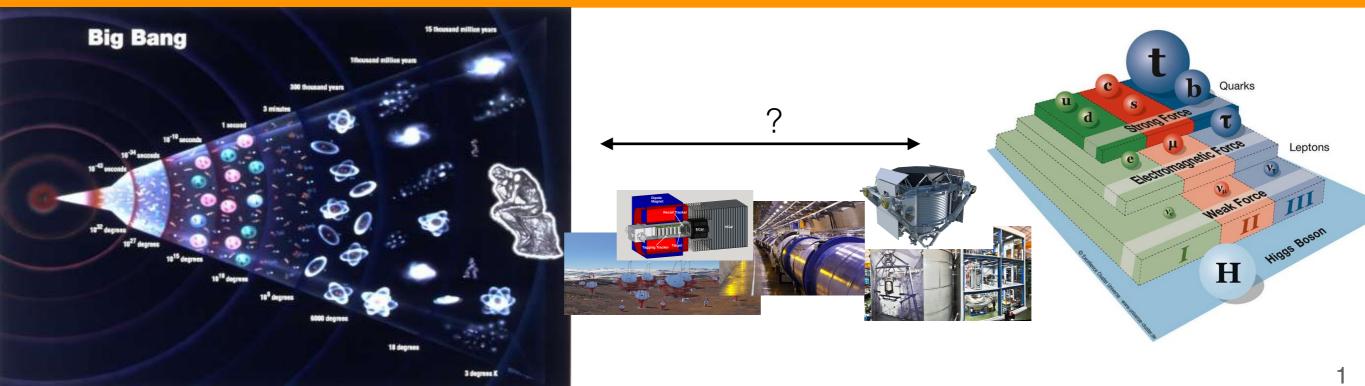
# Dark Matter (from a particle physicists point of view)

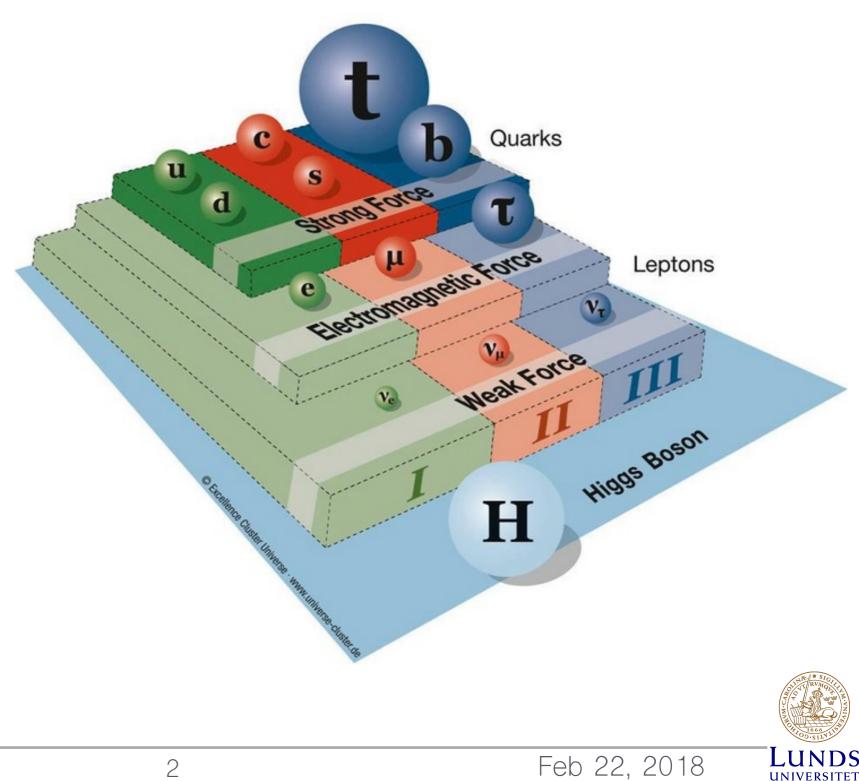
## VT 2018

## Ruth Pöttgen 22 February 2018



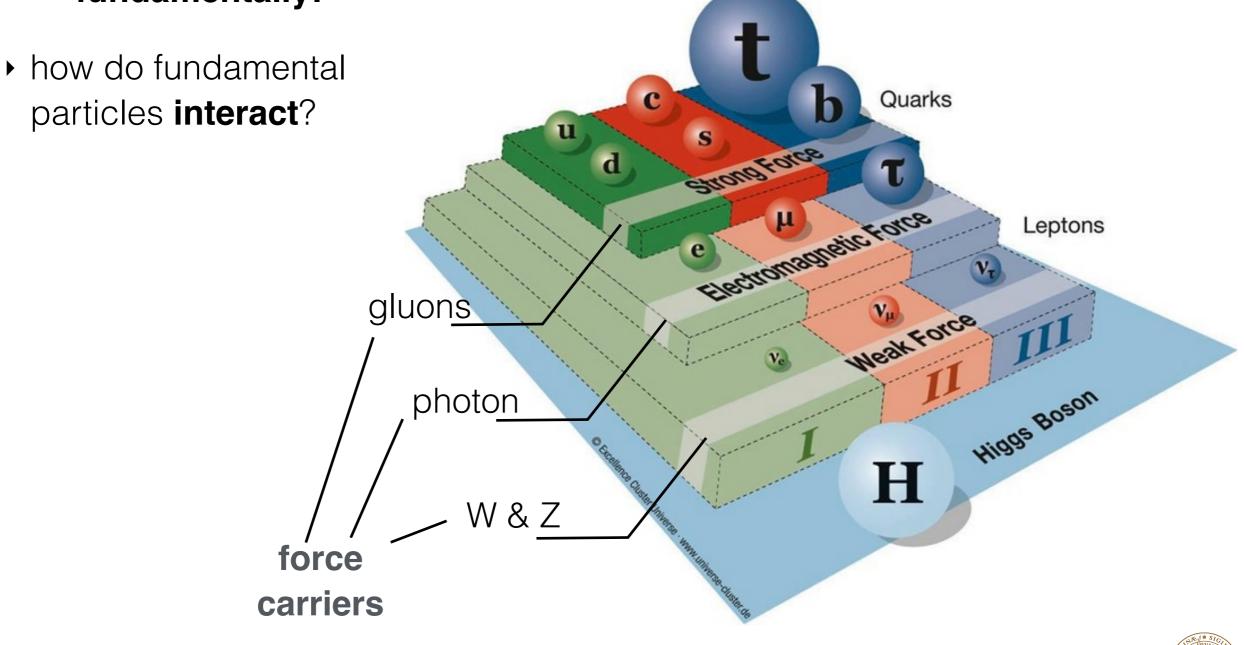
# What is particle physics?

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



# What is particle physics?

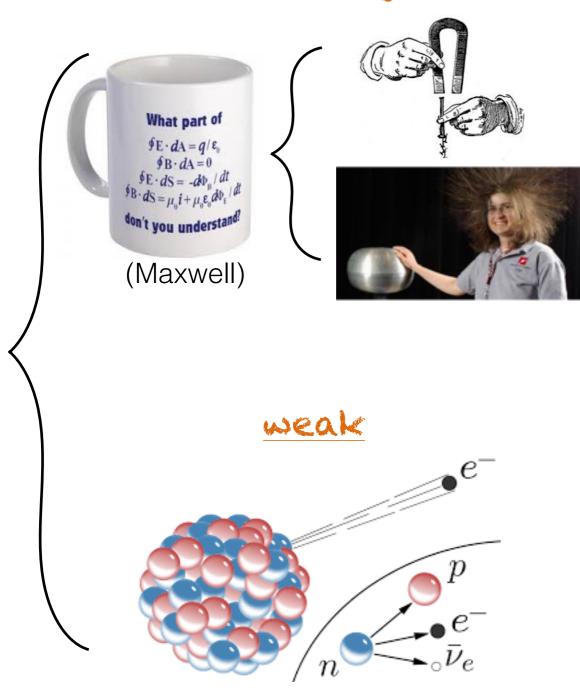
- two main questions:
  - what are things (matter) made of?
    - fundamentally!



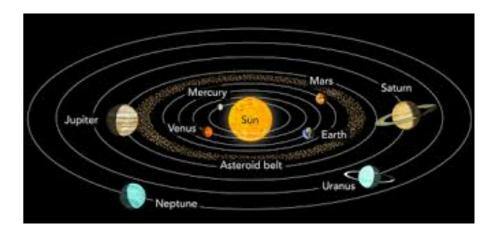


## FFF: Four Fundamental Forces

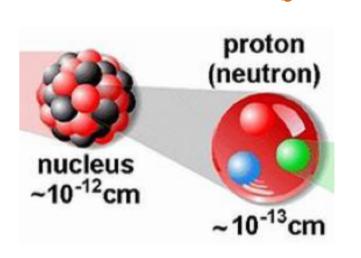
## electromagnetic

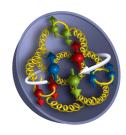






strong





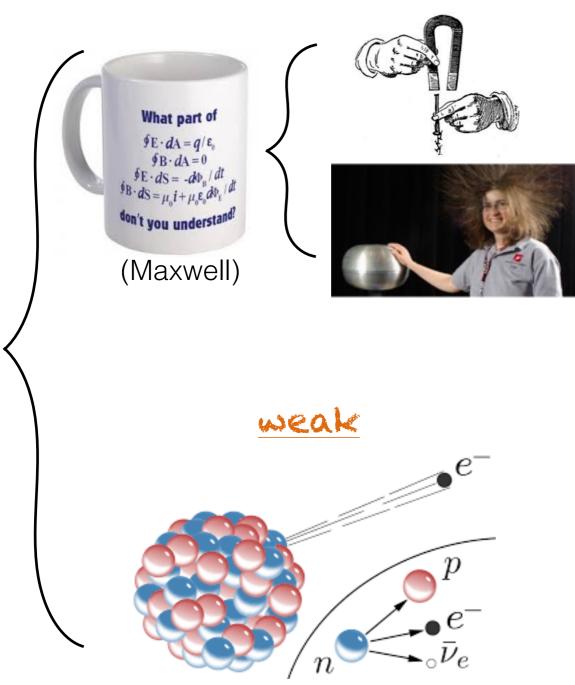


**UNIVERSITE**<sub>1</sub>

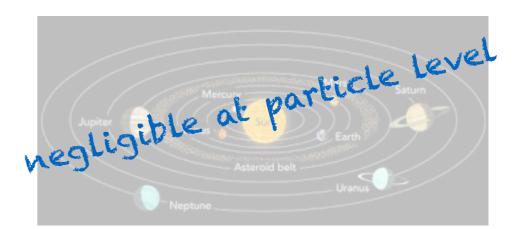
electro-weak

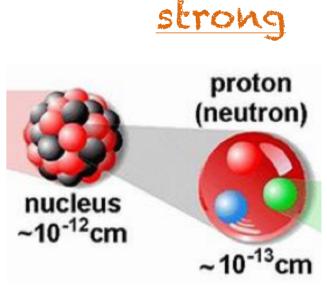
# FFF: Four Fundamental Forces

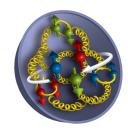










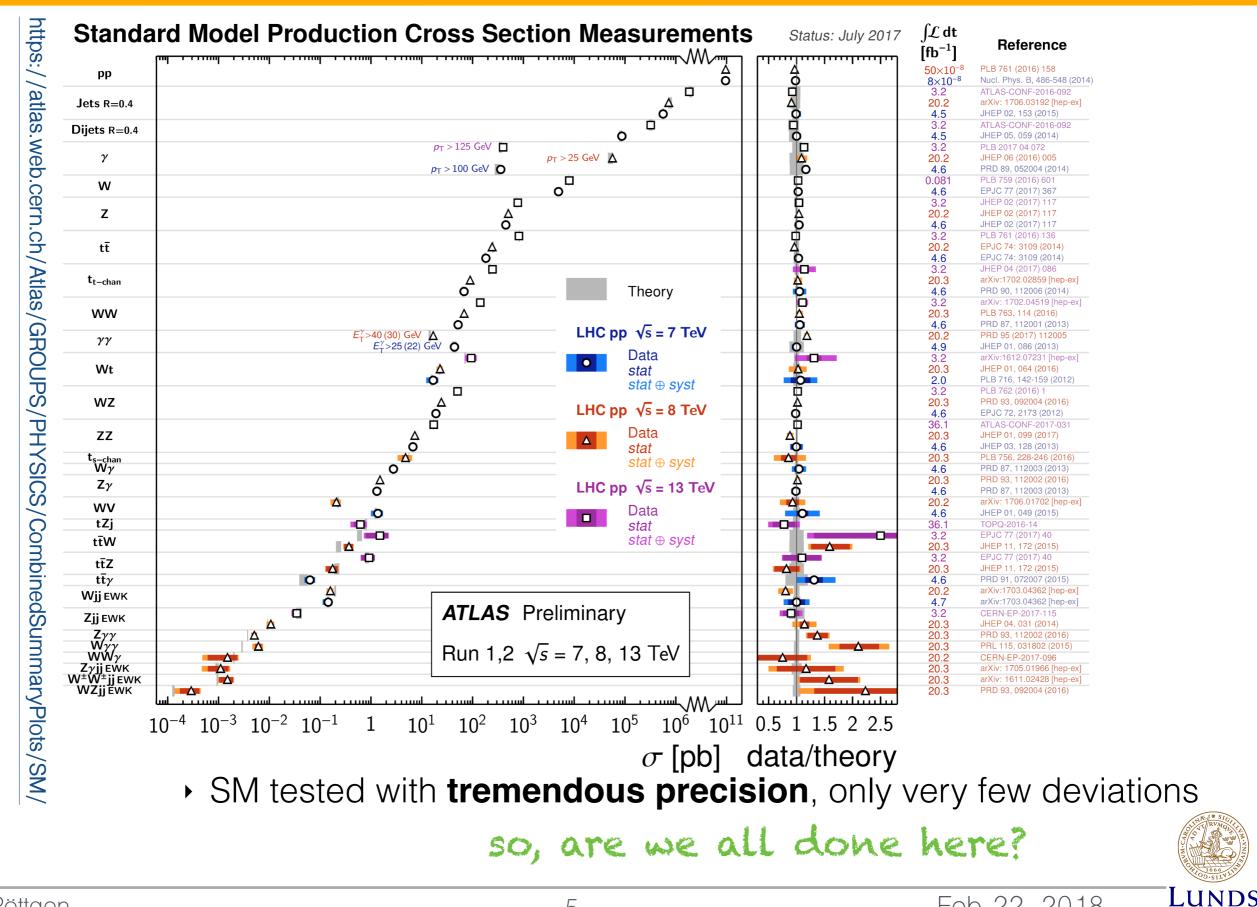




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electro-weak

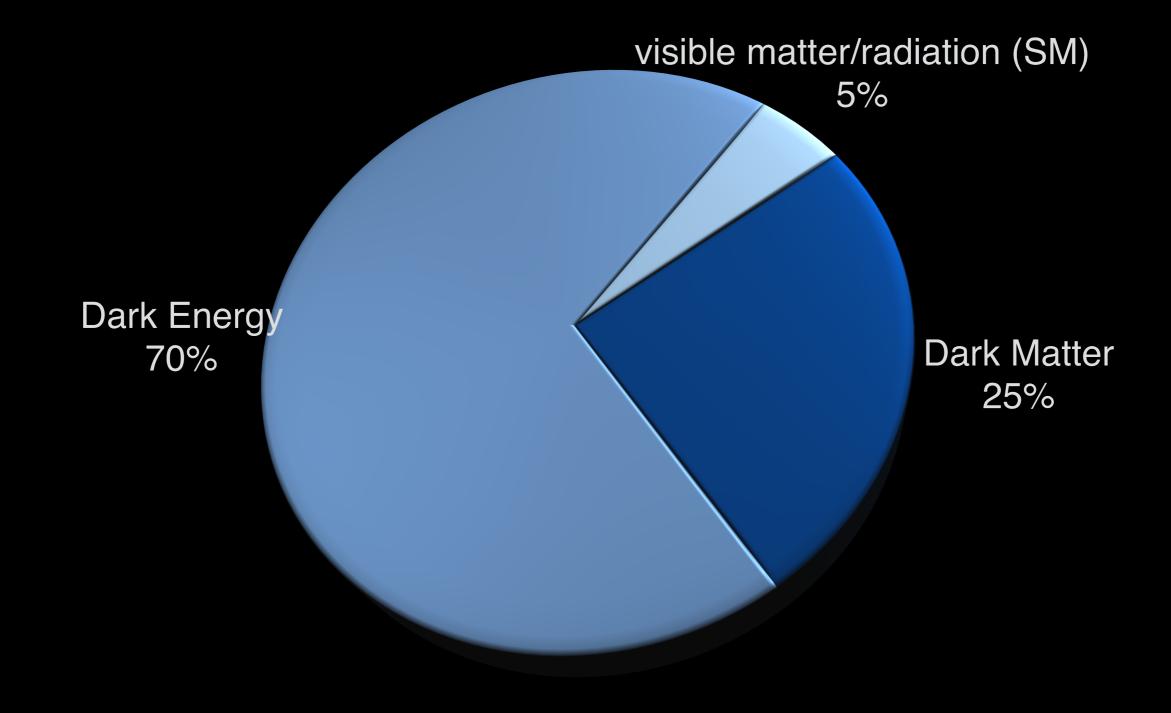
# Standard Model Measurements



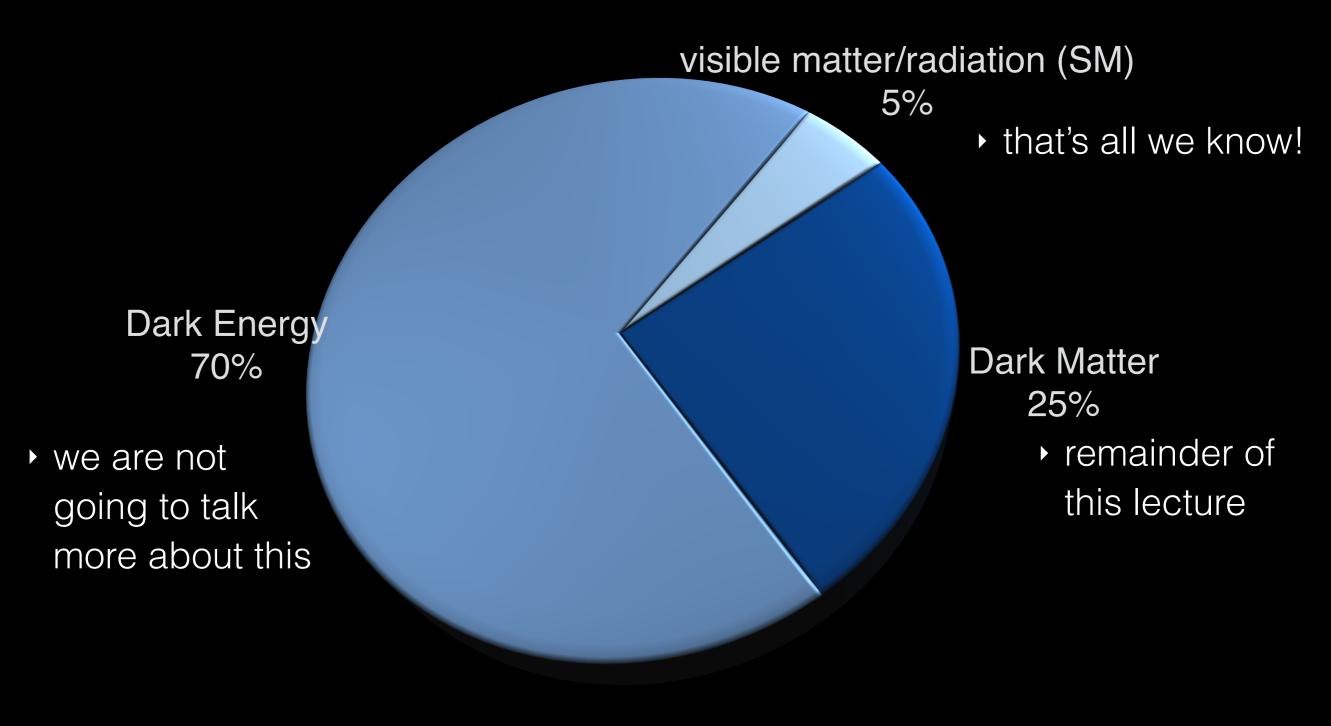


the Universe

the Universe



the Universe



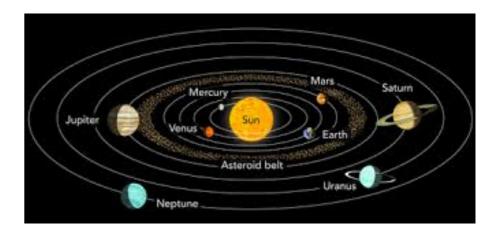
## How do we know Dark Matter is there?

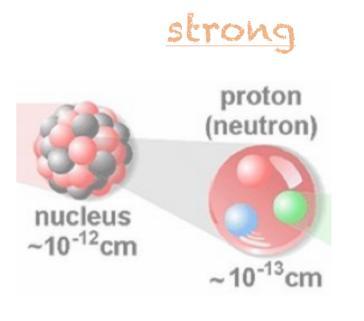
# FFF: Four Fundamental Forces

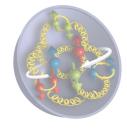
## electromagnetic













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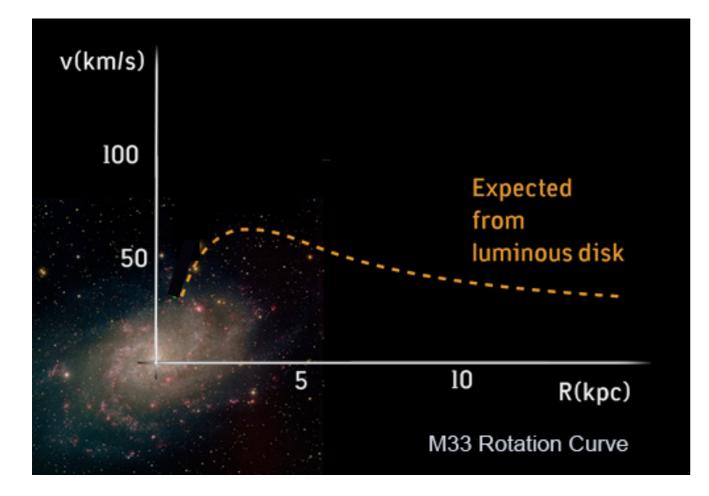
electro-weak

## A bit of Newton

stars in a galaxy orbit the galactic centre from Newton:

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

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





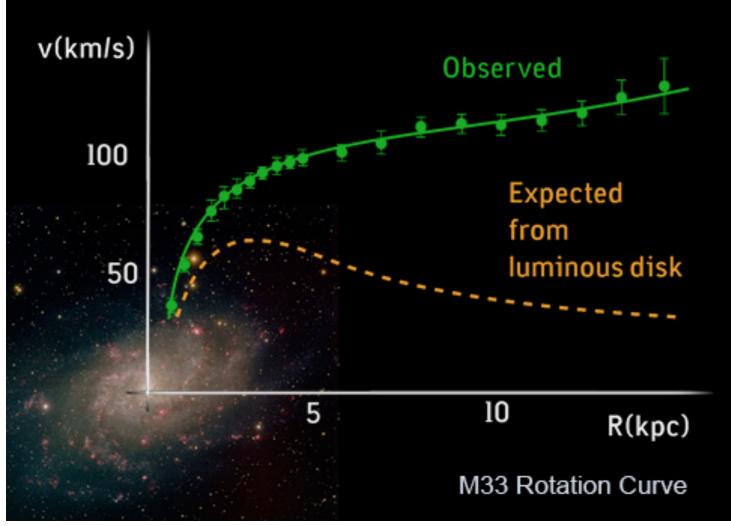
http://www.spitzer.caltech.edu/images/1074ssc2003-06d1-Infrared-Spiral-Galaxy-Messier-81



## **Rotation Curves**

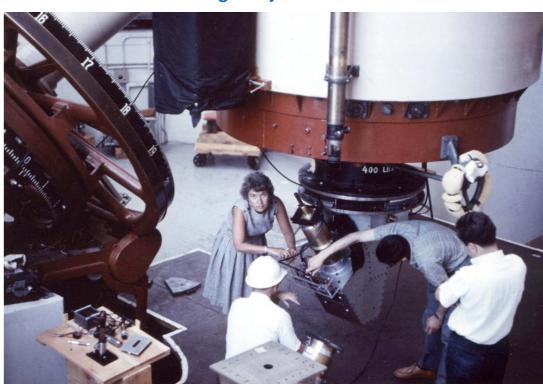
## level of single galaxies

### what's actually observed:



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

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



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

### "more mass than light"

Lunds

# Velocity Distribution in Galaxy Cluster

## level of cluster of galaxies

one of the first to coin the term "Dark Matter": Fritz Zwicky in 1933



<u>https://</u> writescience.wordpress. com/tag/fritz-zwicky/

measured velocity distribution of galaxies in Coma cluster

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

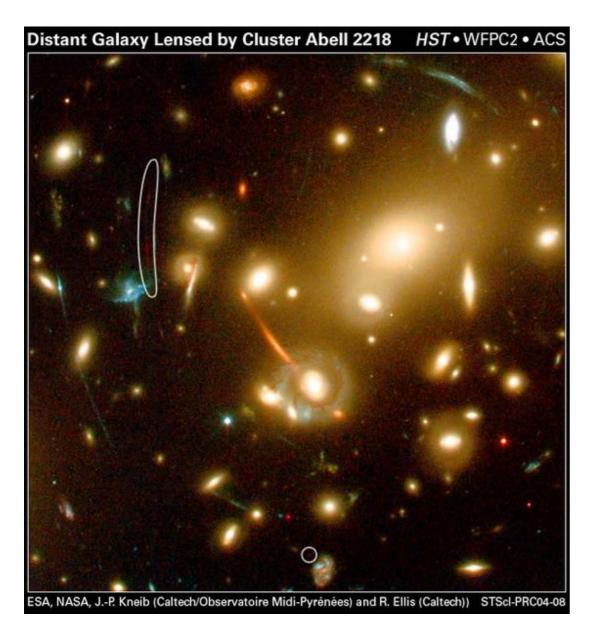
## => dark matter

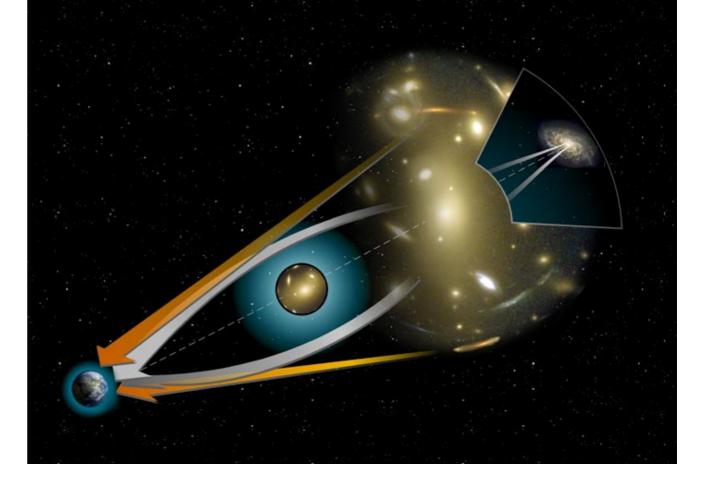


# Gravitational Lensing

### 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

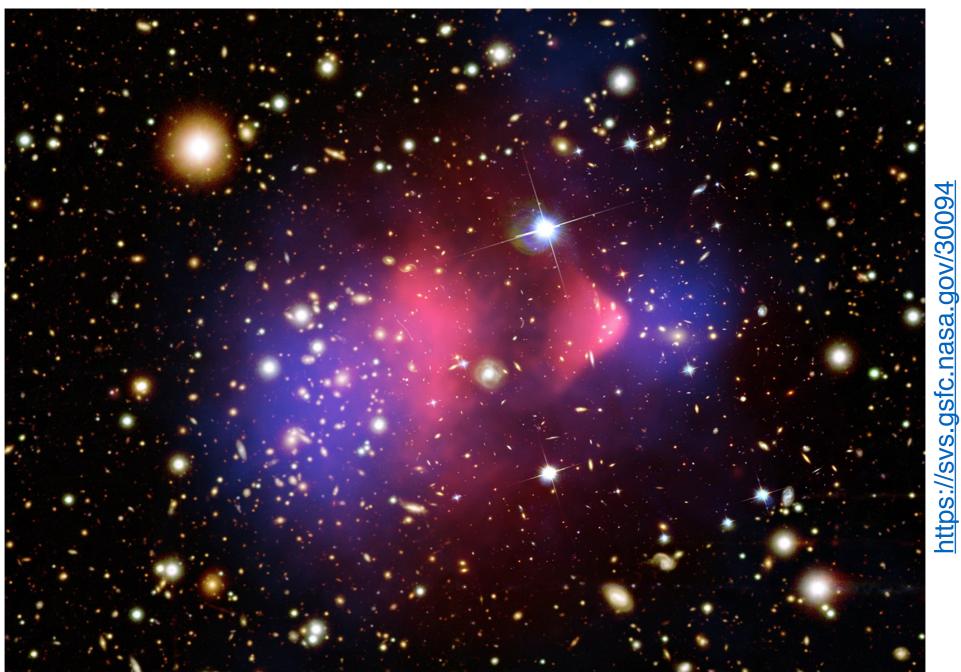


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# Bullet Cluster

remnant of collision of two galaxy clusters

animation



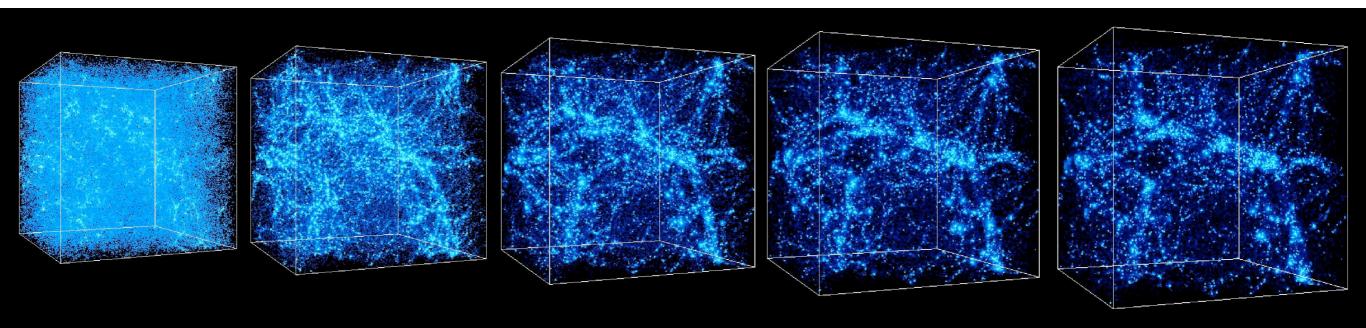
## centre of gravity ≠ centre of visible mass



## Structure Formation

## 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"

- 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



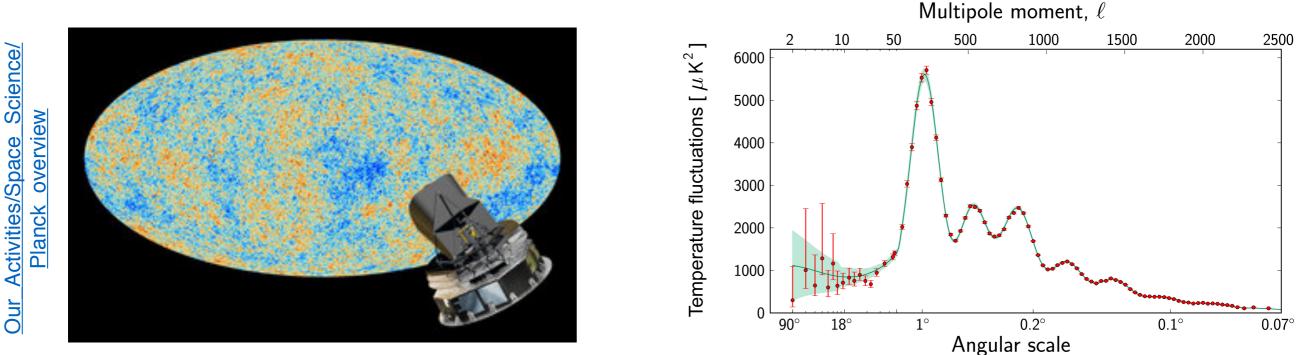
## How do we know how much DM there is?

level of the entire Universe

ESA **PLANCK** mission

# tiny temperature fluctuations (anisotropies) in CMB

a different way of looking at it



cosmological parameters can be estimated from best fit to observation

one of them is the amount of Dark Matter, called "relic density"



http://www.esa.int/

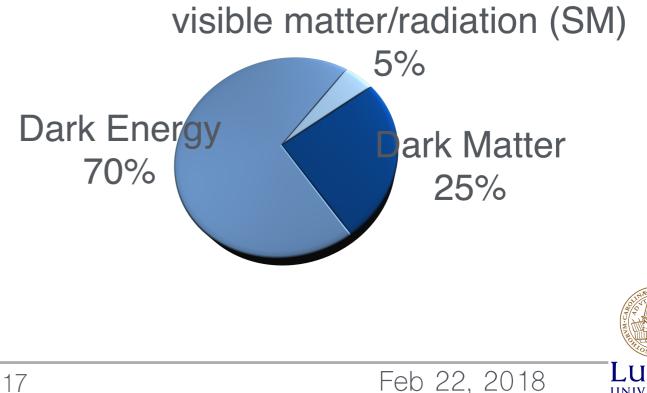
LUNDS

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!

- --> doesn't interact with photons
- --> electrically neutral



### dark!

- ---> doesn't interact with photons
- --> electrically neutral

has mass



### dark!

- ---> doesn't interact with photons
- --> electrically neutral

### has mass

stable (since it is still there)



### dark!

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

### has mass

stable (since it is still there)

non-baryonic (CMB)



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## must be **non-relativistic** (structure formation) —> can't be neutrinos (too light)



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## in fact, can't be any of the SM particles!

Feb 22, 2018

### dark!

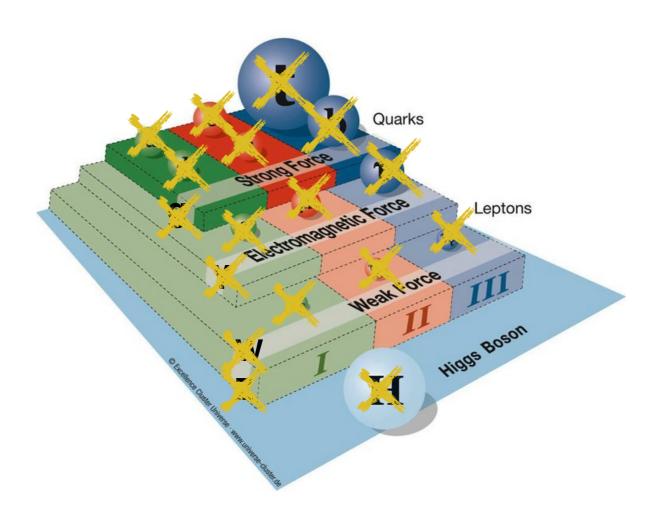
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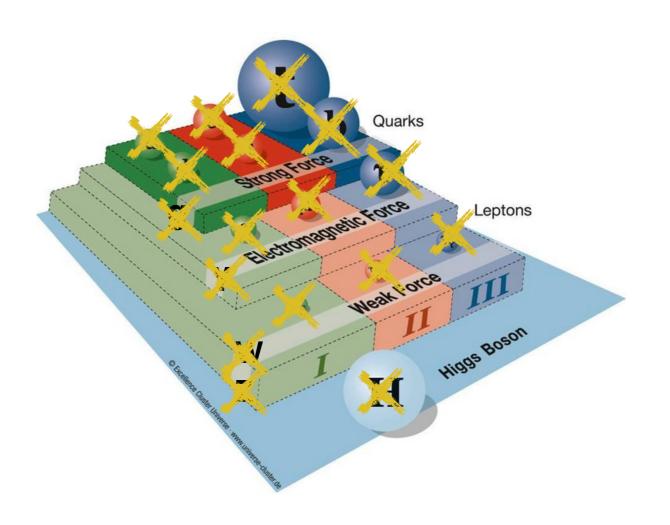
—> doesn't interact with photons
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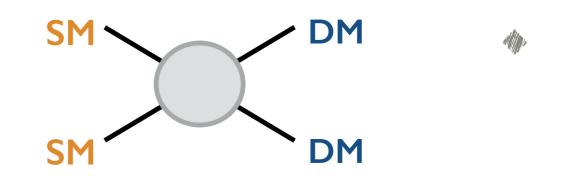
what can it be?

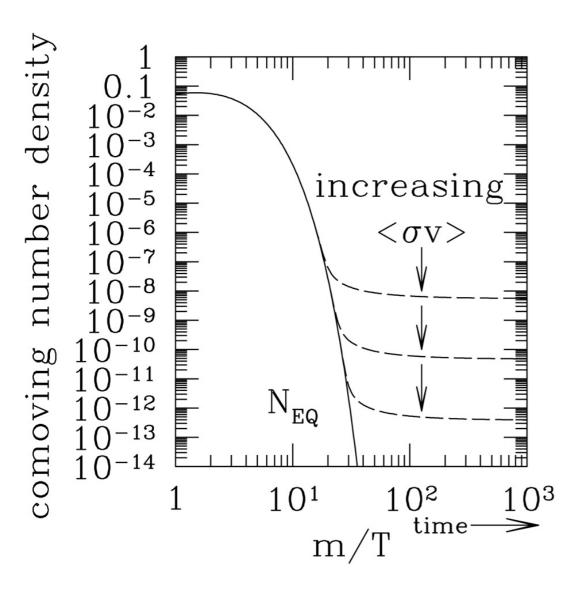


LUNDS

# Relic abundance

- Why Mono-jet?
- equilibrium in the early Universe
- creation and annihilation of DM particles at the same rate



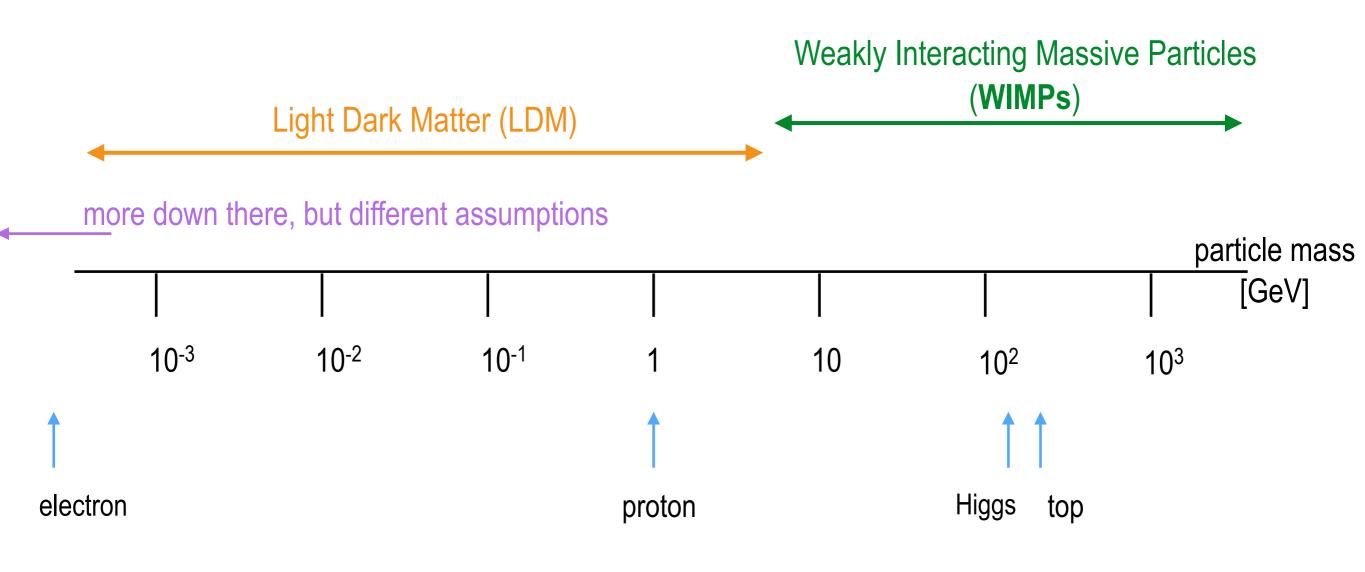


- Universe expanded & cooled
- interaction rate became "too low"
- amount of DM remained stable or "frozen"
   *freeze-out*
- the weaker the interaction, the more DM remained
  - "survival of the weak"
- relic abundance depends on interaction
   cross section and mass of particles



# 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)

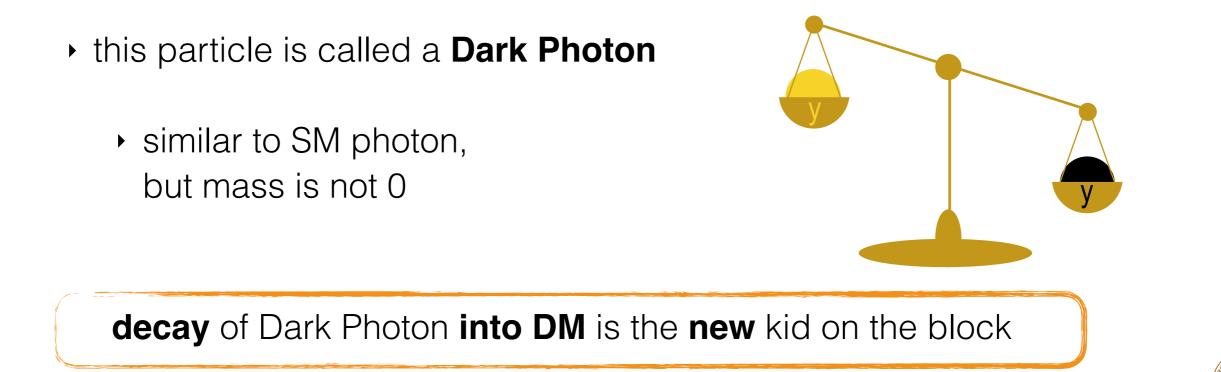
- WIMP miracle
  - without having to cook up some involved theory, these Dark Matter candidates just happen to be in a range that is...
    - ... pointed to by several extensions of the SM
    - ... experimentally well accessible

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





# Other Options

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

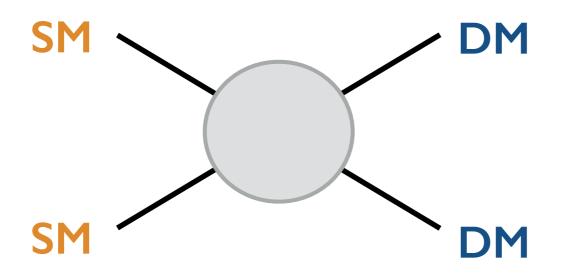
#### axions

- 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

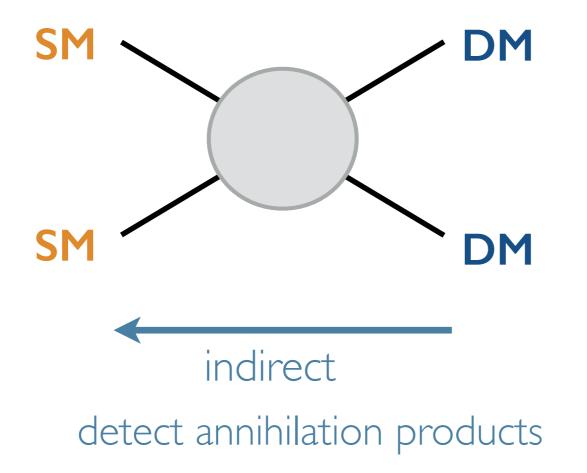
#### sterile neutrinos

- interacts even more feebly than usual ("active") neutrinos
- mixes with active neutrinos
- masses of order keV
- plenty of others...

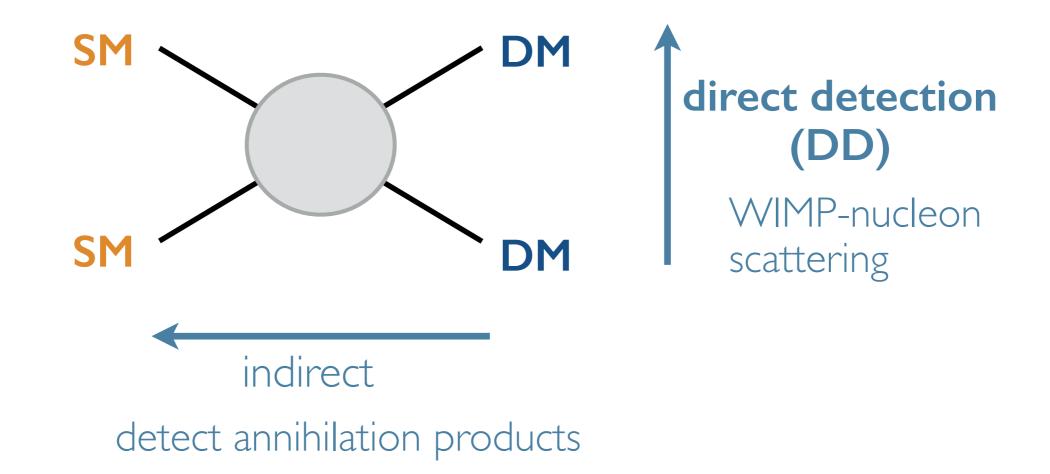






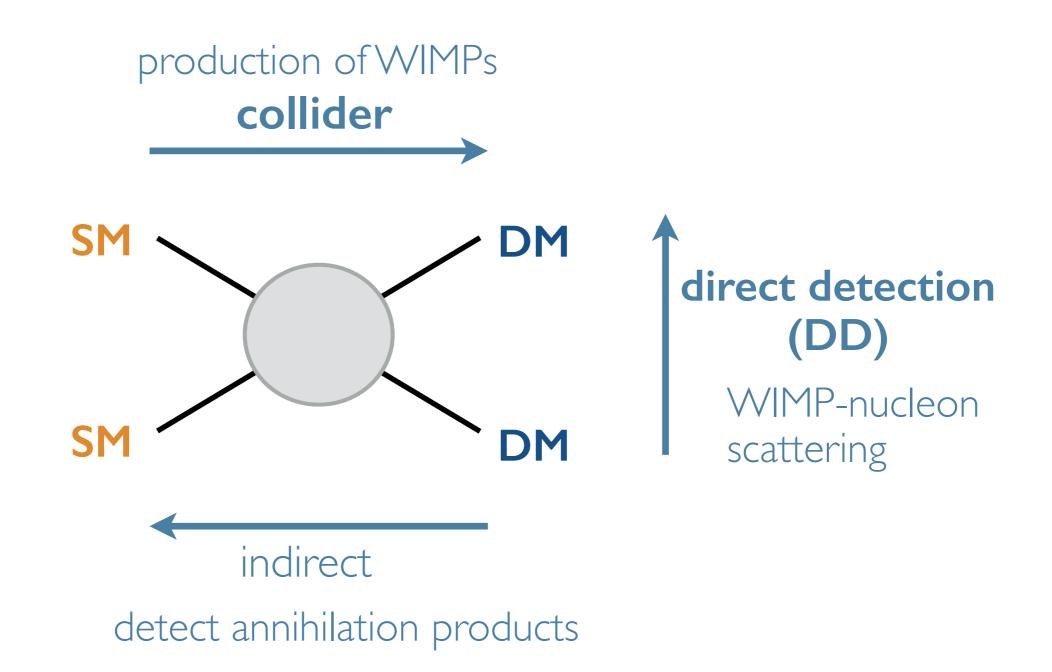




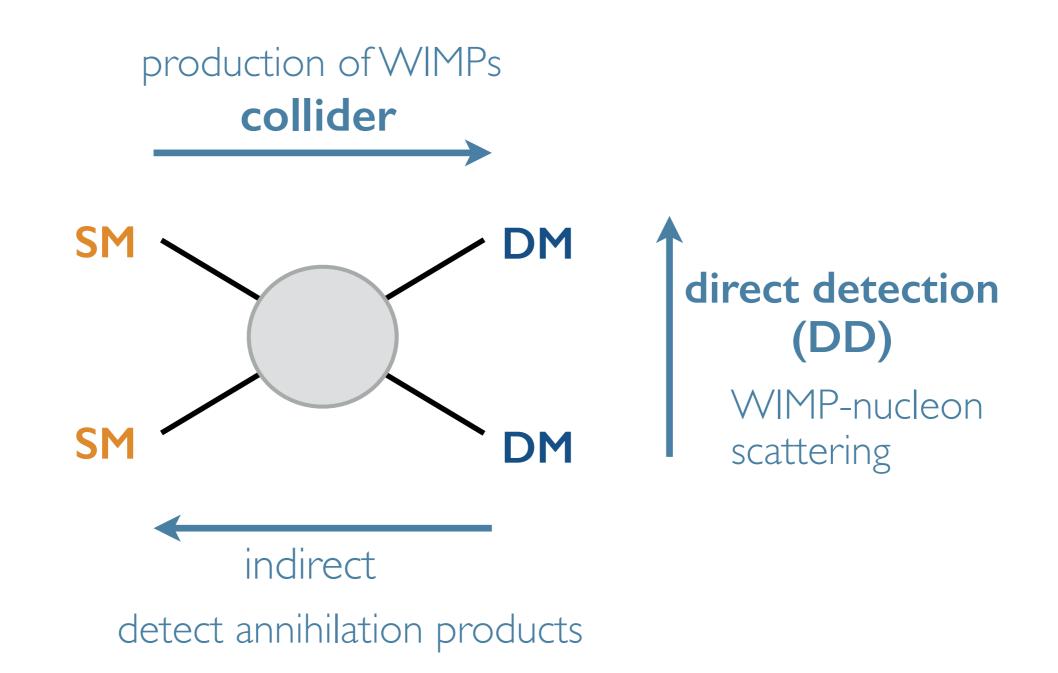




Feb 22, 2018





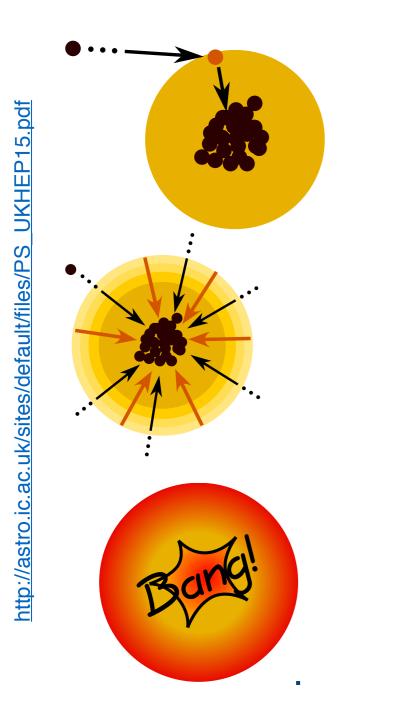


• each would merit their own lecture, of course



# Indirect Detection

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

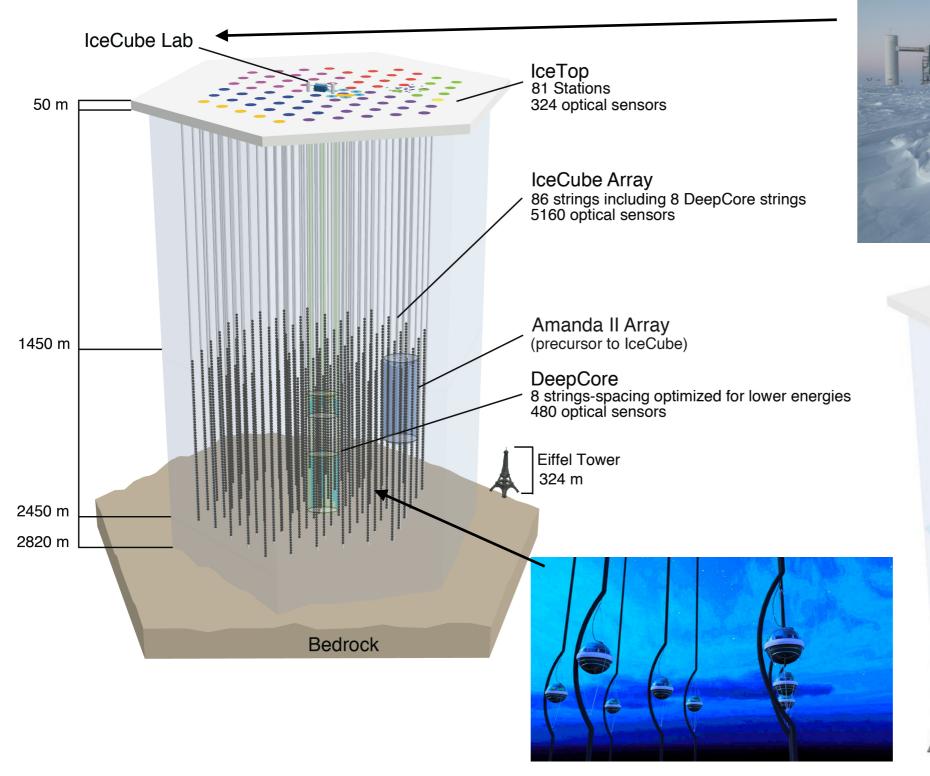


- what comes out can be photons, neutrinos, e+/e-, W+/W-, proton/anti-proton...
- various experiments looking for one or several of these
- usually needs some "extreme" location,
   e.g. South Pole, desert, space...

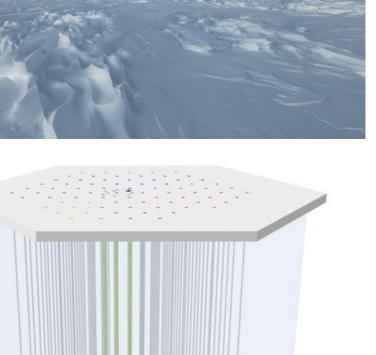


# Indirect Detection – Example: IceCube

#### neutrino detector at the South Pole



#### http://icecube.wisc.edu



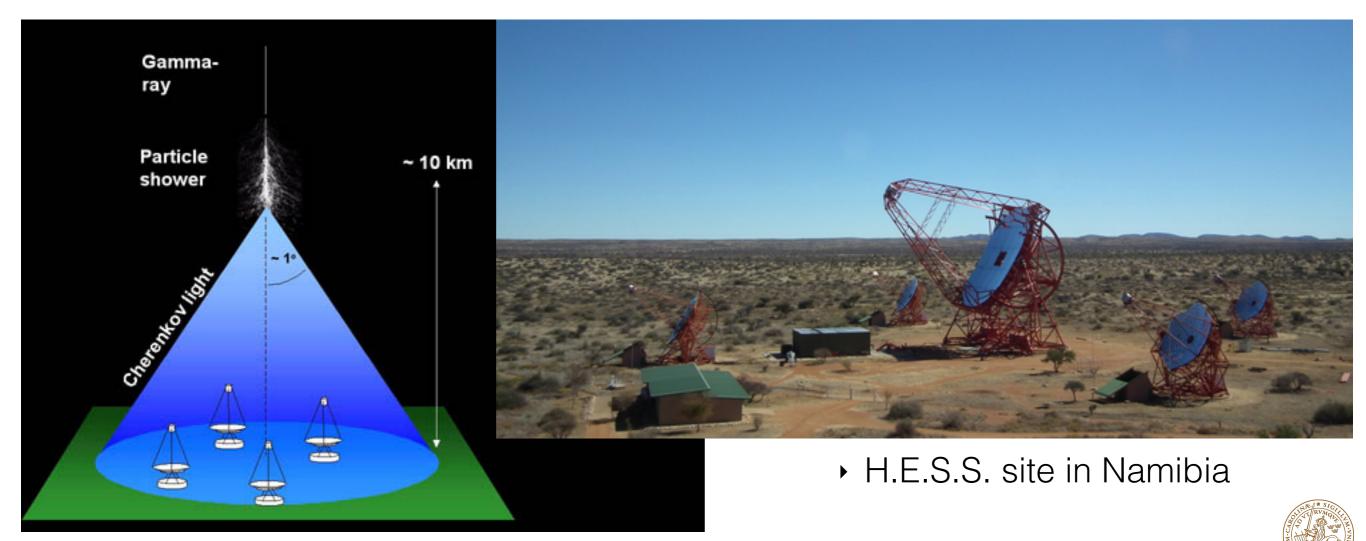


# Indirect Detection – Example: HESS/CTA

H.E.S.S. - High Energy Stereoscopic System

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

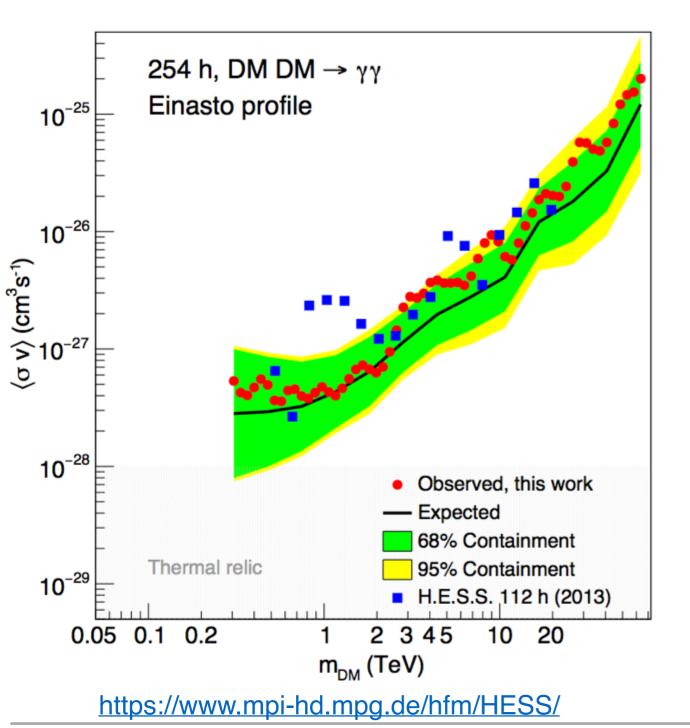
- astrophysics of very high energy gamma-rays (up to O(10TeV))
- ▶ look for line in the gamma ray spectrum (E=m<sub>DM</sub>) from the galactic centre
- Cherenkov light from secondary particles produced in atmosphere
- TeV photon —> ~100 photons /  $m^2$  on ground





## Indirect Detection – Example: HESS/CTA

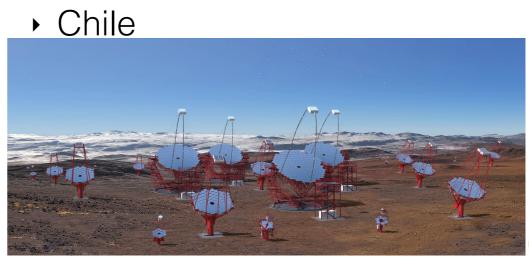
- latest result (Feb 2018, not even published yet)
  - no signal observed



#### https://www.cta-observatory.org

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





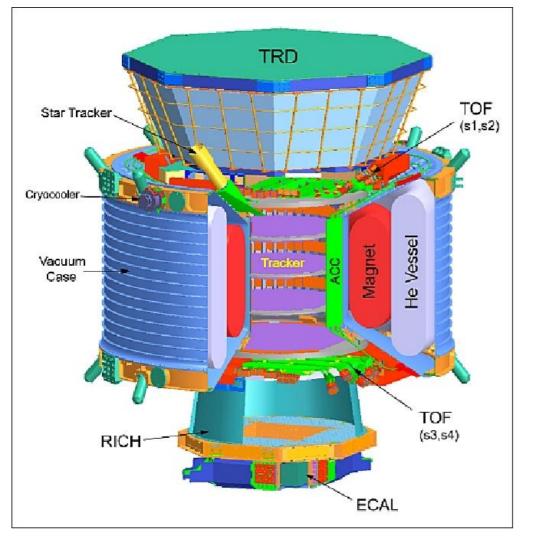


# Indirect Detection – Example: AMS

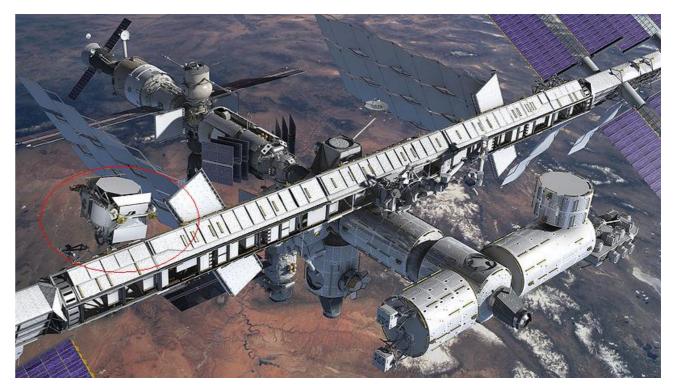
#### http://www.ams02.org

- 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/satellitemissions/content/-/article/iss-utilisation-ams

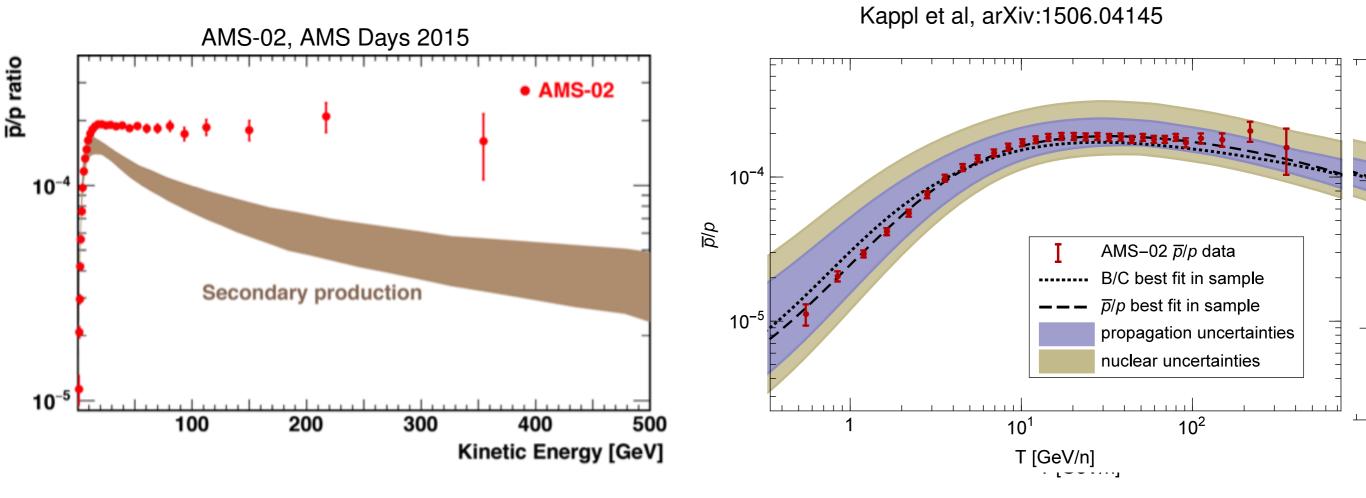


 studies the composition and flux of cosmic rays outside the Earth's atmosphere



# Indirect Detection – Interpretation

- example from AMS
- interpretation can be difficult

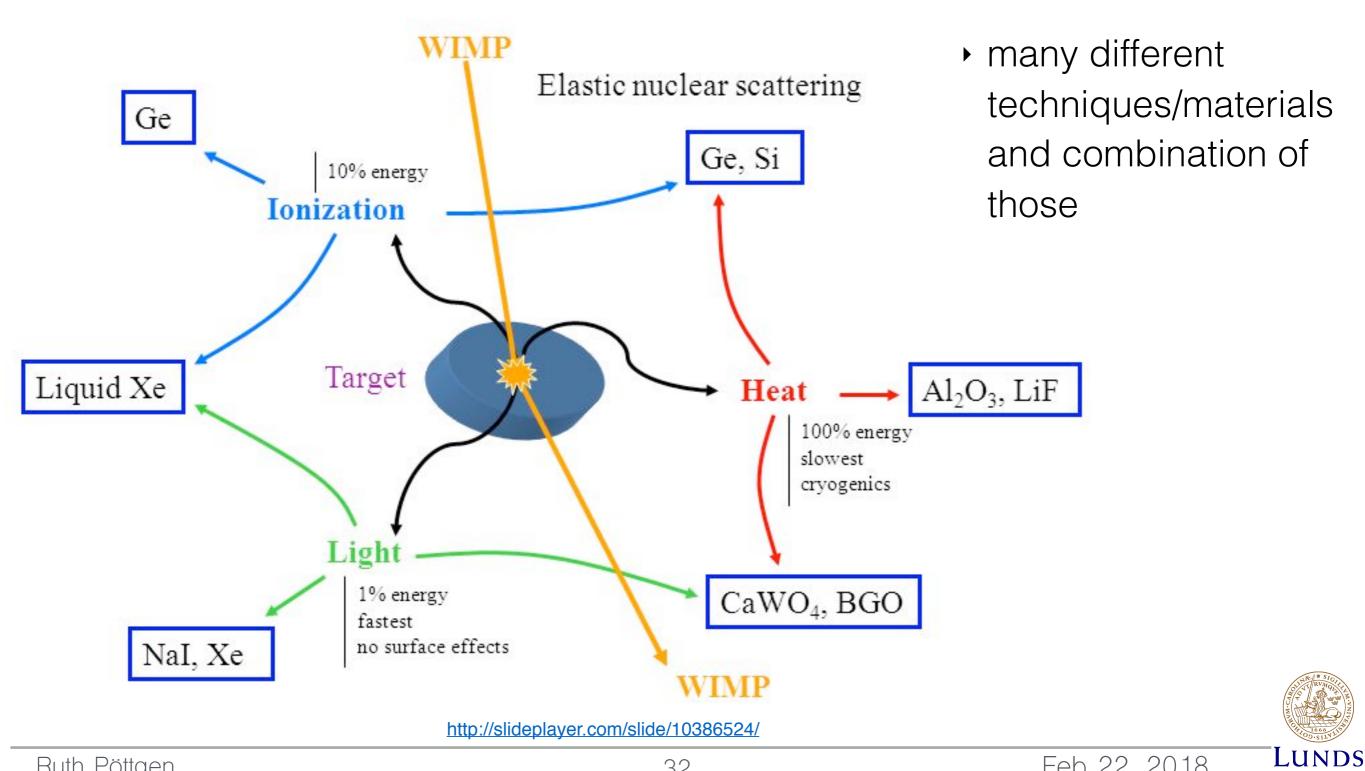


- often not straight forward to exclude astrophysical sources for effects seen
- discovery somewhat difficult



## **Direct Detection Techniques**

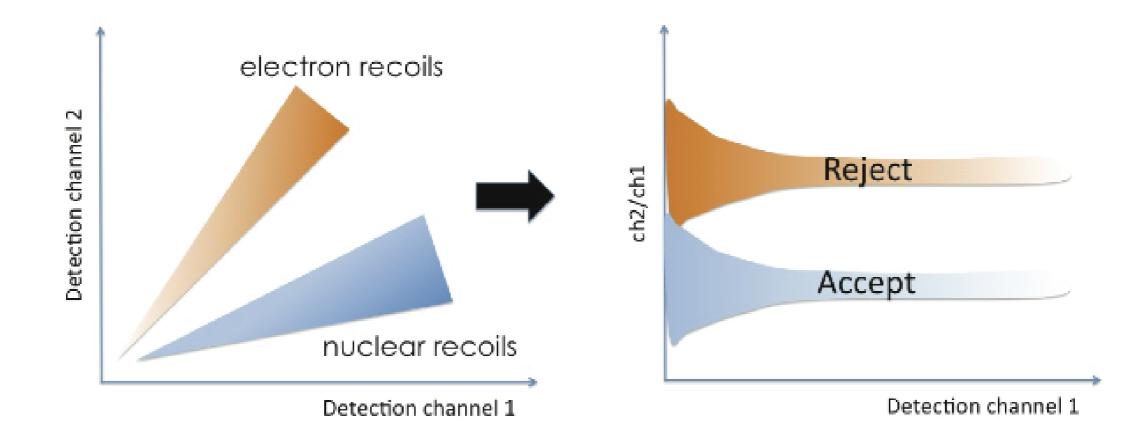
- general principle: detect elastic scattering of WIMPs in a detector
- deep underground to shield from backgrounds from cosmic rays



Ruth Pöttgen

#### **Direct Detection Techniques**

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





# Direct Detection - Example: Liquid Xenon

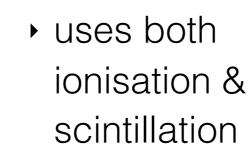
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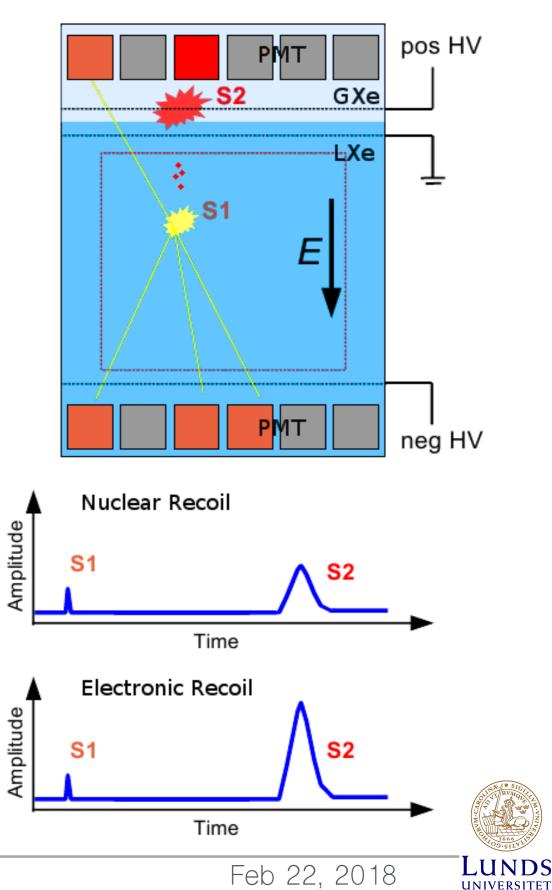
example: Xenon(1T)

http://www.xenon1t.org

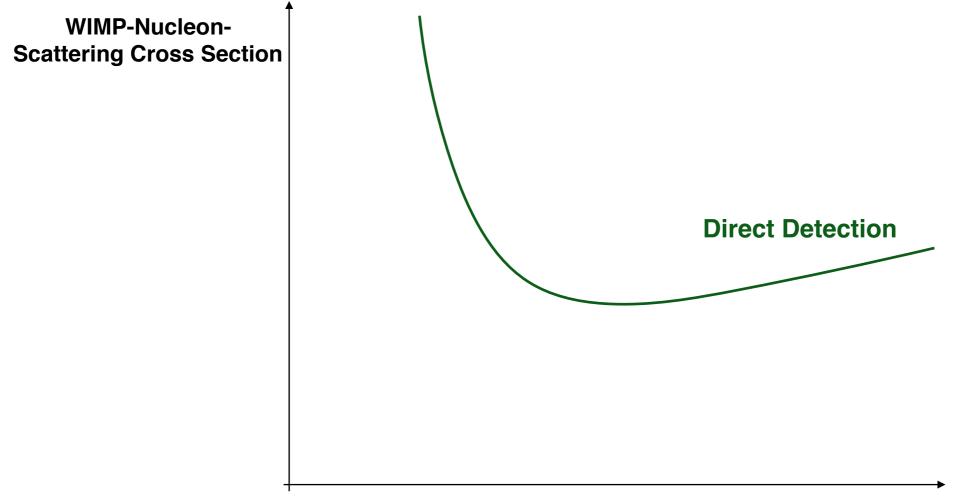
below 1400m of rock



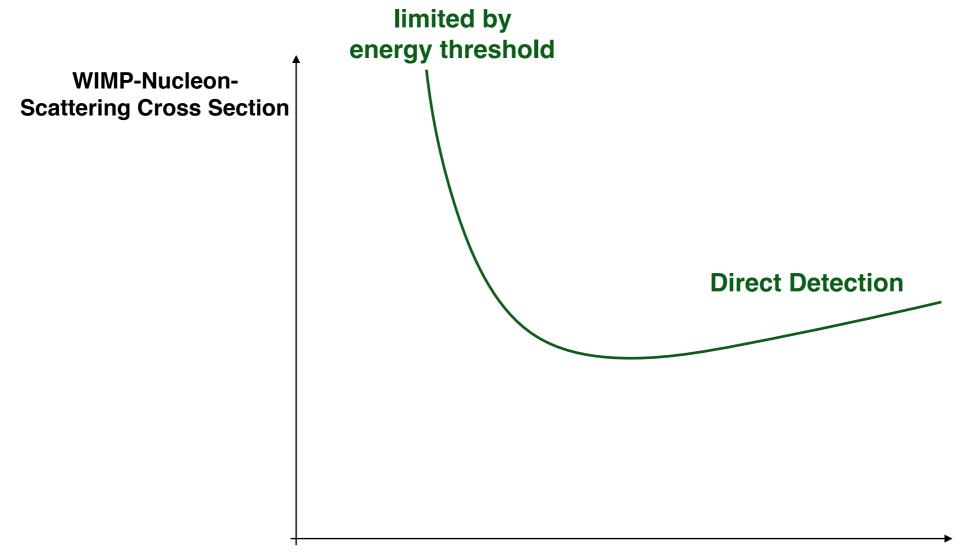
https://arxiv.org/abs/1405.7600

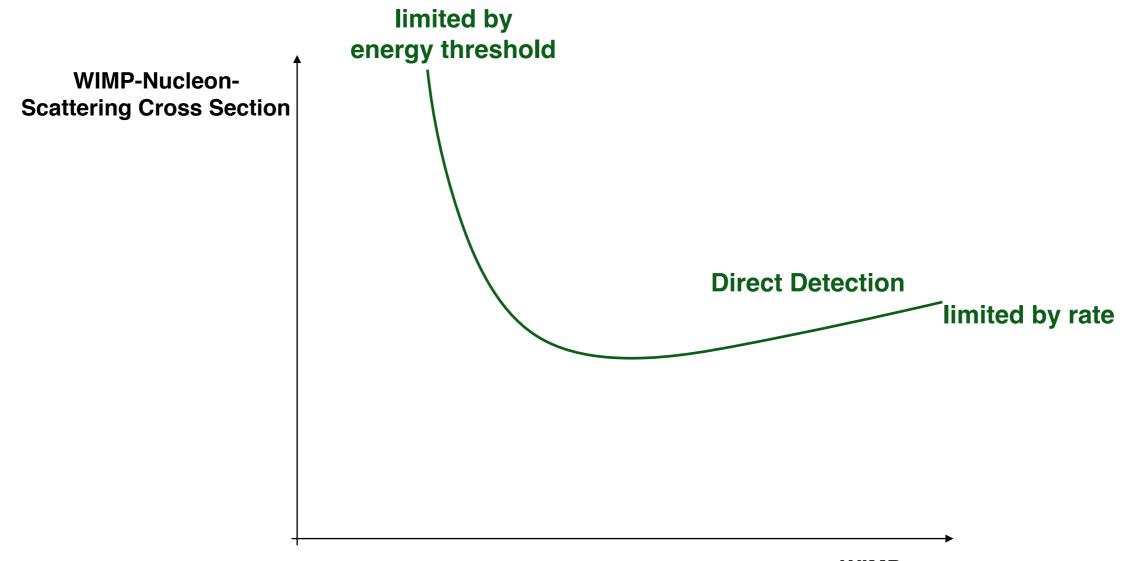


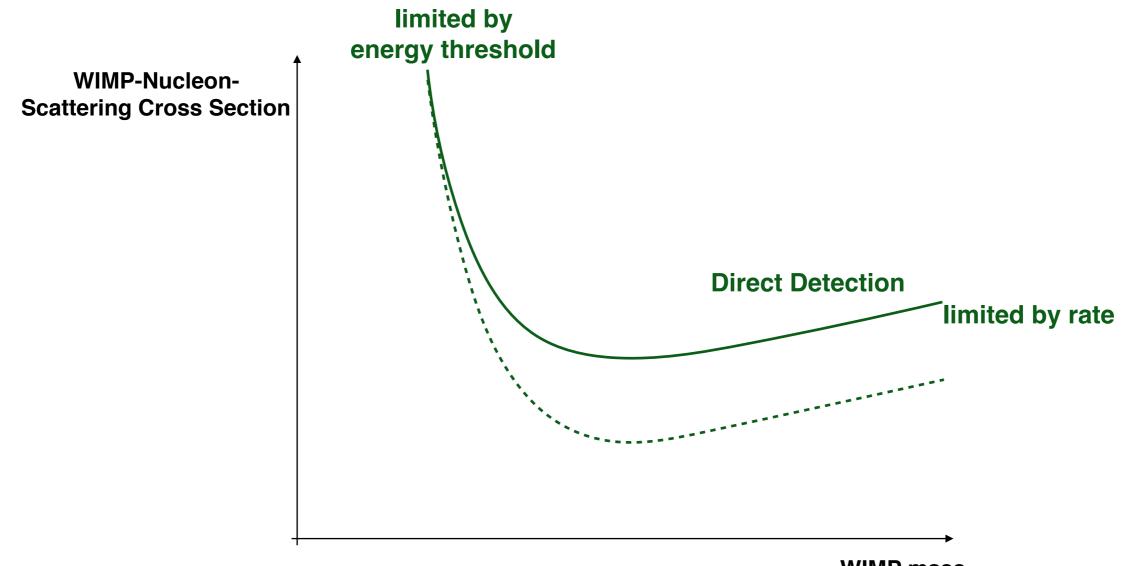
WIMP-Nucleon-Scattering Cross Section







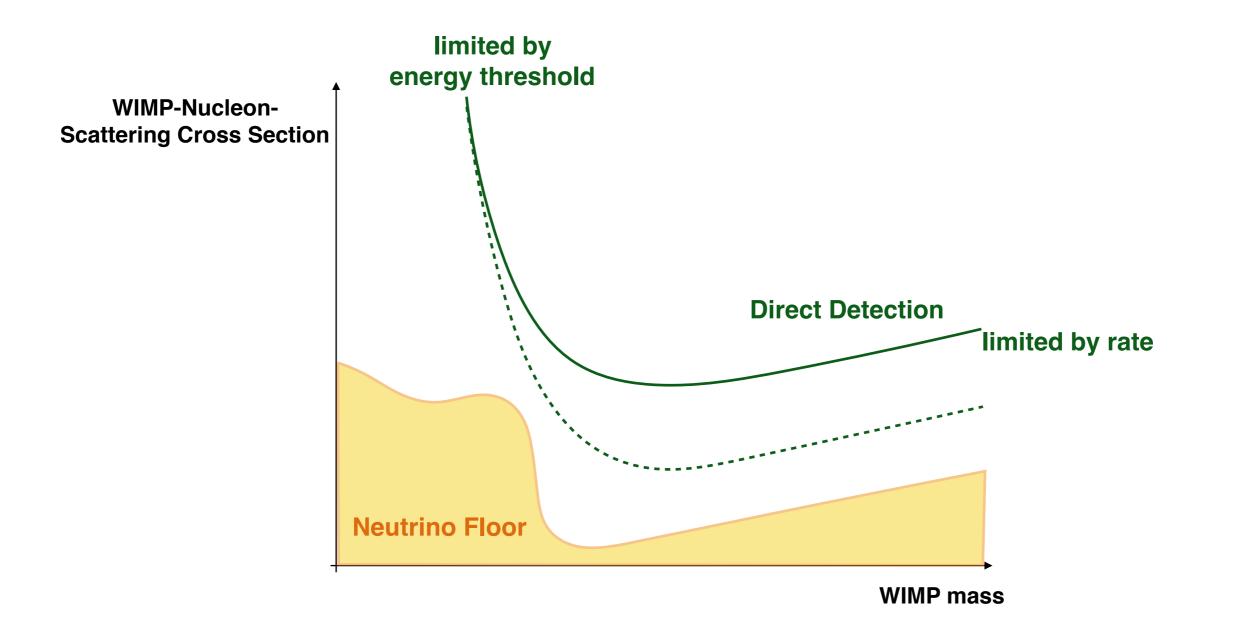




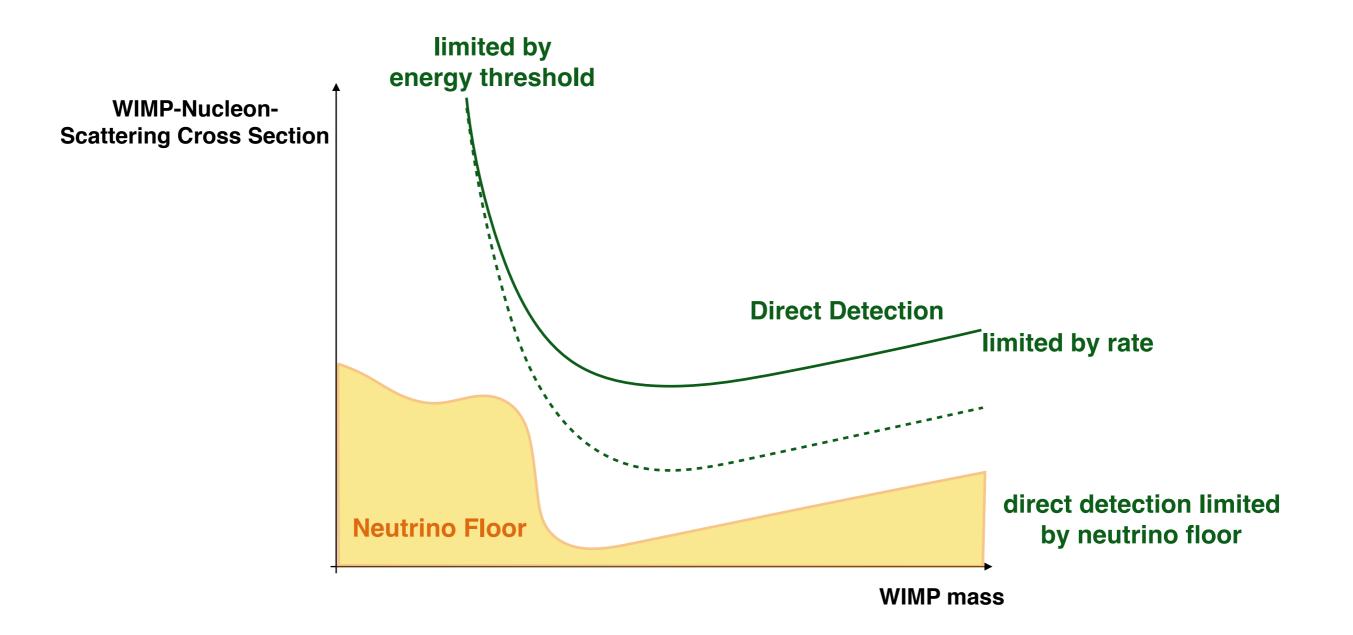




Ruth Pöttgen

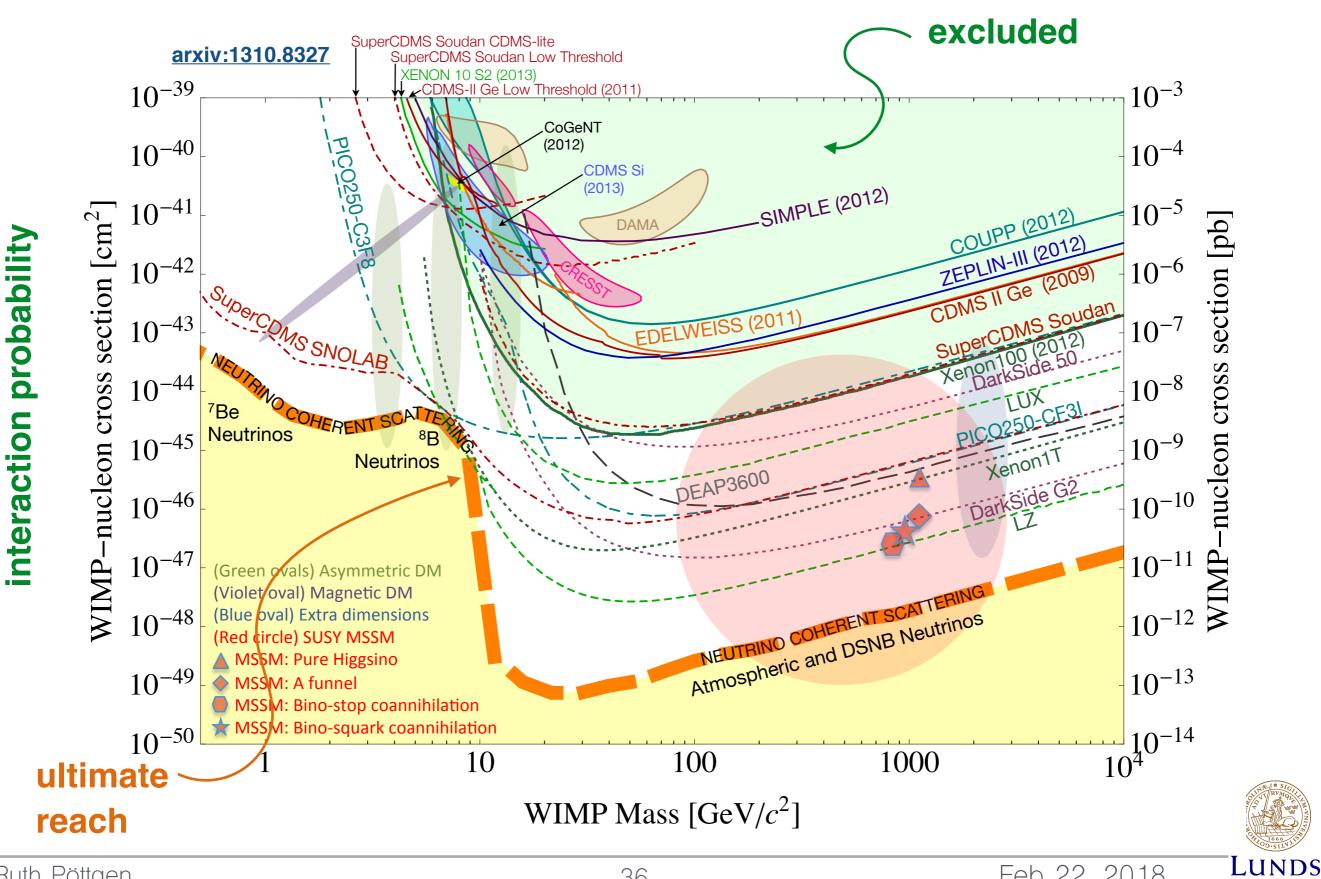


Feb 22, 2018





**Real Life** 



Ruth Pöttgen

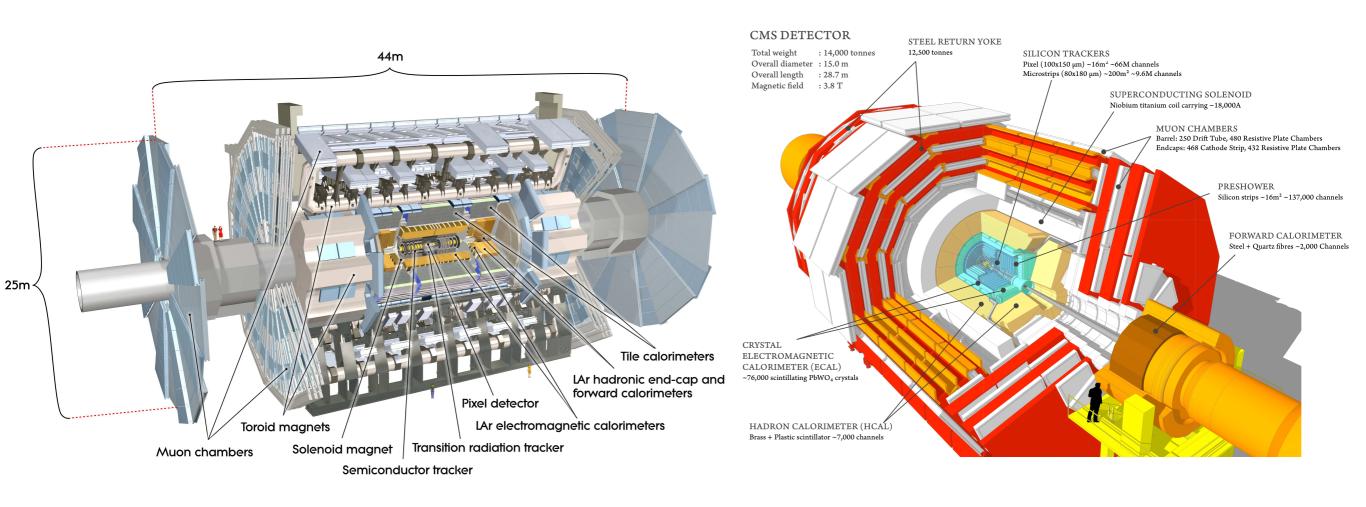
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Collider-based Searches

# i.e. LHC

# Collider Searches - LHC Experiments

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



LHCb, ALICE: more specialised

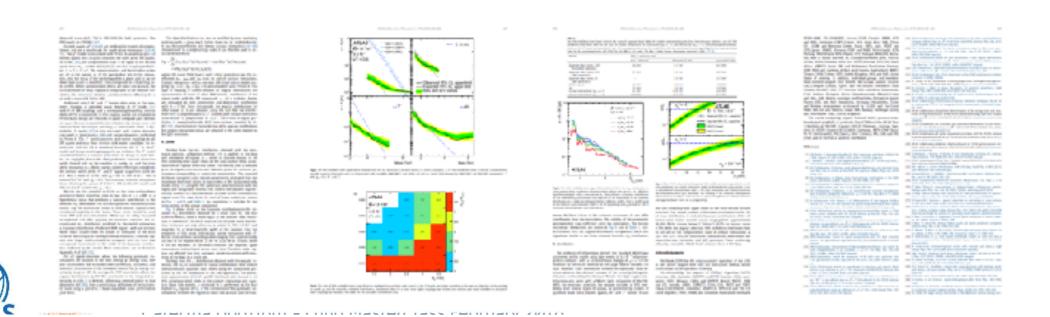


# ATLAS Collaboration

~5000 scientists from 180 institutes in 38 countries

# An ATLAS scientific paper (made in Lund)

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Feb 22, 2018

(from Caterina Doglioni)

Ruth Pöttgen

# ATLAS Collaboration

~5000 scientists from 180 institutes in 38 countries

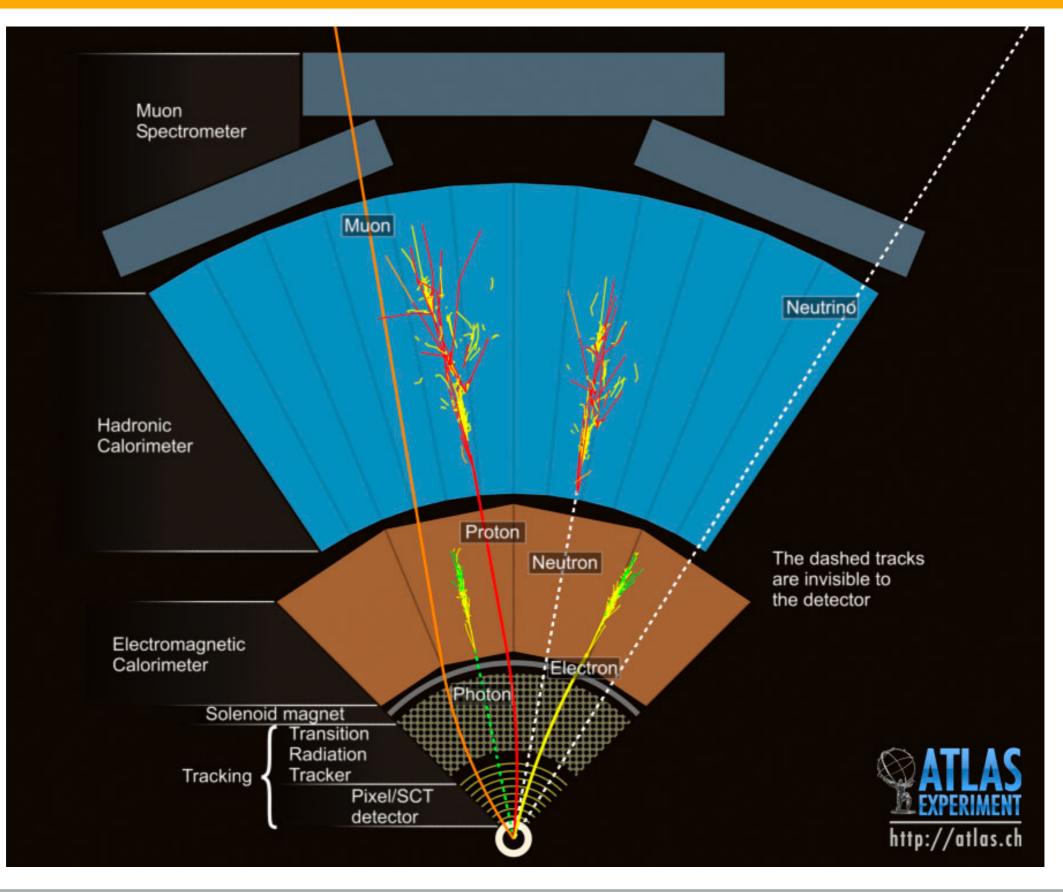
# The author-list of an ATLAS paper



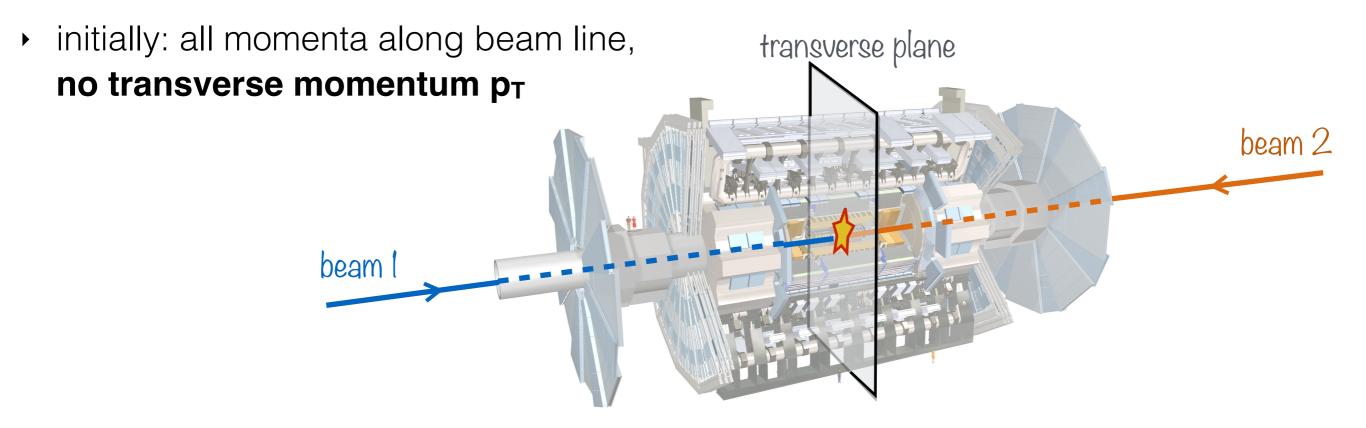




#### Particles in ATLAS

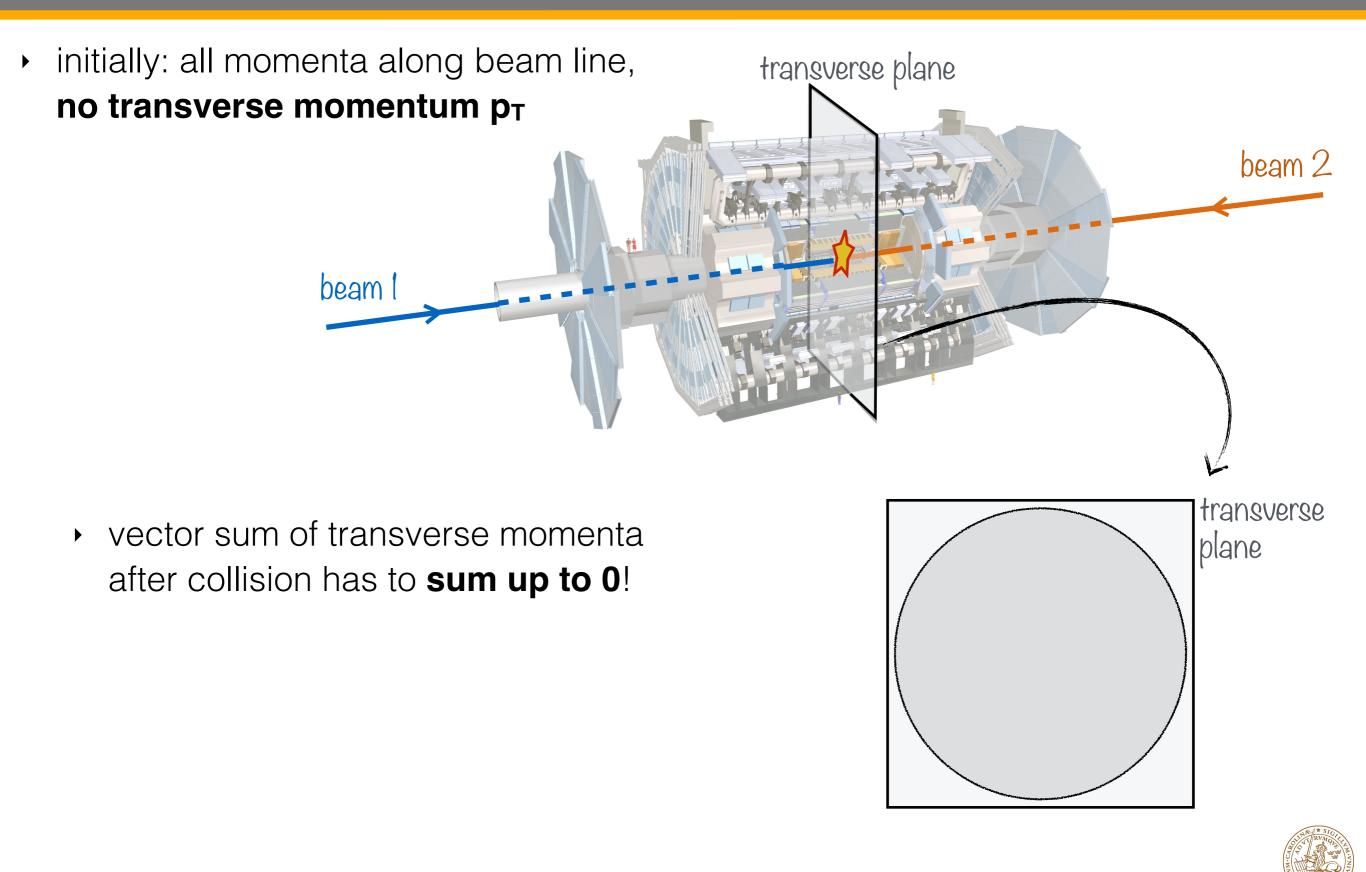




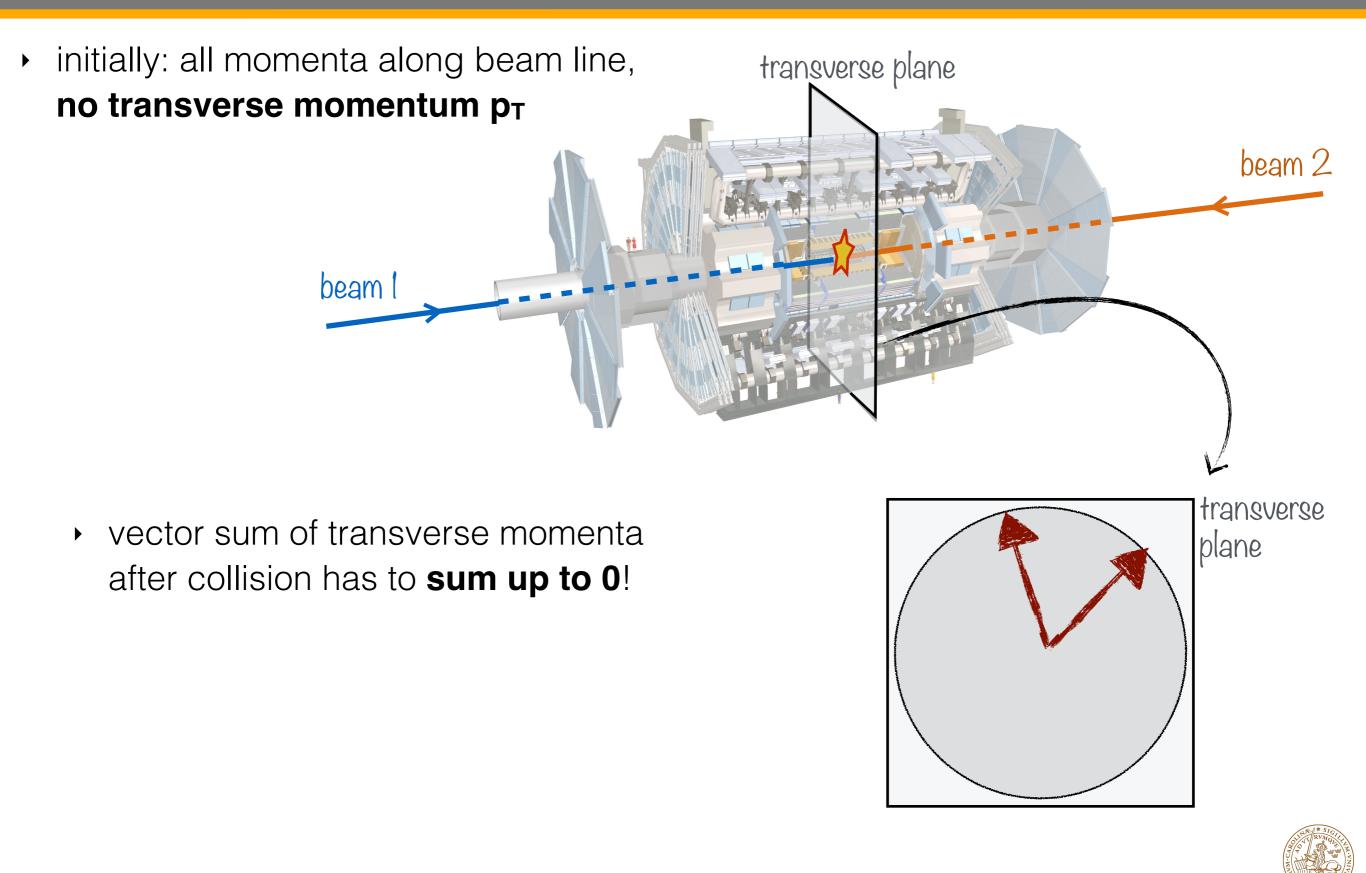


 vector sum of transverse momenta after collision has to sum up to 0!



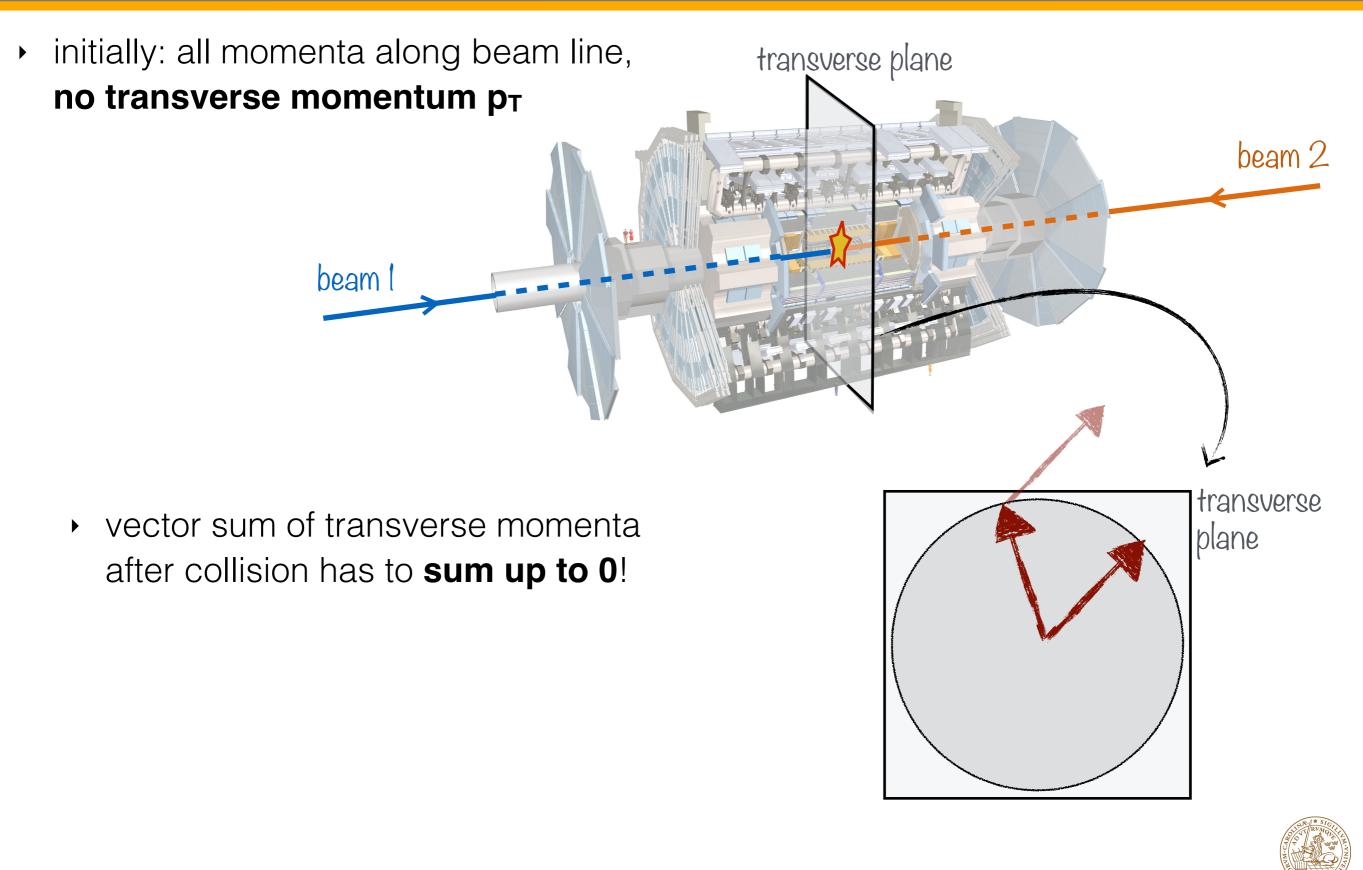


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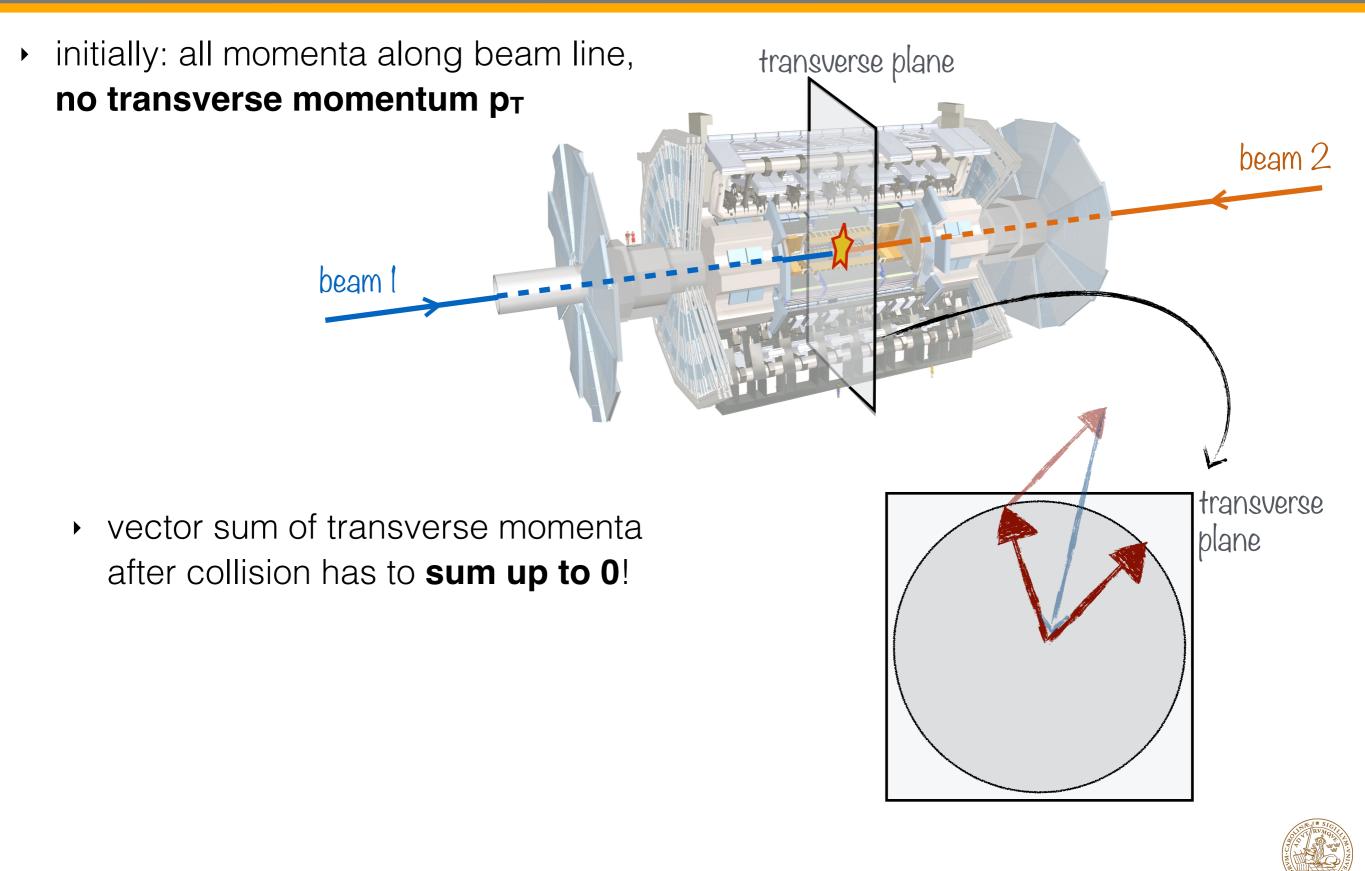


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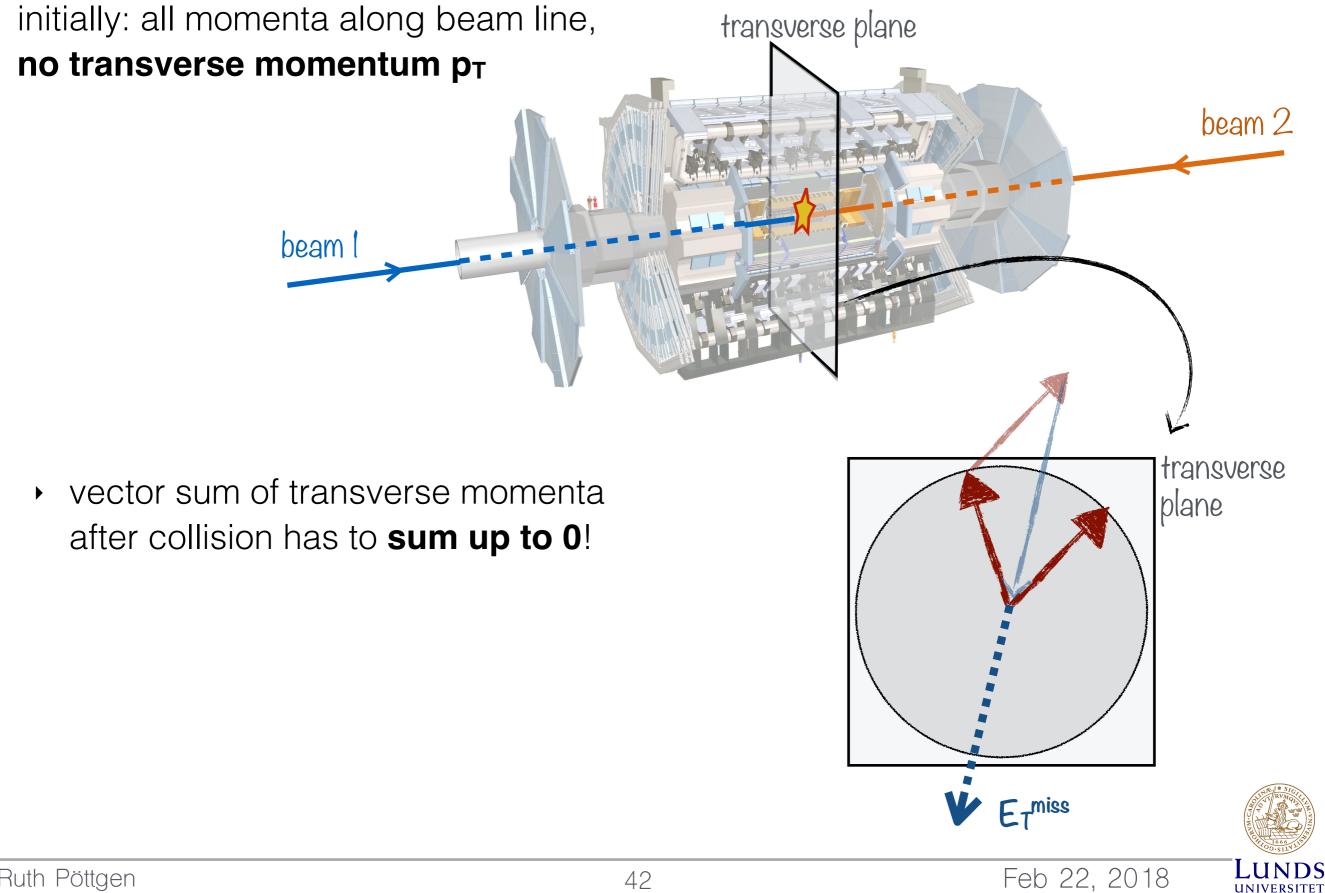


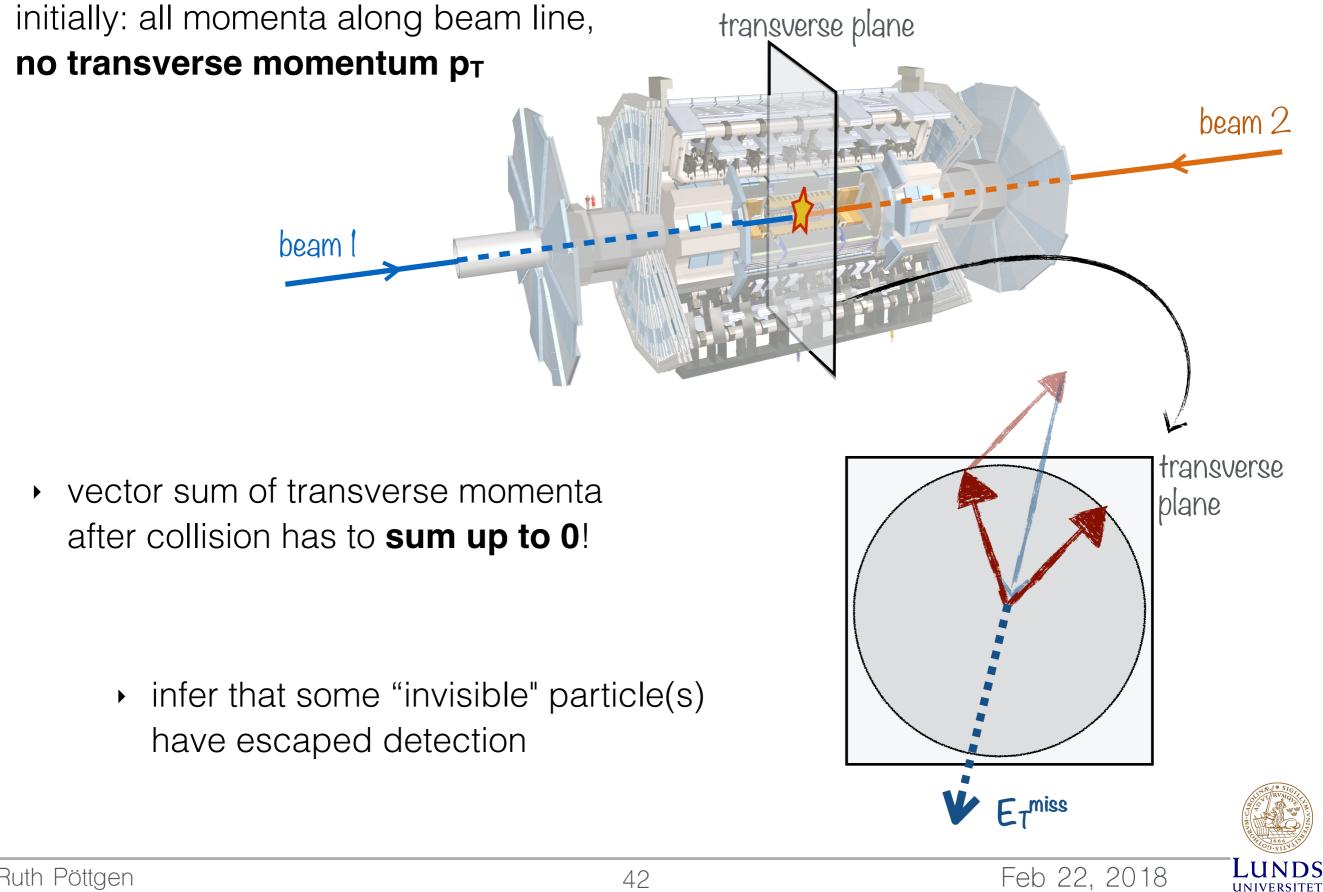






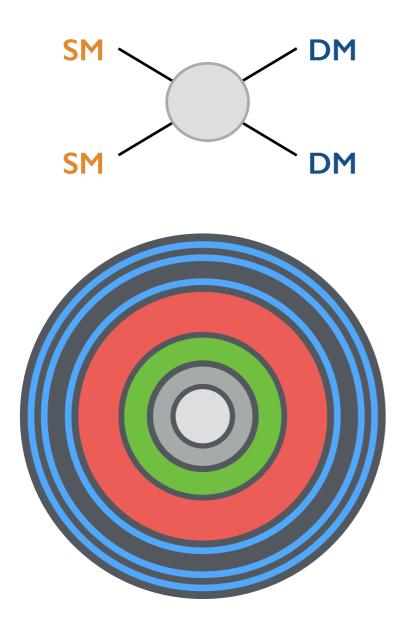






# "Invisible Signatures"

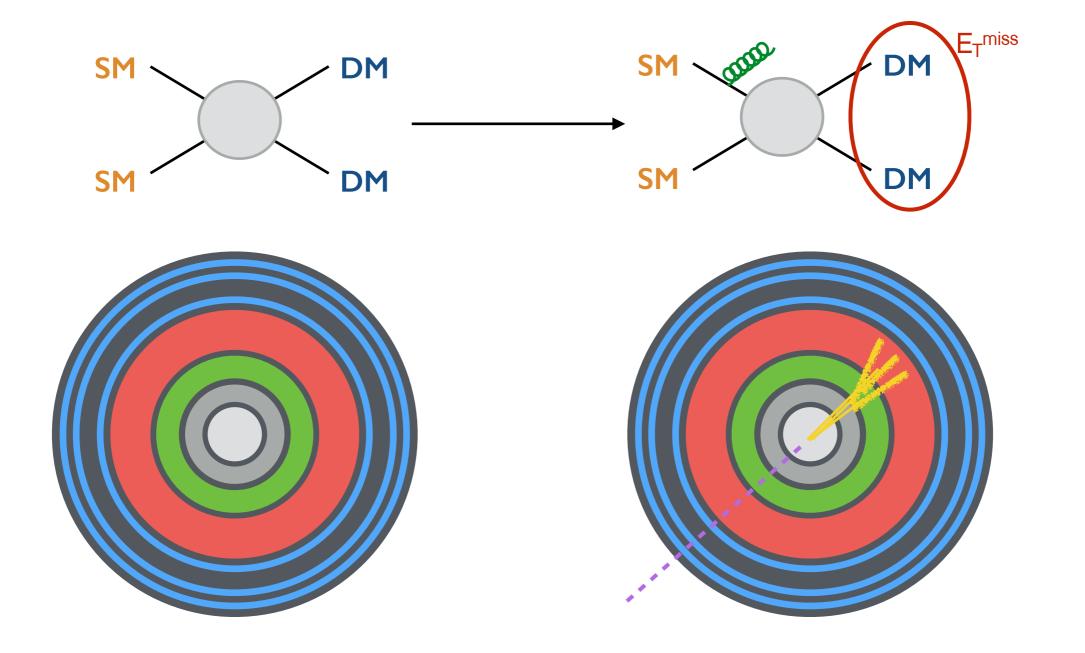
- most of the searches for Dark Matter at colliders use missing energy
- to see anything, there must be something else in the event!



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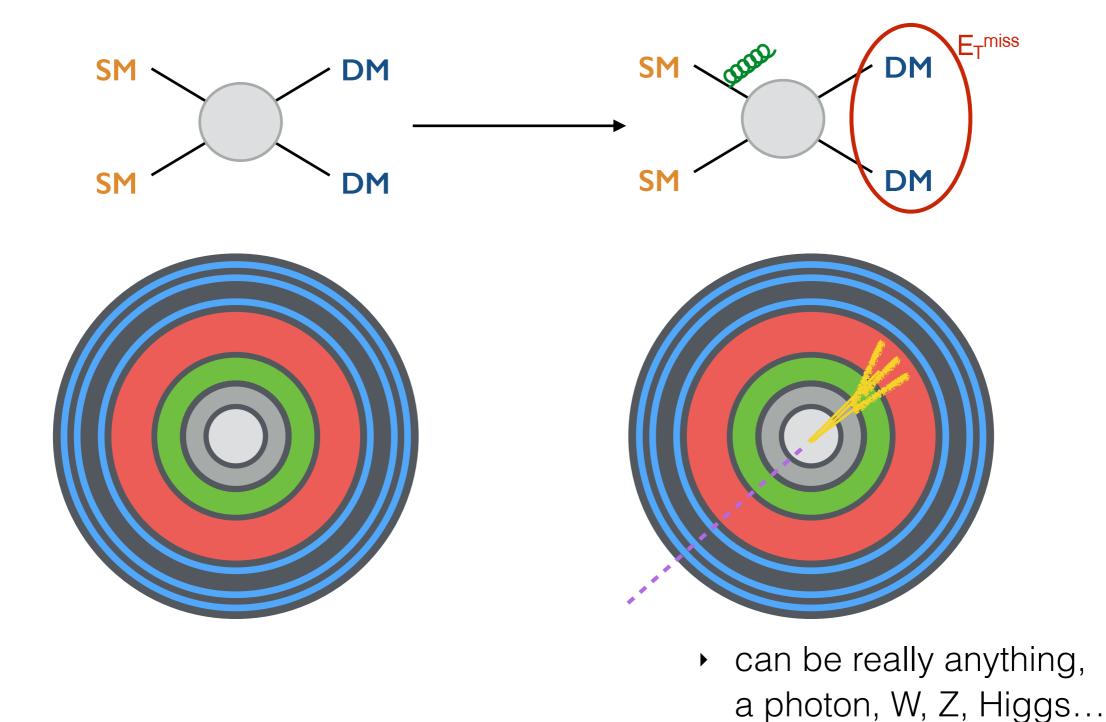
# "Invisible Signatures"

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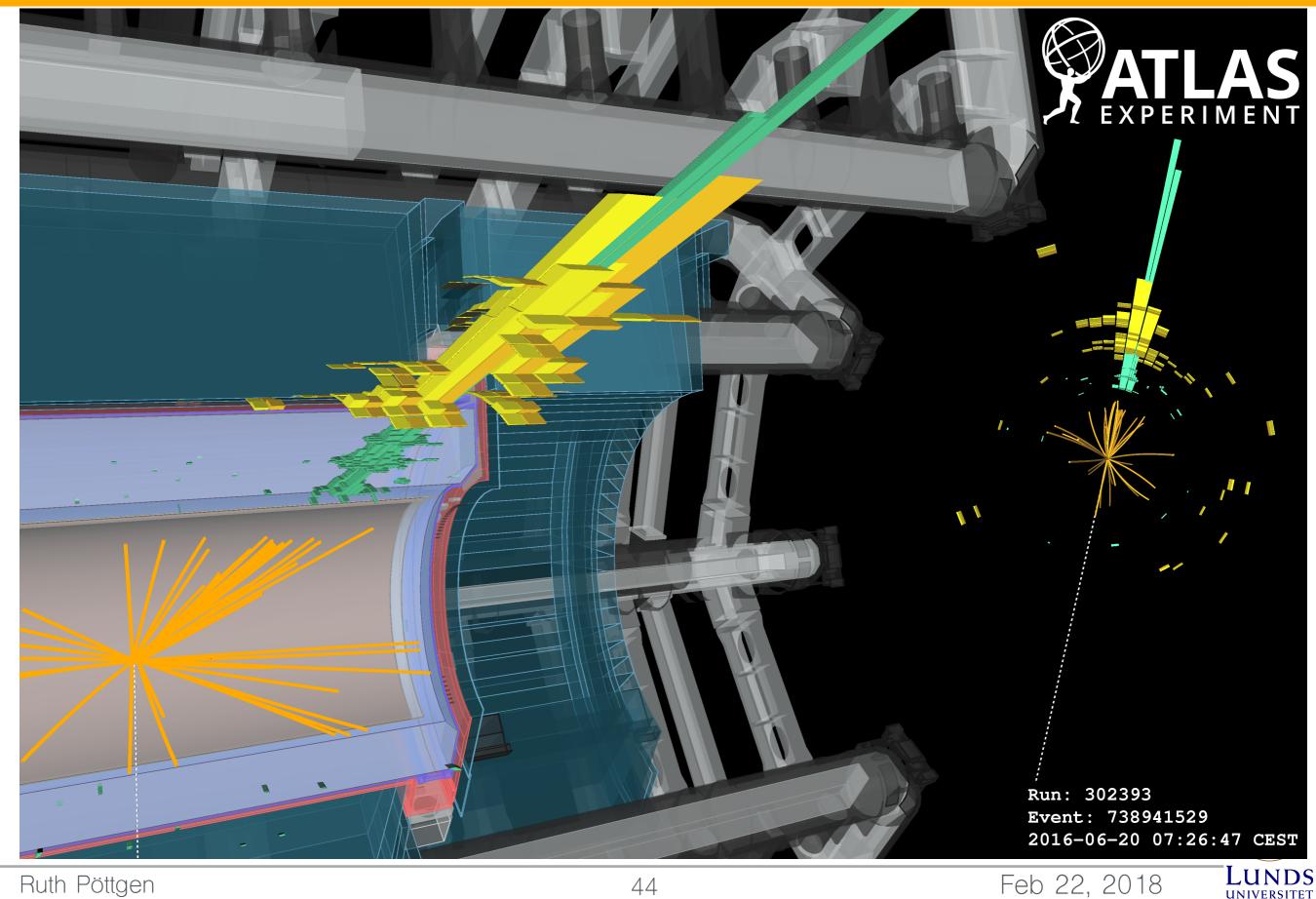
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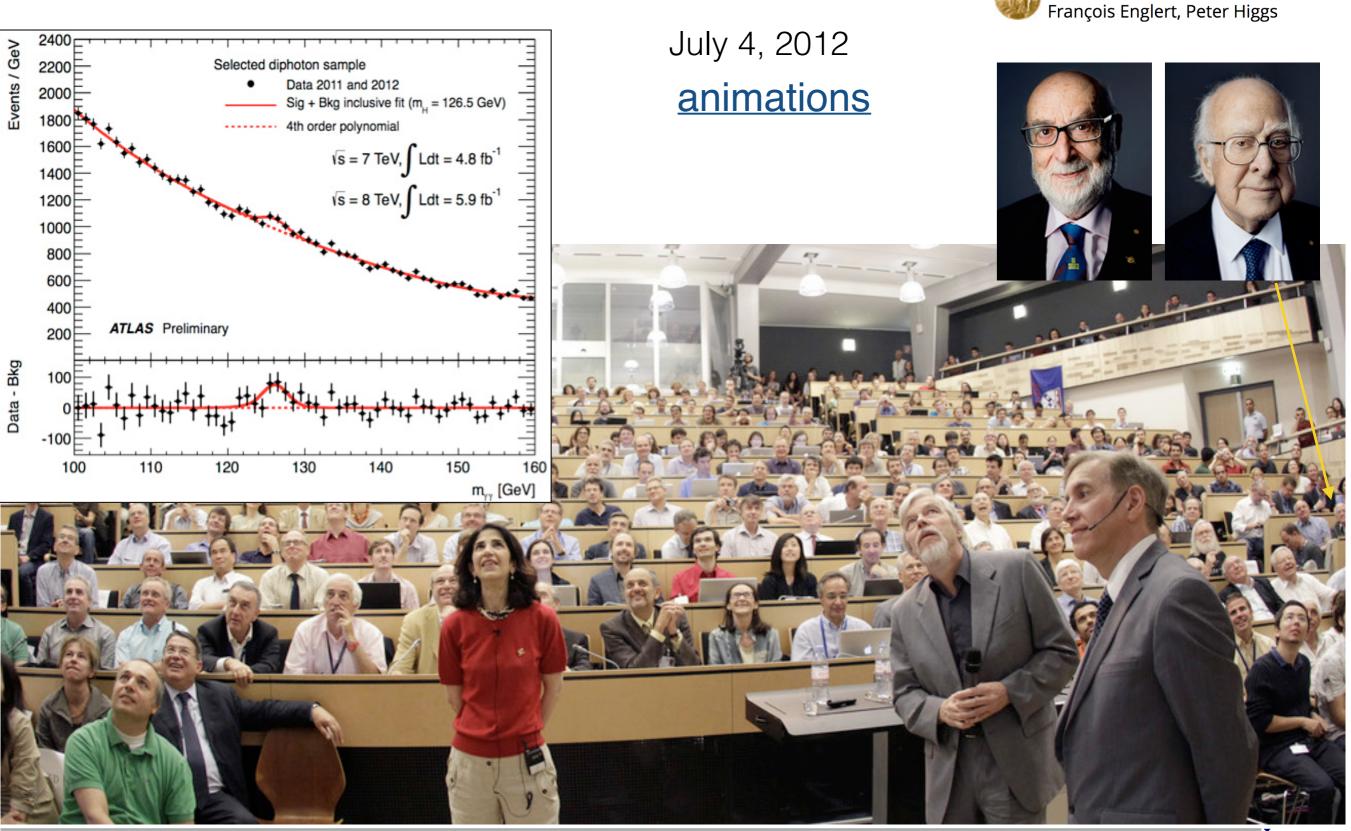


# A jet+invisible event



# The Higgs Boson

#### final missing piece of the SM



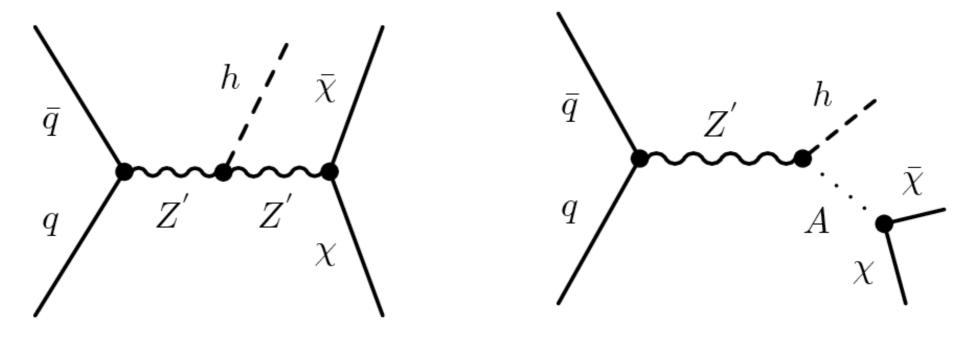
Ruth Pöttgen

The Nobel Prize in Physics 2013

LUNDS UNIVERSITET

# Example: Higgs+E<sub>T</sub><sup>miss</sup>

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

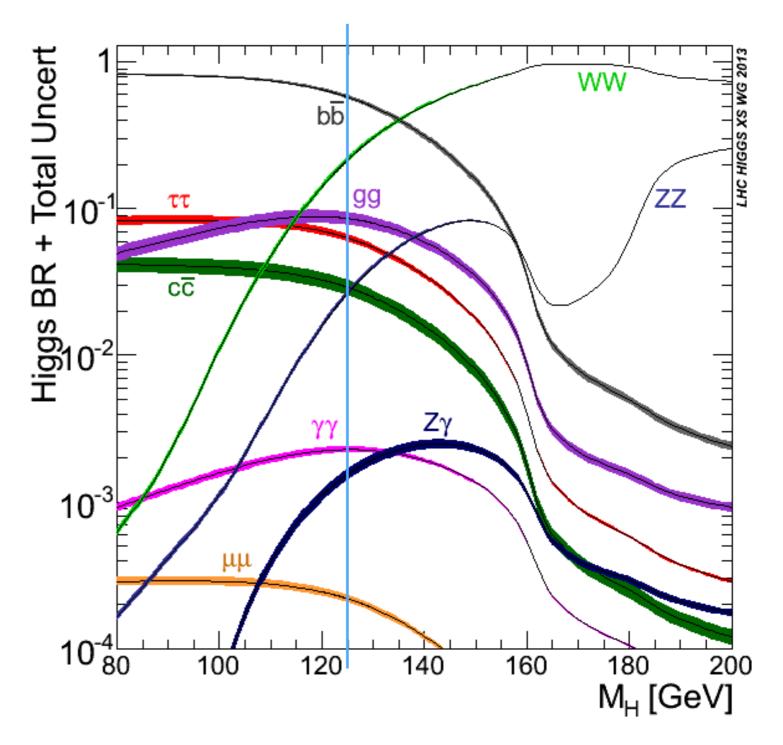


- final state: Higgs + DM
  - but Higgs not stable!



# Example: Higgs+E<sub>T</sub><sup>miss</sup>

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

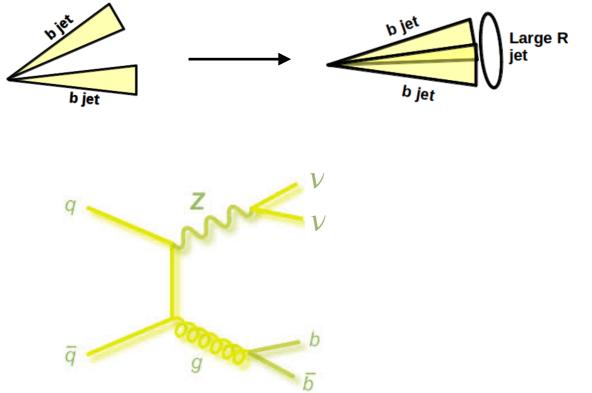


- need to be able to identify jets originating from b-quarks (b-jets)
  - luckily, we are (and we call it *b-tagging*)



# Higgs(bb)+E<sub>T</sub><sup>miss</sup> in a nutshell

- look for collision events that have
  - large amount of E<sub>T</sub><sup>miss</sup>
  - 2 b-tagged jets or 1 big jet made of 2 b-jets
    - high E<sub>T</sub><sup>miss</sup>: 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—>vv => ET<sup>miss</sup>



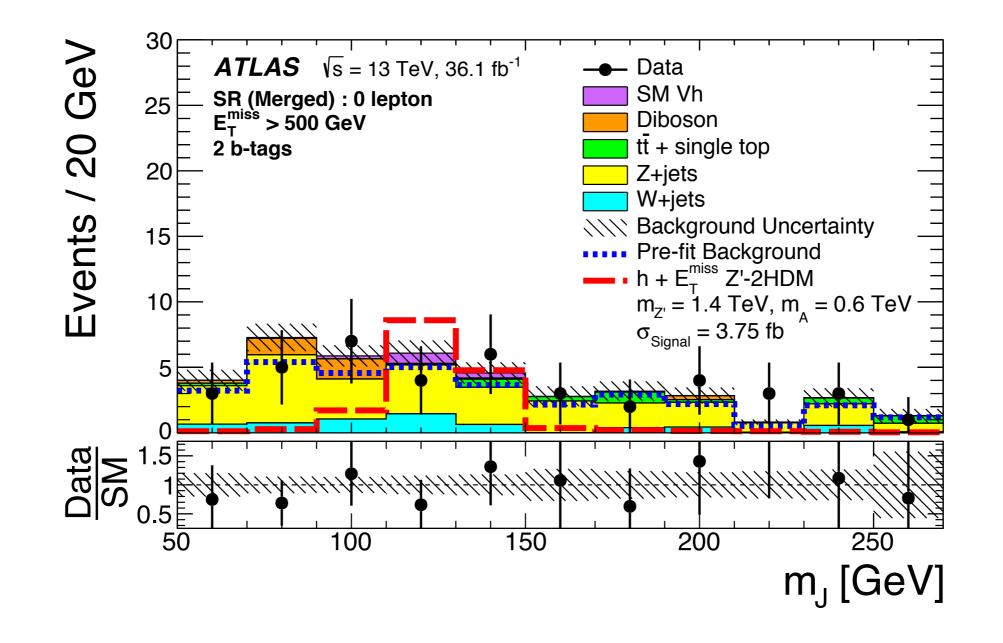
- to estimate this and other backgrounds: use control samples
  - events that have characteristics of a given background process
  - improves confidence in and precision of background simulations

#### statistical evaluation:

fit of background prediction to observed data, quantify the agreement

#### Higgs(bb)+E<sup>50</sup><sub>T</sub><sup>miss</sup> – The Signal Region <sup>PAQ</sup> [GeV] 50 100 150

large amount of information in such plots





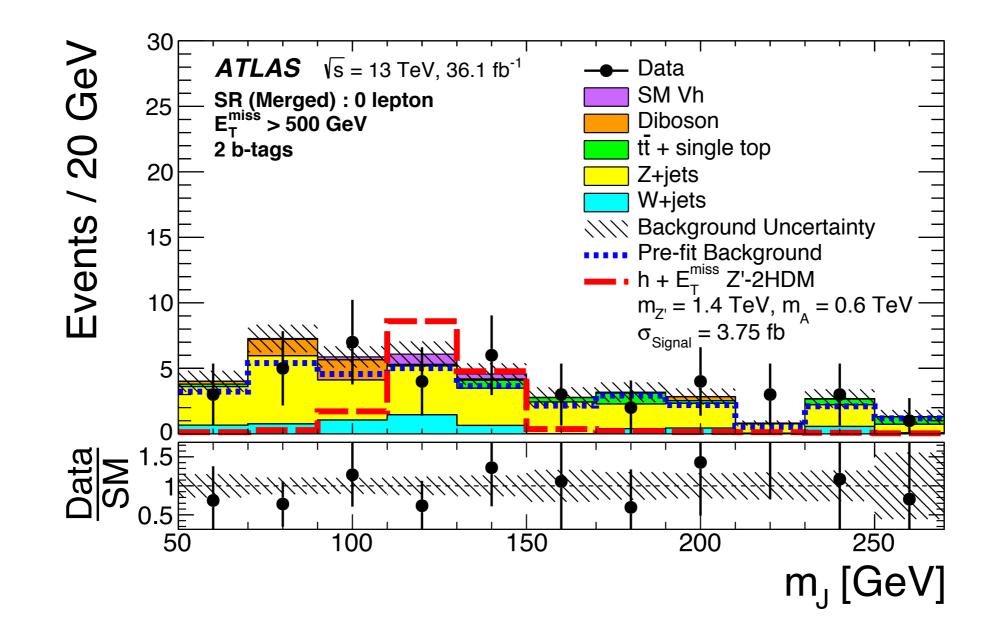
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pag [GeV]

200

#### Higgs(bb)+ $E_T^{miss}$ – The Signal Region $\frac{150}{100}$ 150

large amount of information in such plots



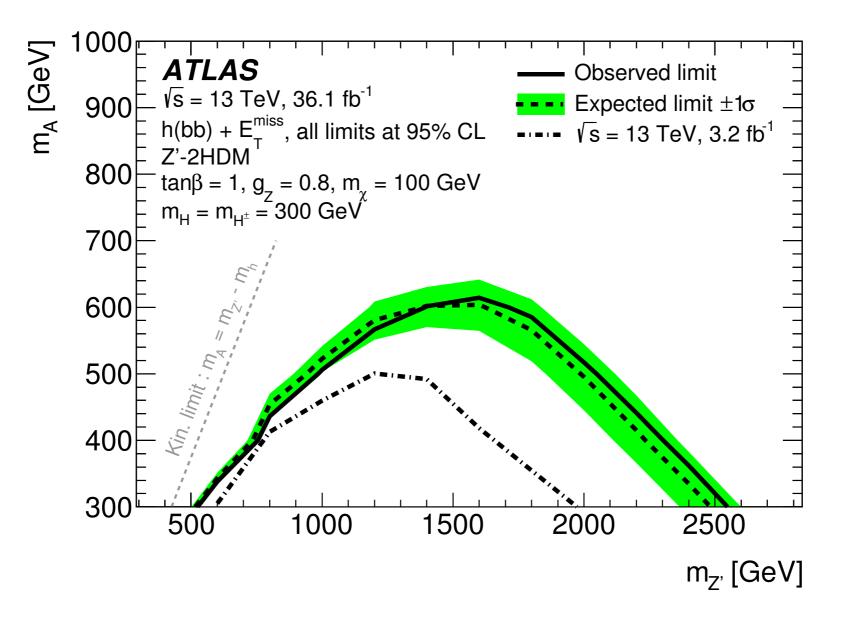
no signal observed!

pag [GeV]

200

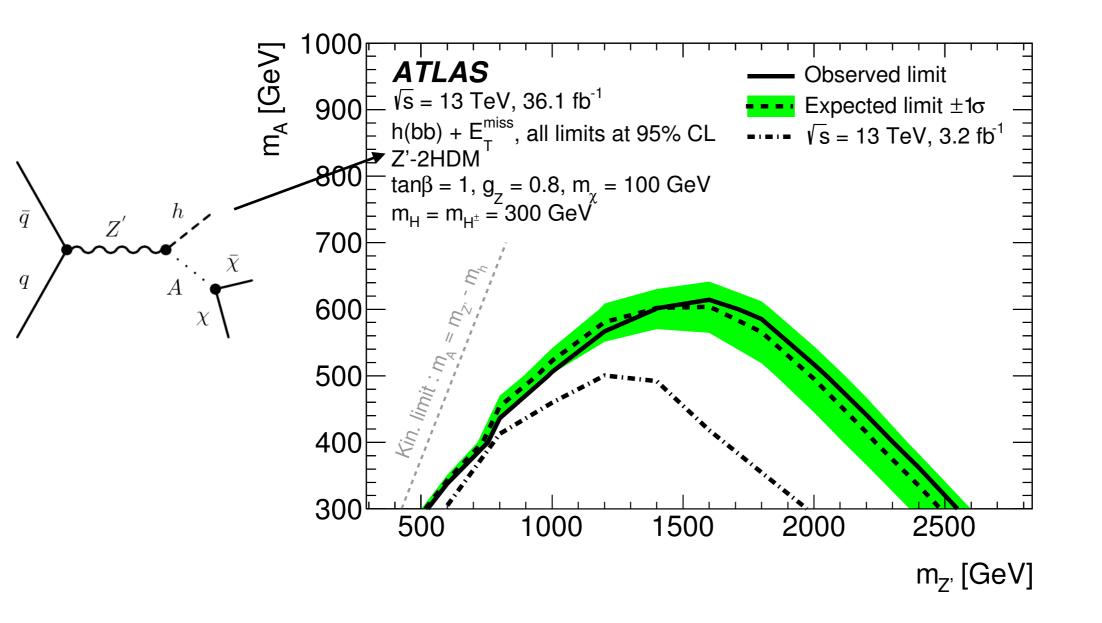


a typical result plot: exclusion bounds ("limits")

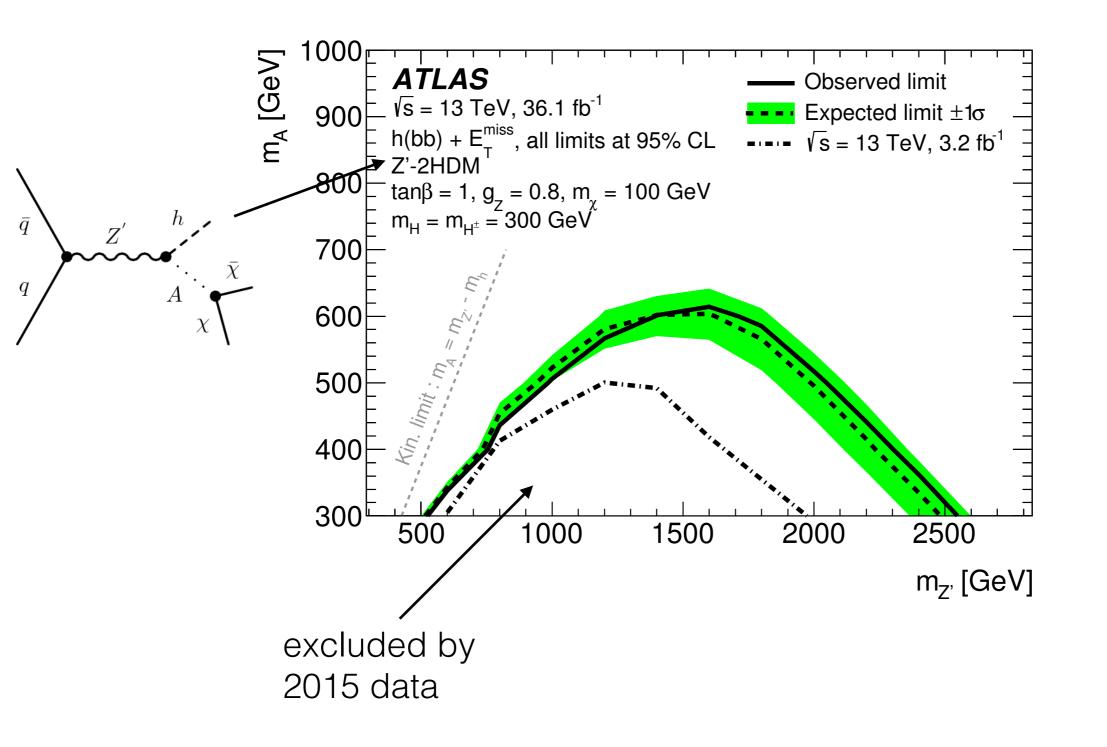


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a typical result plot: exclusion bounds ("limits")

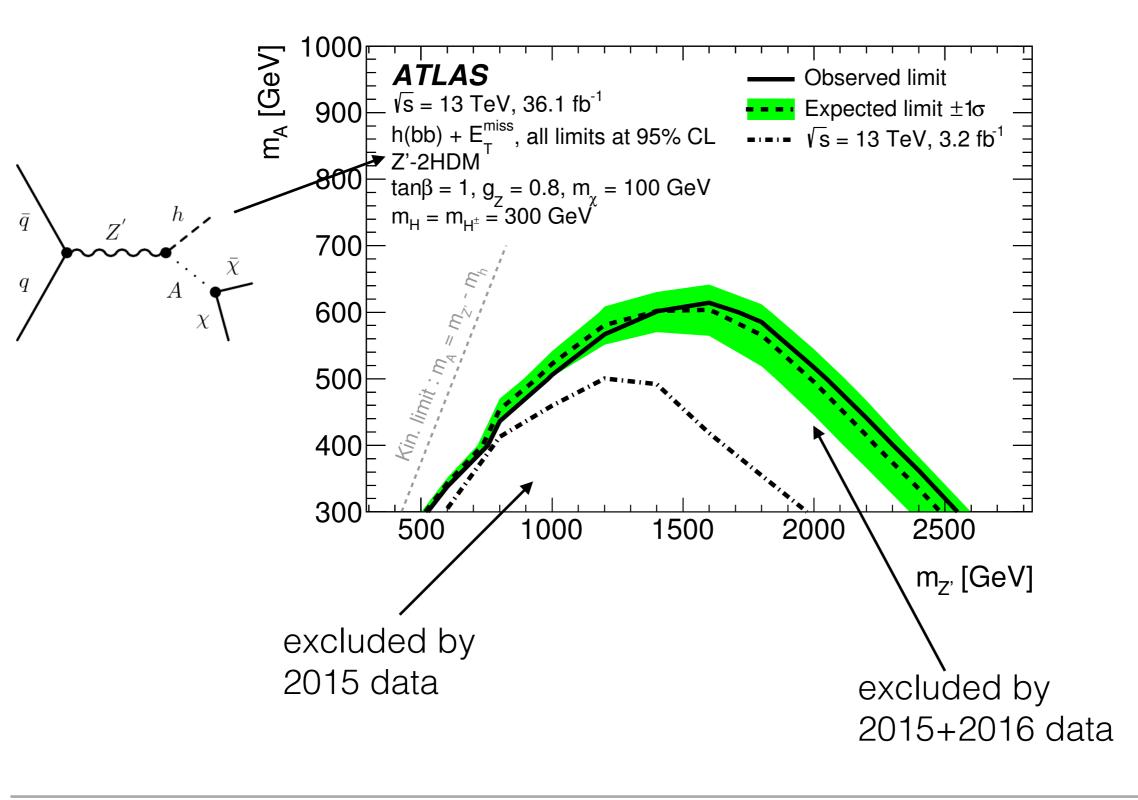


a typical result plot: exclusion bounds ("limits")





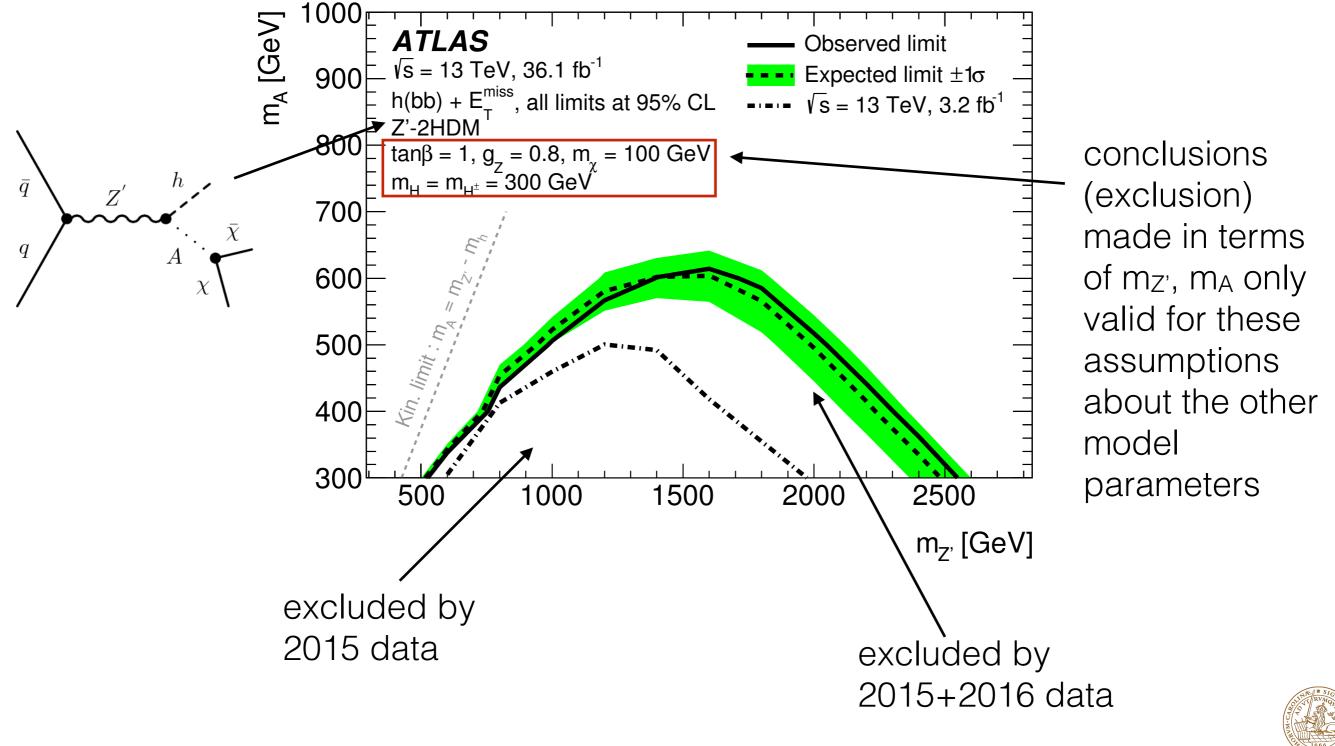
a typical result plot: exclusion bounds ("limits")



50



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

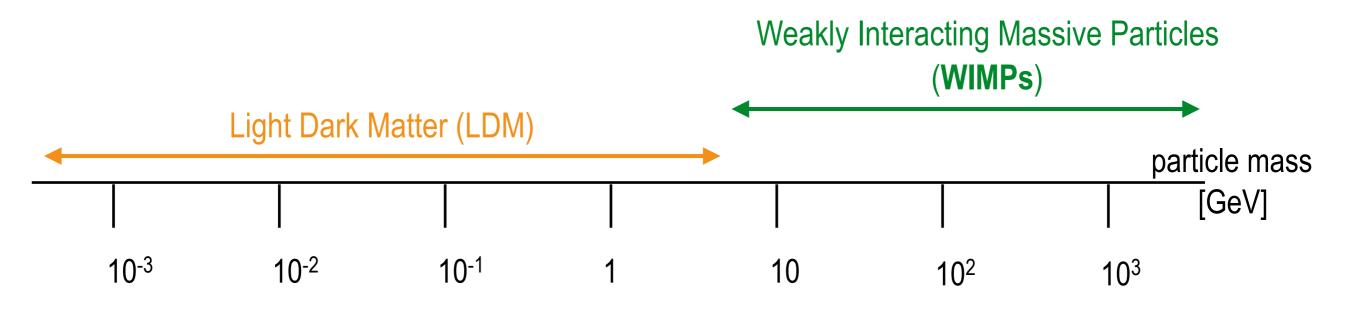




Accelerator-based Search

## 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:  $m_X > some GeV$

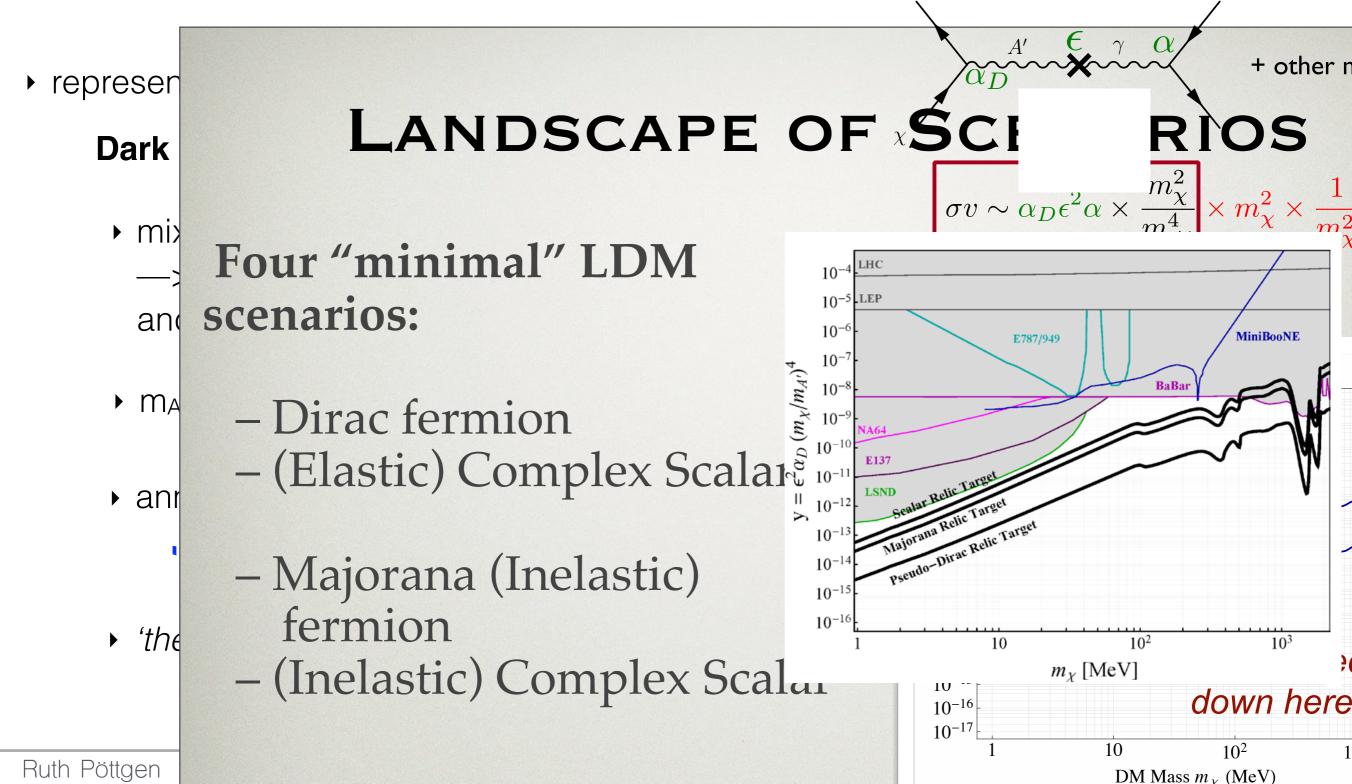


- this isn't really LHC realm anymore
  - take a different approach



## How to evade the Lee-Weinberg bound

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



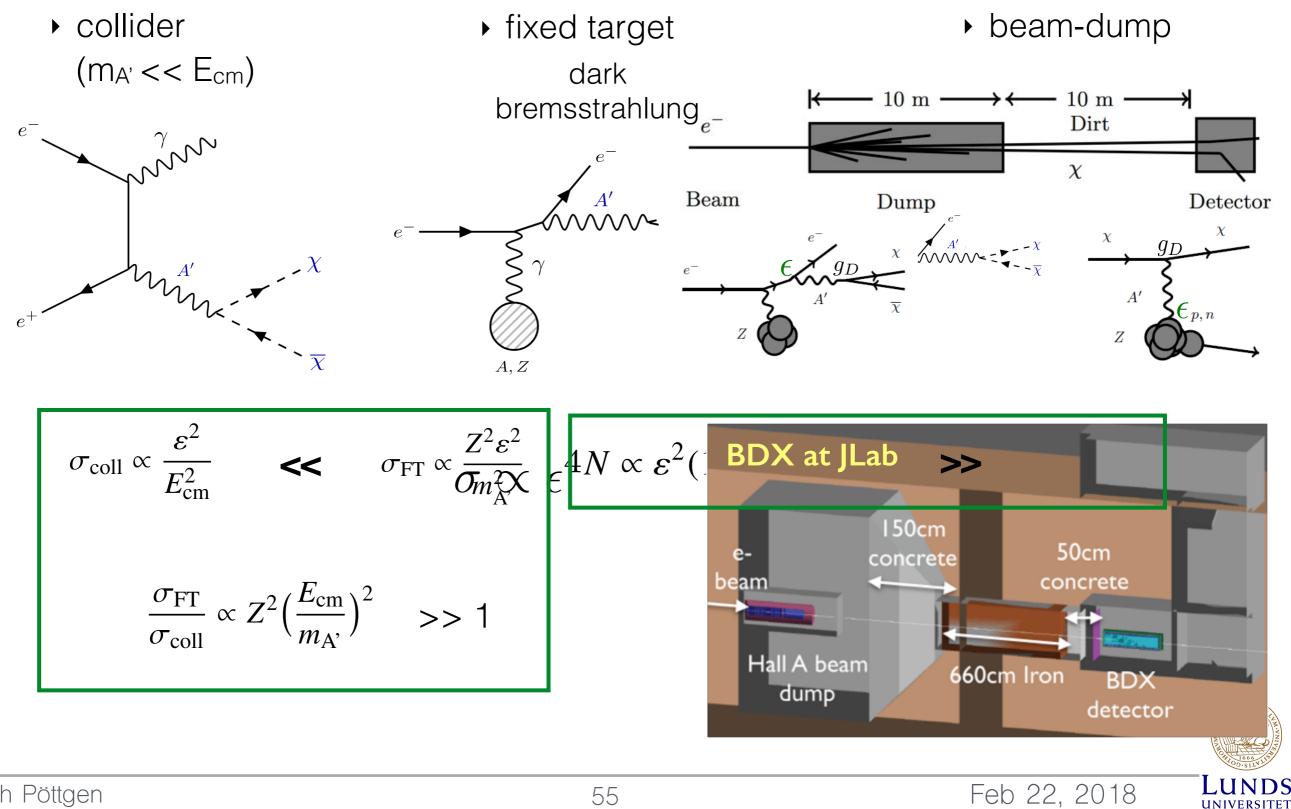
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- ▶ as said, not LHC...
- instead: fixed-target missing momentum experiment

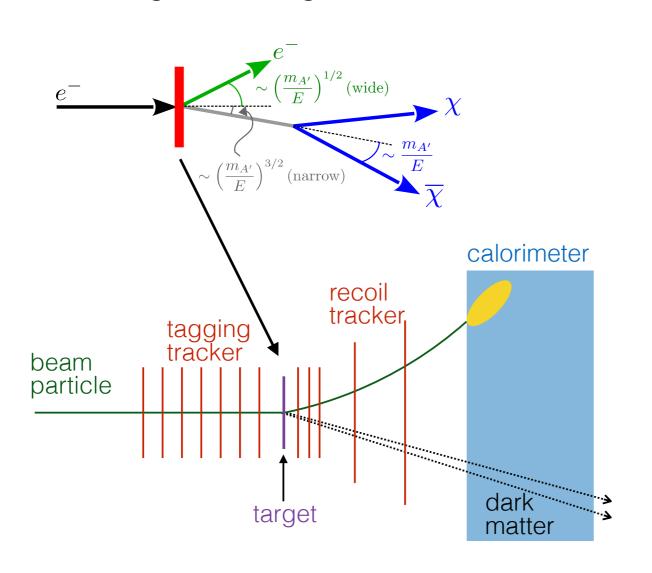


## Why fixed-target?

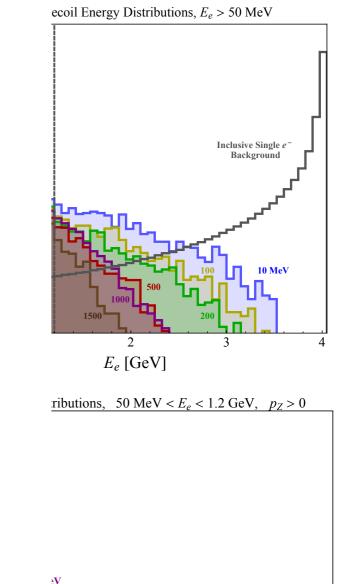
maximise DM yield (production & detection efficiency)

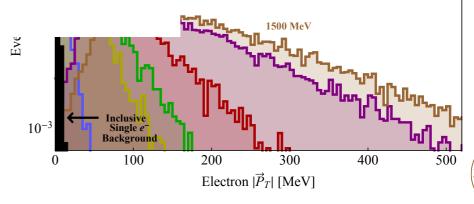


- due to mass of mediator, kinematics distinctly different from SM bremsstrahlung dark
   matter
  - matter mediator carries most of the energy —> soft recail election large missing momentum photon
  - recondensition gets transverse 'kick'
     —> large missing transverse momentum



Ruth Figure 5 | Experimental concept of a 56



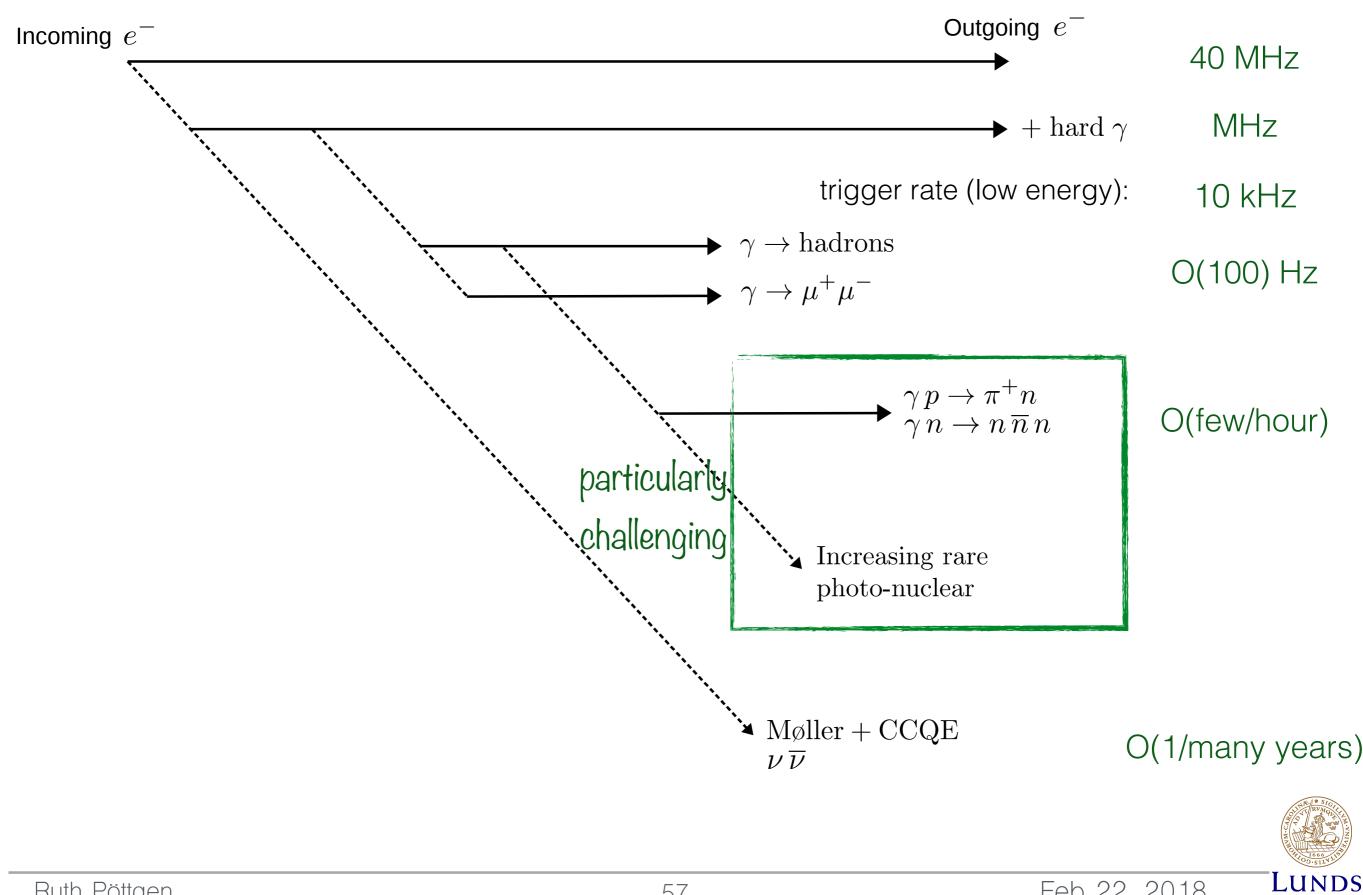


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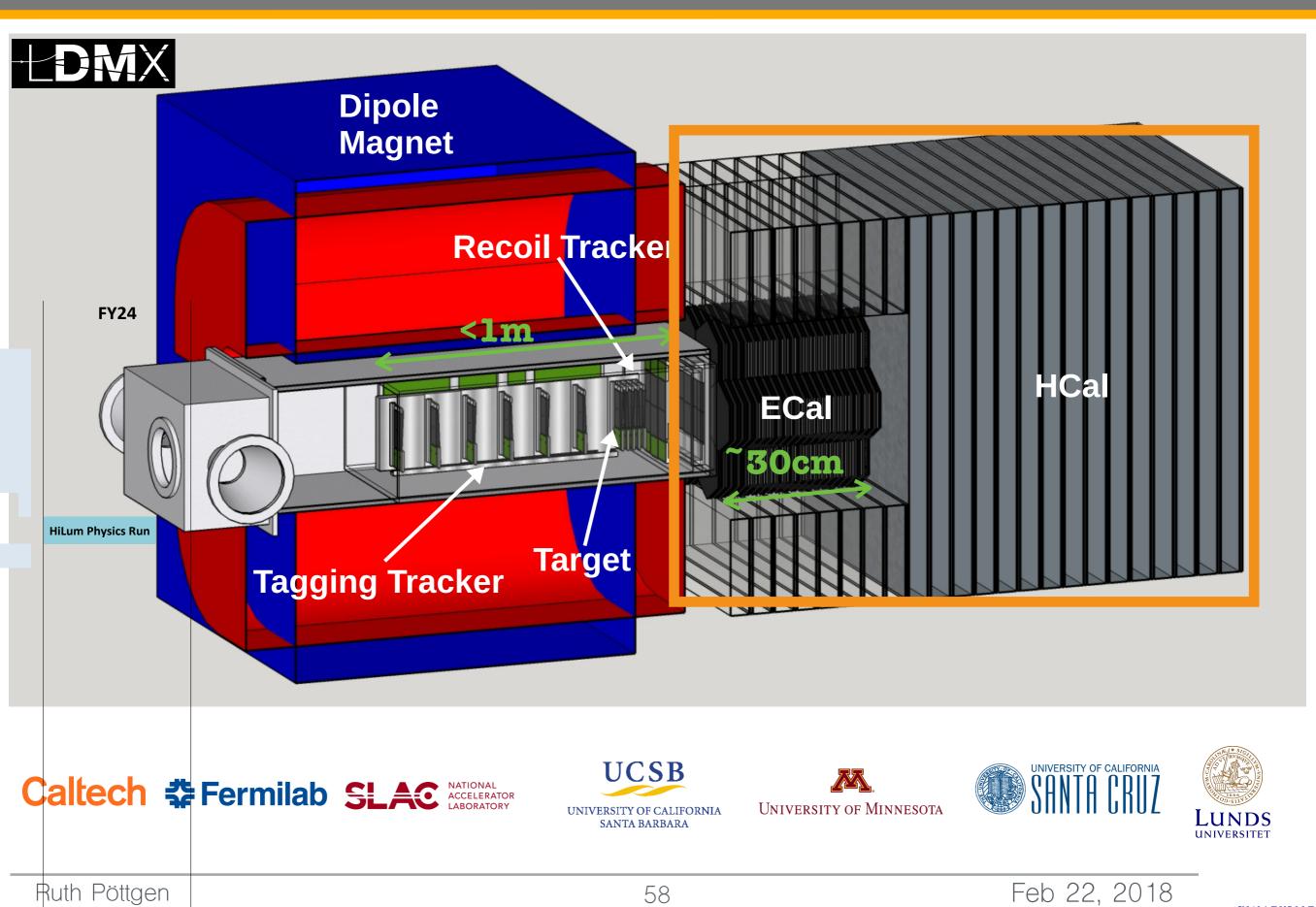
#### Challenge: Backgrounds!



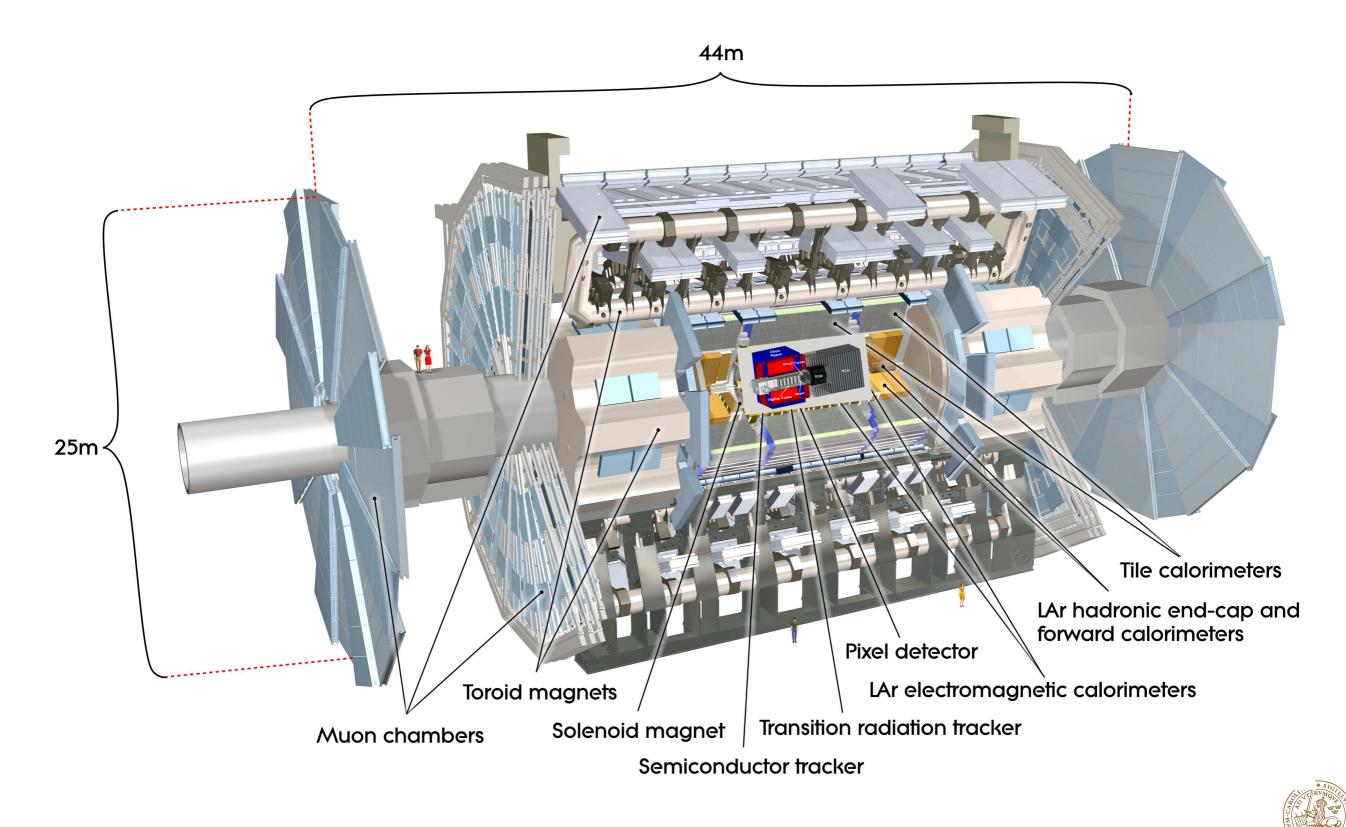


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### Light Dar Matter eXperiment



## LDMX is a small experiment





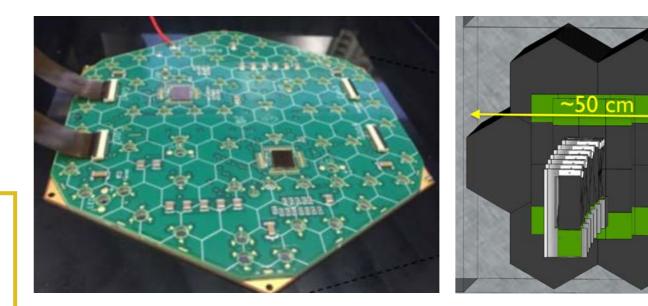
## Electromagnetic Calorimeter (Ecal)

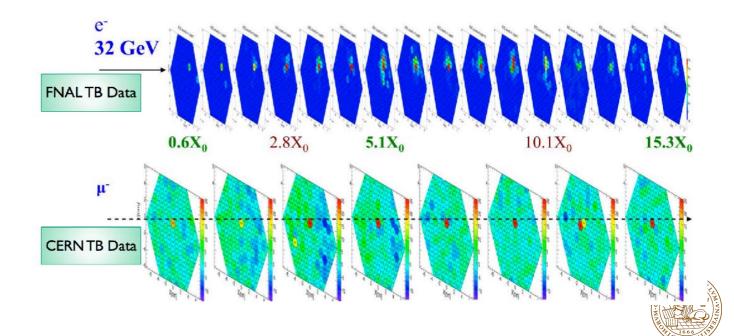
to achieve large number of electrons on target (10<sup>14</sup>-10<sup>16</sup>): high-rate beam (1e/few ns)

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

very similar to forward SiW sampling calorimeter for CMS@HL-LHC

design based on this





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Feb 22, 2018

Lunds



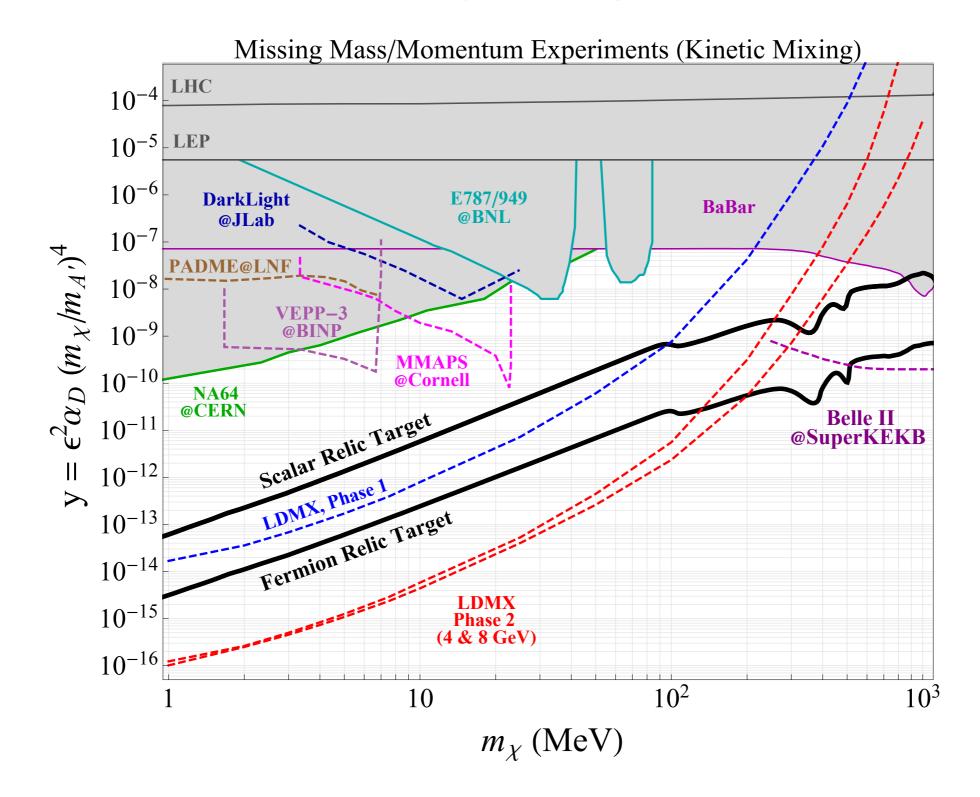
- very young experiment, still in planning phase
- will run at beam energies of 4 20 GeV (<< LHC)</li>
  - either at SLAC (California) or CERN
- detector components re-use methods from other experiments in unique combination —> unparalleled sensitivity
- main challenge: need extremely high background 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! :)

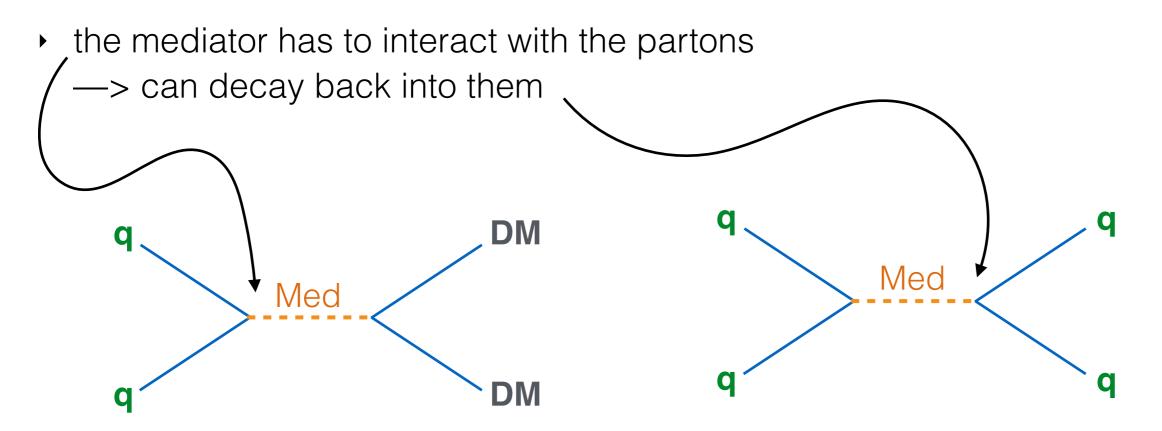




#### Additional Material

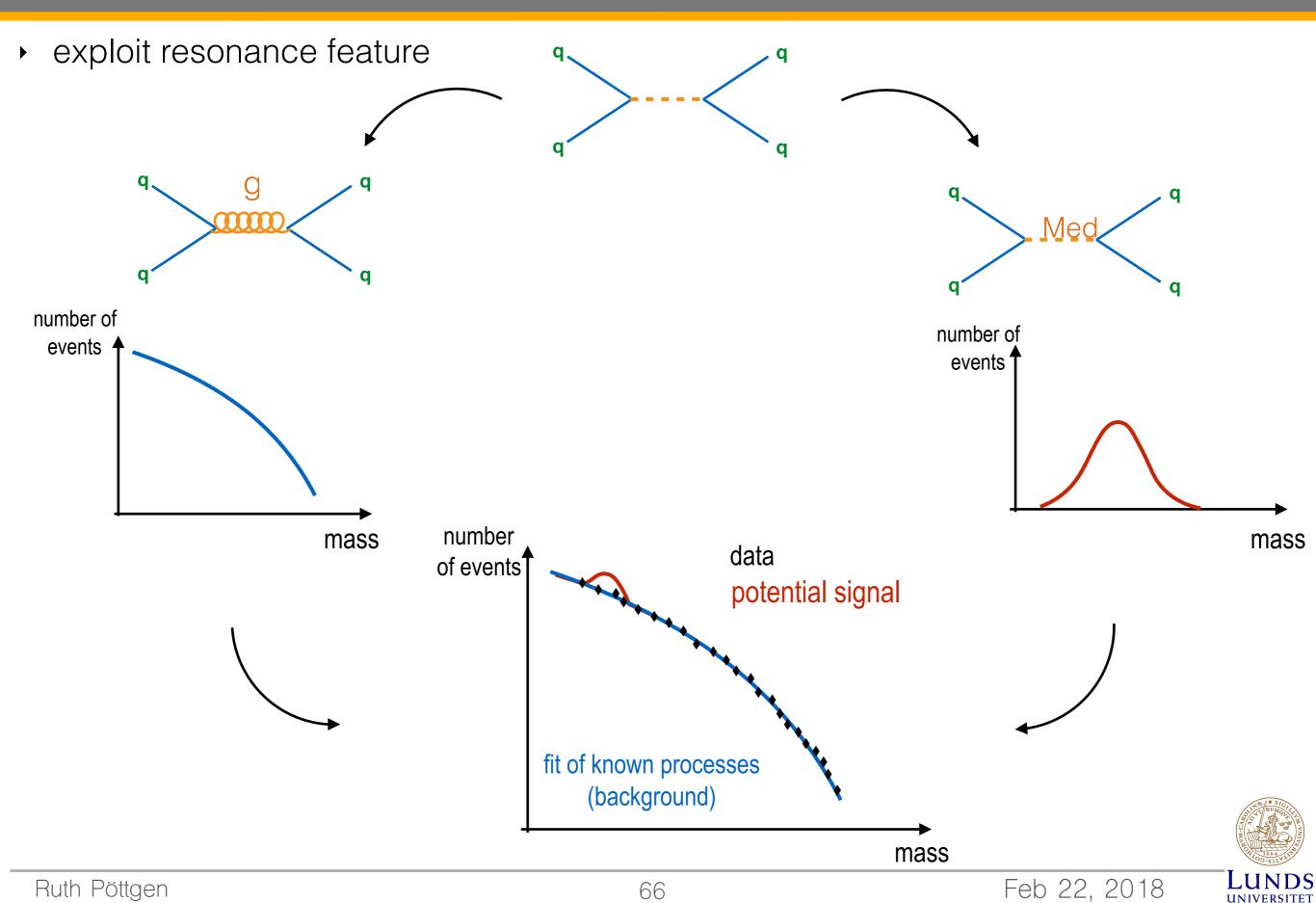
# Visible Signatures (Indirect)

- another approach: look for the mediator!
  - Dark Matter has to interact in order to be produced
     —> there must be a mediator



not looking for a signature of the actual Dark Matter

#### Di-Jet Events



## A beautiful di-jet event

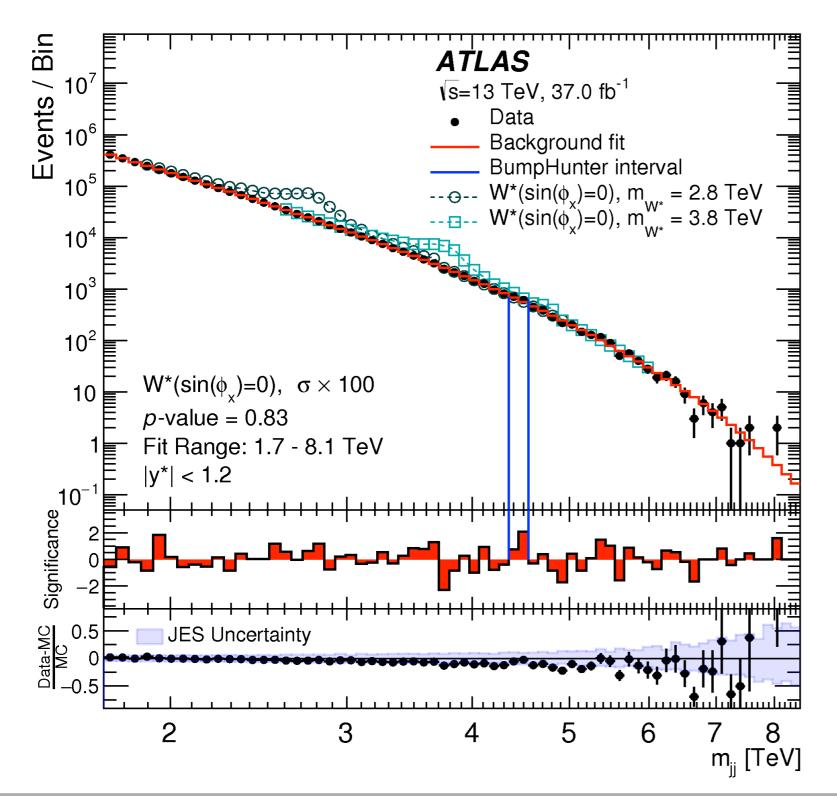


Run: 302053 Event: 2504627221 2016-06-15 00:12:21 CEST

# Mediator Searches

from a real publication

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



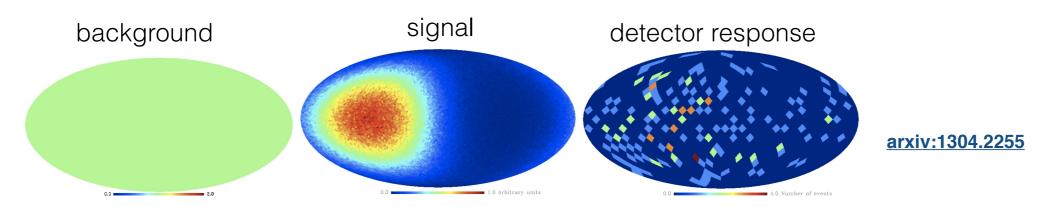
 no clear signal seen so far (but we keep looking! much more data still to be analysed!)



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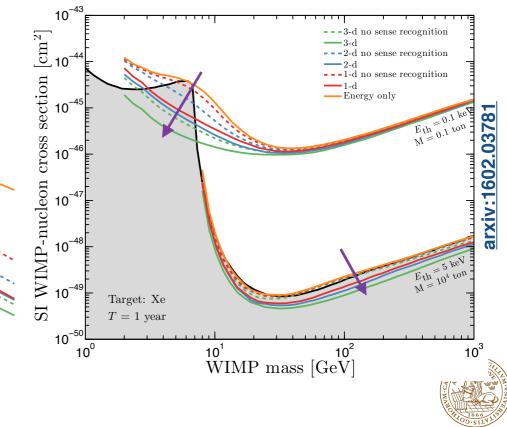
## **Directional Direct Detection**

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



- **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
    - very active area!

adding directional information



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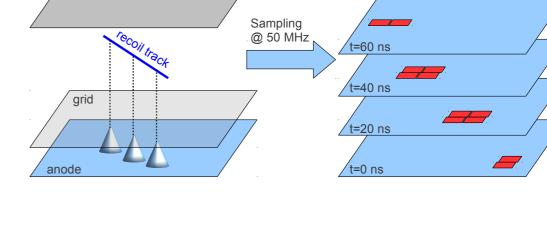
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### **Directional Direct Detection**

- 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



- next step: 1m<sup>3</sup> demonstrator towards 50m<sup>3</sup> TPC
  - very active research area!



cathode

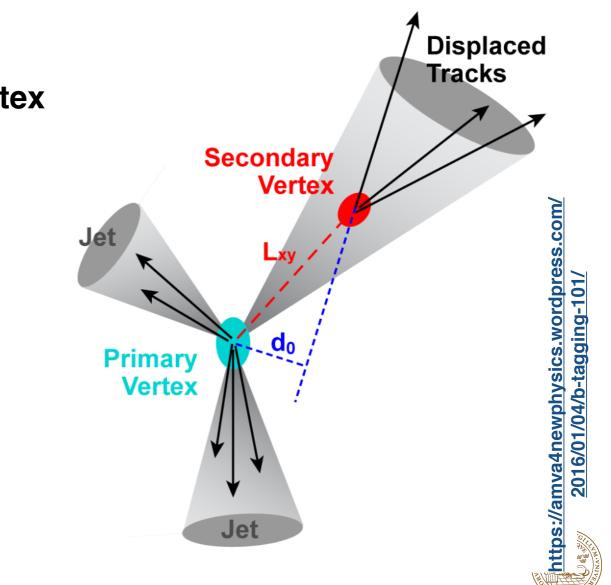


arxiv:1304.2255

# 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



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