Particle Physics
Lecture 5 - Experiments

Content

- Last 4 weeks:
  - nuclear physics, particles & history
  - forces
  - symmetries
  - cross-sections and Feynman rules

- Today:
  - Particle detection
  - Modern particle experiments and open questions

- Next week:
  - Accelerators & ELSA tour
  - Mini-symposium

Particle detection

How to detect particles?

- Charged particles:
- Neutral particles:
- Particles with short lifetime

How to detect particles?

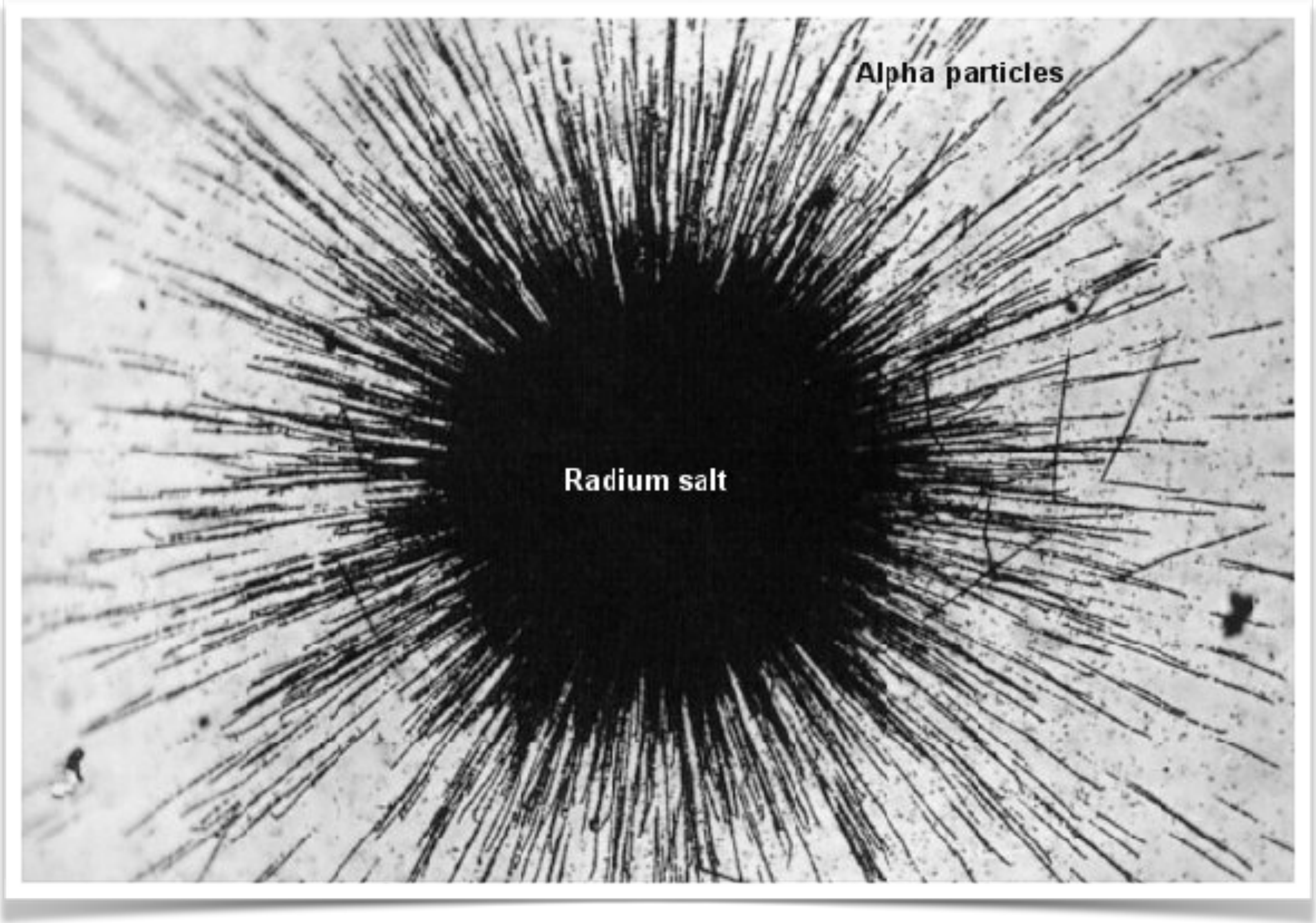
- Charged particles:
  - ionize the medium - electromagnetic interaction

- Neutral particles:
  - force them to lose all their energy —> ‘Calorimetry’
  - neutrino’s: Large volume, low background, wait a long time…

- Particles with short lifetime
  - reconstruct decay products & ‘track’ them to a point of origin

First detectors

- Photographic plate: radiation creates ‘blobs’ [Curie]
- Used in balloon experiments for cosmic ray detection

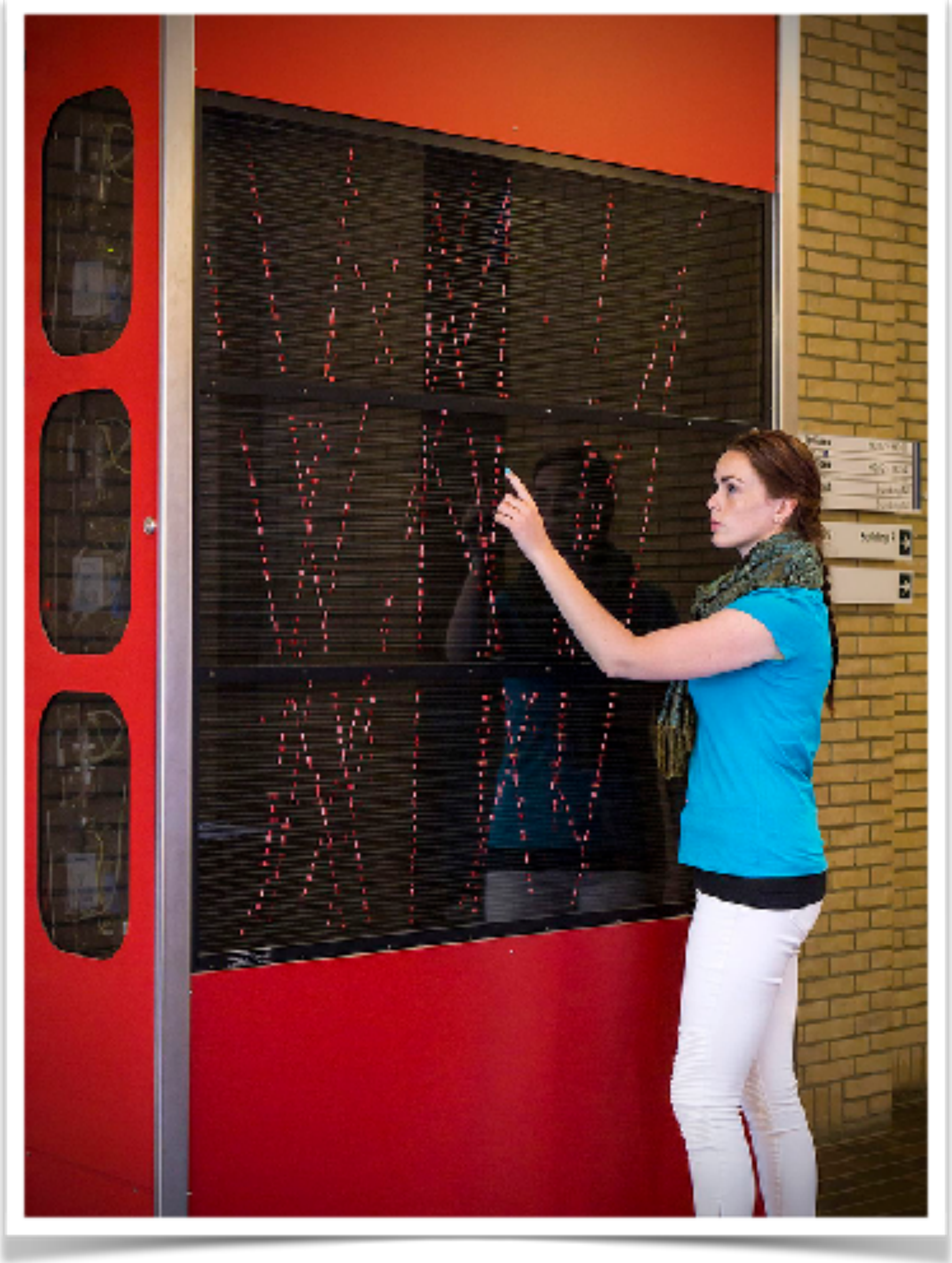


- Can be used to measure ‘intensity’ after a certain time.

First detectors

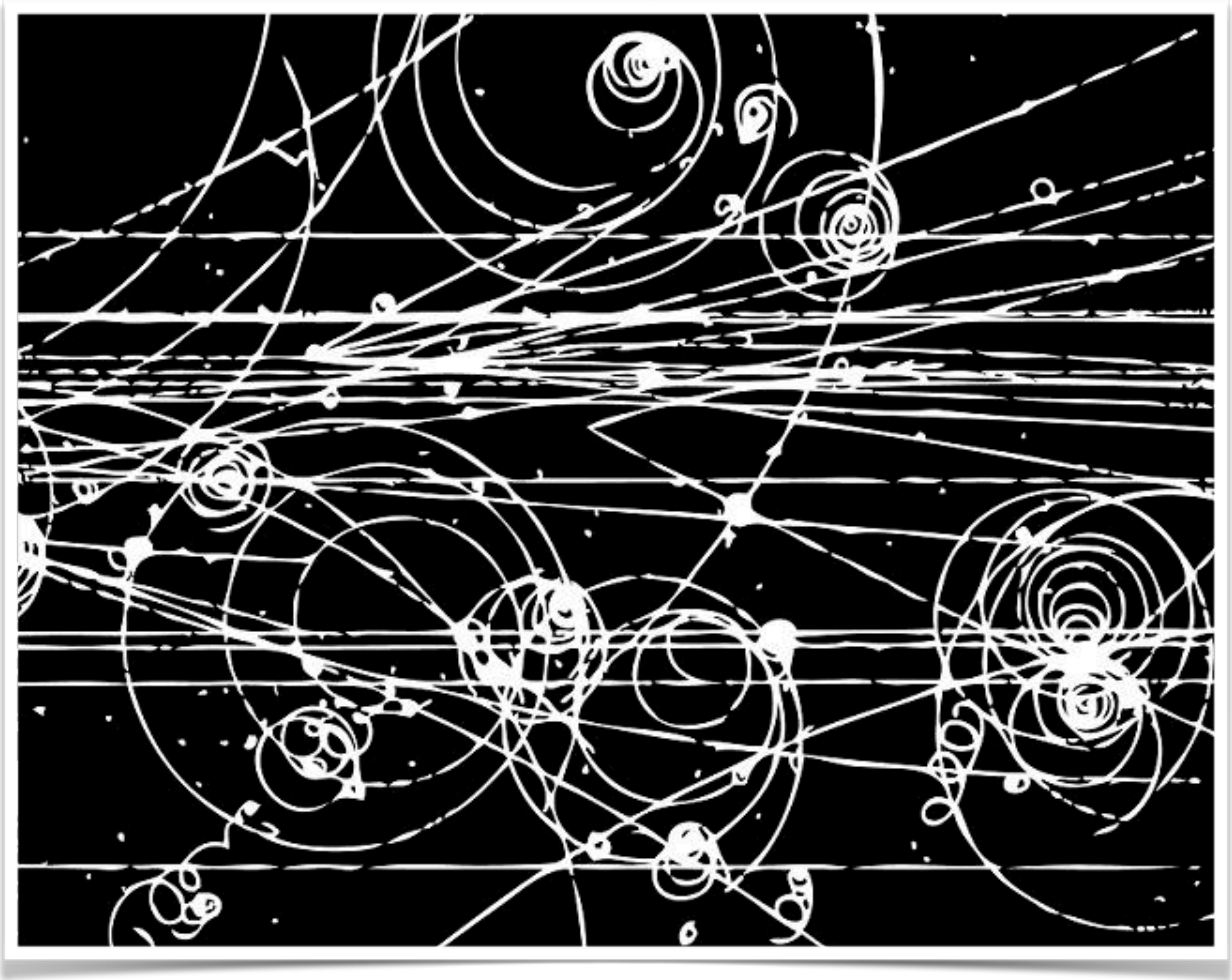
- Spark chamber:
  - particles ionize gas between plates
  - plates are under +- high voltage
    —> create 'lightning'

- Can see particles real-time



https://www.youtube.com/watch?v=DpW08xV3RI8

Bubble chamber



Bubble chamber

- Supercooled gas
- Charged particles create ‘condensation nuclei’ —> tracks

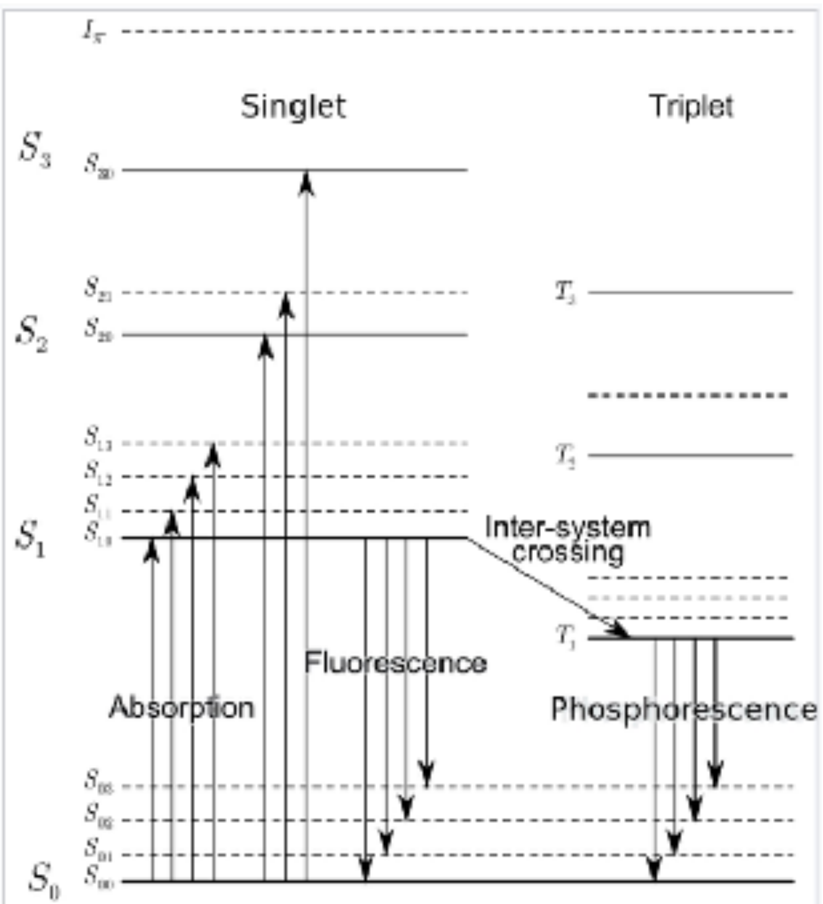
- Can ‘see’ particle decays
- Can be used ‘real-time’
- Can measure distances
  (in combination a with picture)
- With <u>magnetic field</u>:
  can calculate momentum
  - $qvB = mv^2/R$ —> $mv = qBR$

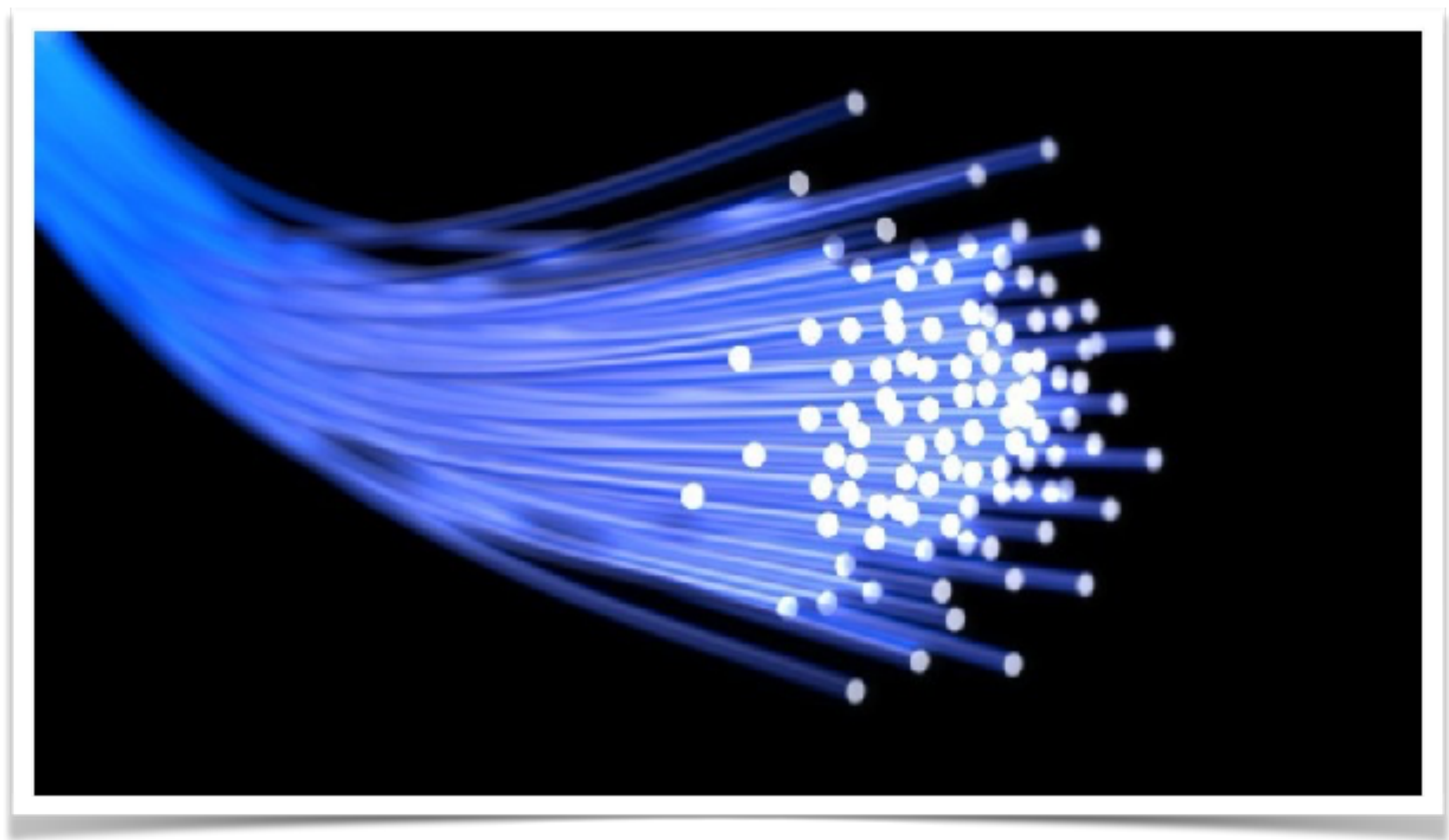
- Not automatic…

https://www.youtube.com/watch?v=rZR8cnF98ns

Scintillation detectors

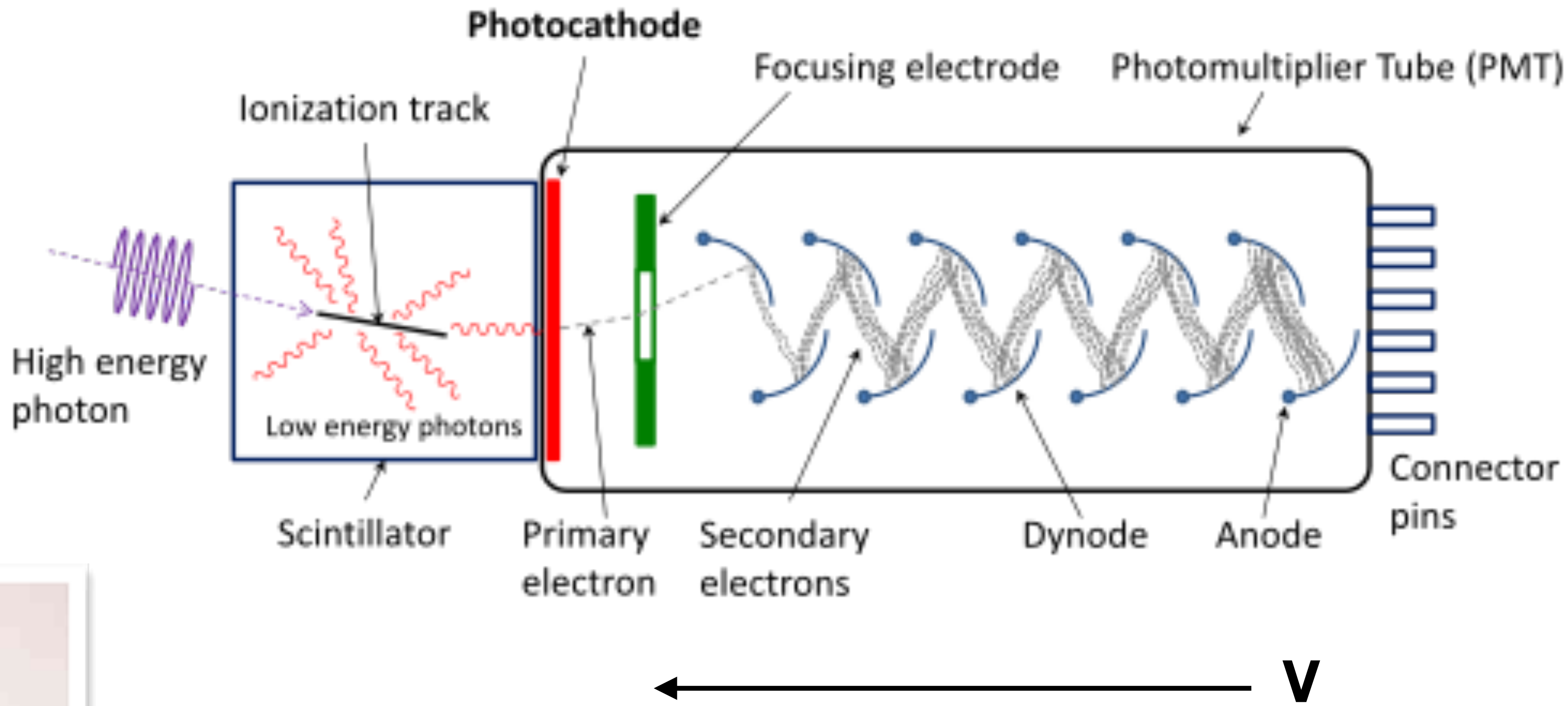
- Particle passes through luminescent/phosphorescent material
  —> material gets excited, and then emits light
  (inorganic crystals, organic materials)





Scintillation detectors

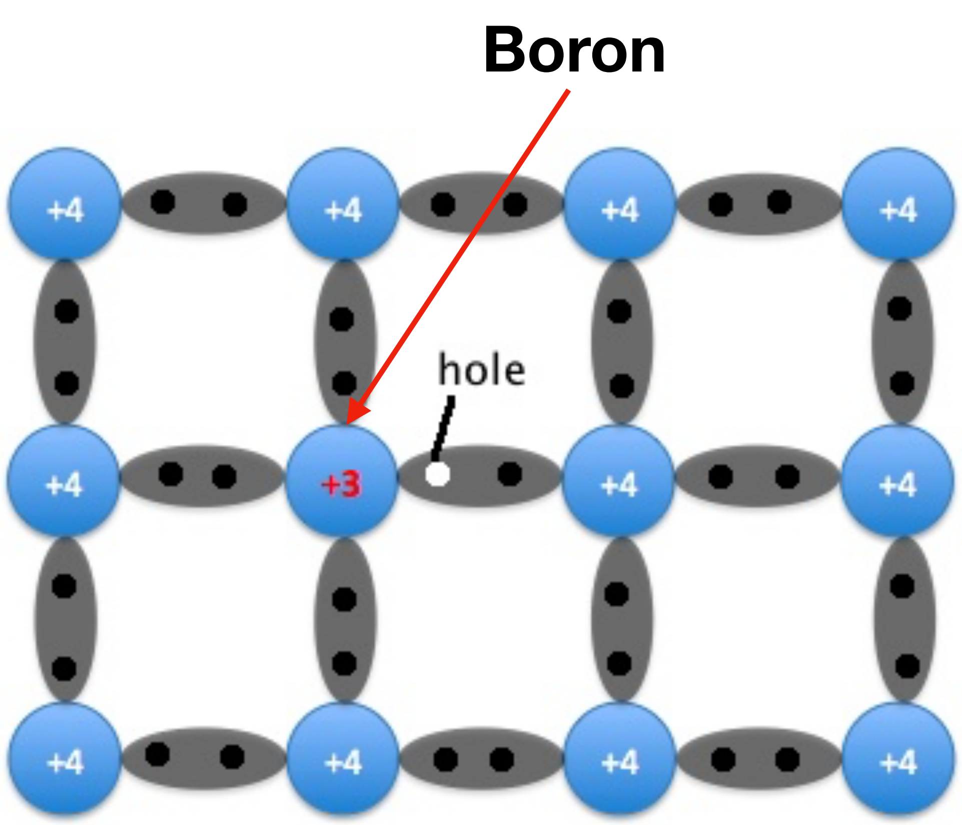
- Particle passes through luminescent/phosphorescent material —> material gets excited, and then emits light
- Capture light with PhotoMultiplier (PM) tube



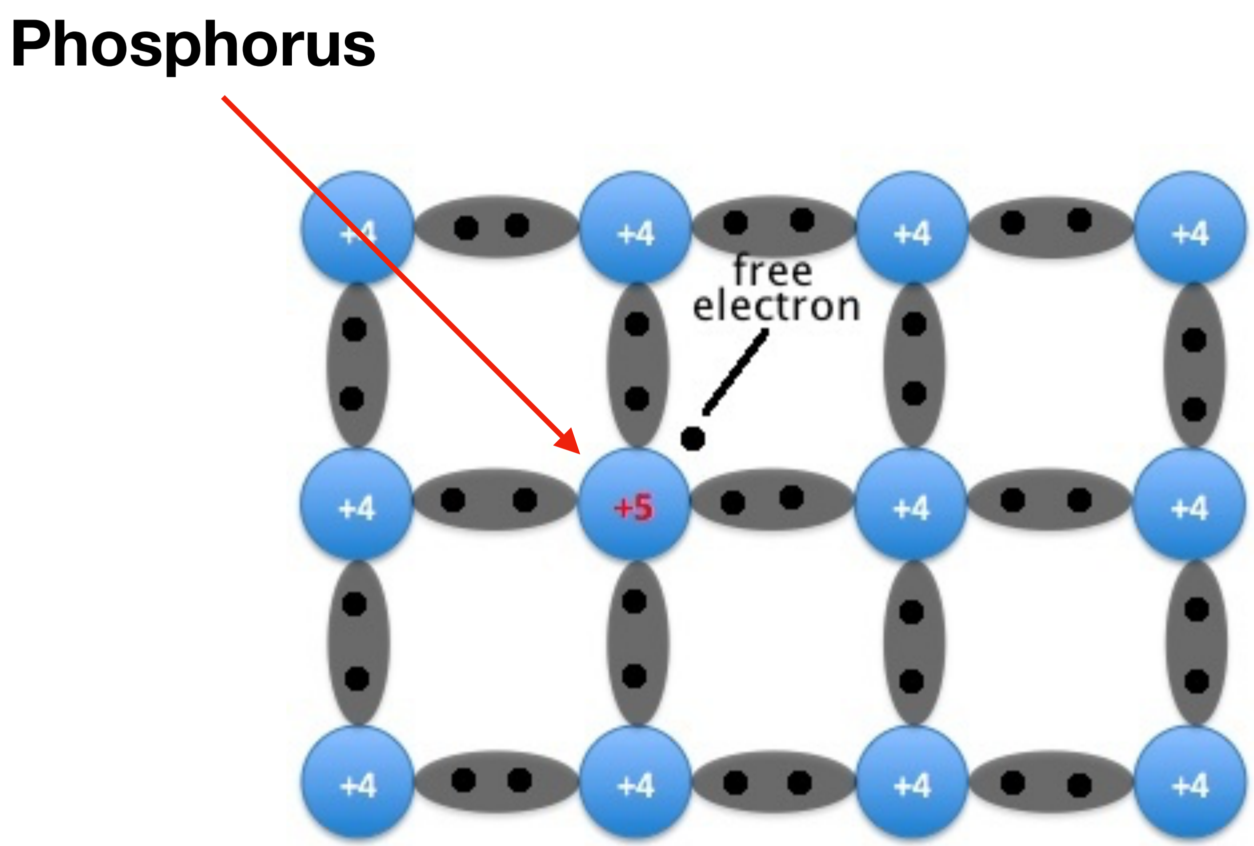
- Detect current —> signal
- ‘Cheap’, efficient, but bulky

Silicon detectors

- Silicon: semiconductor, and largely available
- Add impurities into lattice: introduce free charge carriers (now conducting, but material still electrically neutral!)



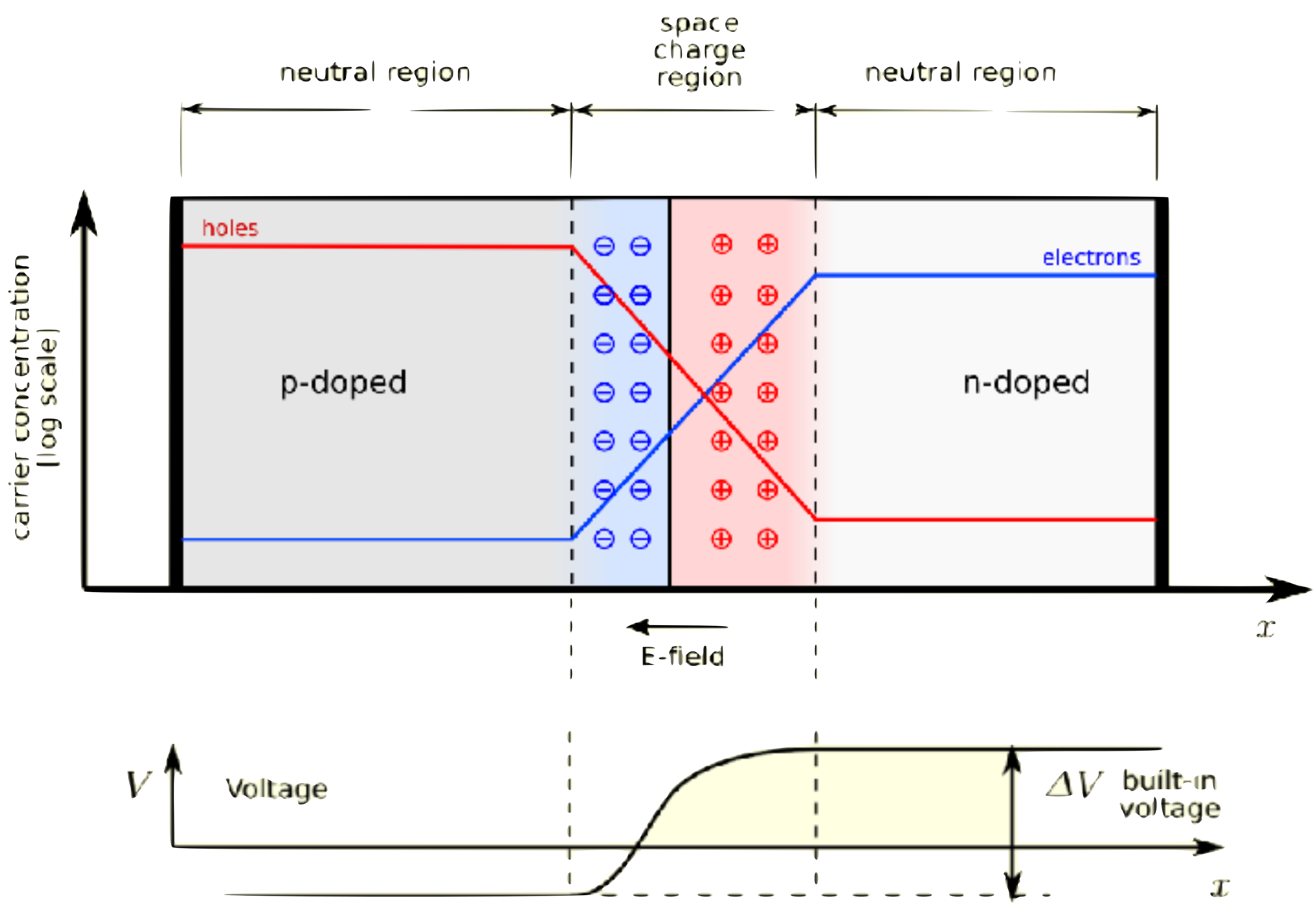
P-type



N-type

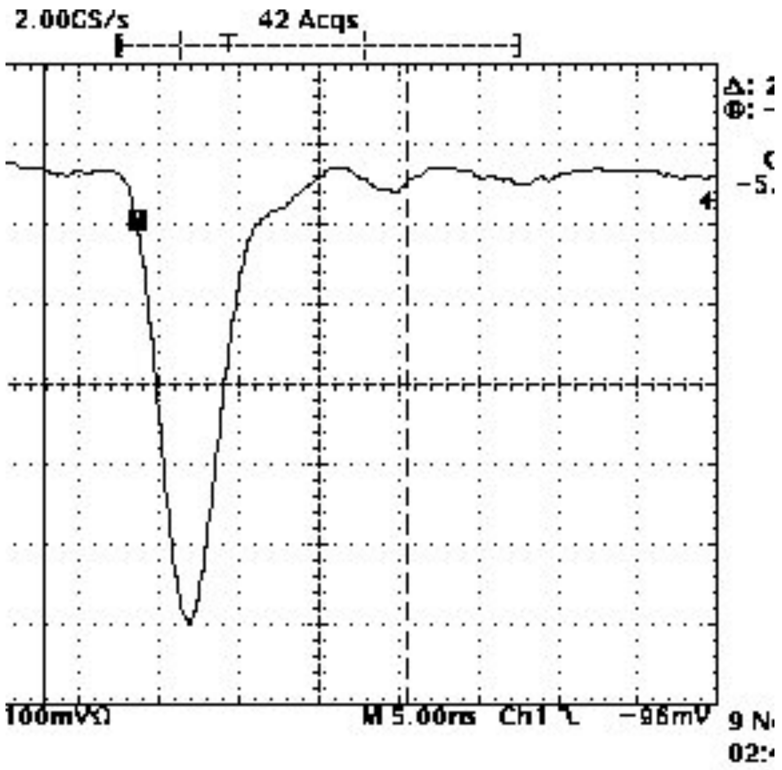
Silicon detectors

- Add P- and N-type materials together: PN junction
  - System naturally reorders: non-conducting 'depletion region'.



Silicon detectors

- Add P- and N-type materials together: PN junction
  - System naturally reorders: non-conducting ‘depletion region’.
- Enhance region by adding ‘reverse bias voltage’
- If ionising particle passes through depletion region:
  - briefly becomes conducting again
  - electric ‘signal’ passes through.
- Enhance, shape, integrate, and readout!

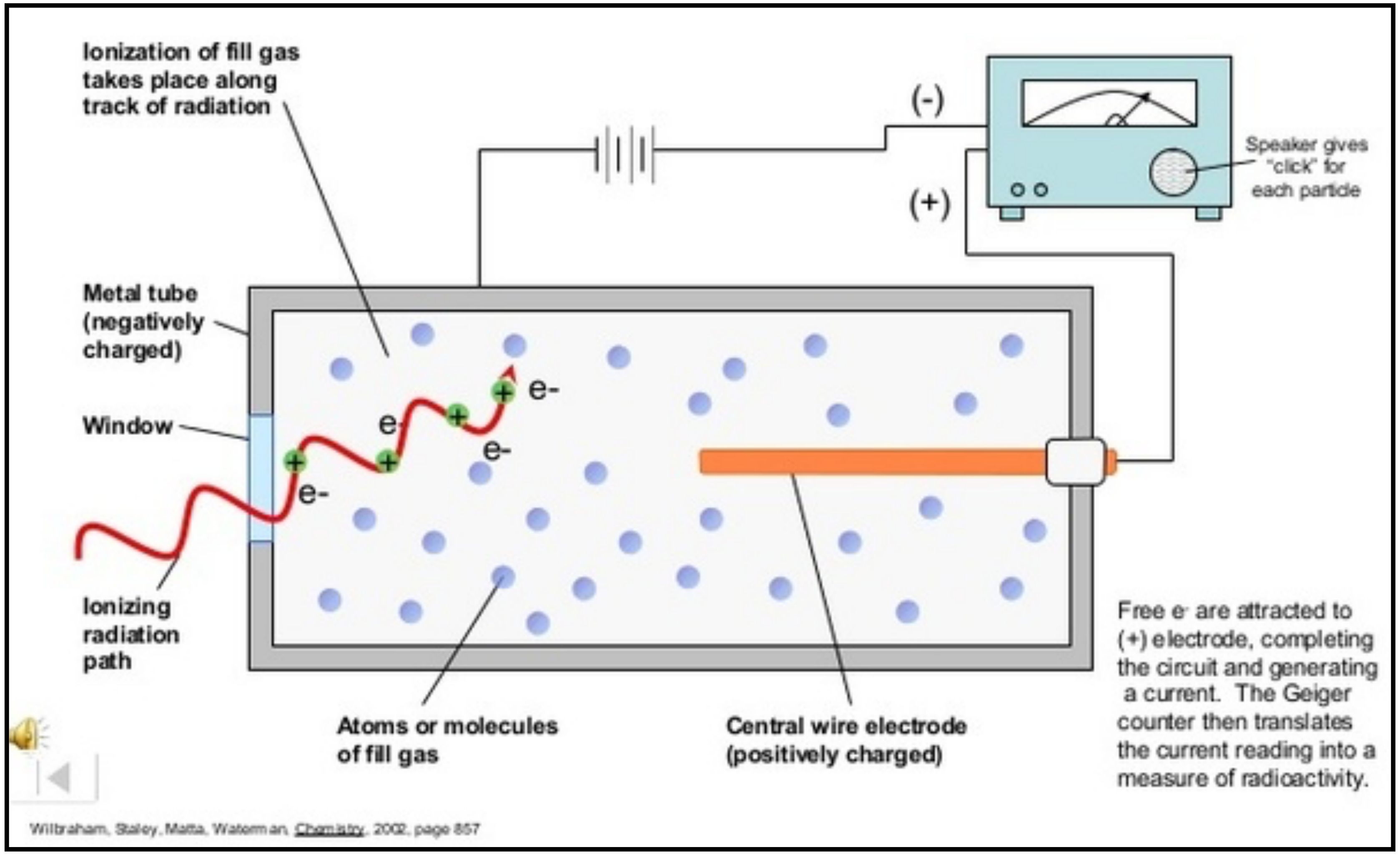


- Very fast! High resolution ‘pictures’!
- Expensive, not very radiation hard, and can be ‘thick’

Gas detectors

- Idea:
  1) Fill an area with gas, which traversing particles will ionize
  2) Find a way to detect these charges

- Geiger-Muller counter

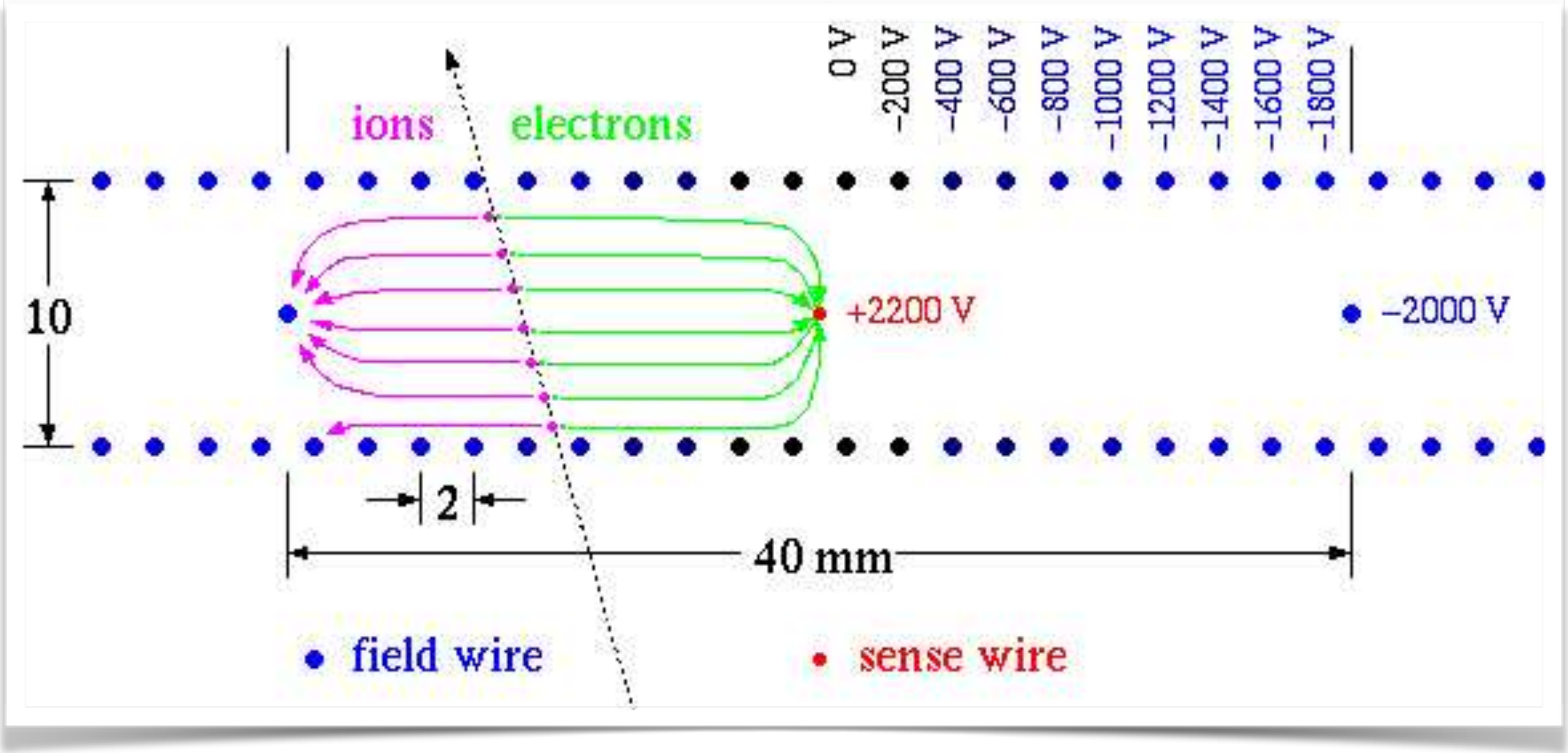


Drift chamber

Belle drift chamber, KEK, Tsukuba, Japan

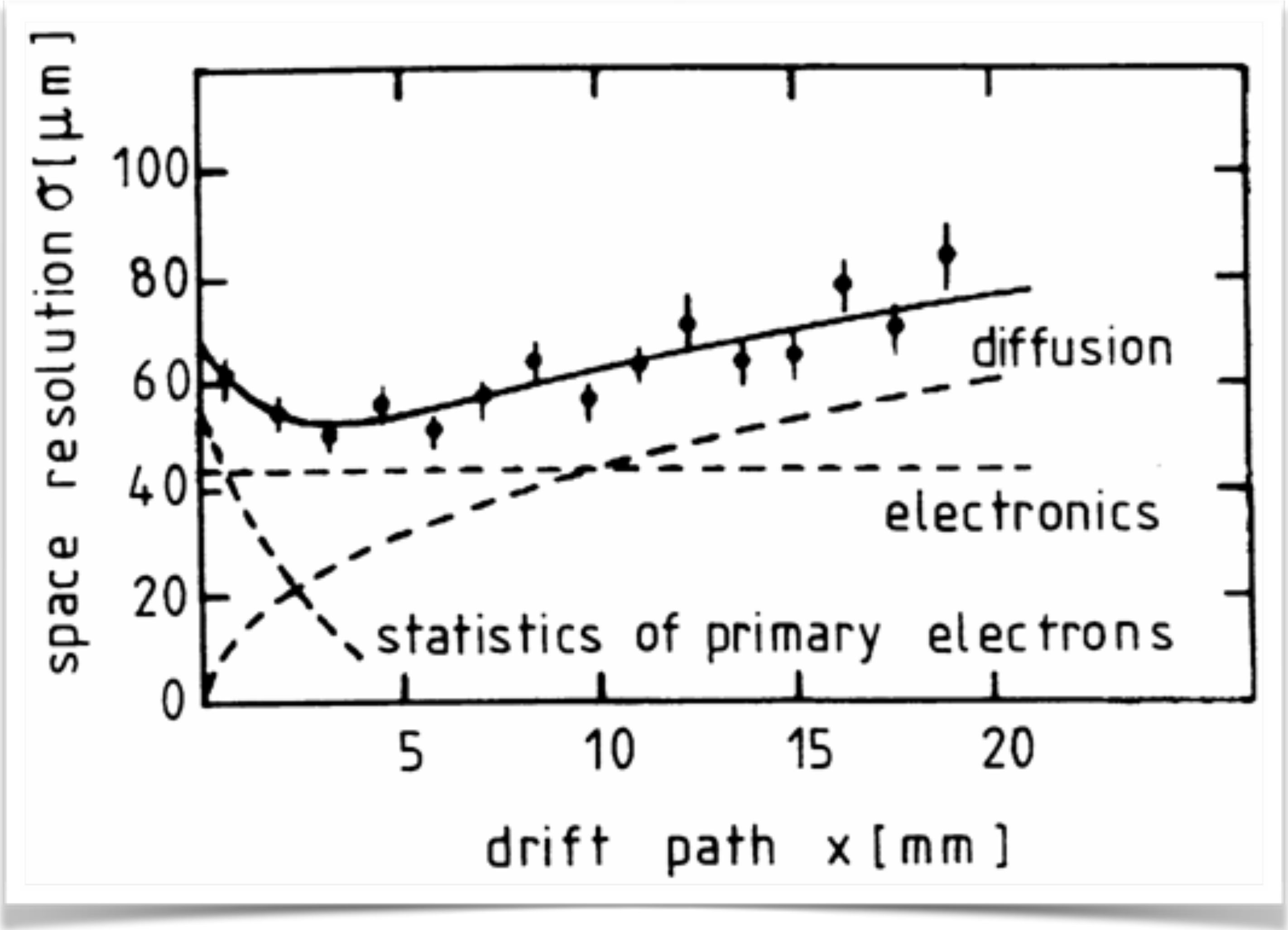
Drift chamber

- Charges ‘drift’ to detection plane under high electric fields



Drift chamber

- Charges ‘drift’ to detection plane under high electric fields
- While they drift, charges undergo diffusion…



Drift chamber

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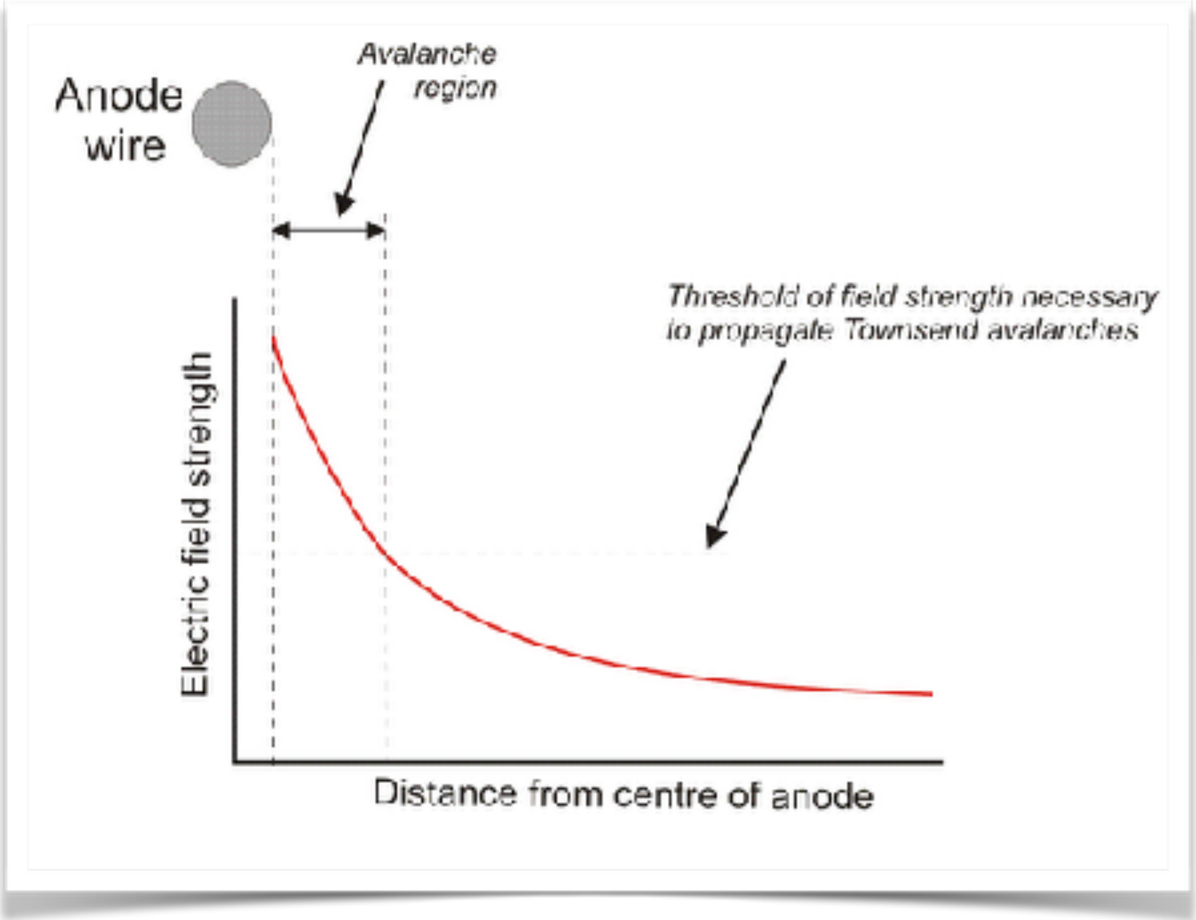
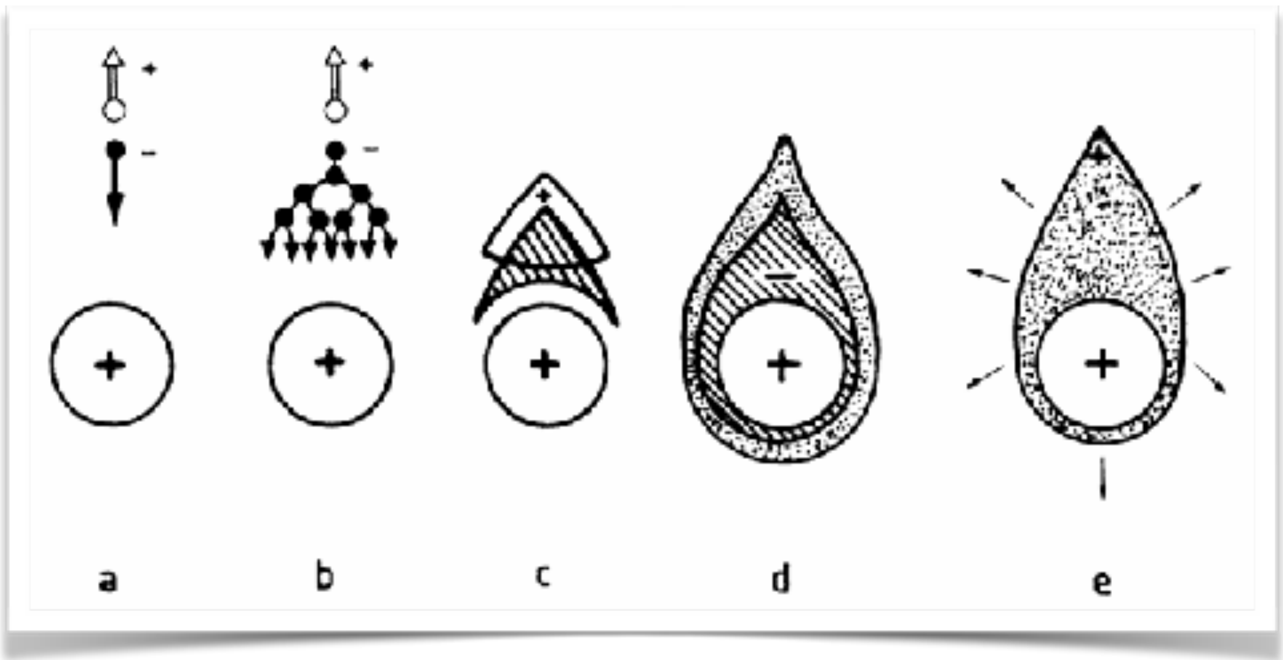
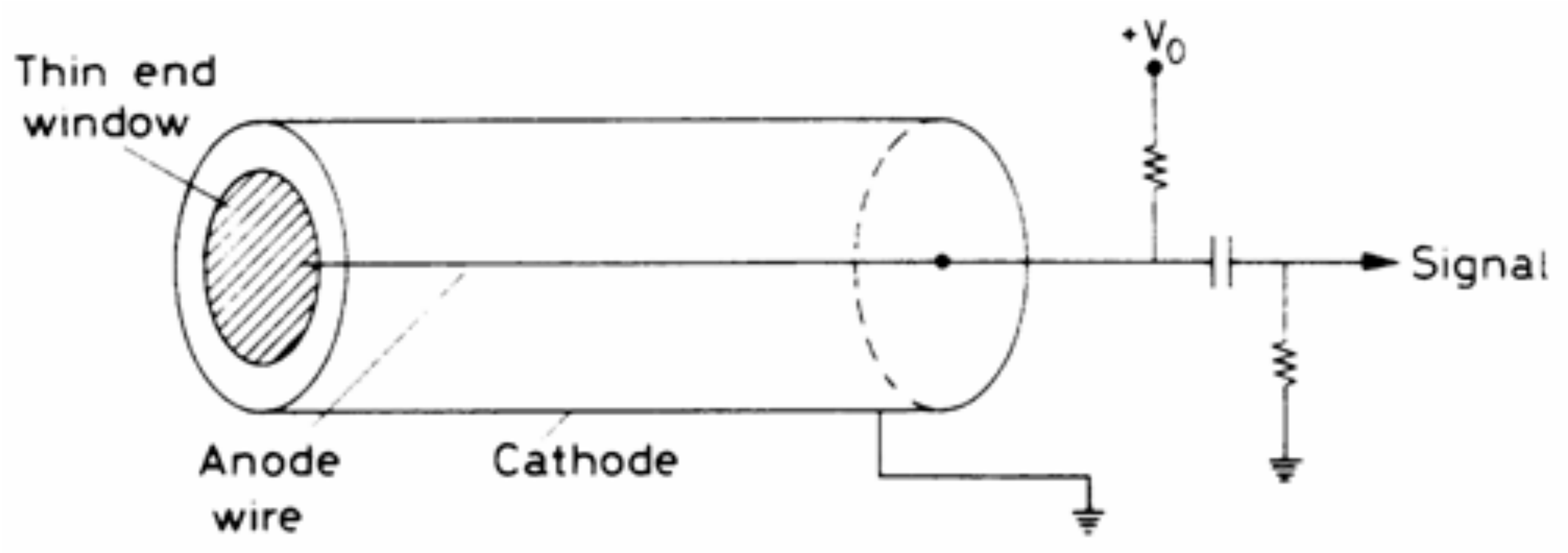
- Near the wire, the acceleration causes multiplication





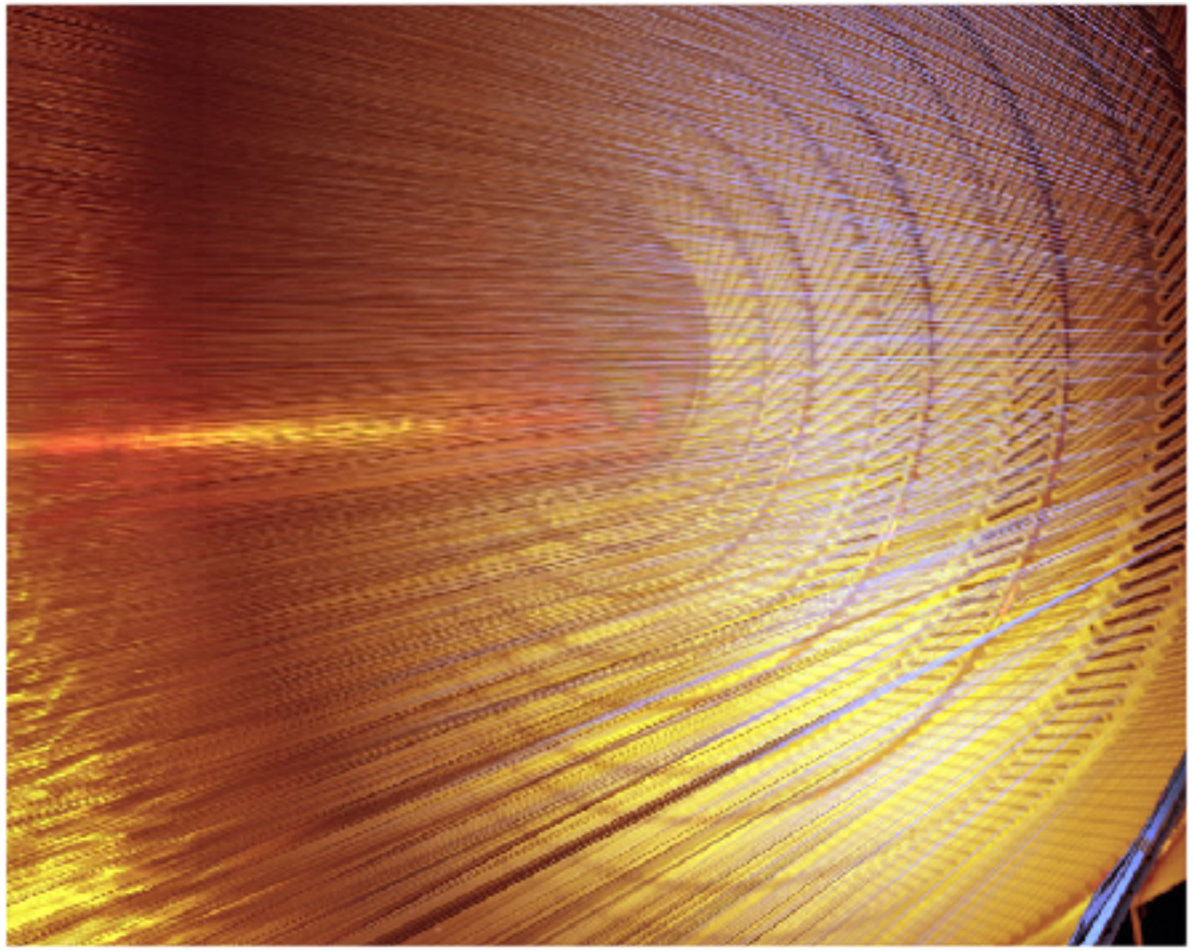
Drift chamber

- Charges ‘drift’ to detection plane under high electric fields
- While they drift, charges undergo diffusion…
- Near the wire, the acceleration causes multiplication
- Finally, the signal is caught by the anode



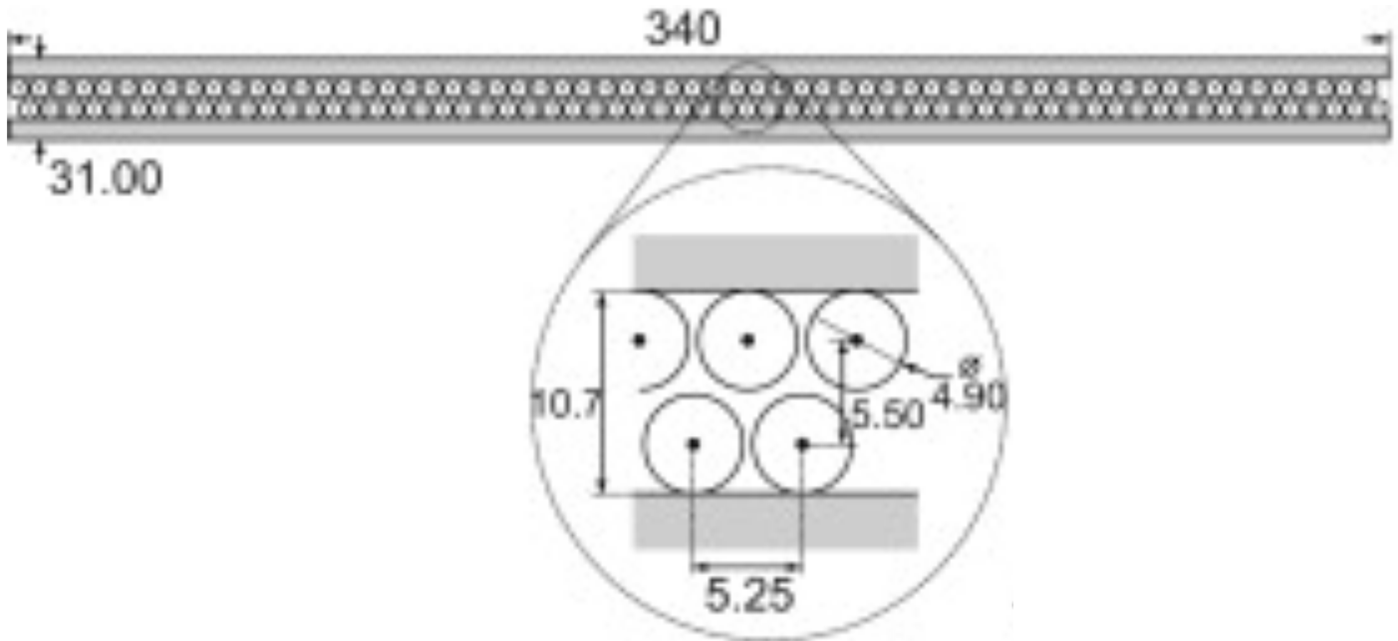
Drift chamber

- z-location of charge = [drift time] x [drift velocity]
  —> constant E-field!
- Choice of drift gas important (Argon: ampl. CO_2: quenching.)
- Radiation hard, 'cheap', and creates (x,y,z) point!
- Usually long drift time, and not great spacial resolution.



Straw tube tracker

- Create many little ‘drift chambers’ with one central wire
- ‘Timing’ measures distance from central wire



- ‘Cheap’ coverage of large areas, and good resolution (~100 um)
- Relatively ‘thin’, and small drift times (~50 ns)
- Only one ‘hit’ per straw possible: 0.5 cm vs 50 um (silicon)

Detecting particle types

- So far: detecting the location of particles. What about ID?
  - Energy loss
  - Cherenkov radiation
  - Time-of-flight

Energy loss

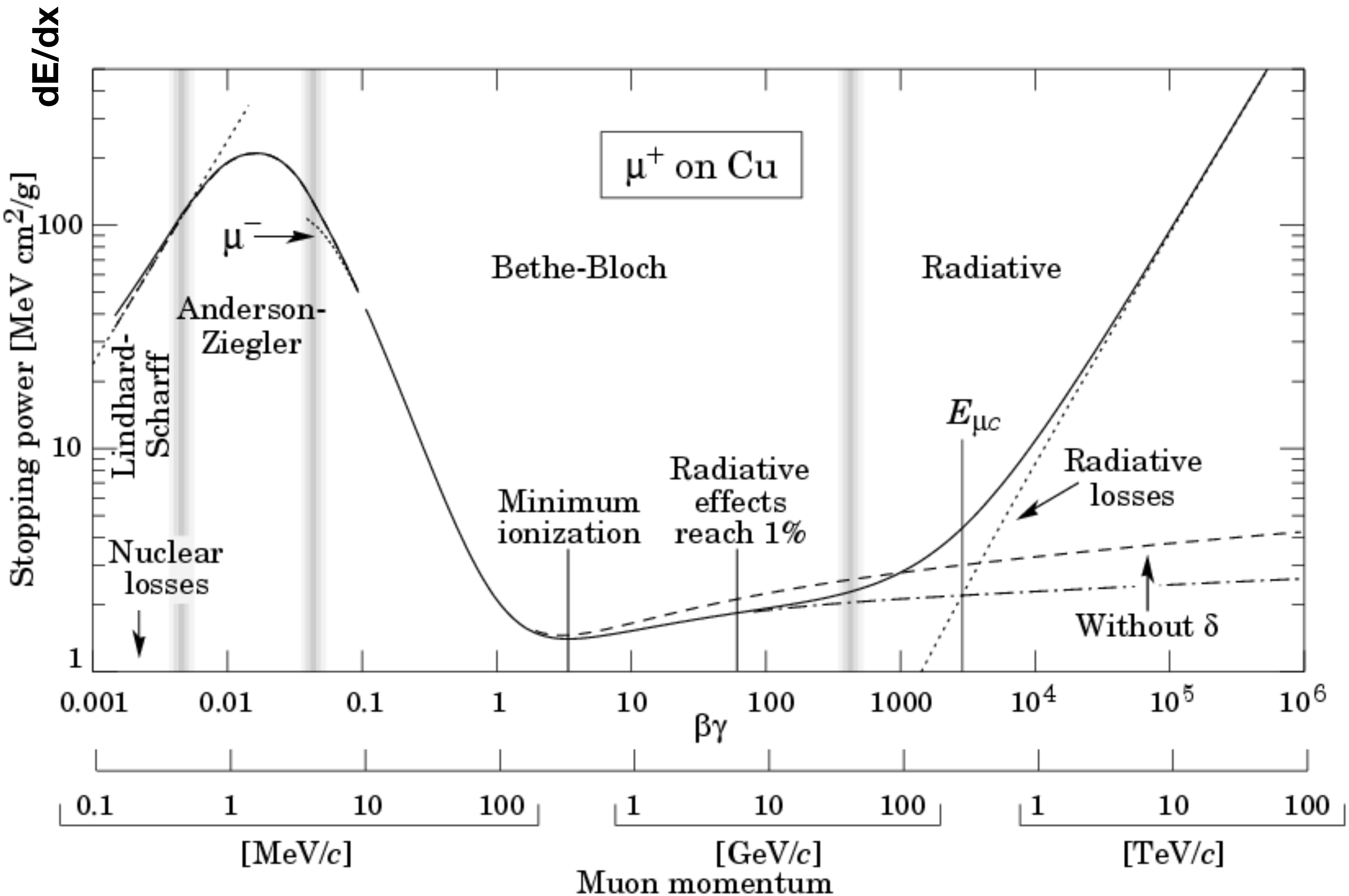
- ‘stopping power’, called dE/dx
  - Mostly through coulomb interactions with material
  - Ionisation of medium: drops as ~1/v^2. Bethe-Bloch equation:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

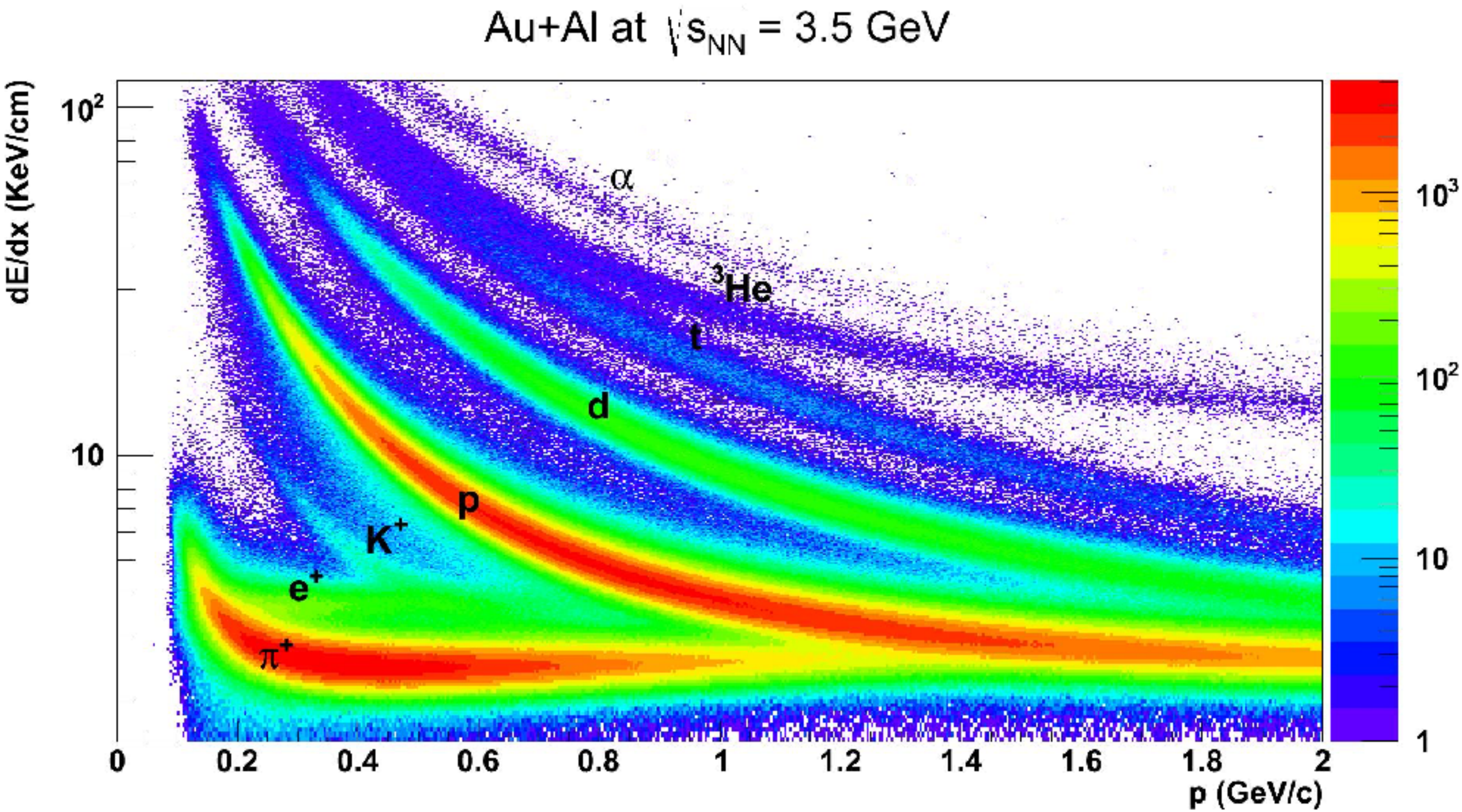
- at low momenta: nuclear effects
- at high momenta: radiation, brehmsstrahlung

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf

Energy deposit

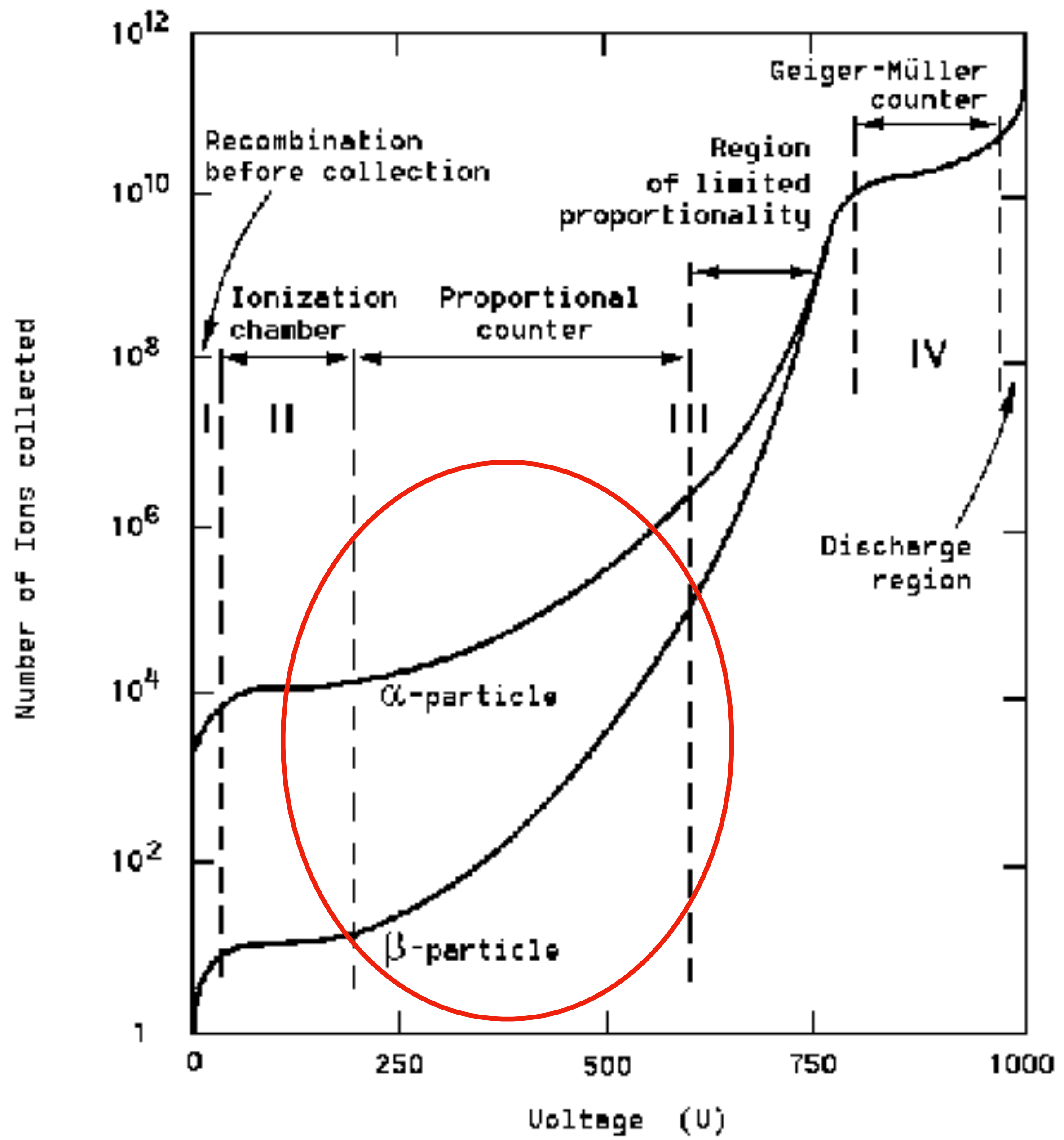


Energy deposit



Energy deposit

- Can detect by measuring the charge deposited (charge ~ E)

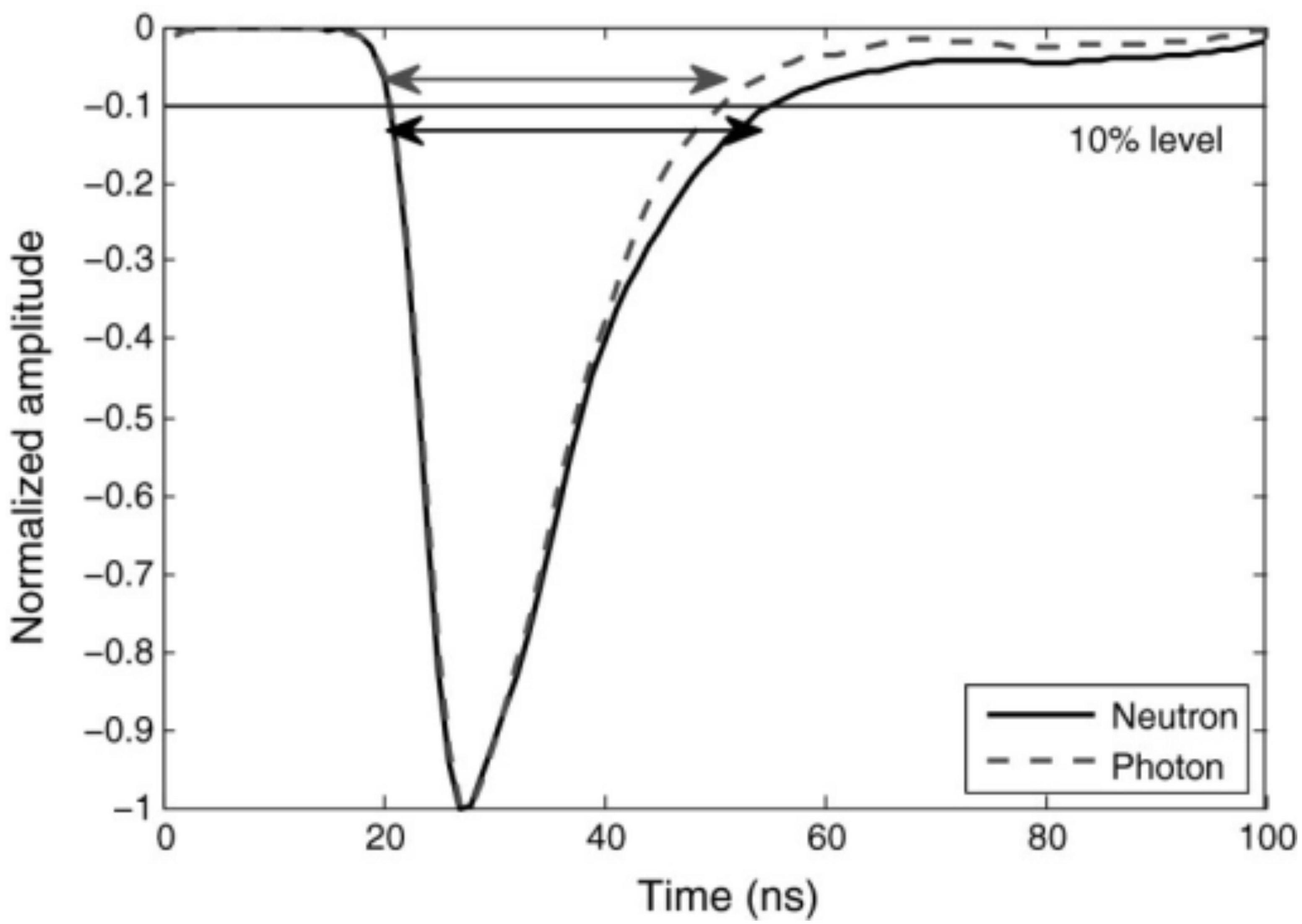


Energy deposit

- Can detect by measuring the charge deposited (charge ~ E)
- By measuring the number of ionisation clusters

Energy deposit

- Can detect by measuring the charge deposited (charge ~ E)
- By measuring the number of ionisation clusters
- Or by measuring the 'time over threshold' of the voltage/current



Cherenkov radiation

- if $v > v_{wave}$ of medium: conic emission of waves

Cherenkov radiation

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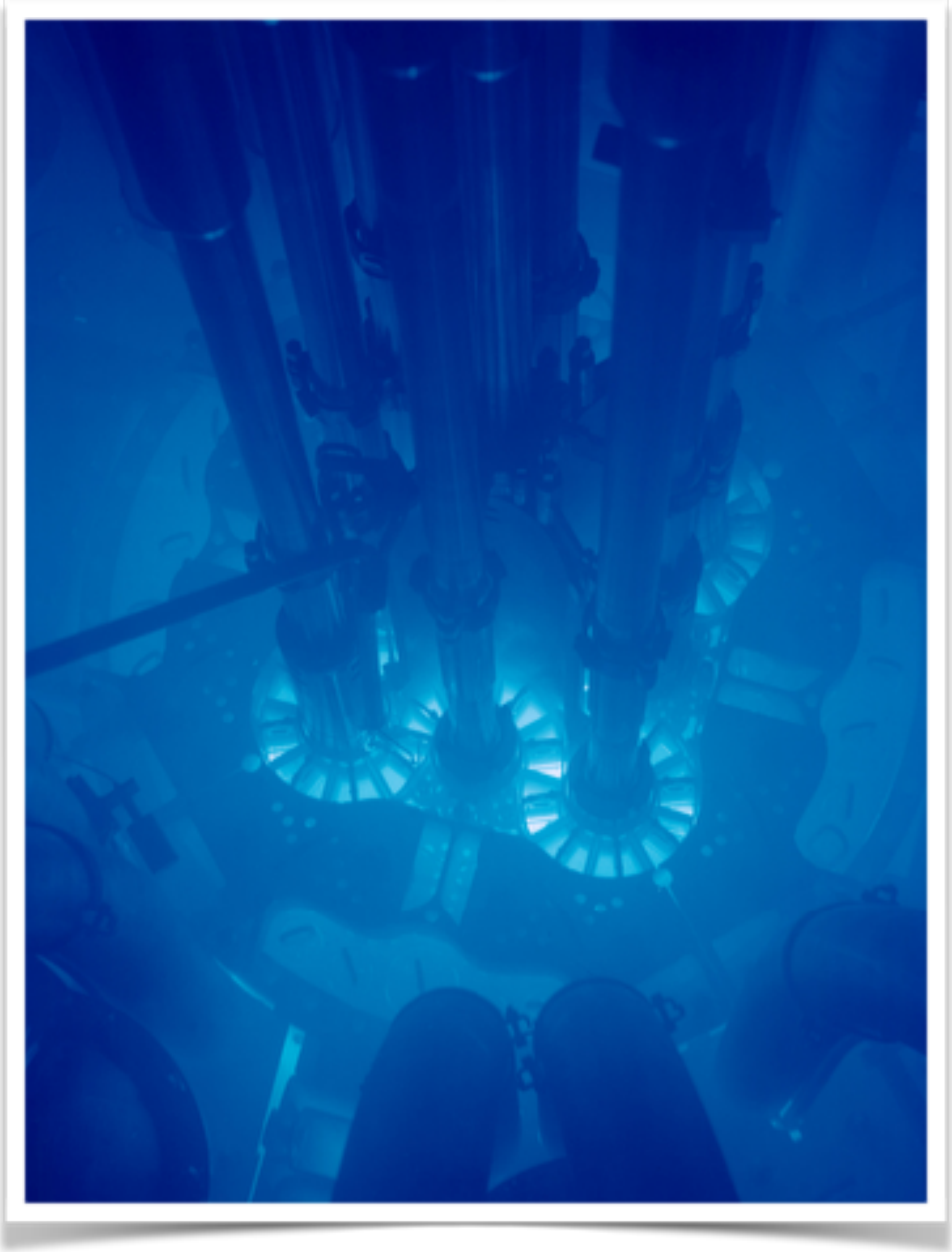
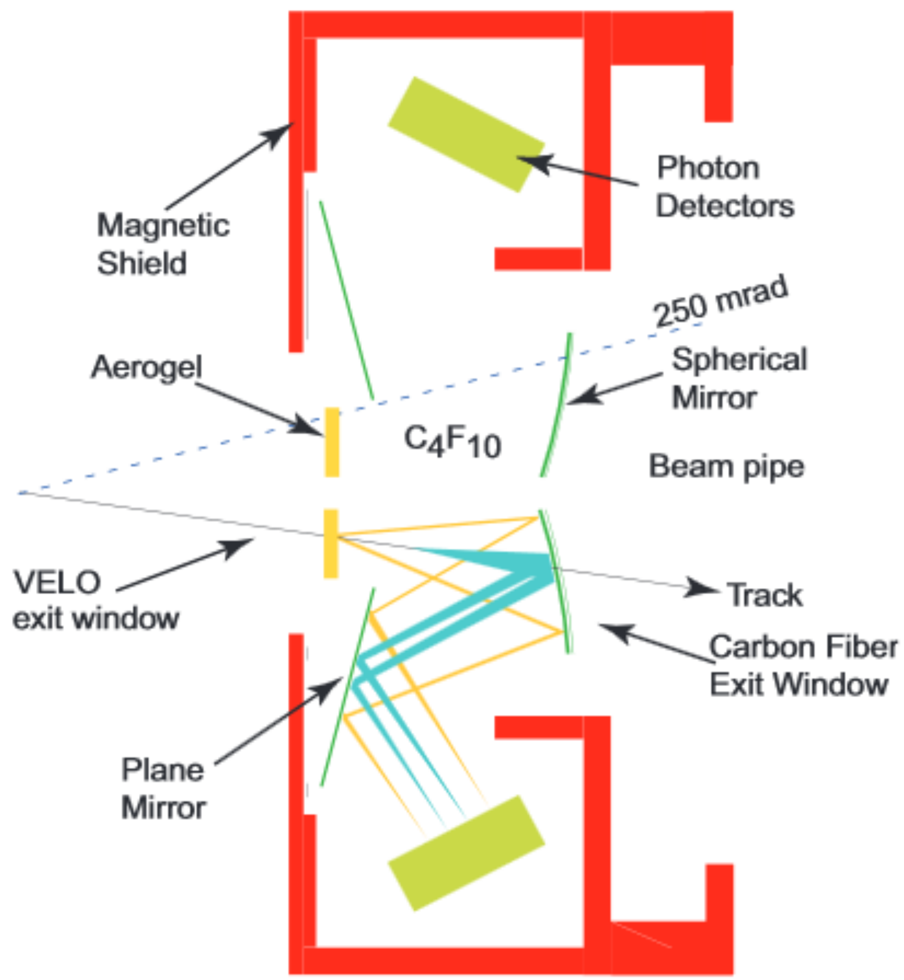
- if $v > c_{light}$ of medium: emission of Cherenkov light

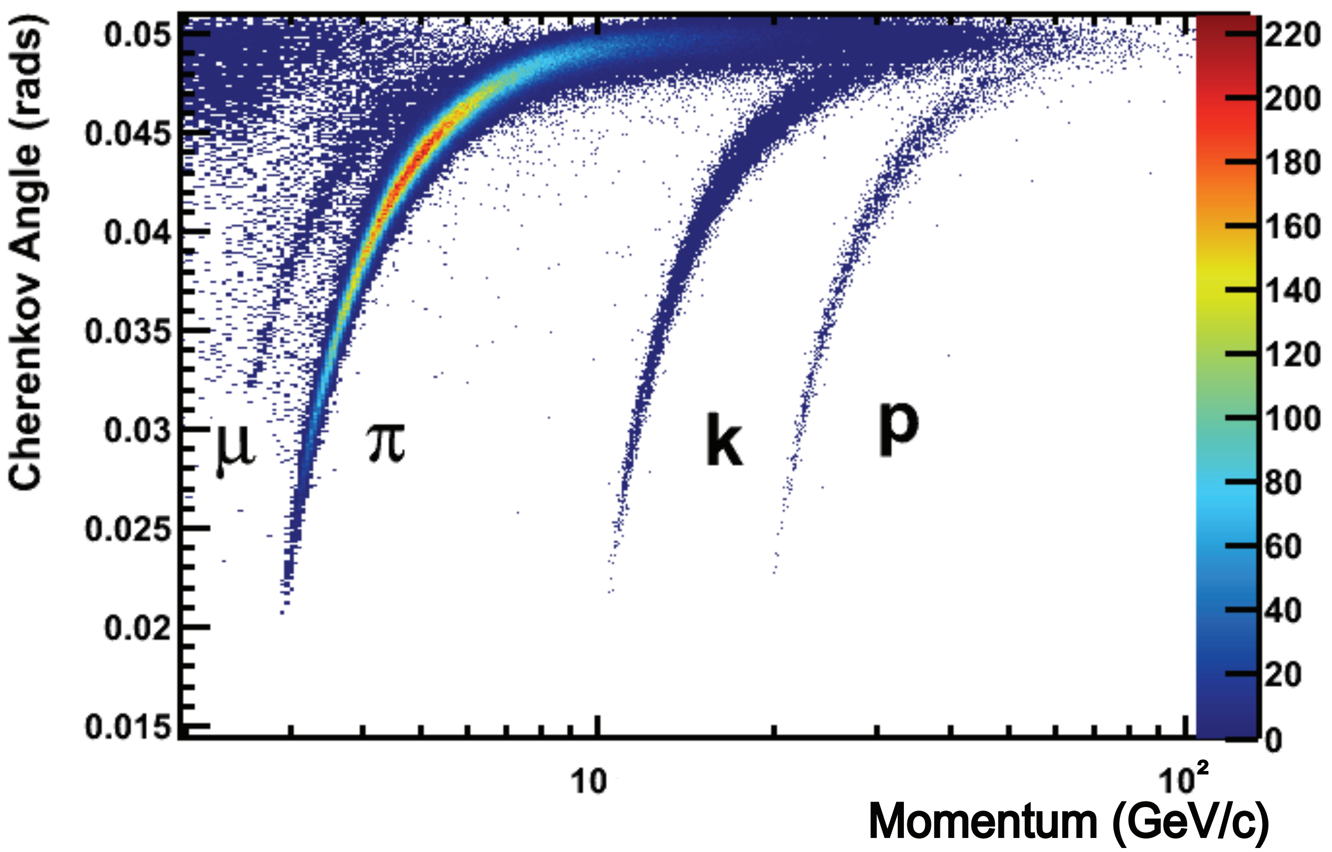


Cherenkov radiation

- if v > v_{wave} of medium: conic emission of waves
- if v > c_{light} of medium: emission of Cherenkov light

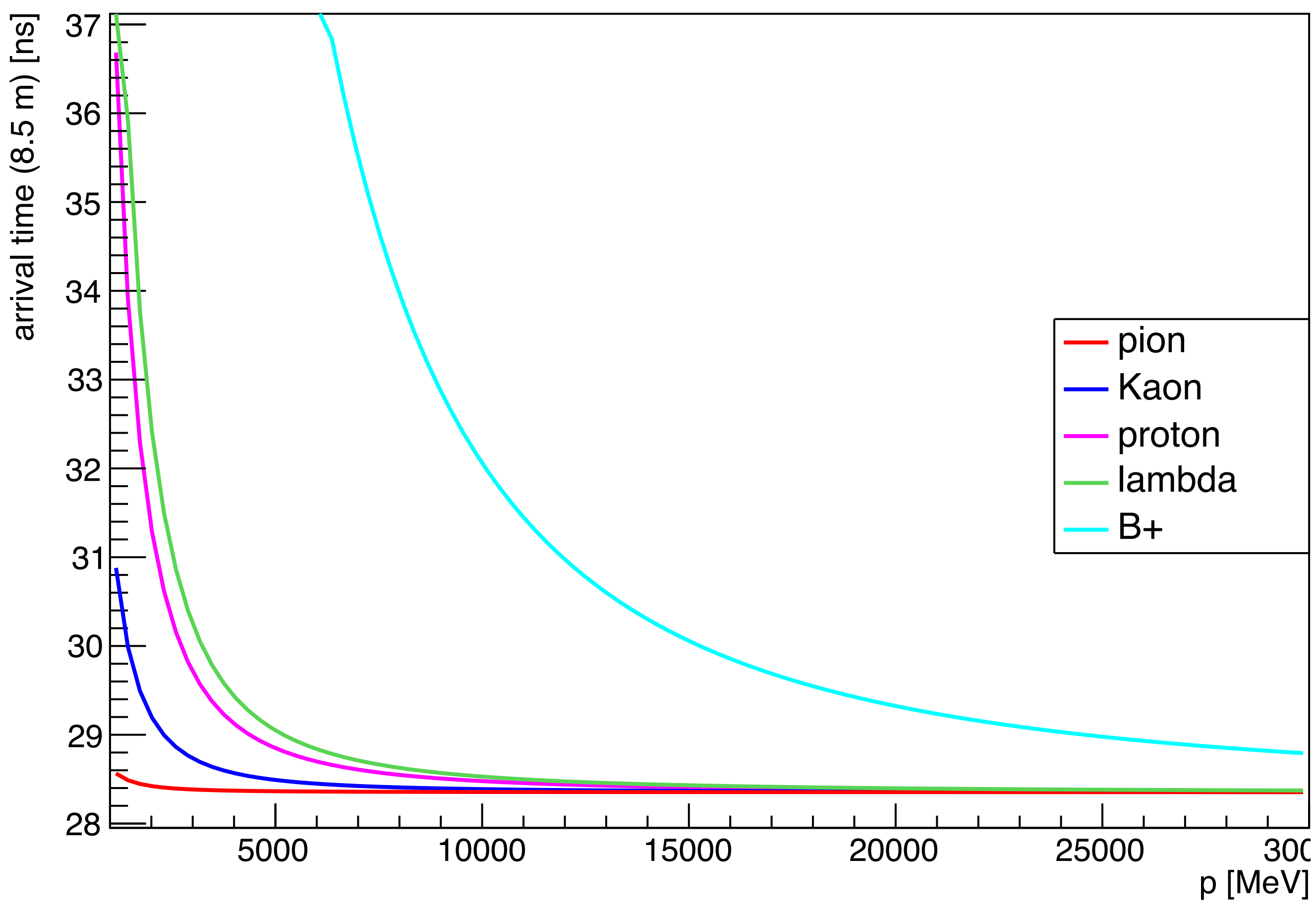
$$\cos(\theta) = \frac{1}{n\beta}$$

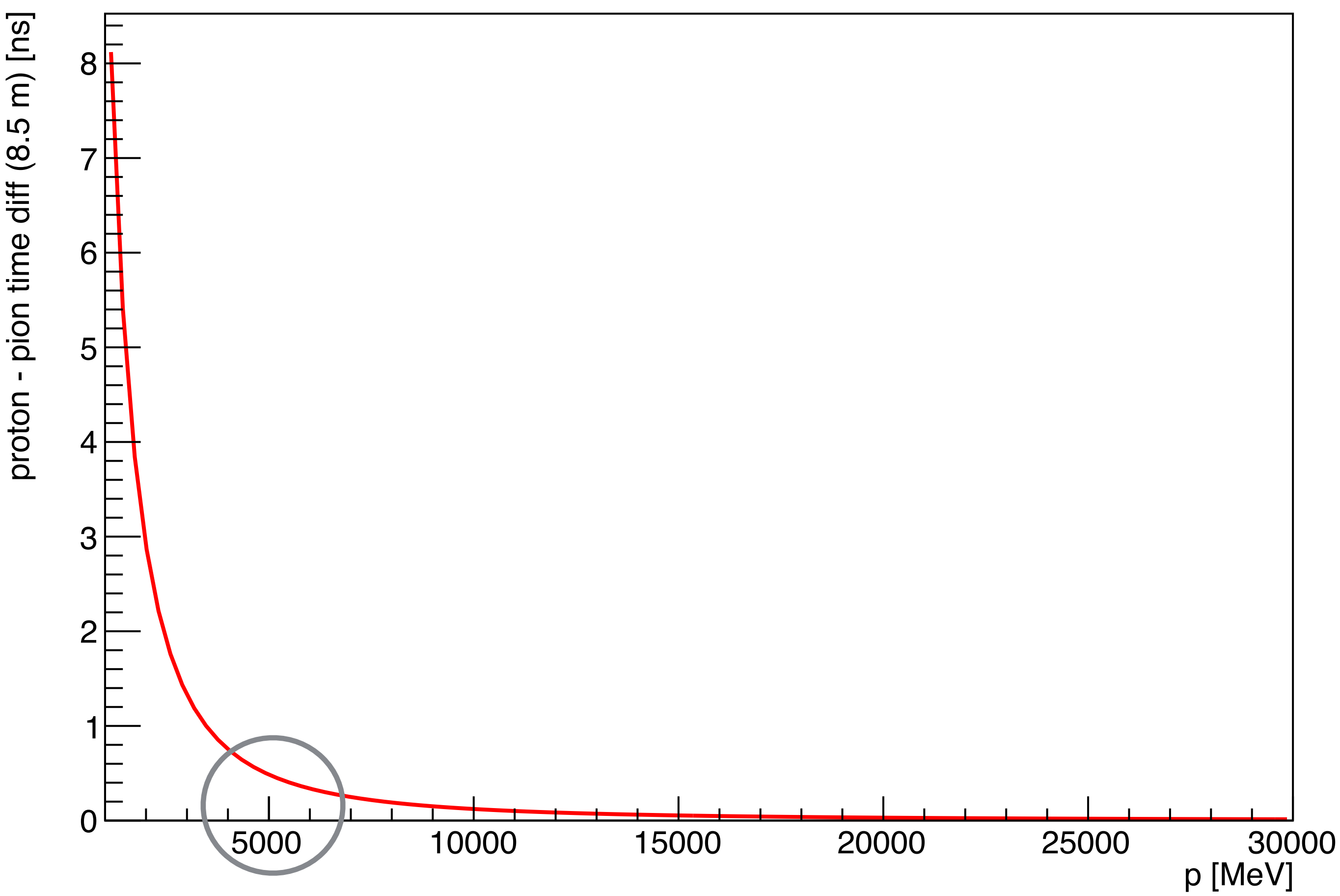




Time-of-flight

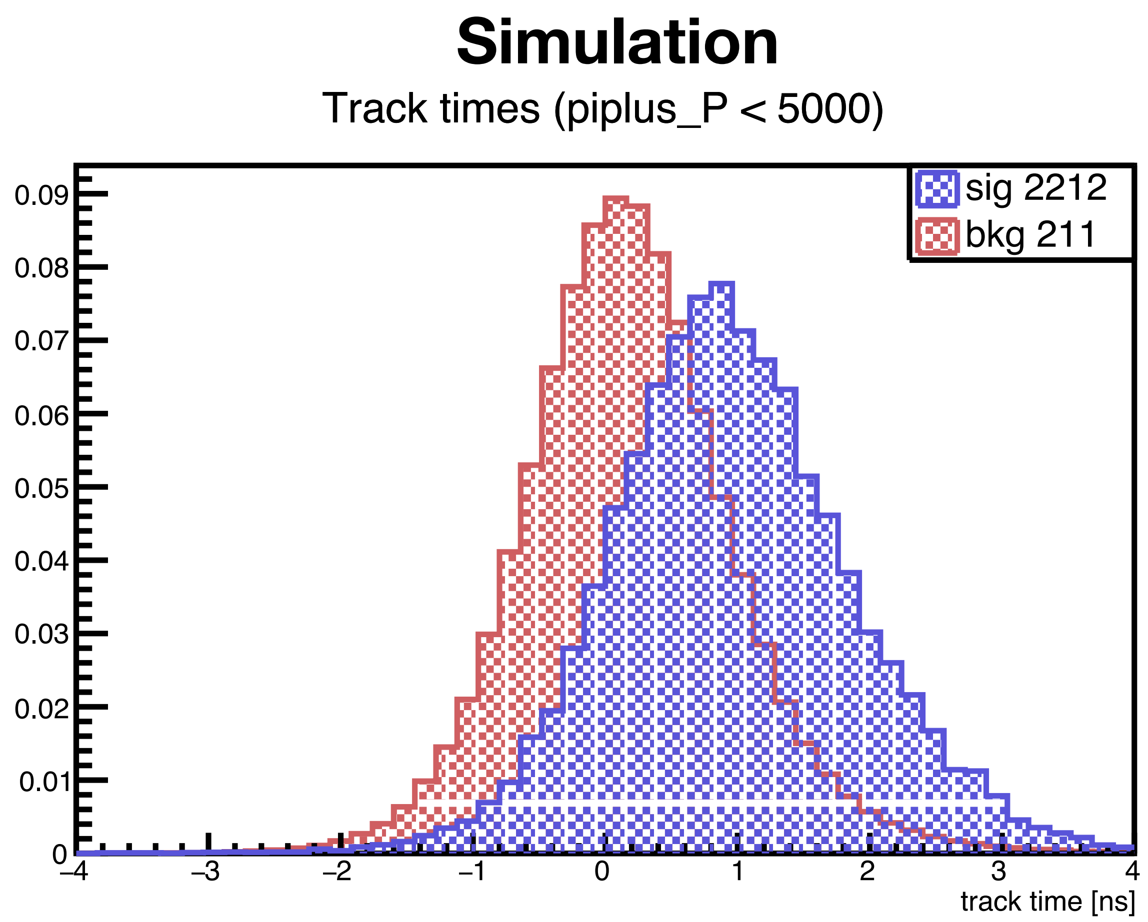
- If momentum not too high: noticeable timing difference

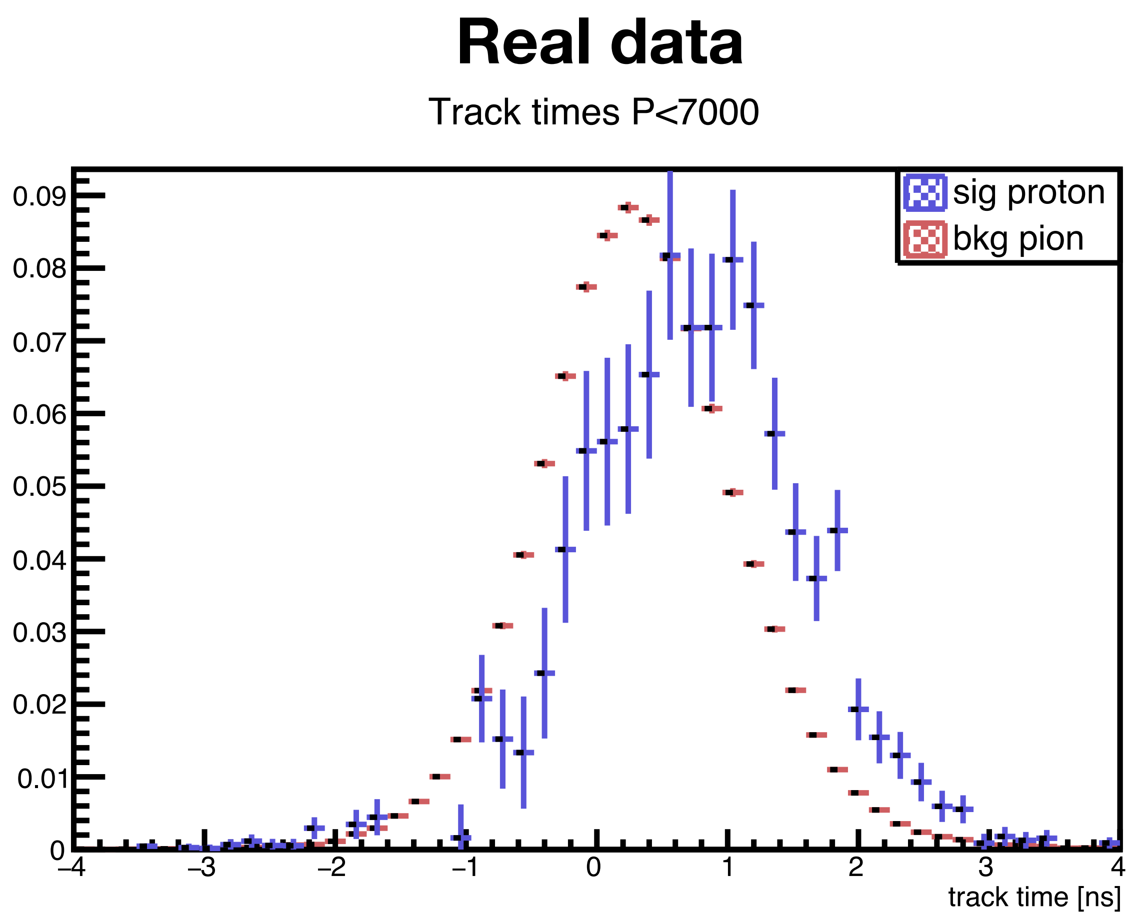




Time-of-flight

- If momentum not too high: noticeable timing difference
- Example: using the (~1 ns) timing of the LHCb straw tube tracker:



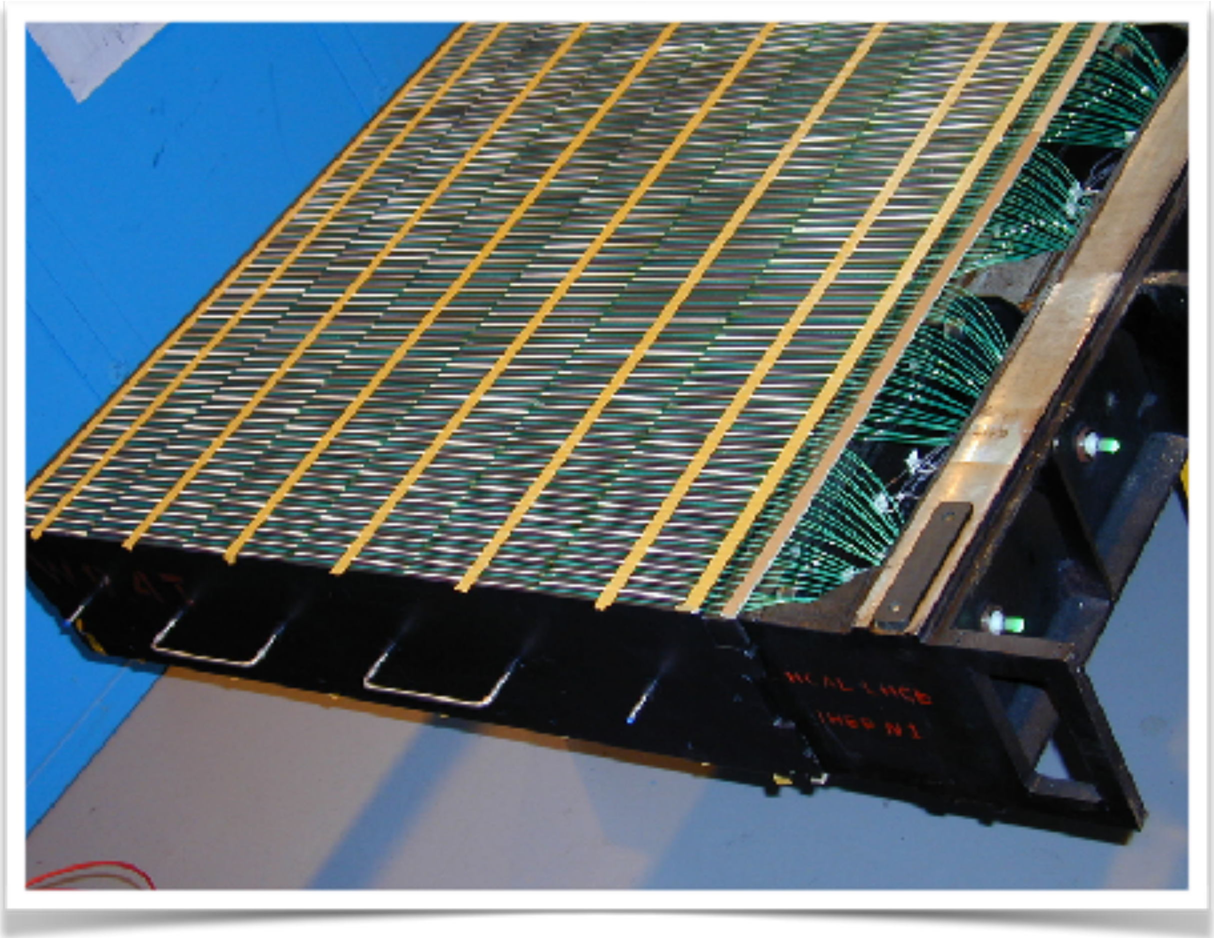


Calorimeters

- Neutral particles: no coulomb —> no charge deposits : neutrons, photons, pi0…
- Get their energy:
  Smash them into lead targets, and count what comes out

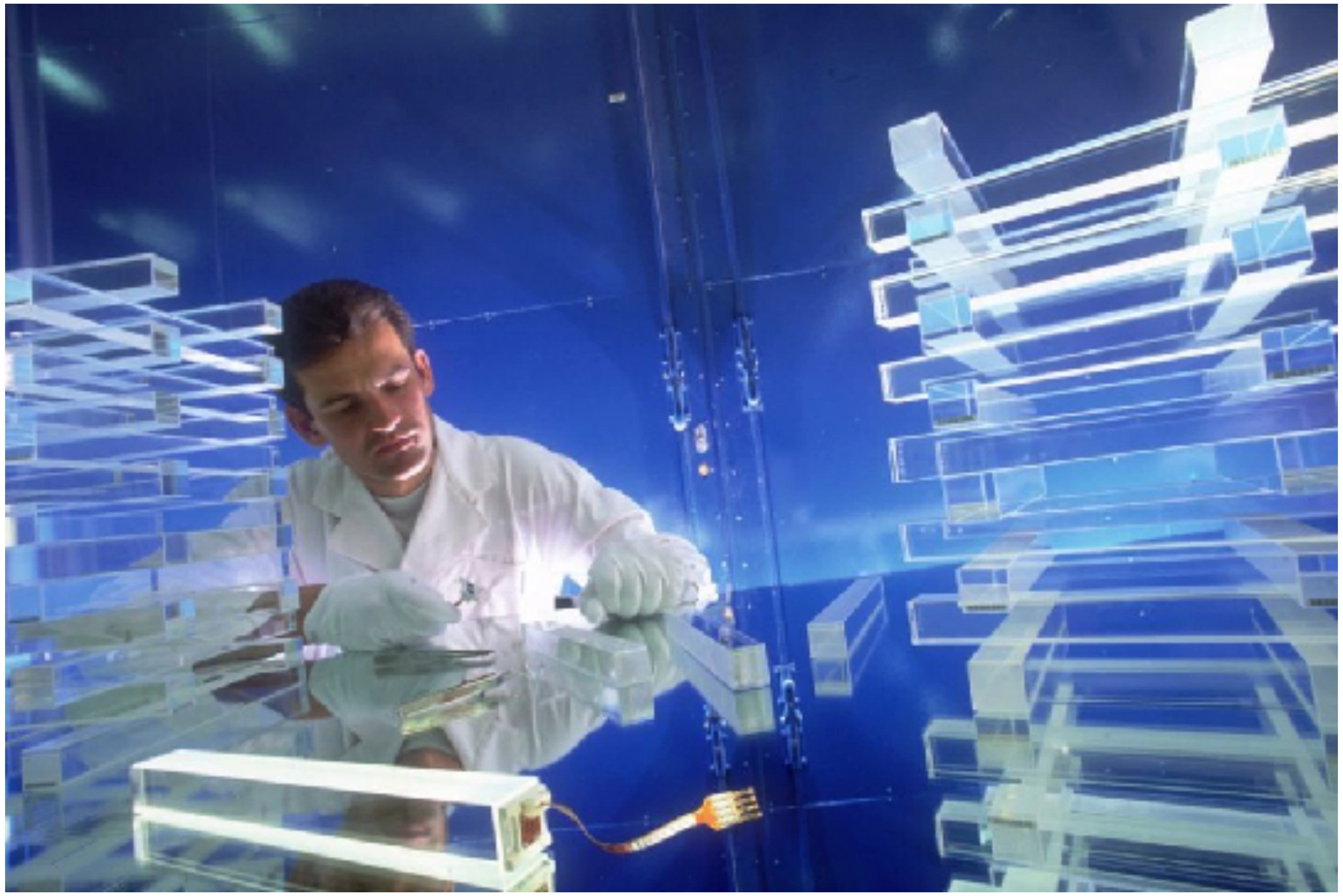
Calorimeters

- 'Shashlik' structure:
  - Heavy layer: ensures loss of energy
  - Sampling layer: measures traversing particles



Calorimeters

- ‘Shashlik’ structure:
  - Heavy layer: ensures loss of energy
  - Sampling layer: measures traversing particles
  (or pay a lot of money for lead-tungsten crystals)



Calorimeters

- 'Shashlik' structure:
  - Heavy layer: ensures loss of energy
  - Sampling layer: measures traversing particles
- Energy resolution: $$\frac{\sigma(E)}{E} = \underbrace{\frac{a}{\sqrt{E}}}_{\textbf{Stochastic term}} \oplus \underbrace{b}_{\textbf{Constant term}}$$

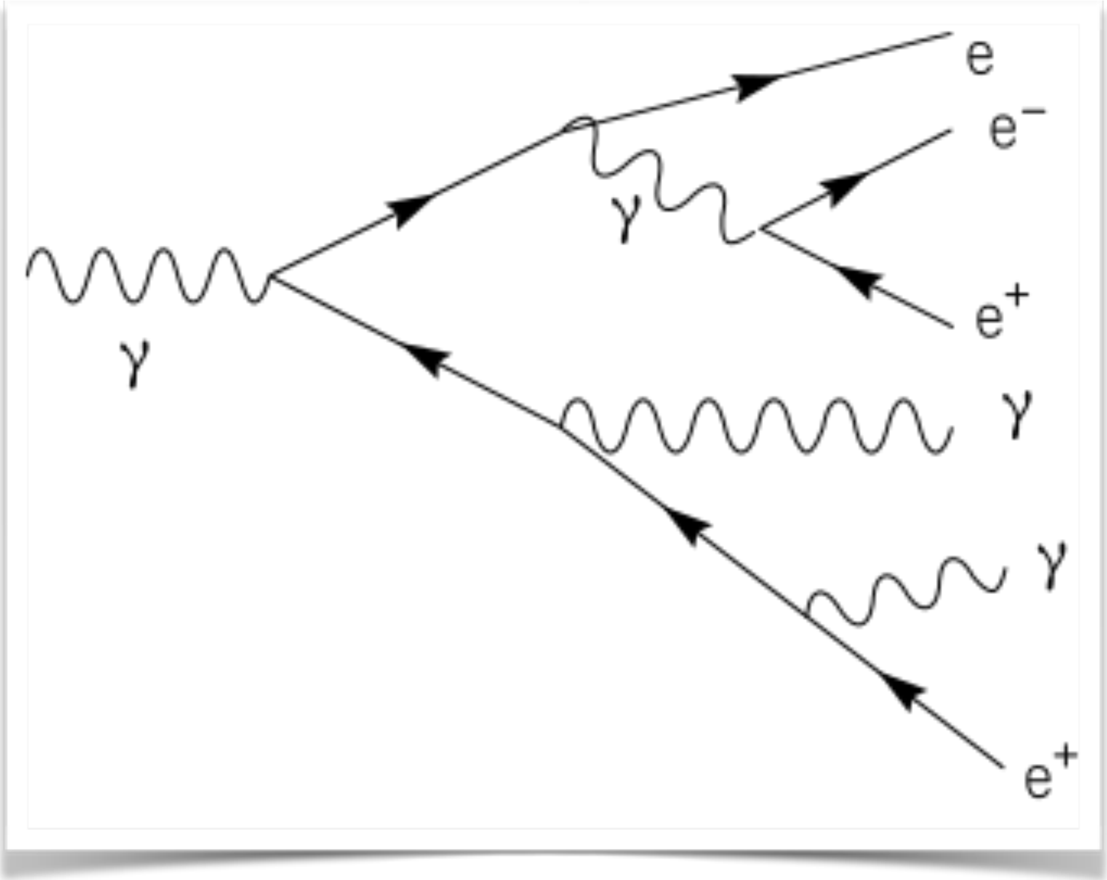
- Stochastic term: 'shower' fluctuations
- Constant term: calibration offset

Showers

- EM showers: pair production vs brehmsstrahlung
- Shower depth: $X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$
  - X_0: radiation length of material
  - E_0/E_c: fraction of the two processes

- Hadronic showers: harder to predict. QCD…

- LHCb:
  EM Calo: a,b = 10%, 1.5%
  Had. Calo: a,b = 80%, 10%



Considerations

- Purpose of detector? Spend your money:

very good momentum resolution

complete (4 pi) coverage

excellent vertex resolution

very fast timing

little energy loss during travel

must deal with high occupancies

good energy resolution

Considerations

- Purpose of detector? Spend your money:

- very good momentum resolution (—> thin mass peaks)
- complete (4 pi) coverage (—> efficiency, closeness)
- excellent vertex resolution (—> good lifetime resolution)
- very fast timing (—> high event rate)
- little energy loss during travel (—> no radiation loss)
- must deal with high occupancies (—> no saturation)
- good energy resolution (—> good for jets & background)

Considerations

- Purpose of detector? Spend your money:

- very good momentum resolution (strong magnet, small pixels)
- complete (4 pi) coverage (lots of detectors)
- excellent vertex resolution (very close to PV, small pixels)
- very fast timing (expensive electronics & detectors)
- little energy loss during travel (thin detector technology)
- must deal with high occupancies (small pixels / gas volumes)
- good energy resolution (expensive calo crystals, small pixels)

Summary

- There are various ways of detecting particles, each with its own advantages/disadvantages.
- Most accelerator-based experiments will have some form of tracking, a magnet, PID, and calorimetry
- A careful consideration is made for every detector setup, optimized for the corresponding physics program.

<u>Jupyter challenge - Top 3:</u>

Jacco	- chi2/ndf = 5.87	, N(Bs) = 1.13 M
1)	- chi2/ndf = 5.52	, N(Bs) = 1.92 M
2)	- chi2/ndf = 5.57	, N(Bs) = 1.92 M
3)	- chi2/ndf = 5.96	, N(Bs) = 0.3 M

<u>Jupyter challenge - Top 3:</u>

Jacco - chi2/ndf = 5.87 , N(Bs) = 1.13 M

1) Nelson - chi2/ndf = 5.52 , N(Bs) = 1.92 M
2) Francesco - chi2/ndf = 5.57 , N(Bs) = 1.92 M
3) Hildebert - chi2/ndf = 5.96 , N(Bs) = 0.3 M

Modern experiments

(note: cherry picked!)

Big questions in physics

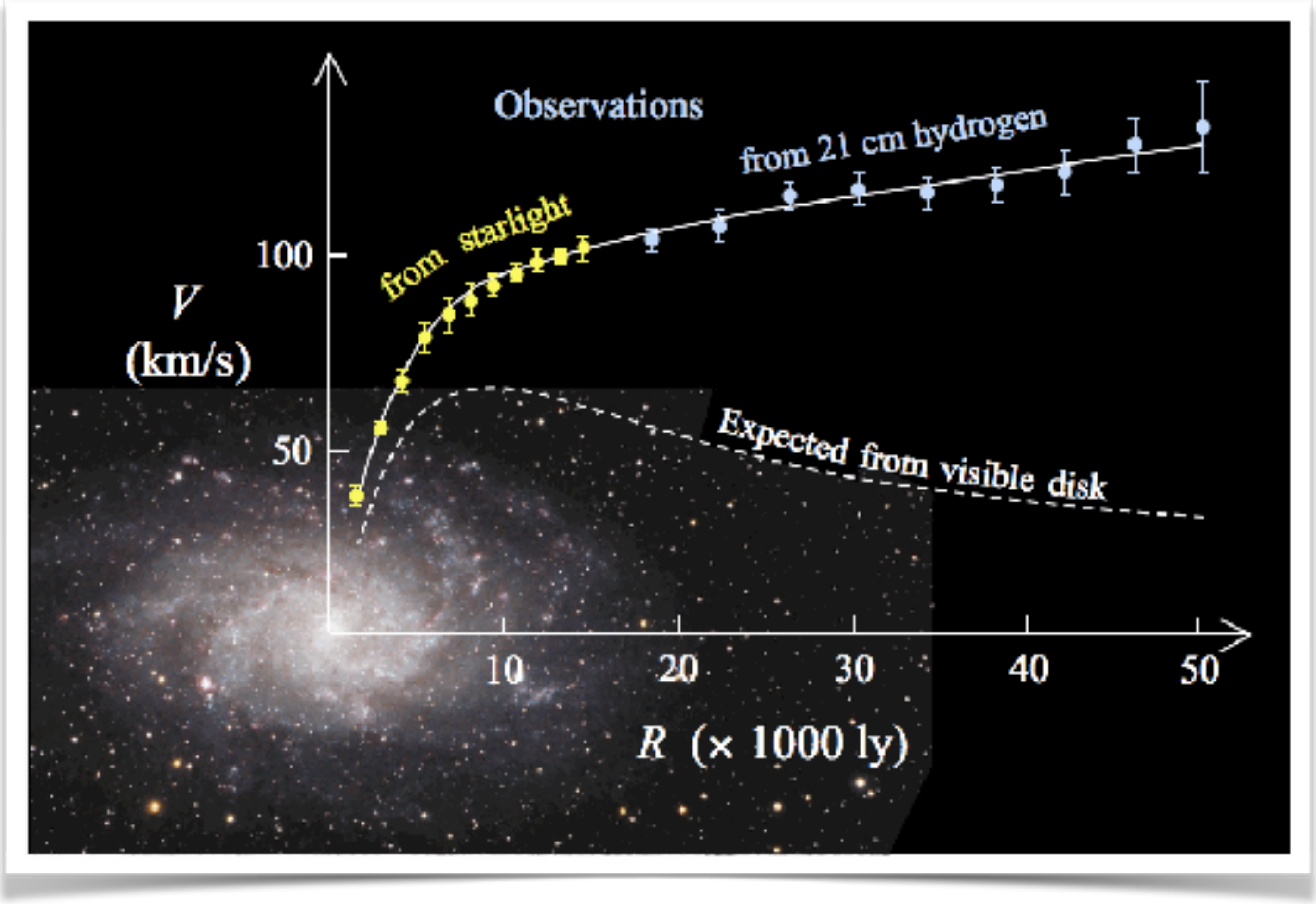
- What is dark matter?
- What is the mass of neutrinos?
- Where do the ultra high energy cosmic rays come from?
- Are protons unstable?
- Where did all the antimatter go?
- What happened during the big bang?

- Why is the Higgs mass so fine-tuned?
- Why are there (only) three generations?
- What is the top quark mass?

http://discovermagazine.com/2002/feb/cover

What is dark matter?

- There is 'dark' mass in the universe, that affects gravitational pull
  - Galaxy rotation curves



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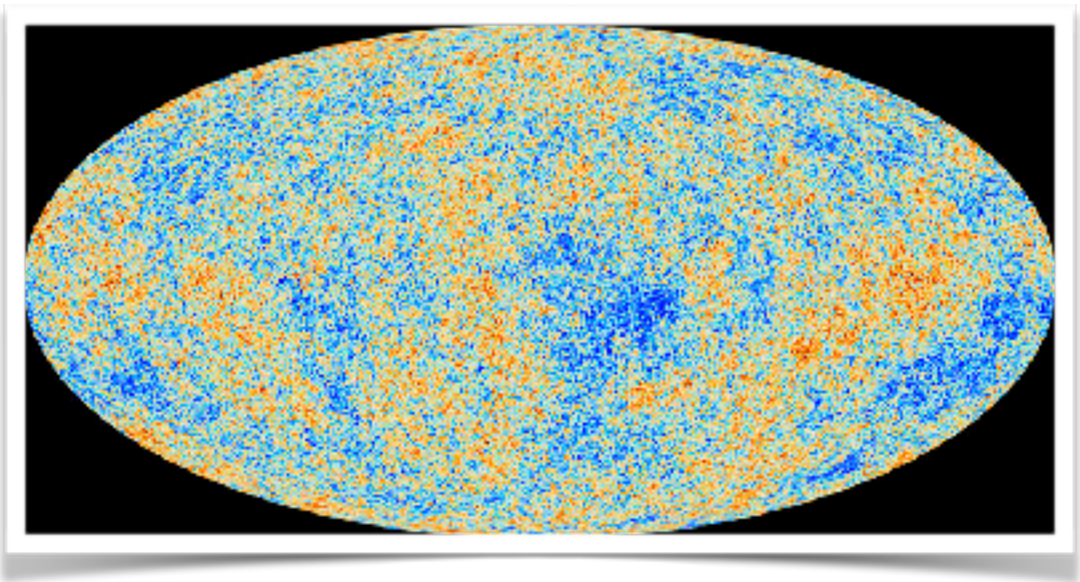
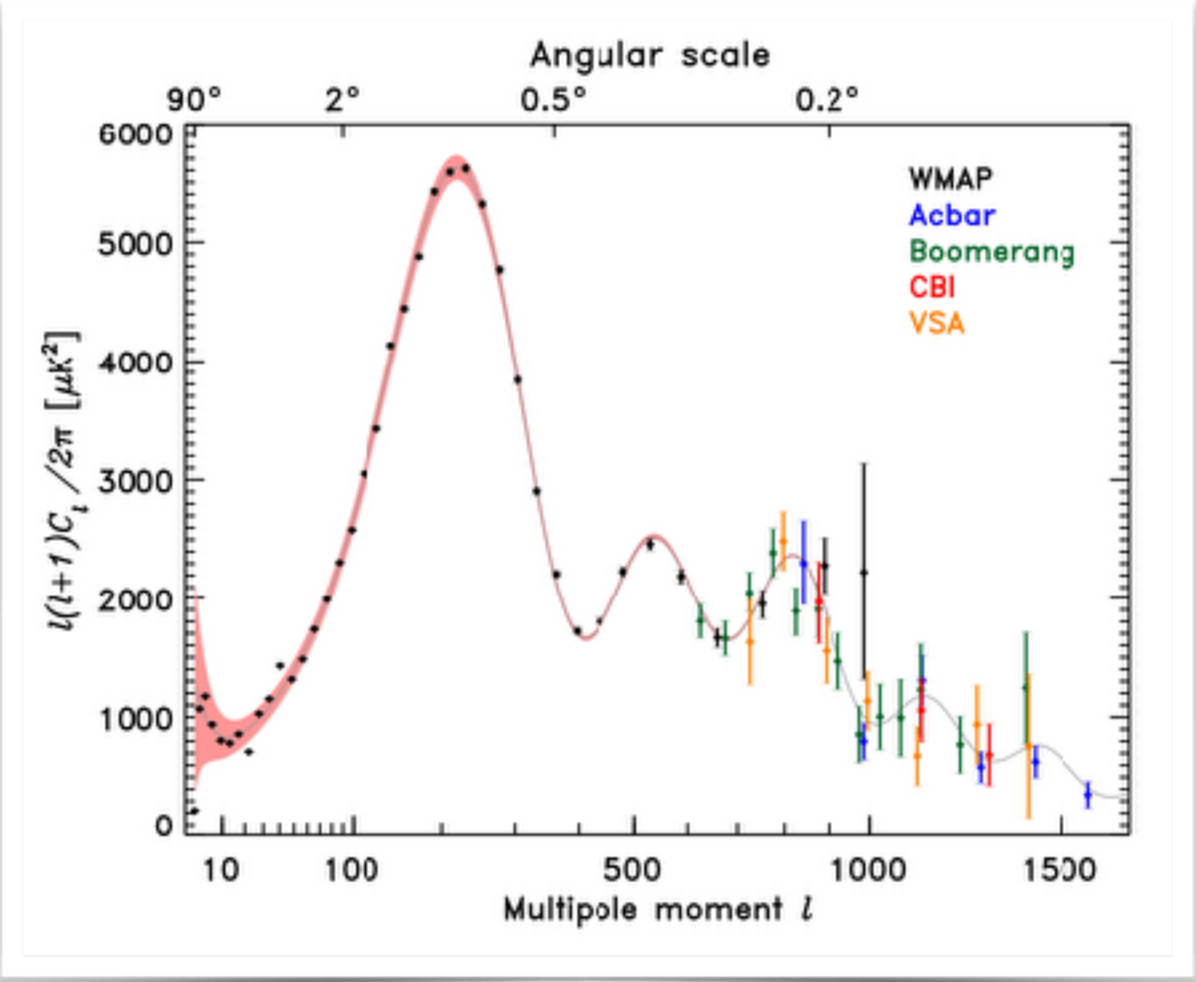
  - Peaks in power spectrum of cosmic microwave background (CMB)

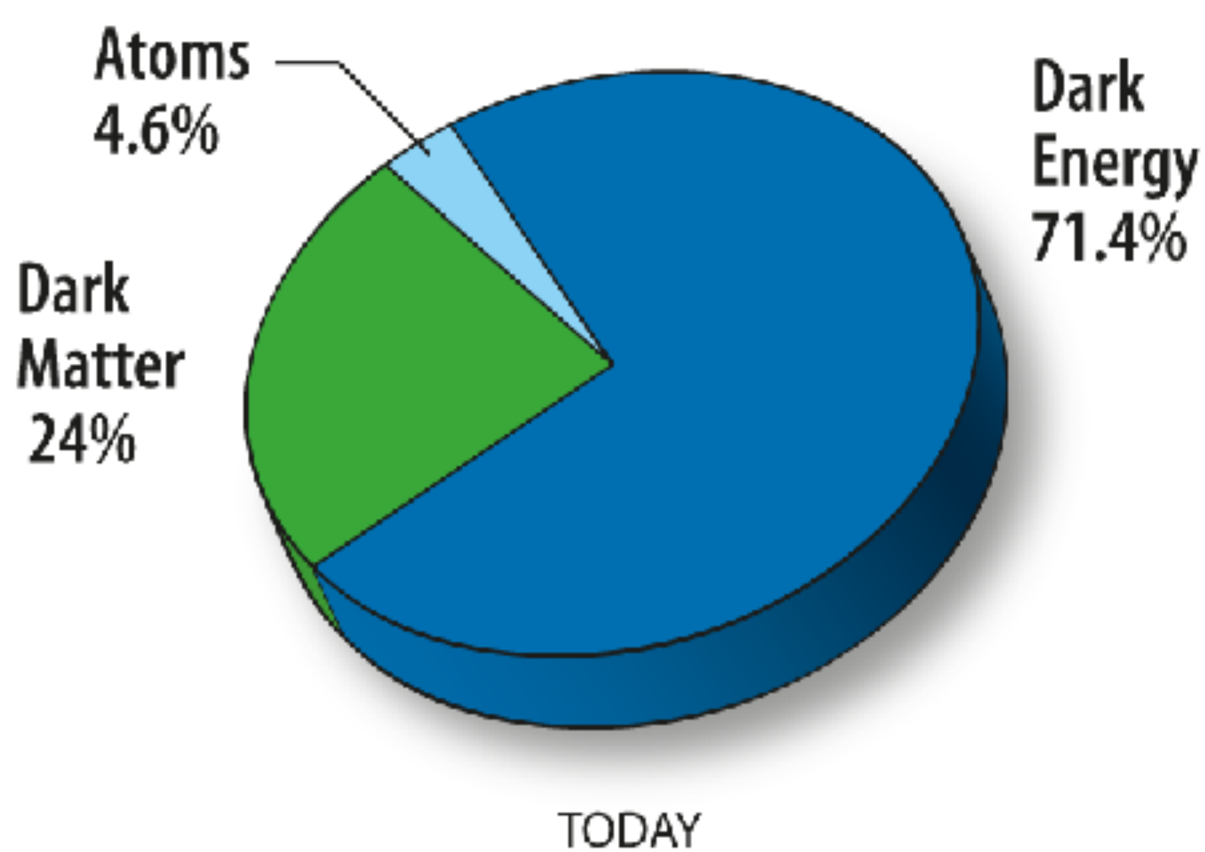




What is dark matter?

- There is ‘dark’ mass in the universe, that affects gravitational pull
  - Galaxy rotation curves
  - Gravitational microlensing
  - Peaks in power spectrum of cosmic microwave background (CMB)

  —> 1/4 of the energy content in our universe!



What is dark matter?

- WIMPs or MACHOs?
- Evidence favours DM particles. But what?
  - must be stable
  - must not interact via QED or QCD
  - lightest SUSY particle? sterile (right-handed) neutrino's?

What is dark matter?

- WIMPs or MACHOs?
- Evidence favours DM particles. But what?
  - must be stable
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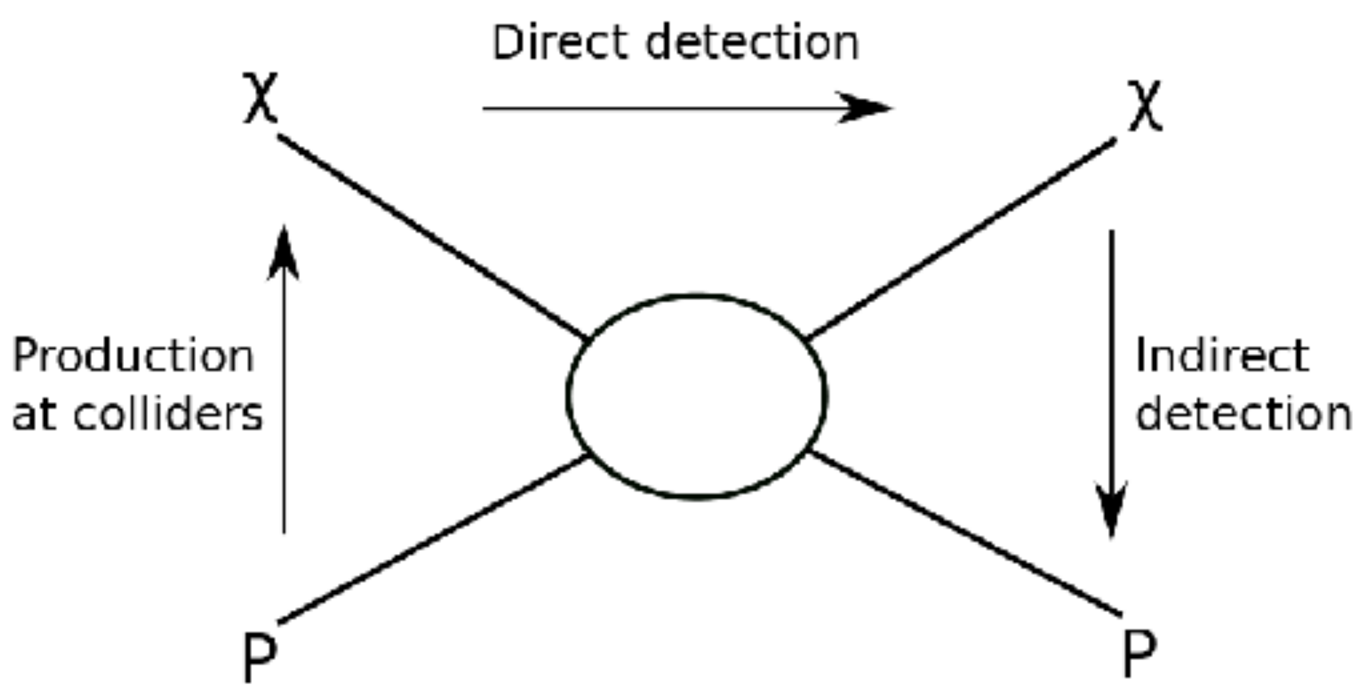
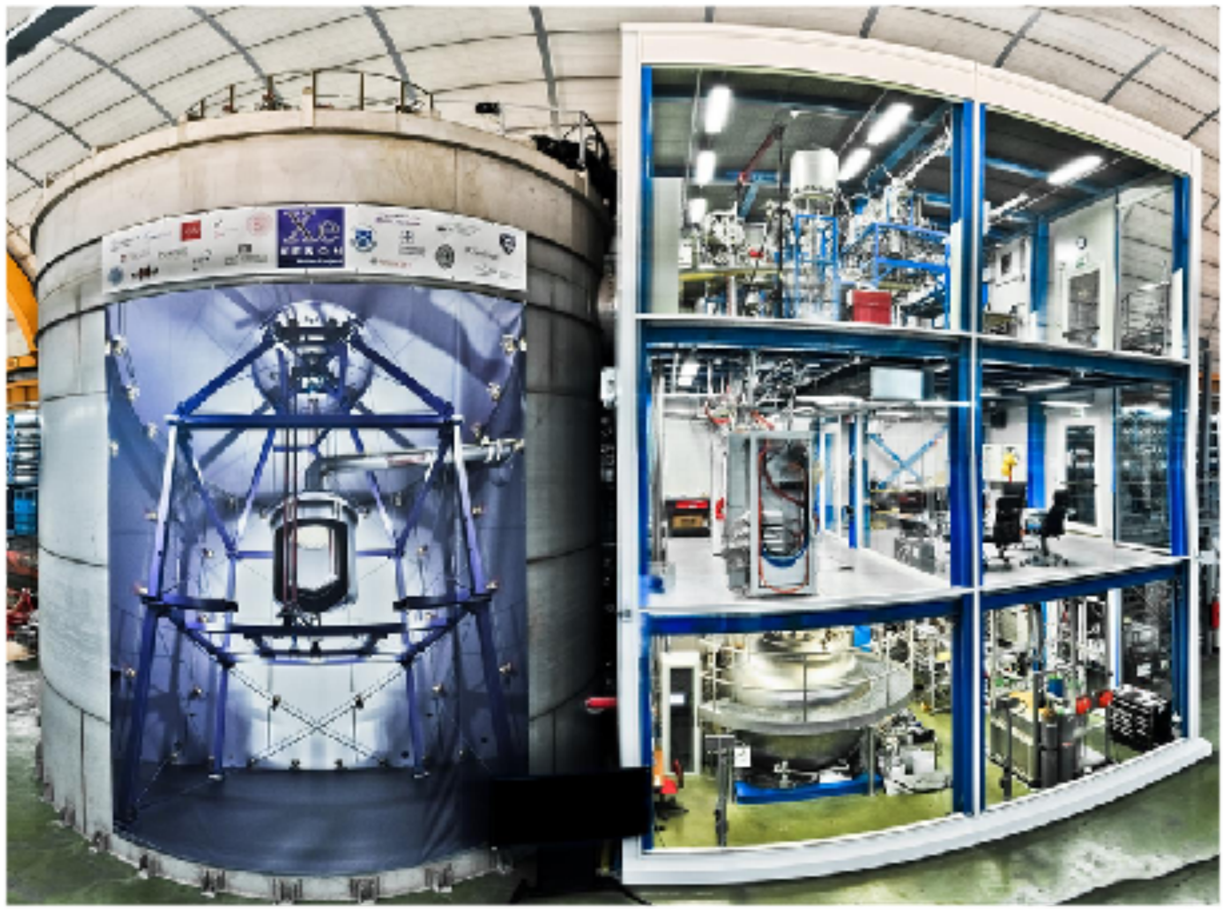
  - lightest SUSY particle? sterile (right-handed) neutrino's?
- 3 ways of searching:



Xenon experiment

- Liquid Xenon drift chamber ("Time Projection Chamber")

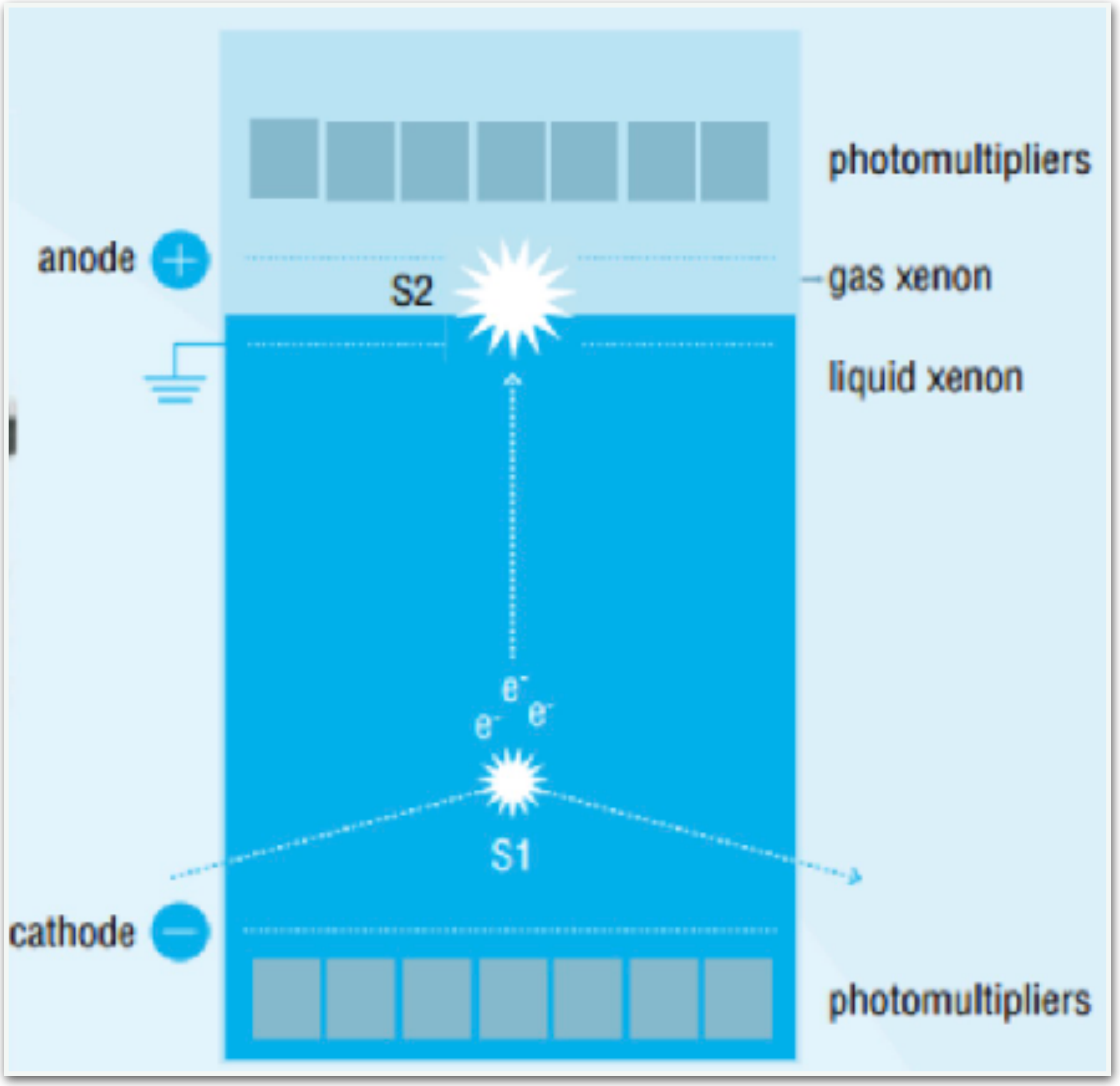


Xenon experiment

- Under a mountain in Gran Sasso, Italy, in an old mine
- Shielded by ultra pure water
- Two signals, S1 (light) and S2 (charge)

- Backgrounds: natural isotopes, cosmic radiation, neutrinos!

- Xenon nT upgrade: ~2020



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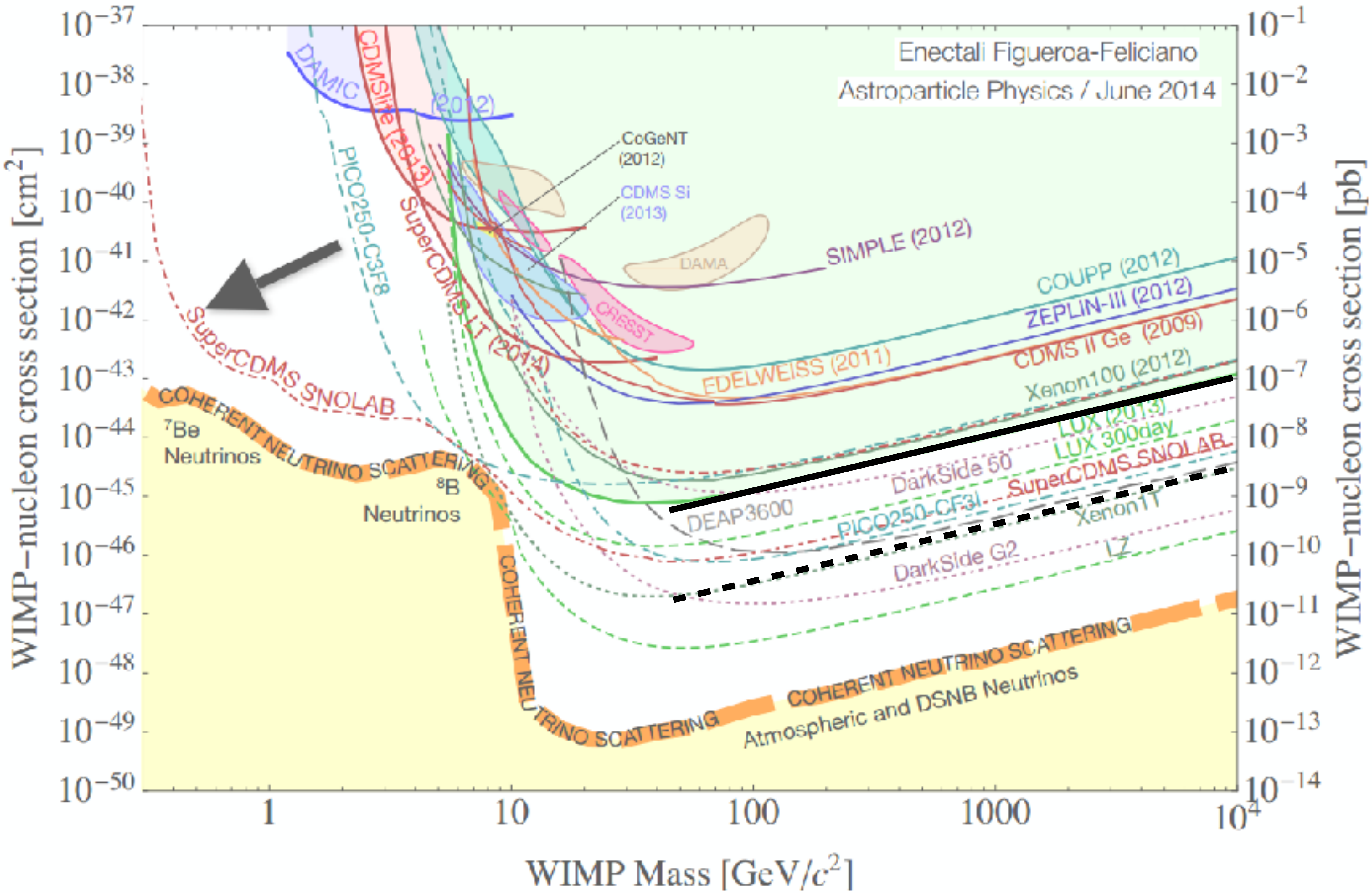

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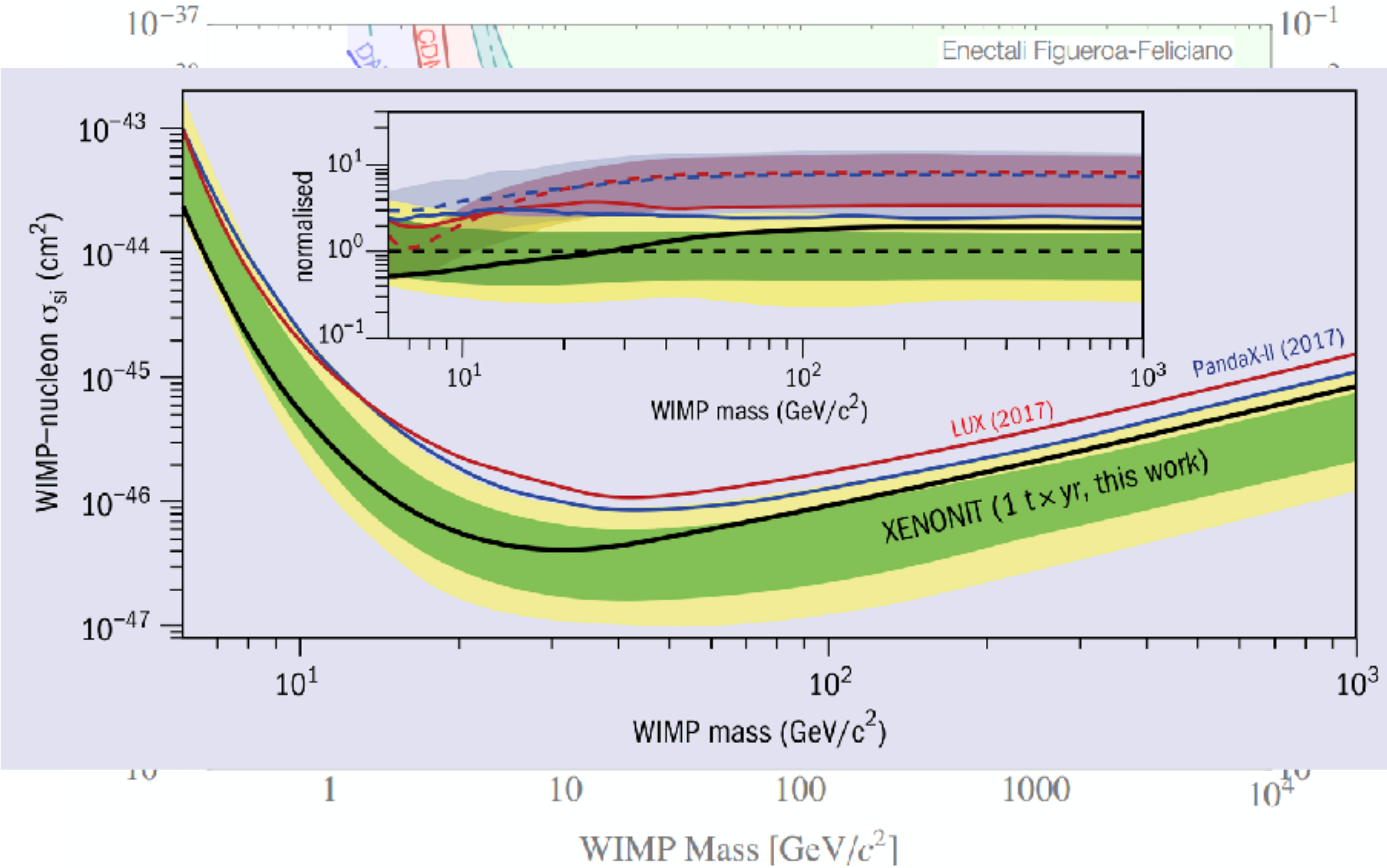
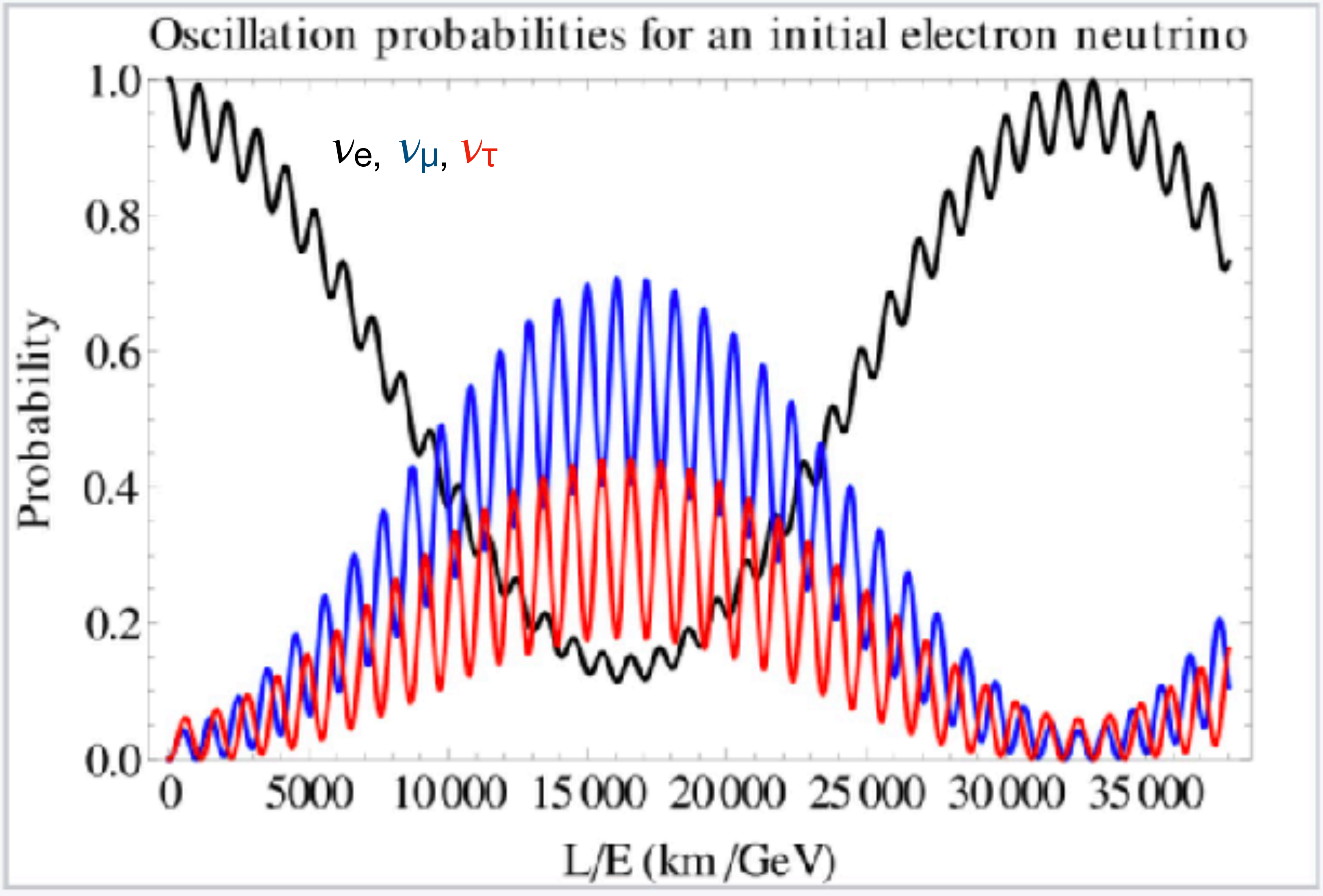


What is the mass of neutrinos?

- 1960: there is a ~50% deficit of electron-neutrinos from the sun
- Since 1998: Neutrinos change flavour on their way here!

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{ (natural units)}$$



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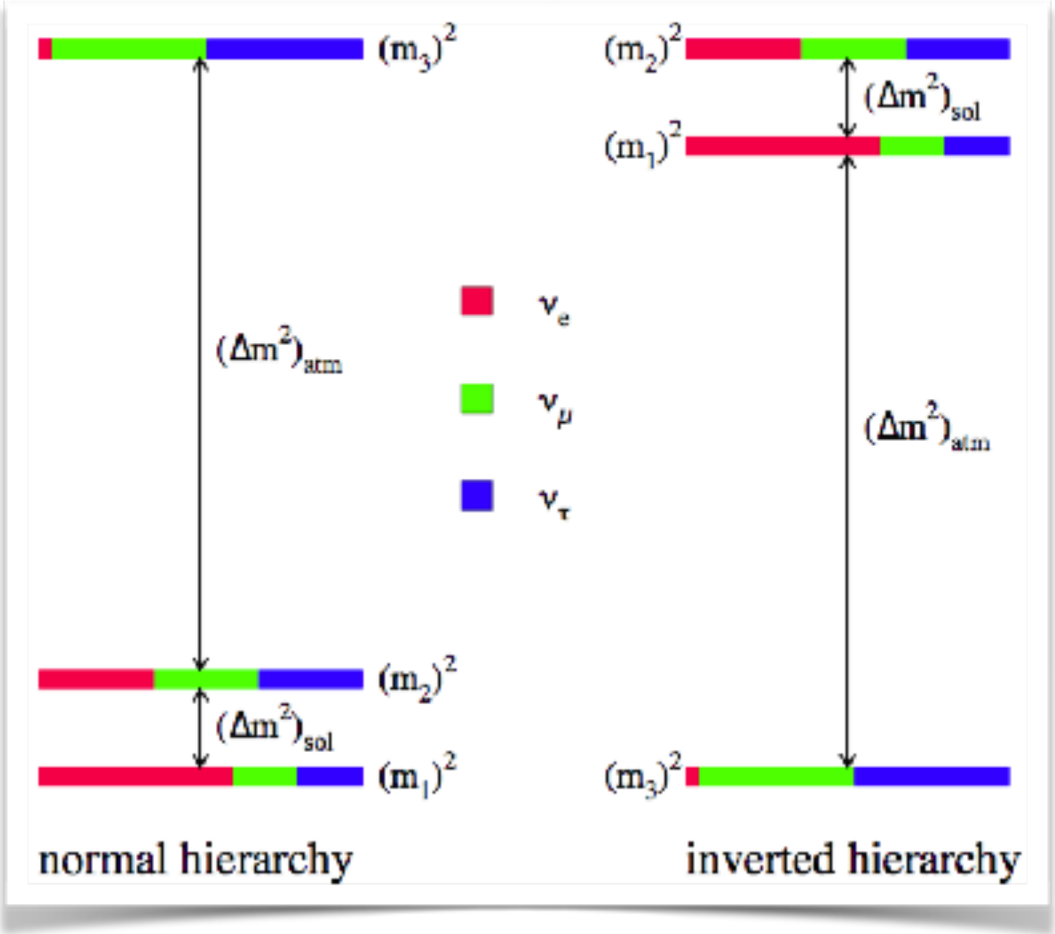

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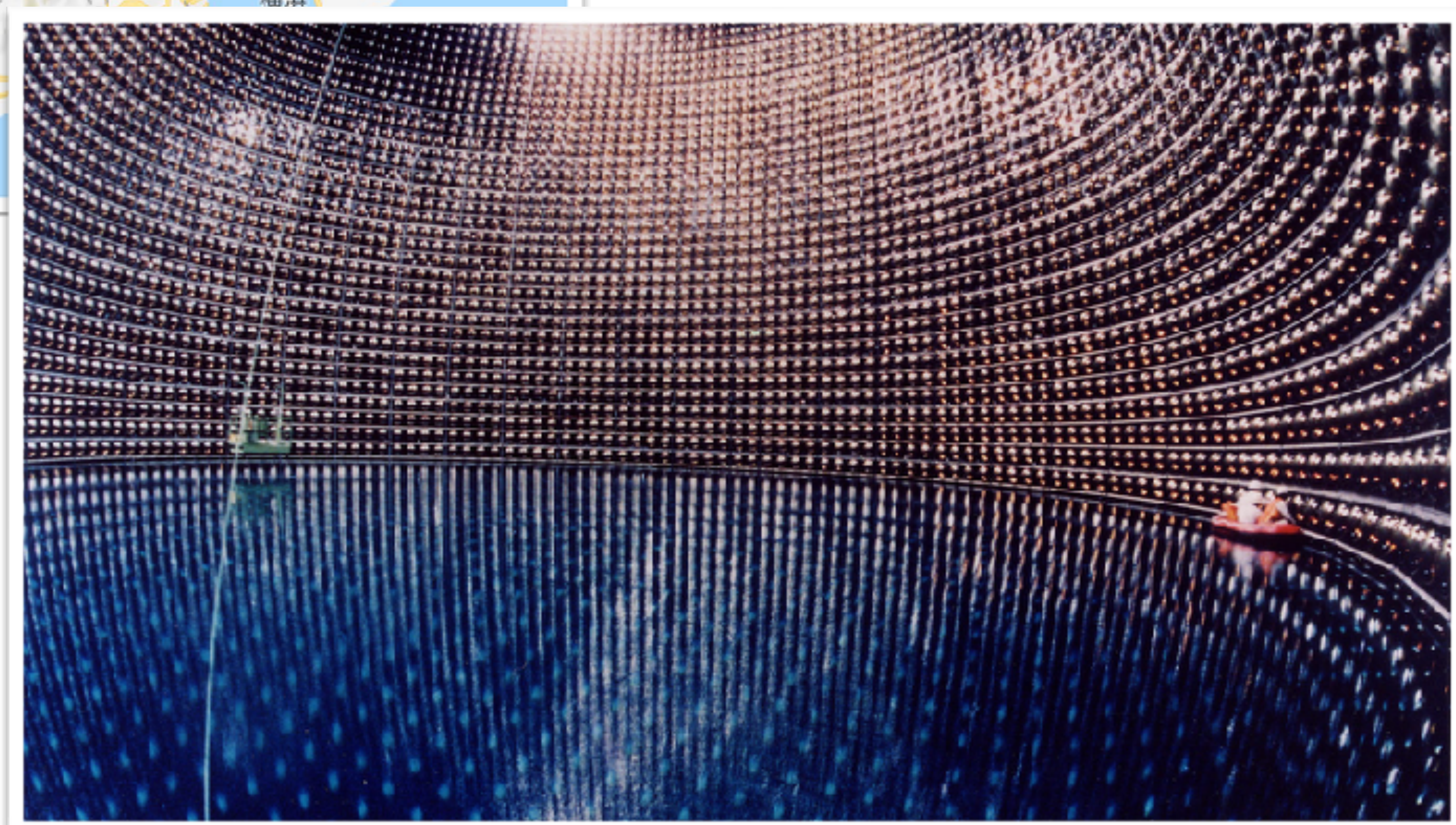
- Mass hierarchy of great importance to
  - Grand Unified Theories,
  - neutrinos are their own antiparticle?
  - types of elements produced in supernovae
  - potential ‘CP-violation’ or ‘leptogenesis’:
    is this why the antimatter disappeared?

Super-Kamiokande

- 1km underground mount Ikeno
- 40m diameter
- 50,000 ton of ultrapure water
- 13,000 PM tubes

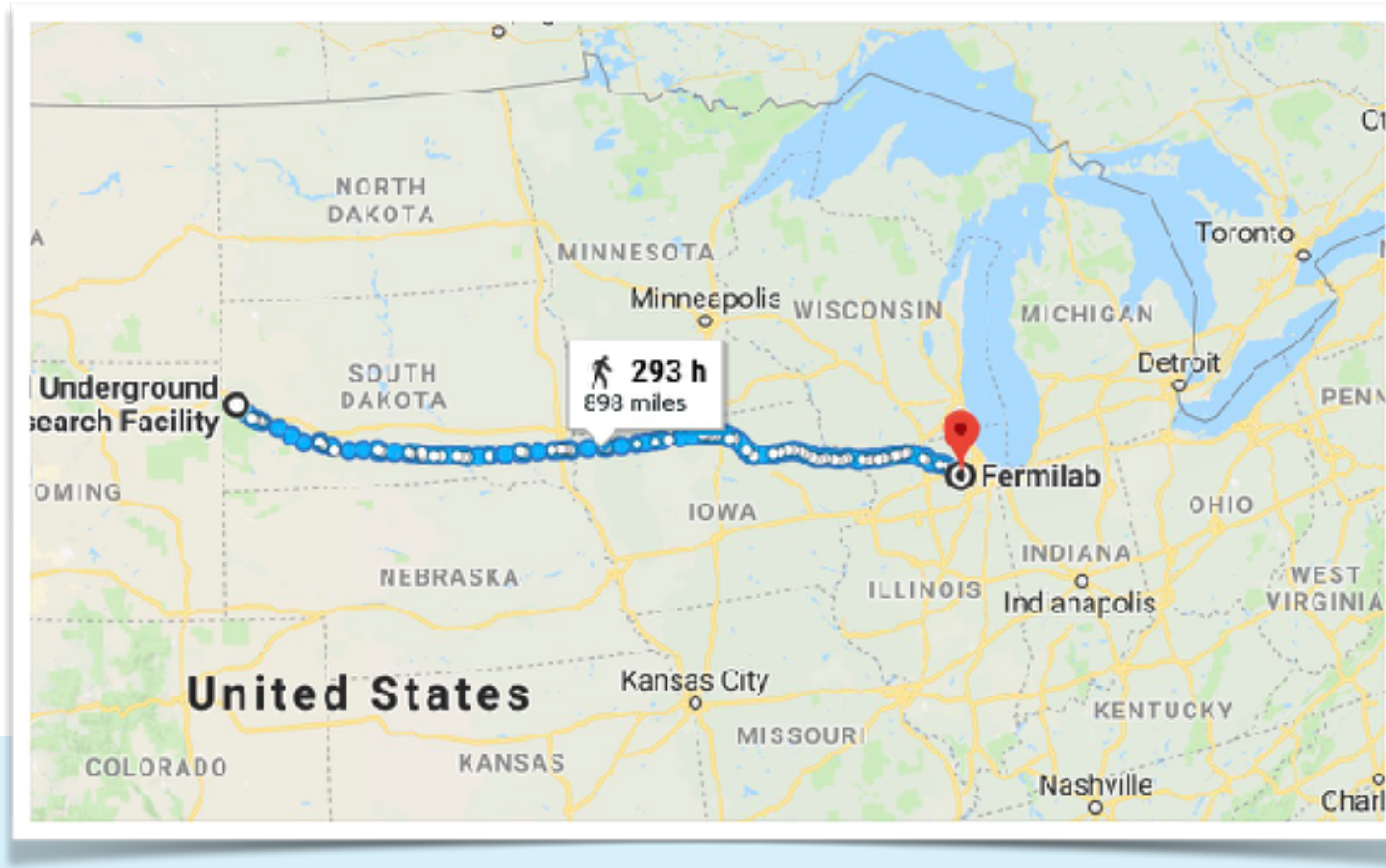
Upgrade: Hyper-Kamiokande: 2025

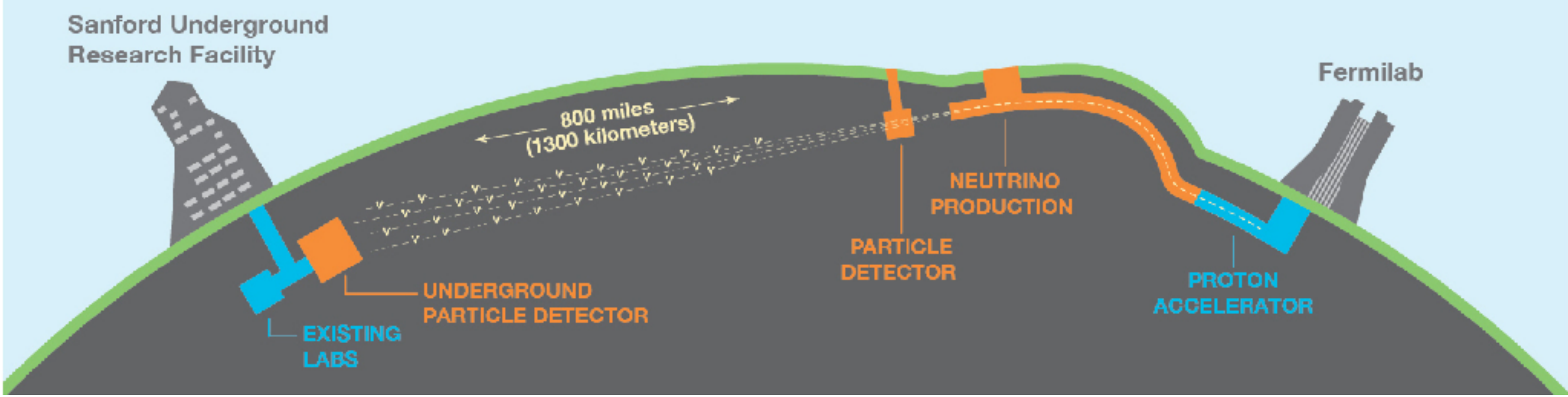


- Sources:
  - reactors
  - atmosphere
  - solar
  - …?

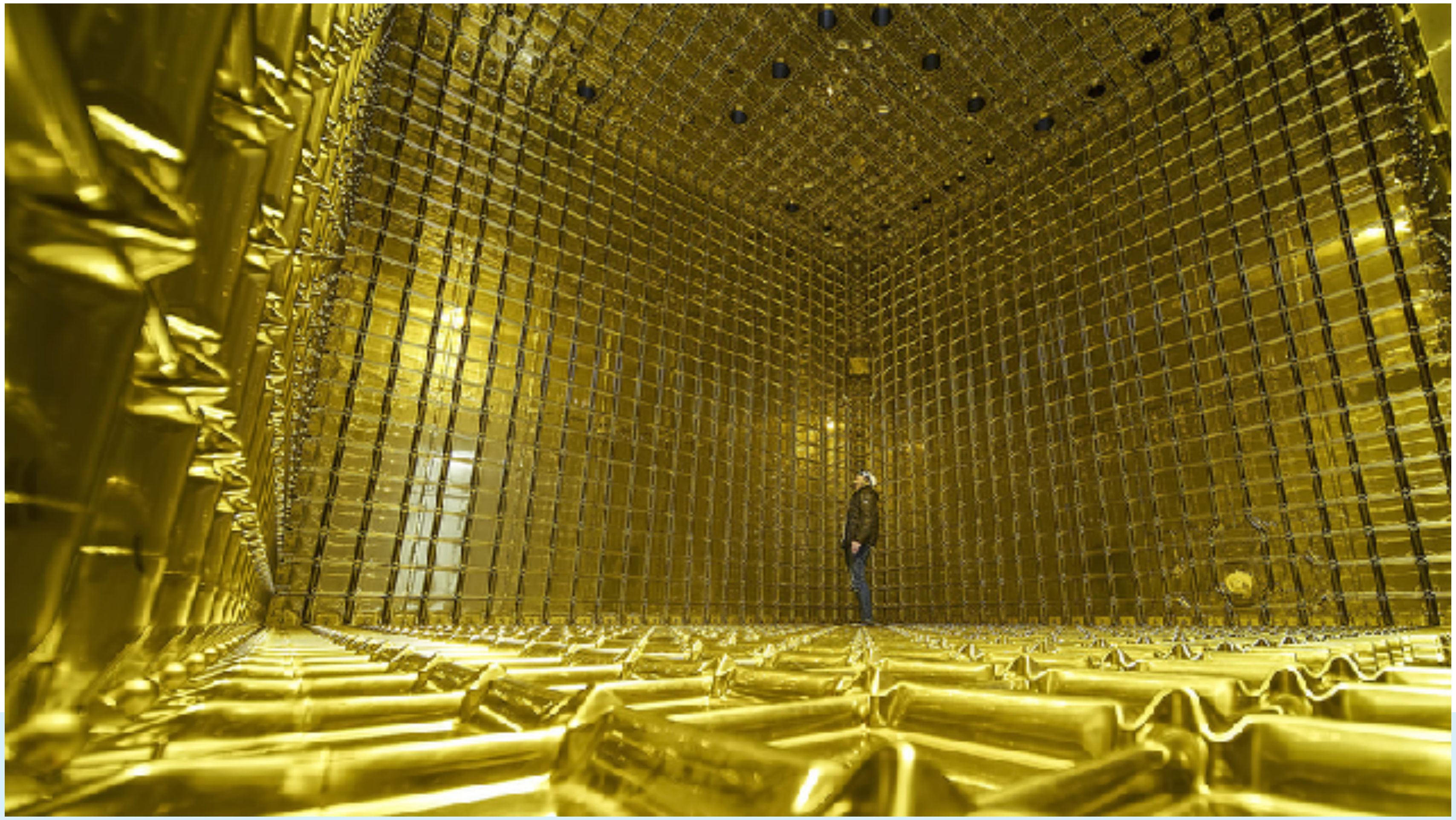
DUNE

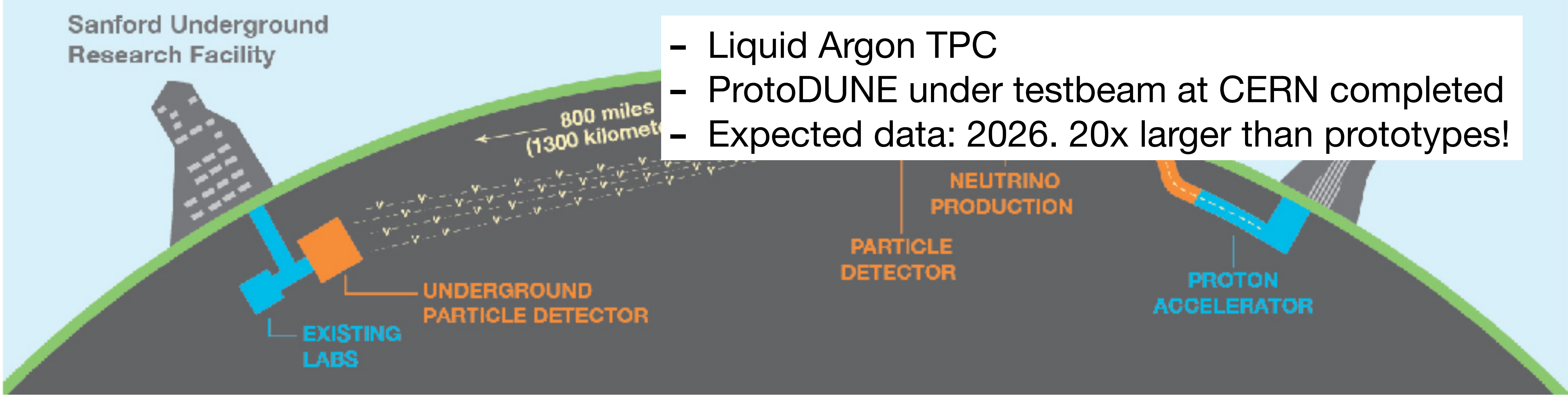
- Long baseline neutrino experiment
- FermiLab accelerator creates beam
- Travel 1300 km underground





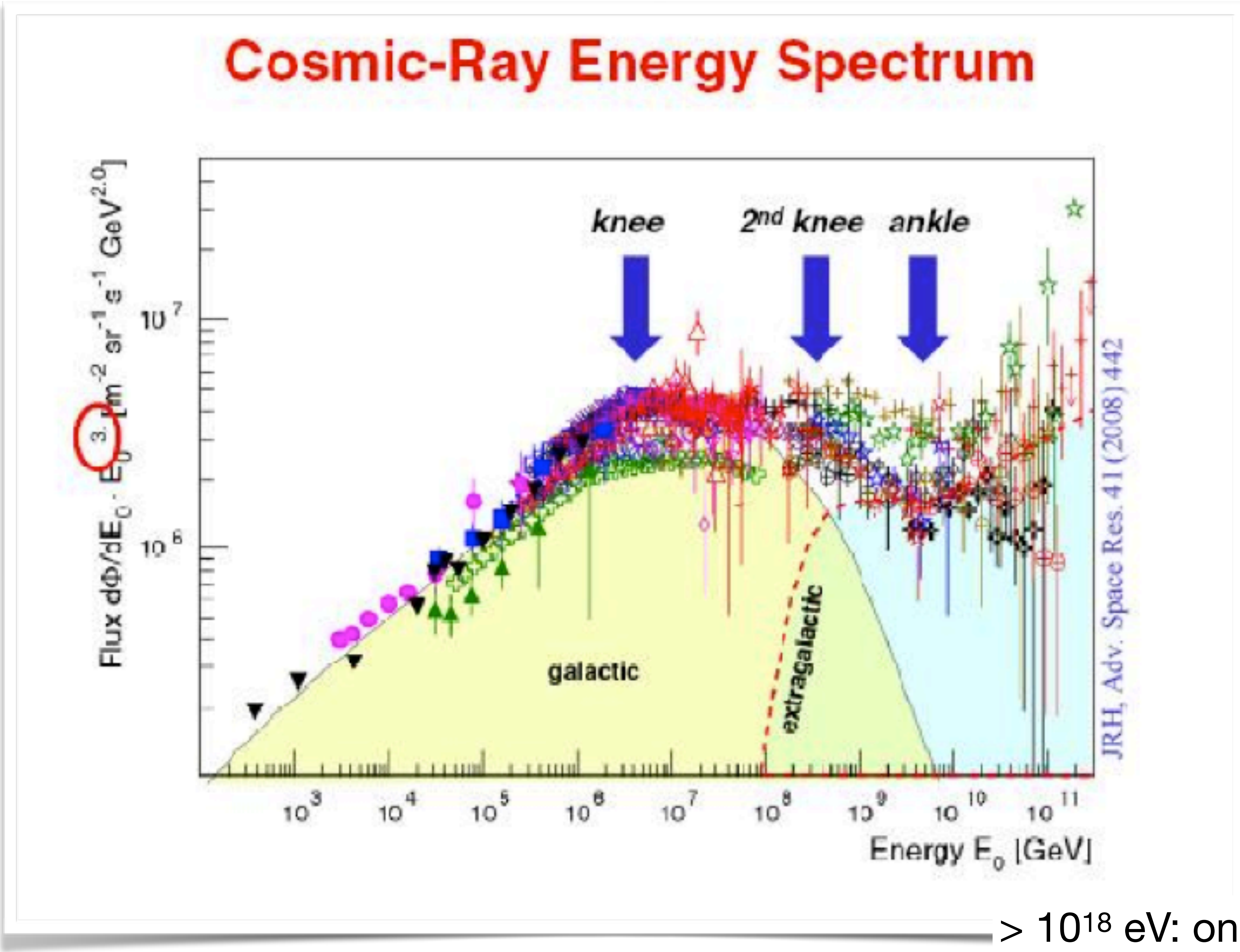
DUNE





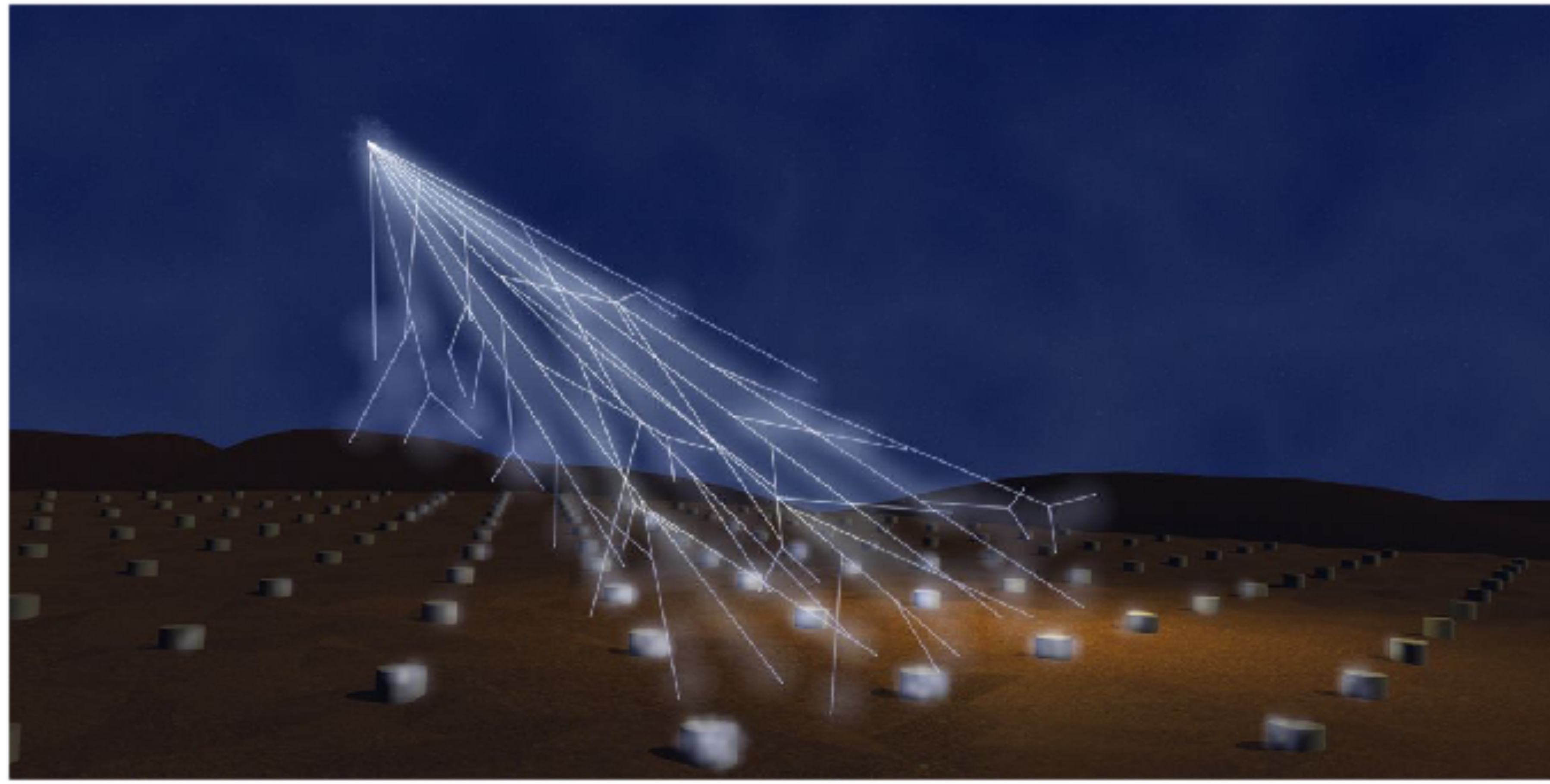
- Liquid Argon TPC
- ProtoDUNE under testbeam at CERN completed
- Expected data: 2026. 20x larger than prototypes!

High-energy cosmic rays



> 10^{18} eV: one per week (per km^2)
> 10^{20} eV: one per century!
—> Where are they from?

Pierre Auger observatory



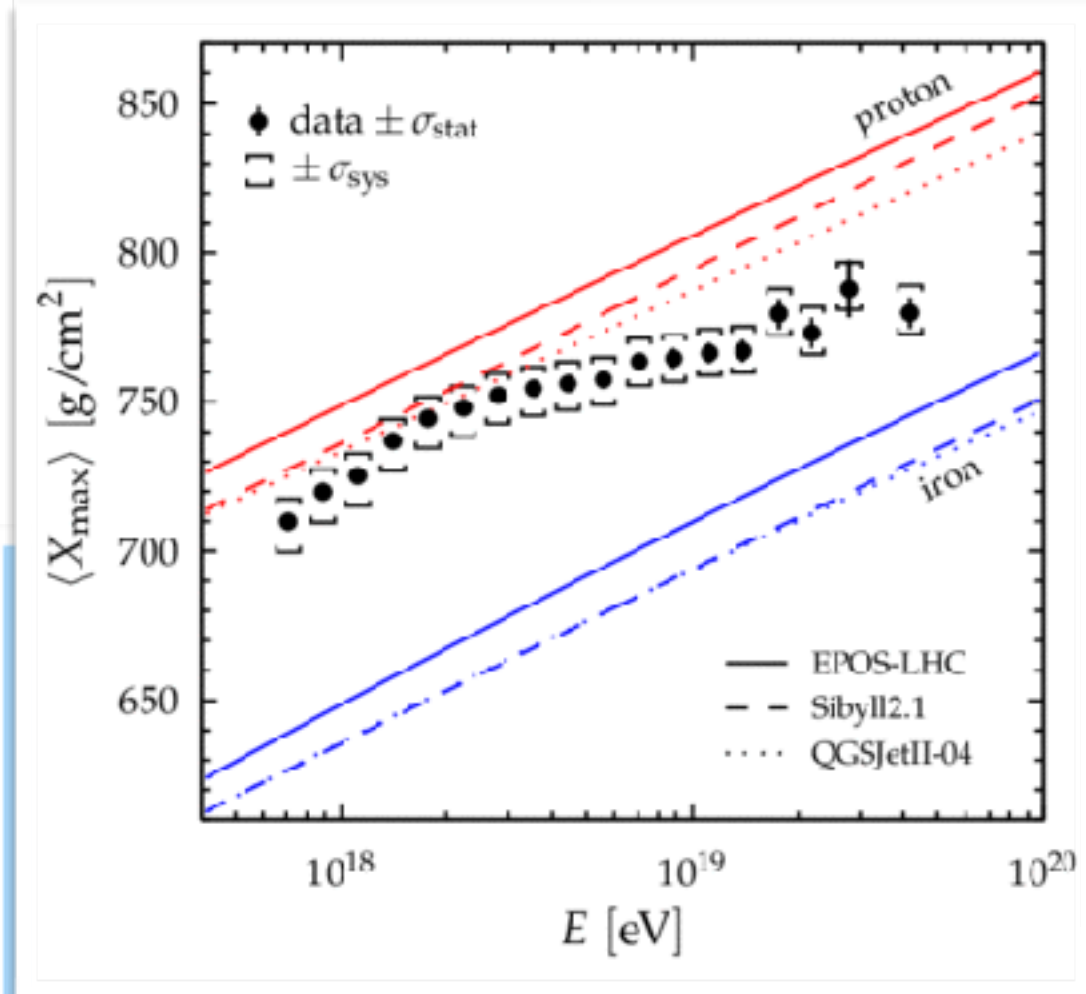
3000 km^2 at high altitude, near Andes

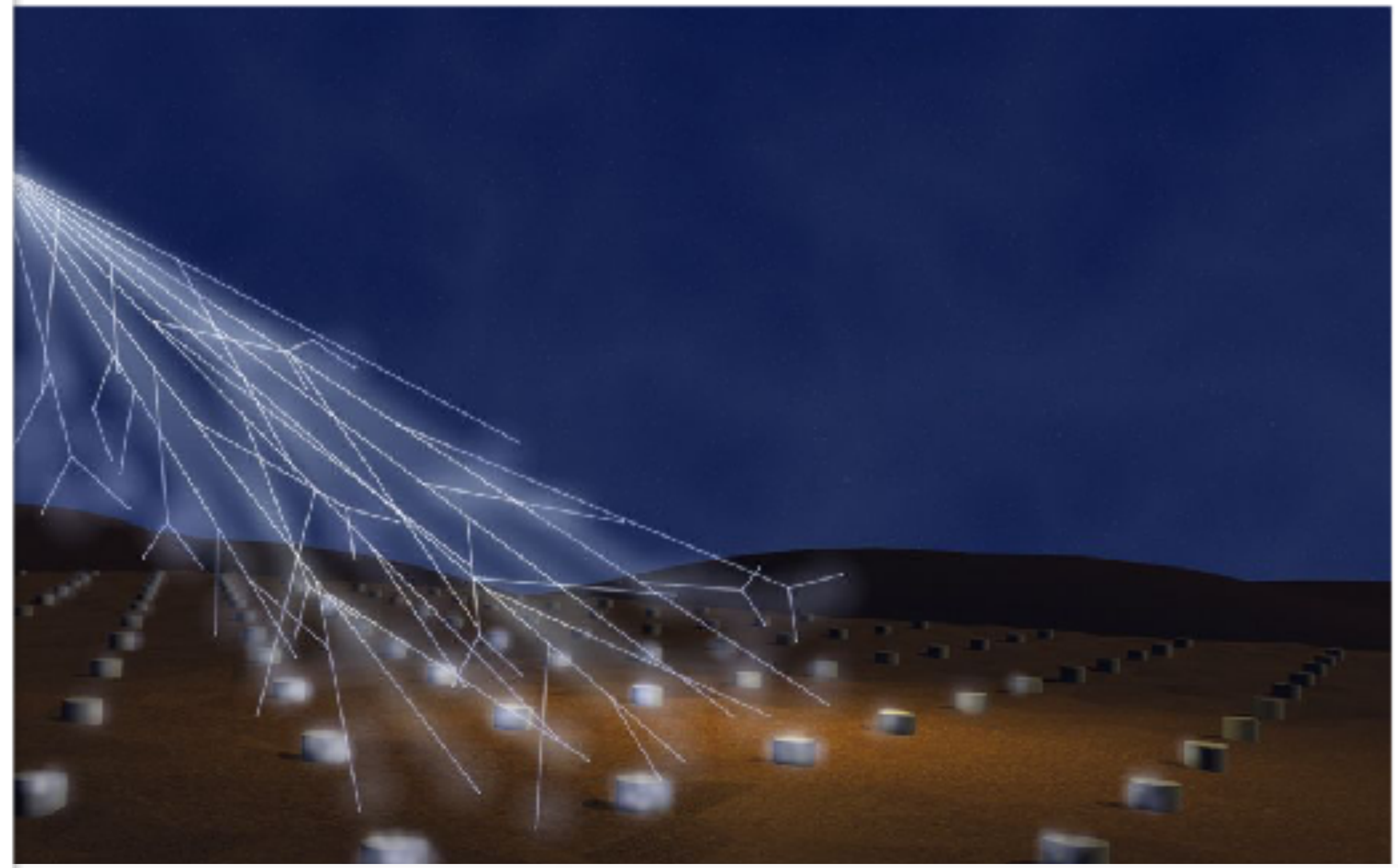
Three detector systems:
- Water Cherenkov tanks
- Sky fluorescence detectors
- AERA radio antennas being added

Measure energy, direction, composition

https://arxiv.org/pdf/1709.07321.pdf

Pierre Auger observatory





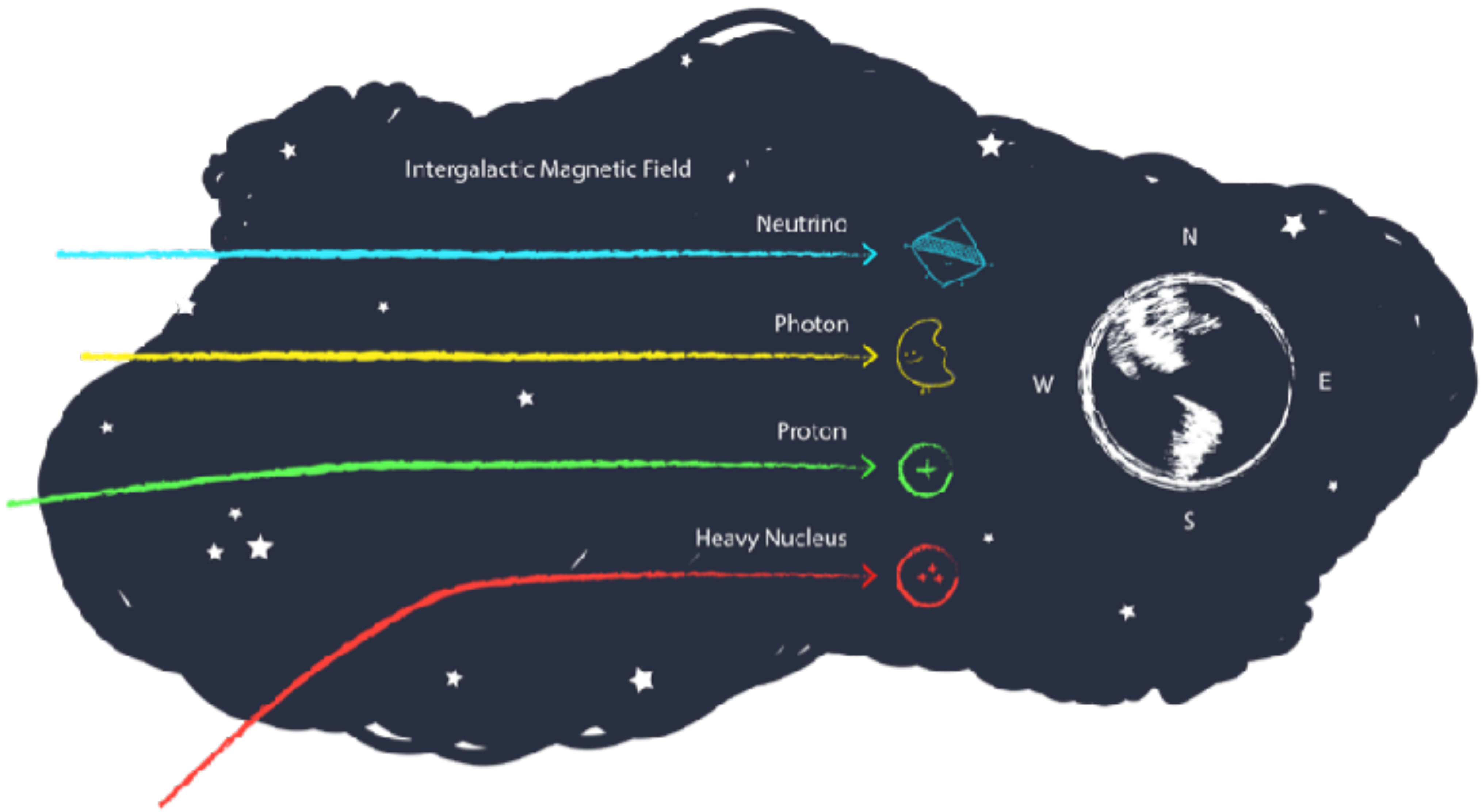
Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

22 September 2017

https://arxiv.org/pdf/1709.07321.pdf

High-energy cosmic rays



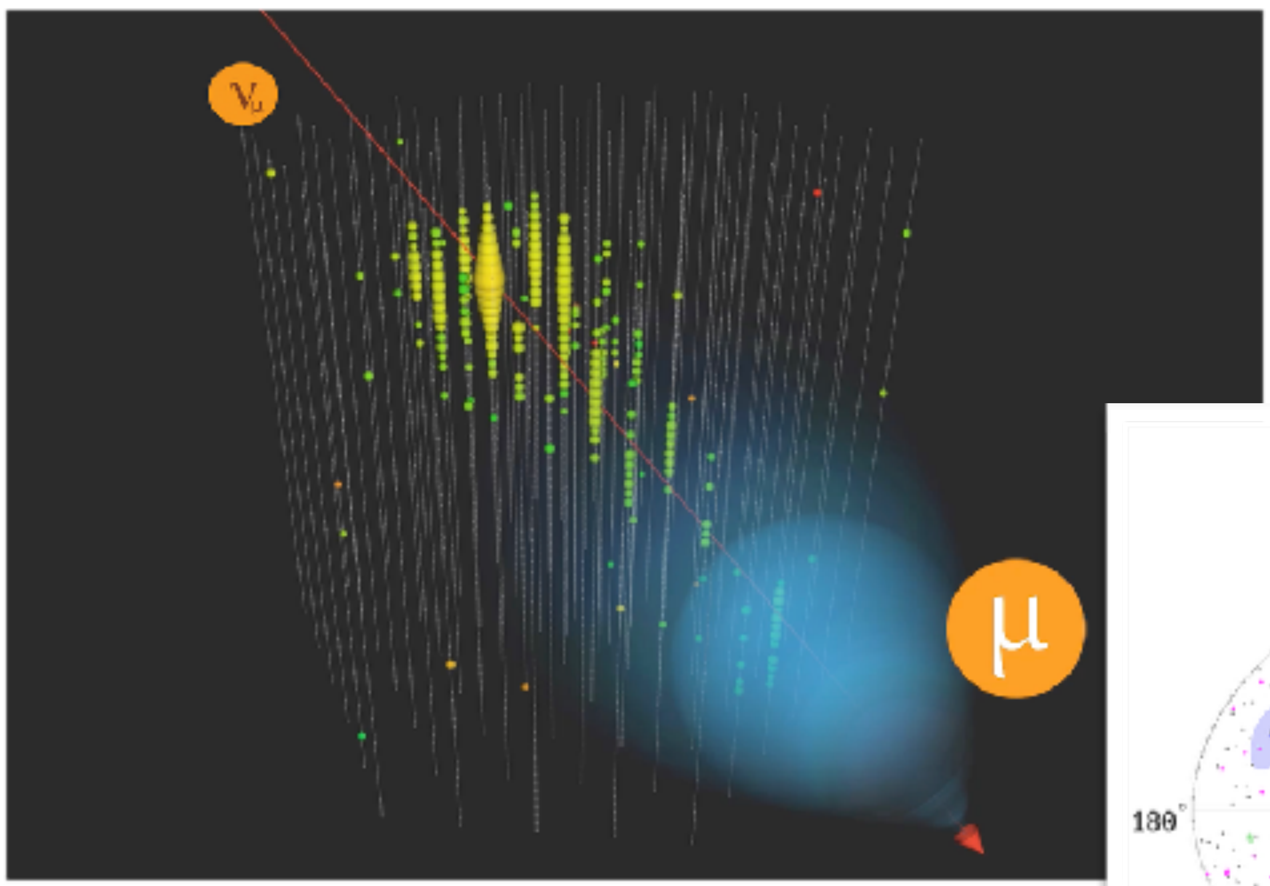
- How to detect high energy, extragalactic neutrinos?

IceCube

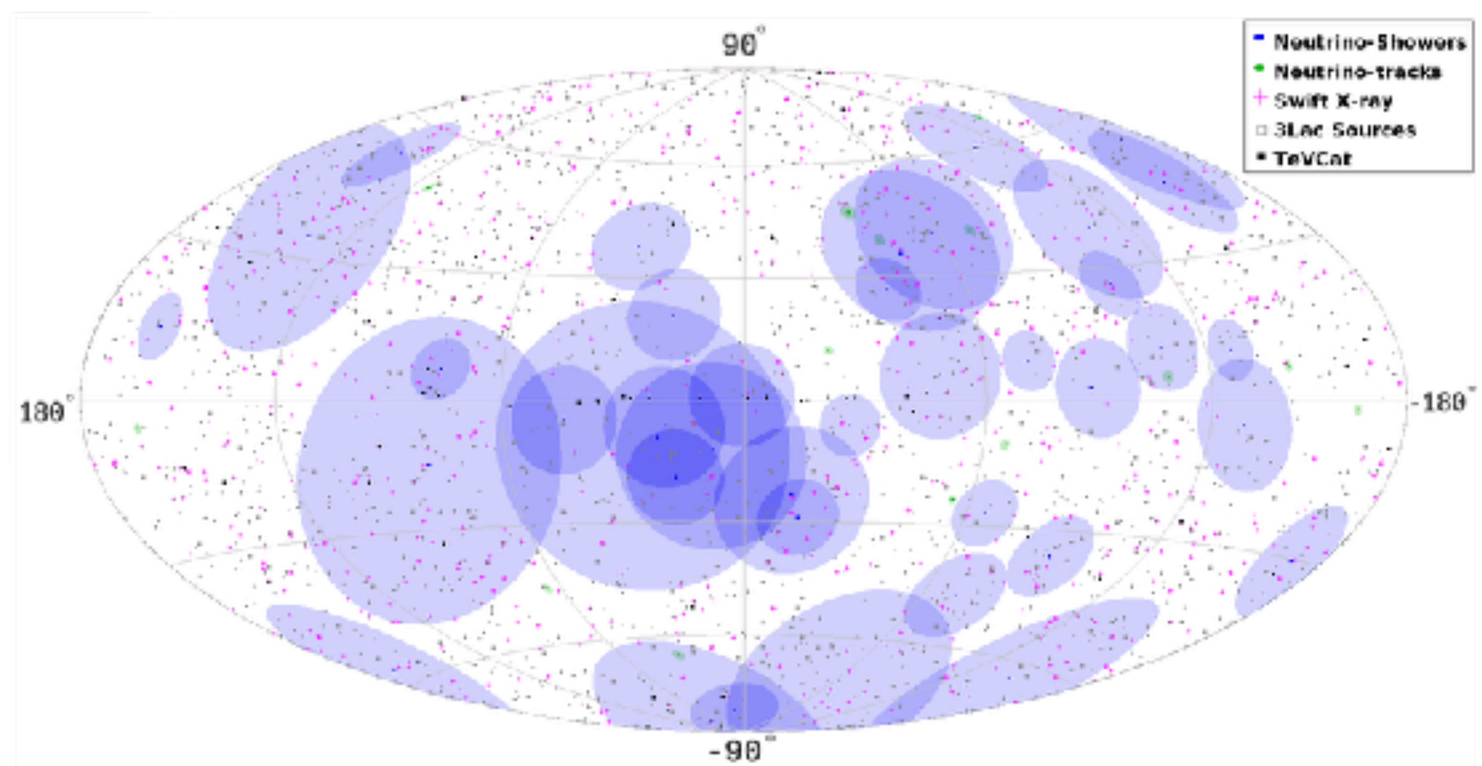
https://www.youtube.com/watch?v=OdWZA5UxmOk

IceCube

- 1 km3 covered with photomultipliers
- 1.5 - 2.5 km under the Antarctic ice
- 60 ‘DOMs’ x 86 ‘strings’



- Searches for point-sources
  —> improving with more data!
  —> ‘Pingu’ upgrade ~2025
- Multi-messenger astronomy



https://arxiv.org/abs/1602.03694

IceCube

- 1 km3 covered with photomultipliers
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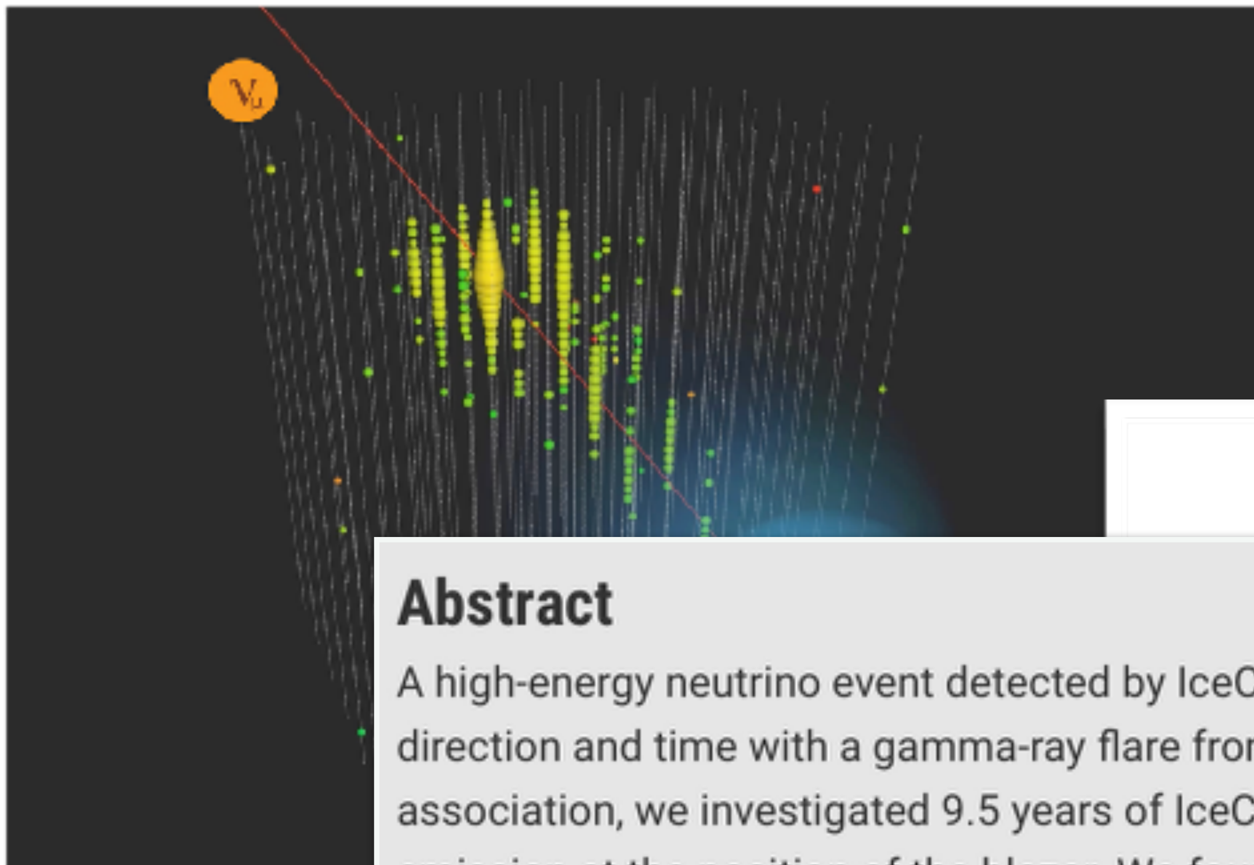
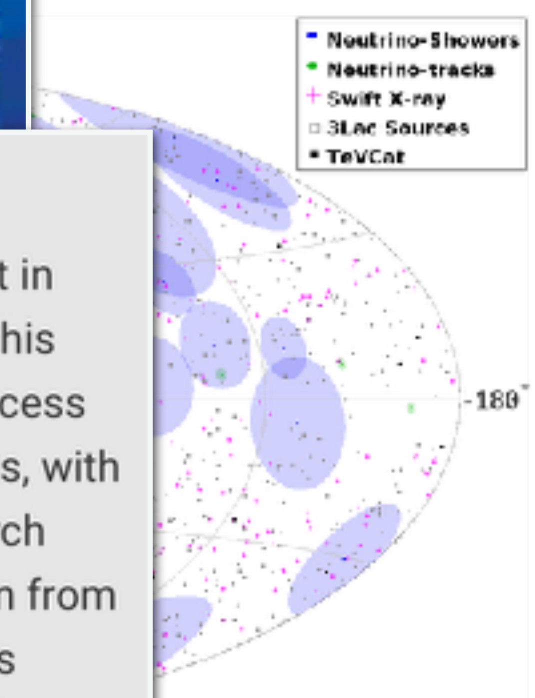


-sources
more data!
le ~2025
stronomy



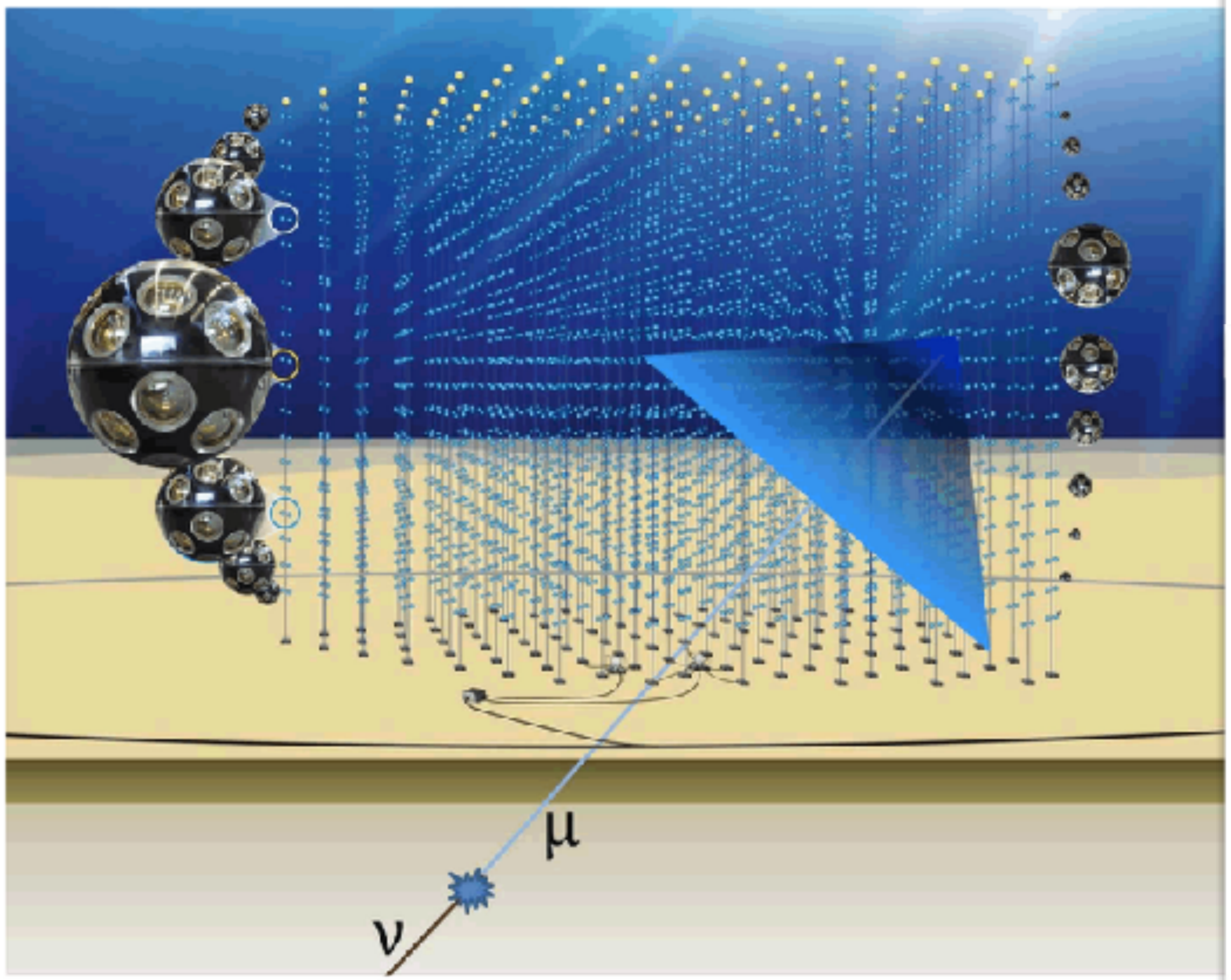
Abstract

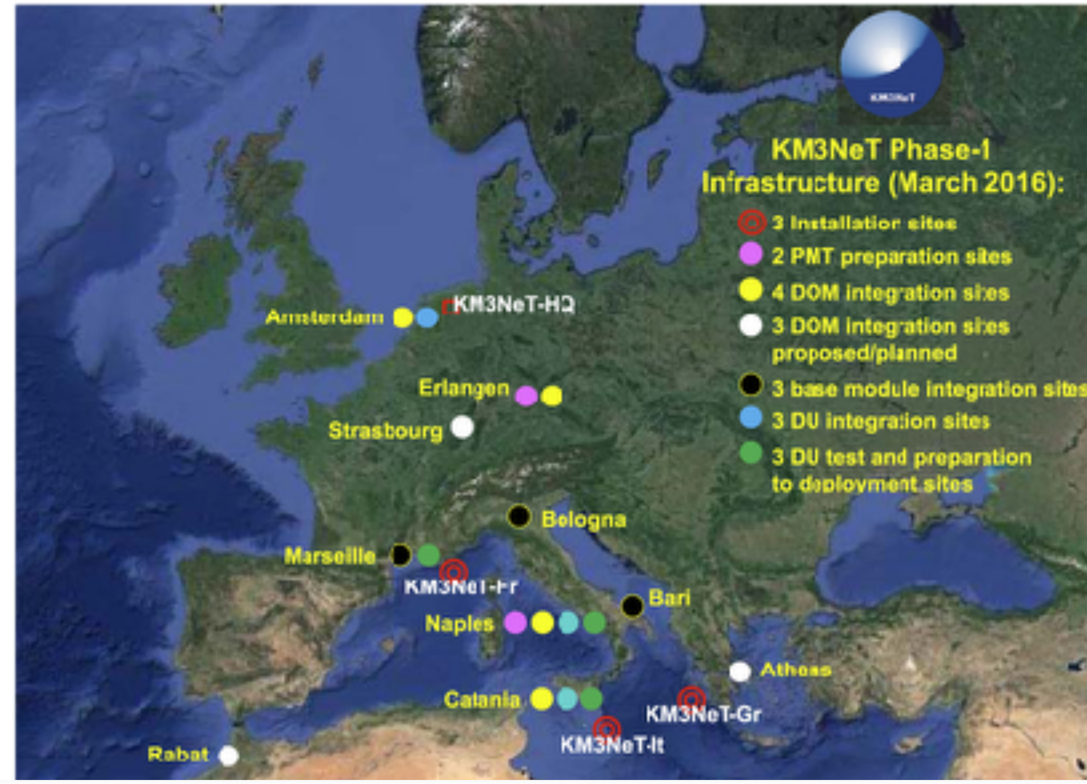
A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.

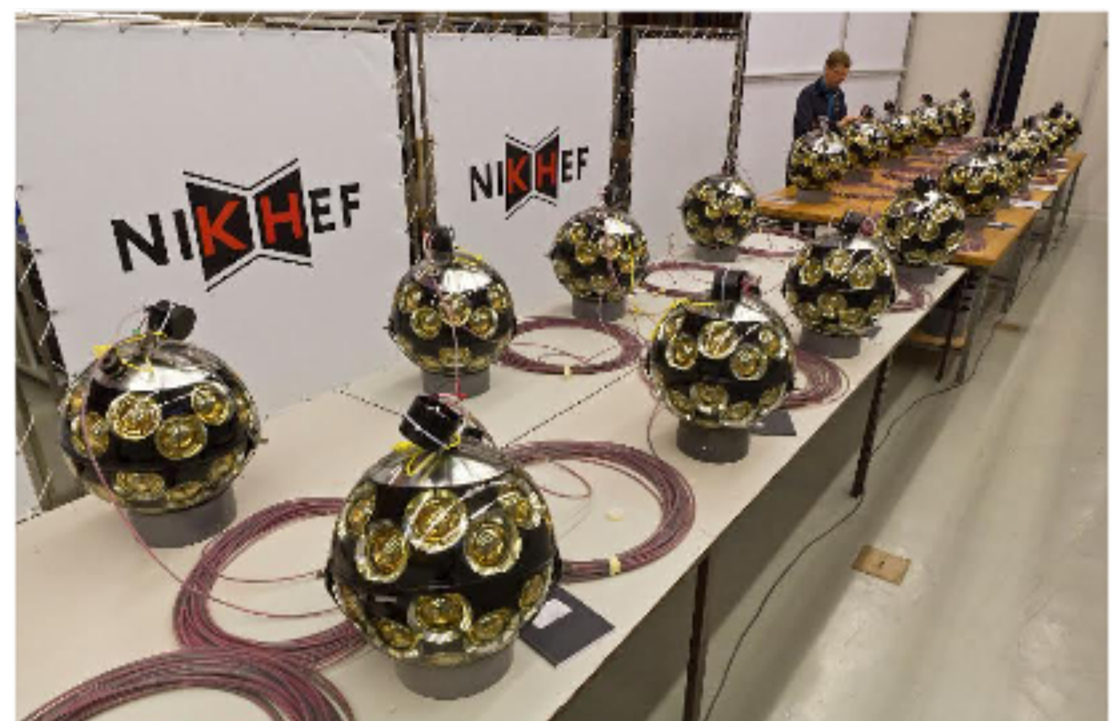
https://arxiv.org/abs/1602.03694

KM3NeT

- Similar idea, using the mediterranean sea
- Currently under construction
- Nikhef: just received 12.3M investment

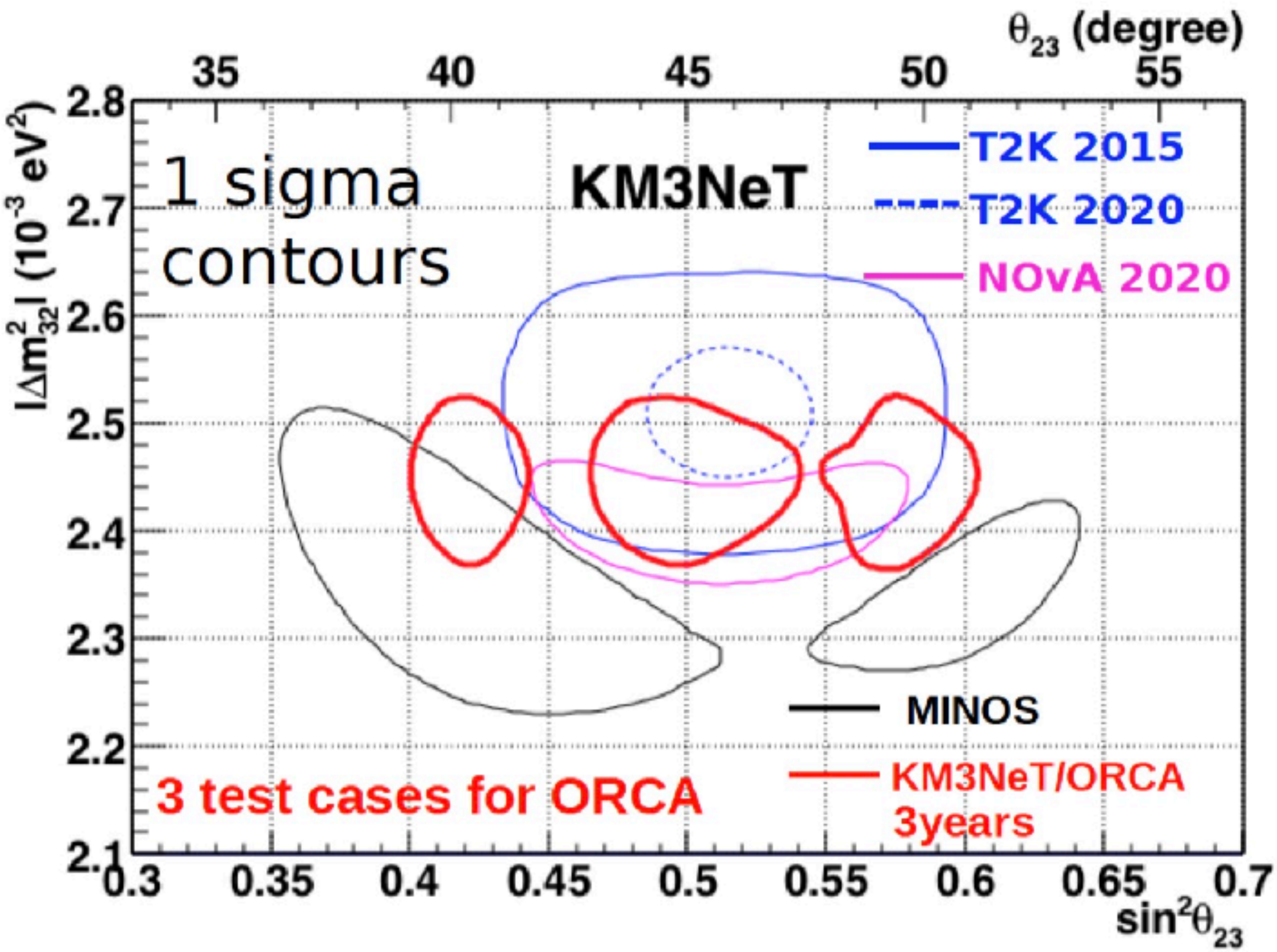






Mass hierarchy prospects

~2023: could be solved!



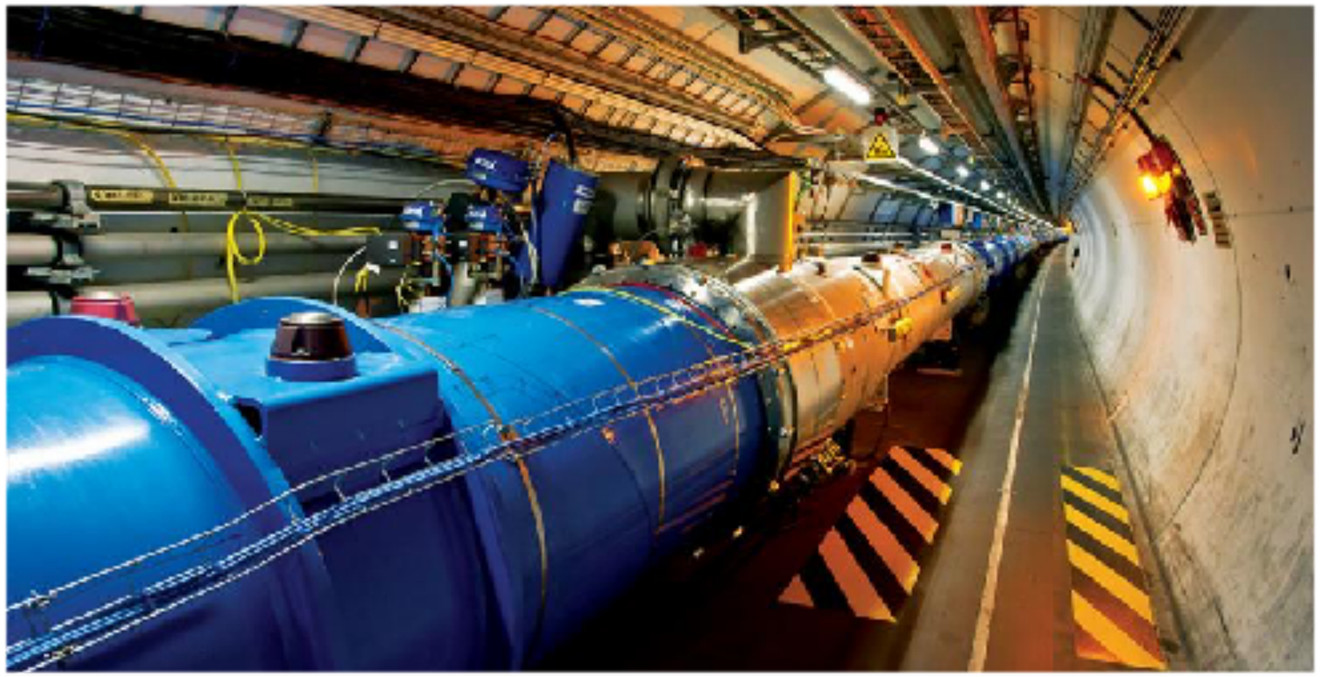
https://arxiv.org/pdf/1701.04078.pdf

Accelerator-based detectors

- Allows for continuous, systematic measurements
- Extremely high precision measurements
  (can build precision instrumentation around a fixed point!)
- A lot of data! (or “integrated Luminosity”)

Accelerator-based detectors

- LHC: proton-proton collider
  - 13 TeV center-of-mass energy
  - 40 million ‘bunch crossings’ / second
  —> sometimes with 20 collisions / ‘bunch crossing’
  Instantaneous luminosity ~ **2 x 10^{34}** / (cm^2 s).

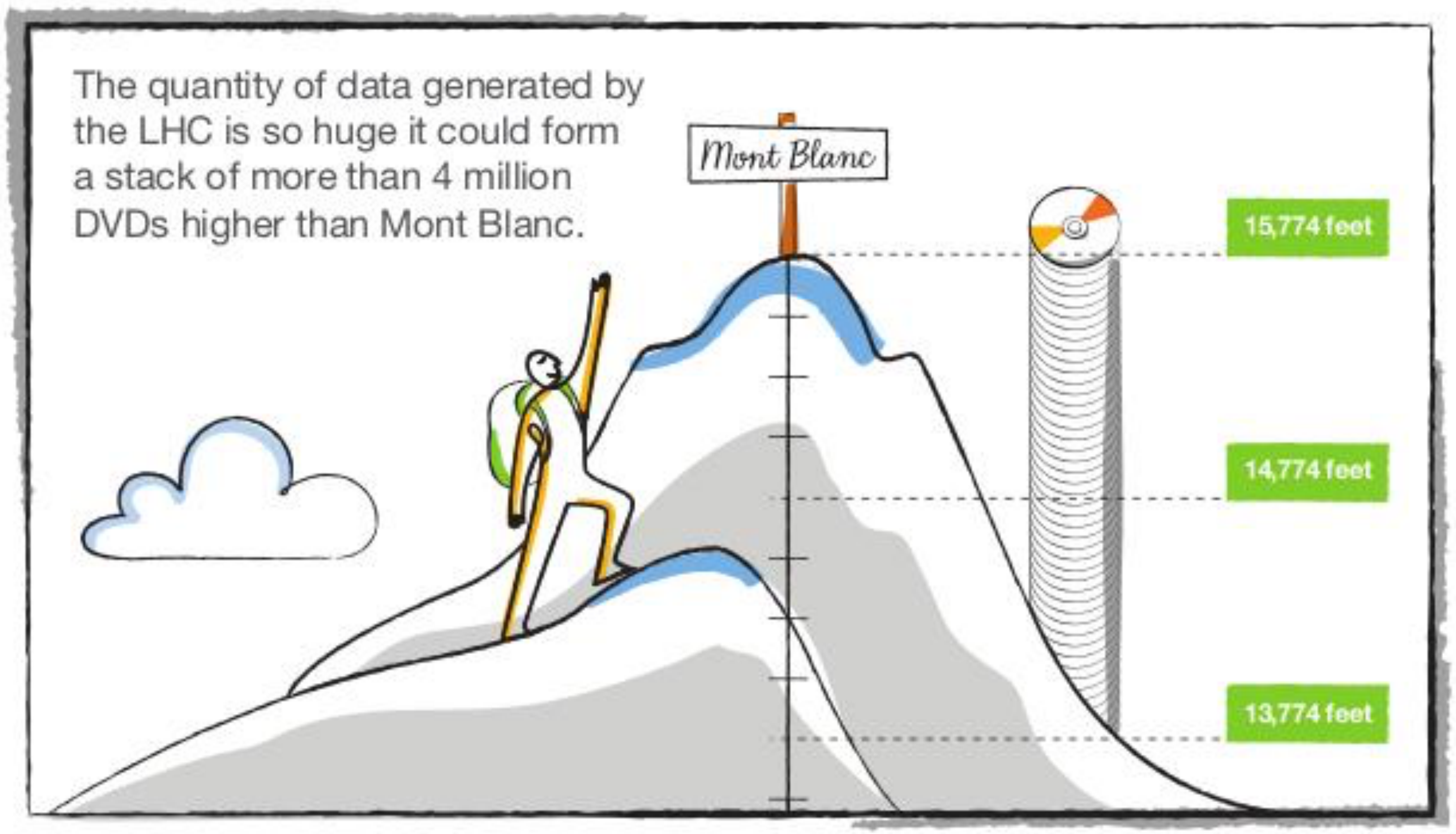


Accelerator-based detectors

- Readout of detectors must be very, very fast (~25 ns)
- Equipment must be very radiation 'hard'
  : Few years of operation —> 35 kGy (= kJ/kg) for a single 'layer'
  : compare to yearly background dose: ~3 mSv
- Often: precision demanded which is not yet possible to build
- Data: ~1MB/'event' —> 40 TB /s ?? —> **not possible?**

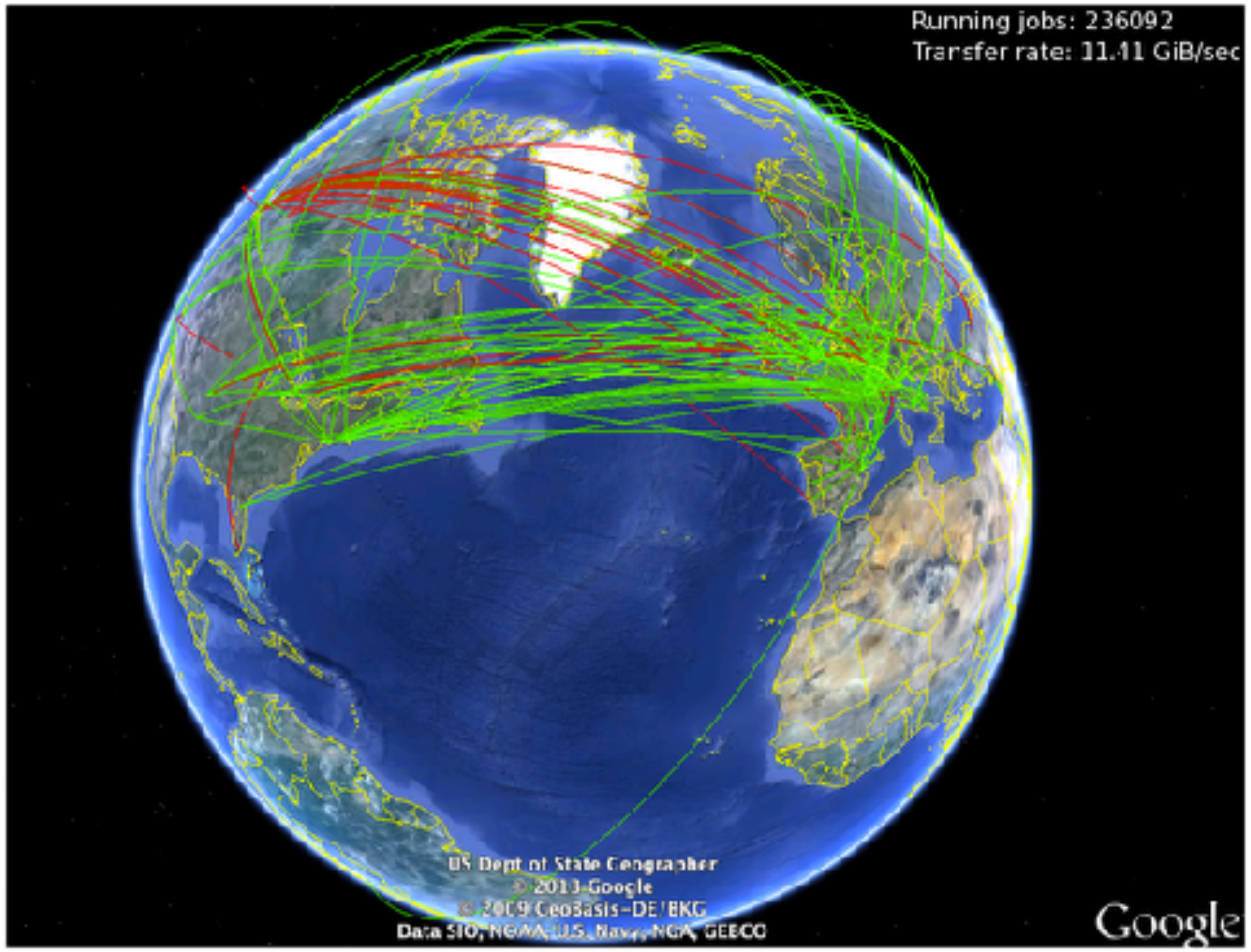
Data size

- Zero-suppress raw data (no 0 and 1's, but build clusters)
- Only send relevant information: **trigger** interesting events
  —> high-performance, cutting edge algorithms
  —> Crucial: don't throw away new particles!
- Real data rate ~ 2 GB/s
- Still enough data to stack DVD's to mt. Blanc every year. (x1.5)



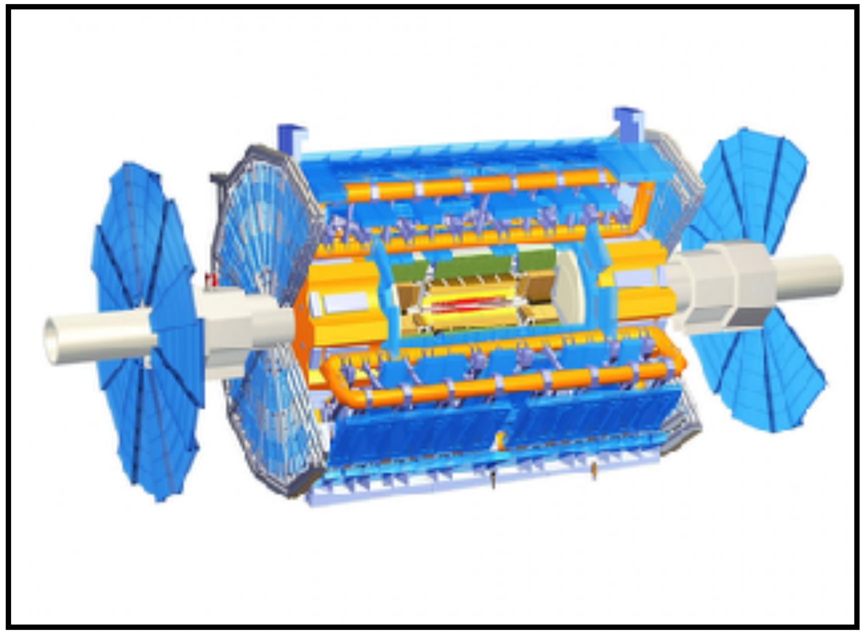
Data size

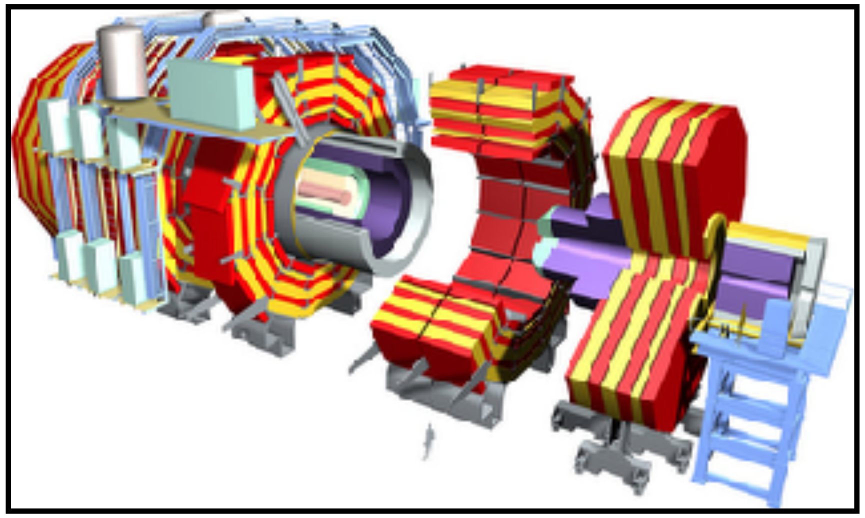
- Infrastructure: World-wide Computing Grid (LCG)
- Reconstructing data
- Simulating data
- User job processing

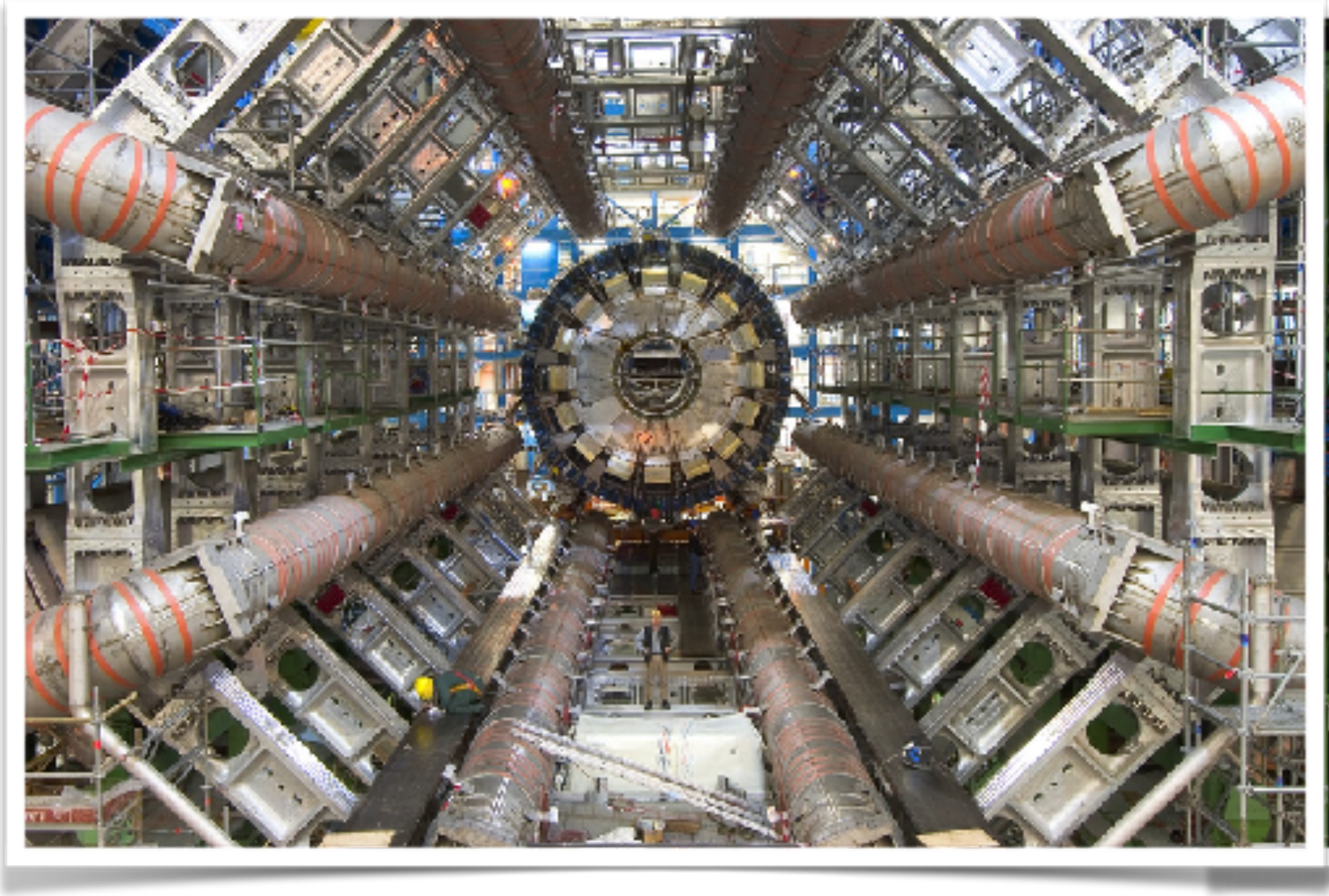


Welcome to the era of tera

ATLAS / CMS



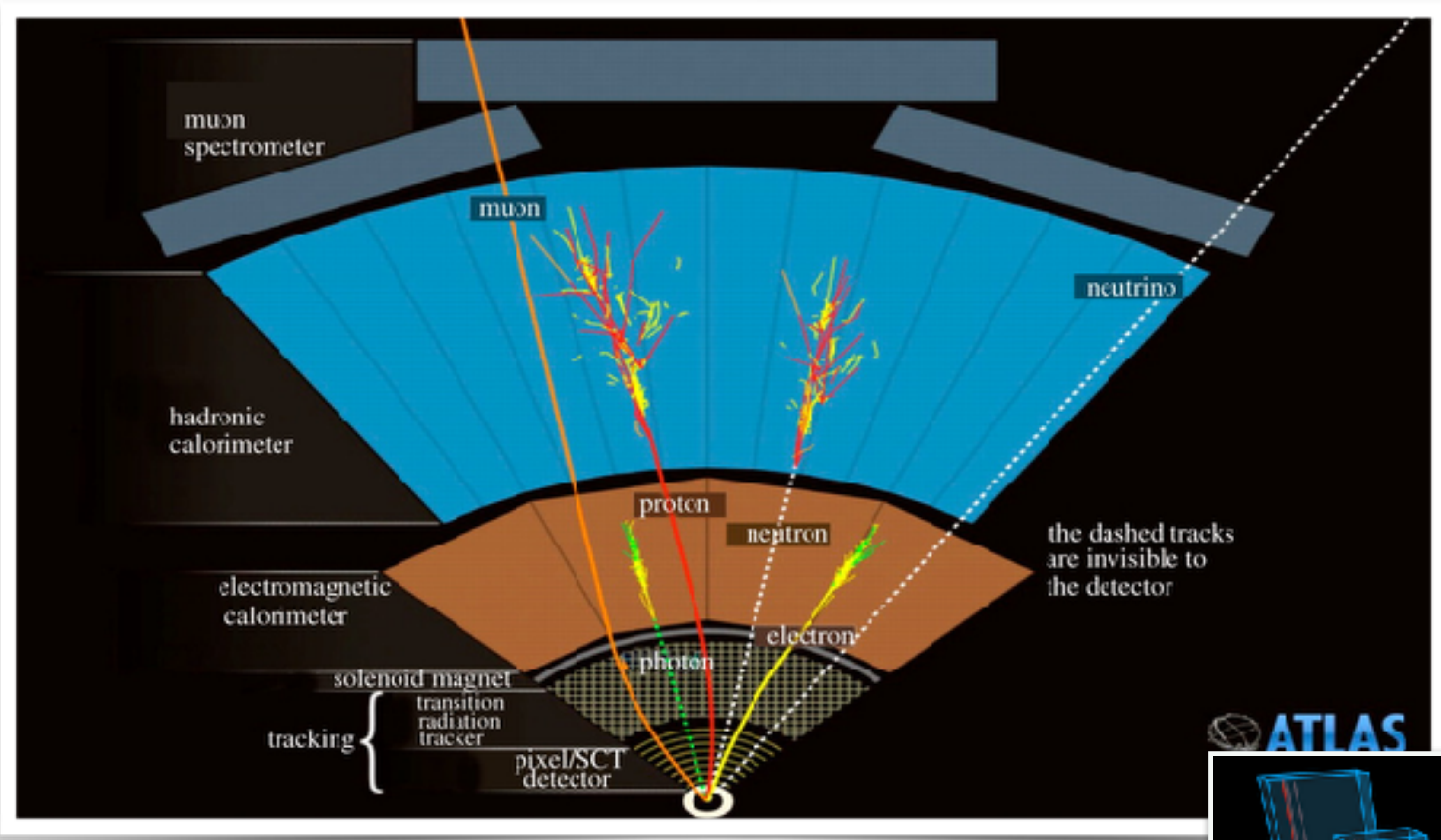


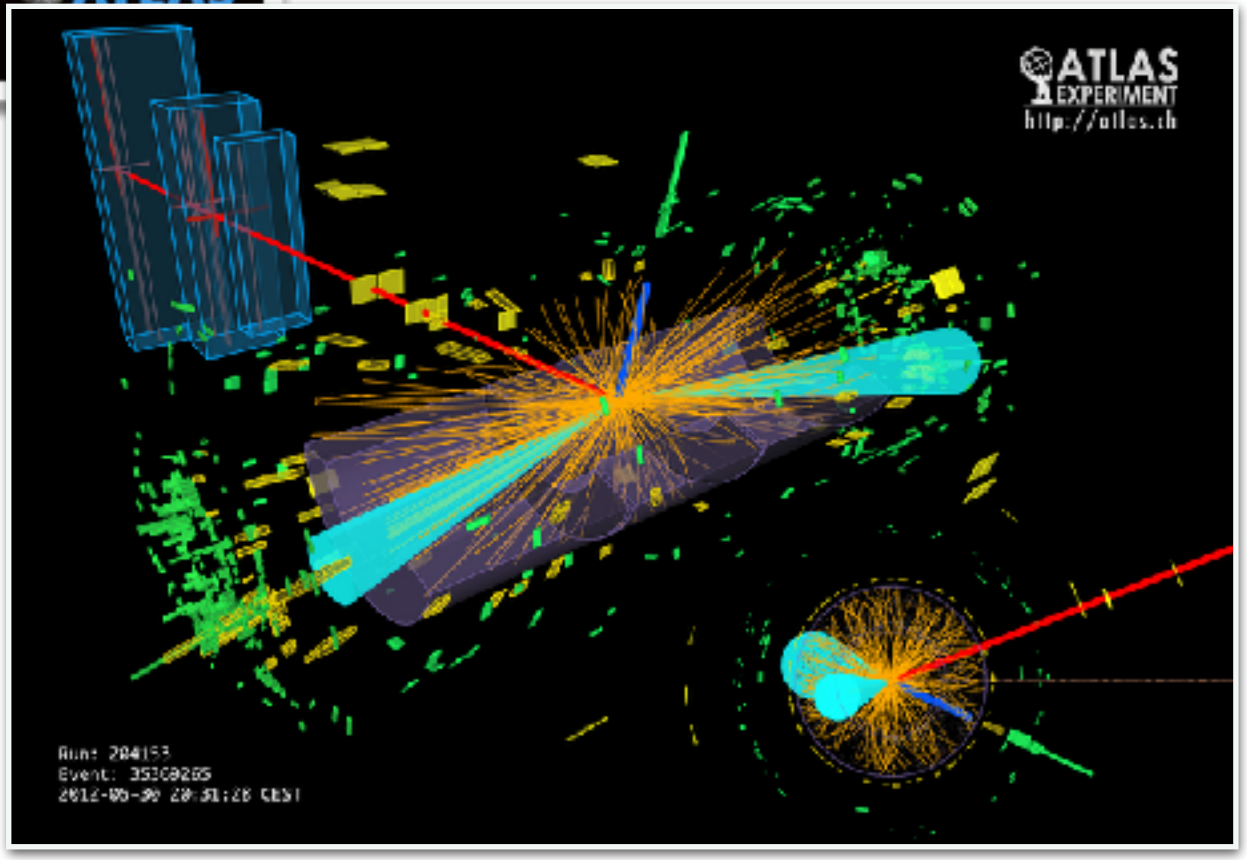


ATLAS / CMS

- ‘General purpose’ detectors
- Collaborations: ~3000 people
- Main goals:
  - direct detection of new particles (SUSY)
  - measuring the top quark mass
  - Studying the Higgs boson properties

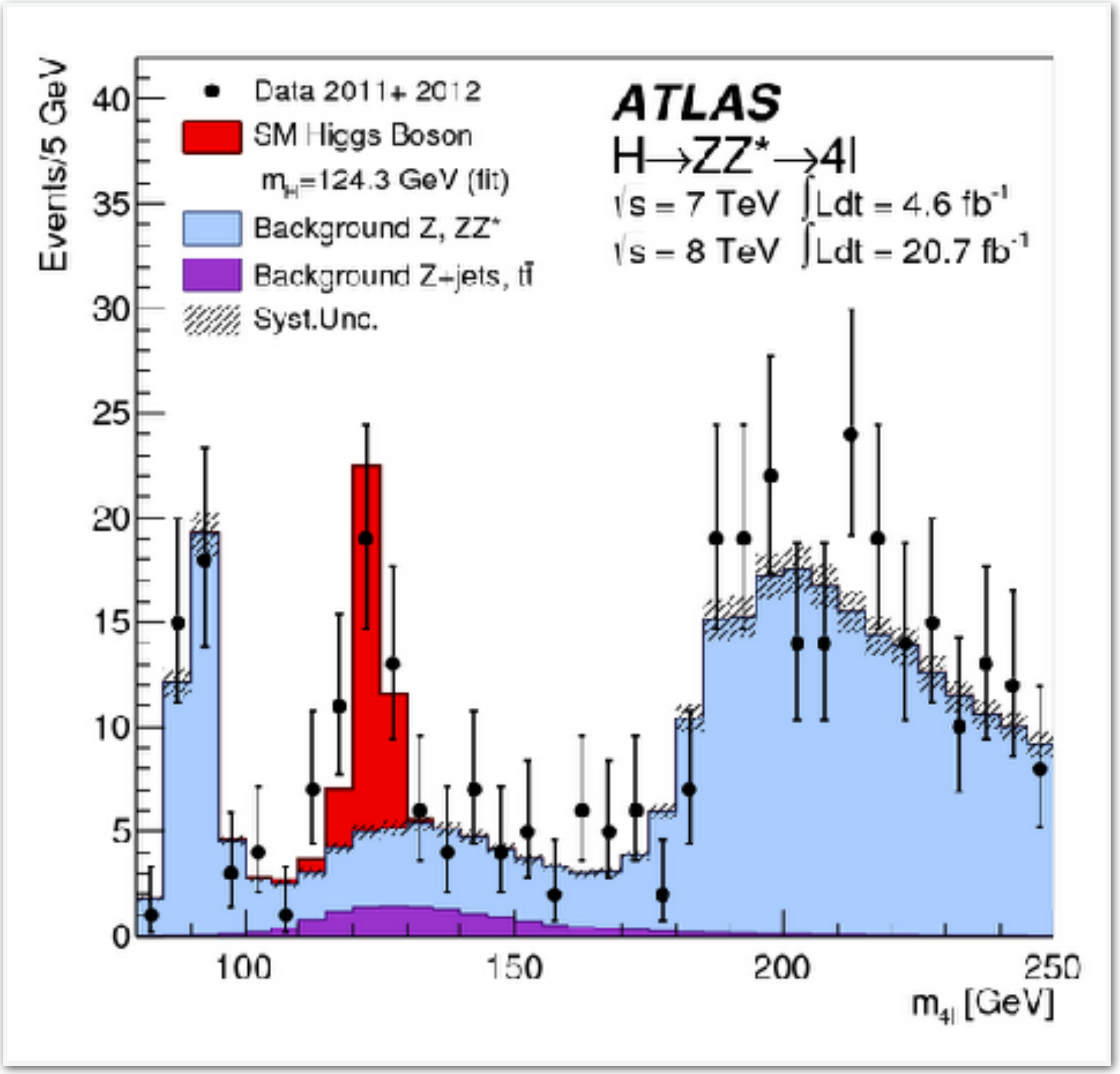
ATLAS

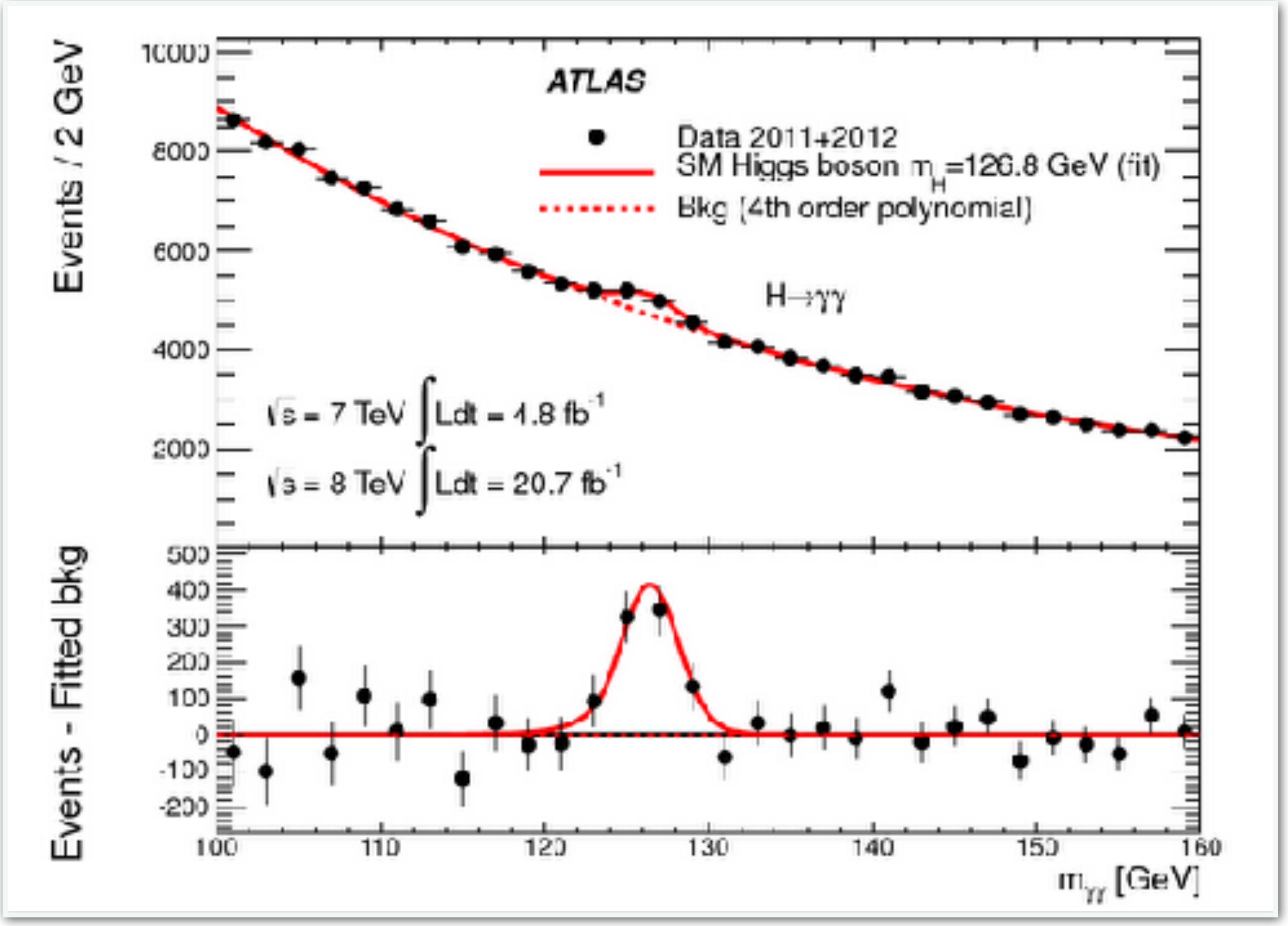

muon
spectrometer
muon
neutrino
hadronic
calorimeter
proton
neutron
the dashed tracks
are invisible to
the detector
electromagnetic
calorimeter
electron
photon
solenoid magnet
transition
radiation
tracker
tracking
pixel/SCT
detector
ATLAS


ATLAS
EXPERIMENT
http://atlas.ch

Higgs

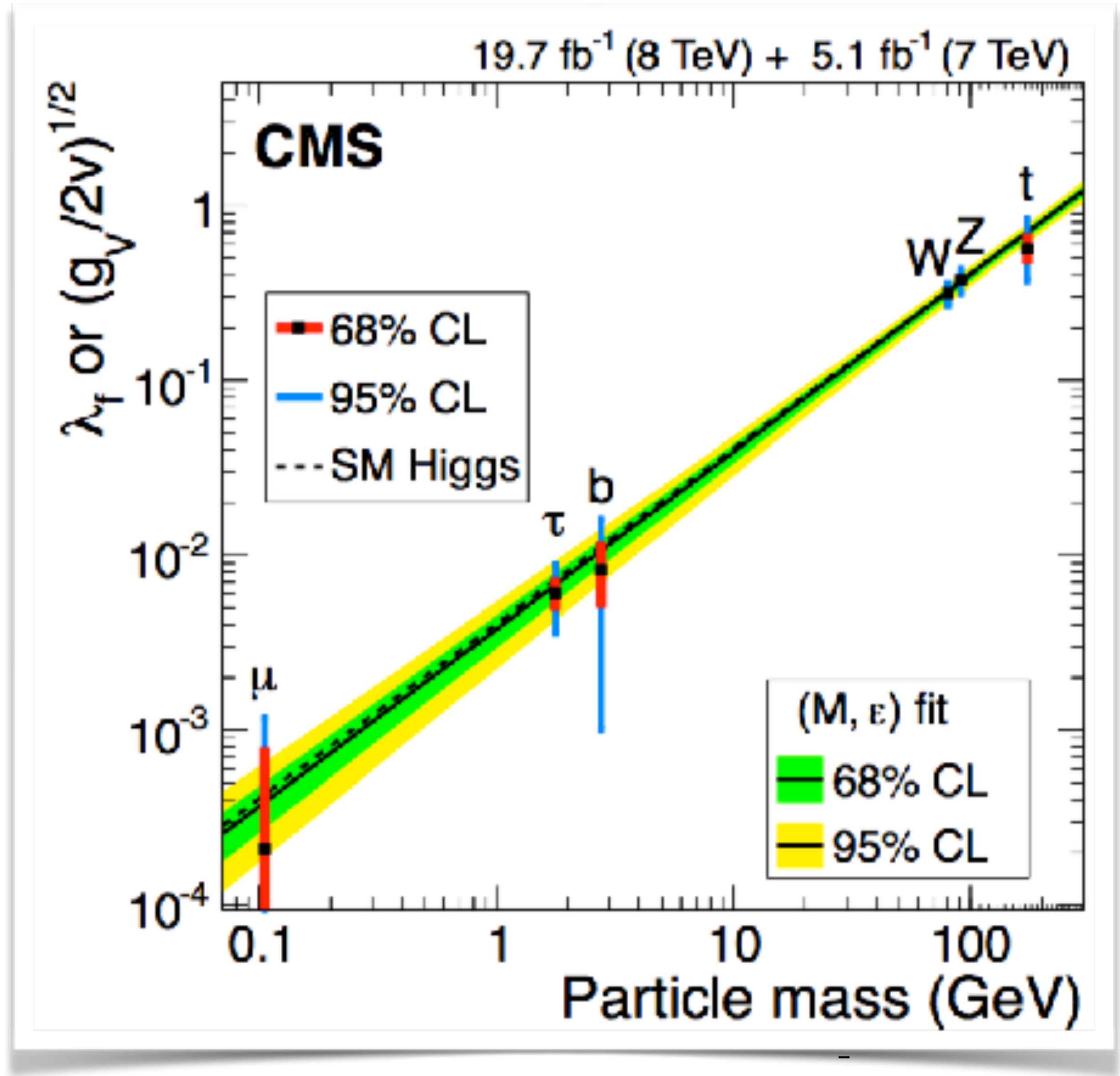
- Various (production and) decay channels
- Discovered in 2012



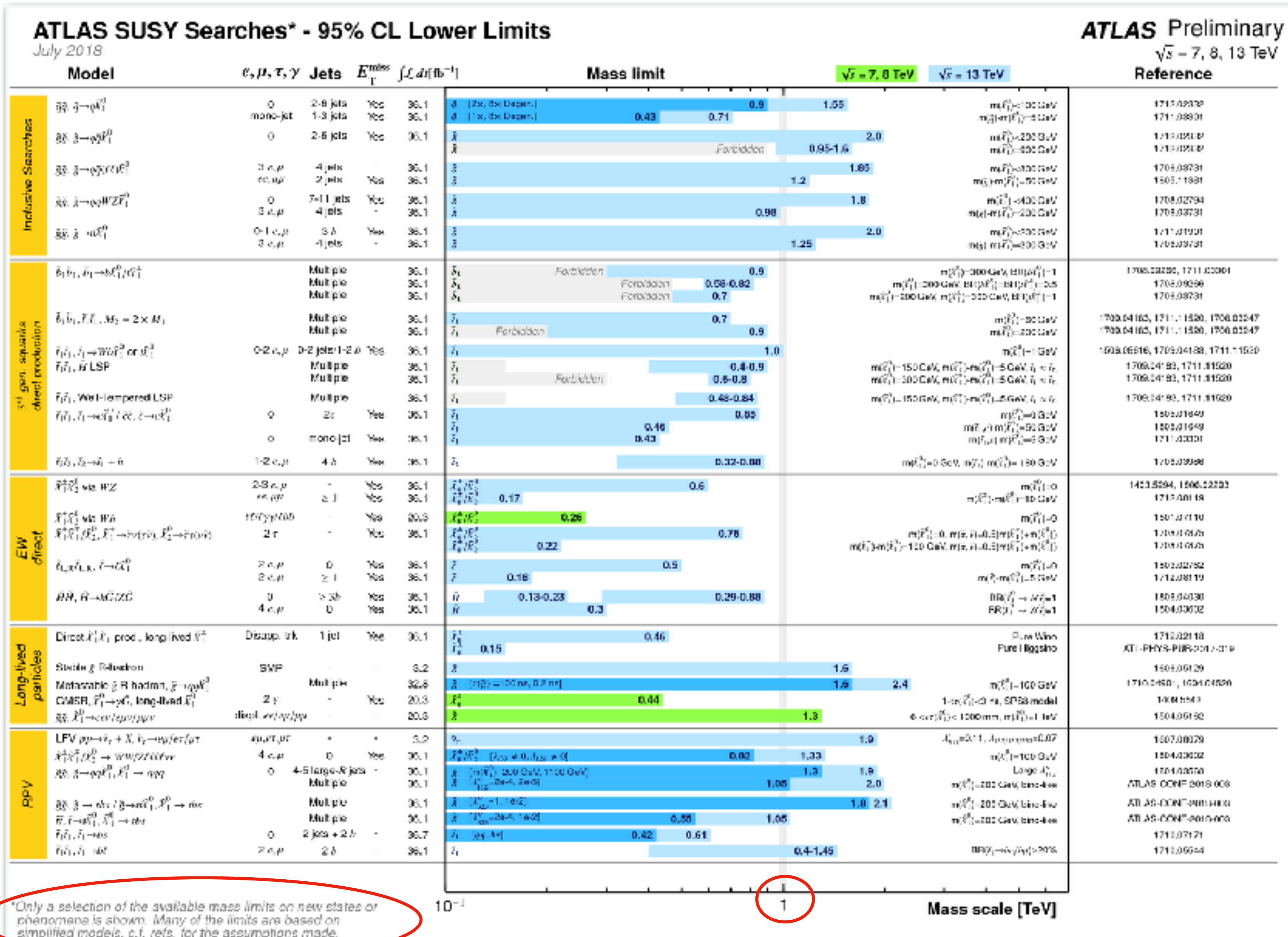


Higgs

- Looks like the SM Higgs boson… but:
- Only spin-0 particle observed so far! —> study properties!
- Coupling ~ mass —> our 'portal' to dark matter?
  —> measure the total decay width / lifetime!
- Is the potential really our $V(\phi)$?
  —> measure λ : self-coupling!

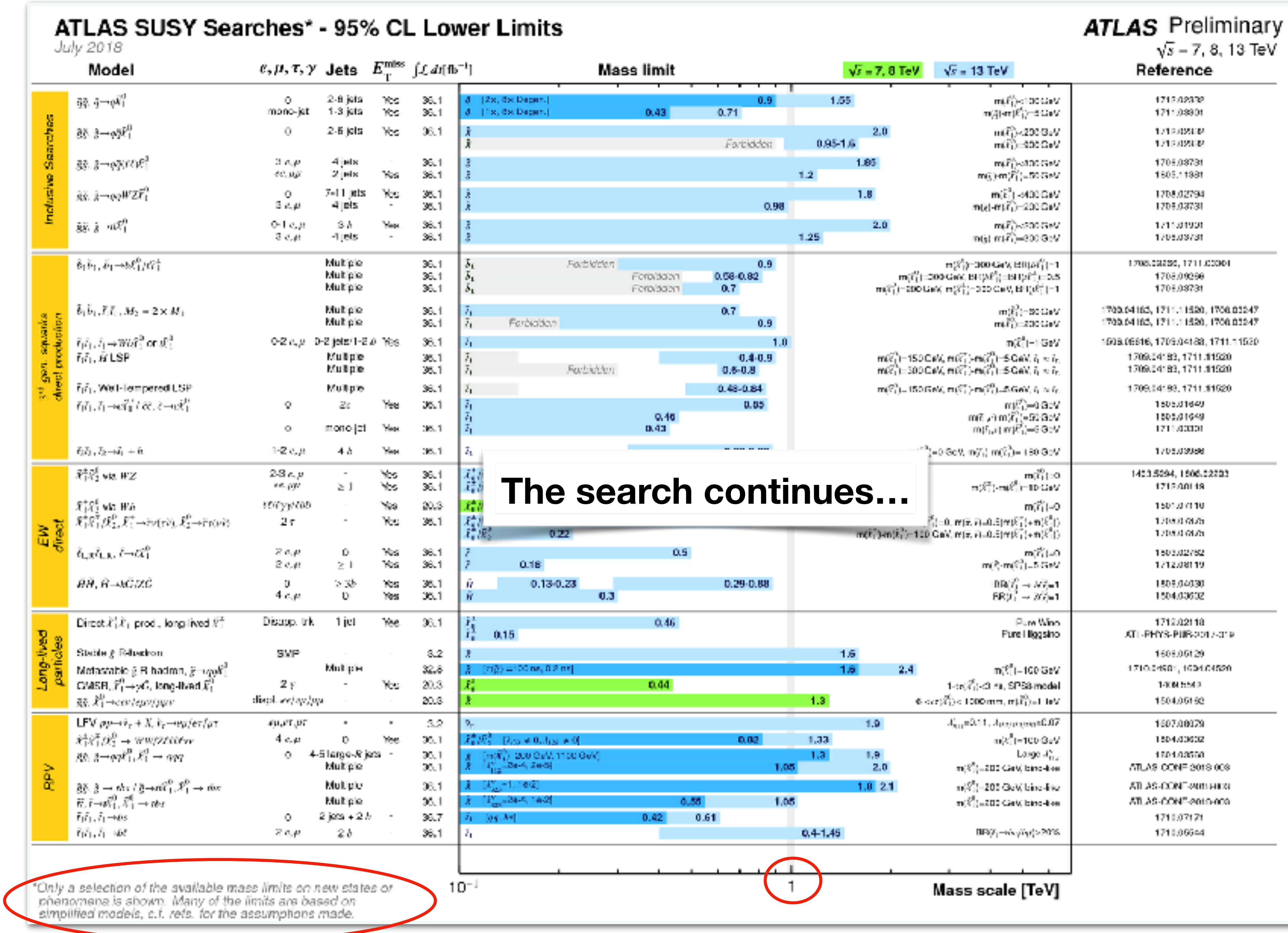


SUSY search limits



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

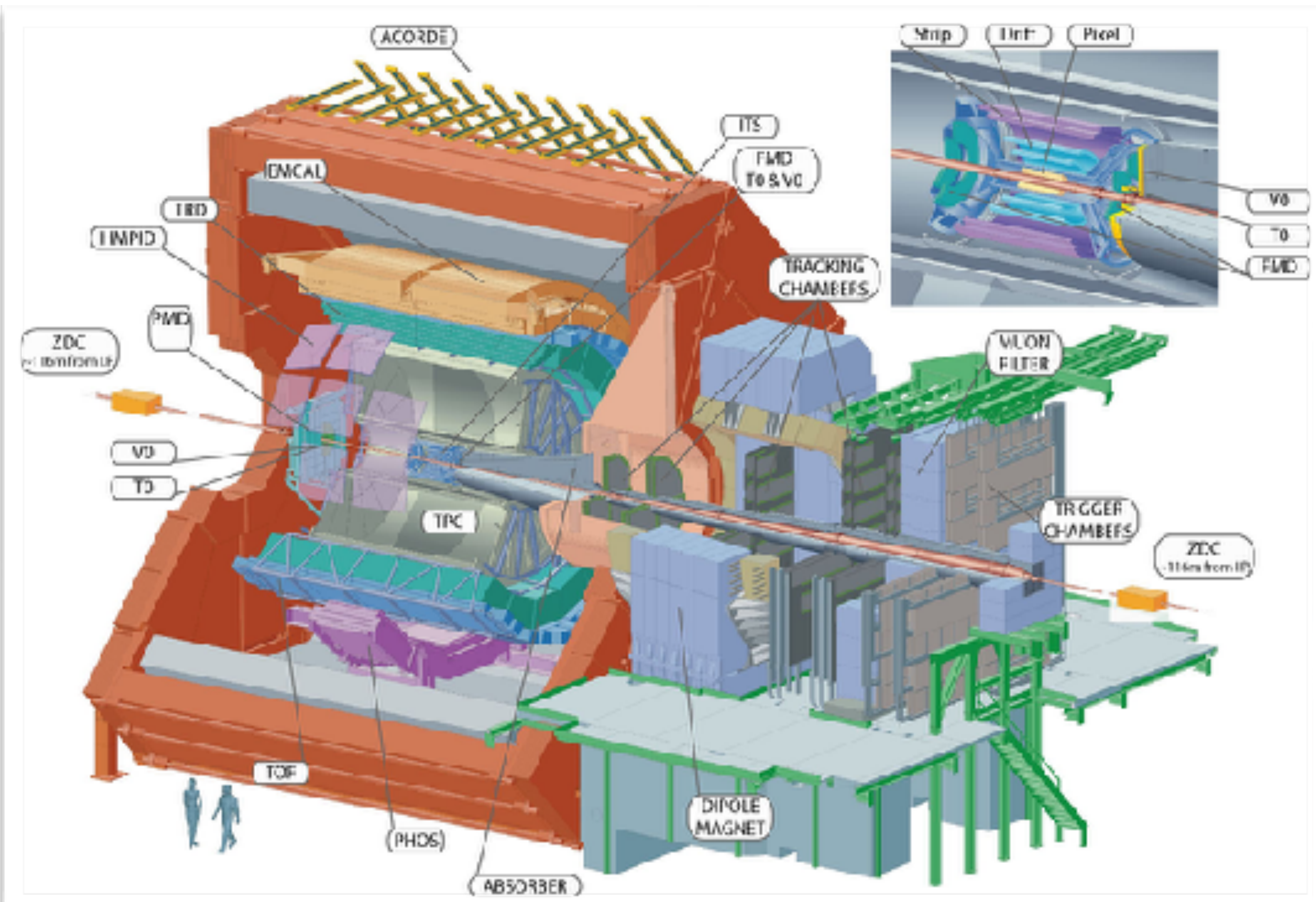
SUSY search limits

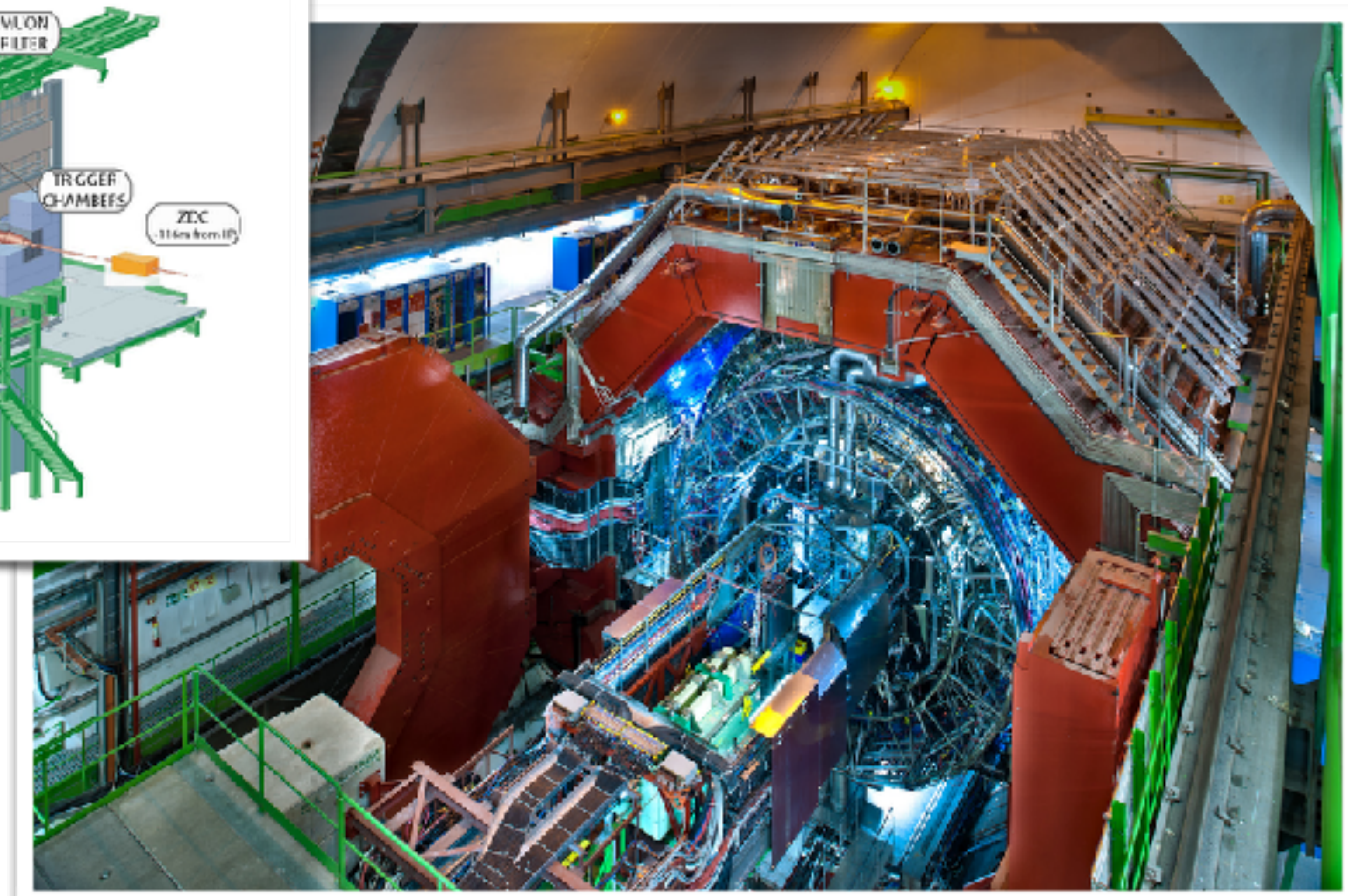


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

ALICE

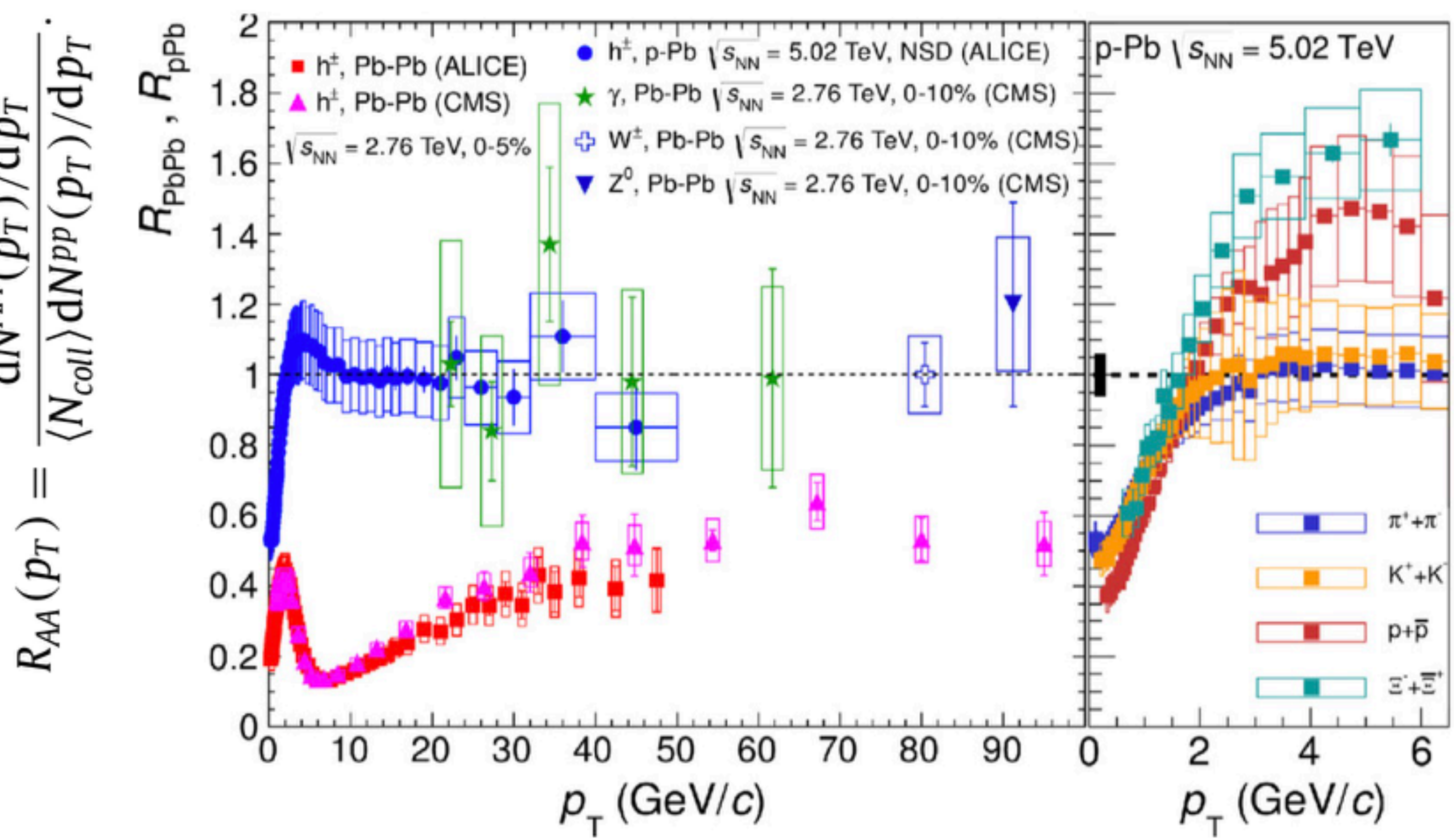
- Studying heavy ion collisions
- Collaboration: ~1500 people





ALICE

- Trying to probe thermodynamics at the big bang:
  —> quark-gluon plasma



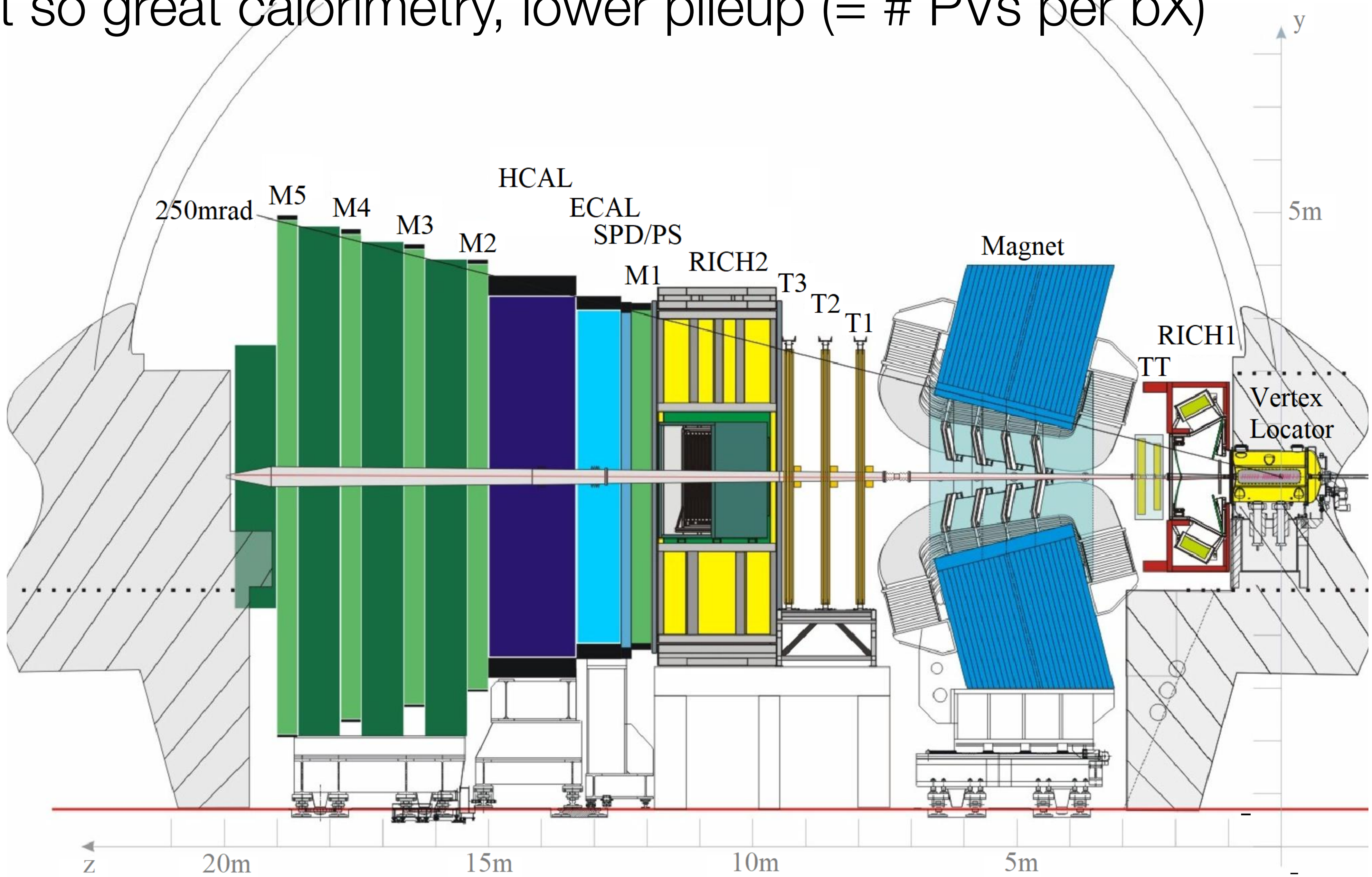
https://www.sciencedirect.com/science/article/pii/S2405428316300144

LHCb

- ‘B’-quark properties
- Collaboration: ~600 people

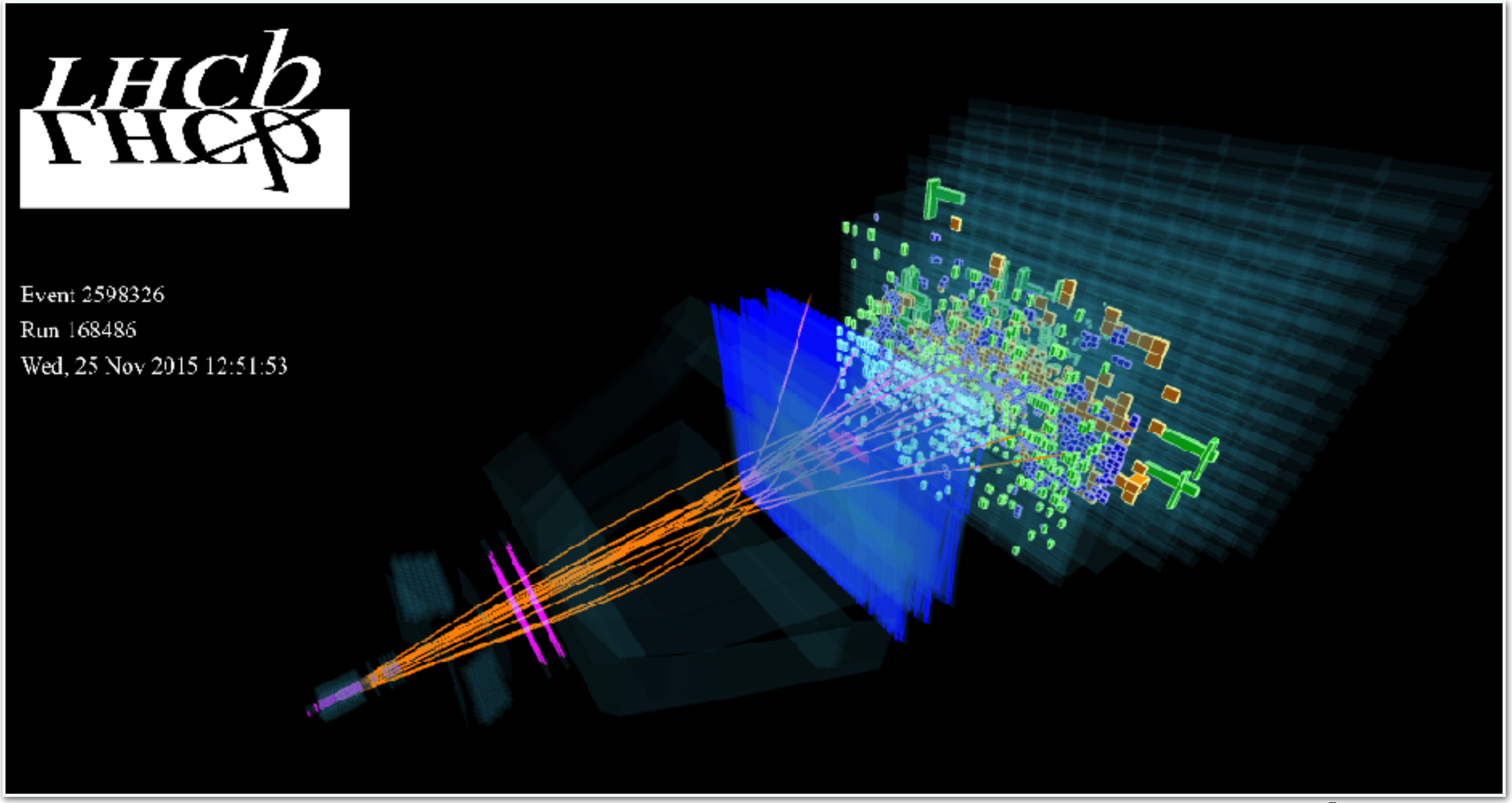
LHCb

- ‘downstream’ coverage
- Excellent momentum & vertex resolution, great PID
- Not so great calorimetry, lower pileup (= # PVs per bX)



LHCb

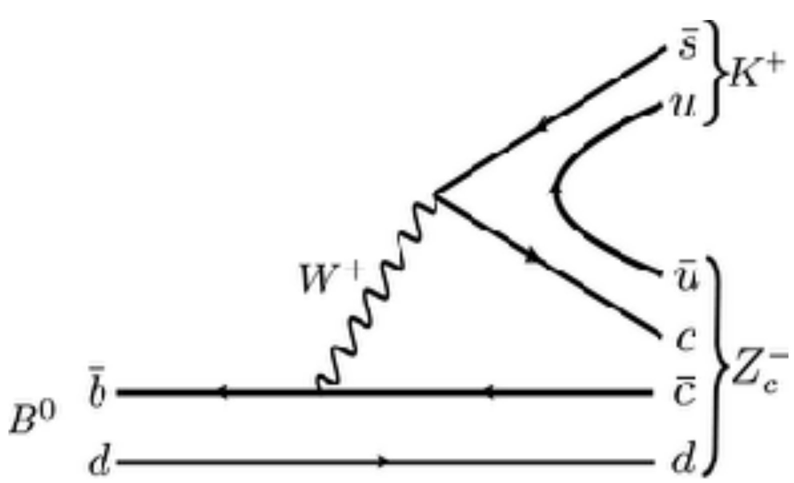
- live event display: https://lbevent.cern.ch/EventDisplay/index.html
- live status display: https://op-webtools.web.cern.ch/vistar/vistars.php

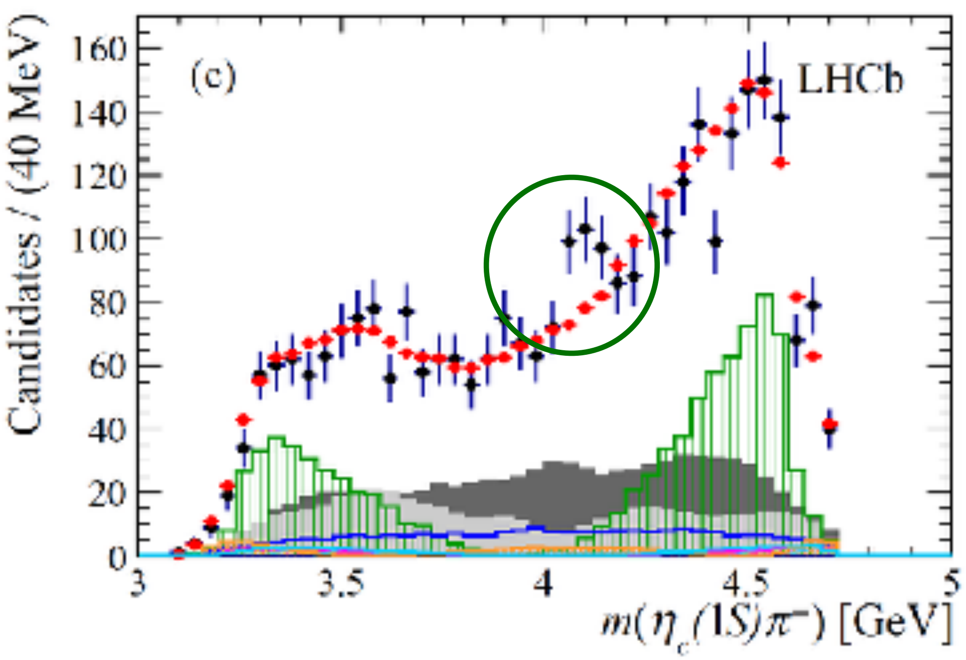


LHCb

- LHCb's mission is to make extremely precise flavour measurements —> new particles could contribute to quantum loops
- If observation ≠ SM prediction: new physics!

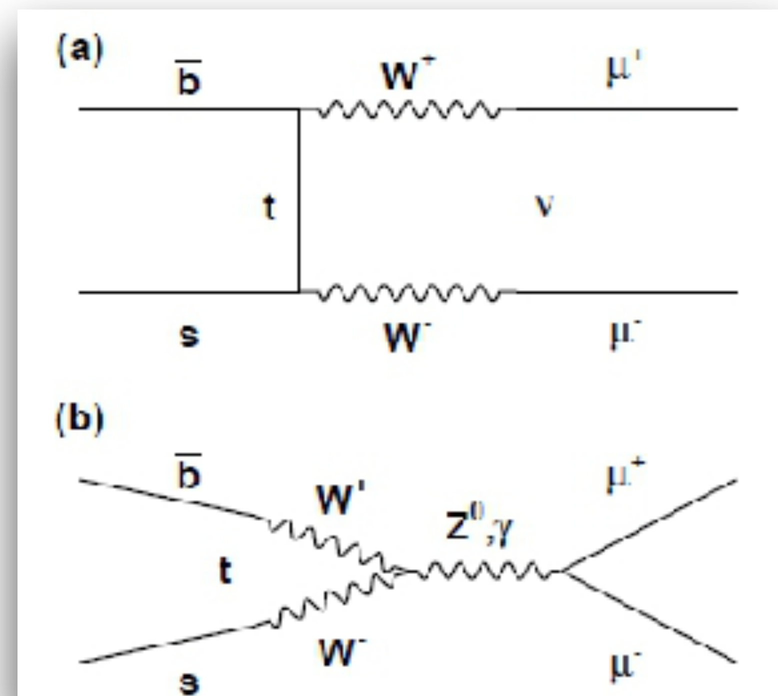
- Very rare decays
- (time-dependent) CP violation
- lifetimes, spectroscopy of new states (X-quarks, where X>3)

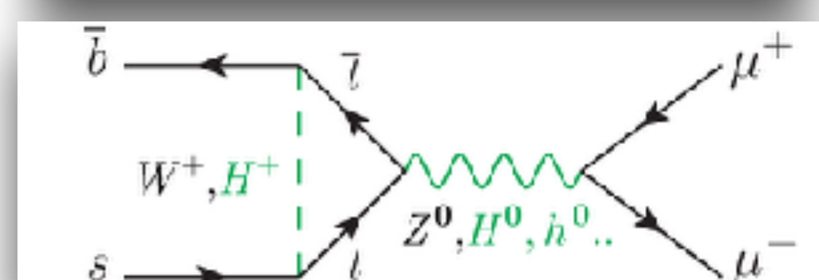


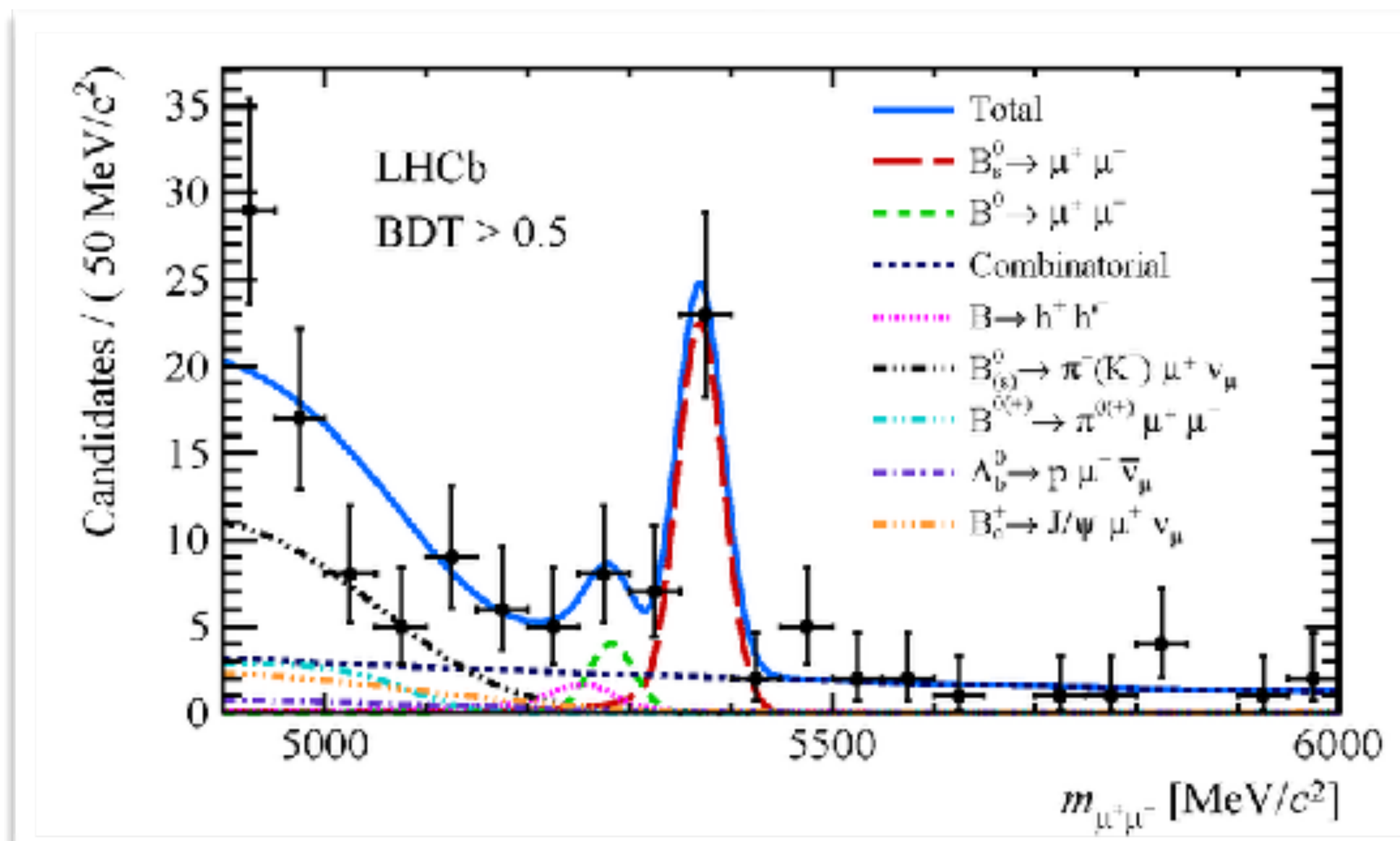


B —> mu mu

- Very rare decay: ~10^{-9} !
- Very suppressed and only via quantum loops —> new particles!
- First observed in 2017
- Seems close to SM, but error still large

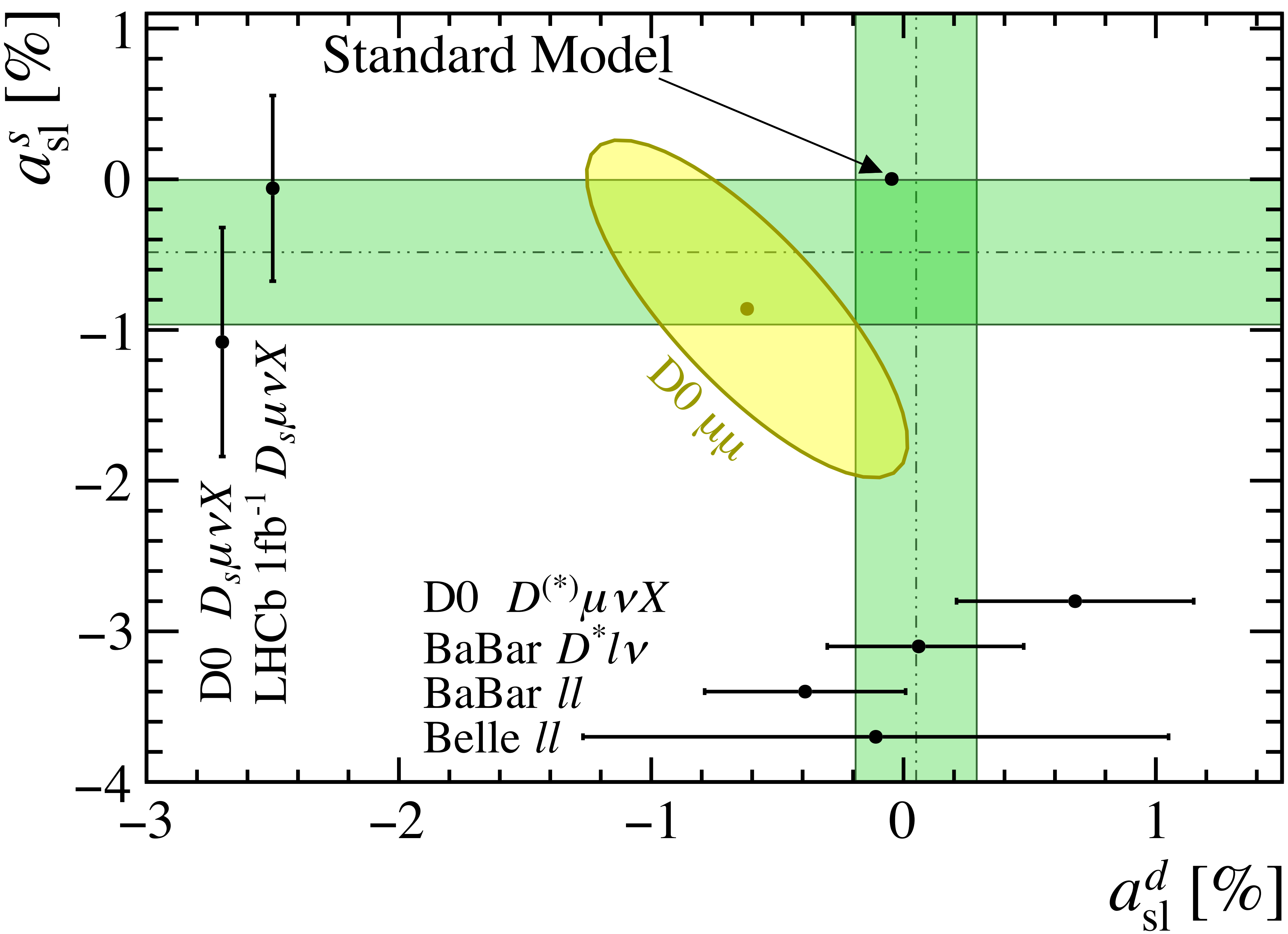






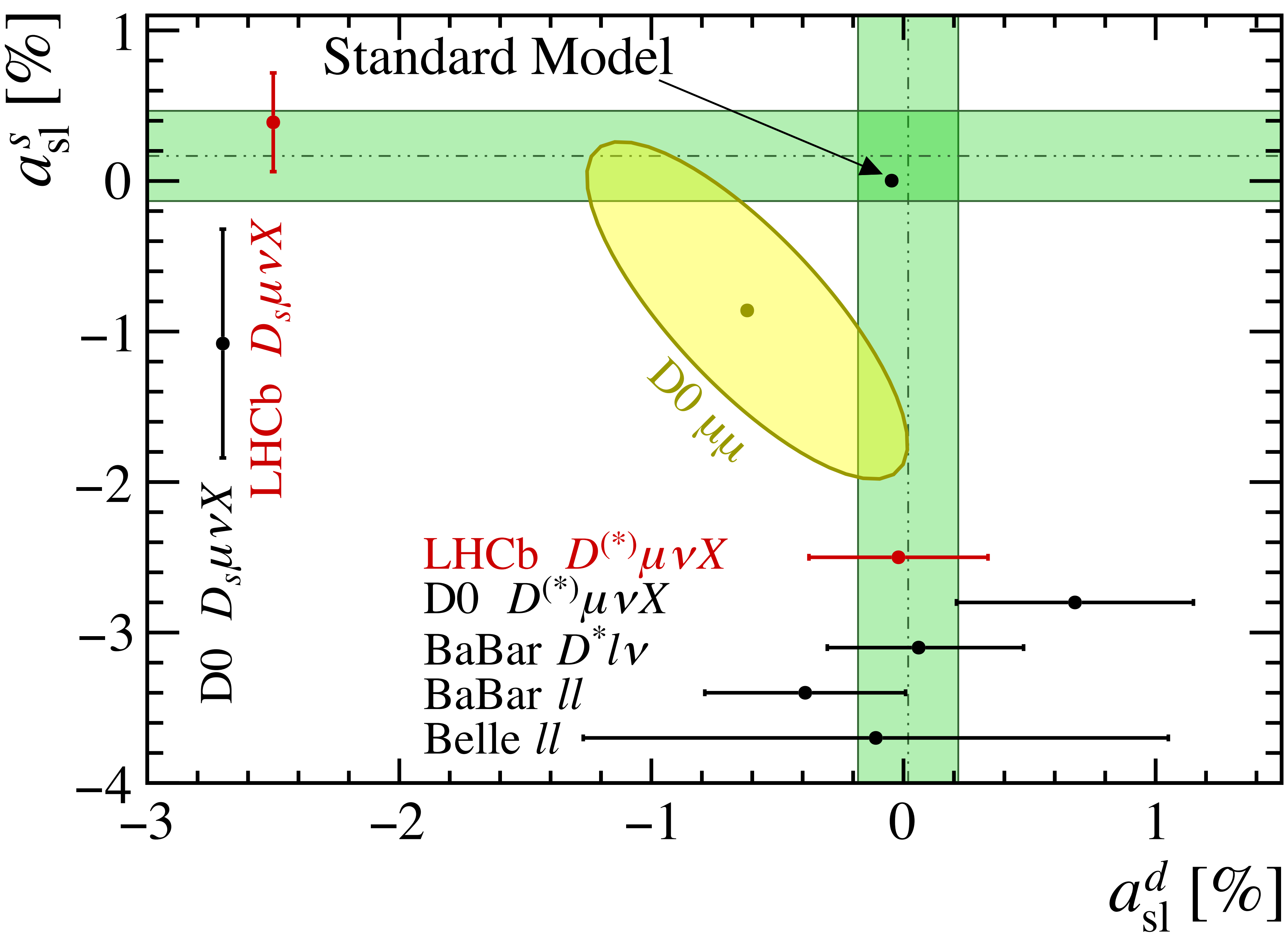
CP violation

- Many modes measured. One exciting relic from ~2010 debunked!



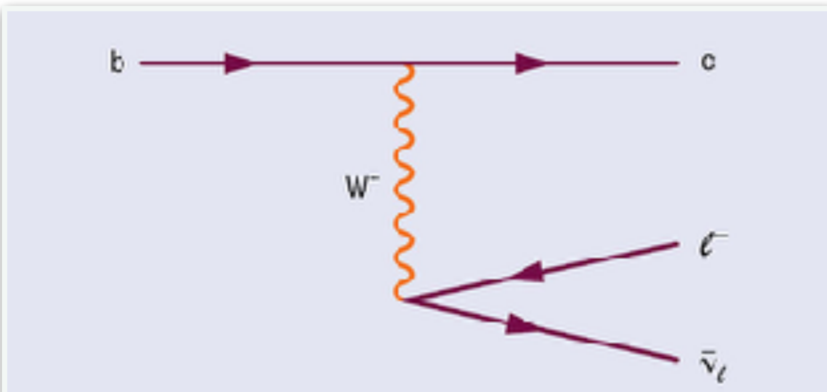
CP violation

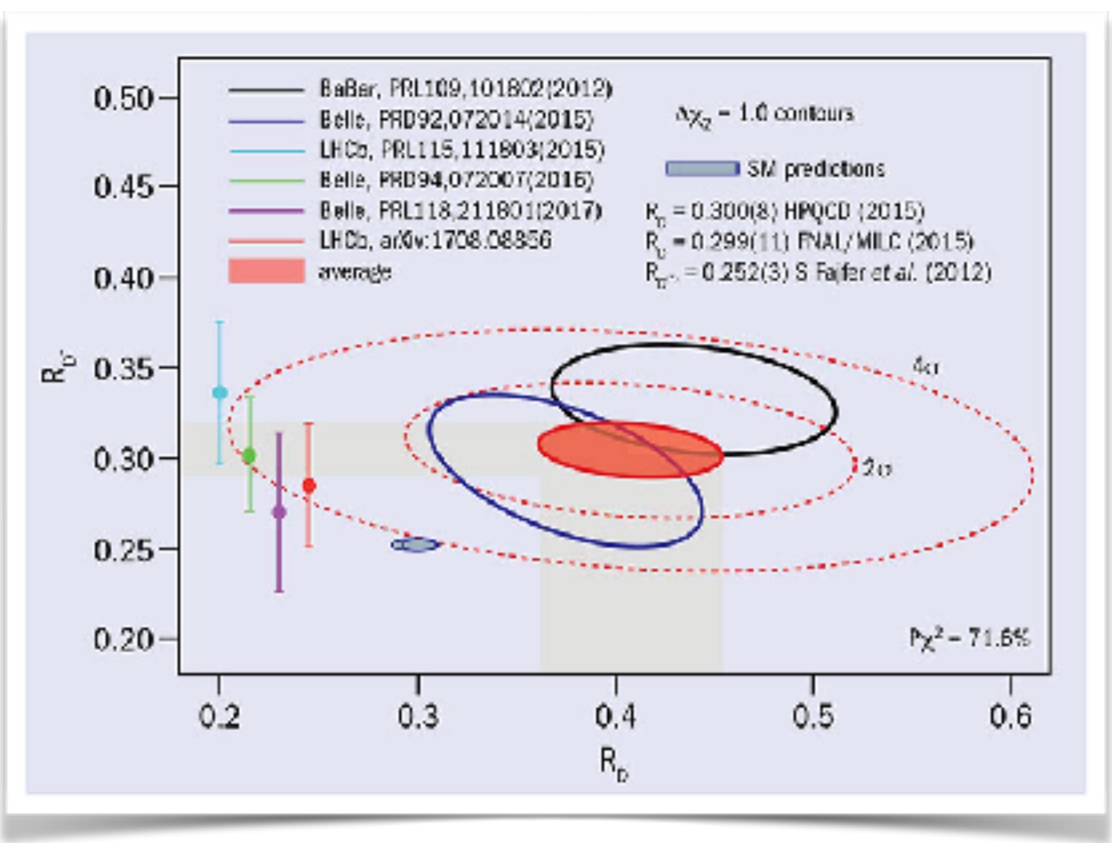
- Many modes measured. One exciting relic from ~2010 debunked!
- Mostly consistent with standard model.

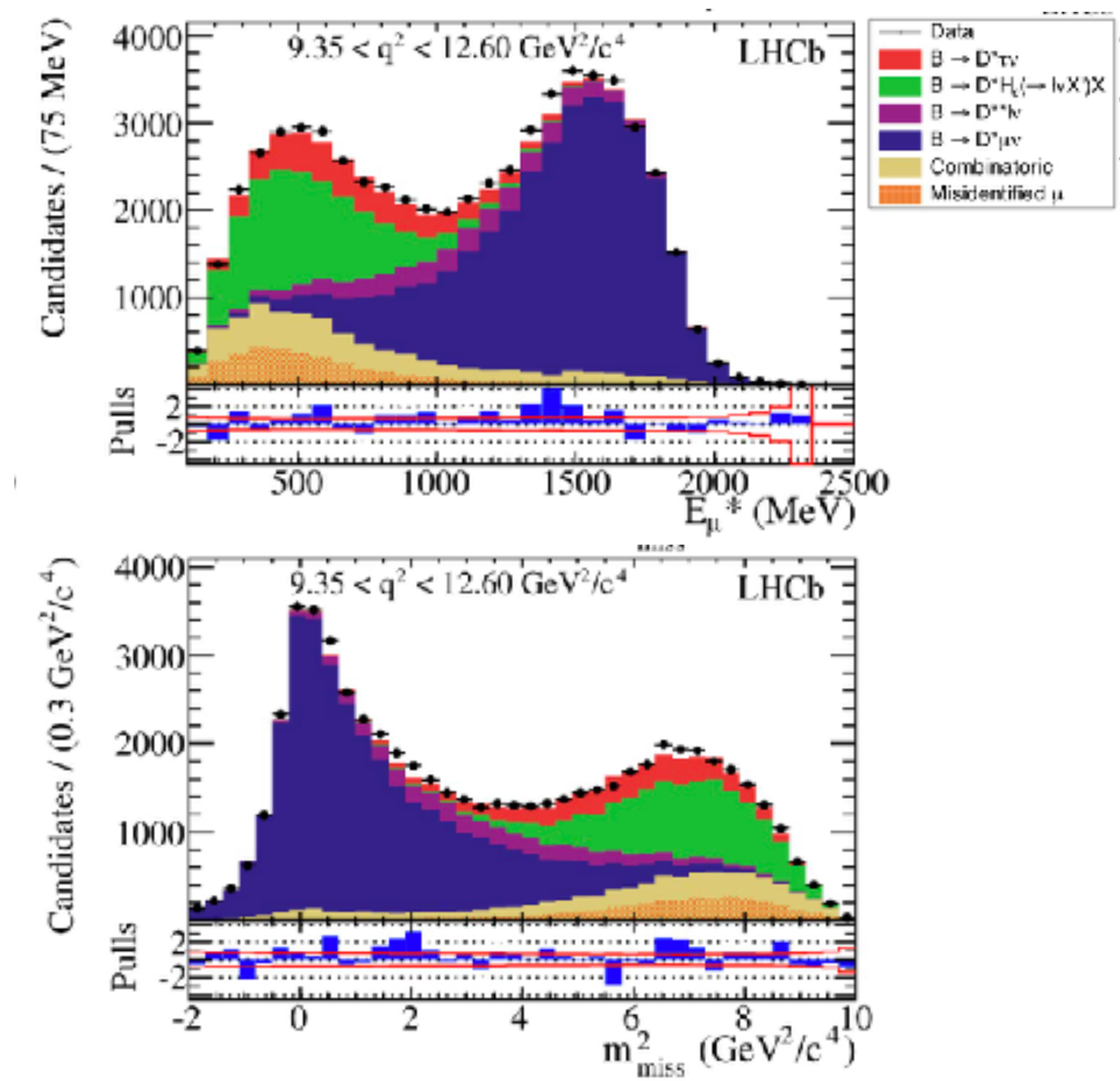


Lepton non-universality

- Standard model: coupling to all leptons is the same ('universal').
  —> Observe: ratio of (B —> D tau) / (B —> D mu): **too high**!



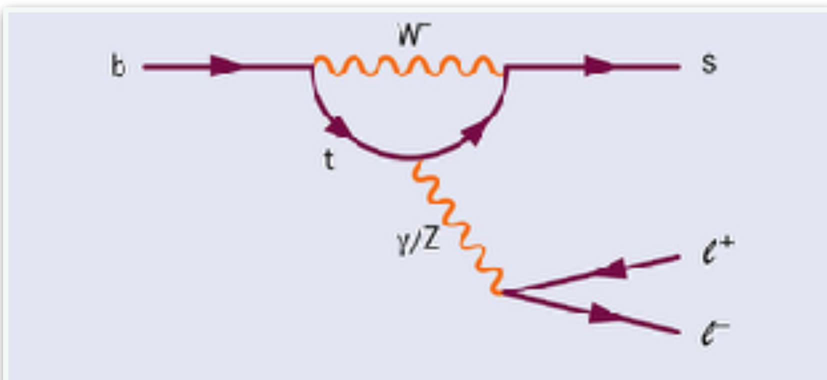


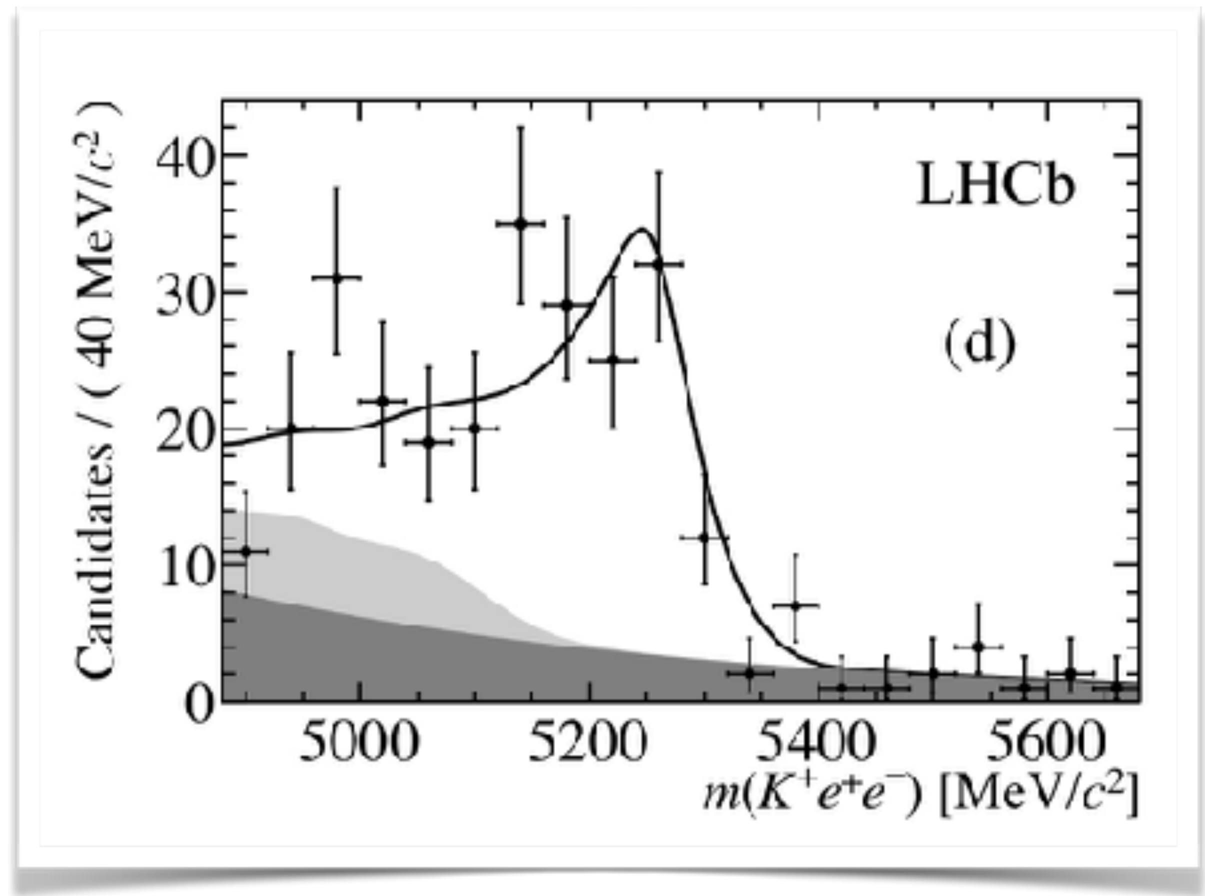


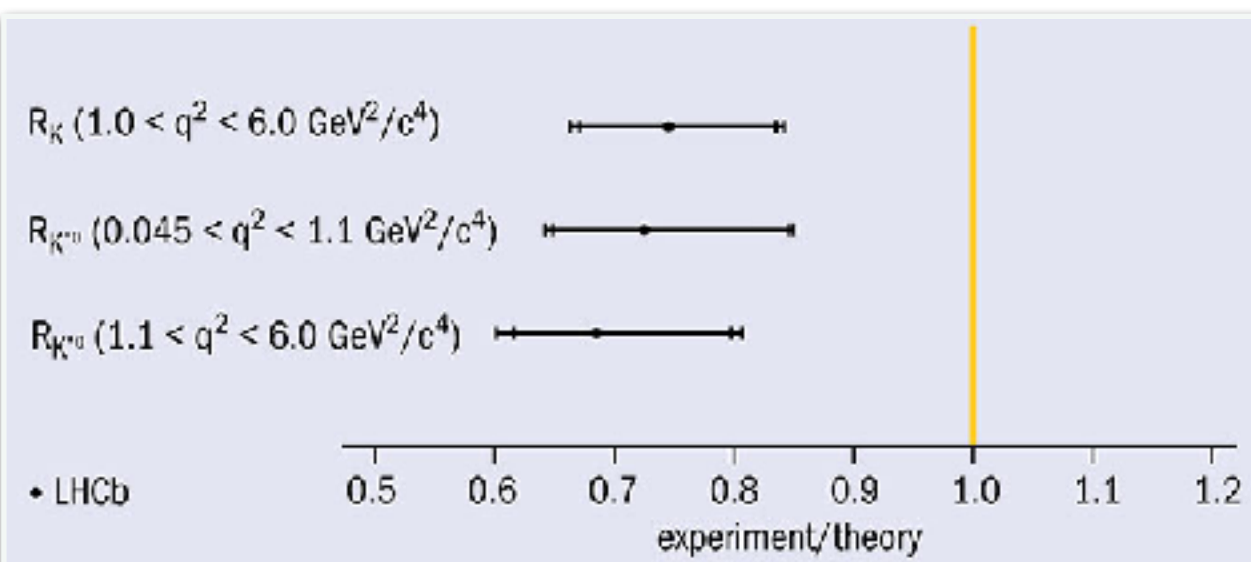
https://cds.cern.ch/record/2152703/files/LHCb-TALK-2016-082.pdf

Lepton non-universality

- Standard model: coupling to all leptons is the same (‘universal’).
  —> transition of [b —> s mu+ mu-] / [b —> s e+ e-]: **too low**!





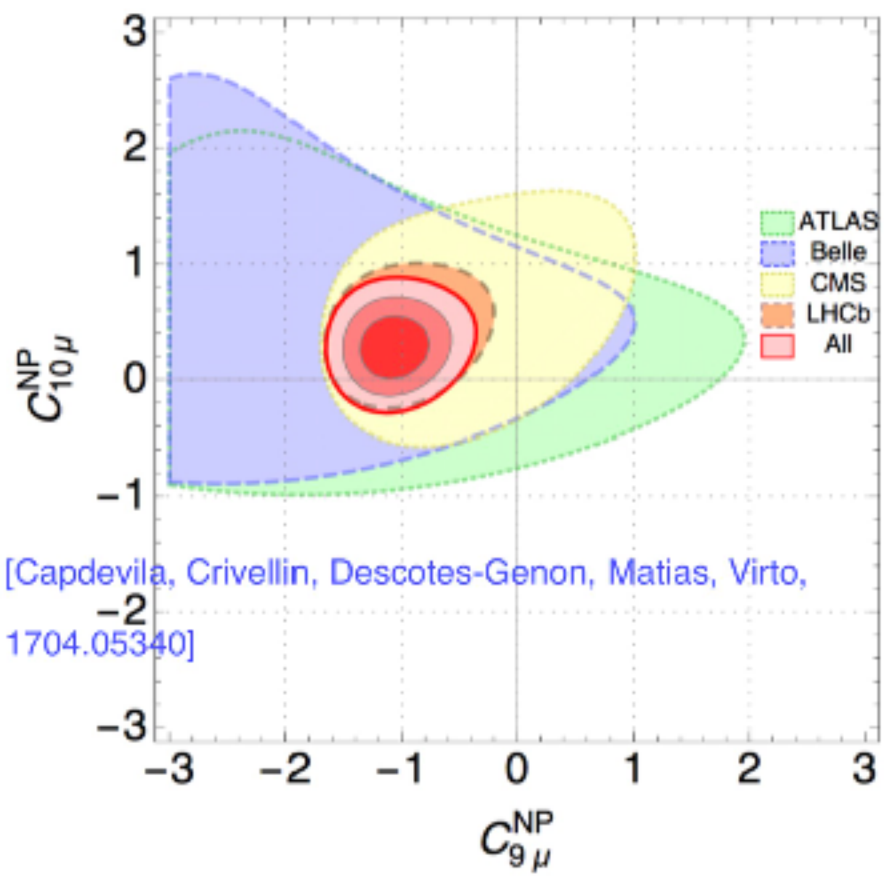


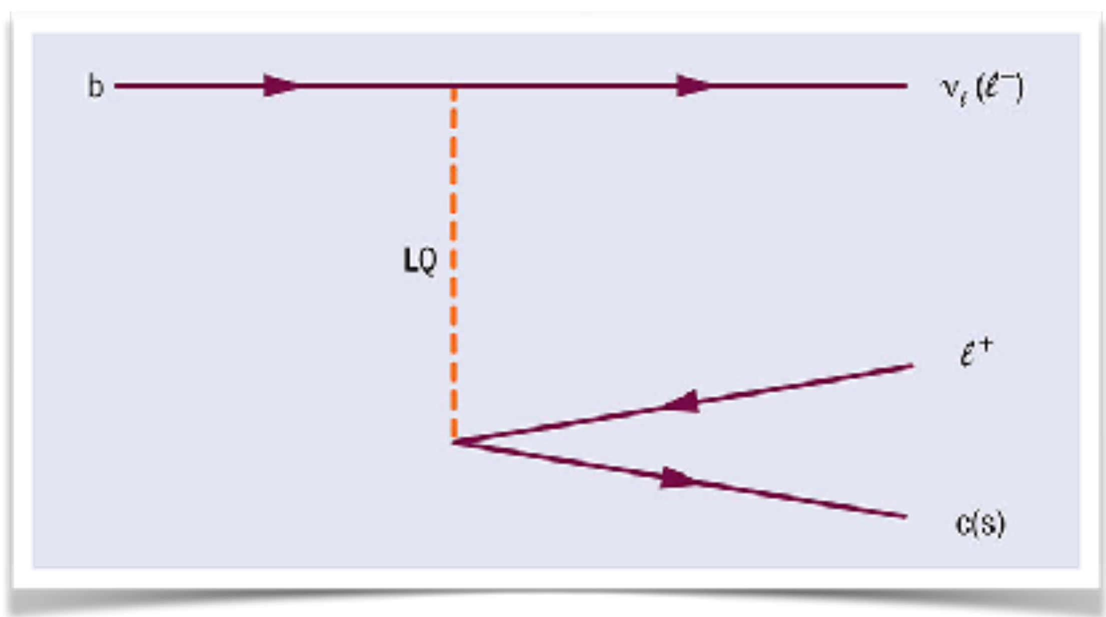
https://arxiv.org/pdf/1406.6482.pdf

Lepton non-universality

- Both can be classified by the same type of 'new interactions'! 'Combination' ~ 5 sigma?
- Potential explanation?
  - ~TeV scale Z' boson?
  - ~TeV LeptoQuark?

} Then Atlas/CMS should see it soon!





https://cds.cern.ch/record/2270937/files/LHCb-PROC-2017-018.pdf
http://benasque.org/2017lhc/talks_contr/244_NP-Kosnik.pdf

Summary

- Many exciting fundamental questions
- Many recent high-profile results
  (and don't forget about the nobel prizes for the Higgs (2013), neutrino oscillations (2015))
- Well underway of shedding light on many mysteries
  —> Many new experiments being set up, within 5-10 years
- Era of multi-messenger astronomy is now!
- LHC: many interesting results, mostly statistically limited
  —> Upgrade of LHC detectors: 2018-2020, will provide answers

- These are **exciting times** to be a particle physicist!

Big questions in physics

- What is dark matter?
- What is the mass of neutrinos?
- Where do the ultra high energy cosmic rays come from?
- Are protons unstable?
- Where did all the antimatter go?
- What happened during the big bang?

- Why is the Higgs mass so fine-tuned?
- Why are there (only) three generations?
- What is the top quark mass?

http://discovermagazine.com/2002/feb/cover

Big questions in physics

- What is dark matter?
- What is the mass of neutrinos?
- Where c
- Are prot
- Where c
- What ha
- Why is t
- Why are
- What is

http://discovermagazine.com/2002/feb/cover