Universität Zürich[UZH]

Physik-Institut

Kern- und Teilchenphysik II
Lecture 11:Dark Matter, Sterile neutrinos and Lepton Flavour Violation

(adapted from the Handout of Prof. Mark Thomson)

Prof. Nico Serra
Mr. Davide Lancierini

http://www.physik.uzh.ch/de/lehre/PHY213/FS2018.html

Physics Beyond the Standard Model

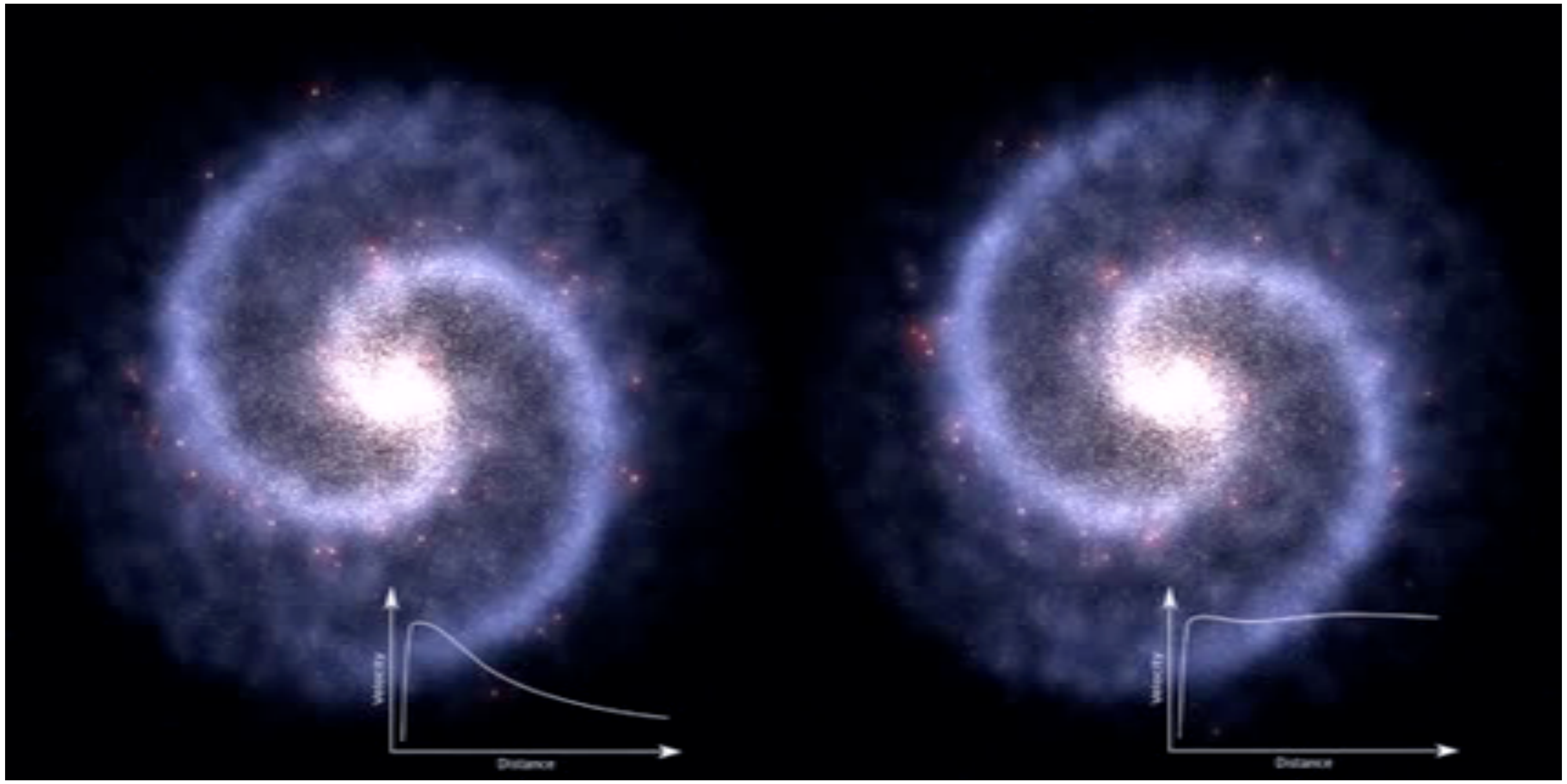
Main Experimental reasons to search for Physics Beyond the Standard Model

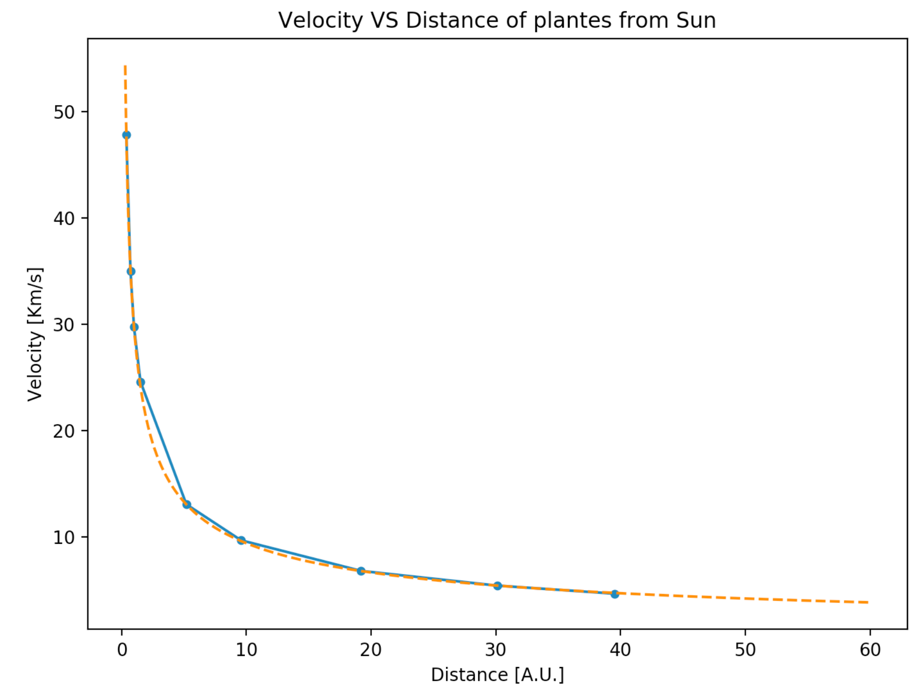
- Existence of Dark Matter
- Neutrino masses and oscillations
- Asymmetry between matter and anti-matter

Among the problems of the SM often the fine tuning problem, the hierarchy problem, the smallness of neutrino masses and the existence of Dark Energy, … are listed. I will not discuss these points.

Galaxy Rotation Curve

Animation from Wikipedia





- If the mass is concentrate in the center we will have $m\frac{v^2}{R} = \frac{K}{R^2}m$
- This implies that $v = \sqrt{\frac{K}{R}}$
- This disagree with observation of the rotation curves of galaxies

Gravitational Lensing

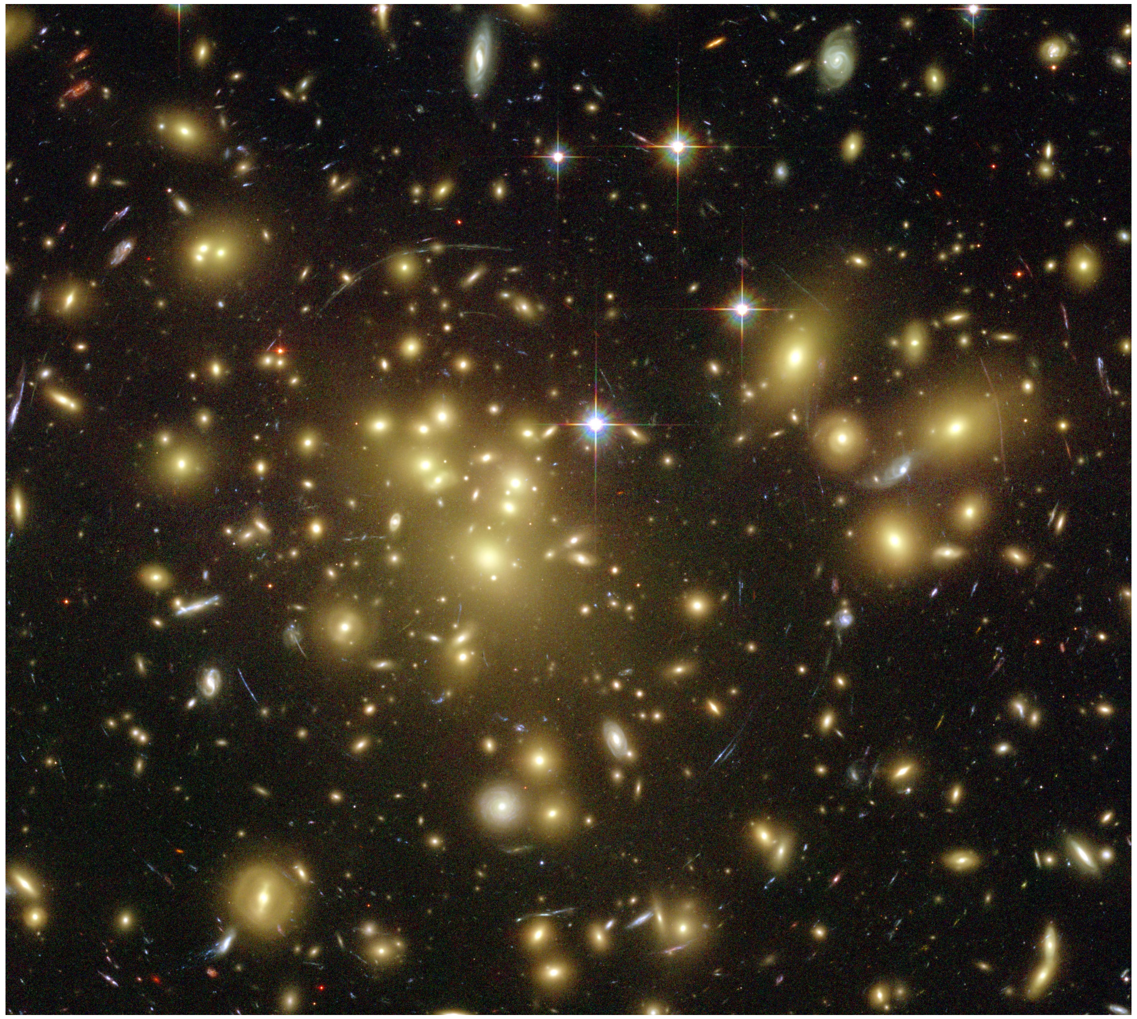
- All particles (including photons) follow geodesics

- In the empty space geodesic are straight lines, while this is not true in when there is a strong gravitational field

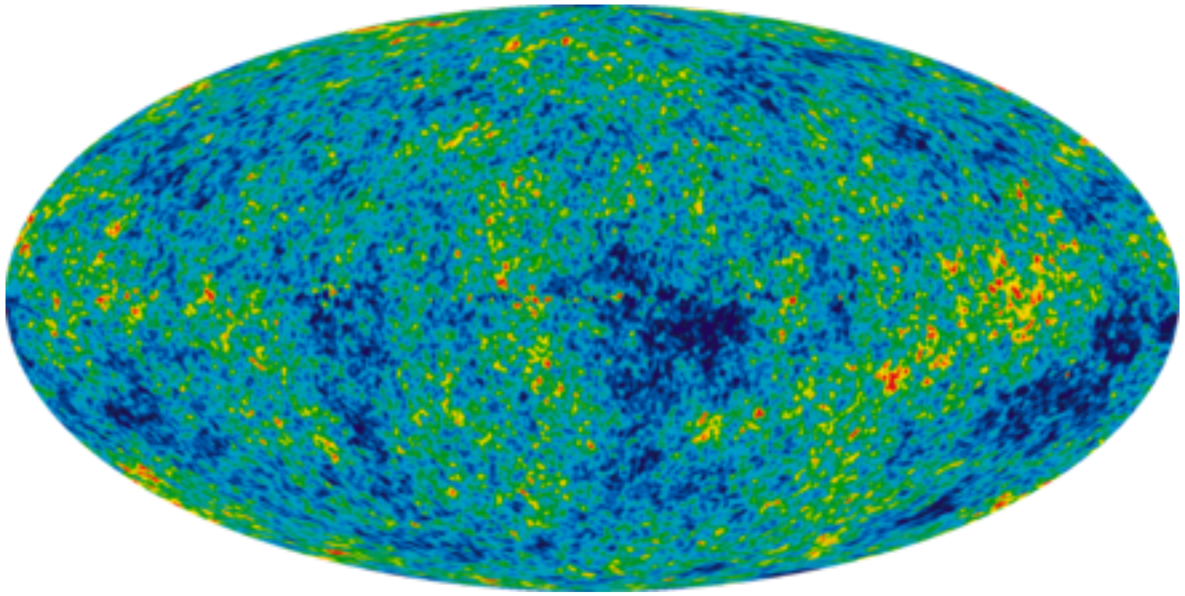
- This allows the mass to act as lensing bending the path of light around massive objects

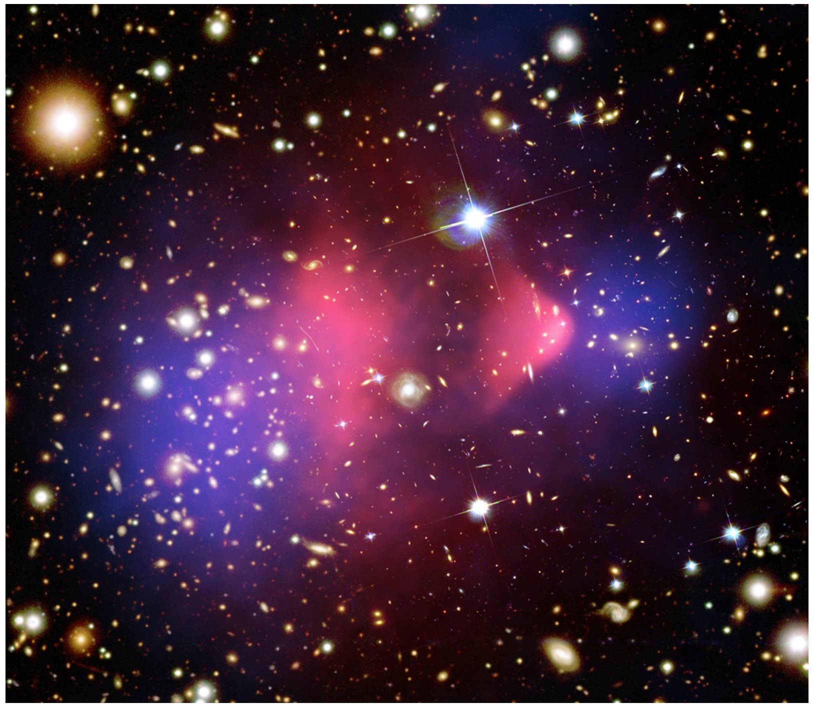
- By measuring the distortion geometry the mass of the intervening cluster can be be obtain

- The discrepancy between the visible mass and the mass measured by gravitational lensing is an evidence of the existence of DM



CMB and the bullet cluster





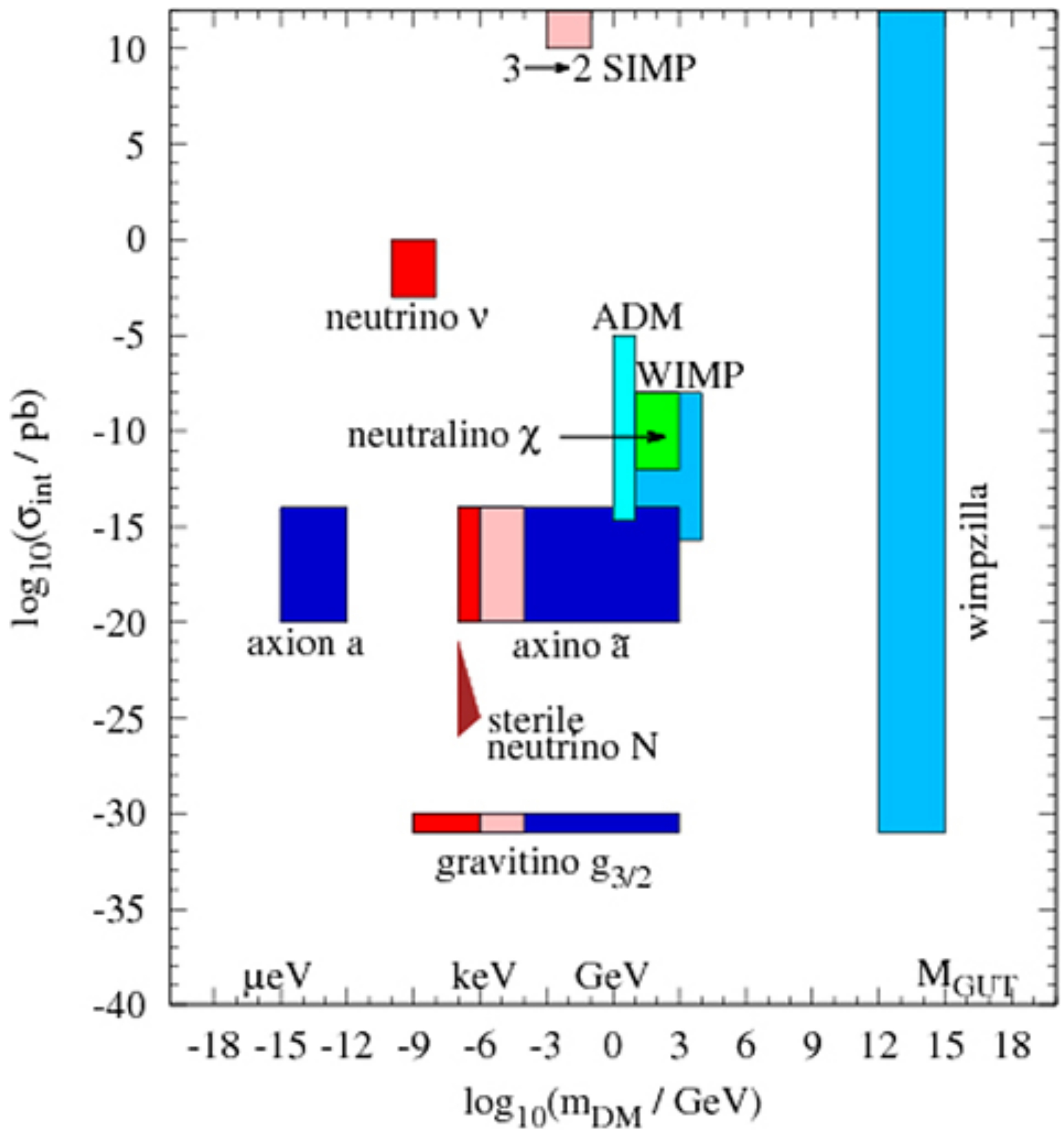
- Matter and DM behave differently, in particular in the interaction with radiation. Anisotropies in the CMB can be decomposed in power spectrum, whose peaks contains cosmological information. This allows to calculate the density of matter and DM in the early Universe. Present measurements provide strong evidence of the existence of DM.

- The collision between the two clusters gases interact electromagnetically slowing down after the interaction, while DM interacts very weakly. This created a displacement between the visible mass and the gravitational mass, supporting the existence of DM.

Dark Matter Candidates

- Several Dark Matter candidates have been proposed spanning a large range of mass and coupling

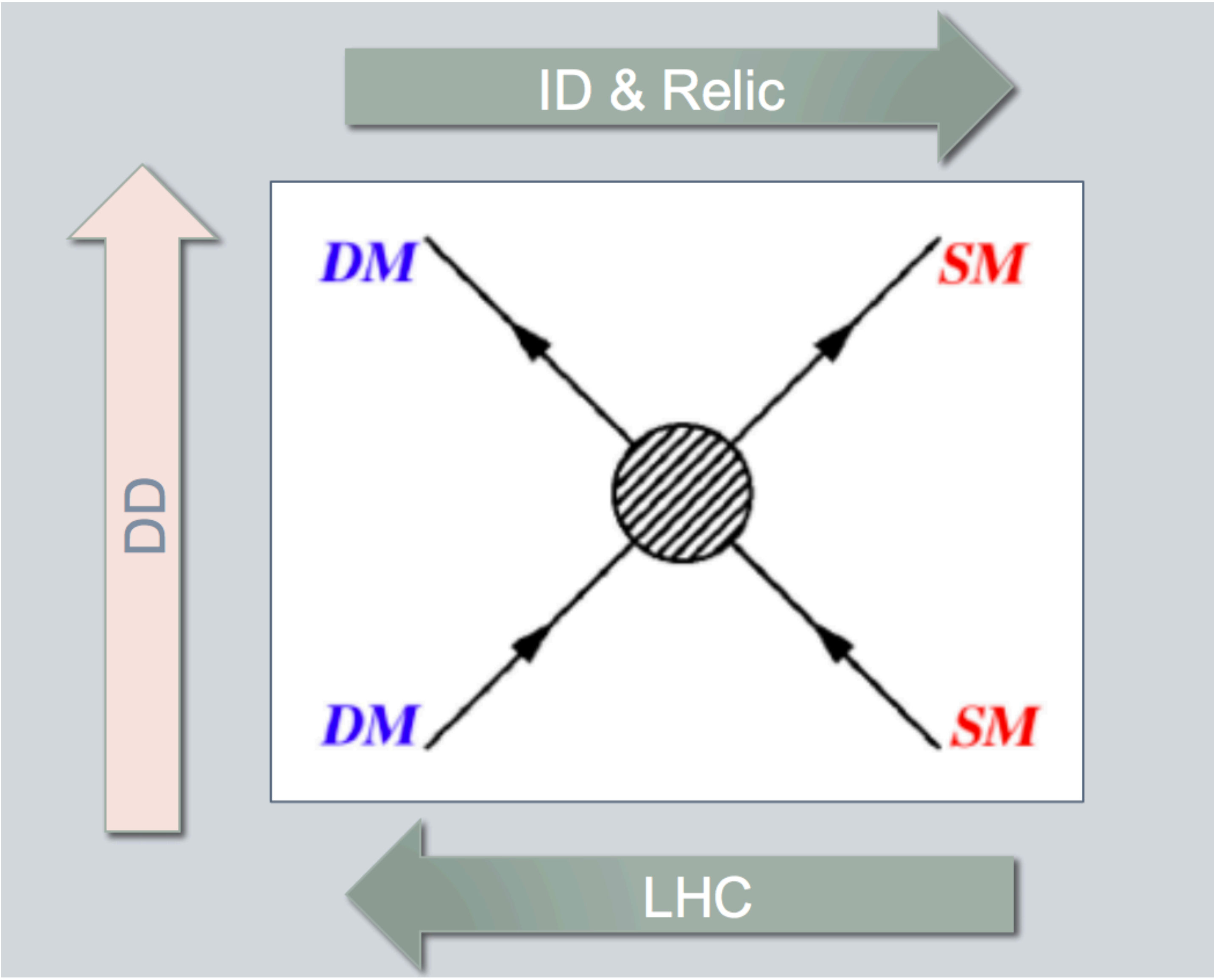
- The search for Dark Matter therefore is performed with various experimental techniques depending on the x-section and mass of the particle



Searching for Dark Matter with Cosmic Gamma RaysAndrea Albert

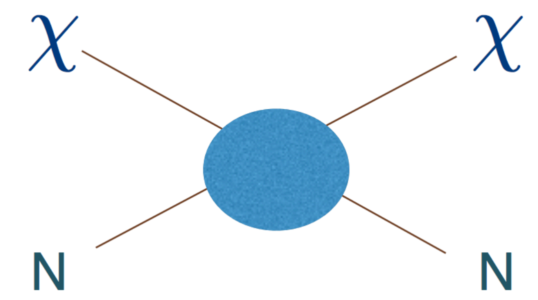
Published August 2016 • Copyright © 2016 Morgan & Claypool Publishers
http://iopscience.iop.org/book/978-1-6817-4269-4/chapter/bk978-1-6817-4269-4ch2

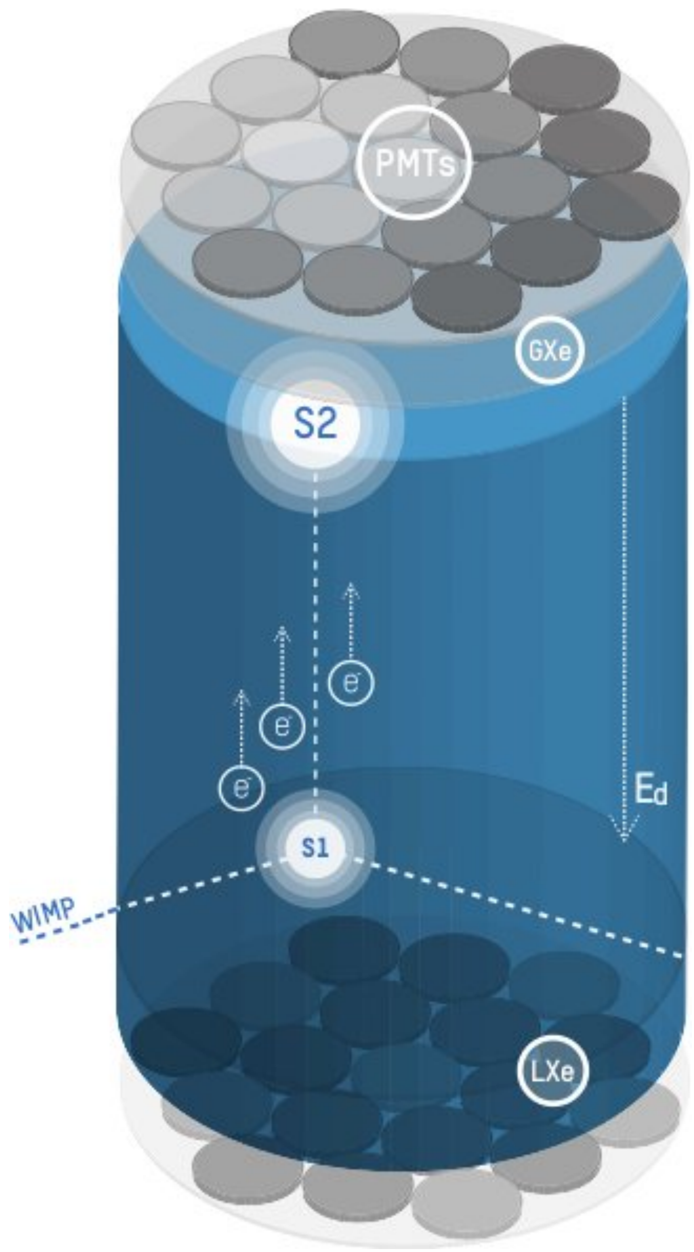
How we search for Dark Matter



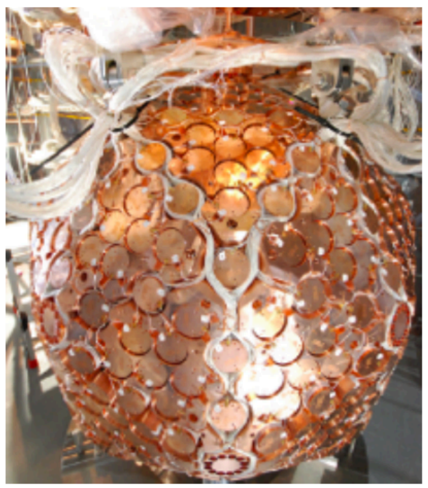
Direct Detection of DM

- Dark Matter particles in present in the solar system can interact with nuclei, this interaction can be measured
- One of the way to direct detect these interaction is to use nobel gas detector, e.g. Xe
- WIMPS interacting in the Xe produce scintillating light that is measured by PMTs (S1)
- In dual phase detectors electrons drift to the GXe where they give a proportional signal ionising the gas (S2)
- The difference in time and the observed 2-distribution in the PMTs allows to have a full 3D reconstruction of the interaction, i.e. define fiducial volume with lower background





Present DD Nobel Gas Experiment



XMASS at Kamioka:

835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
new run since fall 2013
several results

DEAP at SNOLab:

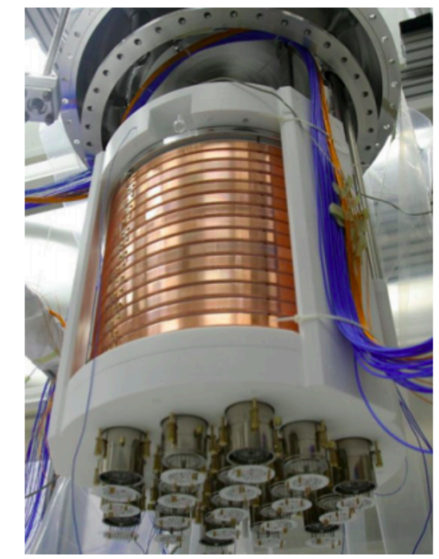
3600 kg LAr (1t fiducial)
single-phase detector
in commissioning
dark matter run in 2016

XENON100

LUX

ArDM

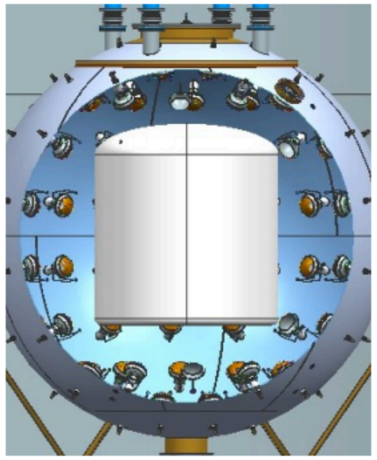
DarkSide-50



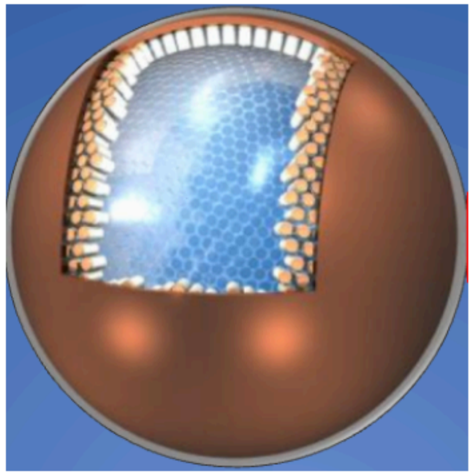
- Xenon:
  - Xenon100, Xenon1T, LUX, PandaX
- Argon:
  - DarkSide-50, ArDM

Future Experiments

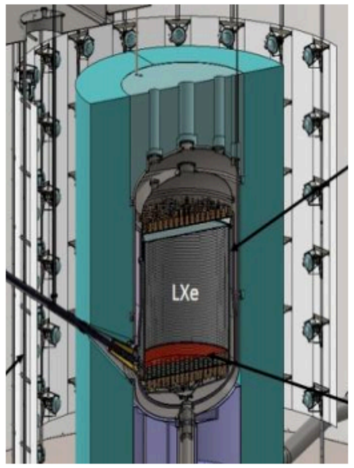
XENONnT: 7t LXe



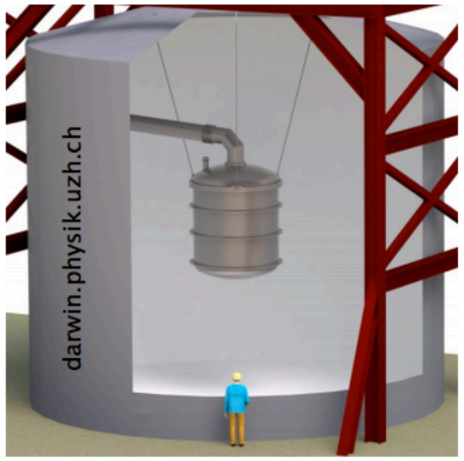
DarkSide: 20 t LAr



XMASS: 5t LXe



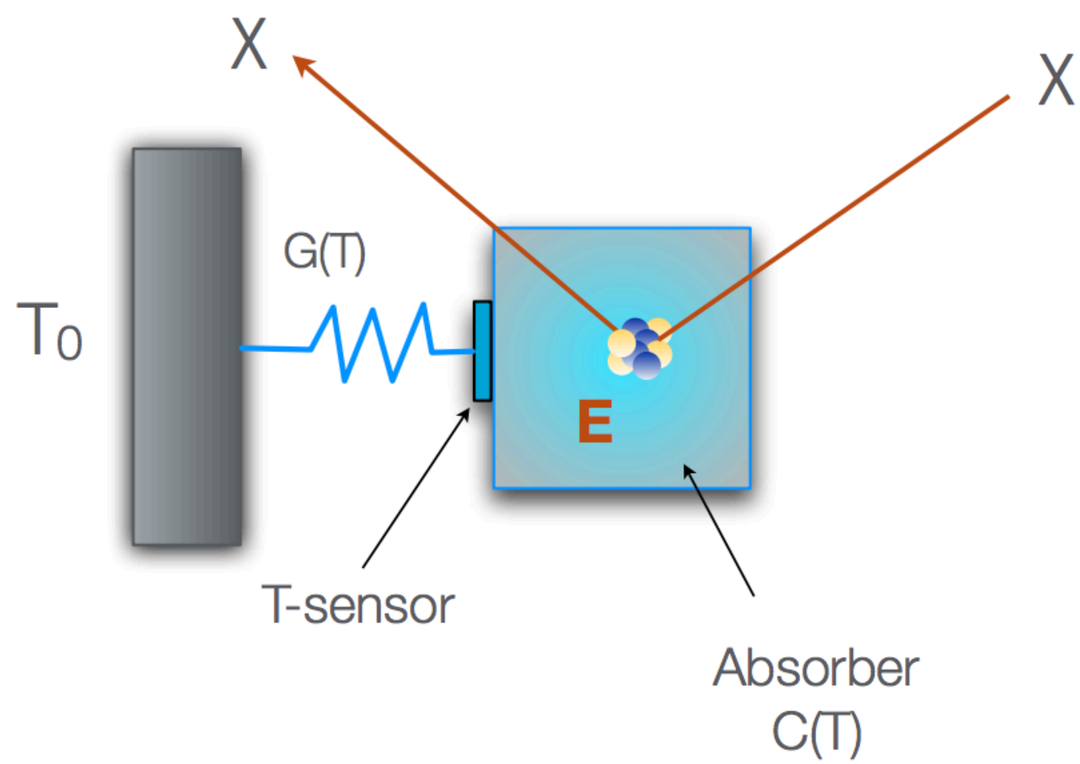
LZ: 7t LXe



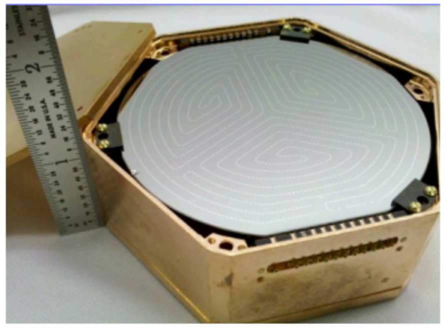
DARWIN: 50 t LXe

- Event rate proportional to the mass, so the challenging is to keep zero background (in some fiducial volume) and increase the mass
- Main backgrounds coming from: cosmics & material activation; natural and anthropogenic radioactivity; neutrino nucleus scattering
- To reject the background:
  - Go deep under ground; Use active shield; Select Fiducial Regions

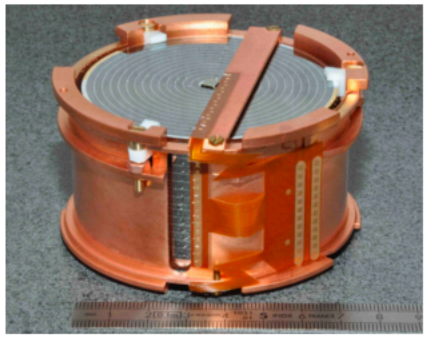
Cryogenic detectors at T ~ mK



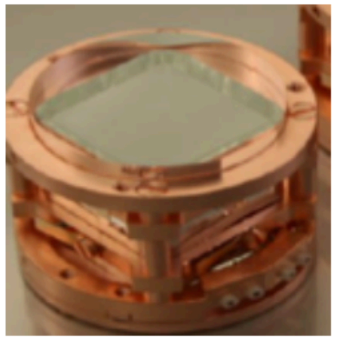
- Detection of the increase in temperature due to the particle interacting in the absorber
- Excellent results for sub-GeV dark matter searches



SuperCDMS: Ge, Si

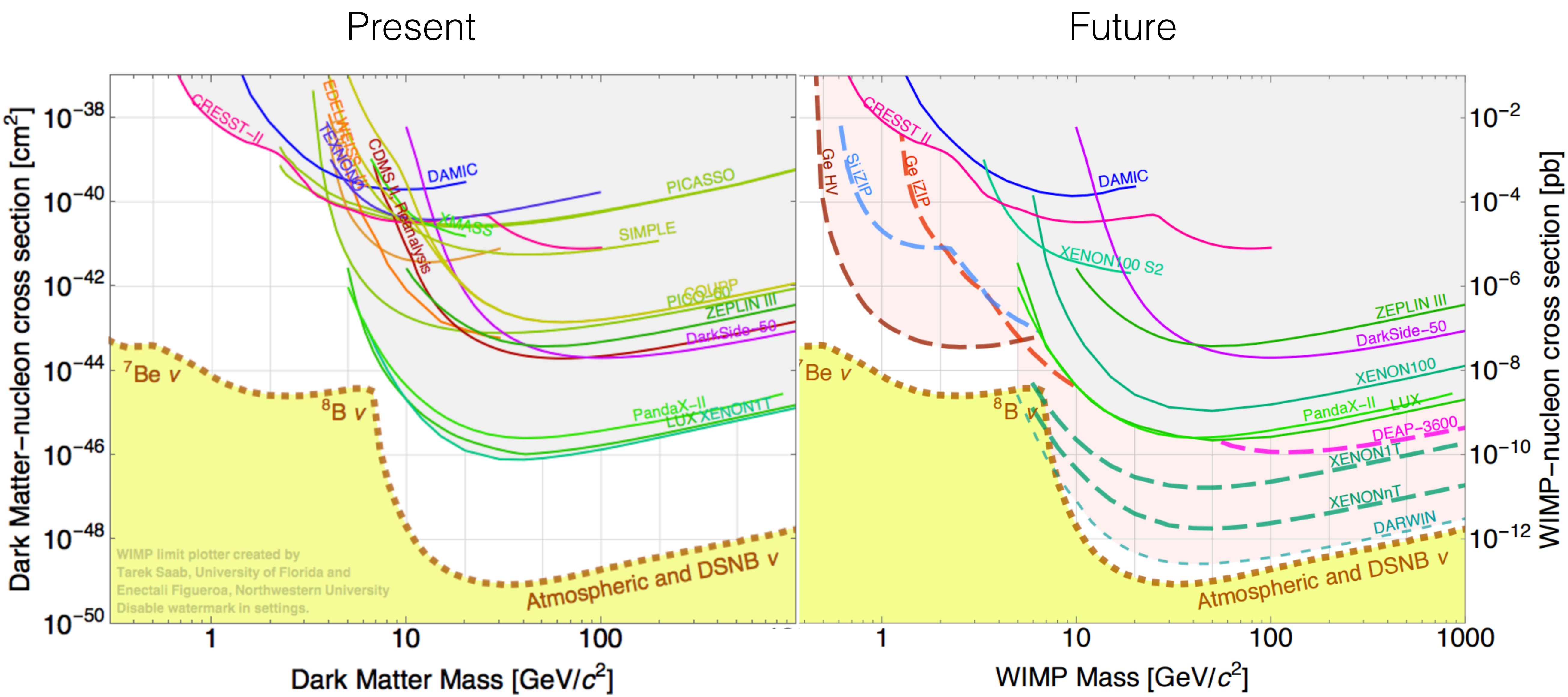


EDELWEISS-III (Ge)



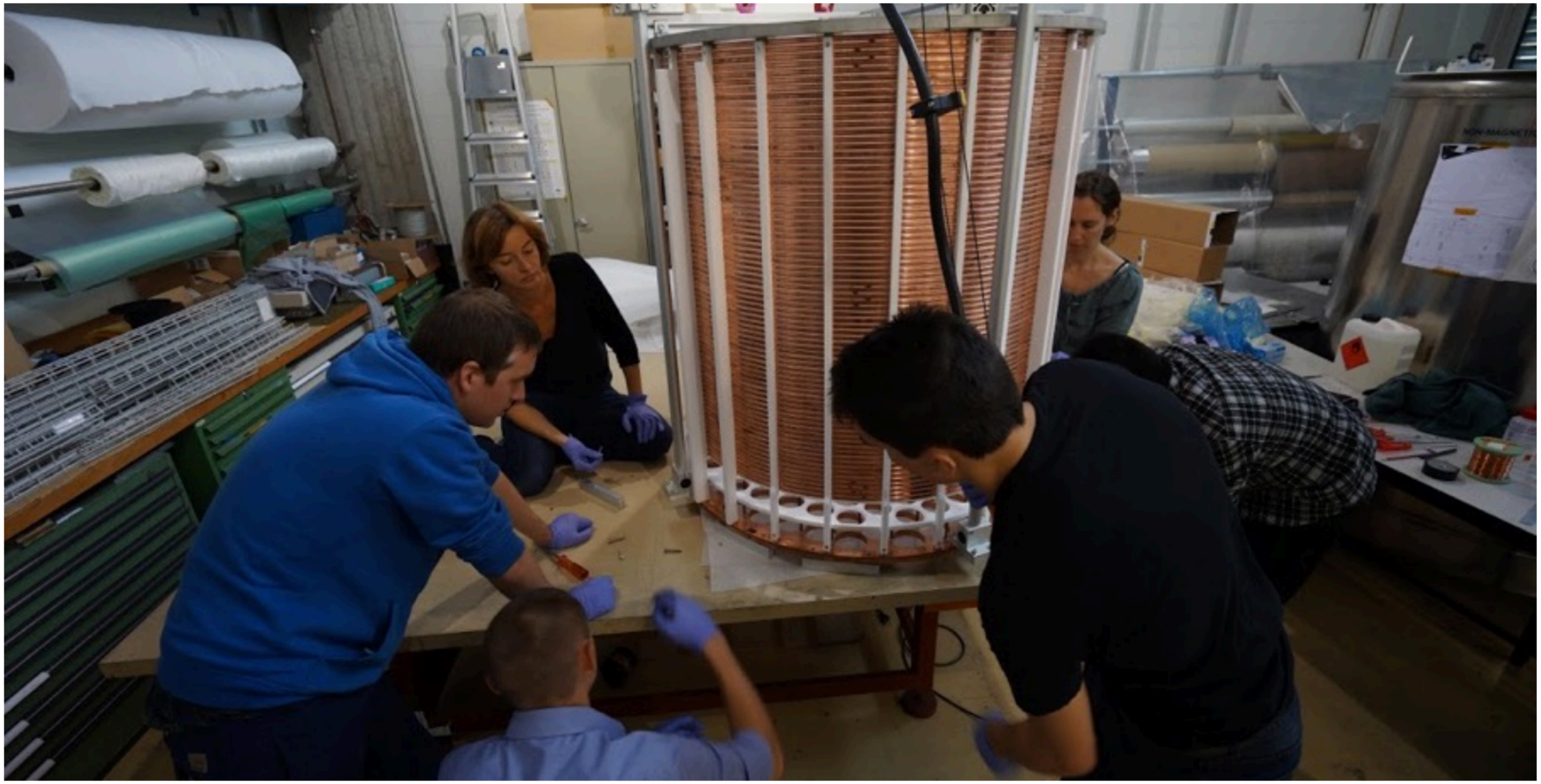
CRESST ($CaWO_4$)

Limits of DD Experiments



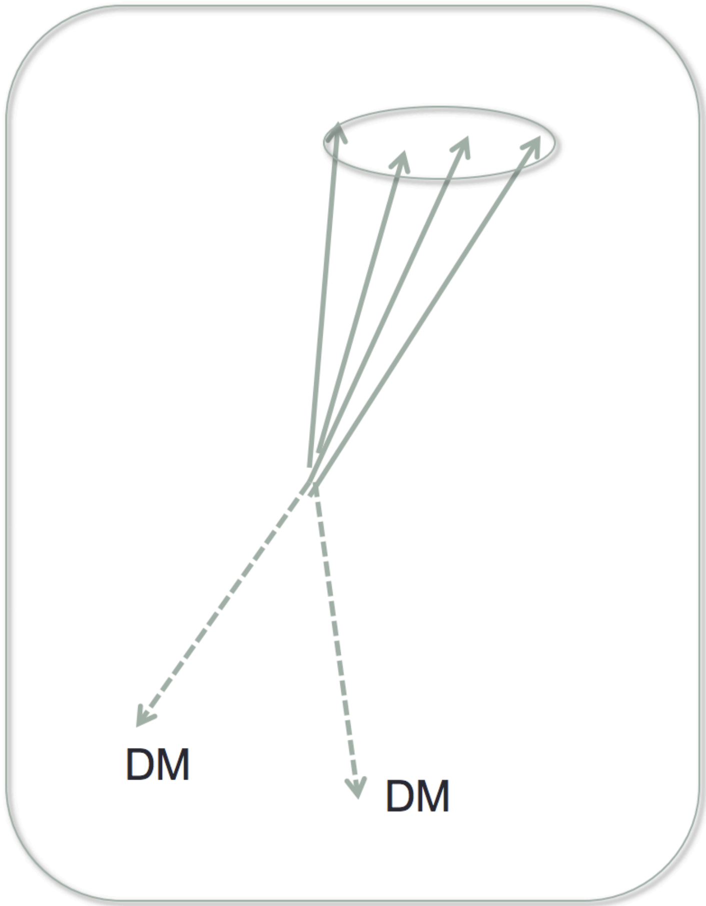
Reference

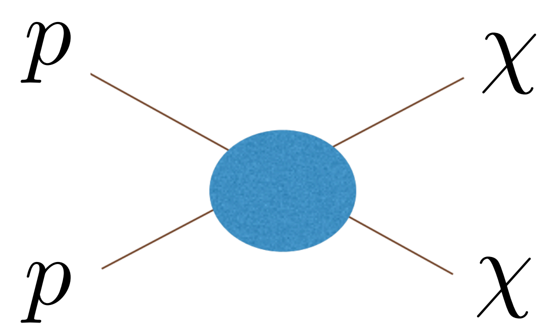
- TPC assembly and first cool down at the Physik-Institut, UZH

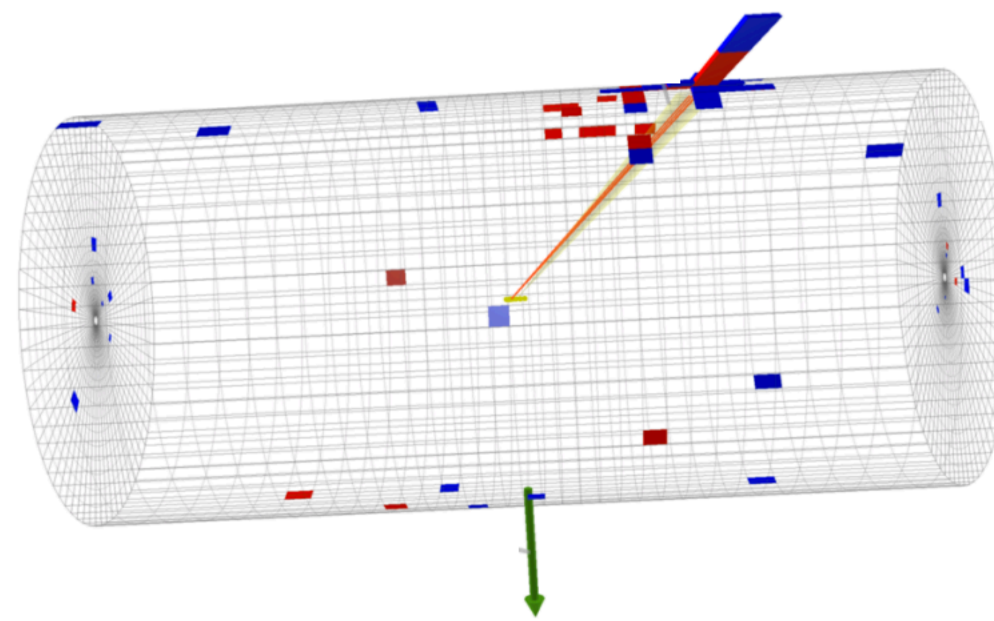


For more details see the talk by Prof. Laura Baudis
http://www.physik.unizh.ch/~lbaudis/baudis_psi2016.pdf

Search for Dark Matter at LHC







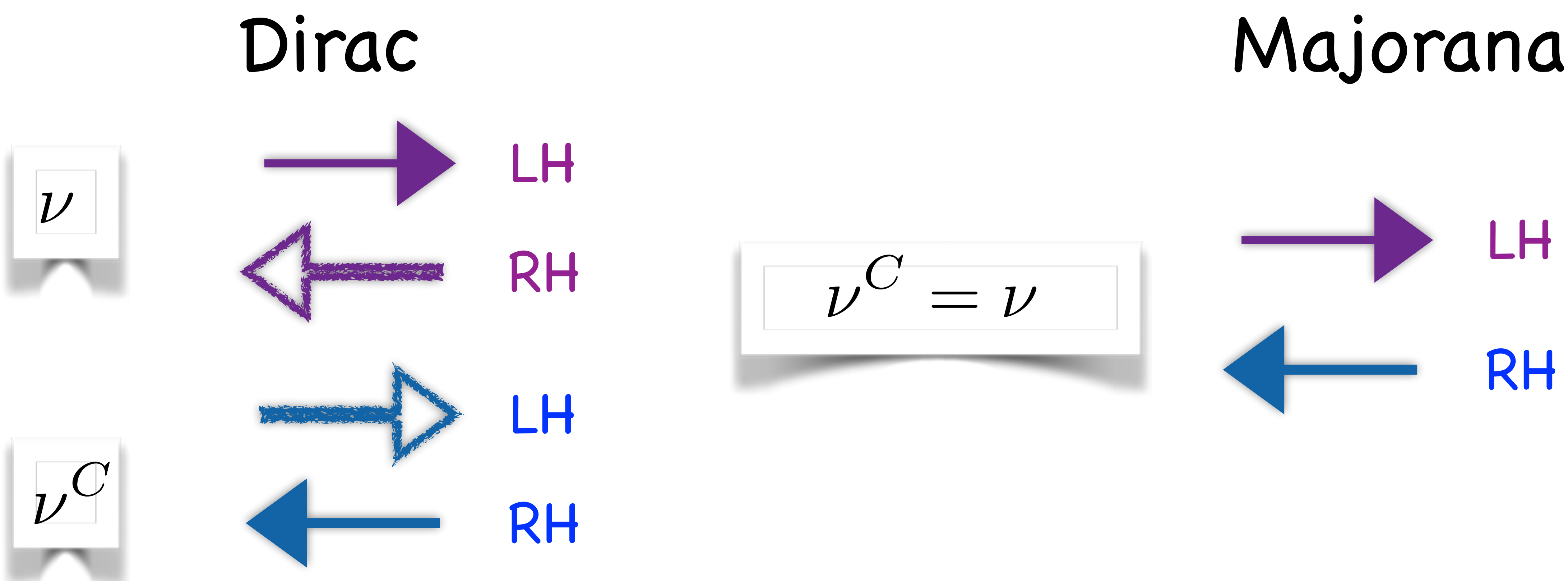
- If DM interacts with SM particles can be produced at LHC
- The experimental signature is a missing transverse energy (MET)

Dirac/Majorana Fermions

Majorana fermion is a neutral fermion that is its own anti-particle

$$\nu^C = \nu$$

All charged fermions must be Dirac fermions, for neutrinos it is not clear if they are Dirac or Majorana particles



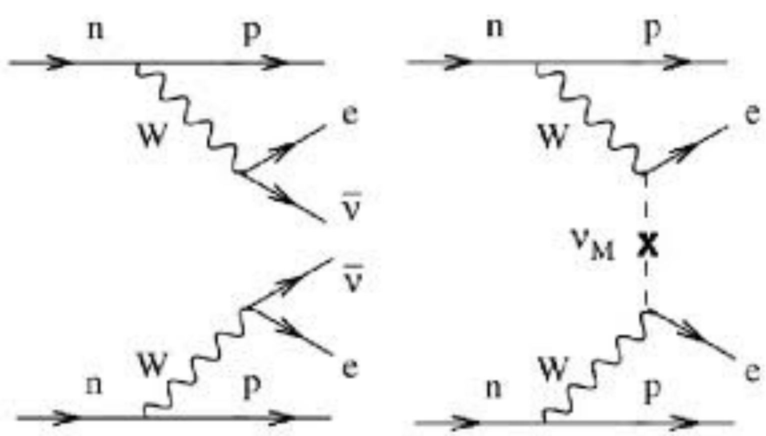
Search for Neutrinoless 2beta decays

$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\,\bar{\nu}_e \qquad (2\nu\beta\beta)$$

Lepton number conserving

$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- \qquad (0\nu\beta\beta)$$

Lepton number violating



Gerda Experiment

Other neutrinoless 2beta and their status can be found here

Sterile neutrinos

- Sterile neutrinos are neutral fermions that do not interact via weak interactions (active neutrinos)

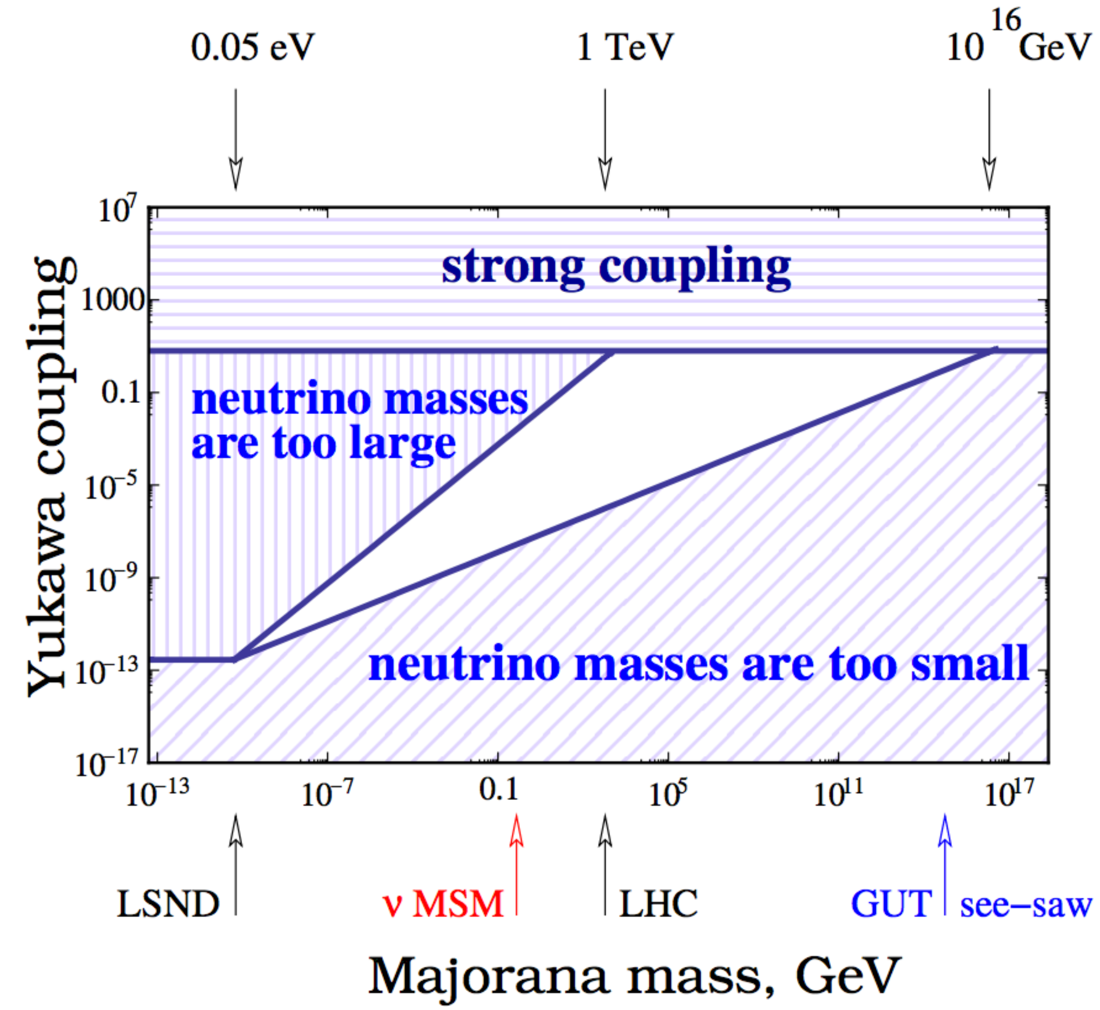
- An example are right-handed neutrinos which are singlet wrt the gauge group of the SM

- RH neutrinos can have Majorana mass, i.e. a mass term that does not derive from the Higgs

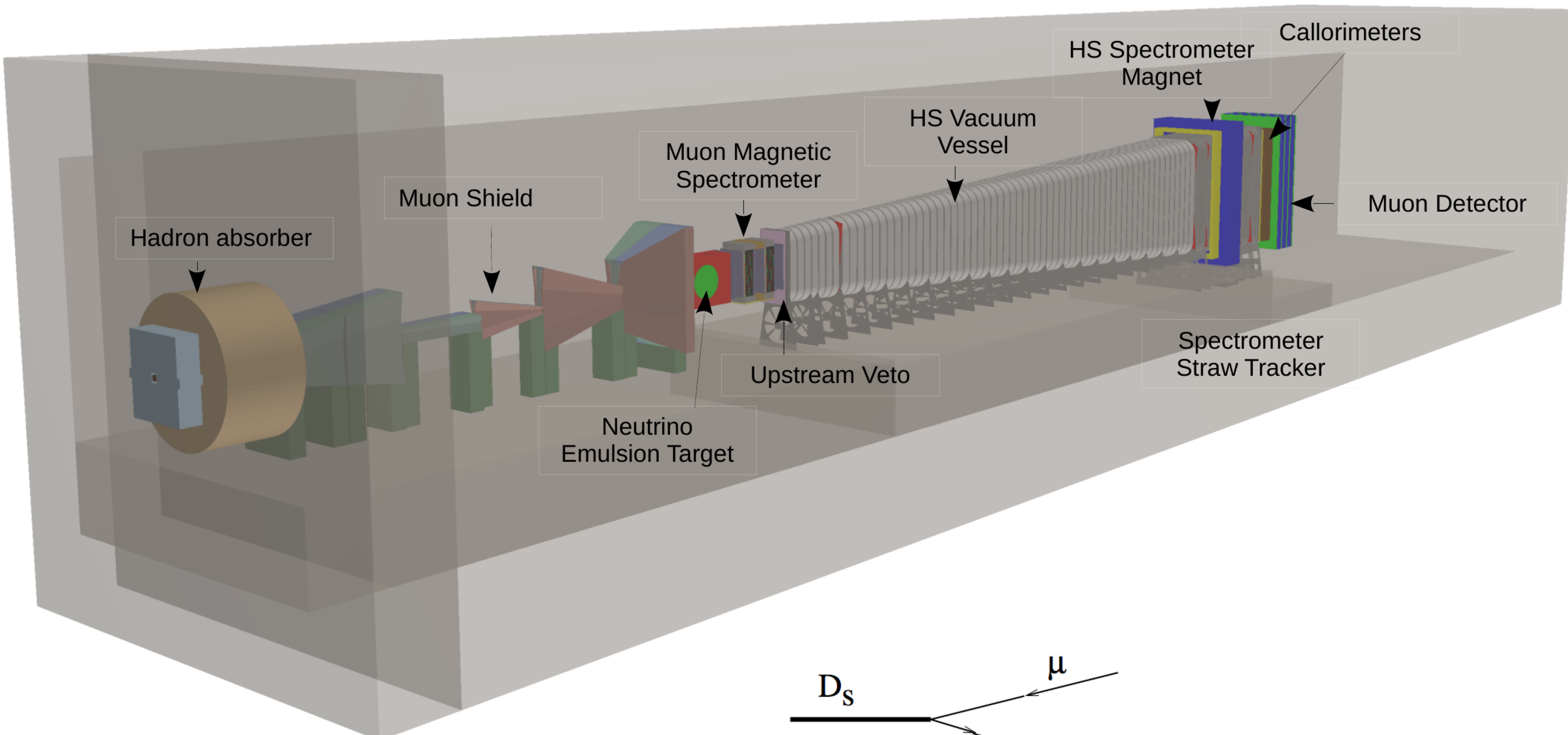
- Majorana masses explained the smallness of neutrino masses via the so-called “seesaw” mechanism

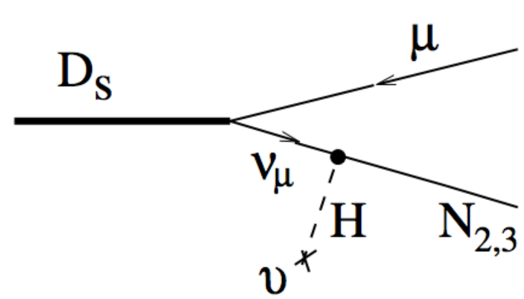
- There are many searches for sterile neutrinos, unfortunately there is a very wide mass range

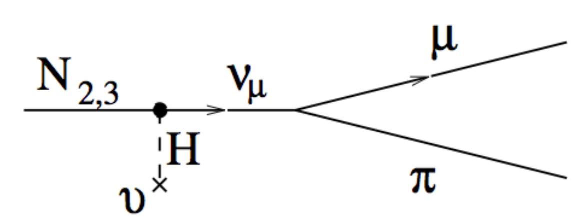
- Several anomalies that could hint to sterile neutrinos in the eV region have been measured but not confirmed (unclear situation)



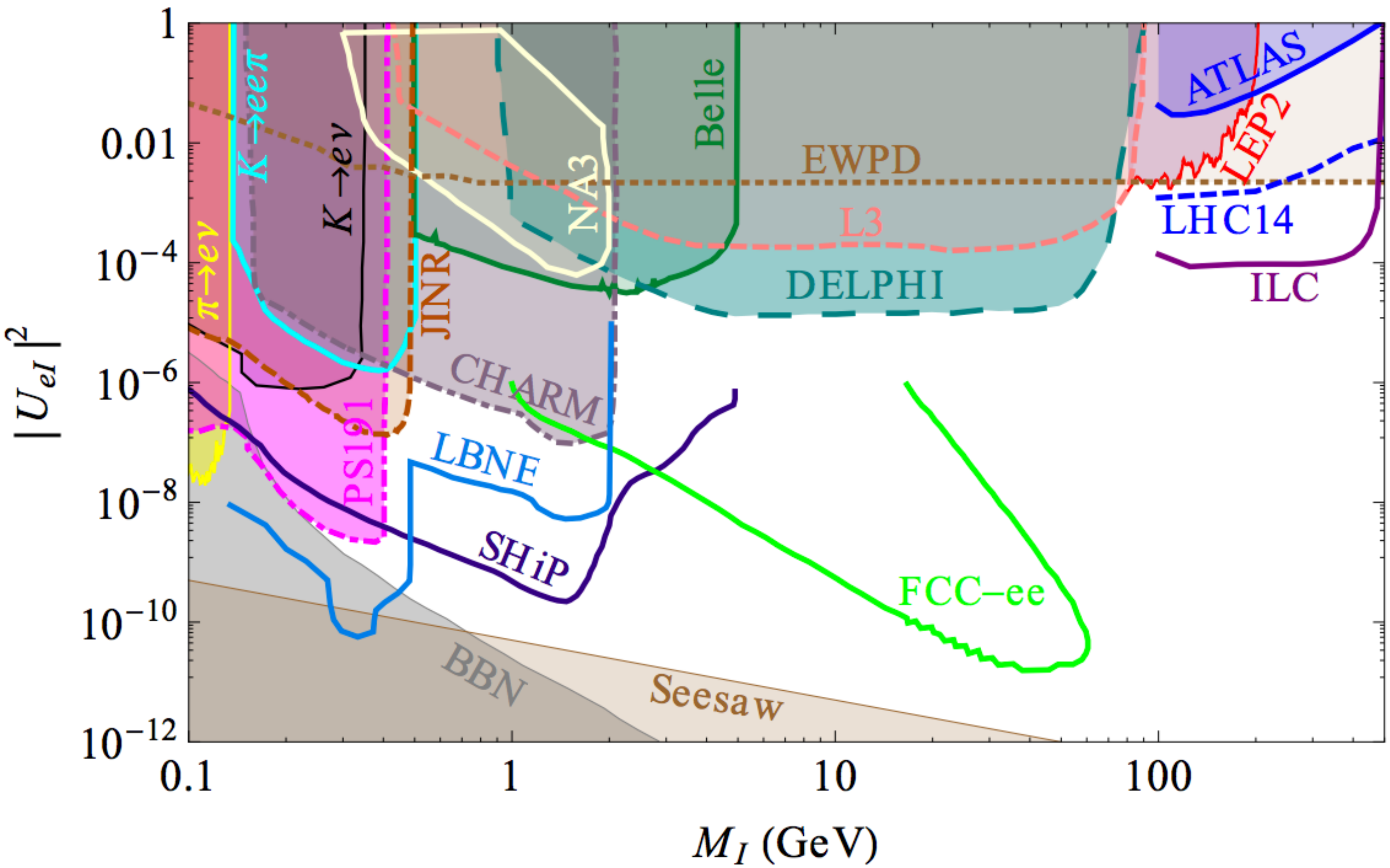
SHiP: searching for HNLs







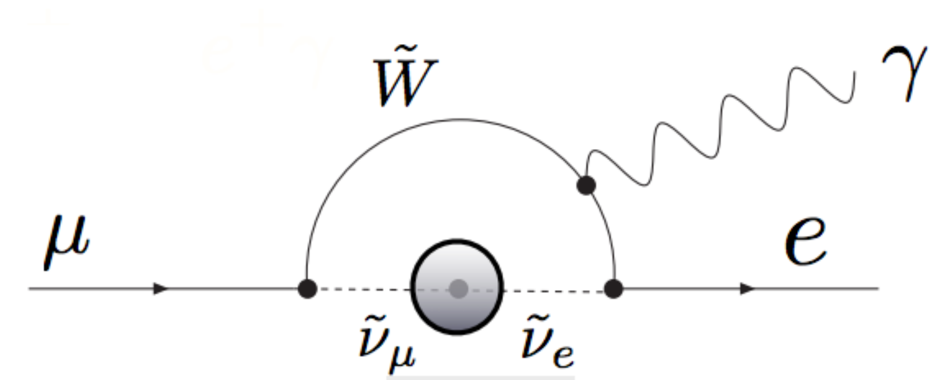
Present and future limits on HNLs



Search for Charged Lepton Flavour Violation

In the SM lepton family is conserved and therefore the following decays are forbidden

$$\mu \to e\gamma,\ \mu \to 3e,\ \tau \to \mu\gamma,\ \tau \to 3\mu,\ B^0 \to e^{\pm}\mu^{\mp},\ \ldots$$

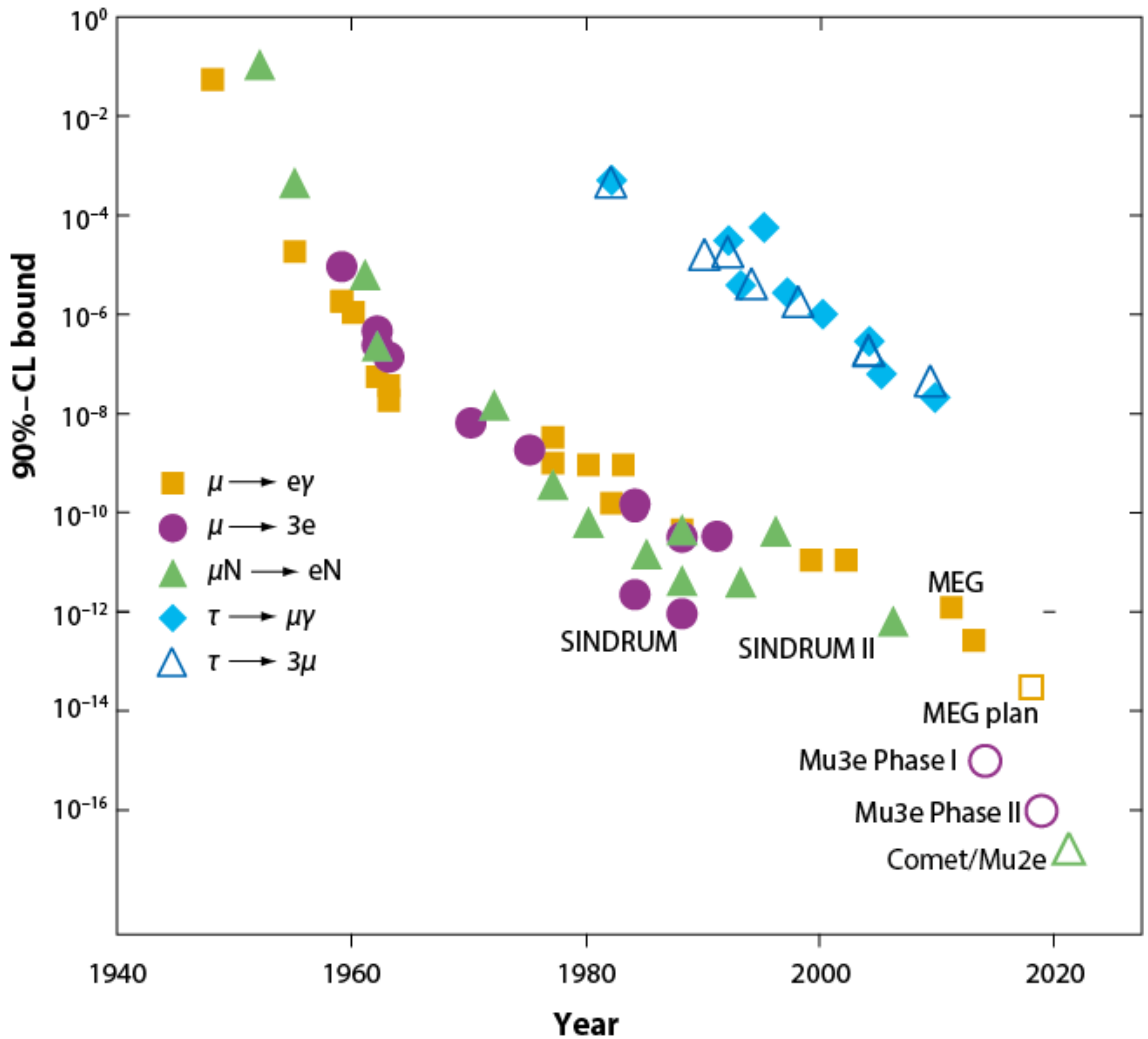


In the SM this decay can be mediated by neutrino oscillations but it is negligibly small

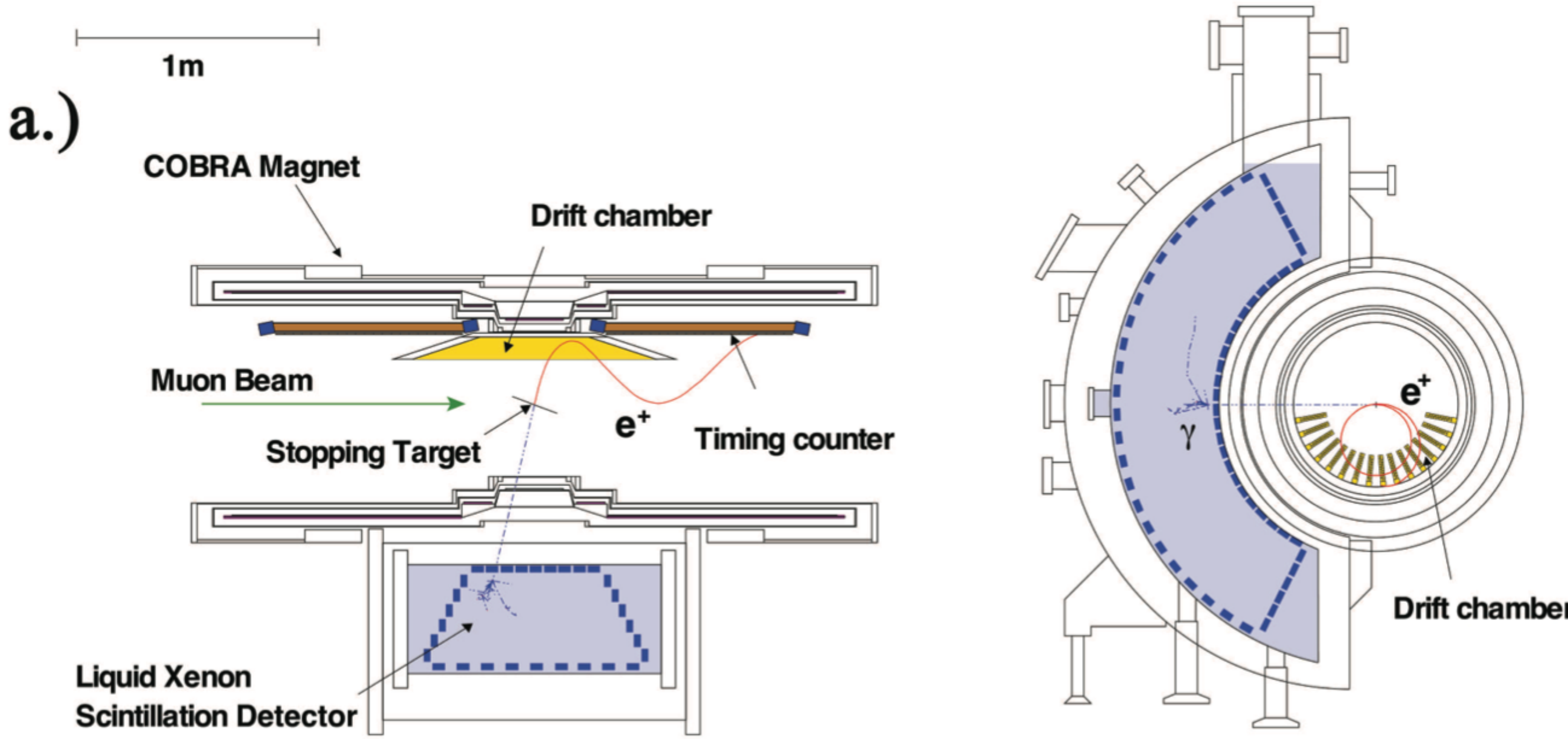
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

> Because their standard-model branching ratios are far too tiny for possible detection, observation of any mode would be certain evidence of new physics. That's what makes such sensitive searches potentially transformative. ***S.L. Glashow***

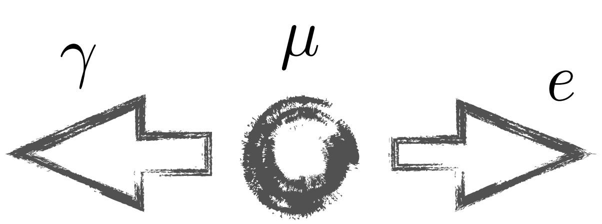
LFV


90%-CL bound
Year
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
1940
1960
1980
2000
2020
$\mu \longrightarrow e\gamma$
$\mu \longrightarrow 3e$
$\mu N \longrightarrow eN$
$\tau \longrightarrow \mu\gamma$
$\tau \longrightarrow 3\mu$
SINDRUM
SINDRUM II
MEG
MEG plan
Mu3e Phase I
Mu3e Phase II
Comet/Mu2e

MEG at PSI

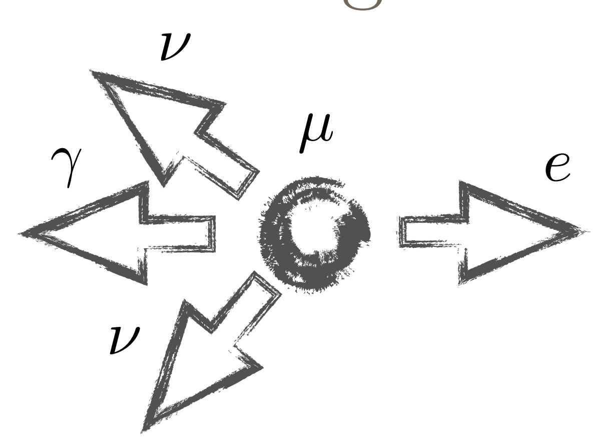


Signal

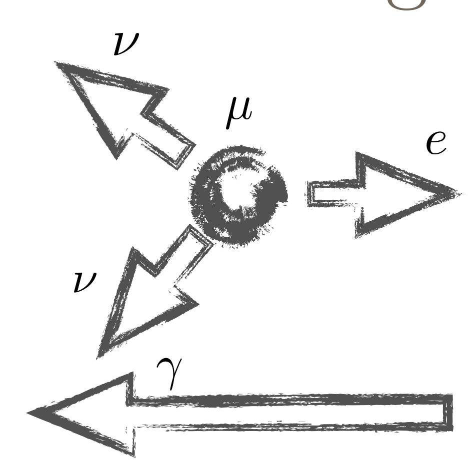


$$B(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$$

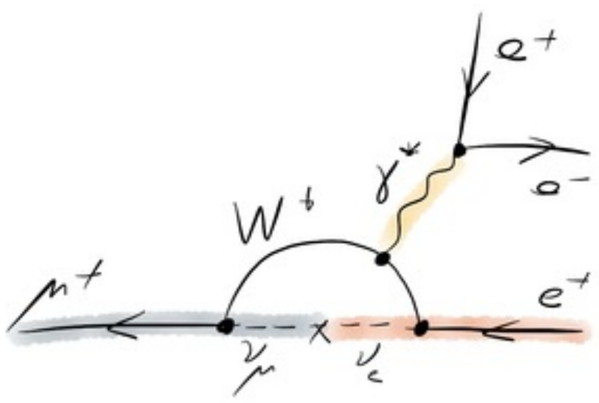
Physical Background

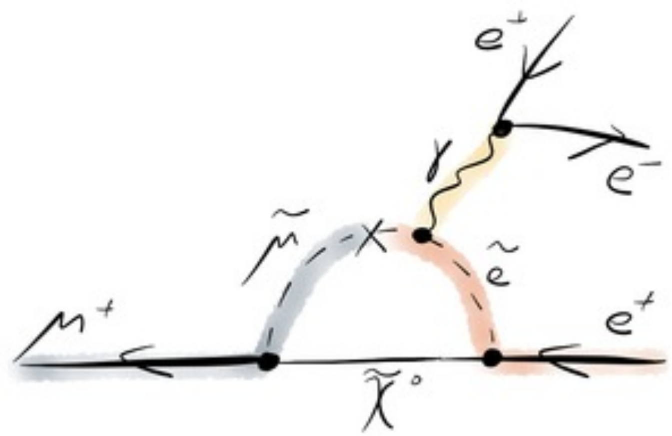


Accidental Background

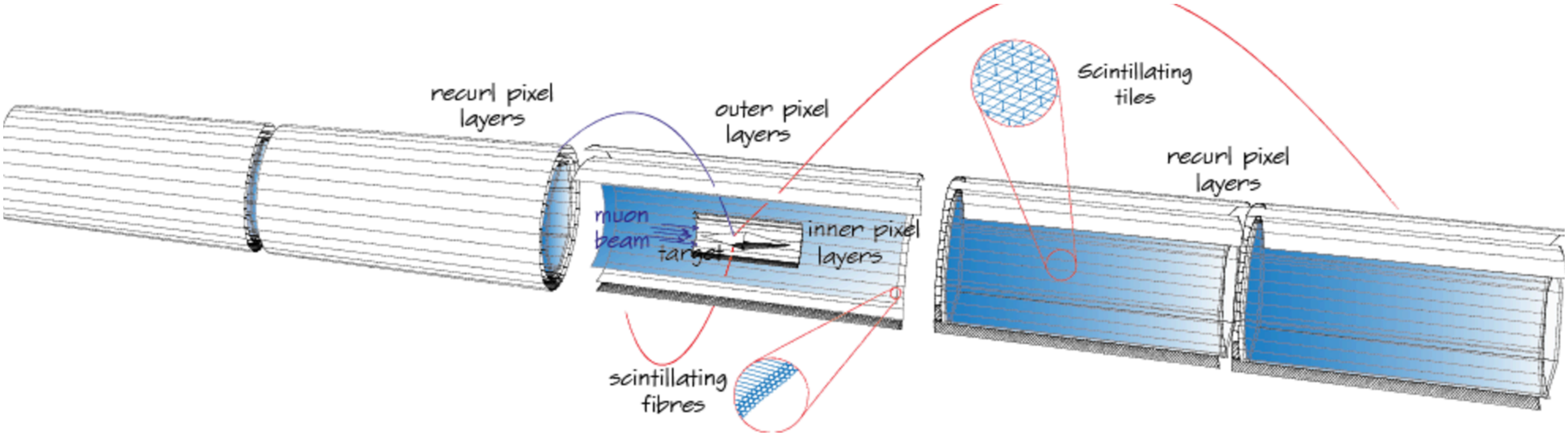


The Mu3e Experiment at PSI





- Negligibly small branching ratio in the SM
- Can be very much enhanced by existence of heavy new particles



Summary

- The Standard Model has been very successful, but it is not considered a complete theory
- How much incomplete is the Standard Model is subject of discussion
- There are several open questions that almost certainly require existence of particles not present in the Standard Model
- Neutrino oscillations is (up to now) the only microscopic evidence of physics beyond the Standard Model, while we have macroscopic evidences (the existence of DM, the Baryon-Antibaryon Asymmetry in the Universe)
- Several searches are going on around the world in various labs
- The last part of the course only provided an incomplete and simplified discussion of some of these experiments