NUCLEAR PHYSICS AT U HEIDELBERG AND MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

Kai Schweda, GSI and U Heidelberg

CBM @ FAIR

Mission:

Systematically explore **QCD matter** at **large net-baryon densities**

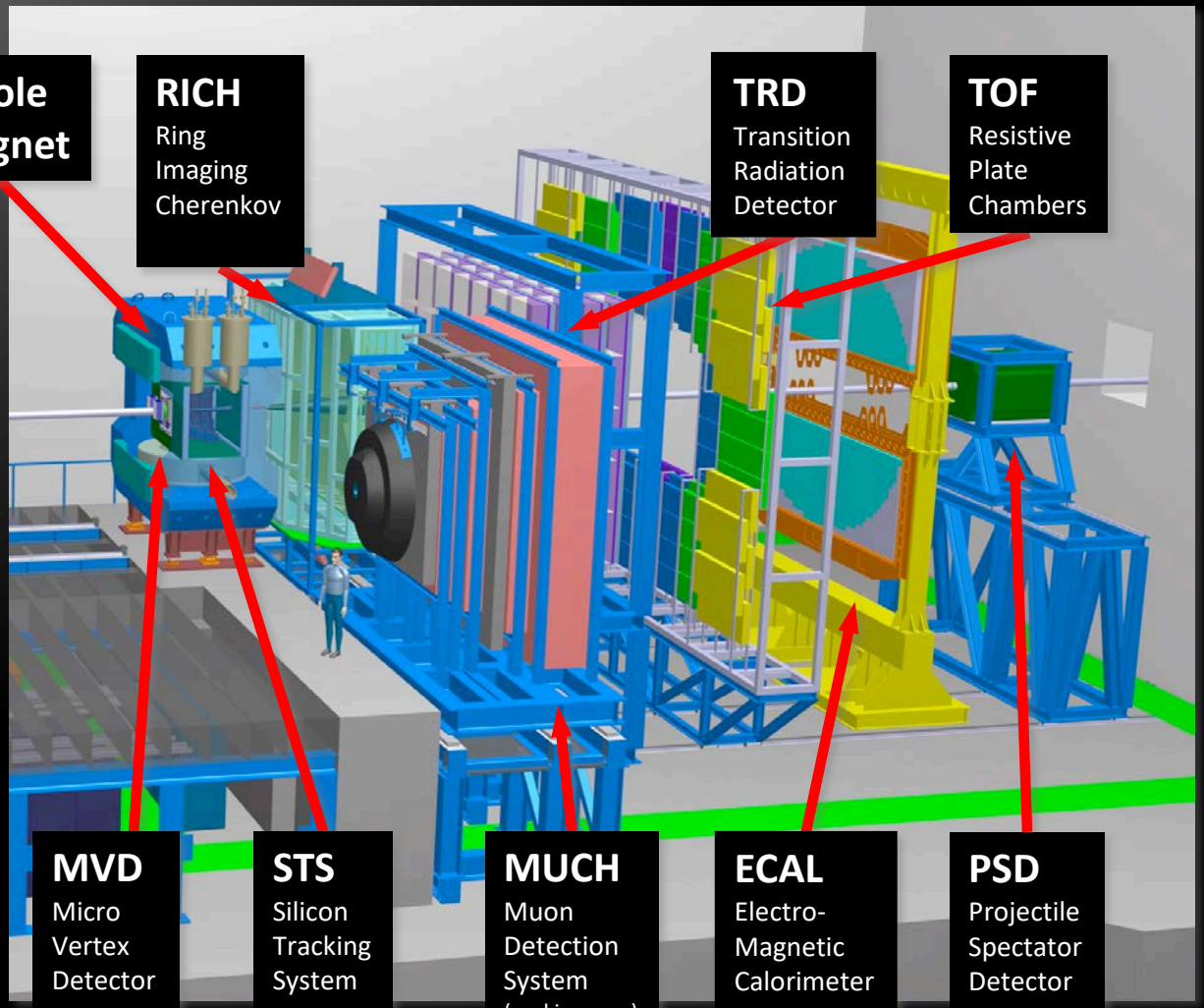
with **high accuracy** and **rare probes**

Norbert Herrmann, U Heidelberg
CBM spokesperson

CBM cave

https://www.youtube.com/watch?v=RPA_btp_r9M

CBM EXPERIMENTAL SETUP



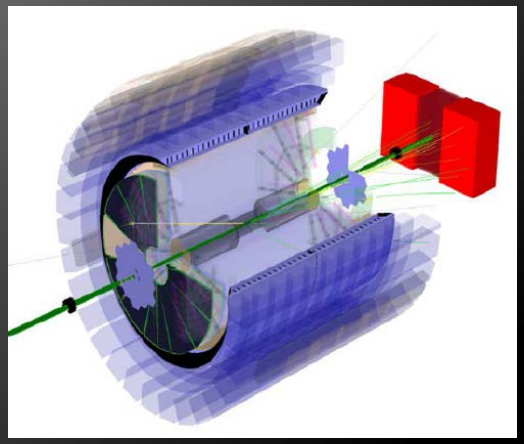
- Tracking acceptance: $2^o < \theta_{lab} < 25^o$
- Free streaming DAQ
- R_{int} = 10 MHz (Au+Au)

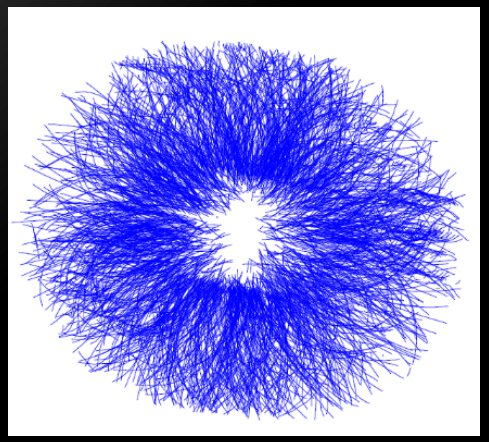
  $R_{int} \approx 0.5$ MHz
  full bandwith:
  Det. – Entry nodes
  reduced bandwidth
  Entry nodes – Comp. farm

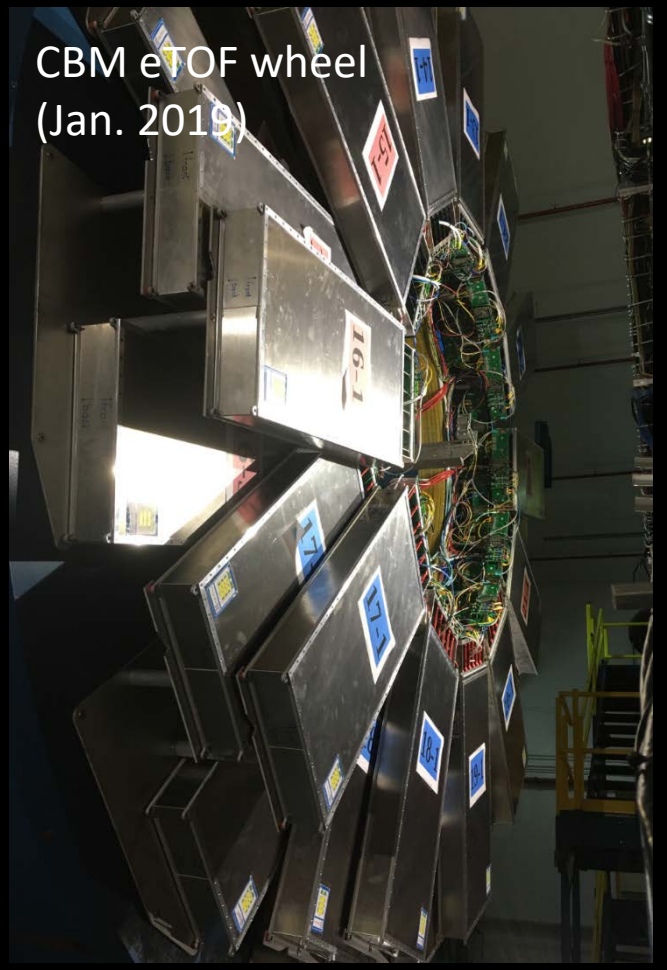
  with
  R_{int} (MVD)=0.1 MHz
- Software based event selection

HD involvement: CBM-TOF & data analysis

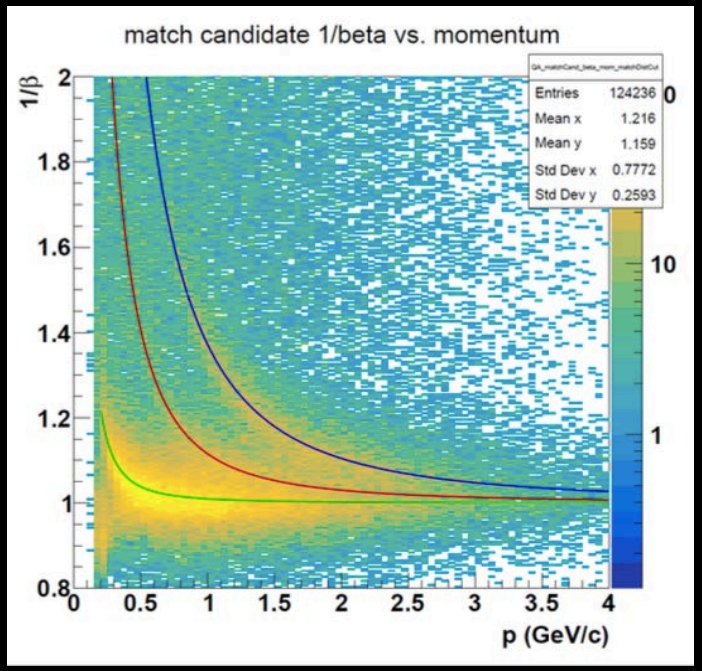
PHASE-0: ETOF & HPC SOFTWARE IN STAR @ RHIC (BNL)







Correlation:
CBM-eTOF
with STAR TPC
from Run18



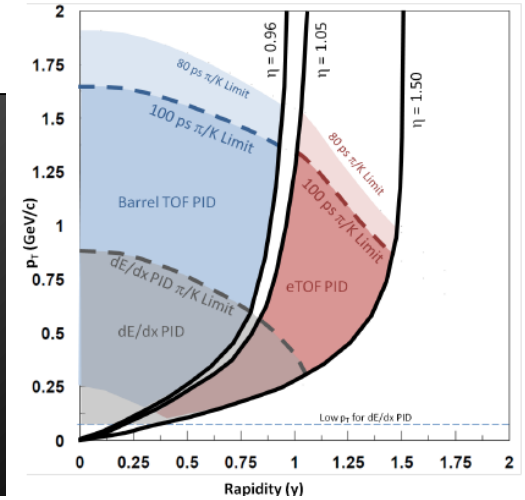
Participating CBM groups:
Univ. Heidelberg,
TU Darmstadt,
GSI Darmstadt,
Univ. Frankfurt,
Tsinghua Univ. Beijing,
USTC Hefei,
CCNU Wuhan

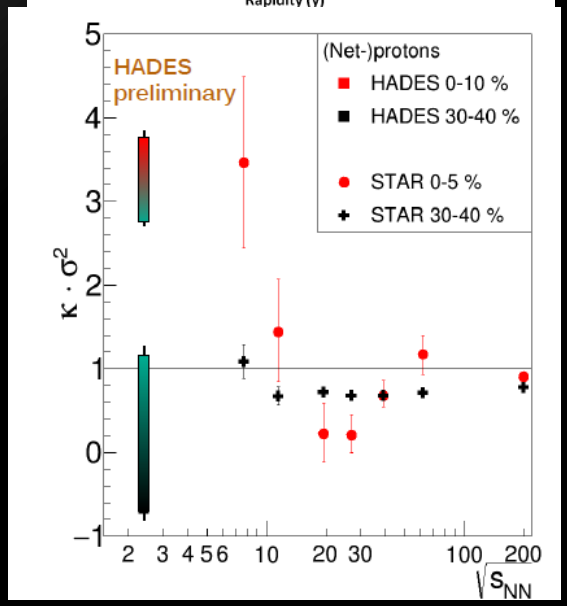
Test module operational	(Oct. 2016)
STAR DAQ interface	(Jan. 2017)
Full sector test	(Spring 2018)
Wheel installation	(Fall 2018)
BES II data taking	(2019/2021)
Transfer of modules to FAIR	(2022/23)

STAR – BES II PHYSICS PROGRAM WITH ETOF

arXiv:1609.05102v1 [nucl-ex]

Physics Program for the STAR/CBM eTOF Upgrade



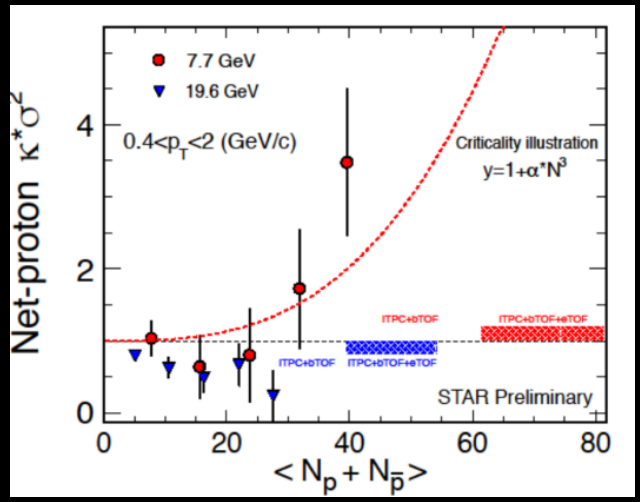


HADES: M. Lorenz, QM 2017
STAR: X. Luo et al, CPOD 2014

Topics to be studied with extended acceptance in energy range :

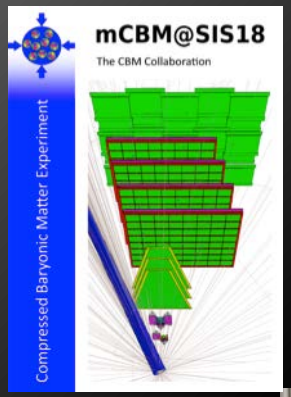
- Excitation function and phase-space distributions of hyperons, hypernuclei, anti-protons, ...
  → Equilibration, phase transitions
- Collective Flow (v1, v2)
  → Equation-of-State, phase transitions
- Dilepton yields
  → Chiral symmetry restoration
- Fluctuations of conserved quantum numbers (baryon, charge, strangeness)
  → Critical point

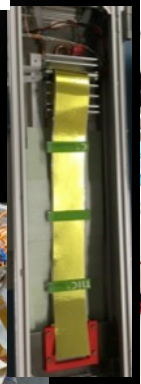
Expected increase in signal strength:



CBM PHASE-0 PROJECT: MCBM

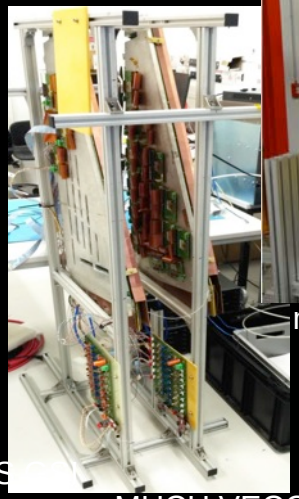
Demonstrator for full CBMdata taking and analysis chain under full load (Au-Au, 10^7 interactions/s)





mMVD$_{2020}$ Frankfurt

mSTS

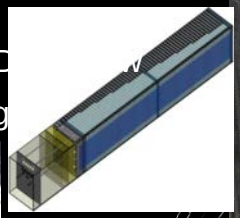


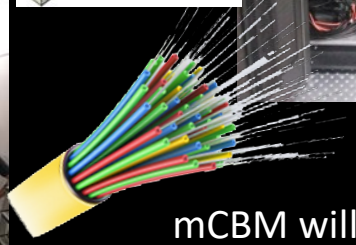
mMUCH VECC

mTRD Münster, Frankfurt

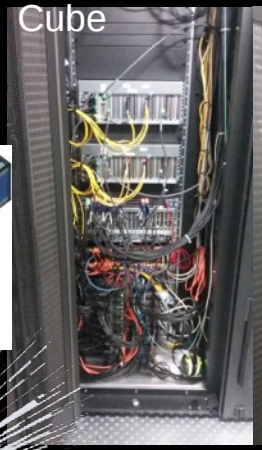
mTOF Heidelberg

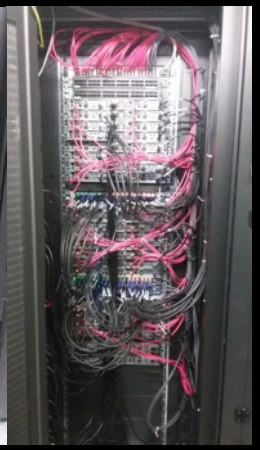
mPSD





mFLES racks @ Green IT Cube





mCBM will focus on:

- Free streaming data transport to a computer farm
- Online reconstruction and event selection
- Offline data analysis

Requested beam time was fully granted by G-PAC

ALICE AT THE LARGE HADRON COLLIDER, CERN

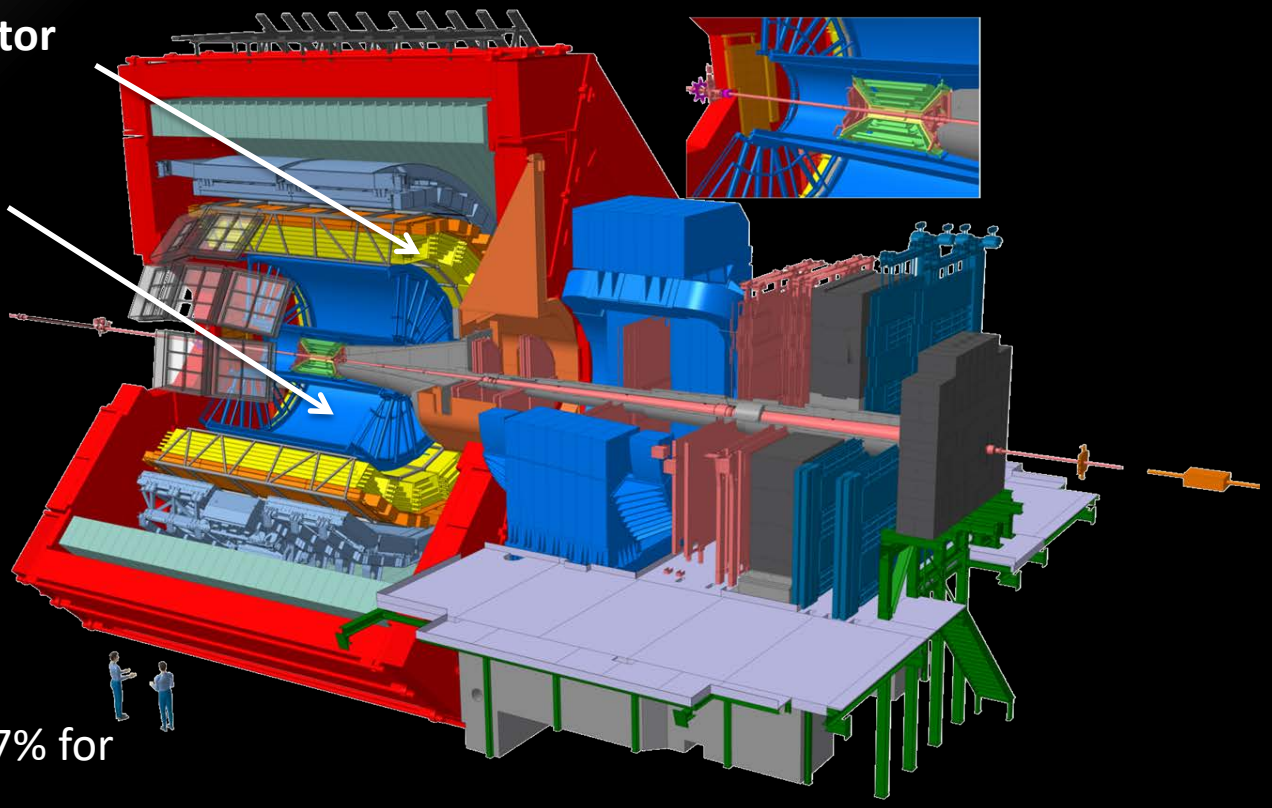
Silvia Masciocchi, U Heidelberg and **group head GSI-ALICE**
ALICE Collaboration Board Chair-Elect

Johanna Stachel, U Heidelberg

Peter Braun-Munzinger, U Heidelberg + EMMI GSI

THE ALICE APPARATUS

- **Transition Radiation Detector** tracking & electron PID
- **Time Projection Chamber** tracking & PID
- Inner Tracker, silicon tracking & PID

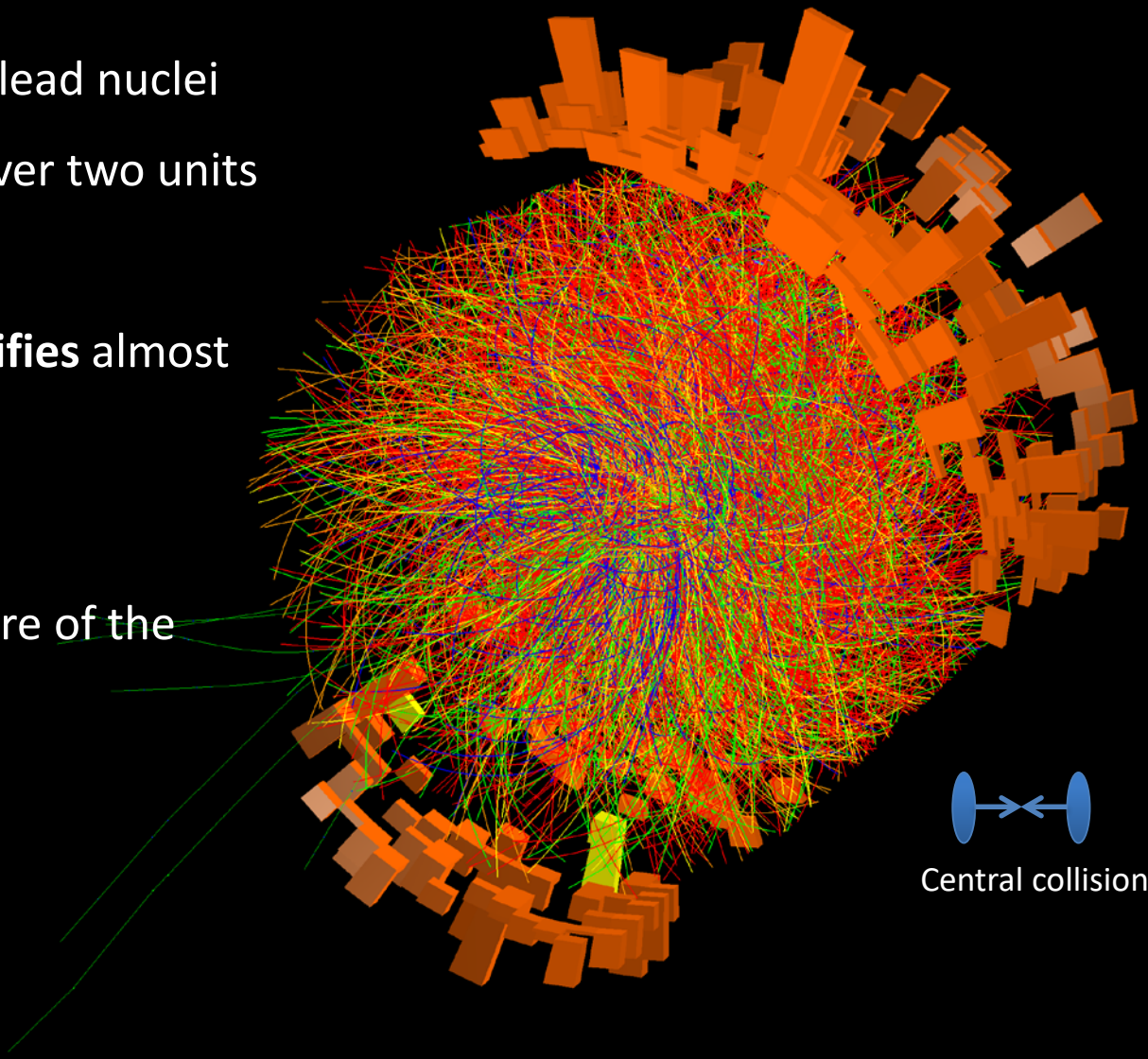


- Particle ID: 0.1-20 GeV/*c*
- Material budget: 0.08 X_0
- Momentum resolution ~1-7% for p_T = 0.1-100 GeV/*c*

CENTRAL COLLISION OF LEAD NUCLEI

- **Single collision** of two lead nuclei
- **4k charged particles** over two units of rapidity
- ALICE **tracks** and **identifies** almost all particles

- **Multiplicity** is a measure of the **medium size**



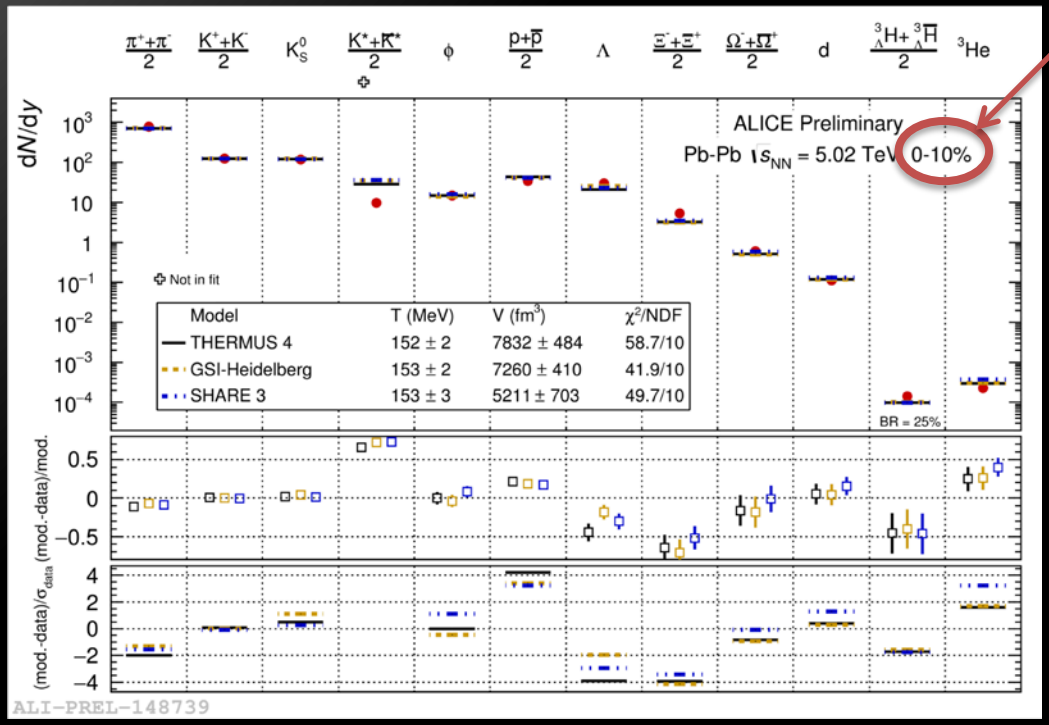
ALICE DATA SET – LHC RUN 1 AND RUN 2

System size

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}	
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~0.9 nb^{-1}	9x central collisions
Xe-Xe	2017	5.44	~0.3 μb^{-1}	6h LHC pilot run
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}	Reference data, initial state
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} , ~59 pb^{-1}	New pp reference, high-multiplicity triggers

236 peer-reviewed publications:
- 2x Nature Physics
- 32x Phys. Rev. Lett.
- 77x Phys. Lett. B (4x from Xe pilot run)
- 7x 500+ citations

PARTICLE YIELDS – STATISTICAL MODEL



E = mc²

Highest multiplicity

QCD-analog of **Planck spectrum**

T = 152 ± 3 MeV, $\mu_B \approx 0$

Increasing experimental precision

→ Some **tension** with **baryons**

(and hadron resonances)

Solution: arXiv:1808.03102

PLB 792 (2019) 304.

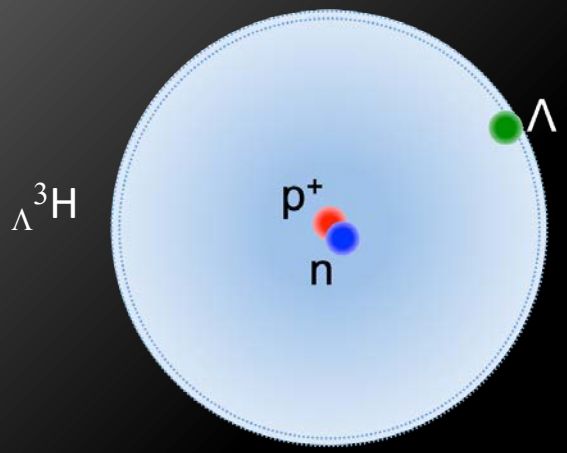
Lattice-QCD results **agree**

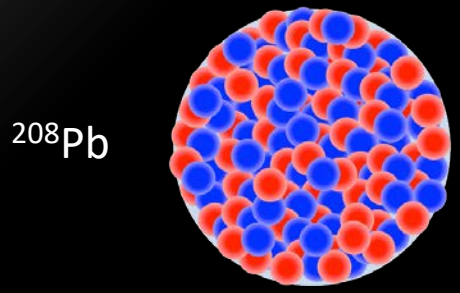
T_{pc} = 156.5 ±1.5 MeV

A. Bazavov et al. (Hot QCD) arXiv:1812.08235

Test of **CPT invariance (mass of ^{3}He vs anti-^{3}He)**
Nature Physics 11 (2015) 811-814.

(ANTI-)- HYPERTRITON $_{\Lambda}{}^{3}H$





Mass = 2990 MeV

Binding energy = 2.3 MeV

Lambda separation energy = 0.13 MeV

Molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + π^- = ^{3}He + π^+

Radius = 10.3 fm

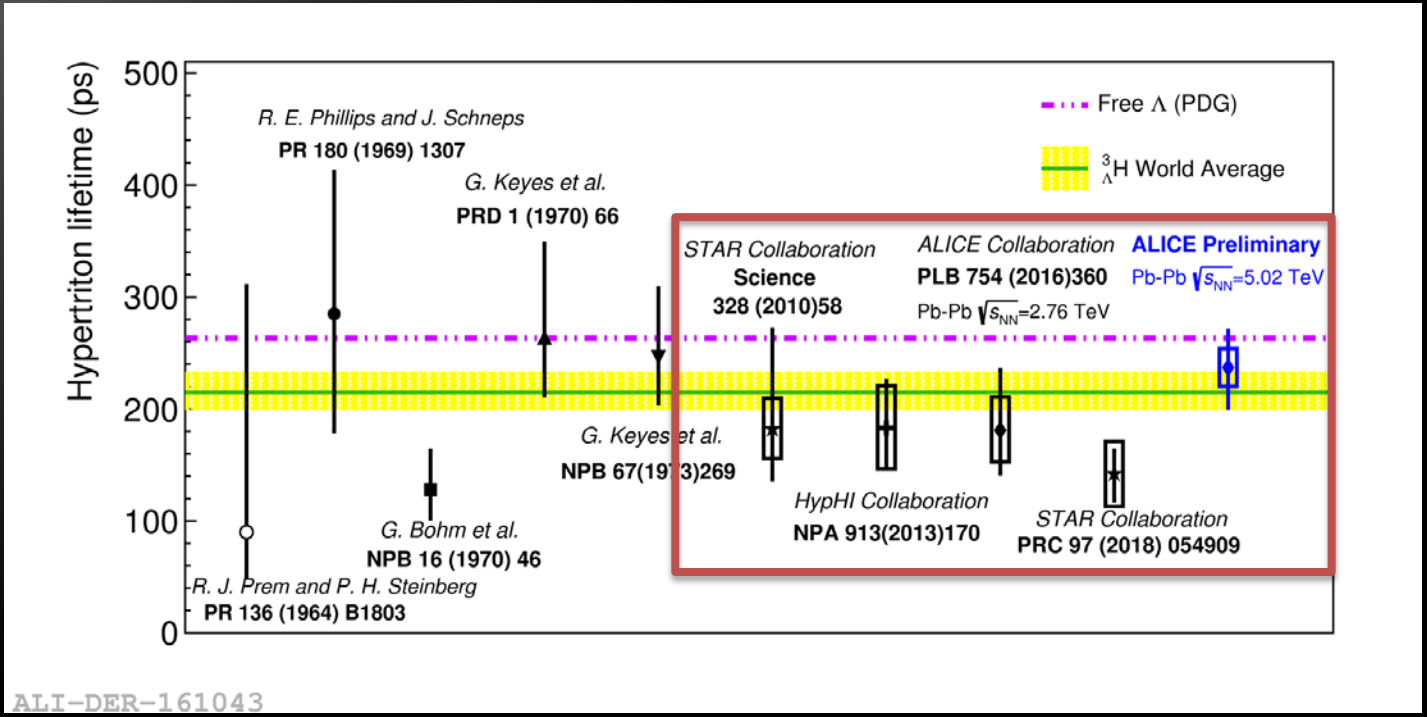
Hypertriton is the ultimate halo state

Not clear: How is this state produced from quarks and gluons ?

Anti-hypertriton discovered by STAR @ RHIC

Science 328,58 (2010).

(ANTI-)HYPERTRITON LIFETIME

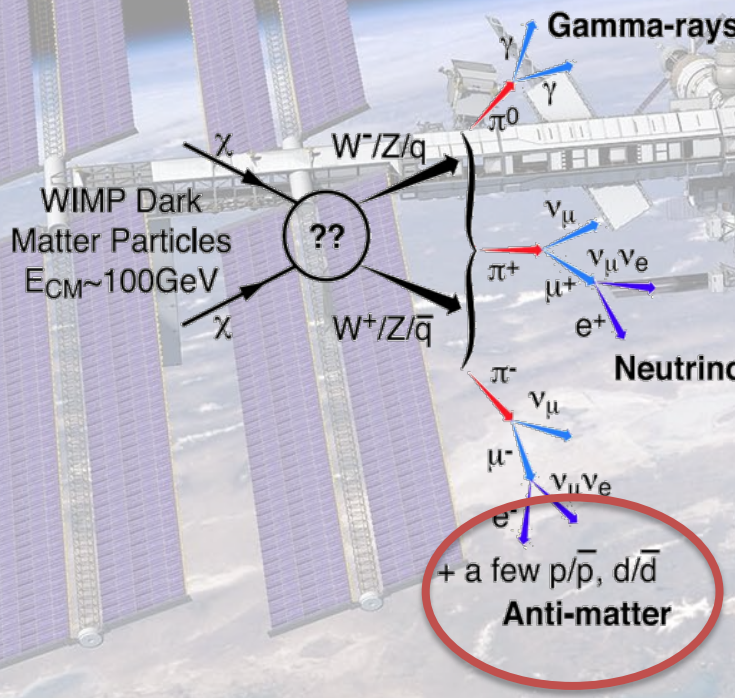


Heavy-ion exp.

Hypertriton lifetime consistent with **free Λ baryon** → reduce uncertainty !

Present **ALICE** data set: substantial **improvement** in **lifetime** & **separation energy**

DARK MATTER SEARCH – NEUTRALINO ANNIHILATION



Lightest **super-symmetric particle** is **dark matter candidate**

AMS-02@ISS is looking for **X-X annihilation**

Produces **(anti)-deuterons**

Cosmic protons + H (interstellar medium)

→ anti-deuteron is irreducible **background**

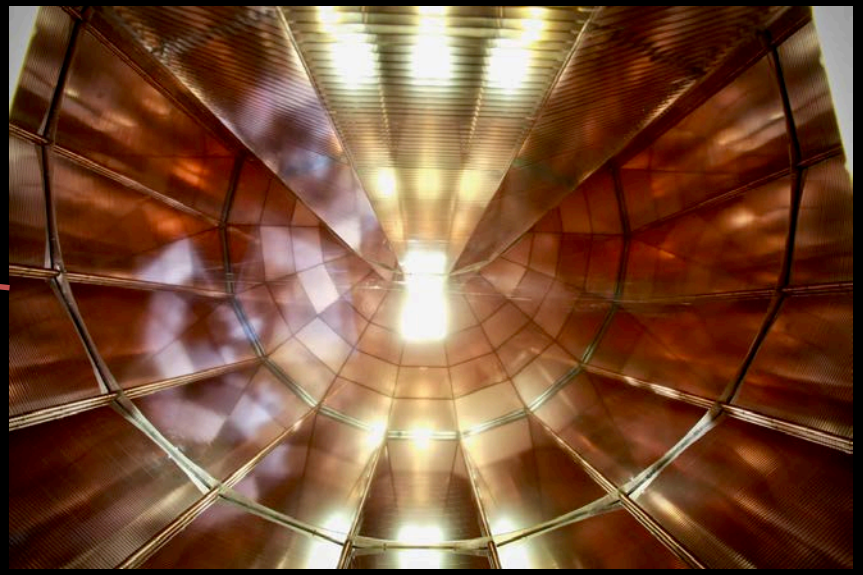
→ **ALICE measures** this **background** at similar kinematic range!

ALICE UPGRADE 2019-2020: GET READY FOR 50KHZ PB-PB COLLISIONS – CONTINUOUS READOUT

72 GEM-4 readout chambers installed

Alignment better than 200 μm

Commissioning starts in October 2019



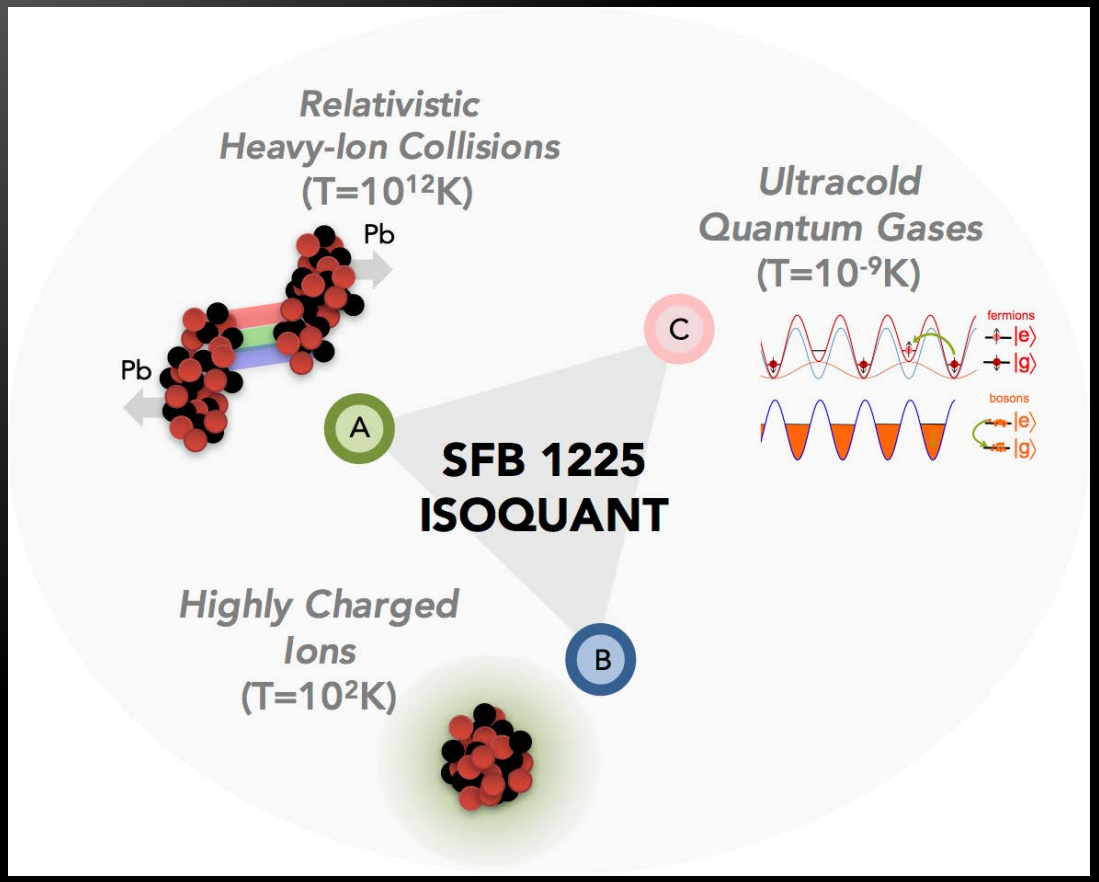
Inner field cage
Mirror image of GEM-4 stacks at central cathode

ALICE AFTER THE UPGRADE

- 2019/2020 LHC long shutdown 2
  ALICE upgrade to Pb-Pb collisions at 50kHz, 100x data set
- 2021 -2024 LHC Run 3
- 2024 – 2025 LHC long shutdown 3 – possibly inner tracker upgrade
- 2025 – 2029 LHC Run 4
- 2030 LHC long shutdown 4
  LOI for successor of ALICE, nearly-massless silicon detector
  https://arxiv.org/abs/1902.01211

- 0.05% X_0
- Wafer-sized sensors
- On-chip power distribution
- Cooling by forced air flow
- Significant reduction of material budget

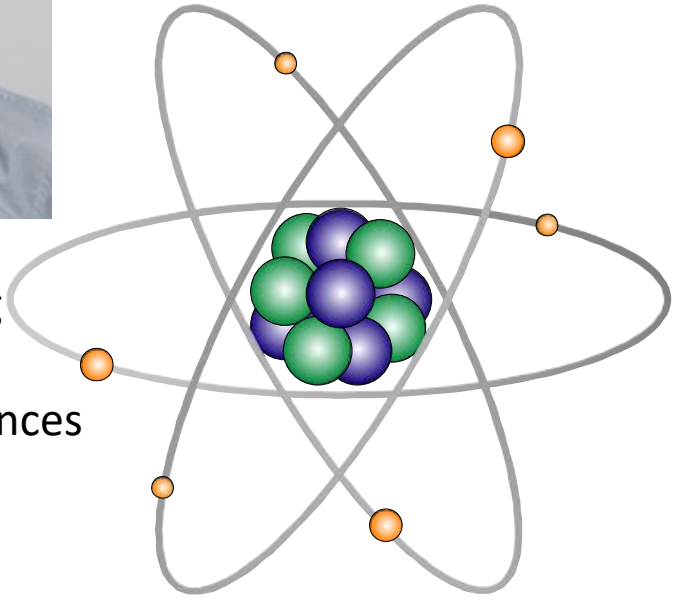
COLLABORATIVE RESEARCH CENTRE 1225 - ISOQUANT



- Goal: quantitative understanding of universal aspects of isolated quantum systems
- Theory and experiment
- Funded by Deutsche Forschungsgemeinschaft
- 2014 – 2020: 10M Euros
- 2020 – 2026: continuation in preparation

The mass of an atom

Klaus Blaum
MPIK Heidelberg
Royal Swedish
Academy of Sciences



= $N \cdot$ + $Z \cdot$ + $Z \cdot$

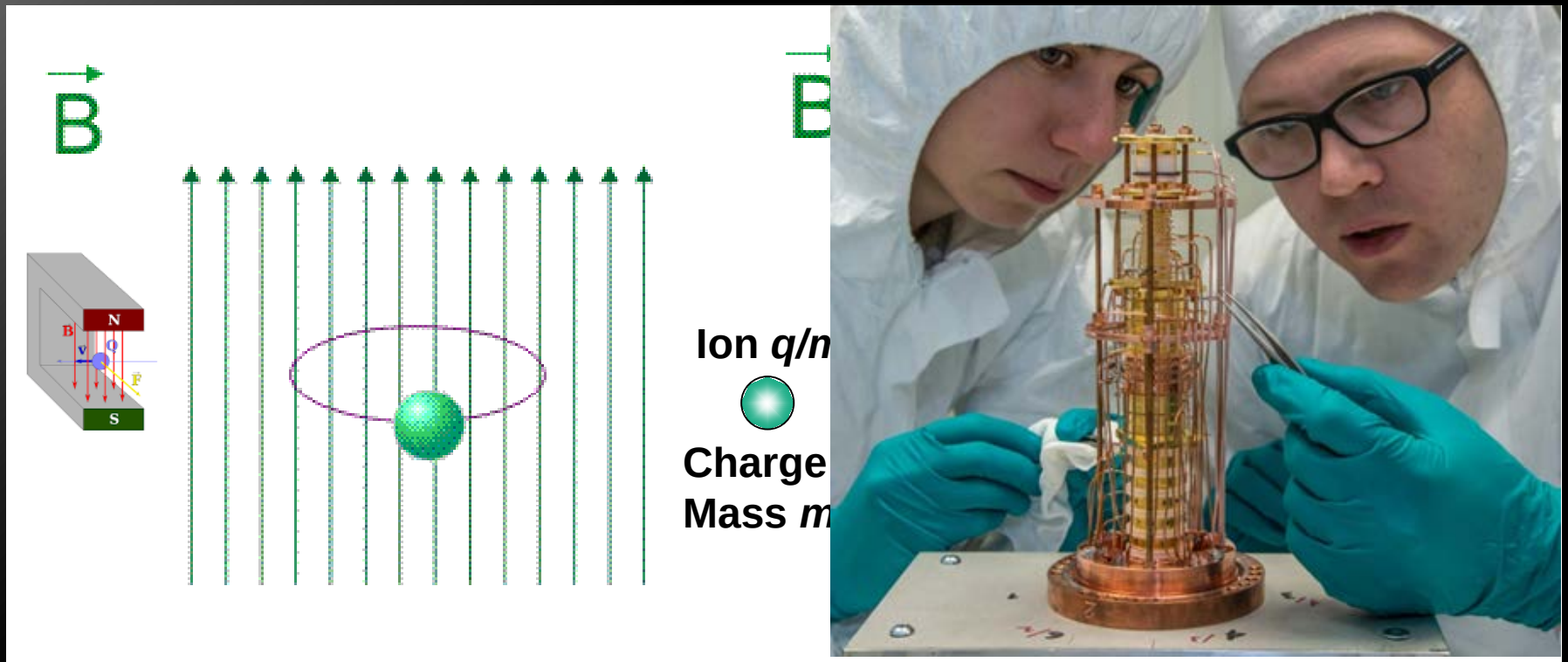
– binding energy

$$m_{Atom} = N \bullet m_{neutron} + Z \bullet m_{proton} + Z \bullet m_{electron} - (B_{atom} + B_{nucleus})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

Storage of ions in a Penning trap



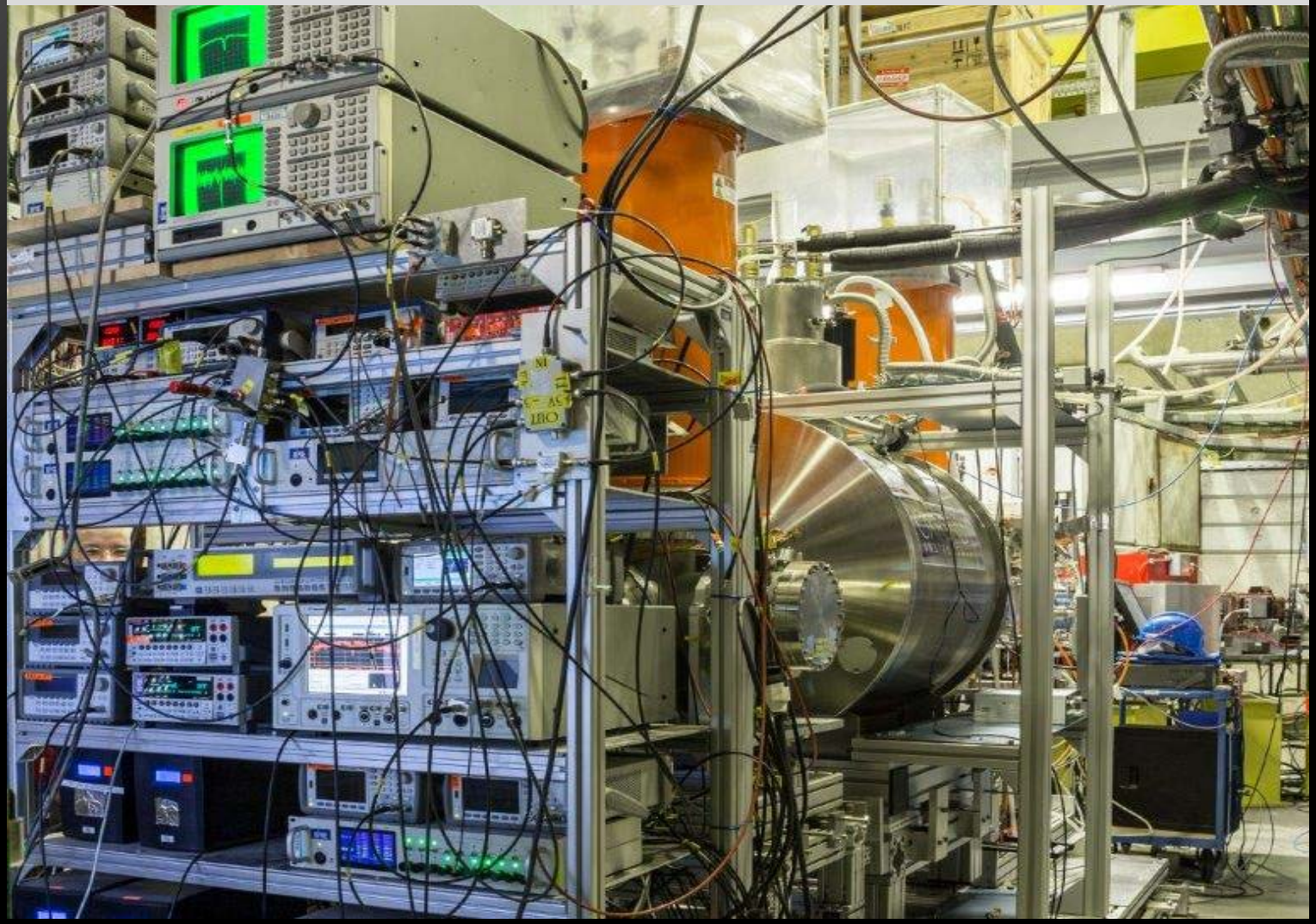
The free cyclotron frequency is inverse proportional to the mass of the ion!

$$\nu_c = qB/(2\pi m_{ion})$$

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).

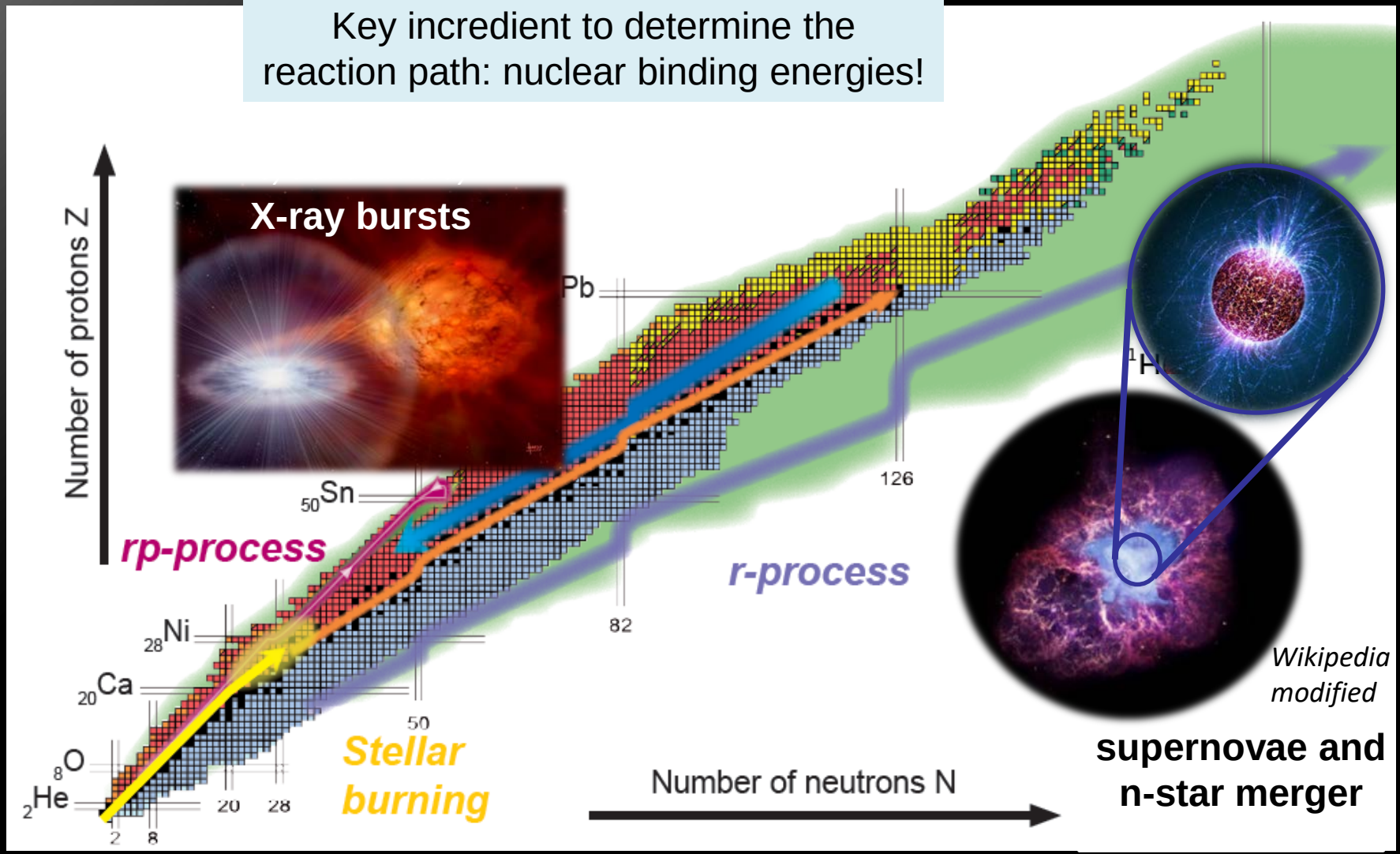
BASE – A Penning-trap setup at CERN

A balance for protons and antiprotons.

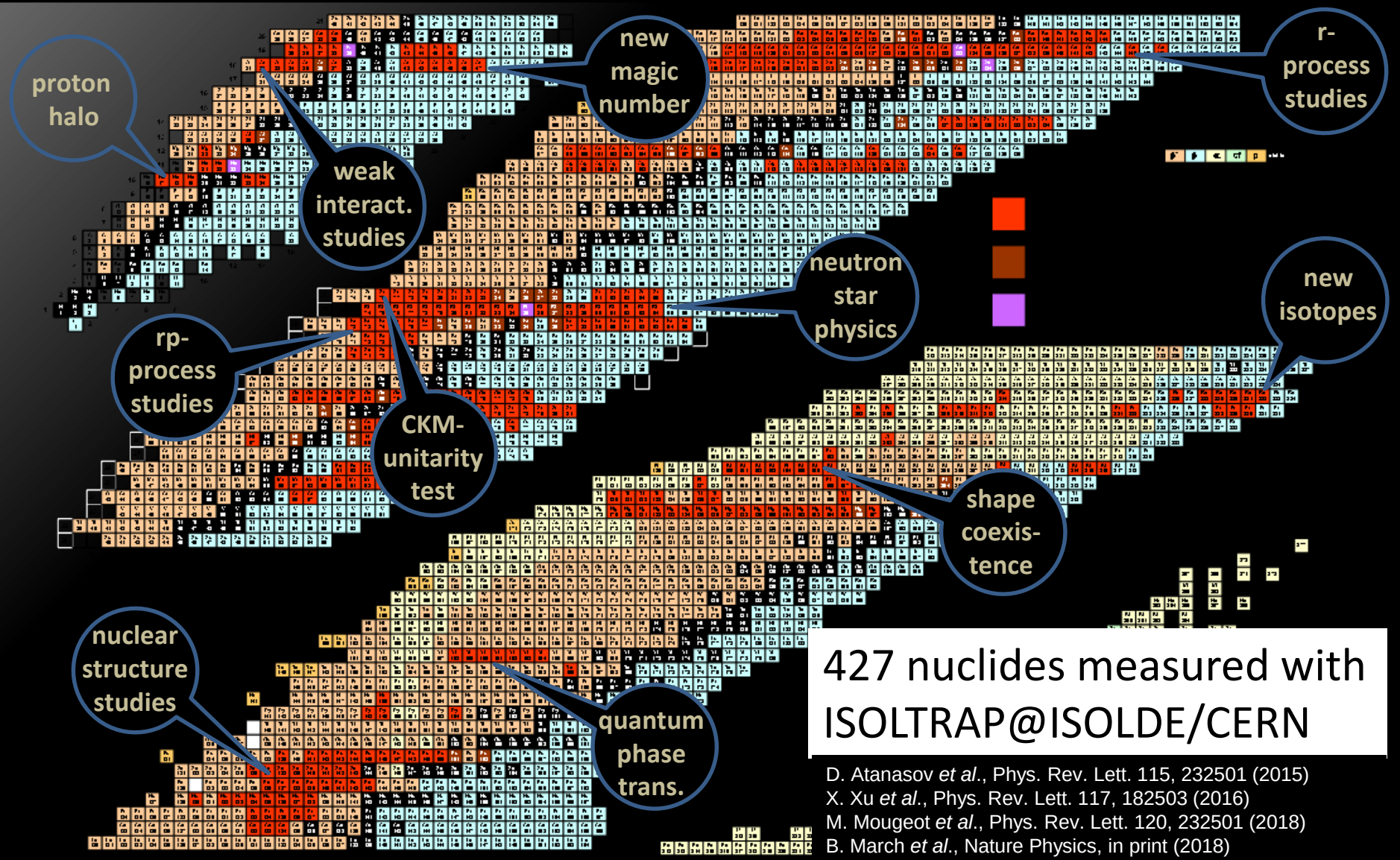


The nucleosynthesis paths

Key incredient to determine the reaction path: nuclear binding energies!



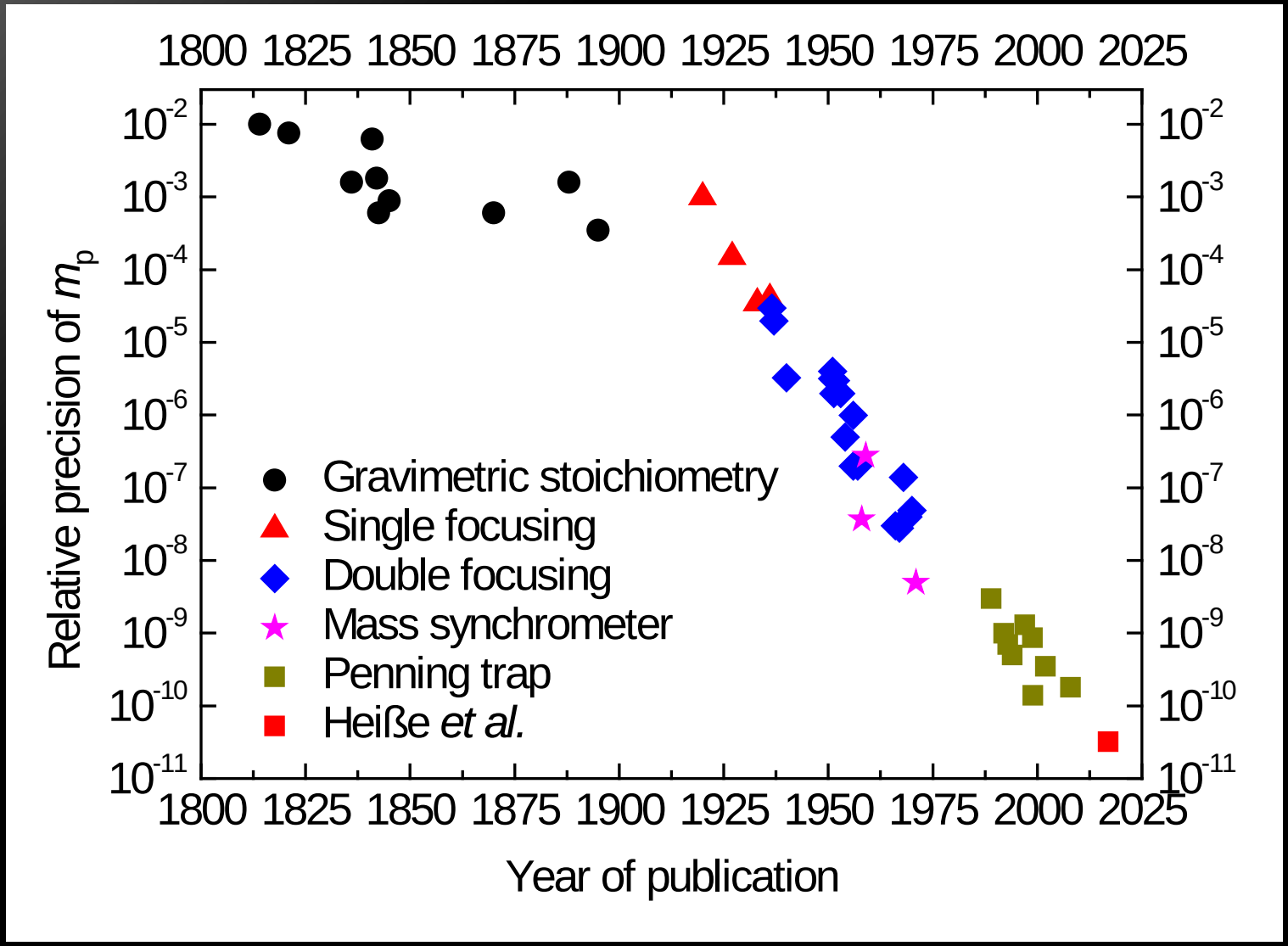
Our contribution



427 nuclides measured with ISOLTRAP@ISOLDE/CERN

D. Atanasov *et al.*, Phys. Rev. Lett. 115, 232501 (2015)
X. Xu *et al.*, Phys. Rev. Lett. 117, 182503 (2016)
M. Mougeot *et al.*, Phys. Rev. Lett. 120, 232501 (2018)
B. March *et al.*, Nature Physics, in print (2018)

The atomic mass of the proton



Courtesy F. Heiße

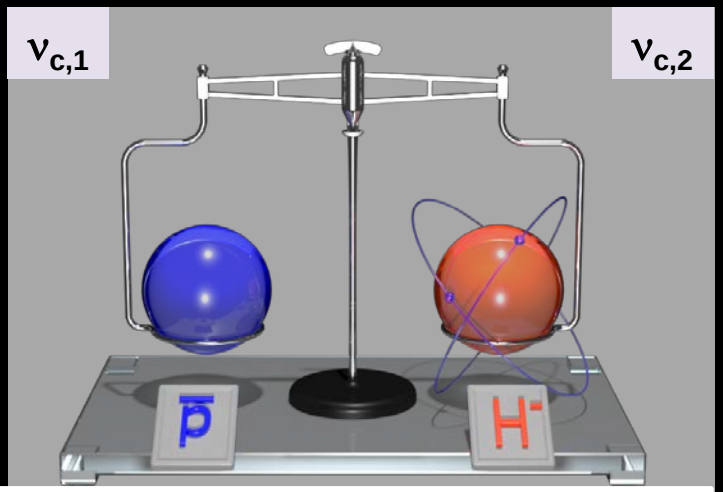
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

Comparison of the proton and antiproton

Compare charge-to-mass ratios *R* of p and $\bar{p}$:

$$(q/m)_{\bar{p}} / (q/m)_p = -1.000\,000\,000\,001\,(69)$$

S. Ulmer *et al*., Nature 524, 196 (2015)



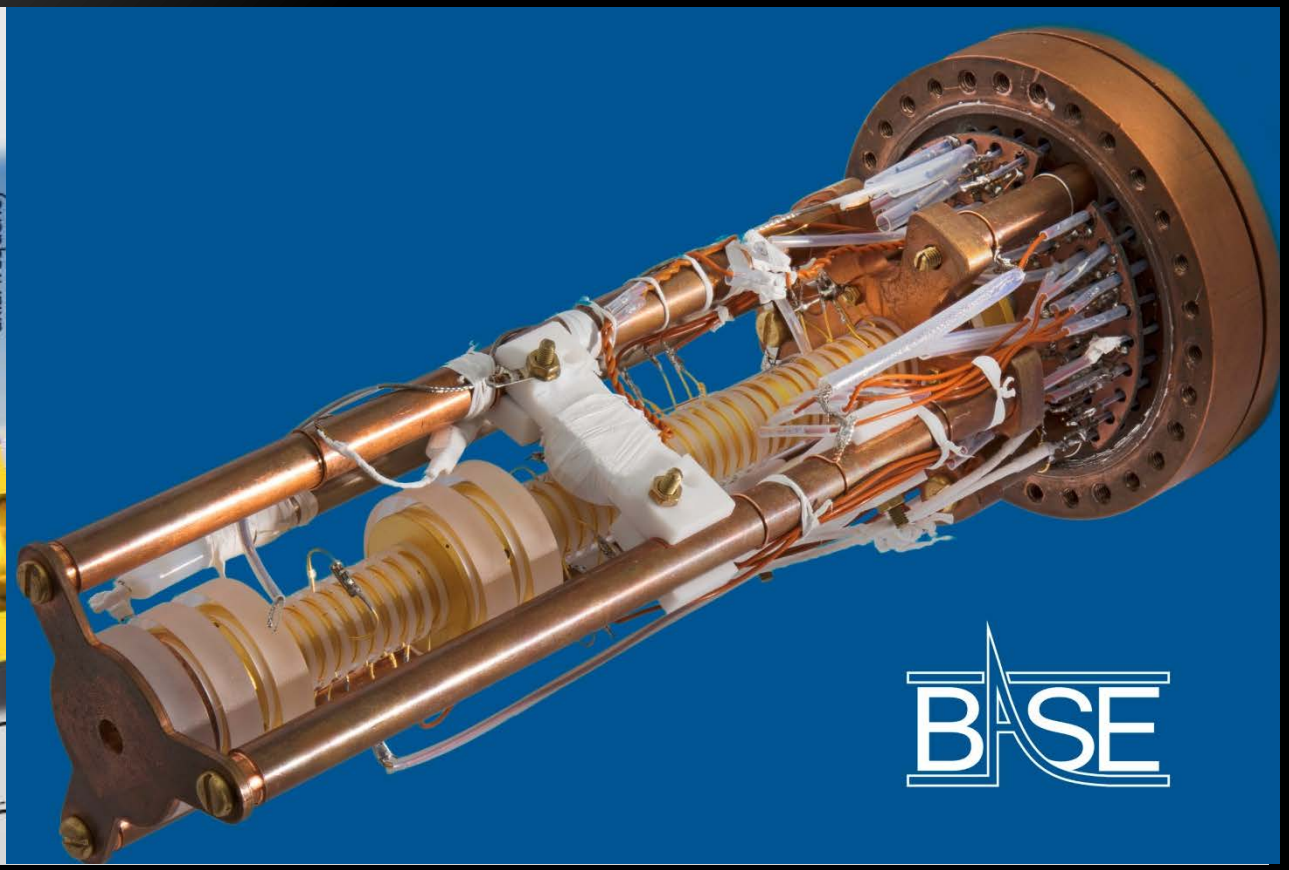
It is not that easy!

$$m_{H^-} = m_p \left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} \right)$$

g-factor proton: G. Schneider *et al*., Science 358, 1081 (2017)
g-factor antiproton: Ch. Smorra *et al*., Nature 550, 371 (2017)

The (anti-)proton magnetic moment

$$g = 2\frac{\omega_L}{\omega_c}$$



$\mu_p = 2.792\,847\,344\,62(82)\ \mu_N$

(0.3 ppb)

G. Schneider *et al.*, Science 358, 1081 (2017)

$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\ \mu_N$

(1.5 ppb)

Ch. Smorra *et al.*, Nature 550, 371 (2017)

What comes next?

Presently running or planned experiments:

5-fold improved neutron mass

10-fold improved $E=mc^2$ test

10-fold improved (anti-)p *g*-factor

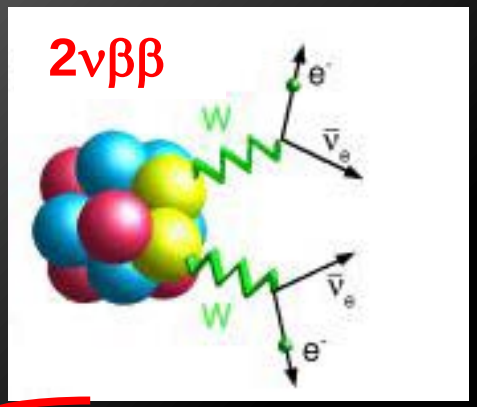
100-fold improved ^{3}He *g*-factor

… going up to $^{208}Pb^{81+}$ with ALPHATRAP

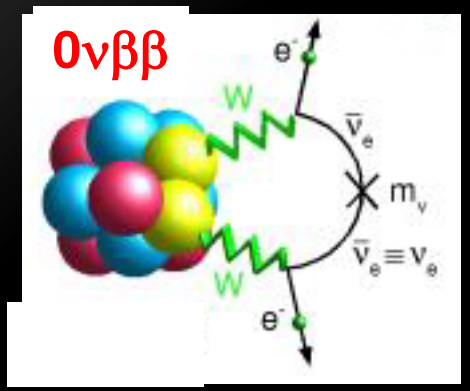
Lepton number violation

Manfred Lindner, MPIK
Honorary Doctor at KTH

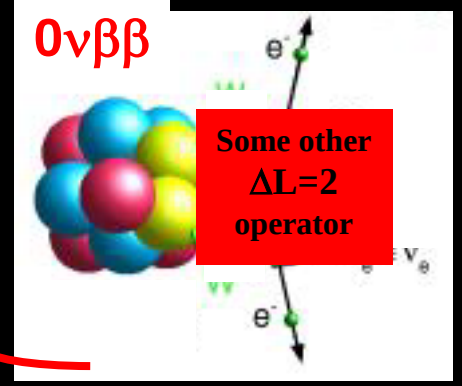
SM



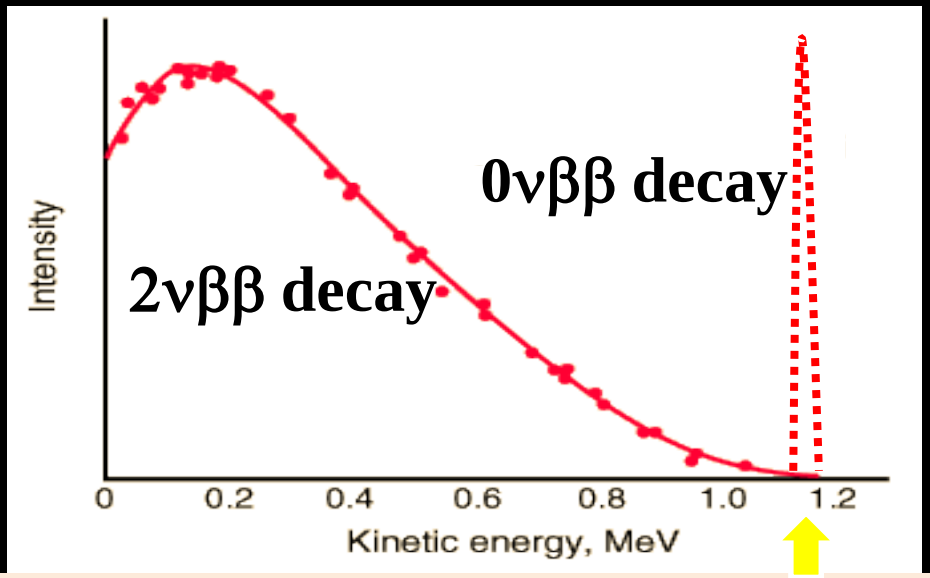
BSM



$T^{1/2} > O(10^{25}y)$



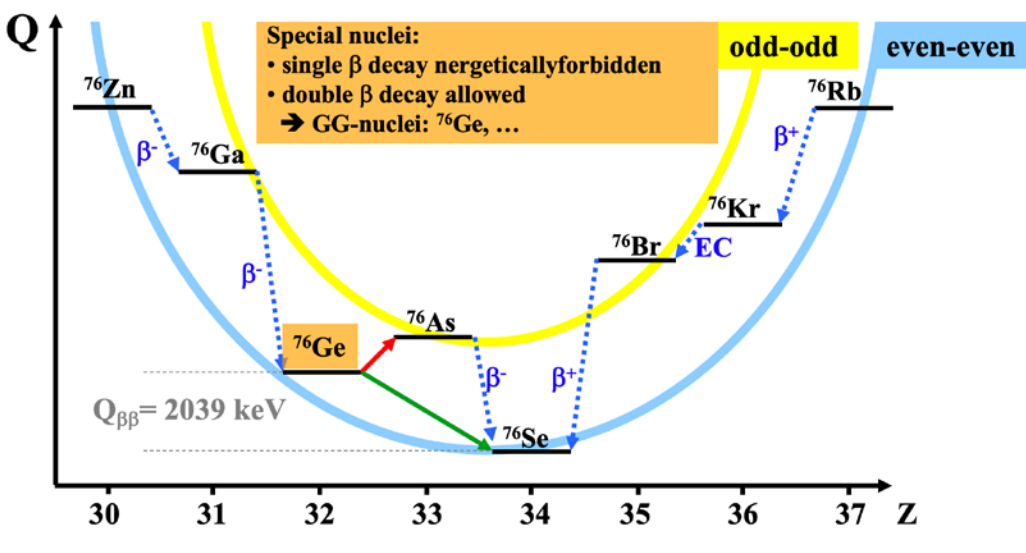
Lepton number L is a fundamental symmtery of the Standard Model (SM)
→ 0νββ decays = new (BSM) physics

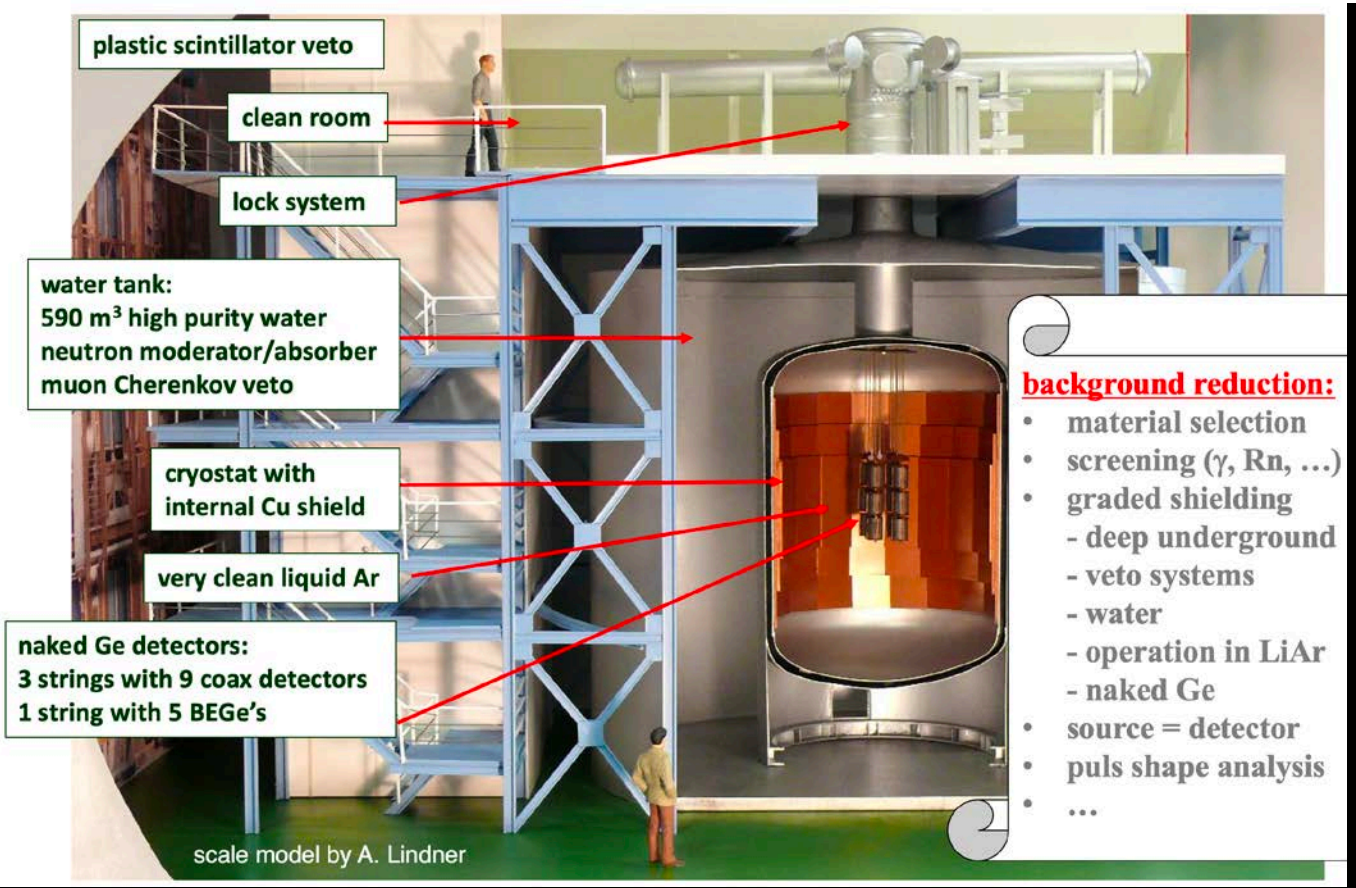


Experimental task: detect endpoint excess

The experiment

Now: GERDA @ Gran Sasso
Next: Upgrade to LEGEND200





➔ **82.4 kg x year exposure**

➔ **achieved background < 10^{-3} cts/keV*kg*yr**

➔ **record senistivity: $T^{0\nu}_{1/2} > 10^{26}$yr**

limit on Majorana mass:

➔ **$m_\nu <$ (0.10-0.23) eV**
(depending on NME)

Science 365, 1445 (2019).

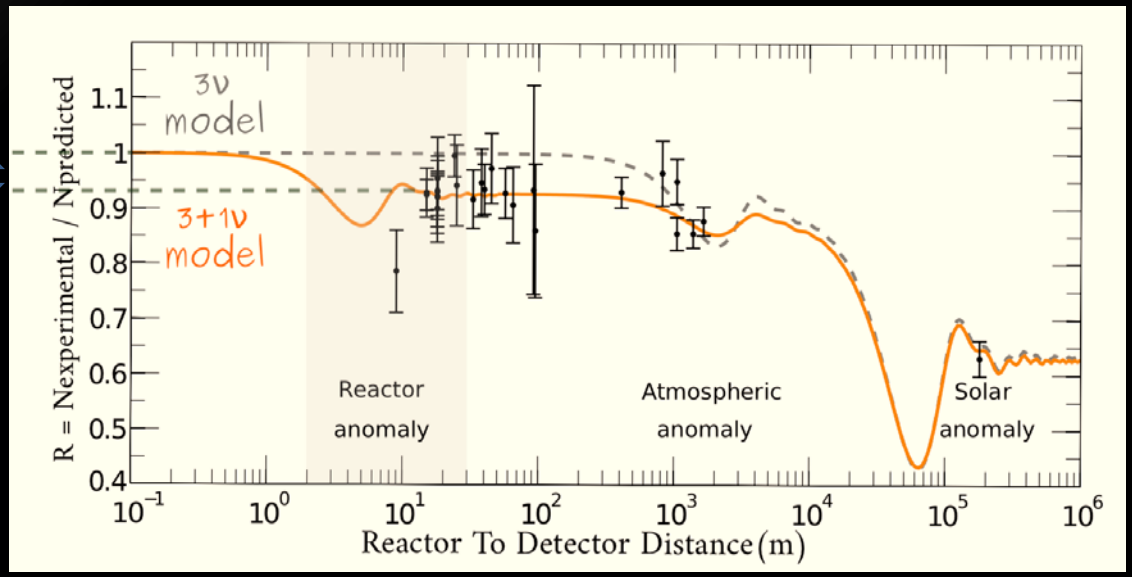
Do sterile neutrino exist?

oscillations of reactor anti-neutrinos have been observed

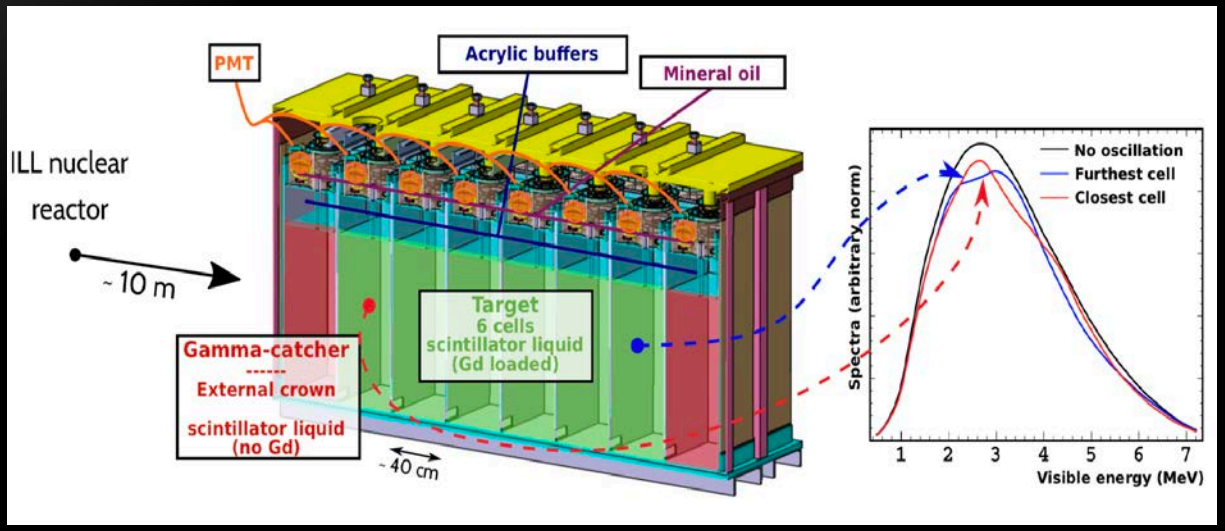
BUT: A significant 6% deficit close to reactor

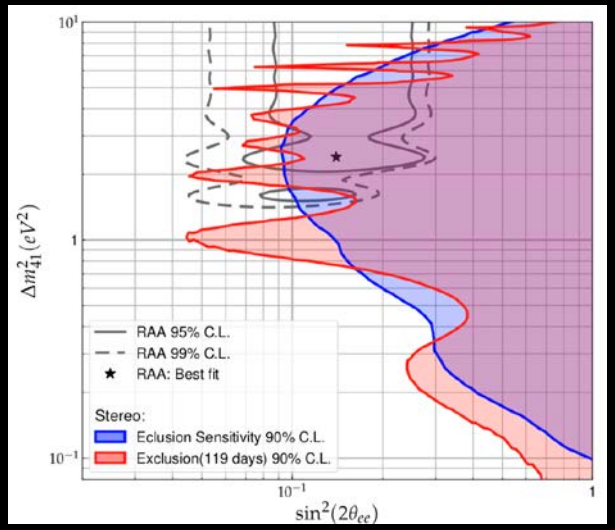
→ 3+1 neutrinos?

STEREO experiment: look for an effect with a segmented detector very close to ILL reactor



Results:





➔ Strong exclusion limits

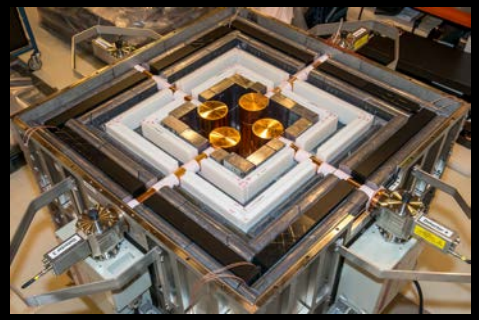
Coherent neutrino scattering

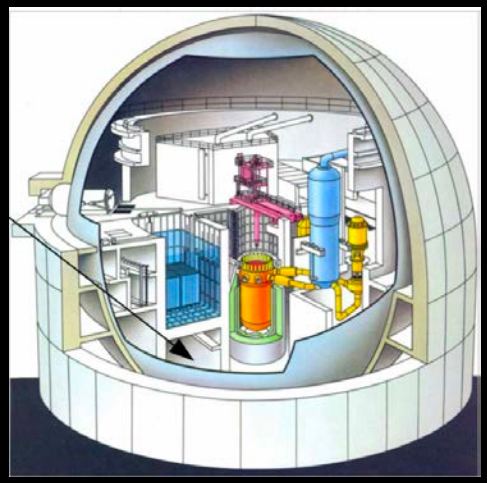
Coherent neutrino scattering predicted 1974 by D.Z.Freedmann

- **Important process**
- **Exciting physics potential:**
  - **Sensitivity to new physics:**
    NSI operators (ν-ν interactions)
    ν magnetic moments
    $\sin^2\theta_W$, at low energies, ...
  - **Understanding nuclear systems:**
    $F(q^2)$ in neutrino light, ...
  - **Connections to dark matter**
  - **cross-sections for nucl. astrophysics**
    supernovae
    BBN, ...
  - **Practical tool**
    monitoring, ...

CEνNS first observed 1917 by COHERENT
with ν's from stopped pion beams
➔ $E_\nu \simeq$ O(50 MeV) ➔ **only partly coherent**

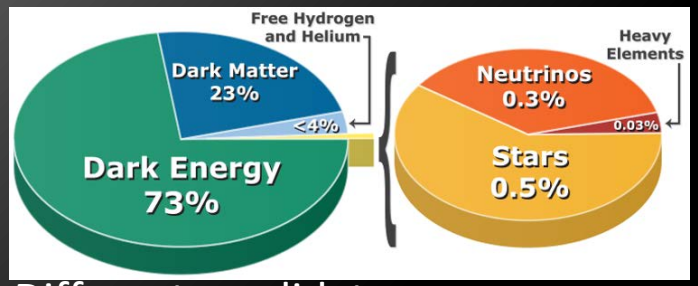
The CONUS experiment:
- 4x1kg low threshold HPGe crystals
- „virtual depth" low backgd shield
- extreme high ν flux
  $E_\nu \simeq$ few MeV ➔ fully coherent
  17 m from core of Brokdorf
  3.9GW ➔ $>10^{14}$ $\nu/(cm^2*s)$





Dark matter

Very strong evidence for the existence of Dark Matter (DM) in the Universe



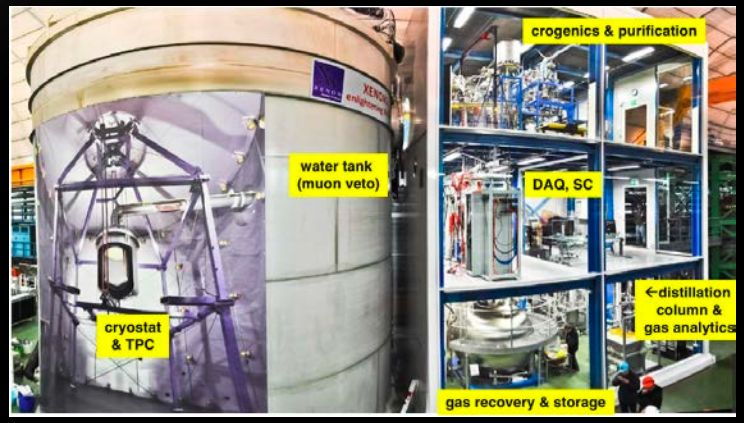
Different candidates

WIMPs are best motivated (←→WIMP miracle)

➔ Important task: directly detect DM

➔ The XENON dark matter program

➔ XENON1T and XENONnT @ Gran Sasso



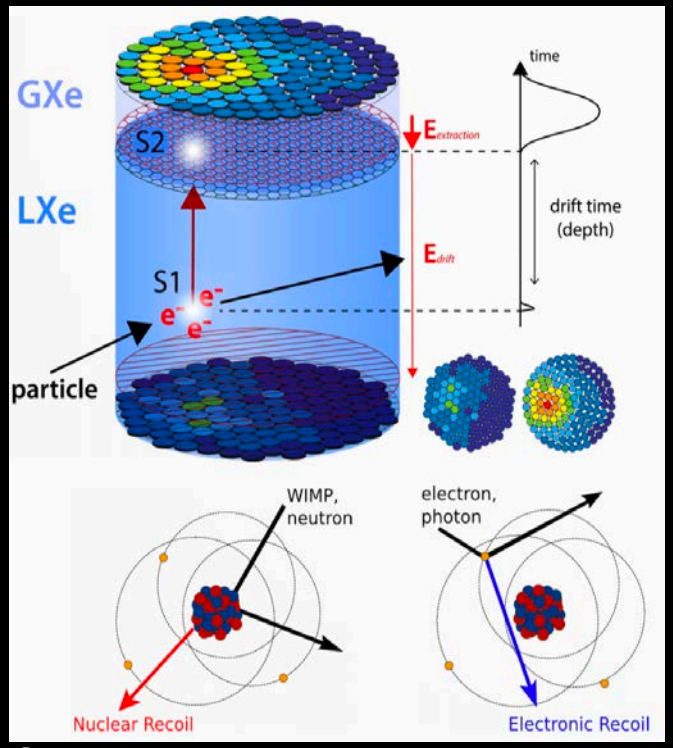
➔ World best limits on WIMPs

➔ TPCs with iquid Xenon

WIMP scatters produce two signals:

S1 = direct light

S2 = light from drift of electron



➔ ultra-pure detector and Xenon gas

E.g. $^{85}Kr/Xe < 10^{-21}$

←→MPIK RGMS system

Theoretical particle & astropartcle physics

Neutrino physics

- 3 flavour oscillations in matter
- GLoBES simulation package
- ν–ν interactions in supernvae
- coherent ν scattering
- ν mass models
- connections to dark matter
- ν-less double β-decay
- sterile ν's
- ...many more

Dark matter:

- dark matter candidates
- Theoretical models
- Implications on BSM physics
- abundance calculations
- thermal and a-thermal production
- ...

Beyond the Standard Model:

- Models of electroweak symmetry breaking
- Unification of forces
- Explanaitions of flavour and parameter regularities
- Conformal extensions of the SM
- Cosmological phase transitions and impact on GR waves
- ...