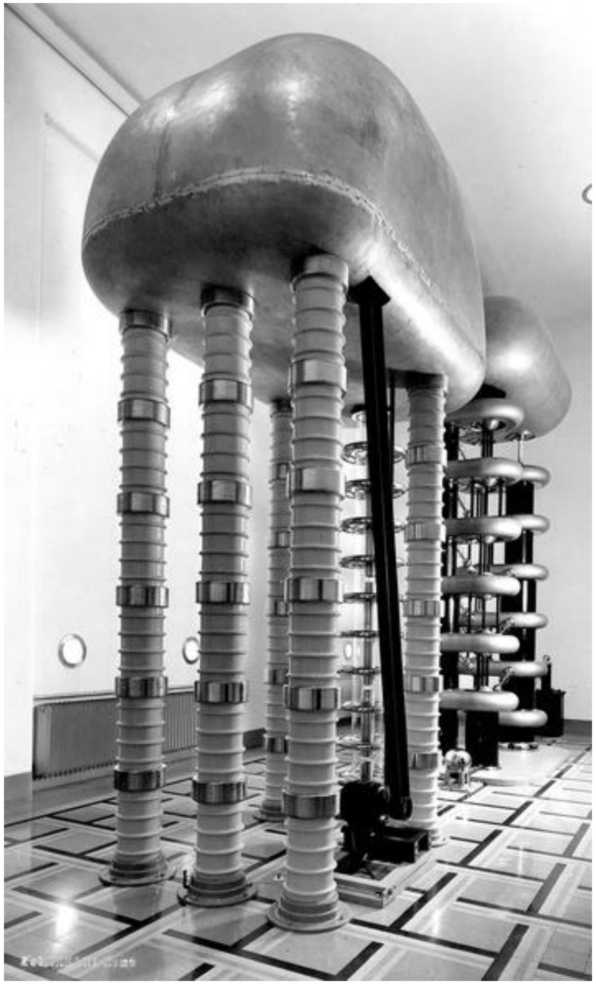
INFN G3 «Experimental Nuclear Physics» Rome

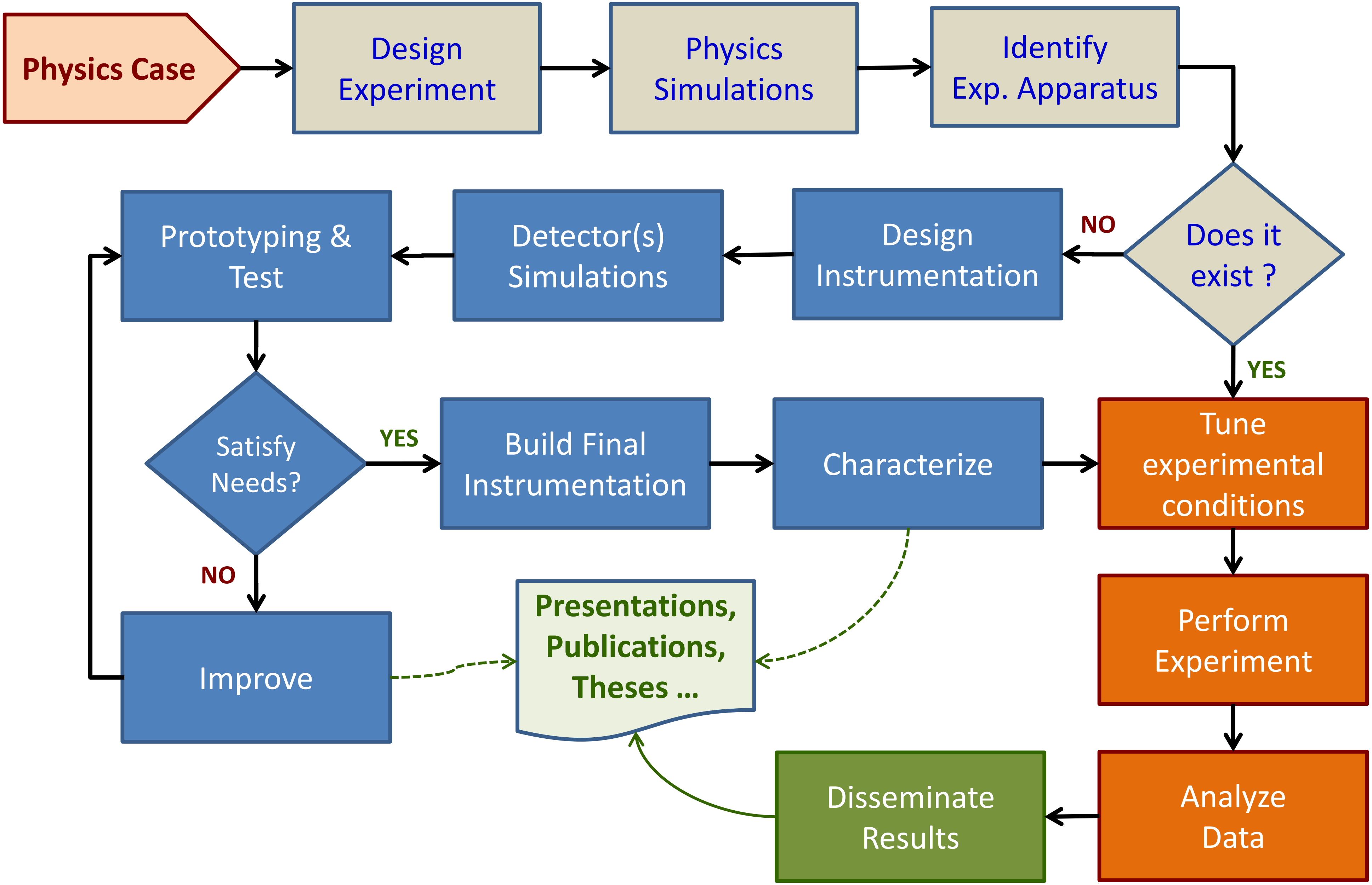
Outline

- ✓ Introduction on CSN3, its research areas and our local experiments
- ✓ Selected topics
  - From Big Bang Nucleosynthesis to Sun
  - Nucleon Dynamics
  - Neutron stars, Parity and Hypernuclei
  - Quark-Gluon Plasma
  - Nuclear fragmentation and hadrontherapy
- ✓ Digression (not so far from main theme)

Evaristo Cisbani
Italian National Institute of Health and INFN-Rome
05/June/2019
Rome



The experimental researcher flow chart



Do no forget: need funds!

INFN CSN3 Research Areas

3rd (out of 5) National Scientific Commission of INFN

http://www.infn.it/csn3/

Use accelerators to investigate nuclear physics processes

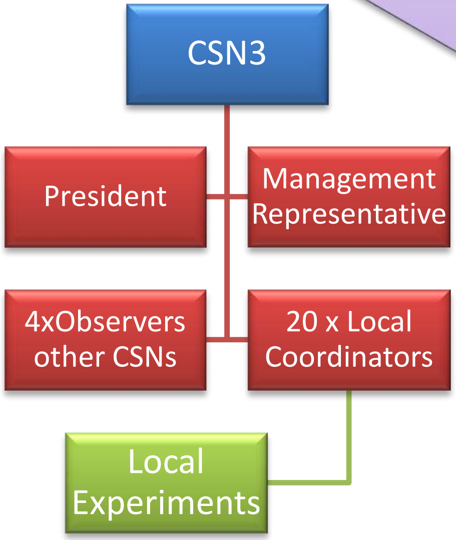
INFN CSN3

Phase Transitions of Nuclear and Hadronic Matter

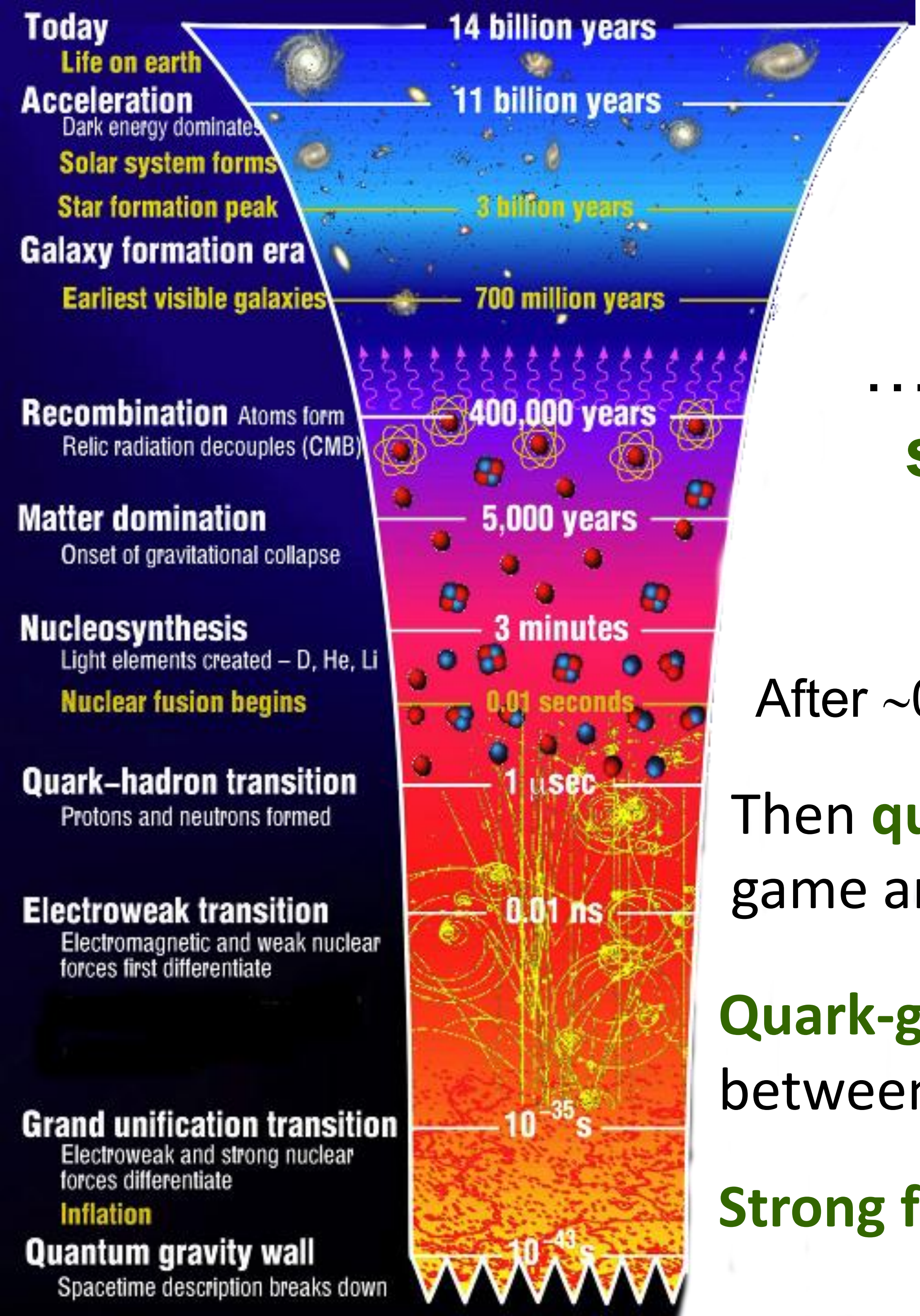
Quarks and Hadrons Dynamics

Nuclear Structure and Reaction Dynamics

Nuclear Astrophysics and Inter-disciplinary Researches



More than 700 researchers involved all over Italy



Universe Evolution

A ~~long~~ swift journey
… a lots of **nuclear** and **sub-nuclear/hadron** physics involved

After ~0.01 s **nucleosynthesis** began

Then **quark confinement** entered the game and **nucleons** got formed

Quark-gluon plasma has dominated between ~0.01 ns and 1 μs

Strong force appeared at ~10^{-36} s

Experiments @ INFN Gruppo3 – Rome

Energy

keV

MeV

GeV

TeV

Laboratory
Underground
Nuclear
Astrophysics

p,α – light nuclei

Astrophysics:
- **Nucleosynthesis**,
- Chemistry of universe,
- Barionic density …

FOOT

Light-medium nuclei fragmentations

Hadrontherapy:
- Treatment plan
- On line dosimetry

Radioprotection in space

MAMiBOnn

γ – p, nuclei reactions

e⁻ JLab12

EIC

γ, e – p, nuclei

QED-QCD interactions

Hadron, nucleon structure and dynamics

Structure of nuclei and neutron stars

Quarks e gluons dynamics (QCD)

ALICE
A JOURNEY OF DISCOVERY

p-p, p-Pb e Pb-Pb

Phase transition in hadronic matter (**quark-gluon plasma**)

Laboratory
Underground
Nuclear
Astrophysics

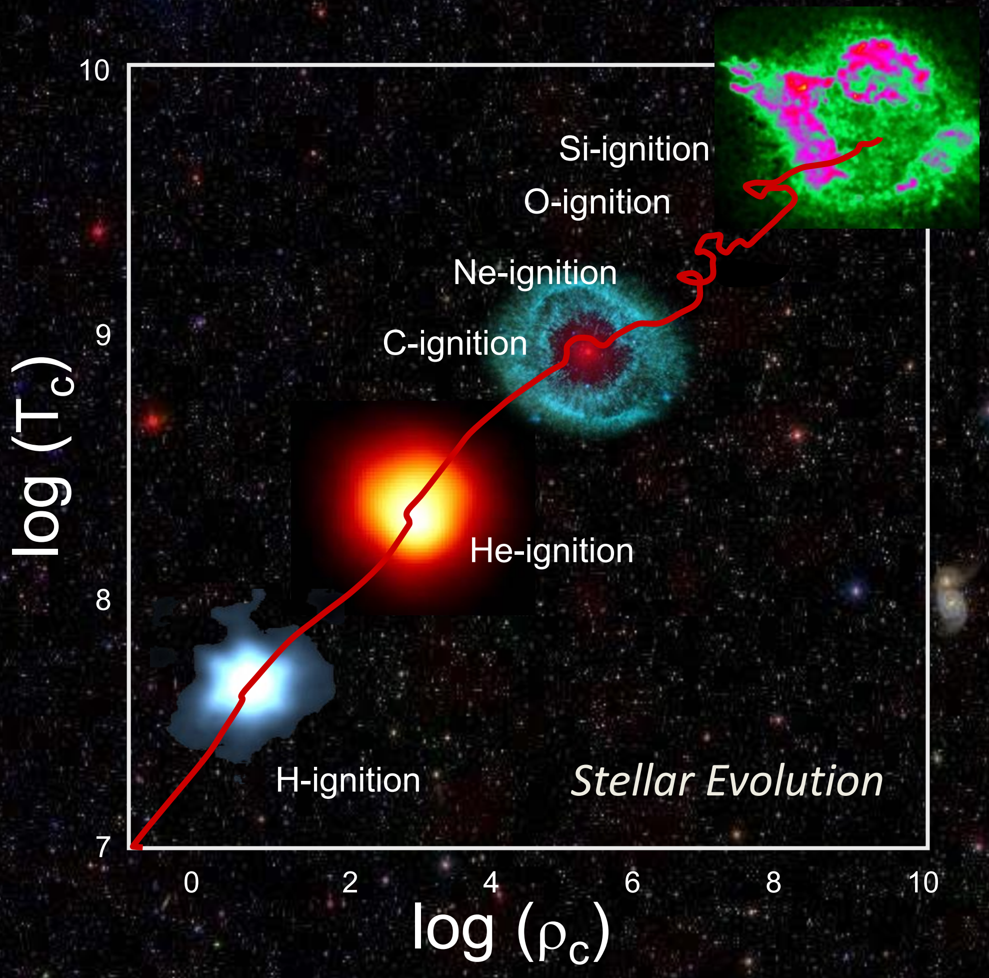
Nuclear Astrophysics
Big Bang Nucleosynthesis (BBN)

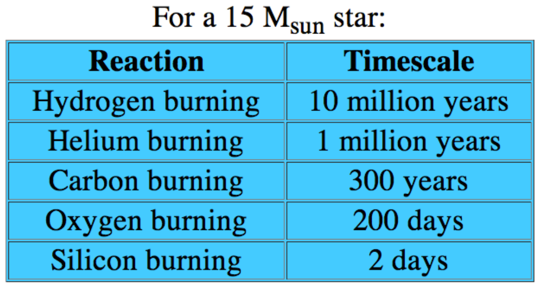
https://luna.lngs.infn.it/

Contact: **Carlo Gustavino**

carlo.gustavino@roma1.infn.it

Why Nuclear astrophysics?



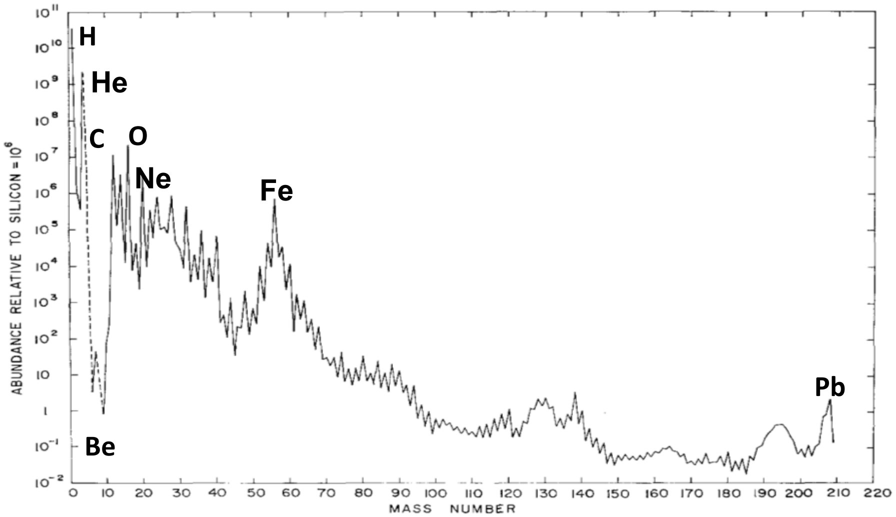


For a 15 M_{sun} star:

Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days

Nuclear reactions are responsible for the **synthesis of the elements in the celestial bodies** and **BBN**.
High precision data are required

- Understanding the Sun (and stars)
- Stellar population
- Evolution and fate of stars
- Big Bang Nucleosynthesis
- Isotopic abundances in the cosmos
- …



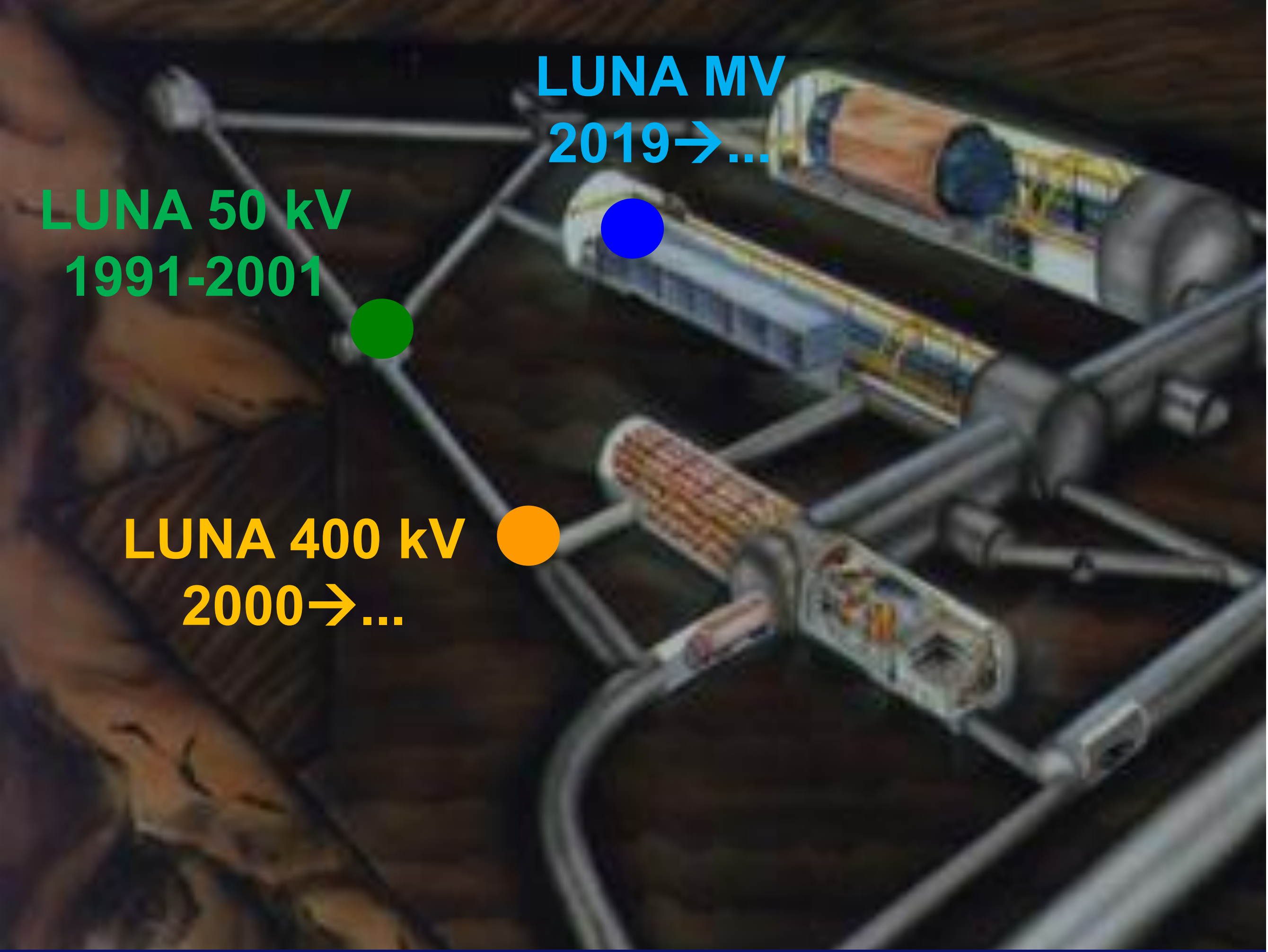
Where is one of the best and peculiar place to study nuclear astrophysics?

Accelerators go deeply underground

Gran Sasso National Laboratories

Laboratory
Underground
Nuclear
Astrophysics

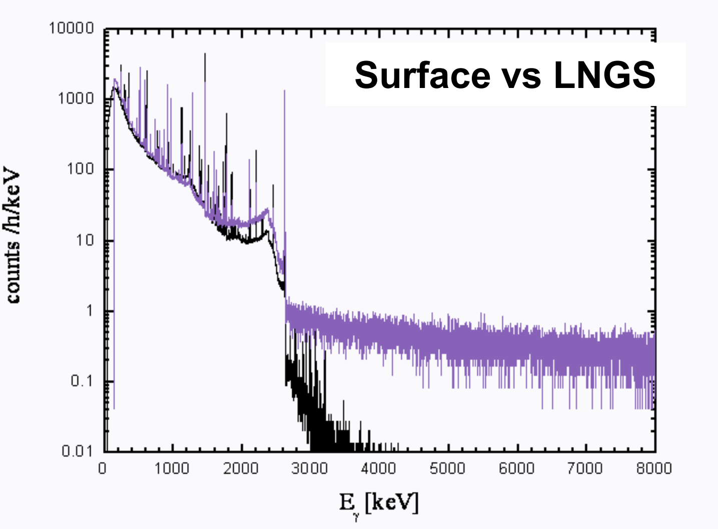
Background reduction with respect to Earth's surface: $\mu \sim 10^{-6}$
$\gamma \sim 10^{-2}$-10^{-5}
neutrons ~10^{-3}

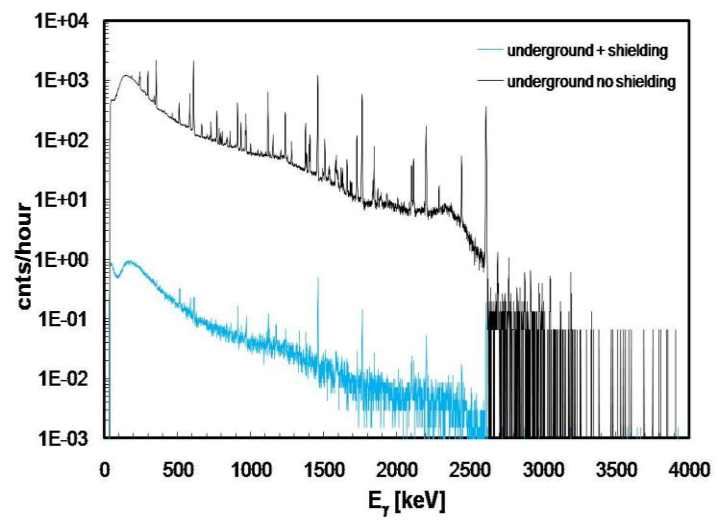


LUNA MV
2019→...

LUNA 50 kV
1991-2001

LUNA 400 kV
2000→...





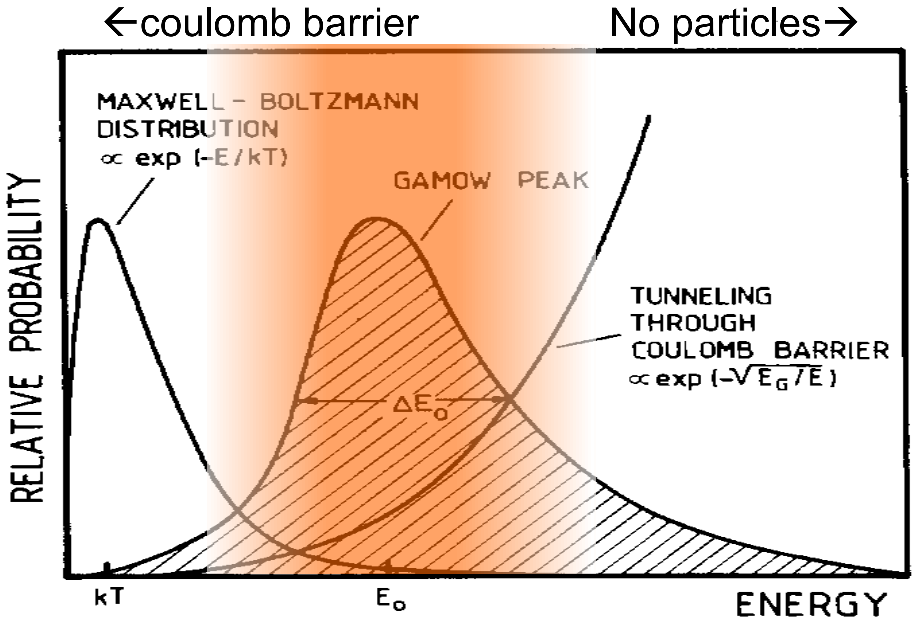
Rome - 05/June/2019

INFN Nuclear Physics Group - Rome

Why Underground Measurements?

Nucleosynthesis fusion processes have **very low cross section** due to the Coulomb barrier and they occurr in the **Gamow Peak** (highest tunneling probability) ➔ Cosmic Radiation is a huge background ➔ **underground accelerator**

←coulomb barrier No particles→



Astrophysical Factor

Tunnel prob. in Coulomb Barrier

$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$

$E_0 \approx 200$ keV

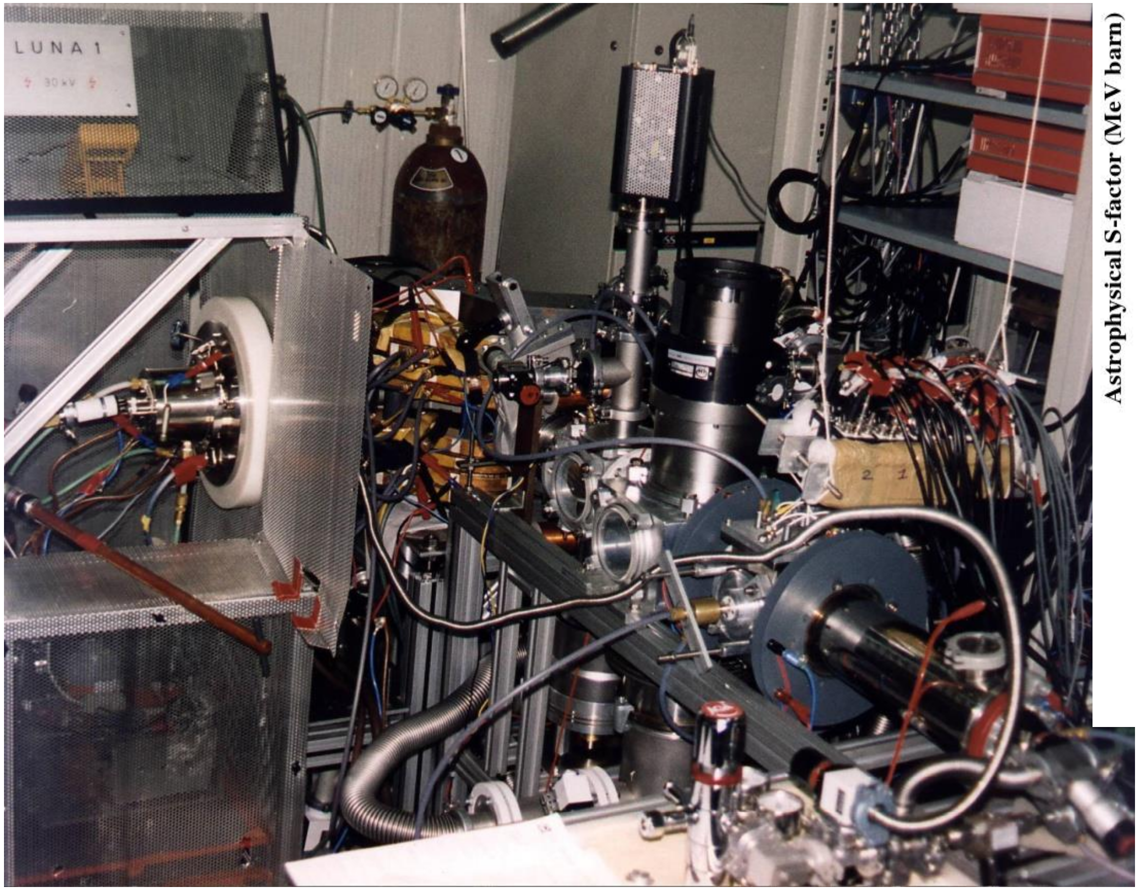
$1/\lambda^2$

LUNA/400 Experiment @ Gran Sasso National Laboratories uses proton/alpha 400 KeV accelerator

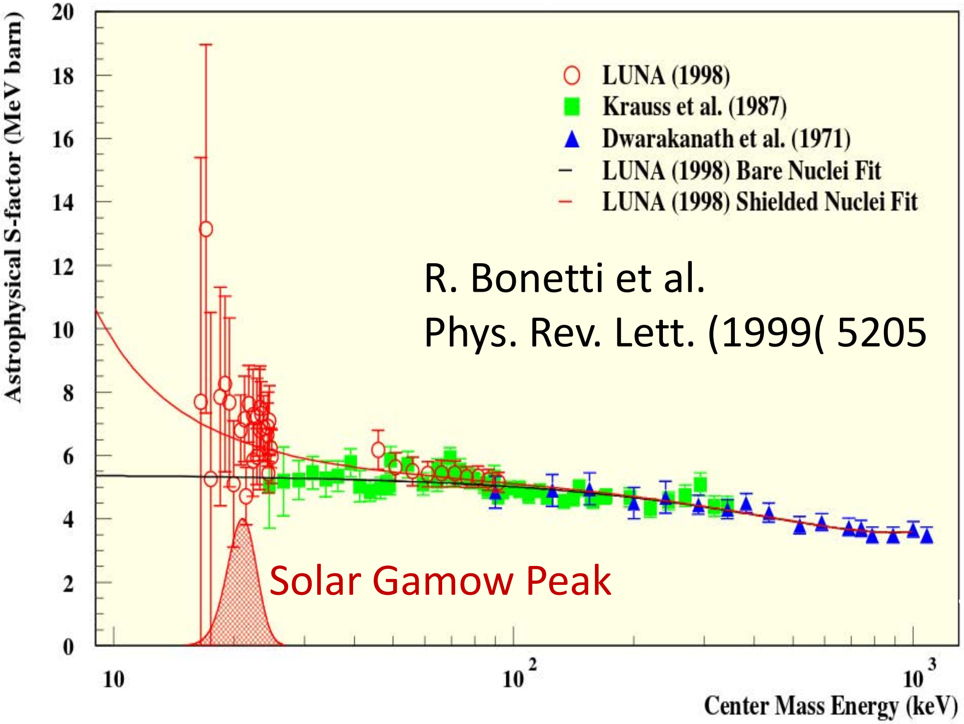
soon LUNA/MV with 1 MeV and heavier ions accelerator!

1991: The birth of underground Nuclear Astrophysics

Thanks to E. Bellotti, C. Rolfs and G. Fiorentini



$^3He(^3He, 2p)^4He$



R. Bonetti et al.
Phys. Rev. Lett. (1999(5205

Solar Gamow Peak

$E_{beam} \approx 1 – 50$ keV

$I_{max} \approx 500\ \mu A$ protons, ^3He

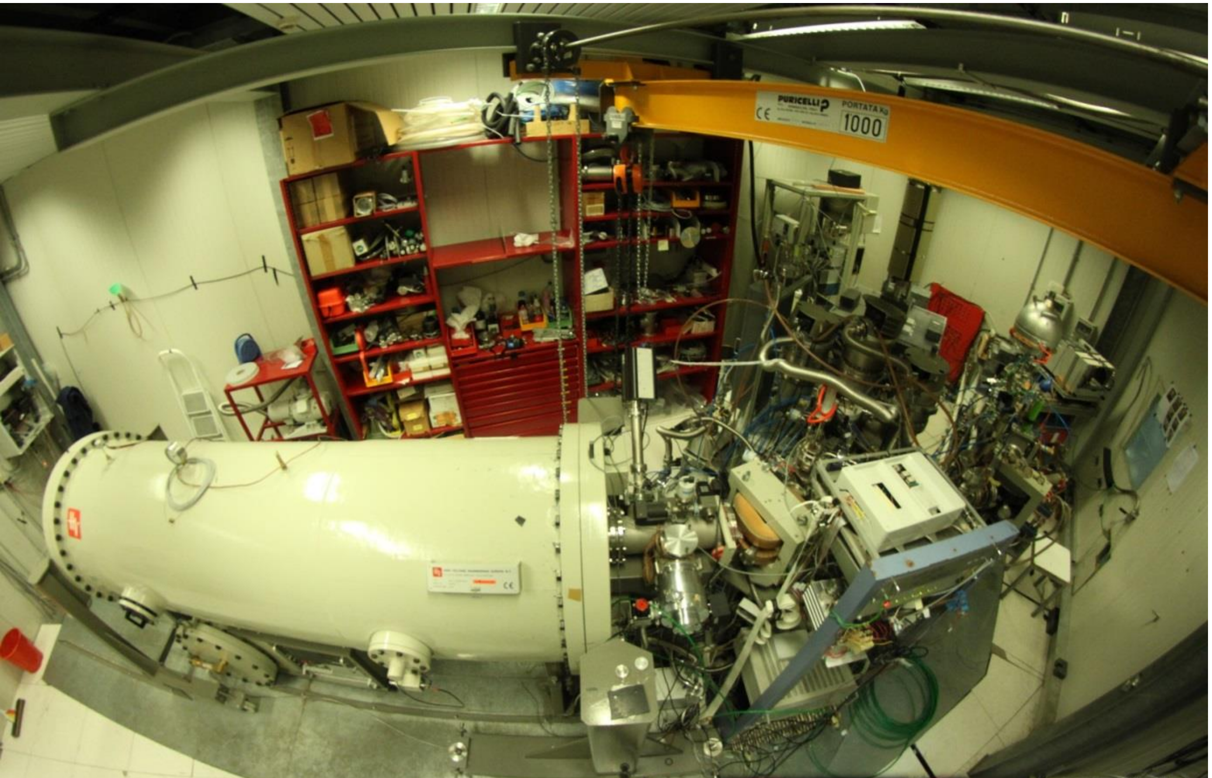
Energy spread ≈ 20 eV

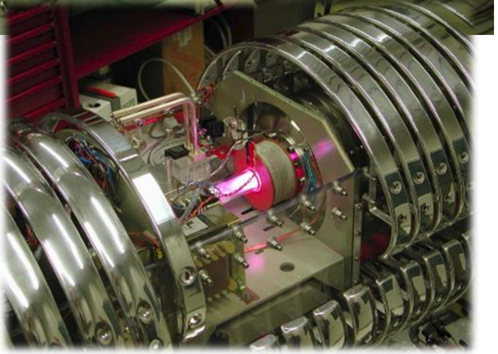
- First measurement below the Gamow peak of a key reaction in p-p chain
- $\sigma(16.5\ keV)=20\pm10$ fb →2 events/month
- No evidence for a narrow resonance → SSM valid → neutrino oscillations

LUNA 400 kV @ LNGS

Still the world's only operating **underground accelerator**

Laboratory
Underground
Nuclear
Astrophysics



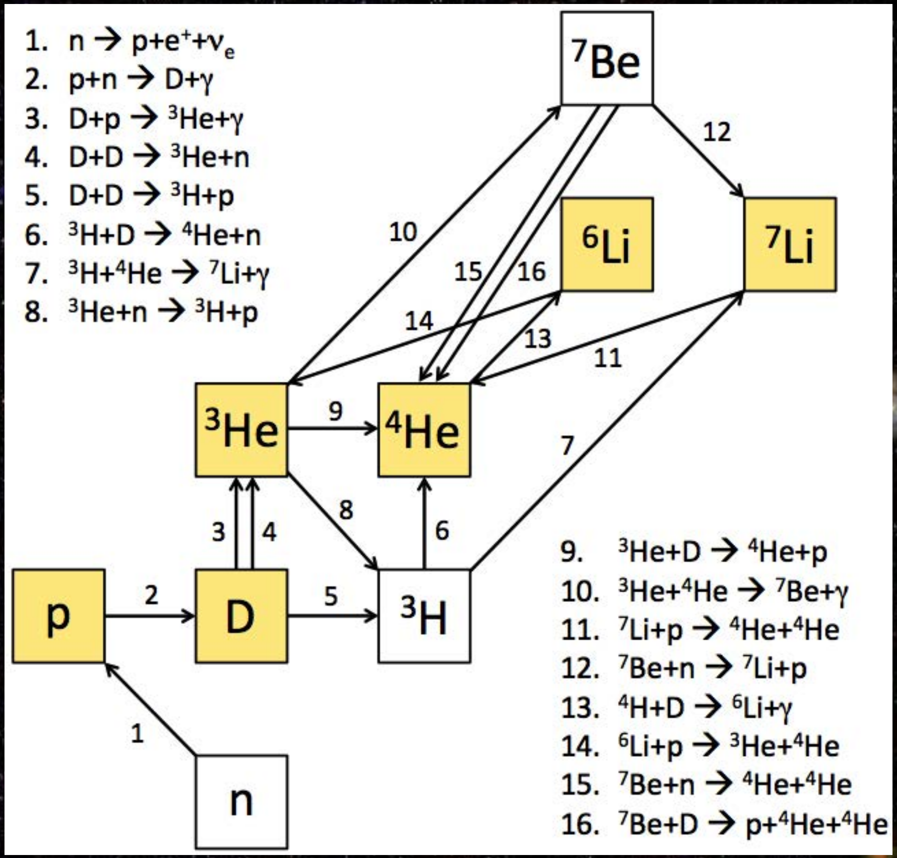


$E_{beam} \approx 50 – 400$ keV
$I_{max} \approx 300\ \mu A$ protons,^{4}He
Energy spread ≈ 70 eV

- $^{14}N(p,\gamma)^{15}O$ (CNO-I cycle)
- $^{3}He(^{4}He,\gamma)^{7}Be$ (Sun, BBN)
- $^{25}Mg(p,\gamma)^{26}Al$ (Mg-Al Cycle)
- $^{15}N(p,\gamma)^{16}O$ (CNO-II Cycle)
- $^{17}O(p,\gamma)^{18}F$ (CNO-III Cycle)
- $^{2}H(^{4}He,\gamma)^{6}Li$ (BBN)
- $^{22}Ne(p,\gamma)^{23}Na$ (Ne-Na Cycle)
- $^{2}H(p,\gamma)^{3}He$ (BBN)
- $^{13}C(\alpha,n)^{16}O$ (s-process)
- $^{12,13}C(p,\gamma)^{13,14}N$ ($^{12}C/^{13}C$ ratio)
- $^{22}Ne(\alpha,\gamma)^{23}Na$ (s-process)
- …

Big Bang Nucleosynthesis

BBN is the result of the competition between the relevant **nuclear processes** and the **expansion rate of the early universe** (0.01 s – 3 m):



1. n → $p+e^+ + \nu_e$
2. p+n → D+γ
3. D+p → ^{3}He+γ
4. D+D → ^{3}He+n
5. D+D → ^{3}H+p
6. ^{3}H+D → ^{4}He+n
7. ^{3}H+^{4}He → ^{7}Li+γ
8. ^{3}He+n → ^{3}H+p
9. ^{3}He+D → ^{4}He+p
10. ^{3}He+^{4}He → ^{7}Be+γ
11. ^{7}Li+p → ^{4}He+^{4}He
12. ^{7}Be+n → ^{7}Li+p
13. ^{4}H+D → ^{6}Li+γ
14. ^{6}Li+p → ^{3}He+^{4}He
15. ^{7}Be+n → ^{4}He+^{4}He
16. ^{7}Be+D → p+^{4}He+^{4}He

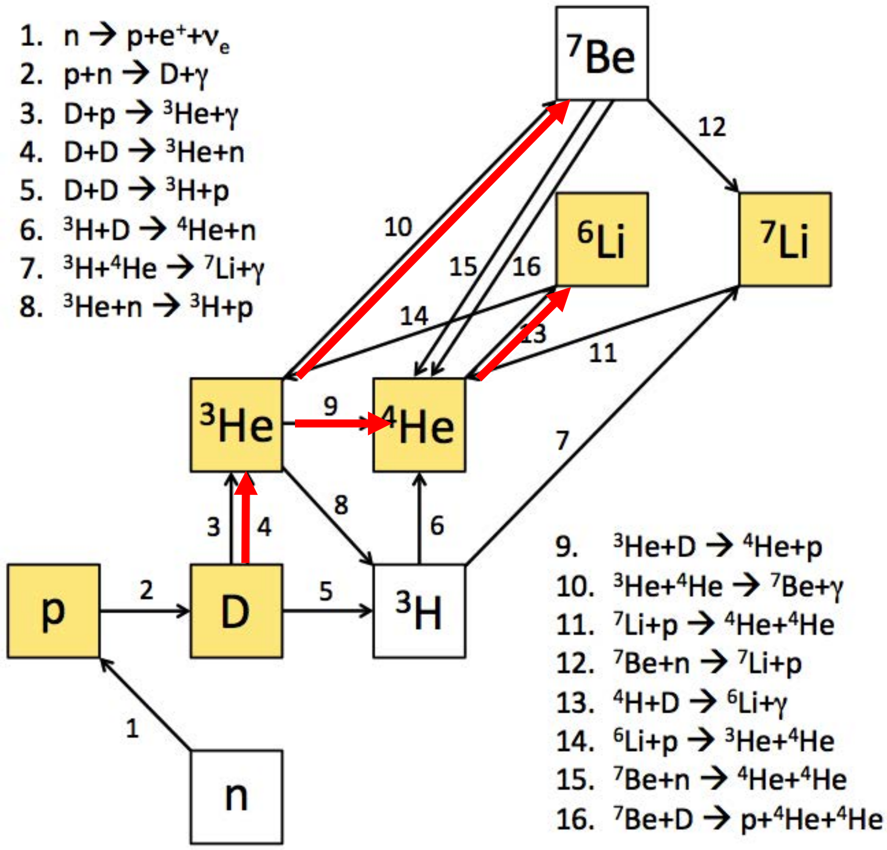
$$H^2 = \frac{8\pi}{3} G\rho$$

$$\rho = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \boxed{N_{\mathrm{eff}}}\right)$$

Calculation of primordial abundances depends on:

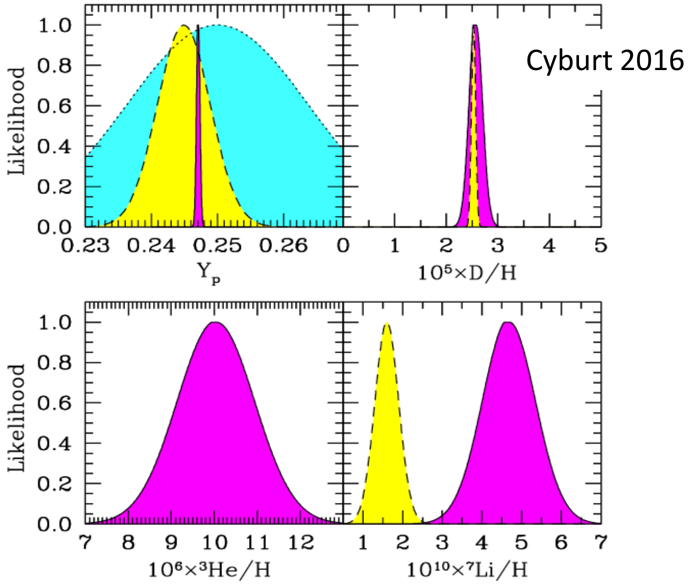
- Baryon density Ω_b
- Particle Physics (N_{eff}, α..)
- Nuclear Astrophysics, i.e. Cross sections of relevant processes at BBN energies

Theory Vs observations



1. $n \rightarrow p+e^+ + \nu_e$
2. $p+n \rightarrow D+\gamma$
3. $D+p \rightarrow {}^3He+\gamma$
4. $D+D \rightarrow {}^3He+n$
5. $D+D \rightarrow {}^3H+p$
6. ${}^3H+D \rightarrow {}^4He+n$
7. ${}^3H+{}^4He \rightarrow {}^7Li+\gamma$
8. ${}^3He+n \rightarrow {}^3H+p$
9. ${}^3He+D \rightarrow {}^4He+p$
10. ${}^3He+{}^4He \rightarrow {}^7Be+\gamma$
11. ${}^7Li+p \rightarrow {}^4He+{}^4He$
12. ${}^7Be+n \rightarrow {}^7Li+p$
13. ${}^4H+D \rightarrow {}^6Li+\gamma$
14. ${}^6Li+p \rightarrow {}^3He+{}^4He$
15. ${}^7Be+n \rightarrow {}^4He+{}^4He$
16. ${}^7Be+D \rightarrow p+{}^4He+{}^4He$

Isotope	BBN Theory	Observations
Yp (^{4}He)	**0.24771±0.00014**	**0.254±0.003**
D/H	**$(2.41\pm0.05)\times10^{-5}$**	**$(2.53\pm0.03)\times10^{-5}$**
^{3}He/H	**$(1.00\pm0.01)\times10^{-5}$**	**$(0.9\pm1.3)\times10^{-5}$**
! **^{7}Li/H**	**$(4.68\pm0.67)\times10^{-10}$**	**$(1.23^{+0.68}_{-0.32})\times10^{-10}$**
^{6}Li/^{7}Li	**$(1.5\pm0.3)\times10^{-5}$**	**<~10^{-2}**



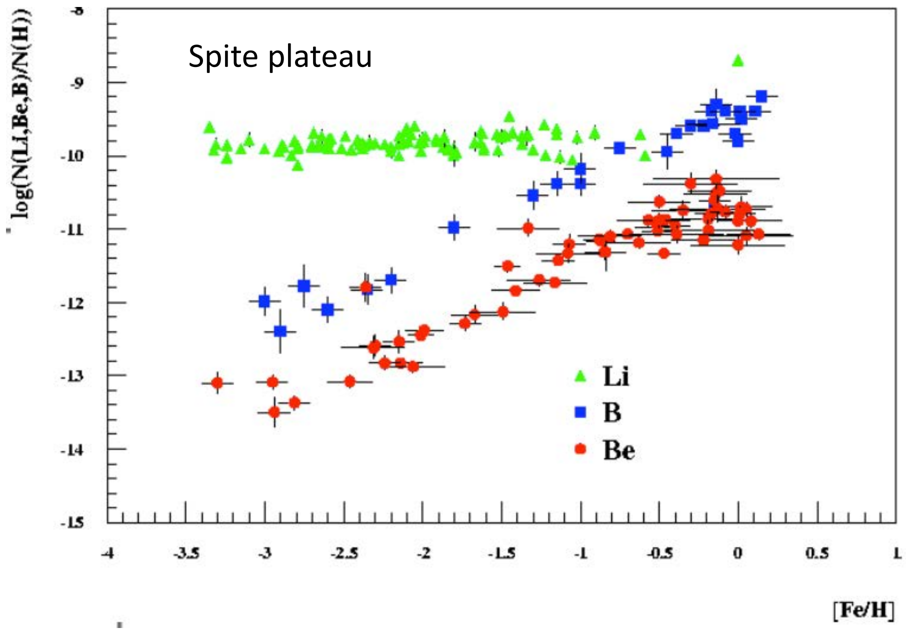
^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.

^{7}Li: Long standing "Lithium problem"

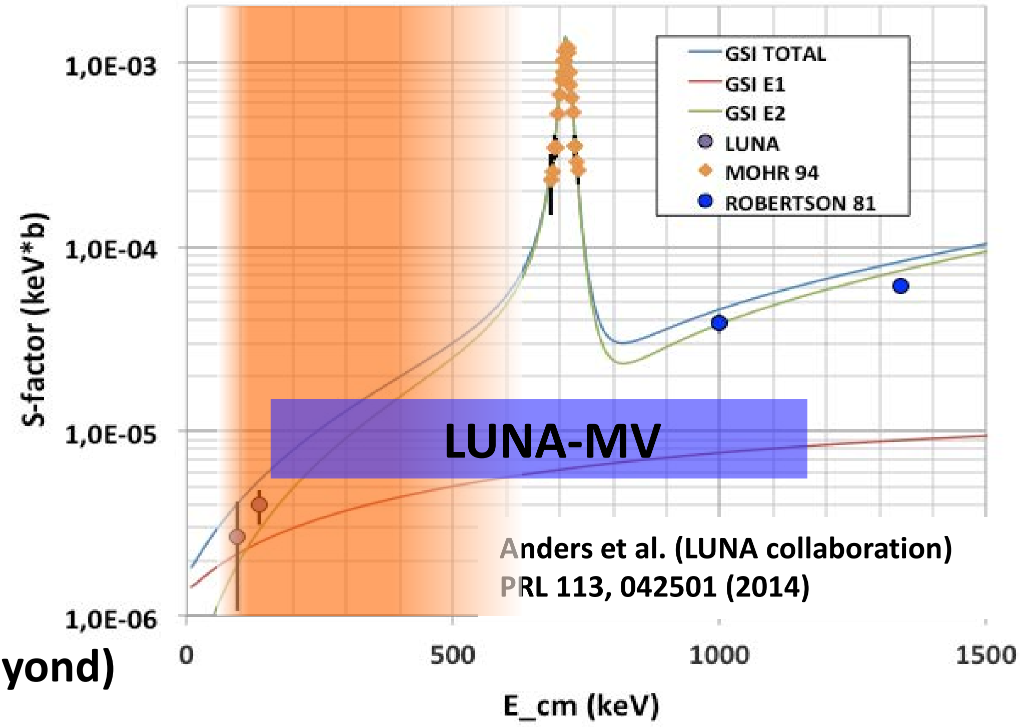
^{6}Li: "Second Lithium problem"?

The Lithium problem(s)

- Observed ^{7}Li abundance is about 3 times lower than foreseen: Well established "Lithium problem".
- Debated claim of a huge abundance of ^{6}Li (Asplund2006).



- Systematics in the measured ^{7}Li, ^{6}Li and abundances in the metal-poor stars of our Galaxy.
- Unknown processes before the birth of the galaxy
- New physics, e.g. sparticle annihilation/decay (Jedamzik2008), long lived negatively charged particles (Kusakabe2010)
- **…Nuclear physics, i.e. the lack of knowledge of the relevant nuclear reactions.**



Anders et al. (LUNA collaboration)
PRL 113, 042501 (2014)

Important opportunity for LUNA-MV (2019 and beyond)

D(p,γ)^{3}He reaction @ LUNA400

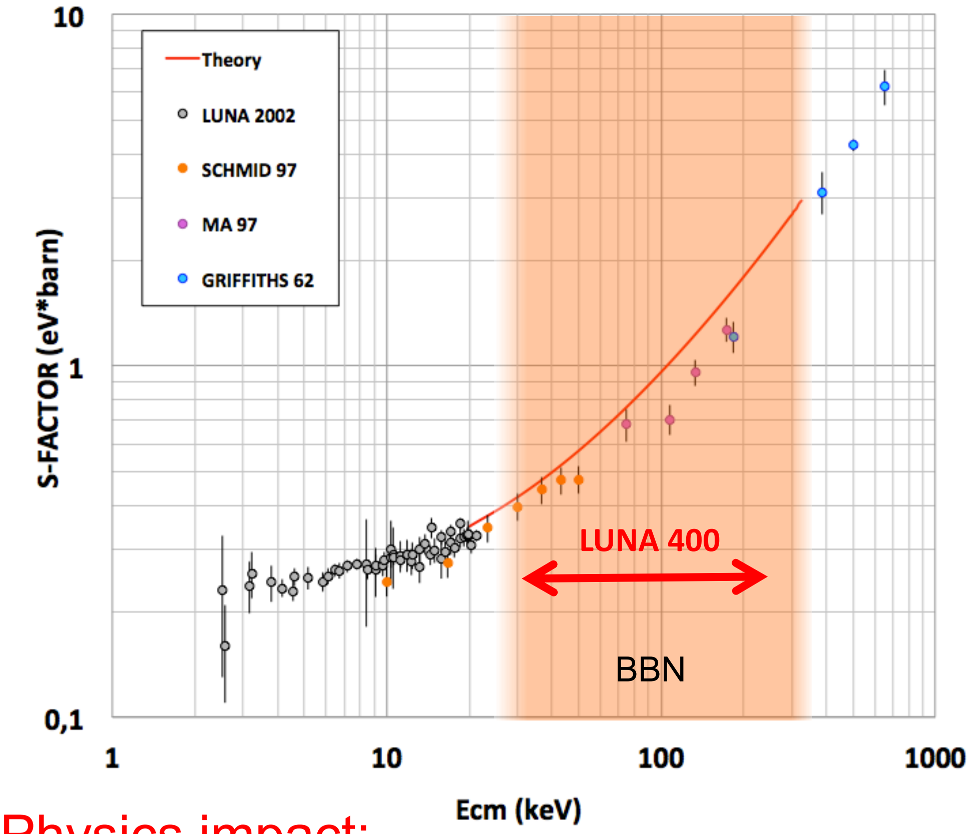
Reaction	Rate Symbol	$\sigma_{^2\mathrm{H/H}} \cdot 10^5$
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062
$d(d,n)^3\mathrm{He}$	R_3	± 0.020
$d(d,p)^3\mathrm{H}$	R_4	± 0.013

(Di Valentino, C.G. et al. 2014)

- The error budget of computed abundance of deuterium is mainly due to the D(p,γ)^{3}He reaction
- Measurements (9% error) NOT in agreement with recent “Ab-Initio” calculations.

Measurement goal:

- Cross section measurement at 30<E_{cm}(keV)<260 with ~ 3% accuracy
- Differential cross section measurement at 100<E_{cm}<260

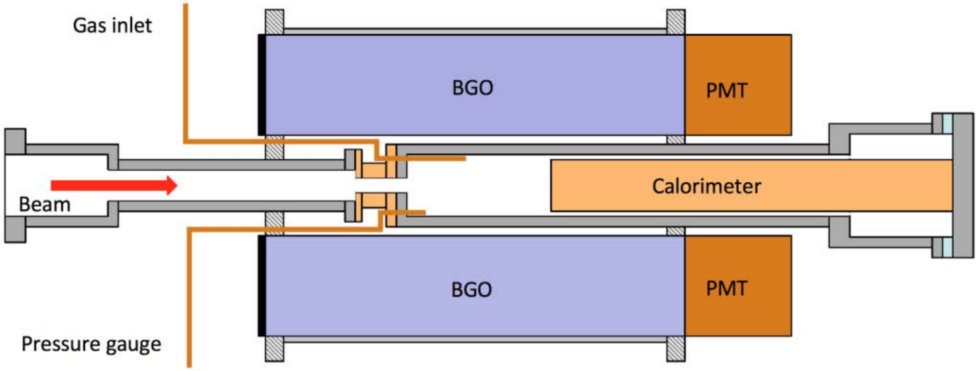


Physics impact:

- *Cosmology: measurement of Ω_b.*
- *Neutrino physics: measurement of N_{eff}.*
- *Nuclear physics: comparison of data with “ab initio” predictions.*

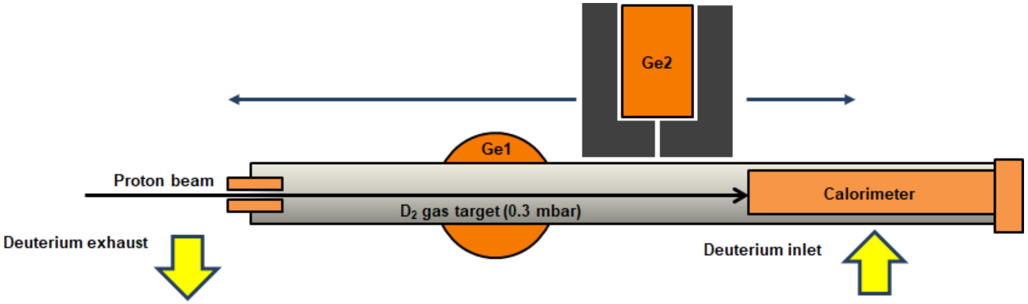
D(p,γ)^{3}He reaction: setup

High efficiency (~60%, ~4π acceptance)



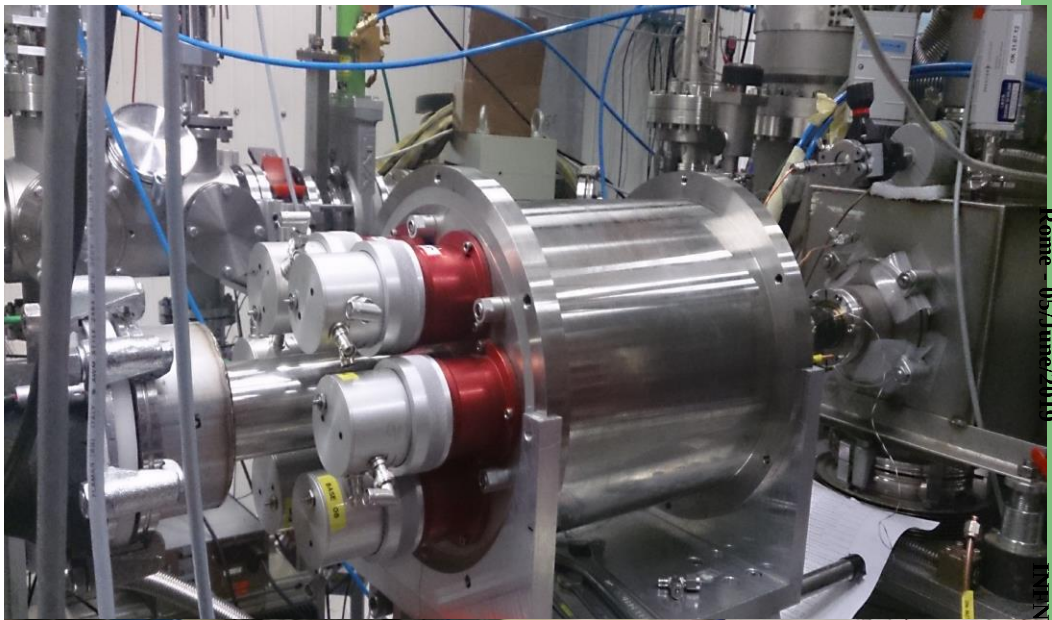
BGO scintillators

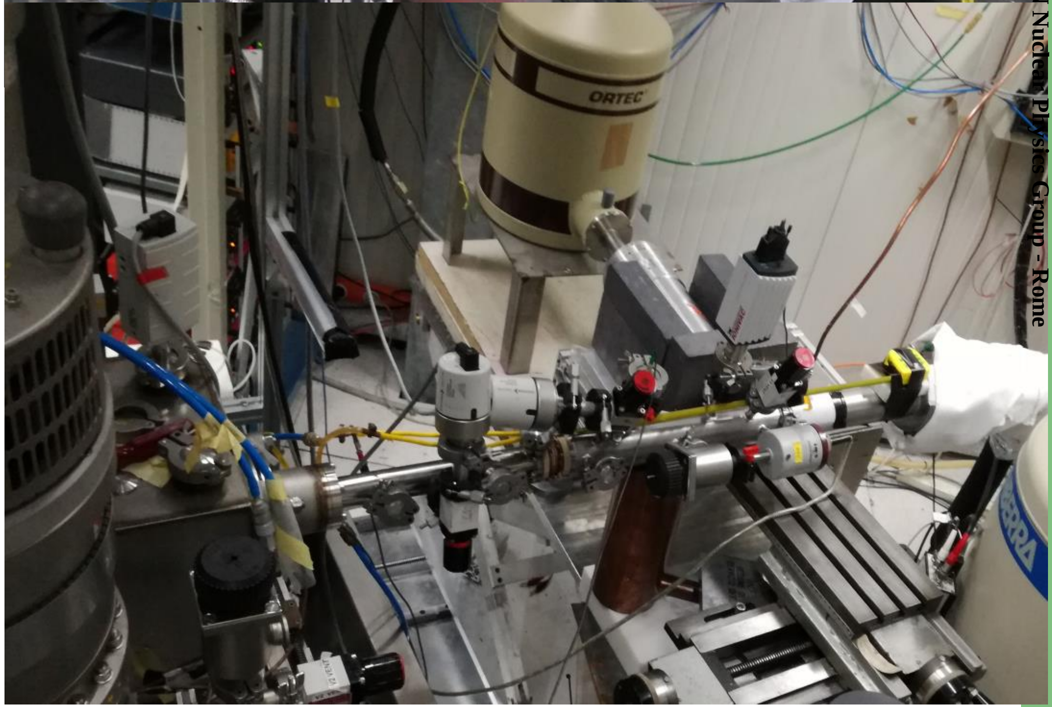
High energy resolution (~10 keV @ 6 MeV)



2 x Ge(Li) sensors

- **Tabletop setup**
- **Need very accurate calibration**





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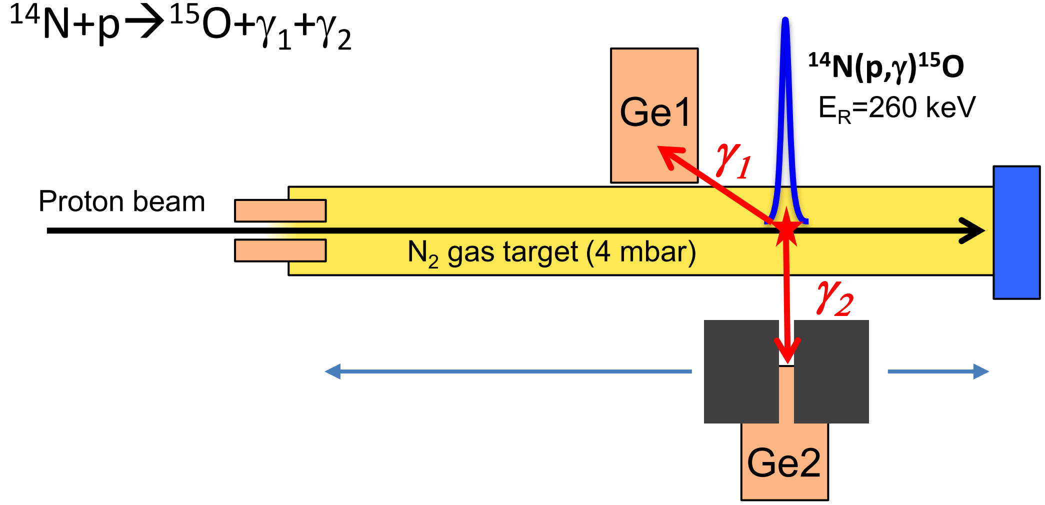
Systematics: efficiency

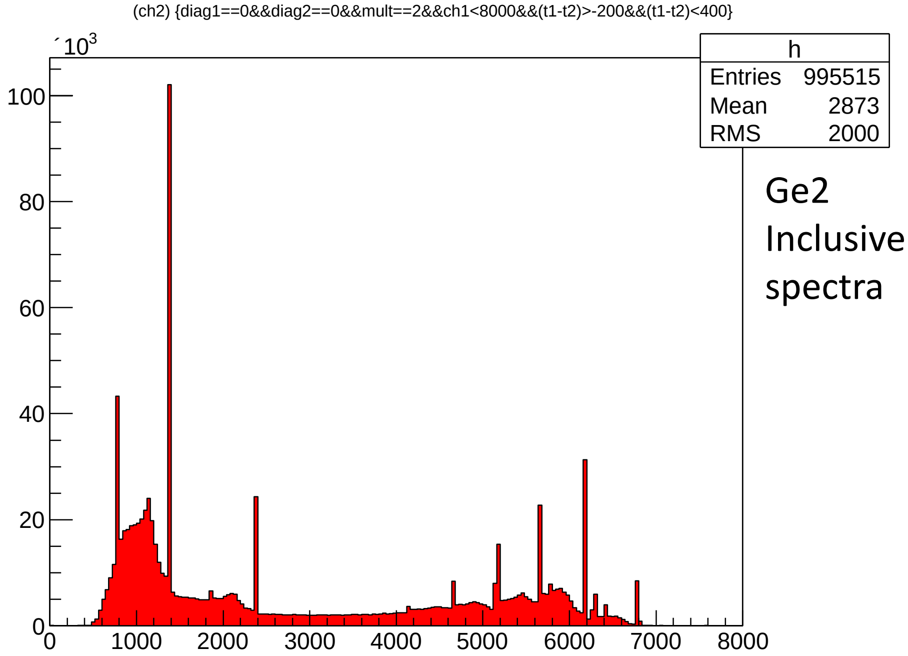
$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot I_{beam} \cdot \rho(z) \cdot \boxed{\varepsilon(z)}} W(\vartheta\,(z))\,dz$$

HPGe Source	Method
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement
DETECTOR EFFICIENCY	Calibration with ^{14}N(p,g)^{15}O reaction
ANGULAR DISTRIBUTION	Peak Shape Analysis

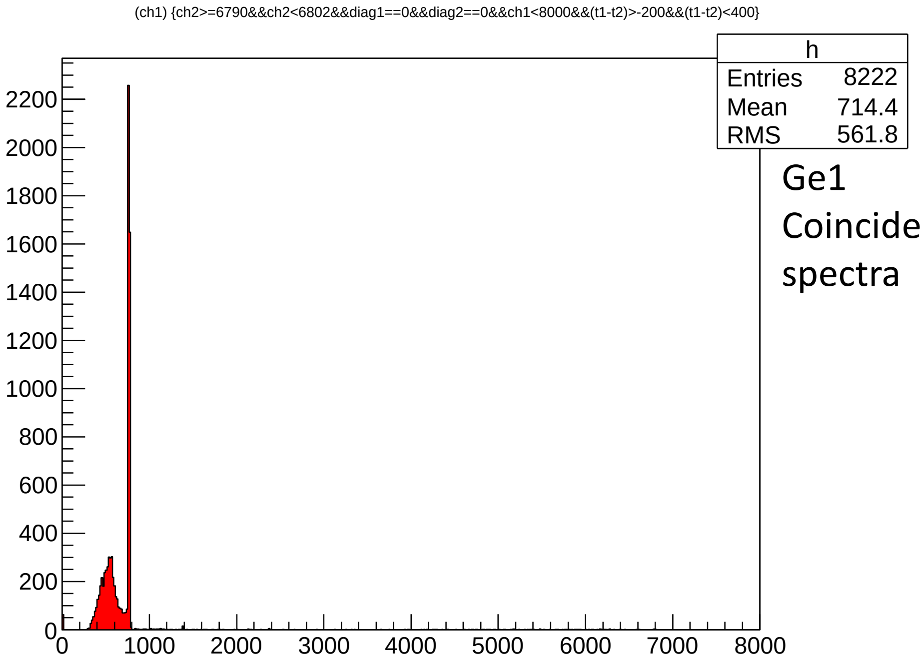
Calibration exploiting the reaction:

$^{14}N+p \rightarrow {}^{15}O+\gamma_1+\gamma_2$





Ge2
Inclusive
spectra

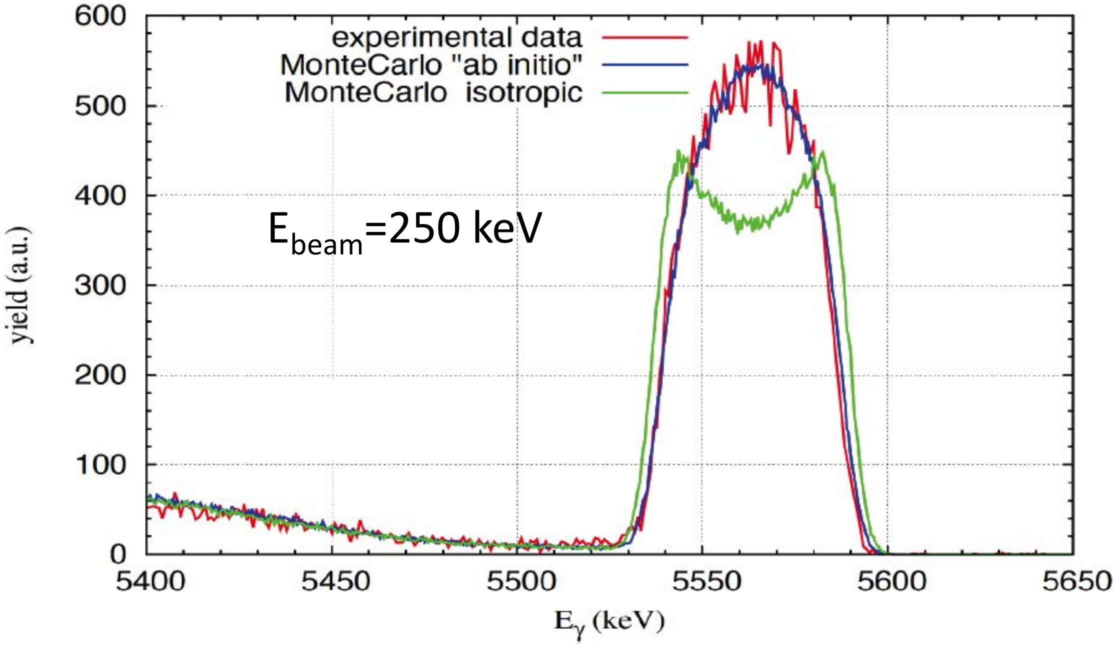


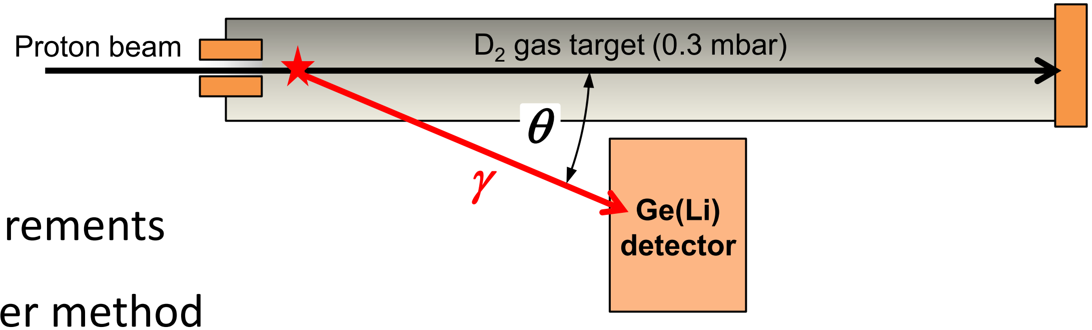
Ge1
Coincidence
spectra

Systematics: Angular Distribution

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot I_{beam} \cdot \rho(z) \cdot \varepsilon(z)} \boxed{W(\vartheta(z))}\, dz$$

HPGe Source	Method
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement
DETECTOR EFFICIENCY	Calibration with ^{14}N(p,g)^{15}O reaction
ANGULAR DISTRIBUTION	Peak Shape Analysis





Moreover:

- Beam induced background →Dedicated measurements
- Instrumental bias (dead time, pile-up,..) →Pulser method
- Energy loss→Ziegler formulae/direct measurements
- Detailed simulation to correct second order effects

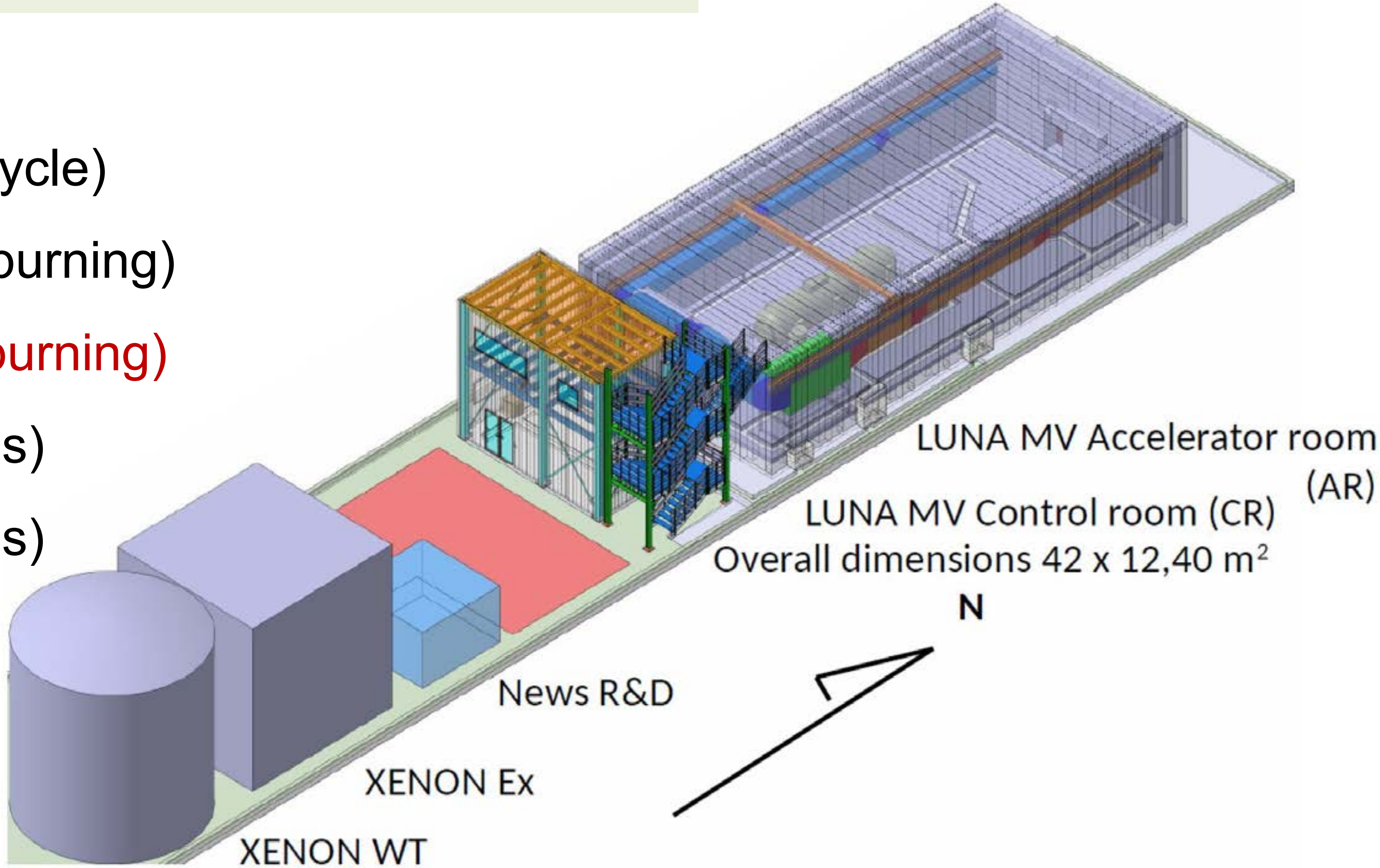
$$\boxed{E_\gamma} = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p m_d}{2(E_p + m_d + p_p \boxed{\cos(\vartheta_{lab}))}}$$

Next: LUNA MV

First run scheduled in June 2020

Starting program:

$^{14}N(p,\gamma)^{15}O$	(CNO I Cycle)
$^{12}C+^{12}C$	(Carbon burning)
$^{12}C(\alpha,\gamma)^{16}O$	(Helium burning)
$^{13}C(\alpha,n)^{16}O$	(s-process)
$^{22}Ne(\alpha,n)^{25}Mg$	(s-process)

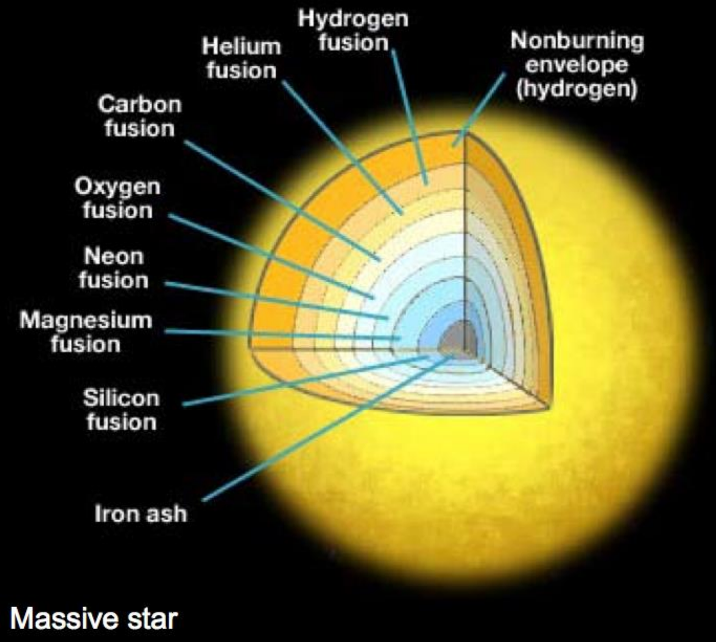


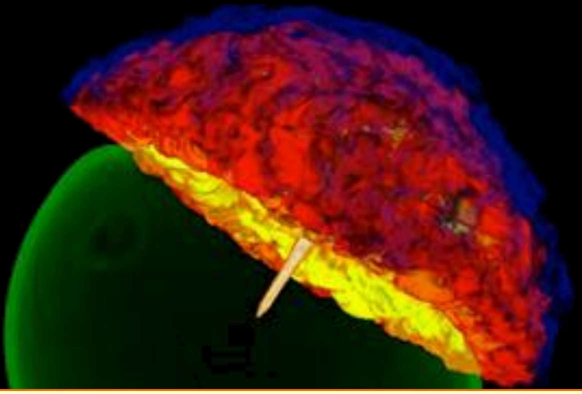
Terminal Voltage ≈ 0.2 – 3.5 MV

$I_{max} \approx$ 100-1000 μA protons, ^{4}He, $^{12}C^{+}$, $^{12}C^{++}$

An experimental apparatus and an LNGS facility

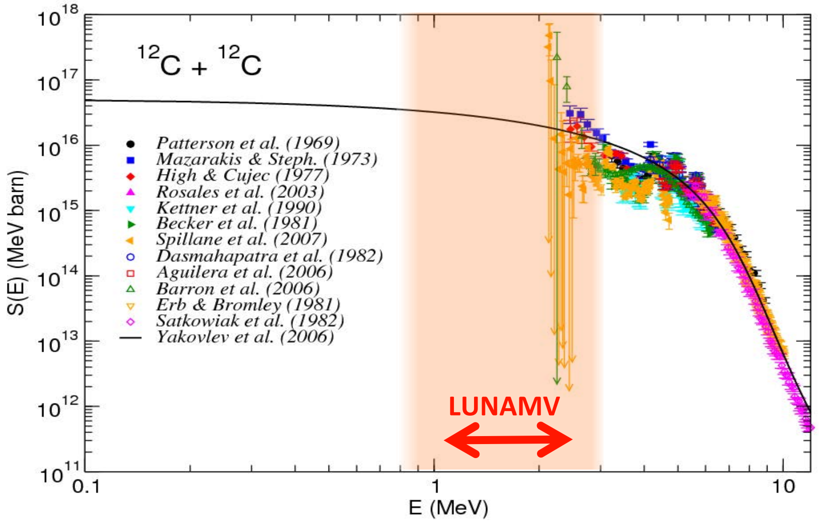
Carbon Burning & Type Ia supernovae





- Critical mass for the fate of a star
- Population of WD, novae, SN1a←→ SN, NS, BH.
- Duration of quiescent carbon burning
- Complex chains involving C→Si nuclei
- Affects s-process
- Strongly affects the abundance of elements
- Type 1a supernovae outcomes

$$\begin{aligned} {}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\ {}^{4}He \\ &\rightarrow {}^{20}Ne +{}^{4}He \\ &\rightarrow {}^{23}Na + p^{+} \\ &\rightarrow {}^{23}Mg + n \\ &\rightarrow {}^{24}Mg + \gamma \end{aligned}$$



Interested in Nuclear Astrophysics ?
Contact Carlo Gustavino
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The italian collaboration
@ JLab

e$^-$ JLab12

Nucleon structure/dynamics ← **QCD**
Neutron Star, parity and hypernuclei
Dark Matter Search

https://www.ge.infn.it/jlab12/

Contact People:
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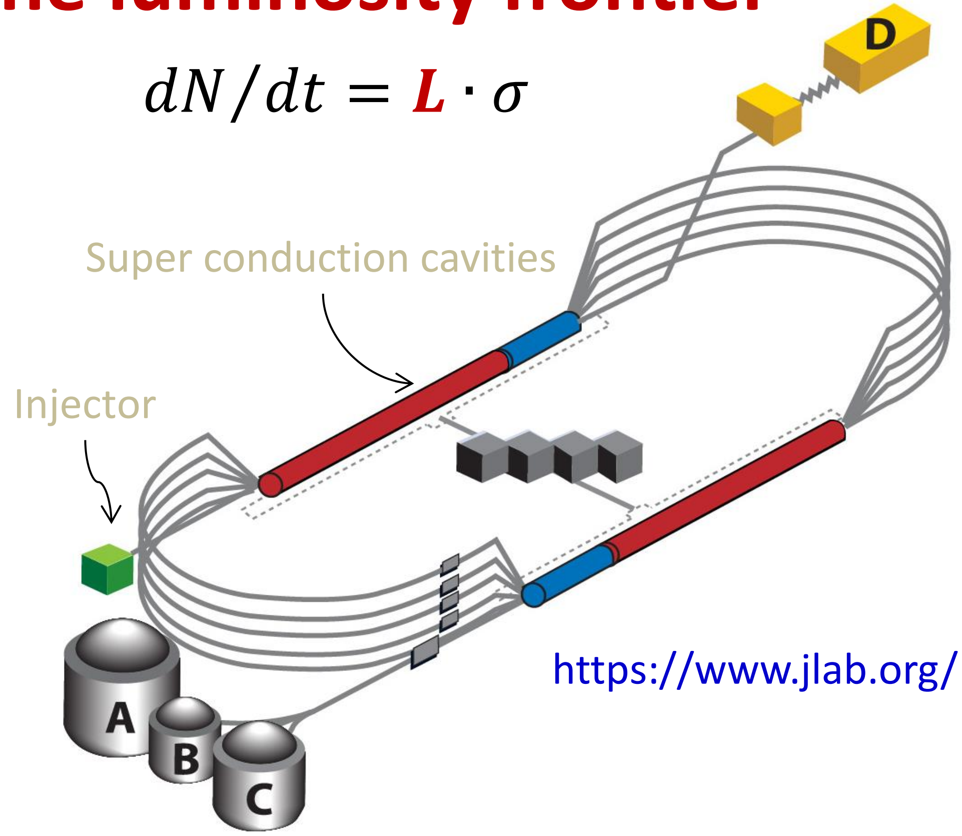
The italian collaboration @ JLab

e⁻JLab12

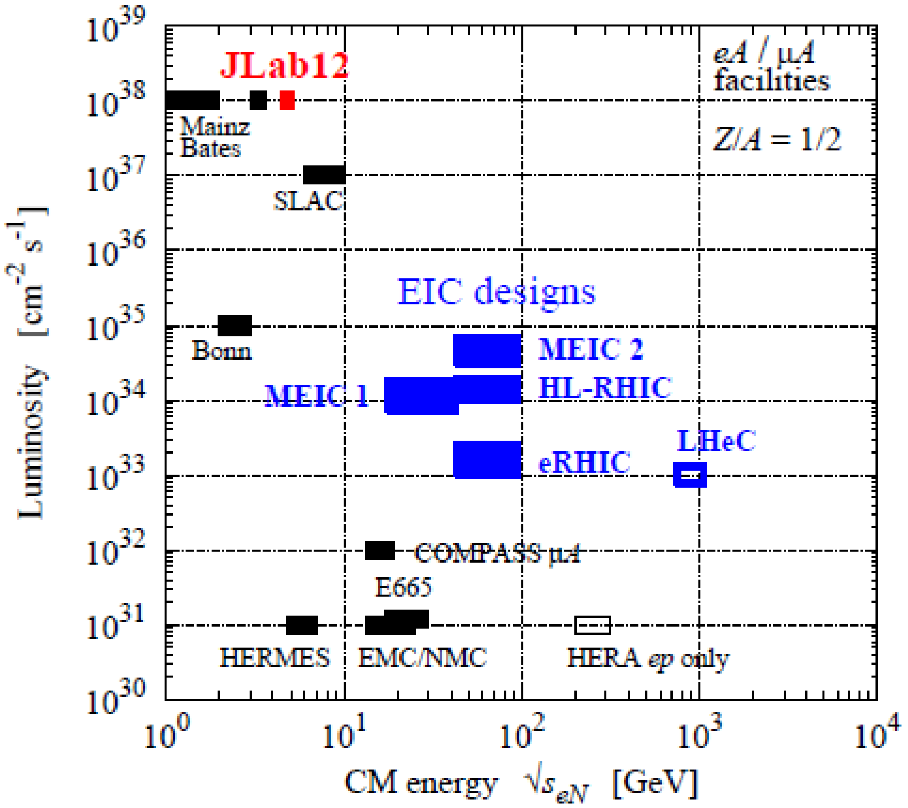
At the luminosity frontier

$$dN/dt = \boldsymbol{L} \cdot \sigma$$

CEBAF Linear electron accelerator
T. Jefferson National Laboratory
(Virginia/USA)



https://www.jlab.org/



- *Energy up to* ***12 GeV*** with $\delta E/E \sim 10^{-4}$
- *Emittance:* ~ few nm-rad
- *Polarized beam:* long. **~ 85%** (1kHz helicity flip)
- *Current* $\le$ ***100*** $\boldsymbol{\mu A}$ 100% duty factor (CW, 499 MHz)
- *4 experimental Halls*
- *Targets: from H to Pb (also polarized)*

JLab Physics

Nucleon Structure

Form Factors, Partonic distributions, origin of the nucleon spin, nucleon size and mass

Nuclear Structure

Nuclei quark structure and their propagation in the nucleare medium (EMC effect, nuclear transparency)

Short Range N-N interaction

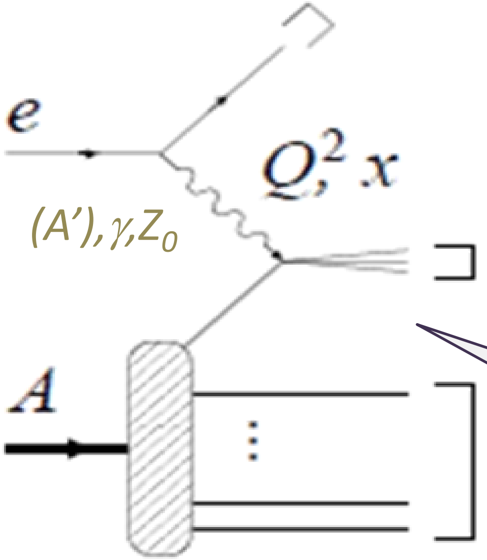
N-Λ Interaction

Hadron Spectroscopy

Search of hybrid and exotics states

Lattice QCD test

Confinement



Electron–Nucleous scattering processes
QED ⊗ QCD

Parity violation

High precision test of standard model

Quark-s distribution in nucleons

Neutron distribution in medium-heavy nuclei

Dark Matter Search

Beam:
- **High intensity**
- «high» energy
- **polarized**
- low emittance

Targets:
- from H to Pb
- **polarized**
- **stand high beam intensity**

Detectors:
- large acceptances
- support high background
- hadron identification
- precise reconstruction

Nucleon, still a mystery!

- Mass origin

  Sum of quarks mass makes ~2% of nucleon mass

  - Confinement / QCD
  - Internal dynamics

  ~50% of proton momentum carried by gluons

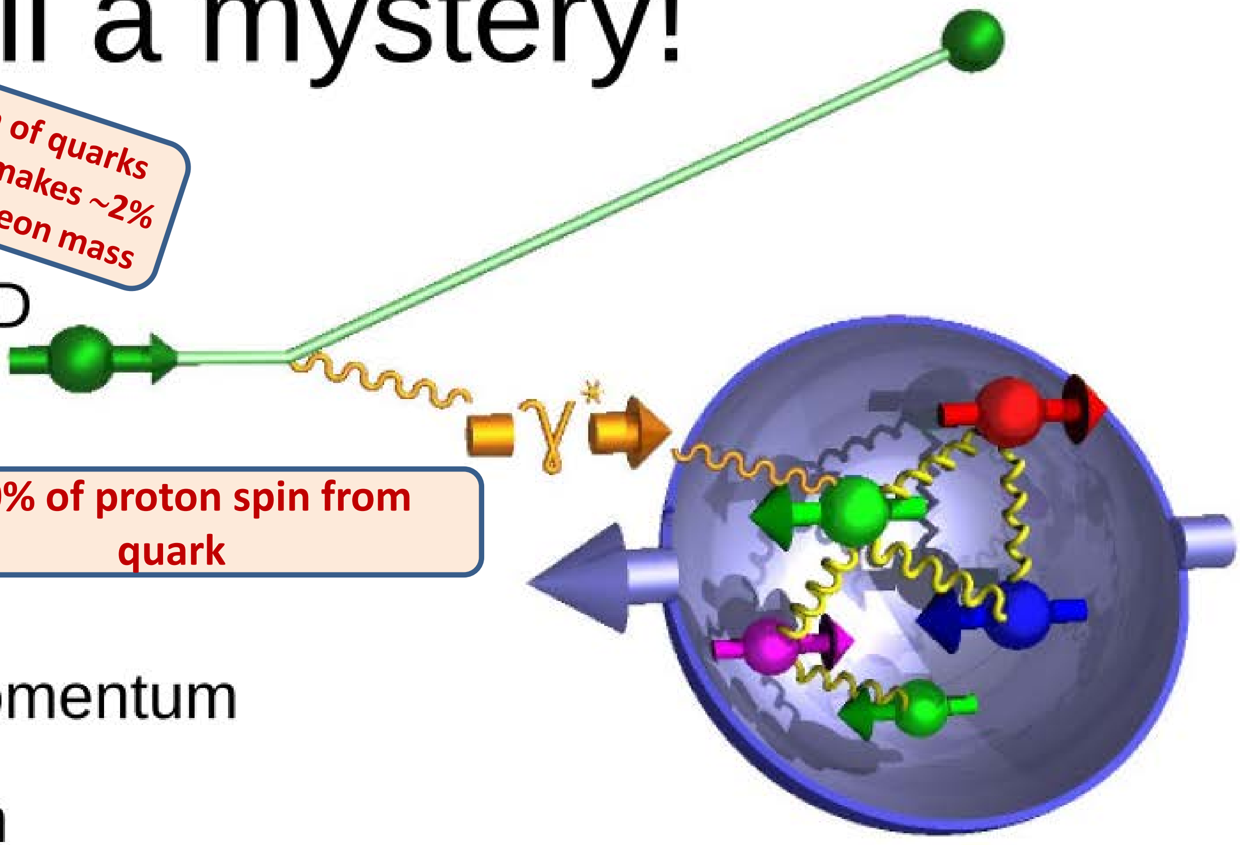
- Spin origin

  ~20% of proton spin from quark

  - Orbital Angular Momentum
  - Gluon Contribution
- (Proton) radius

  Recent measurment (Pohl et al. 2010) strongly disagrees with ep scattering data

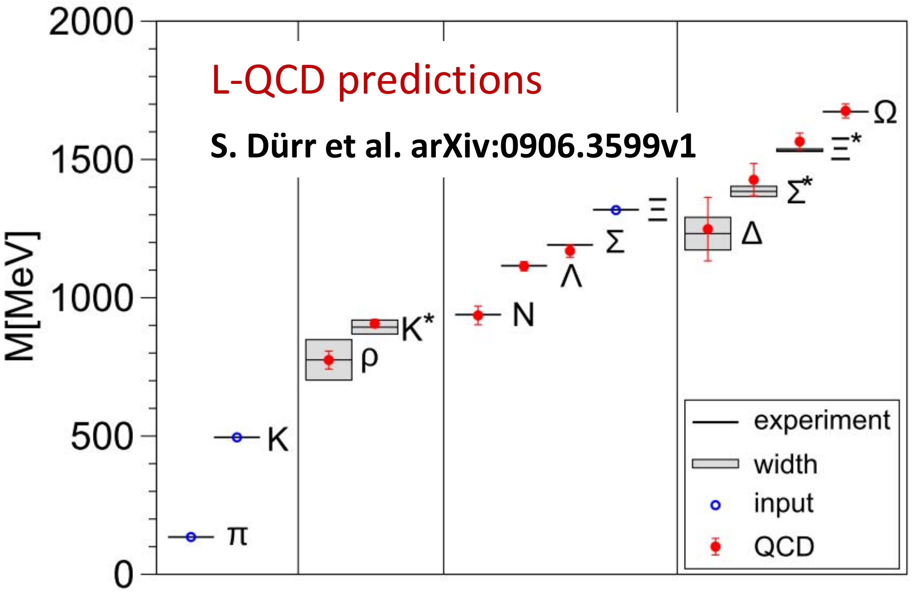
- QED-QCD reaction mechanisms



sample image
(actual product may vary)

Nucleon (Hadron) mass, QCD and confinement

- The mass of the nucleon is determined by the interactions among the three valence quarks rather than their masses; *fraction of the original large energy density remained confined into the hadrons*



L-QCD predictions

S. Dürr et al. arXiv:0906.3599v1

- Lattice QCD predics (relative) hadrons masses pretty well, but it does not provide hits on the mechanism behind the origin of them
- QCD is a Yang-Mills non-abelian gauge theory: the mass gap (**confinement**) is intrinsically a quantum effect – (while Higgs mechanism is classical and enter ElectroWeak gauge theory by quantization) (see F. Wilczek, Origins of Mass MIT-CTP/4379,2012)

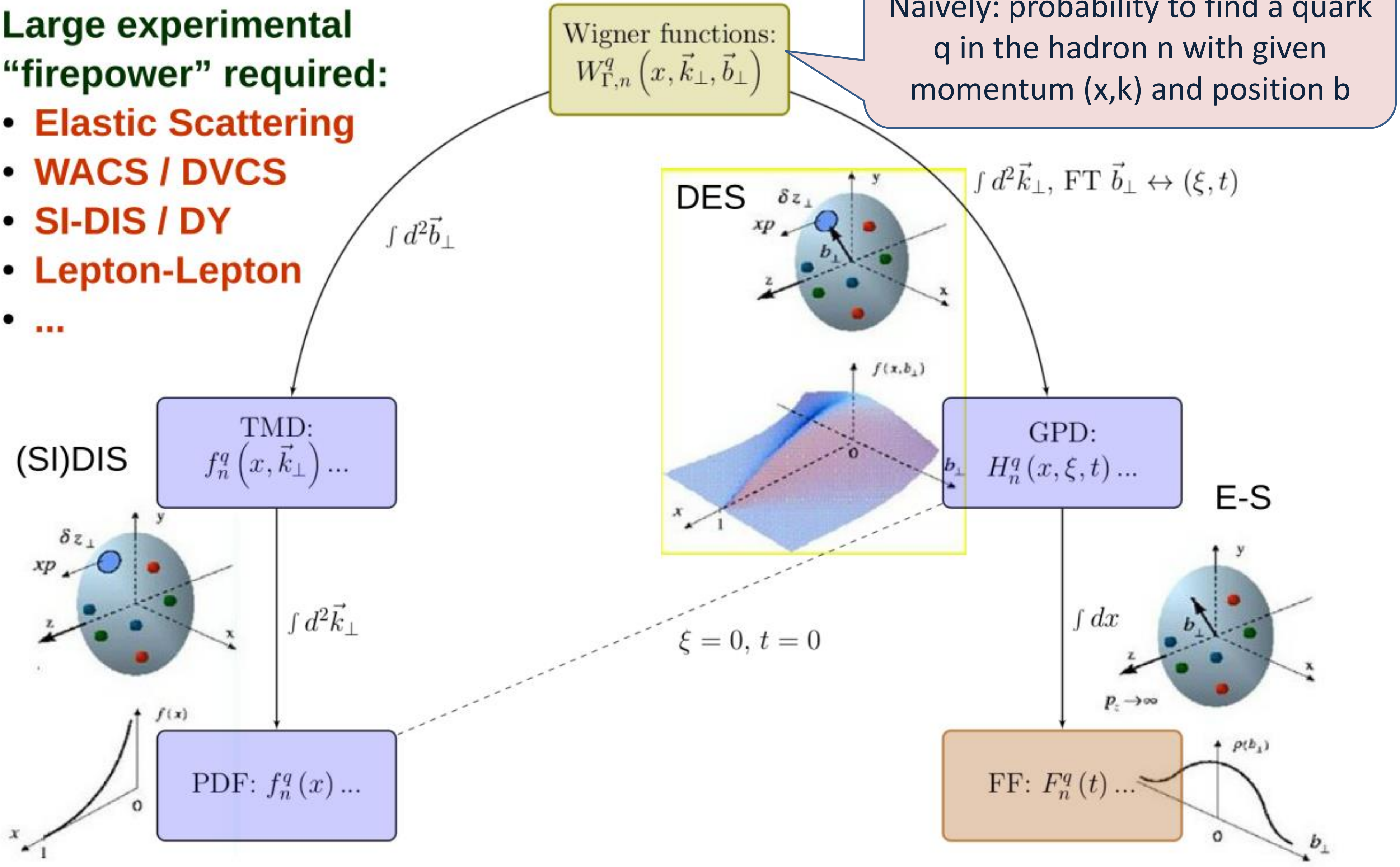
One of the 1M$ Millennium Problem of the Clay Math. Institute

- QCD is poorly known and counterintuitive: **its «explainability» may represent a scientific revolution**

Toward a unified picture of nucleon structure

Large experimental "firepower" required:

- **Elastic Scattering**
- **WACS / DVCS**
- **SI-DIS / DY**
- **Lepton-Lepton**
- **...**



Naively: probability to find a quark q in the hadron n with given momentum (x,k) and position b

Wigner functions: $W^q_{\Gamma,n}\left(x,\vec{k}_\perp,\vec{b}_\perp\right)$

$\int d^2\vec{b}_\perp$

$\int d^2\vec{k}_\perp,\ \mathrm{FT}\ \vec{b}_\perp \leftrightarrow (\xi,t)$

DES

(SI)DIS

TMD: $f^q_n\left(x,\vec{k}_\perp\right)\ldots$

GPD: $H^q_n\left(x,\xi,t\right)\ldots$

E-S

$\int d^2\vec{k}_\perp$

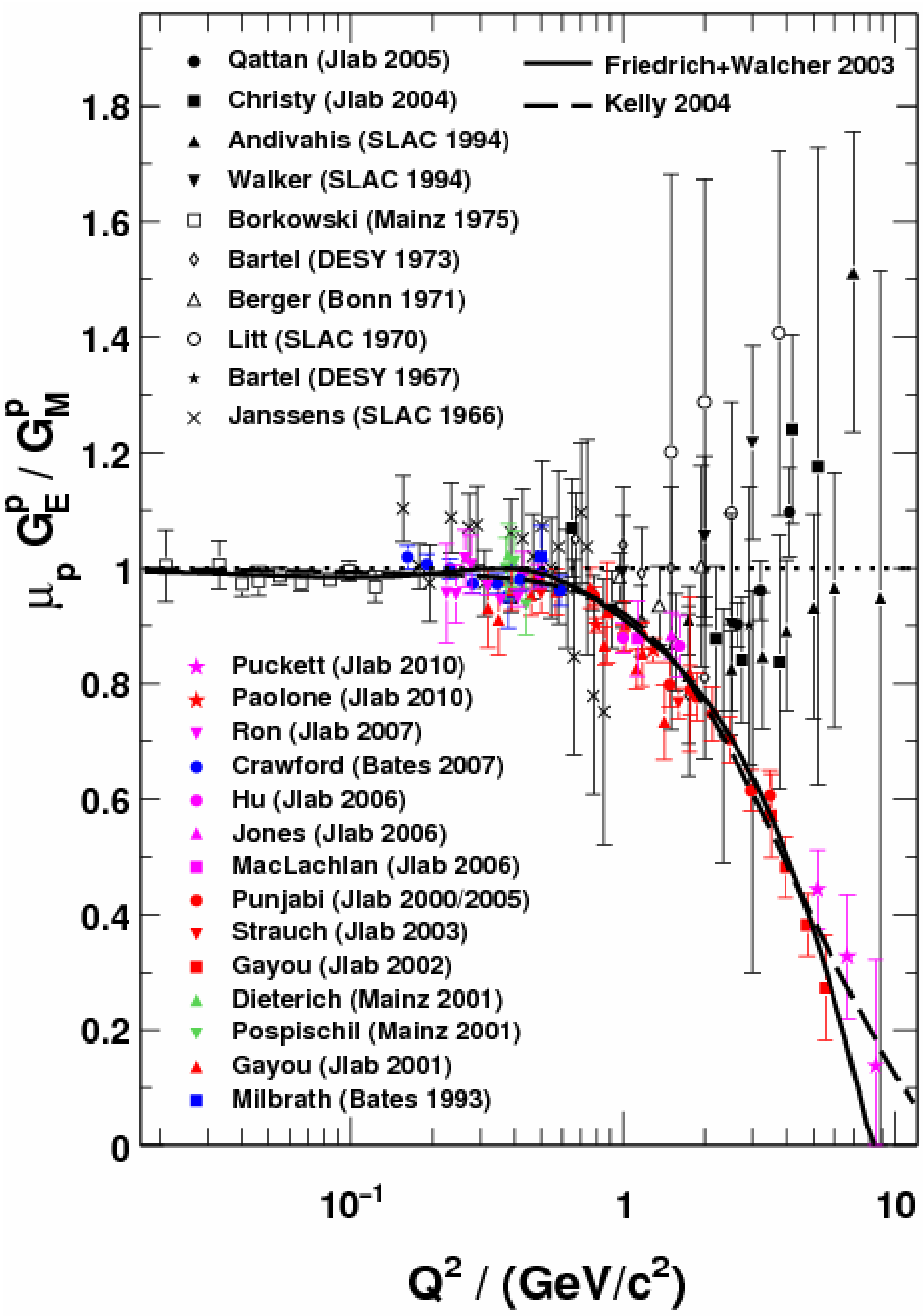
$\xi = 0,\ t = 0$

$\int dx$

PDF: $f^q_n\left(x\right)\ldots$

FF: $F^q_n\left(t\right)\ldots$

Proton Form Factors G_E/G_M – **unexpected discrepancy**



$$\frac{d\sigma}{d\Omega} \propto G_{Ep}^2 + \frac{\tau}{\varepsilon} G_{Mp}^2$$

Rosenbluth Separation: assume single photon approximation

Before 2000: proton G_E/G_M fairly constant with Q^2

$$R_p = \mu_p \frac{G_E(Q^2)}{G_M(Q^2)} \approx 1 - \underbrace{0.13\,(Q^2 - 0.29)}_{Pol.\ \ Transfer\ \ Discr.}$$

$$\mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{P_t}{P_l} \frac{(E_{beam} + E_e)}{2M_p} \tan \frac{\vartheta_e}{2}$$

Polarization transfer from the incident electron to the scattered proton

At JLab, new class of experiments show proton G_E/G_M decreasing linearly with Q^2

Form Factors are an important probe of the **color CONFINEMENT** at all energy ranges!

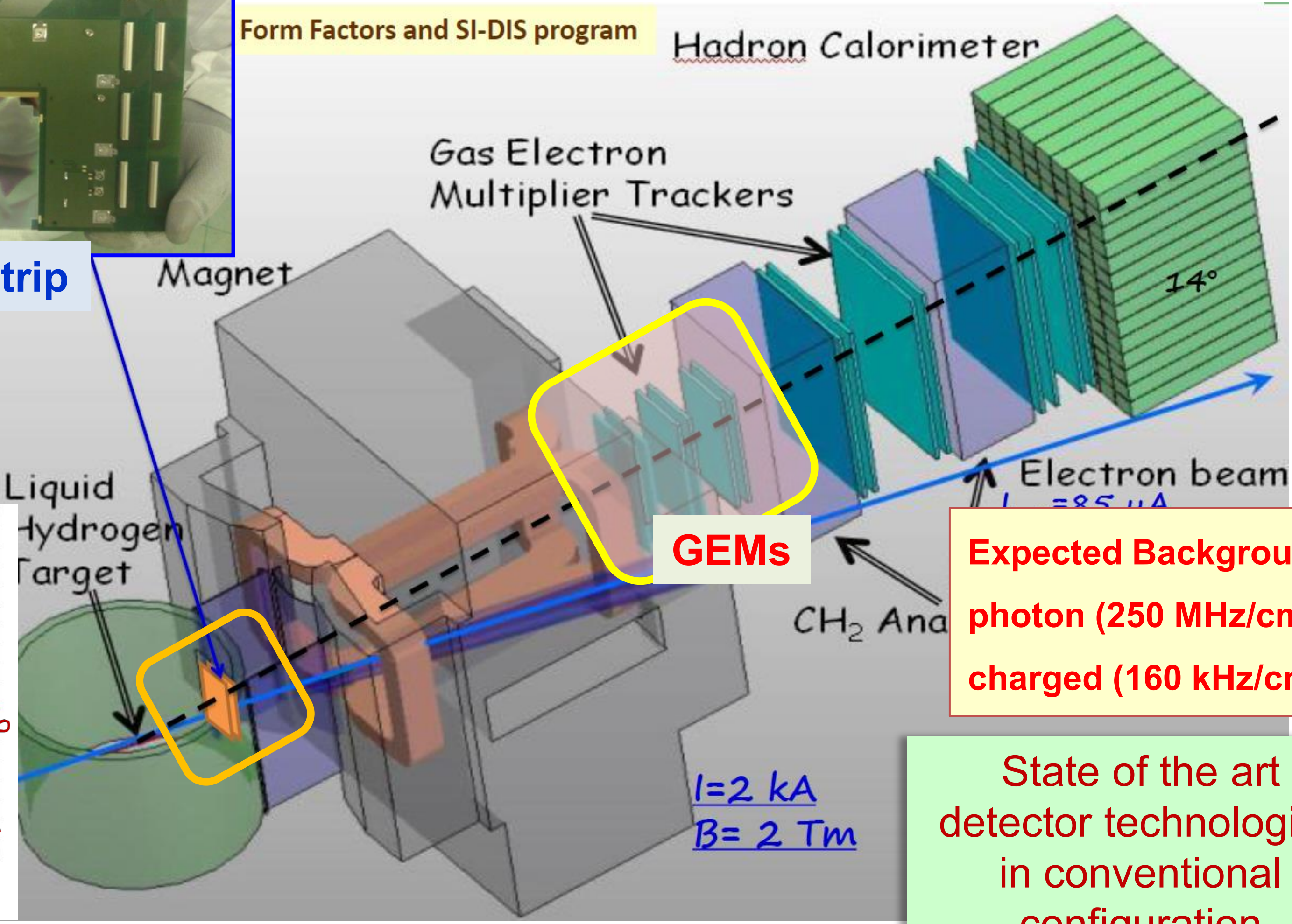
SuperBigbite Spectrometer in Hall A/JLab

Physics Cases:
Nucleon Form Factors, Neutron spin and TMD, Pion structure functions
… an experimental tool for hadron structure investigation

for high luminosity experiments!

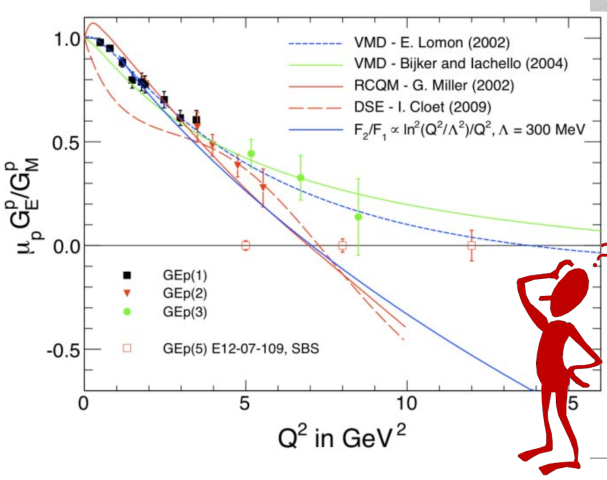
Silicon microstrip

Contact:
franco.meddi@roma1.infn.it

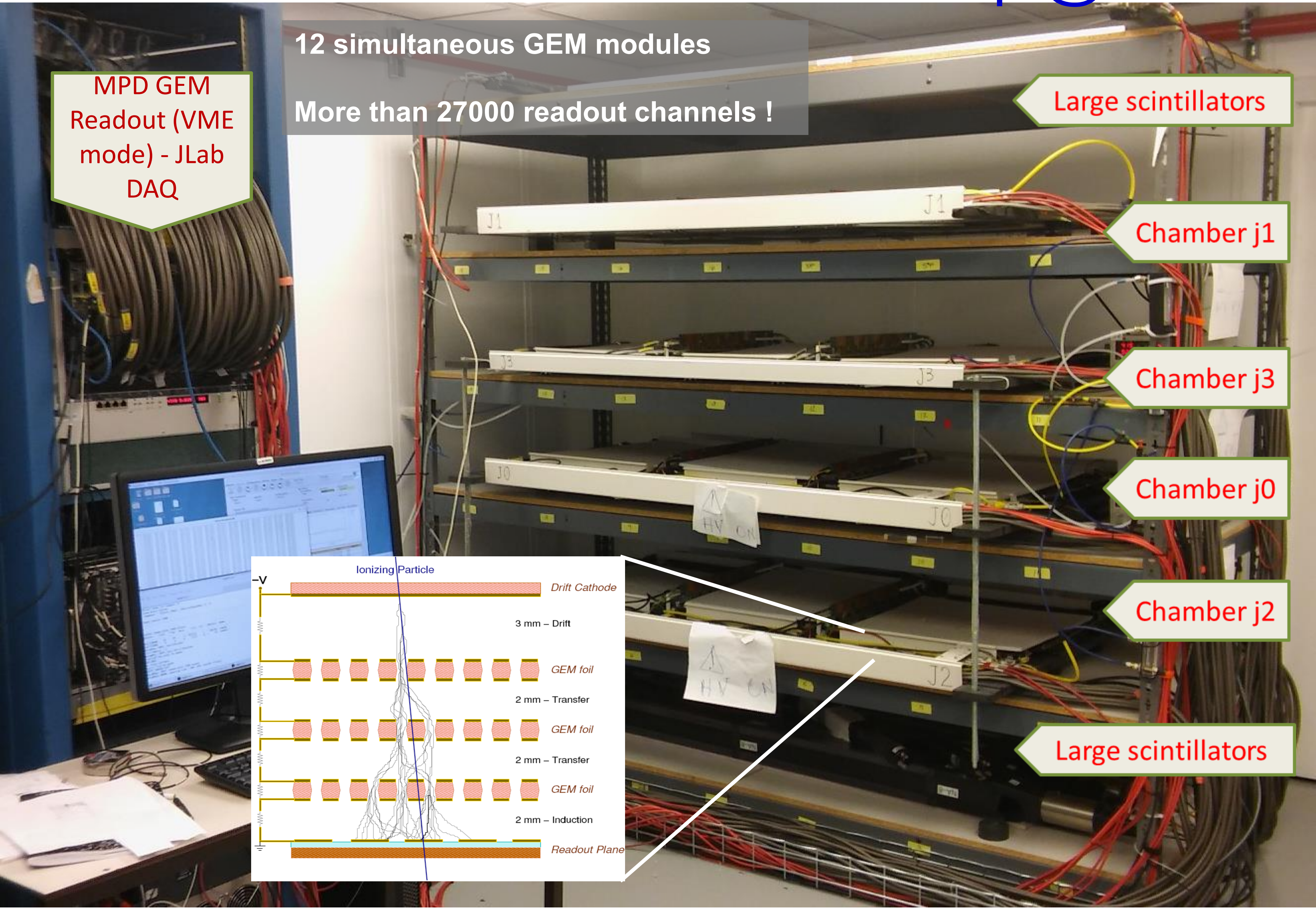


Expected Background:
photon (250 MHz/cm2)
charged (160 kHz/cm2)

State of the art detector technologies in conventional configuration



GEM Tracker / Cosmic Setup @ JLab



12 simultaneous GEM modules

More than 27000 readout channels !

MPD GEM Readout (VME mode) - JLab DAQ

Large scintillators

Chamber j1

Chamber j3

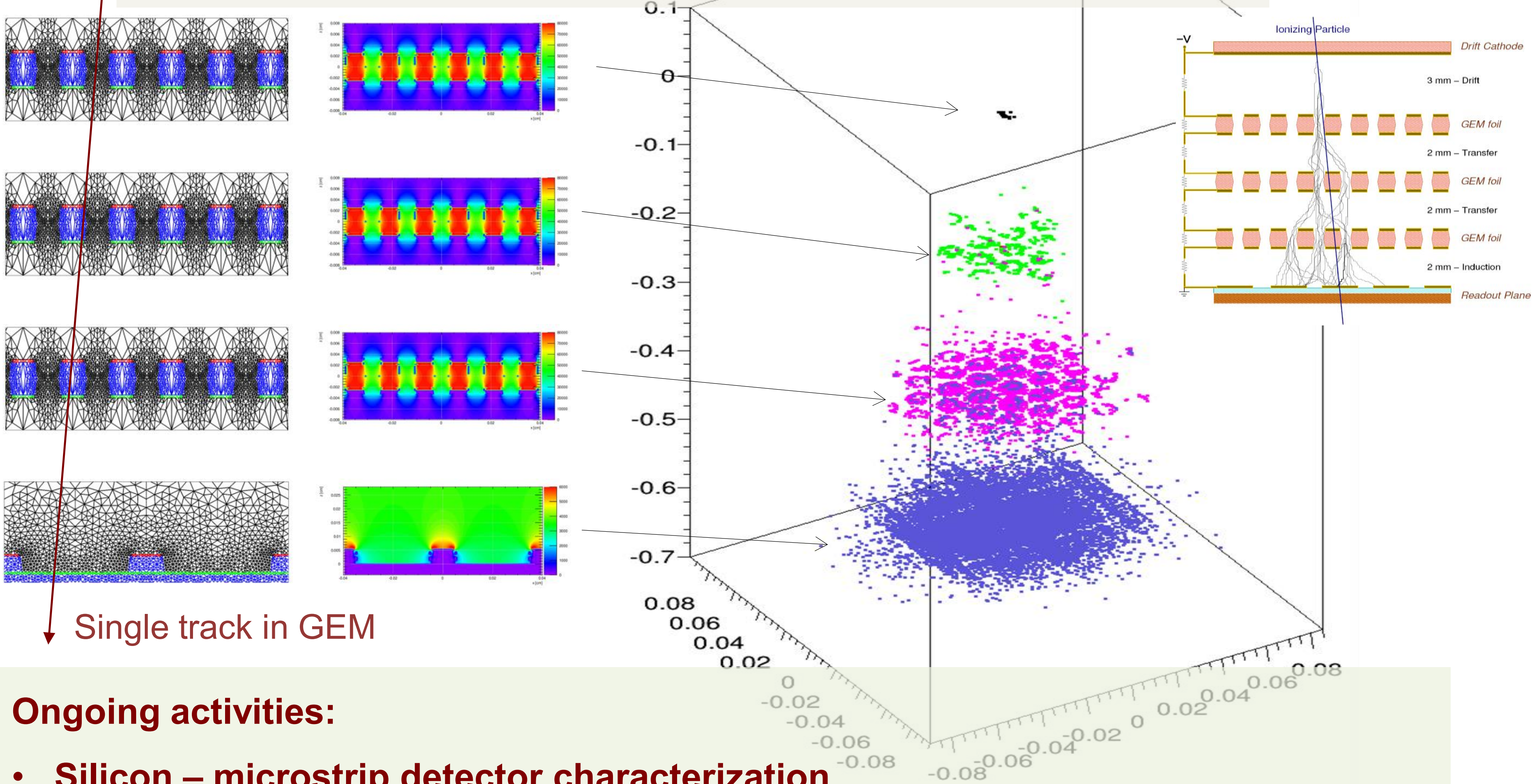
Chamber j0

Chamber j2

Large scintillators

GEM - Garfield++ microscopic simulation

Model → Electrostatic Field → Simulation of electrons/ions avalanche

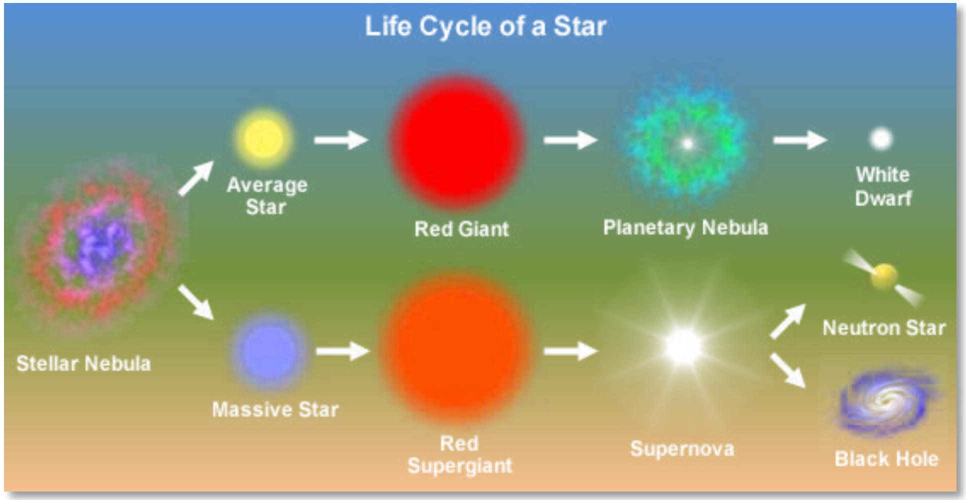


Single track in GEM

Ongoing activities:

- **Silicon – microstrip detector characterization**
- **Commissioning (cosmics and beam) of the GEM tracker**
- **Development of the track reconstruction algorithm (based on neural network)**
- **Microscopic model of the GEM response (by Garfield++)**

The «giant nucleus»: Neutron Star

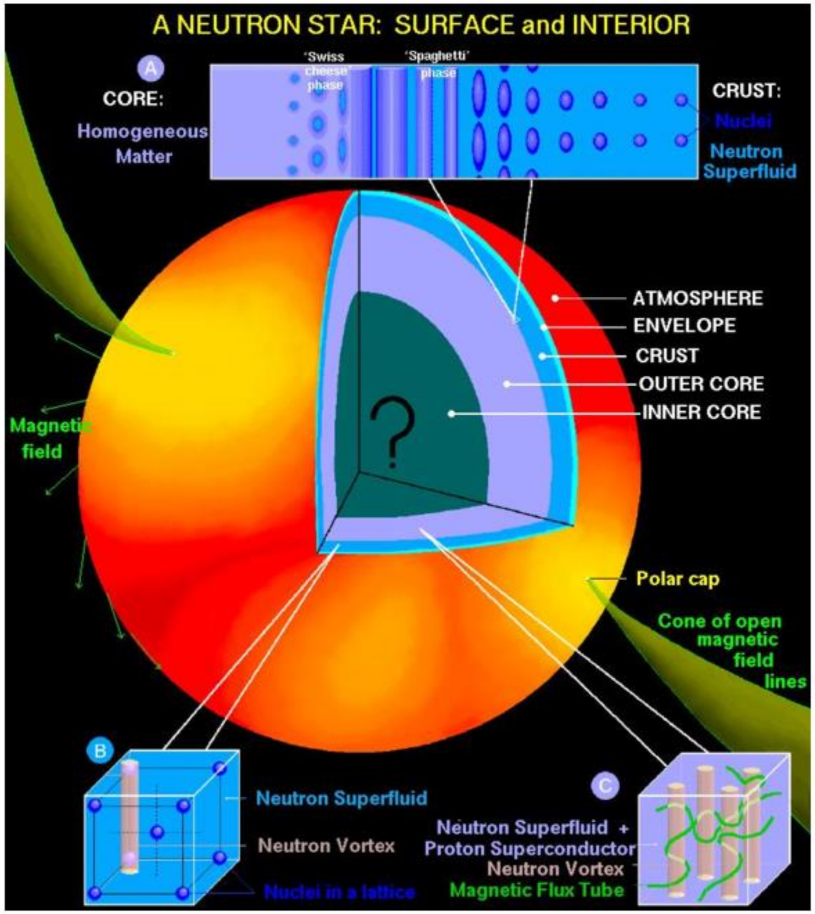


The possible end of a red supergiant star

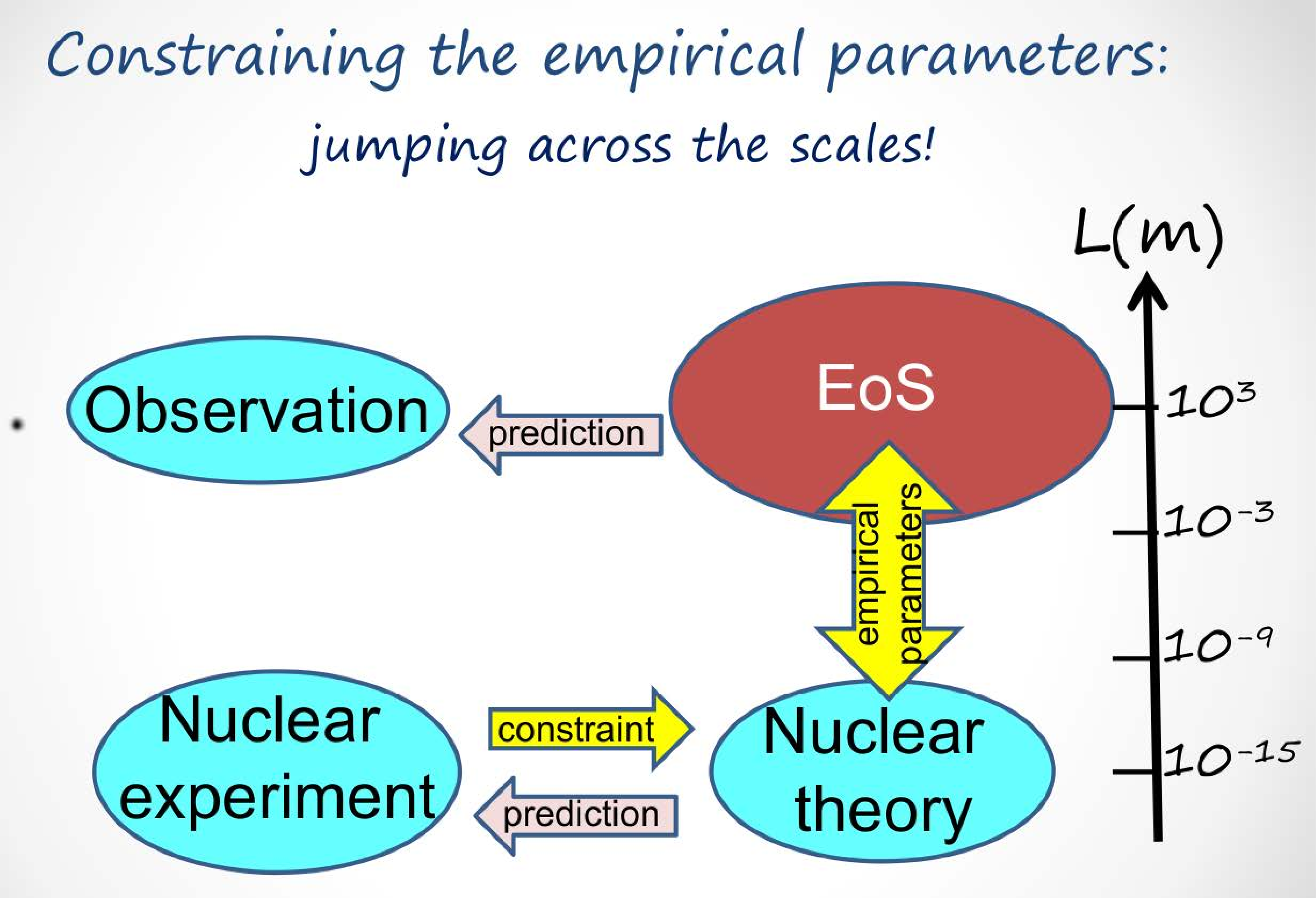
One of the most strongly correlated fermionic system (~10^{17} kg/m^3)

Binary Neutron Star Merger source of a recent (17/08/2017) Multi-messenger observation

- The NS core is supposed to be a sort of neutral fluid of neutrons, protons, muons and electrons in equilibrium (respect to weak interaction)
- This fluid is described by the Equation of State (EoS) of strong interacting matter: relate Pressure, Energy density and Temperature
- The derivation of EoS from nuclear interaction is an extremely complex theoretical problem



Nuclear physics and Neutron Stars



Constraining the empirical parameters:

jumping across the scales!

From Gulminelli CSN3/Apr/2018

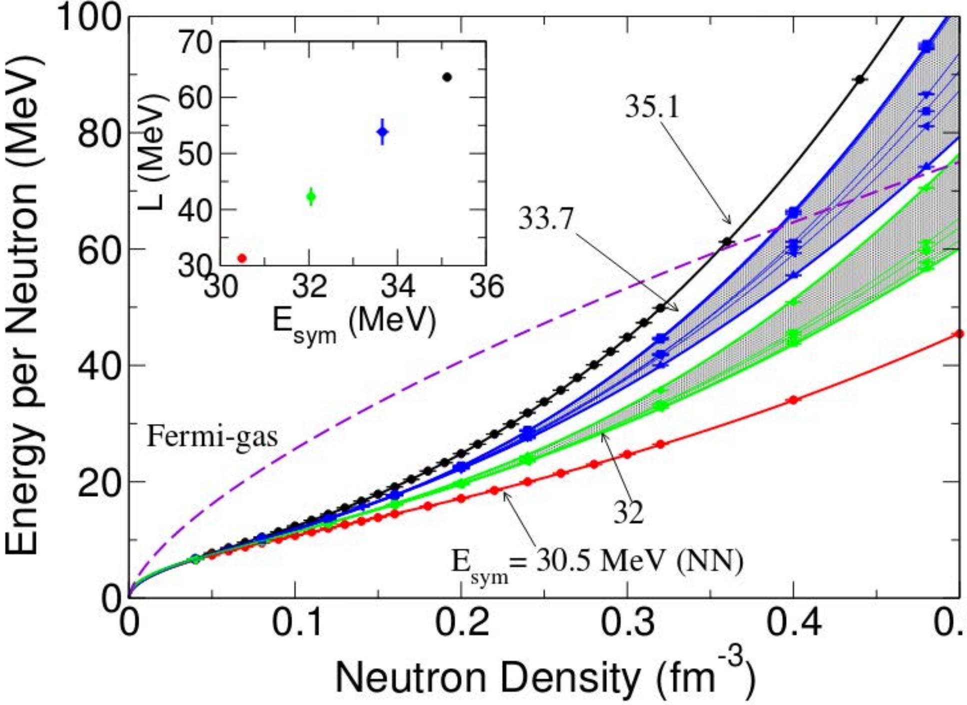
Neutron Star EoS and Symmetry Energy

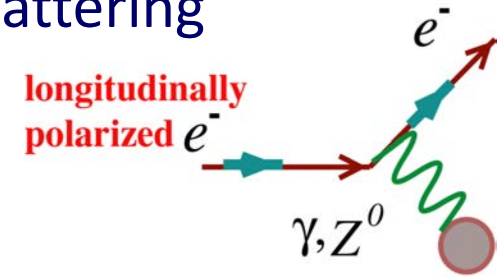
The **EoS** is the derivative of the energy function and strictly related to the asymmetry term (a_a) in nuclear binding energy

$$B = a_v A - a_s A^{2/3} - \frac{a_c Z(Z-1)}{A^{1/3}} - \frac{\boxed{a_a} (N-Z)^2}{A} - a_p A^{-3/4}$$

The **asymmetry term** can be precisely measured from the neutron-proton radius difference in heavy nuclei (PREX* experiments) by **parity violation** in polarized electron elastic scattering

S. Gandolfi et al. Phys. Rev. C 79(2009)054005





$$A_{PV} \sim \frac{G_F Q^2}{4\pi\alpha}\left[\underbrace{1-4\sin^2\theta_W}_{\sim 0} + \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

←Right-Left Asymmetry

Contact: Guido Maria Urciuoli:
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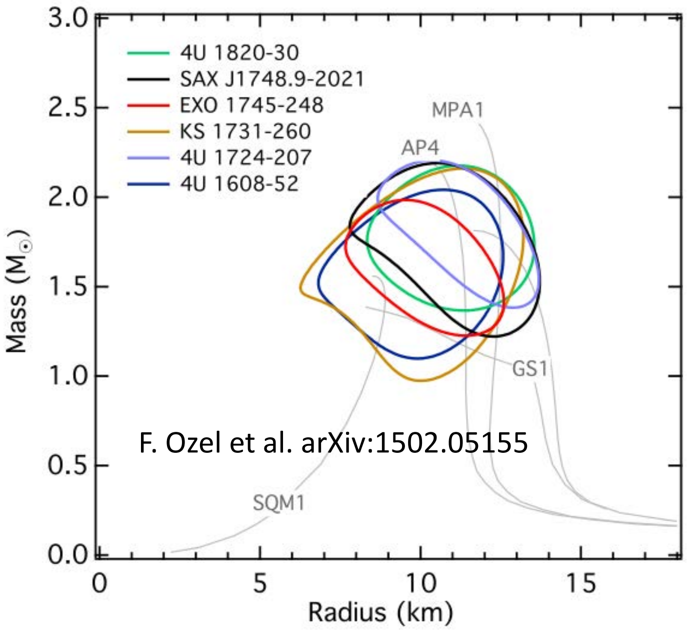
***PREX-II** is going to run shortly (this year) at JLab (Activities on experiment preparation/simulation, data taking and analysis)*

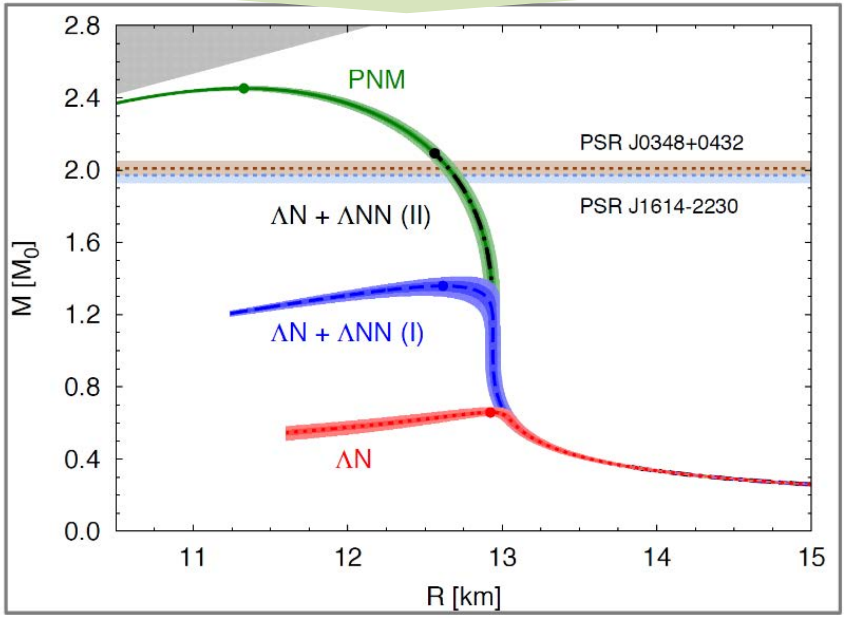
Nucleon Star Mass&Size – Hyperon Puzzle



F. Ozel et al. arXiv:1502.05155

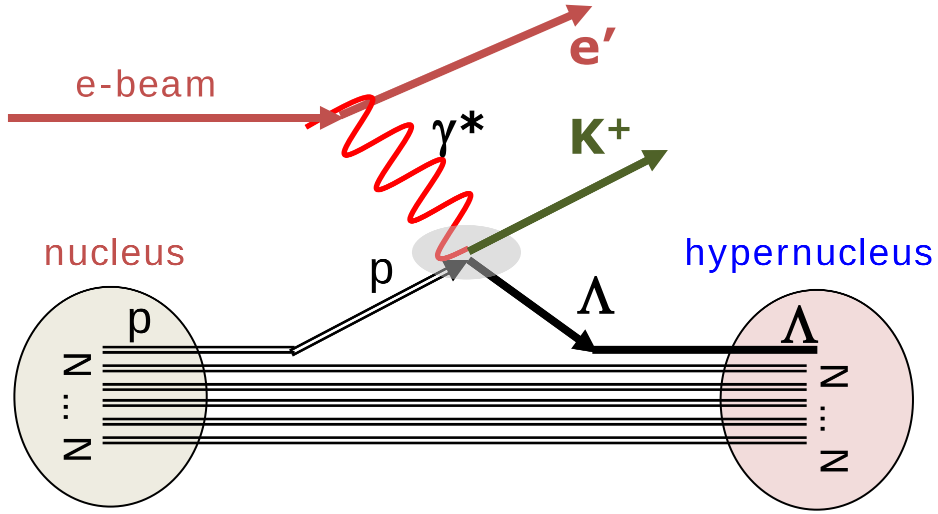
NS with ≥2 solar mass with ~10 km have been observed

At such high density, hyperons (Λ,Σ) can be relevant and **Λ-N interaction becomes** essential to predict NS mass-to-size relation



D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

Λ-N can be investigated by hypernuclear spectroscopy in electron-nucleus scattering



Hypernuclear electroproduction is one of the peculiar physics highlights at JLab.

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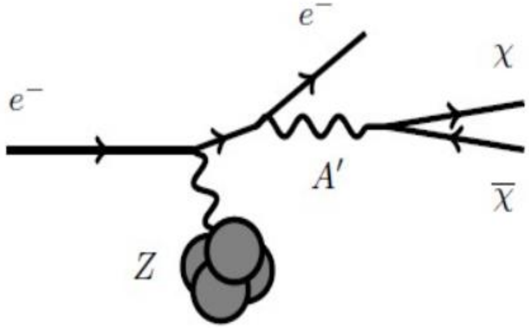
Dark Matter Search

The BDX experiment

Beam Dump eXperiment: LDM direct detection in a e^- beam, fixed-target setup

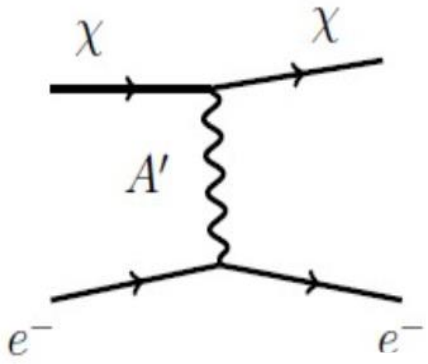
LDM production

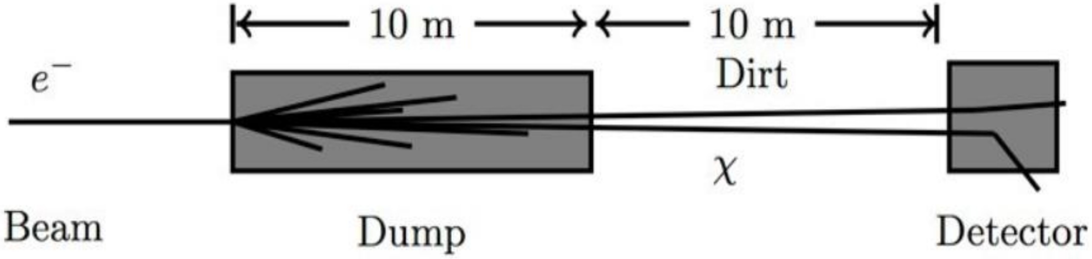
- High-energy, high-intensity e^- beam impinging on the dump
- LDM particles pair-produced radiatively, through A' emission



LDM detection

- Detector placed behind the dump at ~ 20m
- Neutral-current scattering on atomic e^- through A' exchange, recoil releasing visible energy
- Signal: *O*(100 MeV) - EM shower





https://arxiv.org/abs/1607.01390

Dark Matter Search preliminary tests

BDX-mini
tests @JLab

BDX-mini measurement campaign @JLab:

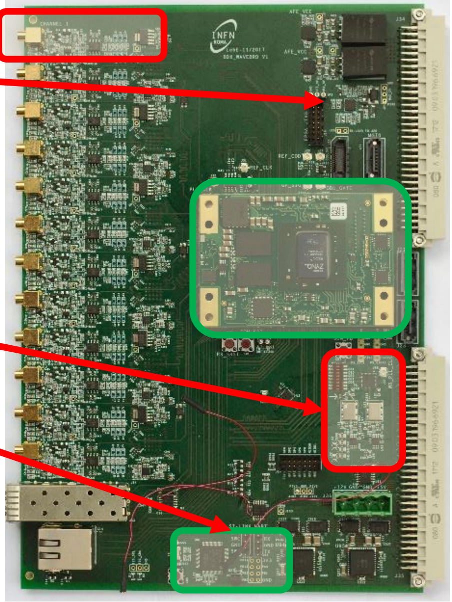
- Detector lowered at beam height in a pipe drilled 25 m behind Hall A beam-dump
- Beam-on measurement foreseen fall 2019 (beam energy 2 GeV ; current 150 μA)
- Currently cosmic data-taking ongoing

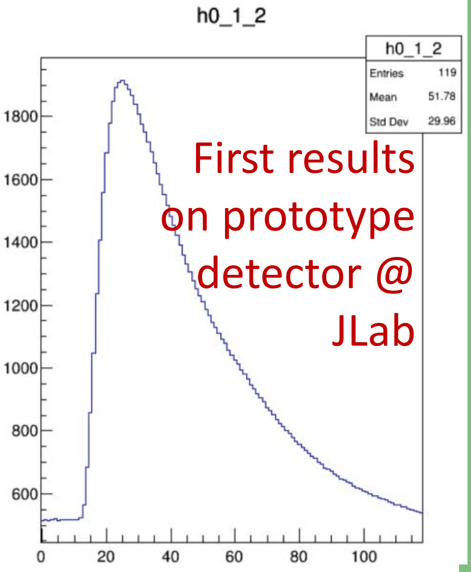
BDX-mini setup is based on “traditional” triggered DAQ. **A test measurement run has been taken with the BDX triggerless system**

RM1 developed the *WaveBoard* digitizer

- The board is based on a Commercial-Off-The-Shelf (COTS) System On Module (SOM) mezzanine card hosting a **Zynq-7030**
- There are 12 analog front end channels
  - 6 dual-channel ultra low-power ADCs (**12/14** bit up to **250MHz**)
  - Pre-amplifier on board: **selectable gain** (either 2 or 50)
  - **HV** provided and monitored on-board
  - pedestal set by DAC
- Timing interfaces:
  - PLL to clean, generate, and distribute clocks
  - External clock and reference signals
  - White Rabbit enabled board
- ARM-M4 controls on-board peripherals (ADCs, DACs, PLL,
- On board peripherals:
  - High speed: GbE, SFP, USB OTG
  - Low Speed: serial, I2C, temperature monitor

Single Channel Front End w/ High Voltage





First results on prototype detector @ JLab

Highly integrated electronics
Toward continuous streaming readout (triggerless system)
The new frontier of DAQ in high energy / nuclear physics experiments

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ALICE

Contact:
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Quark-Gluon plasma

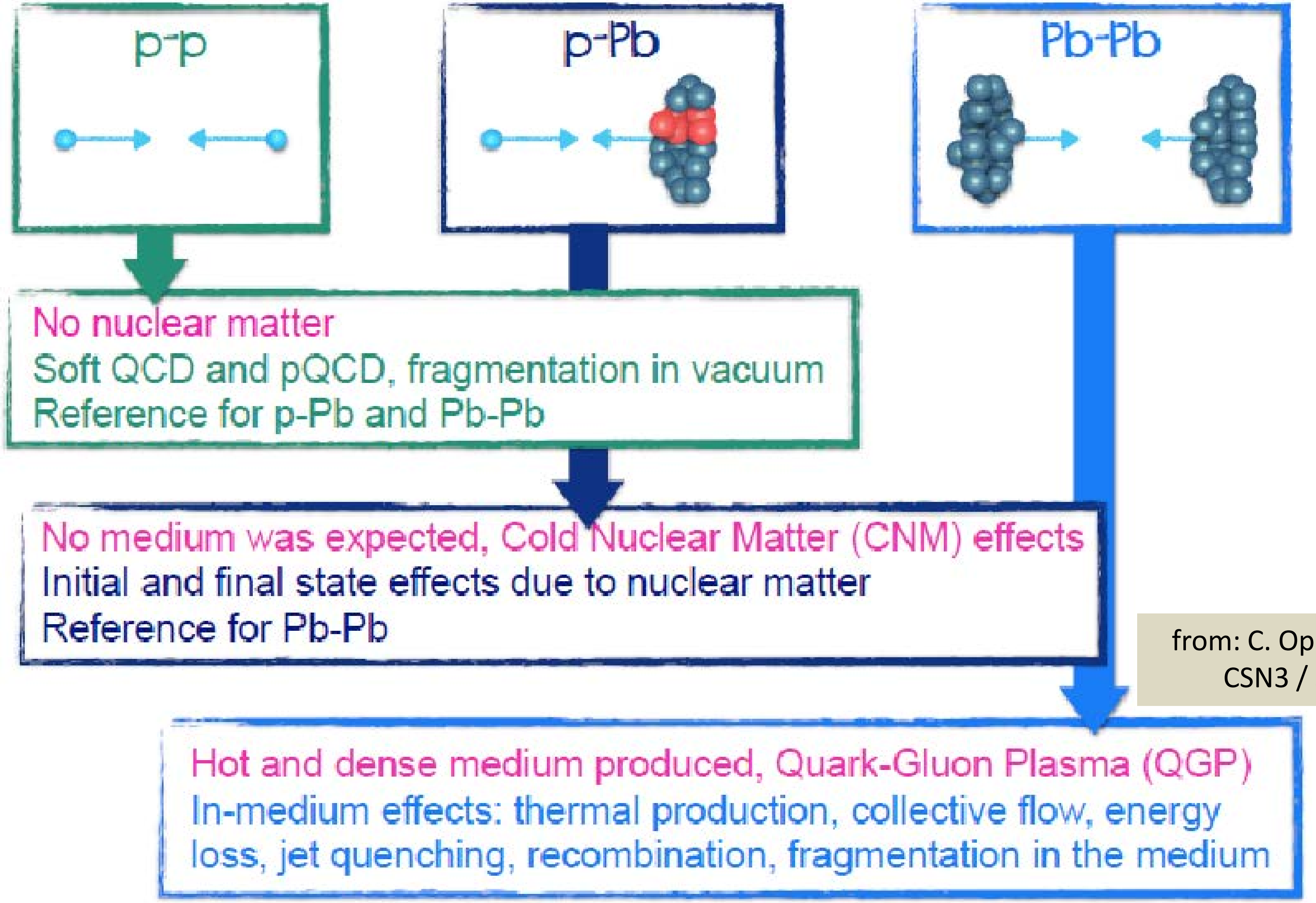
http://aliceinfo.cern.ch/Public/Welcome.html

A Large Ion Collider Experiment

http://alice-collaboration.web.cern.ch/

Contact: Dr. Alessandra Mazzoni
(Maria.Alessandra.Mazzoni@roma1.infn.it)

Understanding QCD by ion-ion collision at LHC



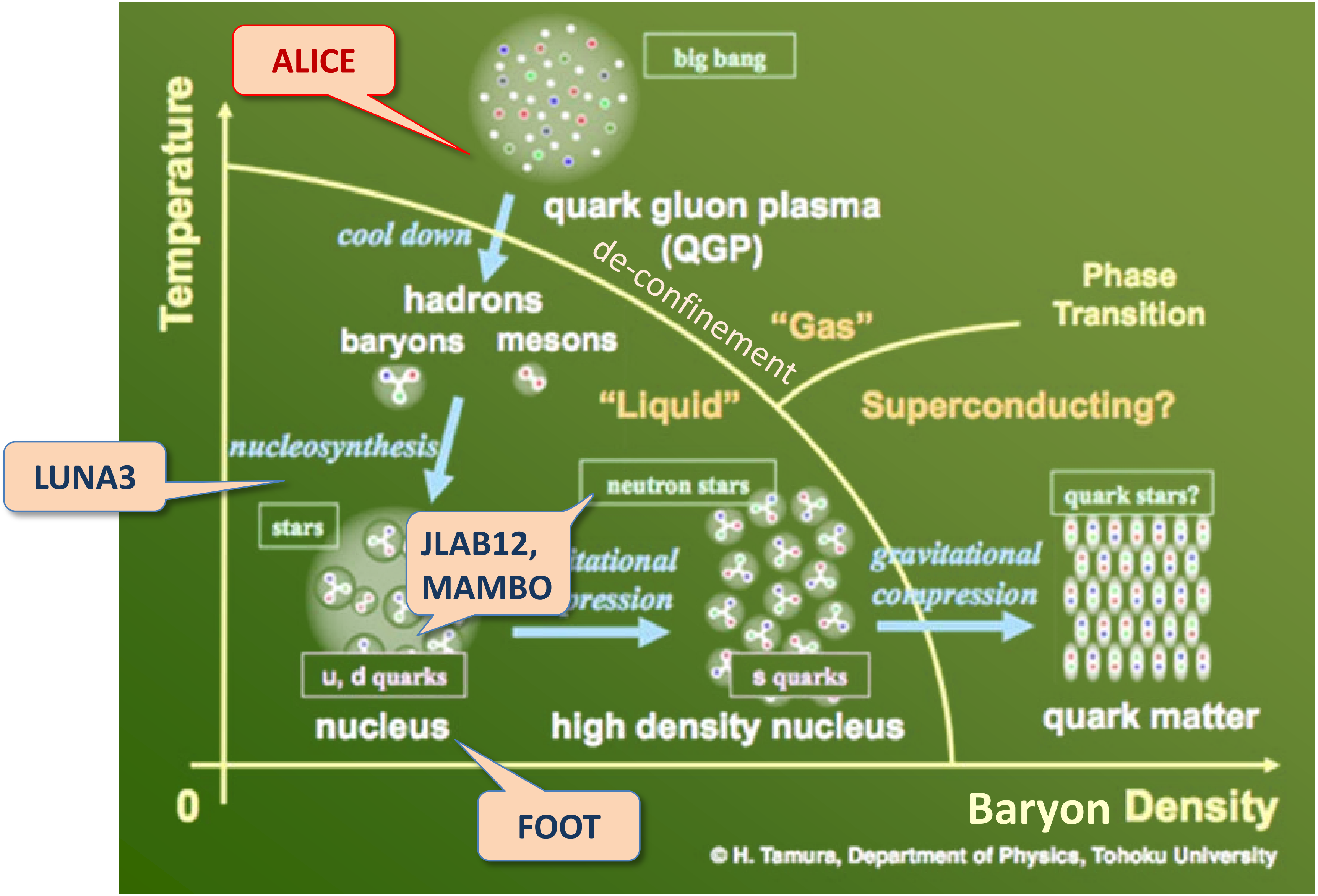
No nuclear matter
Soft QCD and pQCD, fragmentation in vacuum
Reference for p-Pb and Pb-Pb

No medium was expected, Cold Nuclear Matter (CNM) effects
Initial and final state effects due to nuclear matter
Reference for Pb-Pb

Hot and dense medium produced, Quark-Gluon Plasma (QGP)
In-medium effects: thermal production, collective flow, energy loss, jet quenching, recombination, fragmentation in the medium

from: C. Oppedisano
CSN3 / Set/2015

QCD Phase Diagram



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http://www.eicug.org/

EIC

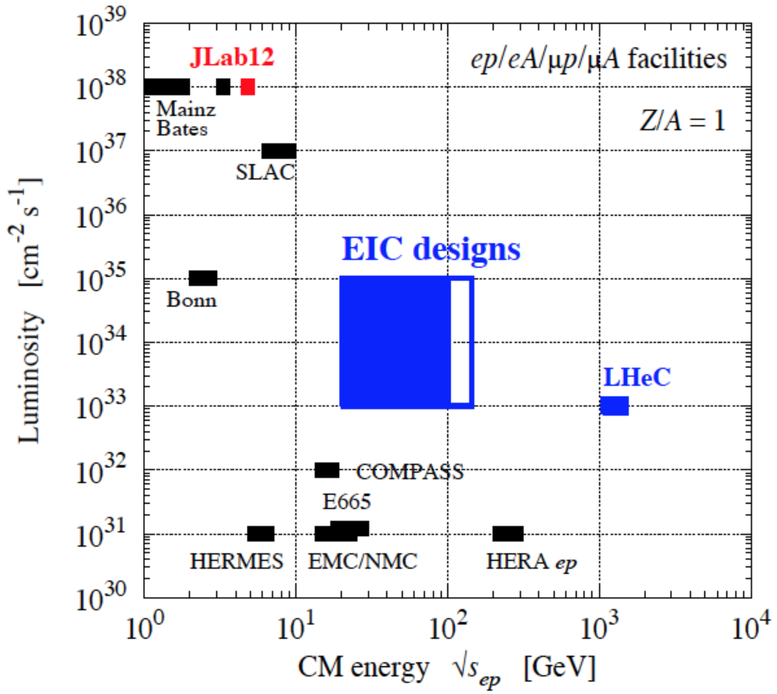
The next frontier of **QCD** experimental investigation
(JLab + ALICE physics and more)

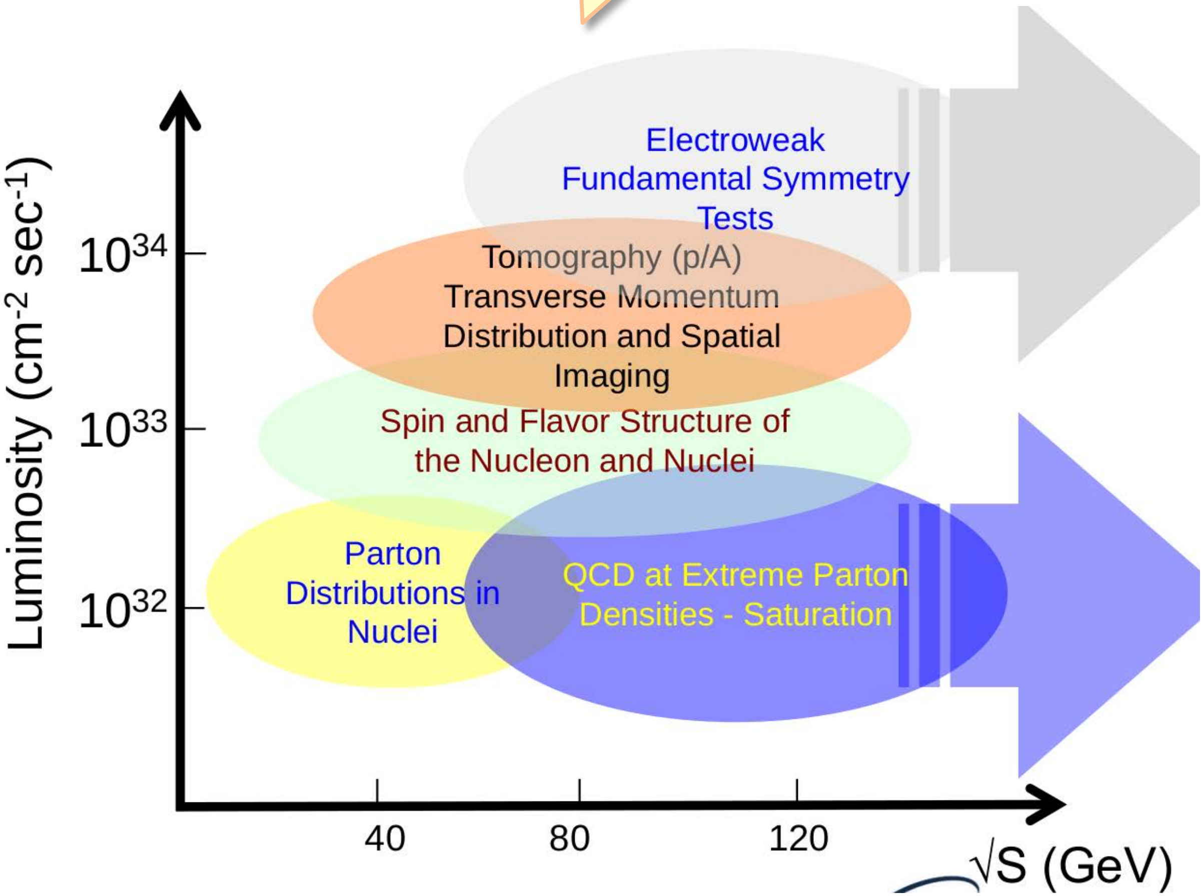
Nucleon/Hadron structure/dynamics
Quark-Gluon Plasma
Standard Model Test

Electron **I**on **C**ollider (EIC)

- **Electron (and positron) and ion beams from proton to Pb/U**
- **Polarization (e, p, d, ^{3}He) >70%**
- **Luminosity up to ≈10^{34}/(cm s)** (1000 x Desy/HERA)
- **CM energy large and variable (20-100 GeV)**
- **Reach very low $x \approx 10^{-4}$**

World's first polarized e-p/light ion and electron-nucleus collider





Electroweak Fundamental Symmetry Tests

Tomography (p/A) Transverse Momentum Distribution and Spatial Imaging

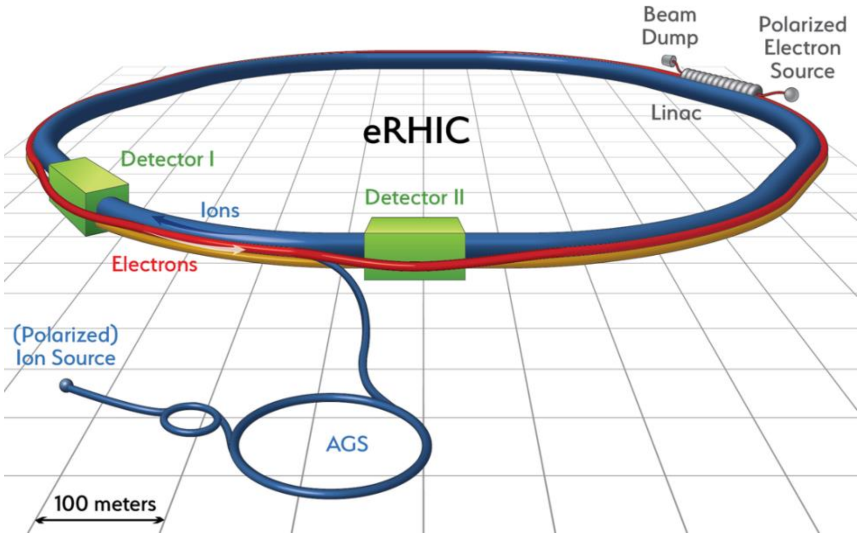
Spin and Flavor Structure of the Nucleon and Nuclei

Parton Distributions in Nuclei

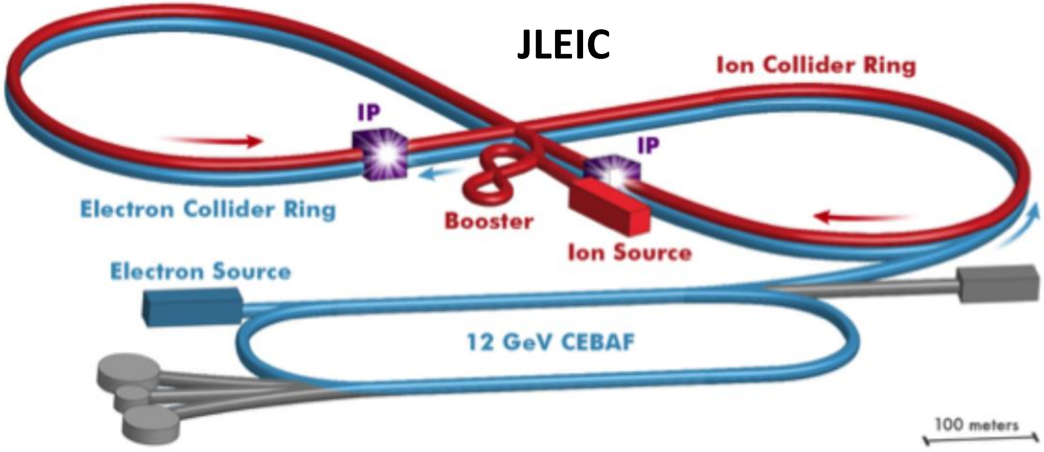
QCD at Extreme Parton Densities - Saturation

EIC options

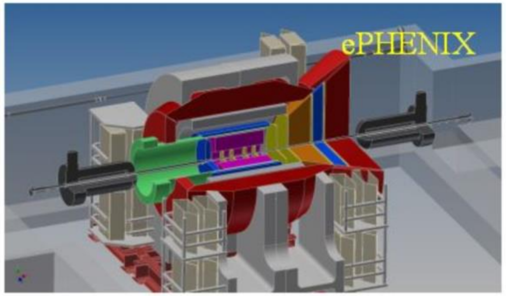
Needs advanced technologies for both acceleration and detection

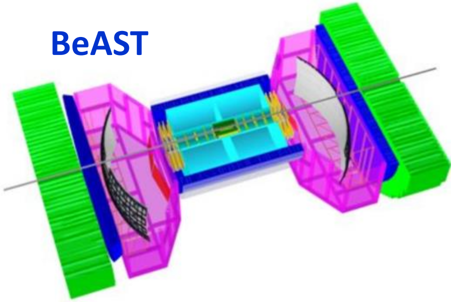


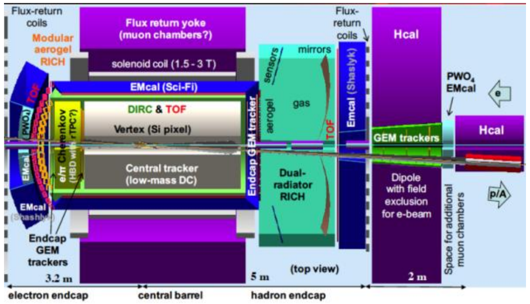
Existing RHIC, 20 GeV e on 275 GeV p



Existing CEBAF, 12 GeV e on 100 GeV p
Optimized for high ion beam polarization





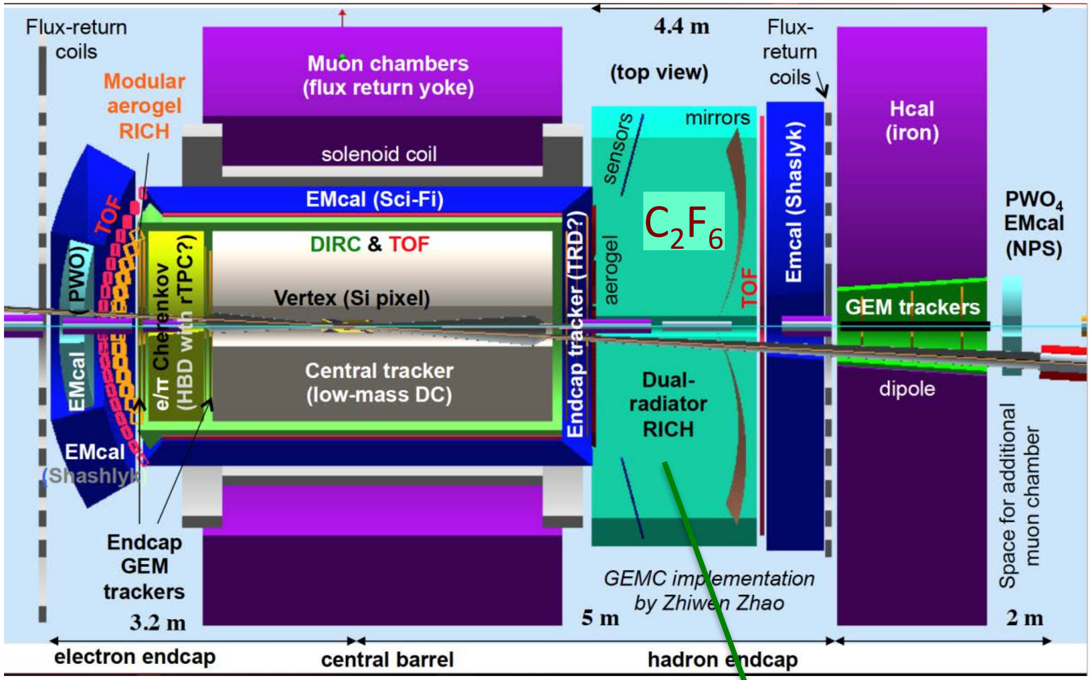


- Inclusive, Seminclusive and Exclusive reactions
- Good Particle ID (for hadrons and leptons)

- Vertex Resolution down to 0.1 mm
- Momentum Resolution (down to ≈100 MeV ≈1%)

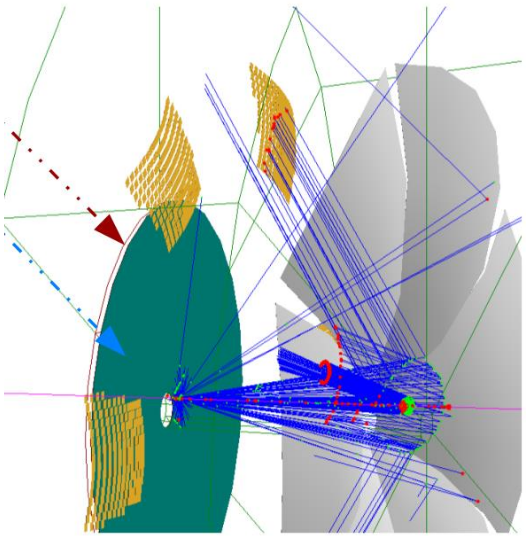
○ Best guess for completion of EIC facility construction would be after 2025, around 2025-2030 - in roughly a decade from now!

Dual-radiator RICH (dRICH)



Goal:

Provide full hadron identification (π/K/p, better than 3 sigma apart) from ~3 GeV/c up to ~50 GeV/c, in the forward ion-side endcap of the EIC detector, covering polar angles up to 25 deg and whole azimuthal angle (360 deg)



How:

- Use two **Cherenkov** radiators: aerogel and gas simultaneously
- Focusing optics (for the gas mainly)
- Six large «petals» with their own mirror and detector surface
- Highly segmented photon detectors

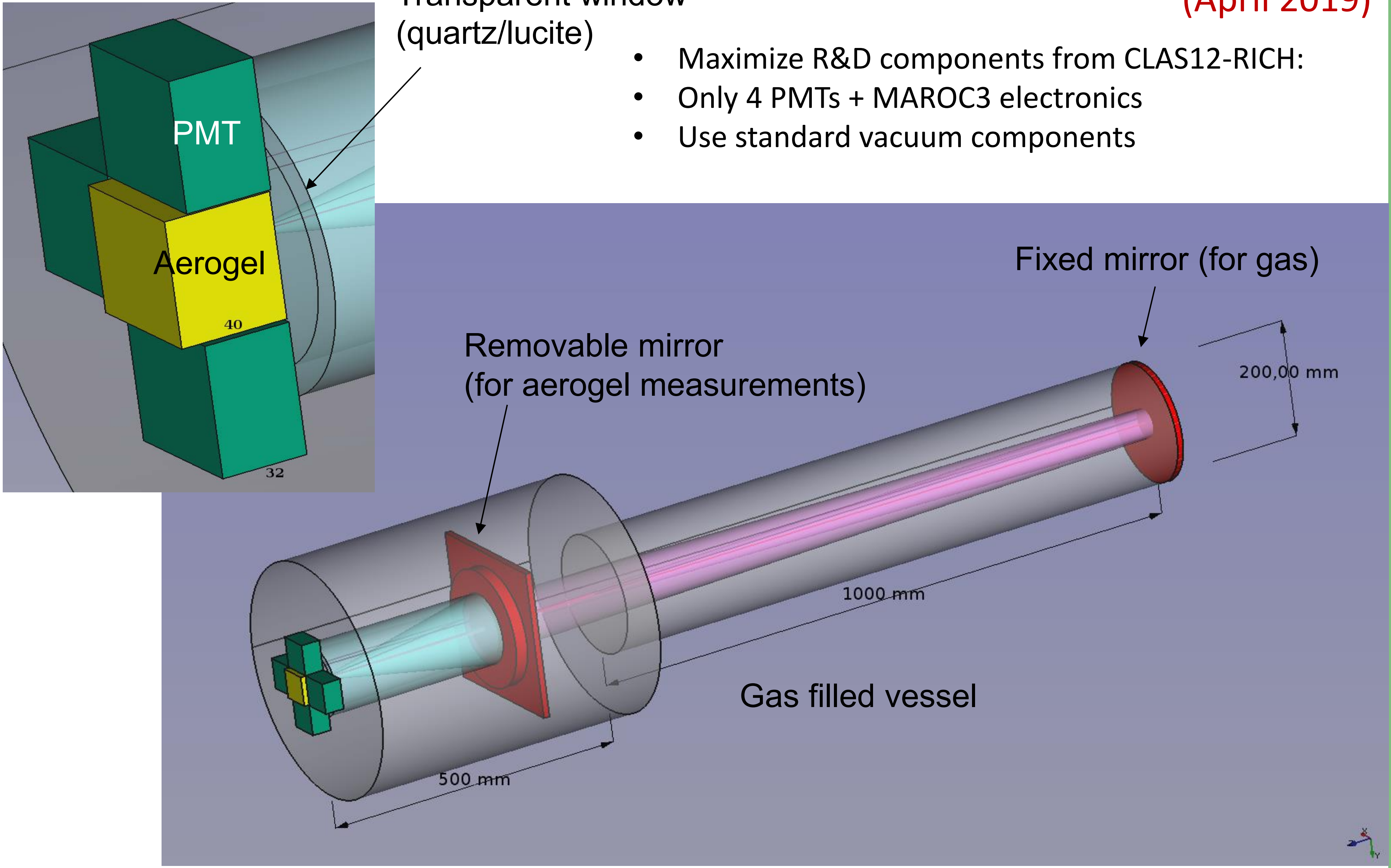
Cherenkov photons are emitted by a charged particle when traveling a medium with speed > speed of light; photons are emitted at an angle related to the speed (then mass) of the particle.

RICH: Ring Imaging Cherenkov detector: designed to reconstruct the Cherenkov angle

dRICH Prototype - preliminary design

(April 2019)

- Maximize R&D components from CLAS12-RICH:
- Only 4 PMTs + MAROC3 electronics
- Use standard vacuum components



Transparent window (quartz/lucite)

Removable mirror (for aerogel measurements)

Fixed mirror (for gas)

Gas filled vessel

dRICH 01/Apr/2019 INFN-FE - L. Barion et al. 46

FOOT

Contact Person:
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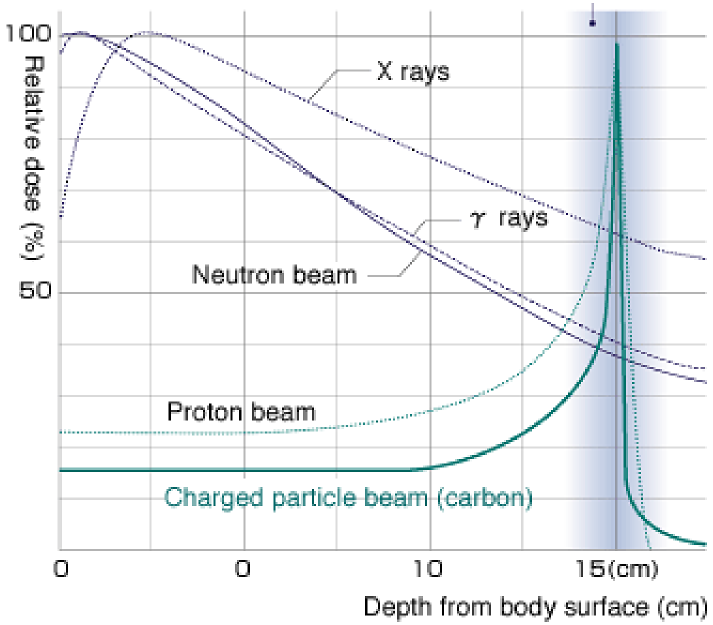
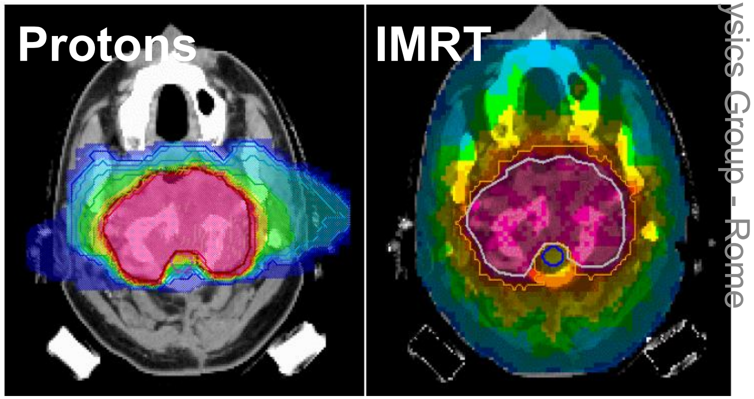
- Cancer Radiation Therapy
- Nuclear Fragmentations

Intermezzo: External Radiation Cancer Therapy

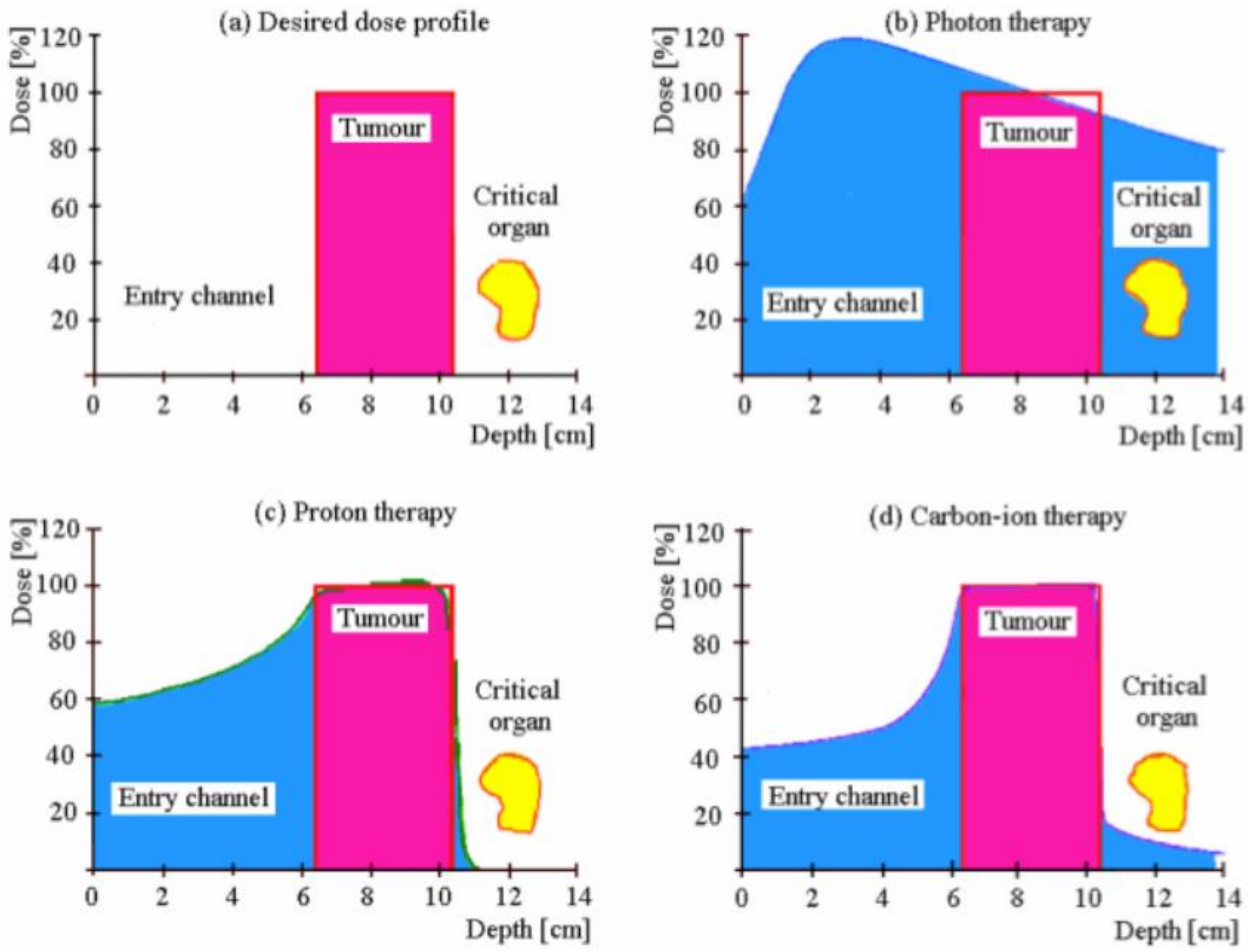
Use particle beams to kill cancer cells (breaking DNA) sparing healthy cells

1. **Conventional radiotherapy** with electrons and photons up to 25 MeV
   - ❑ the best choice for the treatment of the shallow tumors (electrons)
   - ❑ high conformation with IMRT
   - ❑ the most diffused option in radiotherapy treatments
2. **Hadrontherapy (maily proton-therapy)**
   - ❑ more suitable for radioresistant tumors
   - ❑ higher conformation (intrinsic/Bragg Peak)
     - ❑ tumor near critical organs
   - ❑ about 40 centers around the world
3. **Others: BNCT (neutron), (Pion Therapy)**



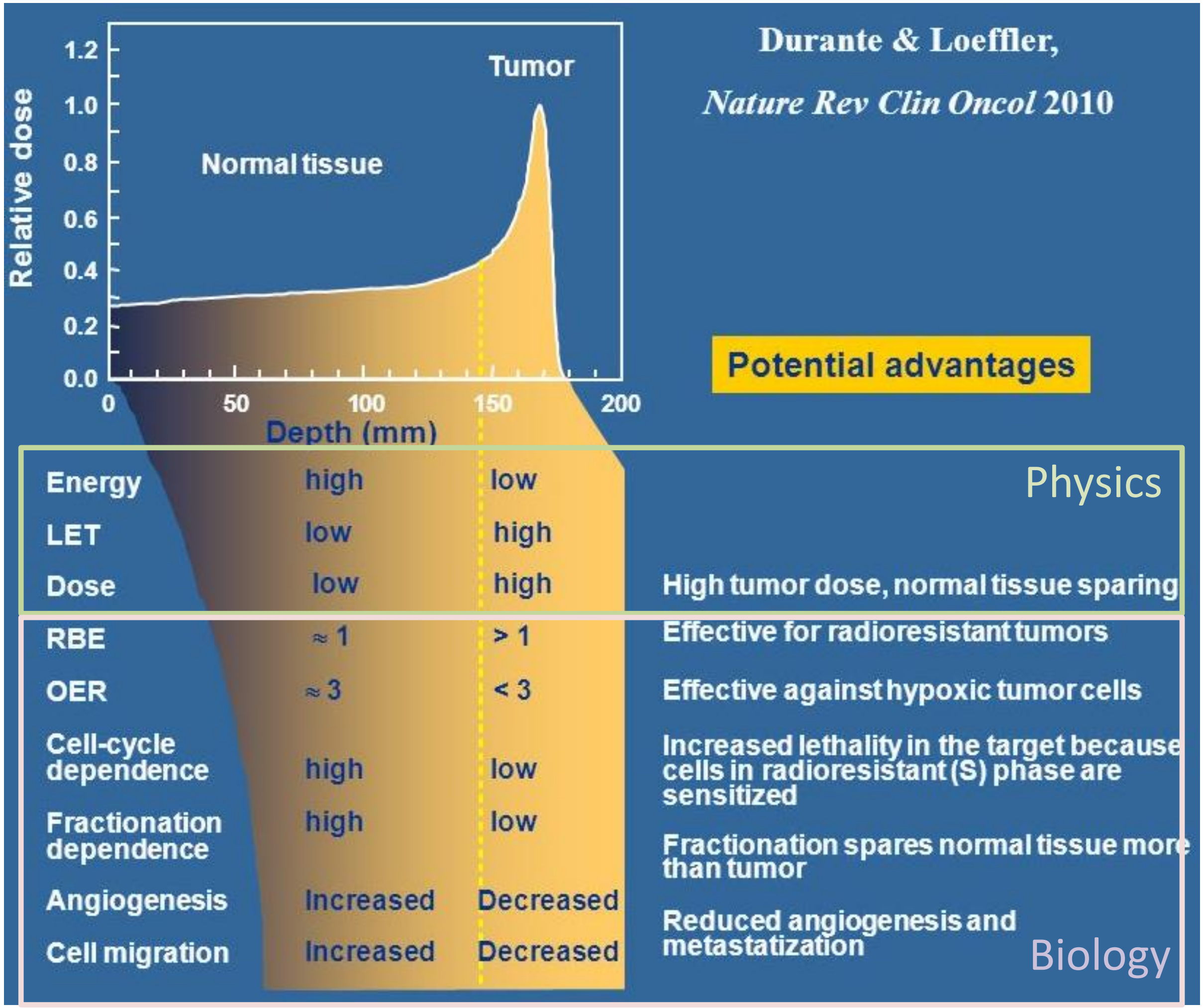


G. Kraft, GSI, Biophysik, Darmstadt
and J. Debus, DKFZ, Heidelberg


(a) Desired dose profile
(b) Photon therapy
(c) Proton therapy
(d) Carbon-ion therapy
Dose [%]
120
100
80
60
40
20
0
2
4
6
8
10
12
14
Depth [cm]
Tumour
Critical organ
Entry channel

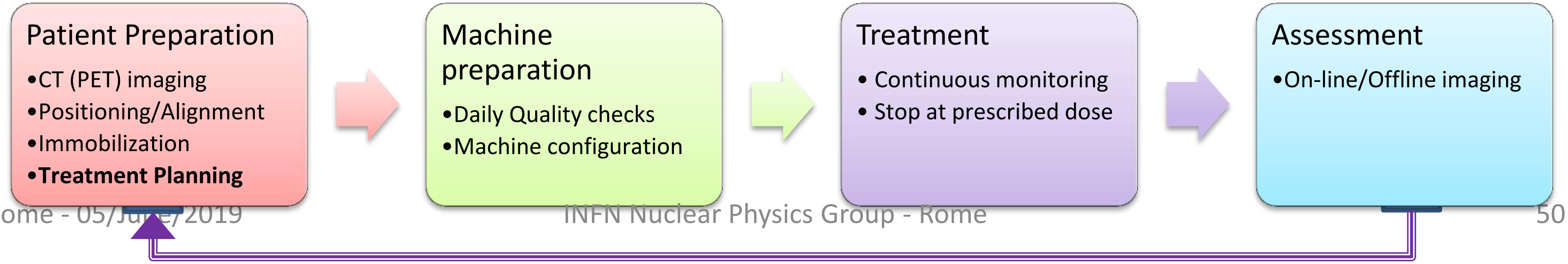
Physics-Biology-Clinics Interplay

Clinical outcomes depend on how well we **know** and **control** the physics and biological processes involved in the hadron therapy and how **make them happen**



Durante & Loeffler, *Nature Rev Clin Oncol* 2010

			Potential advantages
Energy	high	low	
LET	low	high	
Dose	low	high	High tumor dose, normal tissue sparing
RBE	≈ 1	> 1	Effective for radioresistant tumors
OER	≈ 3	< 3	Effective against hypoxic tumor cells
Cell-cycle dependence	high	low	Increased lethality in the target because cells in radioresistant (S) phase are sensitized
Fractionation dependence	high	low	Fractionation spares normal tissue more than tumor
Angiogenesis	Increased	Decreased	Reduced angiogenesis and metastatization
Cell migration	Increased	Decreased	



Patient Preparation
- CT (PET) imaging
- Positioning/Alignment
- Immobilization
- **Treatment Planning**

Machine preparation
- Daily Quality checks
- Machine configuration

Treatment
- Continuous monitoring
- Stop at prescribed dose

Assessment
- On-line/Offline imaging

FOOT in pills

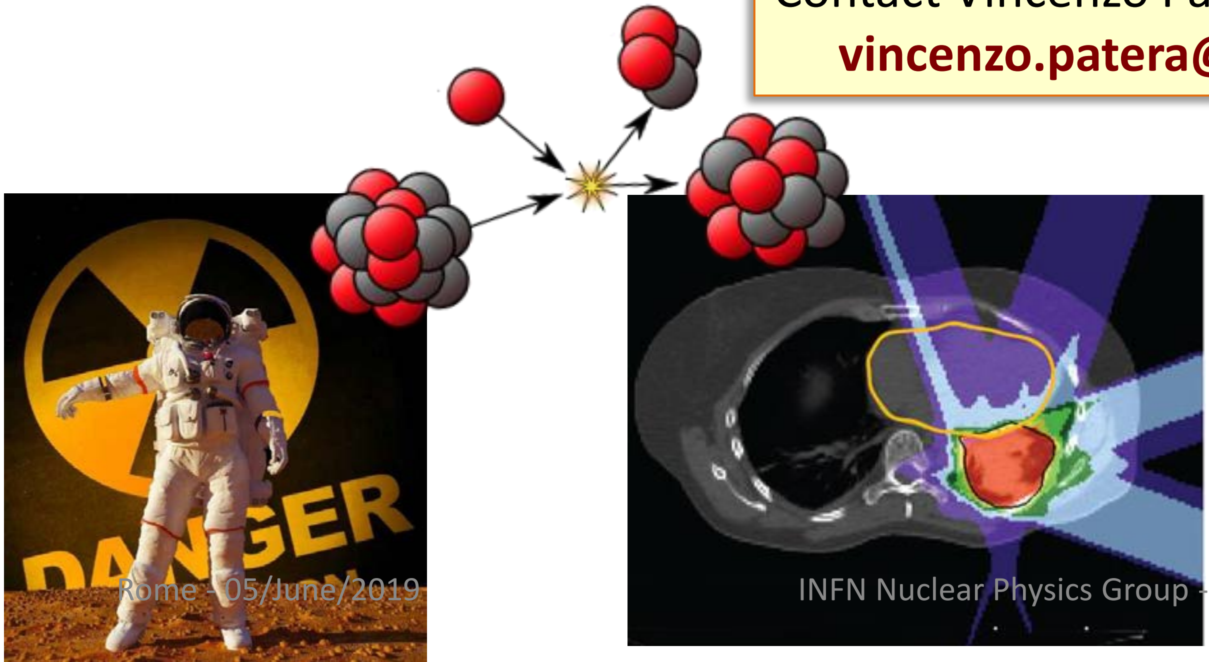
Bologna, Frascati, Milano, Napoli, Perugia, (Pavia), Pisa, Roma1, Roma2, Torino, Trento

Strasbourg, GSI, Aachen, Nagoya

People: ~70 researcher, ~27 FTE

Data taking 2018-2021@ GSI, Heidelberg, CNAO

Contact Vincenzo Patera
vincenzo.patera@roma1.infn.it

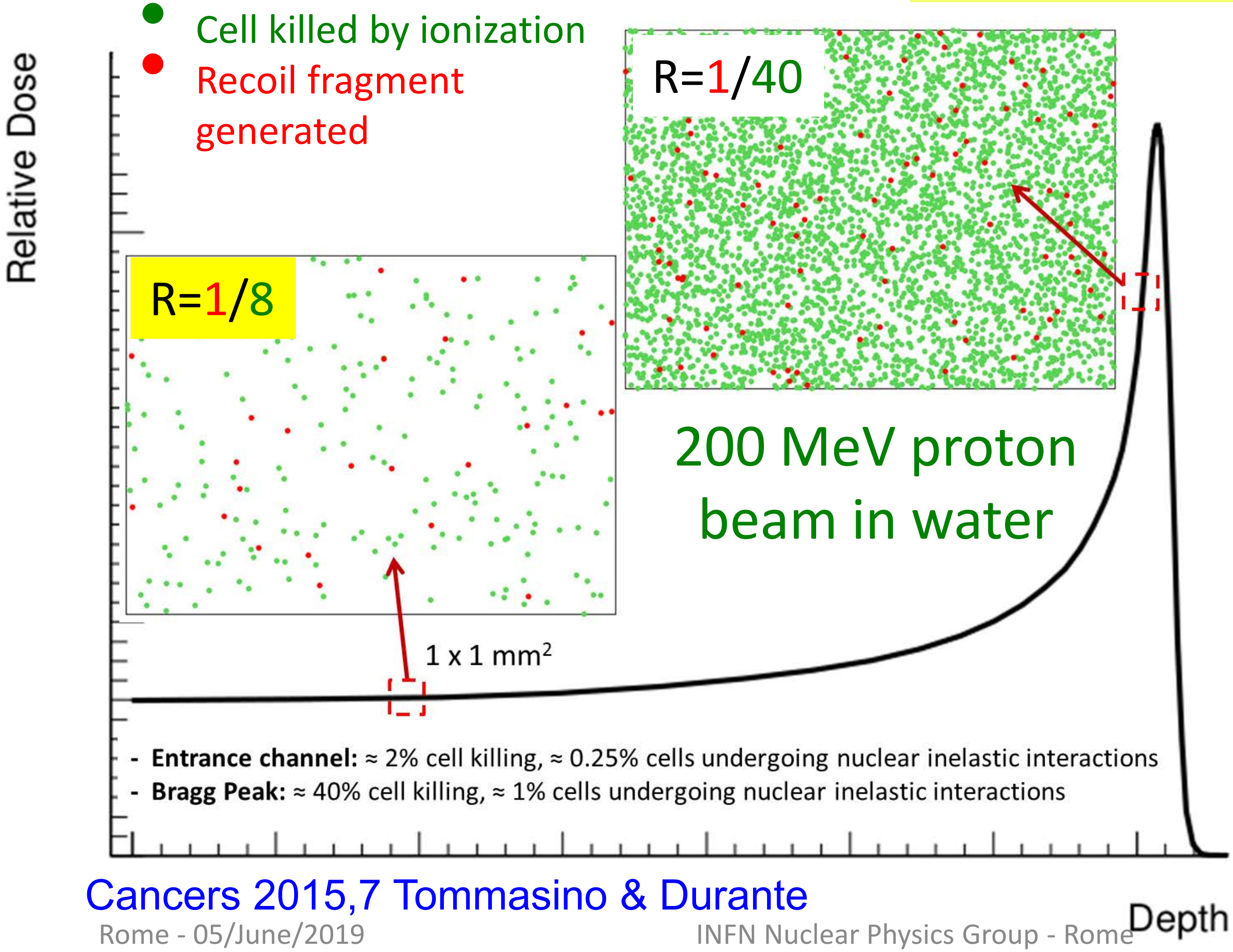


Experiment with translational approach: focus on nuclear physics, physics applied to medicine and radioprotection in space

Motivations: Target fragmentation in proton Therapy

This process gives contribution also outside the tumor region and change the proton RBE

p ➔ ^{12}C,^{16}O @ 150-200 MeV



- ● Cell killed by ionization
- ● Recoil fragment generated

- **Entrance channel:** ≈ 2% cell killing, ≈ 0.25% cells undergoing nuclear inelastic interactions
- **Bragg Peak:** ≈ 40% cell killing, ≈ 1% cells undergoing nuclear inelastic interactions

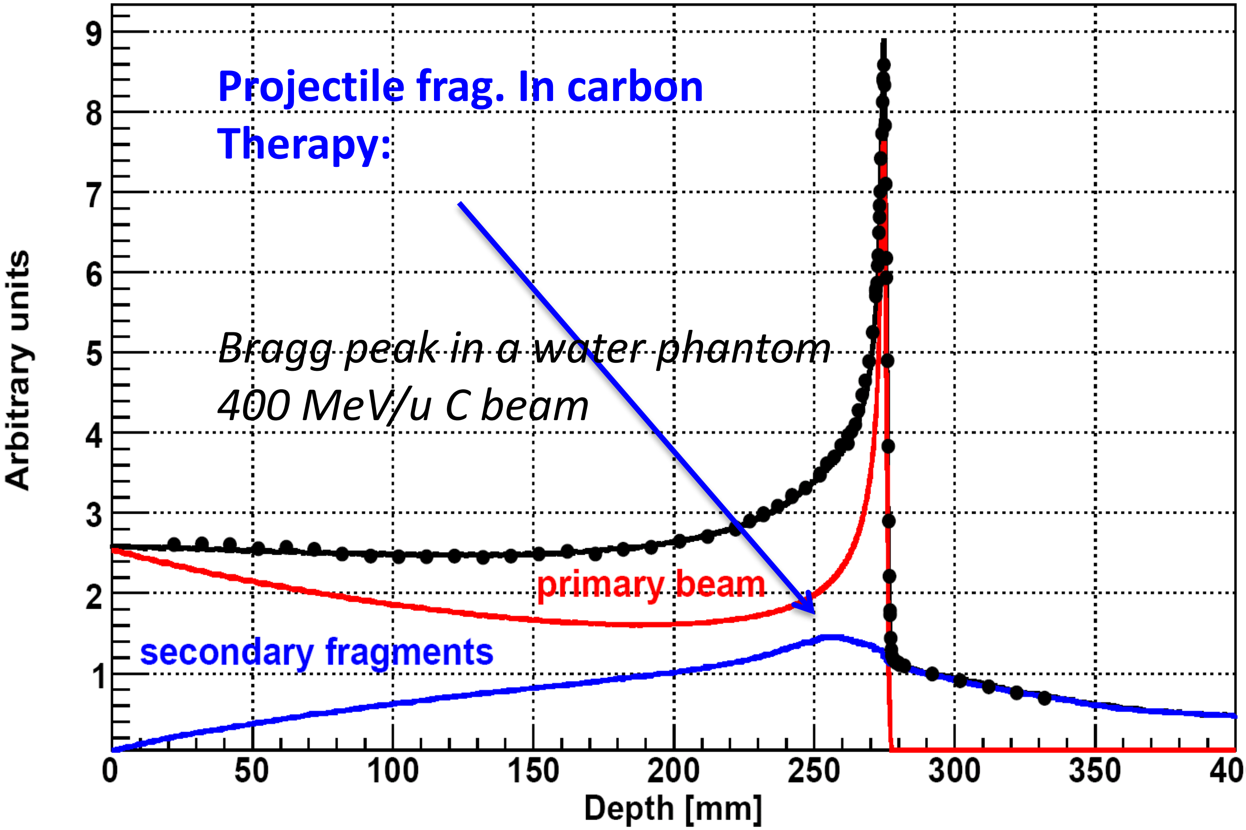
Cancers 2015,7 Tommasino & Durante

About 10% of biological effect in the entrance channel due to secondary fragments (Grun 2013)

Largest contributions of recoil fragments expected from
He, C, Be, O, N
In particular on Normal Tissue Complication Probability
See also :
- Paganetti 2002 PMB
- Grassberger 2011 PMB

Motivations: beam frag. in light ion Therapy

Effect of beam Fragmentation already known to produce mixed particle field of different RBE/LET. Considered in ^{12}C treatment, but still scarce validation data!



Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006

Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Effect to be taken under control also with the new beams in use: ^{4}He, ^{16}O

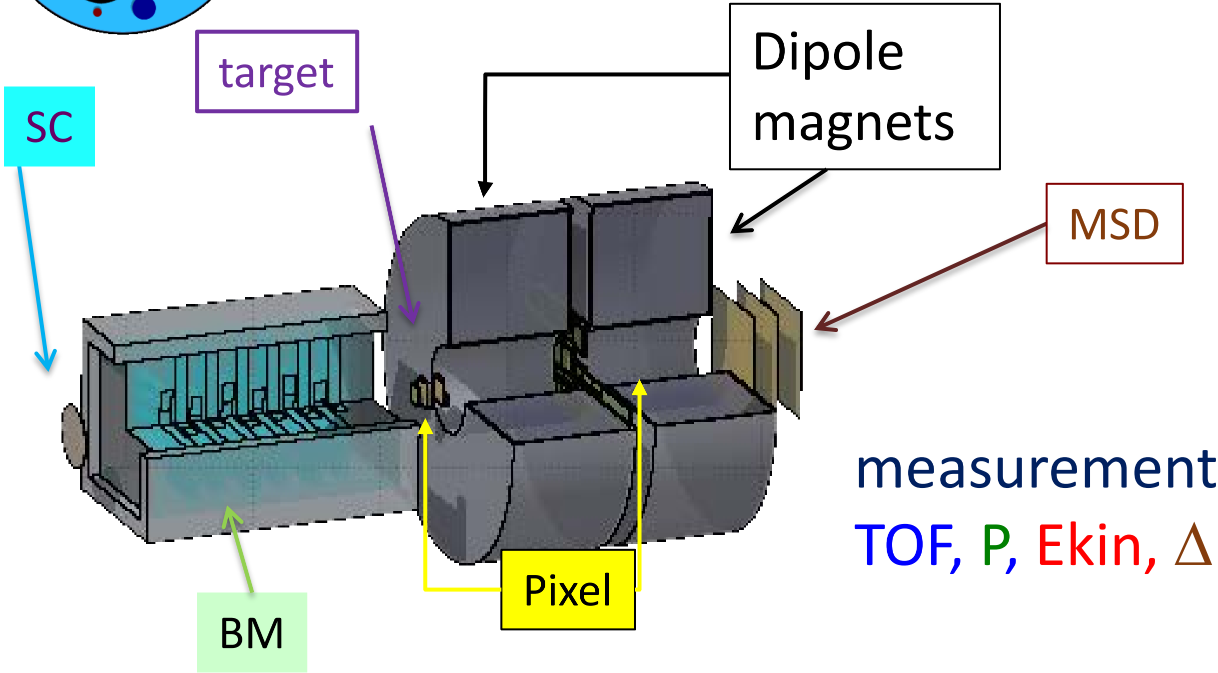
Data useful for TPS

^{12}C ➔ ^{12}C, ^{16}O, H @ 350 MeV/u

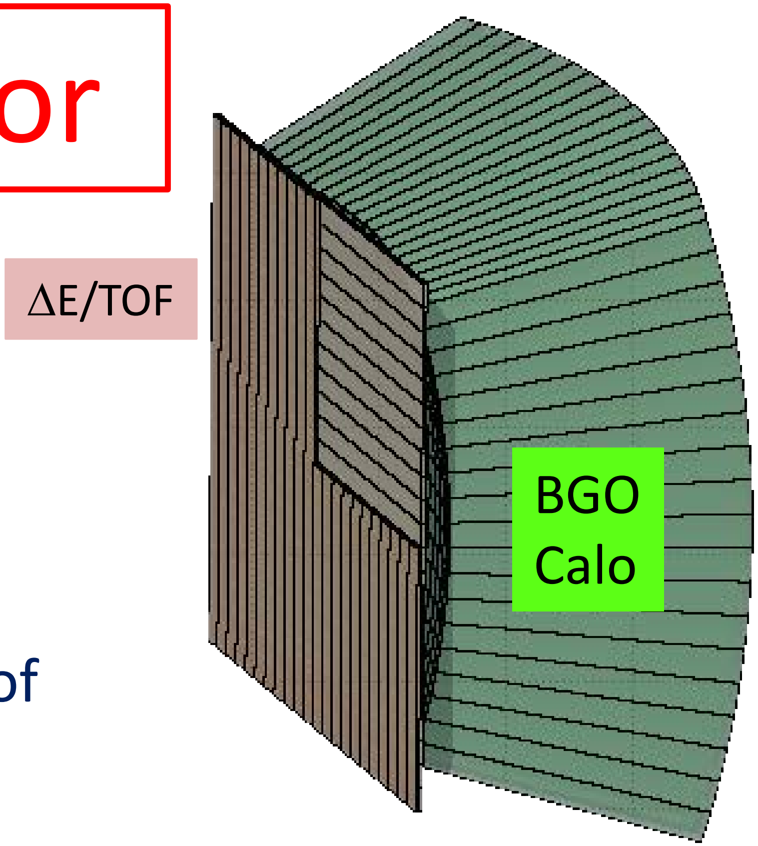
^{16}O ➔ ^{12}C, ^{16}O, H @ 400 MeV/u

^{4}He ➔ ^{12}C, ^{16}O, H @ 250 MeV/u

Electronic Detector



measurements of
TOF, P, Ekin, ΔE



Length < 2.5 meters

- ✓ Start Counter = thin plastic scintillator
- ✓ Beam Monitor = drift chamber
- ✓ Vertex detector = silicon pixel detector
- ✓ Inner Tracker = silicon pixel detector
- ✓ Large tracker = silicon micro strip detector
- ✓ ΔE/TOF Detector = plastic scintillator
- ✓ Calorimeter = BGO crystal calorimeter

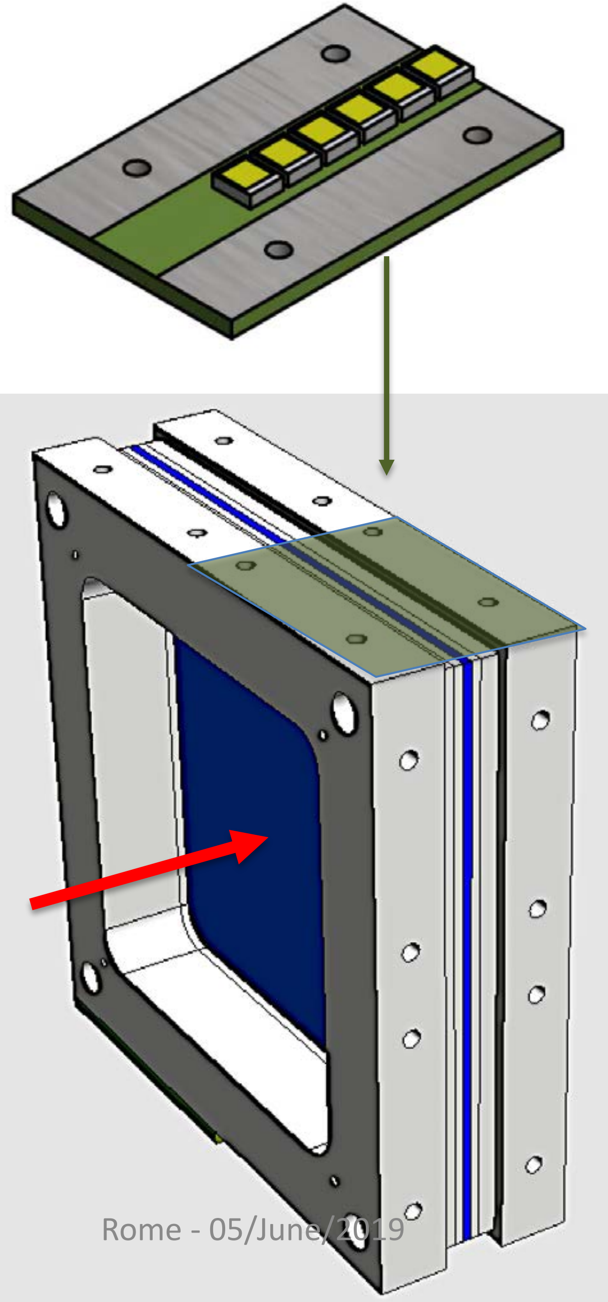
performances @200MeV/u:

$\int_{p}/p$ ~4%

$\int_{TOF}$ ~ 70 ps

$\int_{Ekin}/Ekin$ ~ 2%

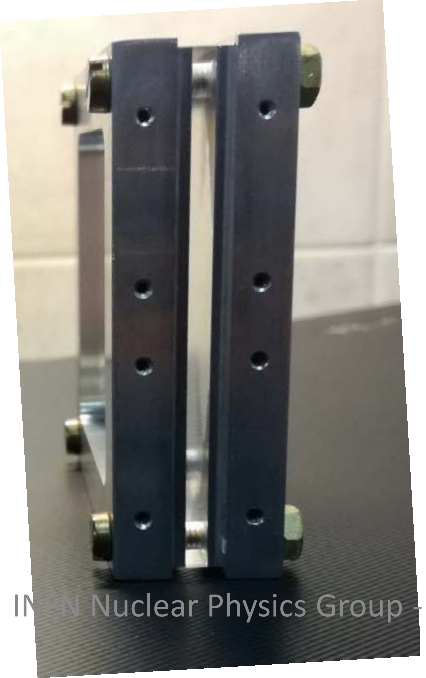
TOF and the Start Counter @ RM1

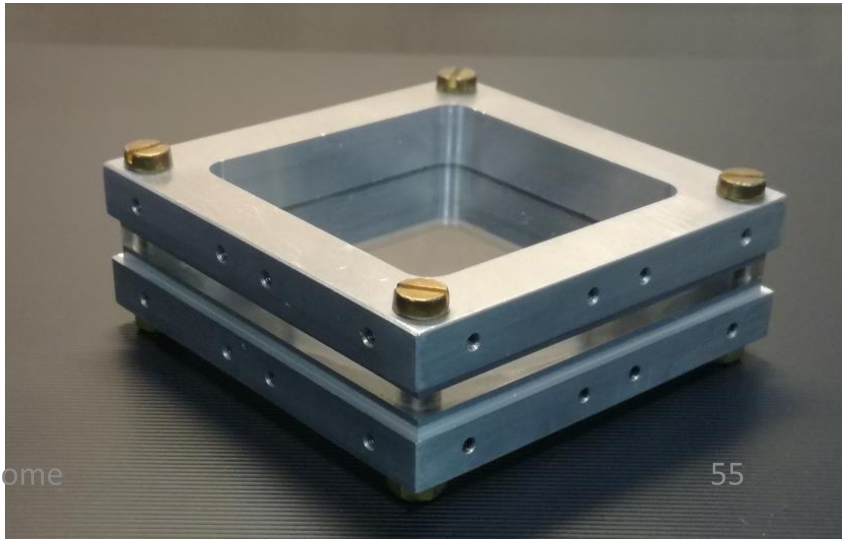


Margarita Detector :

- 250 μm plastic scintillator read out by 48 SiPM (12/side) to improve light collection
- Should improve the time resolution to readout limit ~ 30-40 ps
- Needed for measurements @ 700 MeV/u
- Test beam at CNAO carbon

Contact: Vincenzo Patera
Vincenzo.Patera@roma1.infn.it





!Grant opportunity! Nuclear Physics in Lab

- CSN3 has lauched 2+ grants for master students («laureandi magistrali») and young physicist («neolaureati»)
- The grants consists of 3 month stage in one of the internationaly laboratories where the CSN3 experimental activities are carried on
- Second applications submission deadline June/24th/2019

https://reclutamento.infn.it/ReclutamentoOnline/#!bandi/BORSE

Consider also: thesis grants (for all CSN) are going to be funded by the Rome INFN!

INFN Gruppo3 - Rome – Experiments and contacts

Phase transitions of nuclear and hadronic matter

CERN

ALICE

A JOURNEY OF DISCOVERY

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Quarks and Hadrons Dynamics

JLAB (VA)

e⁻ JLab12

(EIC)

fuido.maria.urciuoli@roma1.infn.it
evaristo.cisbani@roma1.infn.it

Mainz, Bonn,(GE)

MAMiBOnn

Collaboration

francesco.ghio@roma1.infn.it

Interdisciplinary research

vincenzo.patera@roma1.infn.it

FOOT

(Europa)

Nuclear Astrophysics ...

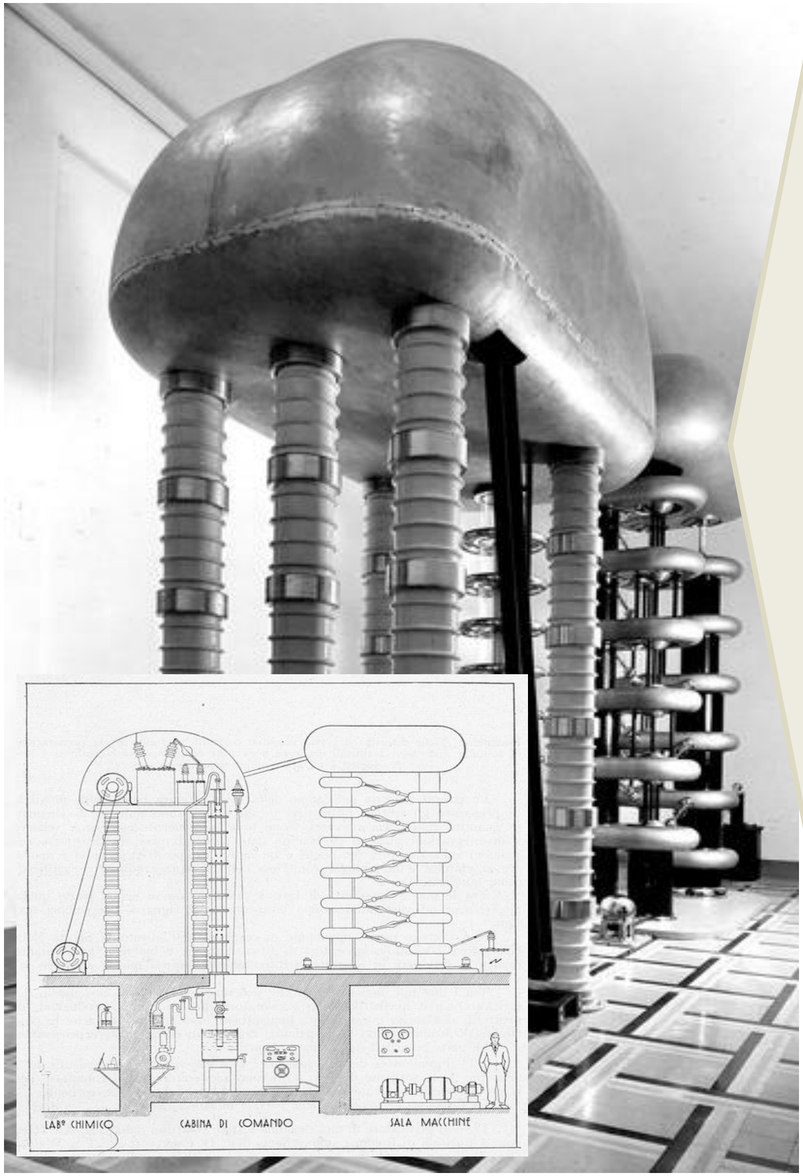
Laboratory
Underground
Nuclear
Astrophysics

carlo.gustavino@roma1.infn.it

Laboratori Gran Sasso

«Healthy» digression

Cockcroft–Walton @ ISS



Now on show at the entrance hall of the INFN central administration building in Frascati National Lab

The **first Italian particle accelerator** (1 MV). Designed by «via Panisperna boys» with strong endorsment from E. Fermi. It began operation in 1939 at the Italian Institute of Public Health (now Italian National Institute of Health)

The accelerator has been promoted and exploited for **medical applications** (e.g. radiopharmaceutical production) and **nuclear physics experiments**

Molecular imaging with radionuclides in ISS/TISP

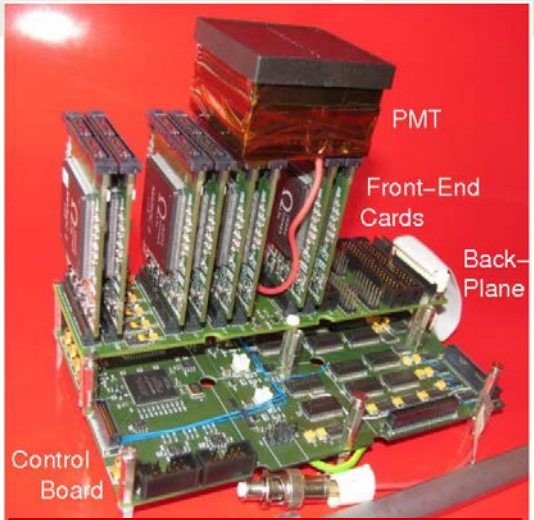
Nuclear Medicine

Compact, dual head, scintimammography

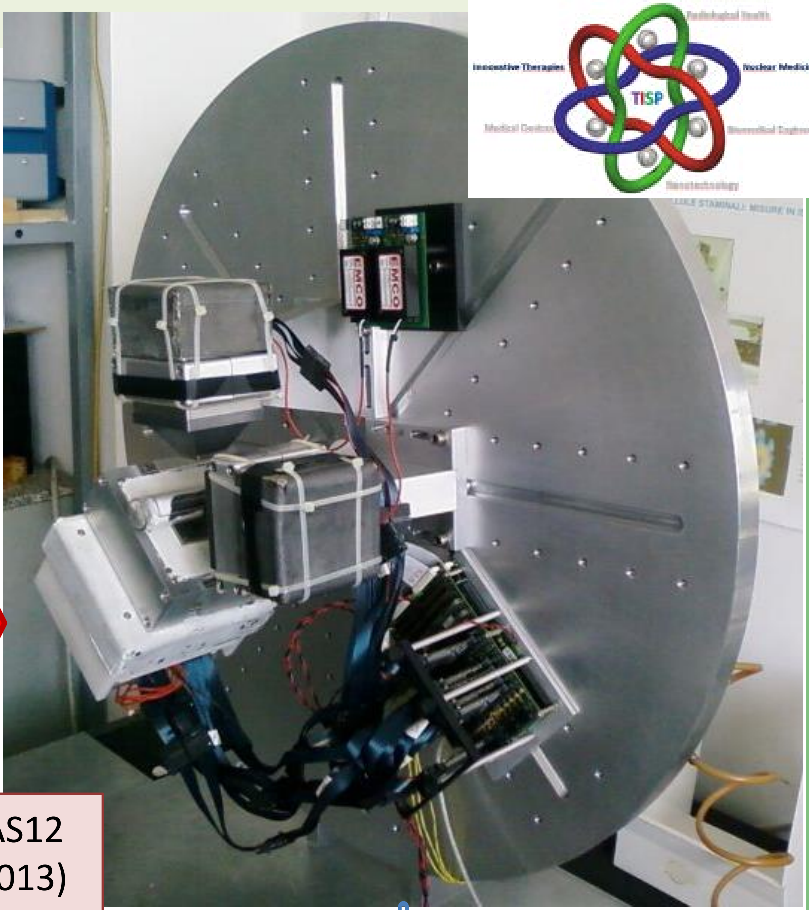
- Early diagnosis of breast cancer
- Breast compression and dual modal system

Open, multi-heads SPECT system

- Therapeutic effectiveness of stem cell in stroke induced heart disease
- Atherosclerotic plaques identification



Custom electronics with advanced features
INFN collaboration



A RICH detector for CLAS12 (CLASMED / premiale 2013)

Pre-production engineering of the MBI device (MBI/Regione Lazio)

Endorectal probe for prostate cancer (TOPEM)

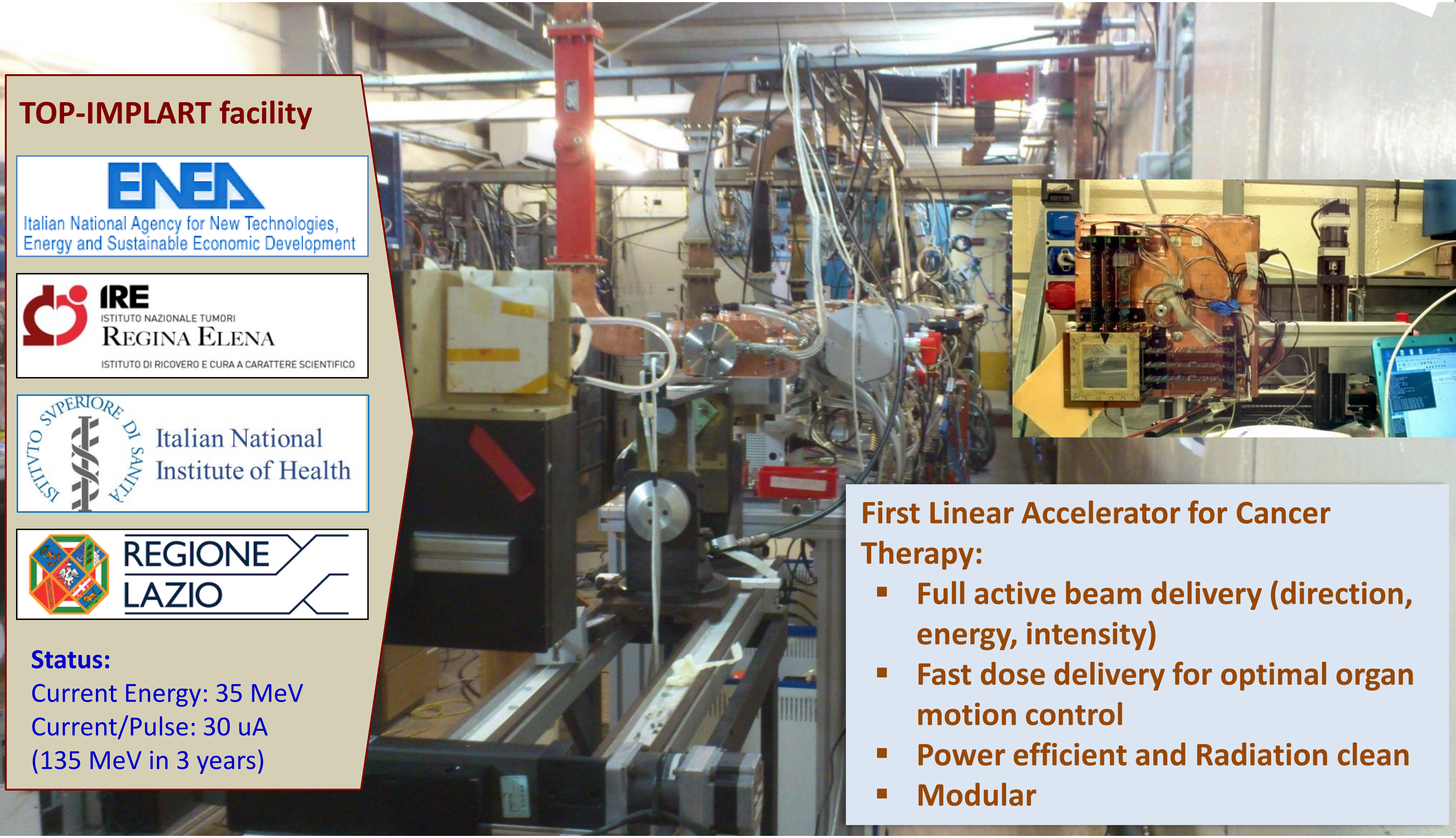
Imaging of beta-radiopharmaceuticals (MetroMRT)

Development of new beta-radiopharmaceuticals (Sondarm)

Contact: evaristo.cisbani@roma1.infn.it

p-LinAc for Cancer Therapy becoming real

Radiotherapy



TOP-IMPLART facility

ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

IRE
ISTITUTO NAZIONALE TUMORI
REGINA ELENA
ISTITUTO DI RICOVERO E CURA A CARATTERE SCIENTIFICO

ISTITUTO SUPERIORE DI SANITÀ
Italian National Institute of Health

REGIONE LAZIO

Status:
Current Energy: 35 MeV
Current/Pulse: 30 uA
(135 MeV in 3 years)

First Linear Accelerator for Cancer Therapy:

- **Full active beam delivery (direction, energy, intensity)**
- **Fast dose delivery for optimal organ motion control**
- **Power efficient and Radiation clean**
- **Modular**

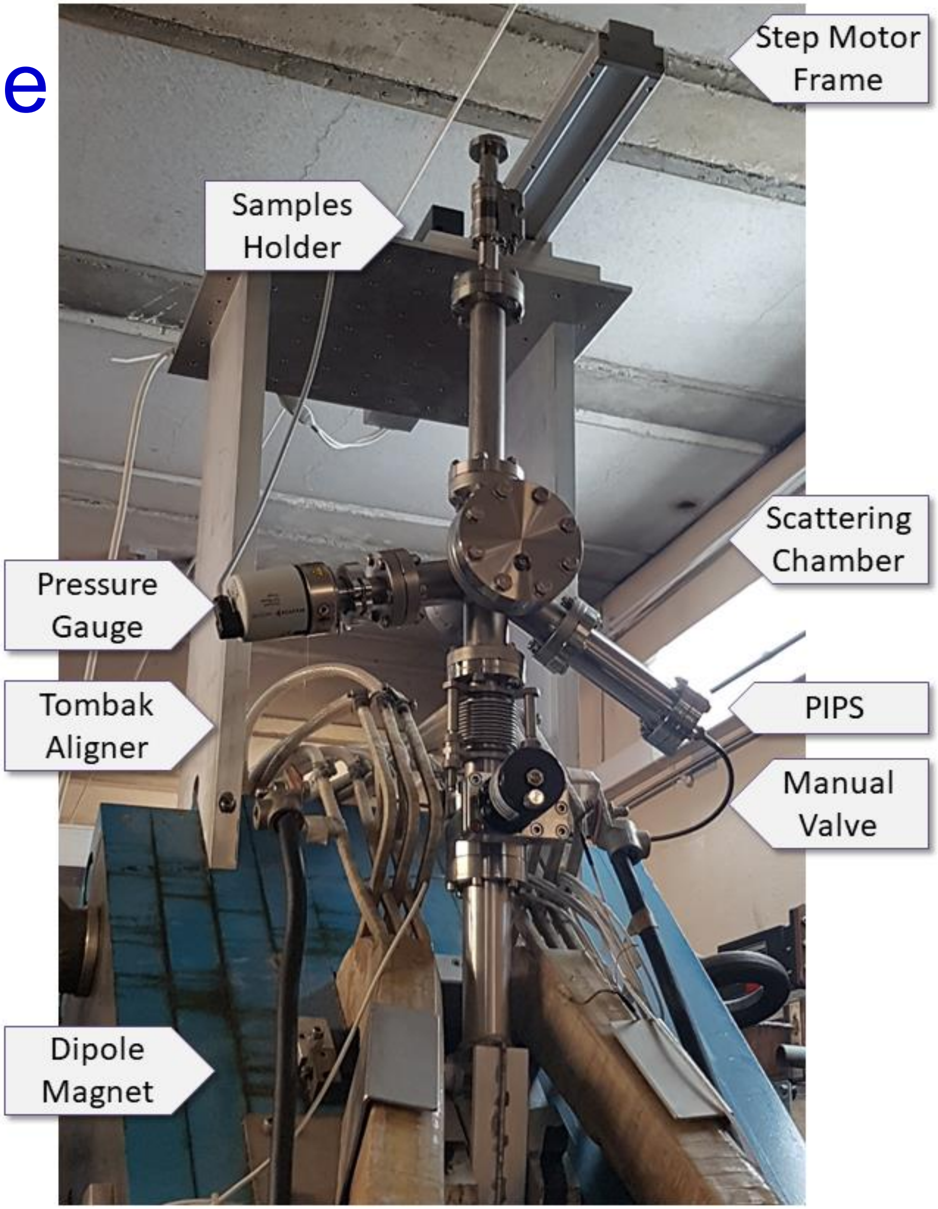
Activities on development of beam diagnostic detectors, **Dose Delivery Monitor**, unique low energy vertical line for radiobiology …

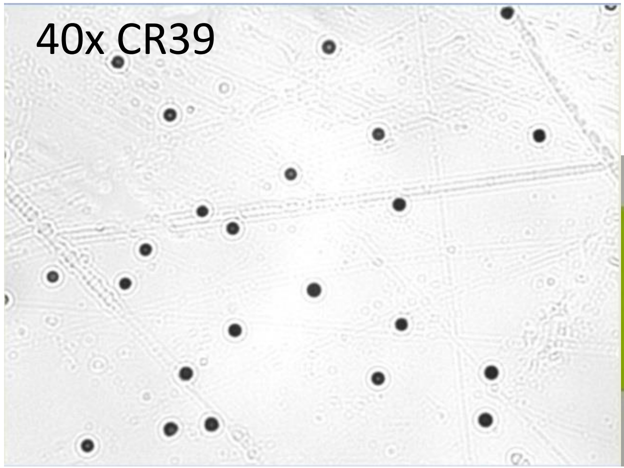
Contact: evaristo.cisbani@roma1.infn.it

Low Energy proton vertical line

- Peculiar facility
- Mandatory to investigate optimal delivery protocols of a the unique LinAc beam
- Conceptually very simple but technically demanding

Activity on the development of a fluence monitor based on Si-detector and nuclear elastic scattering





4-6 MeV protons

Jan/2019: GAF with single pulses «picture»