Present and future of direct search for dark matter with NaI(Tl) scintillators

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07/05/2025
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Foto: Valerio Toso
(Campo Imperatore)

Talk outline

1. Introduction
   a. Evidences of dark matter (slides courtesy of M. Cirelli)
   b. Direct search for dark matter
   c. The case for NaI(Tl) scintillators
2. SABRE status and prospective
3. ASTAROTH: R&D for the next generation

Executive summary

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- DM exists

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- it's a new, unknown corpuscule

dilutes as $1/a^3$ with universe expansion

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no SM particle can fulfil

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- DM exists
- it's a new, unknown particle
- makes up 26% of total energy
  82% of total matter

no SM particle can fulfil

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$$\Omega_{DM} h^2 = 0.120 \pm 0.001$$

(notice error!)

[Planck 2018, arXiv:1807.06209]

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  82% of total matter
- neutral particle

'dark'...

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$$\Omega_{DM}h^2 = 0.120 \pm 0.001$$

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[Planck 2018, arXiv:1807.06209]

- neutral particle — *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*

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  $$\tau_{\rm DM} \gg 10^{17} {\rm sec}$$

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- stable or very long lived
- possibly a relic from the EU

no SM particle can fulfil

dilutes as $1/a^3$ with universe expansion

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[Planck 2018, arXiv:1807.06209]

'dark'...

p/m <<1 at CMB formation

-with itself
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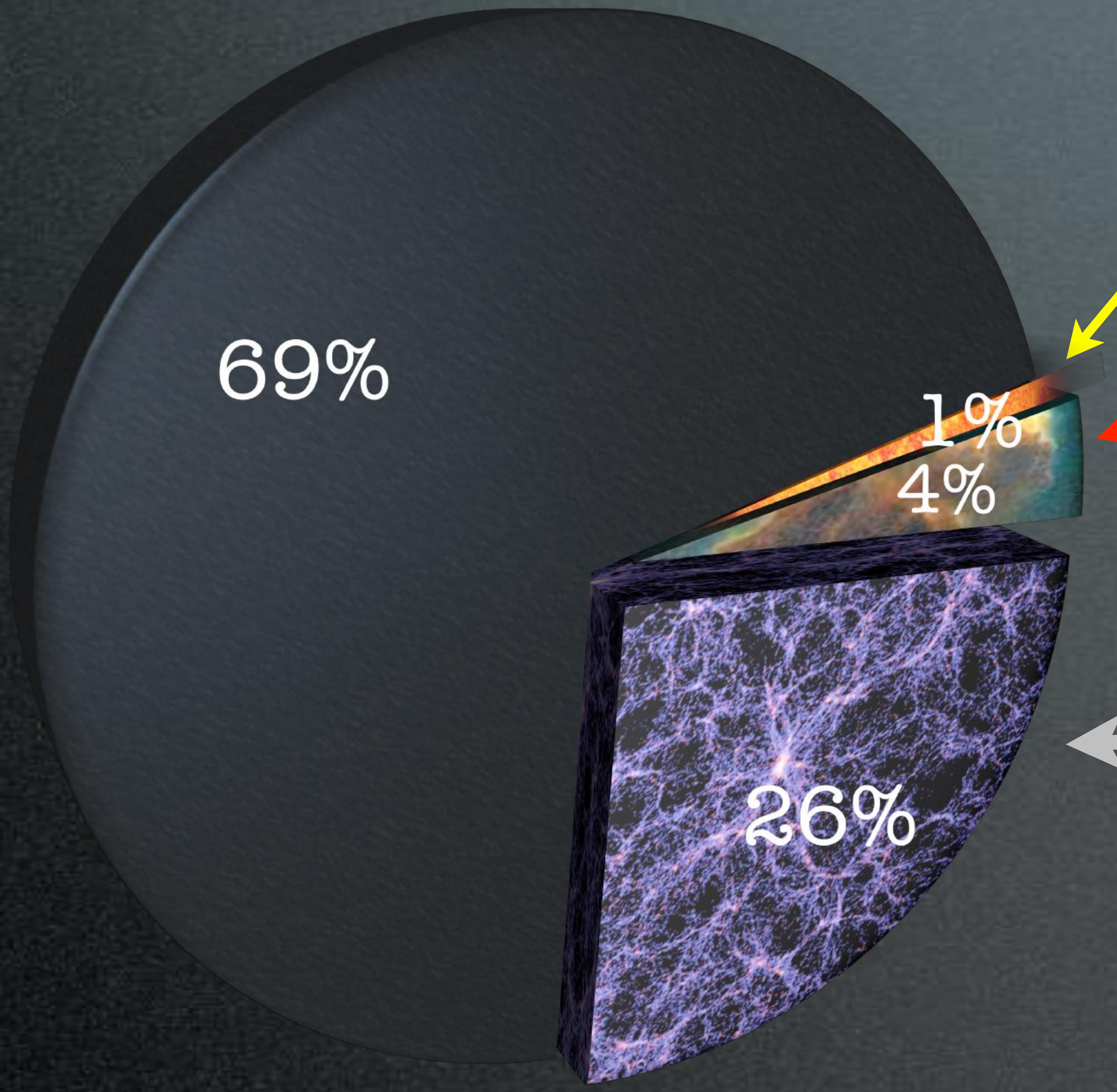
('collisionless')

$$\tau_{\rm DM} \gg 10^{17}{\rm sec}$$

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.26$

$\Omega_{\rm de} \sim 0.69$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07 \right)$

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How do we know that Dark Matter is out there?

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The Evidence for DM

1) galaxy rotation curves

2) clusters of galaxies

3) ‘precision cosmology’

The Evidence for DM

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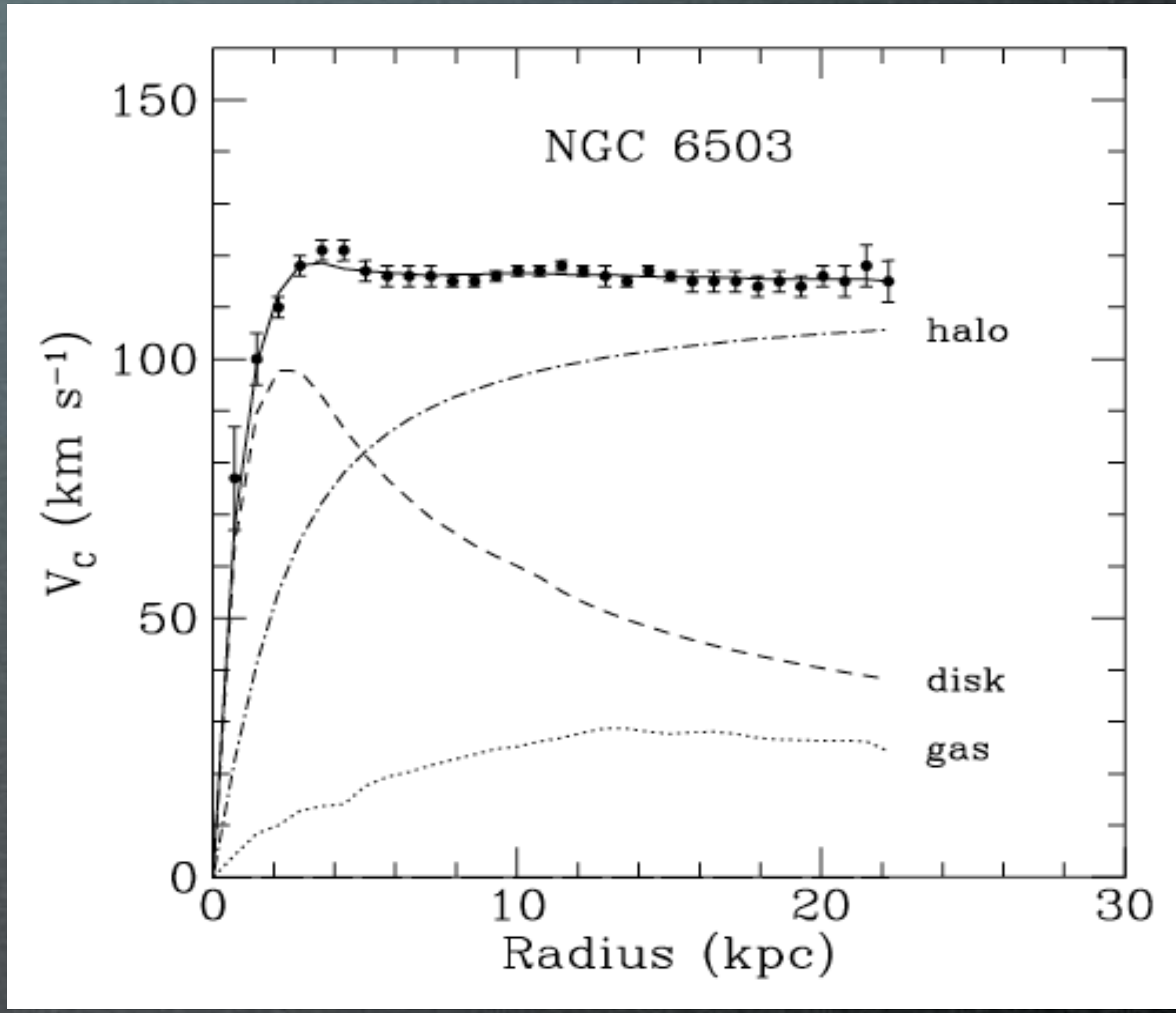
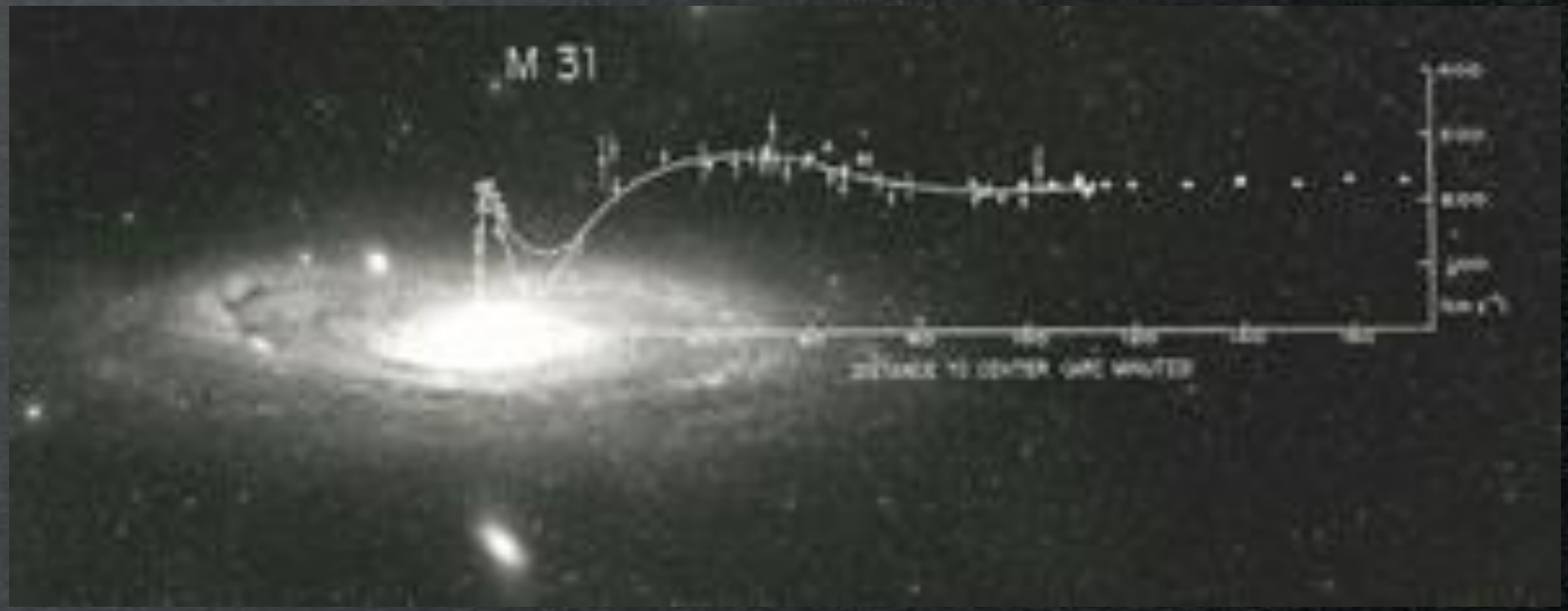


Begeman et al., MNRAS 249 (1991)

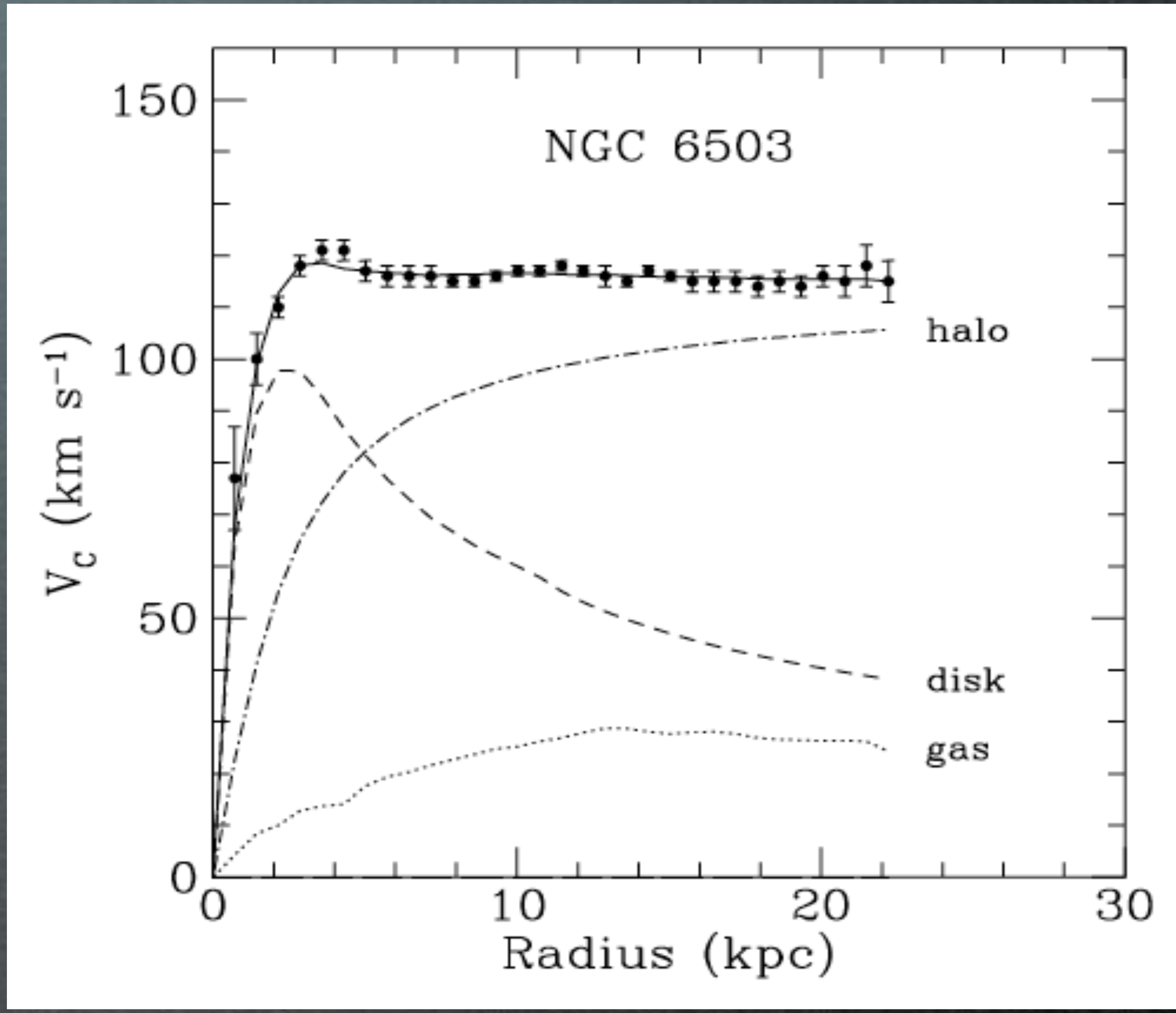


The Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

‘centrifugal’ ‘centripetal’



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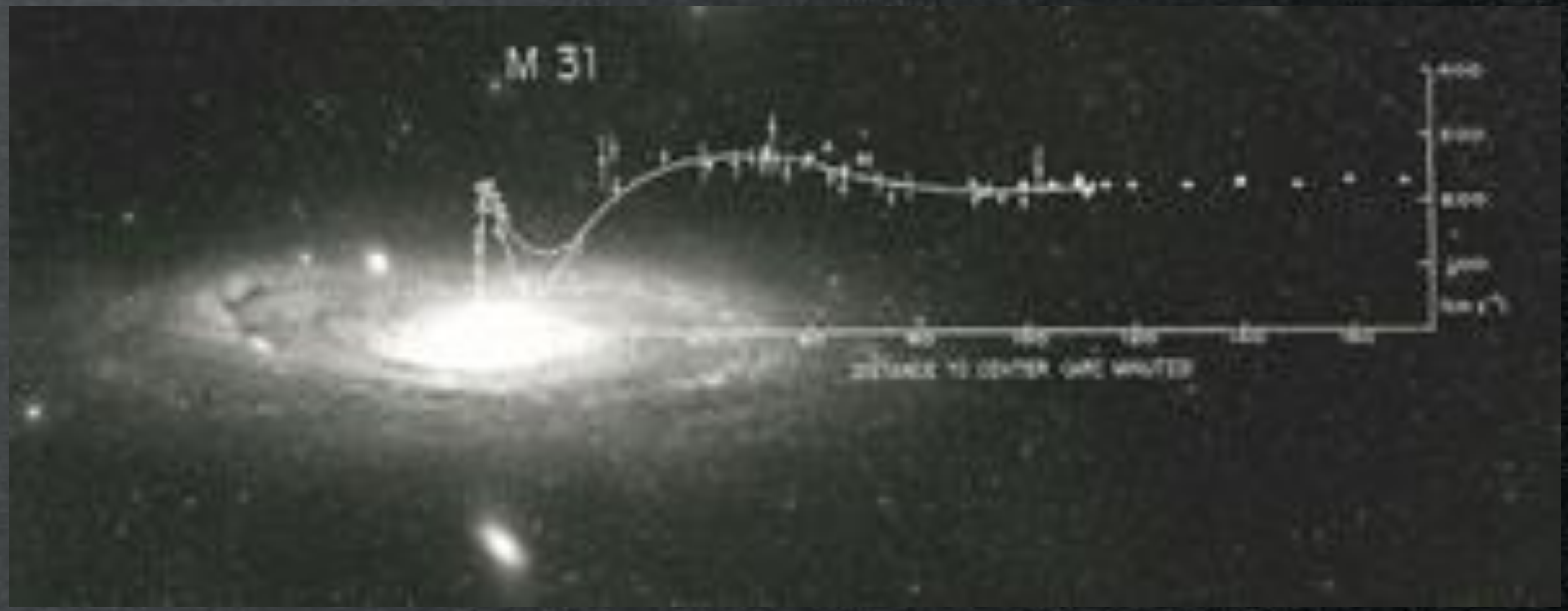

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$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

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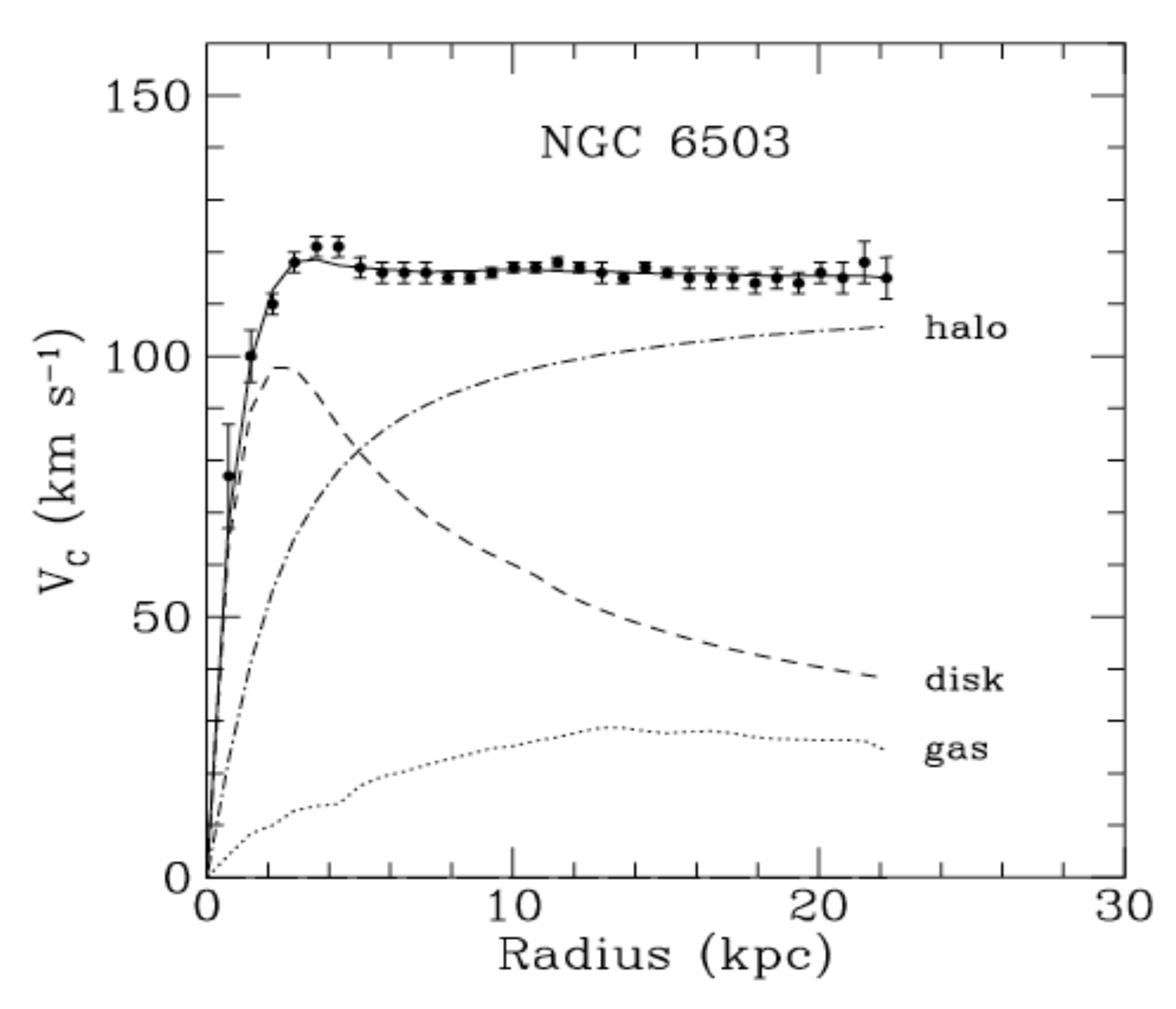
$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

and indeed a 'gas' of non-interacting particles distributes like $1/r^2$



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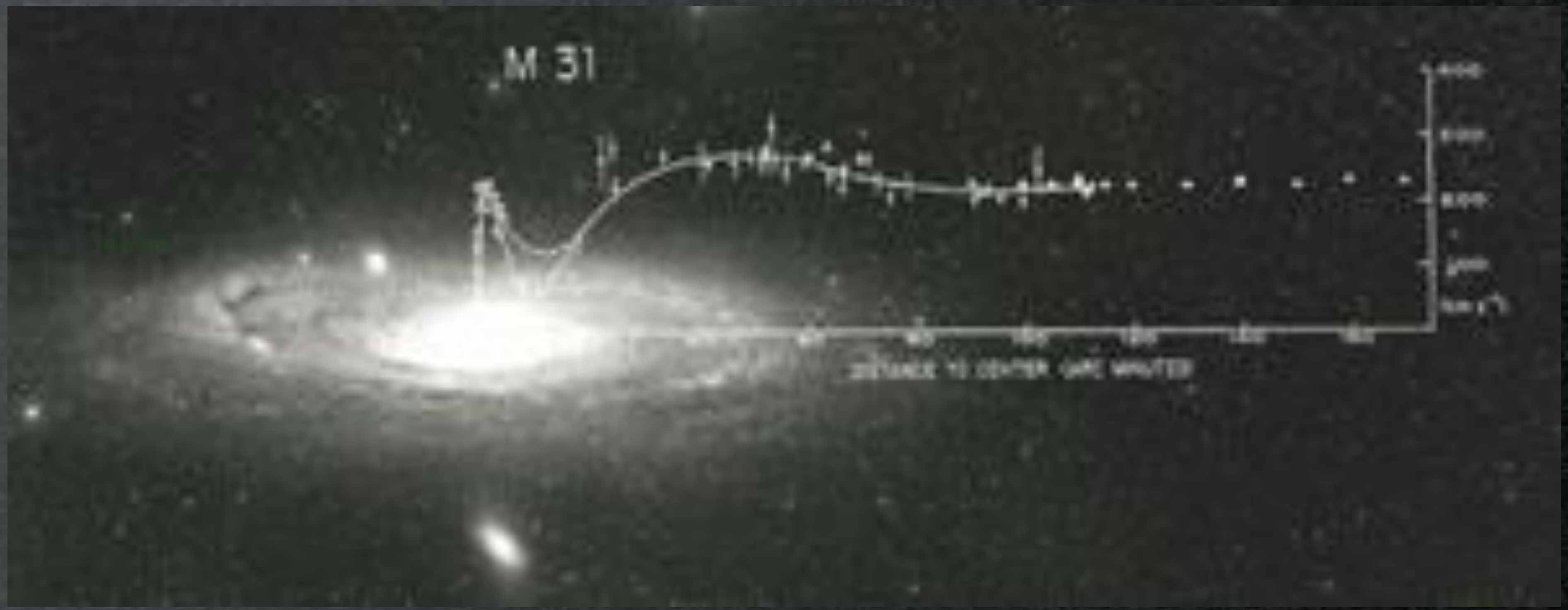

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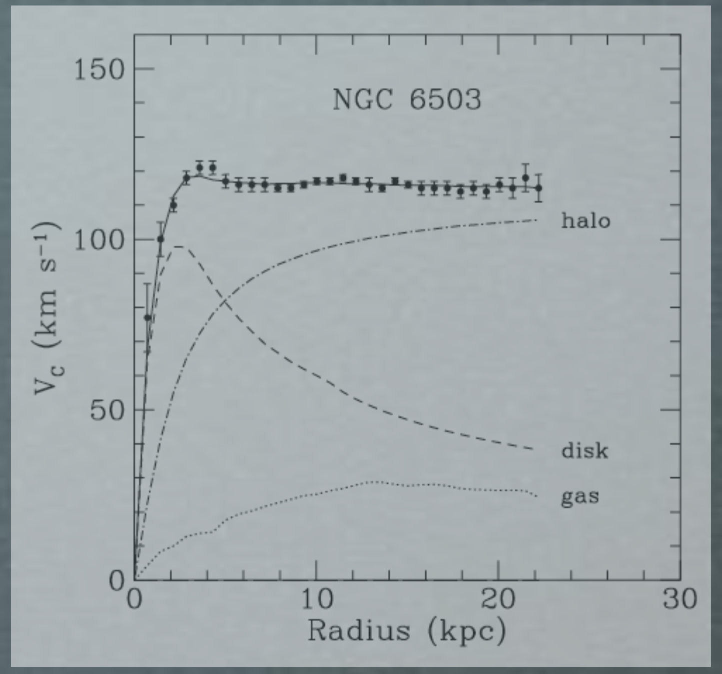

2) clusters of galaxies

- "rotation curves"
- gravitational lensing

"bullet cluster" - NASA
astro-ph/0608407

[further developments]

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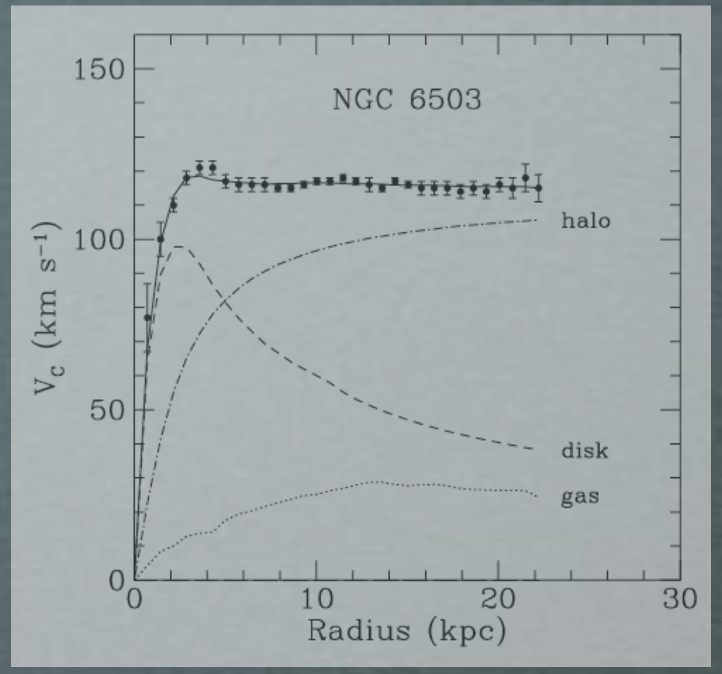

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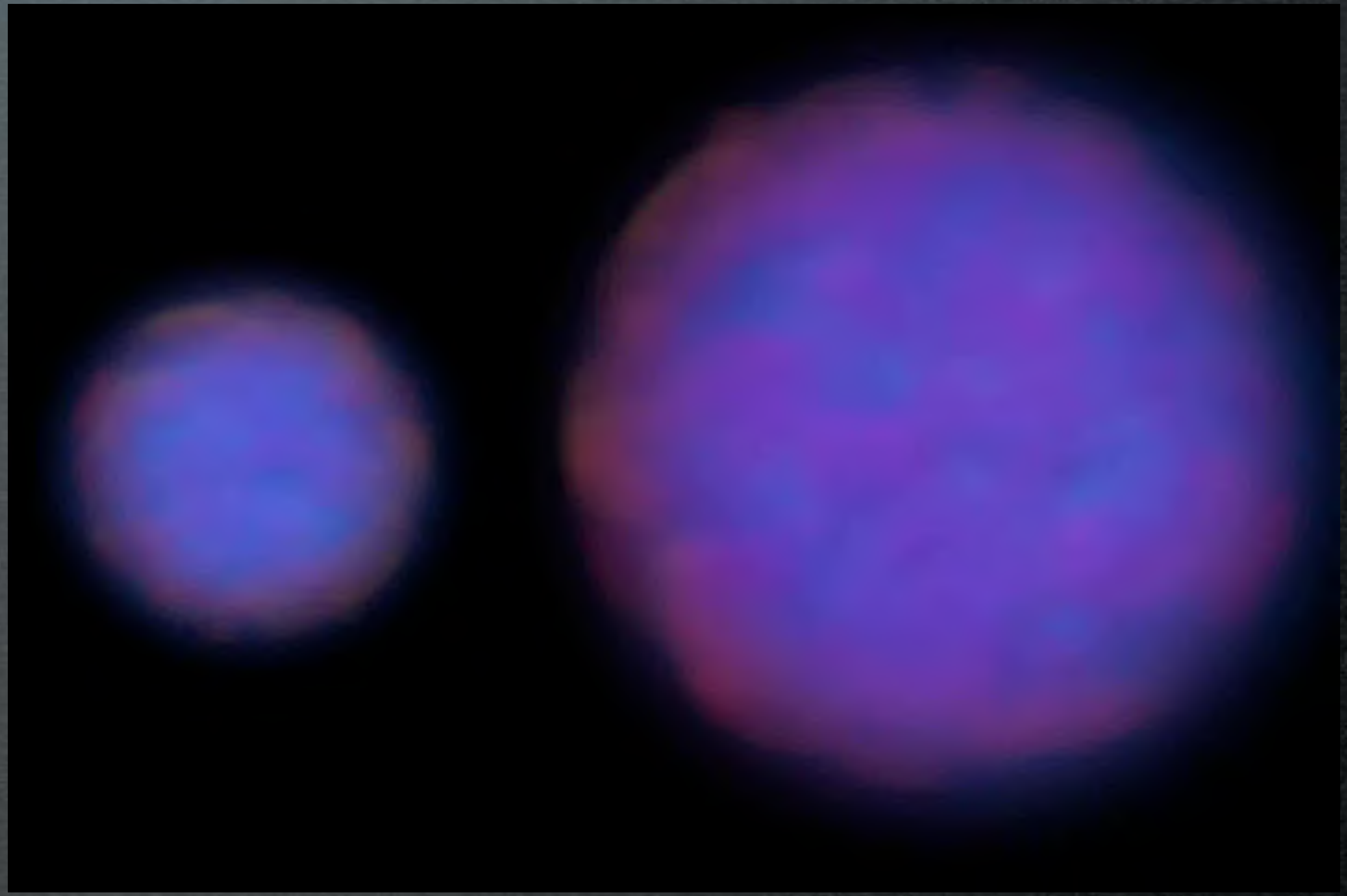

chandra.harvard.edu

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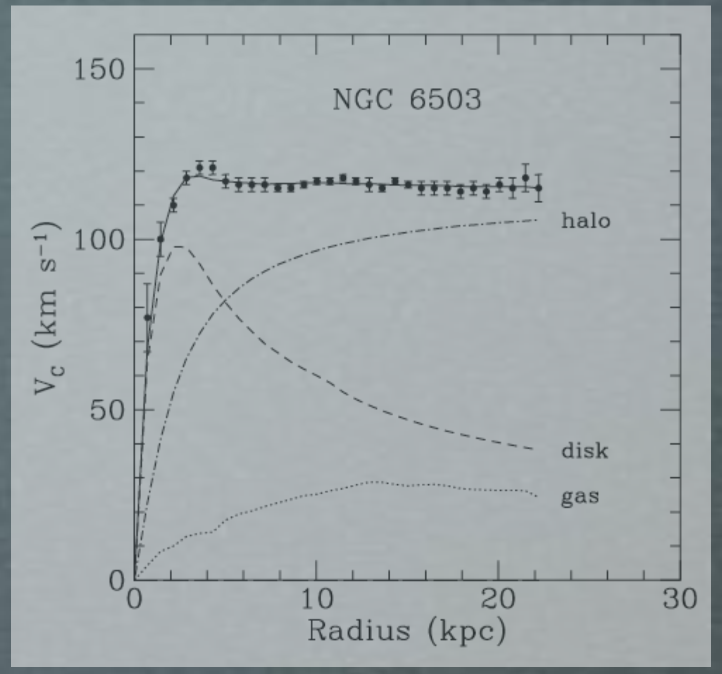

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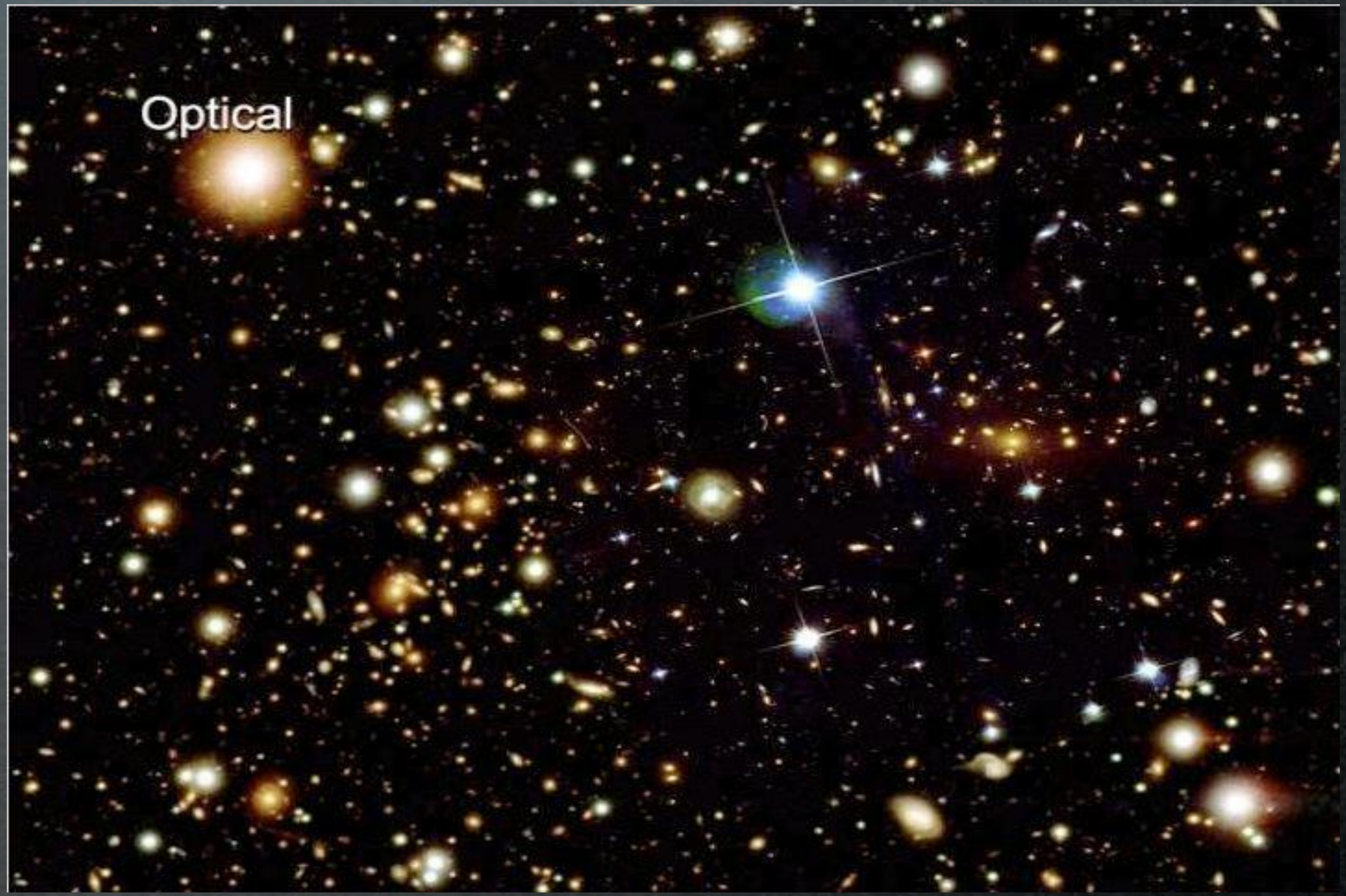

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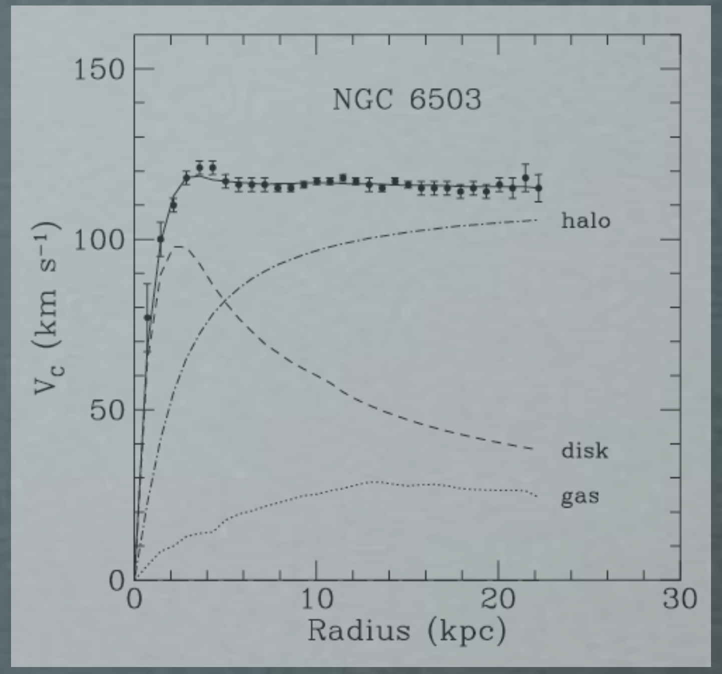

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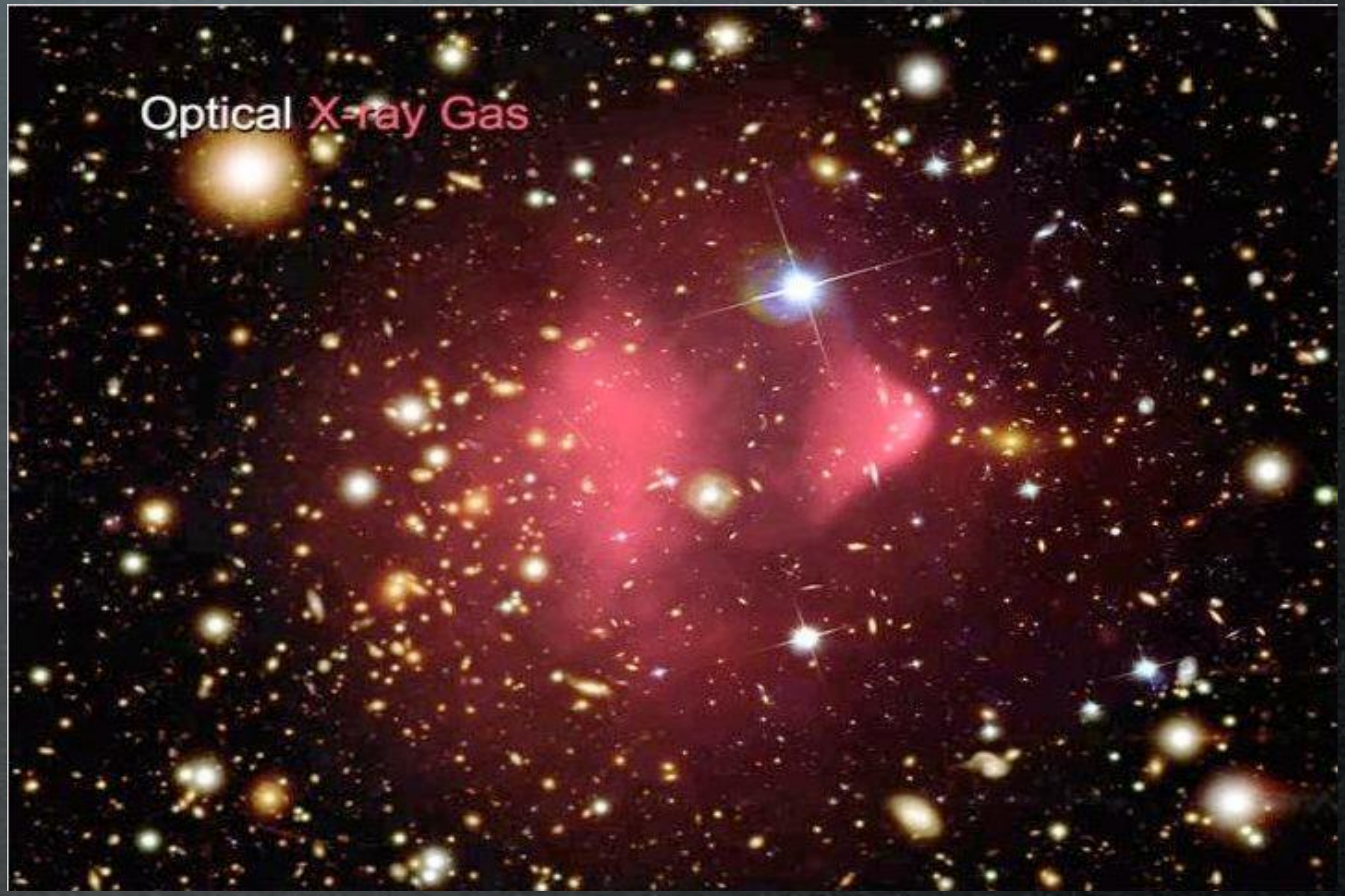

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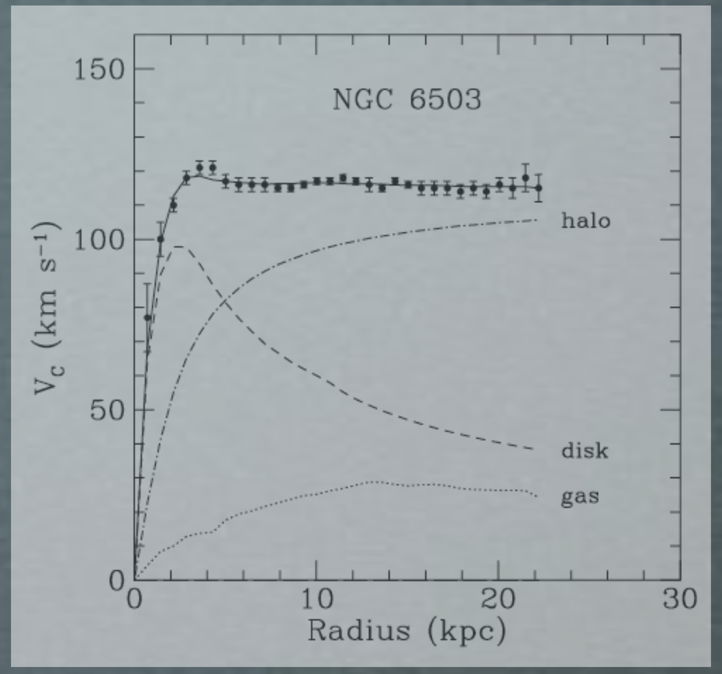

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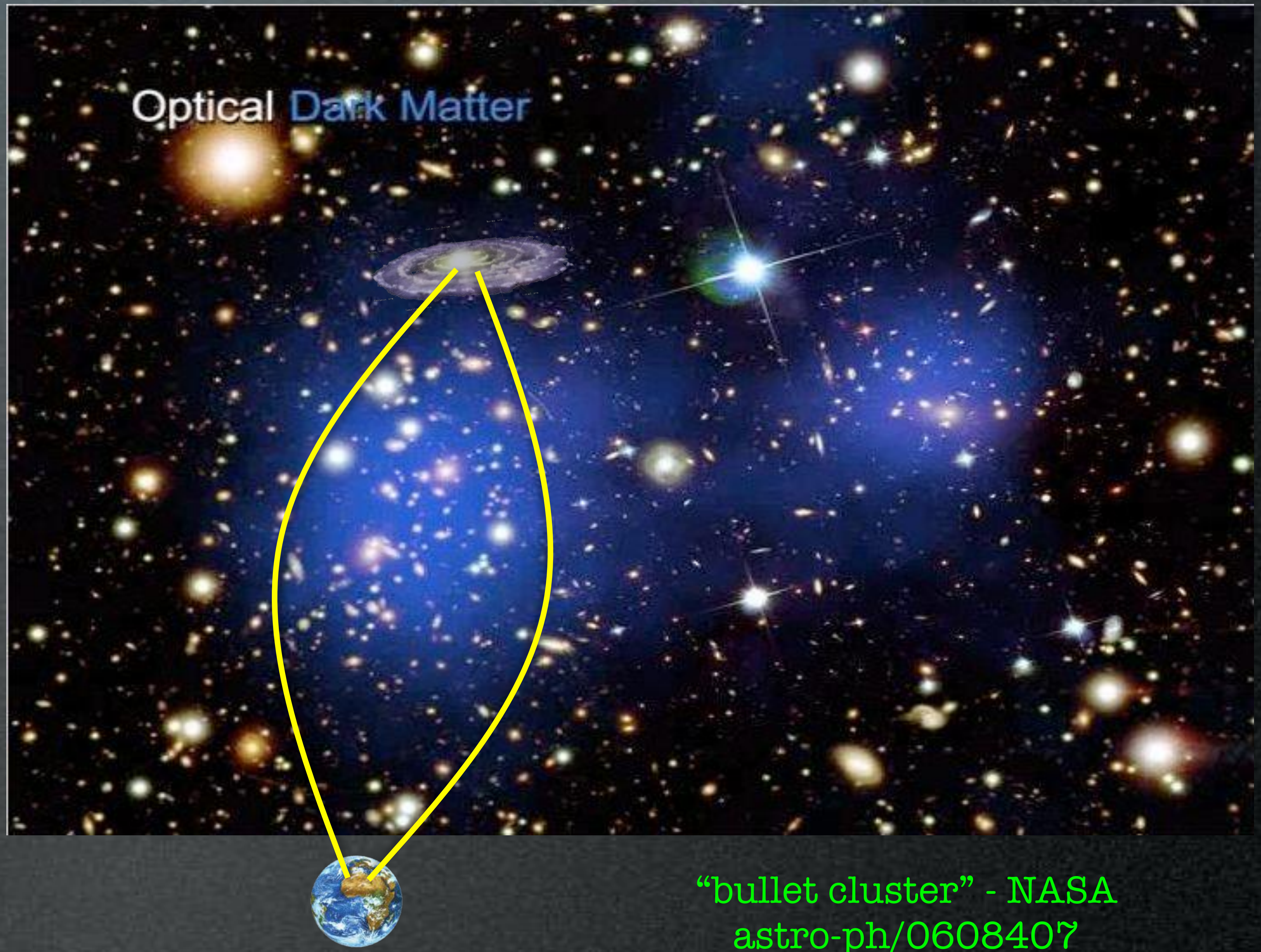

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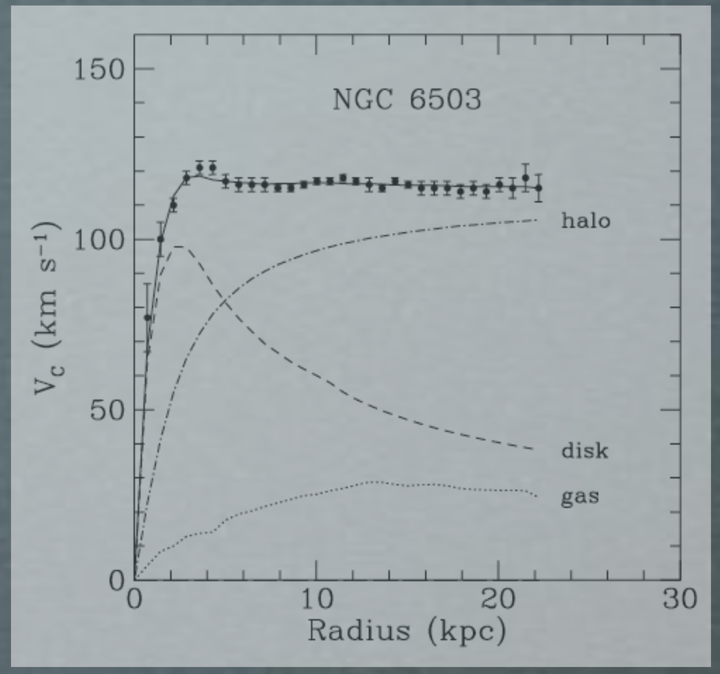

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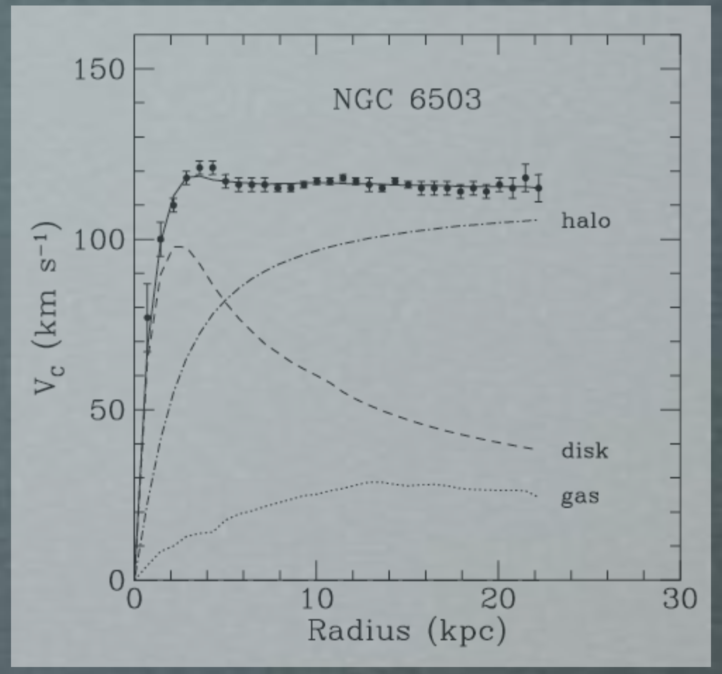

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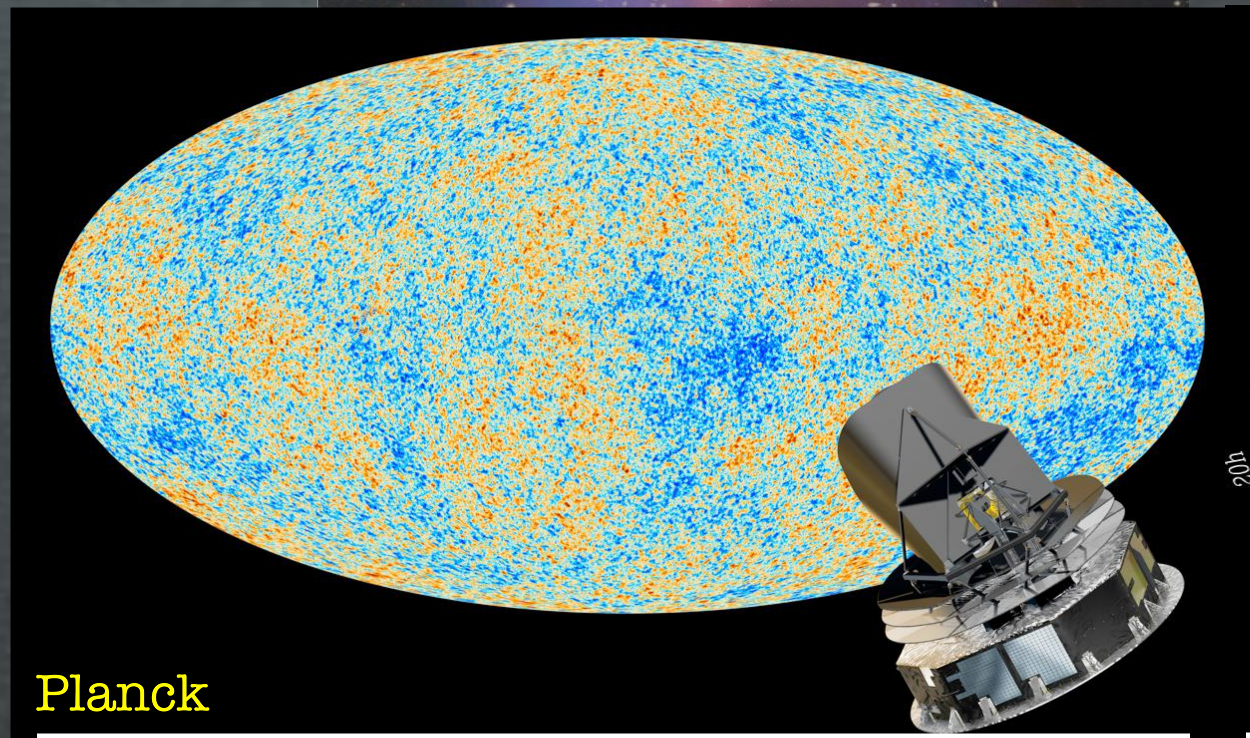
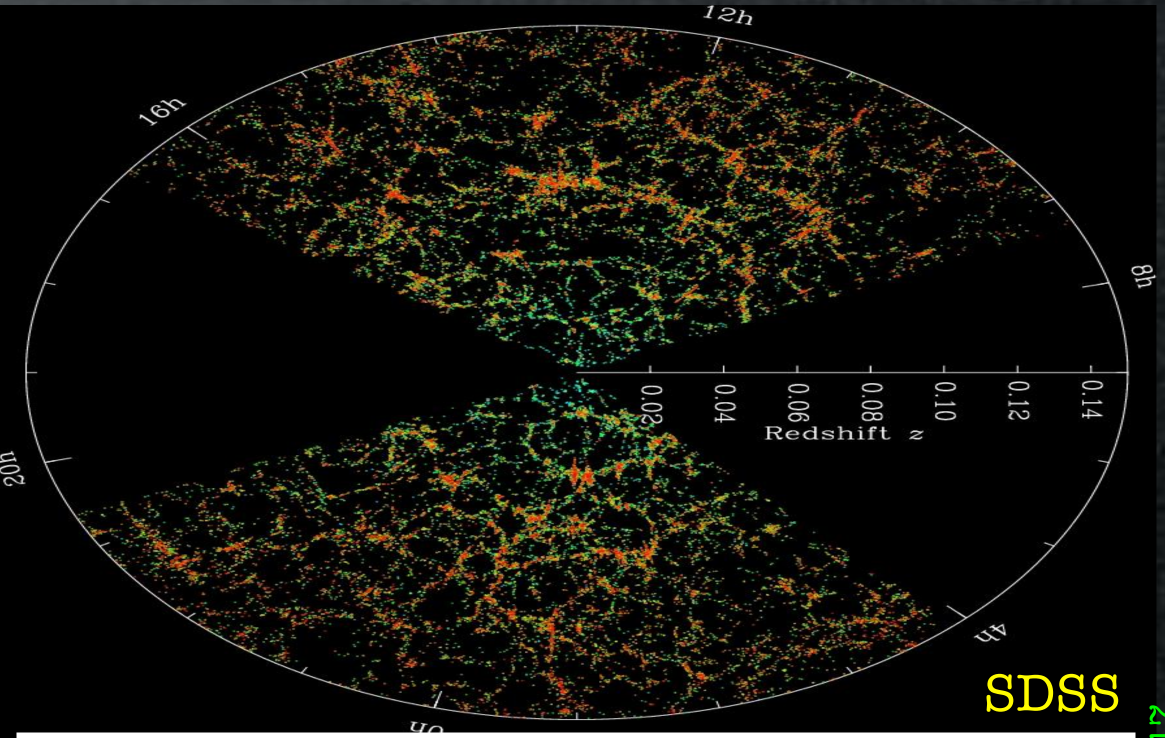
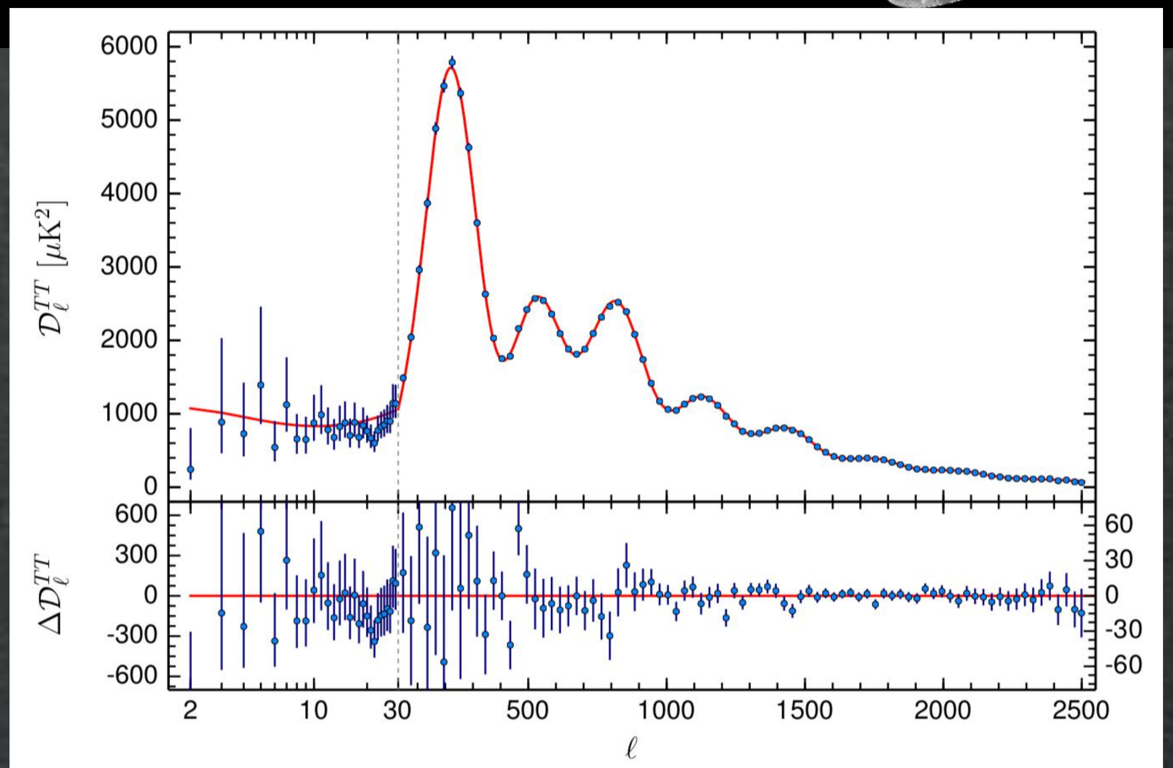
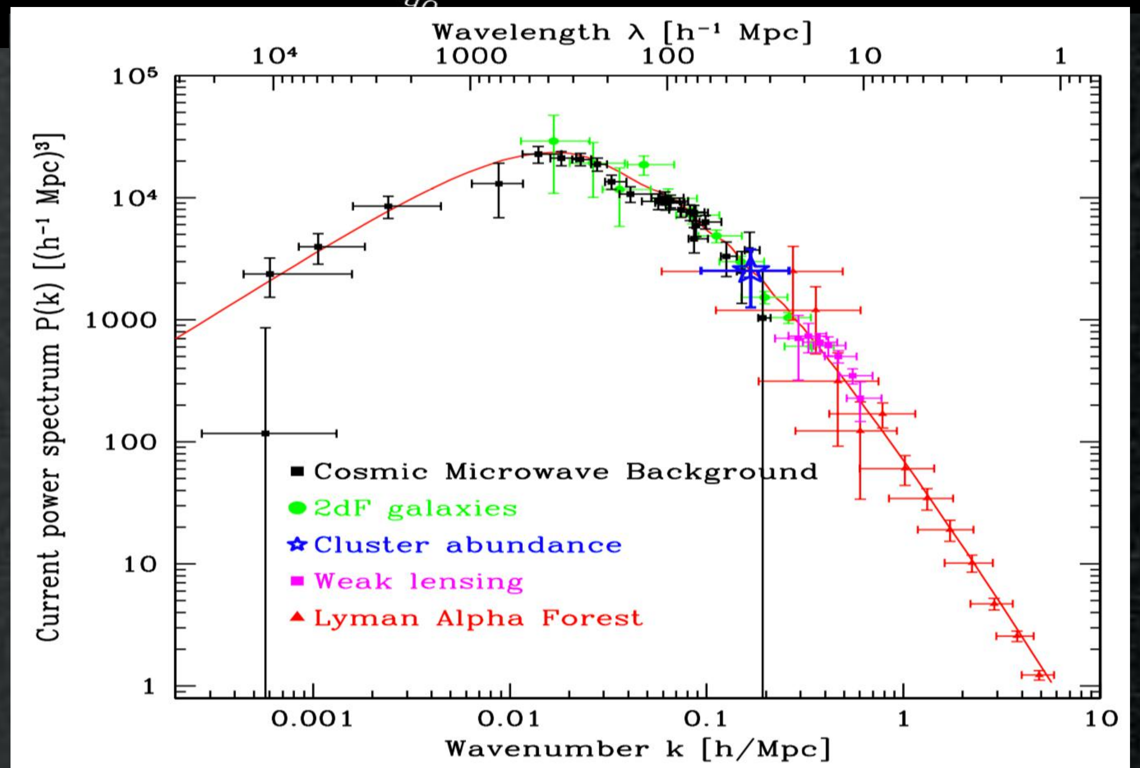




Planck coll. 1502.01582





Tegmark, Zaldarriaga astro-ph/0207047

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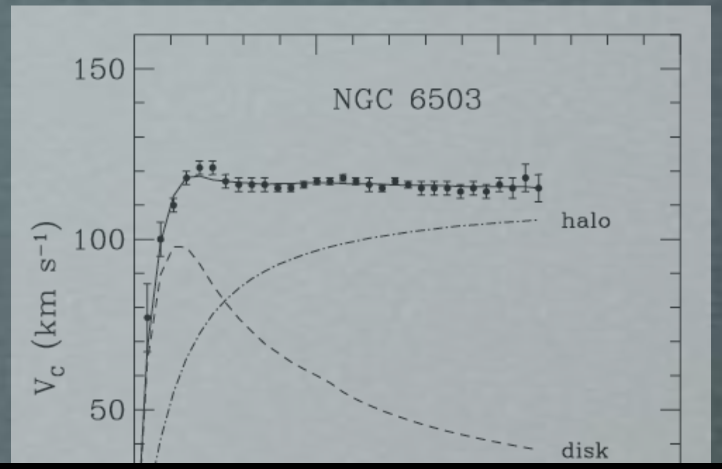

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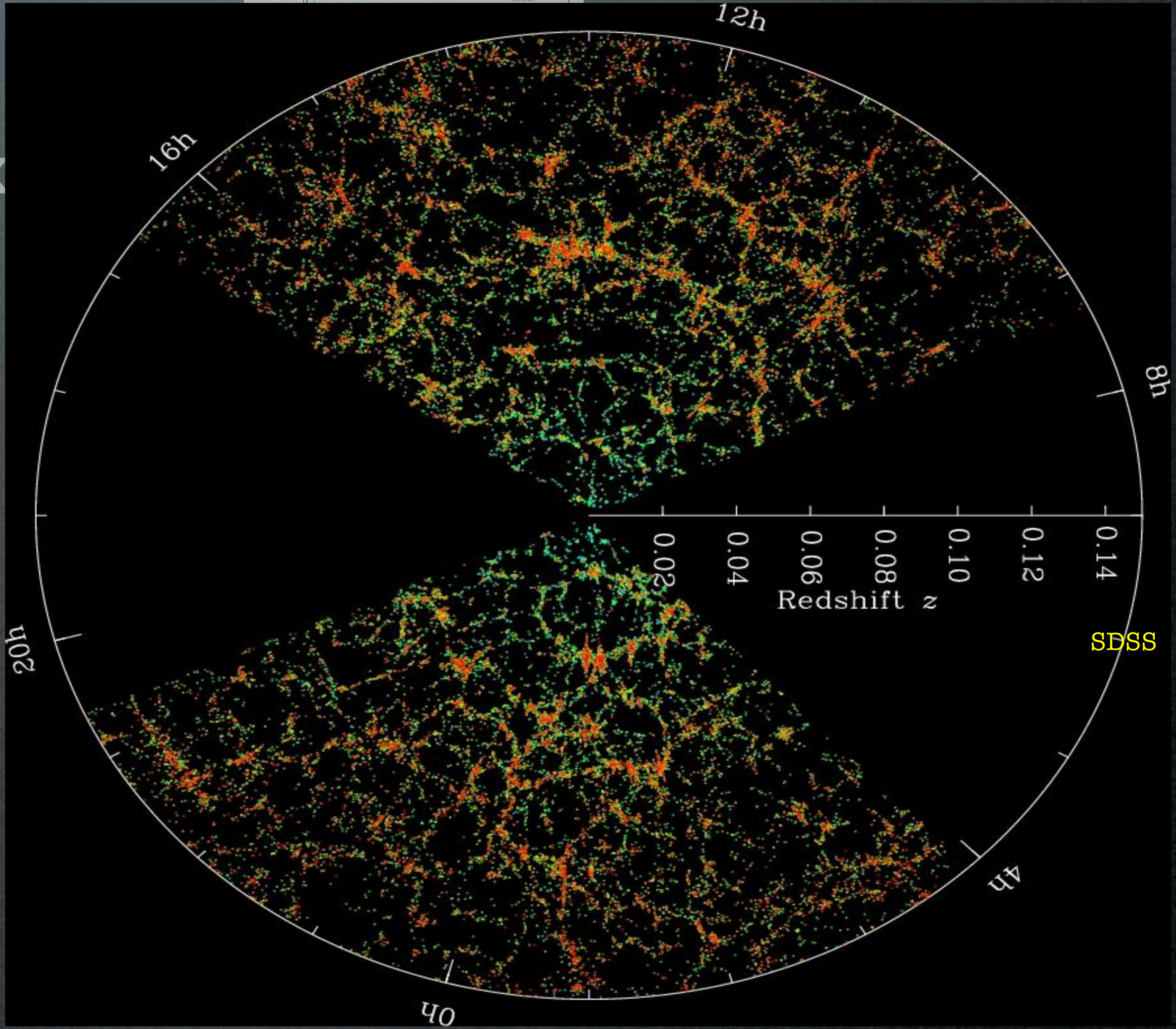
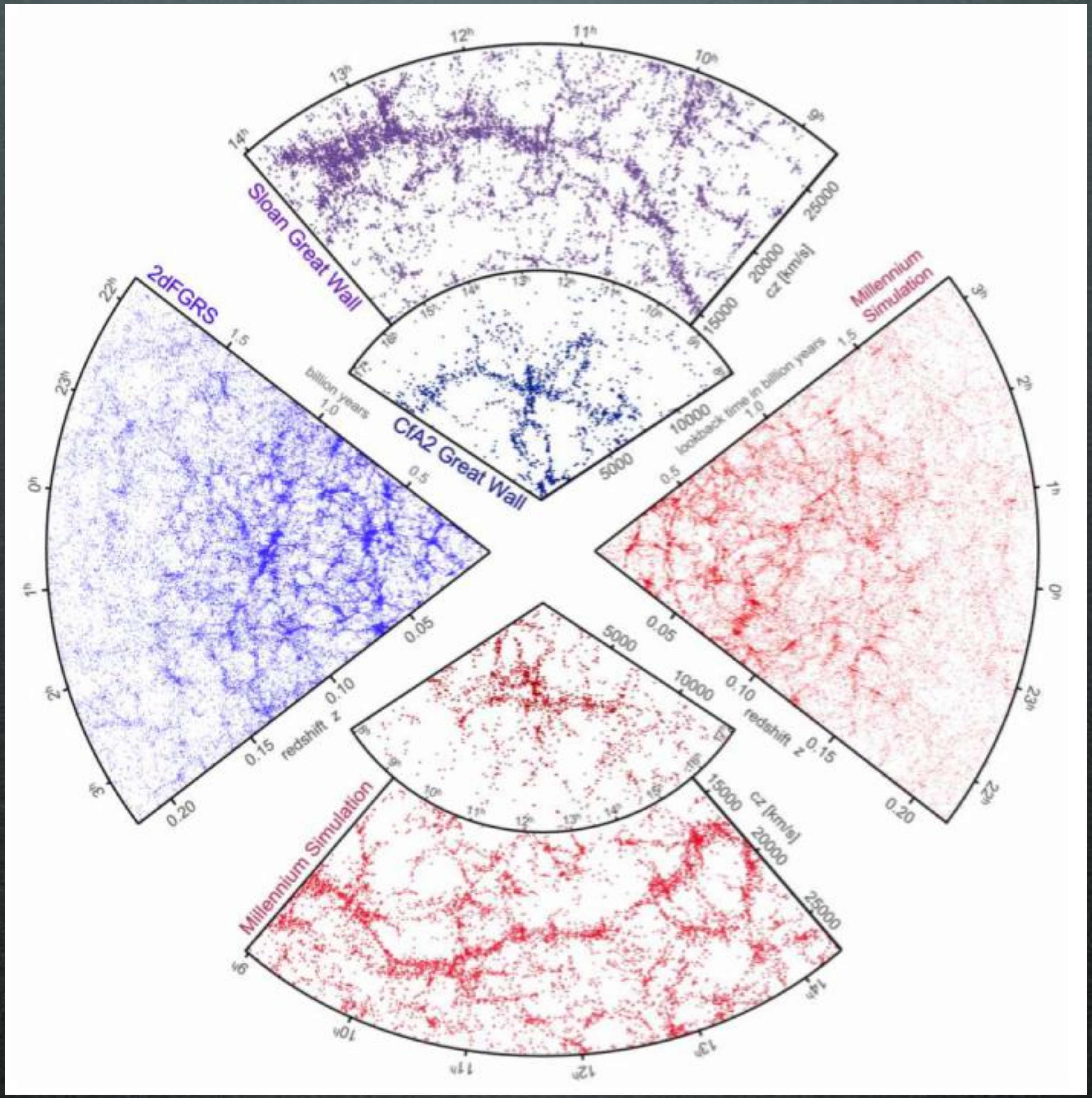


DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



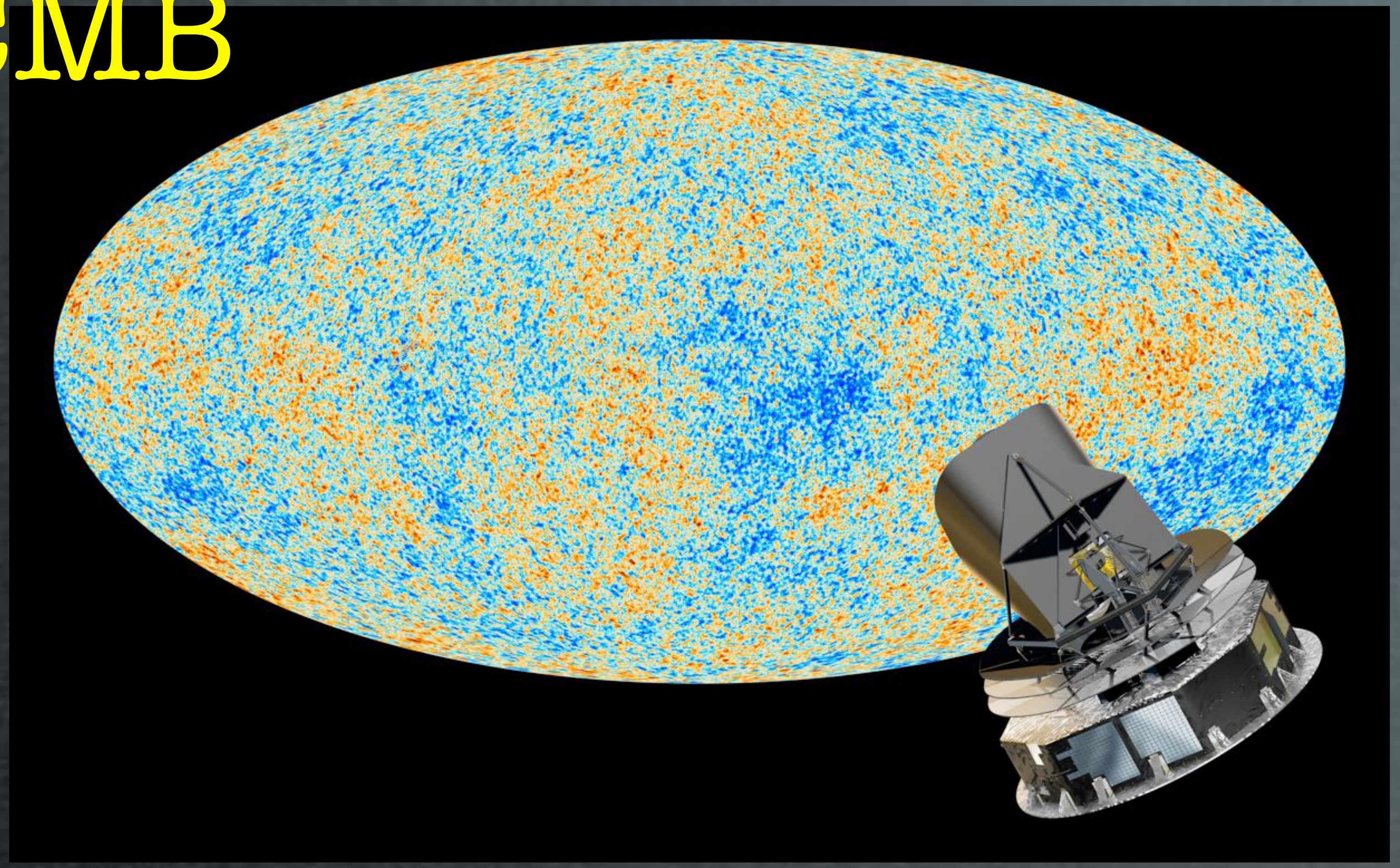
Springel, Frenk, White, Nature 440 (2006)

Of course, you have to infer galaxies within the DM simulation

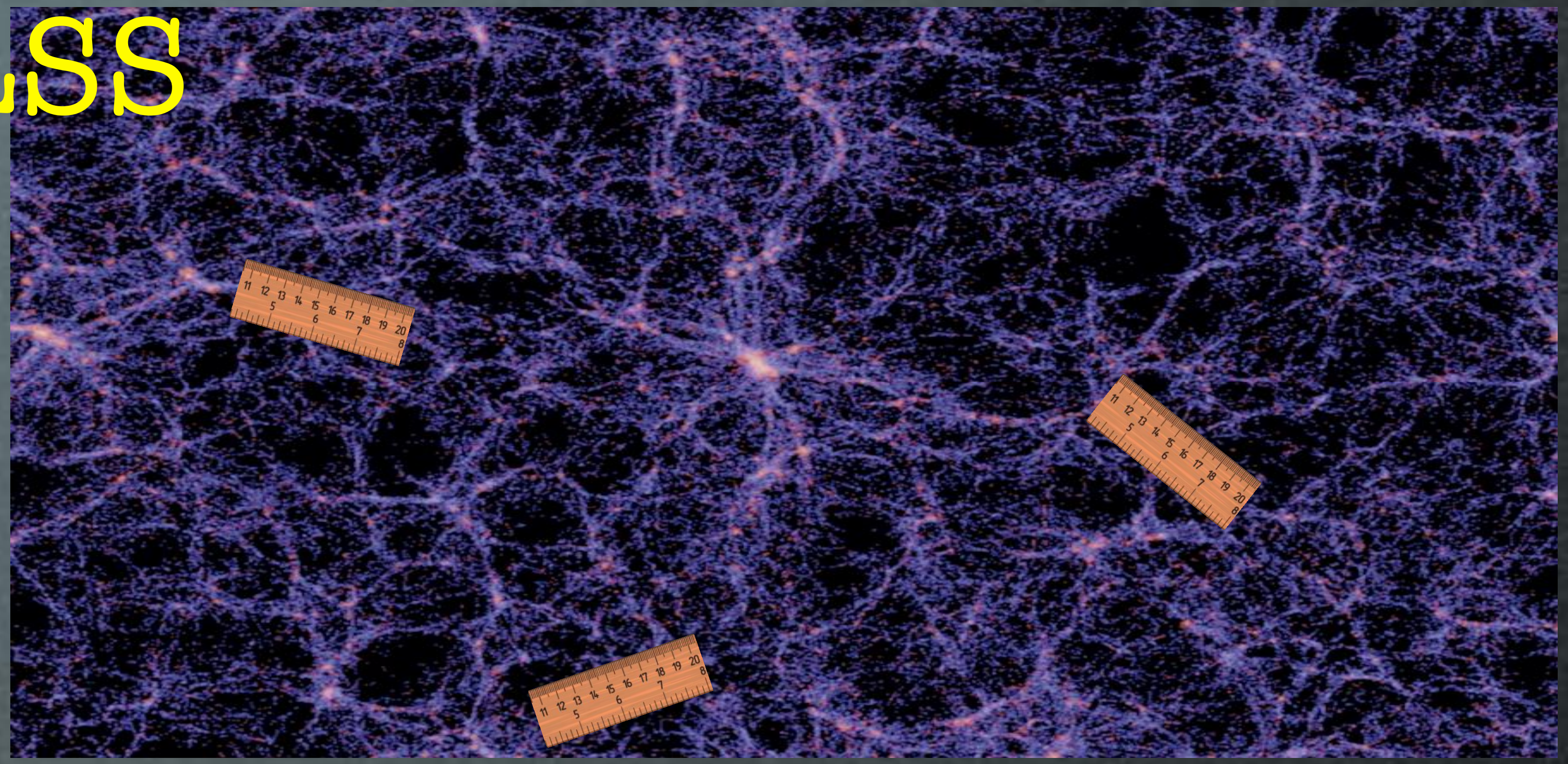
Millennium:
10^{10} particles,
500 h^{-1} Mpc

The Evidence for DM

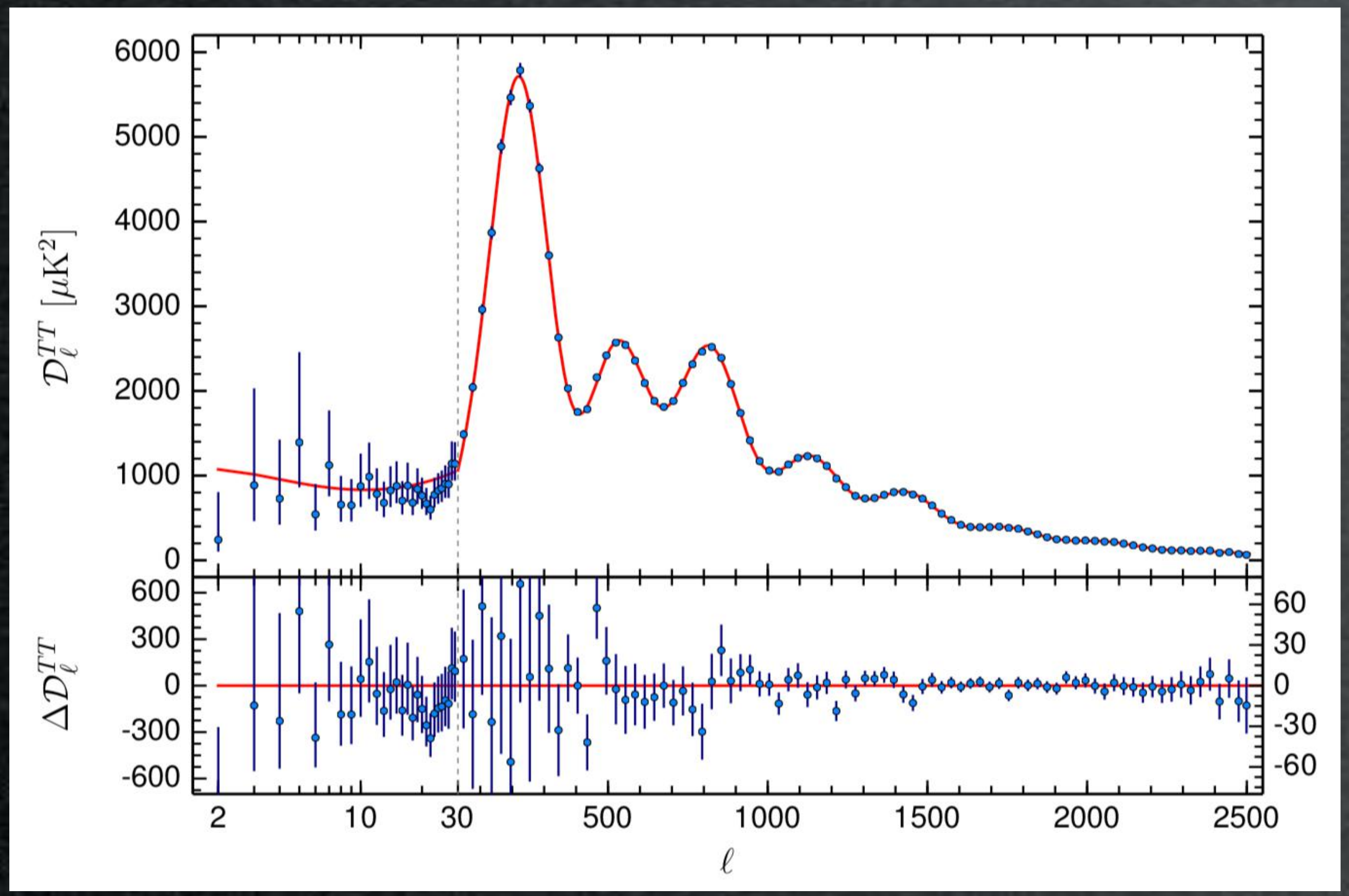
CMB



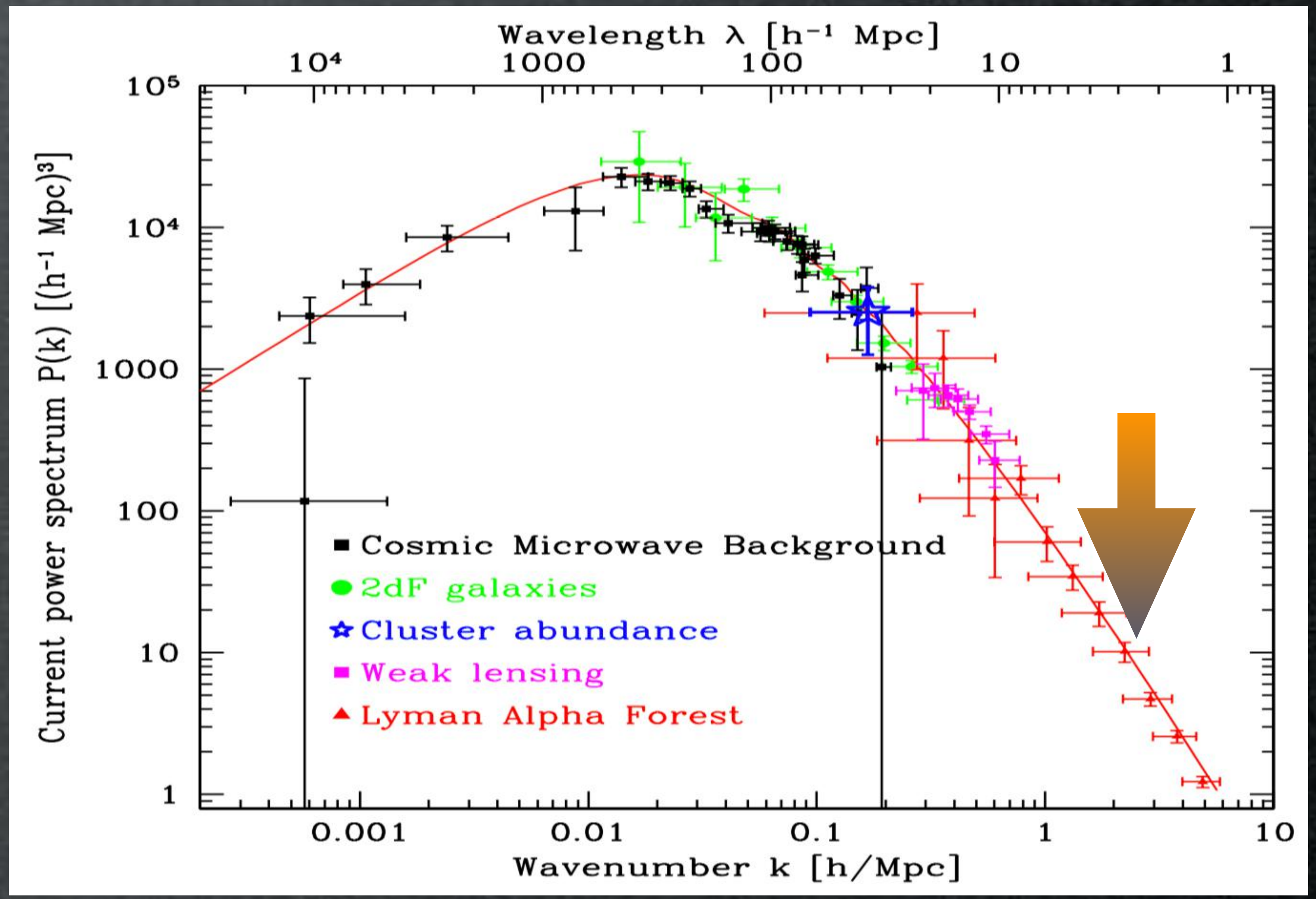
LSS



CMB spectrum



LSS matter power spectrum



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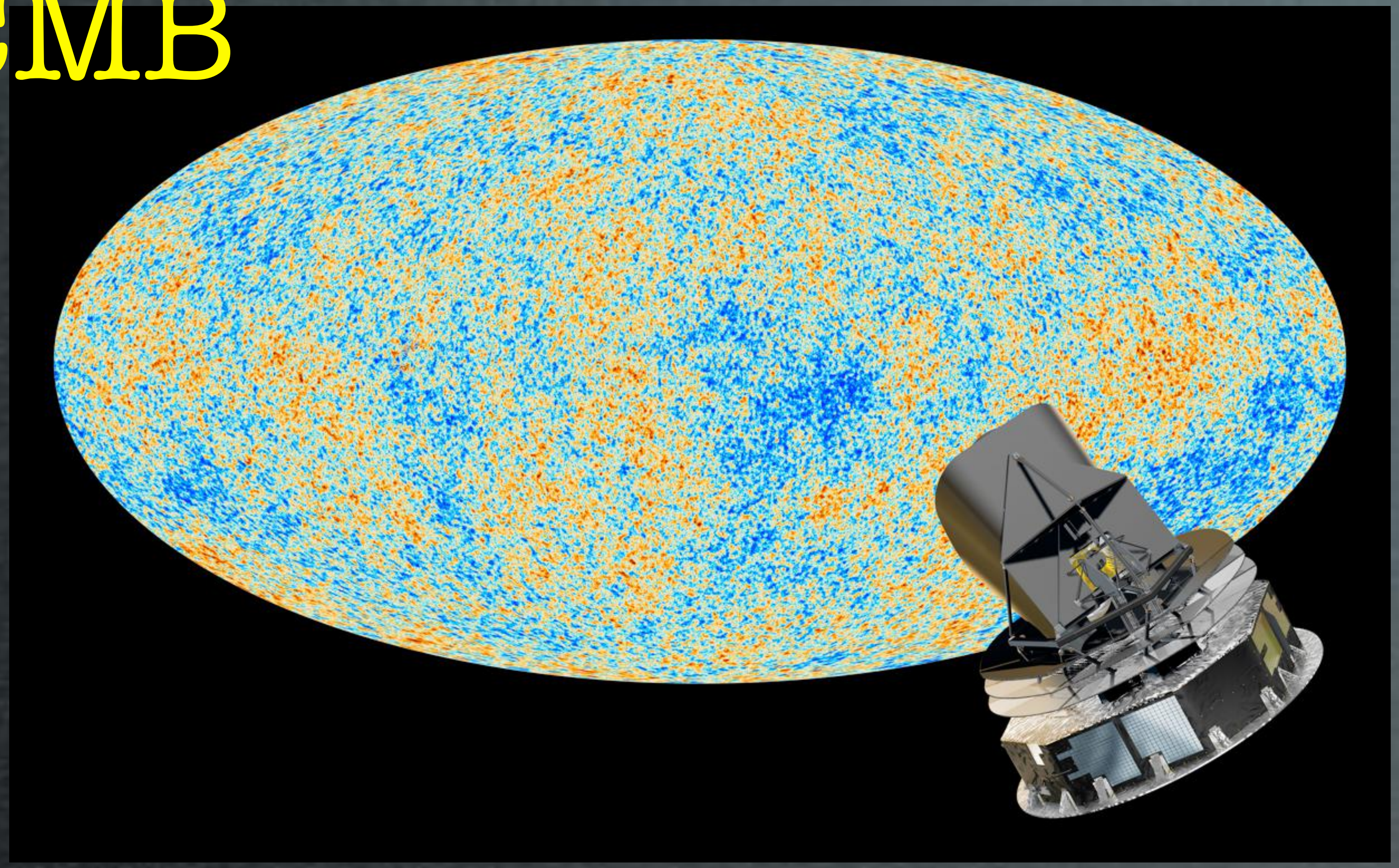

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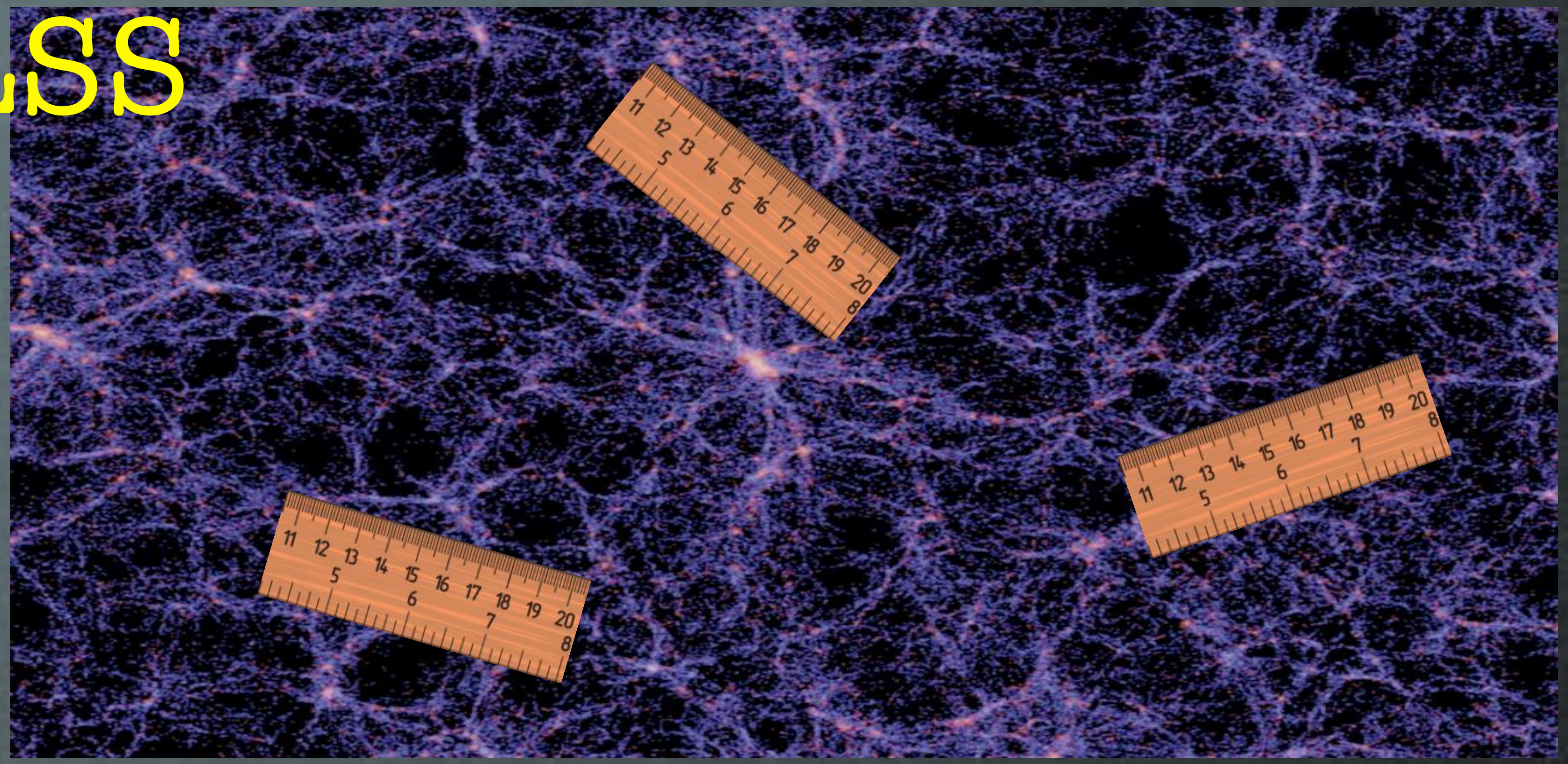

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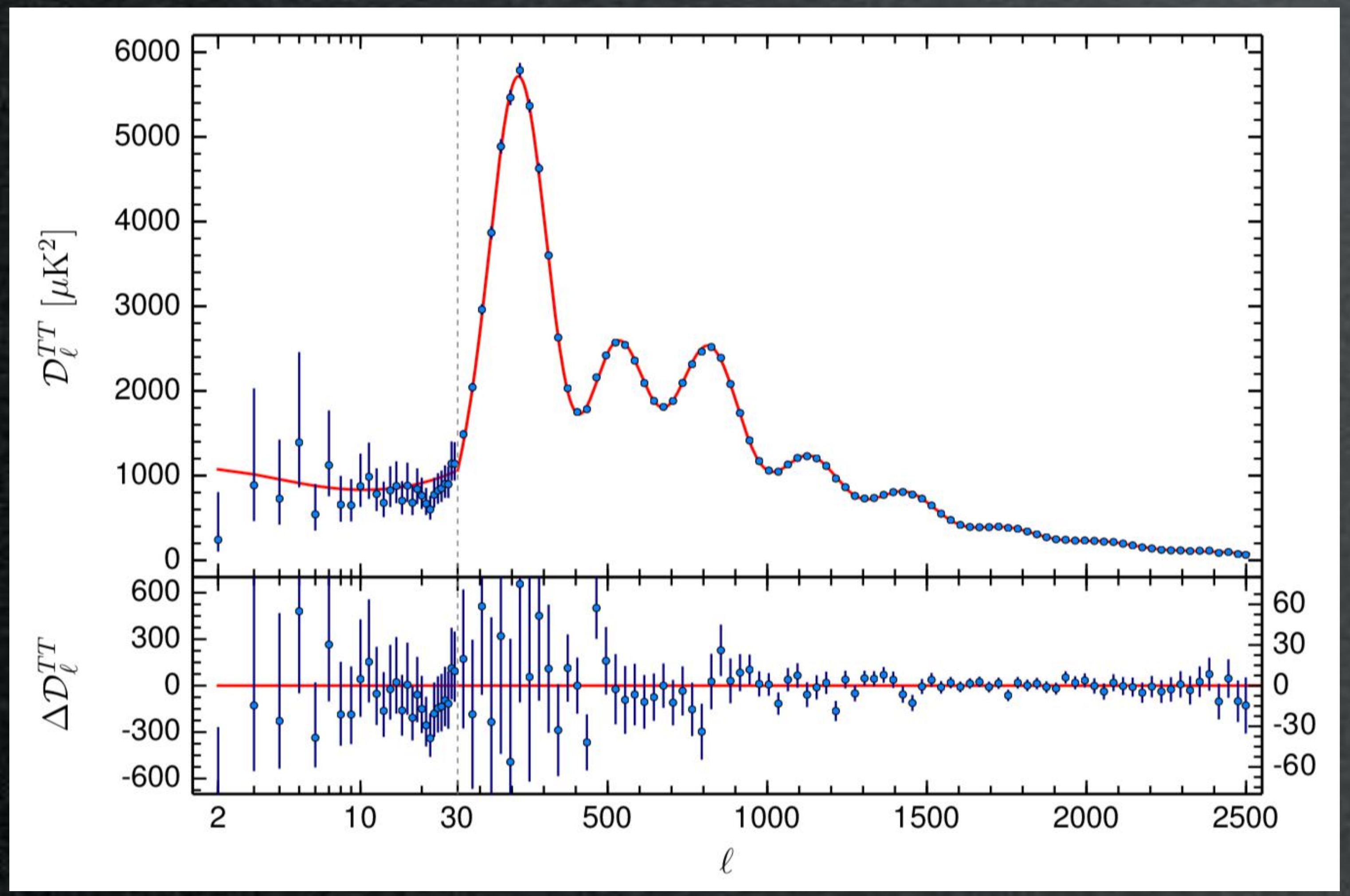

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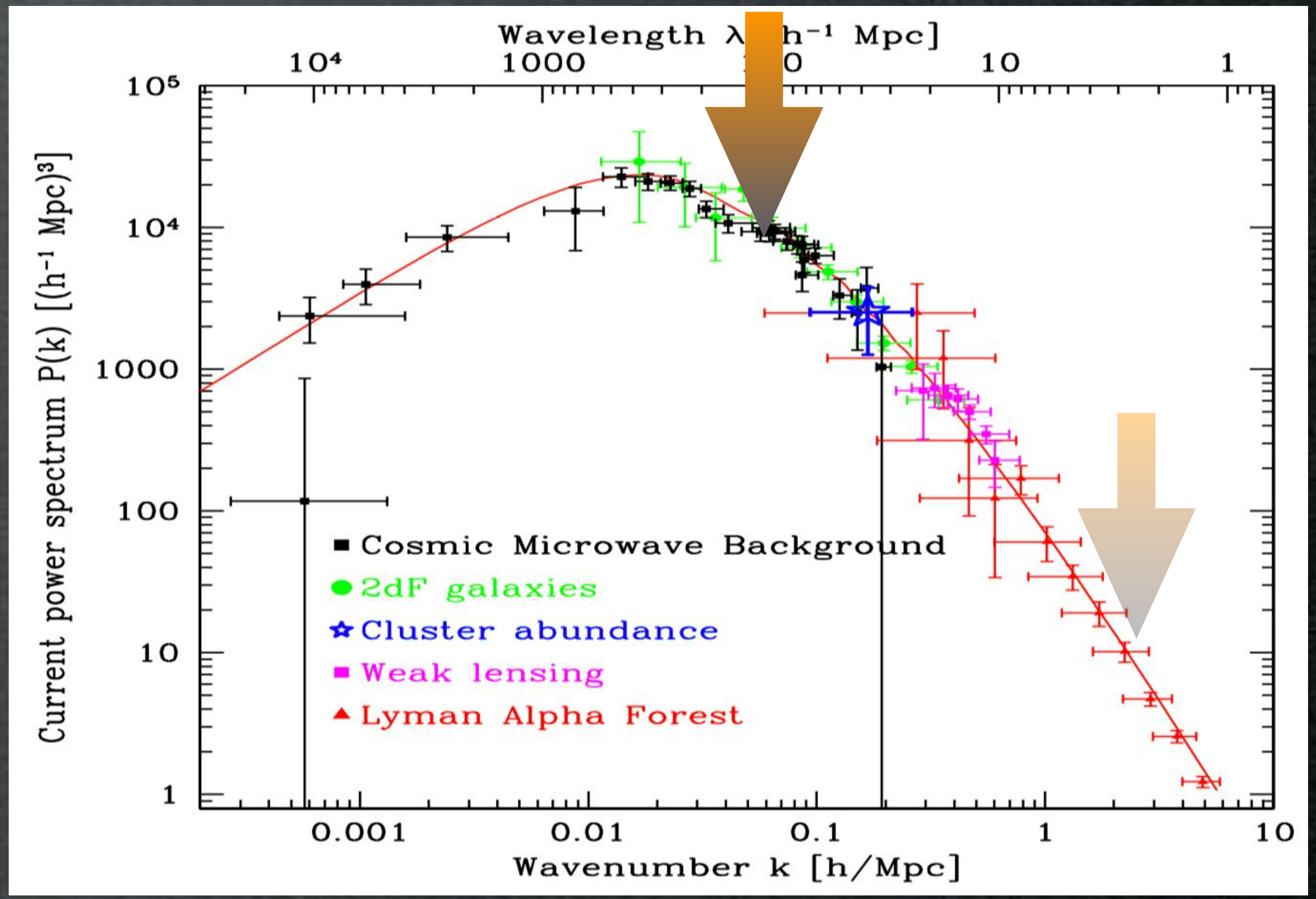

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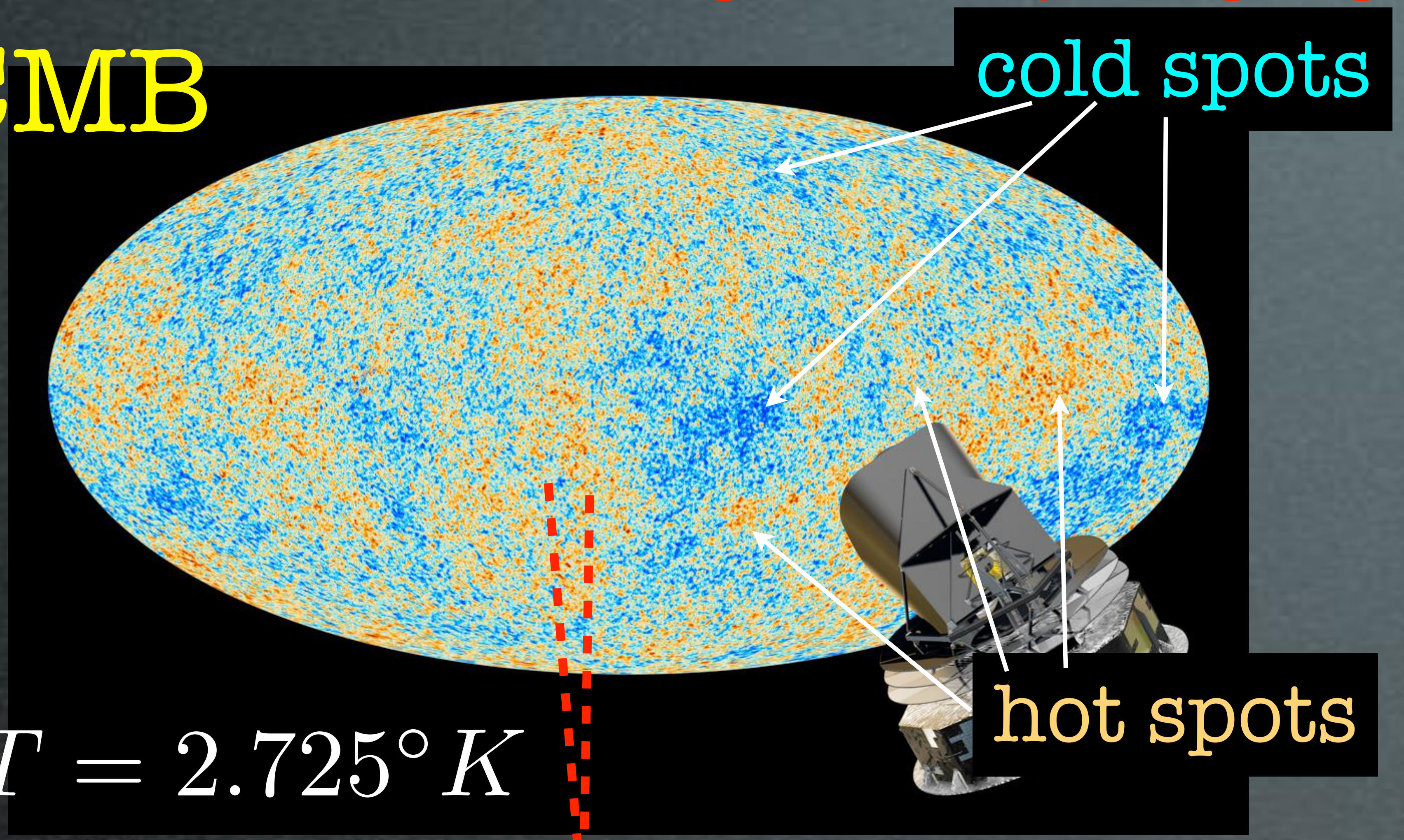
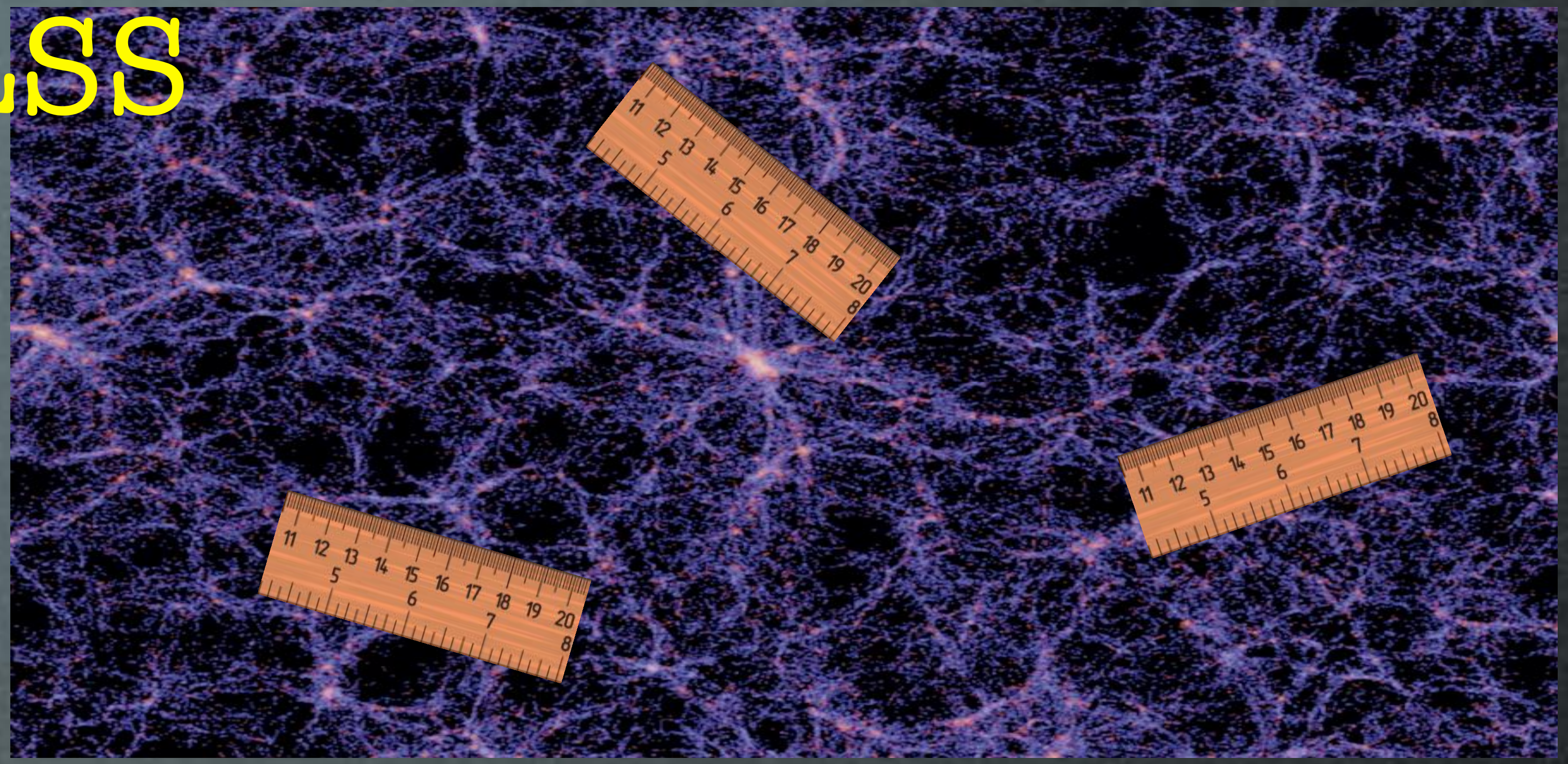


$T = 2.725^\circ K$

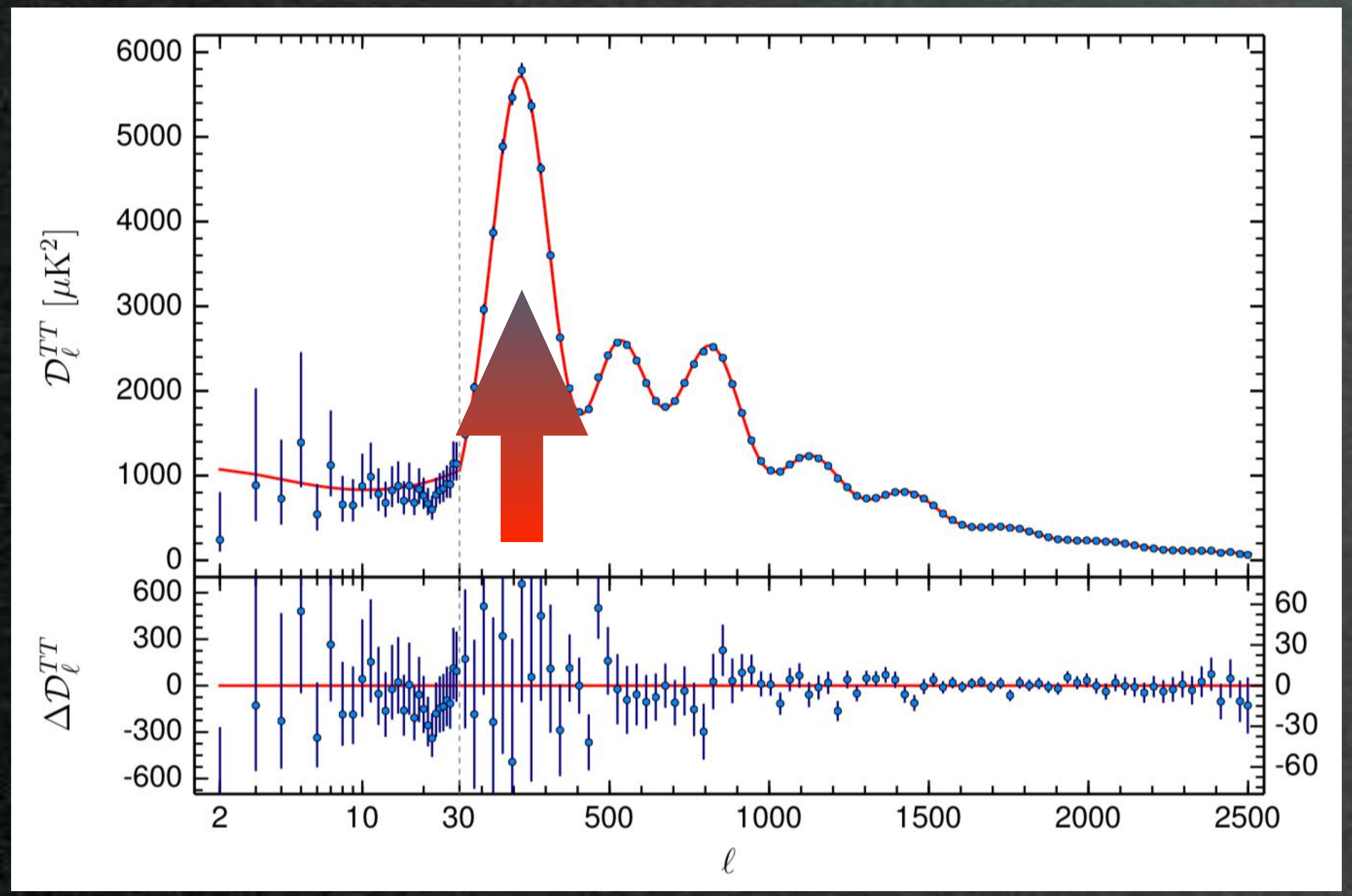
$\frac{\delta T}{T} \sim 10^{-5}$

1°

LSS



CMB spectrum



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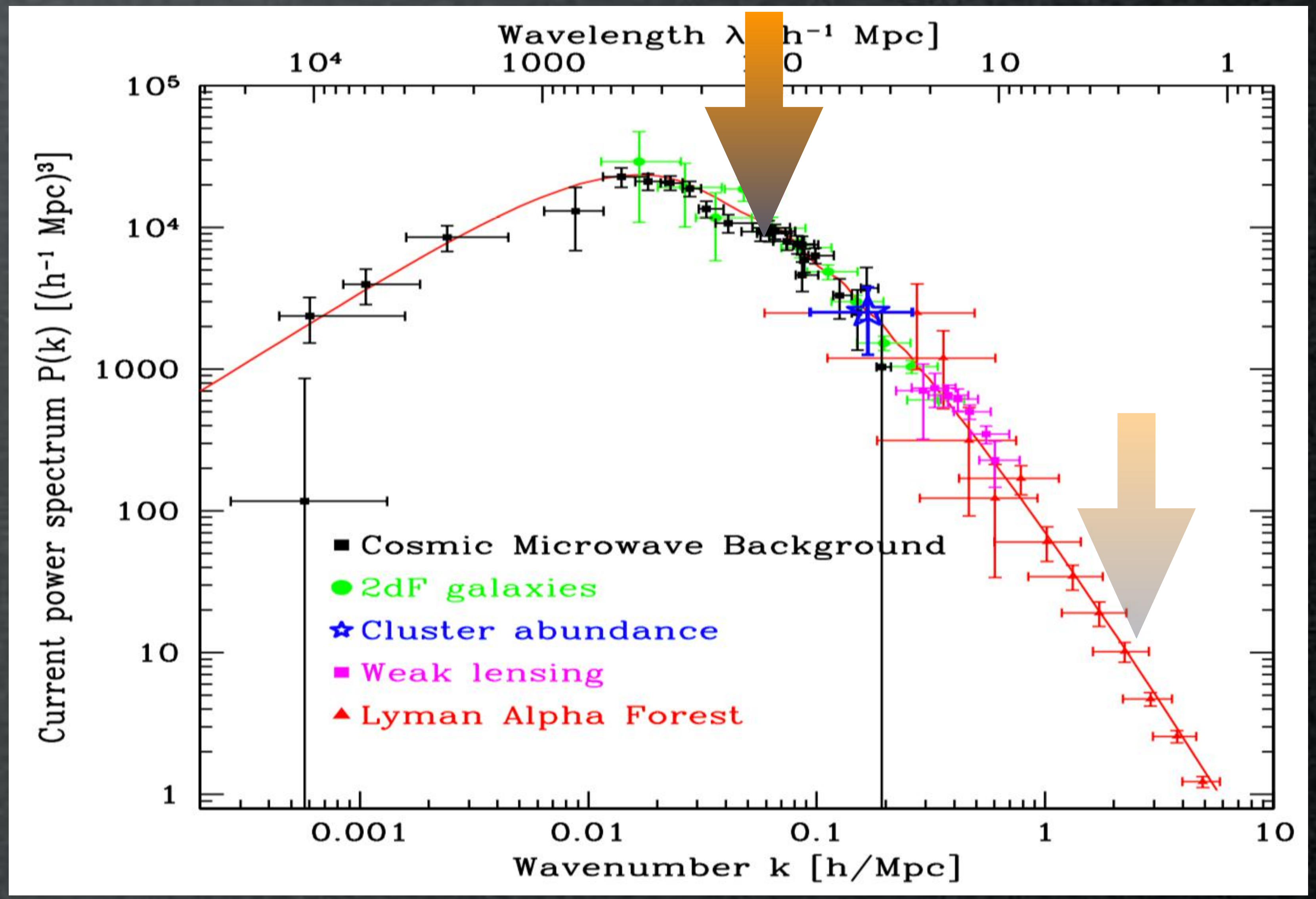

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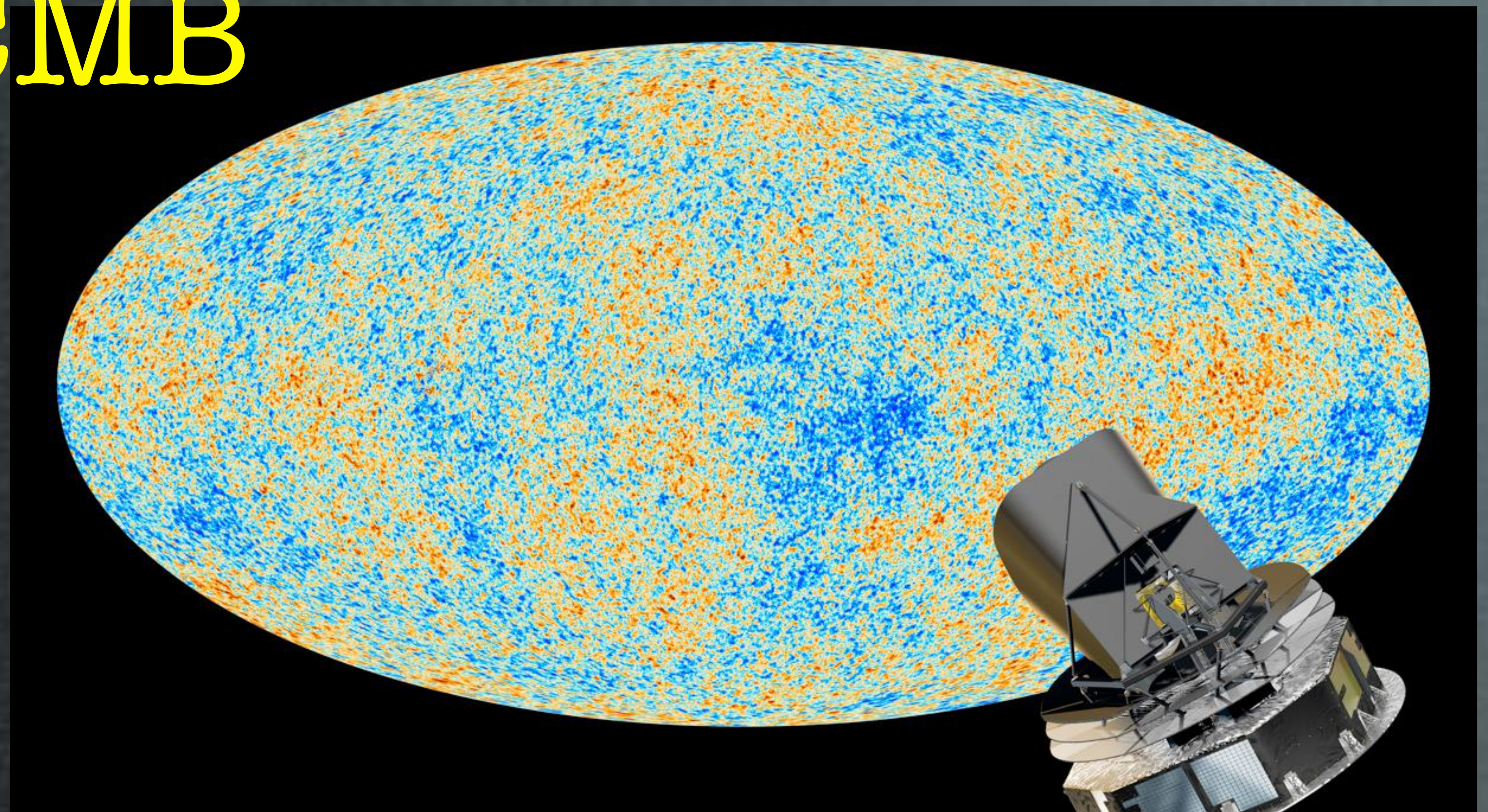

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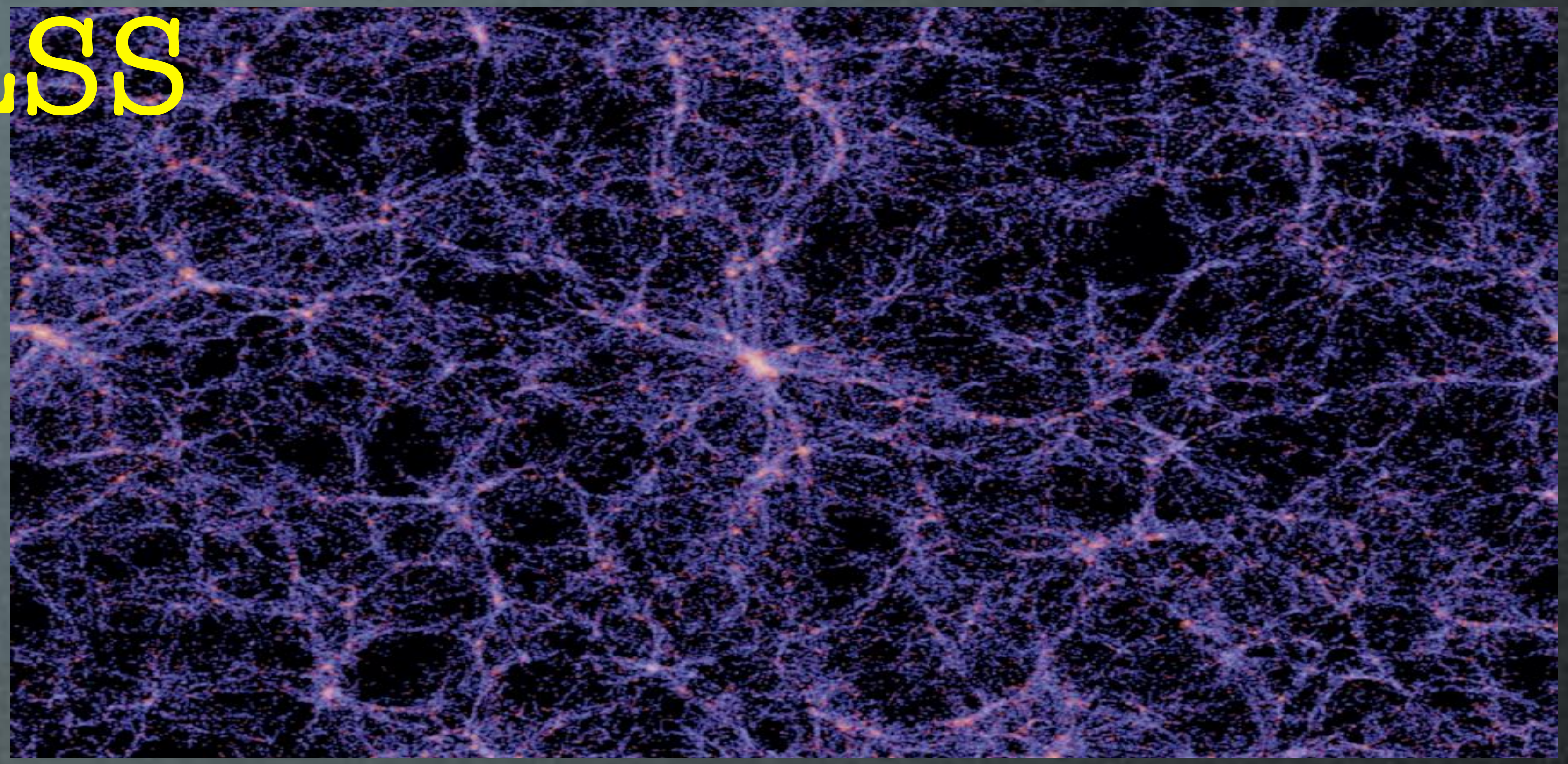
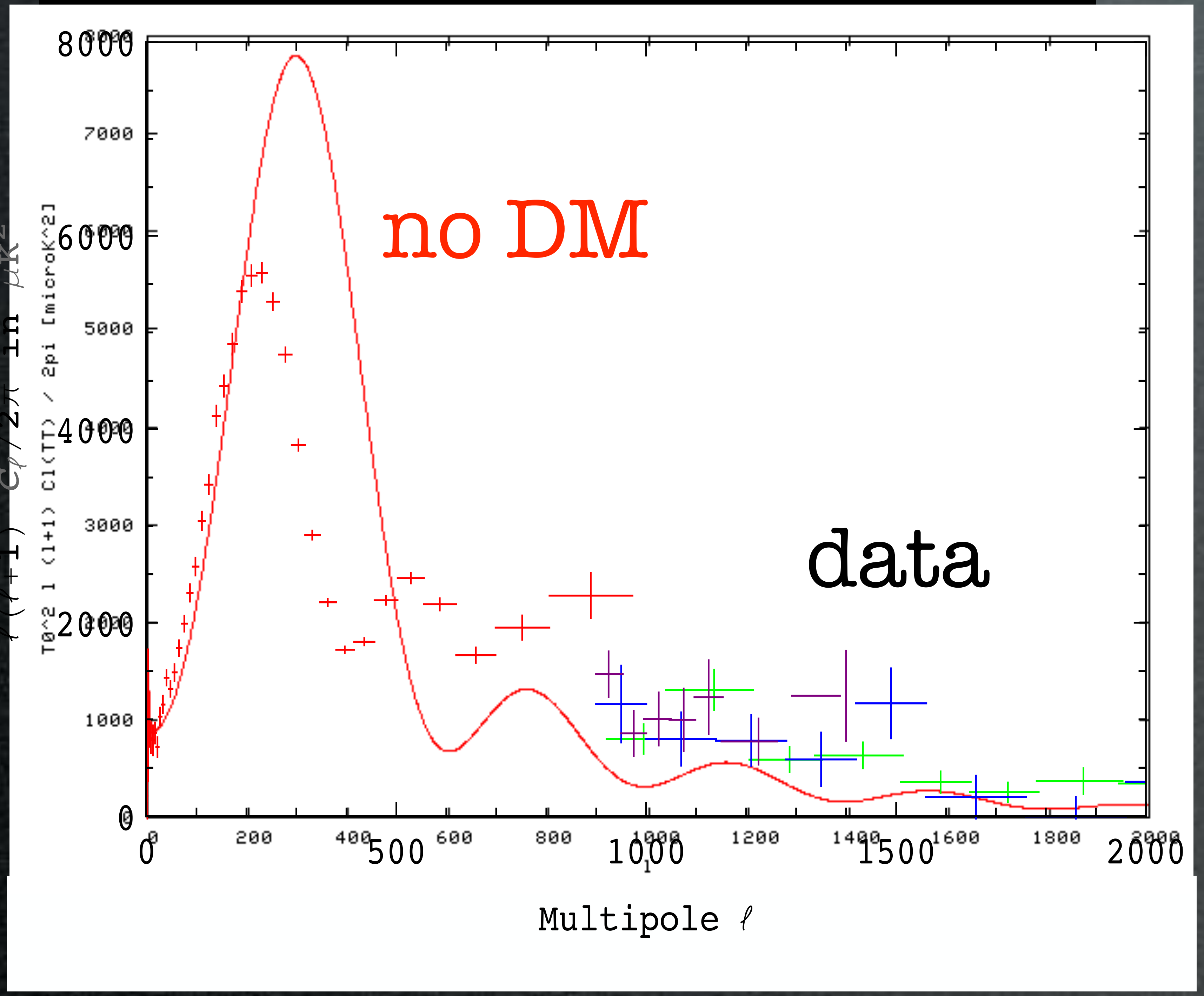
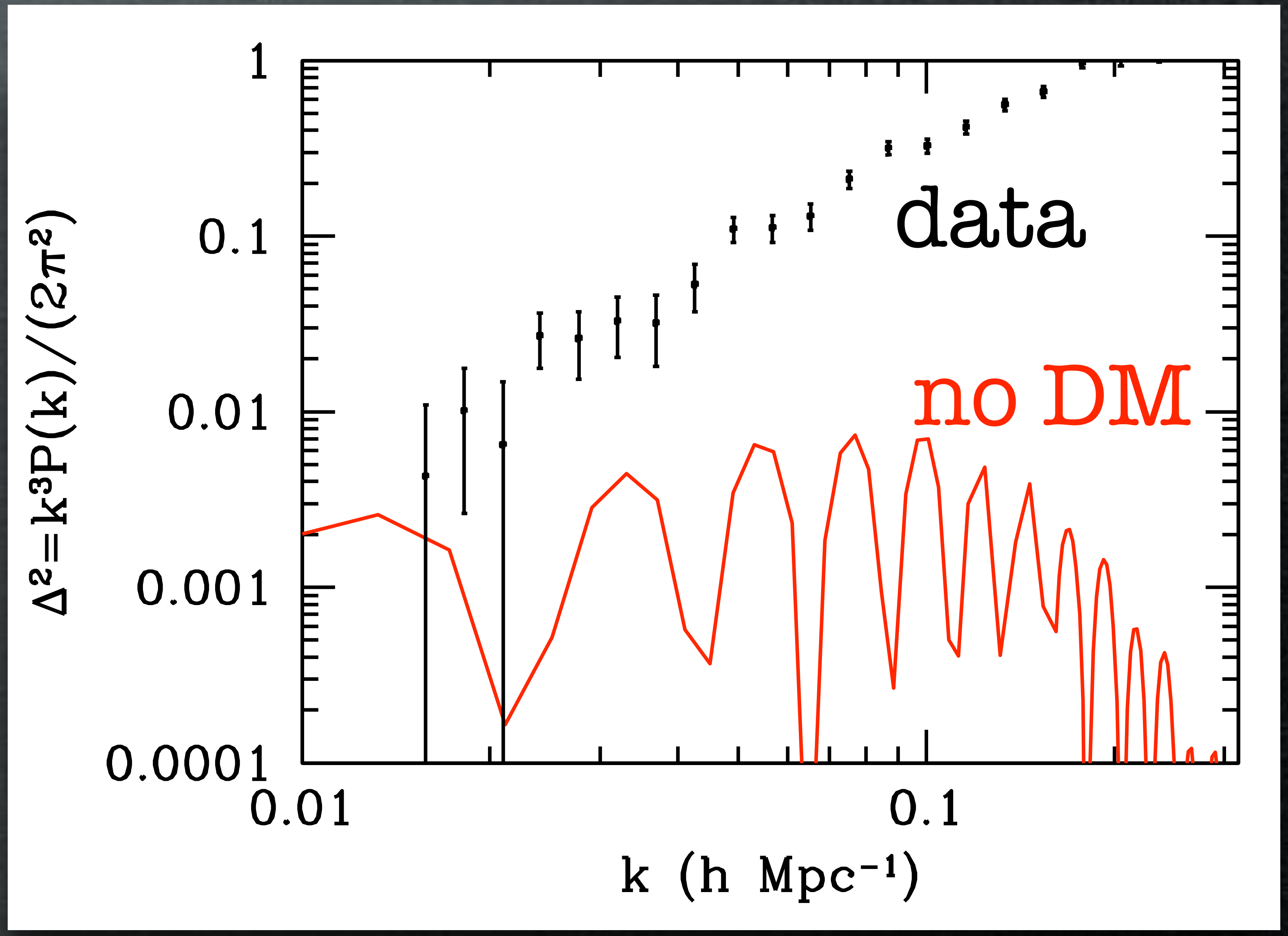


How would the power spectra be without DM? (and no other extra ingredient)



CAMB online

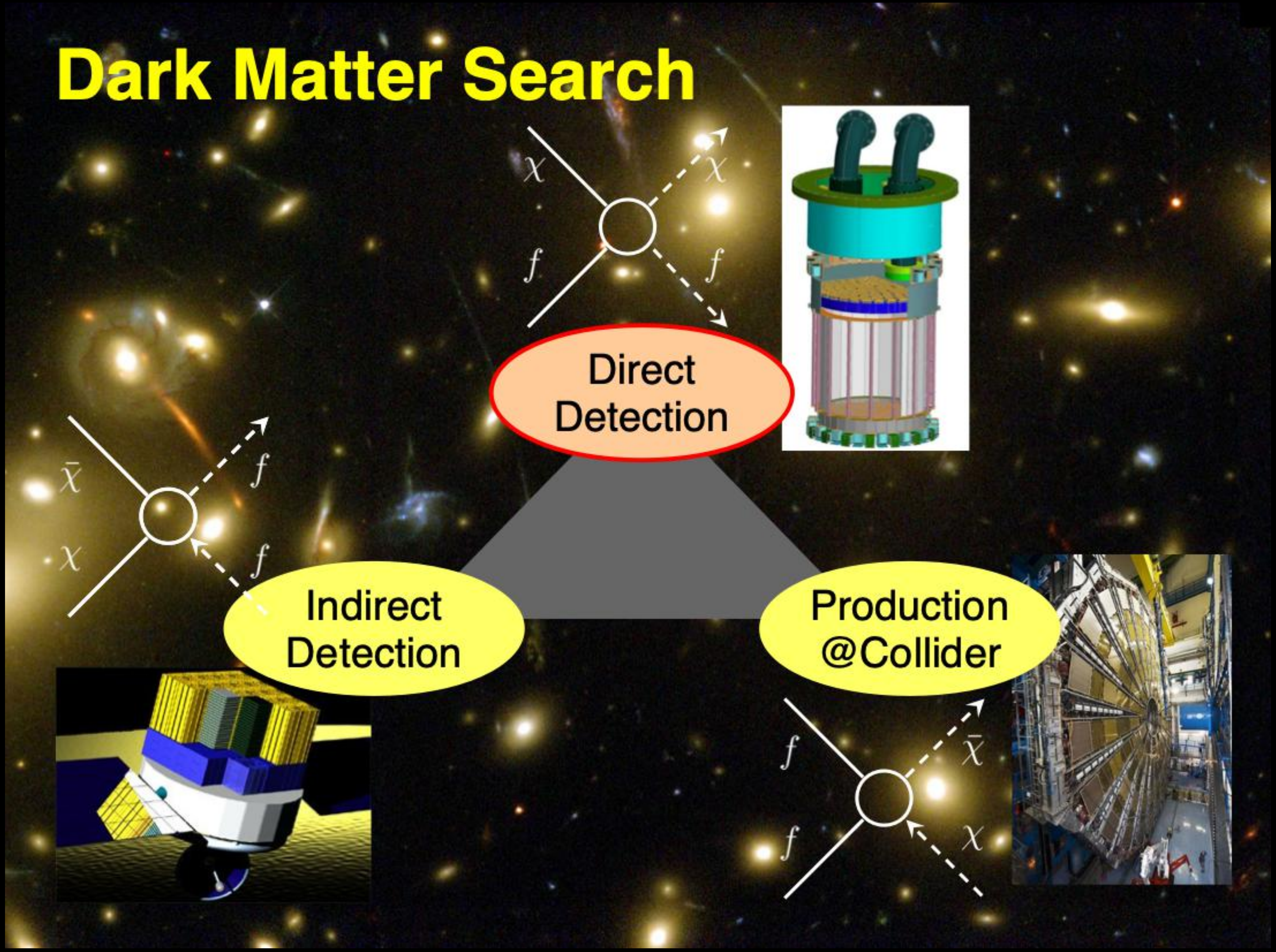
(in particular: no DM => no 3rd peak!)



Dodelson, Liguori 2006

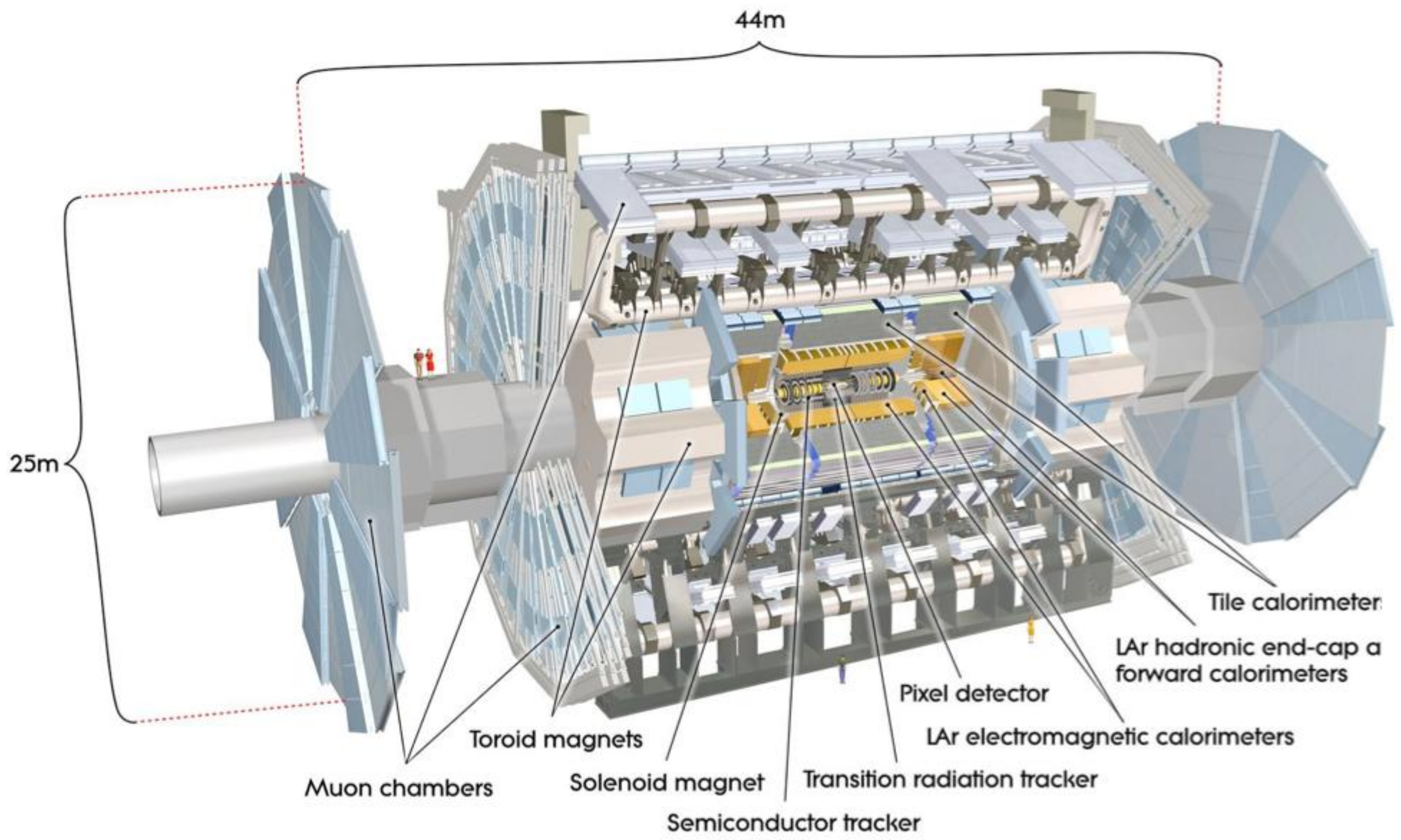
(you need DM to gravitationally "catalyse" structure formation)

Experimental complementary approaches to

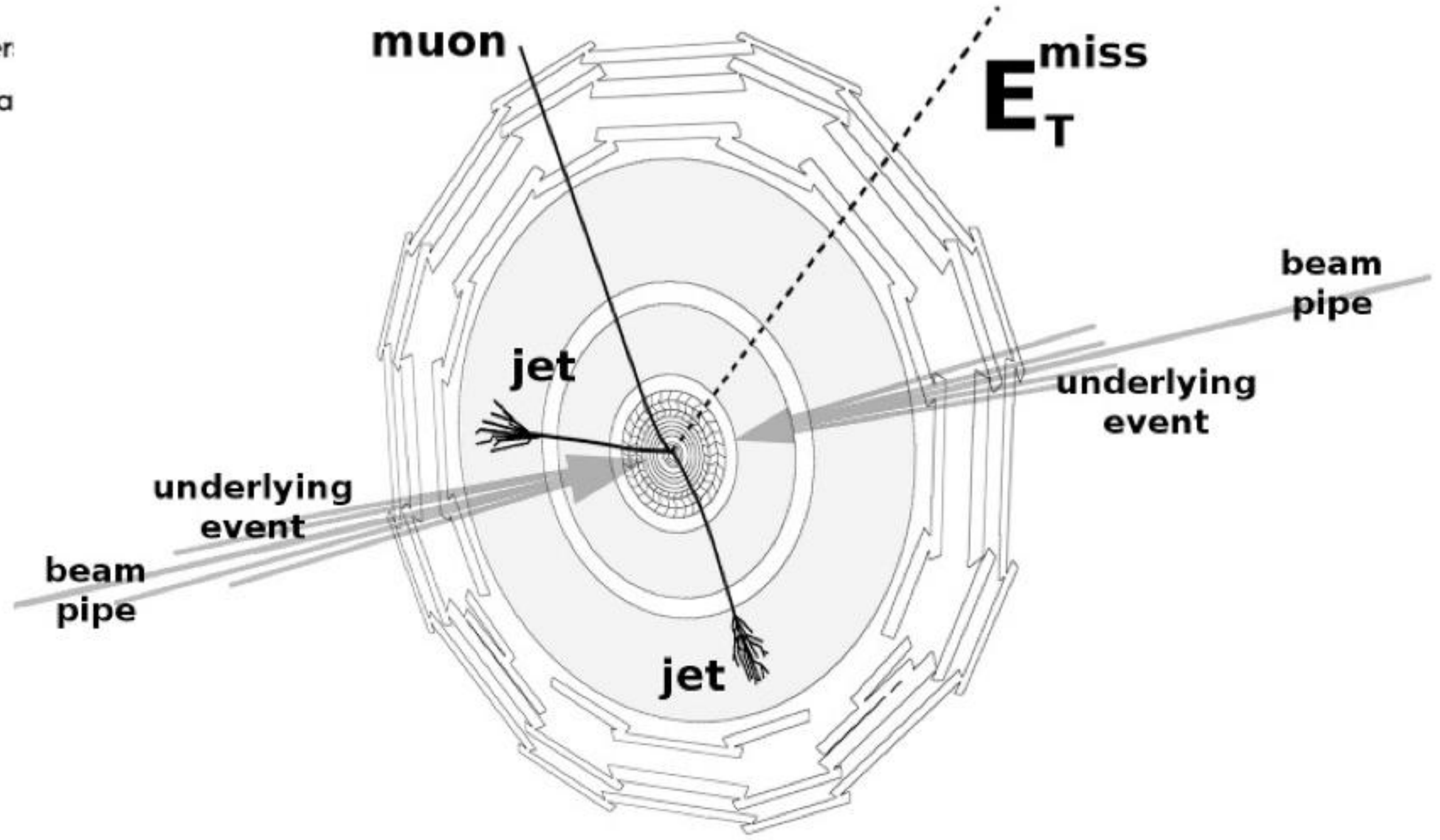


Missing Energy at accelerator experiments

LHC detectors



- ATLAS and CMS are general purpose experiments, ready to explore a large range of physic signatures.
- Typical combination of several sub-detectors to cope with the different physics processes
- As usual magnetic fields are necessary to measure the momentum of charged particles

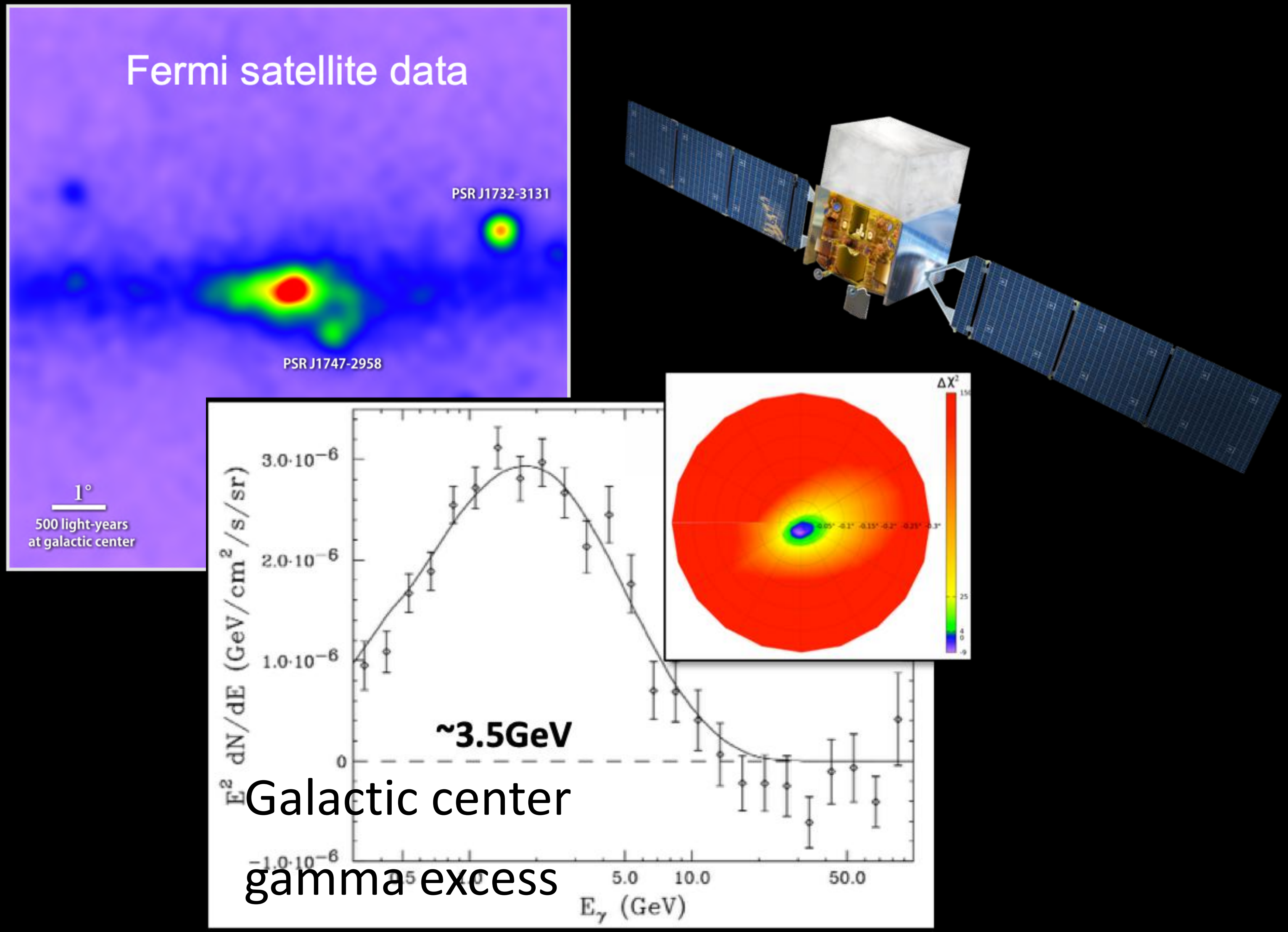


- Measure all 'objects' in the event : electrons, photons, muons, jets of particles
- Infer the 'escaping' transverse energy imposing momentum conservation in the transverse plane
- Sum of x(y) component of the momentum of all jets, electrons, photons, taus and muons

$$E_{x(y)}^{miss} = -(E_{x(y)}^{jets} + E_{x(y)}^{e} + E_{x(y)}^{\gamma} + E_{x(y)}^{\tau} + E_{x(y)}^{\mu} + E_{x(y)}^{soft}) \Rightarrow E_T^{miss} = \sqrt{\left(E_x^{miss}\right)^2 + \left(E_y^{miss}\right)^2}$$

Indirect detection

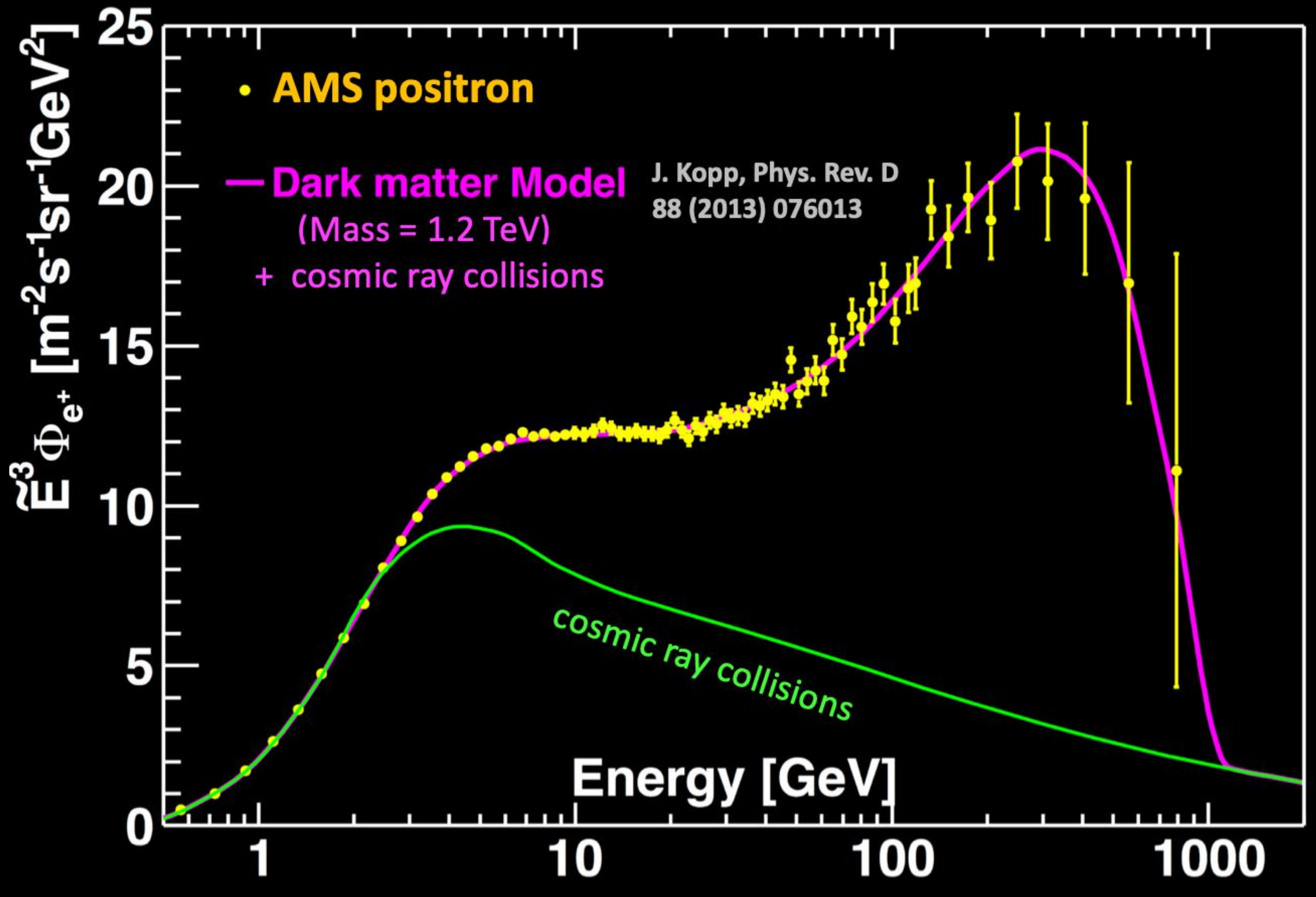
- Look for DM annihilation products in astrophysical signals



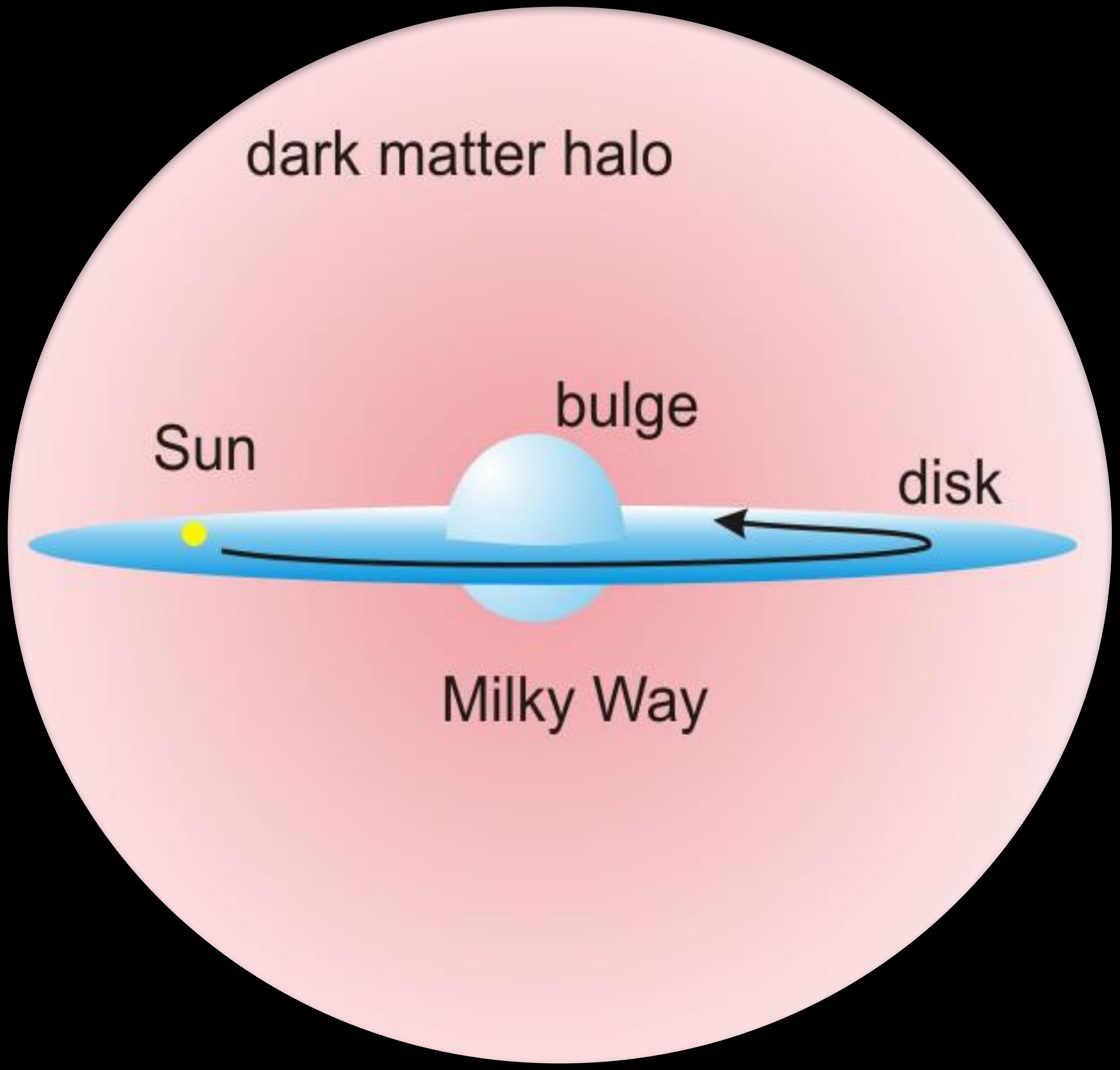
Galactic center gamma excess

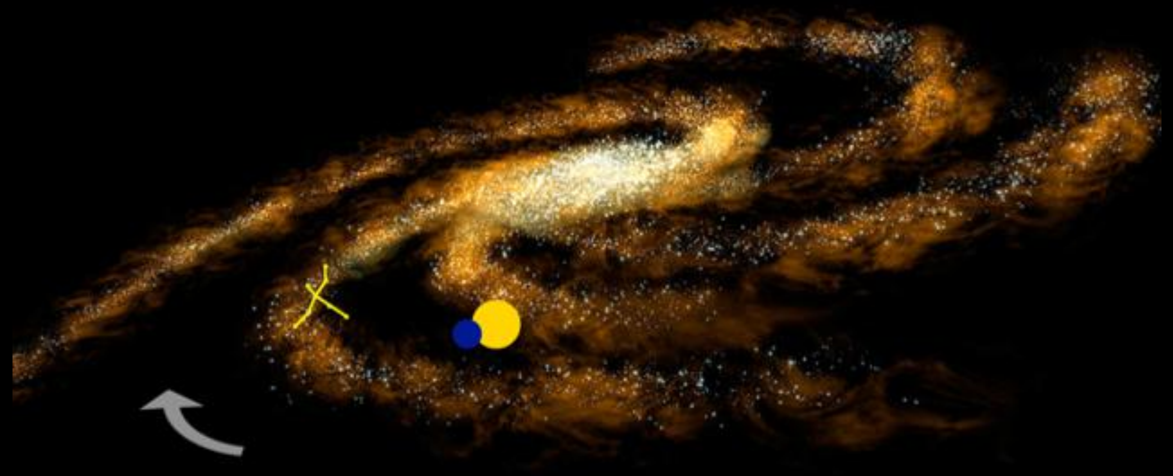
… to be verified by atmospheric Cherenkov telescopes on dwarf spheroidal galaxies

AMS excess in positron spectrum



Dark Matter Halo



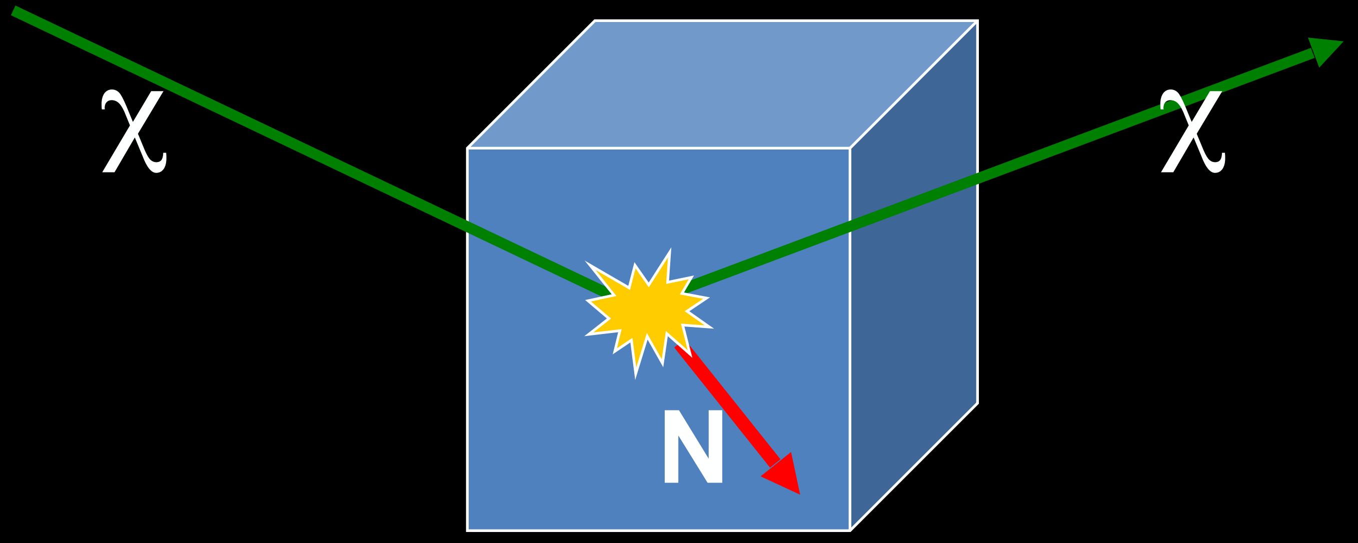


Solar motion is in the direction of Cygnus

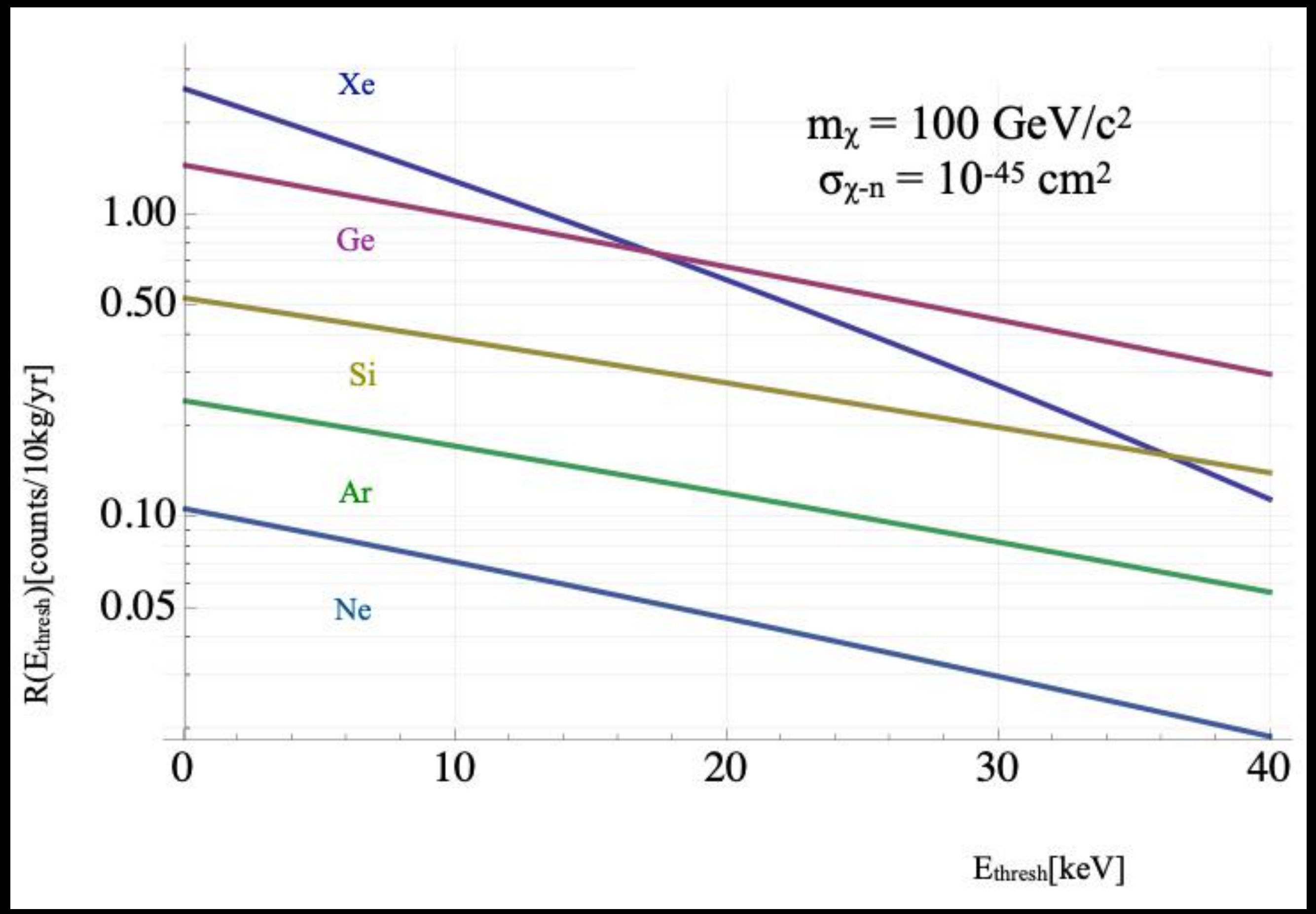
- ✓ The solar system rotates within the DM halo
- ✓ Earth experiences the so called "WIMP wind"
- ✓ Coming from the direction of the Cygnus constellation

Direct interaction signature

- *Disclaimer: this is only the most straightforward hypothesis!*
- Interaction type: elastic scattering off nuclei
- Signal: nuclear recoil energy



- For DM masses in the 10 GeV – 1 TeV range: typical recoil energy is 1keV – 50keV
  Featureless spectrum: just exponential decline

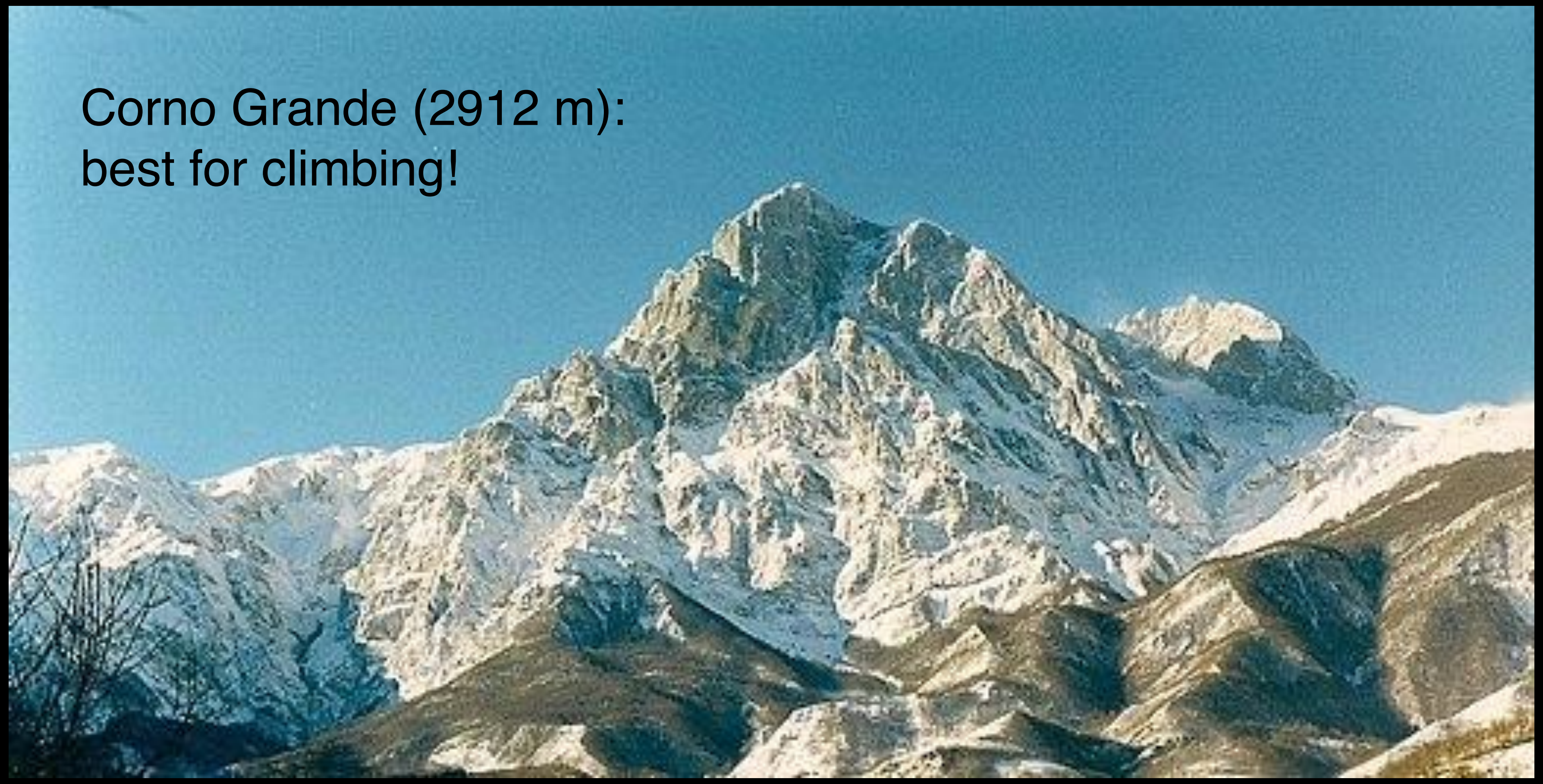


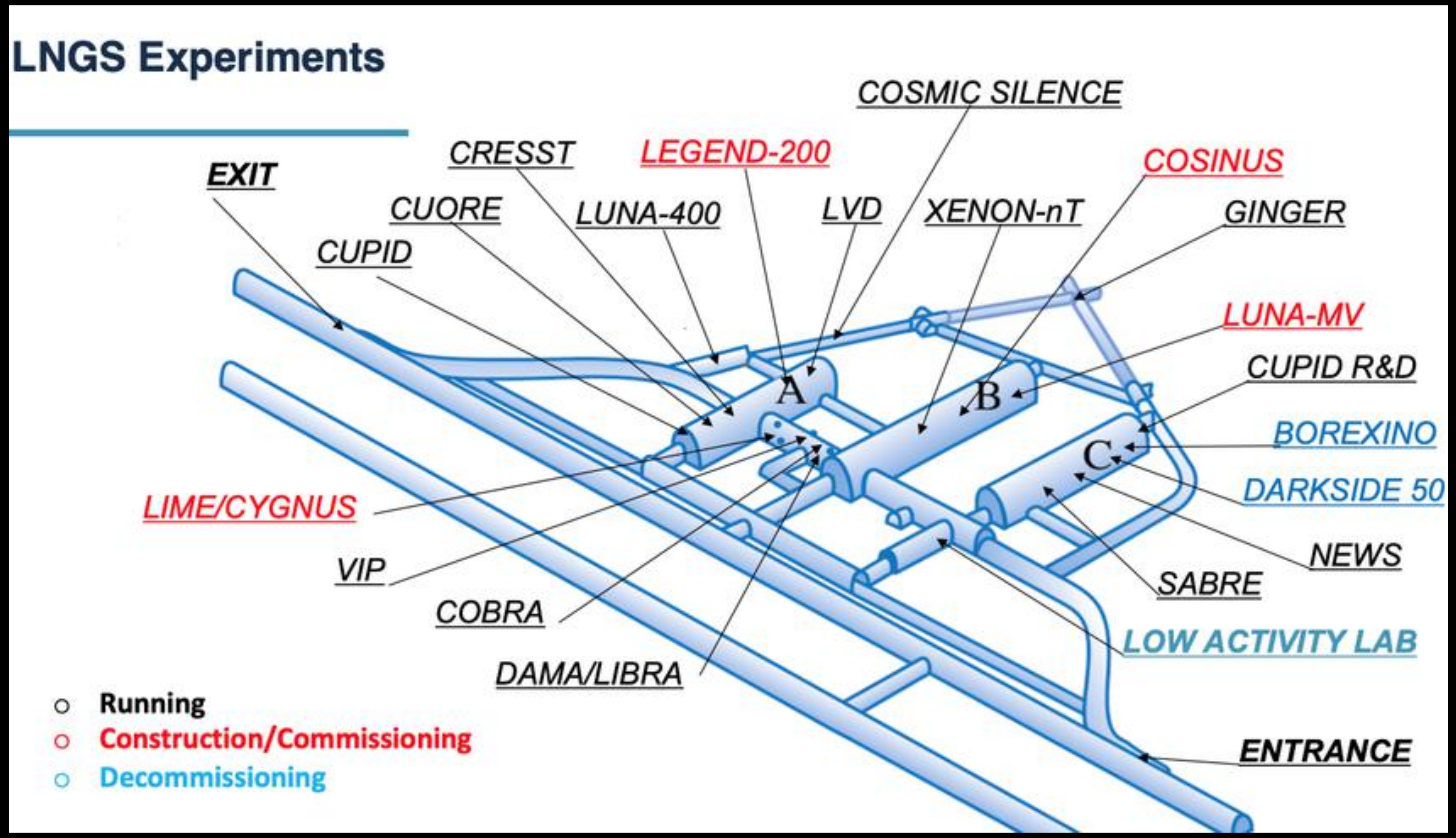
- Challenge: distinguish signal from background at such low energies

- Interaction probability is mostly unknown, though different models have their own estimates in the range $\sigma = 10^{-48}$–10^{-41} cm^2

Very low expected rate ~ 10^{-1} to 10^{-6} events/kg/day

Underground locations





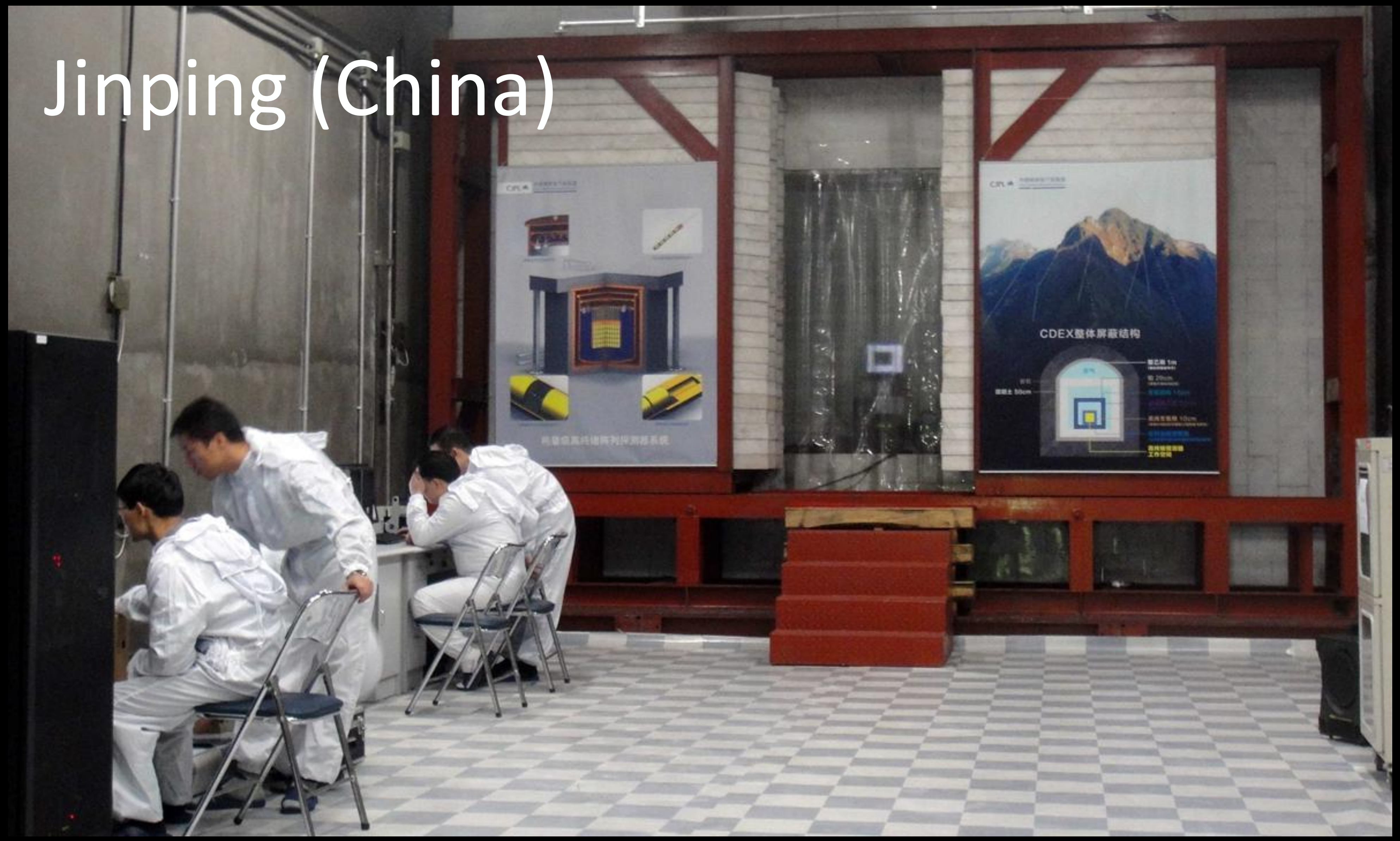
1. Go under a mountain:

Laboratori Nazionali del Gran Sasso
by Instituto Nazionale di Fisica Nucleare (INFN)
360000 m^3 of experimental space
largest in the world and the only ad-hoc excavation

Underground locations

2. Use a mine:

Kamioka (Japan)

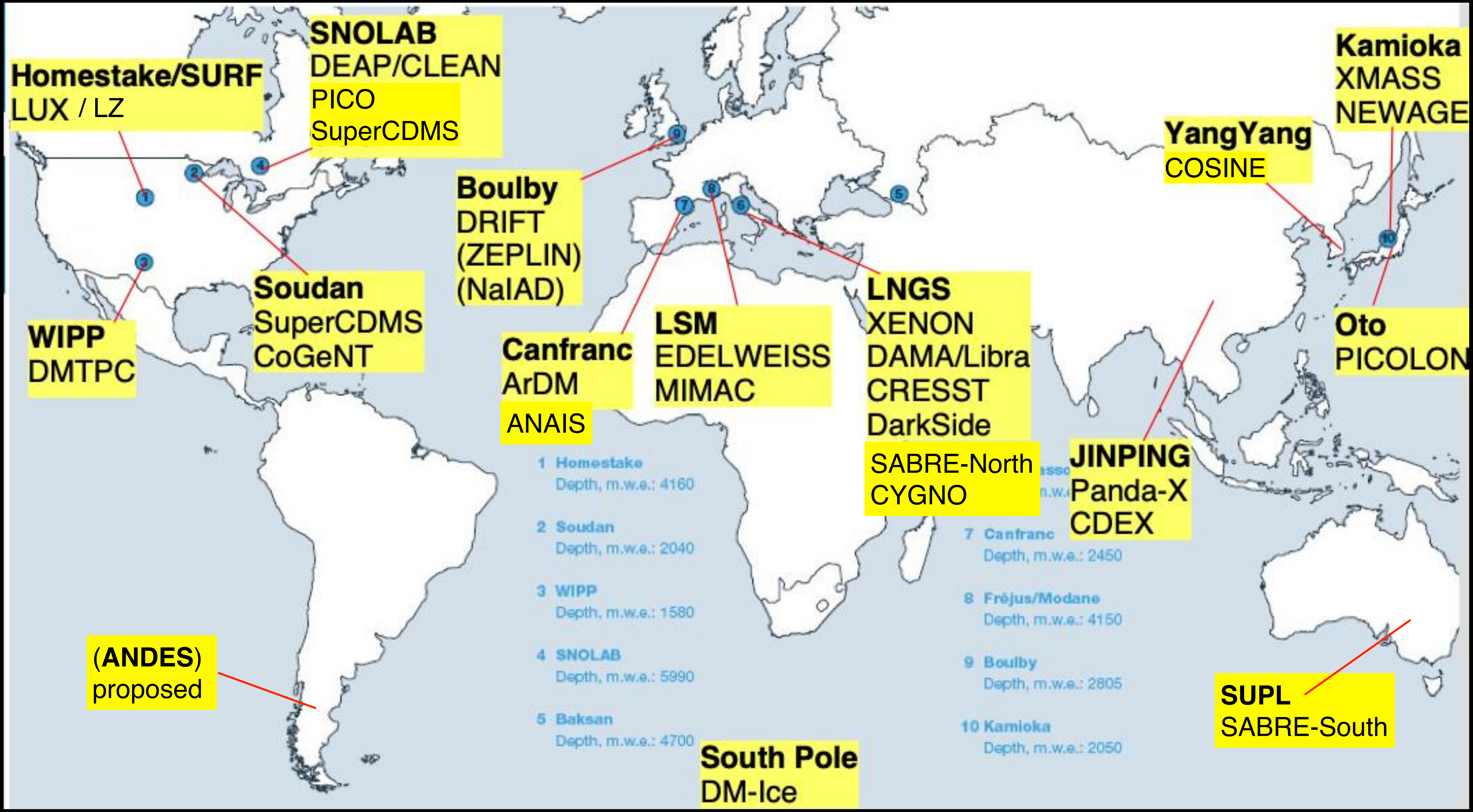


Jinping (China)

SNOLab (Canada)

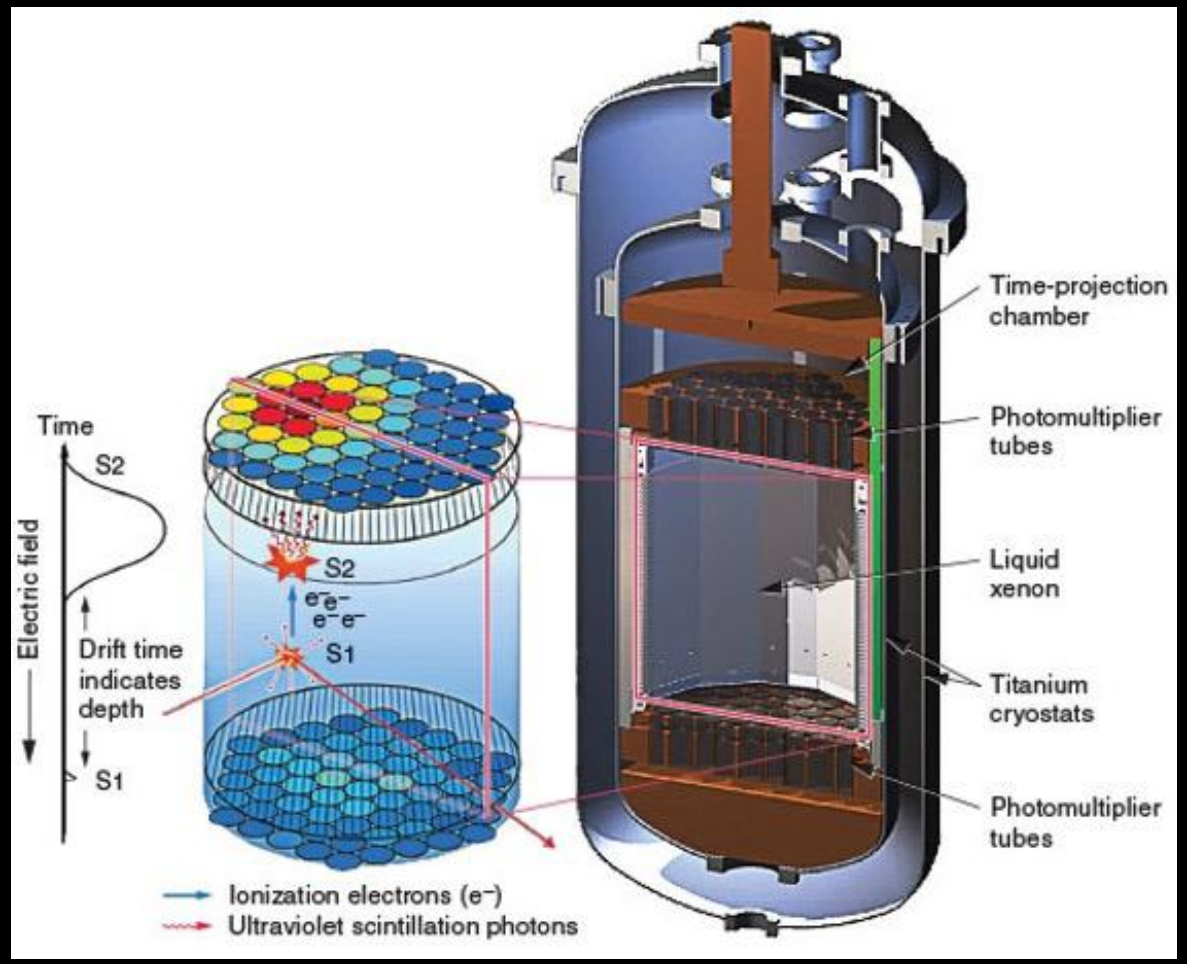
SURF (USA)

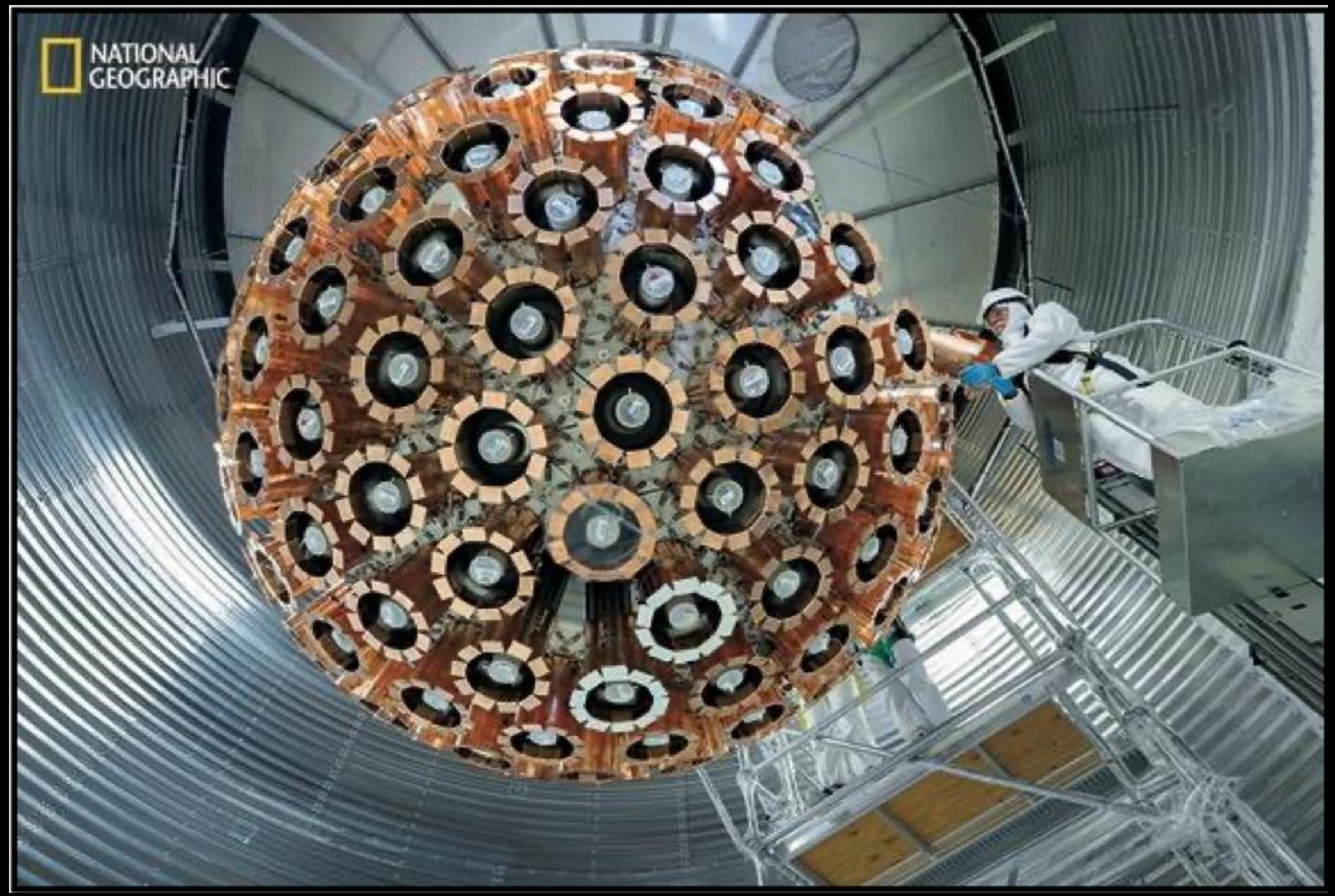
Underground DM projects



Noble liquids

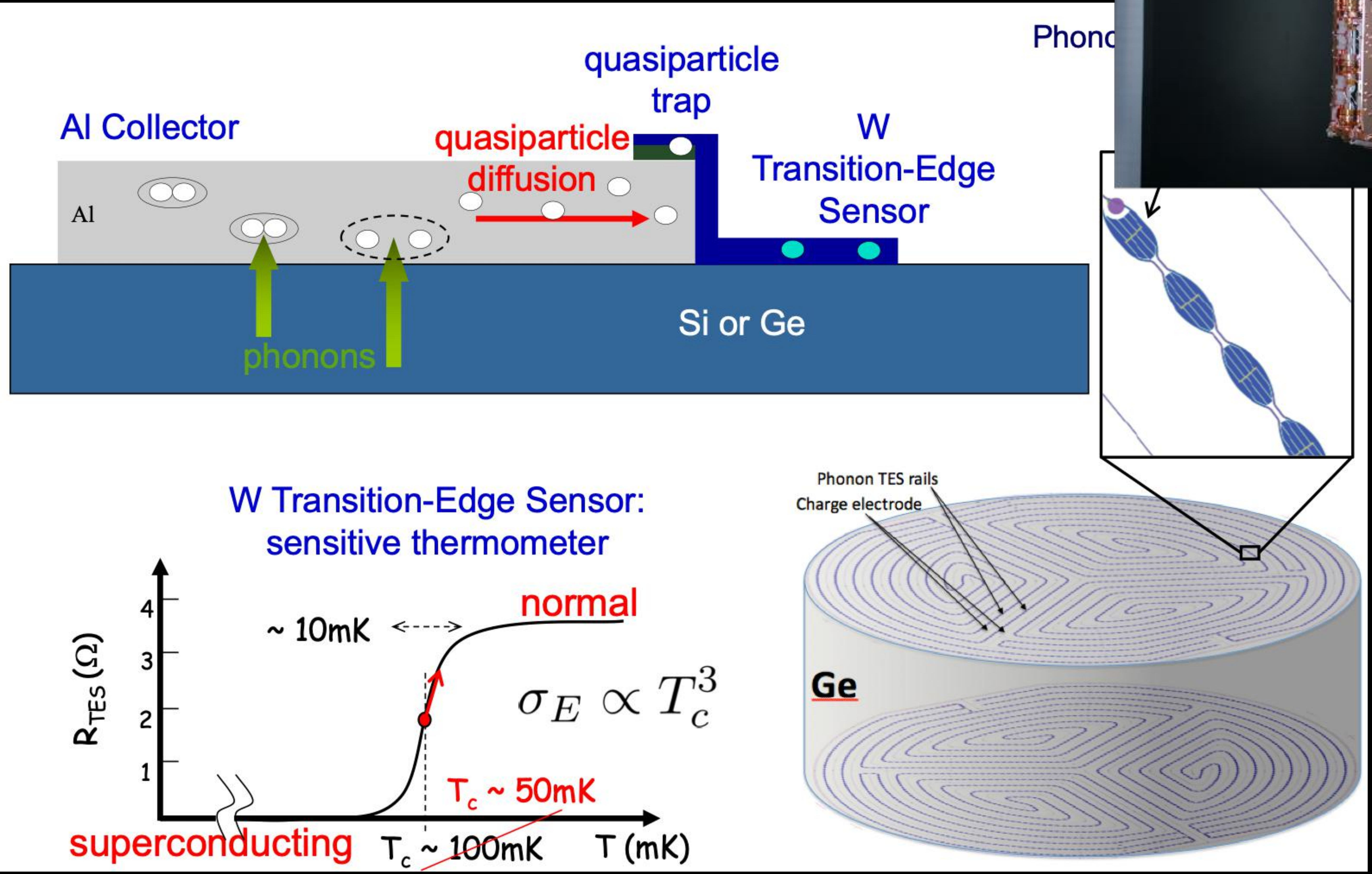
- Liquid Argon (87 K) or Xenon (165 K)
- LZ in USA (6t Xe), Xenon in Italy (7t Xe), PandaX in China (4t Xe), Deap in Canada (4t Ar), DarkSide in Italy (20t Ar, und. constr.)
- Very good for Dark Matter mass in 10 GeV - 1 TeV range





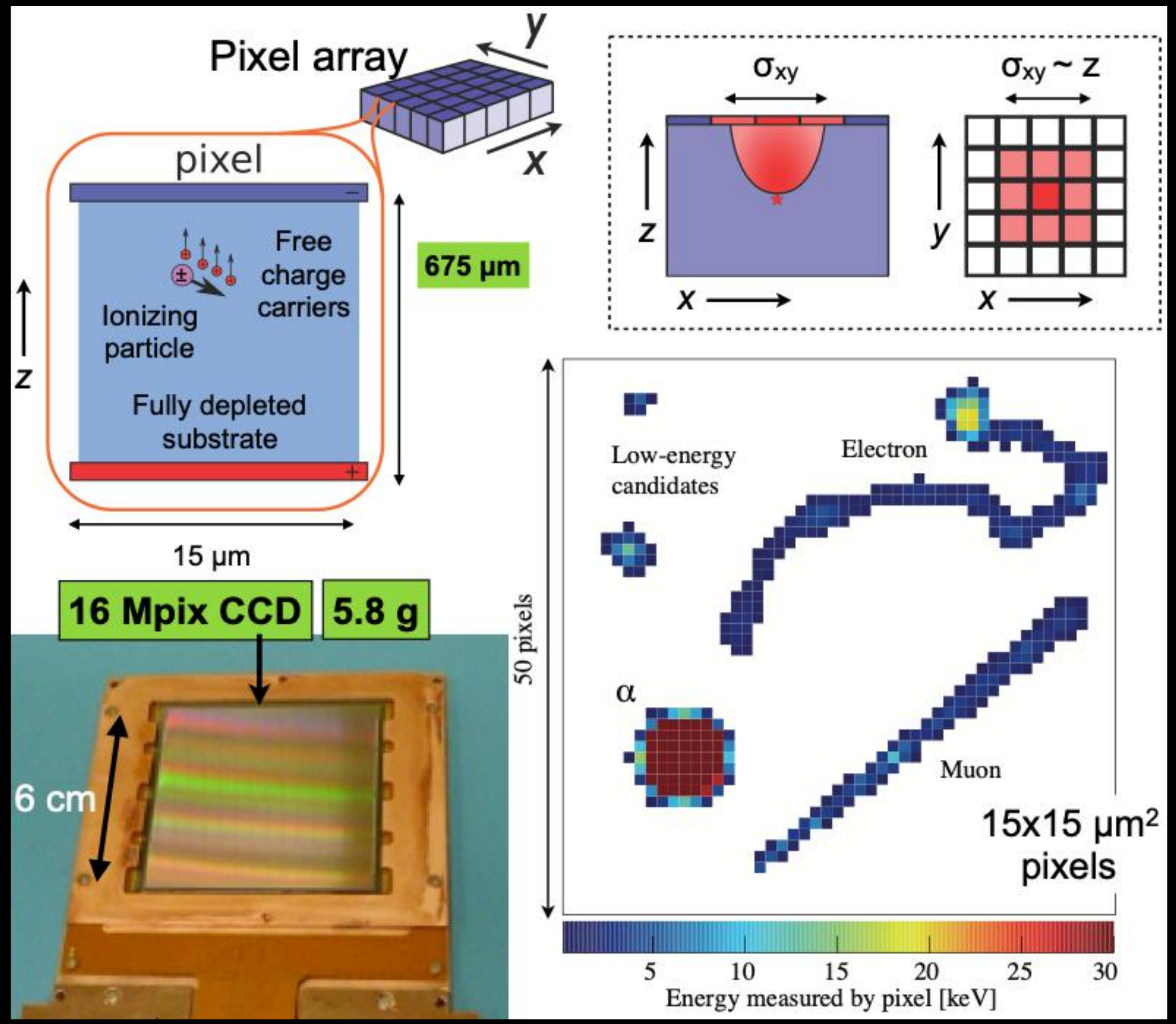
Solid state, a.k.a. bolometers

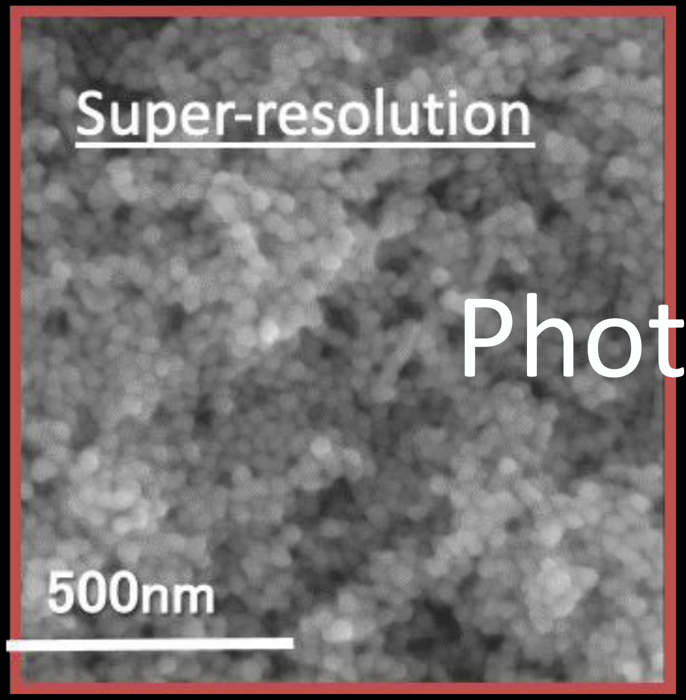
CDMS (USA+Canada): Ge and Si
CRESST (Italy): $CaWO_4$
Very good for light dark matter: < 2 GeV



and many more

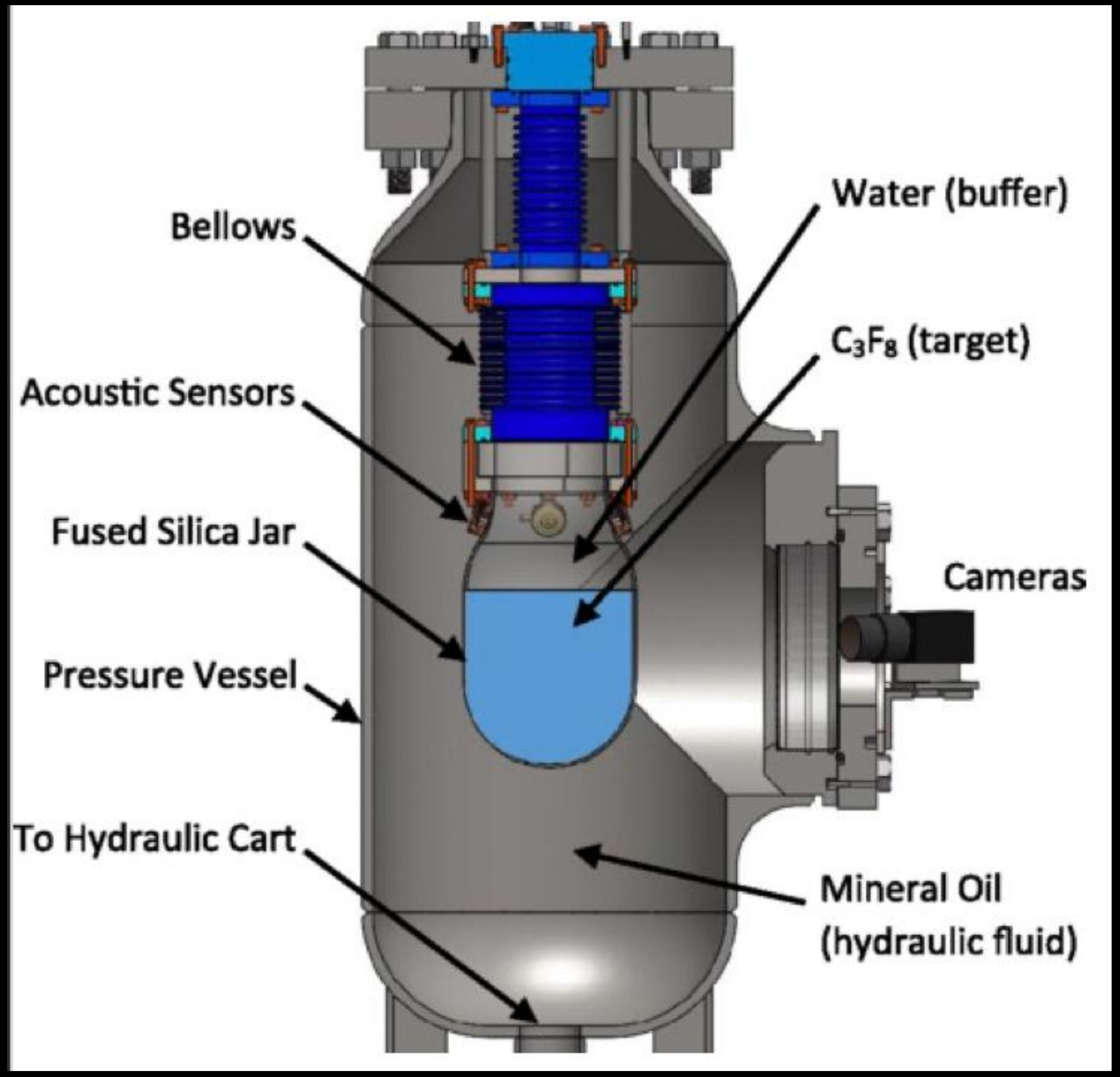
Skipper CCDs



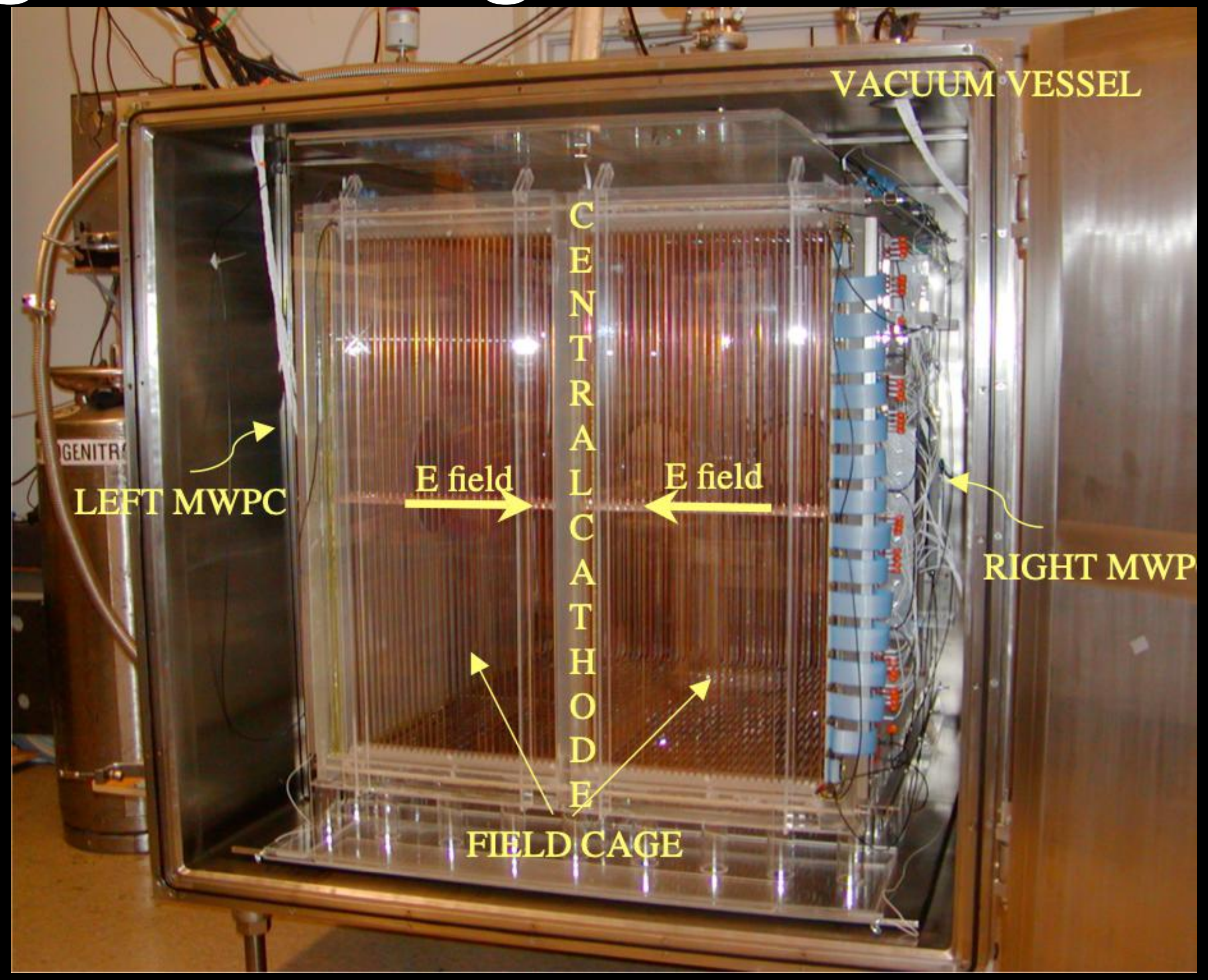


Photographic emulsion

Bubble chambers

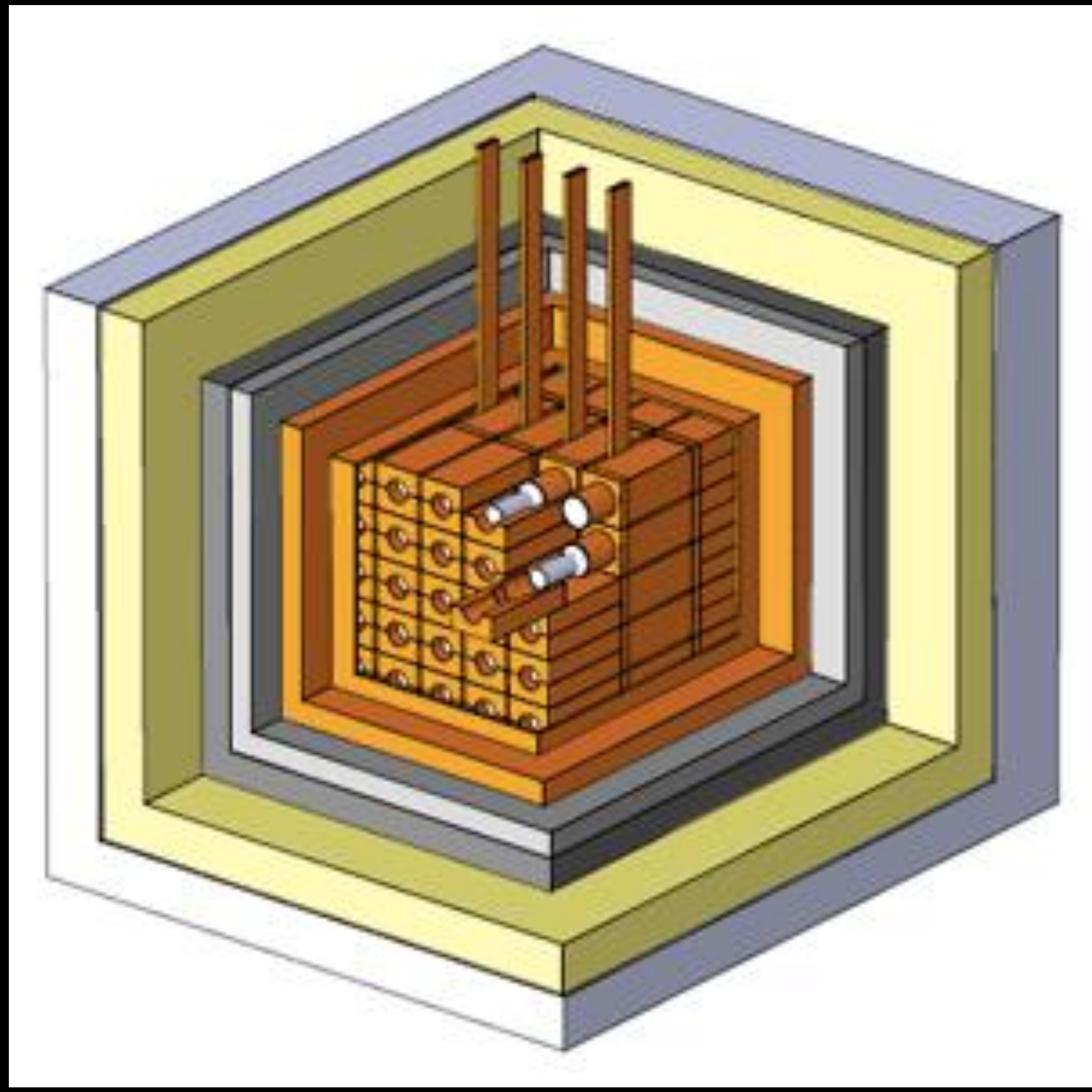


Negative ion gas TPC



DAMA/LIBRA

- Underground location: LNGS
- Technique: NaI(Tl) scintillating crystals
- Detector's module:
  10 kg crystal
  paired with two 3" PMTs
- Geometry: 5x5 crystal matrix
- Total mass: ~250kg
- Energy threshold:
  - 2 keV (phase 1)
  - **1 kev (phase 2)**



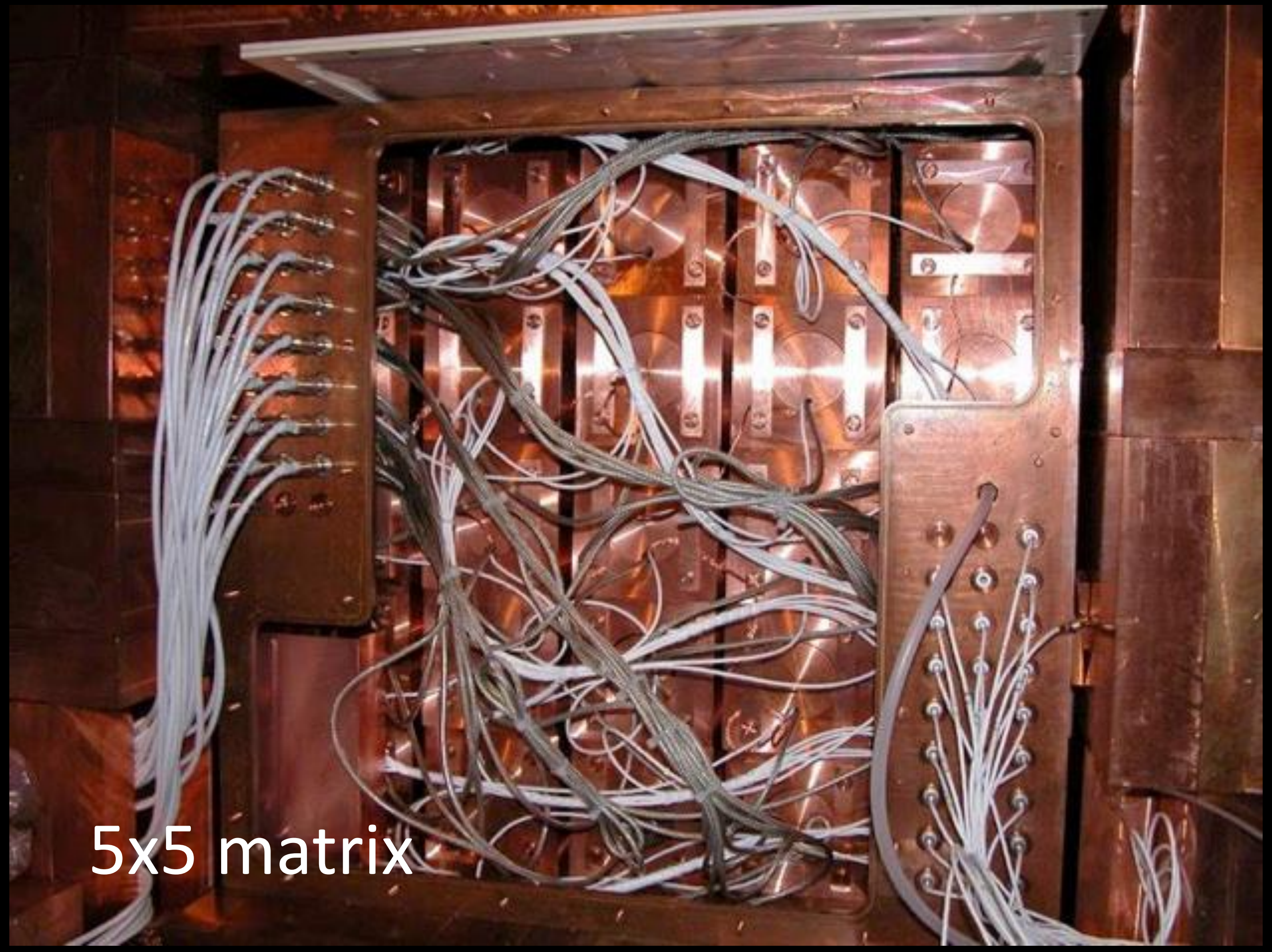
DAMA timeline

1. DAMA/NaI (100kg): 1996-2002
2. DAMA/LIBRA (250kg) Phase I : 2003-2010
   - New crystals, mass upgrade
3. DAMA/LIBRA (250kg) Phase II: 2011-2019
   - New PMTs (low radioactivity, low noise)
   - Low Energy Threshold: 1 keV
4. Concluded DAMA/LIBRA in 2024

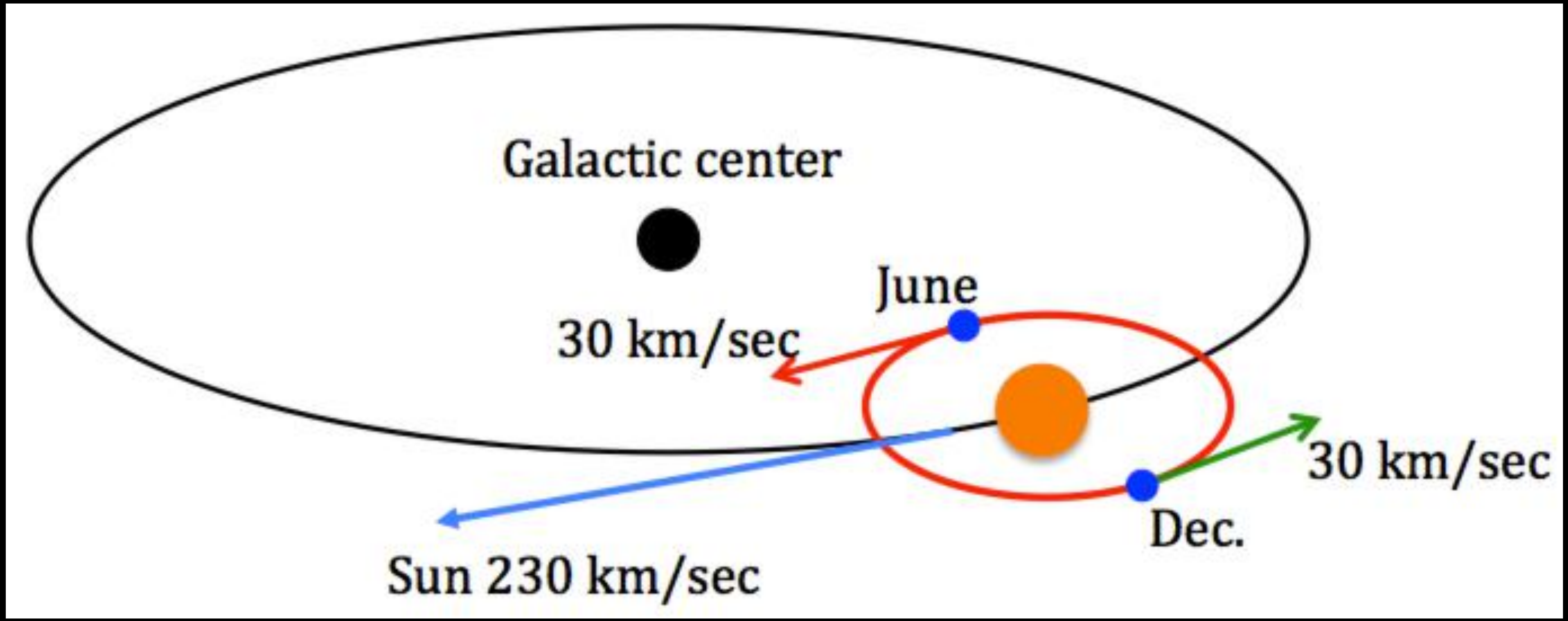
R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648.

Results first released in 2018

Nucl. Phys. At. Energy 2018, 19(4):307-325
arXiv:2110.04734



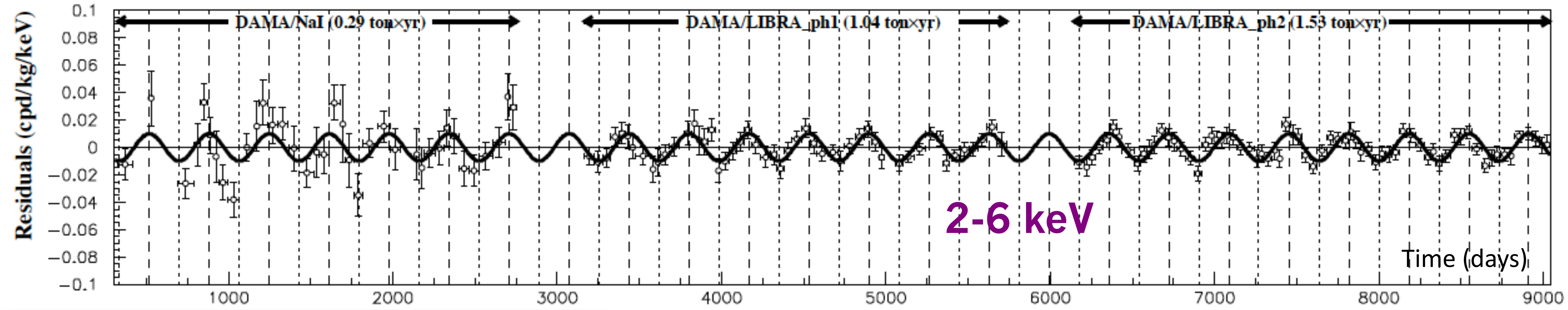
Annual Modulation DM signature



$$\frac{dR}{dE_R}(t) = S_0(E_R) + S_m(E_R) cos\omega(t - t_0)$$

Annual modulation is a model independent signature of Dark Matter interaction

DAMA/LIBRA signal



Nucl. Phys. At. Energy 2018, 19(4):307-325
[arXiv:2110.04734]

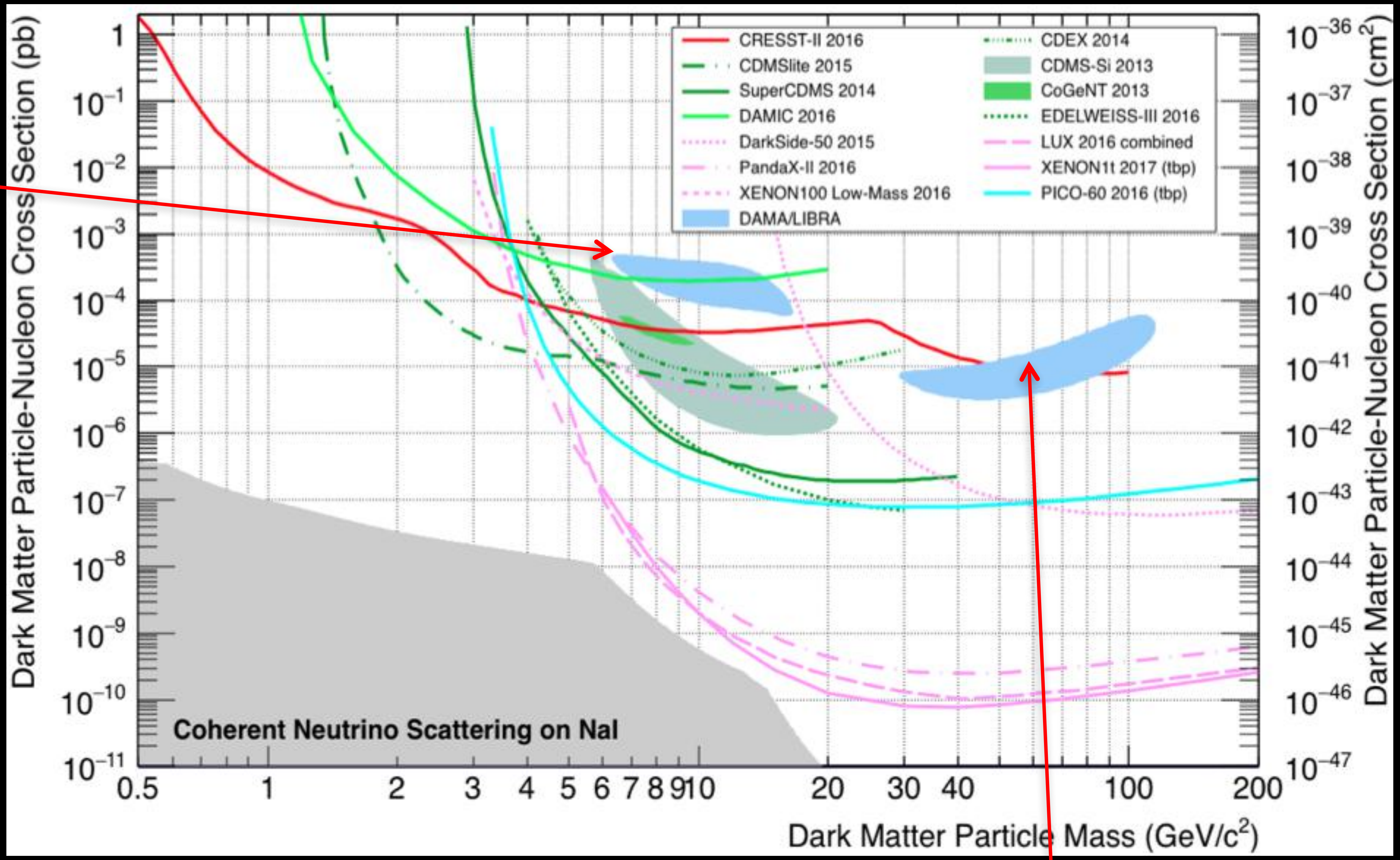
- 22 annual cycles (DAMA/NaI + DAMA/LIBRA-Phase1 + DAMA/LIBRA-Phase2)
- Exposure: 2.86 ton x yr
- g.o.f.: χ^2/ndf = 130/155
- Significance: 13.7 σ
- Period: T = (0.9983±0.0007) year
- Phase: (142±4) days vs. exp. DM phase 152.5 days (Jun 2nd)
- Amplitude: (0.0101±0.0007) cdp/kg/keV, i.e. ~ 1% of the experimental rate.

(old) interpretation of DAMA/NaI + DAMA/LIBRA-Phase1 results

Interaction on Na nuclei

M_{wimp} ~ 10 GeV

σ ~ 10^{-40} cm^2



In the simplest interpretation of SI WIMP-nucleus interaction there are two allowed regions with very similar χ^2

Interaction on I nuclei

M_{wimp} ~ 80 GeV

σ ~ 10^{-41} cm^2

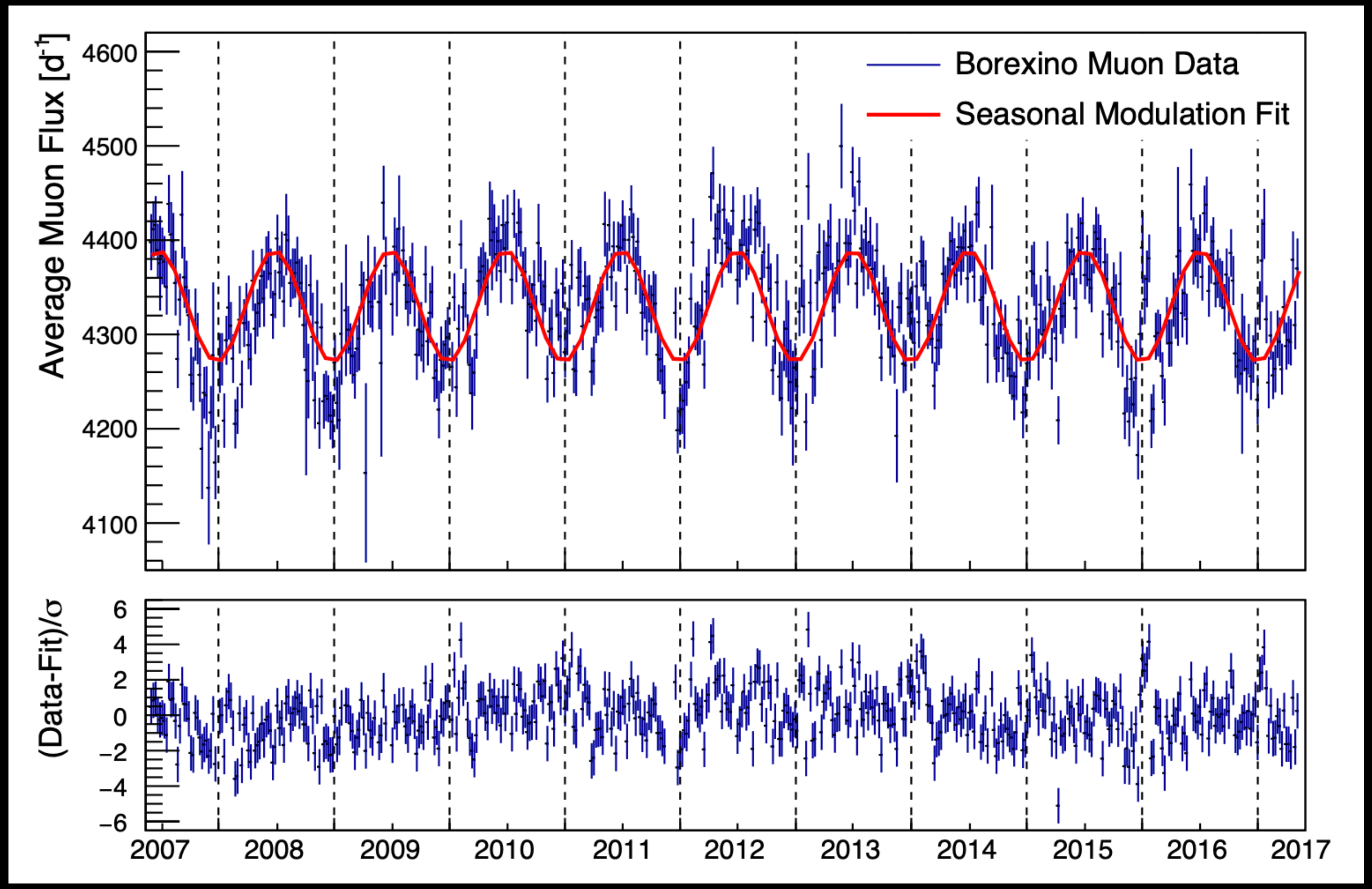
However there are several assumptions here:

- ✓ Astrophysics: DM halo
- ✓ Dark matter candidate: WIMP
- ✓ Nature of interaction: elastic and Spin Independent
- ✓ Target of Interaction: nuclei

DAMA alternative explanations?

JCAP02(2019)046

- The rate of cosmogenic muons is known to modulate due to seasonal expansion/contraction of the troposphere which changes the pion/kaon mean free path.
- Observed at LNGS by MACRO, Borexino, LVD, GERDA.



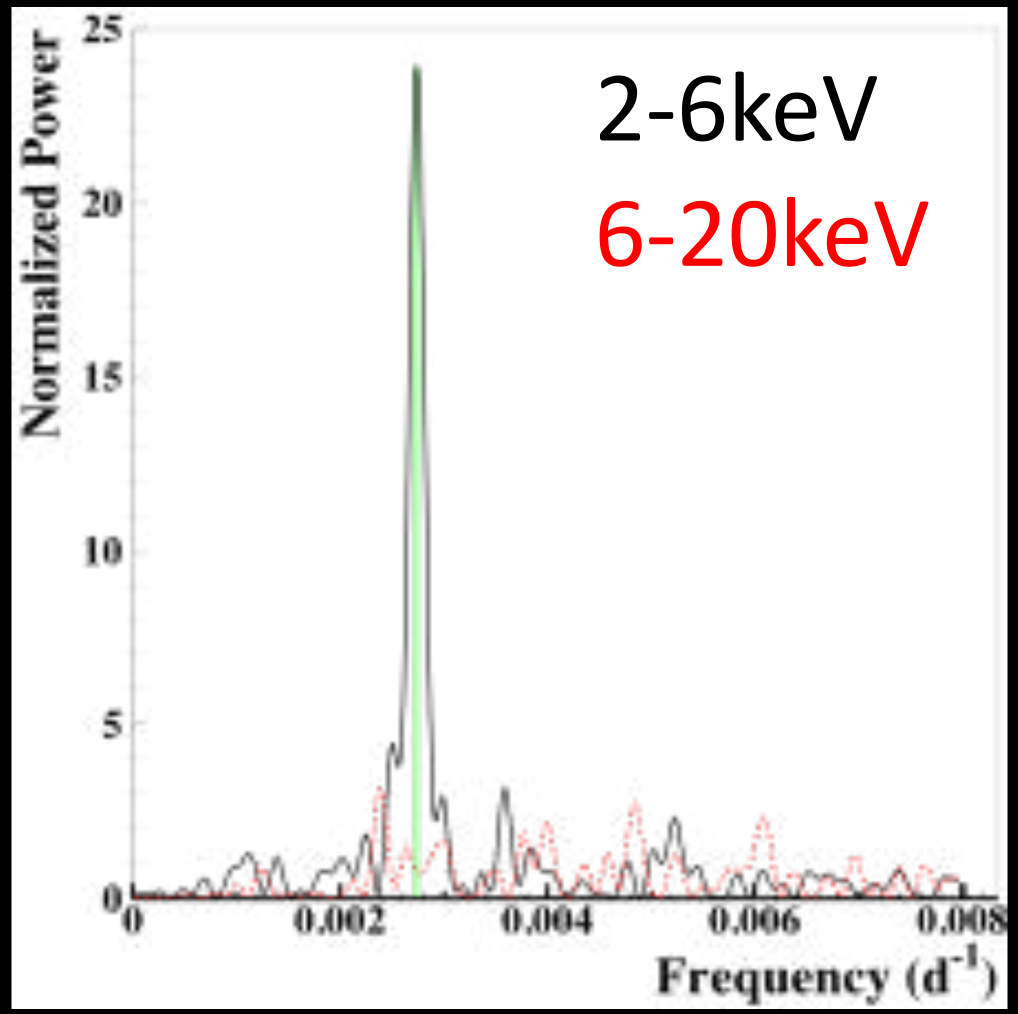
- Could muon-induced background such as neutrons explain D/L modulation?
- Could there be other explanations of terrestrial origin? (e.g. radon emanation)
- Long standing questions: tens of papers written on the subject.
- **No convincing alternative explanation so far**

Why is DAMA robust?

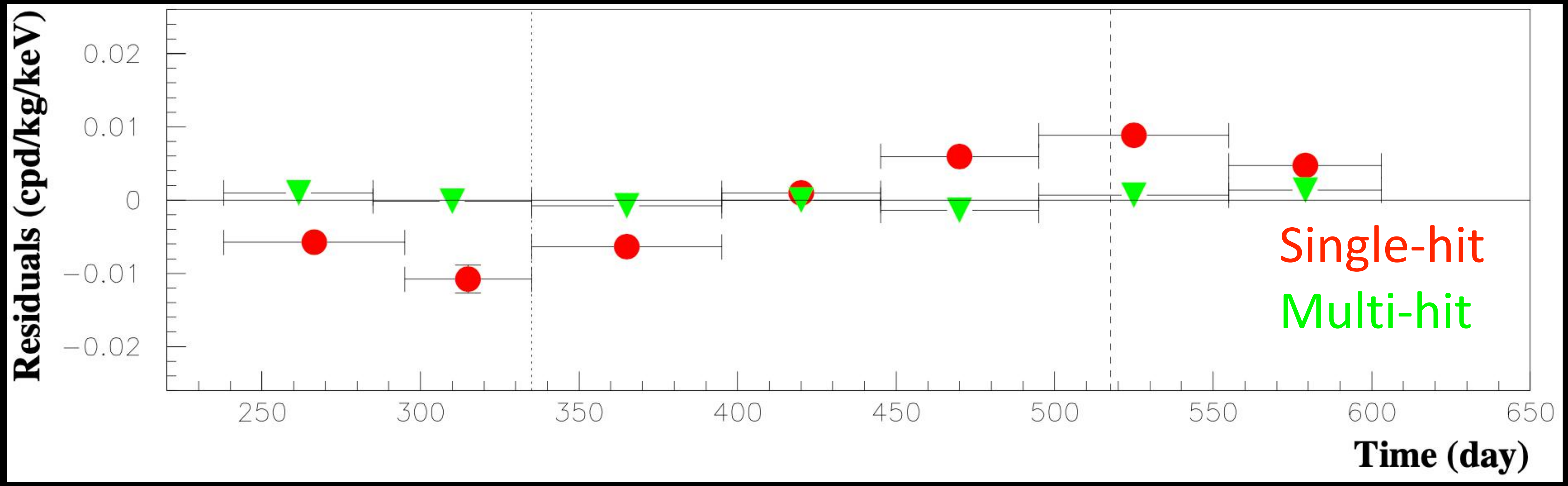
1) Instrumental sources of modulations investigated and excluded:

- ✓ radon
- ✓ temperature
- ✓ gas pressure
- ✓ noise
- ✓ energy scale
- ✓ efficiencies
- ✓ environmental neutrons

2) No modulation > 6keV

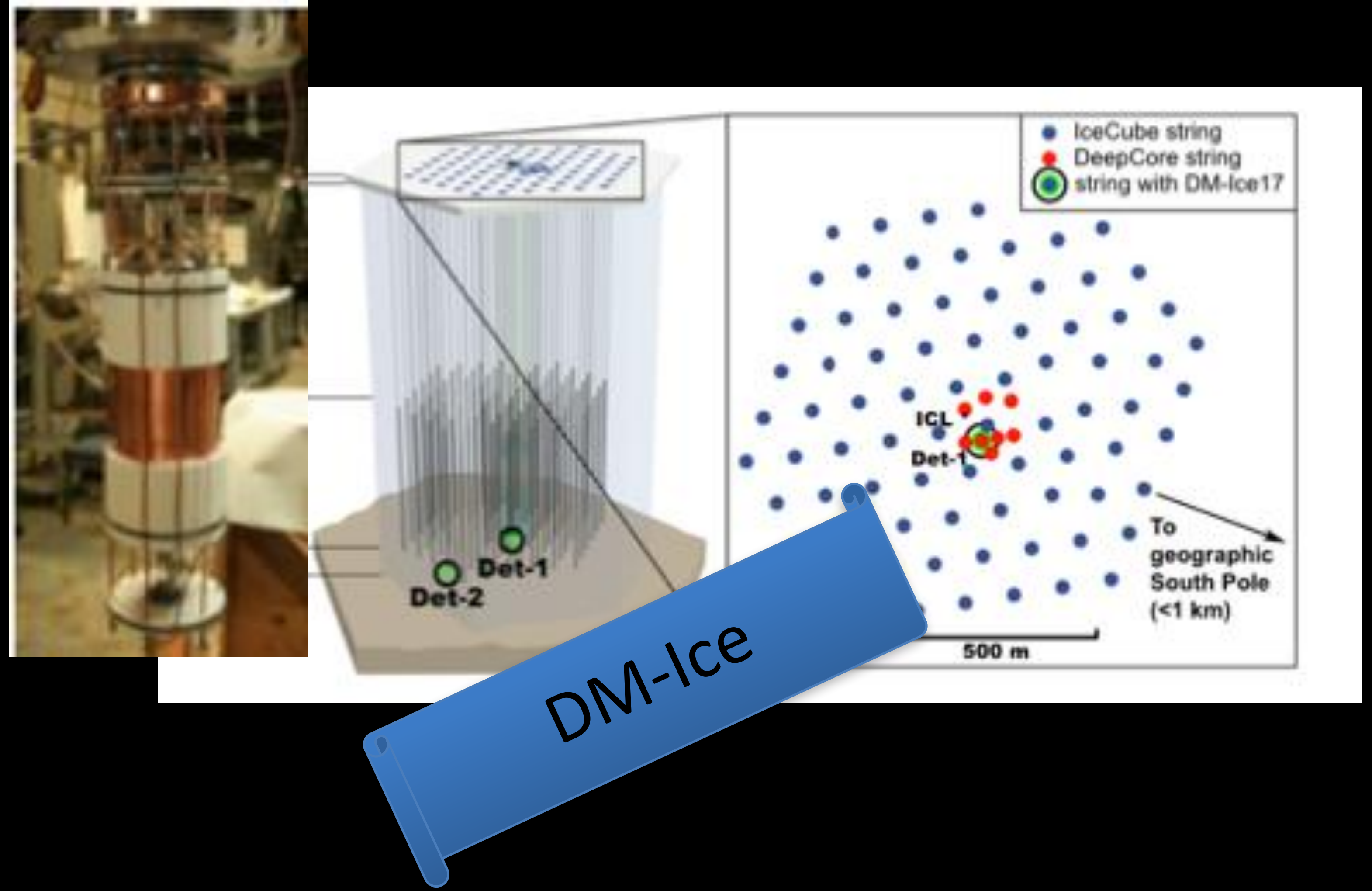


3) No modulation in multi-hit events

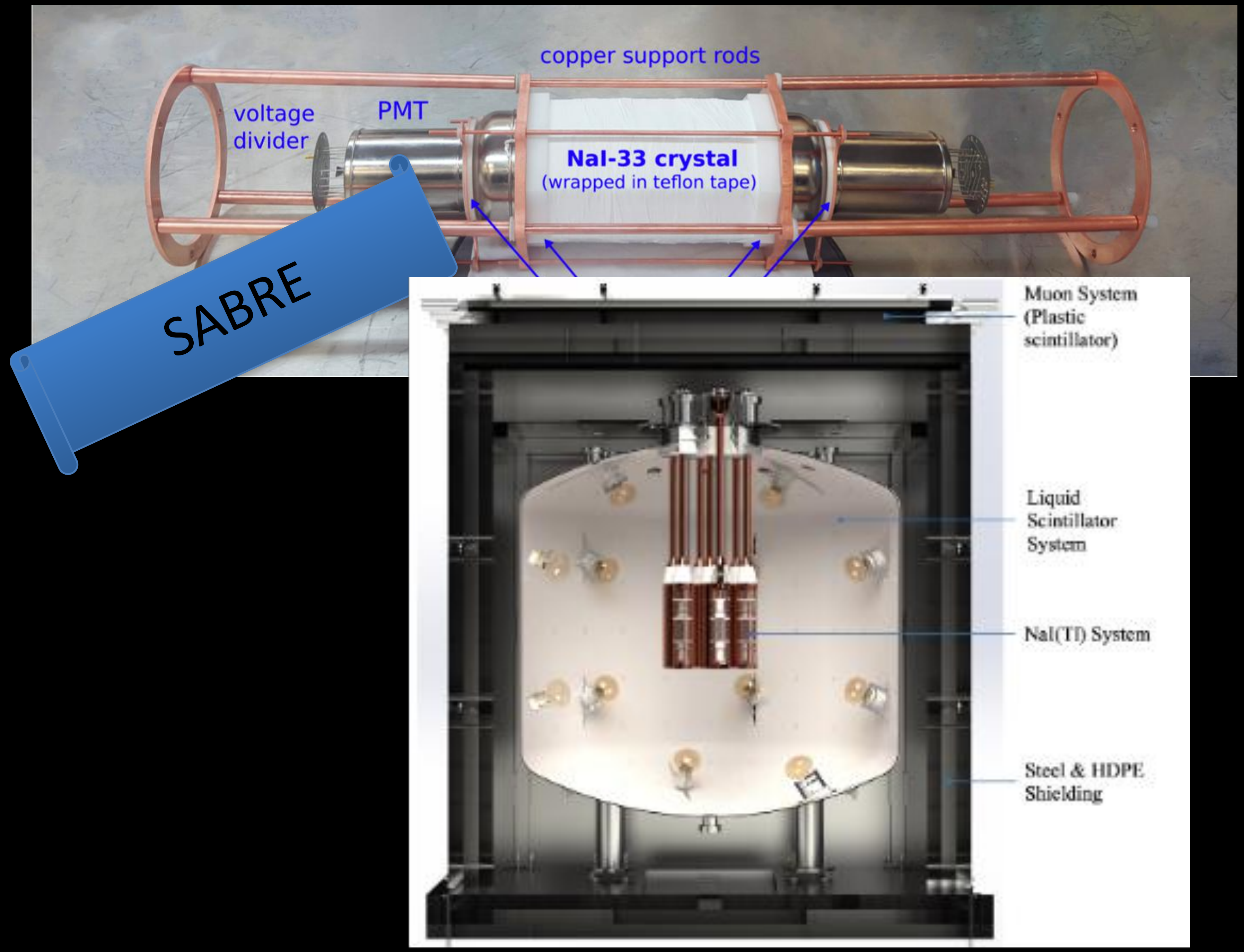


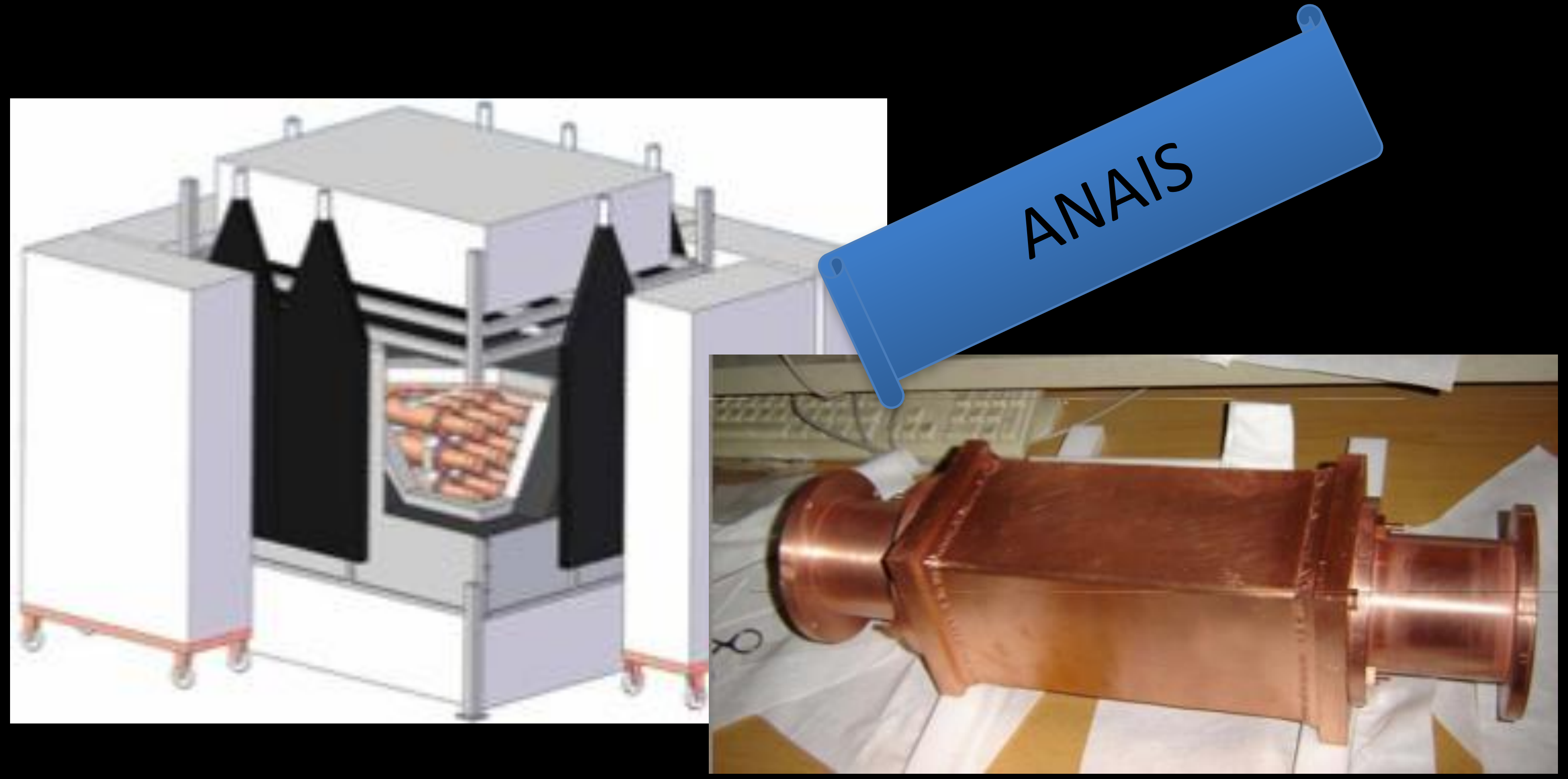
4) Phase DAMA/LIBRA: (142±4)d
compare: phase cosmic muons (187.7±0.7)d

See R. Cerulli @IDM 2024 for the most recent discussion



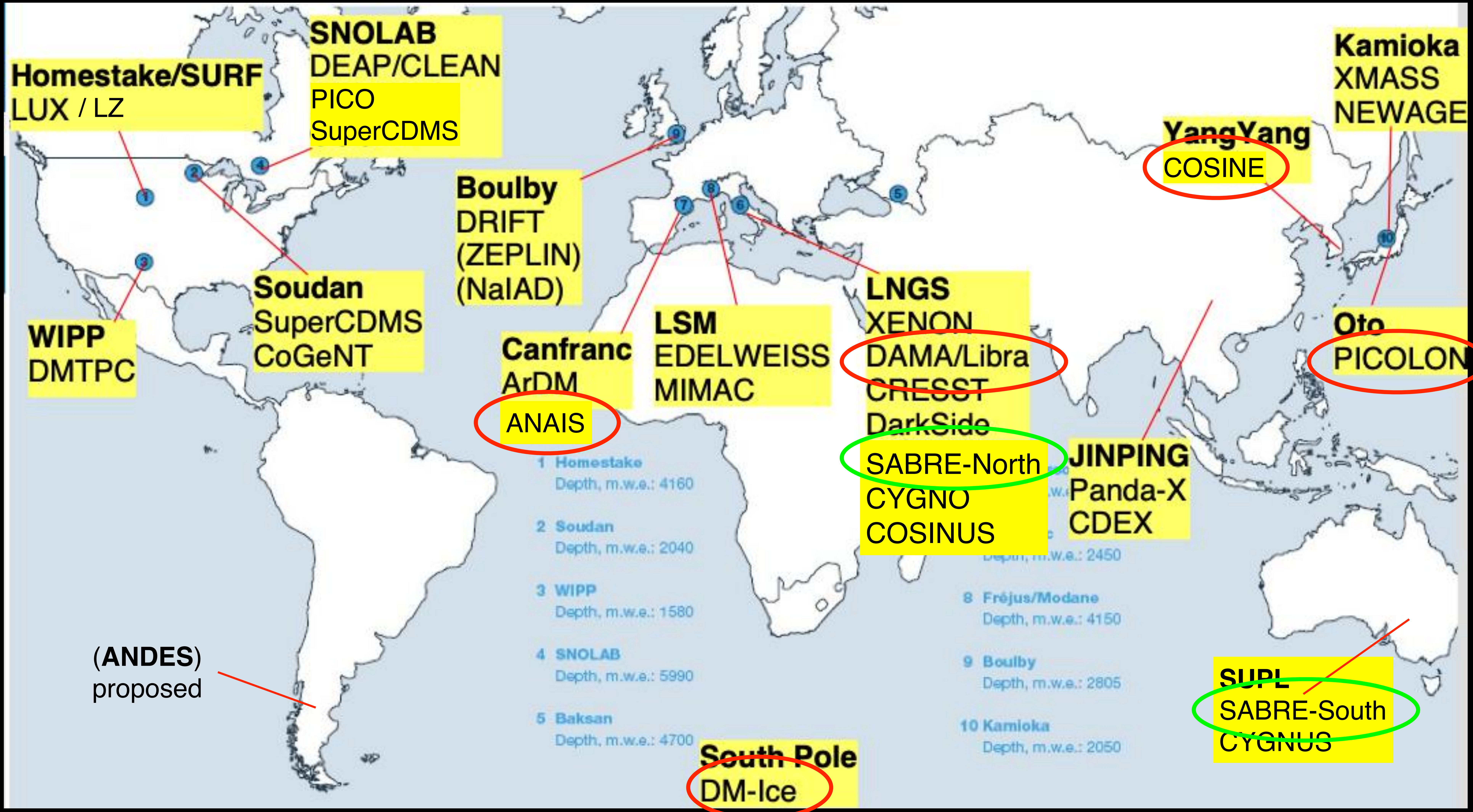
A world wide effort
to verify this result with
NaI(Tl)





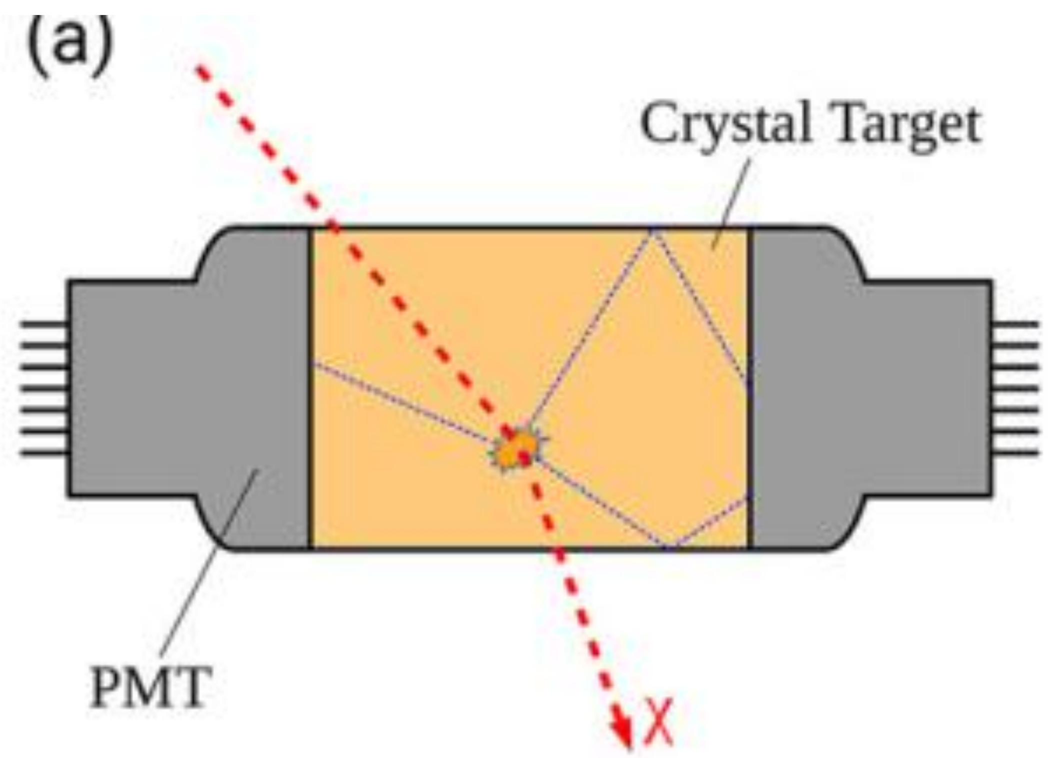
+ PICO-lon at Kamioka (japan)

Underground projects



Part 2: SABRE-North status and perspectives

The choice of NaI and NaI-based DM experiments



	Location	Target	Mass (kg)	Status	Notes
DAMA-NaI DAMA/LIBRA	LNGS	NaI(Tl)	100 250	completed	
ANAIS-112	LSC	NaI(Tl)	112.5	running	
COSINE-100	Y2L	NaI(Tl)	106 (61.3)	upgrading	
COSINE-200	Yemilab	NaI(Tl)	~200	suspended?	
SABRE-North	LNGS	NaI(Tl)	~50	**in preparation**	
SABRE-South	SUPL	NaI(Tl)	~50	**in preparation**	
COSINUS	LNGS	NaI	~1	**in preparation**	bolometer
PICOLon	Kamioka	NaI(Tl)	?	R&D	
ASTAROTH	LASA	NaI(Tl)	n.a.	**R&D**	SiPM
ANAIS+	LSC	NaI	n.a.	**R&D**	SiPM

- well-known experimental technique, scalability
- possibility to grow large (~10 kg) crystals
- high duty cycle, high light output and good alpha/beta PSD
- possibility to carry on routine calibration in the keV range
- sensitivity to different DM scenarios and interactions

Disadvantages:

- hygroscopic crystals
- growing large crystals with the required radio purity has proven very challenging

The SABRE strategy

- SABRE Proof-of-principle (PoP) and PoP-dry achieved a background of ~1 **cpd/kg/keV**

  We aim to ~ 0.5 cpd/kg/keV

- Strategy to lower the **background:**
  - For internal backgrounds

    → SABRE North & South: **zone refining** expected to reduce Pb of factor ~ 3, K of ~ 10

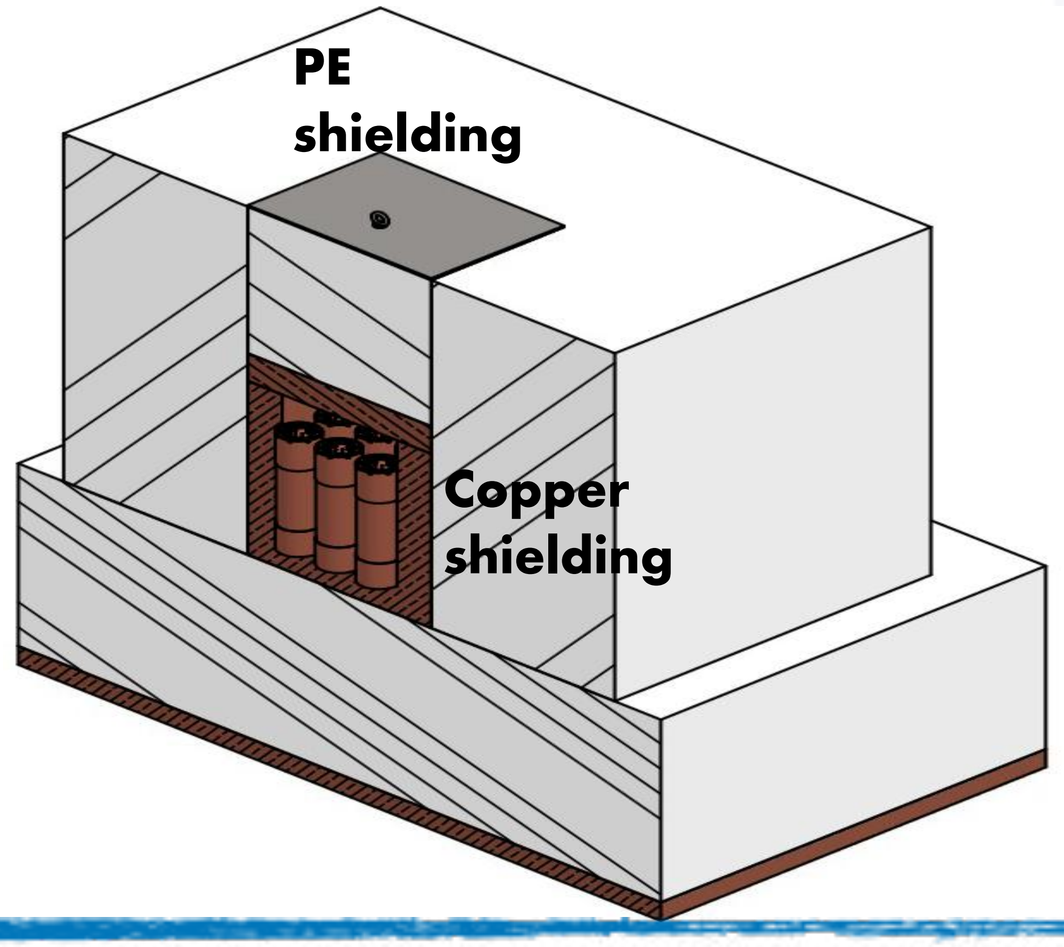
  - For external background:

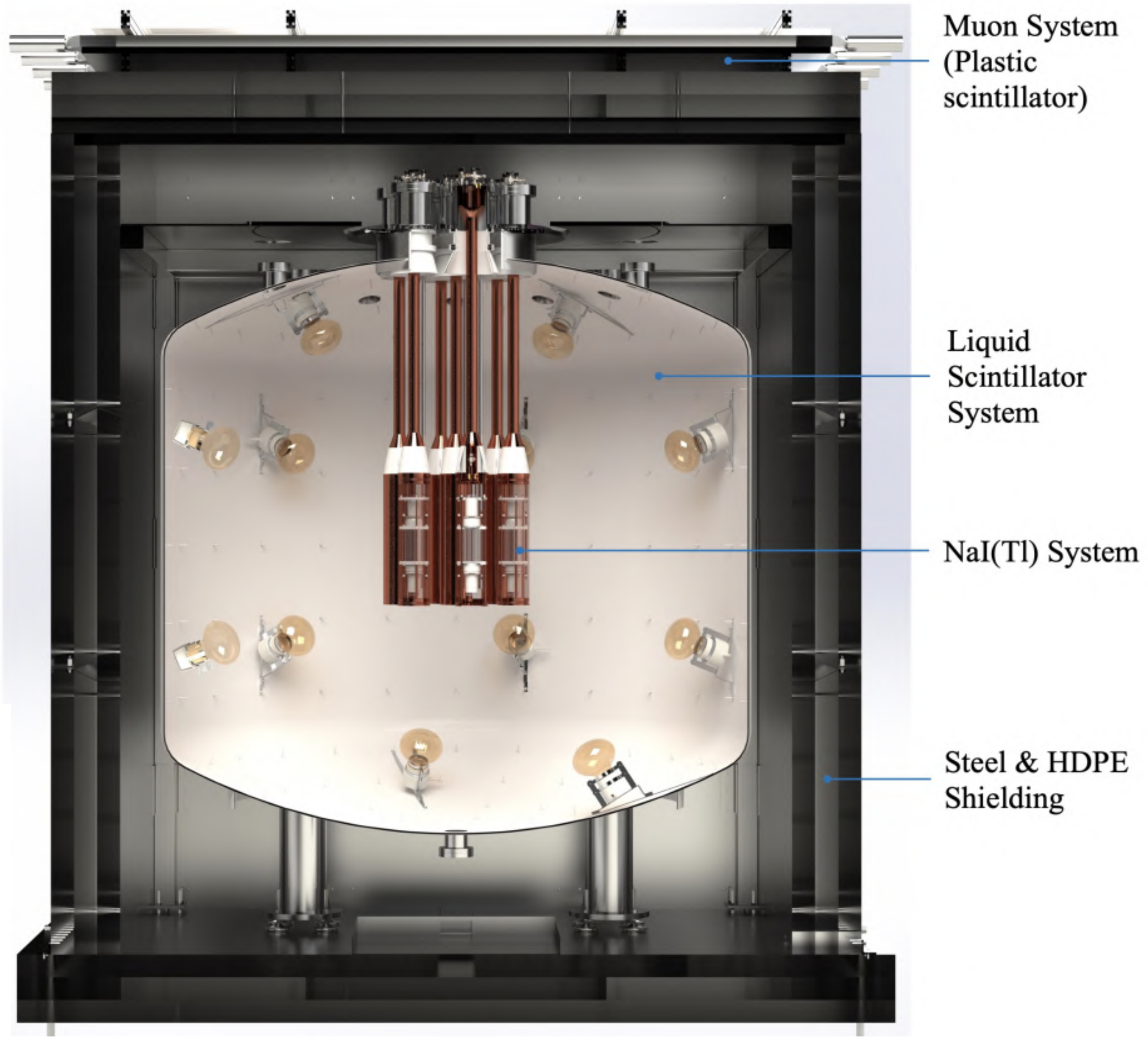
    → SABRE North: improve passive shielding

    → SABRE South: Liquid Scintillator (LAB)

    + Muon Veto

SABRE North





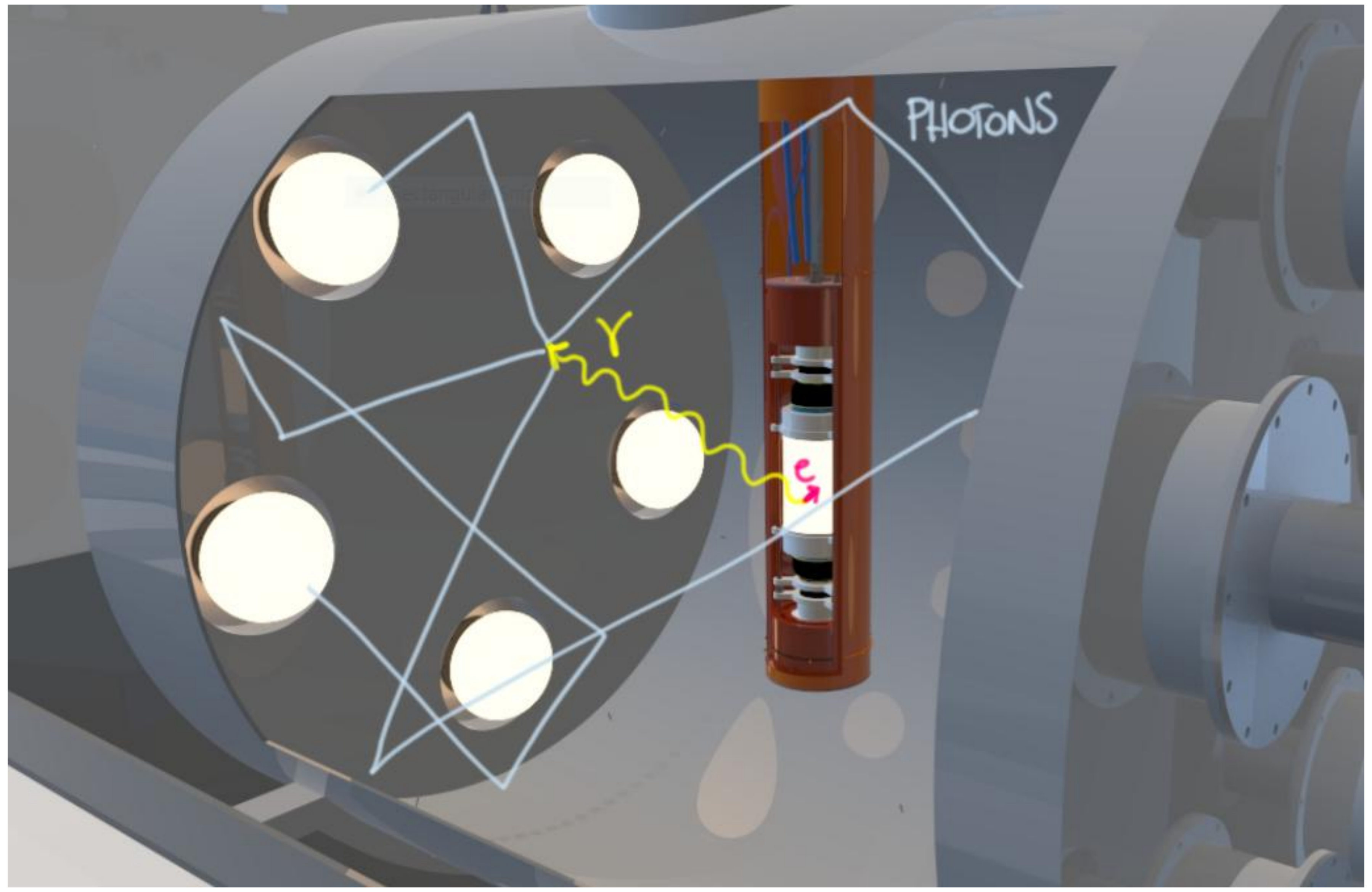
SABRE South

Internal backgrounds in NaI(Tl) crystals

Main contributions in ROI:

- ^{238}U, ^{232}Th
  - must be at the level of 10 ppt
- ^{40}K
  - must be at the level of a few ppb
- ^{87}Rb, ^{210}Pb, ^{3}H

no longer an option for SABRE North, due to the phase out of organic scintillators at LNGS



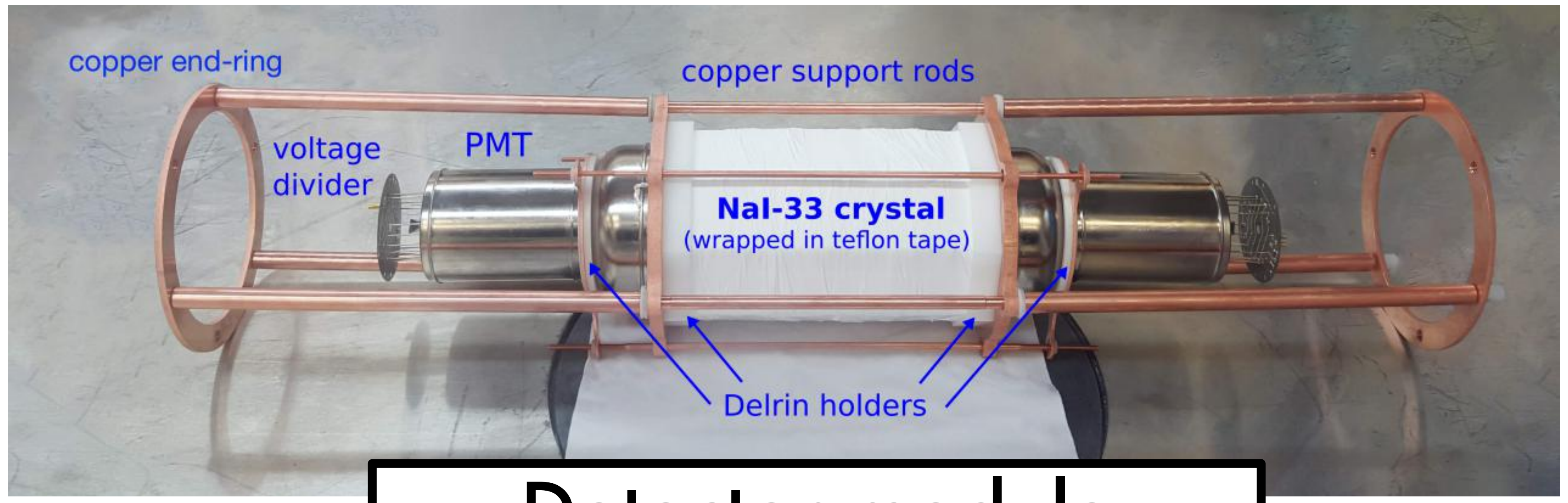
Internal contaminations:

Our initial effort focused on the reduction of Potassium content (clean powder, active veto).

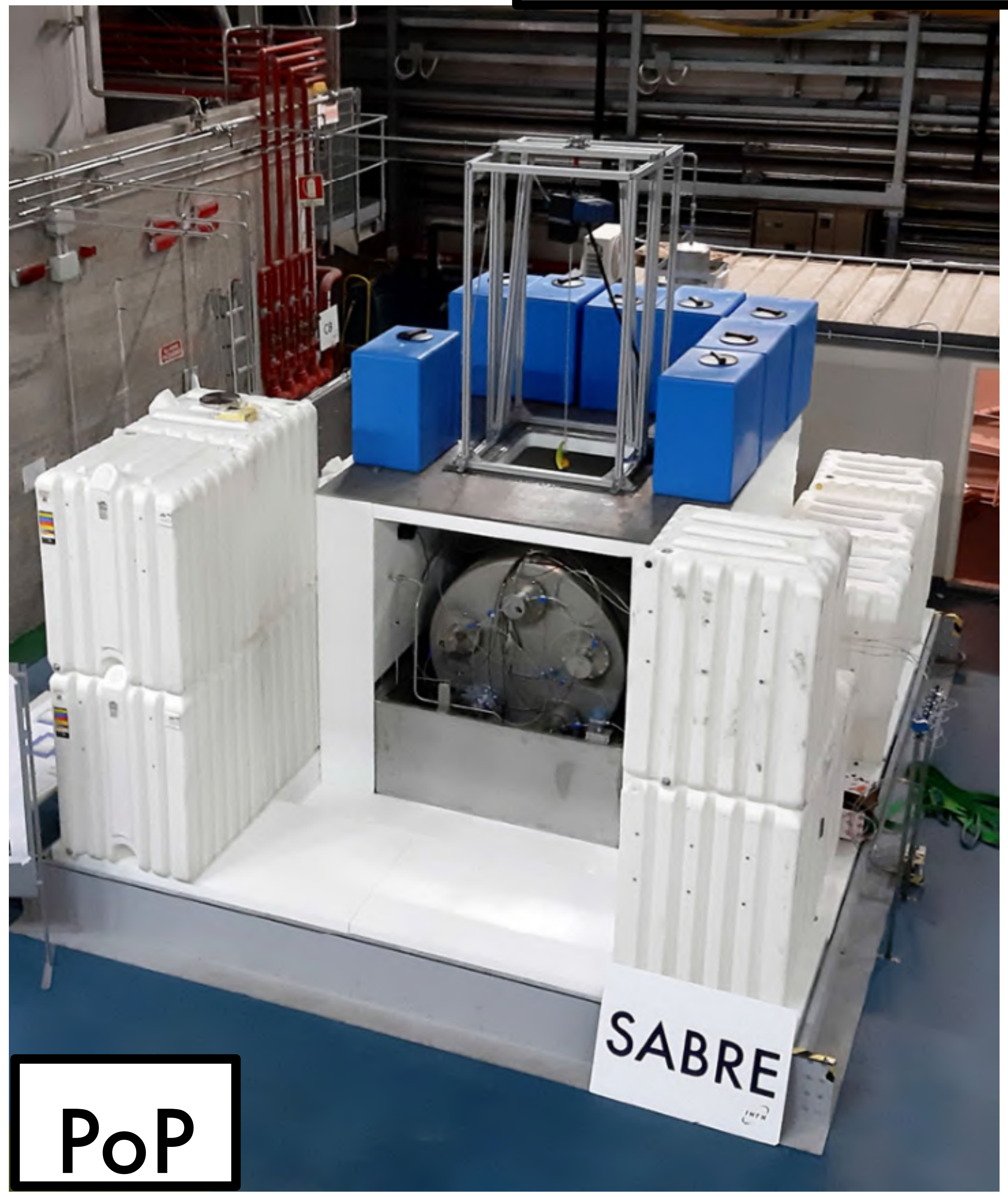
Cosmogenic activation

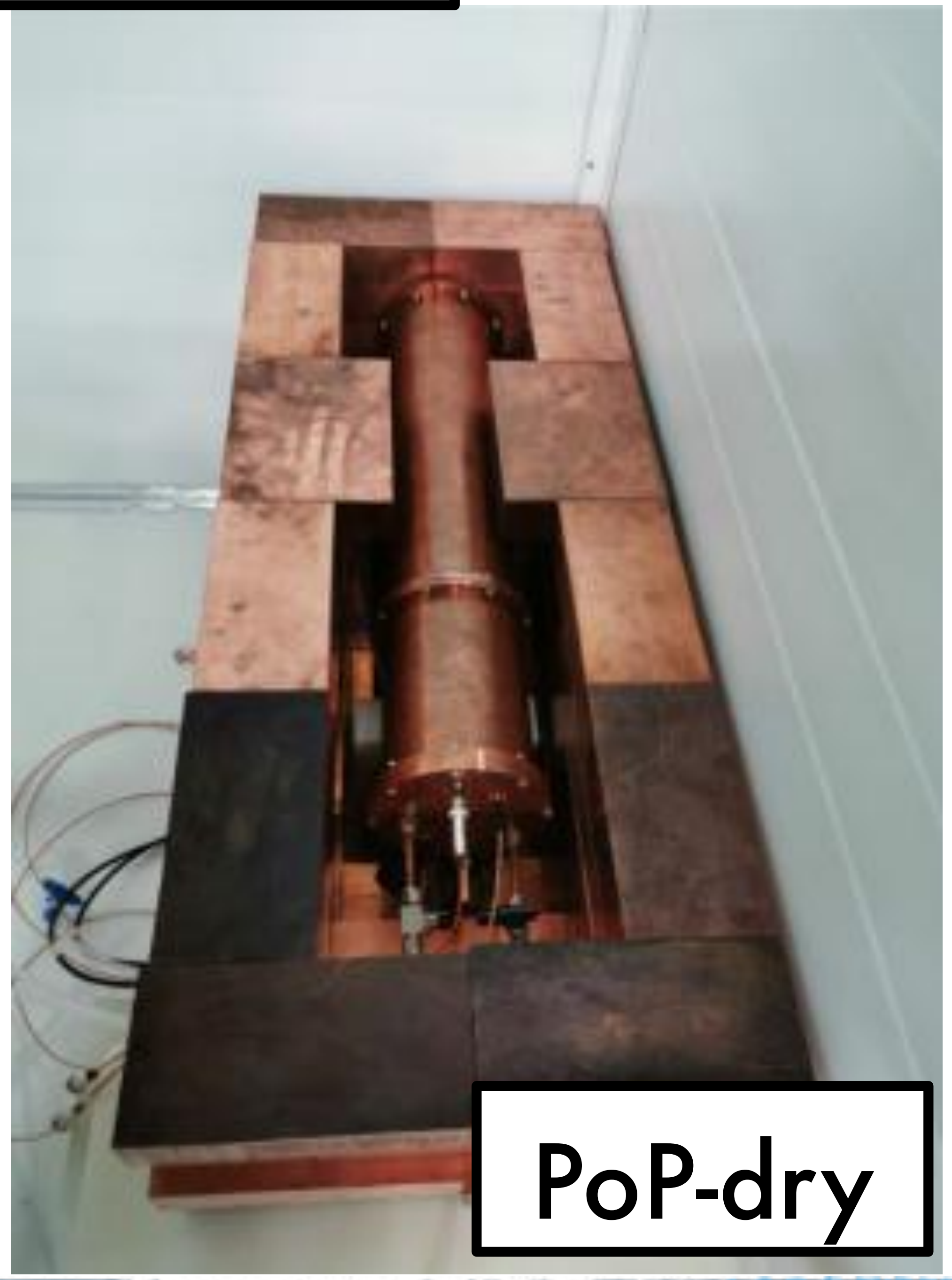
Cosmogenic activation in the ROI mainly comes from ^{3}H, ^{113}Sn, ^{109}Cd, ^{22}Na.
Minimum order of 1 yr underground cooling from cosmogenic activity required (or underground growth).

The SABRE Proof-of-Principle
@LNGS (2018-2022)



Detector module

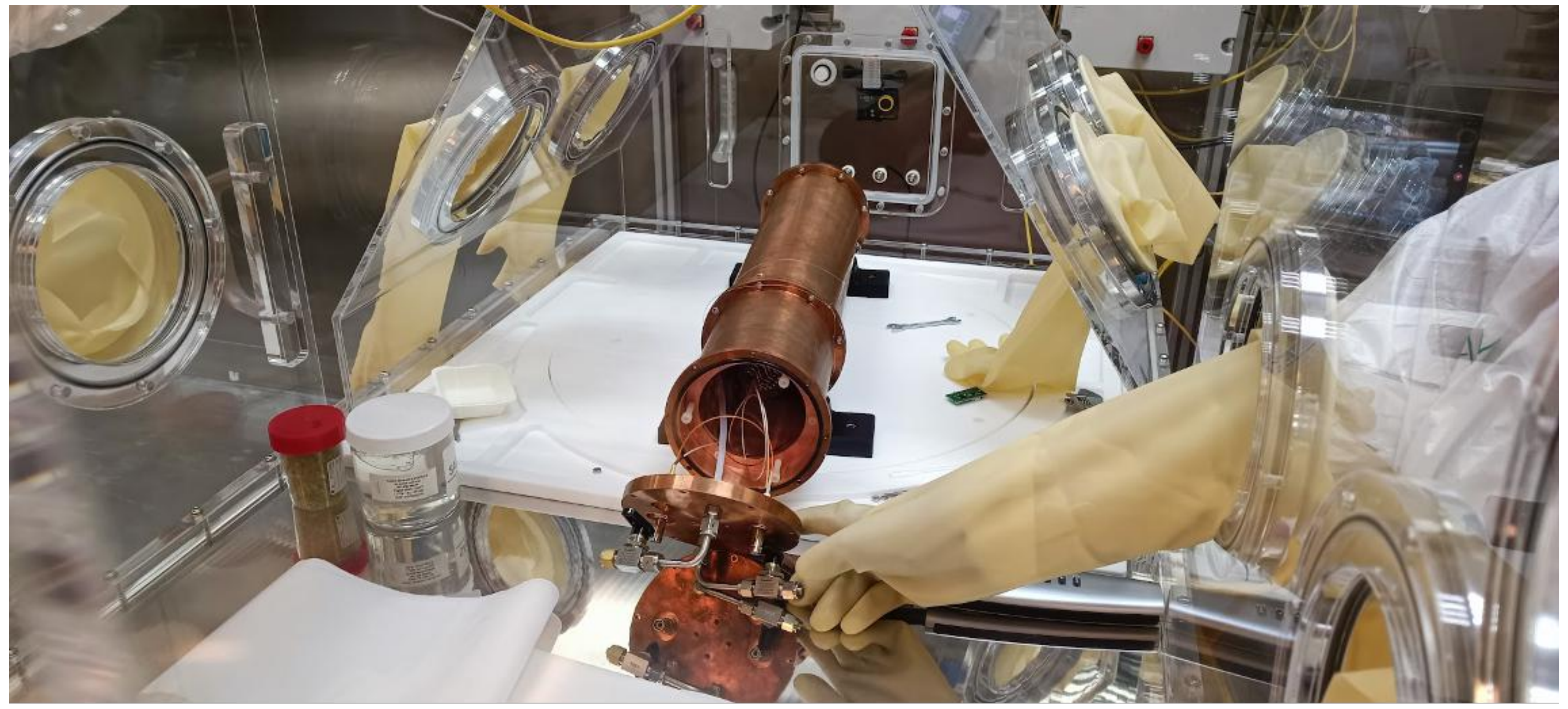


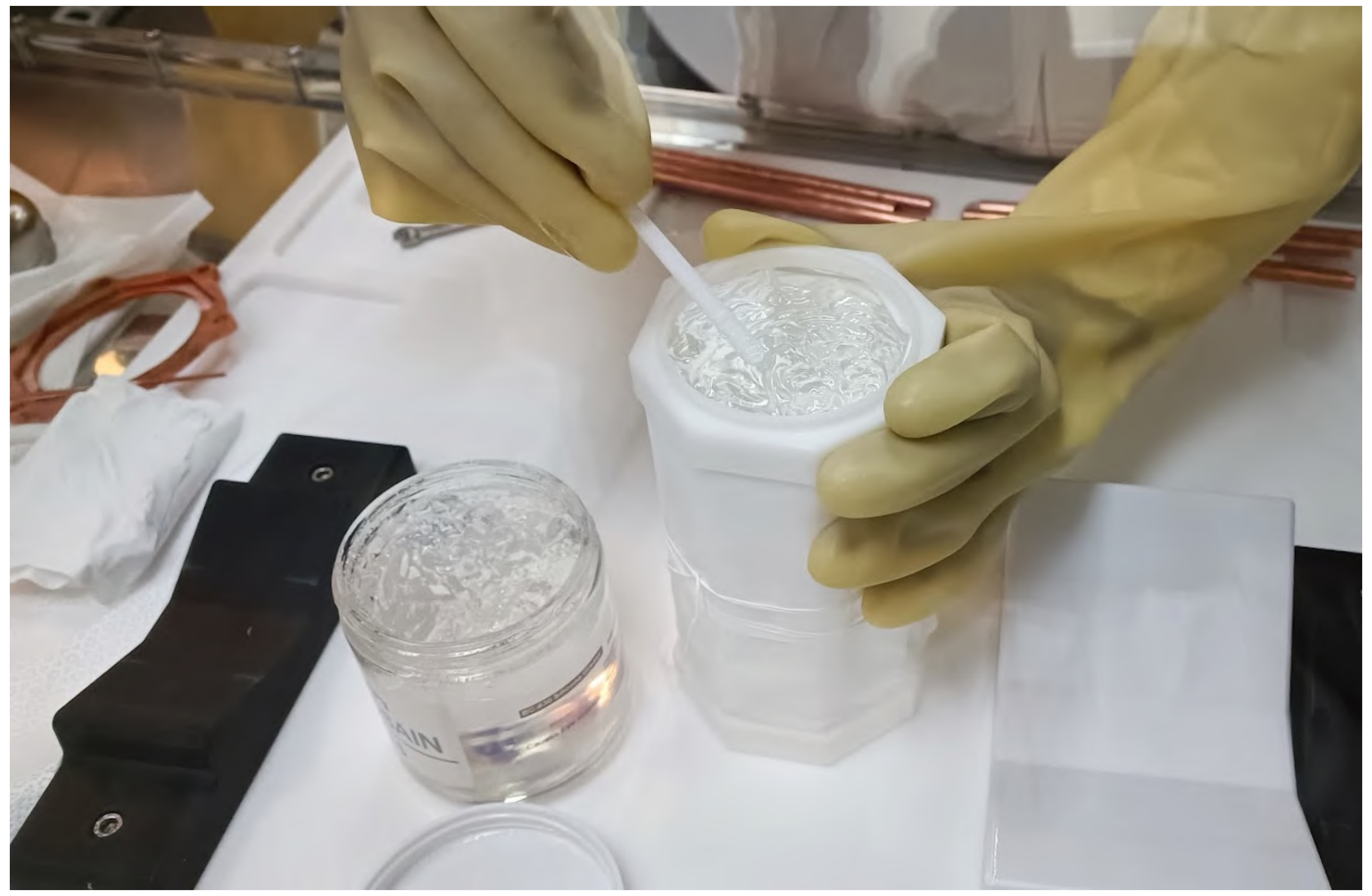


- Run in 2020 with liquid scintillator and NaI-33 crystal
    - 2 tons active veto with 10 x 8-inch PMTs + H_2O shielding
- Exploited successfully ^{40}K tagging with sensitivity at the level of 1 ppb
- Demonstration by direct counting of first crystal production after DAMA/LIBRA with **background in [1,6] keV of order 1 cpd/kg/keV**
- PoP-dry run in 2021/22: passive shielding with additional layer of copper
    - confirmed background level

Crystal operations in glovebox (2022-23)

- 09/2022 change of teflon reflector in NaI-33
- 11/2022 change of tefon reflector in NaI-33
- 12/2022 first assembly of NaI-37
- 01/2023 second assembly of NaI-37

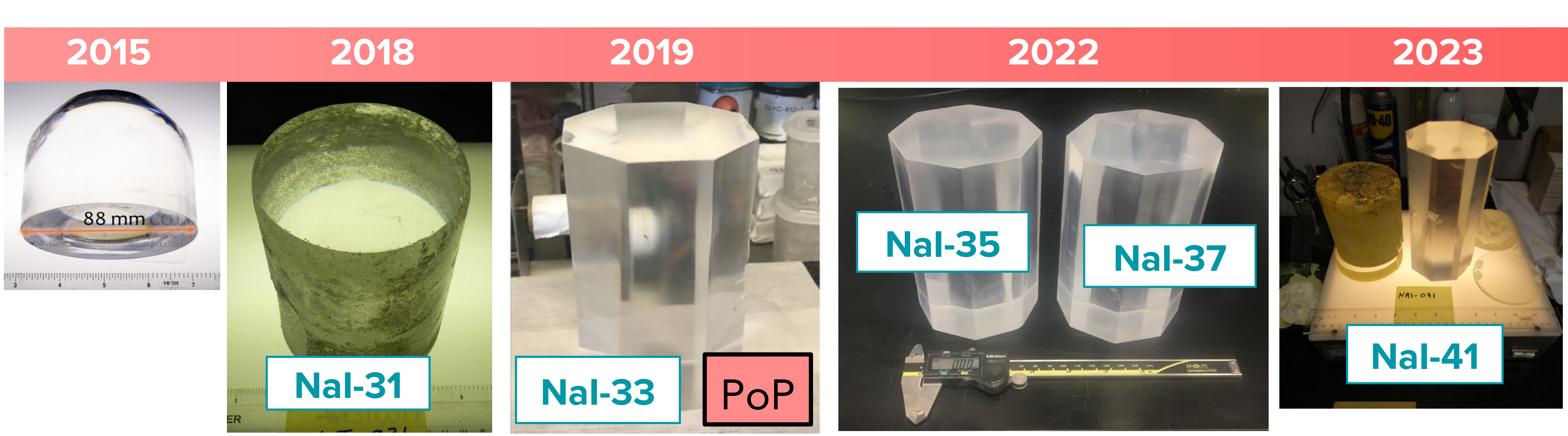




All operations successful and moisture level in the glove-box kept always below 5% RH

SABRE crystals R&D

- R&D carried out by PU, INFN and ARC Centre of Excellence for DM
- Radioclean NaI powder *Astrograde* by Sigma Aldrich now Merck, Germany
- Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)
  - Vertical Bridgeman method in fused silica vessels



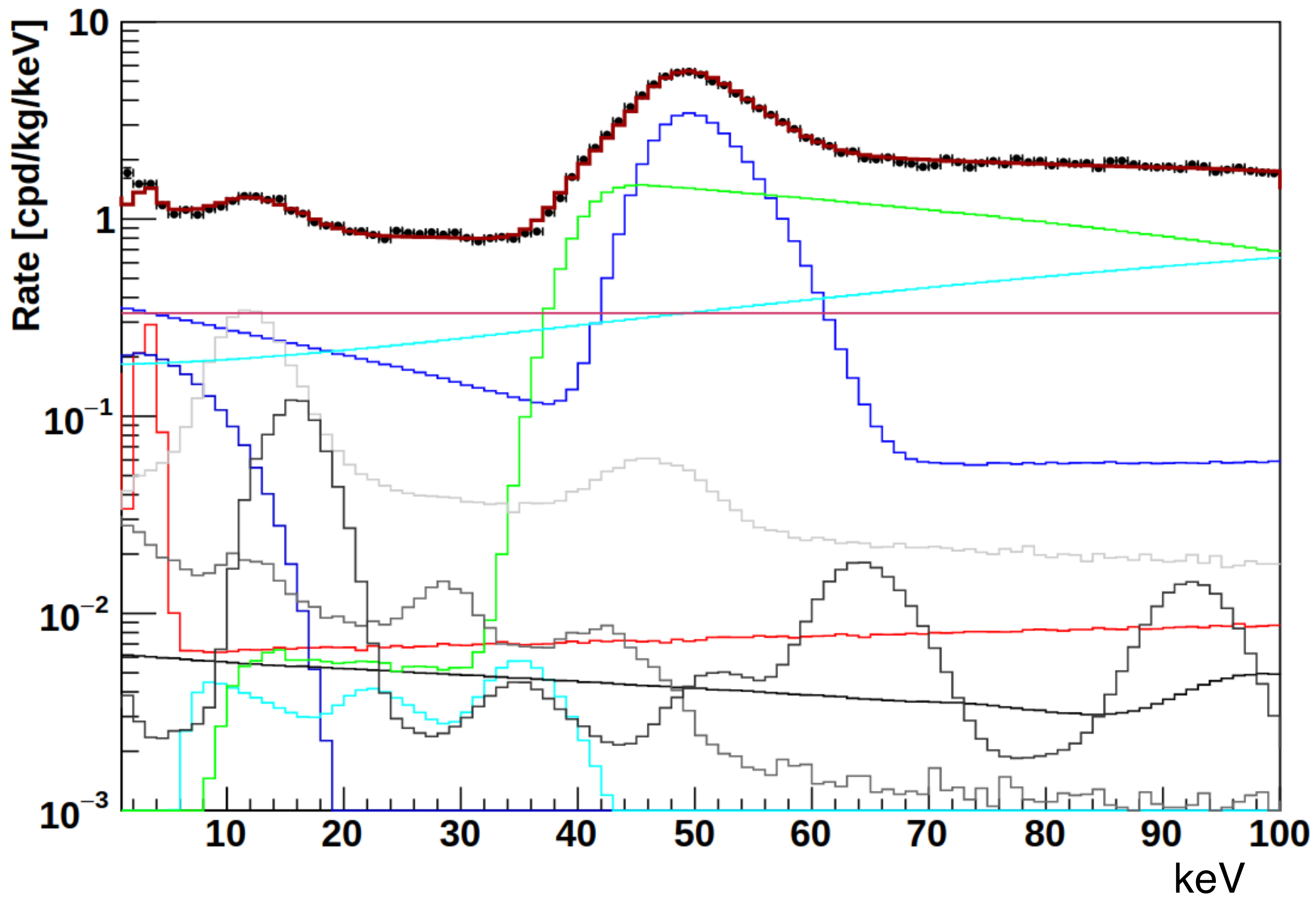
Expected in 2025: NaI-42 grown after zone refining

- NaI-33: background ~ 1 cpd/kg/keV → close to DAMA/LIBRA Phase 1
- NaI-35, NaI-37: reproducibility within factor 2
- NaI-41: grown from chuncks rather than powder → demonstrated same optical quality

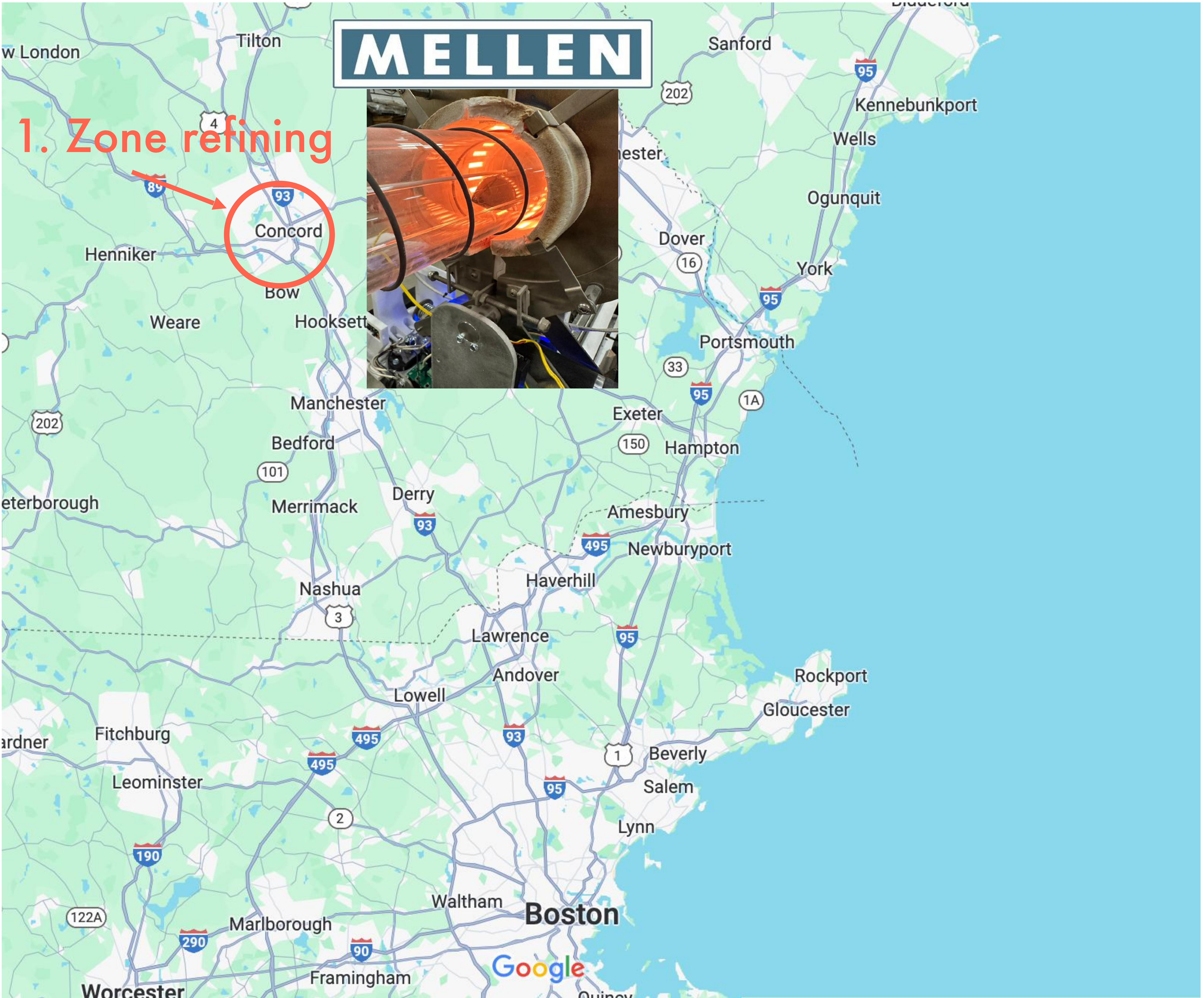
SABRE background model (NaI-33)

- Background model updated since Eur. Phys. J. C (2022) 82:1158
- Background from reflector is not dominant (now constrained from direct measurements)
- Dominant backgrounds: ^{210}Pb in crystal bulk and external background

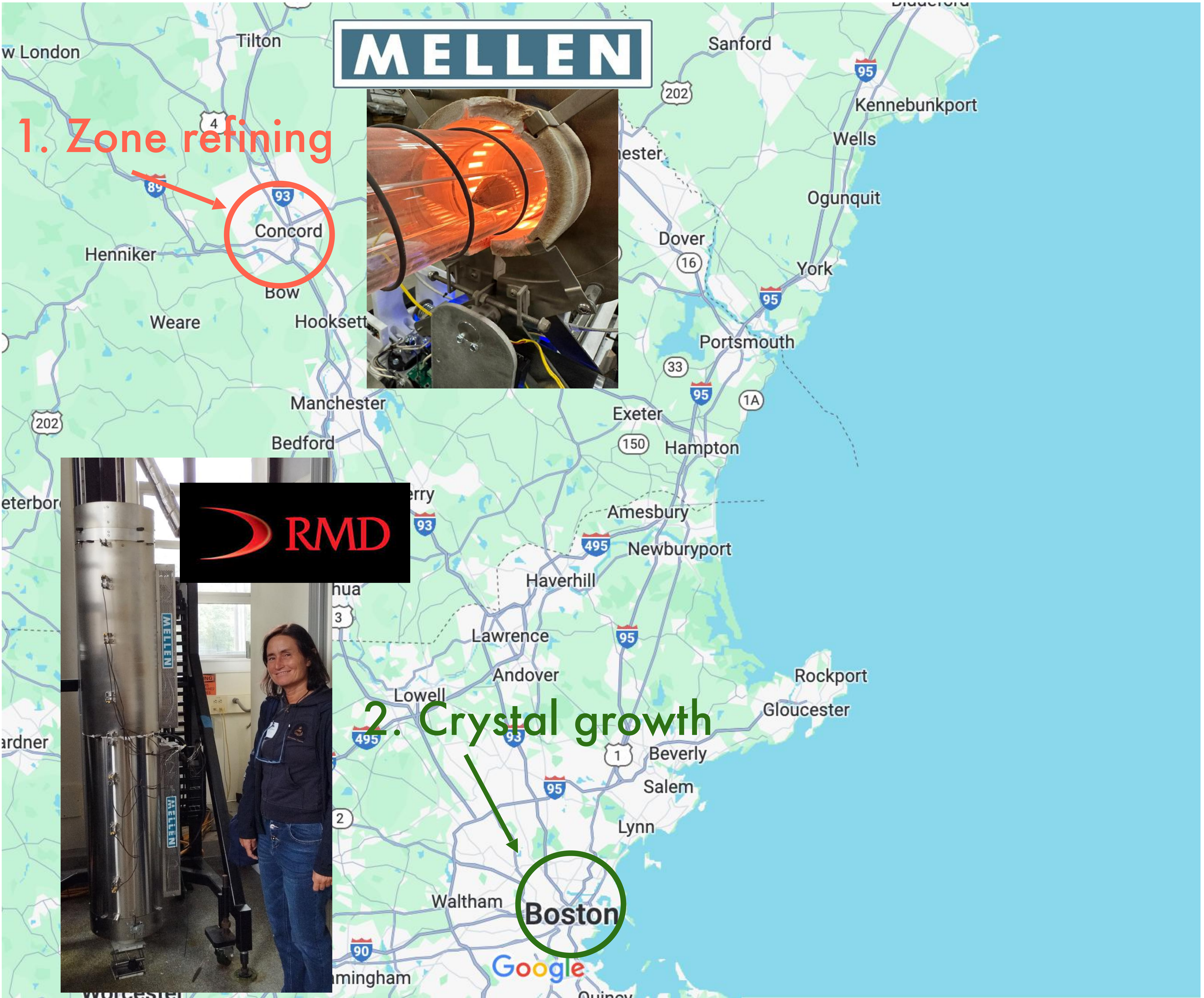
Source	Rate in ROI [1,6] keV [cpd/kg/keV]	Activity from fit
40K	0.125	0.16±0.01 mBq/kg
210Pb bulk	0.333	0.49±0.05 mBq/kg
210Pb reflector bulk	0.054	11±1 mBq/kgPTFE
210Pb reflector surface	0.023	<0.6 mBq/m2
3H	0.198	24±2 mBq/kg
129I	0.0003	1.03±0.05 mBq/kg
238U	0.006	5.9±0.6 mBq/kg
232Th	0.0003	1.6±0.3 mBq/kg
PMT	0.003	1.9±0.4 mBq/PMT
External	0.185	0.89±0.05 relative unit to reference spectrum
Other b's	0.333	297±15 counts
TOTAL	1.26±0.27	



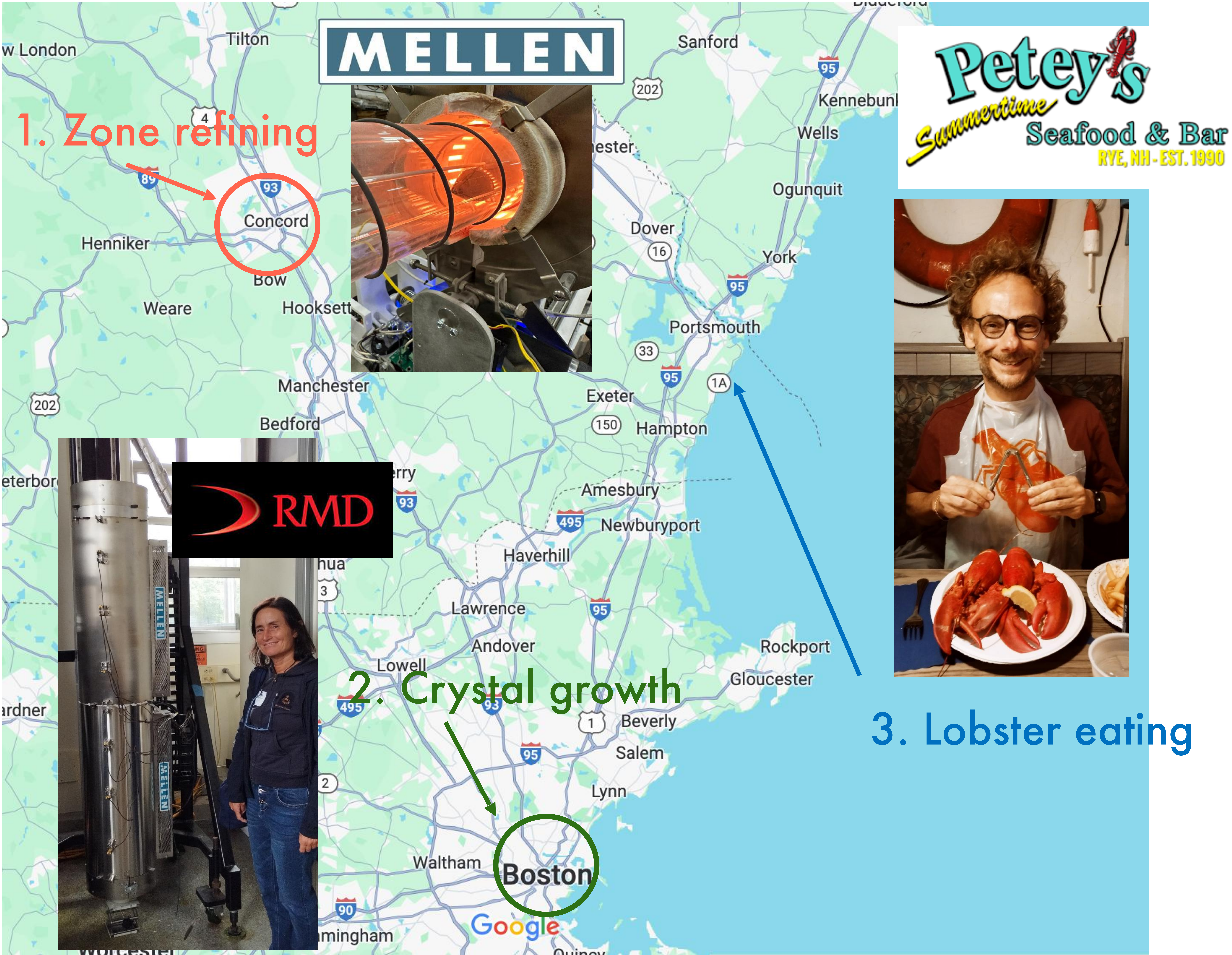
The SABRE strategy



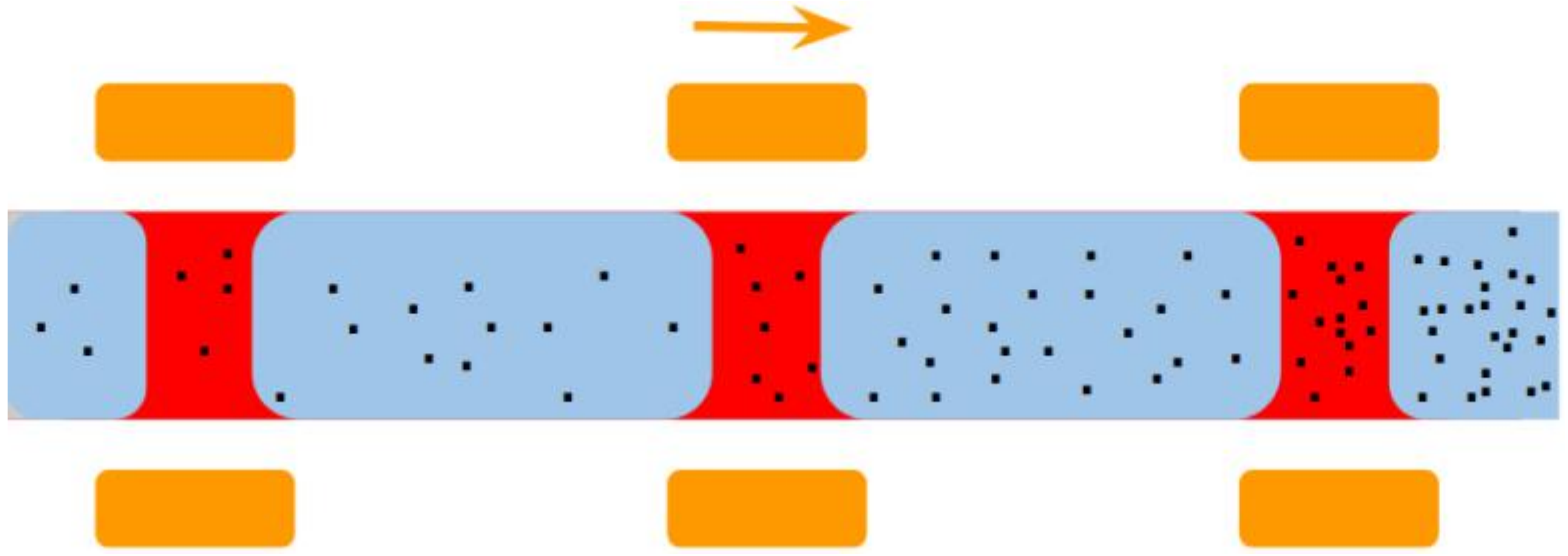
The SABRE strategy



The SABRE strategy



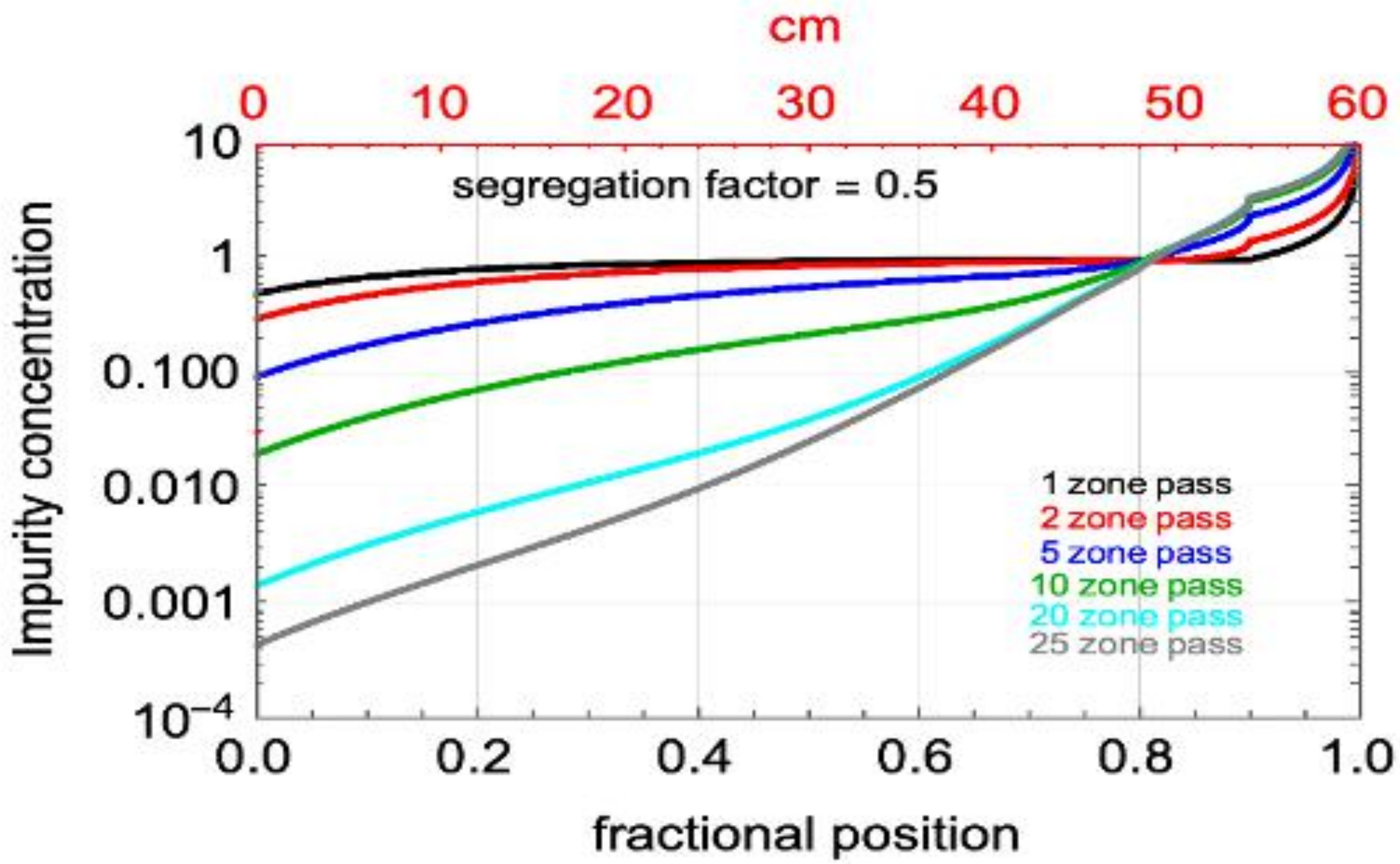
Zone Refining



- Zone refining technique successfully used in semiconductor industry
- Impurities are segregated to one side of the ingot by moving annular ovens
- Tested on NaI *Astrograde* powder by Princeton group at Mellen company, Concord, NH (USA)

Isotope	Impurity concentration (ppb)					
	Powder	S_1	S_2	S_3	S_4	S_5
^{39}K	7.5	< 0.8	< 0.8	1	16	460
^{85}Rb	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.7
^{208}Pb	1.0	0.4	0.4	< 0.4	0.5	0.5
^{24}Mg	14	10	8	6	7	140
^{133}Cs	44	0.3	0.2	0.5	3.3	760
^{138}Ba	9	0.1	0.2	1.4	19	330

Phys. Rev. Applied 16, 014060 (2021)

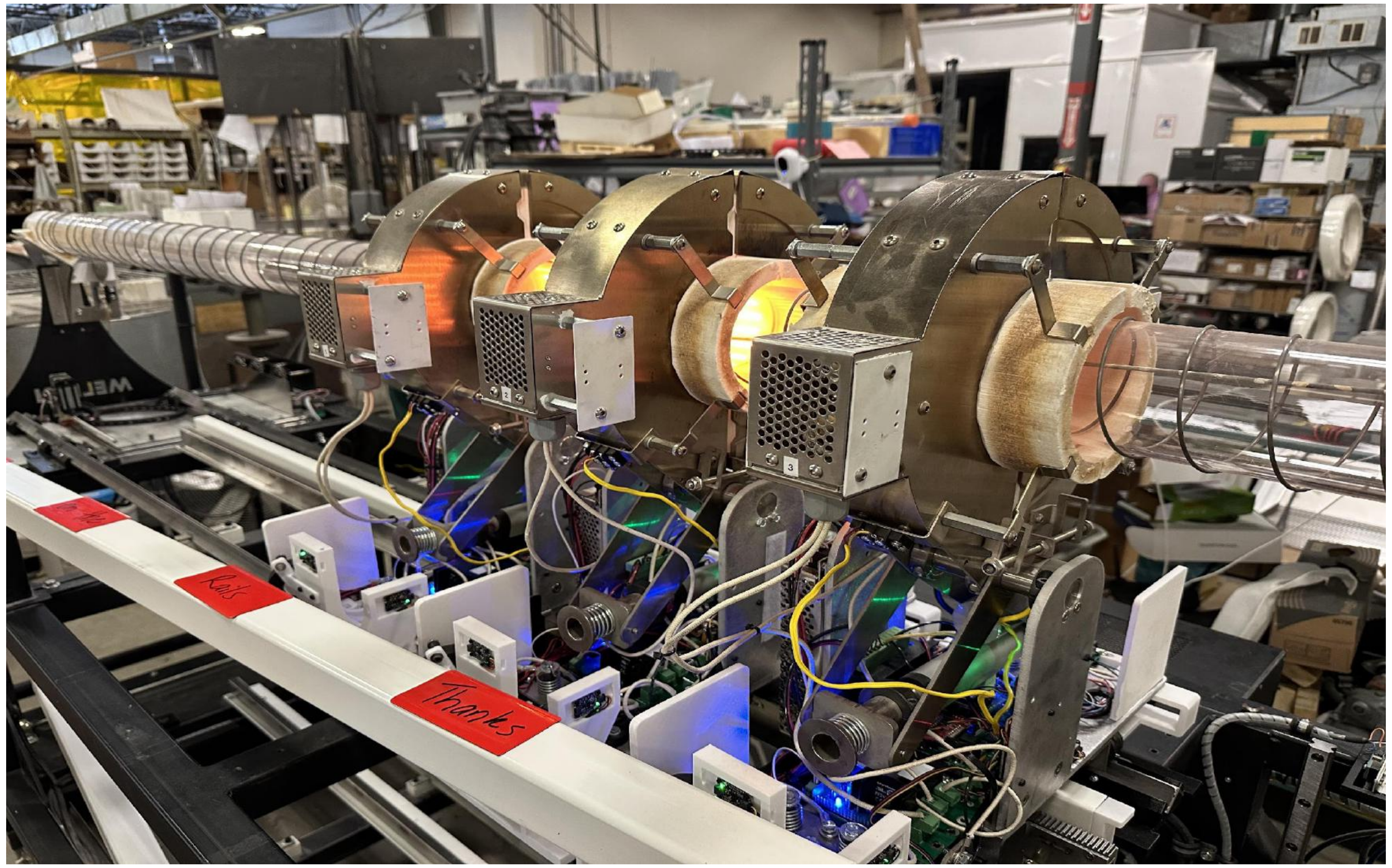


Zone refining could reduce to about 1/3 the Pb content, almost 1 order of magnitude K and possibly other internal contaminants like Rb.

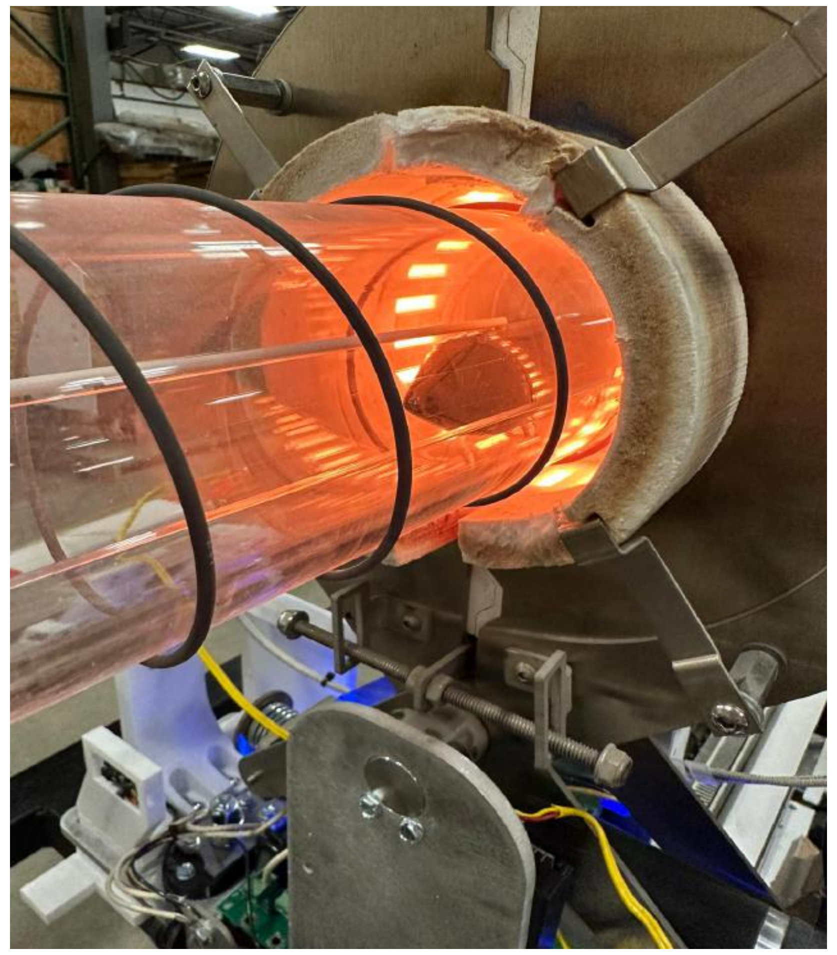
Zone refining of NaI powder

- 4 **RUNs (2023)**: 900g of Astrograde powder each
- 60 cm Fused silica ampoule
- use carbon coating or $SiCl_4$ gas to prevent sticking
- 25->50 passes (1-2 weeks) at 1-2 inch/min
- For each run taken 5 samples from ingot

Zone refiner

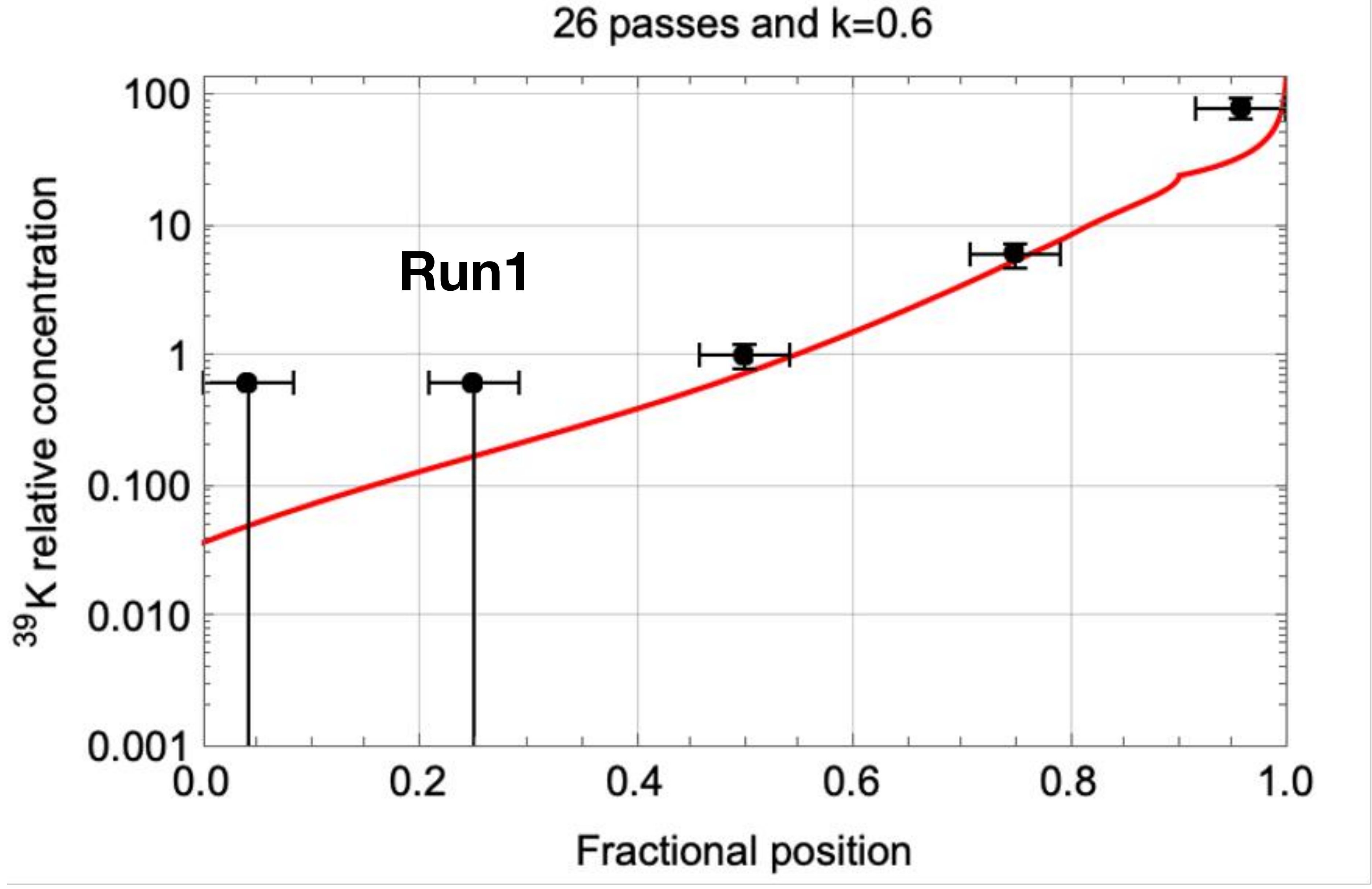


Ampoule



Broken ingot after ZR

Zone refining test results



Sample Run4	^{39}K [ppb]	^{65}Cu [ppb]	^{85}Rb [ppb]	^{133}Cs [ppb]	^{138}Ba [ppb]	^{208}Pb [ppb]
powder	7	5	<0.2	1	3.6	1.1
Zone 1	<4	<4	<0.8	<0.3	<0.3	2.0±0.3
Zone 2	<4	<4	<0.8	<0.3	1.2±0.3	1.6±0.2
Zone 3	10.1±0.6	<4	<0.8	<0.3	2.7±0.2	1.6±0.3
Zone 4	21.5±0.7	<4	<0.8	1.1±0.1	8.1±0.5	1.9±0.3
Zone 5	68±2	10±1	<0.8	203±6	17±0.9	1.2±0.3

- Very good suppression of all backgrounds
- Pb seem to have a segregation coefficient > 1, but a recontamination occurred in the glove box at RMD

Strategy for Pb reduction

1. Glove box:
   - Pb contamination probably occurred in the glove box used so far at RMD for material handling
   - Now <u>dedicated</u> glove box from Princeton University
   - Reburbished and instrumented with a pipe for crystal insertion
2. Purging:
   - Pb compounds are highly volatile at the temperature of ZR
   - Under study the possibility to <u>gas purge</u> the volume during ZR

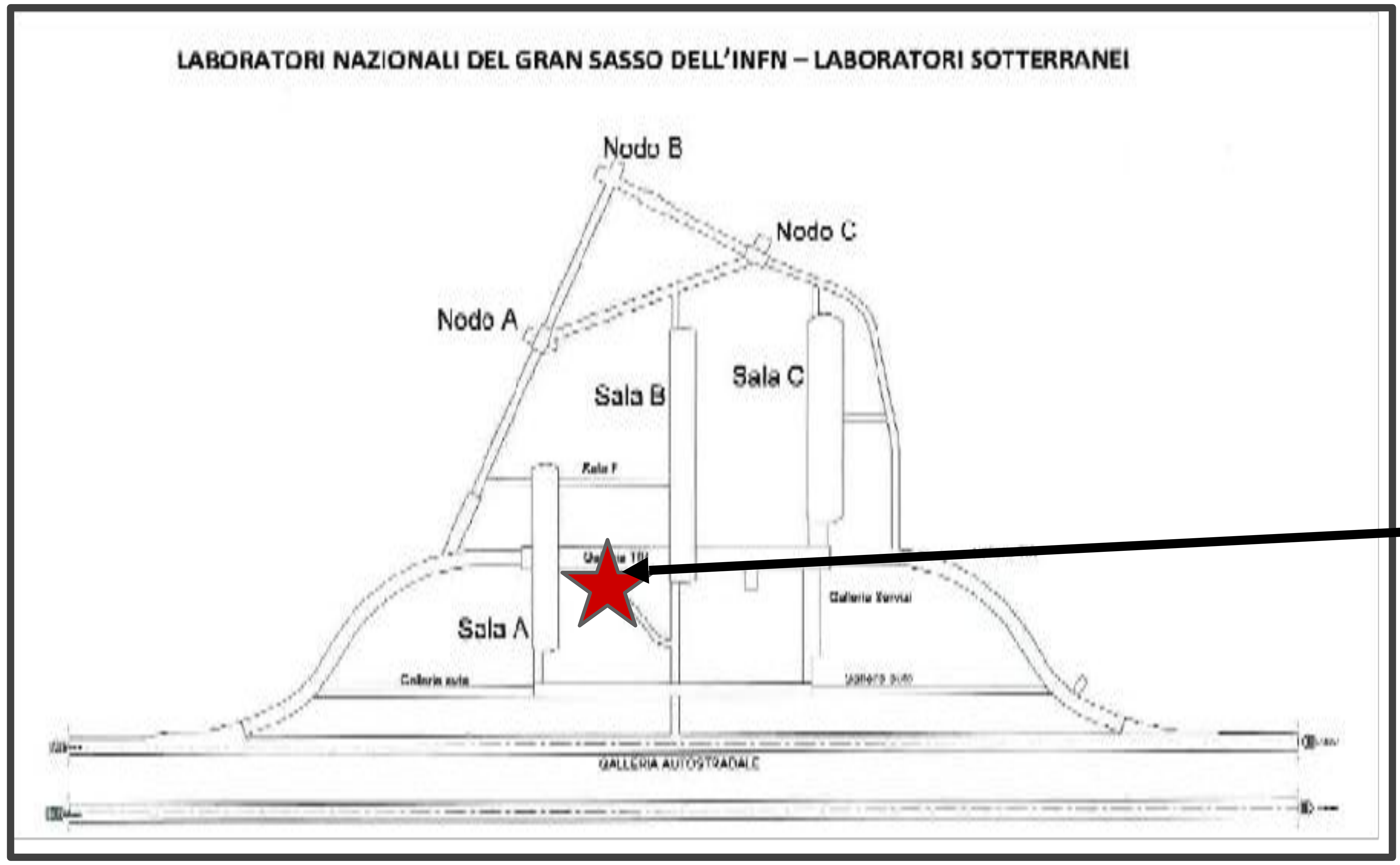
SABRE North new area @LNGS (2024)

New SABRE experimental area in the corridor between Hall B and Hall A

(formerly hosting COBRA and Heidelberg/Moscow $\beta\beta$-decay experiments)

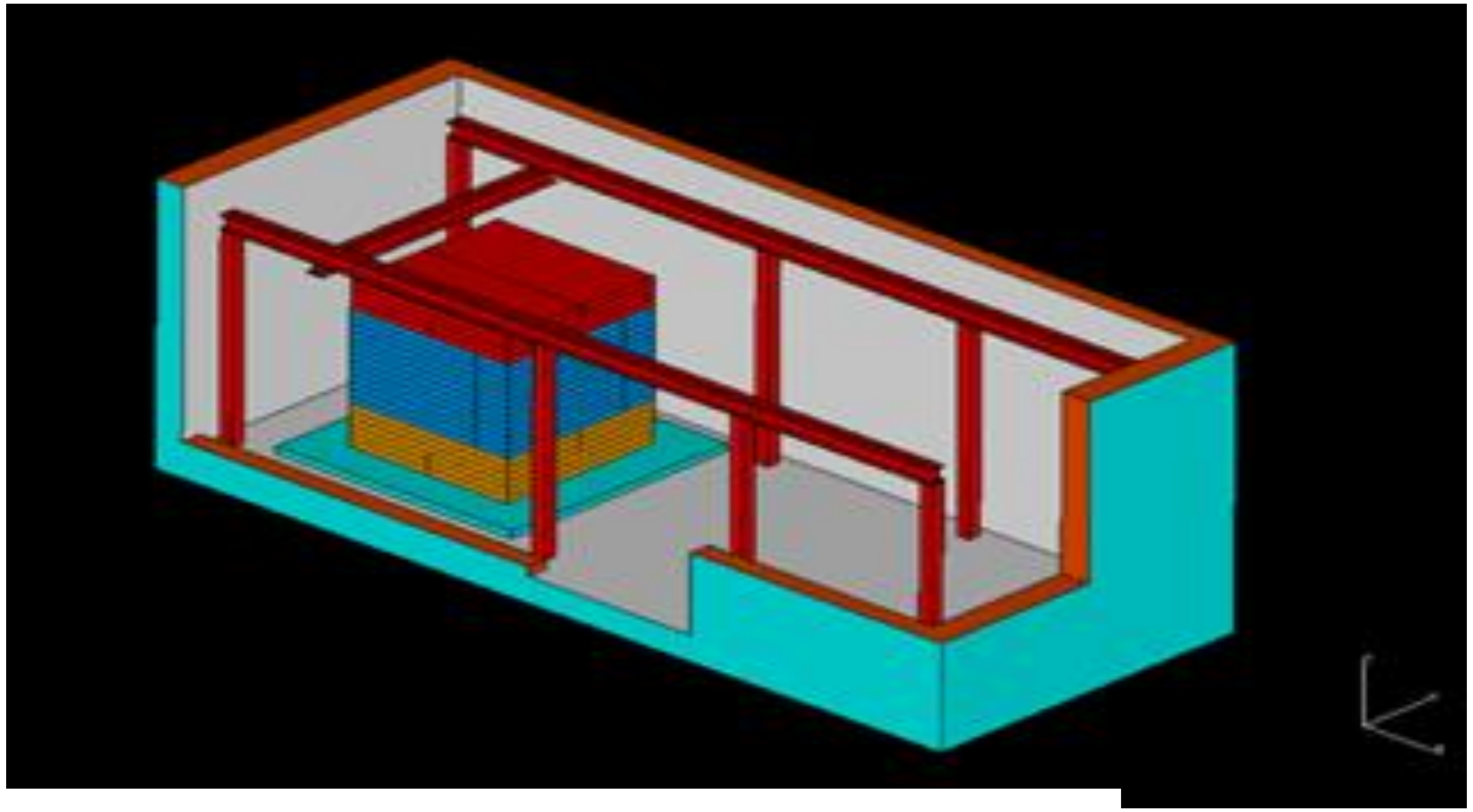
Consists of a two storeys building:

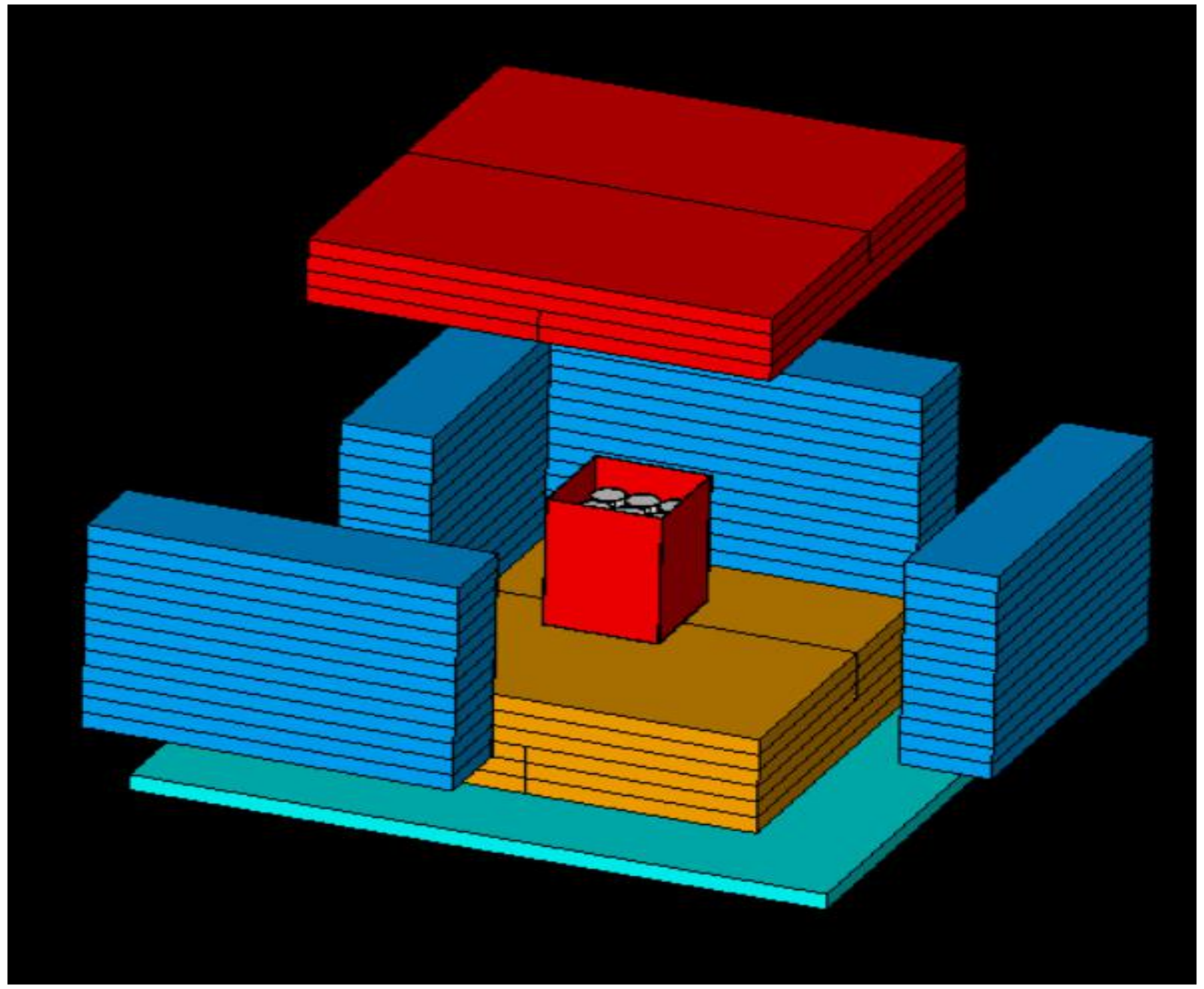
1. Ground floor: set-up SABRE NORTH
2. First floor: DAQ & counting room



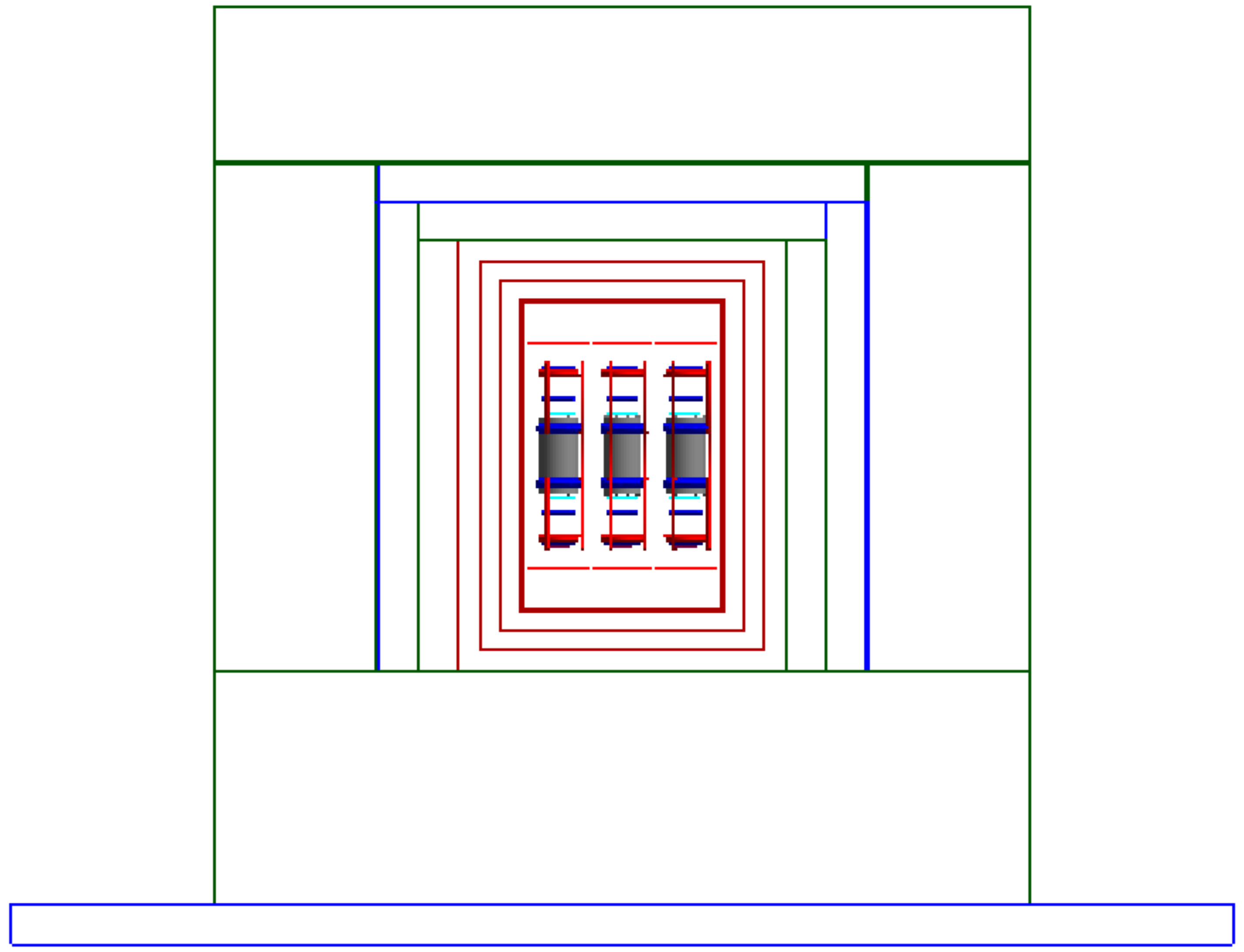
PoP-dry refurbished and moved in

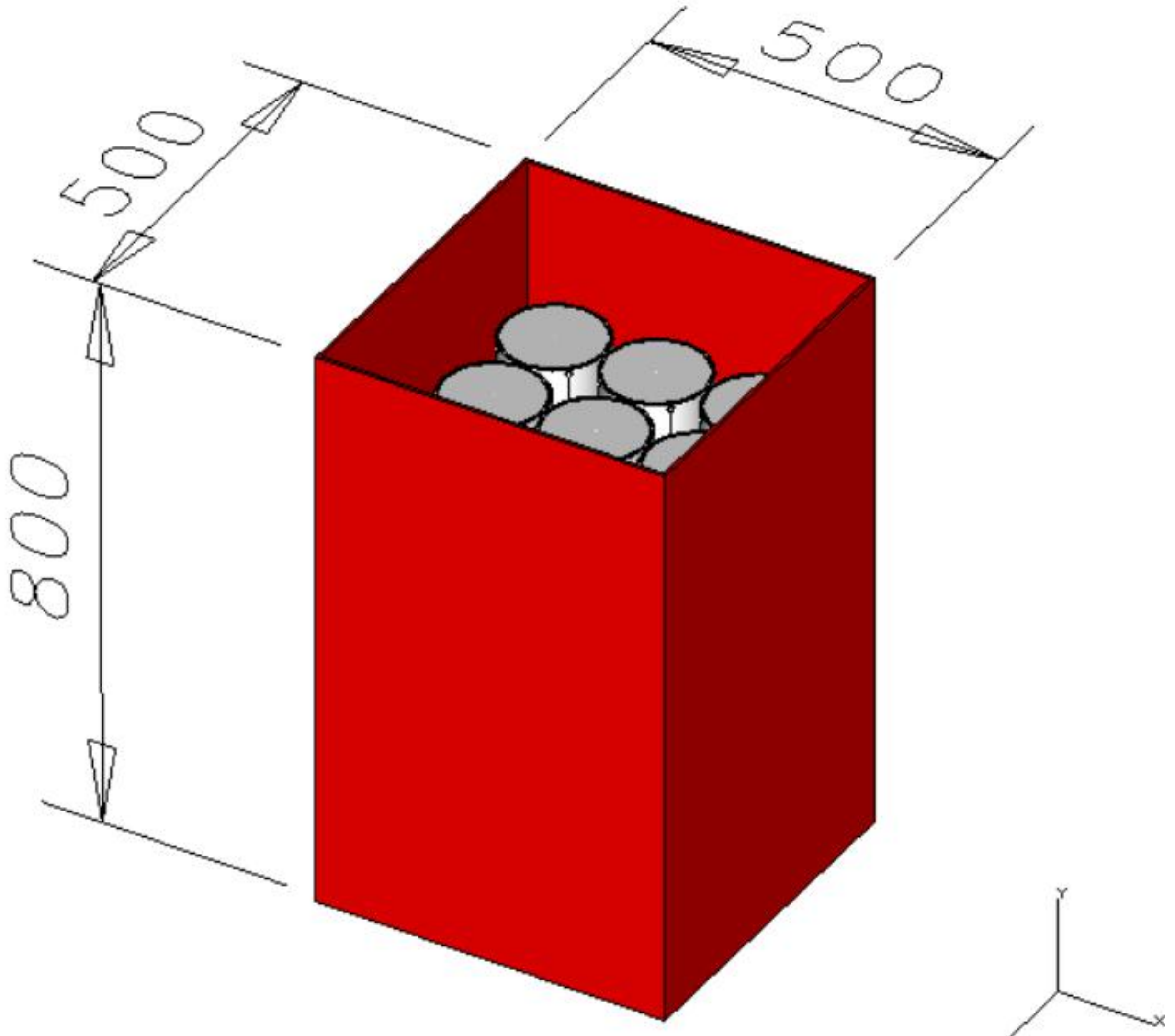
The SABRE North detector



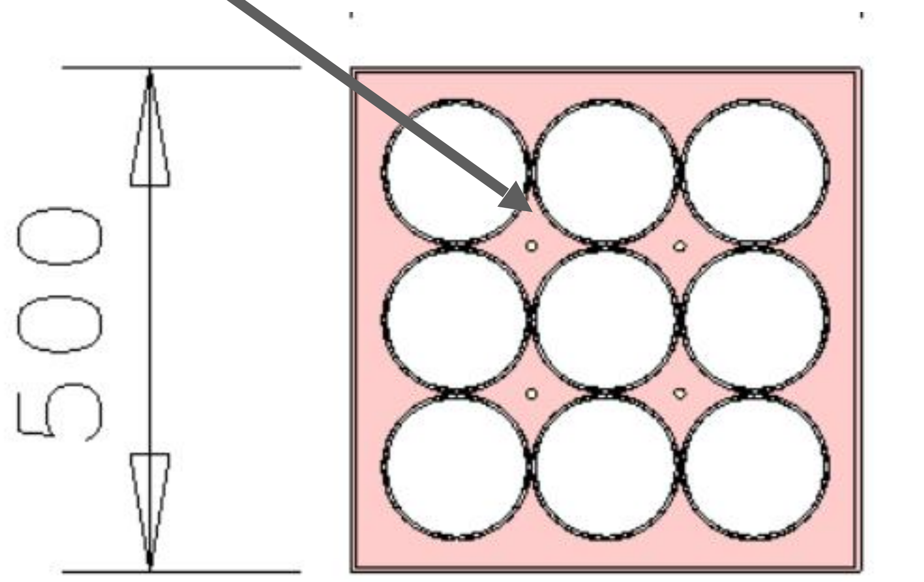


- Reuse of SABRE PoP materials
- Compact set-up (2x2x2.4h m3) to suit the new area



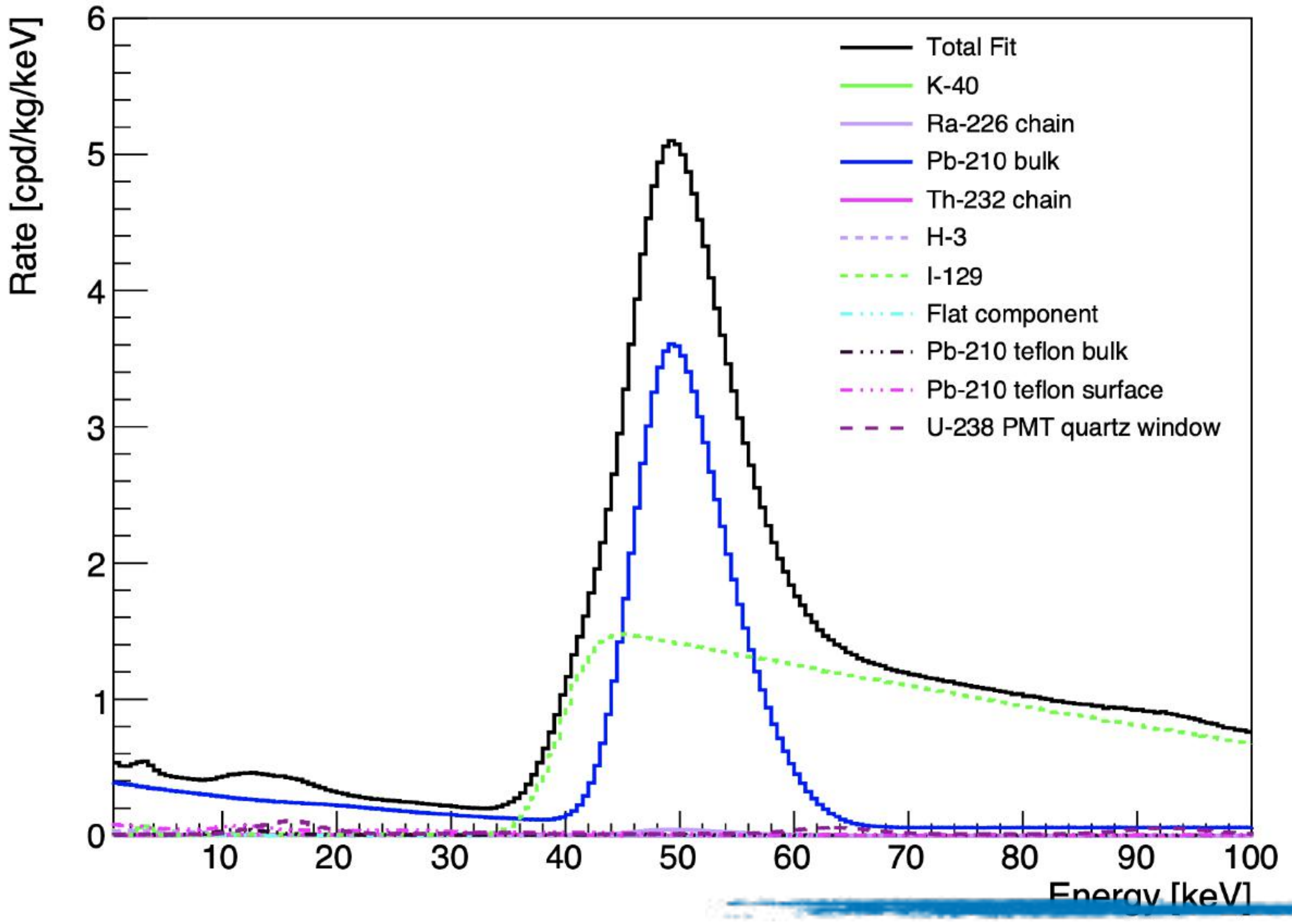


Positioning of calibration tubes.
sources: ^{241}Am, ^{109}Cd, ^{228}Th, ^{176}Lu



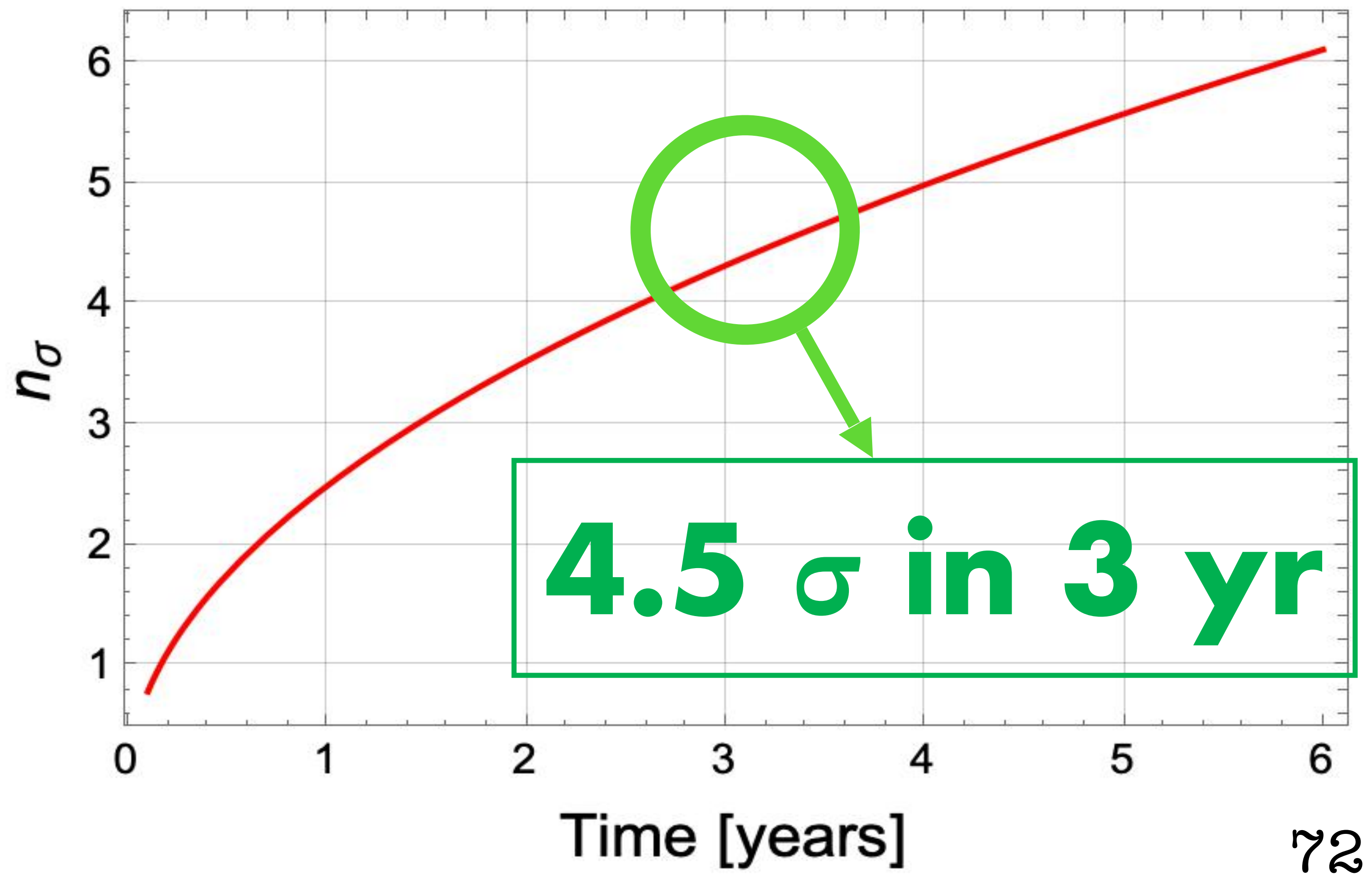
SABRE-North status

Source	Rate in ROI [1,6] keV [cpd/kg/keV]
^{40}K	0.025
^{210}Pb bulk	0.353
^{210}Pb reflector bulk	0.005
^{210}Pb reflector surface	0.060
^{3}H	0.033
^{129}I	0.003
^{238}U	0.005
^{232}Th	0.0004
PMT	0.009
Other backgrounds	0.01
TOTAL	**0.50**

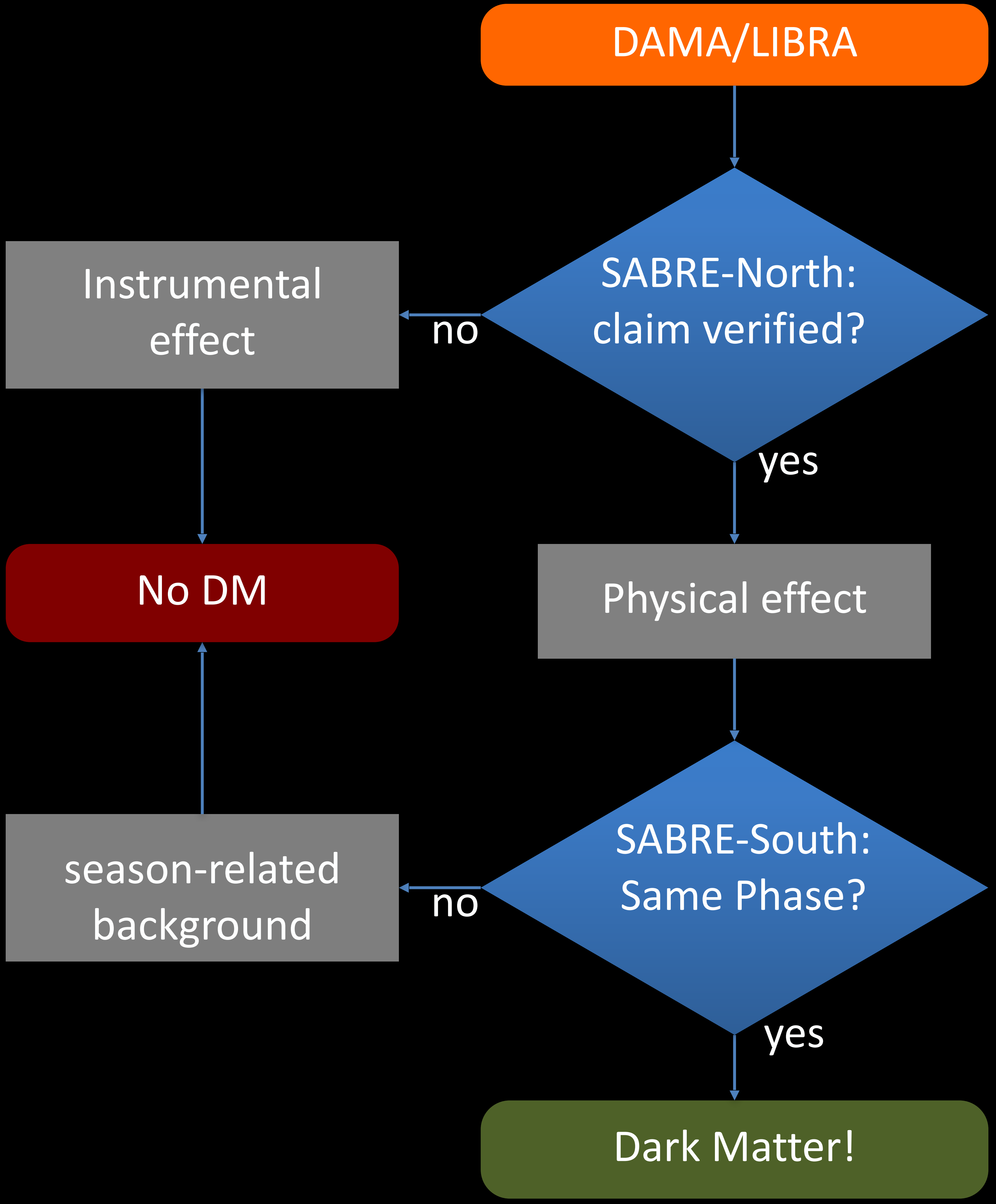


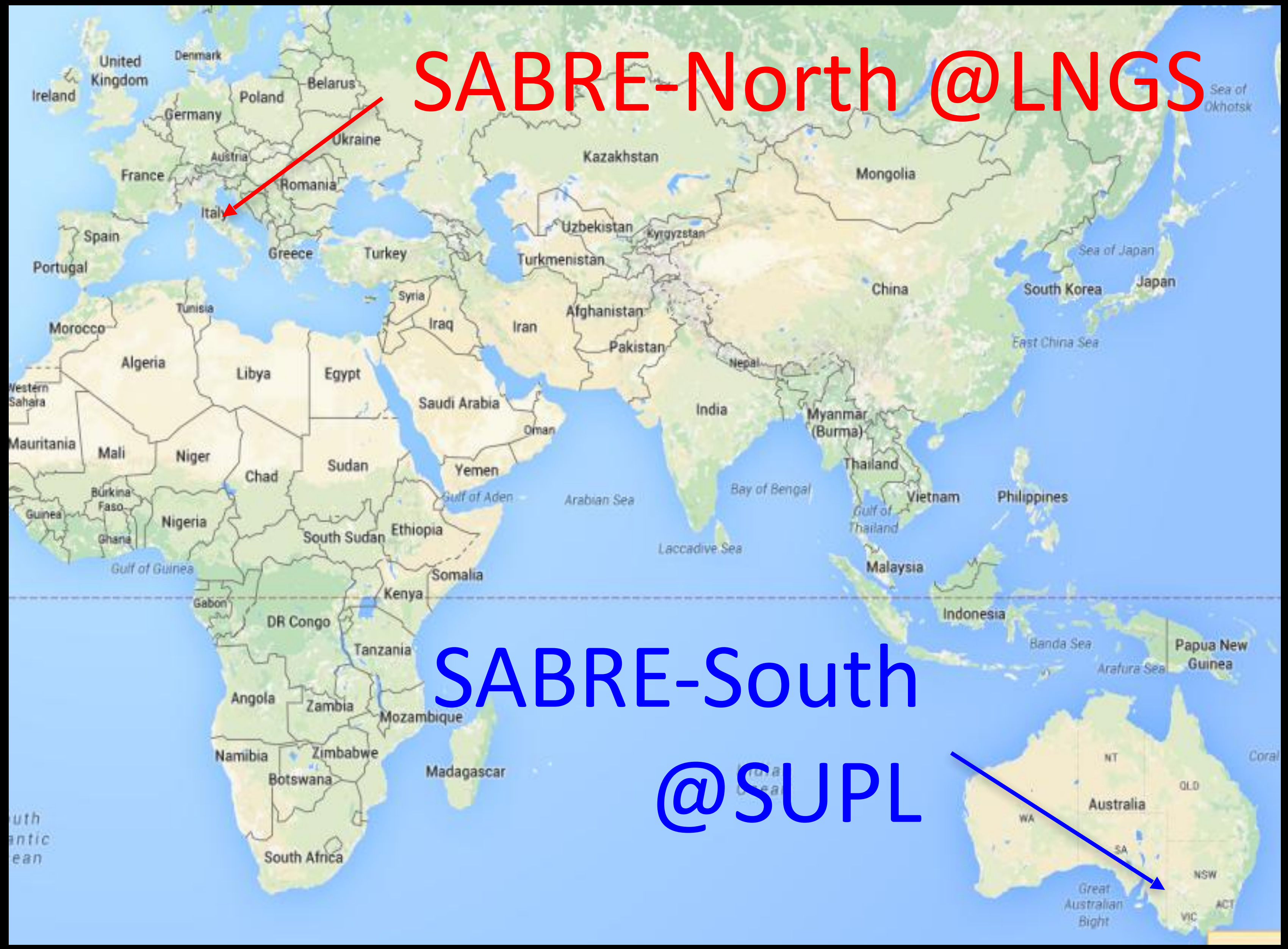
- **NaI-42** crystal grown after Zone Refining coming **summer 2025**
- TDR approved sept. 2024 for the physics phase starting in 2025
  - 3x3 crystal matrix, ~ 5 kg each
  - Fully passive shielding: 25 cm Cu + 50 cm PE
    - enough shielding power
    - negligible background contribution
- Expected background:
  ~ 0.5 cpd/kg/keV (with ZR)
- Schedule:
  - First crystal: end of 2025
  - Last: beginning of 2027

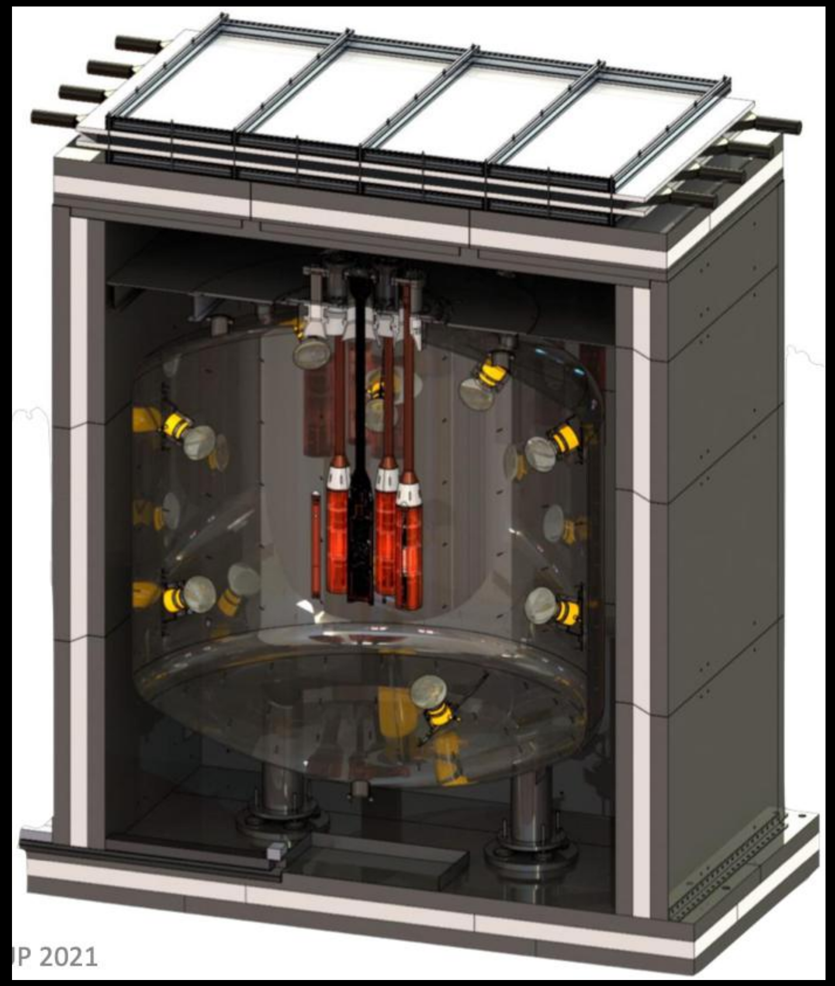
45 kg, 0.5 dru



Double location

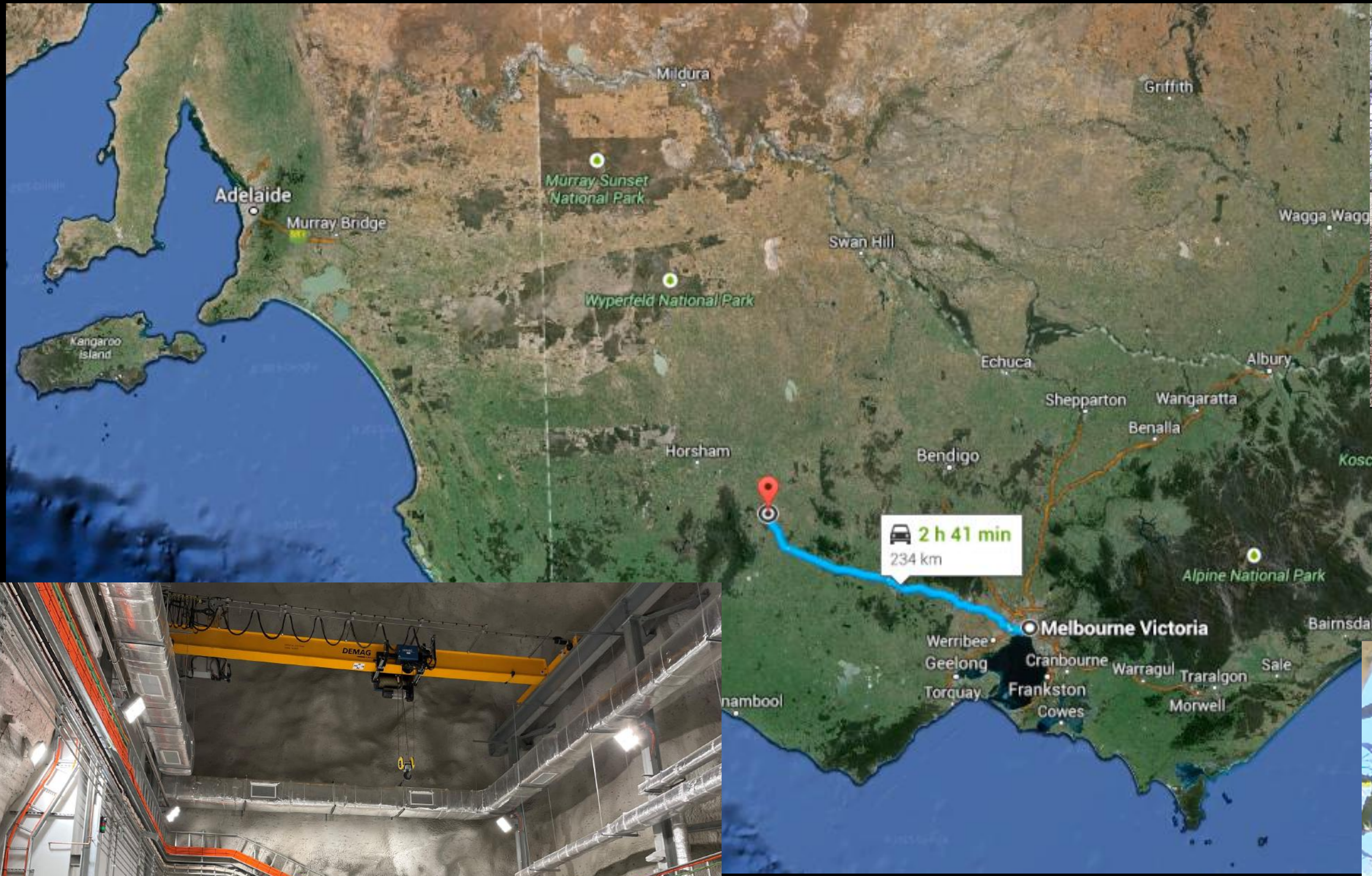


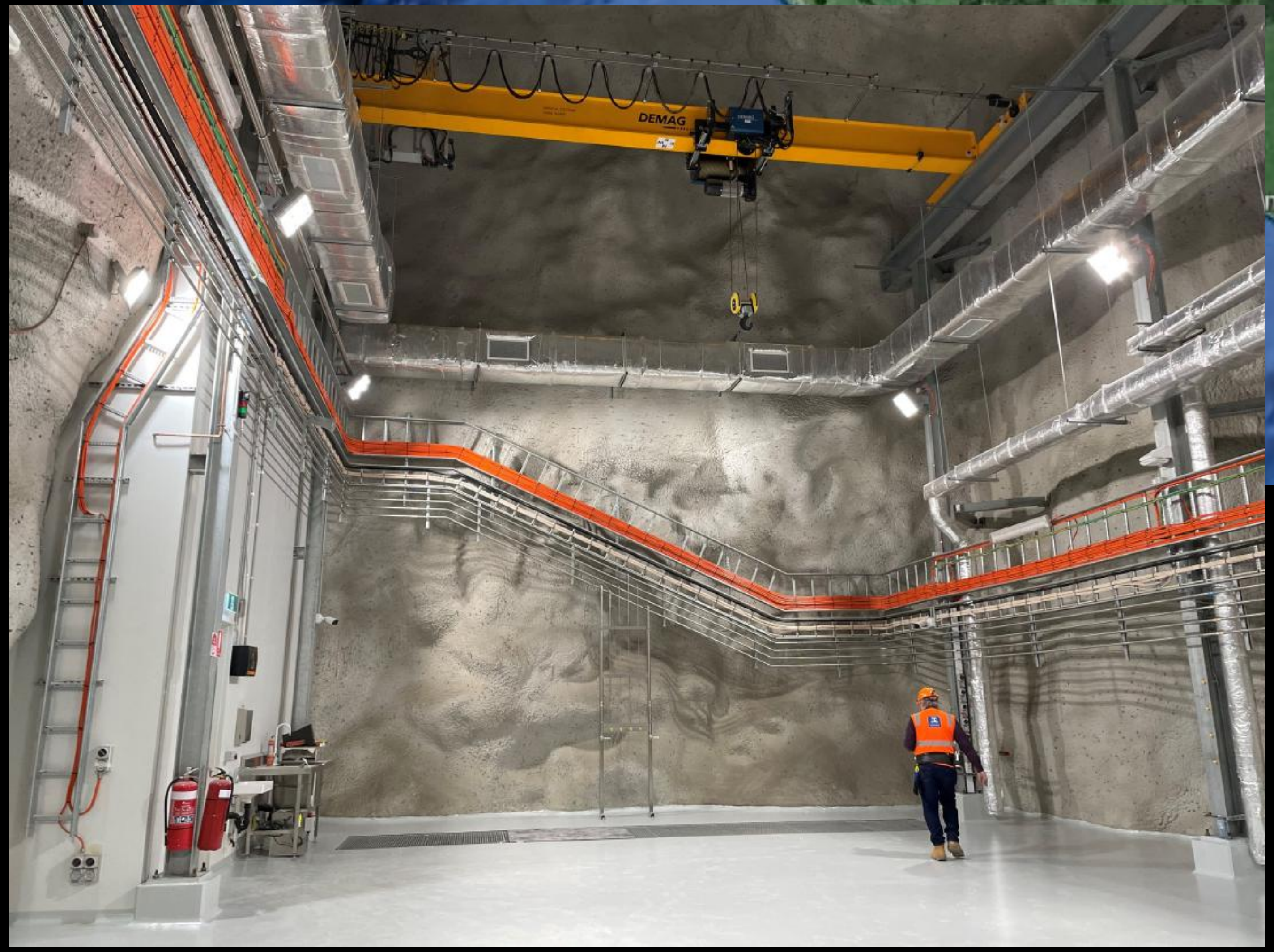




Stawell gold mine

Gold mine in the State of Victoria, ~ 300km west of Melbourne, ~3h drive.





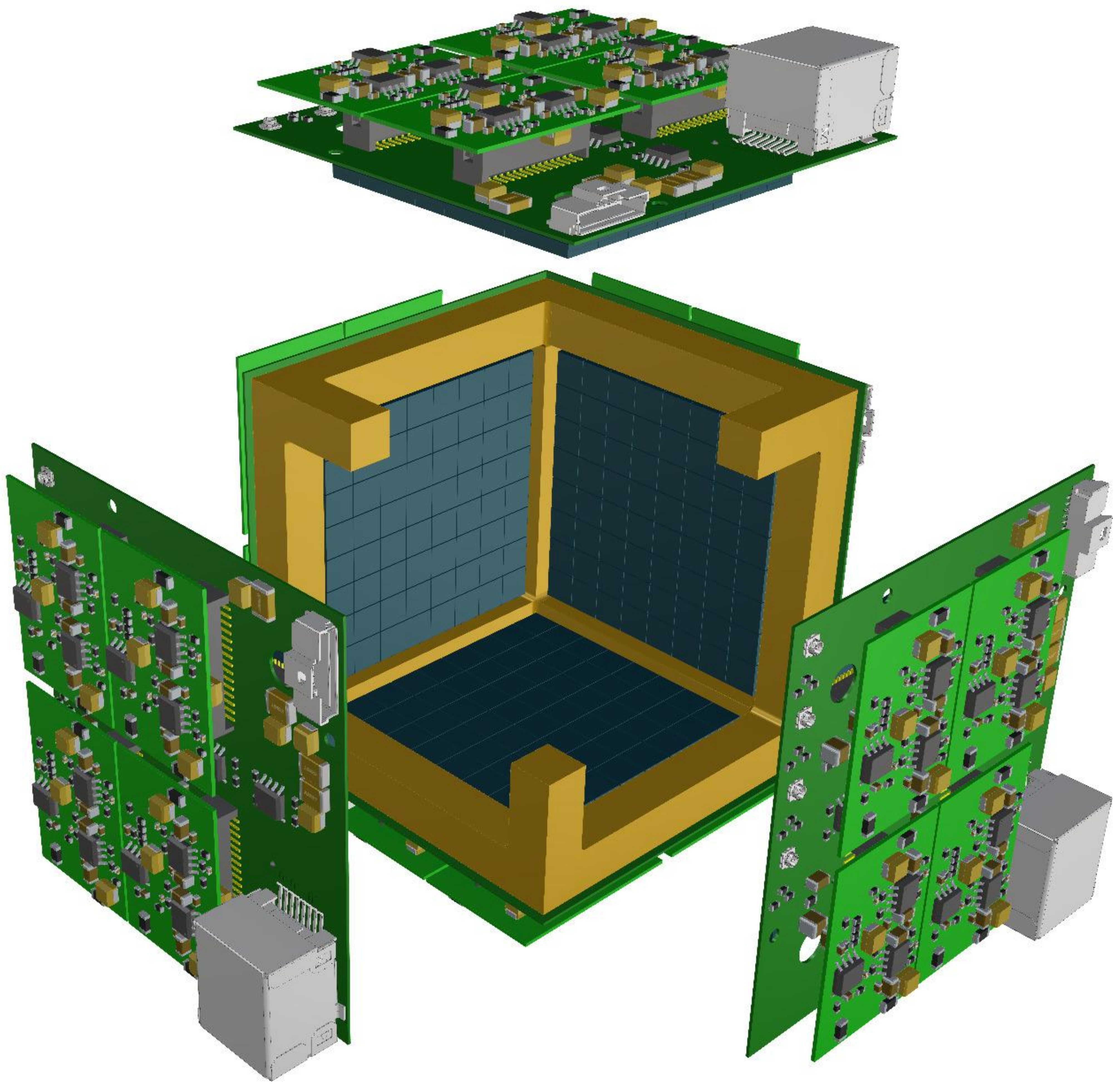
commissioned in 2024

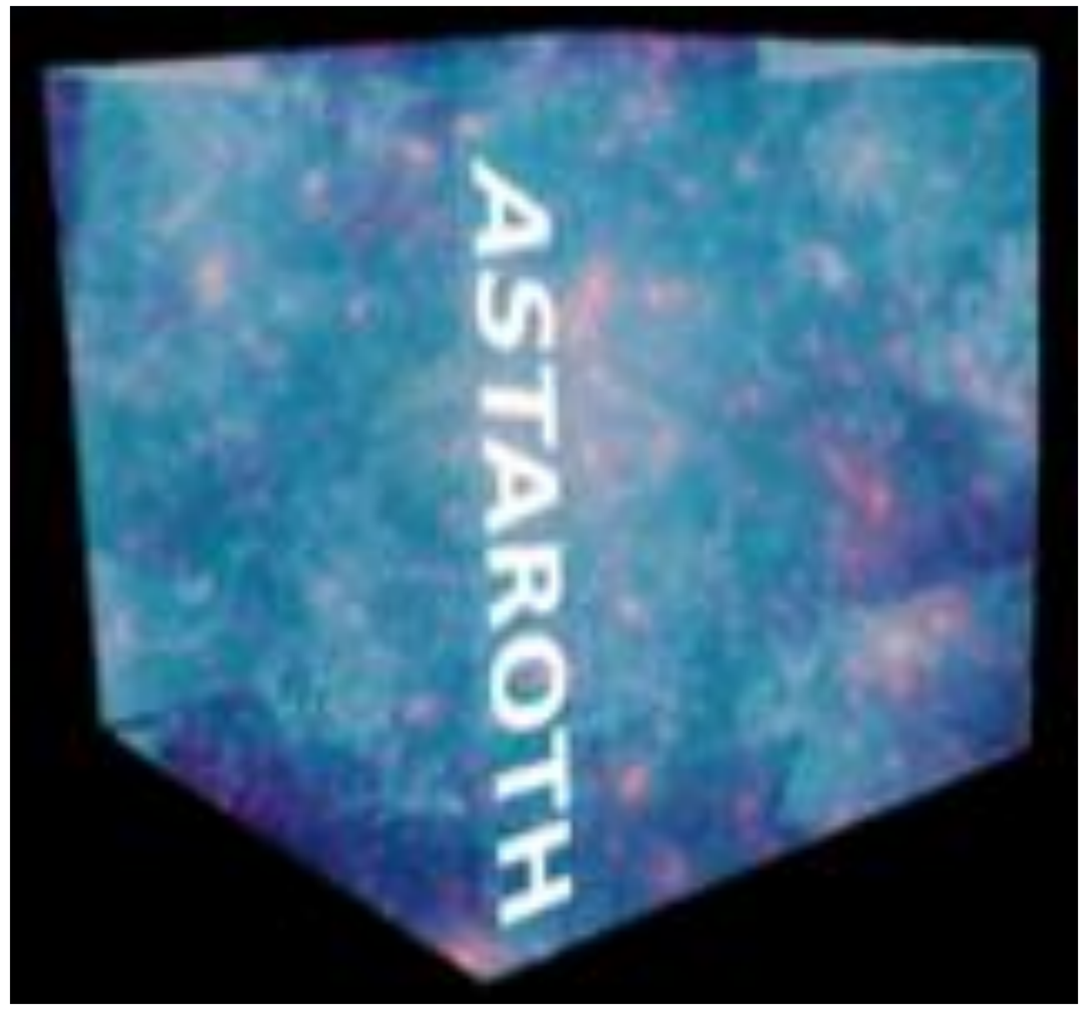
SABRE North and South

- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

Part 3:
ASTAROTH

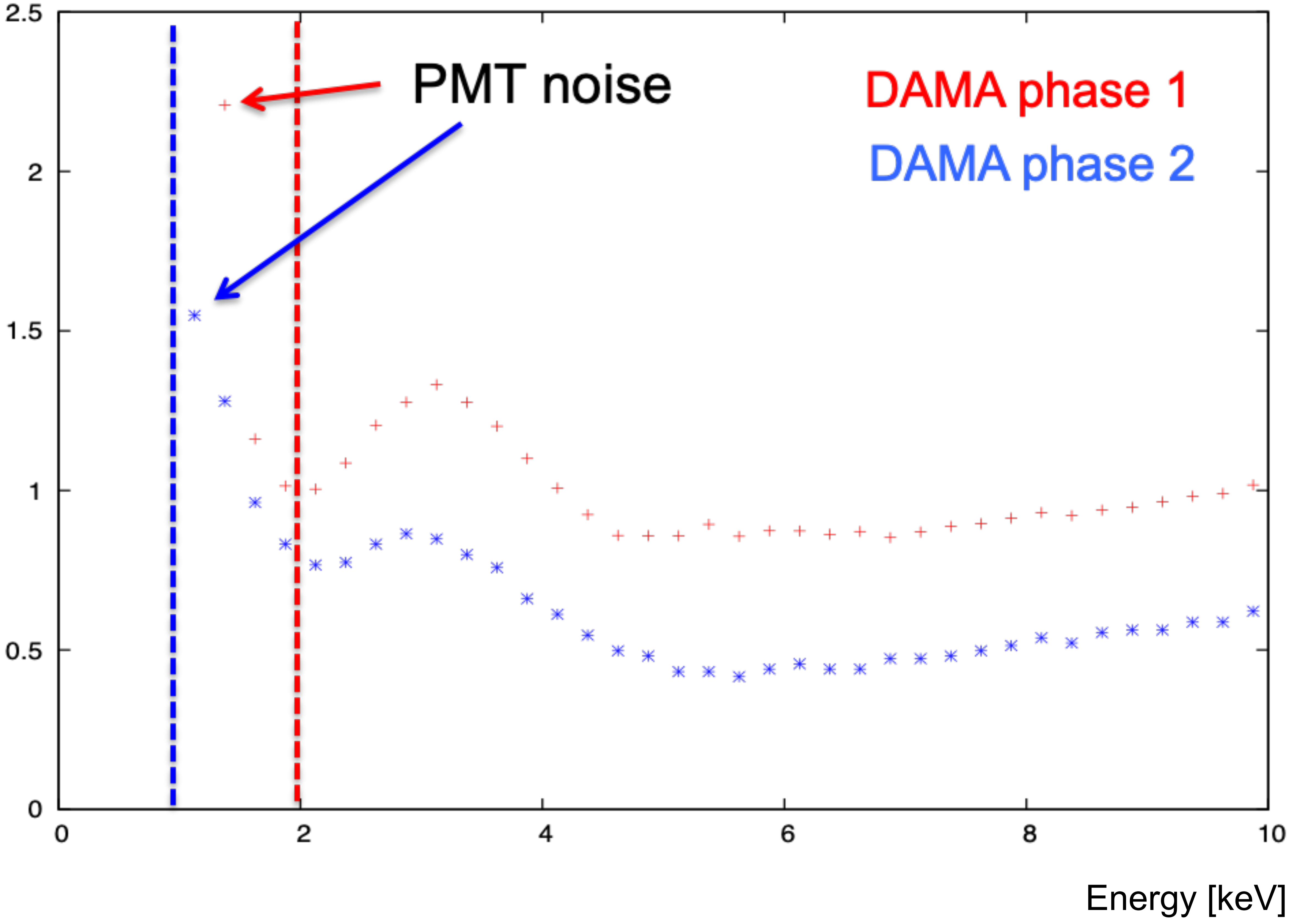
All
Sensitive
crysTal
ARray with
lOw
THreshold

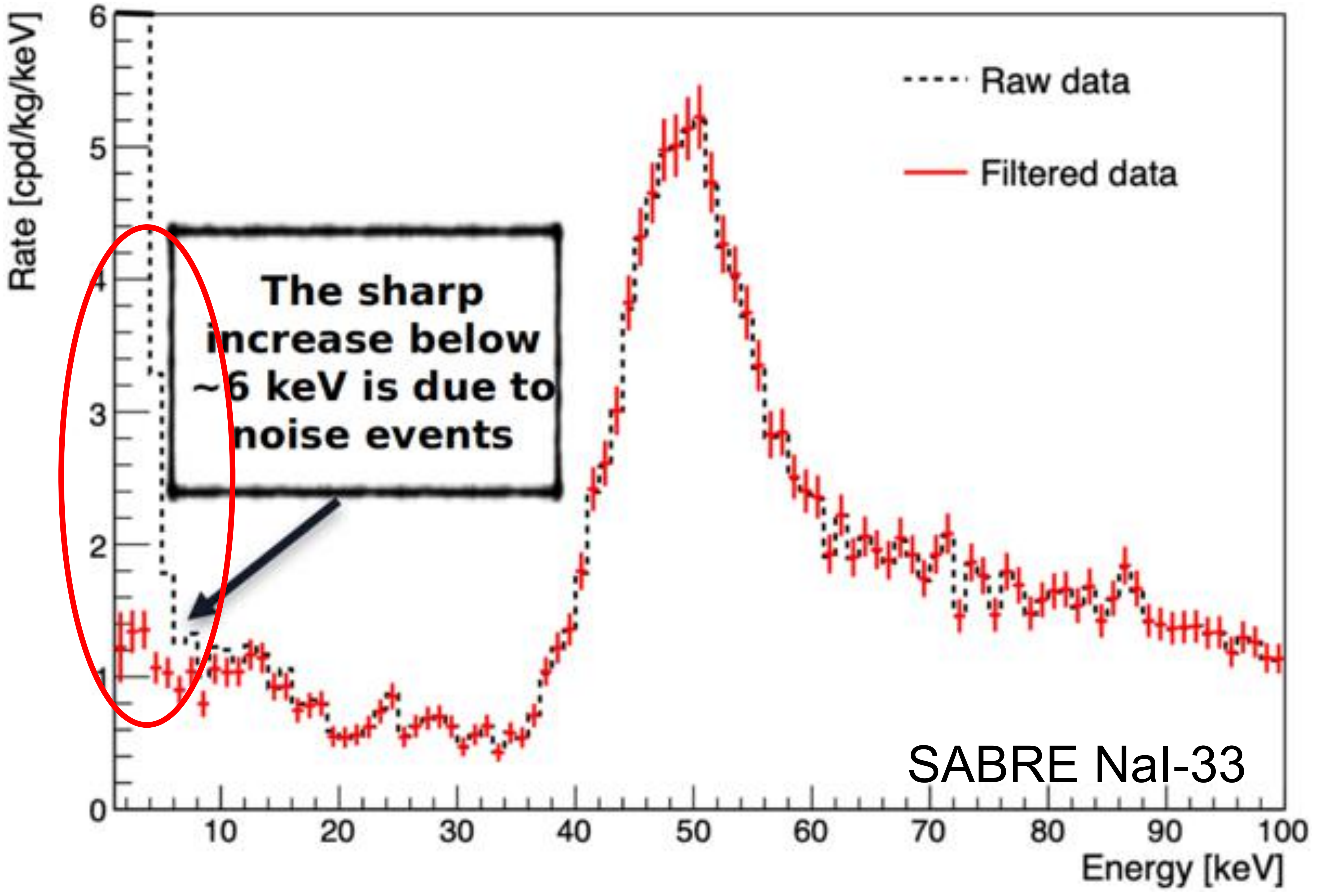




Why ASTAROTH: Surpassing PMTs

S/N at 1 keV ~ 0.01
Hard to go below!

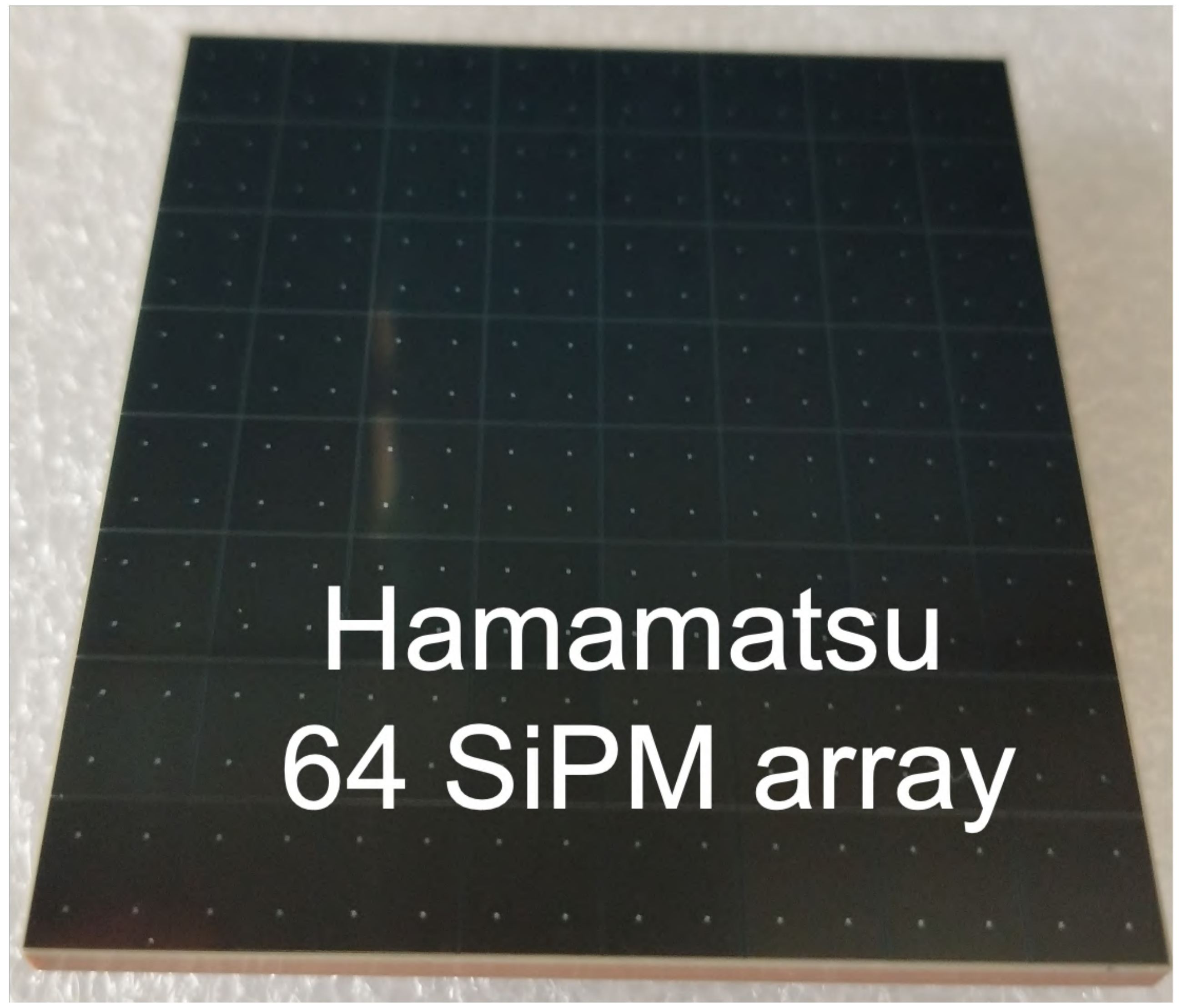




Overcoming the limitations

A next-generation detector should:

- **surpass PMT technology to reduce noise**
- **enhance Light Yield (collected phe/keV).**

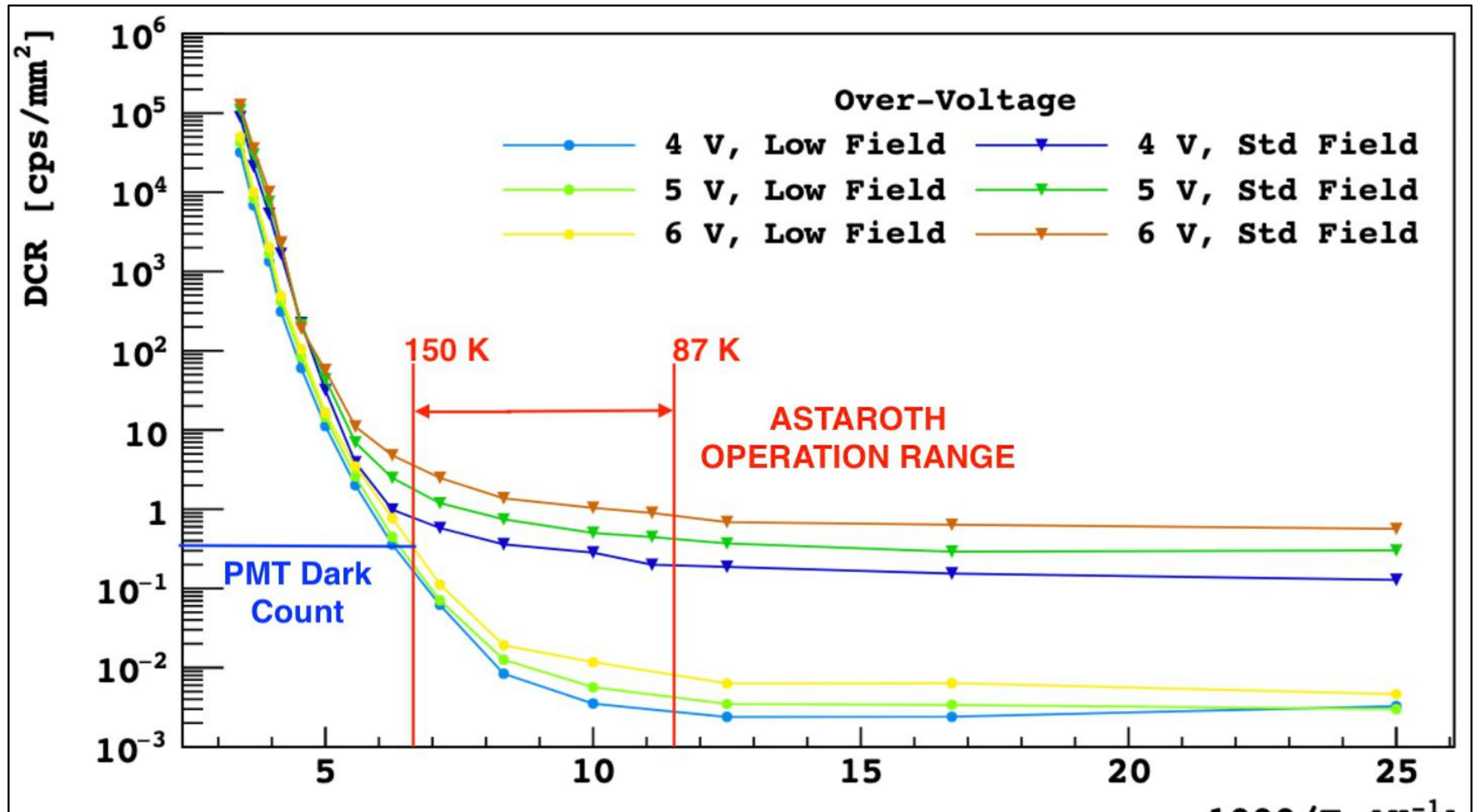


Use of SiPMs implies the need of a cryogenic environment:

- scintillating **Liquid Argon** (LAr, 128 nm) provides cooling power and can double as VETO detector if equipped with PMTs/SiPMs.

Silicon PhotoMultipliers (SiPMs) can replace PMTs:

- arrays have smaller transverse dimensions and can be equipped on all crystal surfaces.
- SiPM technology features lower dark noise than PMTs at **T<150 K.**
- Lower intrinsic radioactivity.
- SiPMs have higher PDE (55%), w.r.t. ~30-35% max QE of PMTs at NaI(Tl) scintillation light wavelength (420 nm).

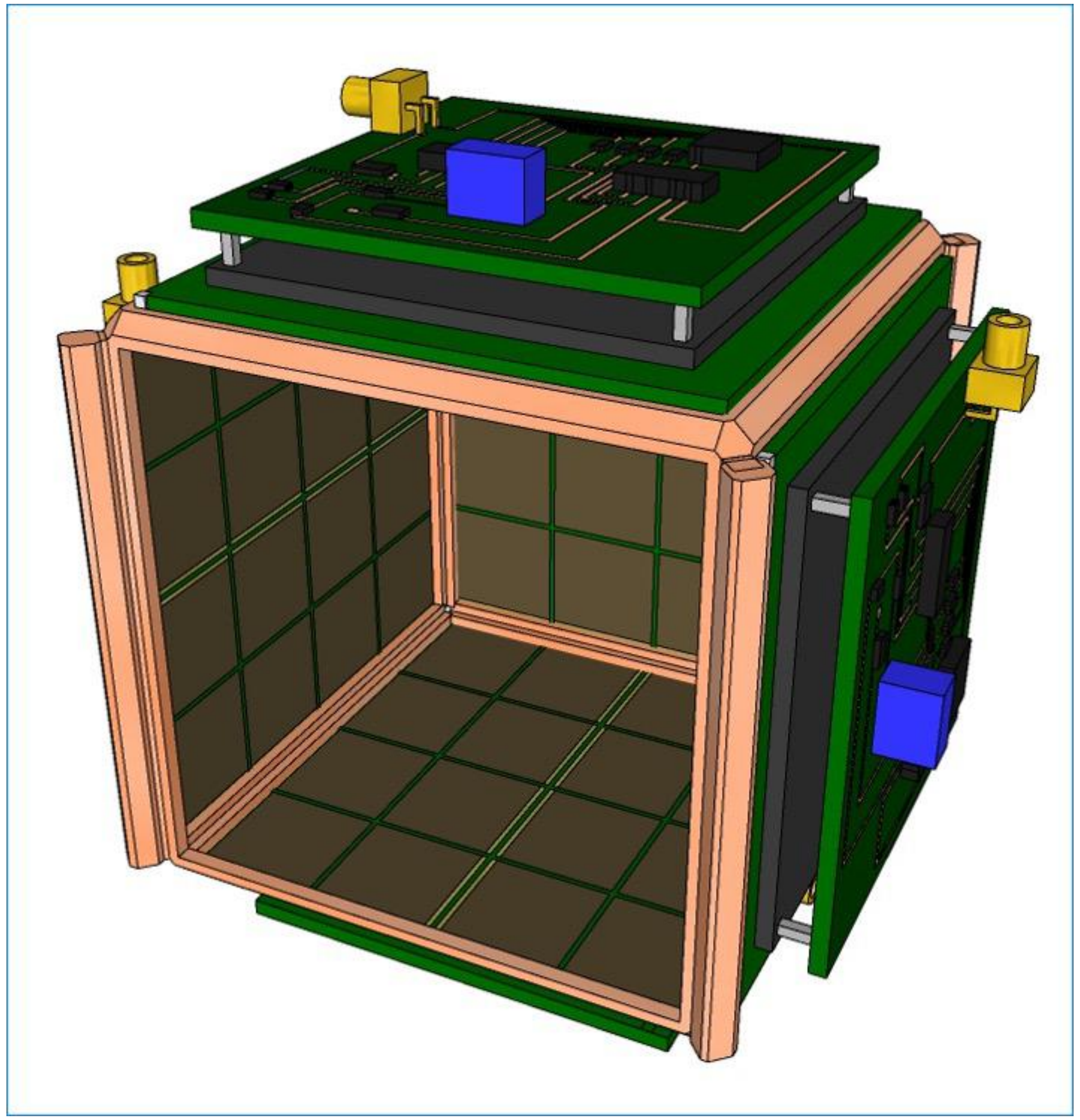


F. Acerbi *et al.*, IEEE Trans.Elec.Dev. **64** (2017) 521-526

The strategy for an enhanced physics reach

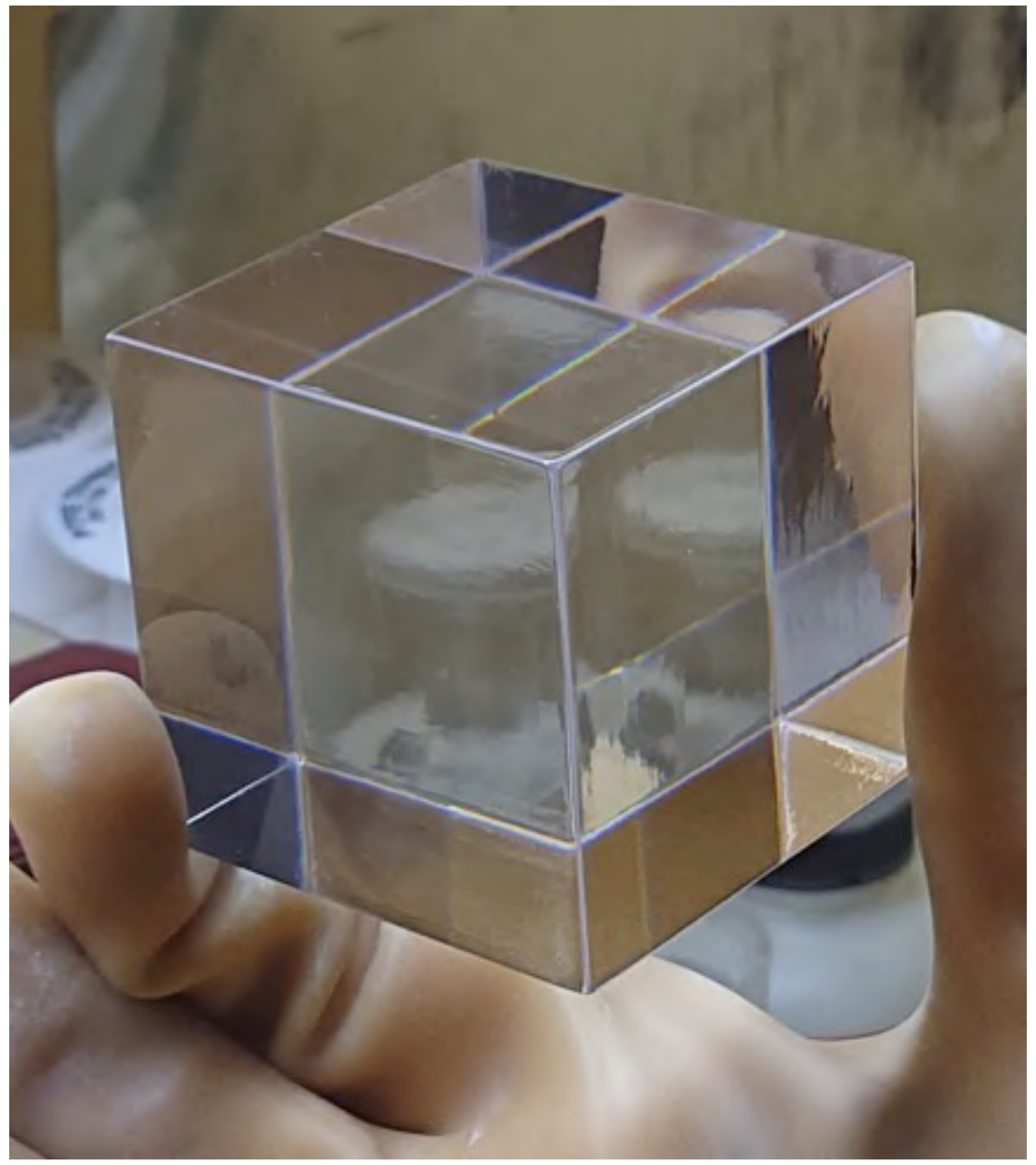
- **small cubic** NaI(Tl) crystals (5x5x5 cm^3)
- read on **all six surfaces** by SiPM matrices
- operating at a tunable temperature **in the range 87-150 K**, to find the optimal operation point for crystal (and SiPM):
  - Not a consistent picture about NaI(Tl) properties at low-T (crystal/set-up-dependent results)
- Use of encapsulated crystals (fused silica, epoxy resins) for easier manipulation and installation.
- **Enhance light collection**: maximized sensitive area, higher PDE
- Push compactness even further with **digital ASIC: add map of light collection**
  - more controlled backgrounds and reduced power dissipation

→ Allow for the first-time access to sub-keV recoil energies for the observation of a DAMA-like annual modulation signal.

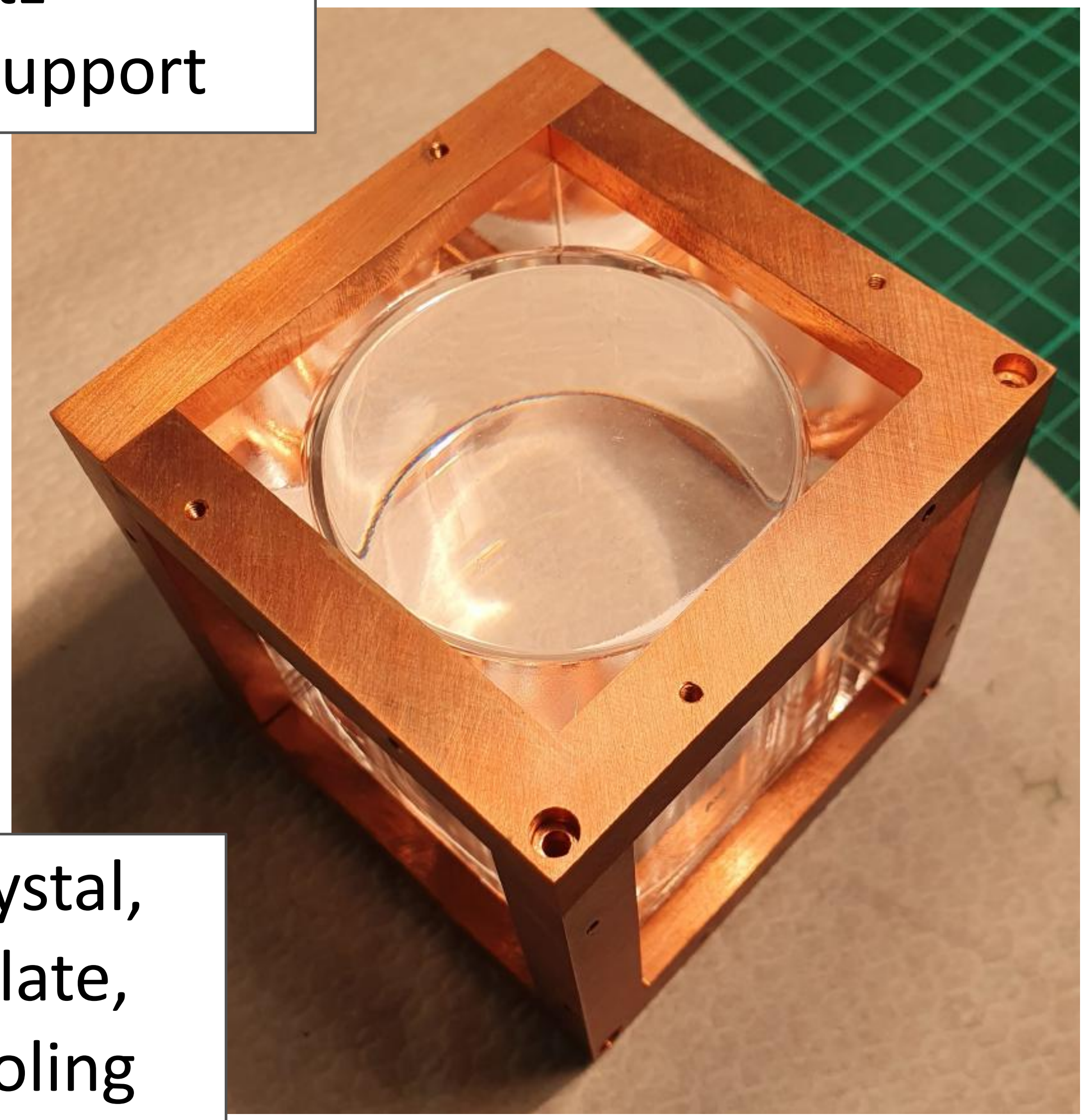


The need for a cased crystals

- NaI is hygroscopic
- SABRE uses naked crystal, mounting them with PTMS in glove box in the enclosure
- ANAIS, COSINE crystals cased by the producer with optical windows
- ASTAROTH operates in a cryostat, need a case with several requirements:
  - (withstand vacuum)
  - withstand several thermal cycles to LAr T
  - fully transparent optical coupling at LAr T
  - low radioactivity materials



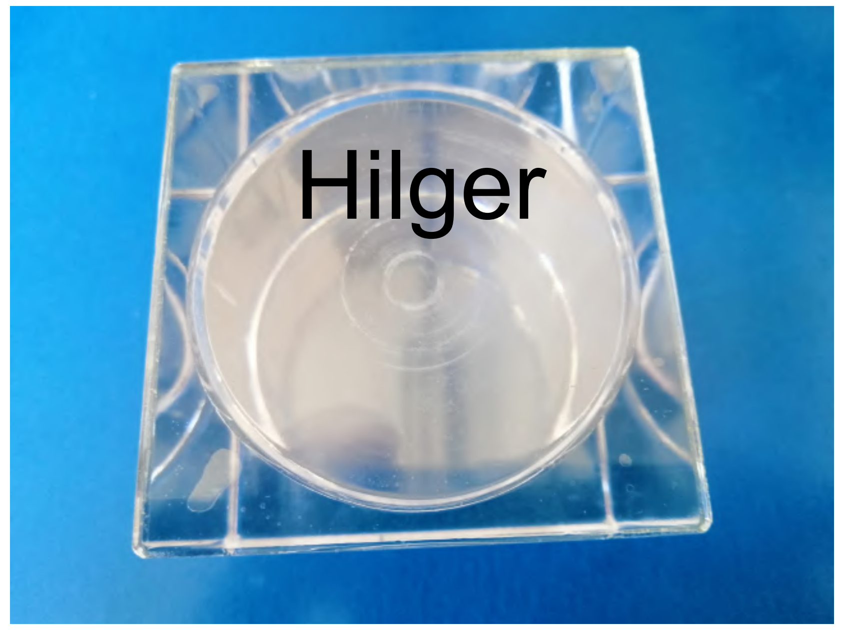
Crystal in quartz container, Cu support



Cylindrical test crystal, easier to encapsulate, used for initial cooling cycles

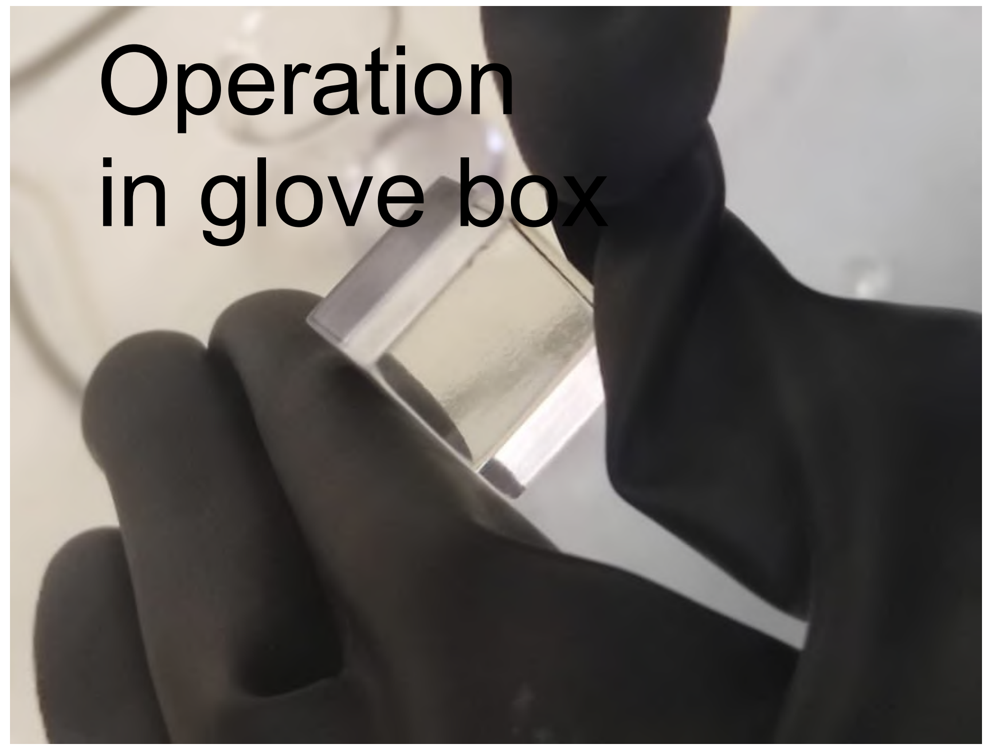
Detector design

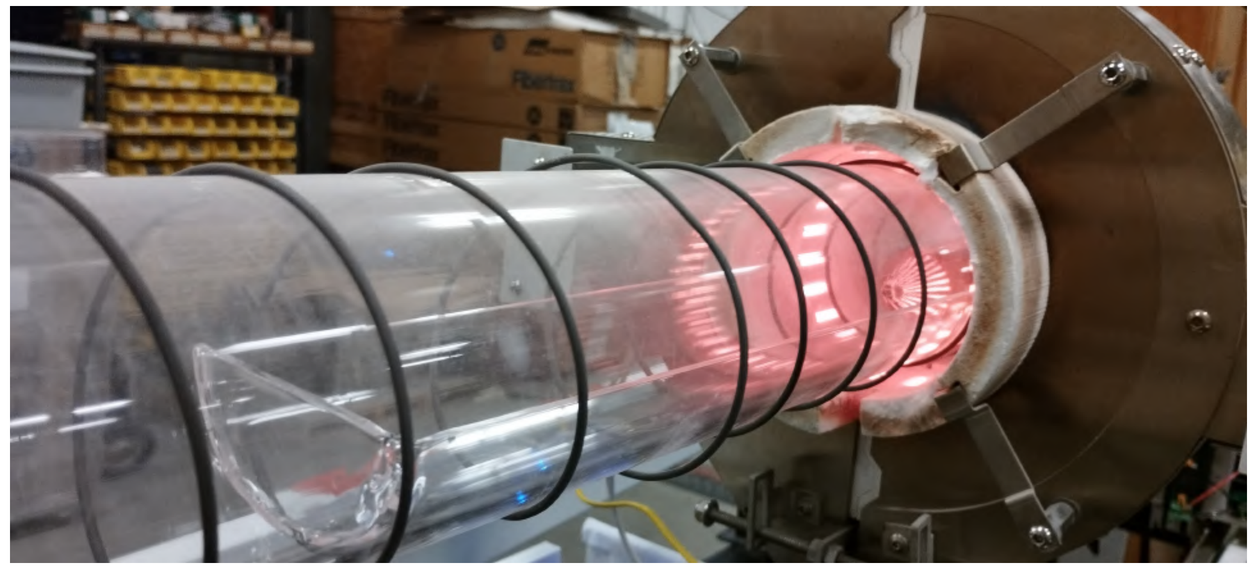
- We worked so far with a cylinder-in-a-cube solution:
  - 50x50 mm NaI(Tl) crystal in 55 mm cubic fused silica case
  - better air-tightness than with cubic crystals
  - Neon gas gap to accomodate different CTE of materials.
- Geant4 simulations and a first data taking => only 35% of light exists due to total reflections
- No case => coat crystals!
- Bicomponent epoxy resins
  - Checked transparency and cryogenic behavior



First epoxy-coated NaI(Tl) crystals

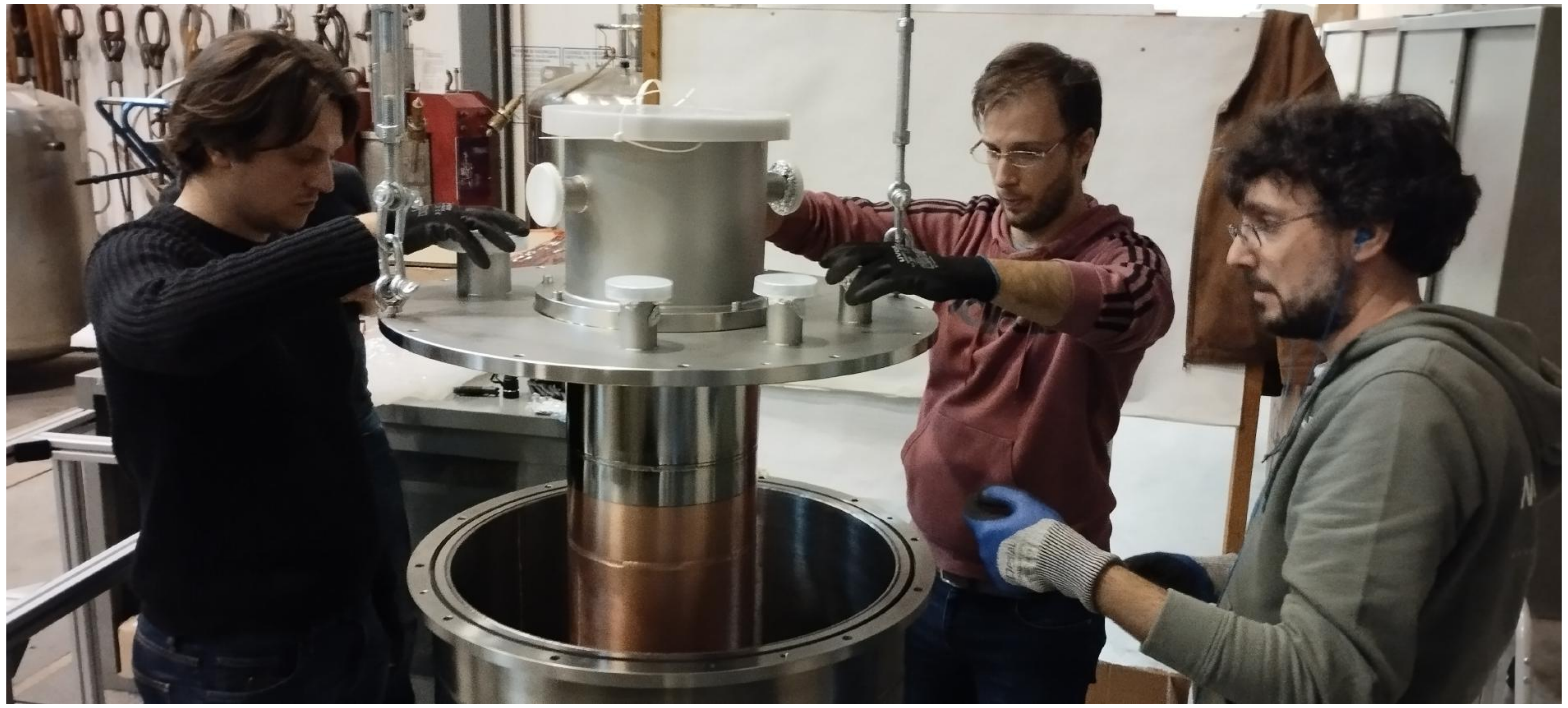
- 21 mm epoxy-coated NaI(Tl) crystals work!
  - 3 resins proved
  - Transmittance under test with a spectrophotometer
- A revolution in handling of NaI crystals, looked at with high interest by many groups
- Scale to 50 mm crystal **in progress**
  - Degassing in ultrasonic bath?
- To be done:
  - optical coupling of SiPM with silicon pads or Si-gel
  - High-purity crystal from SABRE producer RMD (Boston)

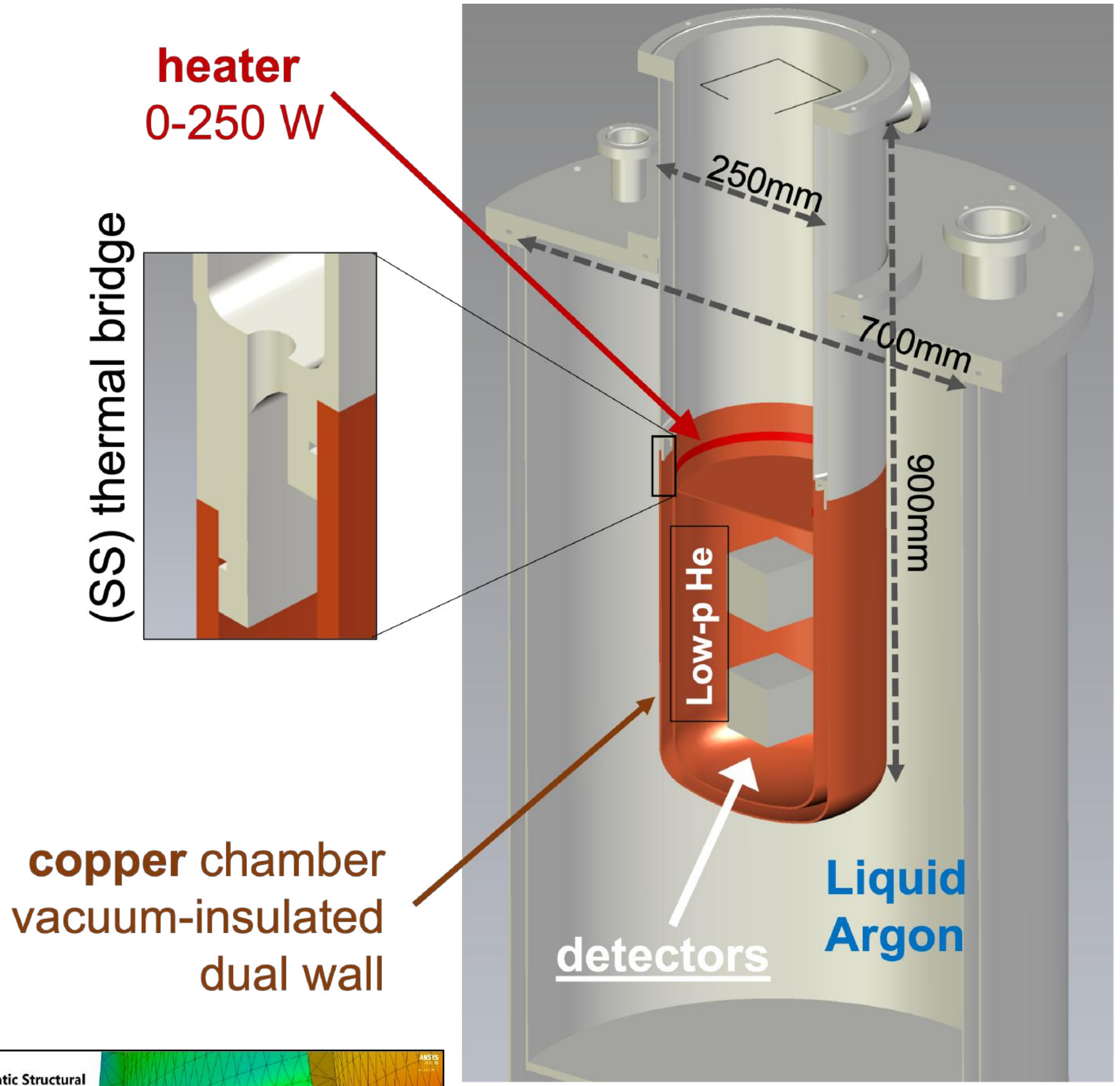


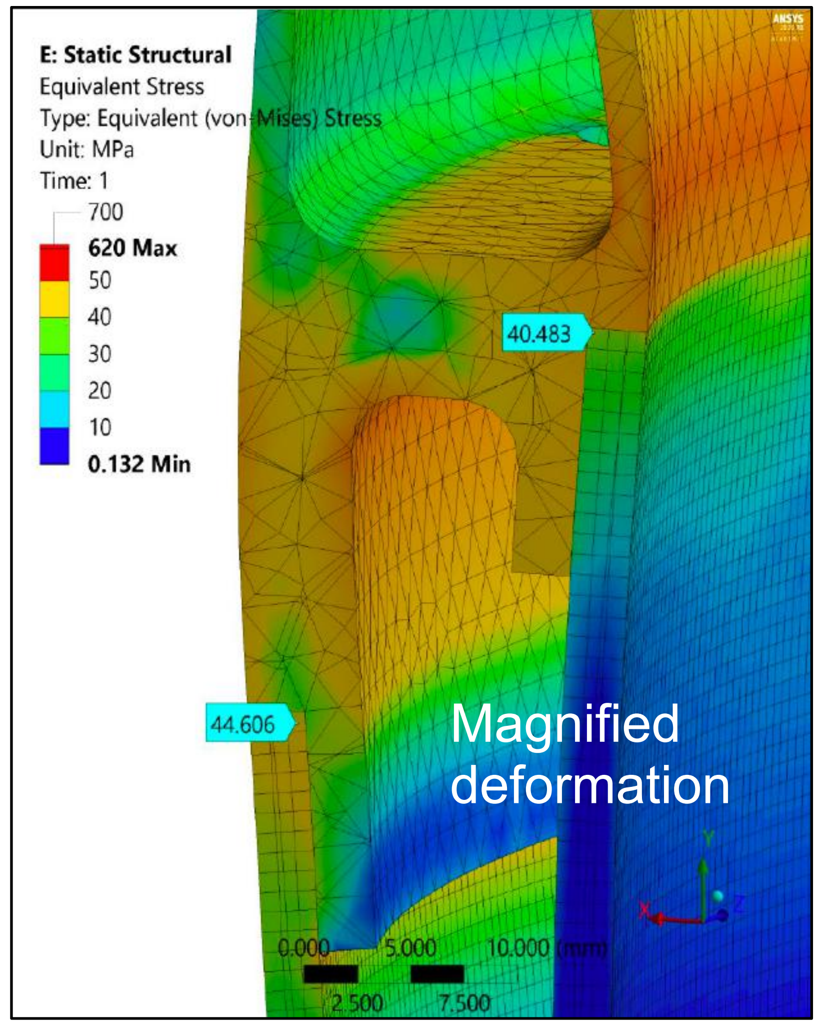


ASTAROTH cryostat

- **Dual-wall, vacuum-insulated** radio-pure copper chamber, featuring a specially designed **Stainless Steel (SS) thermal bridge.**
- Chamber is immersed in a **cryogenic bath providing cooling power** through the SS bridge.
- Heater raises and stabilzes the temperature above that of cryogenic fluid. **Investigated range: 87-150 K.**
- **Helium gas** fills the inner volume, serving as heat-transfer medium to the crystals and SiPMs.
- Constructed by SRV (Parma), installed at LASA May 2023.



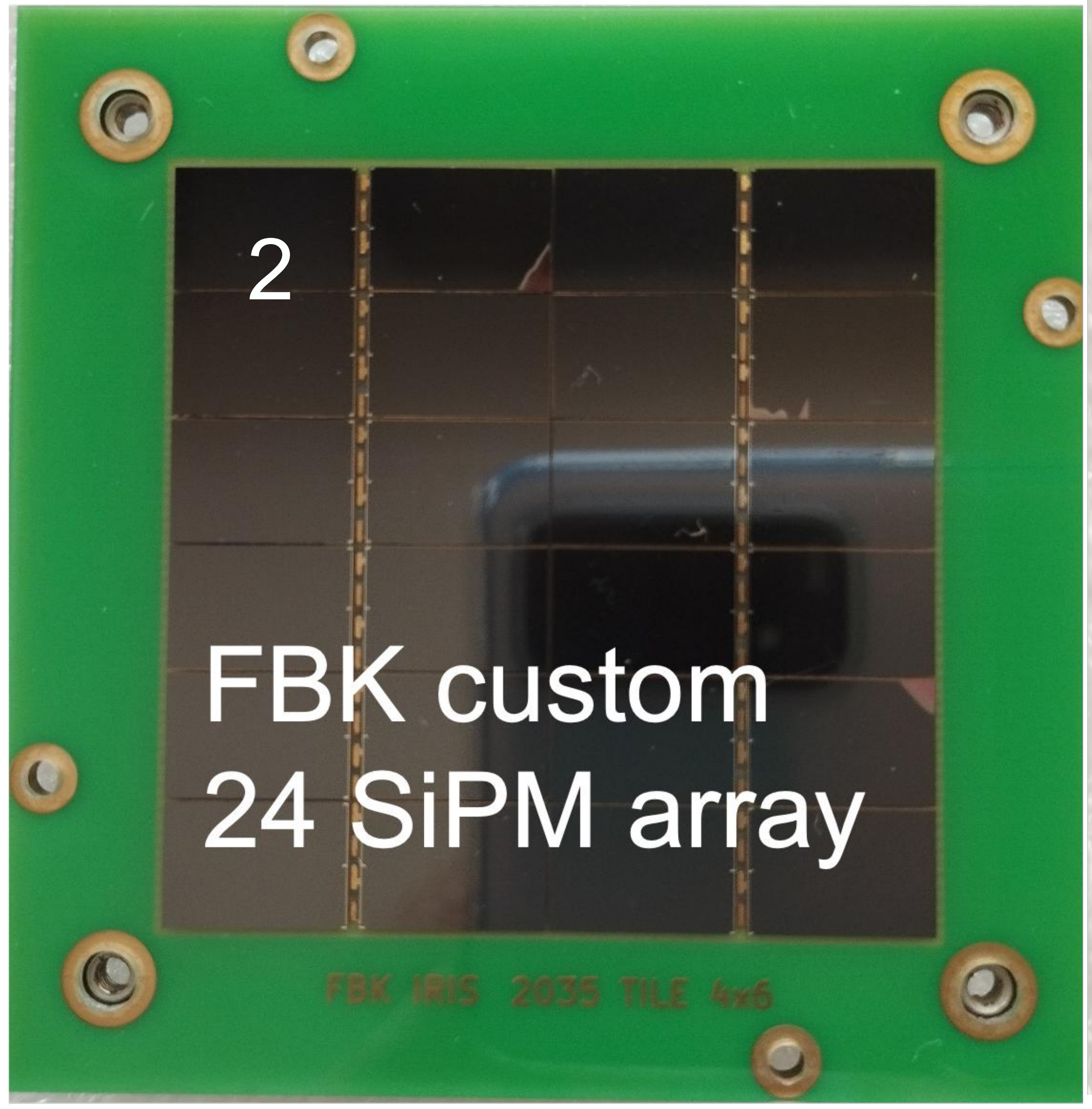


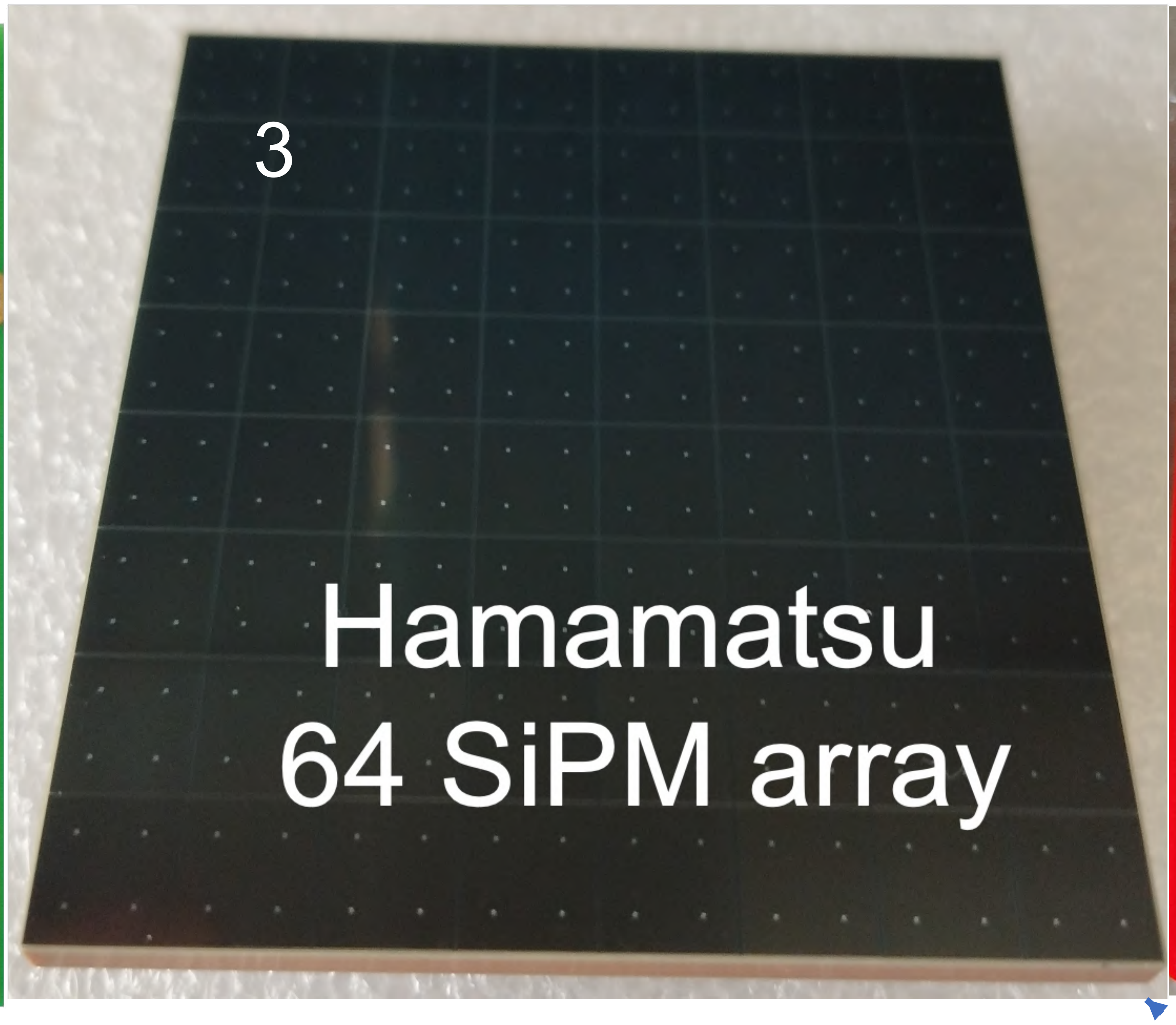


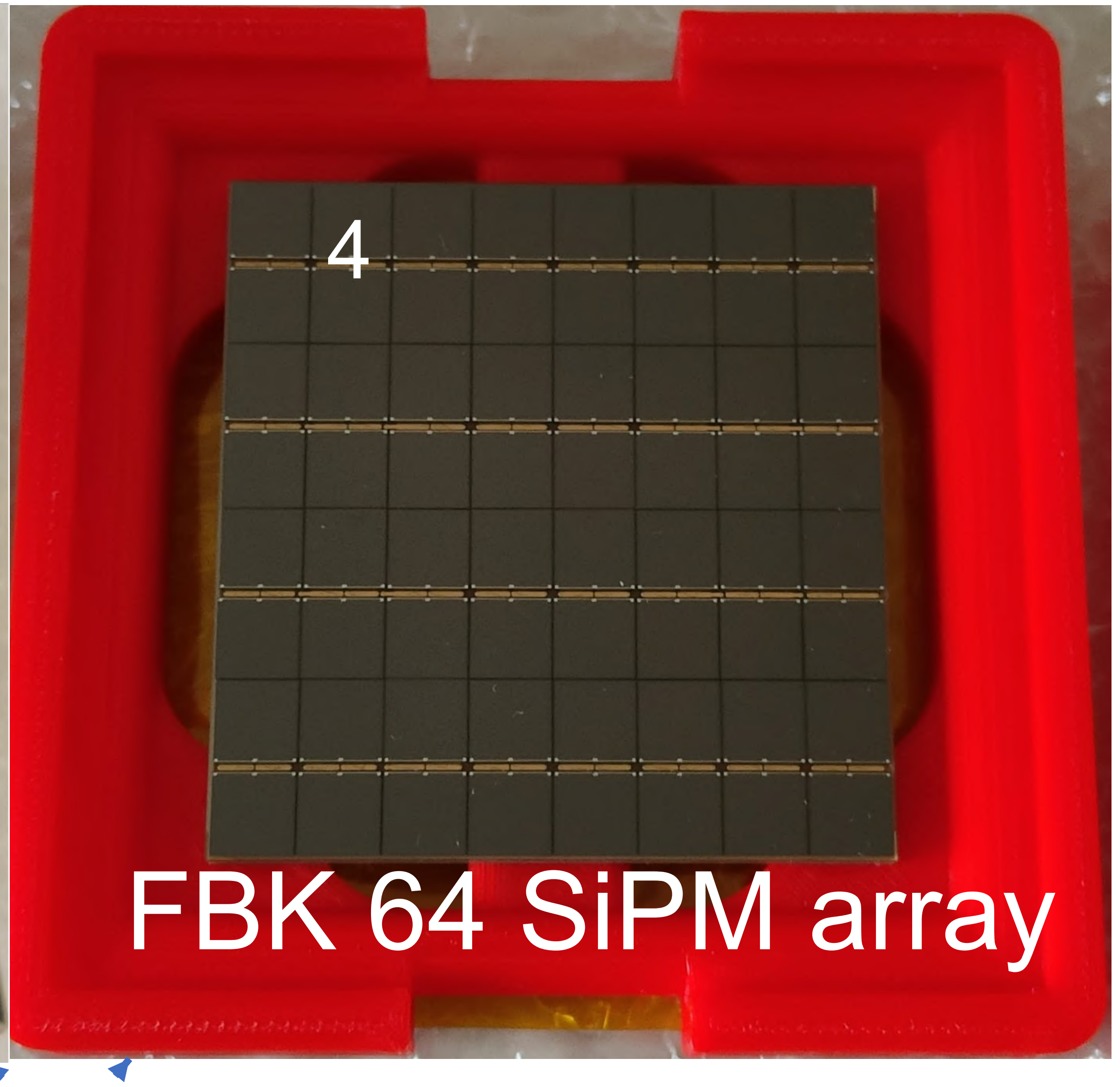
- Thermomechanical ANSYS simulations at Milano and LNGS
- Cryogenic deformation and rupture tests of the materials at LASA
- Eng. paper in preparation

	Firm	Tech	Model	Avail.	Tile size (mm^2)	Devices	Area (mm^2)	Also used	Pitch (mm)	Route	Gang	Ch	Resin	Tested
1	HPK	S13361	3050AS-08	2021	25x25	64	3x3		50	TSV	no	64	silicon	yes
2	FBK	NUV-HD-Cryo	custom	Jun-22	50x50	24	8x12	DS-20k	35	Wire bond	2s3p	4	epoxy	yes
3	HPK	S13361	6050AS-08	Mar-22	50x50	64	6x6	Dune	50	TSV	no	64	silicon	no
4	FBK	NUV-HD-Cryo	custom	Jan-23	50x50	64	6x6	Dune	30	Wire bond	no	64	epoxy	no

SiPM arrays





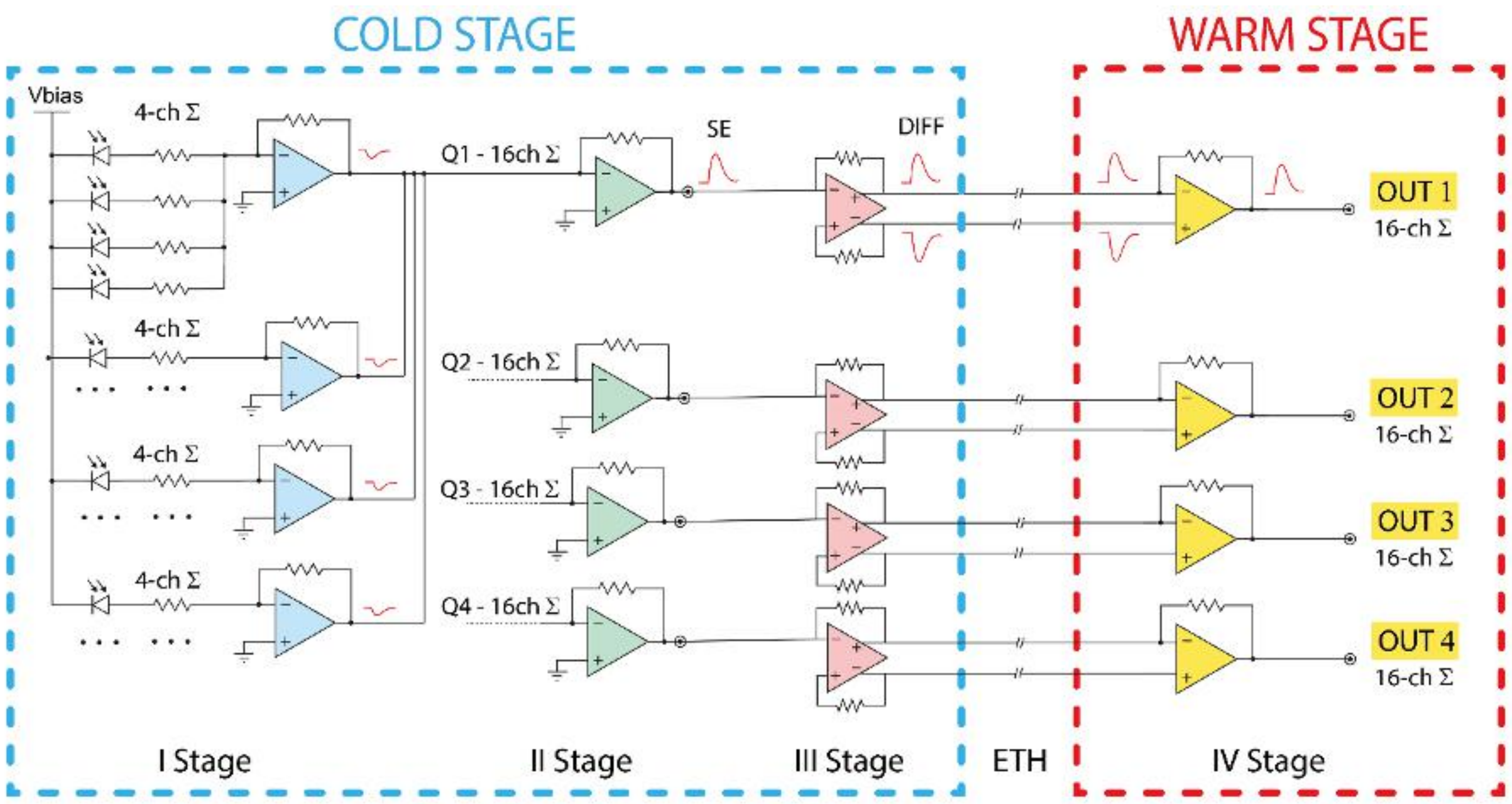


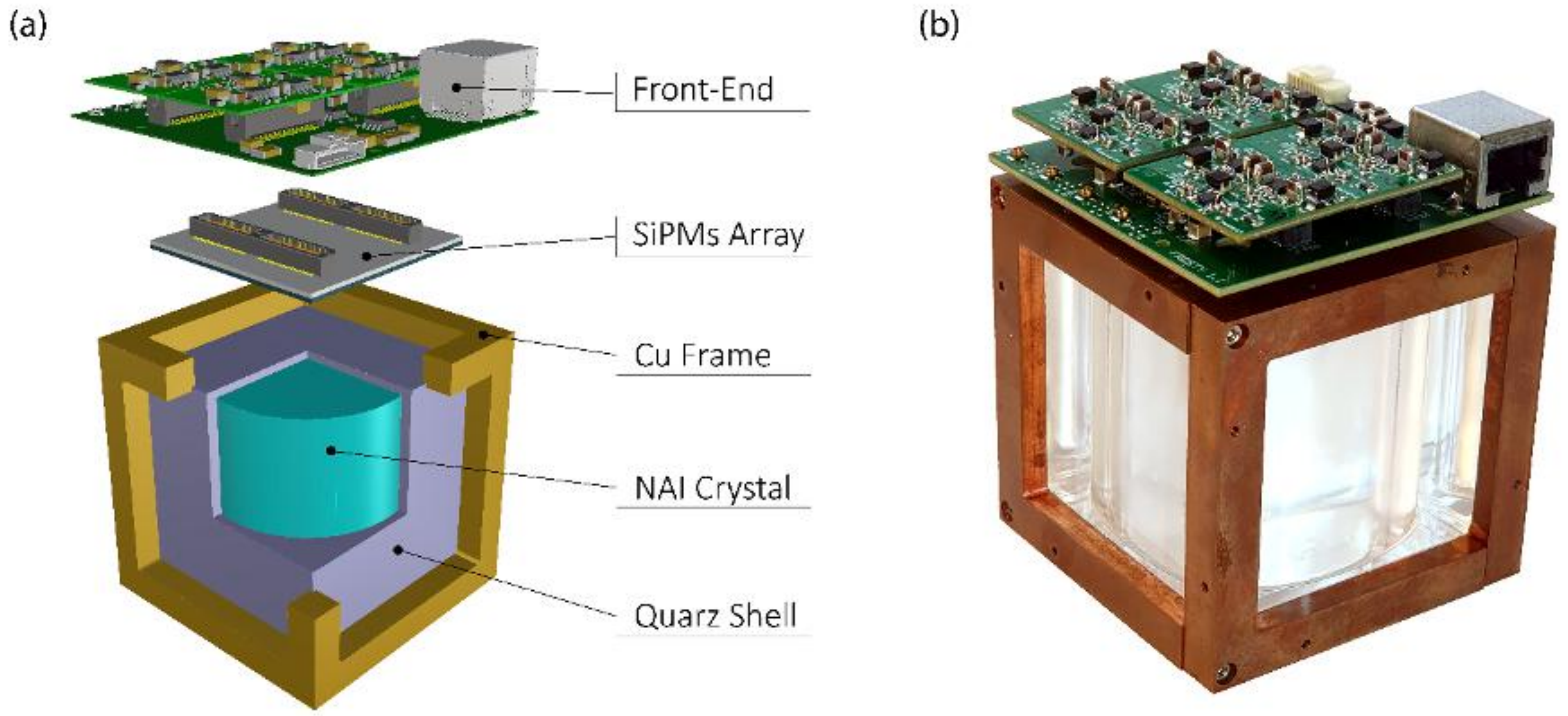
Same connectors

SiPM readout for FBK-2 & HPK arrays

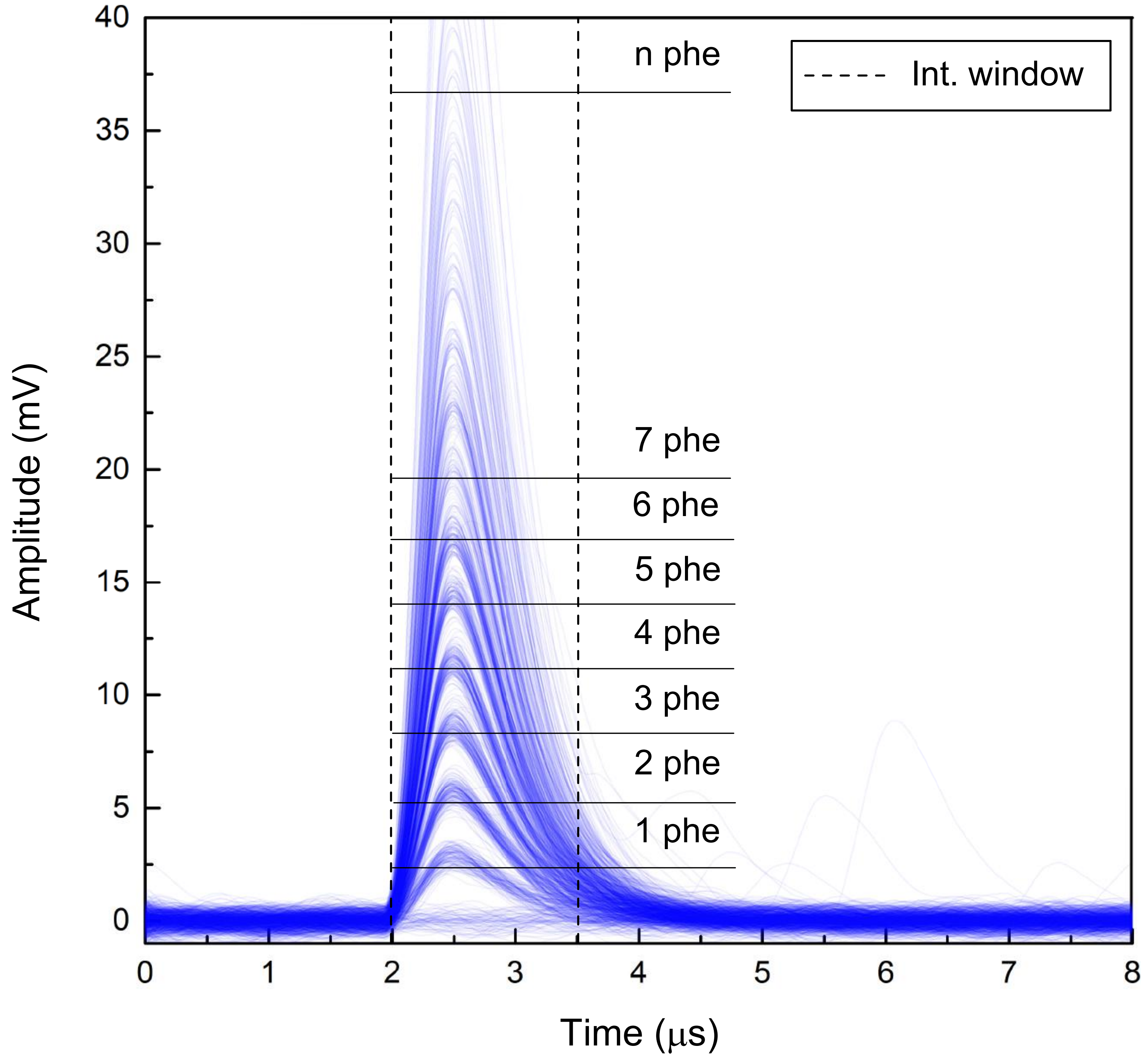
Frontend board of 64-SiPM arrays (HPK & FBK-2)

- More versatile design: 1 motherboard + 4 piggy boards with variable ganging : 1, 4, or 16 SiPM.
- Cryogenic test for some SiGe Op-amp
- 4 channels out, differential on CAT7 ethernet cable.
- Warm board to convert back differential -> single-ended

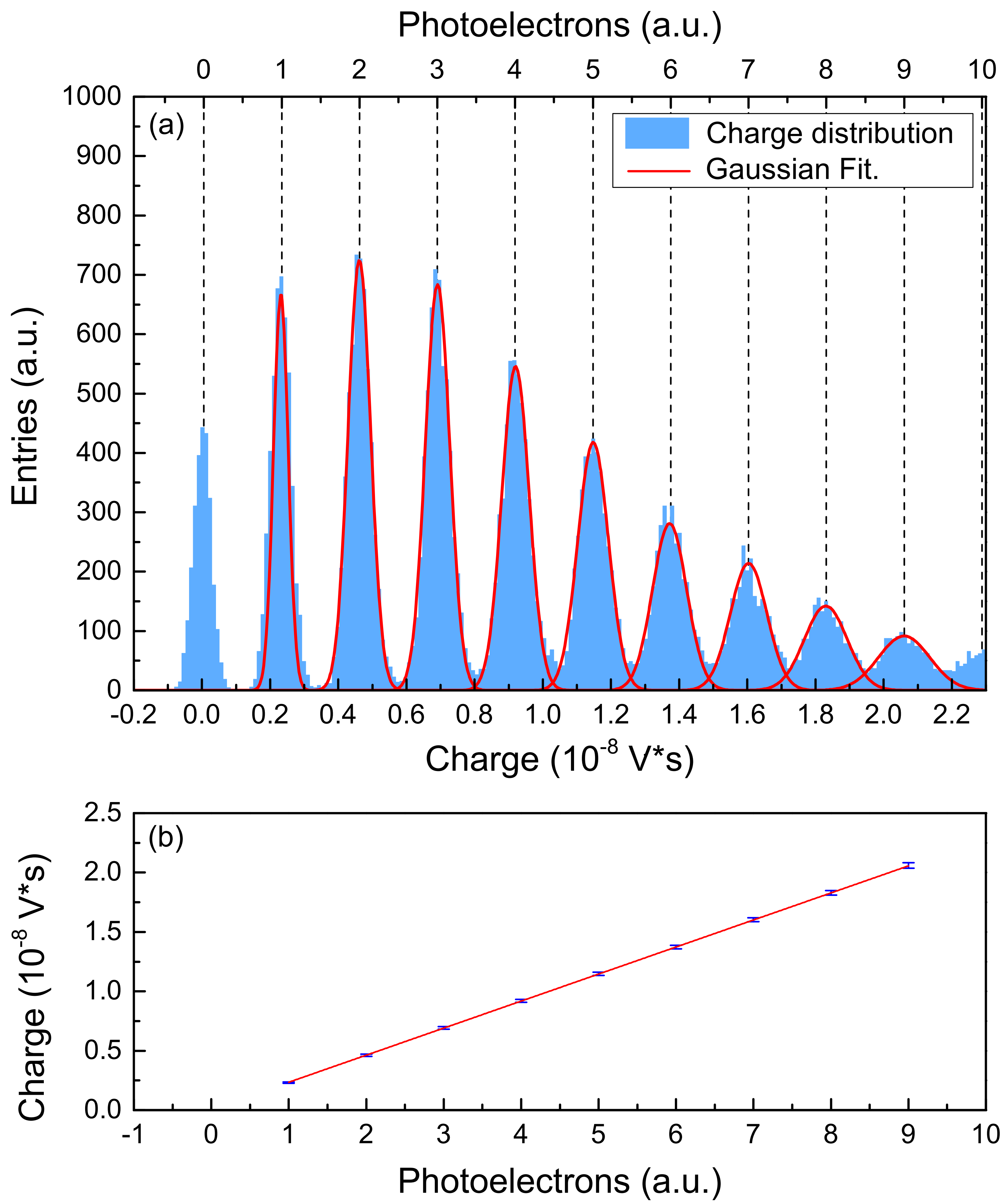




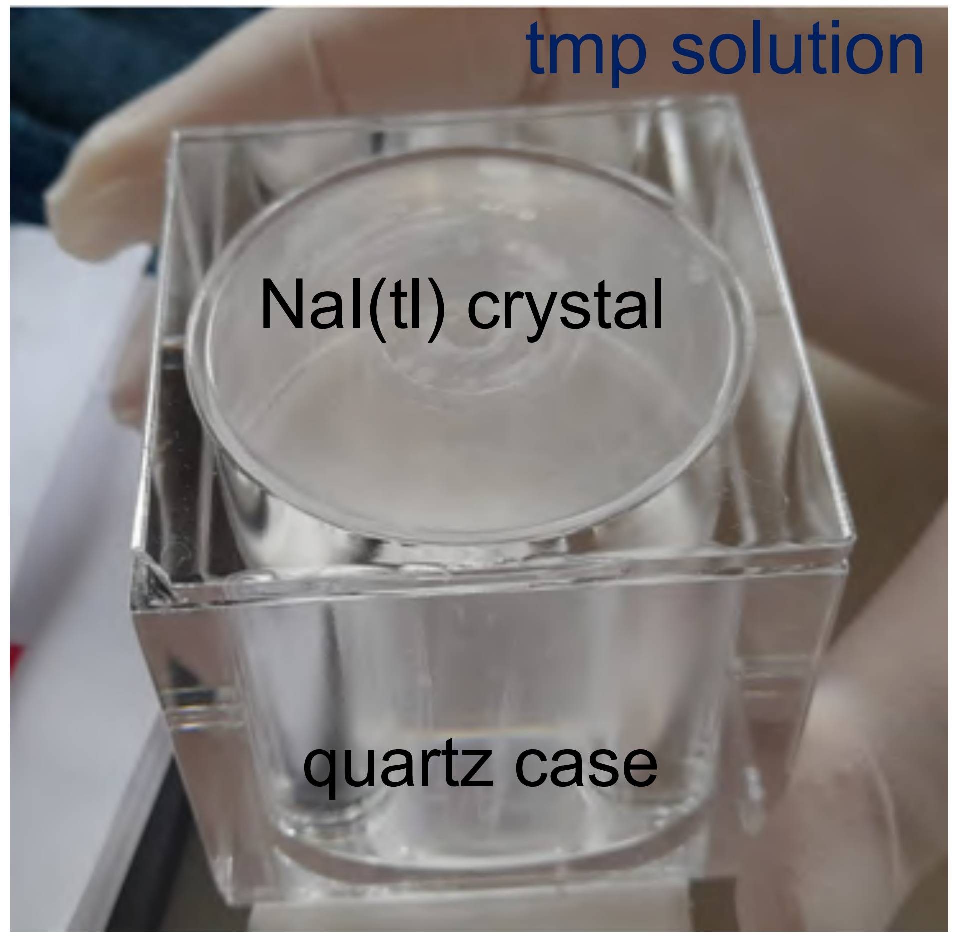
Laser calibration (in LN_2)

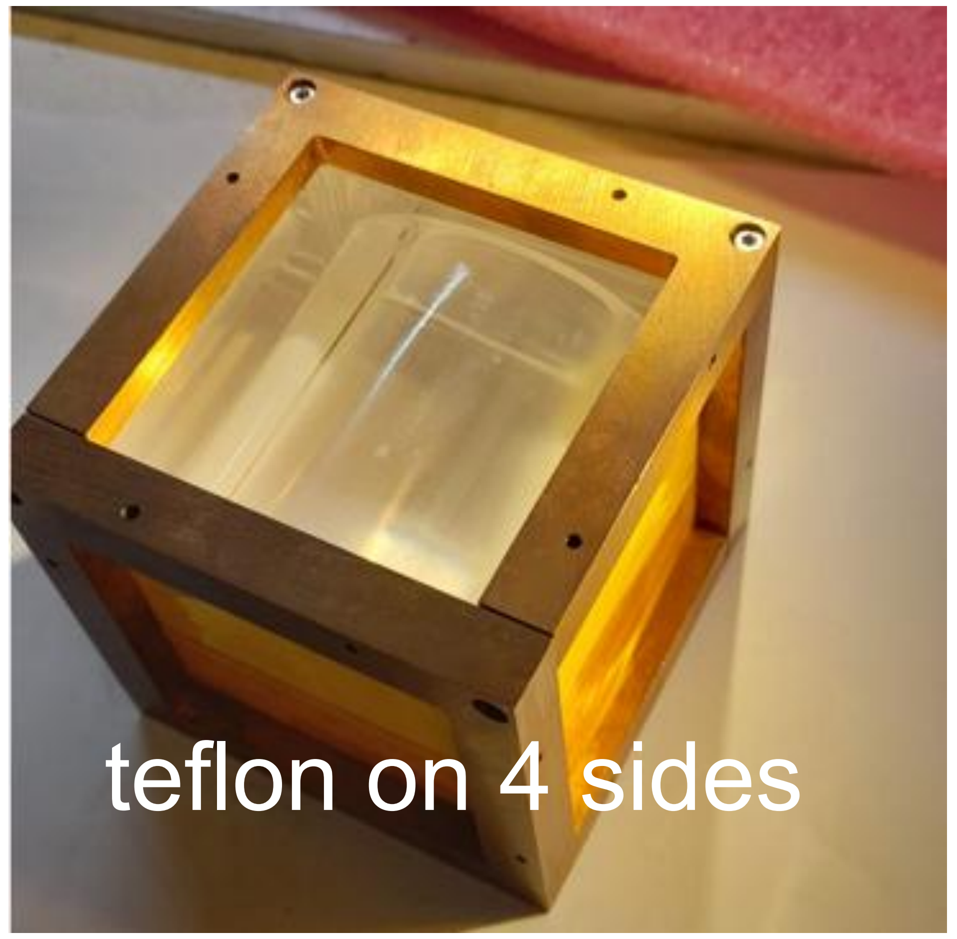


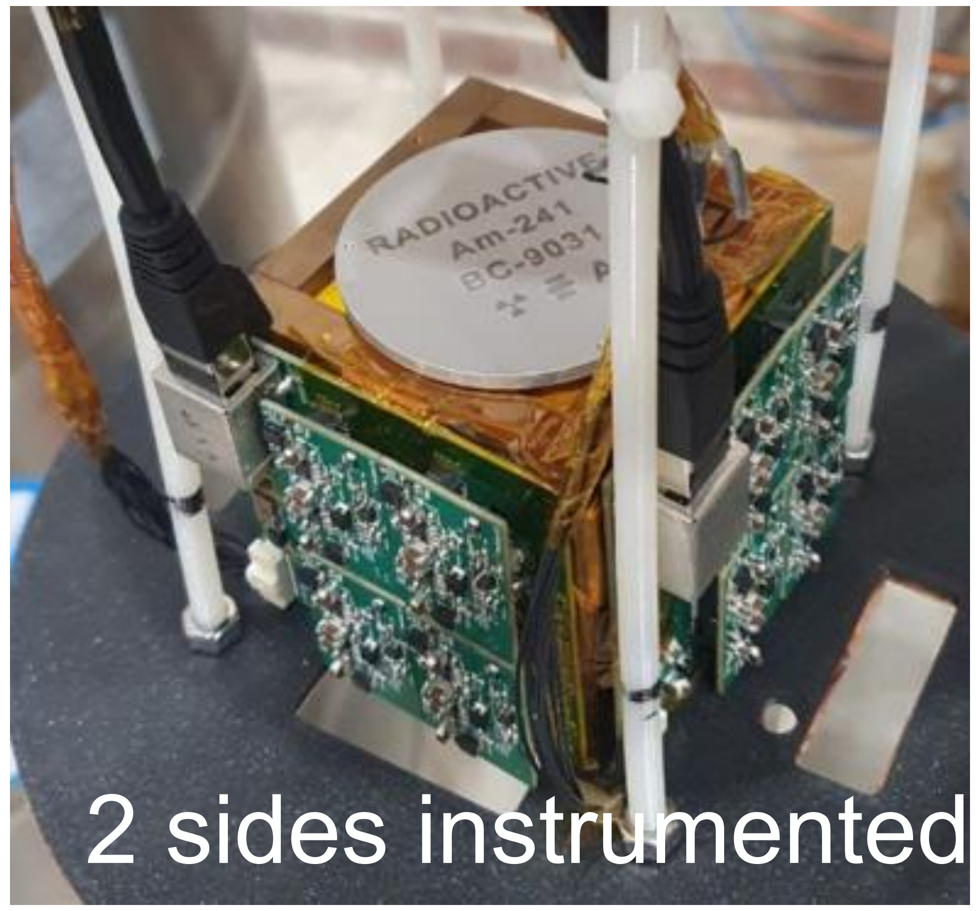
Excellent performance of SiPM and electronics



ASTAROTH ^{241}Am cryogenic source runs



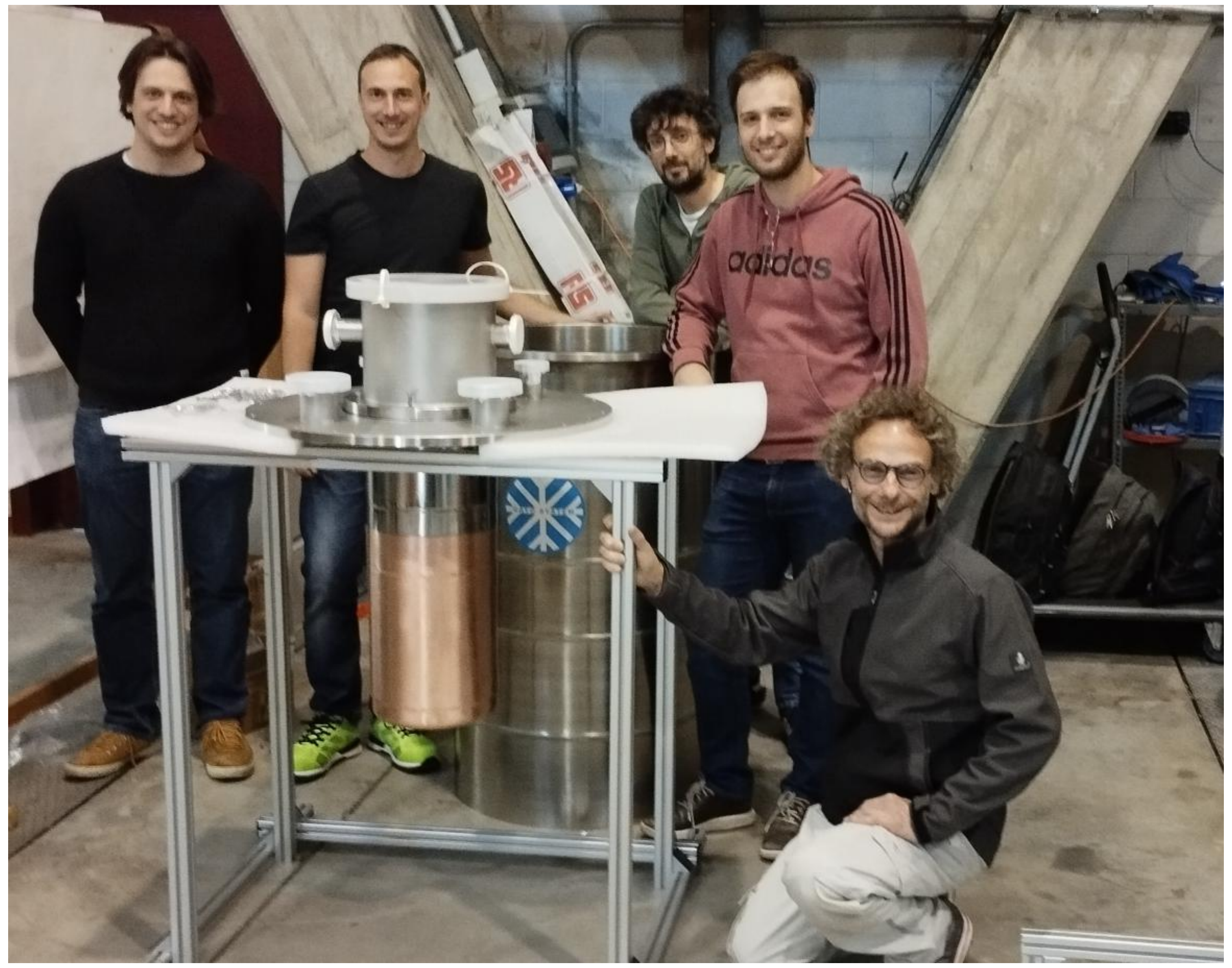


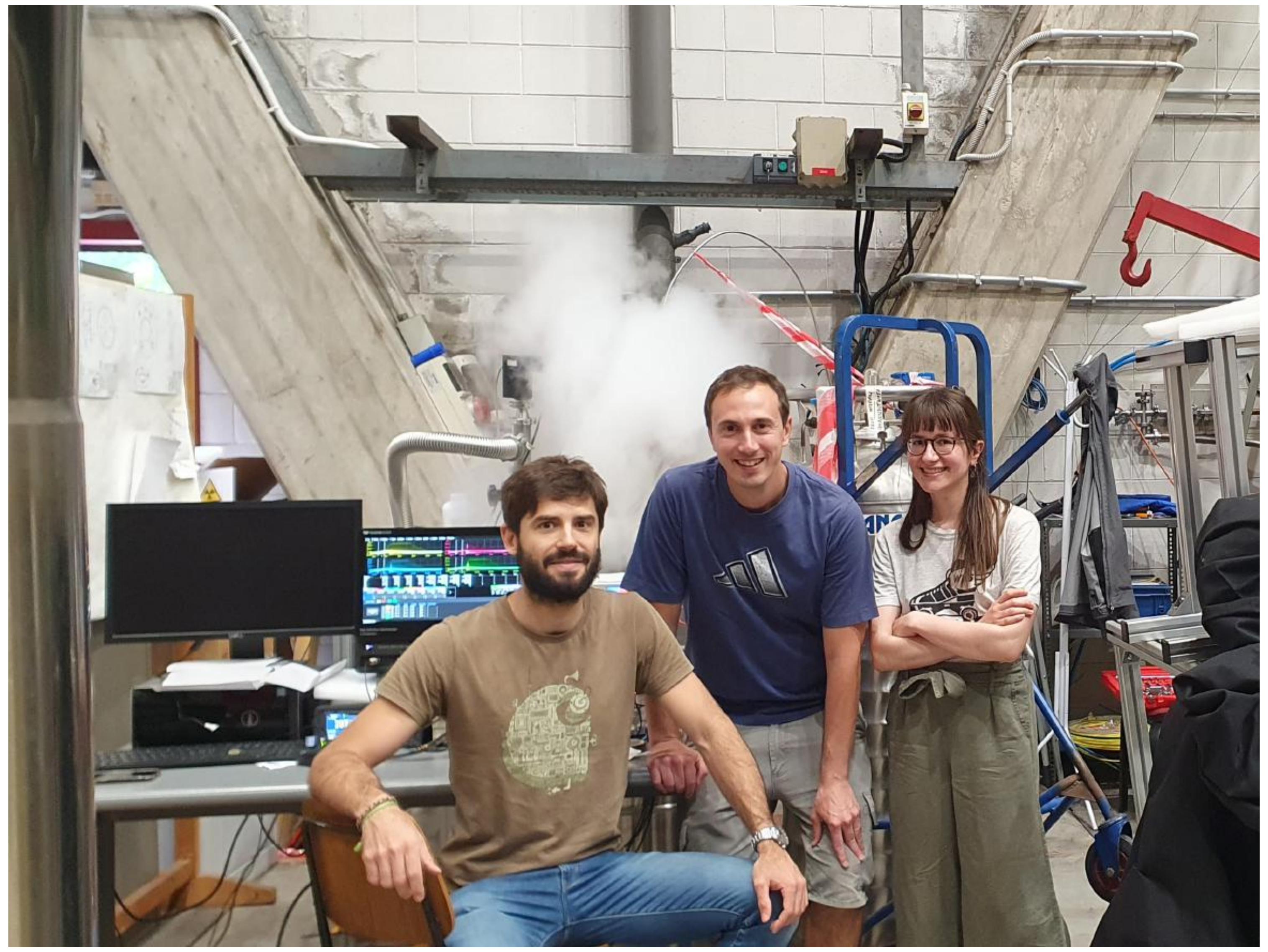


but only one array
acquired at a time

June 2024
March 2025

INFN
LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata





Where do we stand?

ASTAROTH Phase-1 completed: 2020-24

- Demonstrate the viability of the technology
- Preliminary outcomes:

1. Ph.e. yield **~ 7.2 ph.e./keV** (1 array)
   already better then expected!
   -> with several ways to improve
2. Blank run (no crystal):
   instrumental noise < 1 Hz
3. High γ rate from:
   1. External backgr.
   2. Electronics radioactivity
   3. Crystal bulk and surface radioactivity
   4. Muon disruptive interactions

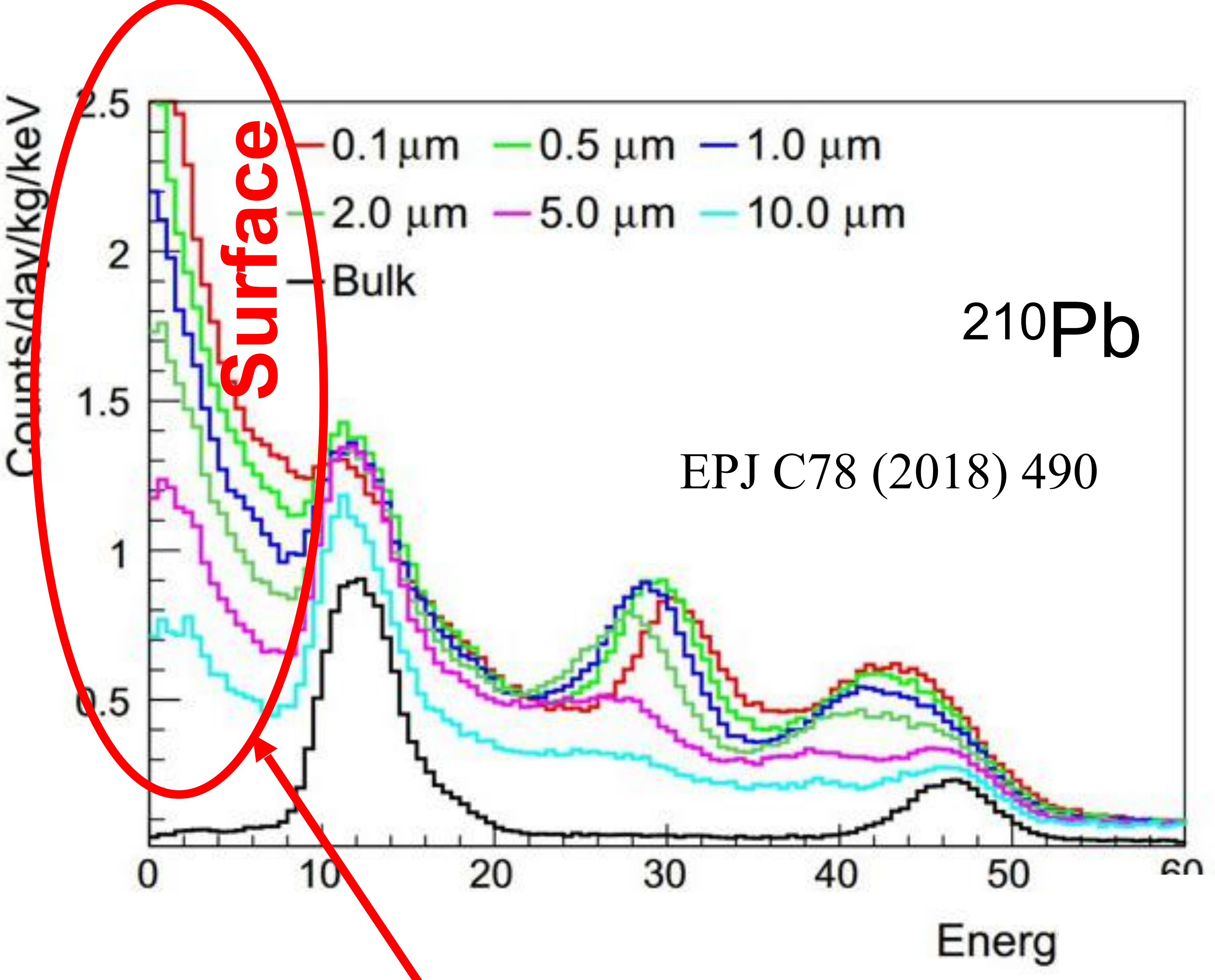
ASTAROTH_BEYOND approved by INFN for 2025-27

Motivations:

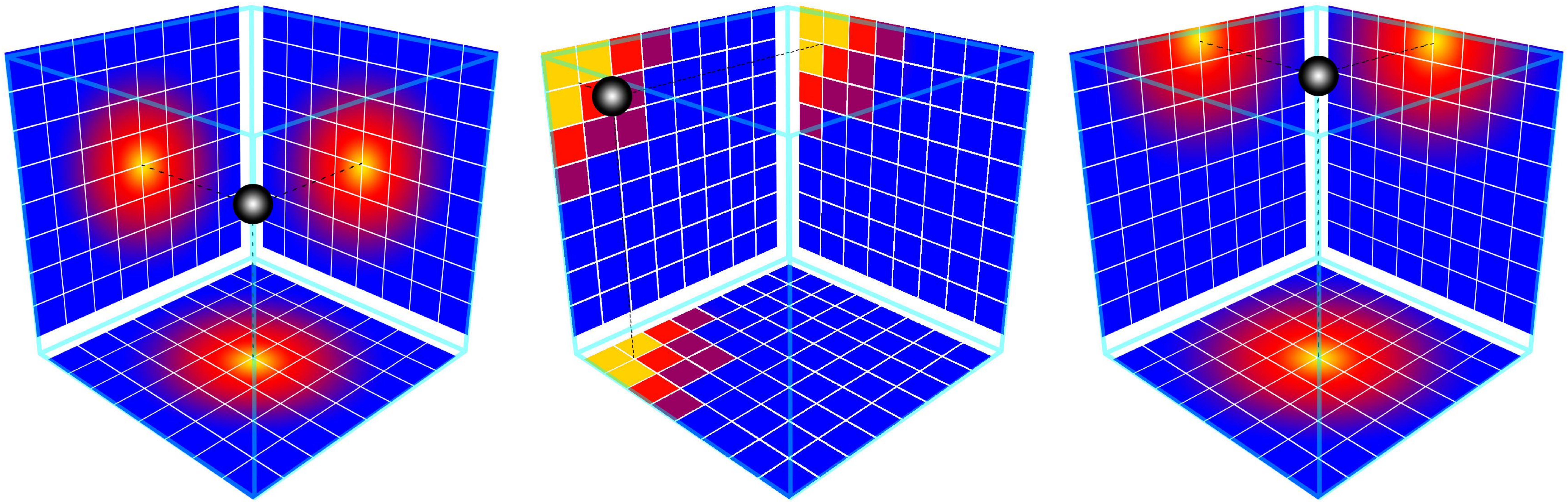
+ maximize light collection
+ implement LAr veto detector
+ low radioactivity
crystal + electronics
+ ASIC to reject surface background
+ underground site (final year)

This shows that the goal of ASTAROTH of demonstrating a S/N ~ 1 at 1keV and a sub-keV threshold <u>is at hand</u>

Reject surface background by light map?



^{210}Pb (radon daughter) can be implanted on the surfaces (observed by COSINE, SABRE) and impact the ROI more than buk

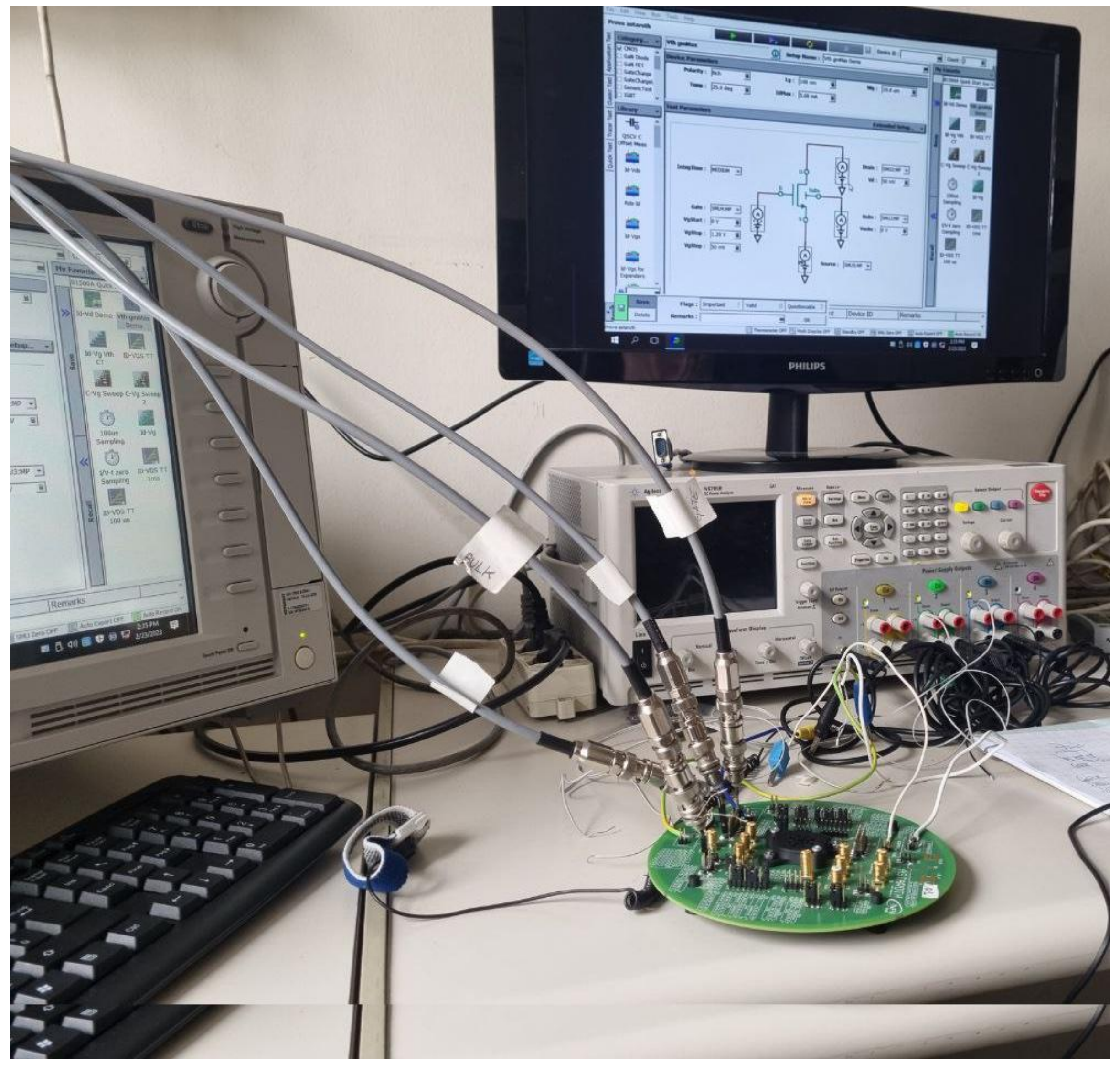


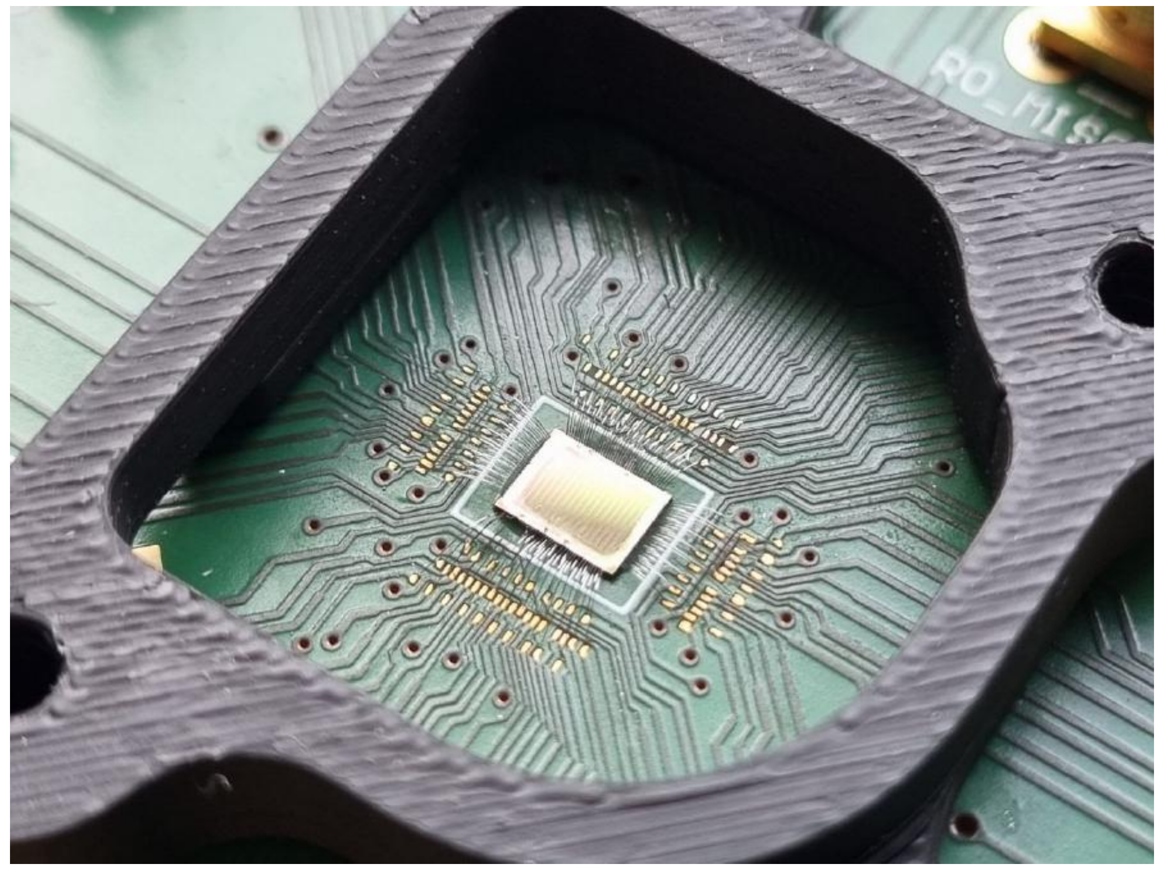
A <u>machine learning algorithm</u> fed with the charge map from (at least) three sides can discriminate surface events
A chip with this capabily working at crygenic temperature has an appeal that goes beyond ASTAROTH

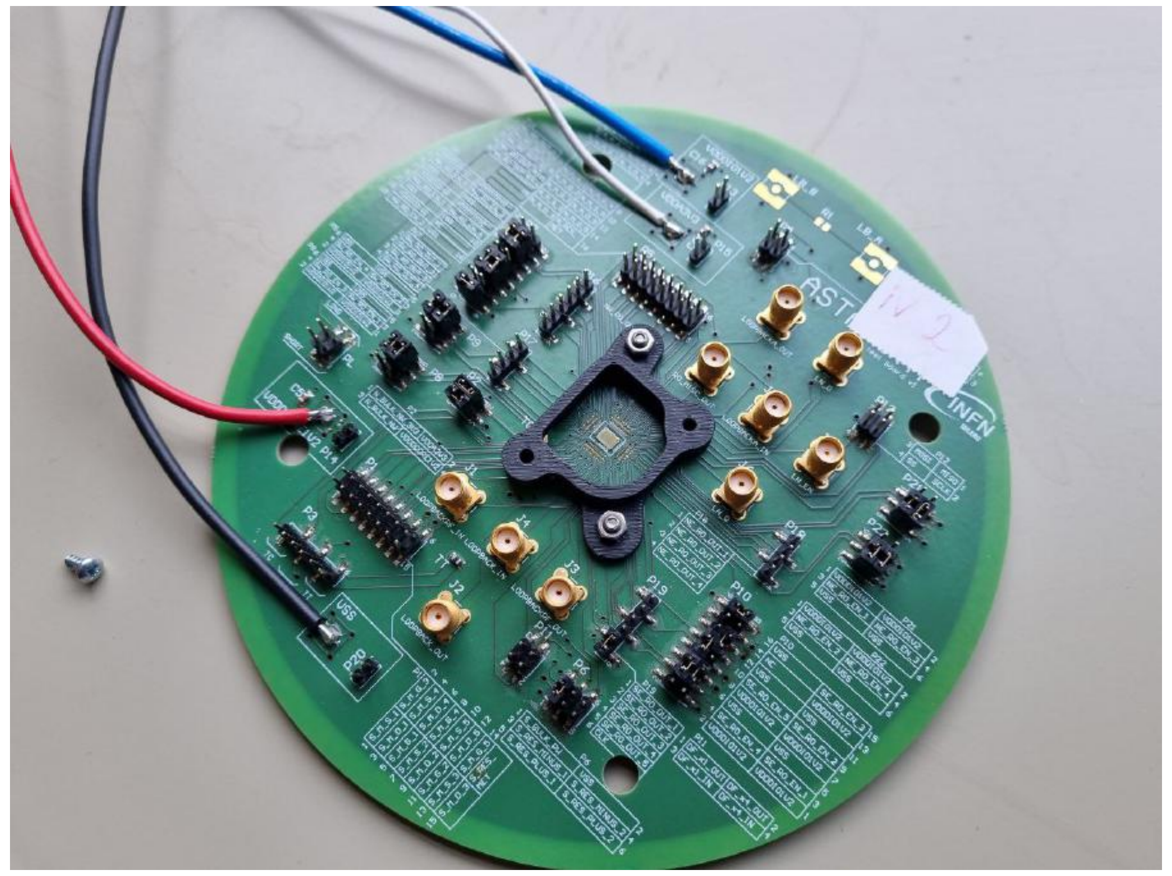
SiPM readout – ASIC technology test at cold

Working on **digital** ASIC:

- Designed a test chip based on Lfoundry CMOS 110nm tech for testing timing properties at (variable) cryogenic temperatures.
- First tested at room T and LN2
- Tested in ASTAROTH cryostat at LASA
    - Temperature range 80K -> RT
- This work is of interest by itself for IC community -> publication in progress
- Final Goal: ASIC with digital map of the light in the array





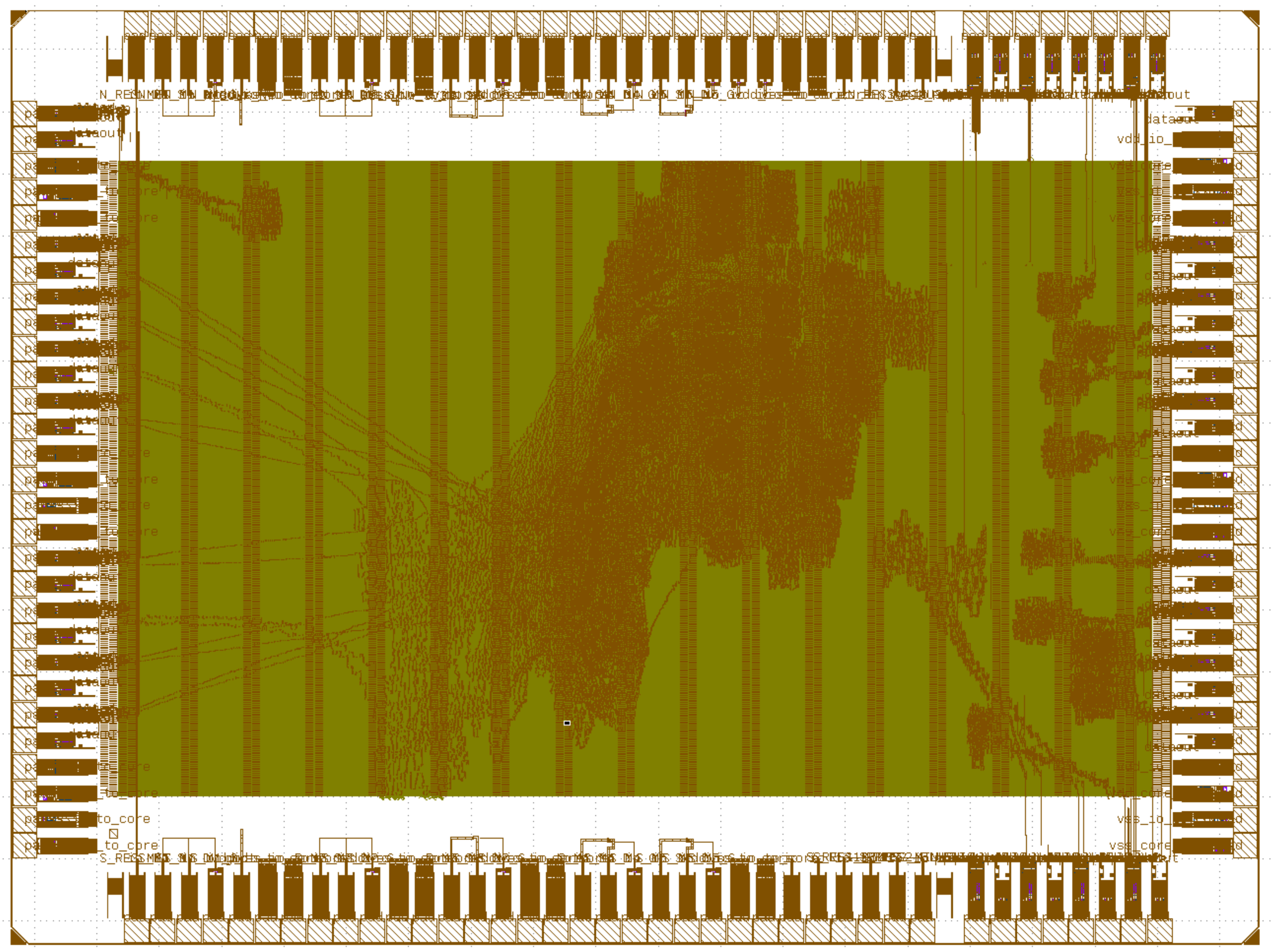


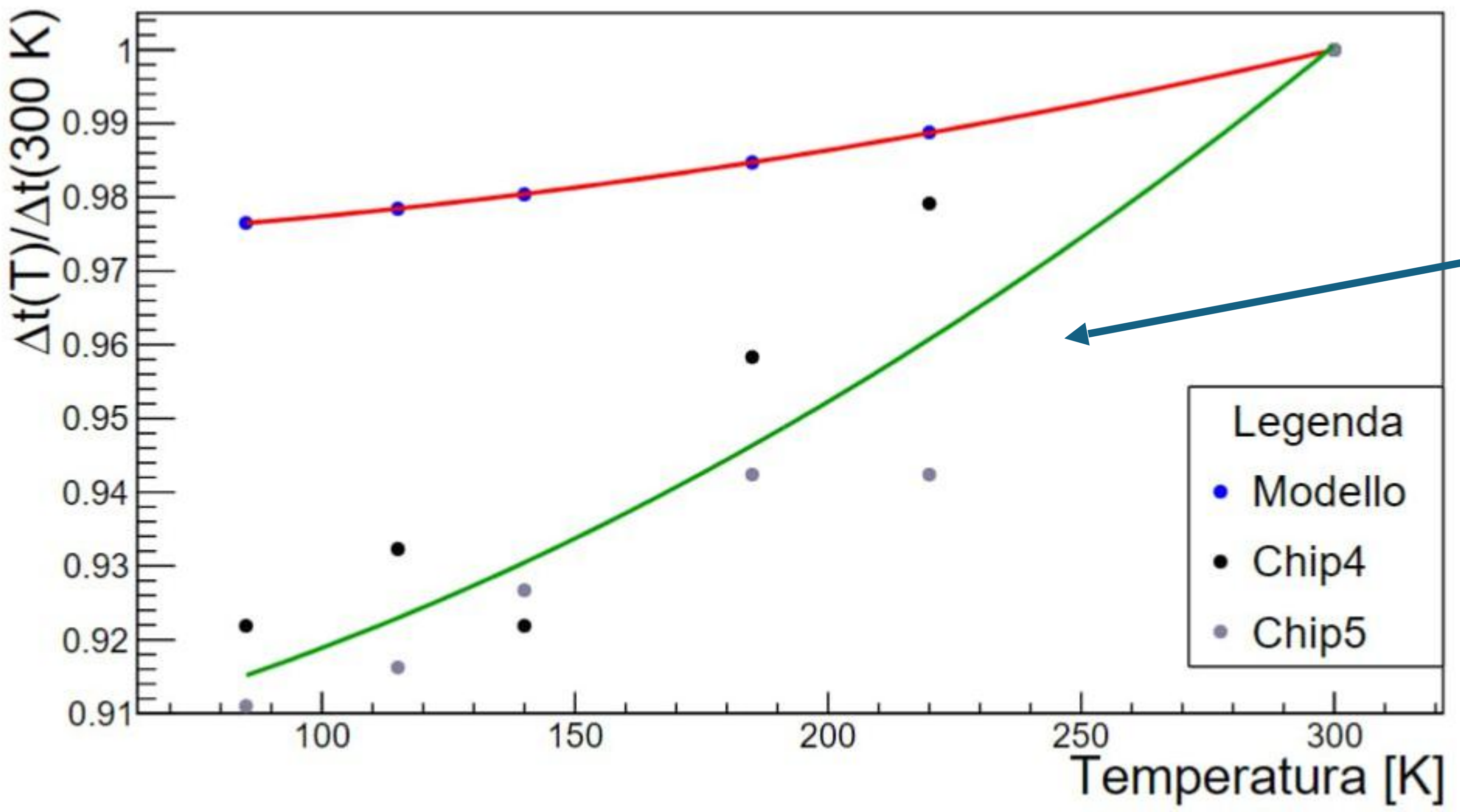
(V. Liberali, A. Stabile, L. Frontini, V. Trabattoni)

Chip ASTAROTH

Andreani A., et al, "Modelling and Verification of MOS Transistors at Cryogenic Temperature", 2023 12th International Conference on Modern Circuits and Systems Technologies (MOCAST)

2023





Context:

- Use of MOS transistors in cryogenic detectors to minimize spurious signals.

Objectives:

- Develop a simple model to simulate MOS transistors at cryogenic temperatures.
- Validate the model through measurements on a test chip fabricated in 110 nm CMOS technology.

Main Effects at Low Temperature:

- **Threshold Voltage Increase**: Proportional to the temperature drop from room temperature.
- **Carrier Mobility Increase**: Results in higher drain current when the transistor is on.
- **Resistance Reduction**: Material-dependent effect.

Methodology:

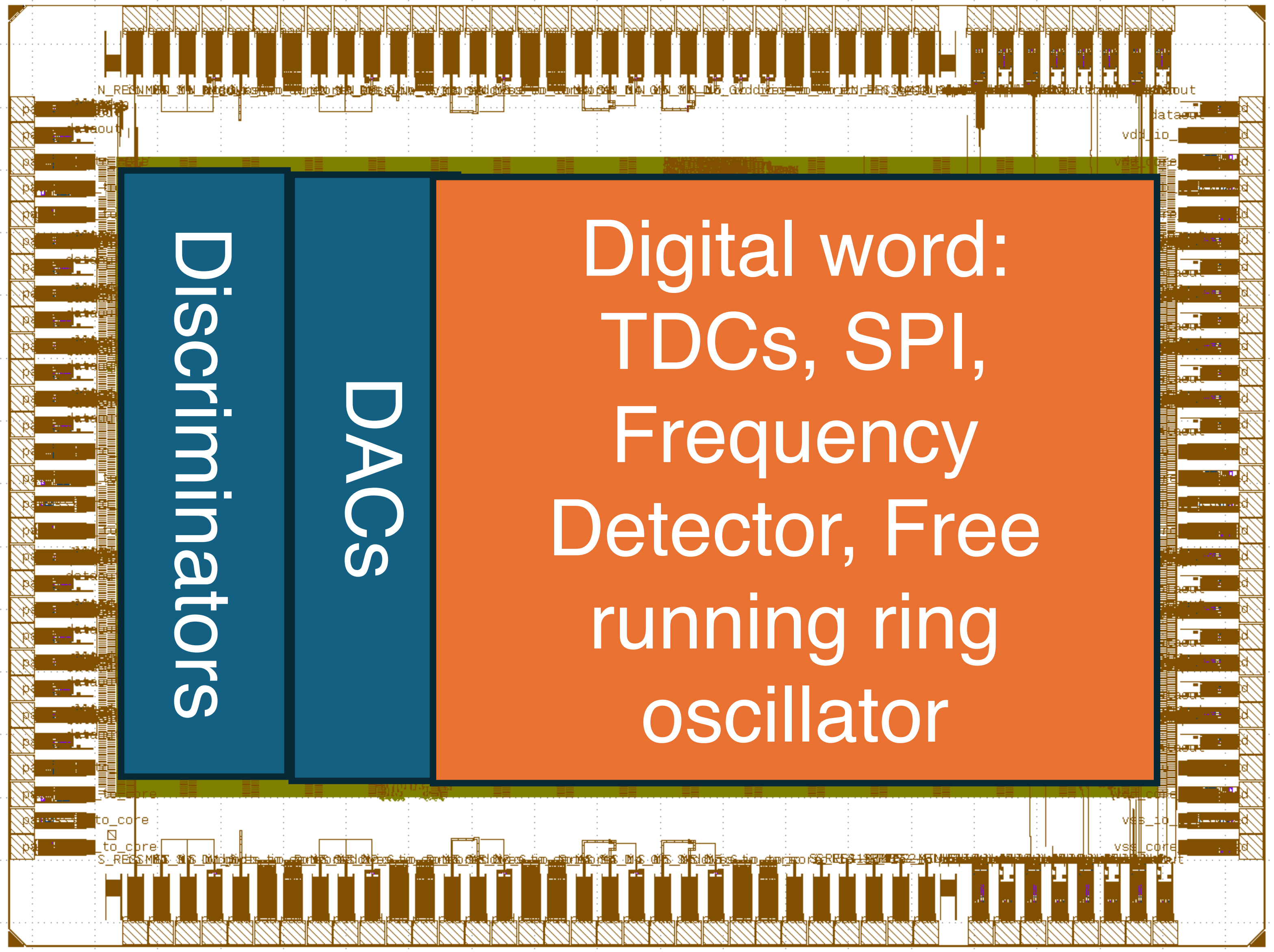
- Test chip with ring oscillators and single transistors
- Simulations conducted with Synopsys Custom Compiler and HSPICE.
- Measurements confirmed a frequency increase (~10%) from 300 K to 77

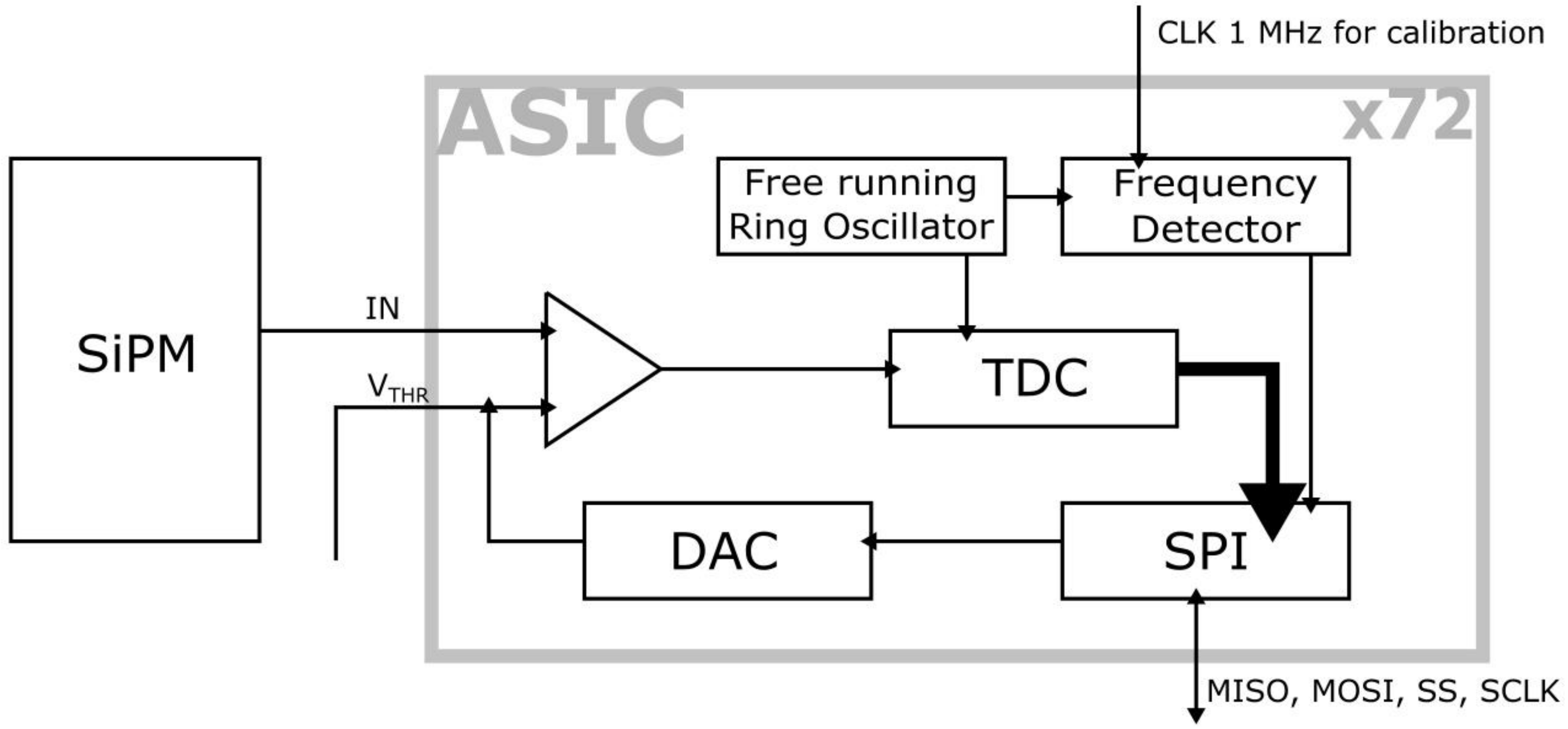
Conclusions:

- 110 nm CMOS technology is suitable for circuits operating at cryogenic temperatures.
- Developed model accurately predicts maximum operating frequency and power consumption at cryogenic temperatures [paper in preparation].

Chip ASTAROTH_BEYOND

2025





Up to 72 channels

Discriminator:

1. Programmable threshold tunable externally or internally (DAC)
2. Receives scintillation charge signals from a Silicon Photomultiplier (SiPM)

Clock Generation:

1. High-frequency clock for the TDC generated by a Digital Ring Oscillator (DRO)

Mixed-Signal Design:

1. Combines digital (SPI, DRO, counters) and analog/mixed components (discriminators, DAC)
2. Digital parts are implemented using standard cells and EDA software
3. Automatic placement and routing (Place & Route)

Silicon-proof:

1. SPI interface, Digital Ring Oscillator (DRO), and simple counters are silicon-proven from the previous Astaroth chip

Control and Data Management:

1. SPI interface
2. Due to low event frequency (<< 1 kHz), output data will be stored in SPI registers to obtain a charge map

Raw resolution

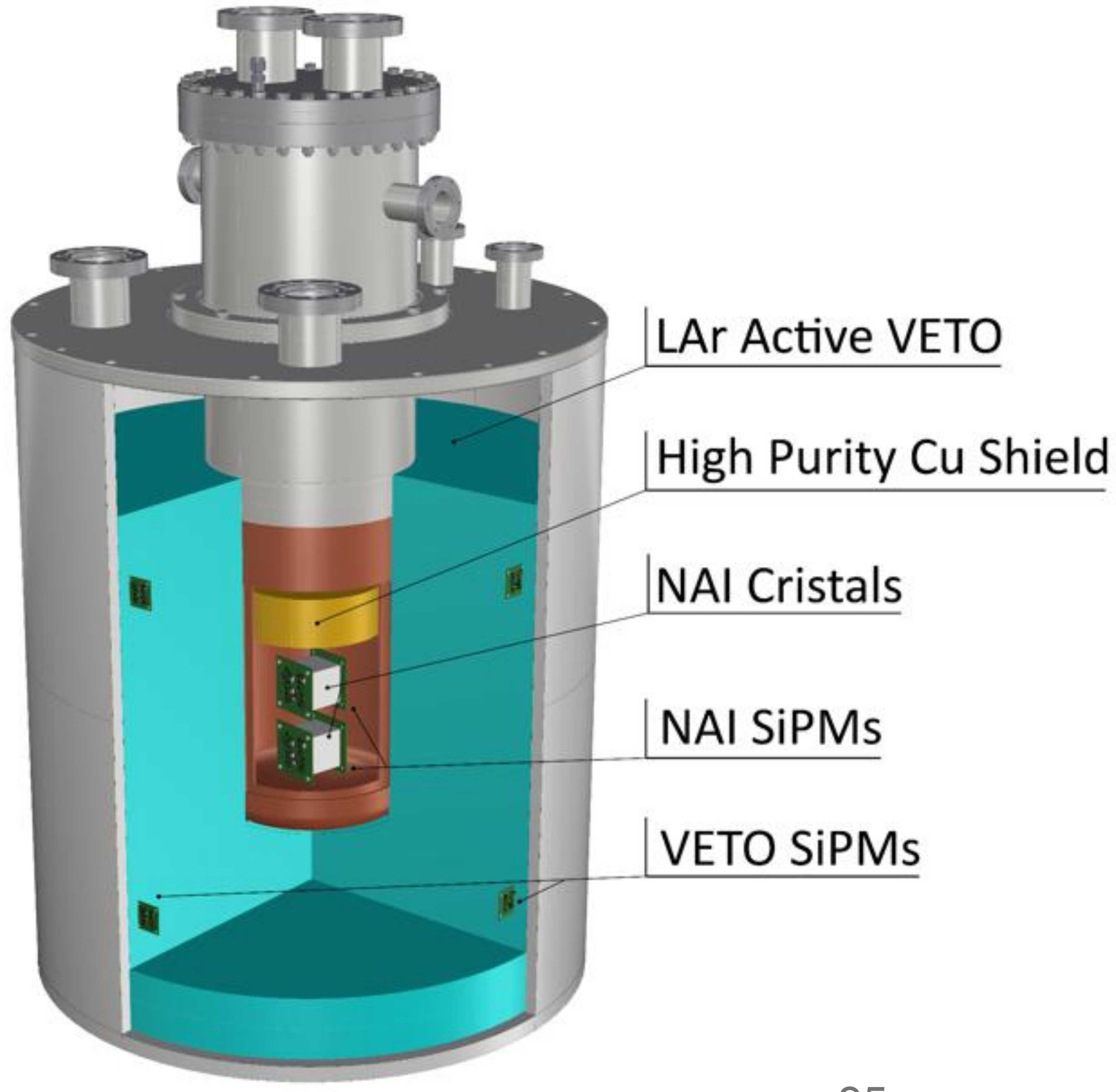
1. To discriminate for 1 to 2 photons a minimum resolution of ns is needed
2. ASIC designers have a strong experience in timing ASIC design: IGNITE < 50 ps

Cryostat and Veto

ASTAROTH accomplished:
cryostat operated multiple times
Temperature stable < 0.1K !!!

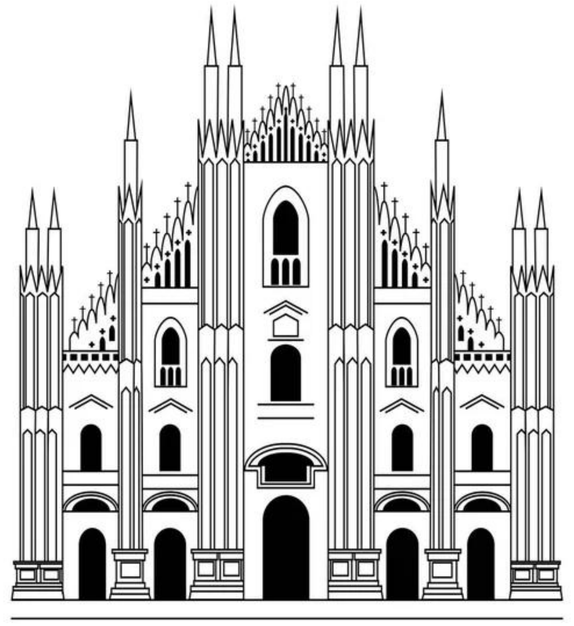
ASTAROTH_BEYOND goal:
- Suppress external backgr:
  LAr veto + SiPM

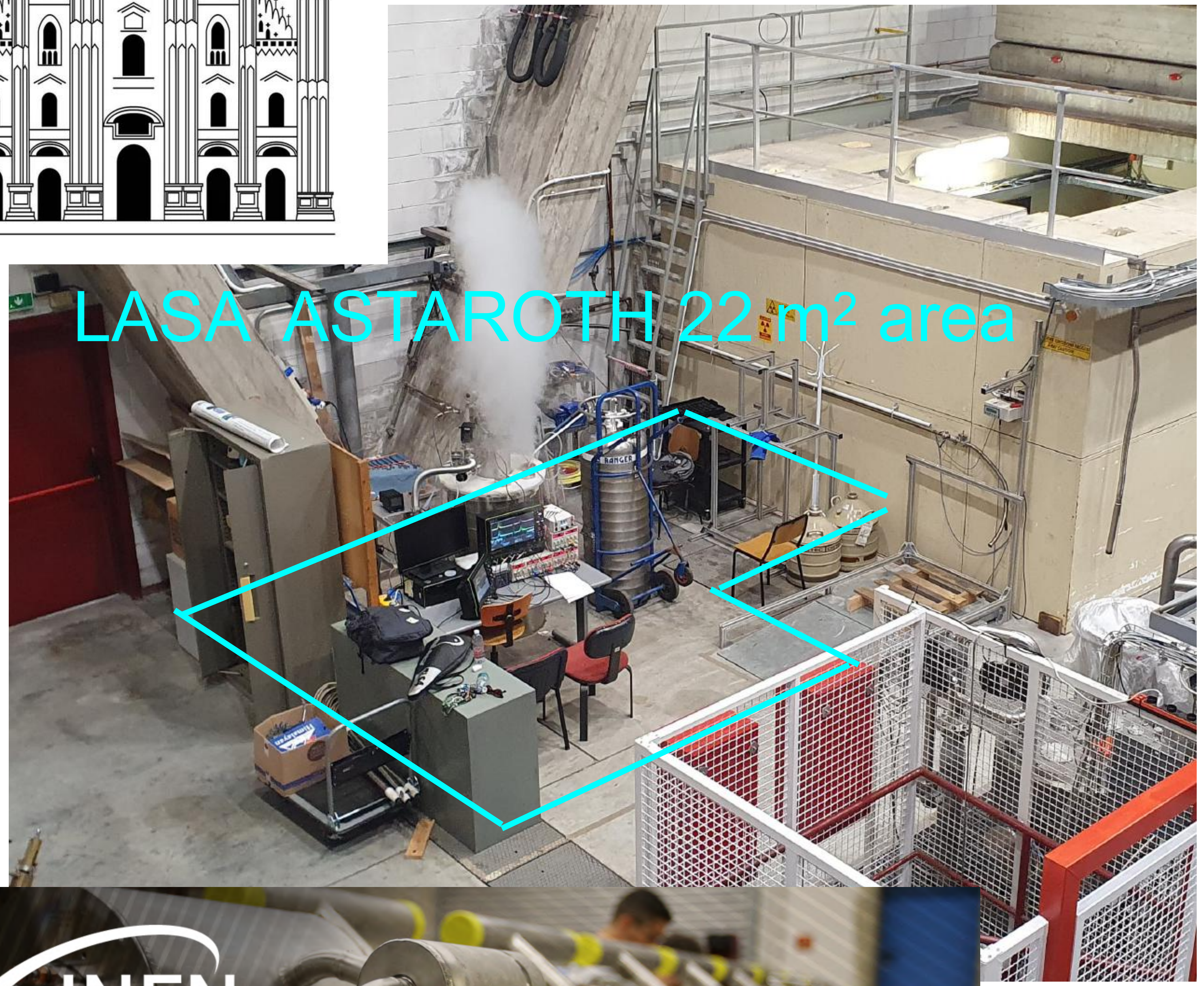
- Switch LN_2 to LAr
- instrument outer volume with SiPM

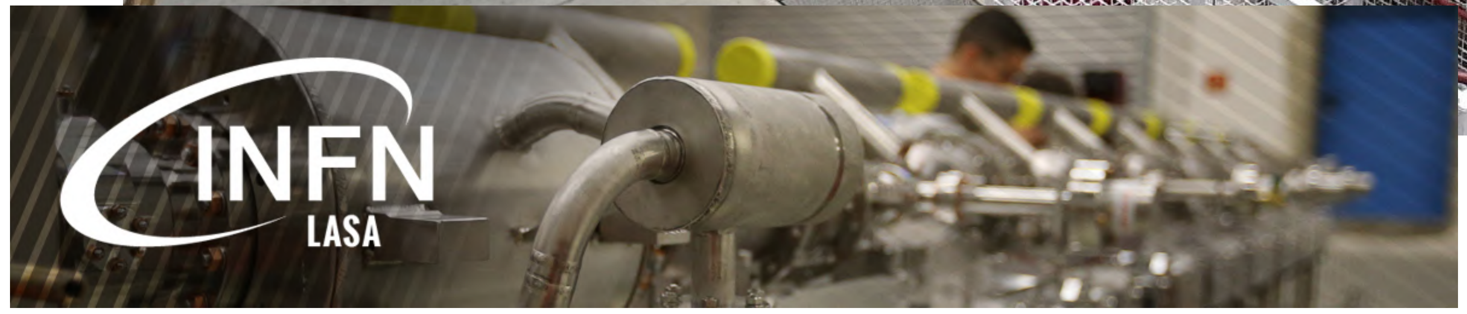


Final underground run (2027)

Muon disruptive interactions in the crystal can last a few minutes (!)
Final year ASTAROTH will go **underground** at LNGS (10^6 less muons)
Letter of interest of the SABRE-North collaboration, having discussed with LNGS director







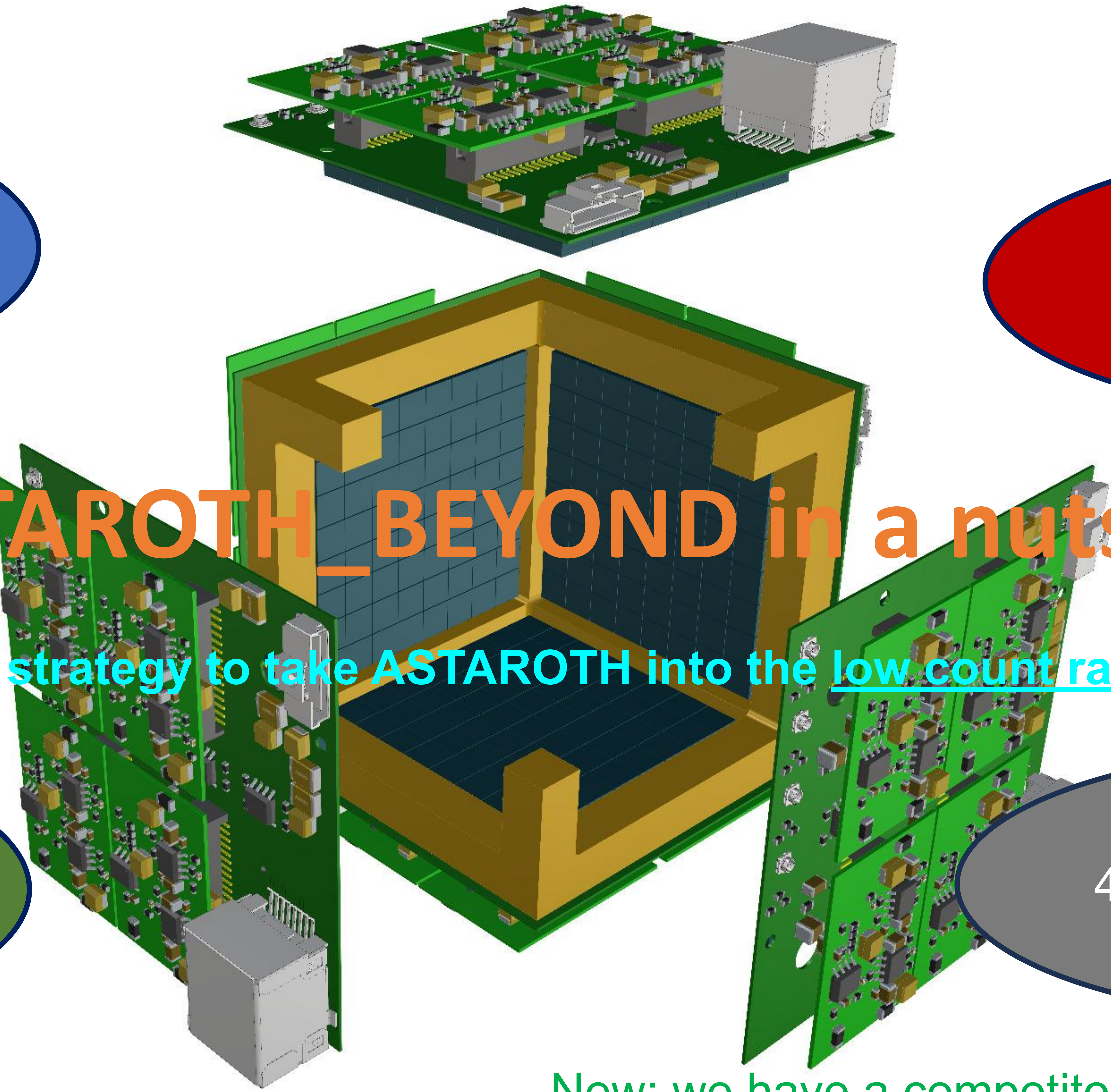
Low muon rate:
Go to LNGS
(last year)

Financed by INFN-CSNV

ASTAROTH (2020-2024) concluded in 2024
ASTAROTH_BEYOND (2025-2027) **approved!**

ASTAROTH_BEYOND in a nutshell

A 4-way strategy to take ASTAROTH into the low count rate domain



1. Maximize light collection
2. Low radioactivity ASIC-based electronics to reject surface background
3. Veto external backgr
4. Run Underground

New: we have a competitors: ANAIS+ (Spain)
ASTAROTH and ANAIS+ were given talks back-to-back at IDM2024, L'aquila July 2024