

CAST EXPERIMENT

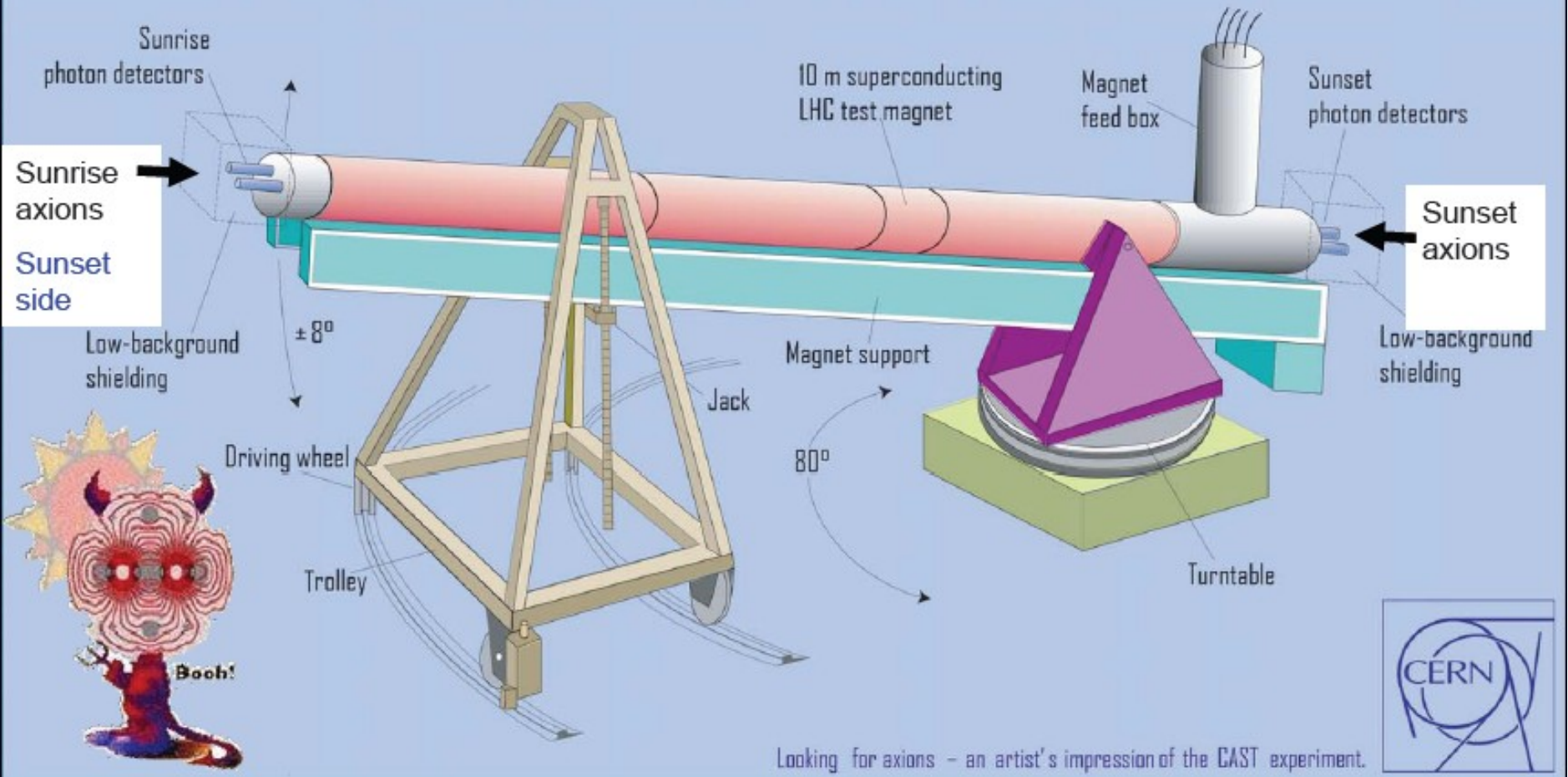
Martyn DAVENPORT – General

Jaime RUZ - 3He System

Theodoros VAFEIADIS - Micromegas

Nom CAST ?

Cern Axion Solar Telescope



Pourquoi Axion?

The Strong CP Problem

QCD predicts that CP (and T) symmetry is broken in strong interactions

This is never observed in experiments !

	Symmetry Conservation		
	C	P	CP
Electromagn.	Yes	Yes	Yes
Strong	Yes	Yes	Yes
Weak	No	No	No

Example: Violation of CP symmetry \implies electric dipole moment of the neutron

Prediction:

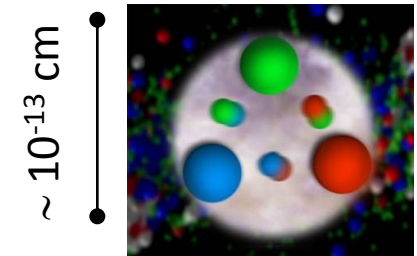
$$|d_n| < \bar{\Theta} \cdot 10^{-16} e \text{ cm}$$

Present experimental limit: $|d_n| < 10^{-25} e \text{ cm} < 10^{-26} \text{ (2011)}$

Difference of a factor of $\bar{\Theta} = 10^{-9}$ between theory and experiment !

A possible solution:

Exclude all CP violating terms in QCD Lagrangian density by introducing a new component.



Axion

- Peccei-Quinn (theoreticians) a propose d'ajouter un 'Champ'/symmetry additionnel dans model standard de QCD pour résoudre le problème

- Effectuer une cancellation précise
- Force/Champ → particule associe
 - Strong → Gluons
 - Electromagnétique → photons, e.m. radiation
 - Weak/Faible → W, Z bosons
 - Gravite → Gravitons

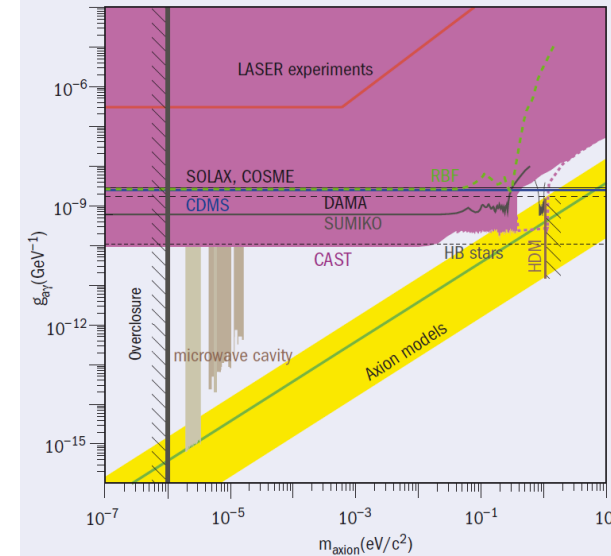
➤ Peccei-Quinn symmetry → **Axions**

- Quel sont les propriétés d'Axion hypothétique?

- Mass/poids **inconnu**
- Puissance d'interaction avec matière **inconnu**
- Relation mass/puissance d'interaction **définie une bande**
 - Le plus massive l'axion,
 - le plus puissant est l'interaction avec matière



Fort



- Si ils sont si léger et il n'interact presque pas avec la matière ...

- Pourquoi l'intéresse?

- Preuve que la solution P-Q est valide (questionne fundamental)
- Axion est une bonne candidate pour la matière noir/dark matter



Lourd

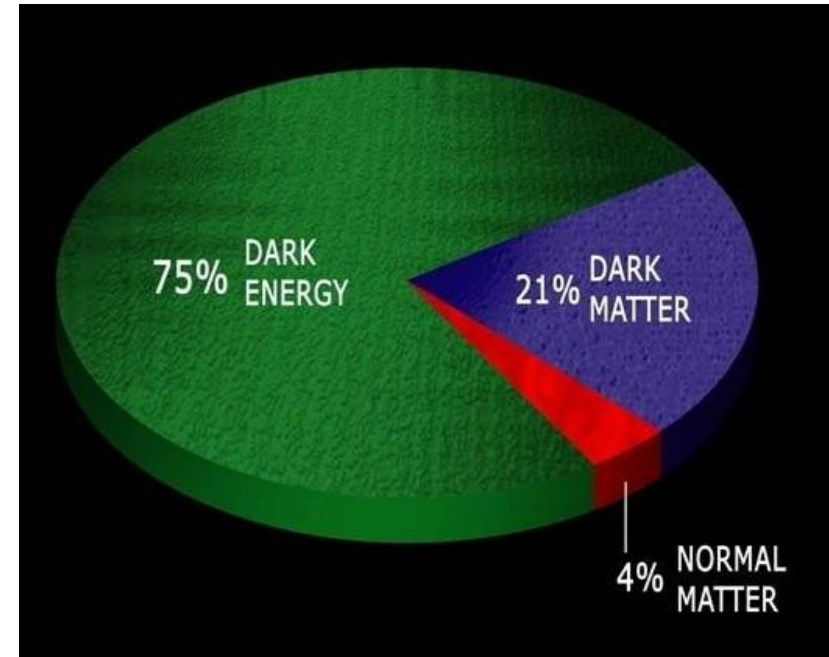
Axions sont peut-etre.... tout ou une partie de la matiere noir (dark matter) dans le universe

- S'ils existent.....

- ❑ Ils ont été crée juste après le big bang
- ❑ Ils sont distribue partout dans le univers
- ❑ Leur longueur de vie est \sim l'age de la univers
- ❑ 'Cold Dark matter' – qui a forme les galaxies

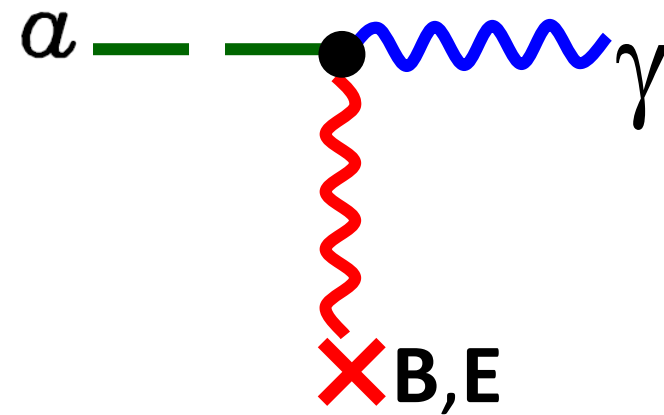
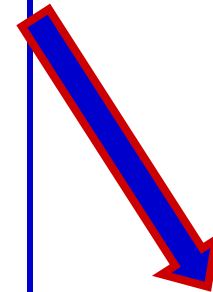
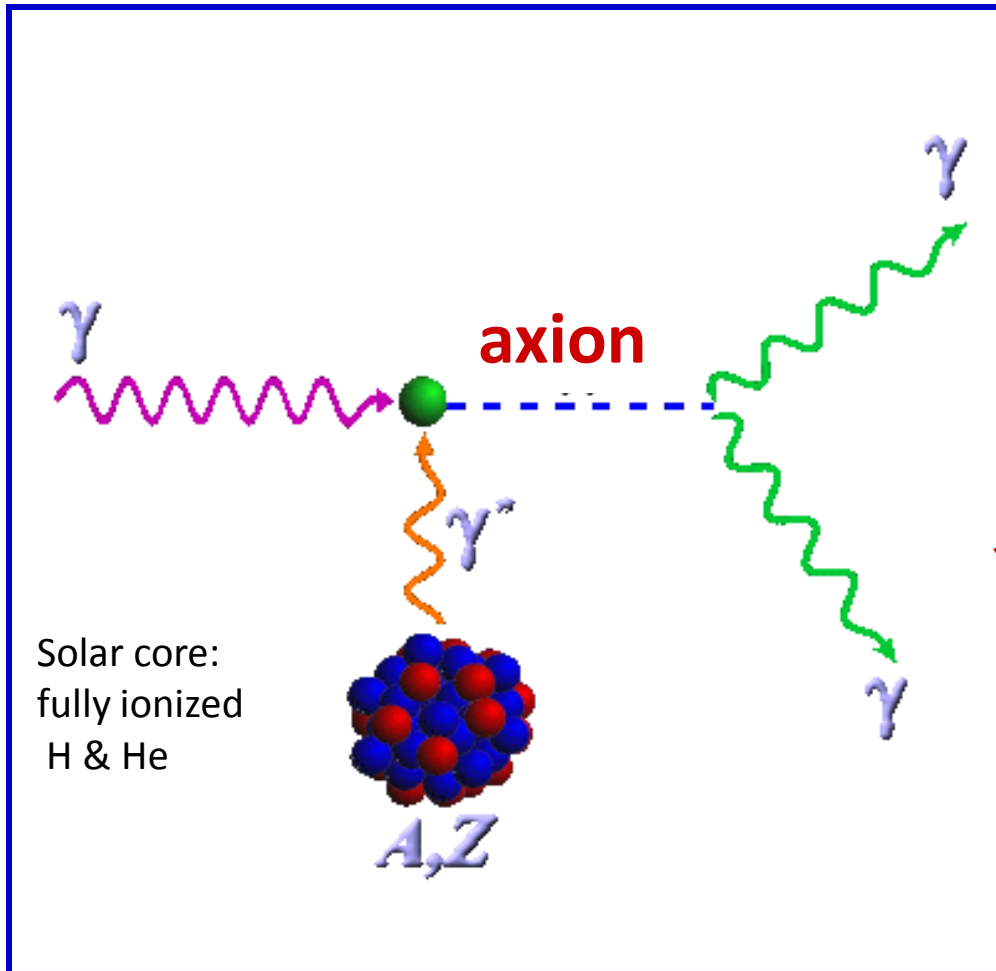
- Mais aussi

- ❑ Ils sont crée tout le temps dans les étoiles
- ❑ Notre Soleil devrait produire une énorme quantité en continue
 - Dans le noyau du soleil (centrale 10% ...temperature 10 million °K)
- ❑ Et le soleil n'est pas loin
- ❑ CAST vise le soleil pour essayer de détecter les axions



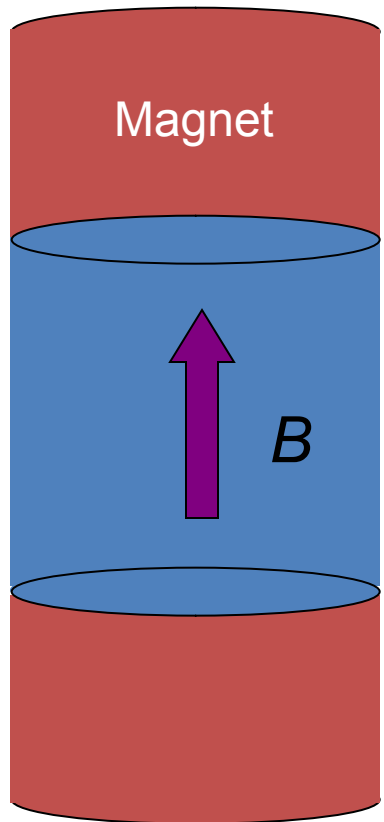
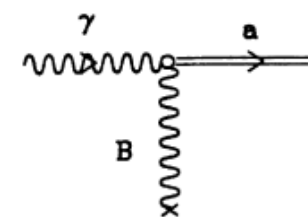
The Primakoff Effect 1951

H. Primakoff

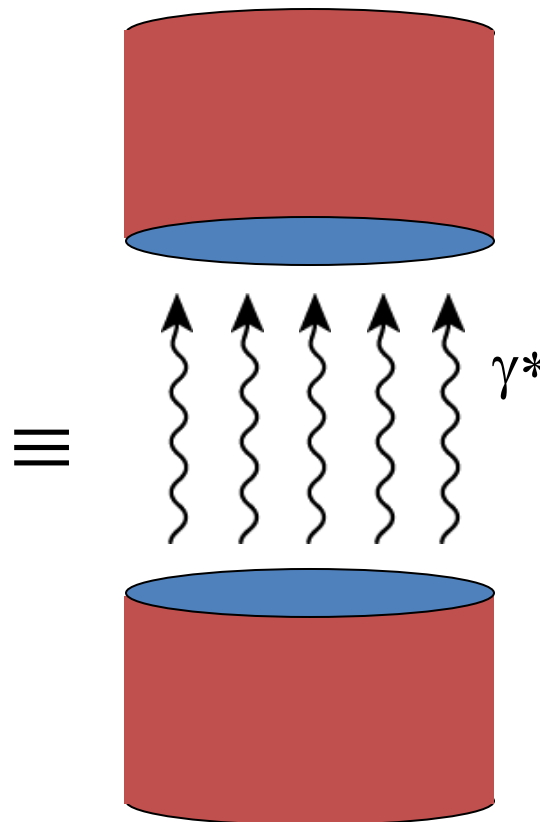


Behind all present axion work!

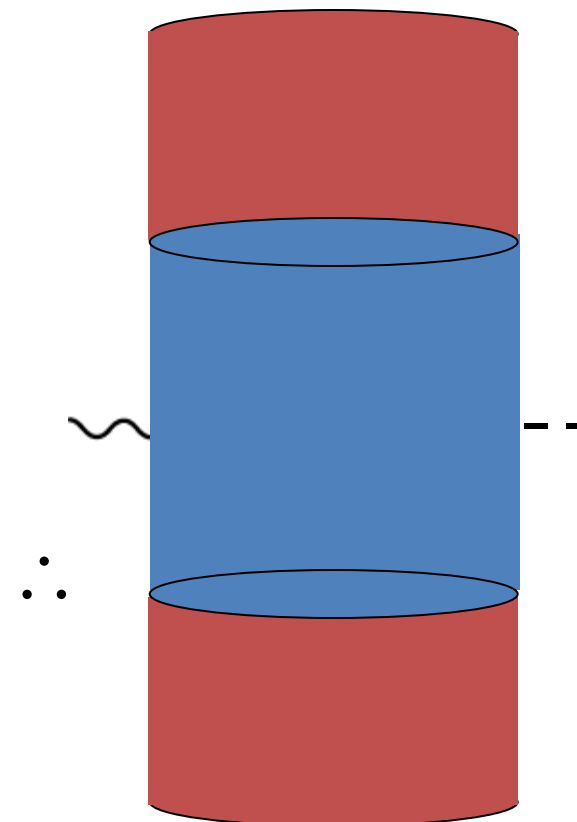
The Primakoff Effect



Classical EM field



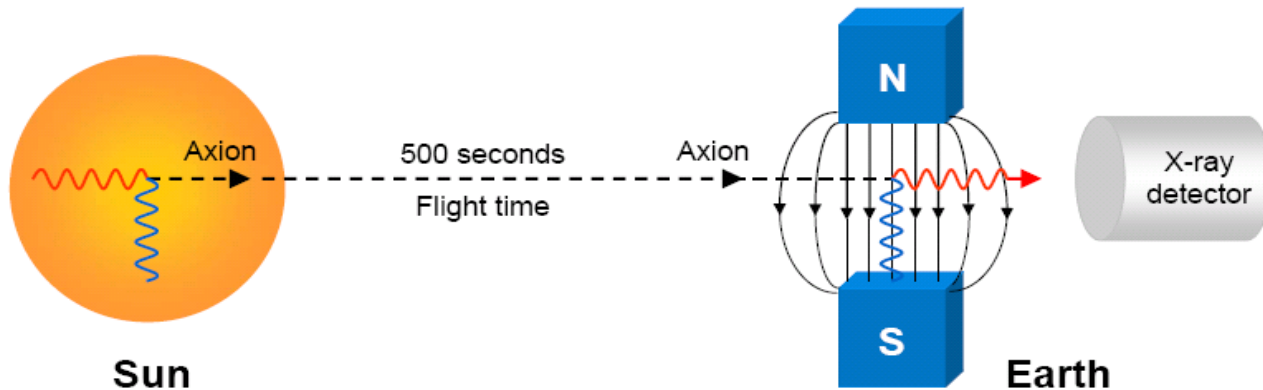
Sea of virtual photons



Primakoff Effect

CERN Axion Solar Telescope:

QCD Axions or other similar exotica → WISPs

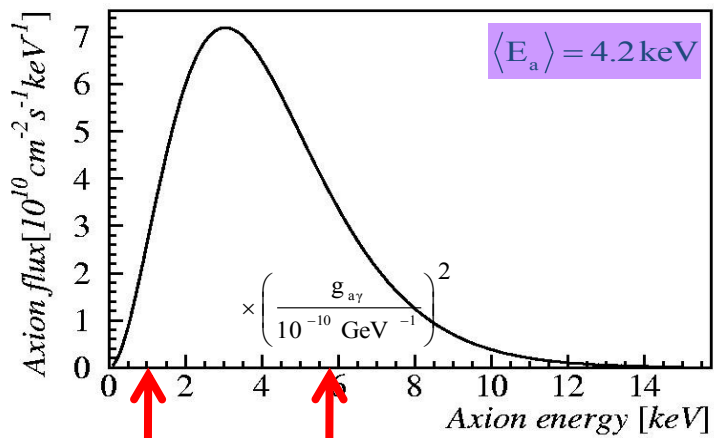


Signal: **excess** of X-rays during alignment over background

Production: Primakoff effect
Thermal photons ($T = 10^8 \text{ K} = \text{keV} = \text{xrays}$) interacting with solar nuclei produce Axions

Detection Inverse Primakoff: axion interacting with a very strong magnetic field converts to a photon

Differential axion flux on Earth



Absorption
15μm PP

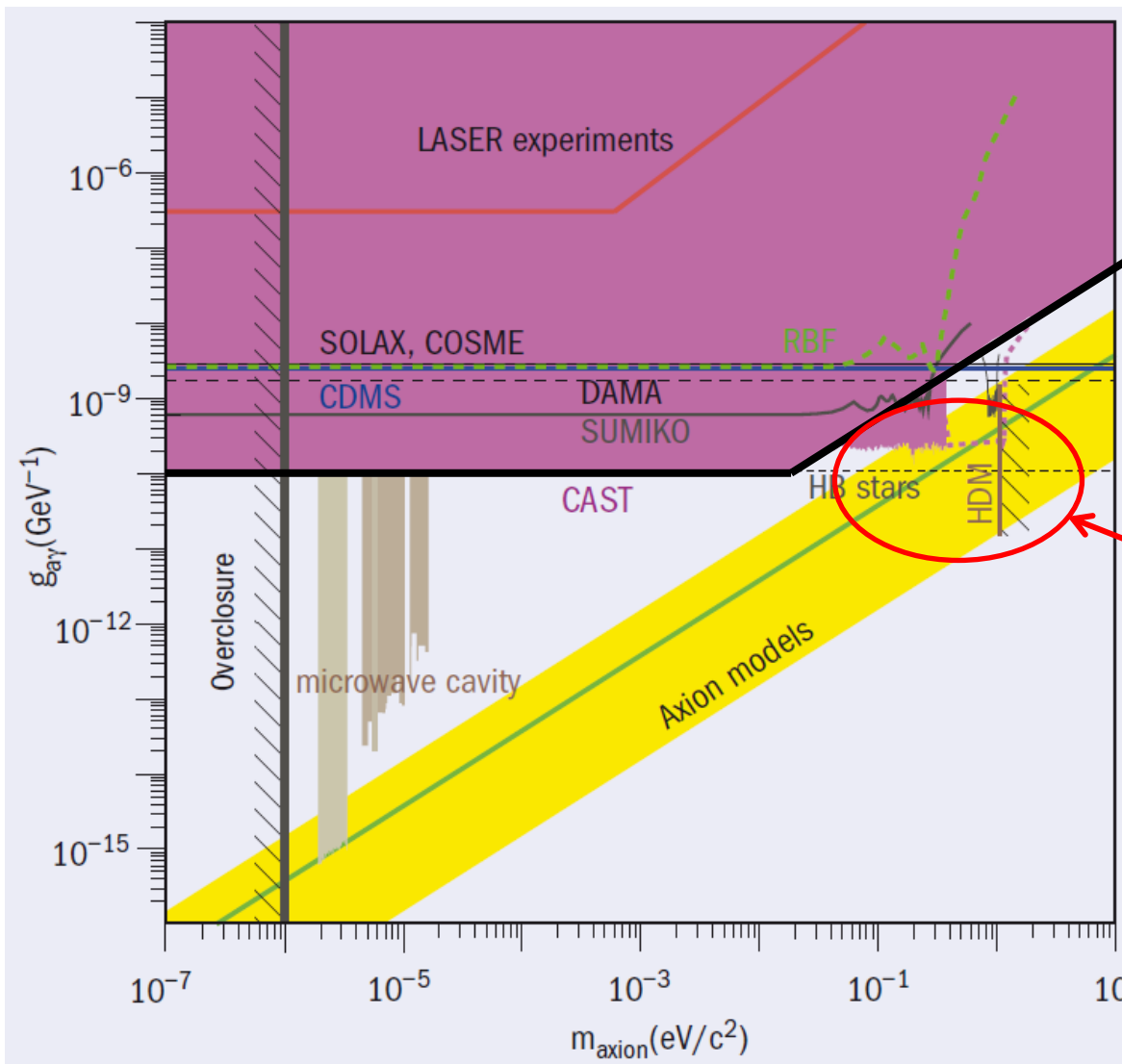
Source Fe55

Expected number of Photons:

$$N_{\gamma} = \int \frac{d\Phi_a}{dE_a} \cdot P_{a \rightarrow \gamma} \cdot S \cdot t \cdot dE_a$$

$$P_{a \rightarrow \gamma} \approx 1.7 \times 10^{-17}$$

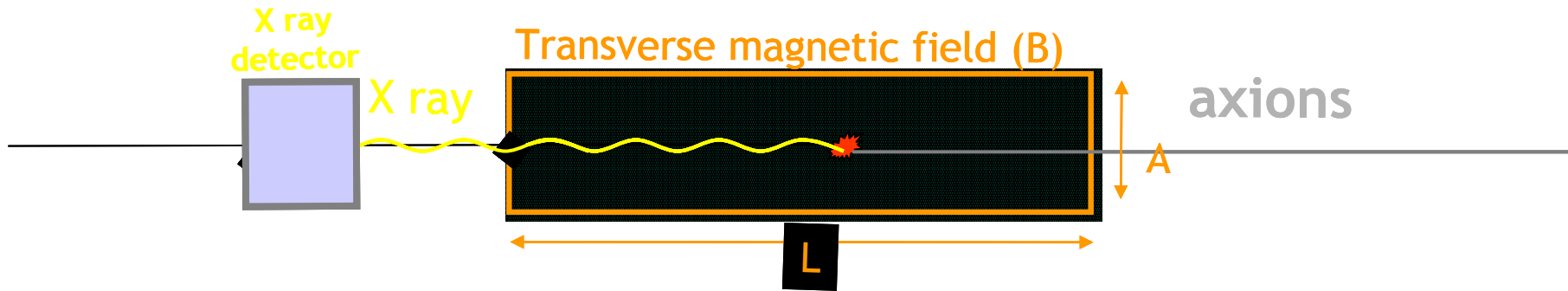
$$\Phi_{\gamma} = 0.51 \text{ cm}^{-2} \text{ d}^{-1} g_{10}^4 \left(\frac{L}{9.26 \text{ m}} \right)^2 \left(\frac{B}{9.0 \text{ T}} \right)^2$$



Limite
vide/vacuum

Comment
entrer dans
le zone
intéressant?

CAST phase II – principle of detection $m_a > 0.02$ eV

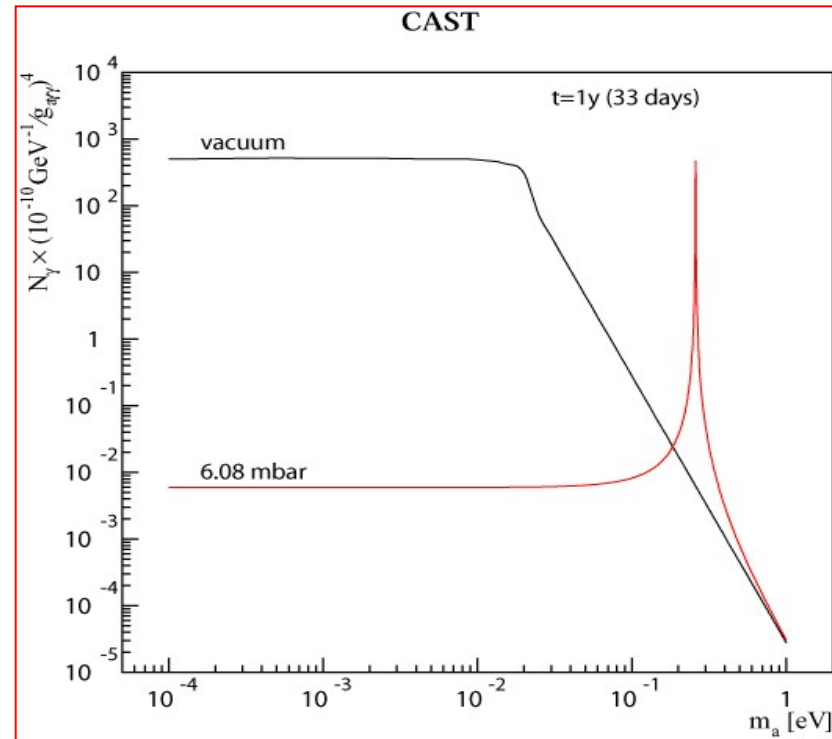


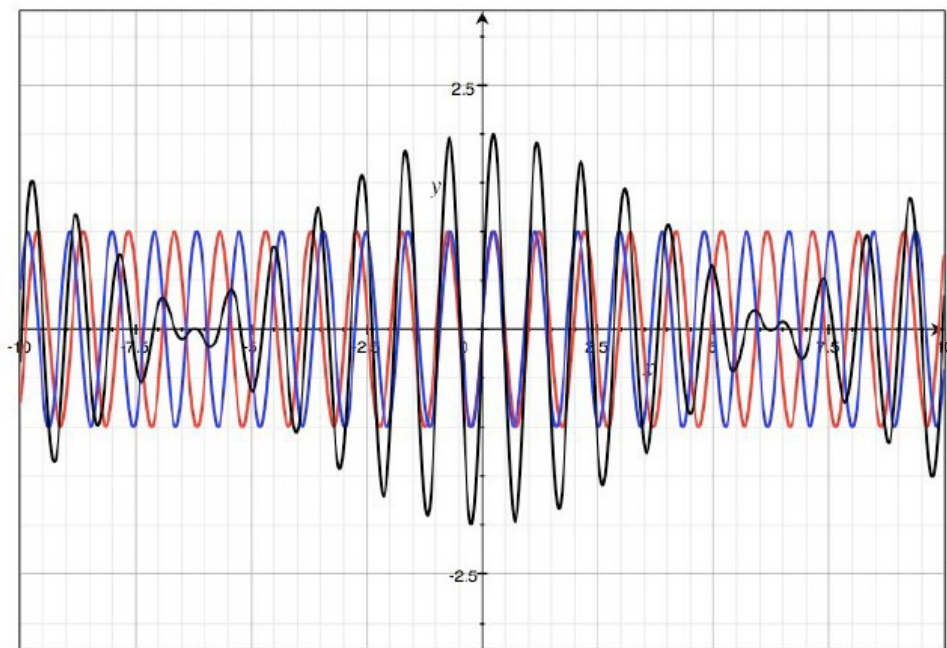
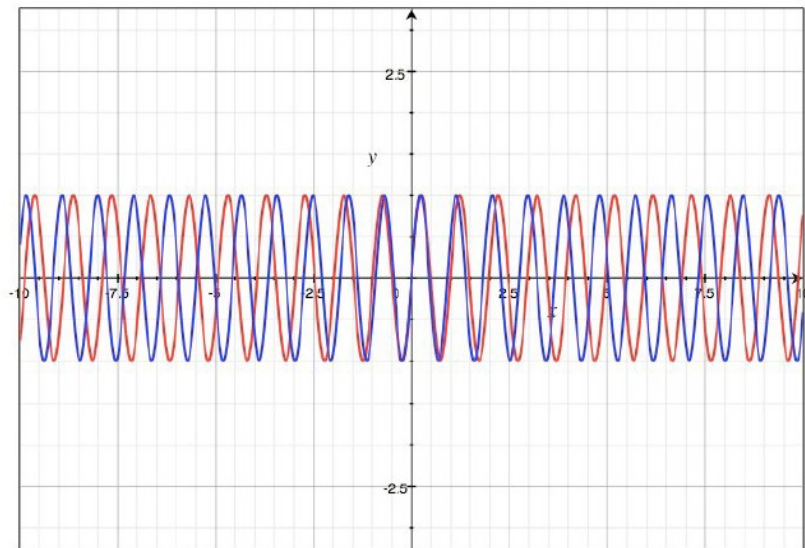
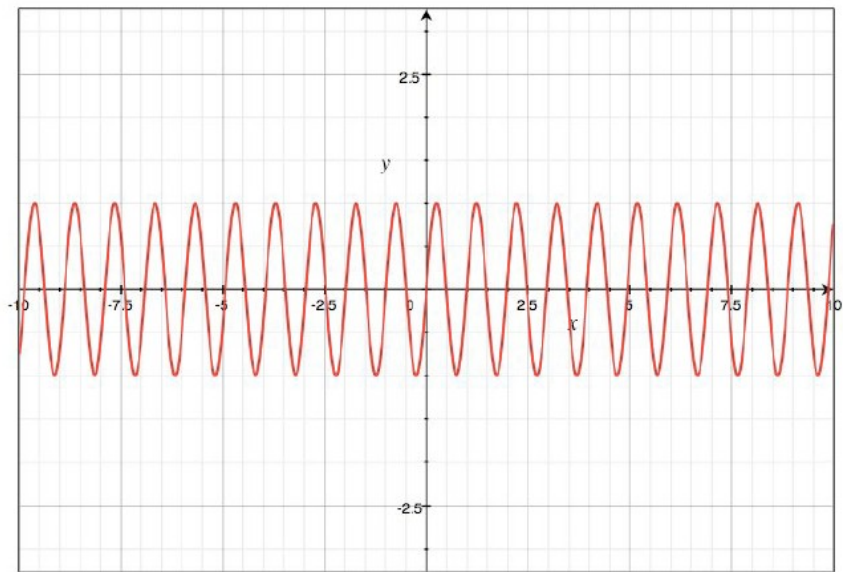
- Extending the coherence to higher axion masses...
- Coherence condition ($qL \ll 1$) is recovered for a narrow mass range around m_γ

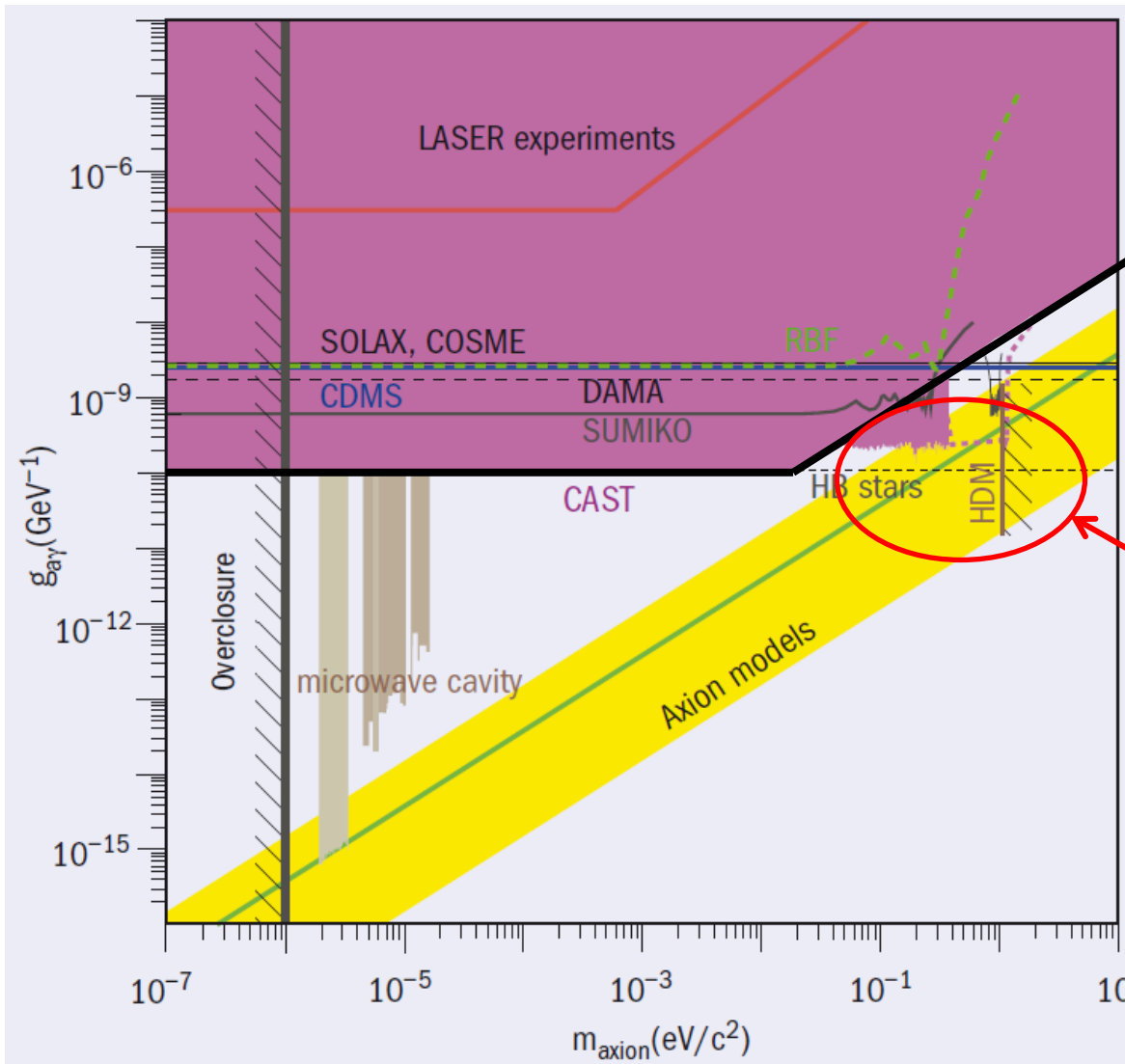
$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9 \sqrt{\frac{Z}{A} \rho} \text{ eV}$$

N_e : number of electrons/cm³
 ρ : gas density (g/cm³)





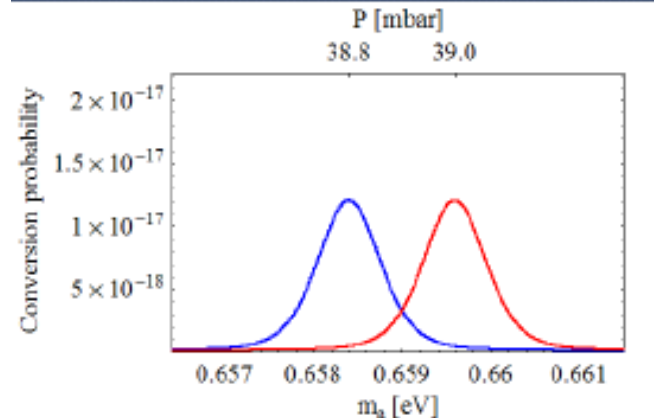
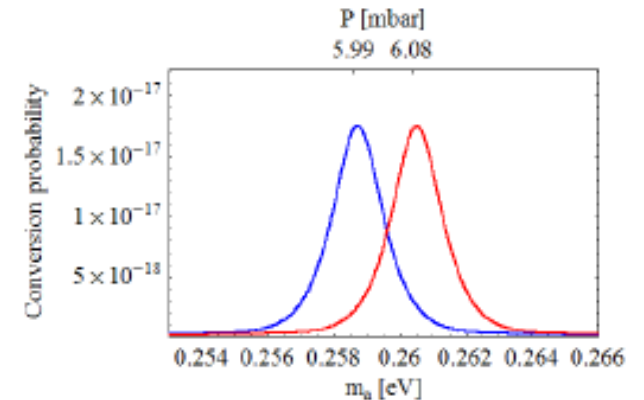


Limite vide/vacuum

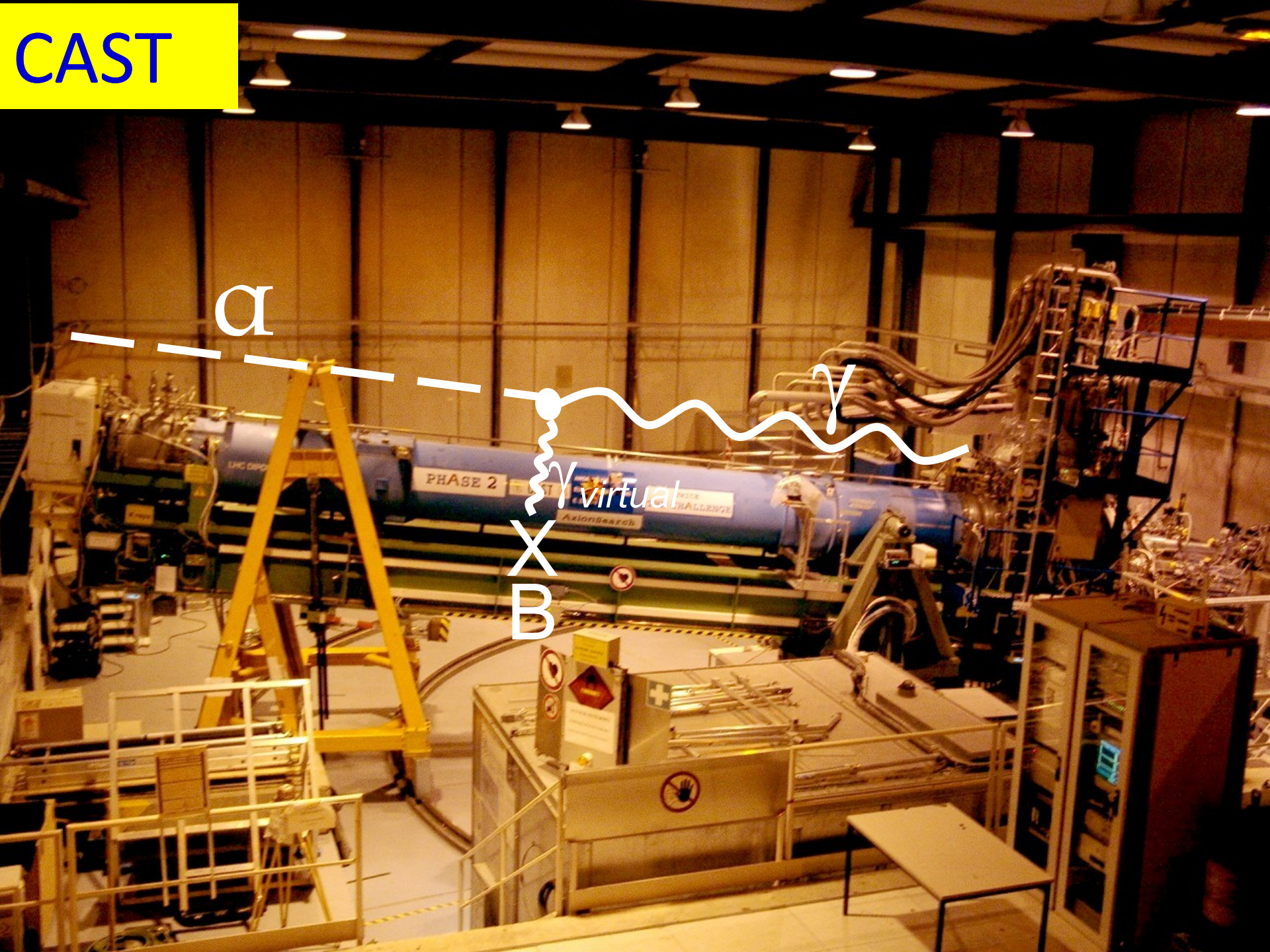
Comment entrer dans le zone intéressant favorable?

Comment entrer dans le zone intéressant?

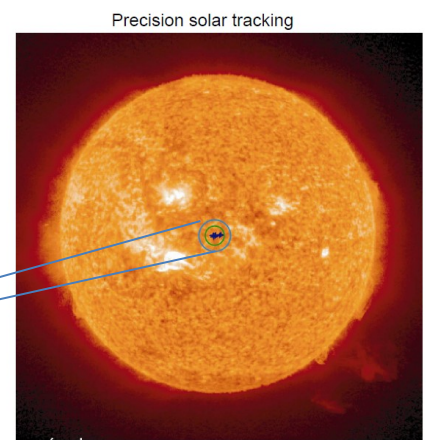
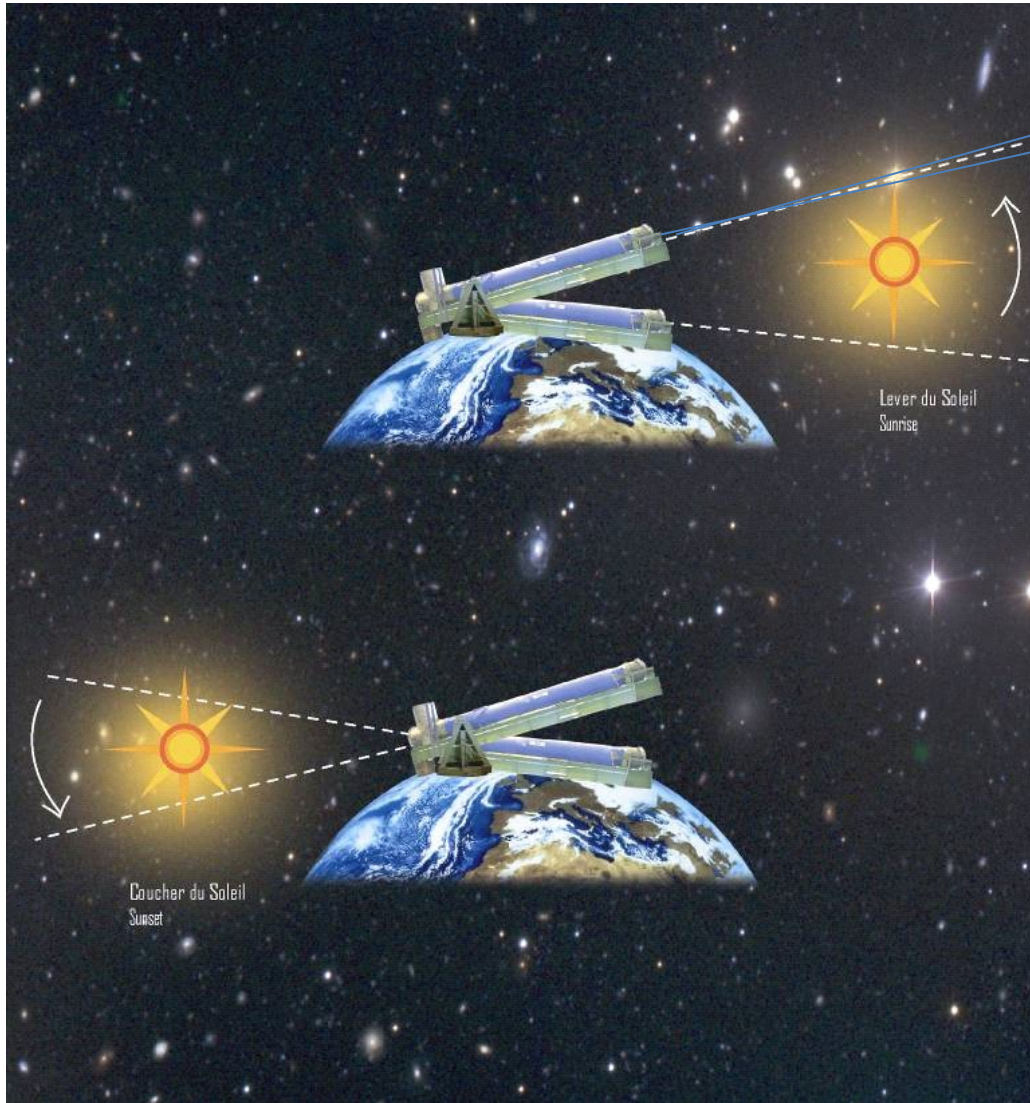
- On ne peut pas changer l'axion
- Mais on peut ralentir le photon
 - Ajouter un gaz – buffer
 - Le photon ralenti, comme la lumière en passant le verre.
 - Les ondes d'axion et photon sortant peuvent être superpose =coherence
 - Le longue d'aimant 9.3m
 - Grande enhancement de signal
 - **Mais**
 - **Cohérence seulement pour une petit gamme de mass.**
- Solution:
 - Balayage de ~ 1000 différent pressions dans le cold bore
 - Avec 'overlap' sure.
 - L'axion est très étroit – il peut tomber entre deux !
 - He system
 - Précise
 - Reproductible (retourner au pression suspect plus tard)
 - Densité homogène le longue d'aimant (pour garder le cohérence)
- Prise des données
 - Ajoute un quantité précise de gaz en plus:
 - Chaque jour (sunrise et sunset voir même pression)
 - Avec du temps et expérience (e manque du temps) – accélérer !



CAST



1. CAST est un HELIOSCOPE. Il suit la course du soleil
terreCAST.ai



Calcul de la position du Soleil toutes les minutes, précision de 0.01 degré - environ 1h30 le matin et 1h30 le soir – Etude du bruit de fond le reste de la journée

CAST EXPERIMENT

- CAST Proposed in 1999
- Magnet
 - ❑ 10m prototype ???? Number? (Ask L Walckiers)
- Helioscope
 - ❑ Design C Rosset PH
 - ❑ Chariot & Turntable & Rails PYLON-GREECE
 - ❑ Mechanics D Rotil
- Experiment
 - ❑ Installation 2001 & 2002
 - ❑ Cryo – recovered from DELPHI
- Surveyed & tracking program 2002
- First runs
 - ❑ End of 2002
 - ❑ 1 detector – TPC
 - L Di Lella + TA1 A Placci

CAST Key points

1. Magnet must follow sun with angular precision of better than 3 mm/10m
 - ❑ X-ray telescope requirement
 - ❑ Over an area 15m horizontal and 2.5 m vertical
 - ❑ Survey GRIDs
 - ❑ Laser check points
 - ❑ Sun filming
2. Highest possible magnetic field
 - ❑ The rate of conversion of axions to X-rays is proportional to $B^2 (L^2)$
 - ❑ Means operating close to the quench limit of magnet
3. X-ray detectors must have highest efficiency & lowest background possible
 - ❑ No trigger
 - ❑ Need also good energy resolution to identify the axion solar energy spectrum
 - ❑ Must work when connected to a high vacuum
 - Intrinsically low background (MM)
 - Or, Enhance S/N by focusing X-rays to spot
4. Sensitive to the largest possible range of axion masses
 - ❑ Vacuum only 0.02 eV
 - ❑ Buffer gas (helium injected into cold bore at 1.8K)
 - ❑ Transparent windows to keep helium in cold bore and transmit soft x-rays.
 - ❑ Bake-outs to remove adsorbed gases

Solar tracking



“Close encounters” Accrochages



Bar en Alu

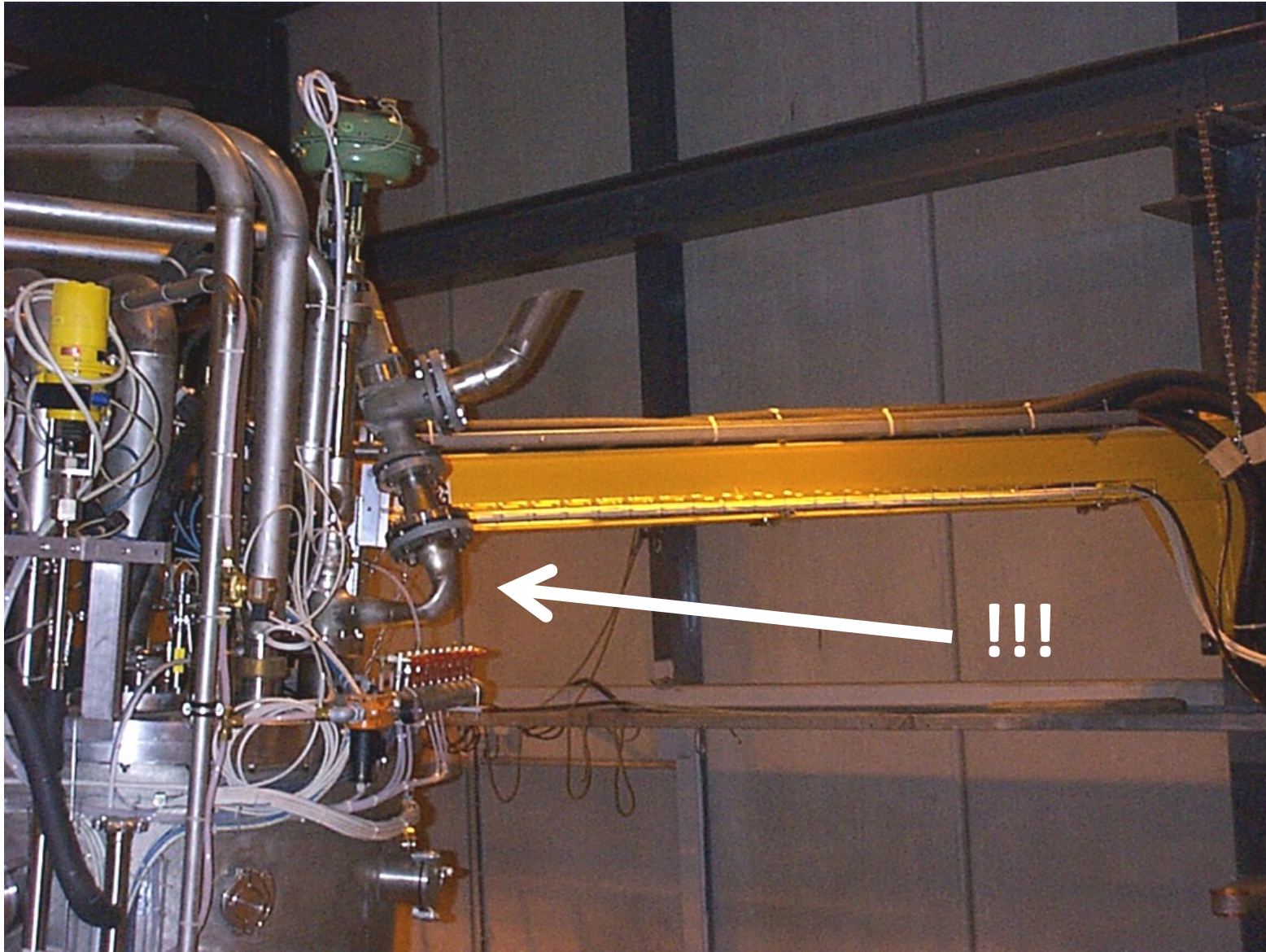
Oublie d'un CERN 'Trainee'

Trainee donne a CAST par Cryo-lab

'Close encounters'

Deplacement d'aimant par ordinateur tard le soir

.....quand on est tout seul et on est assisi dans la salle de controle !



Tracking

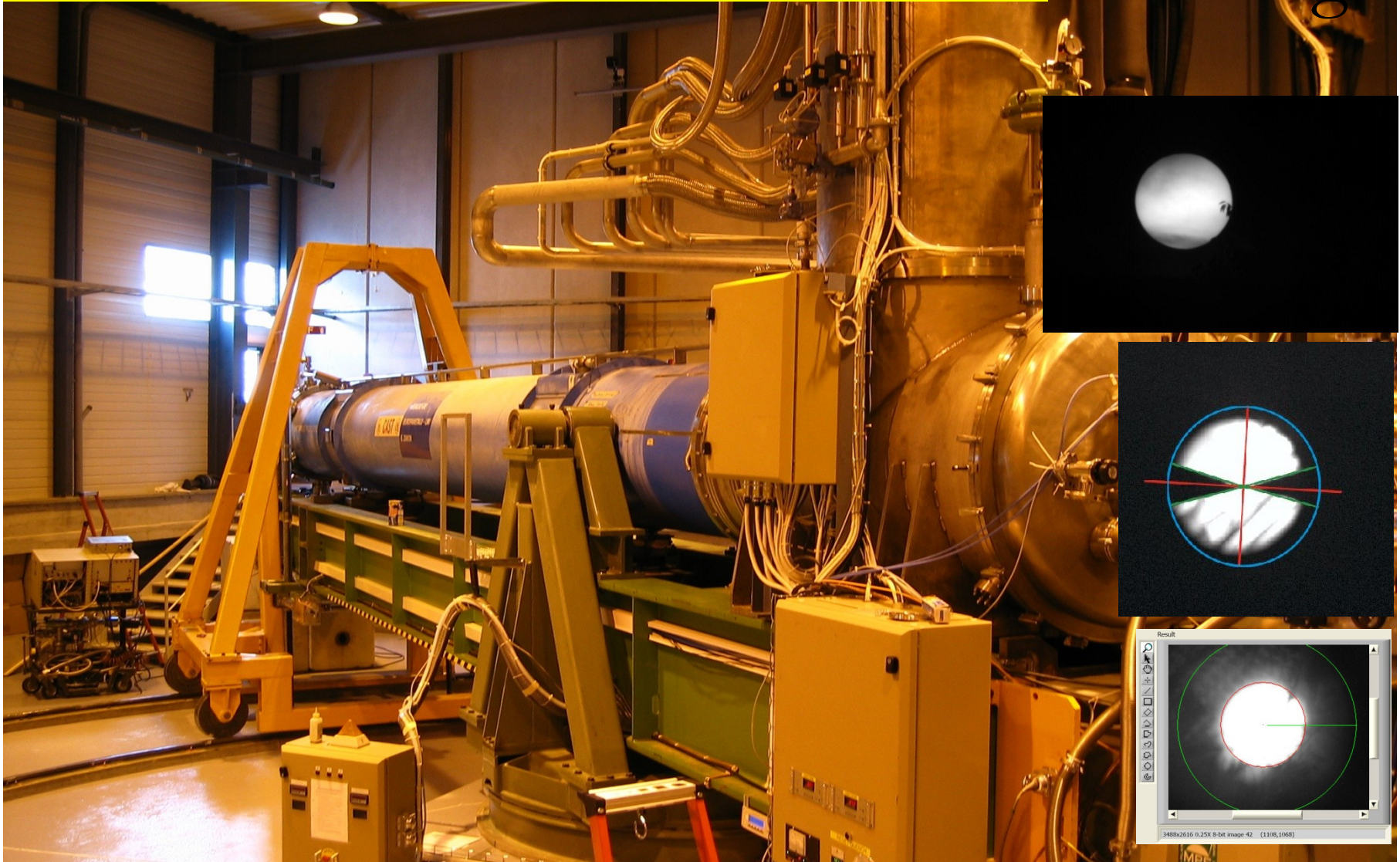
- Encoders H & V
 - ❑ Each minute
 - ❑ Check values
 - compute speeds for next minute
- GRID (geometres)
 - ❑ 10 columns x 9 vertical angles
 - ❑ Mini-GRID for annual check
- Sun filming
 - ❑ Cross-check
- Movement mechanics
 - ❑ Chariot/rails/ verins
 - Plusieurs problems
 - Andrea/Antti/Pierre-Ange/Francois
 - A suivre.....
- Interlocks – Nicolas B
 - Securite personnel
 - Arête movement si alarms (load pins)

Declination δ		Azimut Angle α									
		0°	9,5°	19,4°	30,3°	39,3°	49,4°	60,7°	69,5°	79,3°	86,4°
		0	3.635	7.472	11.208	15.088	18.995	23.324	26.695	30.488	33.191
					-6°: 11.662						
+ 8°	+ 8,0127°	53.194	53.194	53.194	53.194	53.194	53.194	53.194	53.194	53.194	53.194
+ 6°	+ 6,0067°	46.493	46.493	46.493	46.493	46.493	46.493	46.493	46.493	46.493	46.493
+ 4°	+ 4,0120°	39.825	39.825	39.825	39.825	39.825	39.825	39.825	39.825	39.825	39.825
+ 2°	+ 1,9915°	33.095	33.095	33.095	33.095	33.095	33.095	33.095	33.095	33.095	33.095
0°	+ 0,0499°	26.492	26.492	26.492	26.492	26.492	26.492	26.492	26.492	26.642	26.642
- 2°	- 2,0102°	19.815	19.815	19.815	19.815	19.815	19.815	19.815	19.815	19.815	19.815
- 4°	- 4,0114°	13.204	13.204	13.204	13.204	13.204	13.204	13.204	13.204	13.204	13.204
- 6°	- 6,6615°	4.485	4.485	4.485	4.485	4.485	4.485	4.485	4.485	4.485	4.485



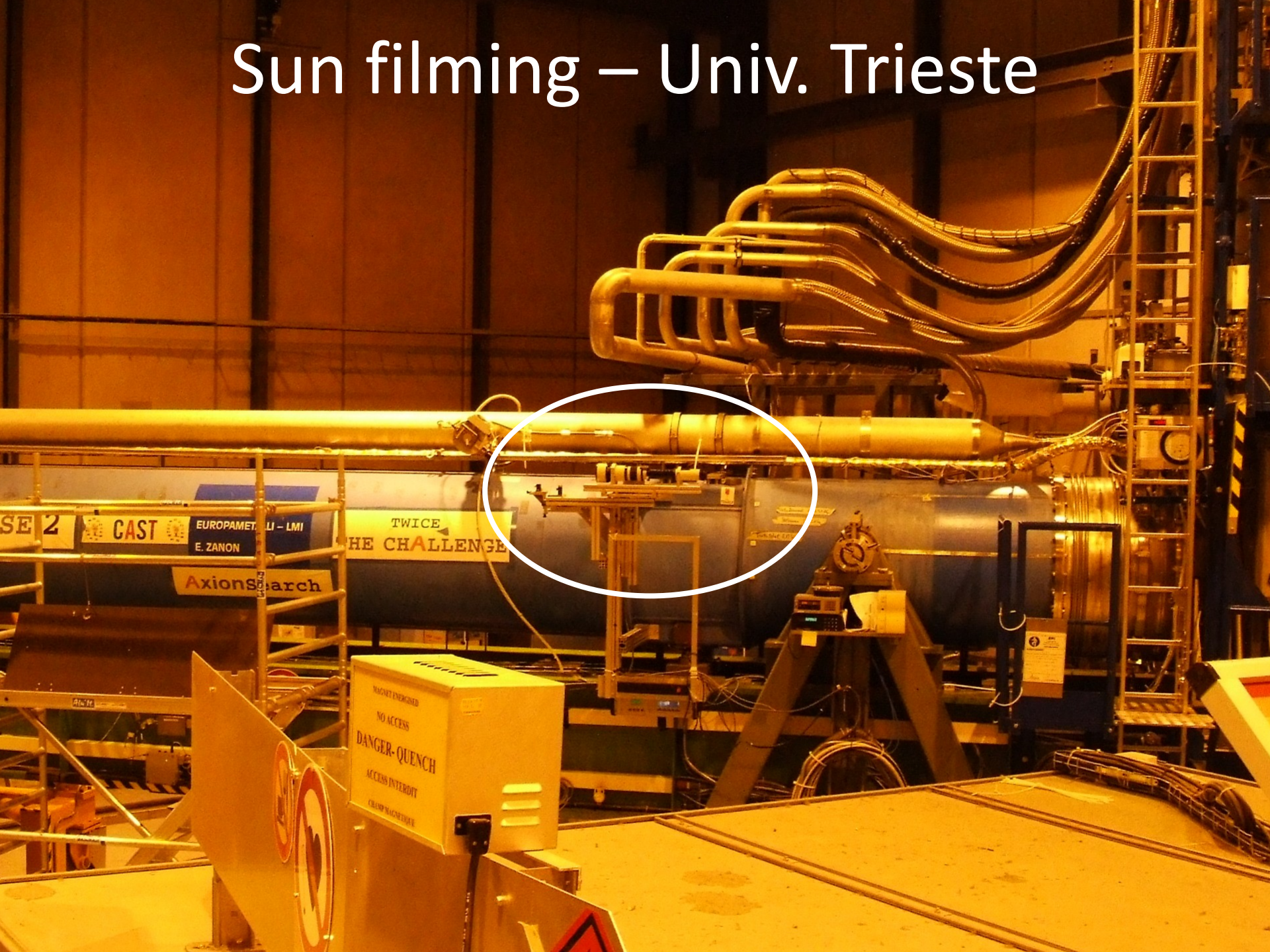
Twice per year (March/September) direct optical check
A camera on top of the magnet aligned with the bore axis
Corrections for visible light refraction are taken into account

Filming



The Magnet Pointing precision is well within our requirements (0.5 mrad)

Sun filming – Univ. Trieste

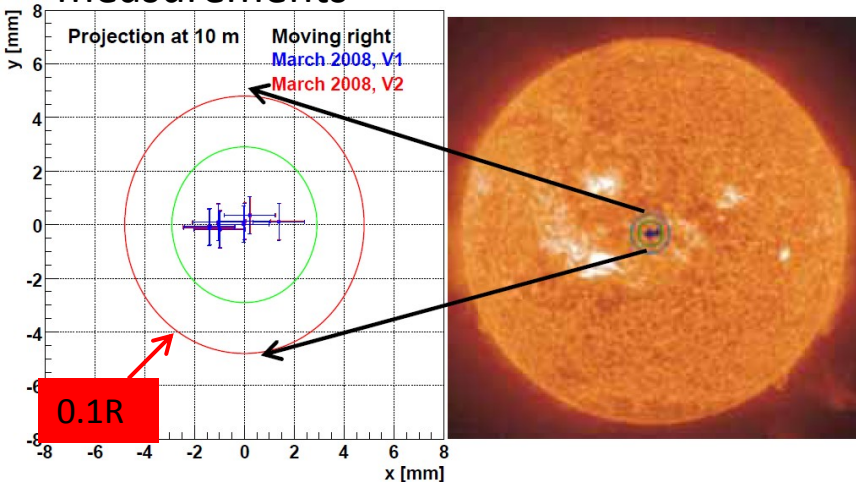


Tracking system precision

Several yearly checks cross-check that the magnet is following the Sun with the required precision

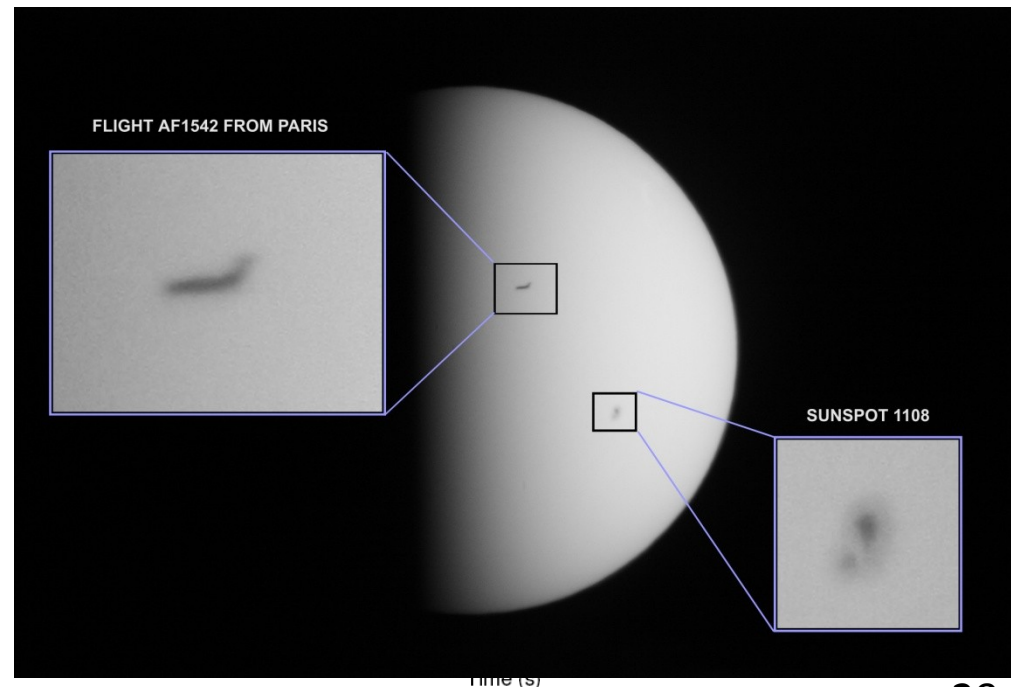
GRID Measurements

- Horizontal and Vertical encoders define the magnet orientation
- Correlation between H/V encoders has been established for a number of points (GRID points)
- Periodically checked with geometer measurements



Sun Filming

- Twice a year (March – September) Direct optical check. Corrected for optical refraction
- Verify that the dynamic Magnet Pointing precision (~ 1 arcmin) is within our acceptance



Sun filming – precision now challenging tracking precision

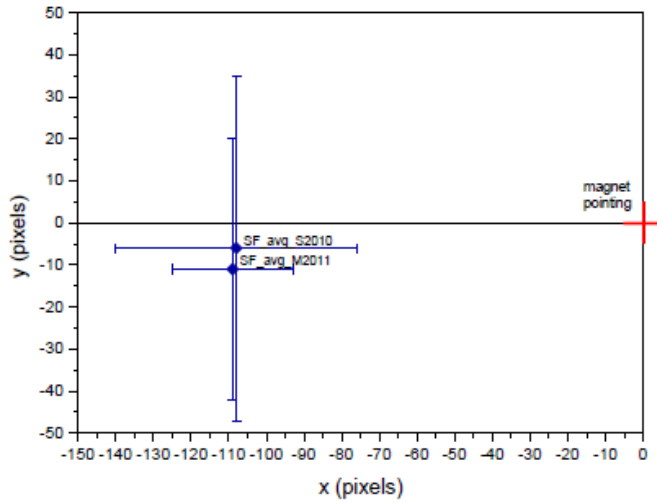
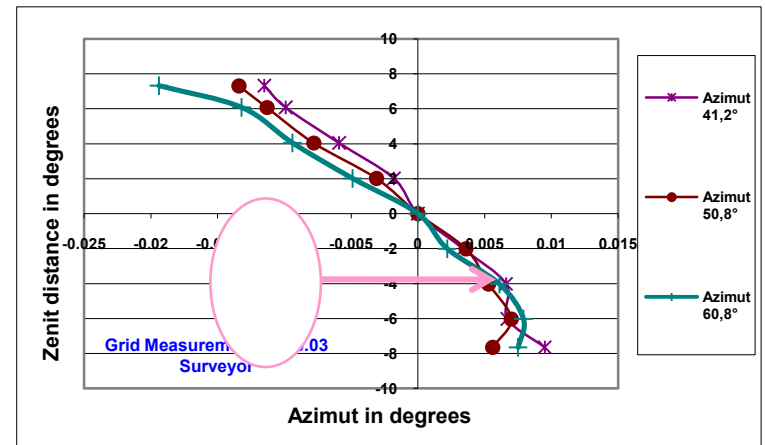
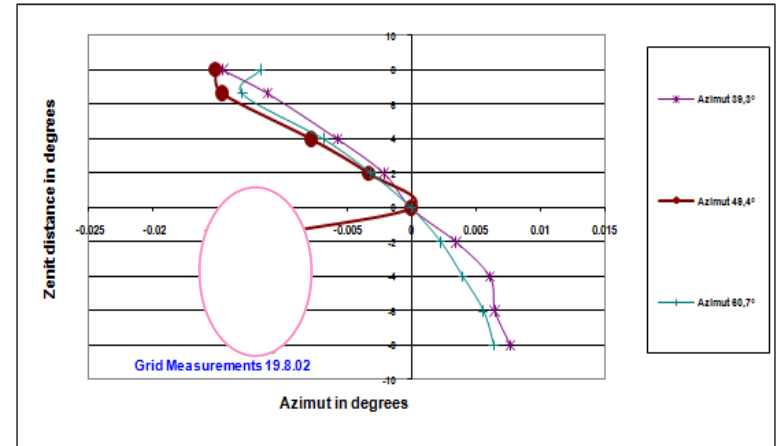
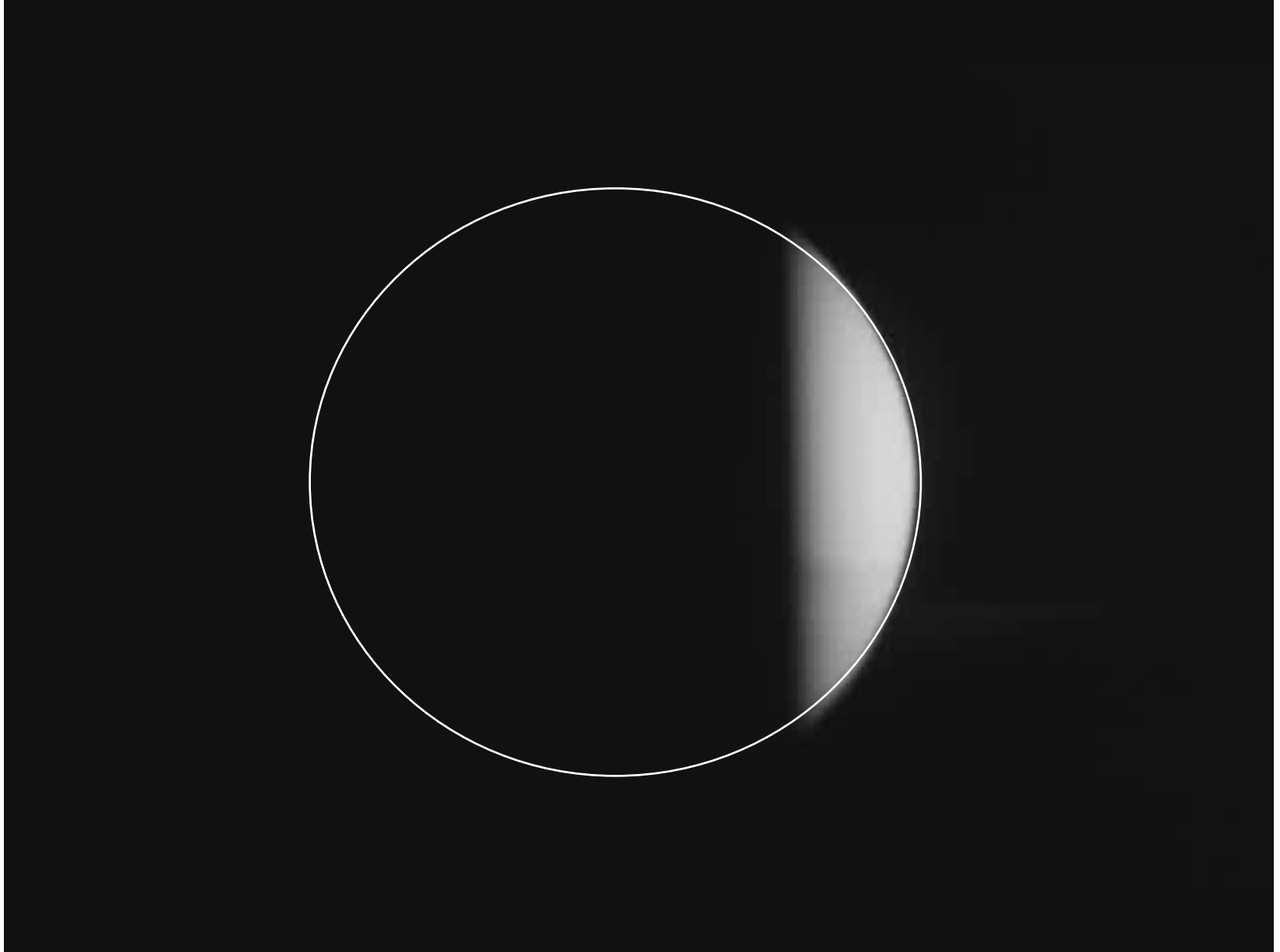


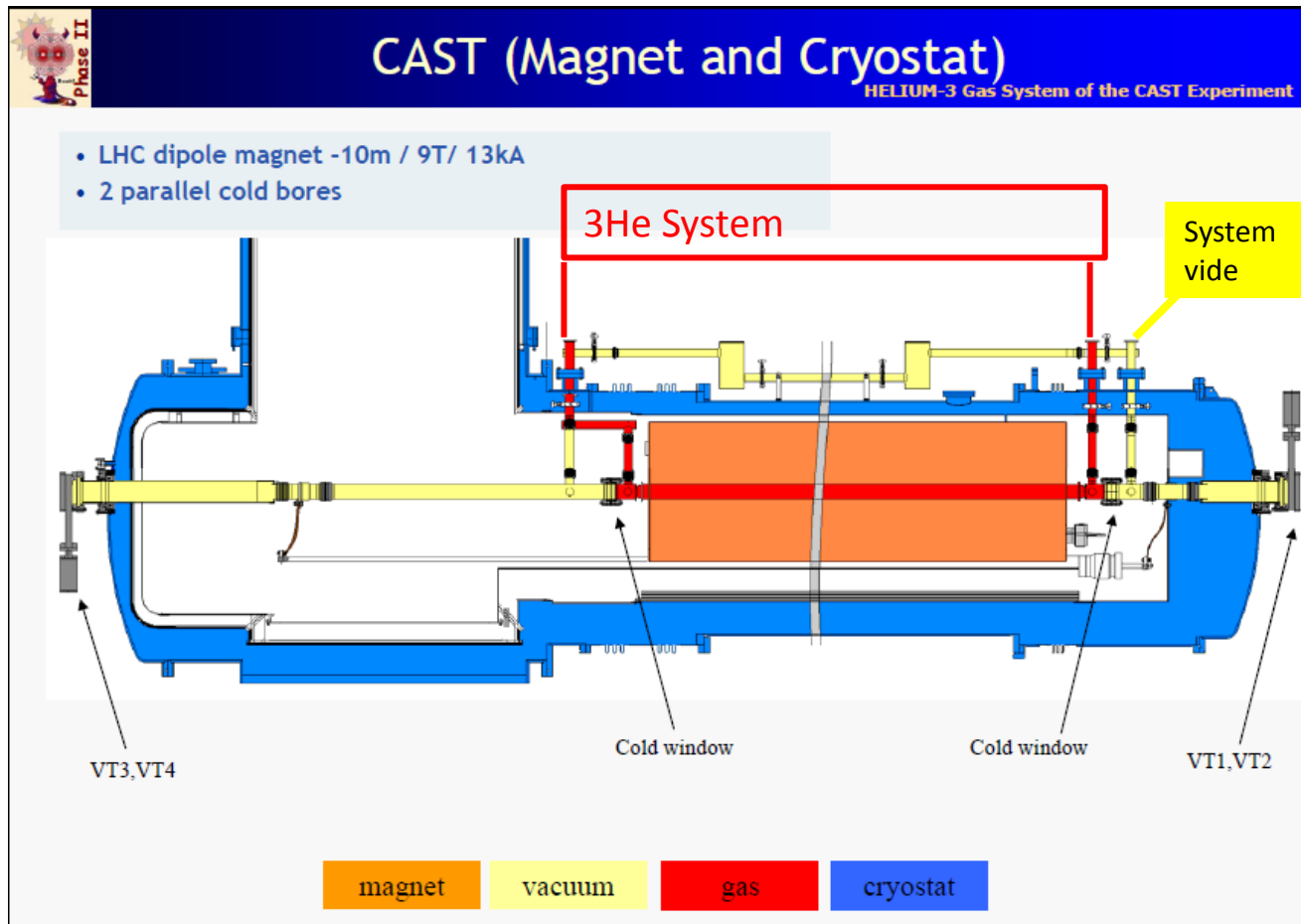
Illustration 3: Comparison between results from September 2010 and March 2011. The red cross represents the magnet pointing (0,0). All errors are summed and assigned to the Sun filming result.



Sun filming September 2010

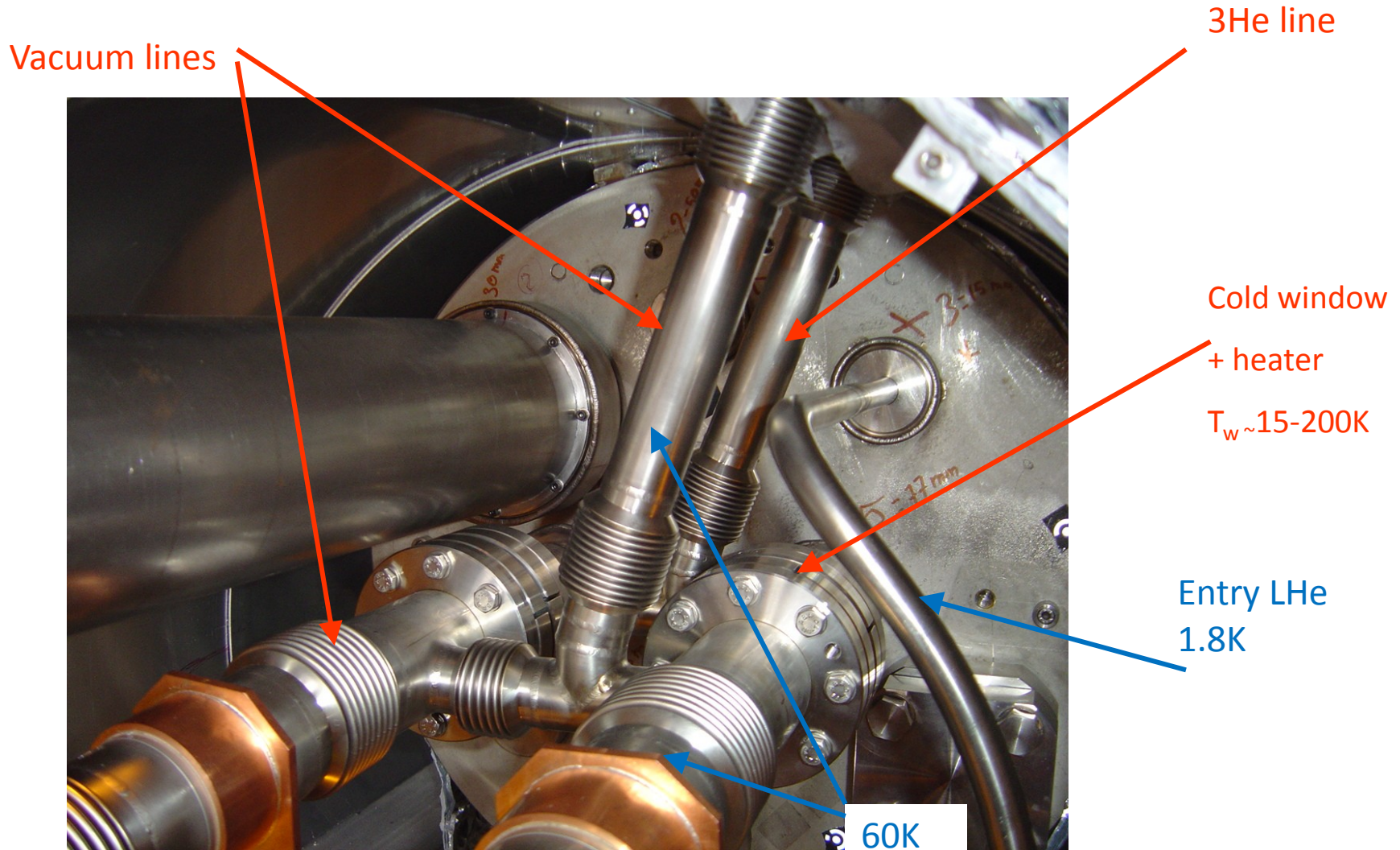


- 13000A ~ 9T
- L = 9.23m magnetic length
- 3-> 10 quench /an
 - ~1 training
 - ~1 'natural'
 - ~1->8 infrastructure
- OFF aimant 8:00-> 17:00 (eviter les glitches)

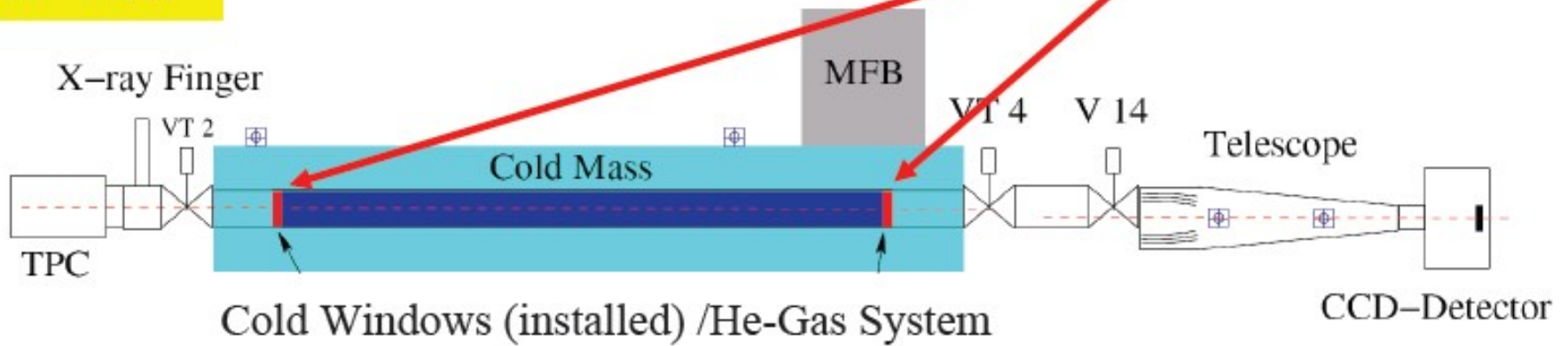
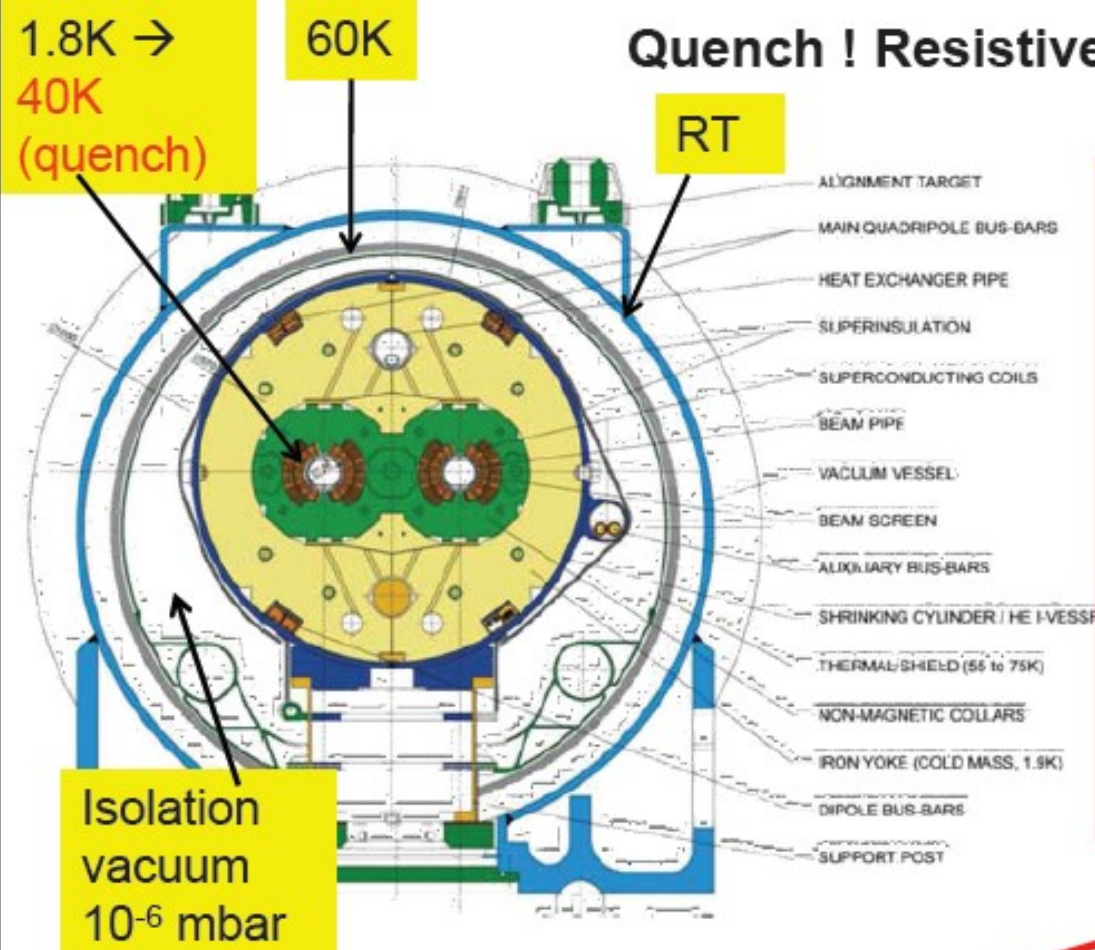


Cryostat MRB

- 500l L He4 1.8K
- Cold bore diam 43mm

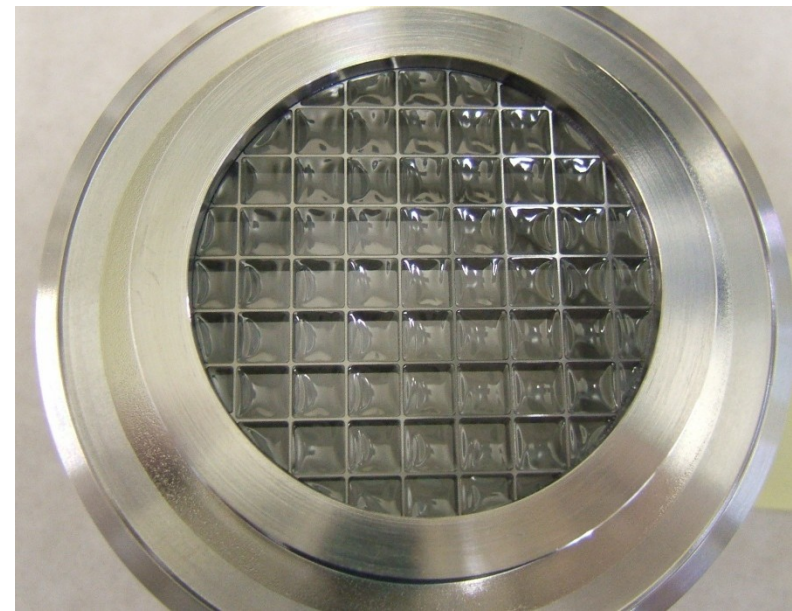
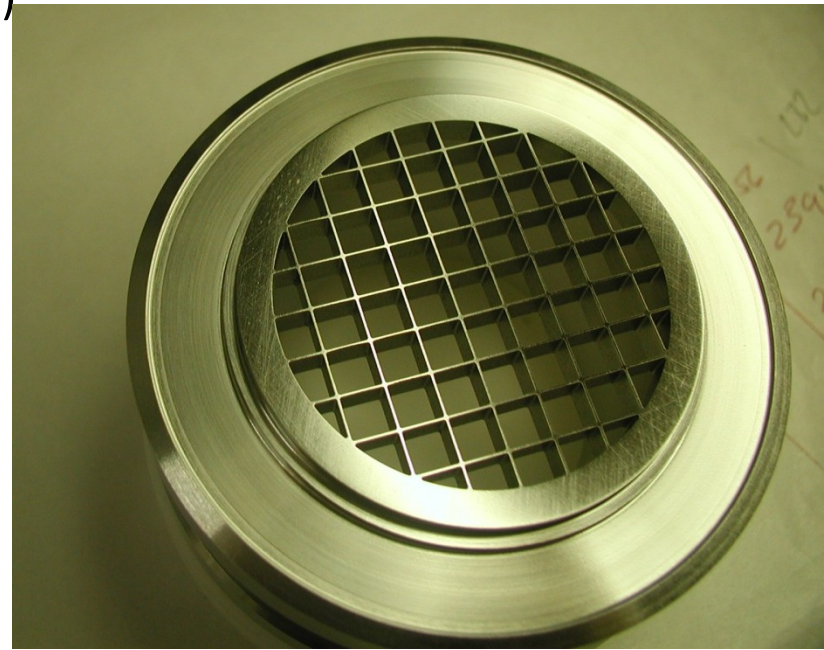


Quench ! Resistive transformation conductor



Fenêtre Froid

- Conception – Saclay
- Développent et mis au point PH—DT (D Fraissard)
 - ❑ Custom bride double CF 63
 - ❑ 316LN inox
 - ❑ Grille- strongback électro- érosion (Wyss /GVA)
 - ❑ Nettinox/électro-polissage Bat 102
 - ❑ Collage 15 μ m polypropylène (bi-axial)
 - + Araldite 2018
 - ❑ Collage d'un anneau de protection
 - ❑ Test cryolab-CERN
 - 1 bar He 300K
 - ❑ Permeation $\sim 10^{-3}$ mbar.l/s
 - Descente a 4.5K 1bar He
 - ❑ Permeation $< 10^{-7}$ mbar.l/s
 - Test a ~ 40 K
 - ❑ 2.5 bar pressurisation rapide (quençh) ~ 40 K
 - ❑ Fenêtre finale
 - Rides
 - Dépassement limite élastique
 - ❑ Fonctionnement parfait dans CAST depuis 2005.



CAST VACUUM

- Lignes vers détecteurs sous vide
 - ❑ Minimiser conduction de chaleur vers aimant
 - ❑ Laisser passer les faible énergie x-rays
- Control RGA
- Etuvage des fenetres (cryopompage)

- Interlocks
 - ❑ System d'interlocks –bêtises venant de la manipulation des détecteurs
 - ❑ Protection fenêtres froid
 - ❑ Alarme en case de risque de fuite ^3He par les fenêtres

Quench (2004)



CAST = *a difficult experiment:*

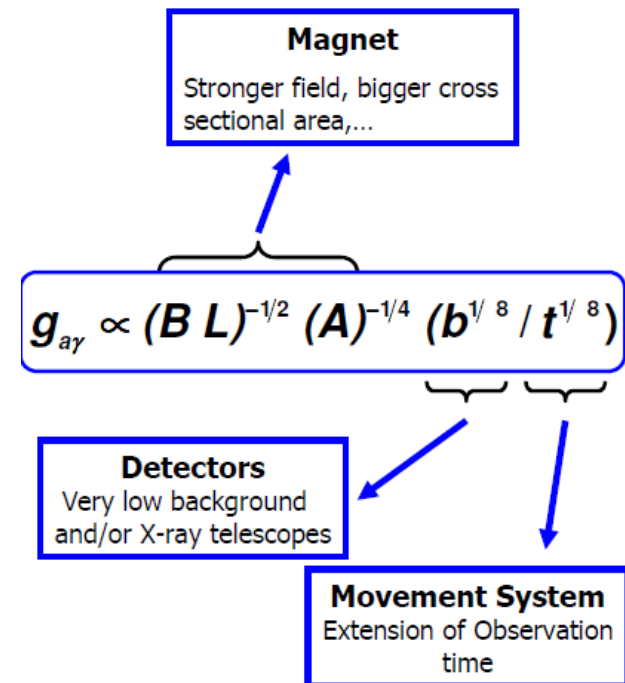
- 1.8K
- superconducting (→ quenches!)
- moving / alignment
- Cryo Fluid Dynamics of buffer gas
→ tracking
- low background X-ray detectors

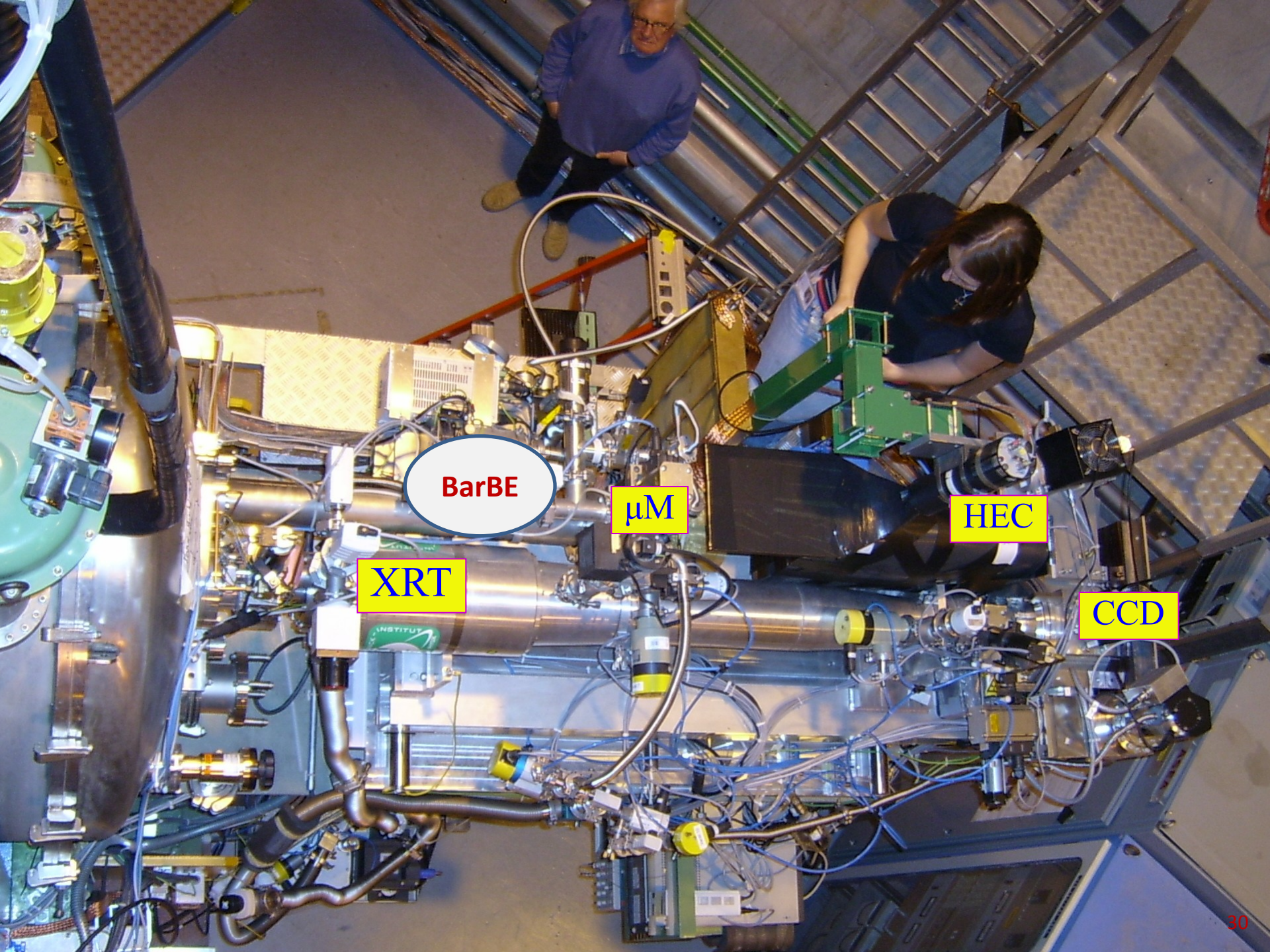
→ **the only(!?) telescope at 1.8K**

Détecteurs

- 2002 TPC (2 bores) 1 semaine
- 2003+2004 + 2006 TPC(2) + MM + XRT/CCD JR Thesis -TPC
- 2008 -> 2011 MM + MM + MM + XRT/CCD

- Détecteurs CAST différent du plupart des détecteurs utilisées au CERN
- On attends des signals 1 /hr
 - ❑ Ne pas 1/ 25 ns
- Les plus bas bruit de fond possible
 - ❑ Matériels pure , sans activité
 - ❑ Blindage spécialise
 - Univ Zaragoza spécialistes (JR)
 - ❑ Bonne mis a la masse electriques
 - Mouvement aimant gêner bcp bruit électrique
- Imaging culpabilité -détecteur
 - ❑ XRT essential
 - ❑ Reduction bruit de fond par software recognition





BarBE

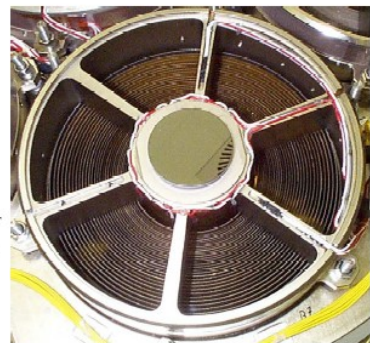
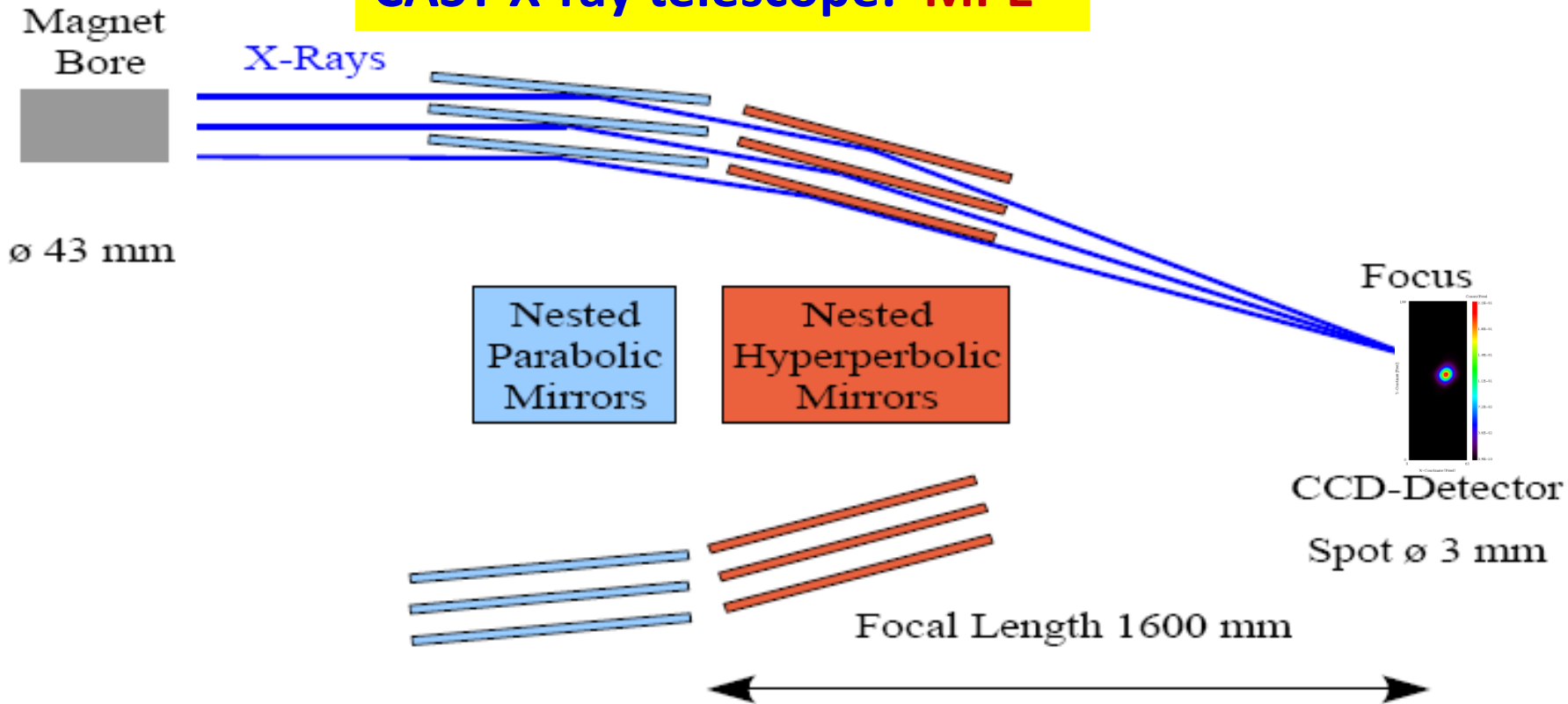
μM

HEC

XRT

CCD

CAST X-ray telescope: MPE

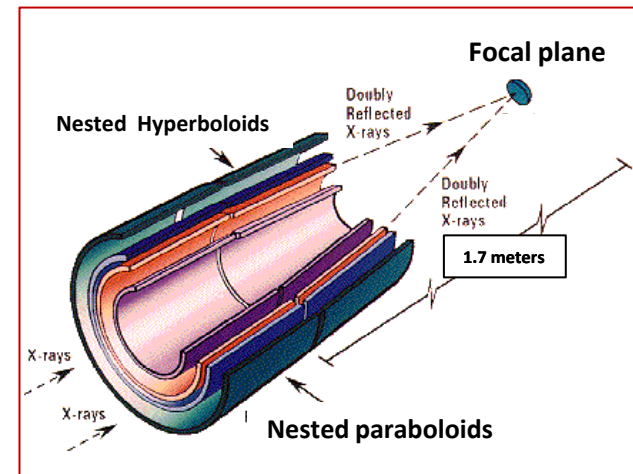


← Spare # from german space program

... not in the original proposal!

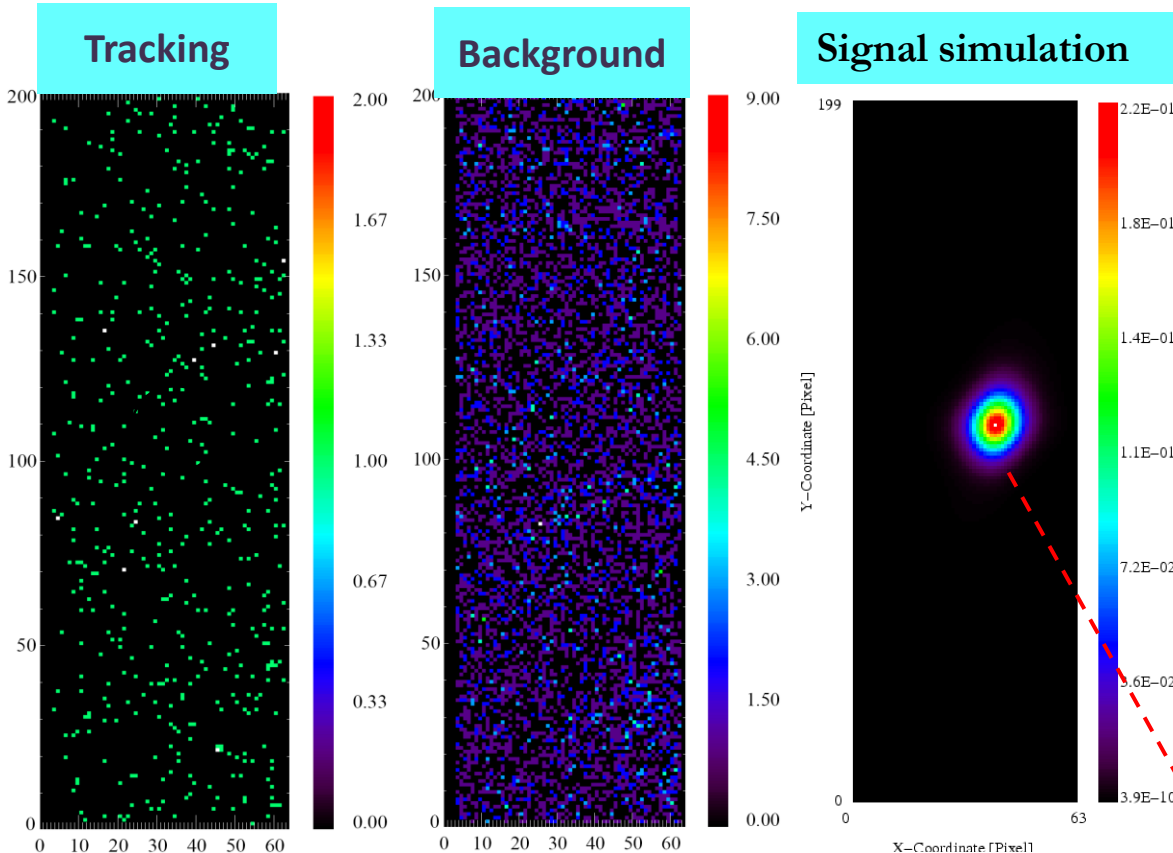
→ unique

→ ID + signal-to-noise improvement



X-ray Telescope / CCD

Reduction ~ 200 surface
43mm \rightarrow 3mm diam
Pixel 150 μm fiducial – radius
11 pixels ($\sim 20\%$ solar radius)



~ 0.3 counts /hr

- Spot position well determined
- Full sensitivity of telescope exploited
- Counts in the spot compatible with background level
- Background rate 1-7keV:
 $\sim 8 \times 10^{-5} \text{cts keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$

Solar axions!
paraphotons, chameleons?

CAST Data taking

- **Phases of CAST**

- **Vacuum 2003—2004**

- m_a 0.0 → 0.02 eV

- **Buffer gas - cold bore**

- **4He 2006 0-14 mbar (1.8K gaz idéal)160 pas7 ans pour arriver a 120 mbar**

- m_a 0.0 – 0.4 eV

- **3He 14 - 120mbar (1.8K gaz idéal)**

- **2008,2009,2010,2011**

- prix 3He → x10 (2500CHF/ litre) ! ~ 750 l in system ~ 2M)

- m_a 0.4 eV → 1.15 eV (a présent ~ 1.10 eV)

- **Pendant tout les années:**

- les détecteurs étaient améliorés
 - et la complexité des systèmes (ex.. 3He) ont augmenté

- **Jaime Ruz (Applied Fellow)**

- 3He système

- **Theodoros Vafeiadis (Doctoral student)**

- Sunrise Micromegas SRMM

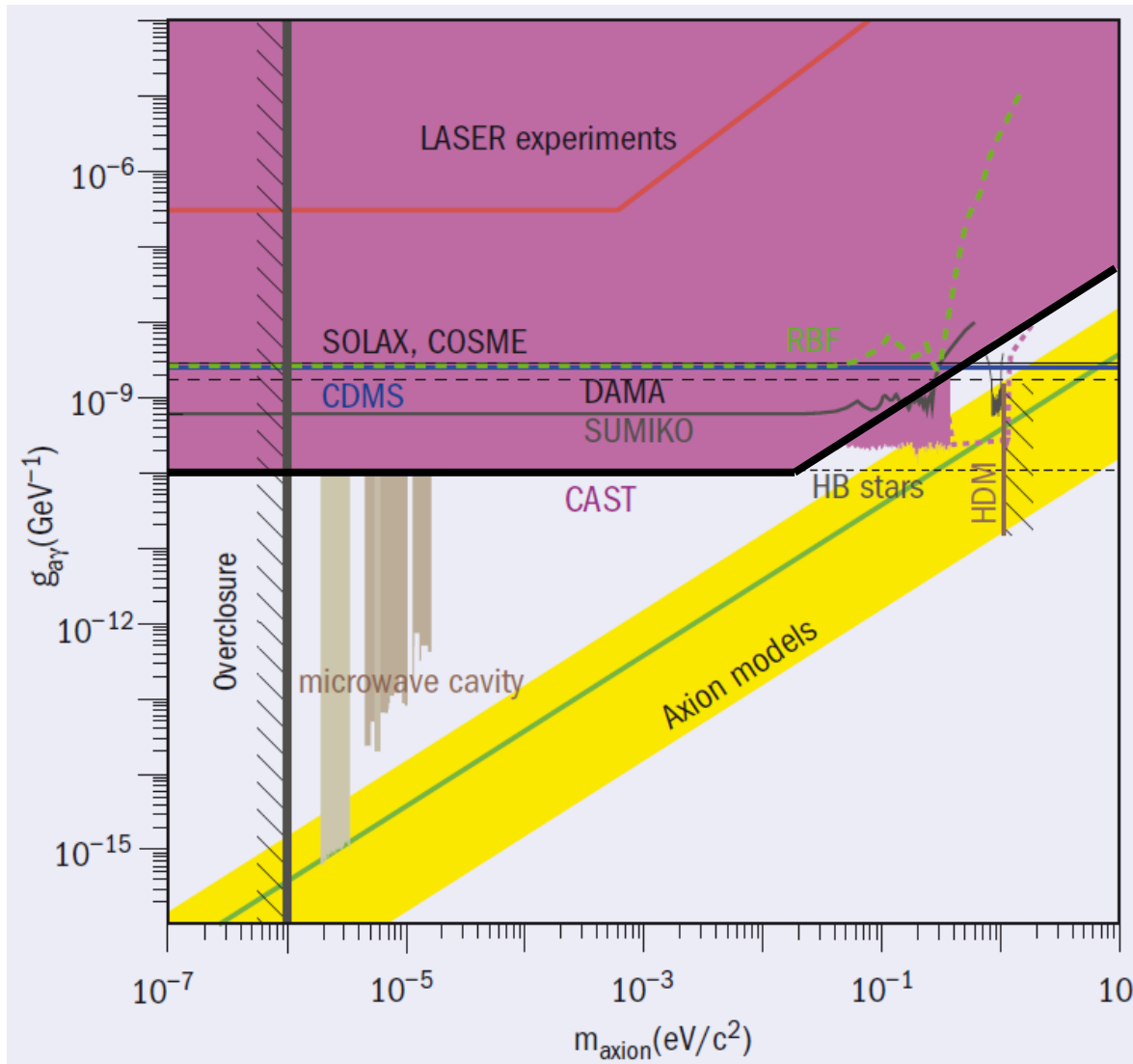
Pressure range (mbar@1.8K)	Year	Gas	Tracking per step	Step (dP)	Approx. Cold Window Temperature (K)
0.0 - 13.34	2006	4He	One full	1.0	120
13.75 - 23.64	2008	3He	Half	1.0 then 1.2	70
23.75 - 37.77	2008	3He	Half	1.2	70
37.78 - 65.15	2009	3He	Half	1.4	18
65.15 - 82.69	2010	3He	Half	1.4	15
82.69 - 108	2011	3He	Half	see scheme	13

Resume des résultats

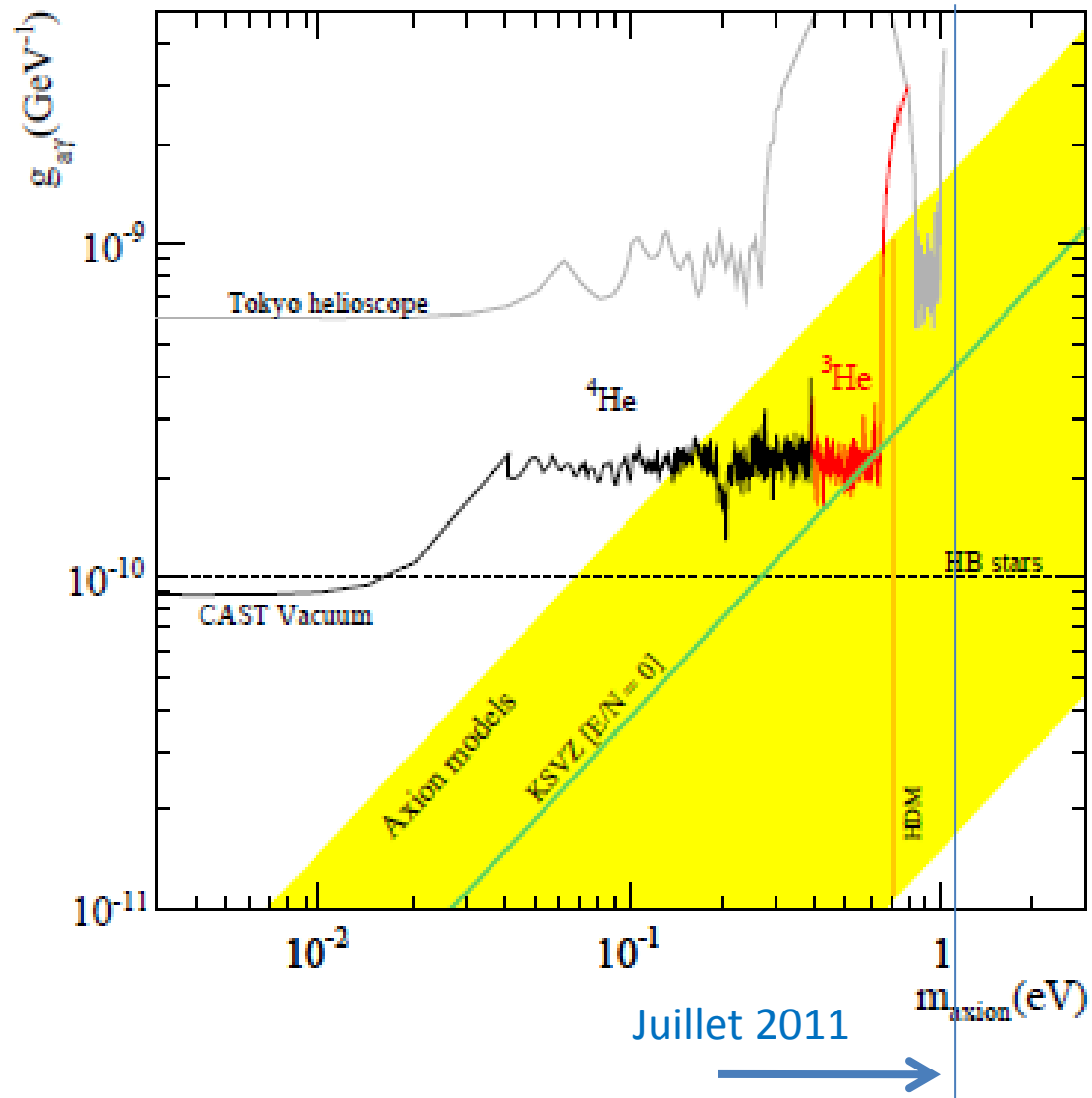
- Pas de signal axions! (Données analysées et publiées)
 - Vacuum/Vide
 - 4He 2006
 - 3He 2008

 - A finaliser l'analyse :
 - 3He
 - 2009, 2010, 2011
 - 1Q2012

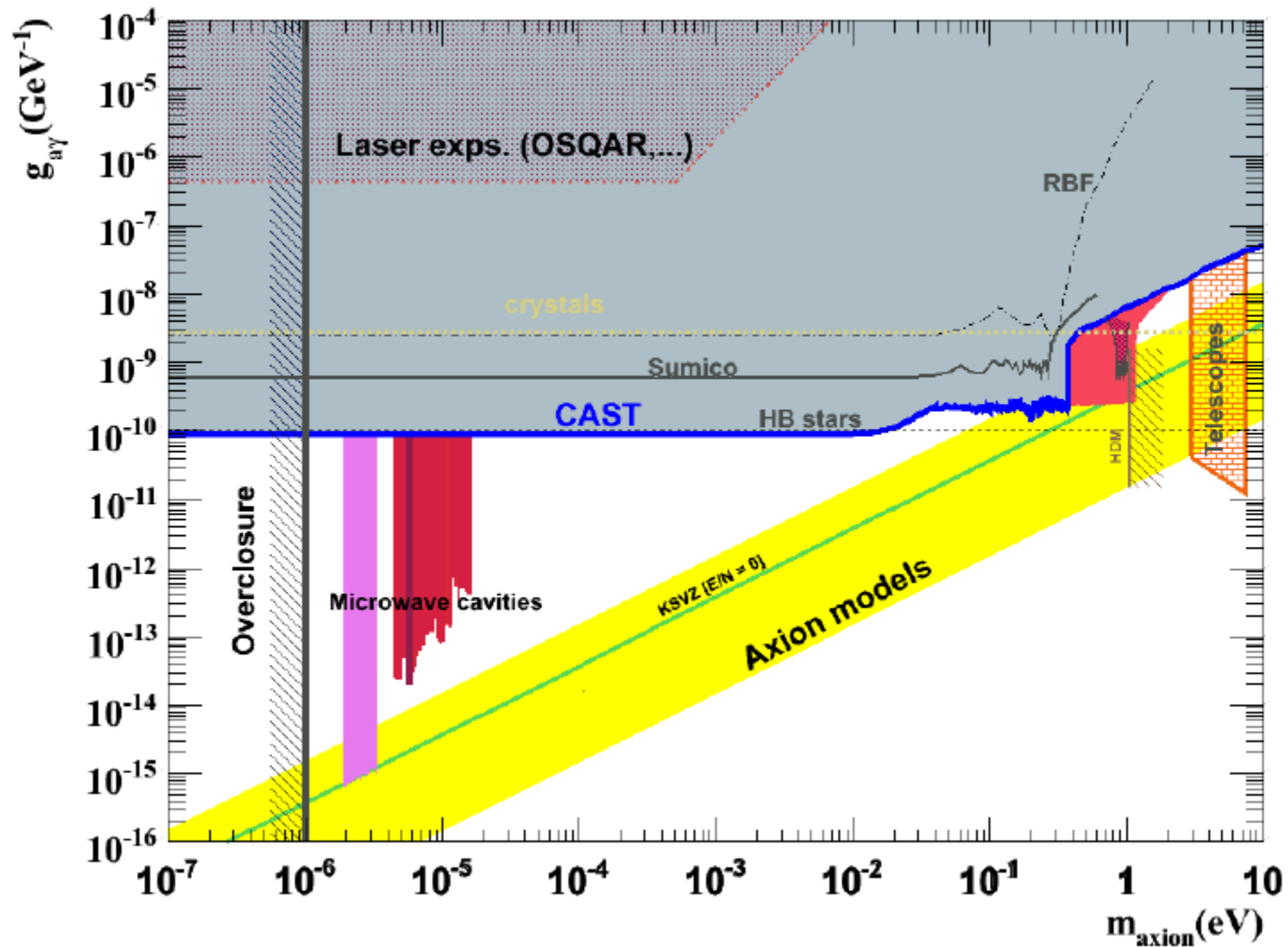
Vacuum limit – CAST dominant



2006 4He et 2008 3He



CAST 2012 – meilleur limite ou découverte?



Conclusions

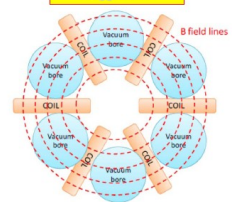
- CAST 10 ans cette année
- Notre program de Physics 3He est presque fini
 - Pas encore du signal mais le meilleur limite mondial
- Merci au PH et PH-DT
 - Pour toute votre aide ces derniers 10 ans
- CAST a une programme de physics pour les prochaines 3-4 ans
 - Il faut rénover certaines systèmes cette automne
 - Pour être prêt a commencer au début de 2012
 - Le comité SPSC va décider sur notre programme Octobre 2011
- Les jeunes membres de CAST ont une projet 'Pharaonique' pour 2015->
- On espère de continuer notre collaboration encore 10 ans.

New "magnet" à la ATLAS

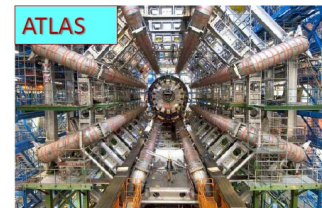
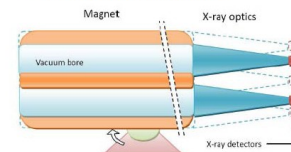


- CAST enjoys one of the best existing magnets than one can "recycle" for axion physics (LHC test magnet)
- Only way to make a step further is to built a new magnet, specially conceived for this.
- Work ongoing, but best option up to know is a **toroidal configuration**:
 - Much bigger aperture than CAST: $\sim 0.5\text{-}1\text{ m}$ / bore
 - Lighter than a dipole (no iron yoke)
 - Bores at room temperature

L. Walckiers'/CERN suggestion



Cross section of the magnet



Back up slides - CAST 2011-2015

CAST renovation Automne 2011

- Systeme mouvement

- ❑ Roulements 3 roues

- ❑ Roues

- Re-alignements

- ❑ Verins

- Replacer

- ❑ Load pins

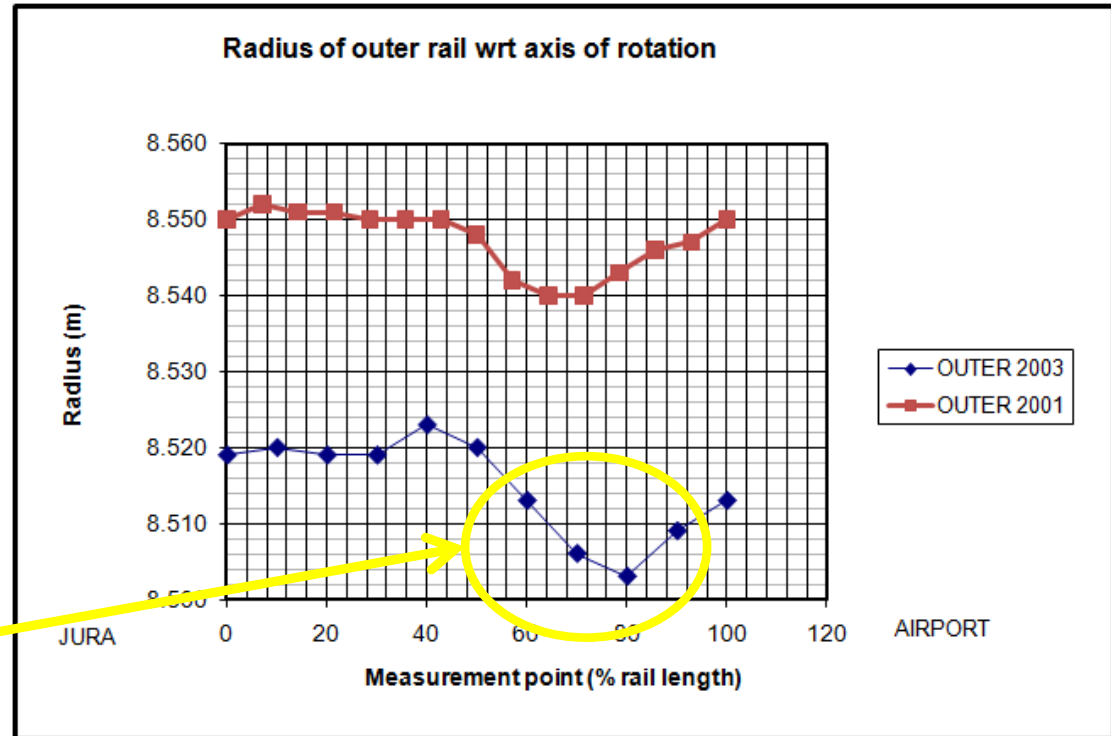
- Enlever et calibrer

- ❑ Rail

- Modifier ?

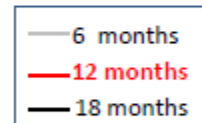
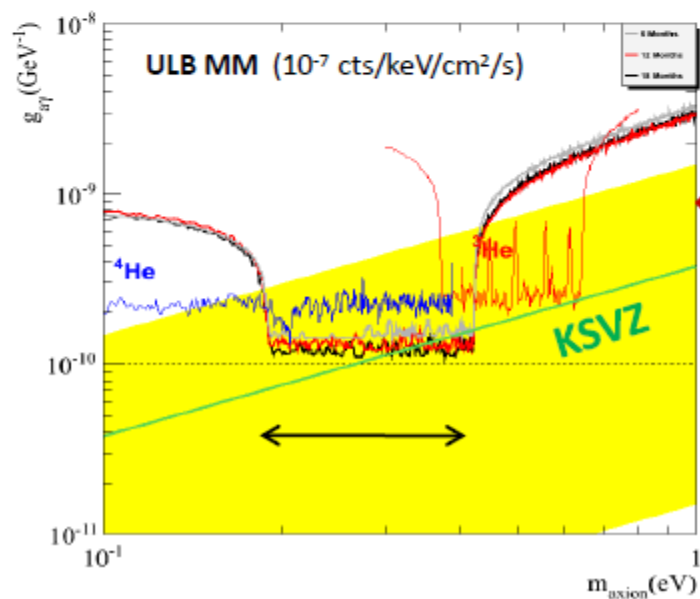
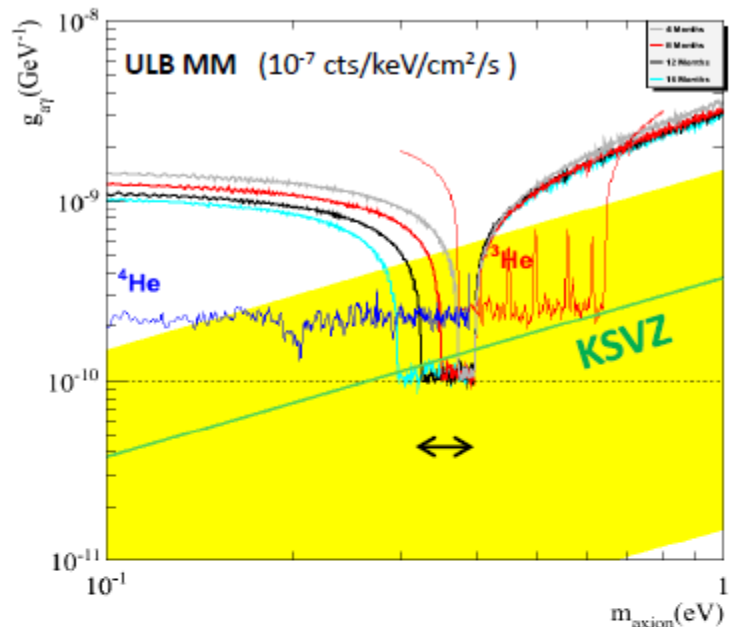
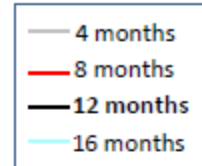
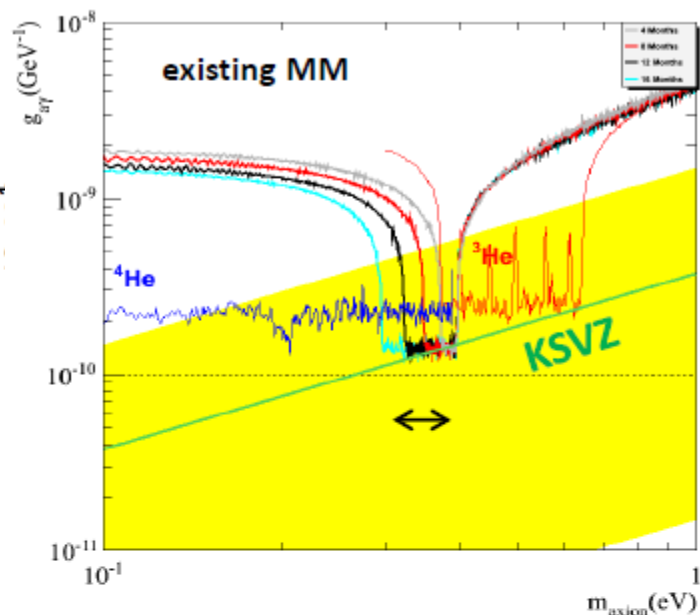
- 13kA cables

- ❑ Changer



Et puis.....La Physique 2012-2014+

Future: repeat ^4He runs with current CAST



← **3.2 - 16 mbar: 6, 12 & 18 calendar months**
(1.5, 3 and 4.5 trackings/step)

- significant improvement in background wrt. 2006
- crossing axion KSVZ model
- could start in autumn 2011 (with present detectors)
- *no competition in sight*

Vacuum revisit – meilleurs détecteurs

- Enlever les fenêtres froid
- Refaire le physique avec le vide dans les cold bores 12-15 mois
- Access aux énergies des photons 10 – 1000 eV
 - Paraphotons
 - Chamelons (énergie noir)

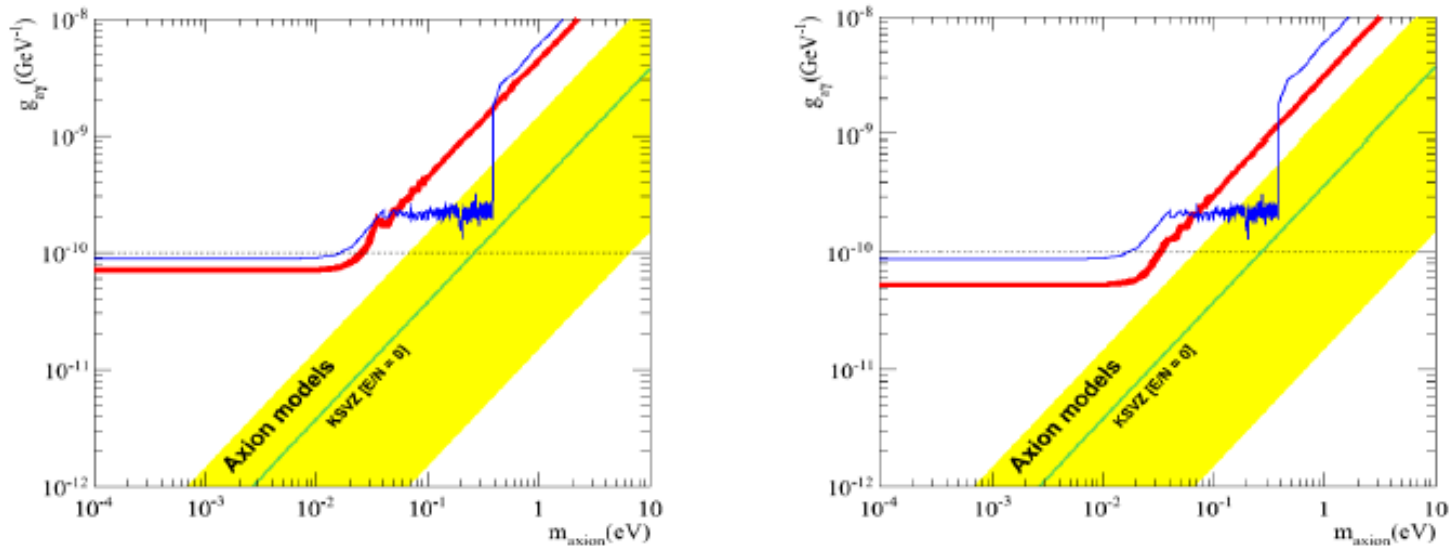
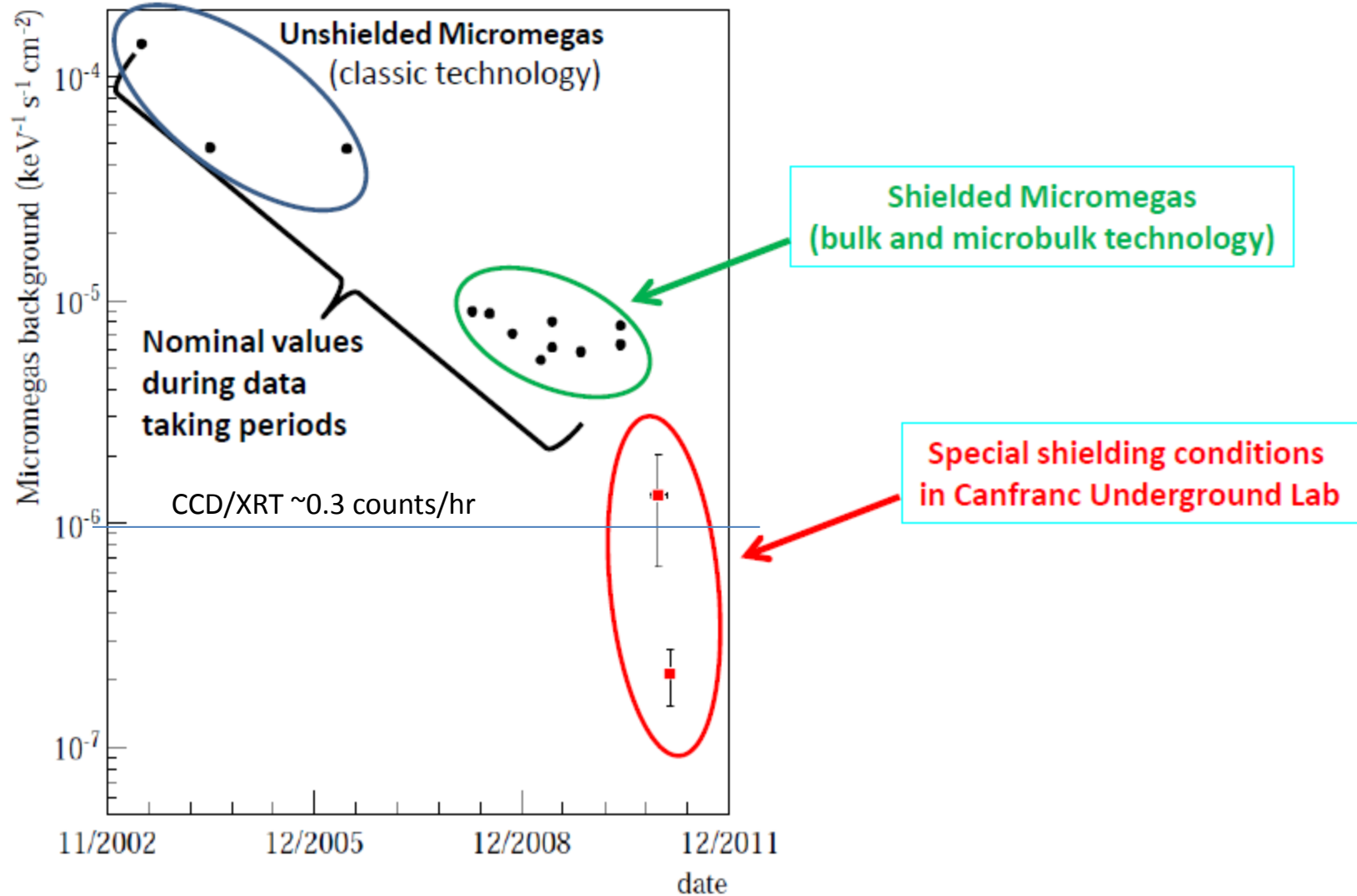


Figure 2.3 *Left:* Scenario 1, with 12 calendar months of data taking and existing Micromegas detector. *Right:* Scenario 2, with 12 calendar months of data taking and ultra-low-background Micromegas detector. The blue curve is the current limit, the red curve the simulated sensitivity.

Background levels of Micromegas detectors in CAST over the last years.



Back up slides - NGAH

Towards a new generation axion helioscope

>> **50 – 100 MEUROs** project

I. G. Irastorza¹, F. T. Avignone², S. Caspi³, J. M. Carmona¹,
T. Dafni¹, M. Davenport⁴, A. Dudarev⁴, G. Fanourakis⁵,
E. Ferrer-Ribas⁶, J. Galán^{1,6}, J. A. García¹, T. Gerialis⁵,
I. Giomataris⁶, H. Gómez¹, D. H. H. Hoffmann⁷, F. J. Iguaz⁶,
K. Jakovčić⁸, M. Krčmar⁸, B. Lakić⁸, G. Luzón¹, M. Pivovarov⁹,
T. Papaevangelou⁶, G. Raffelt¹⁰, J. Redondo¹⁰, A. Rodríguez¹,
S. Russenschuck⁴, J. Ruz⁴, I. Shilon^{4,11}, H. Ten Kate⁴, A. Tomás¹,
S. Troitsky¹², K. van Bibber¹³, J. A. Villar¹, J. Vogel⁹,
L. Walckiers⁴, K. Zioutas¹⁴

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³Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

⁴CERN, Geneva, Switzerland

⁵National Center for Scientific Research Demokritos, Athens, Greece

⁶IRFU, Centre d'Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France

⁷Technische Universität Darmstadt, IKP, Darmstadt, Germany

⁸Rudjer Bošković Institute, Zagreb, Croatia

⁹Lawrence Livermore National Laboratory, Livermore, CA, USA

¹⁰Max-Planck-Institut für Physik, Munich, Germany

¹¹Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel

¹²Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia

¹³Naval Postgraduate School, Monterey, CA, USA

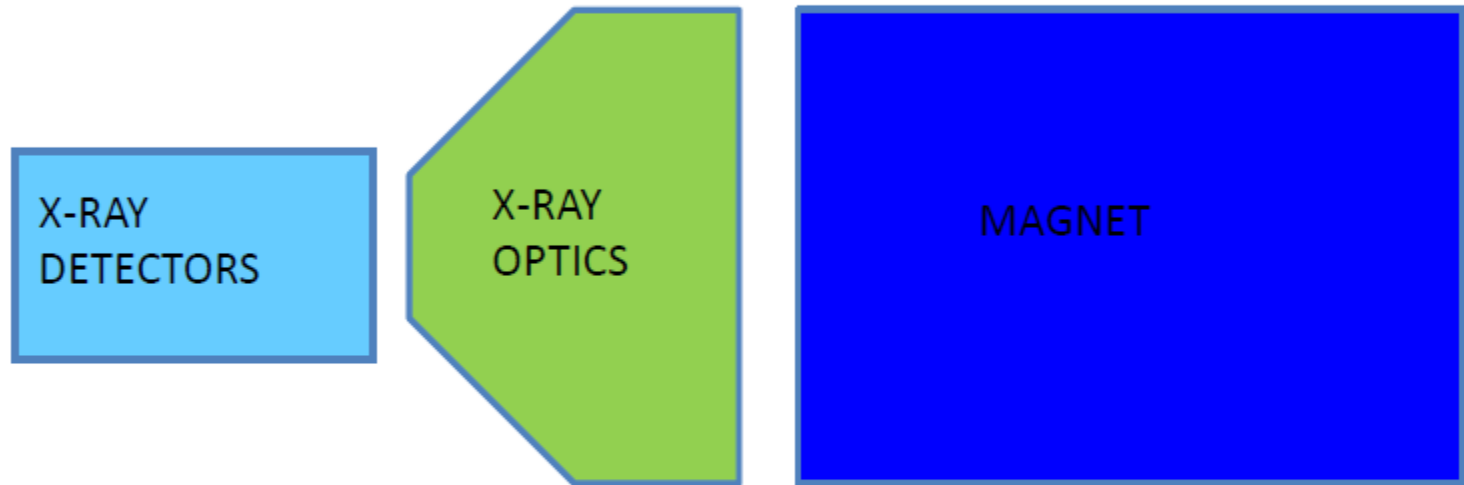
¹⁴University of Patras, Patras, Greece

Motivation, physics case

- Improve CAST results substantially. It is worth? How much we need to improve?
- Physics case:
 - Large region of allowed QCD axions at 0.01-1 eV scale
 - But also: ALPs at low mass. Hints from astrophysics.
- **No other axion detection technique can realistically improve CAST in the midterm.**
- → To push for a NGAH as the next large infrastructure for axion physics is justified scientifically, feasible(?), fundable.

Axion Helioscopes FOM

- 3 elements drive the sensitivity of an axion helioscope



$$\frac{1}{\text{FOM}} \propto g_{a\gamma}^4 \propto \underbrace{b^{1/2} \epsilon_d^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2} \epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

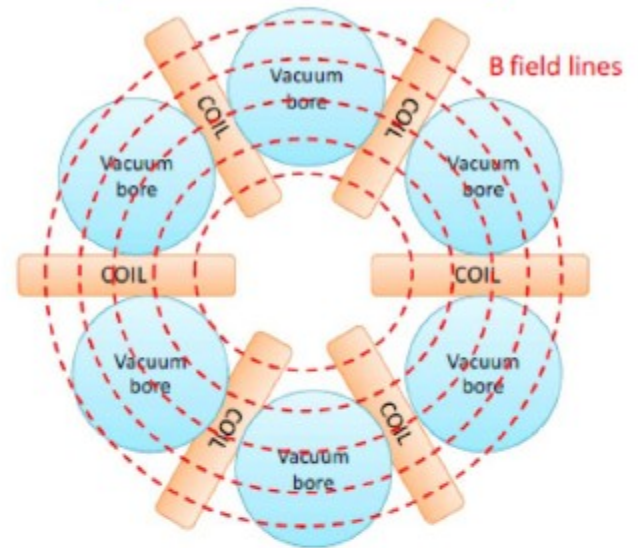
where b is the time- and area-normalized background of the detector, ϵ_d its efficiency; a is the focal spot area of the optics, ϵ_o its throughput, B is the magnet field strength, L its length, and A its cross sectional area; t is the exposure time.

New “magnet” à la ATLAS

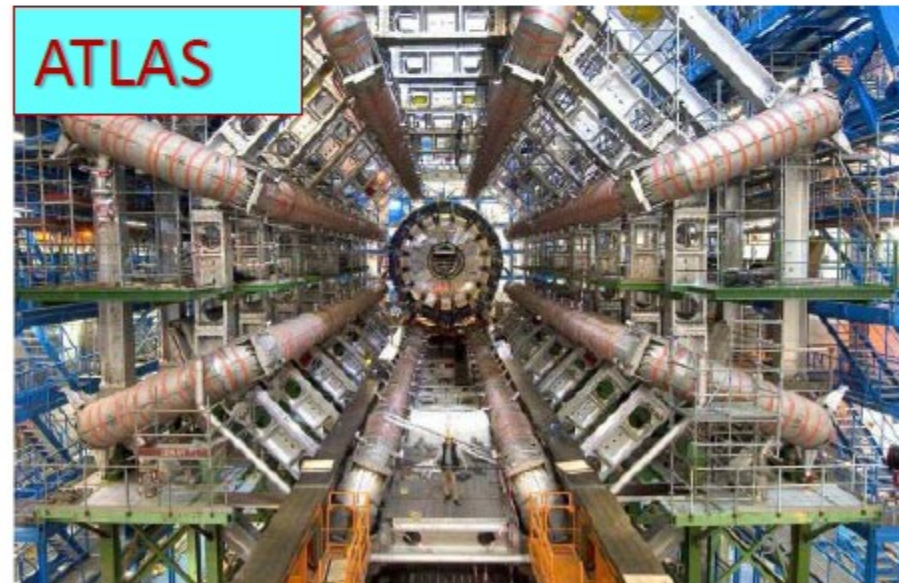
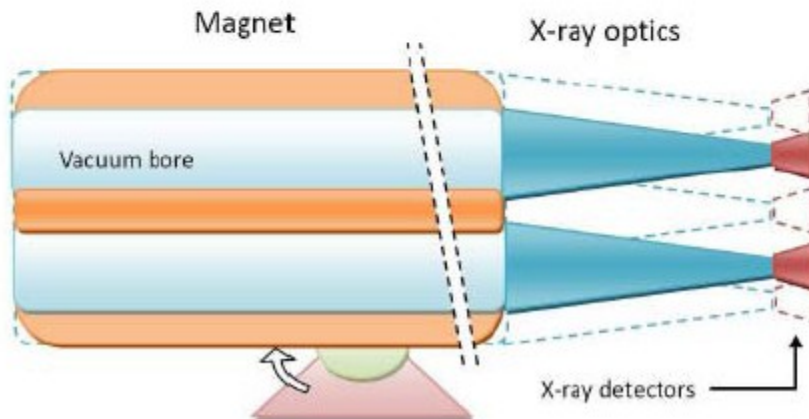


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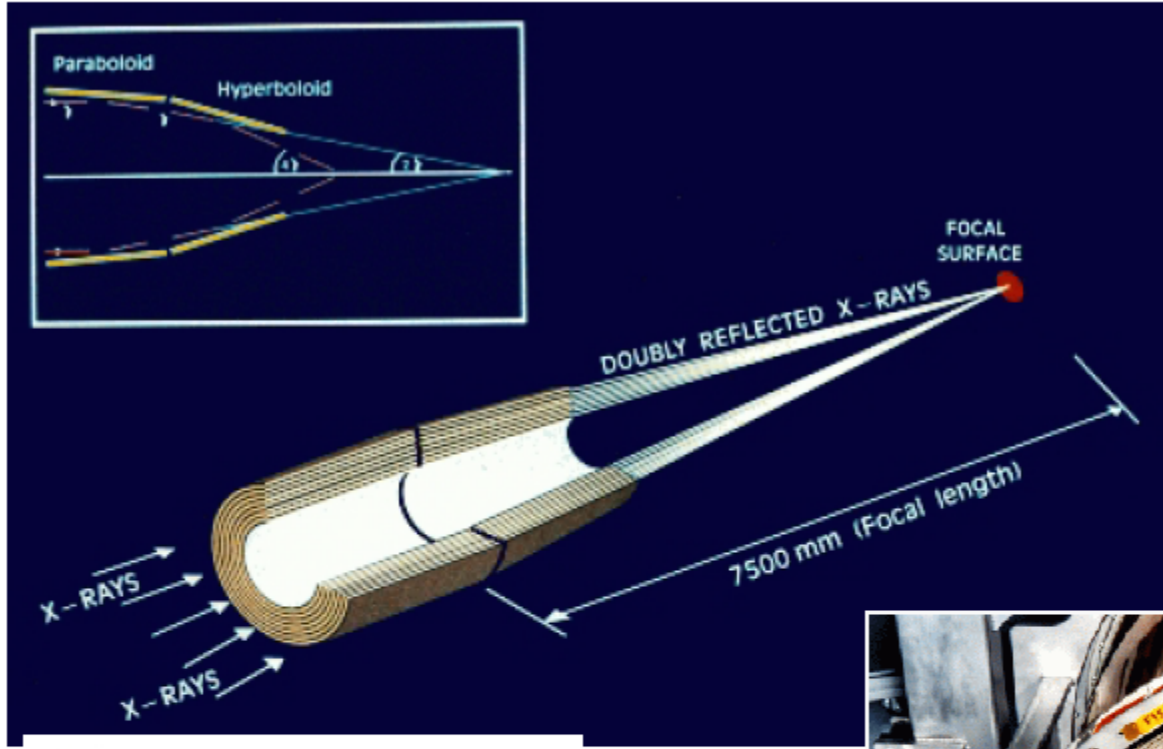
L. Walckiers’/CERN suggestion



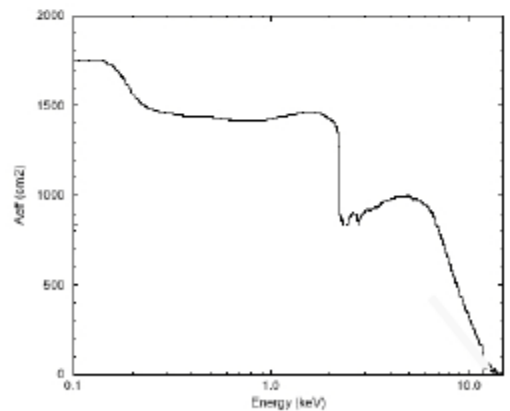
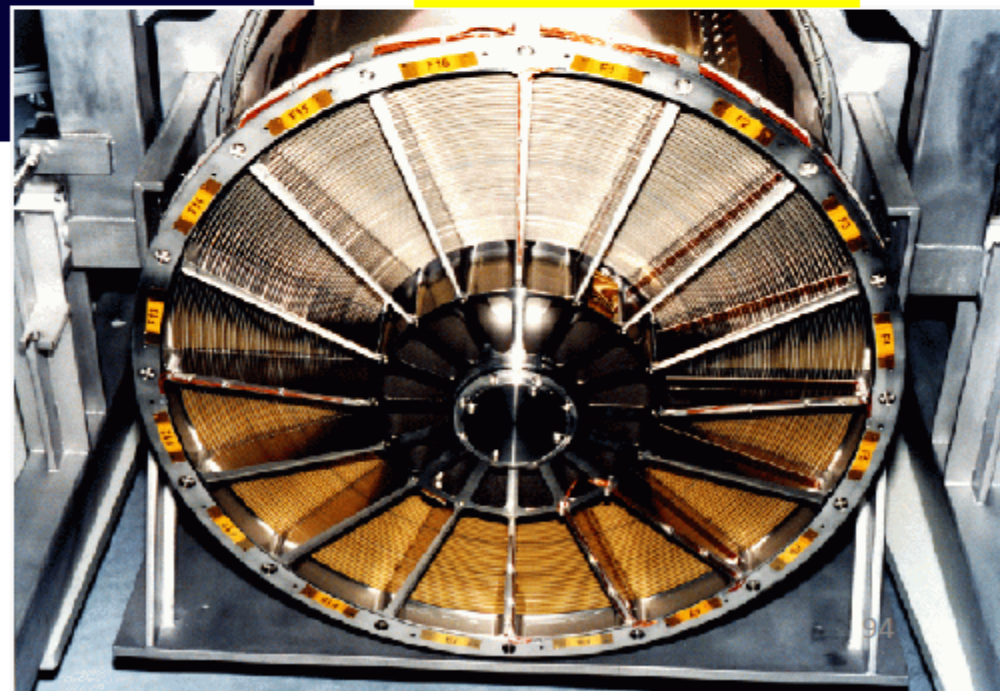
Cross section of the magnet



Light Path in XMM-Newton Telescope



XMM mirror module



Collecting area:
~1900cm² (<150 eV), ~1500cm² (@ 2 keV),
~900cm² (@ 7keV), ~350 cm² (@ 10 keV).

Main experimental challenges

seem reasonable, but need to be demonstrated

- **Goals for the next 1-2 years:**

- **Magnet**

- Built a new magnet, tailored to our needs
- Main goal: $B^2L^2A \sim \times 1000$ better than CAST (desirable), $\times 100$ (minimum)
- Other construction technical issues \rightarrow feasibility study, design study.
- Work already going on. Next steps?

- **Optics**

- Cost-effective large optics (all magnet instrumented). 0.5-1 m², several bores
- Optimization: number of optics, dead space, focal length...
- prospects with Nustar tooling.

- **Detectors**

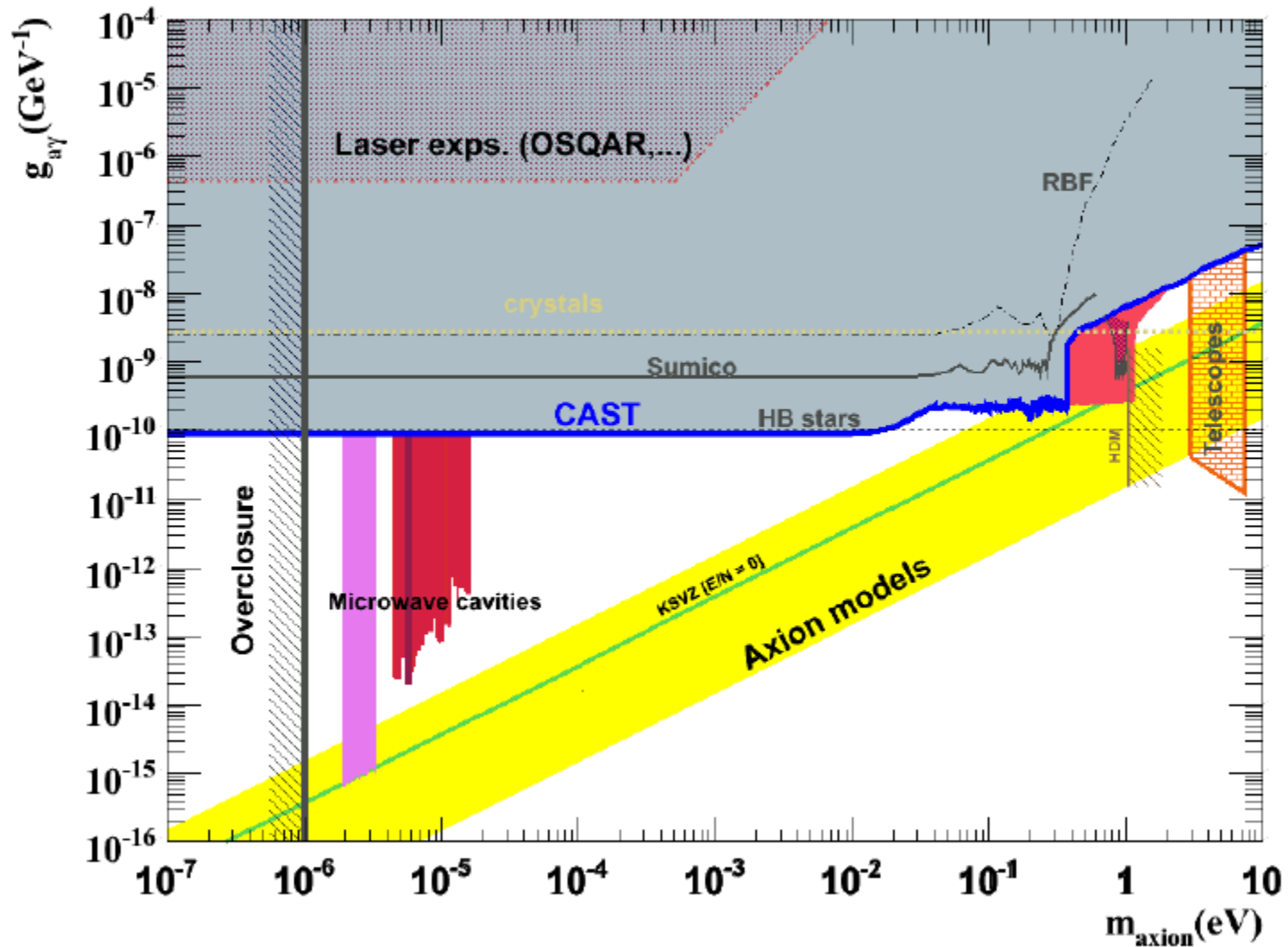
- Main goal: background $\sim 10^{-7}$ c/keV/cm²/s

- **Platform, general assembly engineering**

- 40-50% Sun coverage?

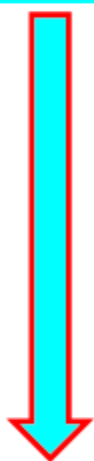
CAST in the Axion MAP soon

Now and ...

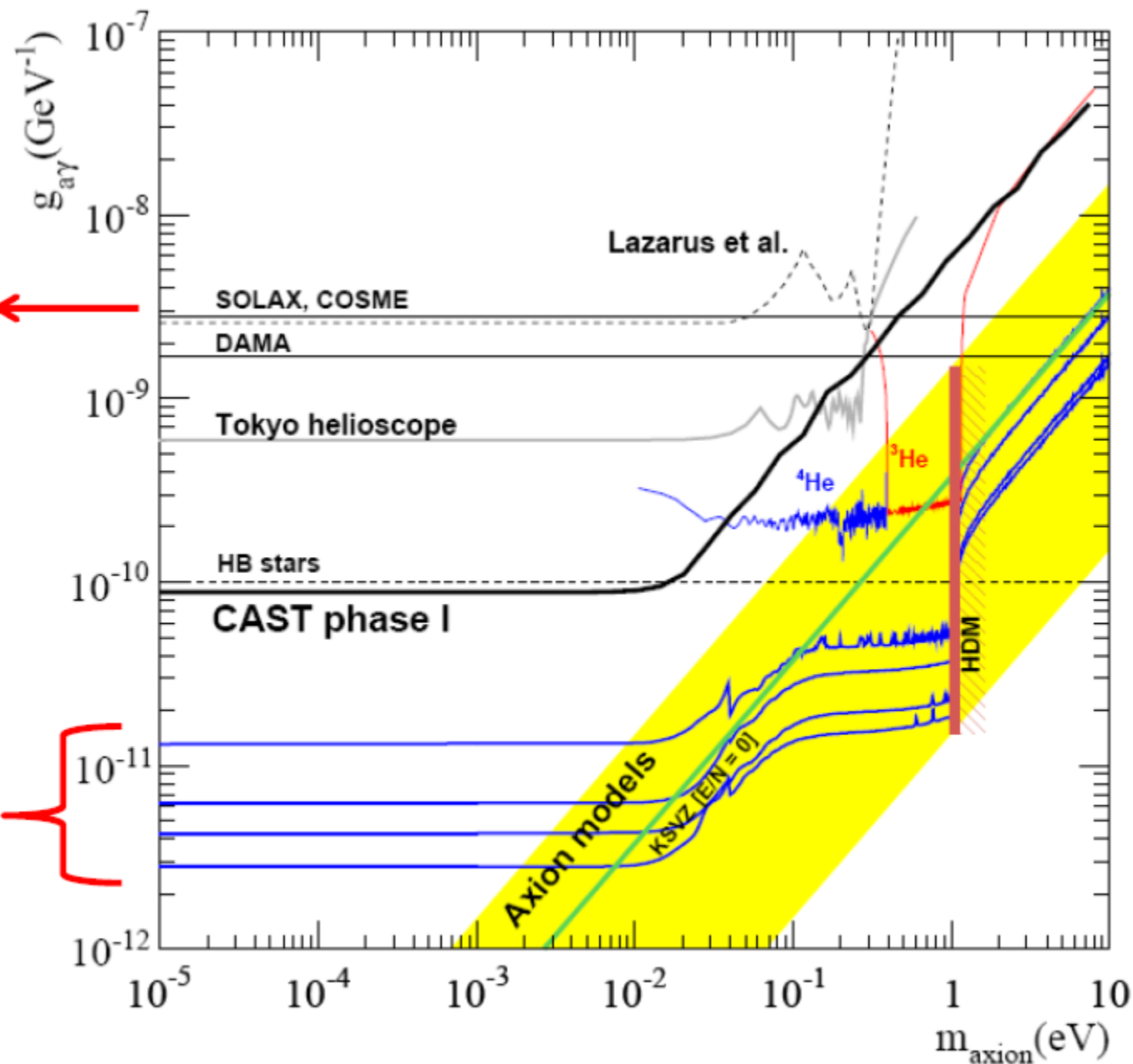


Prospects

1990

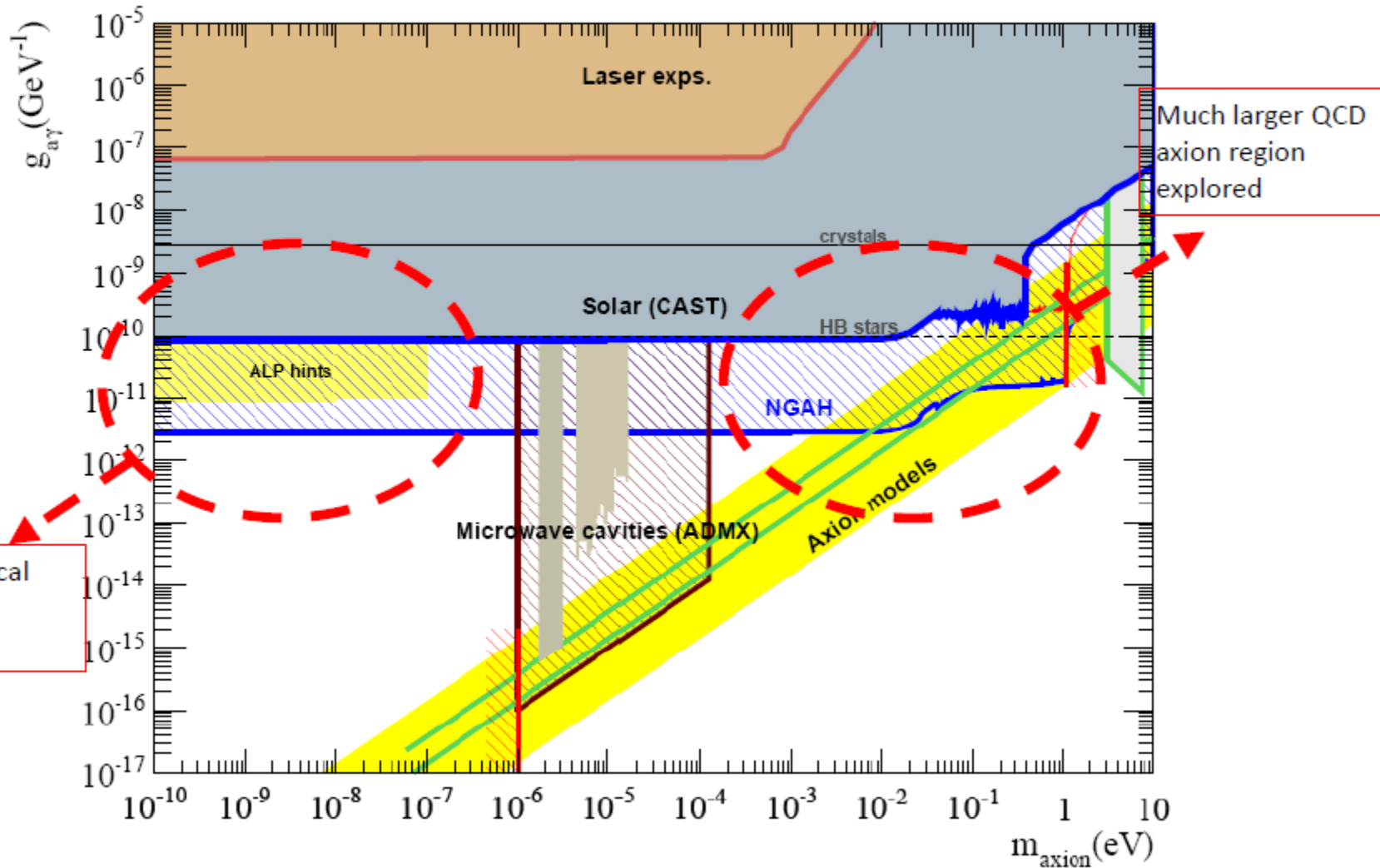


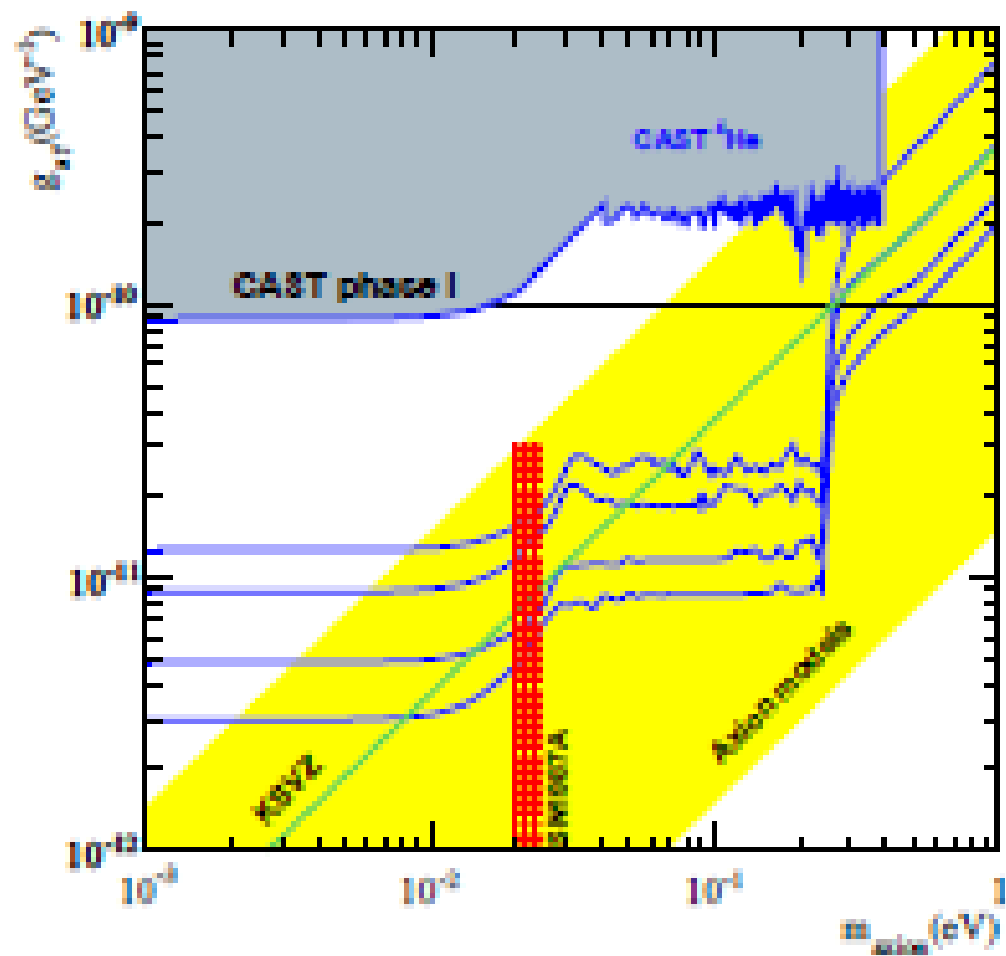
~2020



How much beyond CAST?

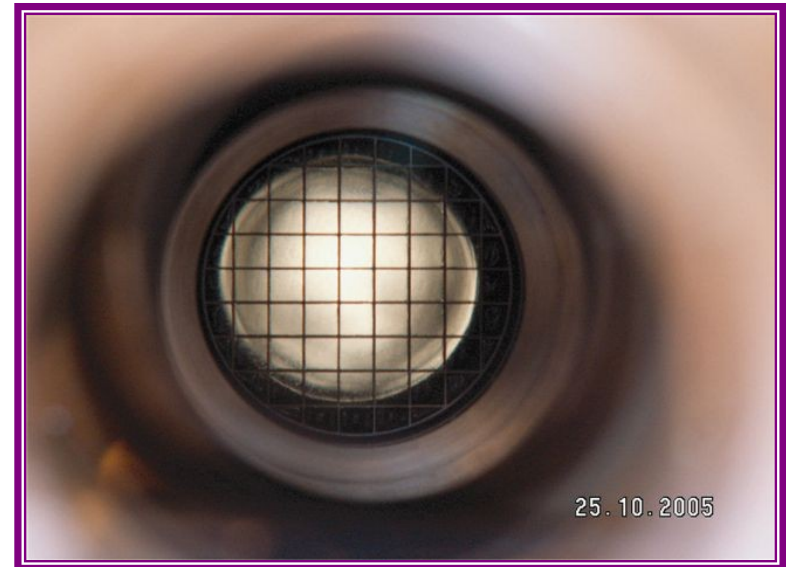
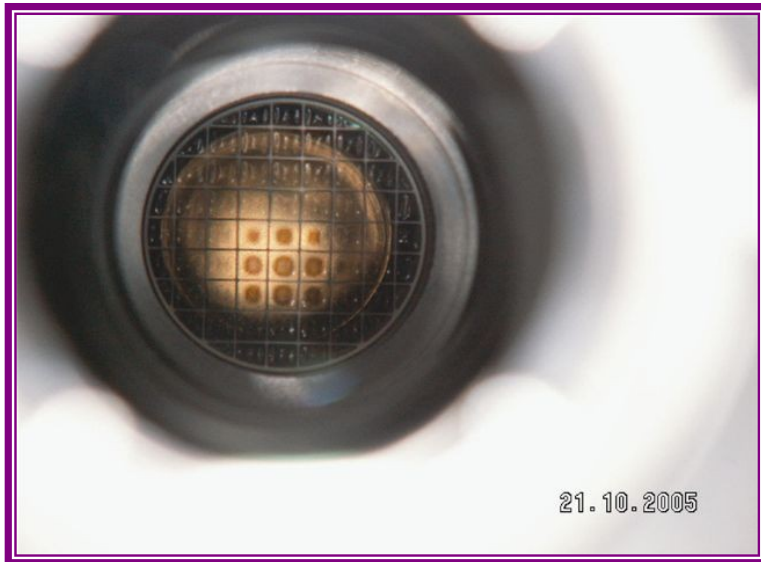
...in ~10 Years





Cold thin Windows

- Observation: “Dark spots” on the windows
 - Condensation of water from residual vacuum (outgassing) of the “warm” side
 - Vacuum better controlled (pumped)
 - Periodic bake out of windows



Precision solar tracking

