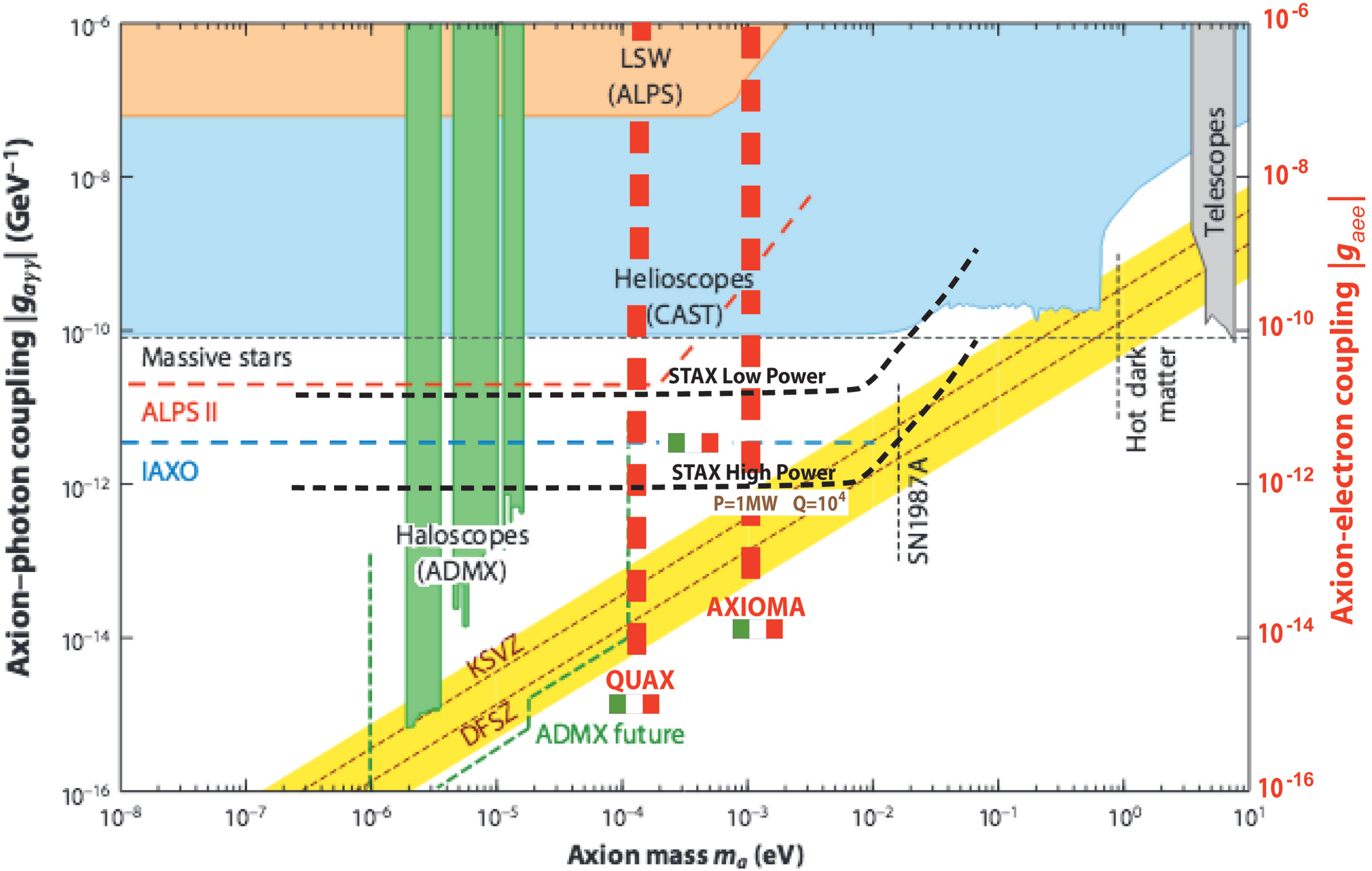
Fundamental Physics & Technological Goals

- Cosmological Axions & ALPS
- Nuclear Clock based on Isomeric Nuclear States
- Dark Energy & Frequency Comb
- Experimental Gravitation

Search for Axion and Axion-Like Particles



Technological Challenges

	Signal power or production probability
ADMX type (vacuum)	$P_{a\gamma\gamma}(W) = 5*10^{-27}\mathrm{W}\left(\frac{V}{500\,\mathrm{liter}}\right)\left(\frac{B_0}{7\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.5*10^{-24}\,\mathrm{gr/cm^3}}\right)\left(\frac{m_a}{2\pi(\mathrm{GHz})}\right)Min(Q_l,Q_a)$
QUAX type (material)	$P_{aee}(W) \approx 10^{-27}\,\mathrm{W}\left(\frac{n_s}{10^{22}\,\mathrm{spin/cm^3}}\right)\left(\frac{V}{100\,\mathrm{cm^3}}\right)\left(\frac{\tau_{\mathrm{rad}}}{10^{-6}\,\mu\mathrm{s}}\right)\left(\frac{m_a}{10^{-4}\,\mathrm{eV}}\right)^3$
STAX type (Regeneration)	$P_{\gamma\to a\to\gamma} = 6*10^{-38}F_{PC}F_{RC}(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\frac{B}{1\,\mathrm{T}}\frac{l}{10\,\mathrm{m}})^4$

Techniques to be developed

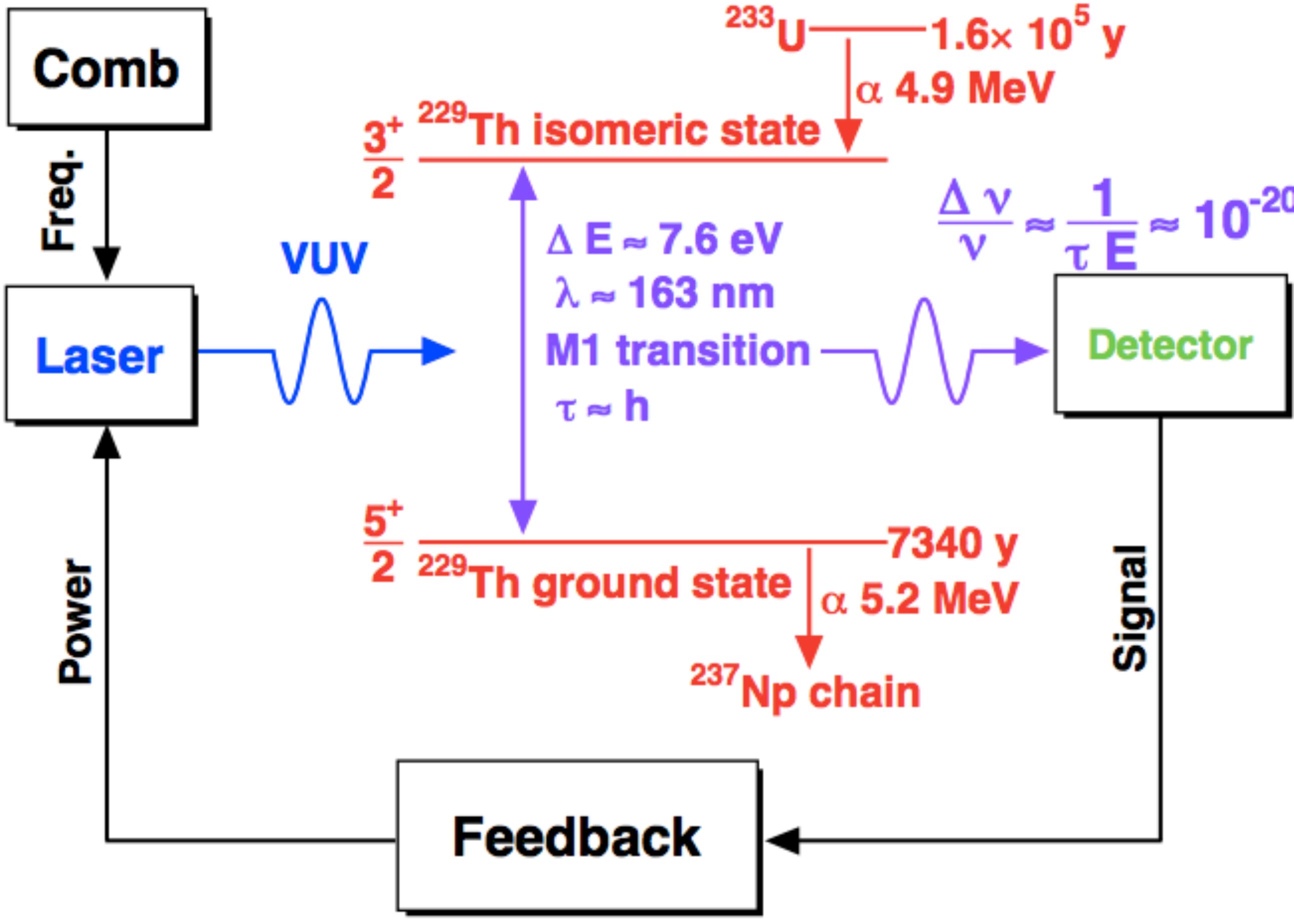
- High dipolar magnetic field
- Millikelvin cryogenics
- High Q microwave cavity in strong magnetic field
- Single photon detector @ microwave energy
- Single spin-flip detection through atomic spectroscopy
- EPR magnetometry

^{229}Th-based Nuclear Clock

1. Lowest nuclear exited state[1],
2. only indirect observation[2],
3. VUV-laser excitation,
4. very narrow linewidth[3],
5. $N = 10^5 \div 10^{12}$ oscillators[4,5],

$$FoM = \frac{\nu\sqrt{N}}{\Delta\nu}.$$

6. Radiotherapy with ^{225}Ac,^{213}Bi decay prod.[6].



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at SPES (LNL) applicative line:
35 MeV, 0.5 mA proton beam,
1.5 mm thick ^{232}Th target (22 g),
production $\sigma(p,4n) \simeq 100$ mb[1],
8.3×10^{17} atoms of ^{229}Th
in 1 week of irradiation.
Disposal of FFs and ^{227,228}Th.

2. Measurement of lowest level:
^{233}U target activity $0.35\times M_U[ng]$,
signal length <10 ms, ($M_U<30$ ng),
$\sim$2% decay into 7.6 eV level,
μcalorimeter resolution <0.5 eV,
$\sigma_E \sim 0.15eV\sqrt{M_U[ng]}$, ($M_U<10$ ng),
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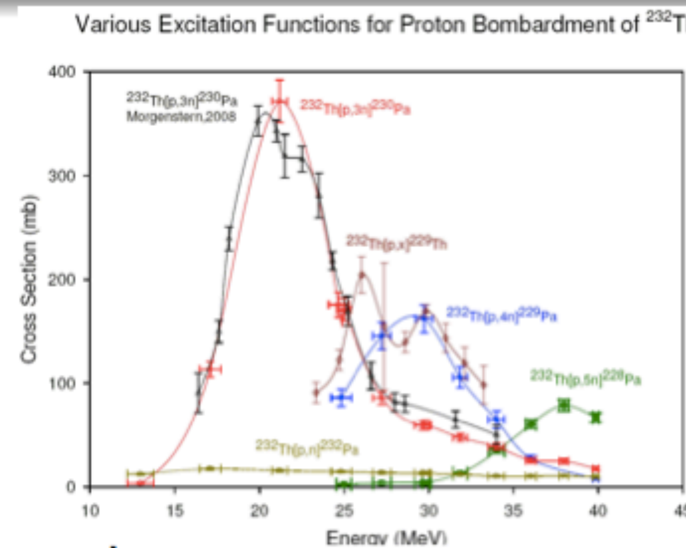

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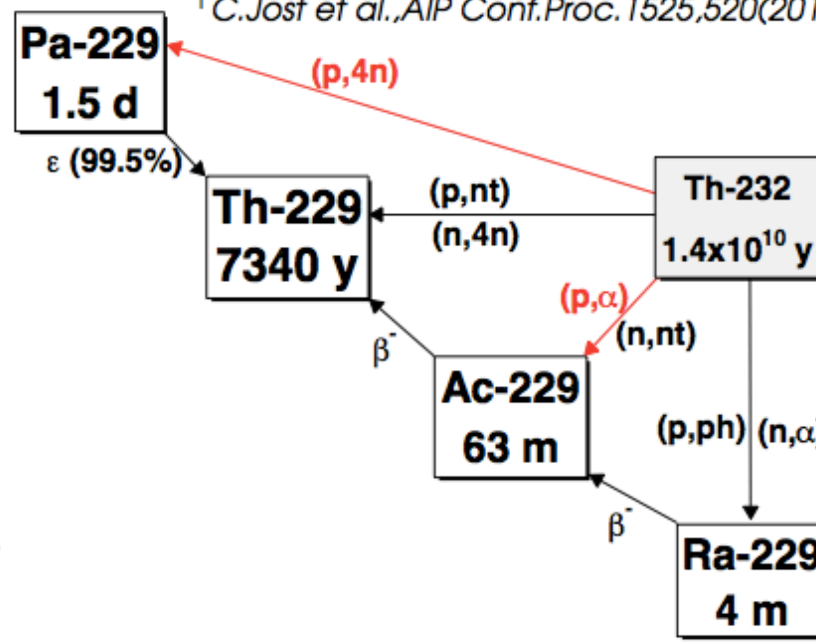
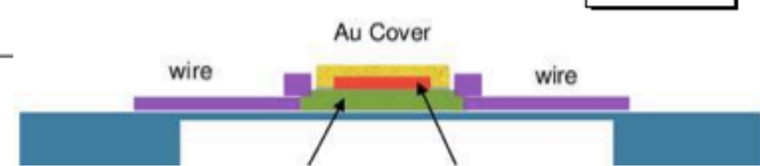
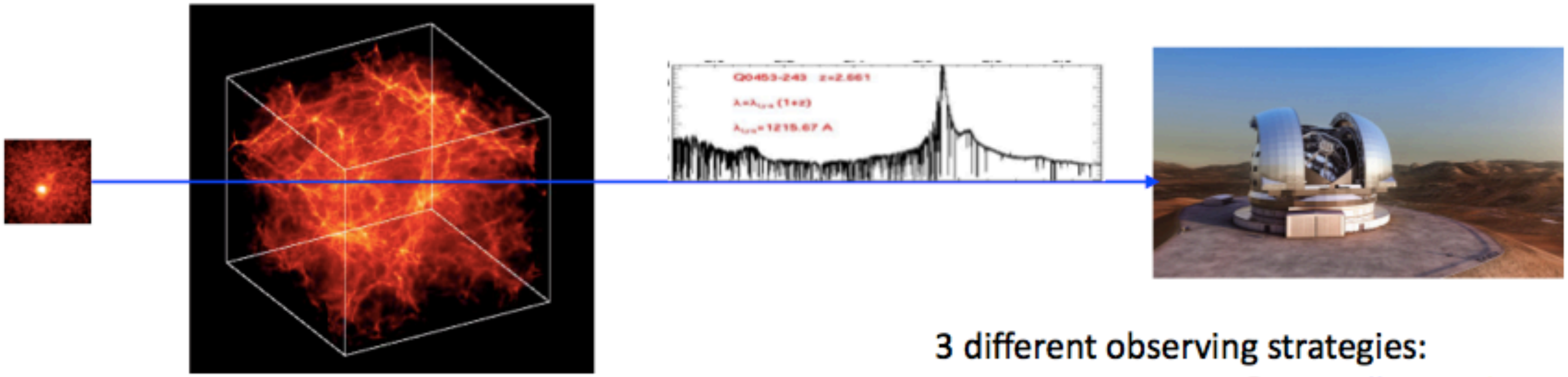




Dark Energy & Frequency Comb



3 different observing strategies:
Best constraints on Ω_{Λ}, smallest σ_{v}, largest signal

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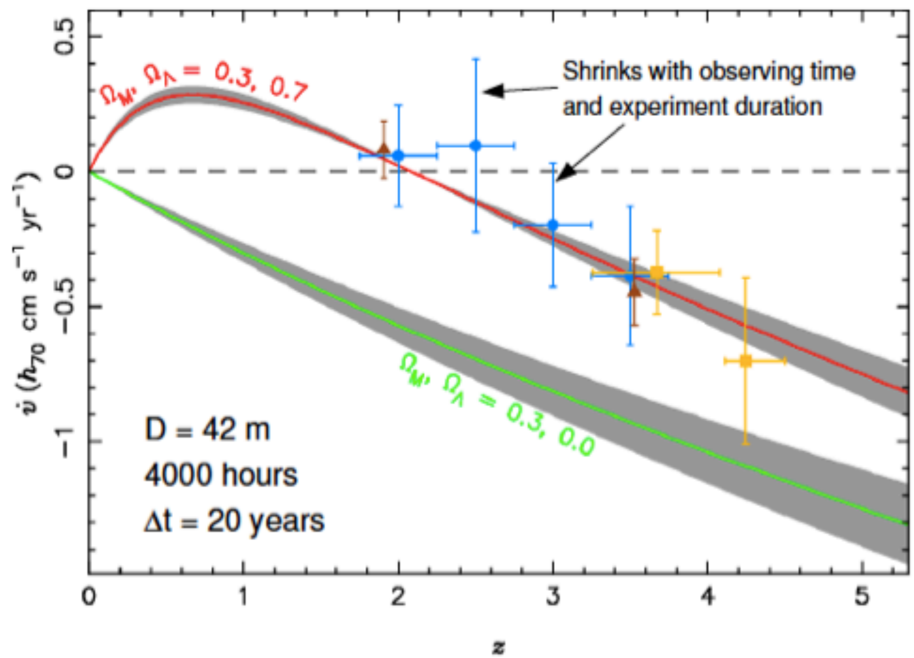
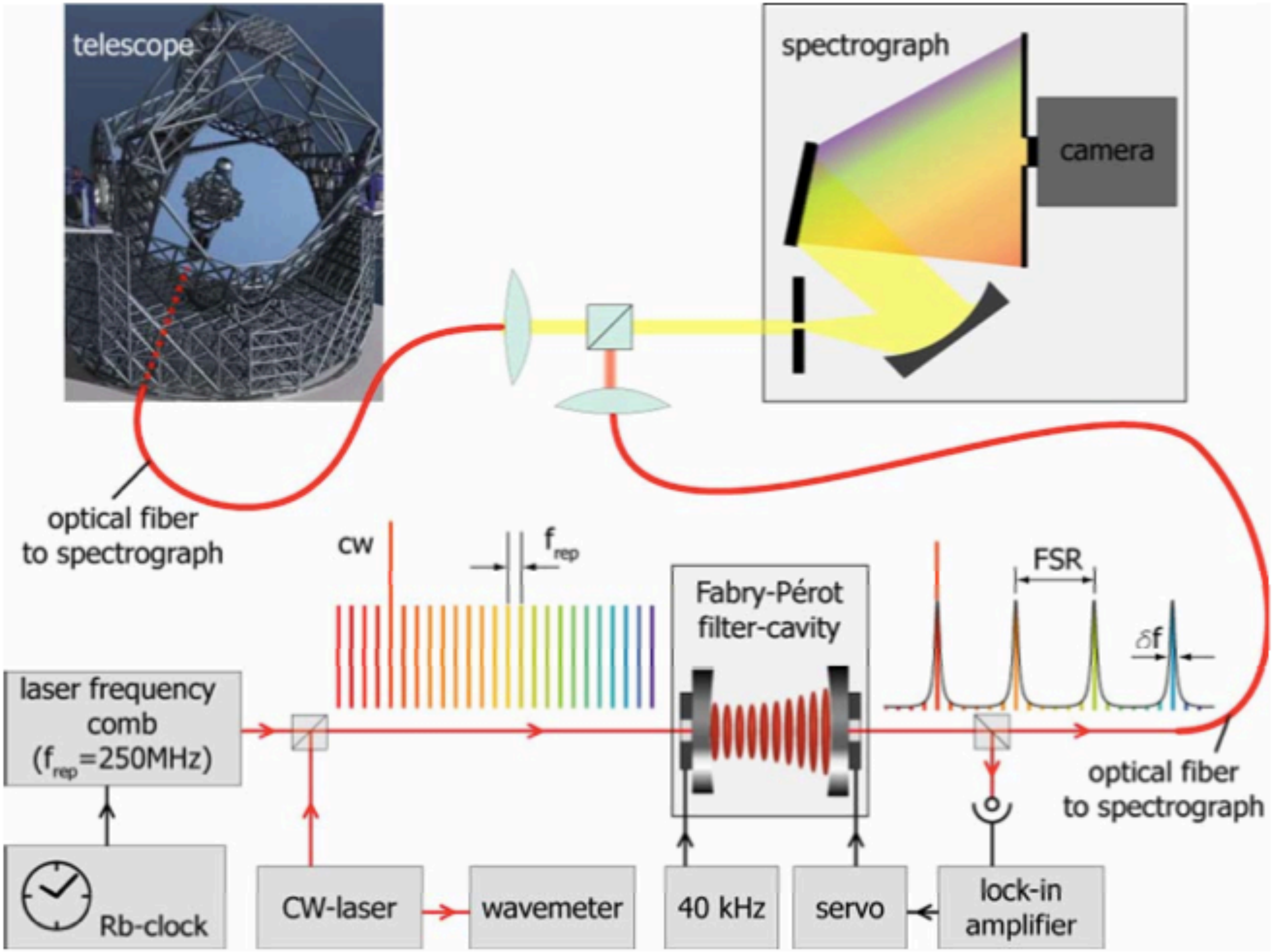


Sandage 1962, Loeb 1998, Liske+ 08

Setup



telescope
spectrograph
camera
optical fiber
to spectrograph
cw
f_{rep}
Fabry-Pérot
filter-cavity
FSR
δf
laser frequency
comb
(f_{rep}=250MHz)
optical fiber
to spectrograph
Rb-clock
CW-laser
wavemeter
40 kHz
servo
lock-in
amplifier

FREQUENCY COMB FOR NEW PHYSICS

- High resolution laser spectroscopy
  - testing QED
  - testing special relativity
  - determination of fundamental constants
  - detect or limit slow time evolution of these constants
- Optical atomic clocks
- Controlling the electric field transients of pulses
  - generation attosecond pulses
- Direct comb spectrocopy
  - high resolution XUV laser spectroscopy
- Calibration of astronomical spectrographs
  - detecting extra-solar planets
  - temporal evolution of constants on cosmological time scales
  - confirm or rule out existence of dark energy
  - solar gravitational red shift

Experimental Gravitation

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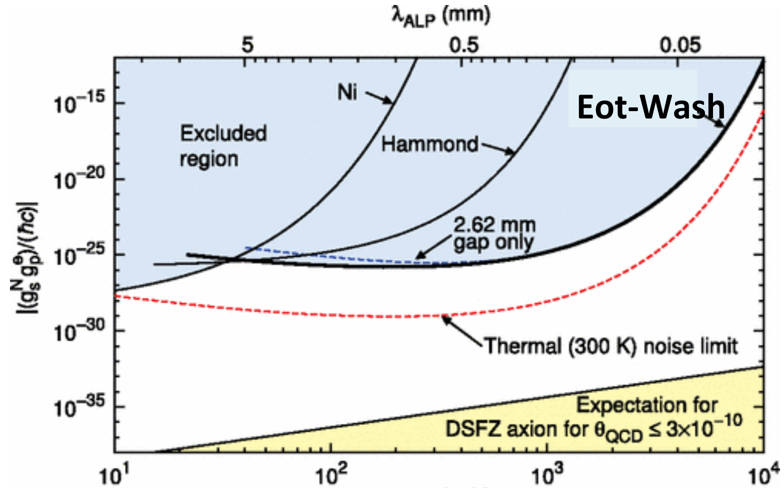
$$V_{\rm md} = \frac{\hbar g_s g_p}{8\pi m_e c}\left[(\hat{\sigma}\cdot\hat{r})\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\right]e^{-r/\lambda}$$



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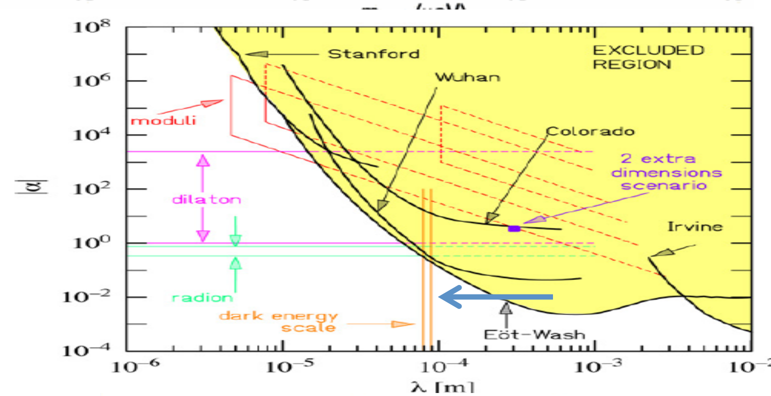
Extra dimensions tens microns size

Atom Interferometry : Magia approach



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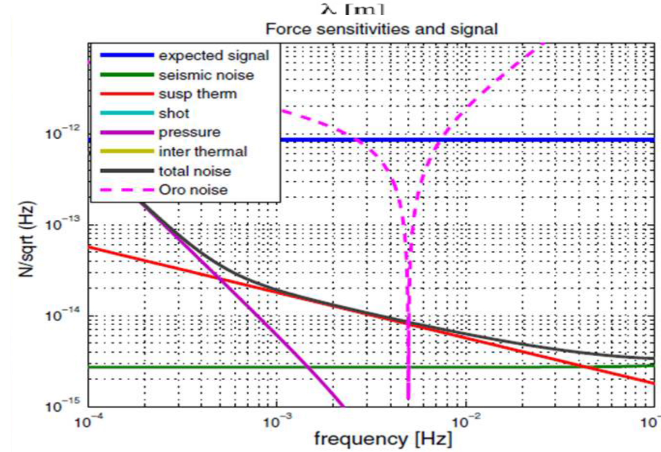
Quantum gravity and Lagrangian points

MOND test



Gravitation with Macroscopic Detectors

The instrumental heritage of few decades of experiments

Best sensitivity to small forces in macroscopic test bodies in 10 – 100 Hz frequency band – Virgo driven
(now comparable in LIGO)
Lowest frequency limit, 100 mHz, inertial suspension in the world – Virgo driven
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Best torsion pendulum torque sensitivity in 1-10 mHz frequency region - LISA driven (Comparable with Eot-Wash)

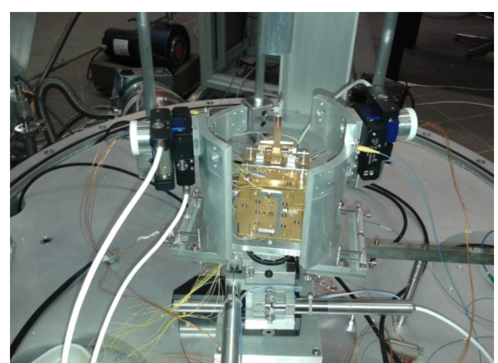
Room temperature and cryogenics acceleration and rotational sensors
(Virgo-LISA – …. driven)

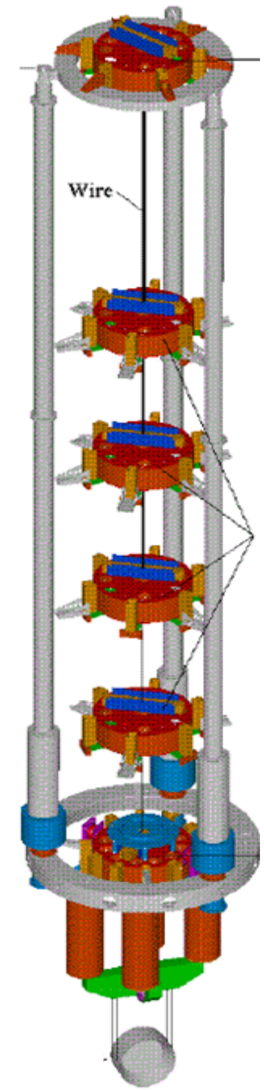
The possibile future instrumental evolution

Enlargement of the detection bandwidth toward 1 Hz region

Inertial suspension lower limit toward 1 mHz

Cryogenic e/o Underground torsion pendulums and beam-balances





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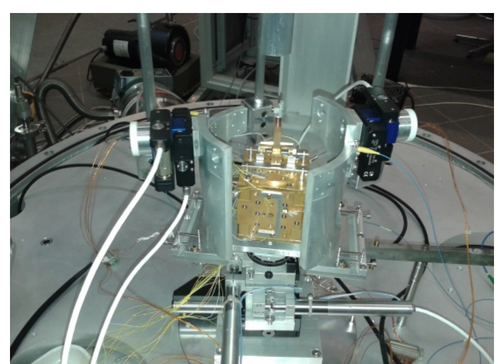

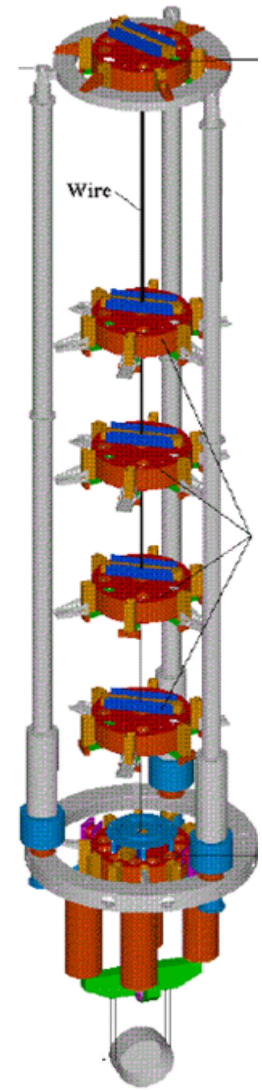

Gravitational and Fundamental Physics Items

Axion like bosons with scalar coupling gs search via monopole-dipole interacion

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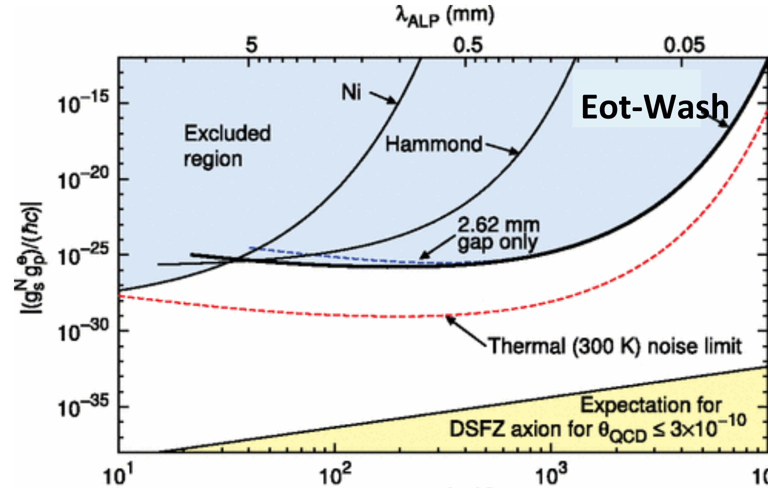

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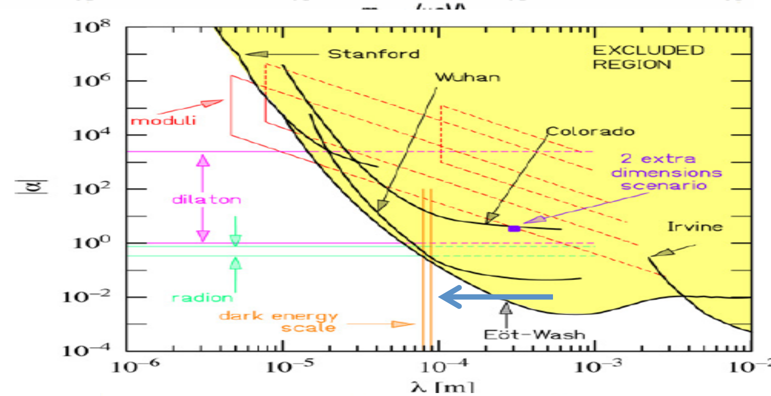
Chamelons



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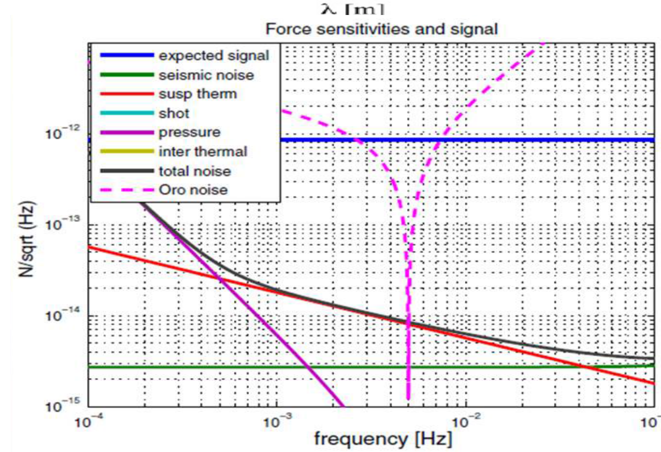
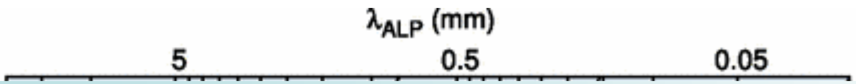
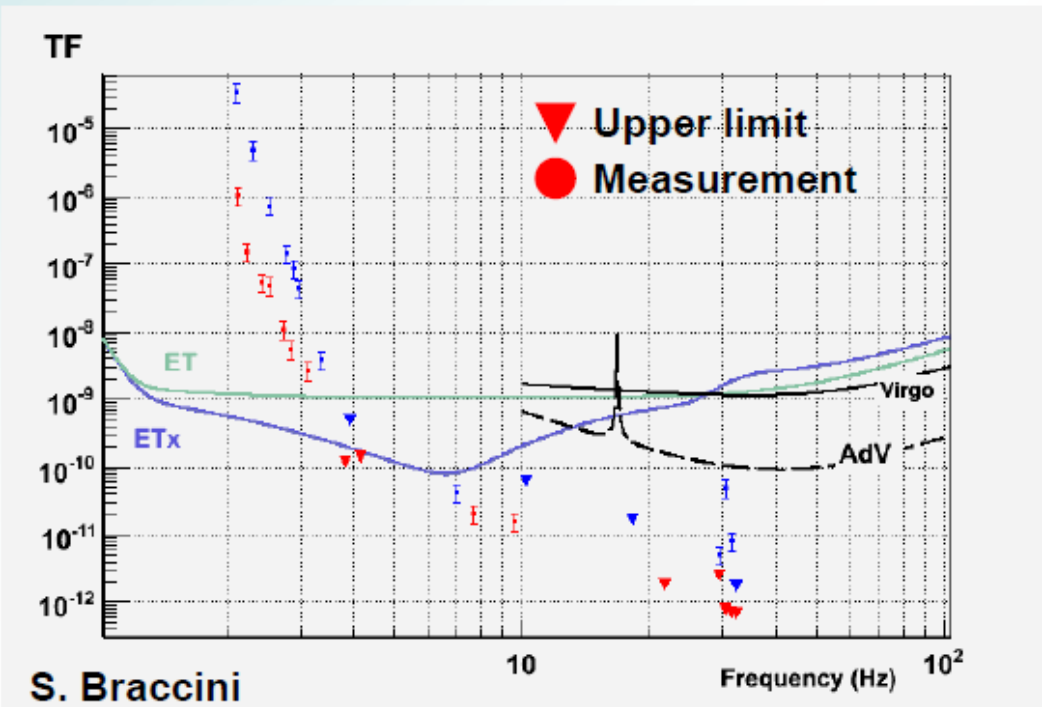
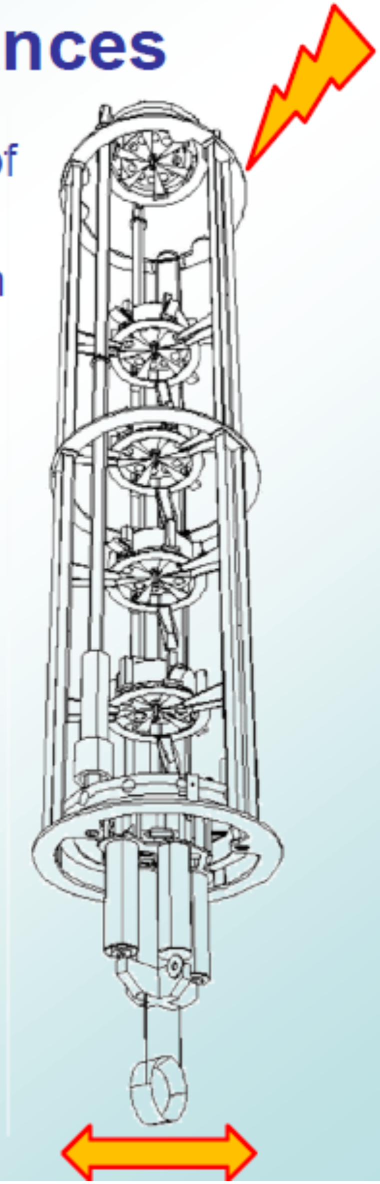




Super attenuator performances

- Direct measurements (or upper limits) of the coupling of excitations at top stage to mirror motion
- Does not include additional effect of inverted pendulum pre-isolation stage (resonance about 40 mHz)





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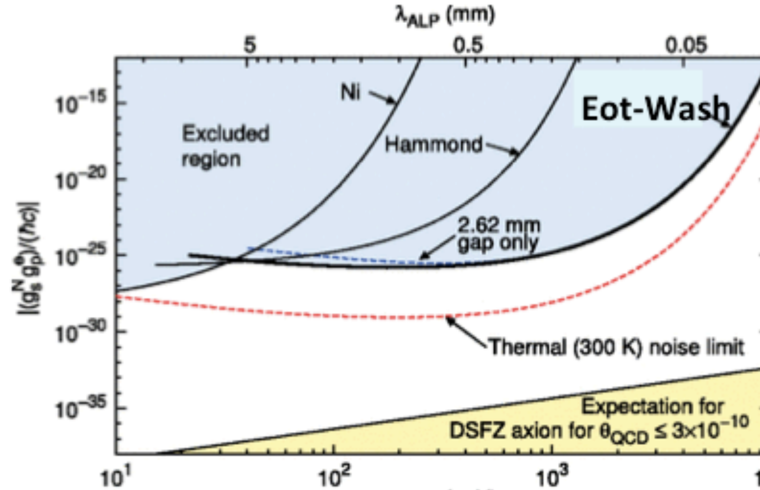

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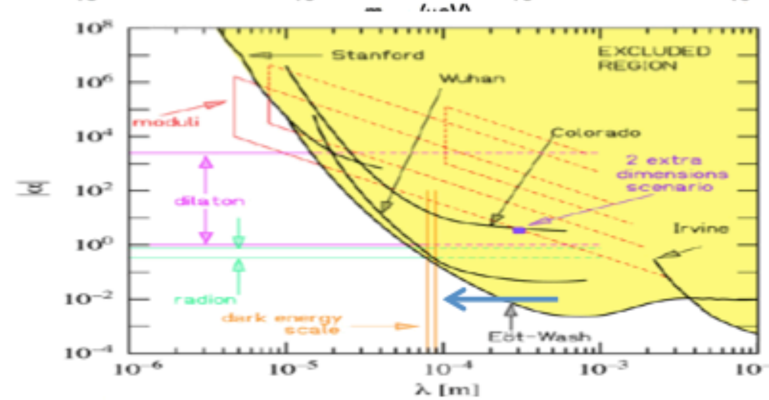

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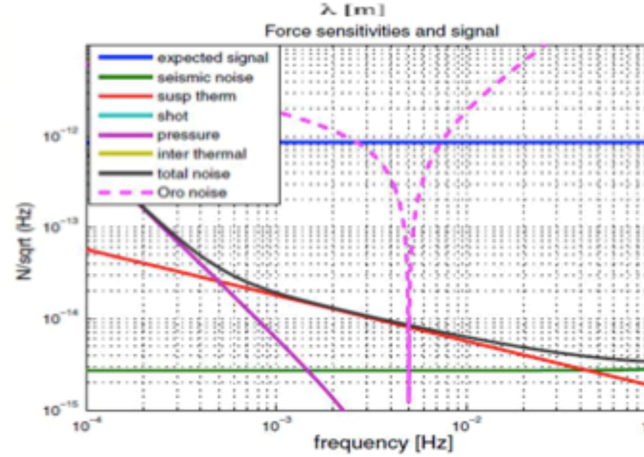

^{229}Th-based Nuclear Clock

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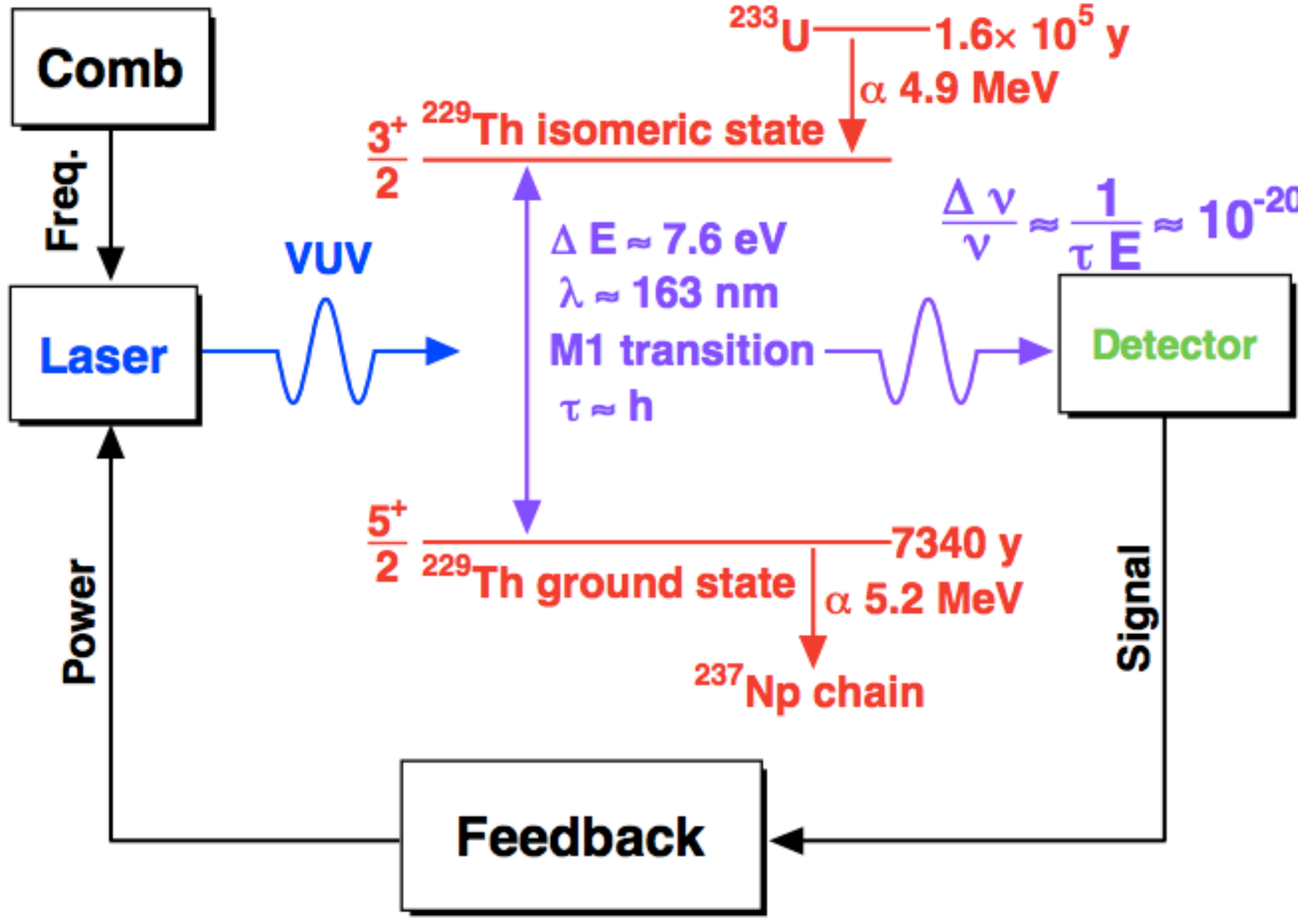

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at SPES (LNL) applicative line:
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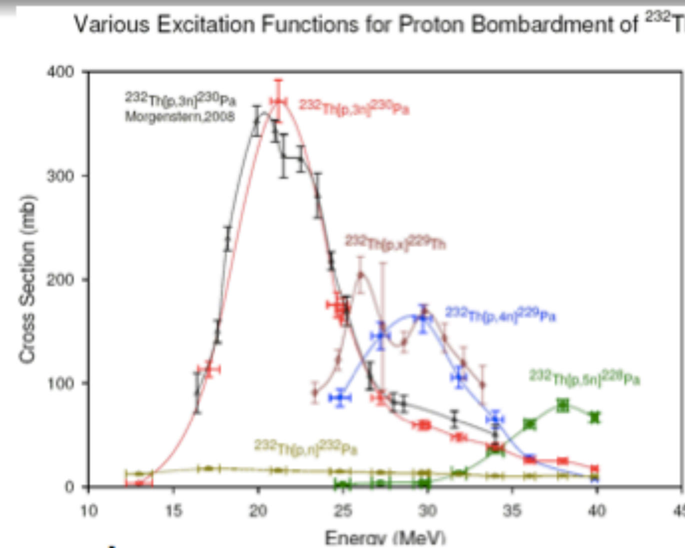

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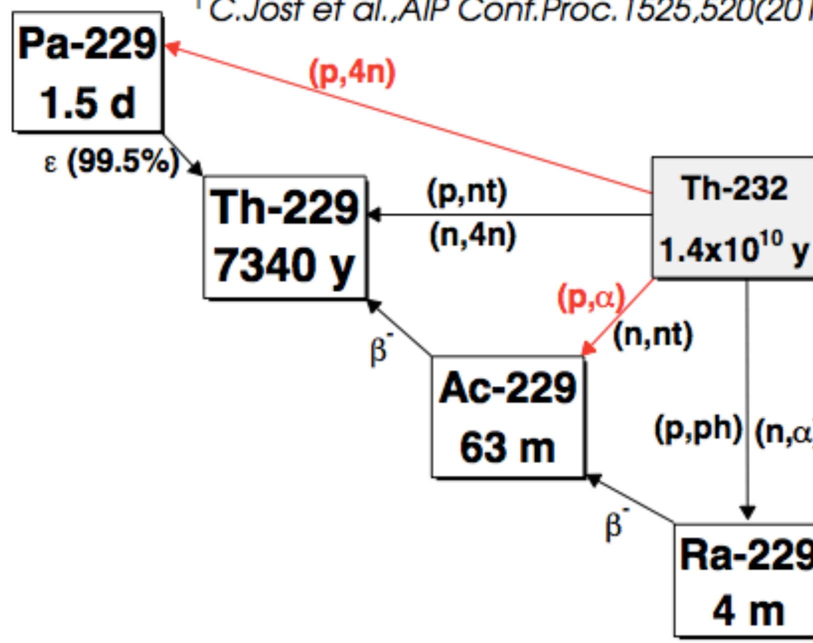

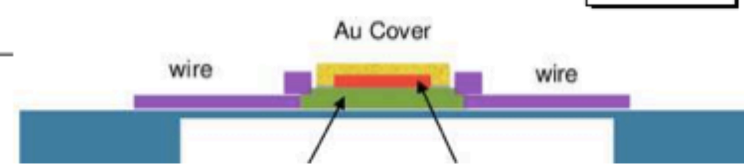

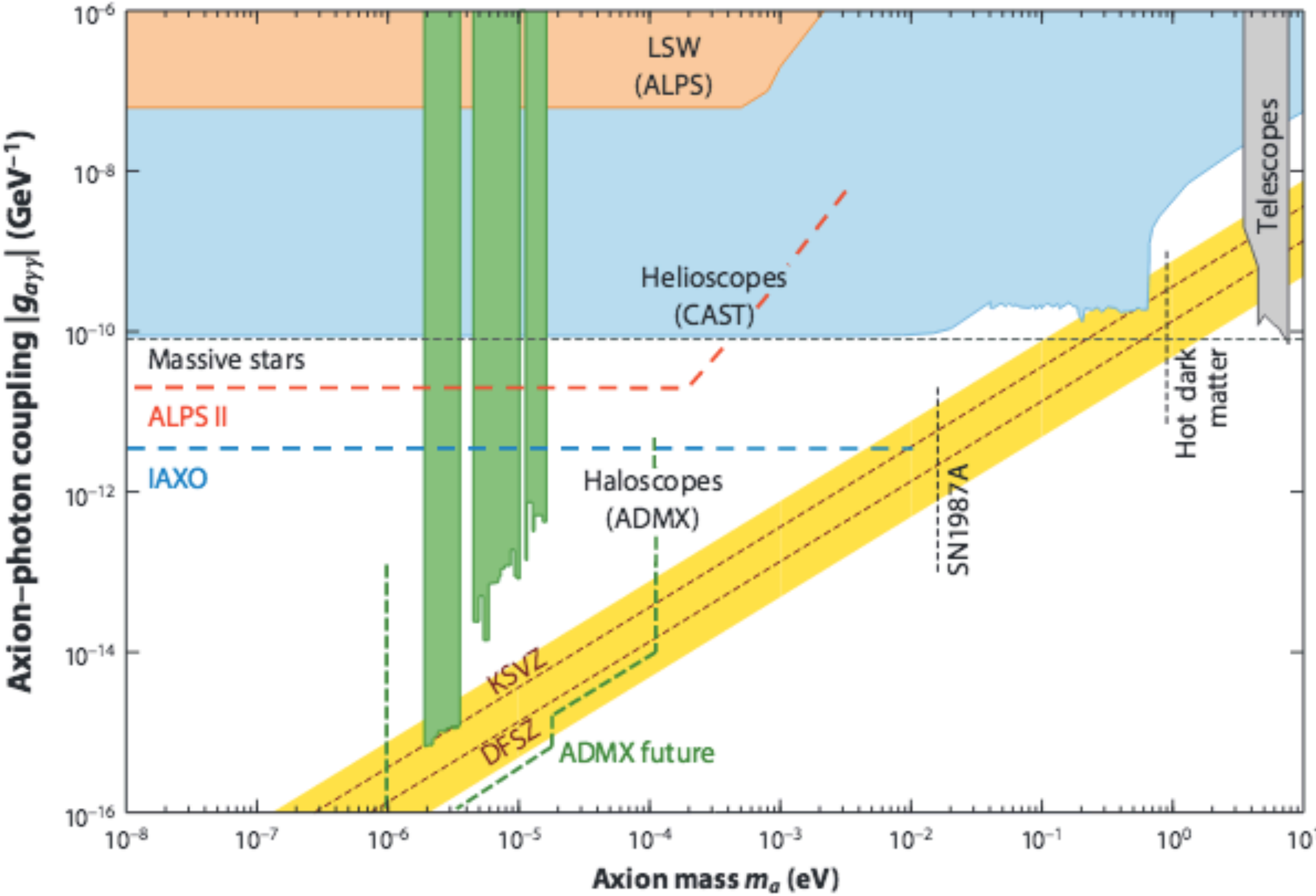
LSW
(ALPS)
Helioscopes
(CAST)
Telescopes
Massive stars
ALPS II
IAXO
Haloscopes
(ADMX)
Hot dark
matter
SN1987A
KSVZ
DFSZ
ADMX future
Axion–photon coupling |$g_{a\gamma\gamma}$| (GeV^{-1})
Axion mass m_a (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-8}
10^{-7}
10^{-6}
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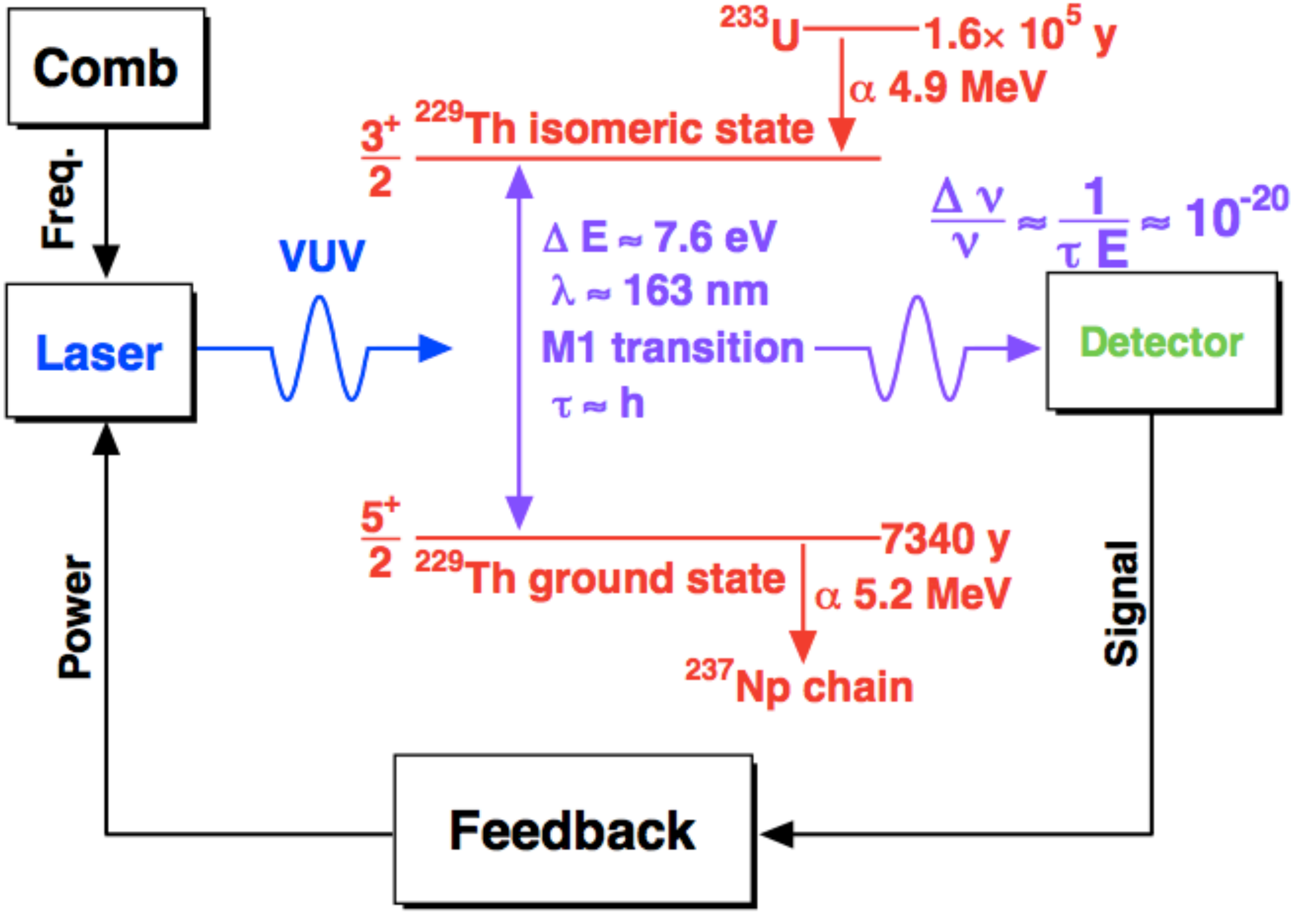

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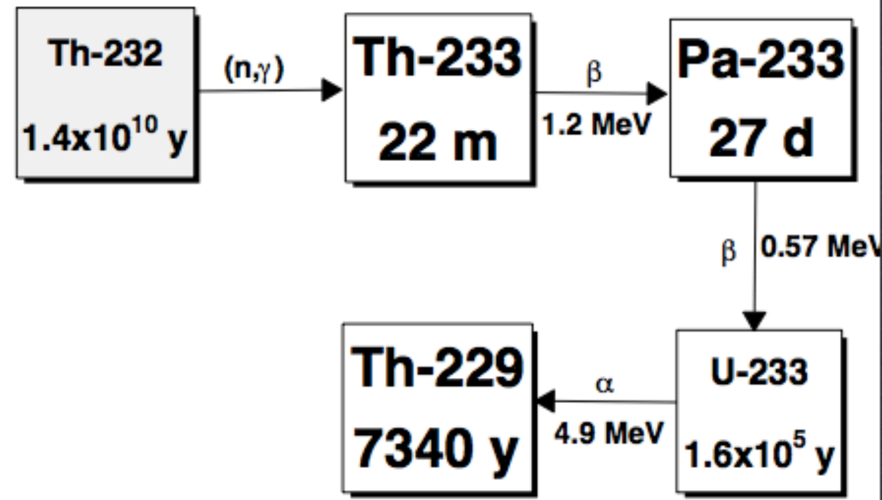
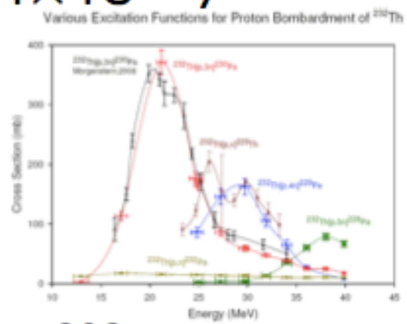
Production of ^{229}Th

Reactor based:

1. from ^{233}U stockpiles, e.g. from HTGR (Germany,89) or PWR (USA,80) reactors, in 10 y aged material fraction of ^{229}Th is 4×10^{-5},





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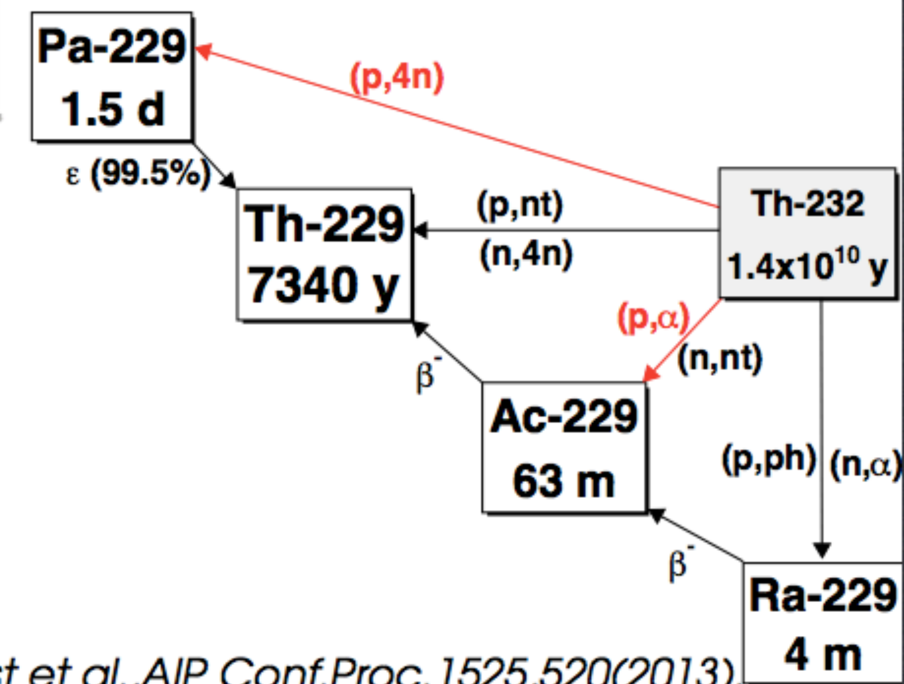

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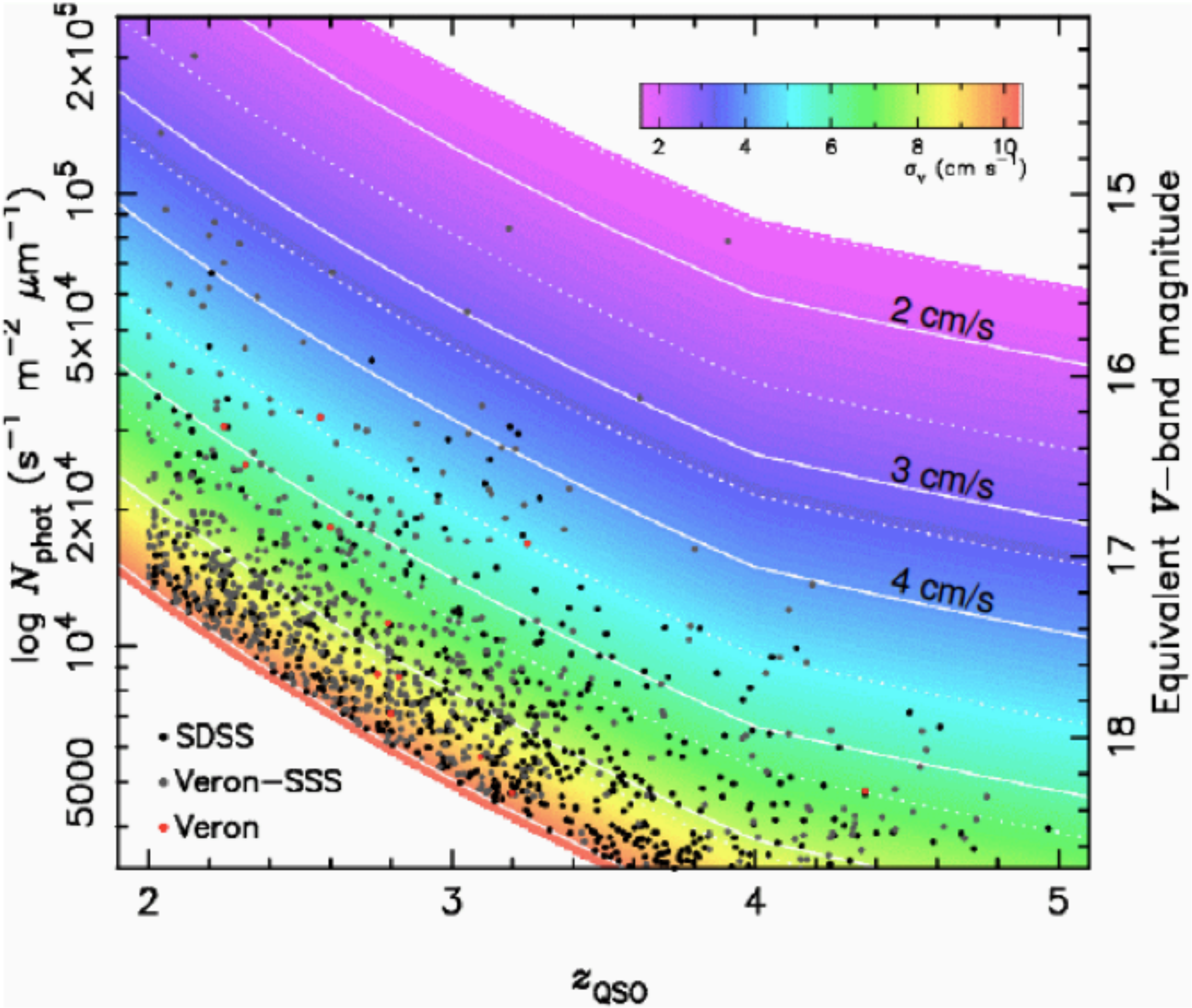
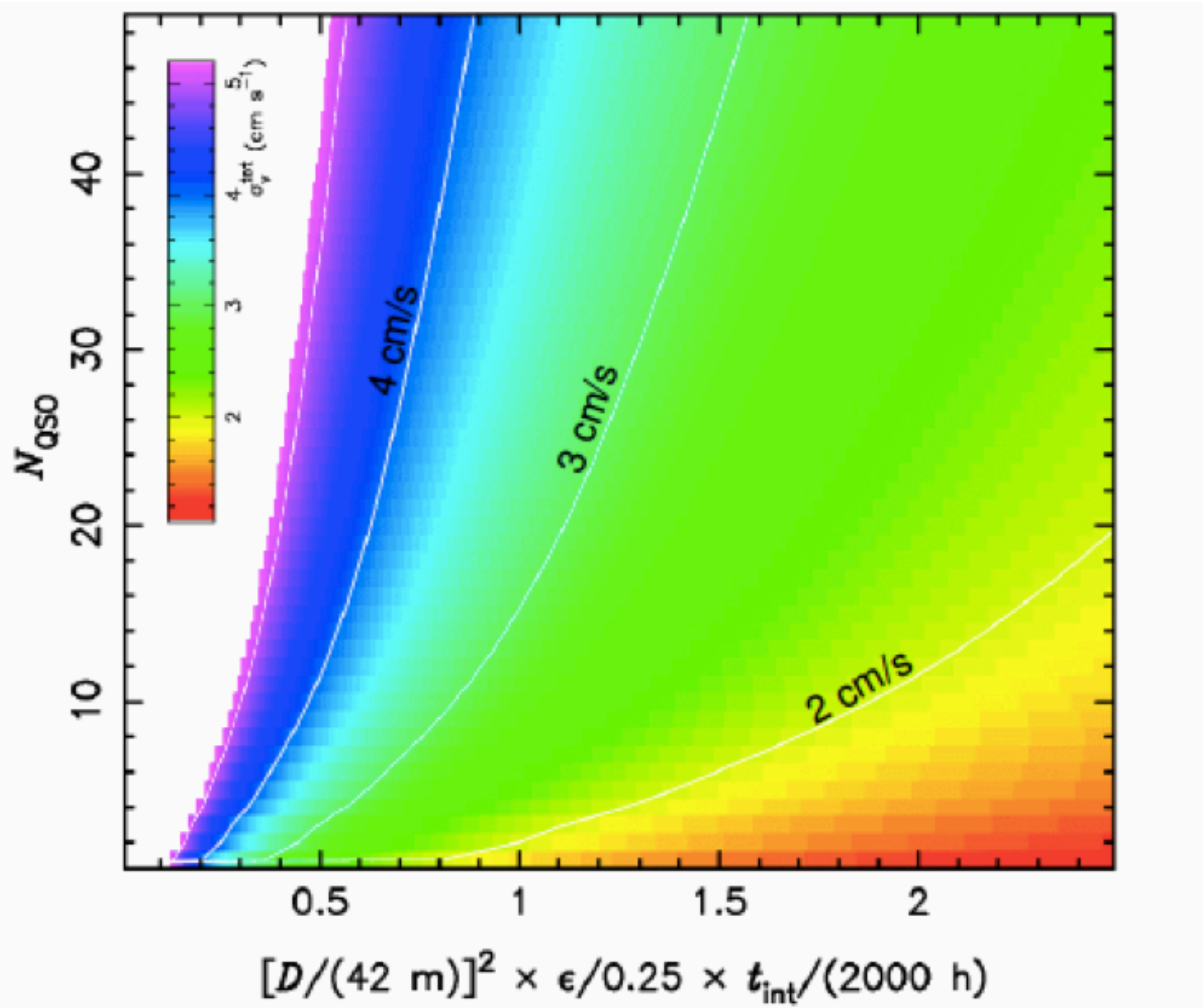
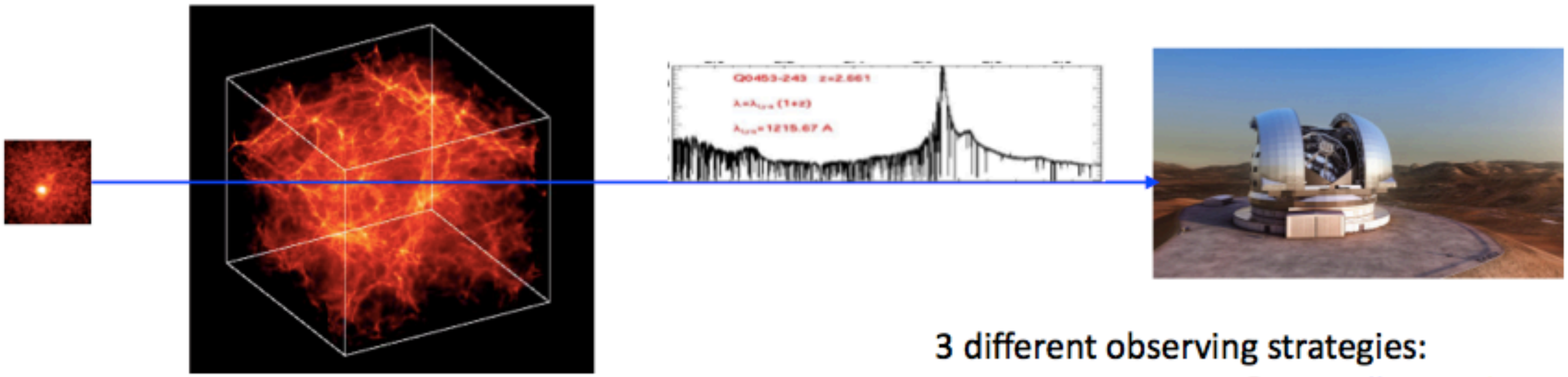
Are there enough photons?





σ_v^{tot} (cm s^{-1})
5
4
3
2
4 cm/s
3 cm/s
2 cm/s
N_{QSO}
10
20
30
40
0.5
1
1.5
2
$[D/(42\ \mathrm{m})]^2 \times \epsilon/0.25 \times t_{int}/(2000\ \mathrm{h})$



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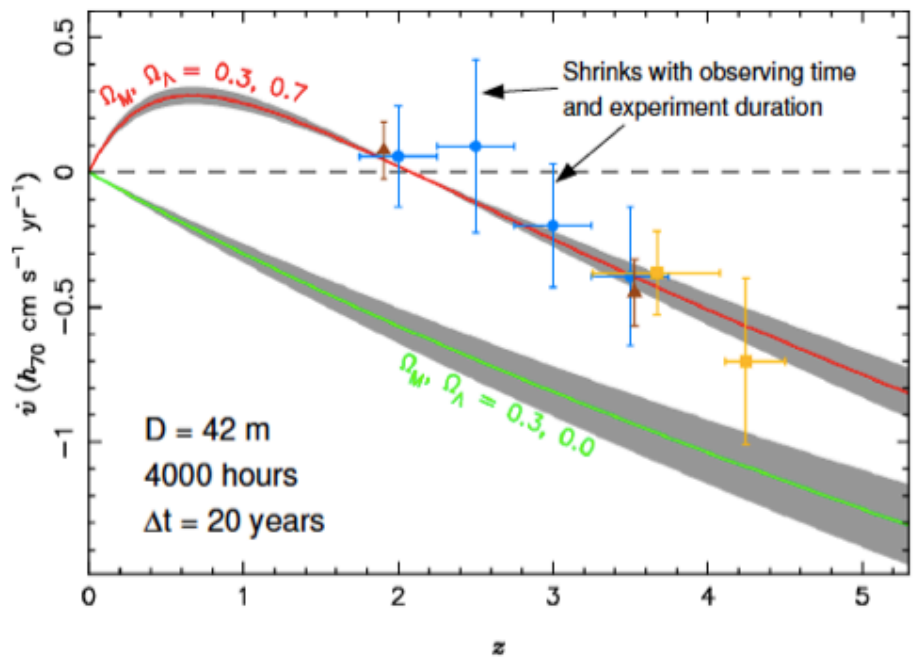
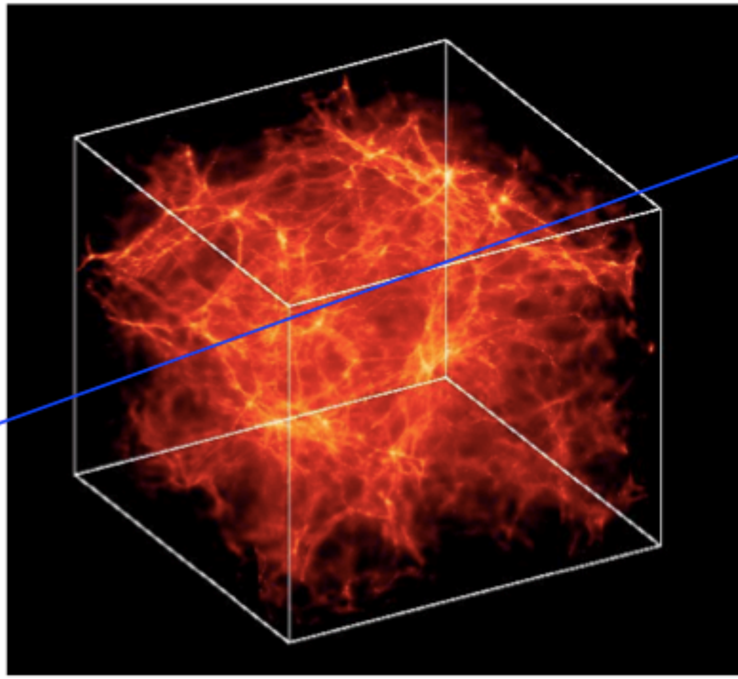
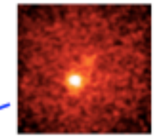


Sandage 1962, Loeb 1998, Liske+ 08

The Intergalactic Medium: Theory vs. Observations

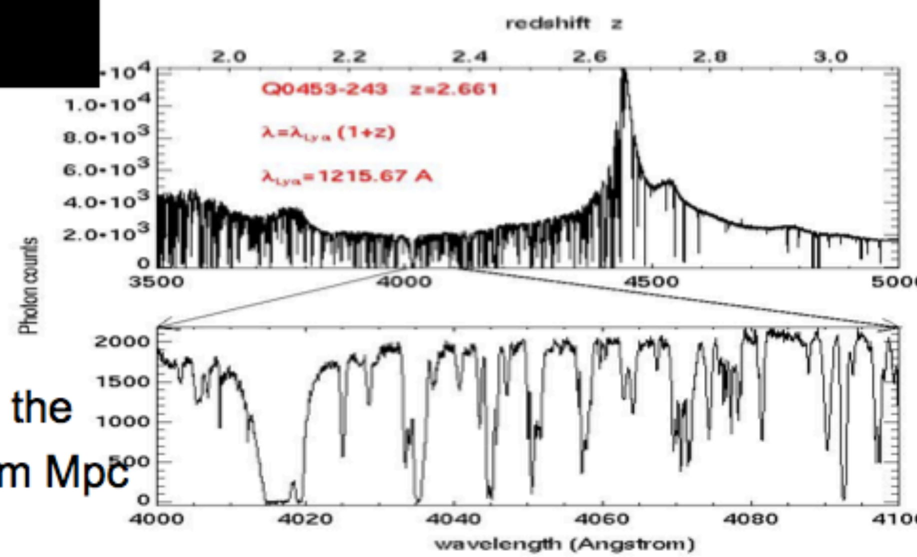




80 % of the baryons at z=3 are in the **Lyman-α forest**

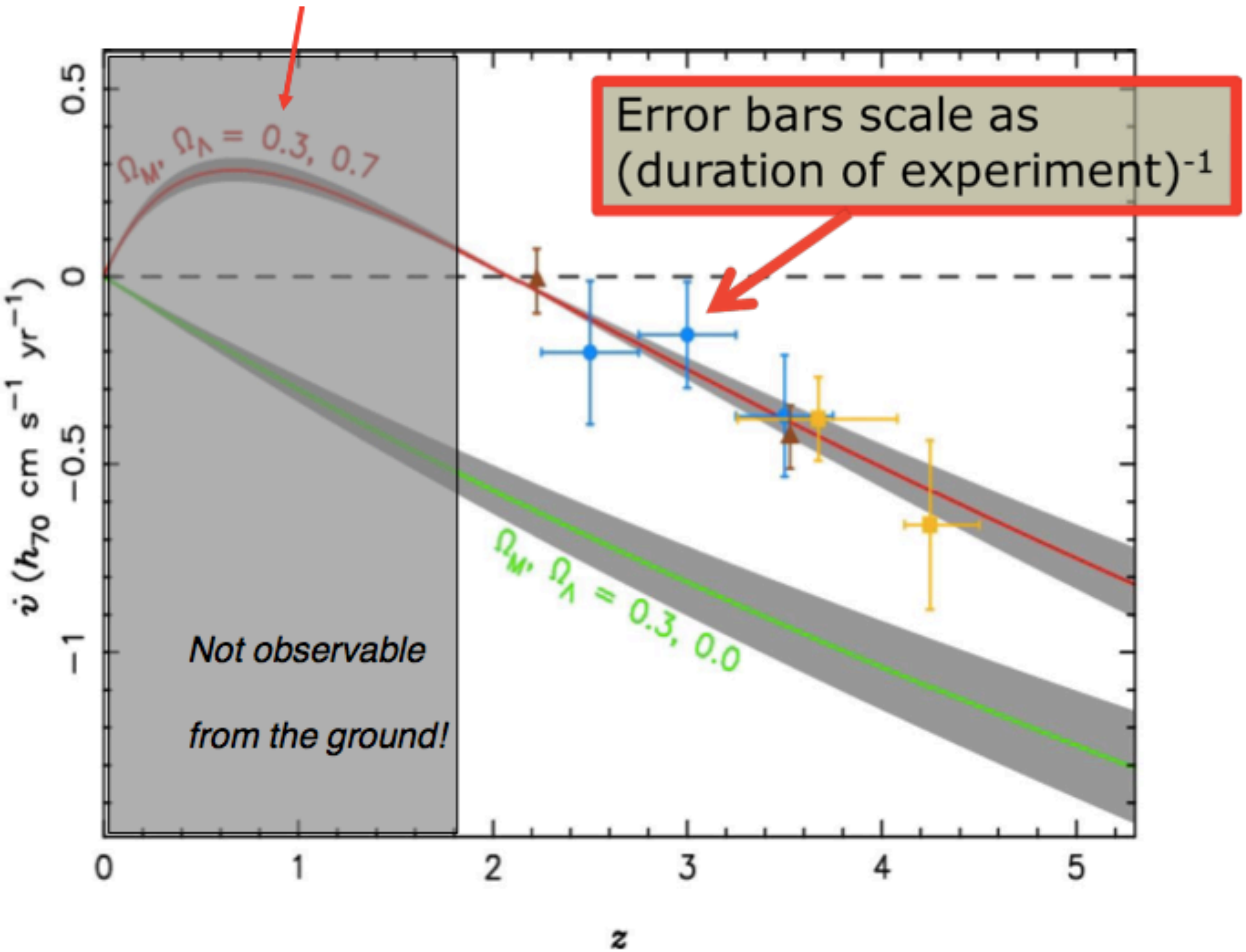
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)

baryons as tracer of the dark matter density field



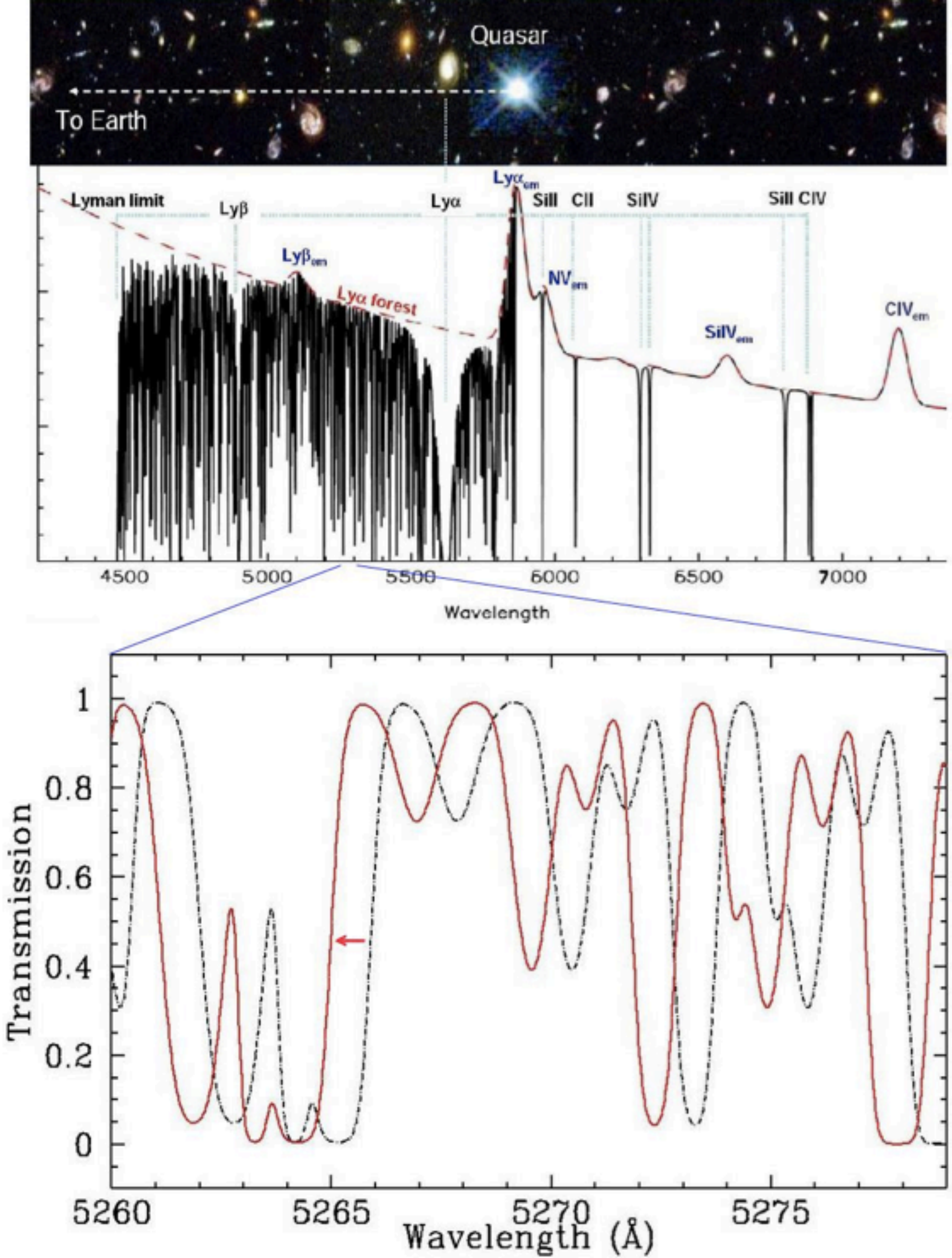
$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

$\tau \sim (\delta_{IGM})^{1.6}\, T^{-0.7}$



- Different coloured points reflect different targeting strategies
- 4000 hrs on 39-m E-ELT over 21.5 years, *or*
- 1200 hrs on 39-m E-ELT over 40 years

Pasquini et al. 2005, Cristiani et al. 2007, Liske et al. 2008



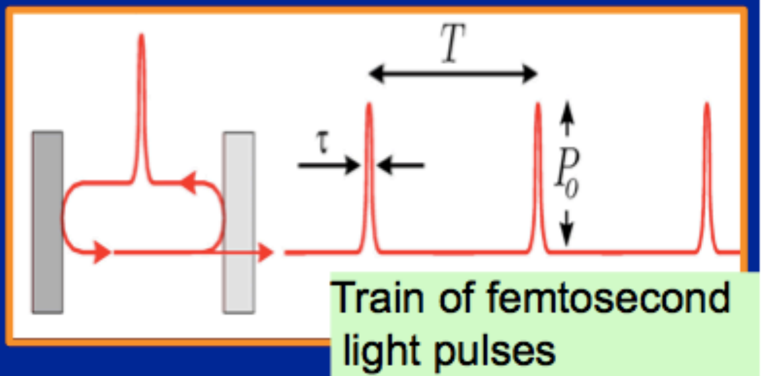
The Lyman Forest

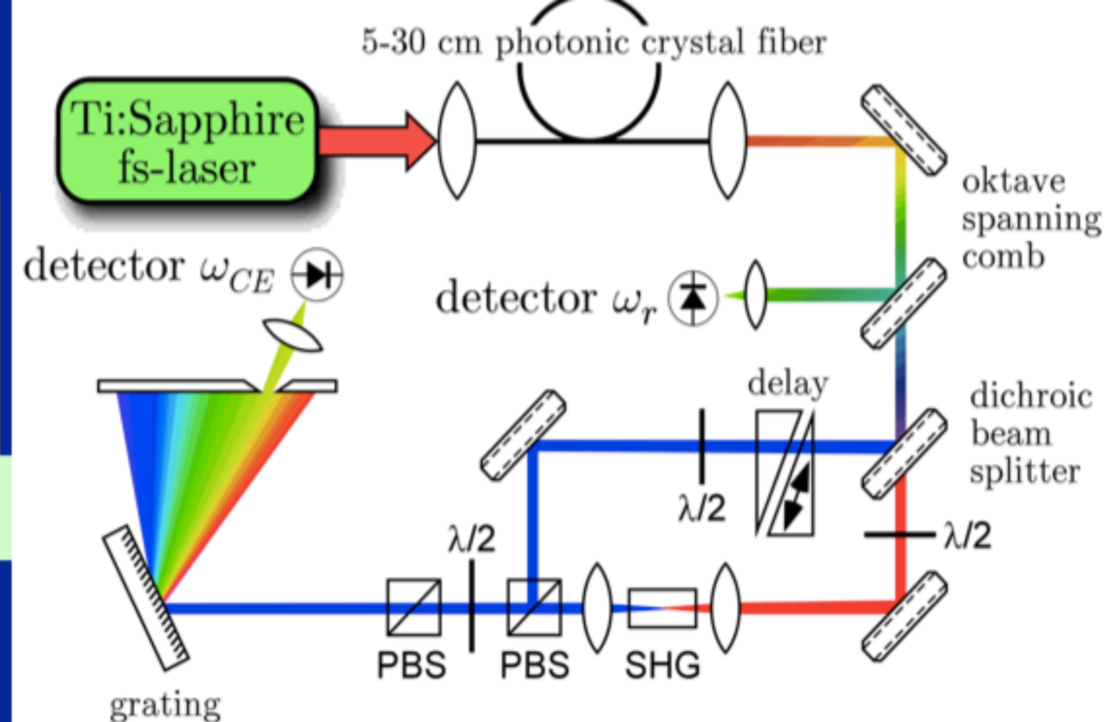
Today and …

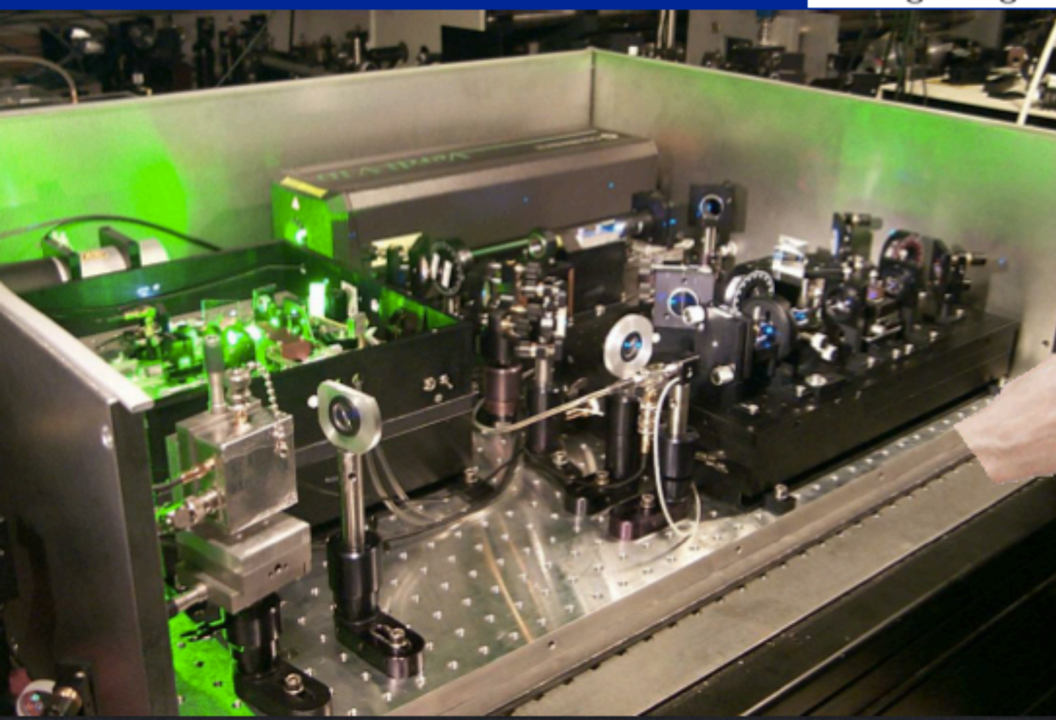
… years after

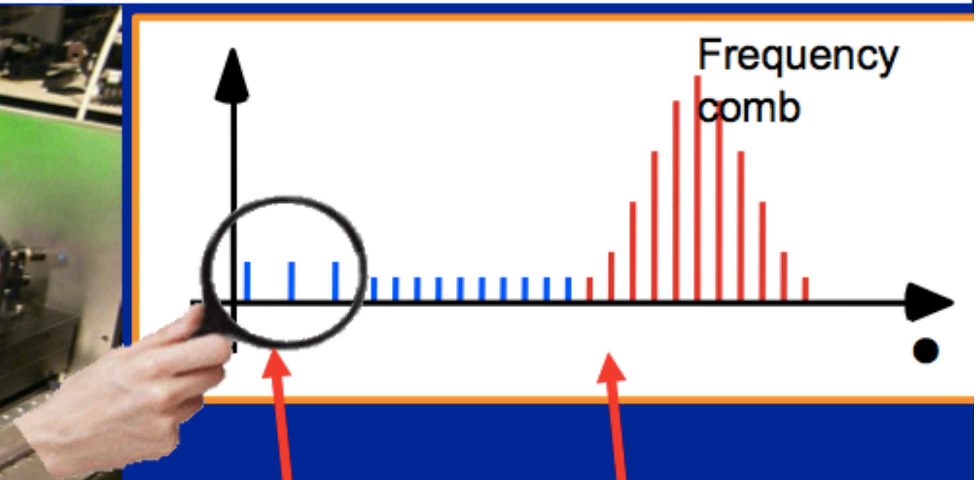
Laser Comb

Thomas Udem (MPQ)









Zero offset and line spacing known with absolute precision (limit = atomic clock.)

Measurement of lowest ^{229}Th level

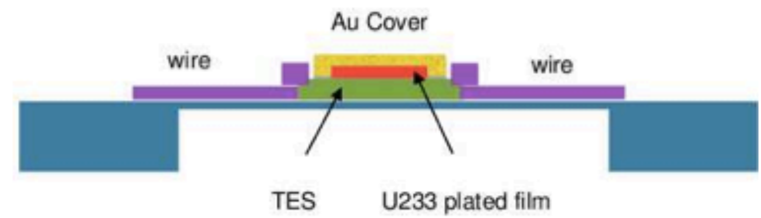
1. ^{233}U target activity,

$$A_\alpha = 0.35 \times M_U[ng] \ .$$

2. $\sim$2% decay into 7.6 eV level,
3. μcalorimeter,
4. signal length 1 ms (R$<$100 Hz $\rightarrow$ $M_U$$<$300 ng),
5. resolution $<$1 eV ($M_U$$<$43 ng),

$$\sigma_E \sim \sqrt{kT^2C} \sim 0.15eV\sqrt{M_U[ng]} \ .$$

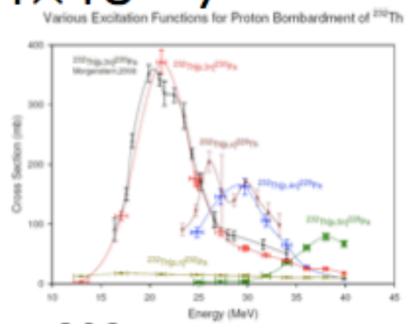
6. calibration 6.2, 11.6, 19.8 eV U atomic levels,
7. background.



Production of ^{229}Th

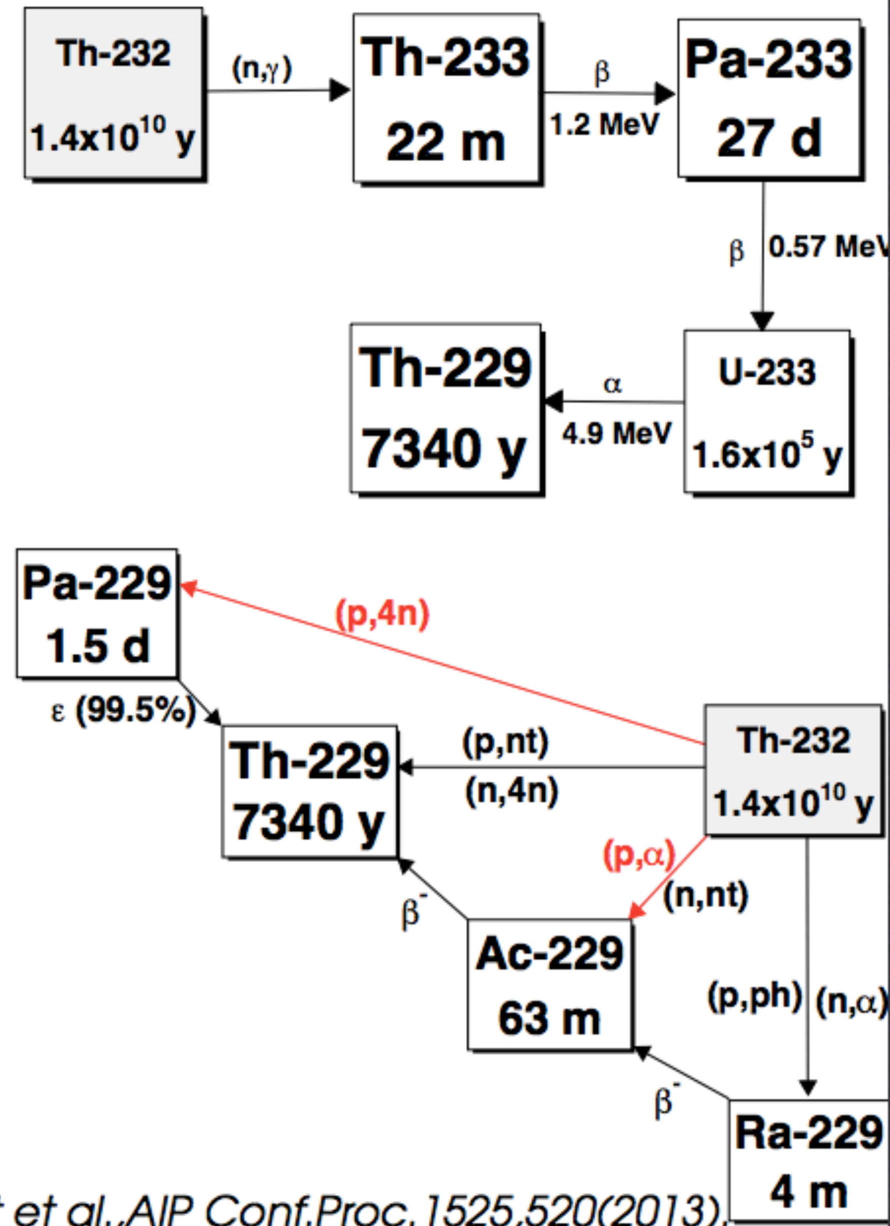
Reactor based:

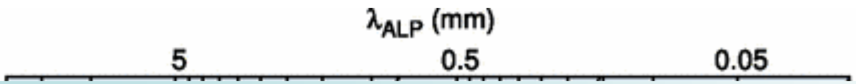
1. from ^{233}U stockpiles,
e.g. from HTGR (Germany,89)
or PWR (USA,80) reactors,
in 10 y aged material
fraction of ^{229}Th is 4×10^{-5},



Accelerator based:

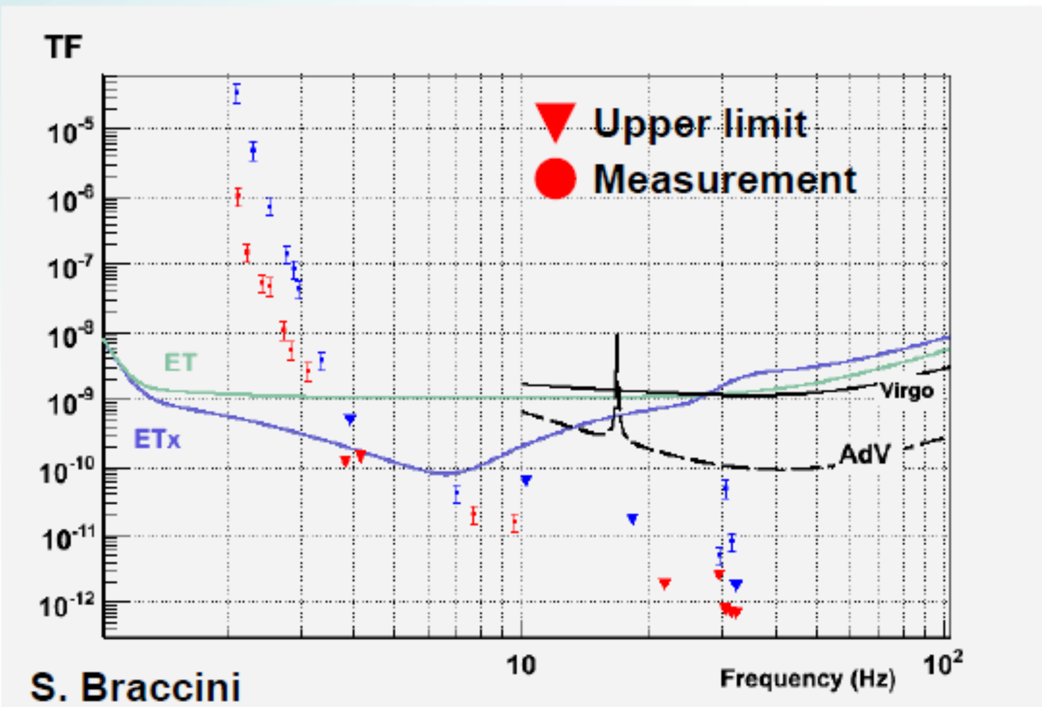
2. $^{232}Th(p,4n)$ and $^{232}Th(n,\alpha)$
at SPES (LNL) applicative line:
35 MeV, 0.5 mA proton beam,
1.5 mm thick ^{232}Th target (22 g),
production $\sigma(p,4n)\simeq 100$ mb[1],
8.3×10^{17} atoms of ^{229}Th
in 1 week of irradiation.
Disposal of FFs and ^{227,228}Th. [1] C.Jost et al.,AIP Conf.Proc.1525,520(2013).

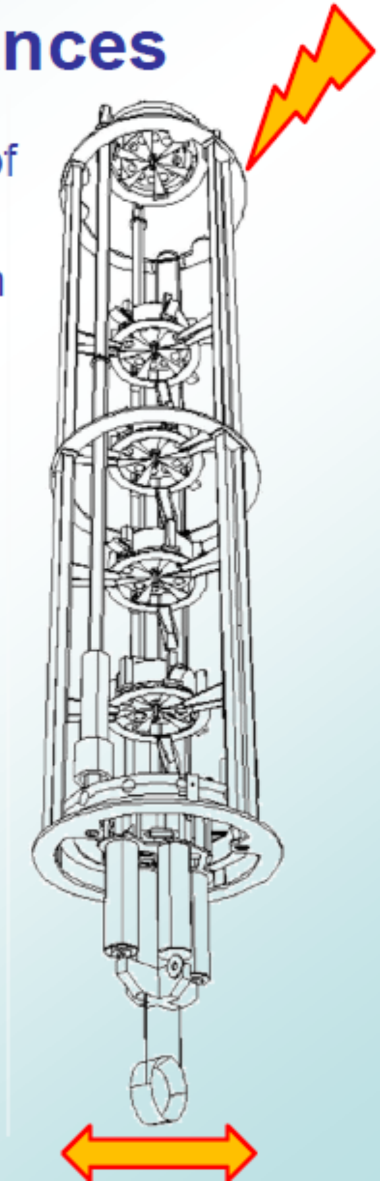




Super attenuator performances

- Direct measurements (or upper limits) of the coupling of excitations at top stage to mirror motion
- Does not include additional effect of inverted pendulum pre-isolation stage (resonance about 40 mHz)





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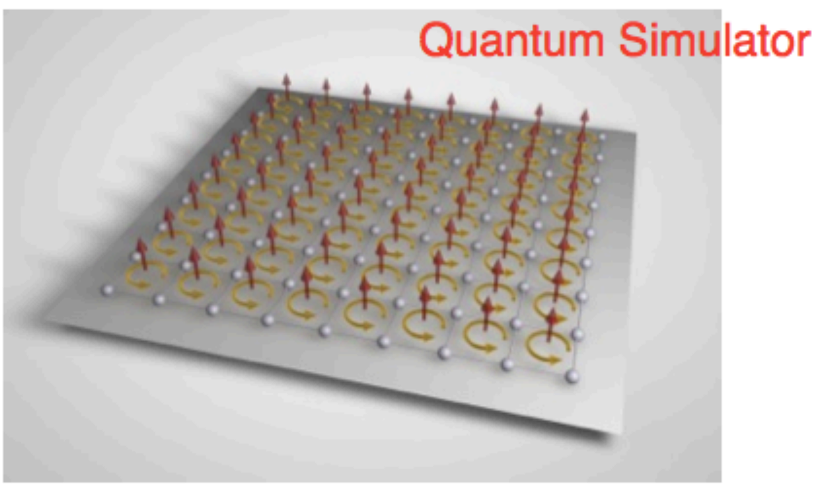
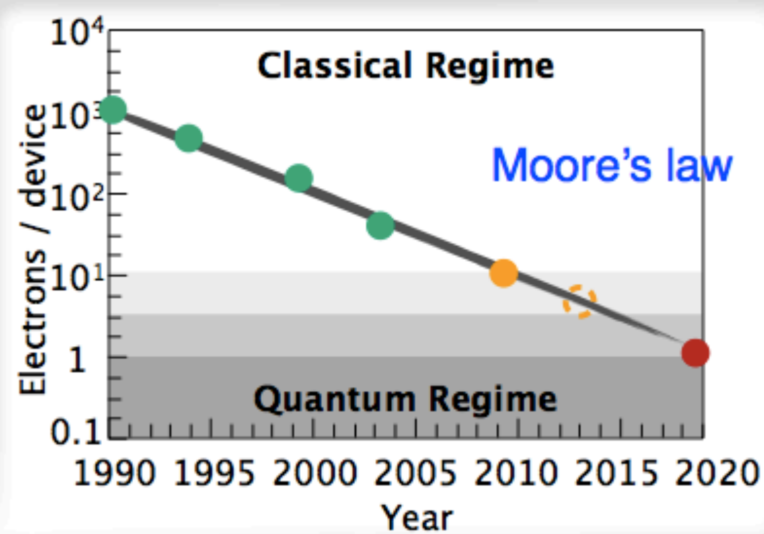
Fundamental Physics

- Cosmological Axions & ALPS
- Experimental Gravitational
- Nuclear Clock based on Isomeric Nuclear States
- Dark Energy : Frequency Comb & NIR TES

Quantum Simulations

- Lattice Gauge Theories
- Quantum Technologies
- Role of European and Italian collaborations





Topics to discuss

- Quantum Metrology
- Quantum Imaging
- Quantum Communication
- Spintronics
- Photonics
- Quantum Opto-Mechanics

Vacuum Energy?

$$\rho_{vac} \propto \int_0^{L_p} d^3k \frac{\hbar\omega}{2} \approx 5 \times 10^{93} \ \frac{\mathrm{Kg}}{\mathrm{m}^3}$$

where to cut off?

Planck length: $L_p = \sqrt{\frac{G\hbar}{c^3}} = 4.1 \times 10^{-35}\,\mathrm{m}$

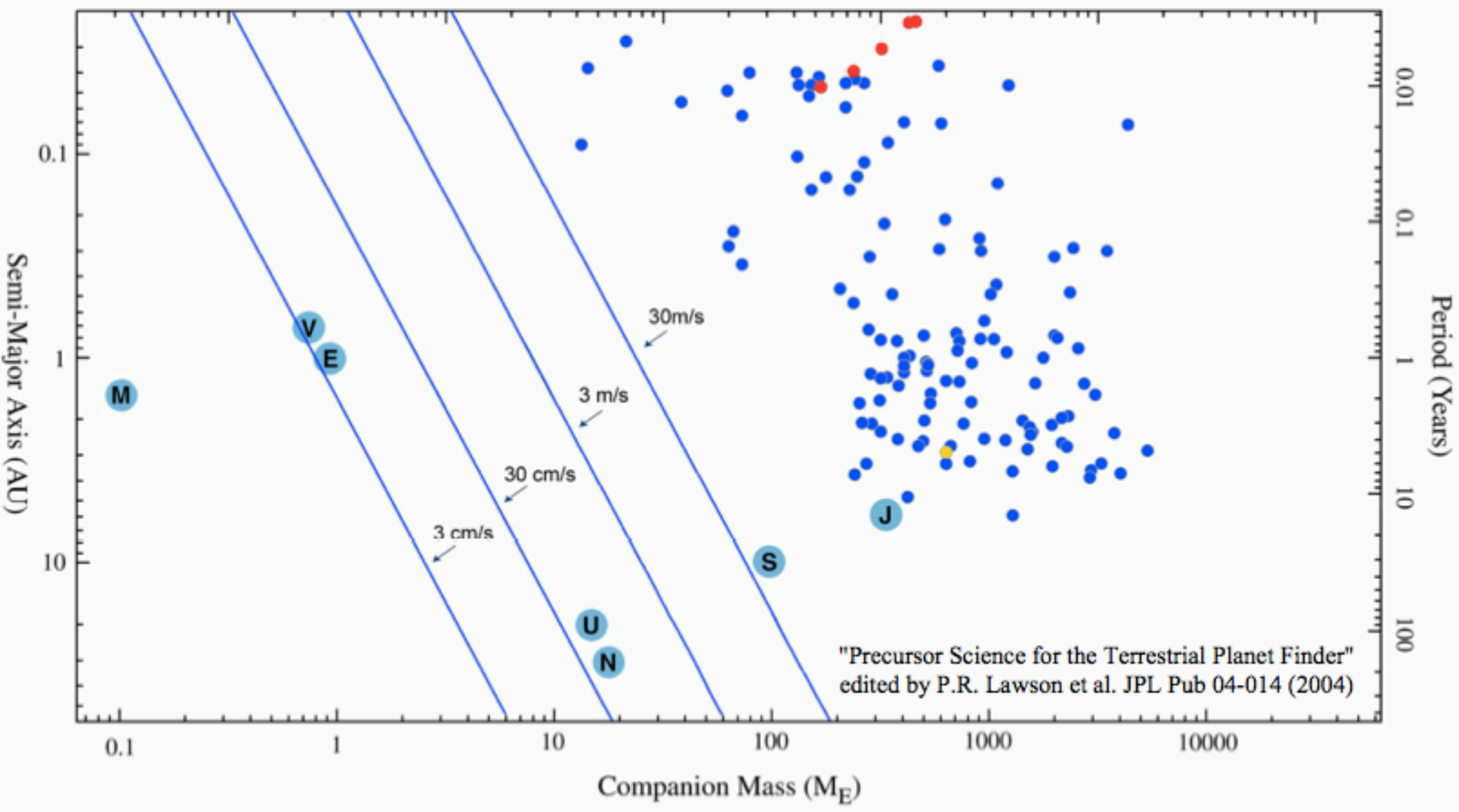
about 120 orders of magnitude too large!*

*Greatest embarrassment in all of theoretical physics. (Michael Turner *Physics Today* 4/2003)

cosmic acceleration ~ 1cm/sec per year.**

**might be measurable with good calibration

Extrasolar Planets discovered so far



Planets discovered by radial velocity (blue), transit (red) and microlensing (yellow)

Possible Drift of the Fine Structure Constants