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Of interest for gw bar:

- DM due to very heavy particles with "strong" interaction (Quark Nuggets, MACROs, Nuclearites..) recently from astrophysical considerations **$\sigma/M \sim 0.1\text{-}10$ $cm^2\ g^{-1}$**

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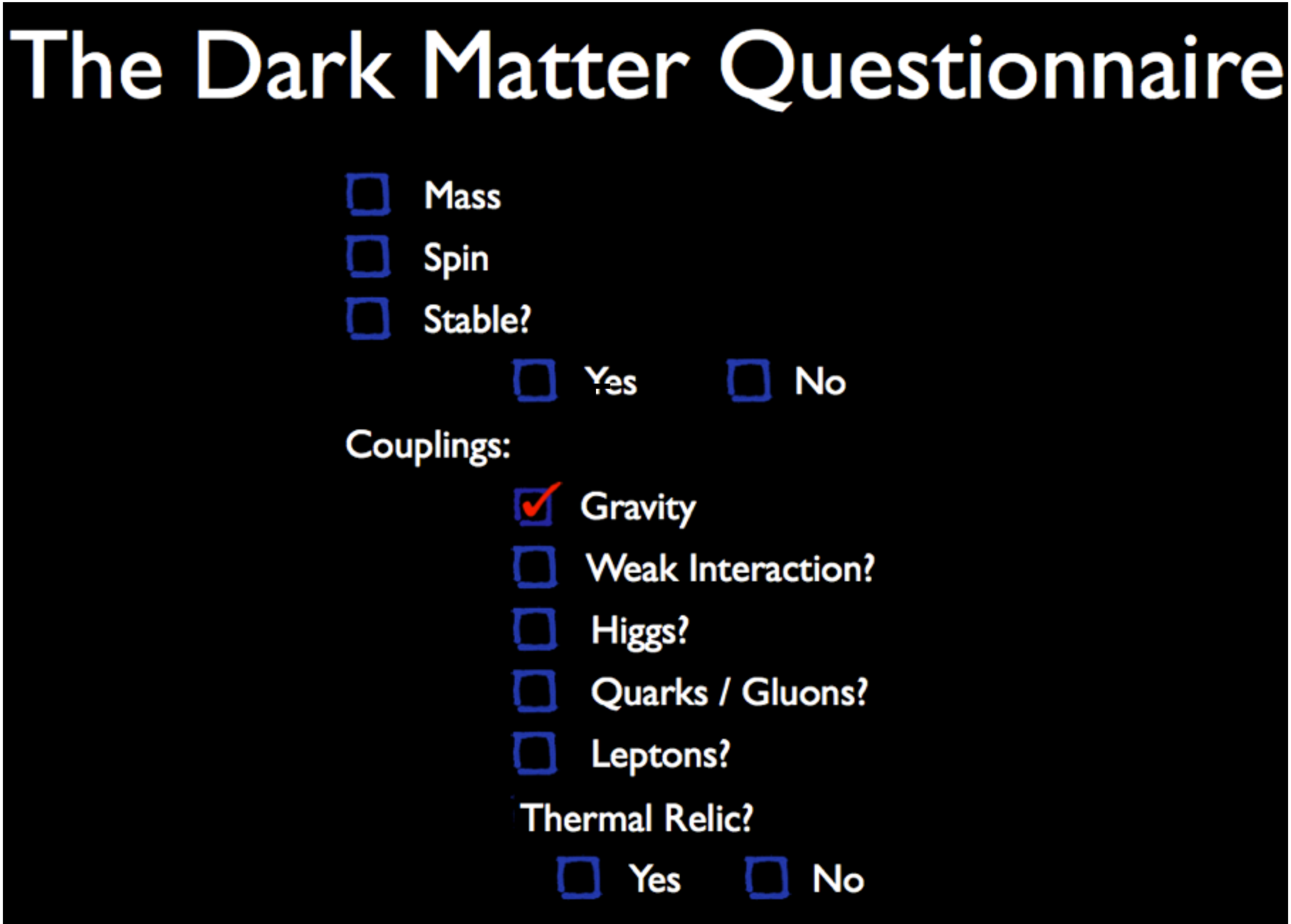
- DM due to very heavy particles with "strong" interaction (Quark Nuggets, MACROs, Nuclearites..) recently from astrophysical considerations **$\sigma/M \sim 0.1\text{-}10\ cm^2\ g^{-1}$**

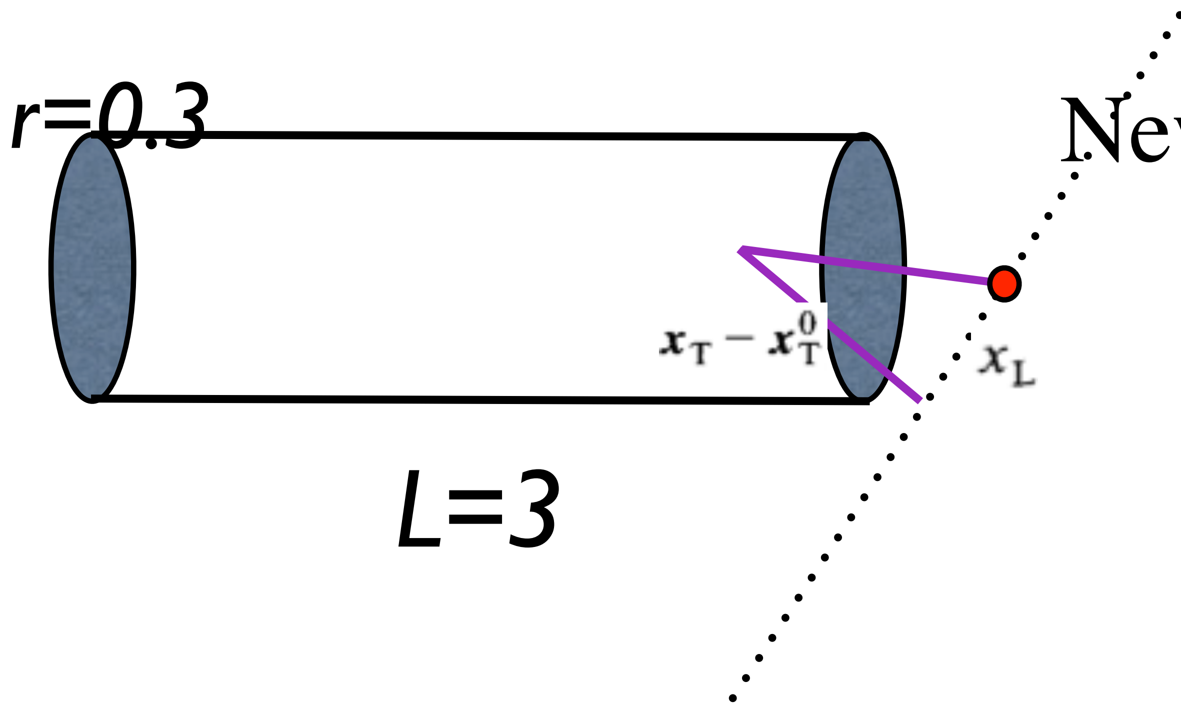
- DM with **gravitational only interactions** (Newtorites if point like, or extended objects like walls, clumps..). Very big objects (MACHO's) already excluded by astronomical observations (micro-lensing experiments limit $10^{-7}\ M_{sun} < Mass < 10^{-3}\ M_{sun}$)

Tim M. P. Tait: Overview talk ICRC 2015 : we don't know very much. But DM should have gravitational interactions!



Newtorite resonant bar response

Bernard DeRujula Lautrup Nucl Phys B242 93 (1984)



$$f = -\frac{Gm\rho}{r^3}\boldsymbol{r},$$

$$r^2 = (\boldsymbol{x}_T - \boldsymbol{x}_T^0)^2 + (x_L - \beta ct)^2.$$

Integrating on time from -∞ to ∞ the amplitude of the n oscillation mode is

$$A_n = -2\frac{Gm}{V\beta c}\int_V \frac{\boldsymbol{u}_n \cdot (\boldsymbol{x}_T - \boldsymbol{x}_T^0)}{(\boldsymbol{x}_T - \boldsymbol{x}_T^0)^2}\,\mathrm{d}^3\boldsymbol{x}.$$

$\mathbf{u}_n$ is the bar oscillation normal n mode; for a thin bar in cylindrical coordinates:

$$u_n^r = \sqrt{2}\sigma_P\pi(r/L)sin(n\pi z/L)$$
$$u_n^z = \sqrt{2}cos(n\pi z/L)$$

Newtorite resonant bar response

The energy variation in the bar is obtained by

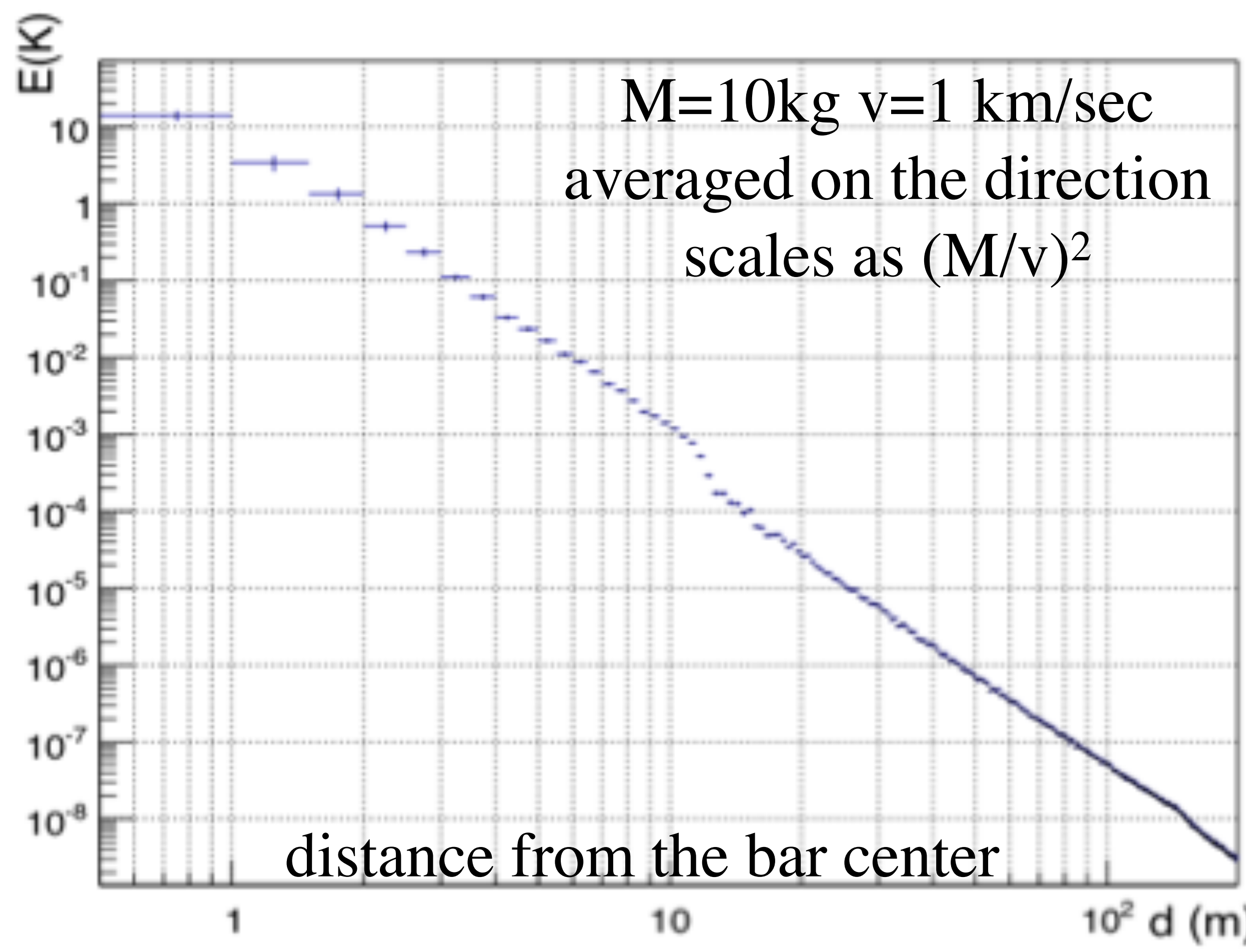
$$\Delta E_n = \frac{1}{2k_B}\rho A_n^2 V$$ (Kelvin units)

For a very thin bar u_n^r =0. For the first longitudinal mode and a vertical track in the bar center:

$$\Delta E \sim 30\pi r^2 \frac{\rho G^2}{k_B L}(\frac{M}{v})^2$$ (Kelvin units)

in NAUTILUS: $\Delta E \sim 2.4(M/v)^2$ M in kg, v km/sec

Numerical integration in the general case



Search of events E>0.1 K in NAUTILUS and EXPLORER

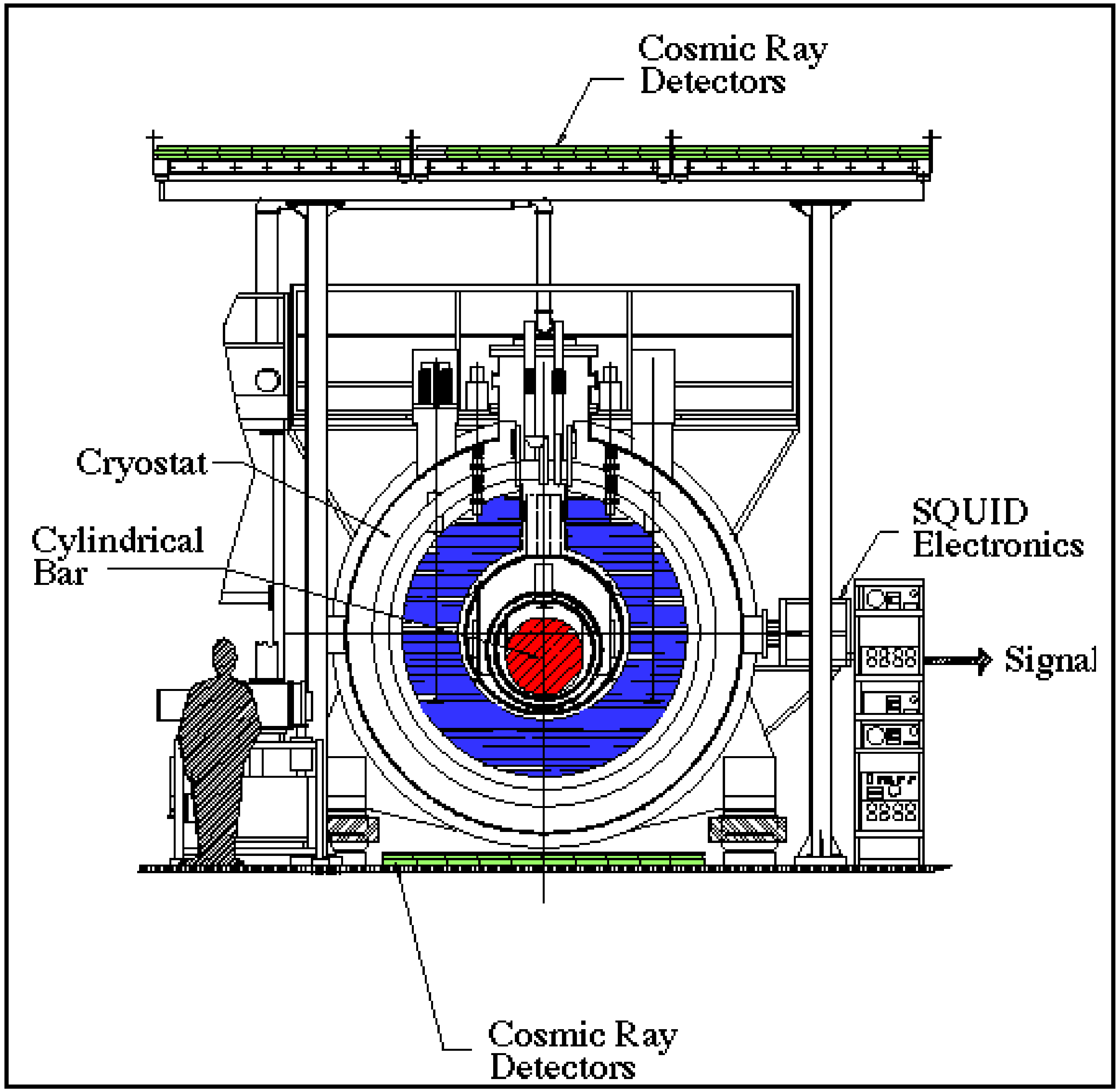
M. Bassan[b,c], E. Coccia[b,c], S. D'Antonio[b], V. Fafone[b], G. Giordano[a], A. Marini[a], Y. Minenkov[b], I. Modena[c], G.V. Pallottino[d], G. Pizzella[a], A. Rocchi[b], F. Ronga[a,*], M. Visco[e]

Two similar detectors,
T~2-3 K:

EXPLORER (CERN)
run ended in JUNE 2010

NAUTILUS (Frascati)
running until end of 2015

Al 2036 bar 2300 Kg
L=3 m r=0.3m



Events E>0.1: selection

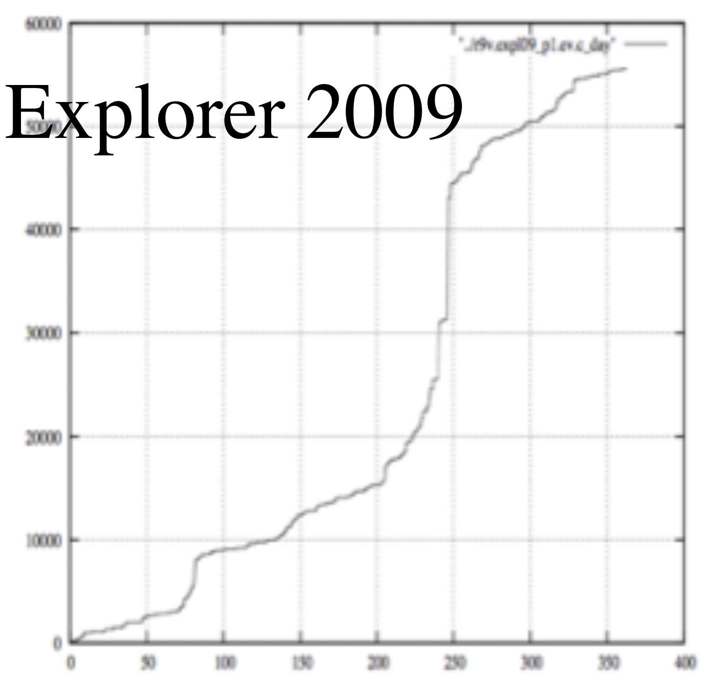
• In this analysis we restrict the search to events with excitation times of the order of 1 msec or less, and we use the standard searches of *gw* burst events with an optimal filter optimized to short signals

• standard cuts: calibration, seismic noise, cosmic rays, T_{eff} (NAUTILUS<2.5 mK, EXPLORER 5mK)

• the usual *gw* searches are done using coincidences between antennas.

additional selection criteria are necessary in this analysis to remove spurious events

1) remove periods with high rate of events E>0.1K



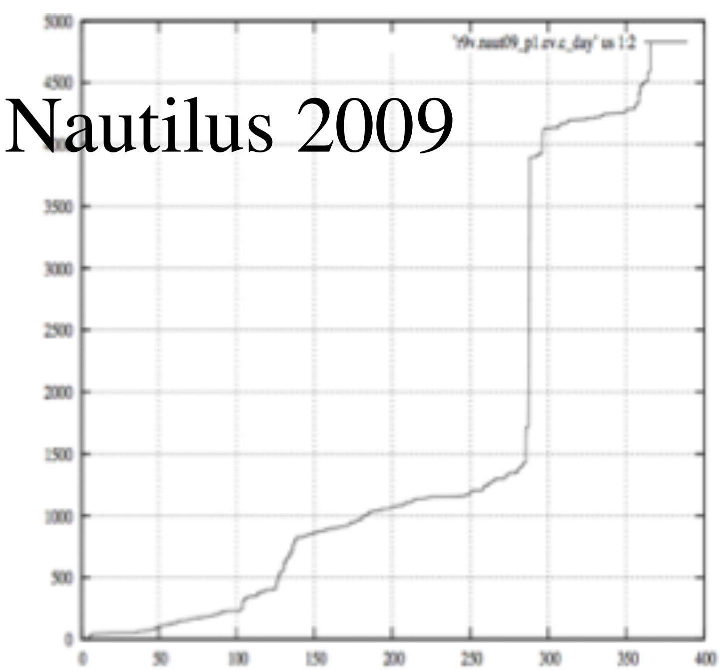
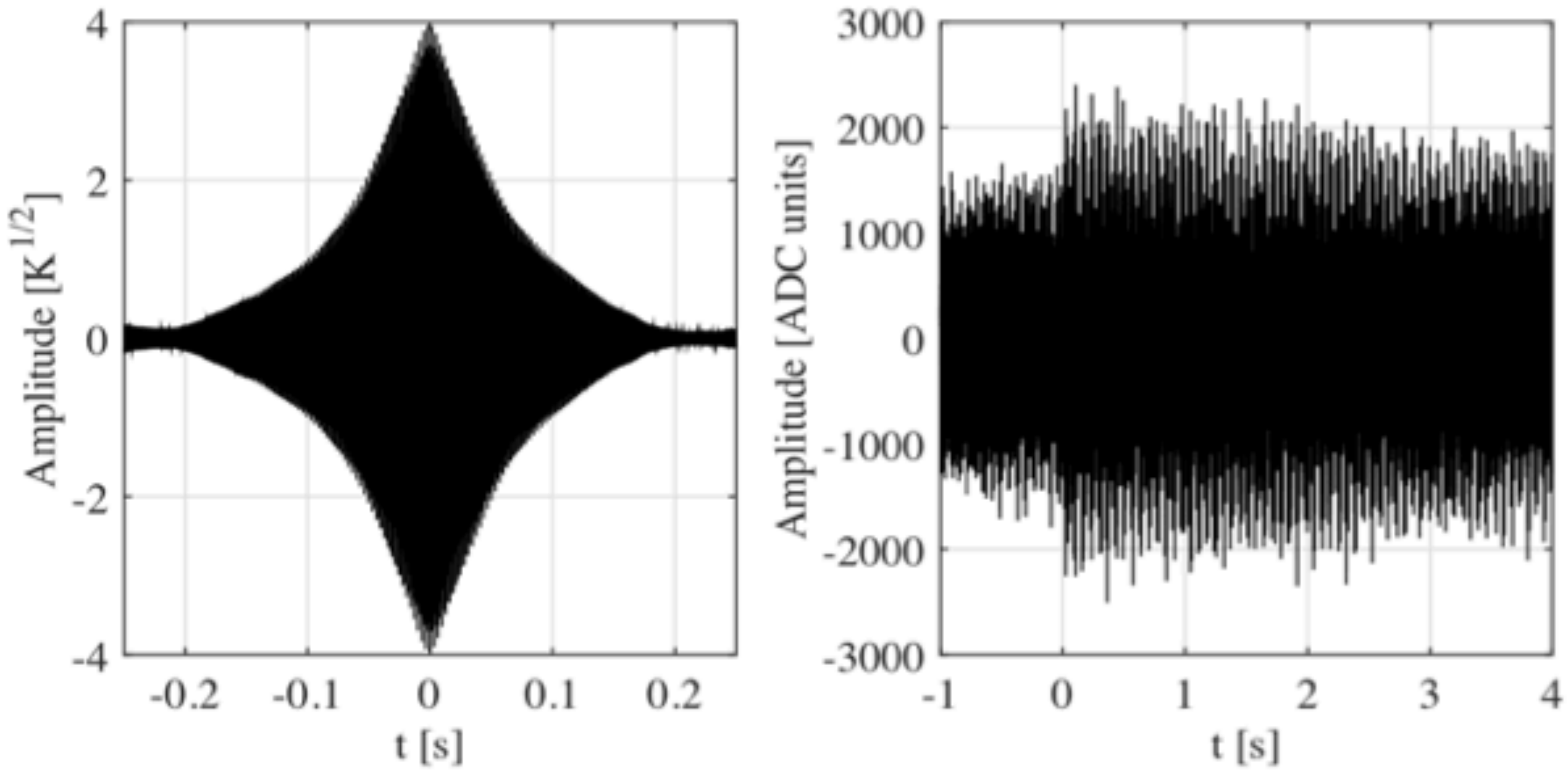


Figure 4: Cumulative distribution of the EX o NA events during year 2009. One can clearly see that there are periods with a rate of events orders of magnitude larger than in the quiet periods of operation.

Events E>0.1 K : selection

2) analyze each single event and select those compatible with the assumption to be produced by a very short excitation, such as we expect to be caused by a newtorite. **Cosmic rays are used as reference**

very short excitation in NAUTILUS produced by a cosmic rays extensive air shower



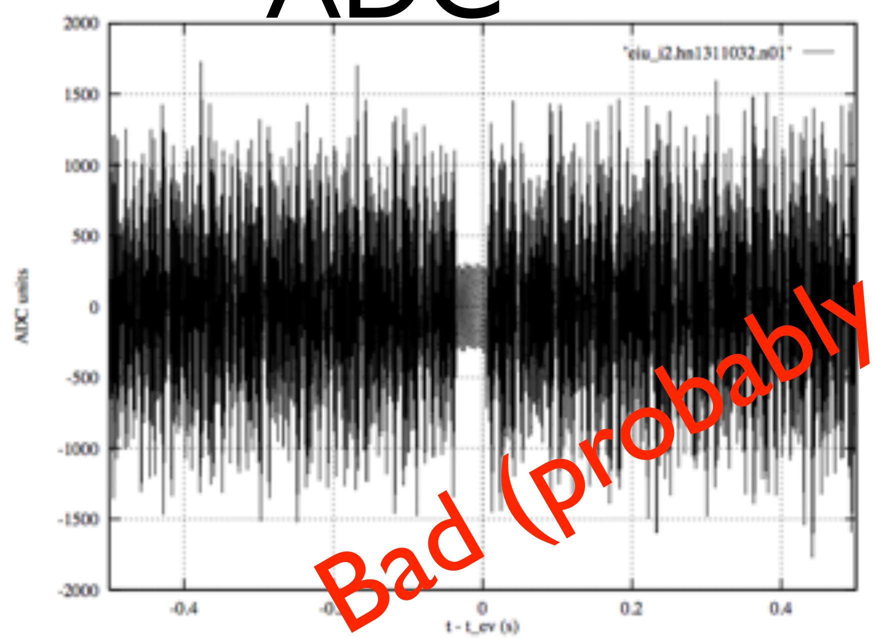
Output of the optimal filter

ADC raw data

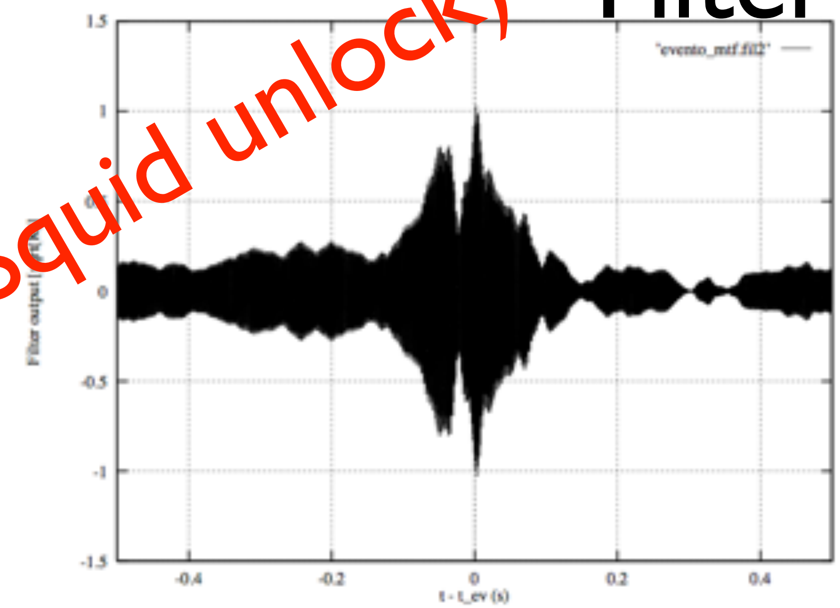
Events E>0.1 K : bad events examples

Examples of events rejected due ADC and shape of the optimal filter

ADC

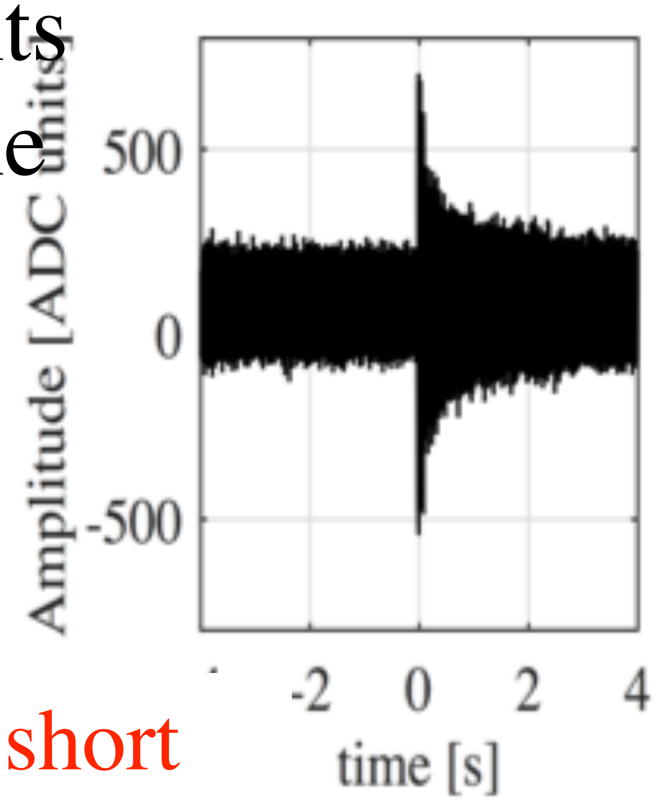


Filter

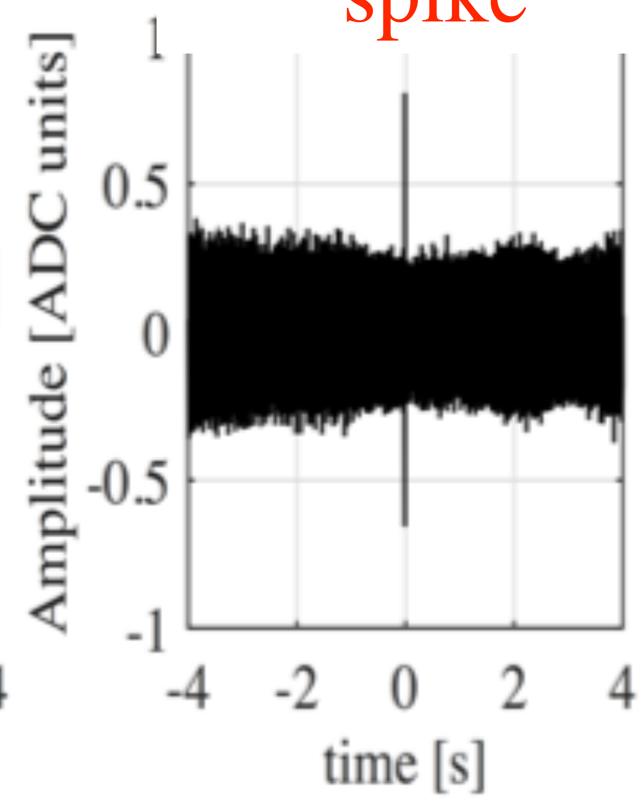


Bad (probably Squid unlock)

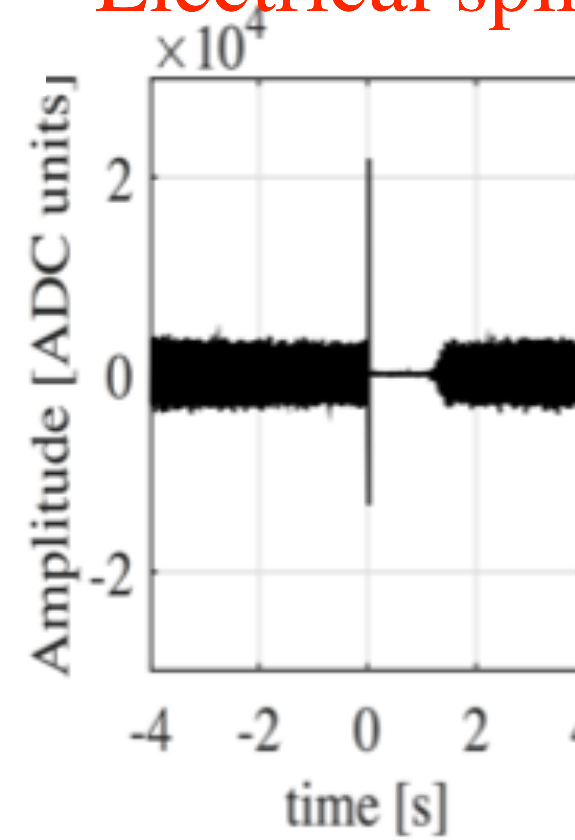
Examples of events rejected due to the raw ADC signal



Too short decay time



Electrical spike



Electrical spike

Events E>0.1 K : results

Nautilus rates 2005 2014 : note that rates changes with year

Ev/year

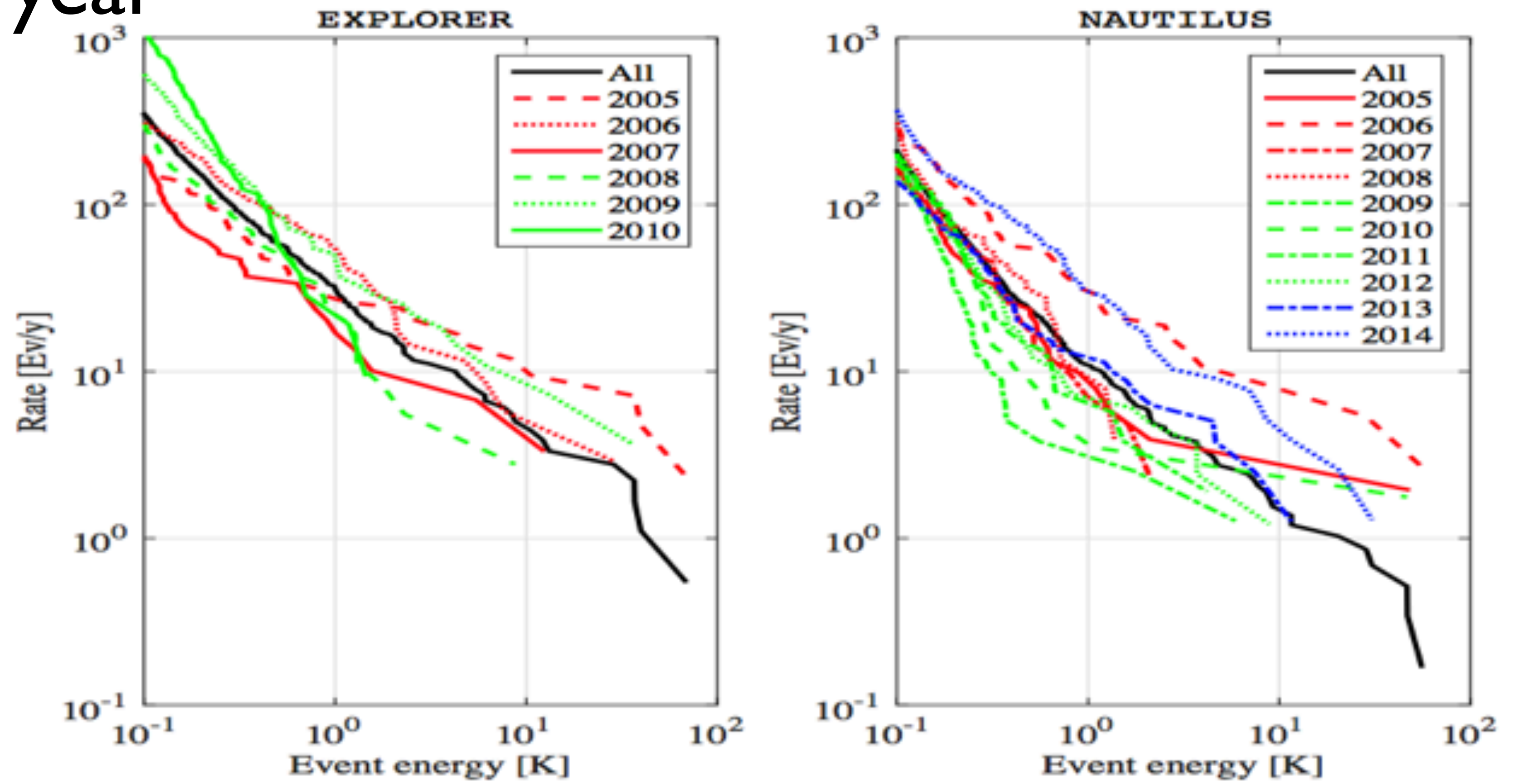
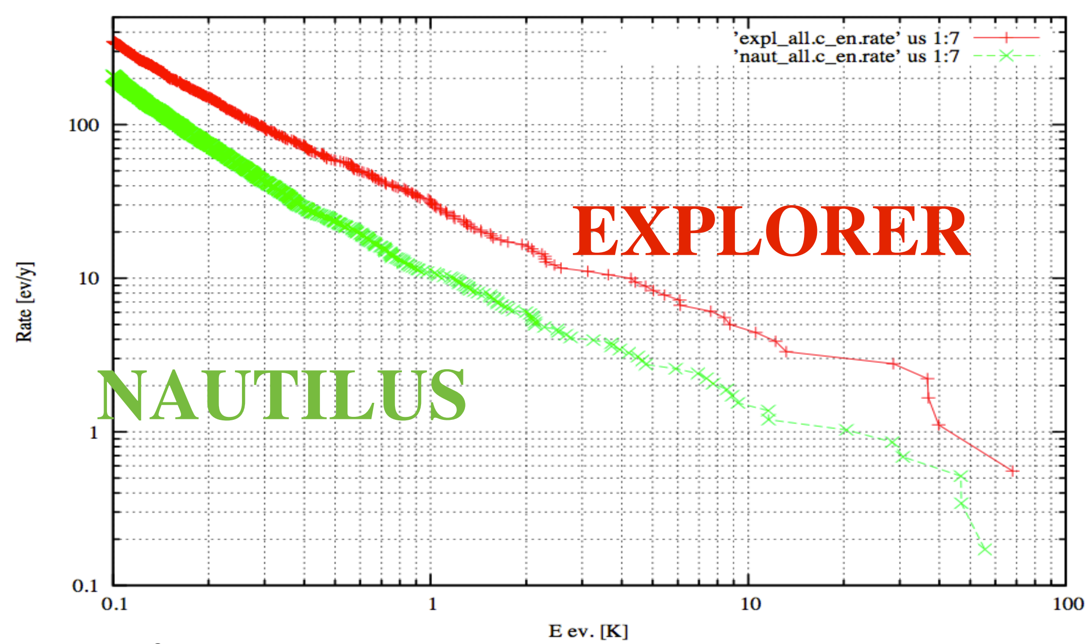


Figure 9: Rate of events of energy larger than the abscissa value for Explorer (left) an
Nautilus (right). The different lines are the results at each different year, the overall result i
shown with linespoints.

Nautilus rates 2005 2014 compared with the Explorer rate 2005 2010 : **NAUTILUS much better**



F Ronga INFN Frascati Taup 2015

Events E>0.1 K : detection efficiencies

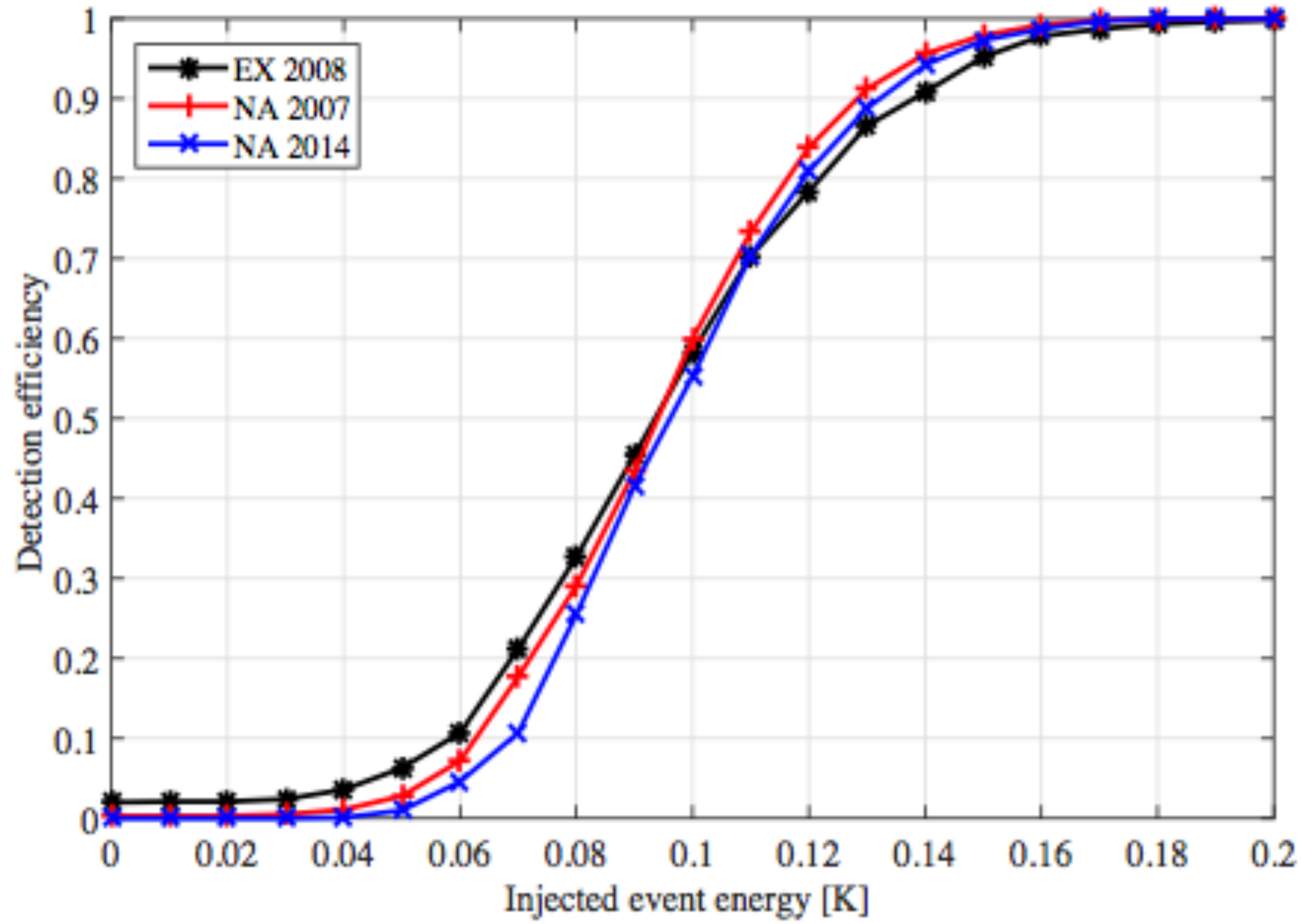
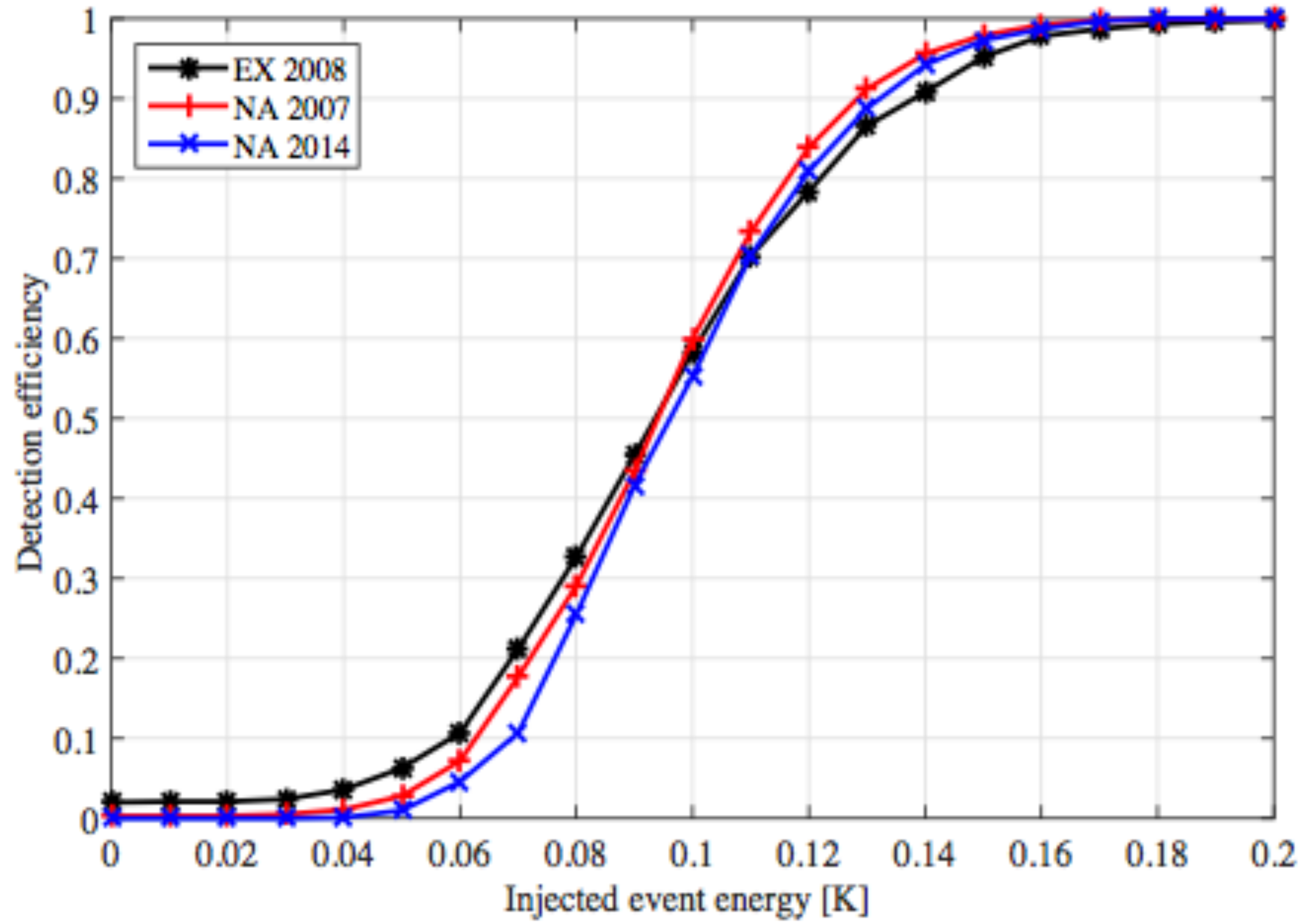


Figure 10: Detection efficiency in three data sets

E[K]

Events E>0.1 K : detection efficiencies

•randomly choose N time stamps inside the good operation periods and extract from the filtered data a time segment around those times



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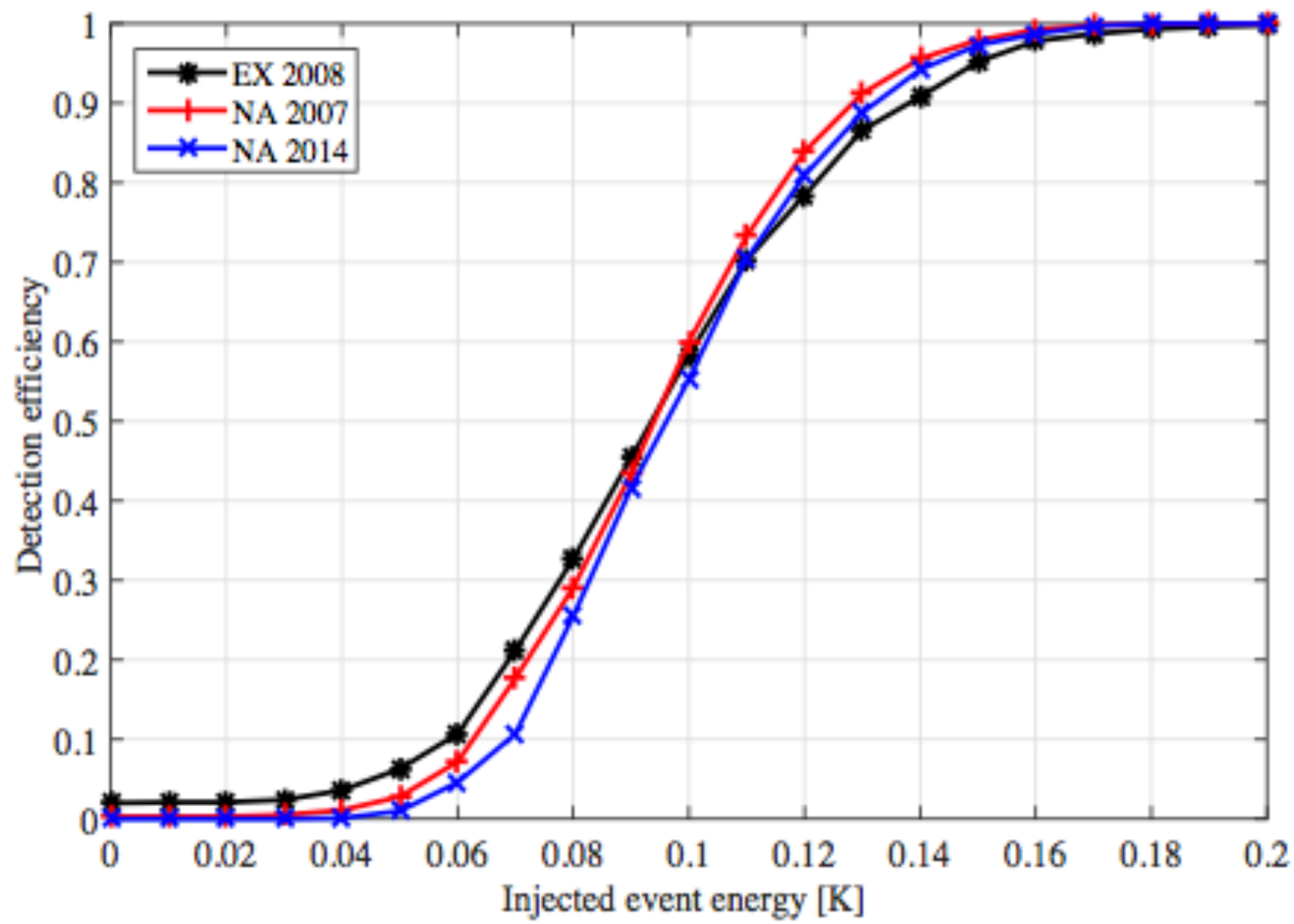
• inject in those time segments a copy of **a real good event (cosmic ray shower)** scaled to a given value of energy, repeating this for different energies



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• apply to this new time segments (data+event) the selection procedures used to identify bad events and count how many we would reject , at any value of injected energy

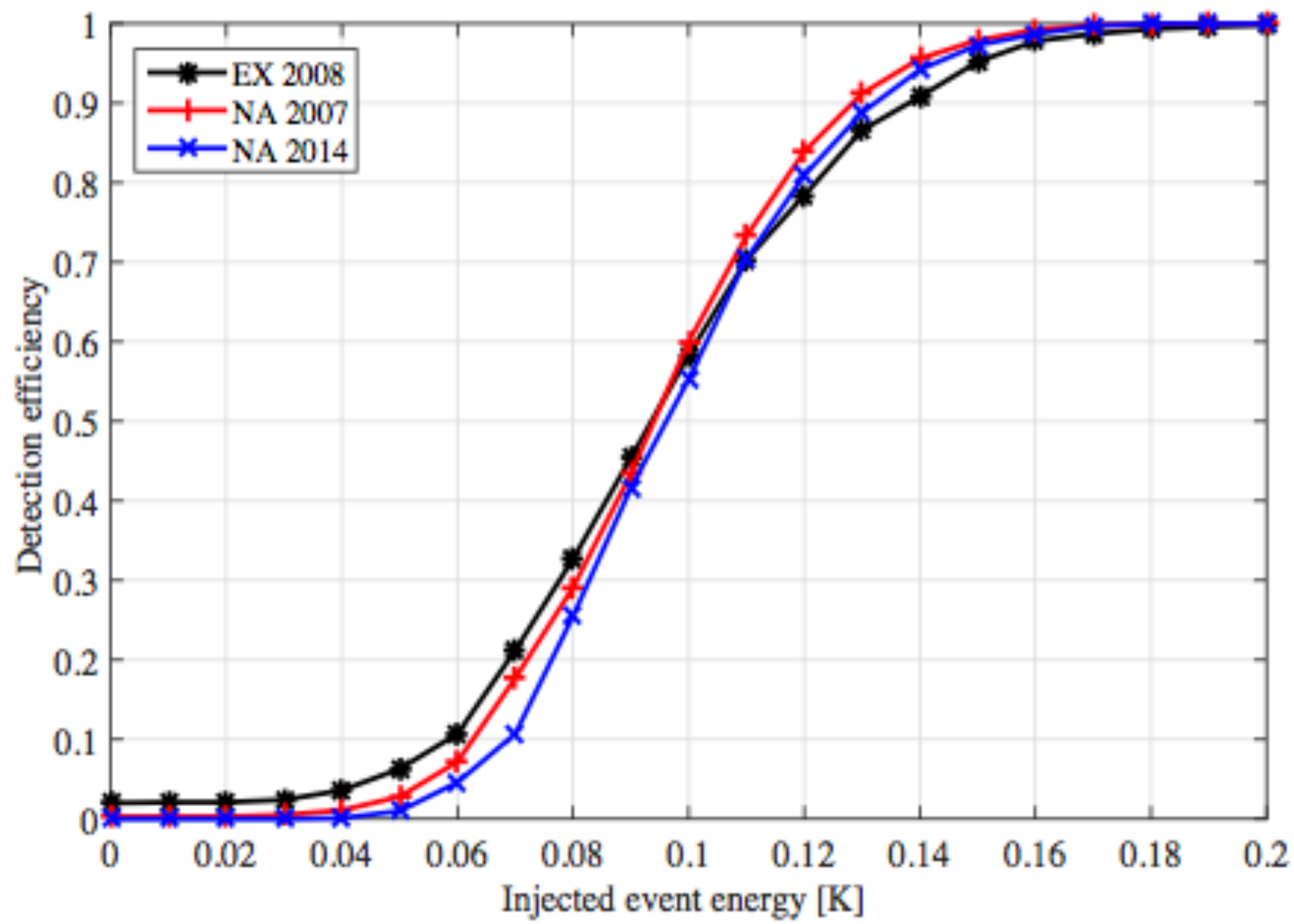


Figure 10: Detection efficiency in three data sets

E[K]

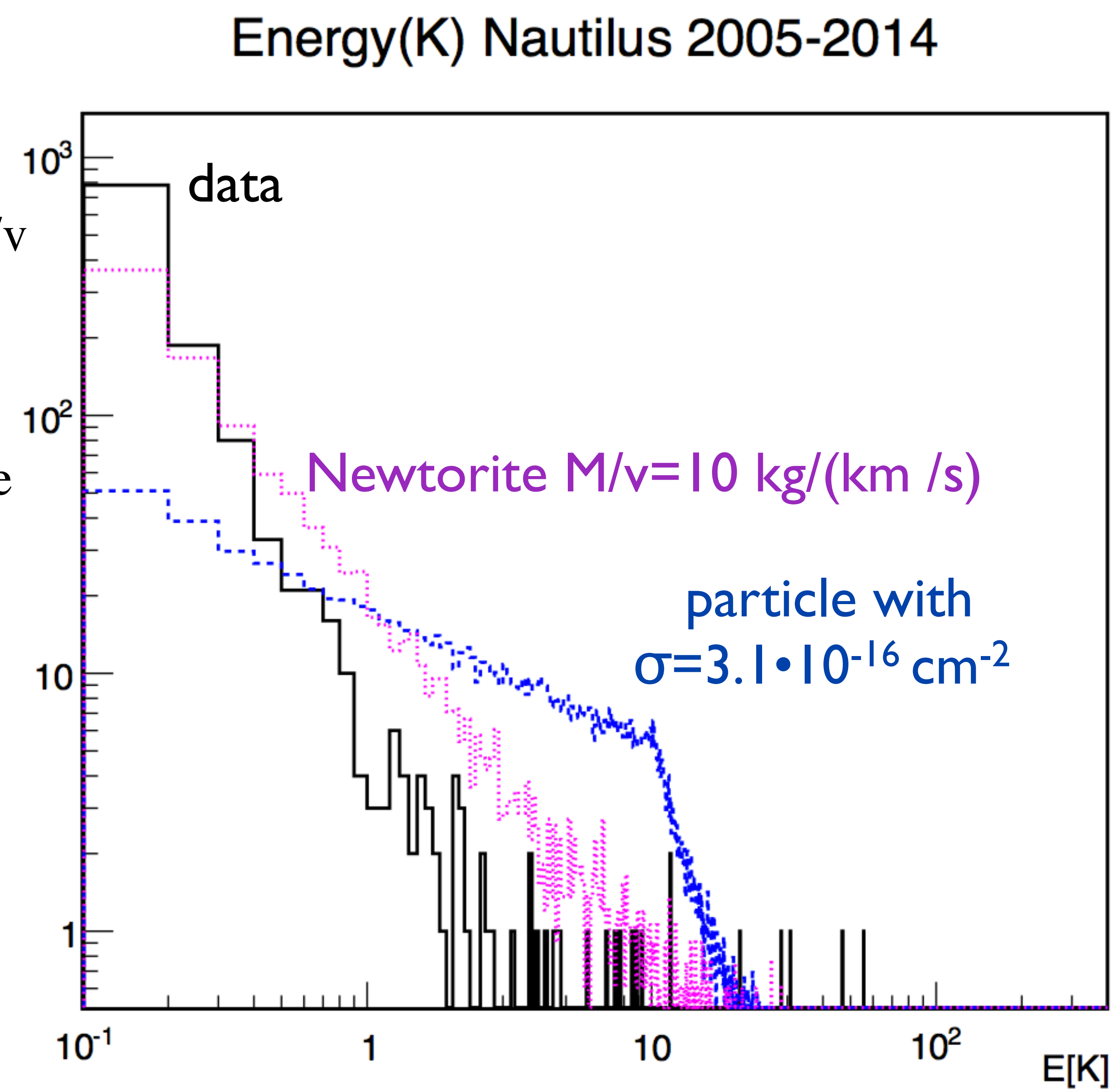
Events E>0.1K : data Montecarlo comparison

• For the Newtorite upper limit we use only the NAUTILUS data (more noise in Explorer)

• The shape of the newtorite energy distribution is not very different from the one of the noise. This does not depend very much from the particular M/v. As M/v increases increases the sensitive volume and therefore the fraction of small events.

• This mean that is important for newtorite to select data with low noise, **best data NAUTILUS 2011 (largest event 5.9 K)**

• For a particle with hadronic interaction (MACRO, nuclearite ecc.) the shape in general is different and increasing σ increases the differences with the data distribution. **For this kind of particle we can use the full EXPLORER NAUTILUS data set**



Newtorite 90% C.L. Upper limits

Nautilus 2005-2014 Livetime=2129.1 days
Note the linear increase of acceptance with M/v

- Upper limits computed with **the optimum interval method.** Used in the Dark matter community =Maximum number of events with the expected Montecarlo energy distribution compatible with data

M/v ($kg\ km^{-1}\ s$)	acceptance ($m^2 sr$)	events upper limit	flux upper limit ($cm^{-2}s^{-1}sr^{-1}$)
1	33.4	545	$8.9 \cdot 10^{-12}$
2	85.3	365	$2.4 \cdot 10^{-12}$
5	209	253	$6.5 \cdot 10^{-13}$
10	426	257	$3.5 \cdot 10^{-13}$
20	888	244	$1.5 \cdot 10^{-13}$
40	1652	248	$8.3 \cdot 10^{-14}$
60	2398	242	$5.5 \cdot 10^{-14}$

Table 5: Nautilus 2005-2014, newtorites upper limits. Note the linear increase of the accep tance with M/v.

- Since the energy distribution doesn't change very much with M/v the events uper limit is ~ constant with M/v

Nautilus 2011 Livetime=278.8 days

M/v $kg\ km^{-1}\ s$	events upper limit	flux upper limit ($cm^{-2}s^{-1}sr^{-1}$)
1	37	$4.5 \cdot 10^{-12}$
2	23	$1.1 \cdot 10^{-12}$
5	22	$4.3 \cdot 10^{-13}$
10	22	$2.1 \cdot 10^{-13}$
20	22	$1.0 \cdot 10^{-13}$
40	22	$5.5 \cdot 10^{-14}$
60	21	$3.5 \cdot 10^{-14}$

Table 6: Nautilus 2011. newtorites upper limits. Livetime=278.8 days, 160 events $\geq$ 0.1K

Used software in the web site:

http://titus.stanford.edu/Upperlimit/.

Newtorite Upper limits vs mass

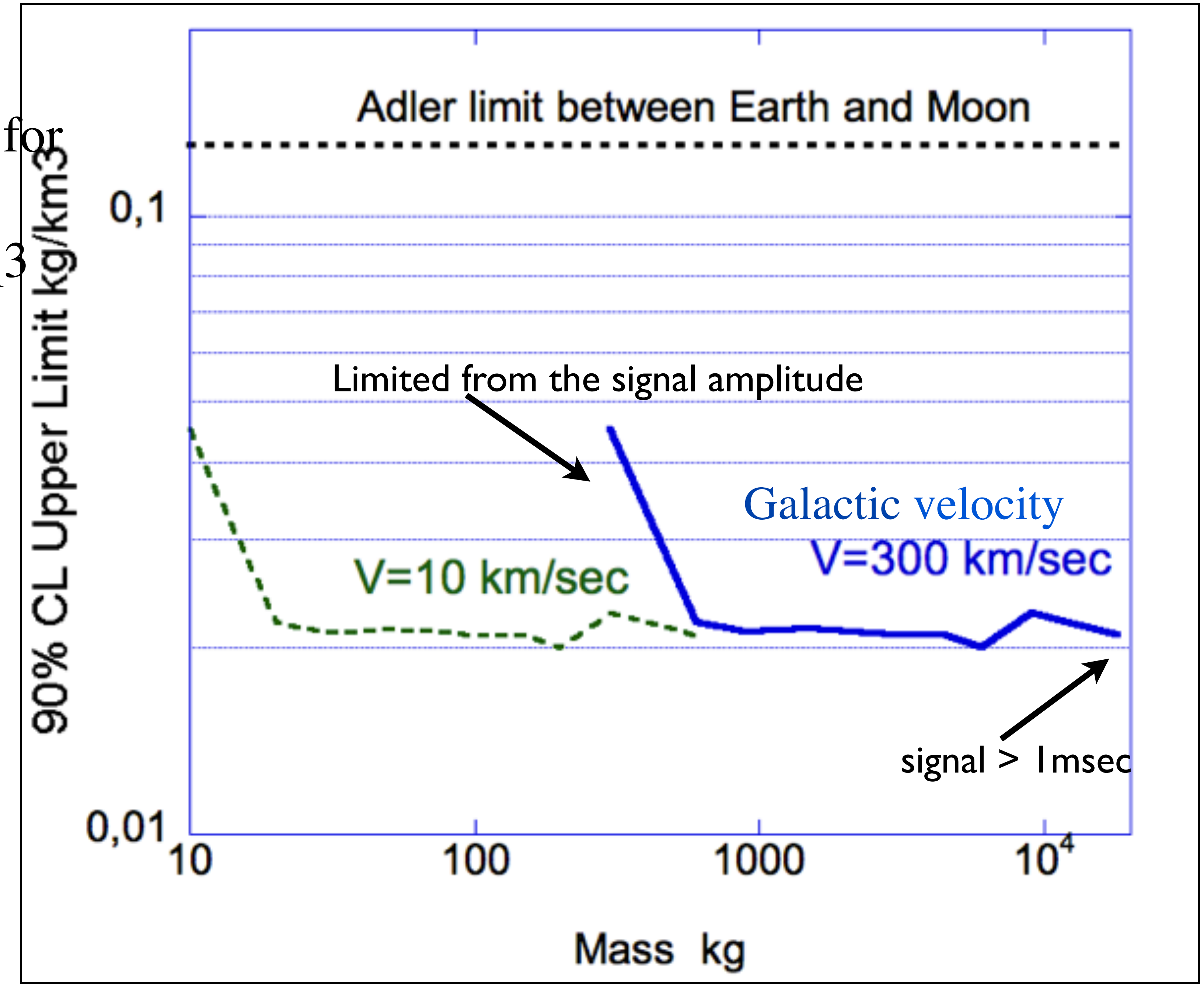
- Adler obtained a direct upper limit 0.13 kg/km^3 **of the mass of Earth-bound dark matter** lying between the radius of the moon orbit and the geodetic satellite orbits S. L. Adler, J. Phys. A 41, 412002 (2008) [arXiv:0808.0899 [astro-ph]]

- Our limit is better than the Adler limit in the range of sensitivity of the bar

- Pitjev has found a much better limit for possible DM inside the Earth-Sun orbits of the order of $1.4 \cdot 10^{-7}$kg/km^3 N. P. Pitjev and E. V. Pitjeva, Astron. Lett. 39, 141 (2013) [Astron. Zh. 39, 163 (2013)] [arXiv:1306.5534 [astro-ph.EP]].

- **very far from DM = 5•10^{-13}kg/km^3**

- this upper limit is on the Earth : trapping effect from the earth gravitational field could increase the DM density



Newtorite limits improvements

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- **Coincidence** ~ a factor 300 with two bar with the performance of NAUTILUS at distance 1.5 meter (Montecarlo simulation using the real data) in 10 years of data taking

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• **Large array** : to increase the geometrical acceptance, to reach the Earth-Sun bound 1000 or more bar are needed. Too much!

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•**Better sensitivity:** the intrinsic quantum limit of a bar noise is $\Delta E = \hbar\omega_0 = 6\ 10^{-31}$ Joules **very far** from the current noise ~ 1mK ~ 1.38 10^{-26} Joules. But a very large R/D is needed. With a much lower noise could be possible to increase the distance between bars and therefore increase the geometrical acceptance

LIGO

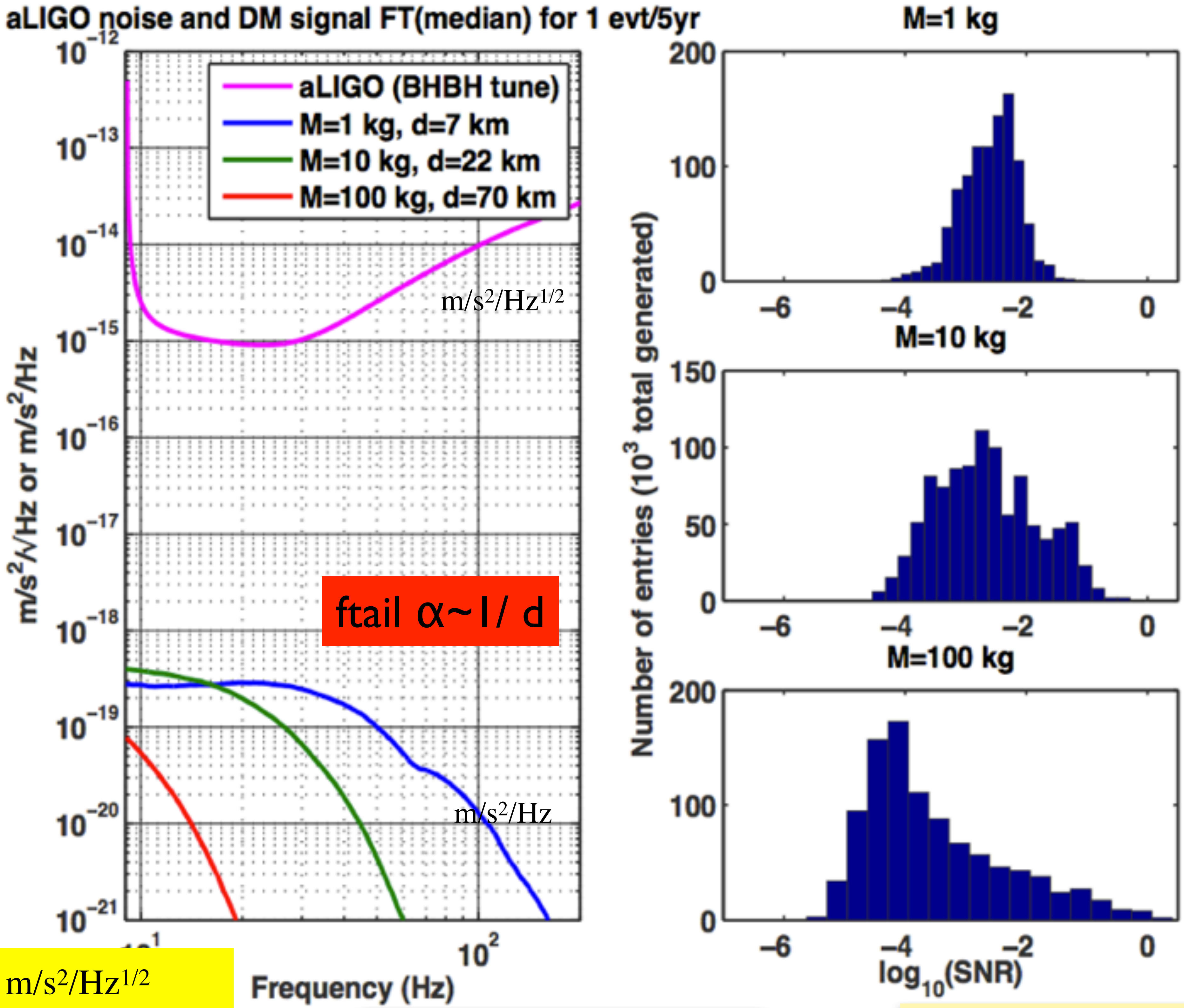
Signal in aLIGO

Random angle and position

Signal from gravitational interaction is small but DM may have long range non-minimal interaction - lot of room for model building and testing

SNR was obtained by integration. Searches should be done using templates.

No coincidences between non-colocated interferometers due to solid angle



Bar sensitivity 1 kHz ~ $4E^{-14}$ $m/s^2/Hz^{1/2}$

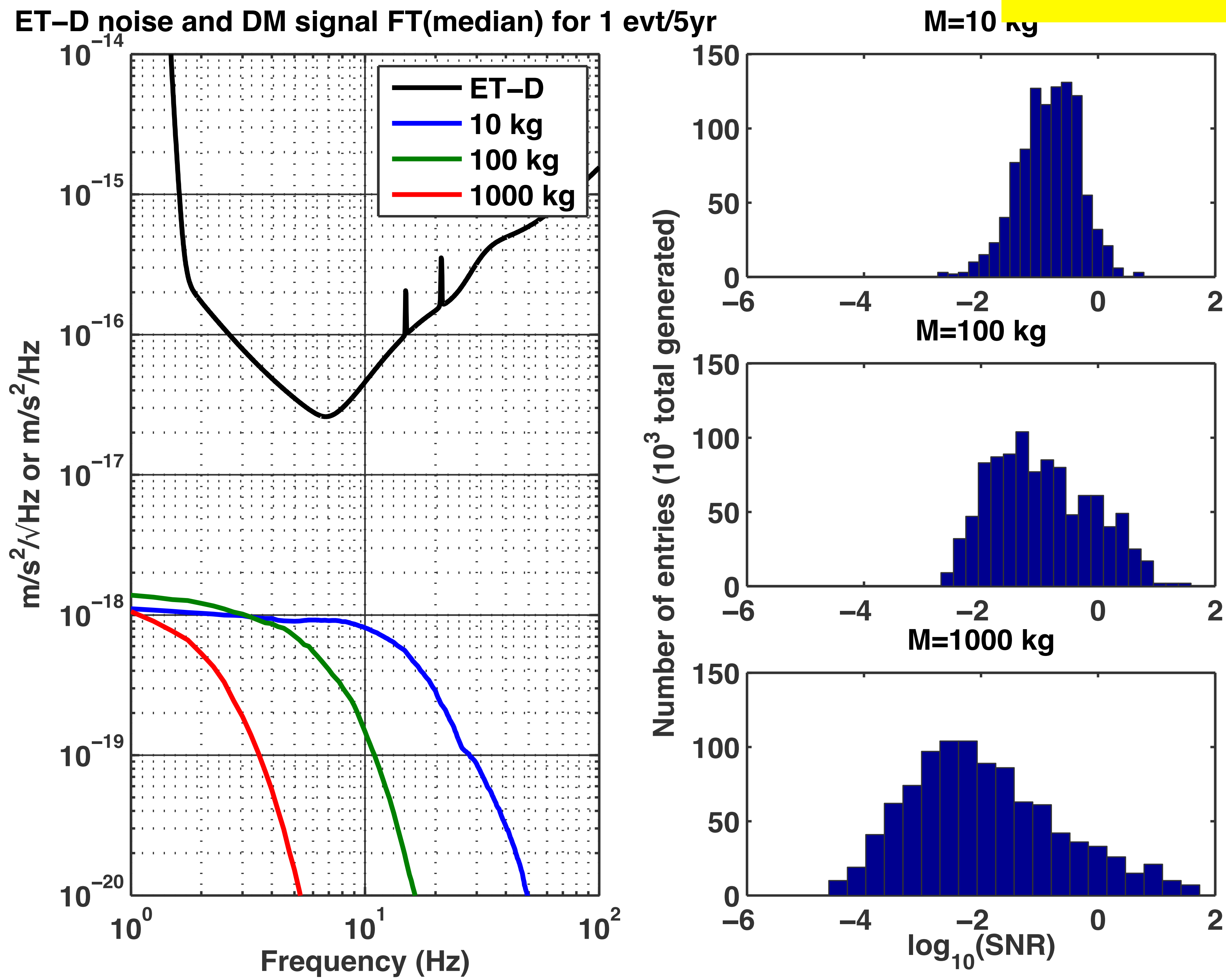
~$2E^{-16}$ at the quantum limit

LIGO

Signal in ET

Three interferometers are co-located. Coincidence and wave form analysis allows background rejection.

Correlated noise?

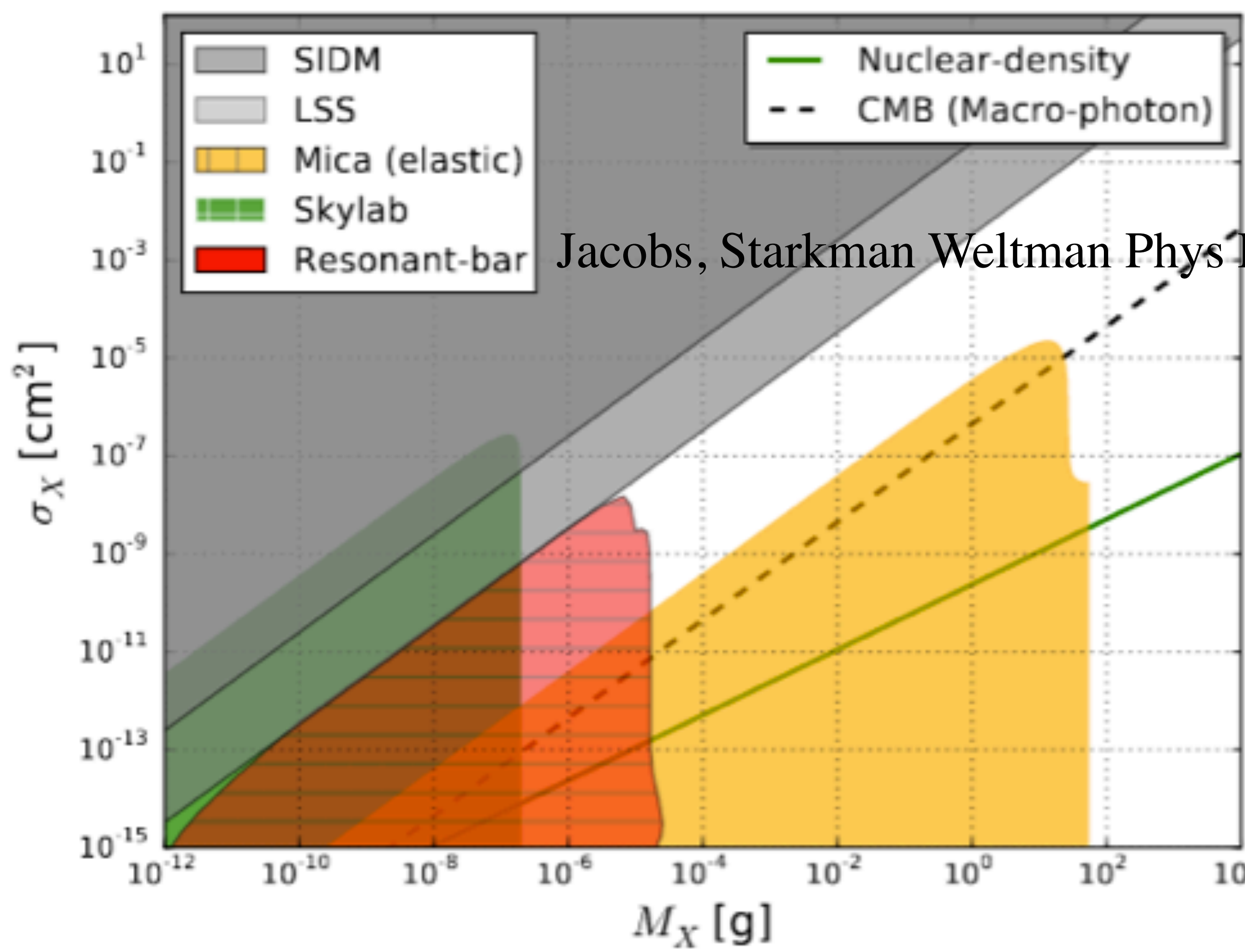


GW bars are interesting for other DM candidates and limits constraints models ..

Interest of bar results for other kind of DM candidate #1 MACRO

Resonant bar detector constraints on macro dark matter
David M. Jacobs (Cape Town U., ACGC & Cape Town U., Dept. Math.), Glenn D. Starkman (Case Western Reserve U. & Case Western Reserve U., CERCA), Amanda Weltman (Cape Town U., ACGC & Cape Town U., Dept. Math.). Apr 10, 2015. 5 pp.
Published in **Phys.Rev. D91 (2015) 11, 115023** e-Print: **arXiv:1504.02779** **[astro-ph.CO]** | **PDF**

The authors of this paper uses our limits for “nuclearites” presented at ICRC 2013 (**arXiv:1306.516**₄ *Quark nuggets search using 2350 Kg gravitational waves aluminum bar detectors*)
to evaluate limits on their “MACRO” model (MACRO a generic massive particle with cross section of the order of the particle area, no ionization). In the bar the signal is due to the heating.



Jacobs, Starkman Weltman Phys Rev D

astrophysical considerations

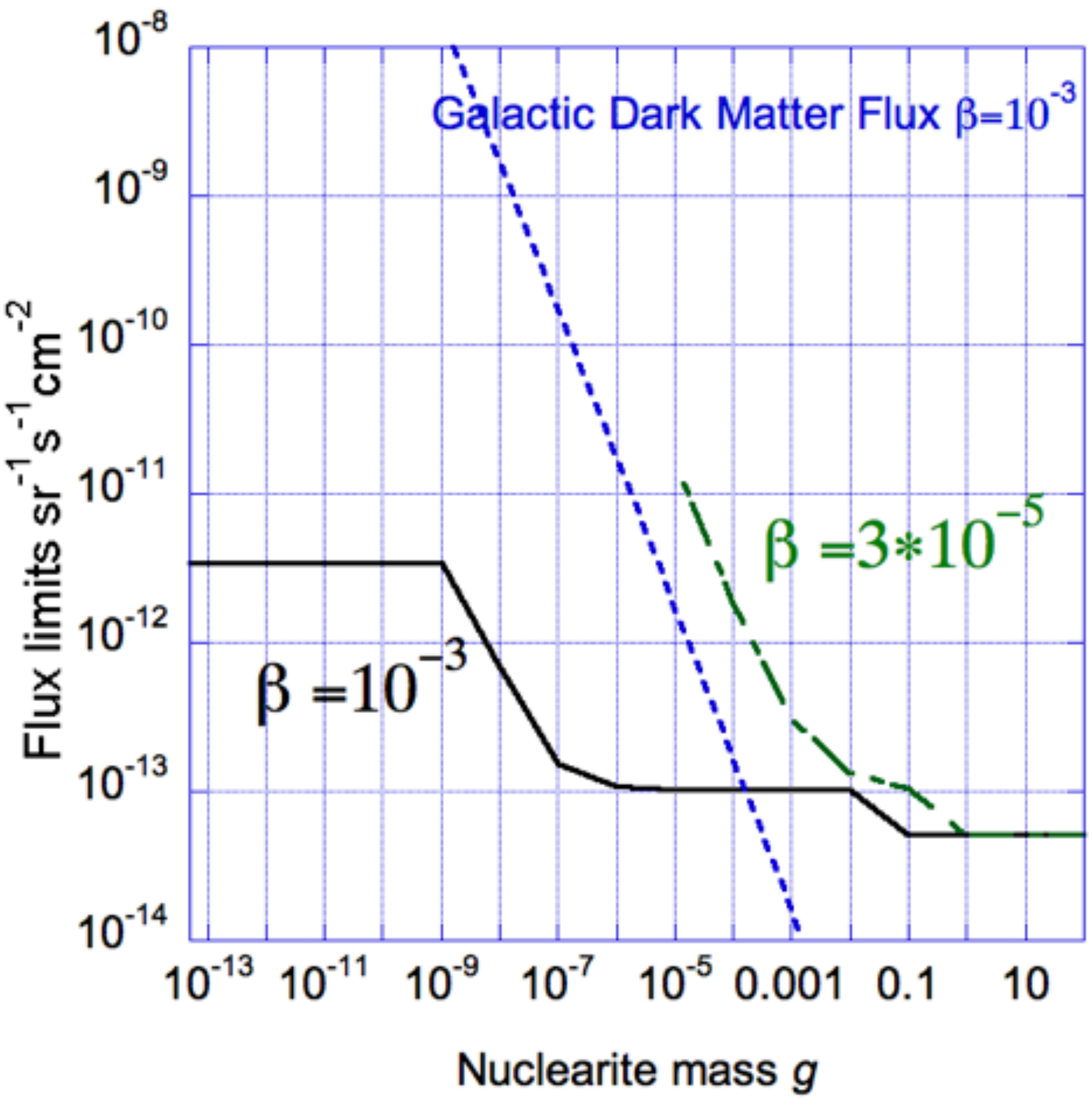
$\sigma/M \sim 0.1\text{-}10 \ cm^2 \ g^{-1}$

Interest of bar results for other kind of DM candidate #2 Nuclearite

particular case of MACRO with strange quarks. Mass cross section link

$$\sigma = A = \begin{cases} \pi \cdot 10^{-16}\,\mathrm{cm}^2 & for\ M < 1.5\,ng \\ \pi\left(\frac{3M}{4\pi\rho_N}\right)^{2/3} & for\ M > 1.5\,ng \end{cases}$$

where $\rho_N = 3.6 \cdot 10^{14}\,g/cm^3$ is the nuclearite density and M its mass



- Other experiments above sea level using track etch detectors have obtained lower limits.
- The interest in this search is the "more robust" calorimetric technique (calibrated on a beam)

Interest of bar results for other kind of DM candidate #3

The Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors

Asimina Arvanitaki, Savas Dimopoulos, Ken Van Tilburg. Aug 7, 2015. 5 pp.

e-Print: **arXiv:1508.01798 [hep-ph] | PDF**

Abstract (arXiv)

The fine structure constant and the electron mass in string theory are determined by the values of scalar fields called moduli. If the dark matter takes on the form of such a light modulus, it oscillates with a frequency equal to its mass and an amplitude determined by the local dark matter density. This translates into an oscillation of the size of a solid that can be observed by resonant-mass antennae. Existing and proposed resonant-mass detectors can probe dark matter moduli with frequencies between 1 kHz and 1 GHz, with much better sensitivity than force measurements

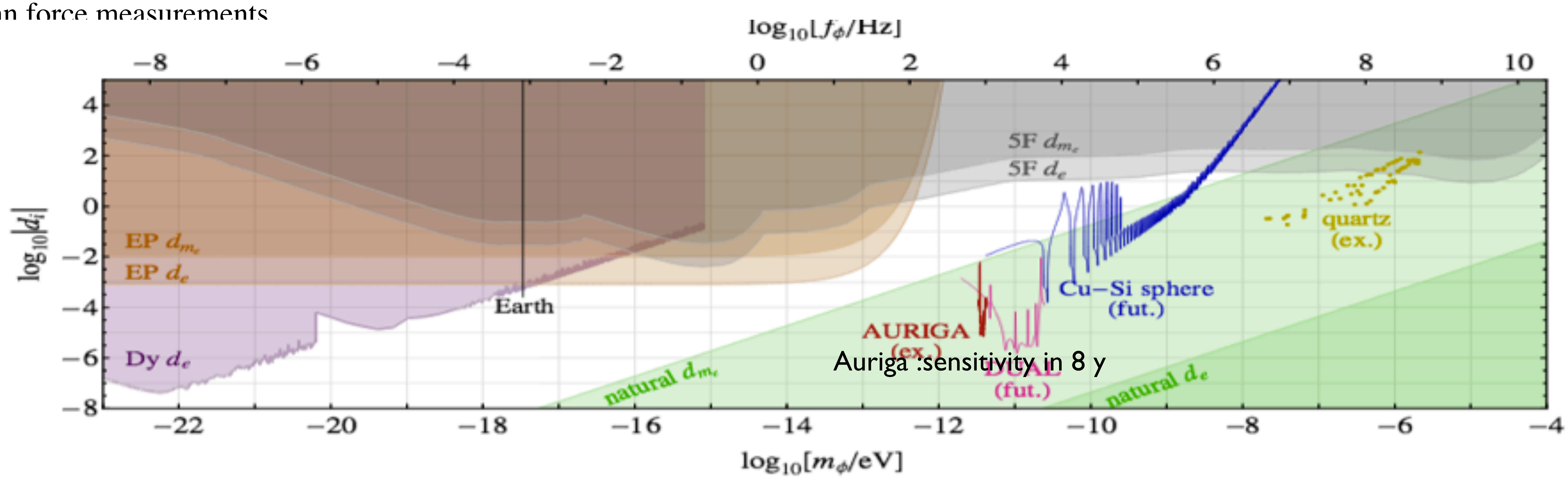


FIG. 1. Scalar field parameter space, with mass m_ϕ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_i = d_{m_e}$) and electromagnetic gauge modulus ($d_i = d_e$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted by the green regions, while the other regions represent 95% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-year reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.

Conclusions

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- interferometer: Advanced Ligo, Virgo , ET, Lisa (space) **Much better prospects particularly for the Einstein Telescope (ET), up to a three-fold coincidence!**

Backup

De Rujula idea (1984); but for newtorites is not necessary to have a compact detector..

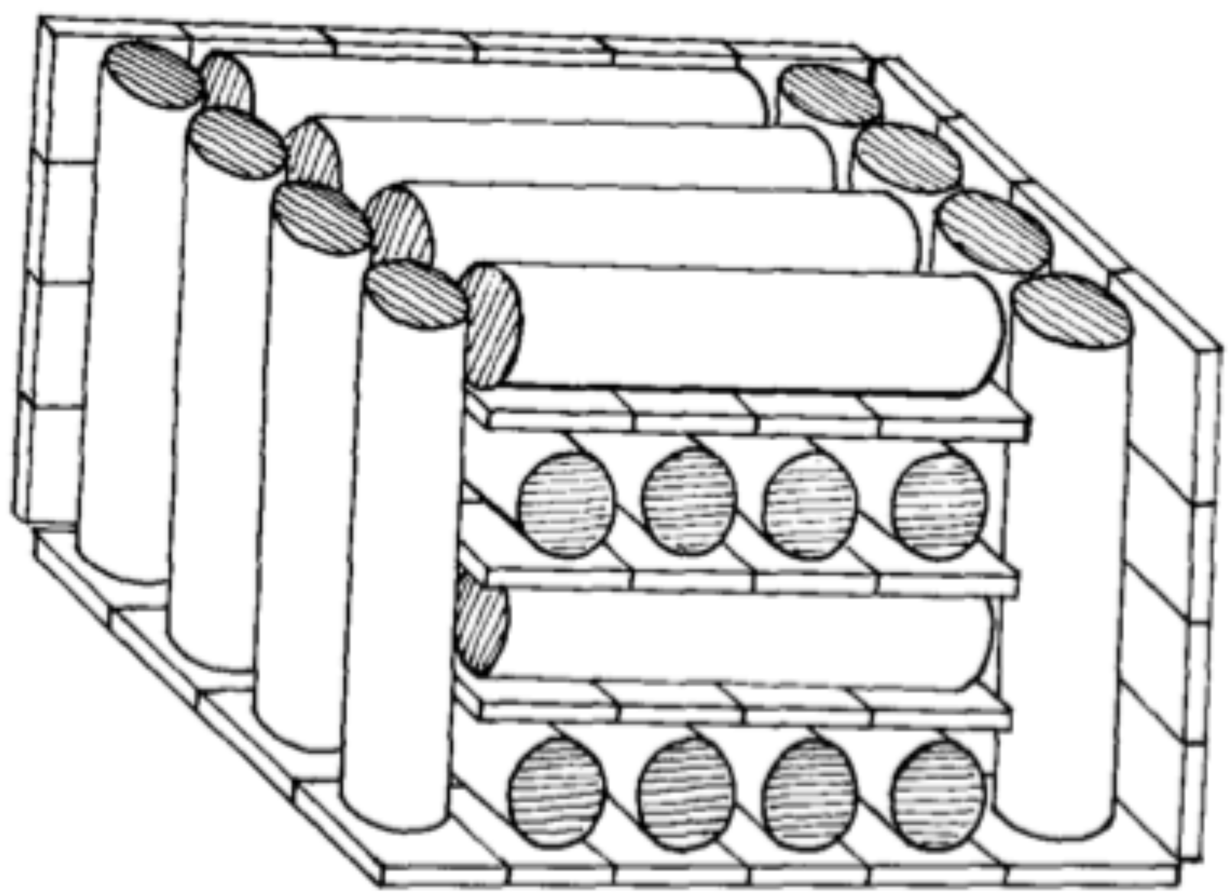


Fig. 12. A possible geometry for a direction-sensitive gravitational wave antenna with the capability of detecting monopoles and newtorites.

GW Bar as particle detector, cosmic ray showers

Max 4.1 K ~ 28 TeV in the bar

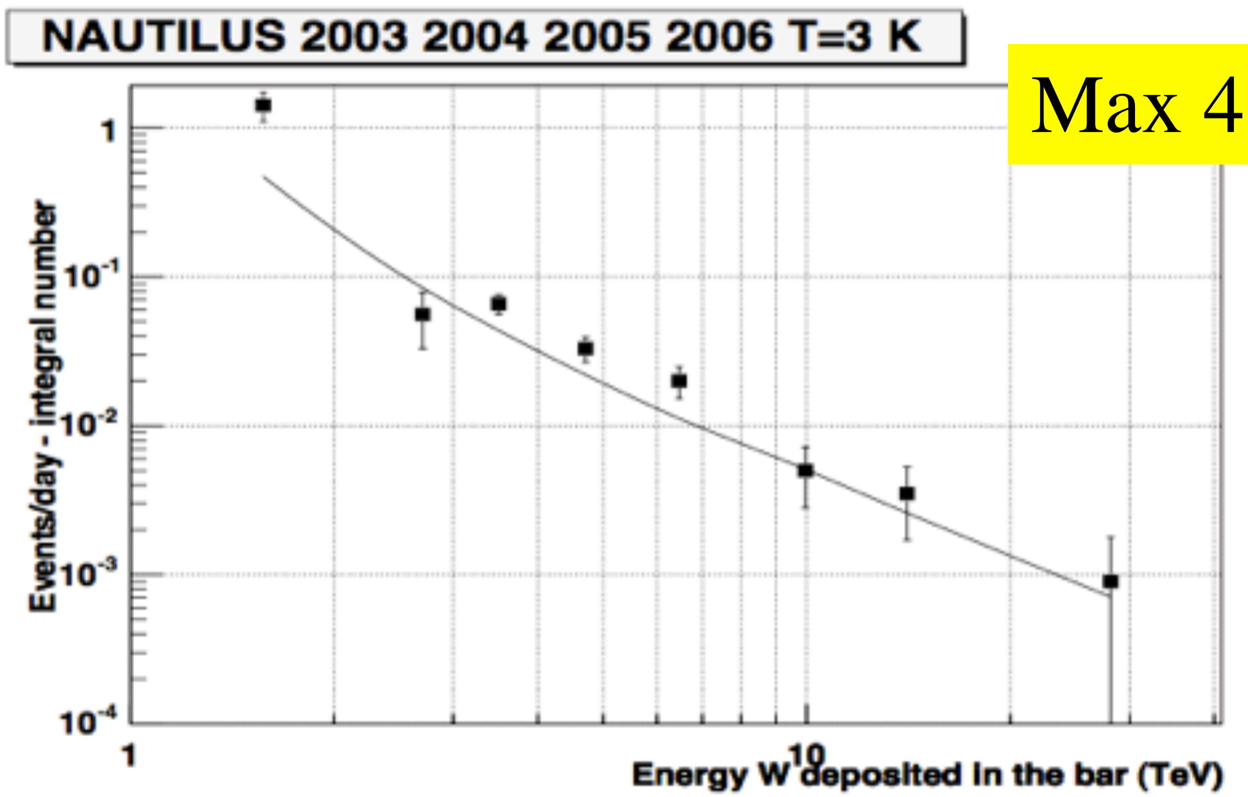
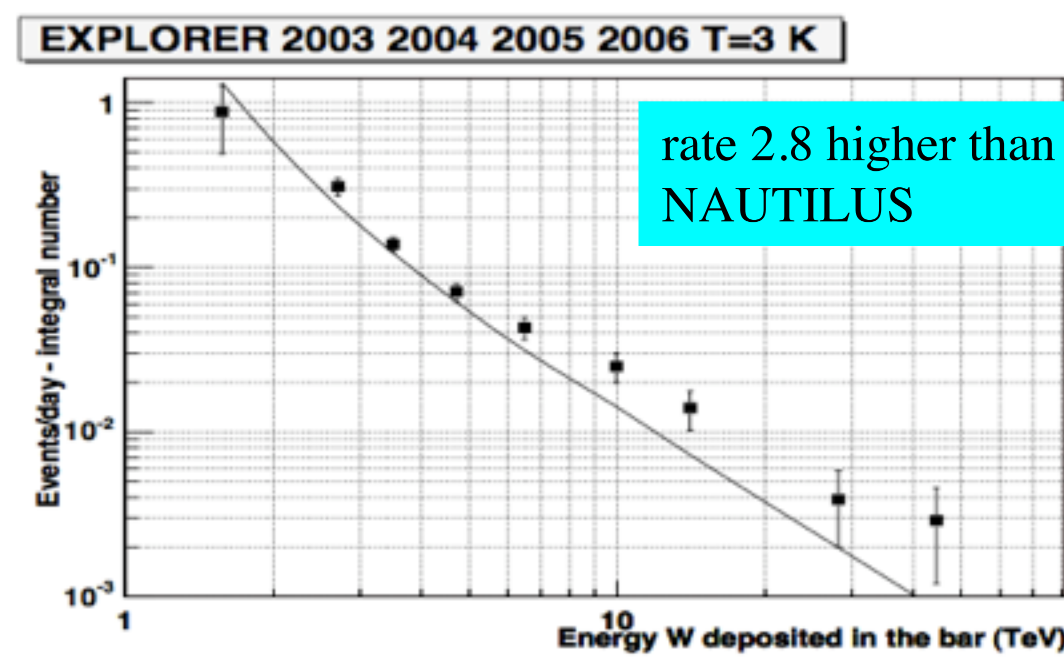


Fig. 8. NAUTILUS 2003-2006 : The integral distribution of the event rate after the background unfolding, as in fig.5, for the four years 2003-2006, compared with the expected distribution (continuous line). The prediction is computed using the data of Table 1.

Max 670 K ~ 360 TeV in the bar



rate 2.8 higher than in NAUTILUS

In Explorer biggest event
~360 TeV in 1022 days - expected ~0.1
from the extrapolation at lower energies

Fig. 11. EXPLORER 2003-2006 : The integral distribution of the event rate after the background unfolding, as in Fig.5, compared with the expected distribution (continuous line). The prediction is computed using Table 1 multiplied by a factor 2.8 (see text).

Introduction: Energy loss of a point-like particle only gravitationally interacting (Newtorite)

- at a microscopic level the process is similar to the energy loss of *a charged particle like a muon in a media* (the main difference is that the main contribution for a charged particle is due to the electrons)

$$\frac{dE}{dx} = 4\pi N G^2 \frac{(M)^2 m}{V^2} \log(\frac{b\max}{b\min})$$

N = Avogadro number, M,V particle mass and velocity, m nucleus mass, bmax~ 1 meter, bmin~ 10^{-15} m

very small numbers! for aluminum and V=1km/sec M=1kg

dE/dx~5 10^{-21} Joules/m directly in mechanical oscillation.

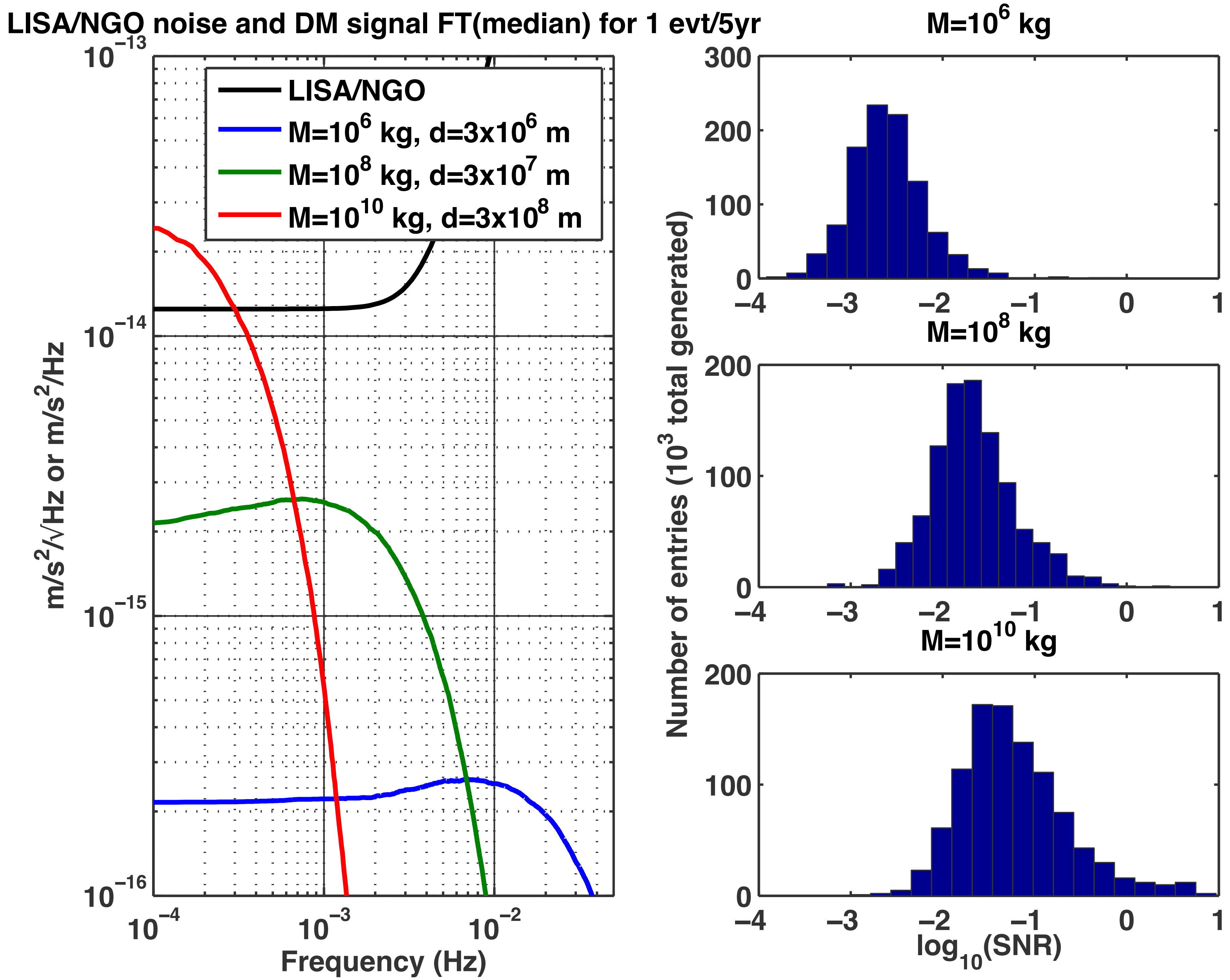
We survive to the collision because this number is very small!

The bar detectors are sensitive to this small amount of energy!

6

LIGO

Signal in LISA

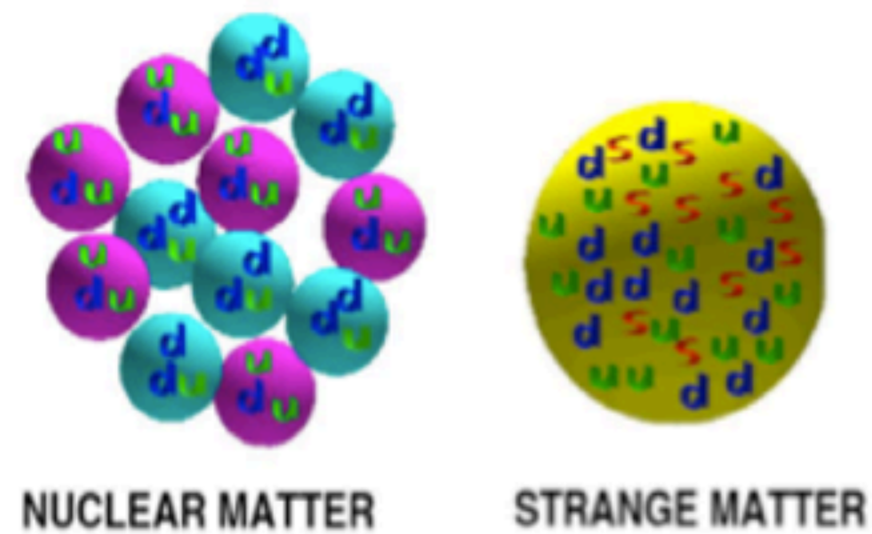


Nuclearite : a neutral quark nugget with strange quarks

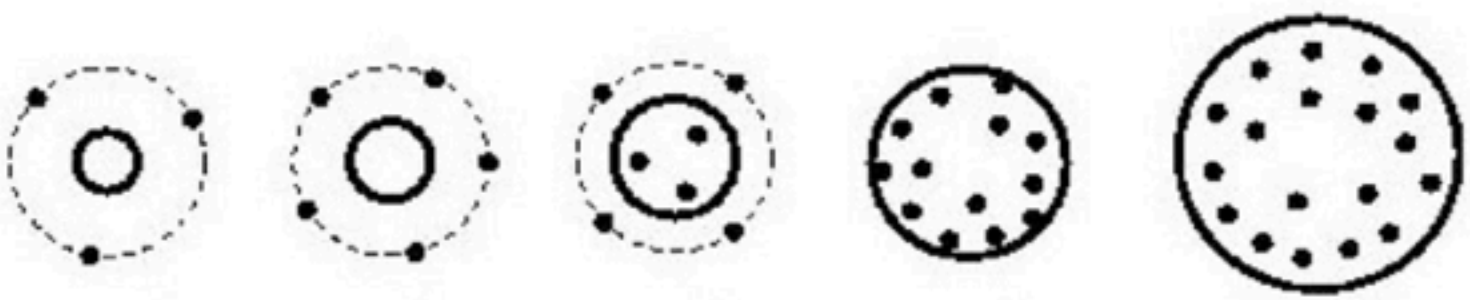
Strange Quark Matter (nuclearites, strangelets)

E. Witten, Phys. Rev. D30 (1984) 272A. De Rujula, L. Glashow, Nature 312 (1984) 734

- Aggregates of u, d, s quarks + electrons of ~ equal number, density: 3.5×10^{14} g cm^{-3}.
- Ground state of nuclear matter (E/A < 930 MeV).
- Stable for any baryon number A (few < A< 10^{57}).



..a qualitative picture…

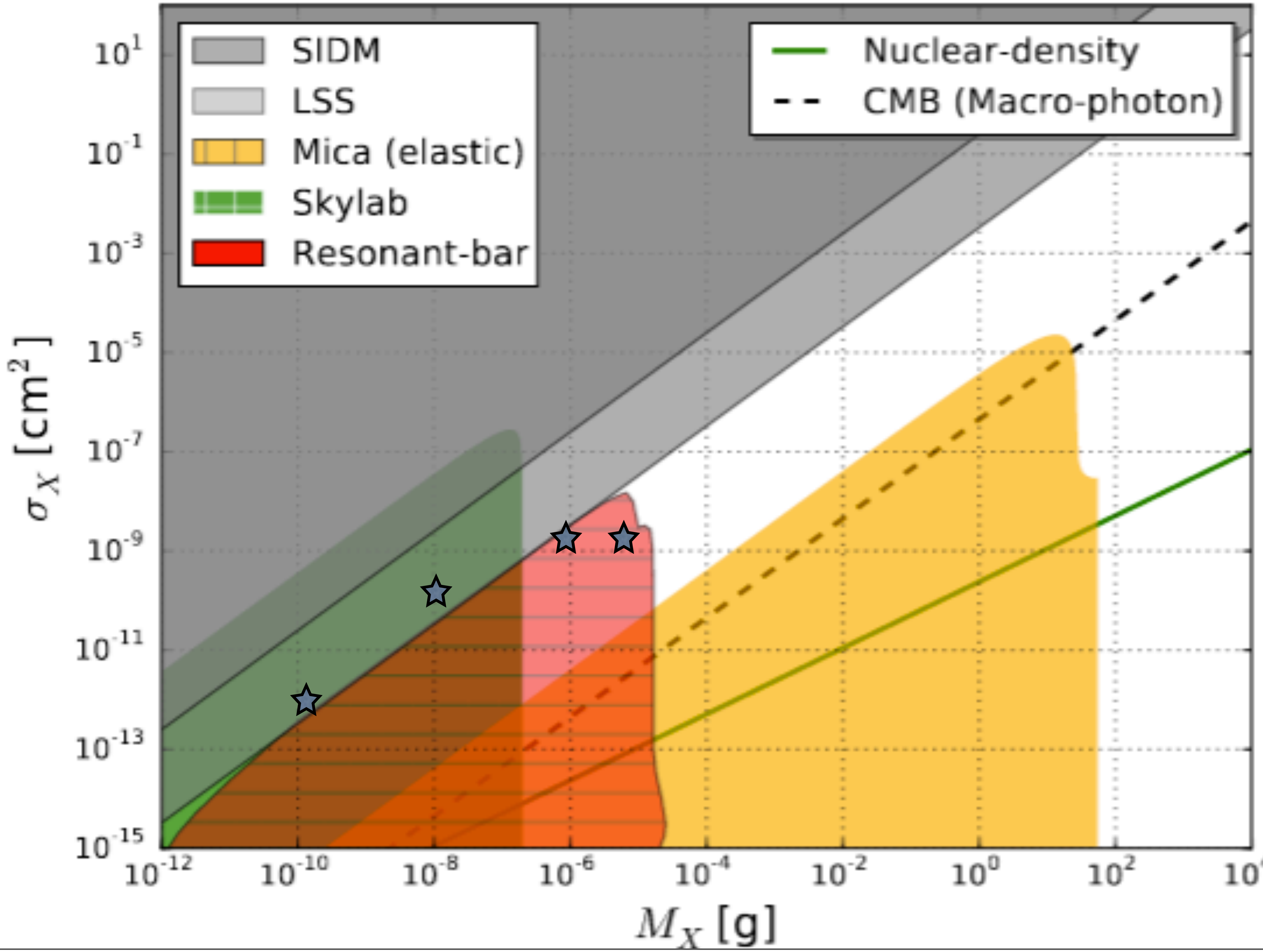


(black dots are electrons)

M (GeV) 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

➢ Nuclearites : core + electrons , neutral, A > 10^{6} CDM candidate

➢ Strangelets : positively charged, A < 10^{6} Cosmic ray component


SIDM
LSS
Mica (elastic)
Skylab
Resonant-bar
Nuclear-density
CMB (Macro-photon)
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
σ_X [cm^2]
M_X [g]

Interest of bar results for other kind of DM candidate #1 MACRO

our results with this analisys

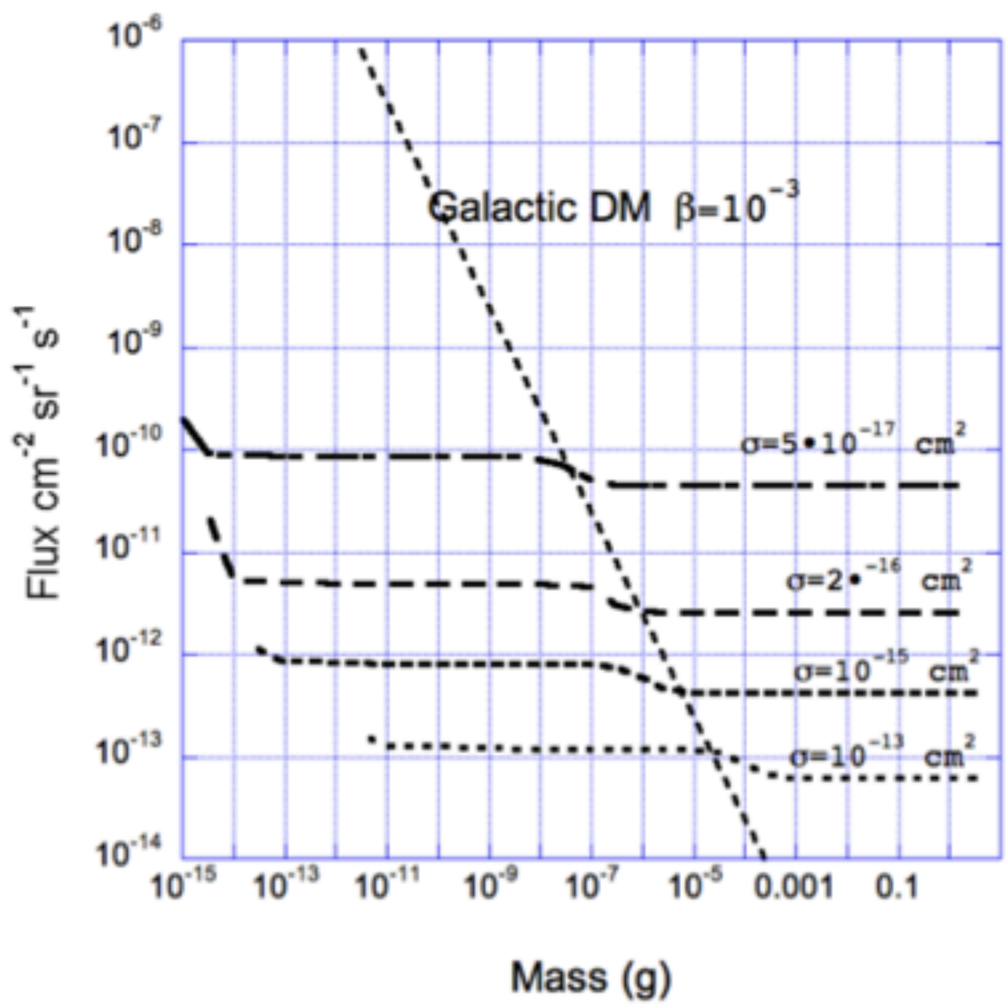
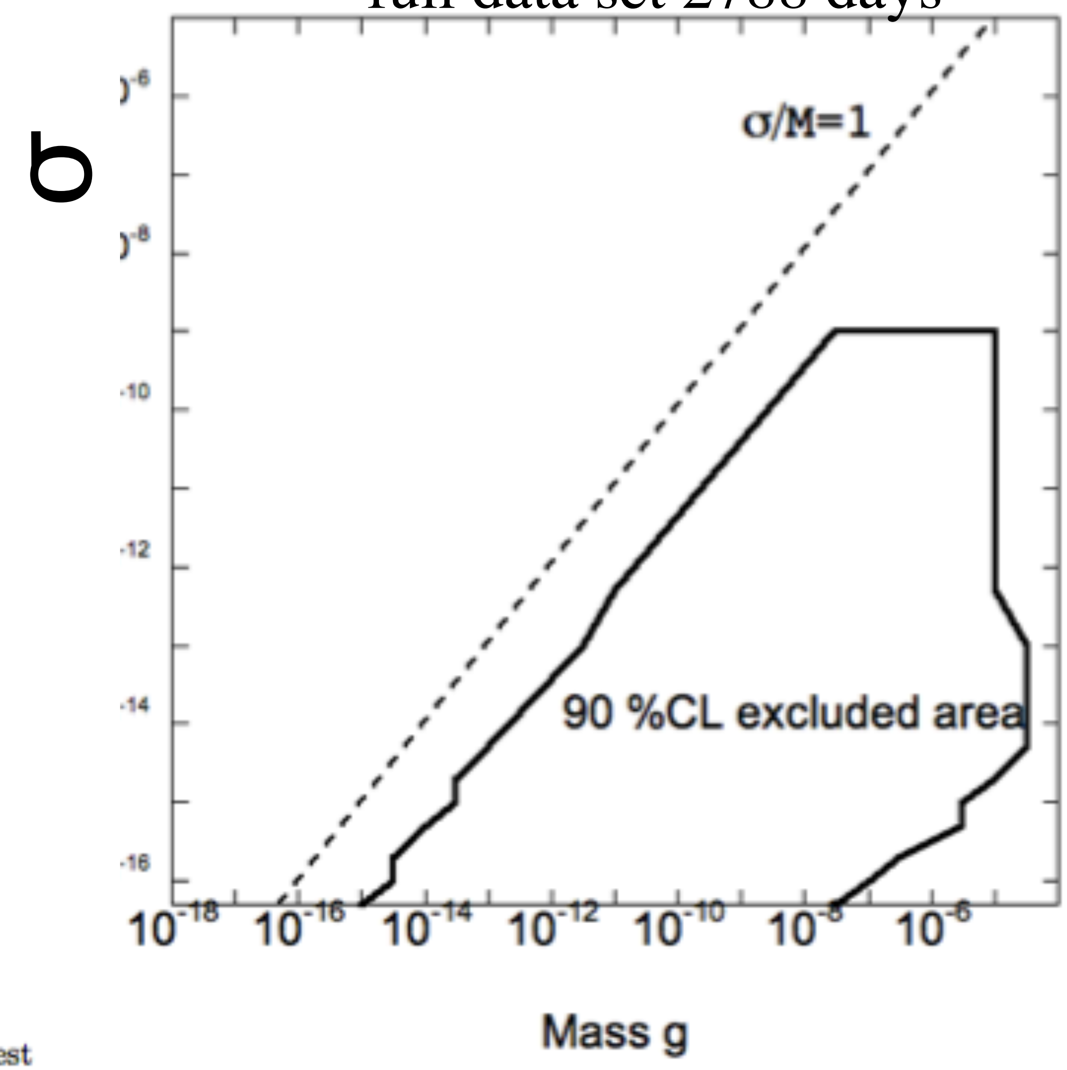


Figure 14: 90 % CL flux upper limits vs MACRO mass for different cross sections. The lowest mass limit on abscissa is set by a mass large enough to cross the atmosphere.

Our evaluation NAUTILUS + EXPLORER full data set 2788 days

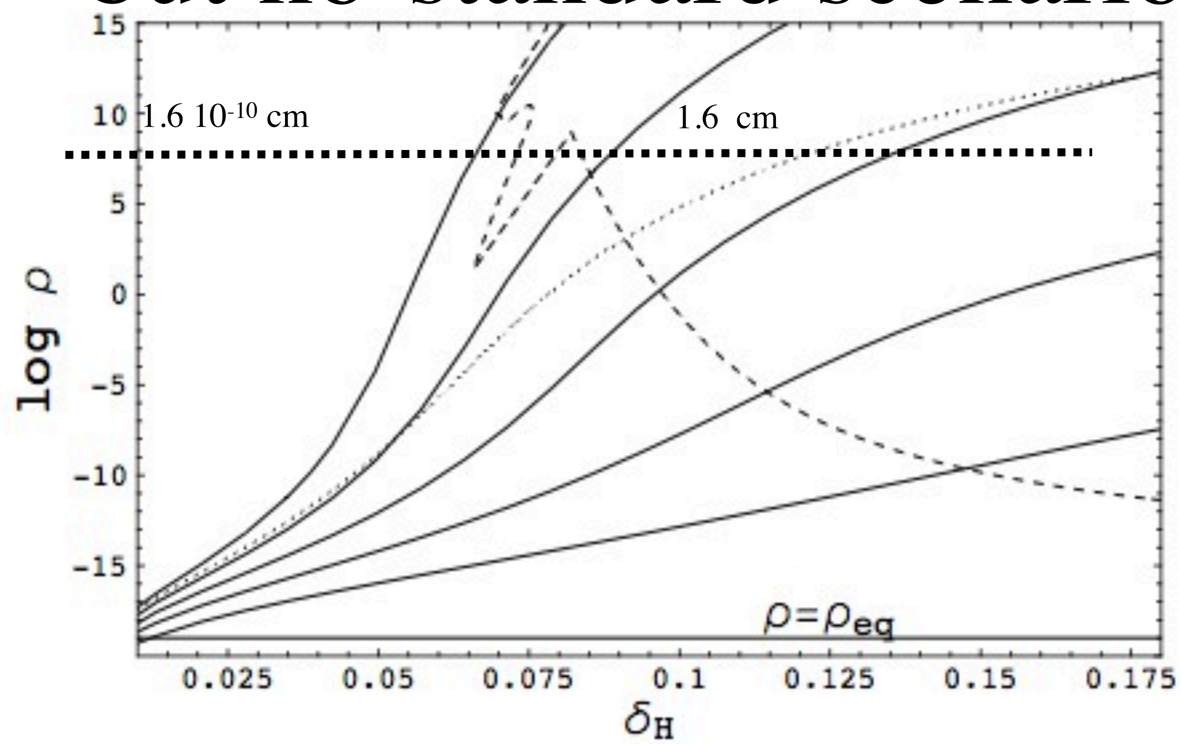


90 % CL excluded regions in the plane cross section - mass. The line ference. The study of cosmological halos may suggest a value σ /M=0.1.

Dark matter could be in “clumps”

Berezinski et al. arXiv:1002.3445v2 and PRD

- in the standard cosmological scenario and for neutralinos the minimum clump mass is quite large (10^{-7} 10^{-5} Msun)
- but no-standard scenario are possible



according to this plot clumps radius could range from very small ($<<10^{-10}$)cm to very big dimensions of astrophysical interest

Clumps of astrophysical dimensions are of interest for LISa

FIG. 6: The mean density ρ (in g cm^{-3}) of DM clumps as function of the perturbation δ_H in the radiation density on the horizon scale; solid lines from top to bottom are for clump masses $M = 10^{-10}$, 1, 10^{10}, 10^{20}, 10^{30} g. The dashed line is the bound on the clump density from primordial black holes overproduction with threshold $\delta_c = 0.7$. The time of two-body gravitational relaxation inside the clump core is less than the age of the Universe for clumps above the dotted lines, if the DM particle mass is $m \geq 10^{11}$ GeV.