Searching for gravitational wave signal as counterpart of gamma-ray bursts.

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ROG Collaboration

Gamma Ray Bursts (GRBs) and Gravitational Waves (GWs) Association

- **GRBs** likely arise from shocks in a relativistic fireball that is triggered by rapid accretion on to a newly formed massive object.
- Proposed **GRB progenitors** include **binary neutron star mergers (**Eichler, Livio, Piran, Schramm, 1989) **and collapsar -** the collapse of a rotating star to a black hole - classical source for GW.

Gravitational Waves and γ-bursts may have the same sources

Summary

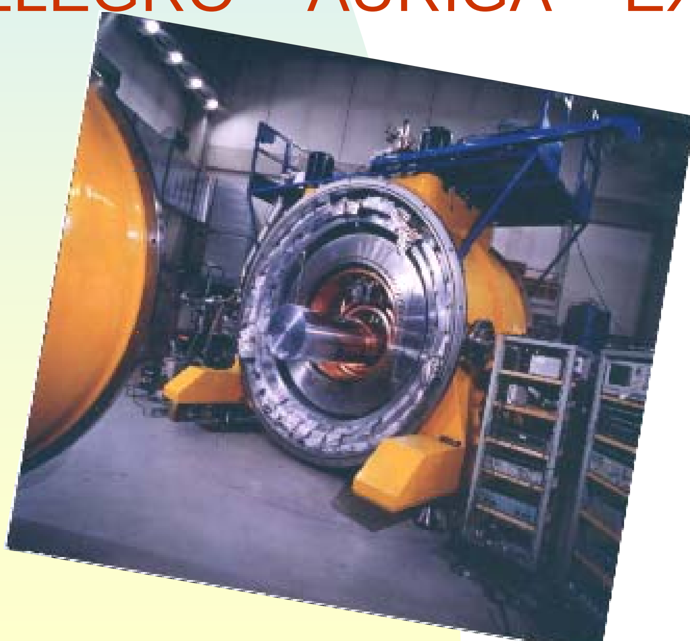
- Resonant cryogenic detectors.
  -Present sensitivity-.

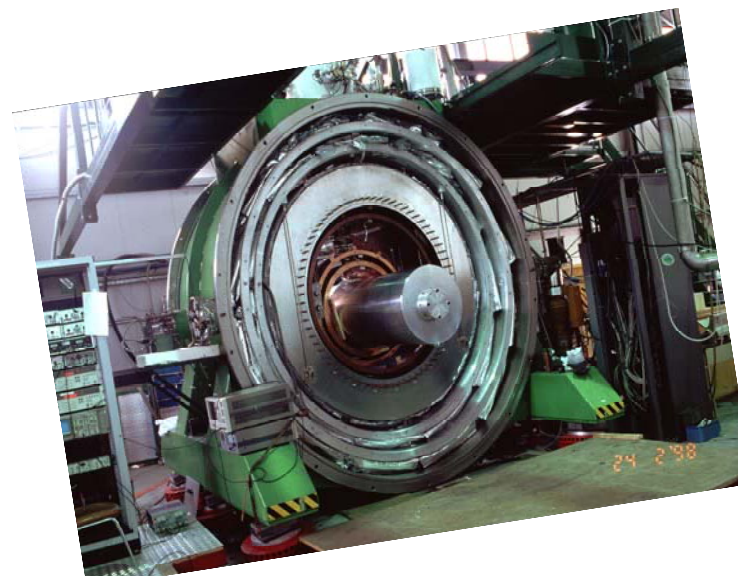
- Proposed analysis procedures
  - for detecting association between the two emissions (GW & γ-b_s)-

- Experimental results

IGEC Collaboration
- 5 cryogenic GW resonators-

ALLEGRO AURIGA EXPLORER NAUTILUS NIOBE





IGEC

ROG → EXPLORER, NAUTILUS

	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Bar Material	Al5056	Al5056	Al5056	Al5056	Nb
Bar Mass [kg]	2296	2230	2270	2260	1500
Bar Length [m]	3.0	2.9	3.0	3.0	2.75
Freq. - [Hz]	895	912	905	908	694
Freq. + [Hz]	920	930	921	924	713
Q ± [1E6]	2	3	1.5	0.5	20
Bar Temp. [K]	4.2	0.25	2.6	0.1	5
Misalignment *	6°	5°	3°	2°	16°

* Angle between bar axis and the perpendicular to the Earth great circle closer to the five detectors.

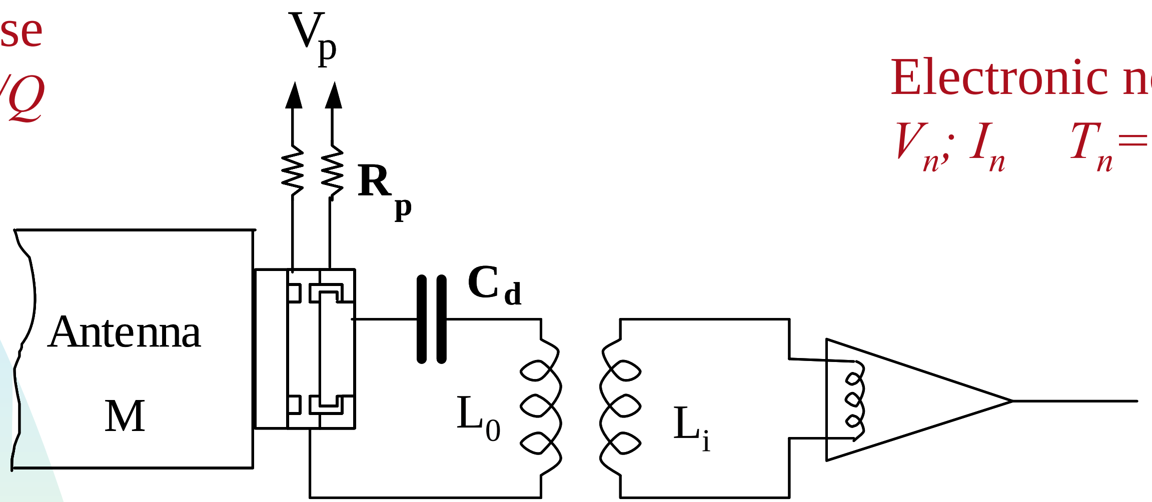
- **almost parallel** detectors
- resonant **frequencies** span from **694 to 930 Hz**
- typical **frequency bandwidths** per each resonance **~ 1 Hz**
- typical **amplitude thresholds** for bursts search in 1997–1998 at resonances:

$H_{th} \sim 1.5 - 4 \times 10^{-21}$ /Hz *Fourier component of the g.w. burst amplitude*

$h_{th} \sim 1.5 - 4 \times 10^{-18}$ *strain g.w. amplitude for a conventional ~1ms burs*

MAIN FEATURES

Thermal noise
$S_F = MkT\omega_r/Q$



Electronic noise
$V_n; I_n \quad T_n = \sqrt{V_n^2 I_n^2}/k$

The mechanical oscillator

Mass **M**
Speed of sound $\mathbf{v_s}$
Temperature **T**
Quality factor **Q**
Res. frequency $\mathbf{f_r}$

The transducer

Efficiency β

The amplifier

Noise temperature $\mathbf{T_n}$

Minimum energy change detectable :

$$\Delta E_{min} = kT_{eff} \simeq kT/\beta Q + 2kT_n$$

The detector sensitivity to short GW bursts

measurable with SNR=1

in terms of GW amplitude h:

$$\Delta l/l = h = L/\tau_g v^2 (kT_{eff}/M)^{1/2}$$

L : bar length
τ_g:burst duration
V:sound velocity

M : bar mass

For NAUTILUS, EXPLORER:

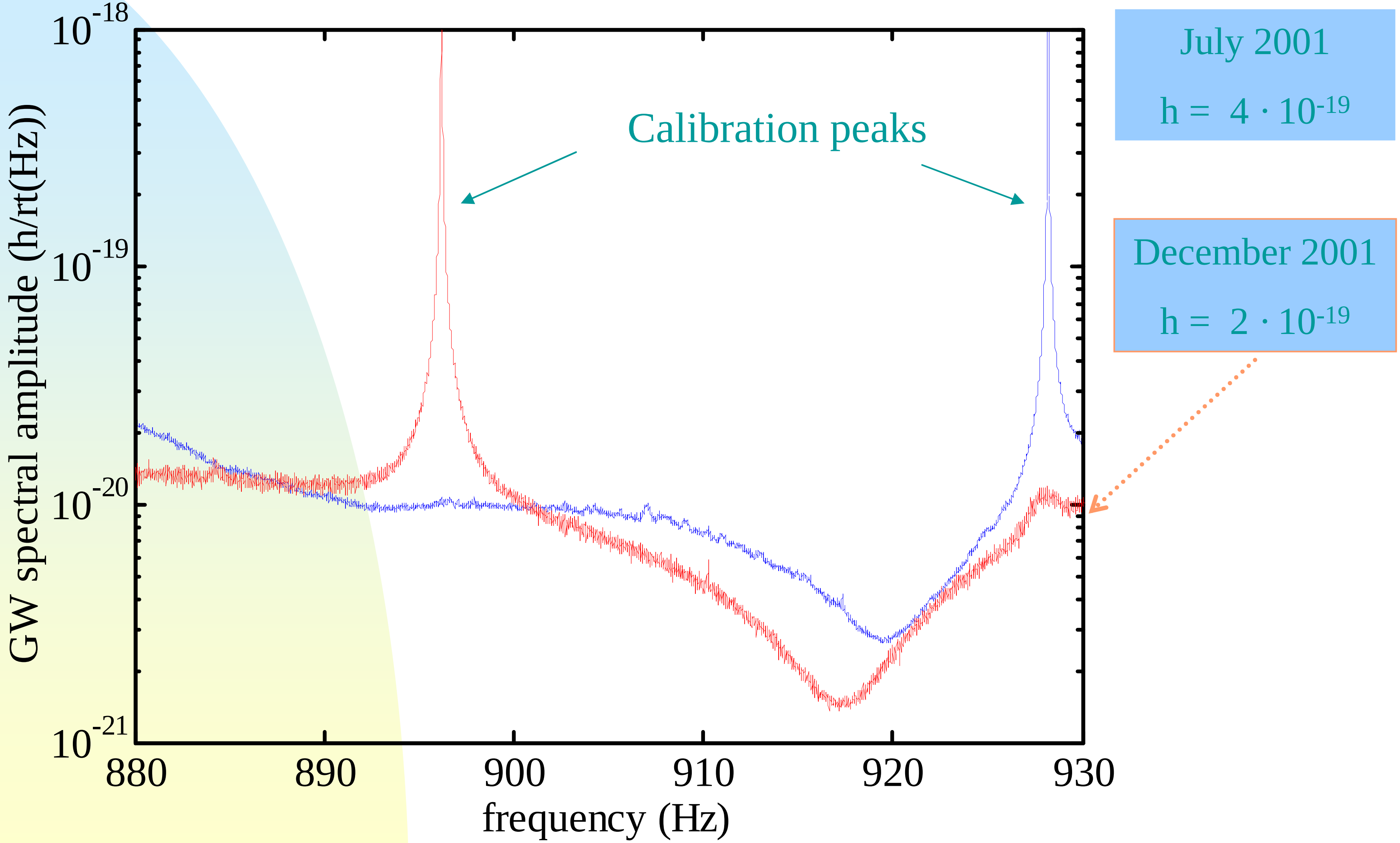
$$h \simeq 8\ 10^{-18}\ (T_{eff})^{1/2}$$

for a typical Galactic burst:

(10 kpcs, 1ms, 10^{-3} $M_\odot$)

h=10-18

EXPLORER PERFORMANCES



NAUTILUS sensitivity

Strain sensitivity, i.e. minimum impulsive signal detectable with SNR = 1,

$$\tilde{h}_{min} \approx \left(\frac{T}{MQ}\right)^{1/2} \quad [1/\sqrt{Hz}]$$

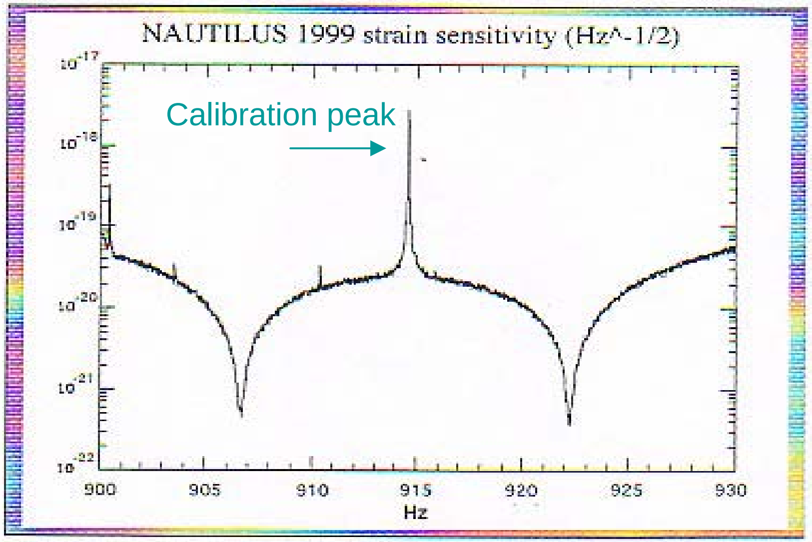
T Thermodynamic Temperature
M Mass
Q Quality Factor

$$\Delta f \approx \left(\frac{\beta}{T_n}\right)^{1/2} \quad [Hz]$$

ß Capacitive transducer efficiency
T_n Electronic temperature noise

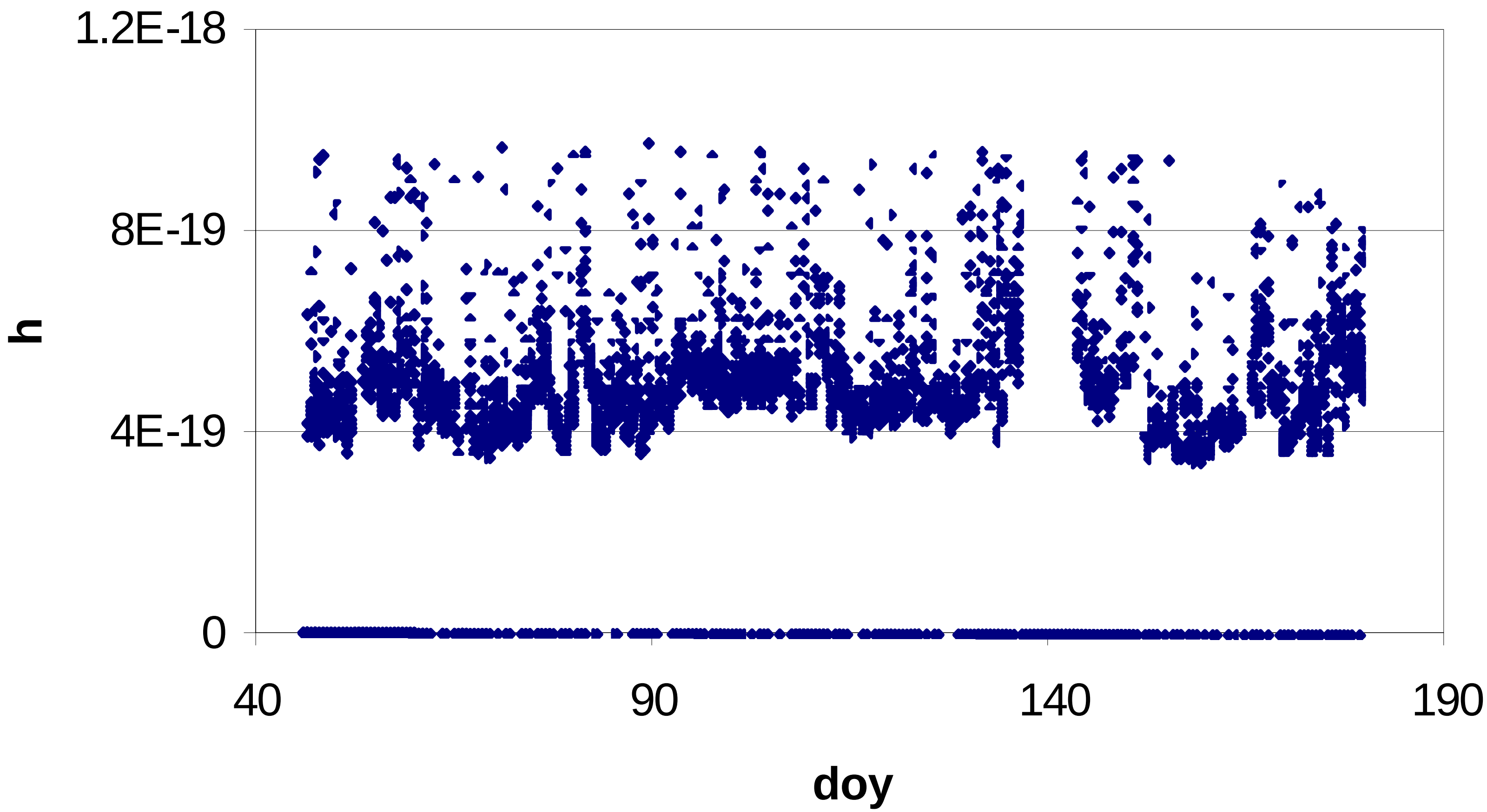
$$\tilde{h}_{min} \approx 3 \cdot 10^{-22} 1/\sqrt{Hz}$$

$$\Delta f \approx 1 Hz$$



The bandwidth of the antenna can be increased acting on the transducer-amplifier of the signals, by increasing ß and/or decreasing T_n

OPERATIONS DURING 2001



Explorer and Nautilus 2001

- **EXPLORER (CERN)**
- ON from March to December
- Bandwidth = 9 Hz
- T = 2.6 K
- Duty Cycle=267/294=91%
- Average sensitivity

  h=4.5 10-19 →

  1.2 10-4 M0 in GC

- **NAUTILUS (LNF)**
- ON from January to December
- Bandwidth = 0.4 Hz
- T = 1.5 K
- Duty Cycle=291/365 =80%
- Average sensitivity

  h=5. 7 10-19 →

  2 10-4 M0 in GC

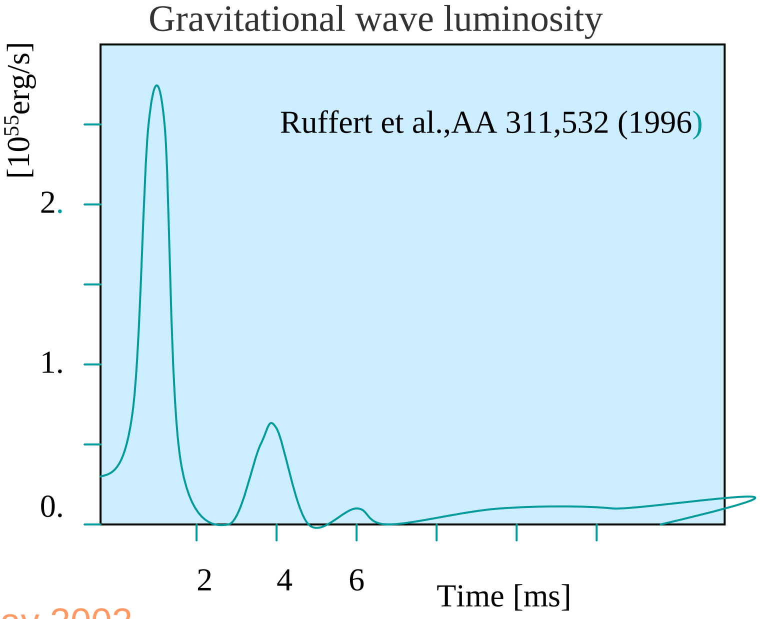
Coincident operation for 213.5 days

Typical theoretical prospect for detection for a single GRB event:

$h \sim < 10^{-21}\ 10^{-22}$ GW amplitude

@ R ~ 1 Gpc

@ 1 Khz



Theoretical previsions:

According to the rather well established *fireball* [see ref.] concept:

GRBs produce gravitational radiation in **two** phases.

- The first phase is during the formation of the compact object.

($\Delta T \sim 10^3$ s).

- The second phase is from the acceleration phase of the ultra relativistic eject.

($\Delta T \lesssim 0$ s)

Piran 1999,2000
Frontera et al. 1999
Sari et al. 1998
Rees & Meszaros 1993,1994
‘
‘

Interpretation of real GW detector data

- **Investigate a <u>wide time window</u> to include several possible delays.** As matter of facts, taking in account the recent astrophysical hypothesis: $t_{GWB}-t_{GRB}=\Delta t\sim 1000$ s

- **Do it also in <u>non-stationary noise</u> condition.** GW data are often dominated by the contribute of non-gaussian, non stationary noise.

<u>In order to consider these fundamental items, **studies of adaptive algorithms** are required.</u>

Interpretation of real GW detector data

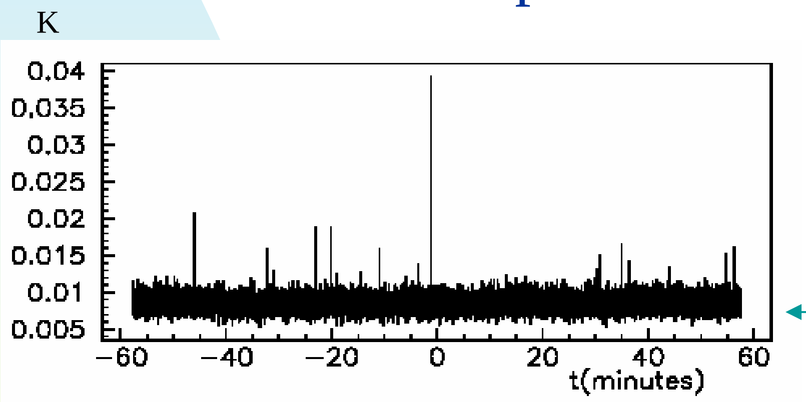
Cumulative techniques have been proposed to detect a statistically significant association between GW signals and GRBs.

- L.S.Finn, S.D.Mohanty, J.D. Romano. Phys. Rev. D **60 ,** 121101 (1999).
- G. Modestino, G. Pizzella , A&A., **364**, 419 (2000).
- M.T. Murphy, J.K. Webb, I.S. Heng MNRAS. **316** , 657 (2000).
- P. Bonifazi, G.V. Pallottino, A.V. Gusev, A.Kochetkova, Ak. Postnov, V. Rudenko, V.N. Vinogradov CNR-IFSI-2001-28
- G. Modestino and A. Moleti Phys. Rev. D **65**, 022005 (2002).

“Detecting an association between GR and GWB”

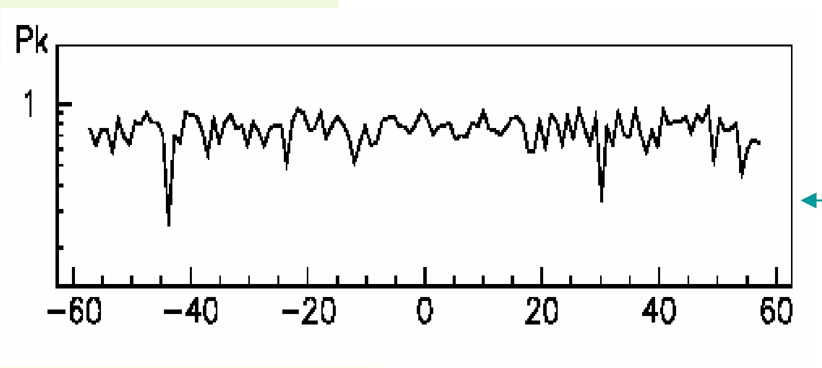
G.Modestino and G.Pizzella, A&A 364,419 (2000)

- The test indicates the presence of many coherent (Δt=cost) contributions and overcomes the problem of the single spurious peaks.



Overlapping 91 data stretches

← Average



← Kolmogorov test

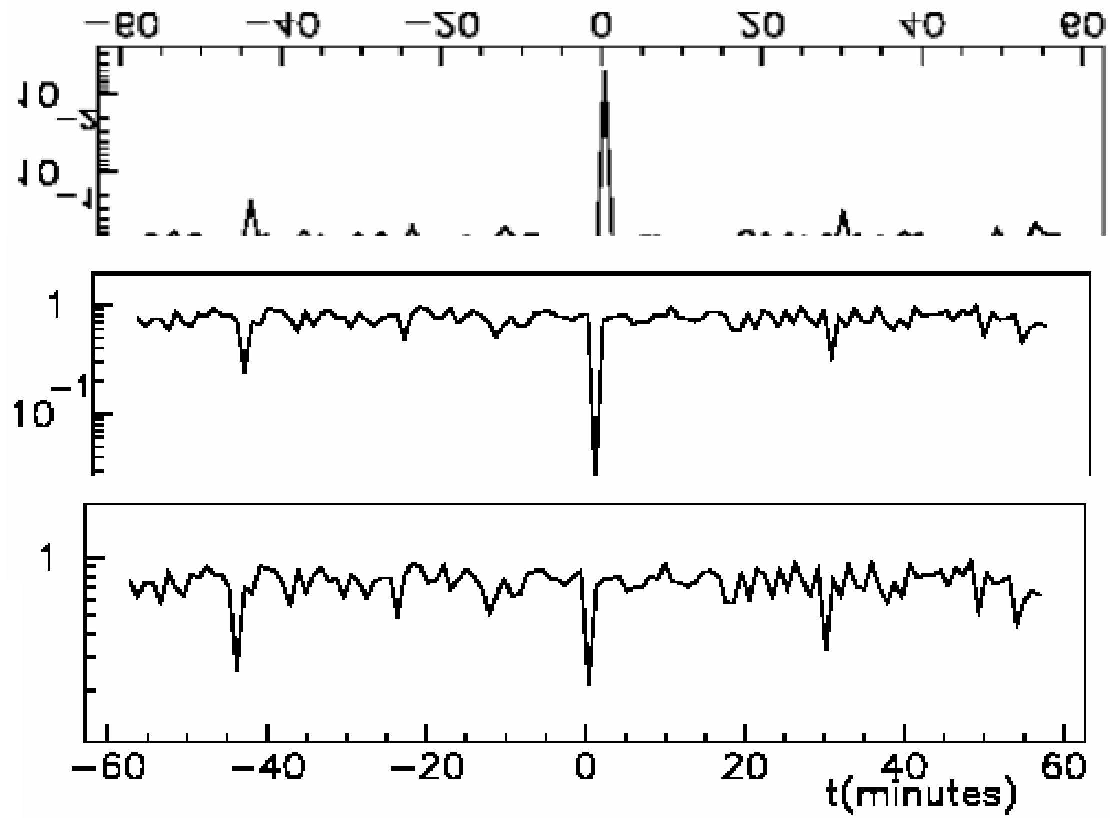
G.Modestino and G.Pizzella, A&A 364,419 (2000)

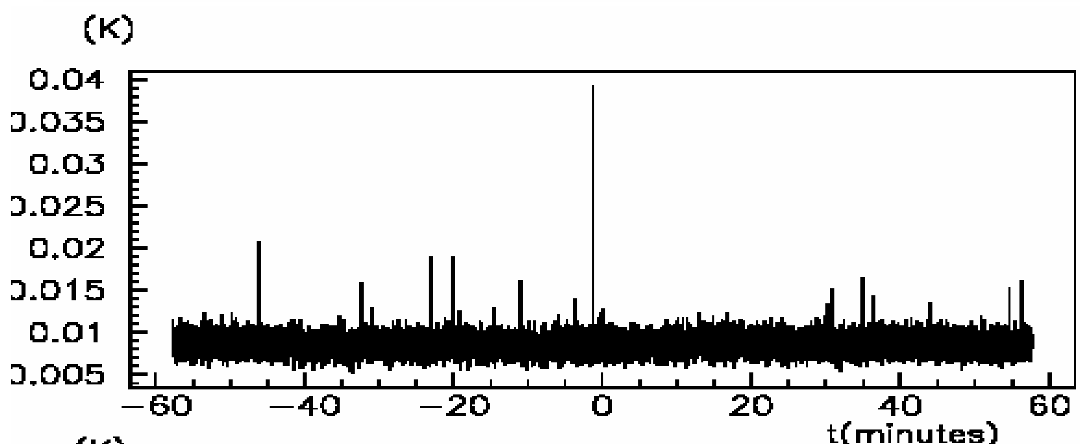
Adding signals of 16mK

at zero time

during the same minute centered at zero time but packet at a 15 s time interval

during the same minute centered at zero time but packet at a 10 s time interval





Proposed techniques:

"Detecting an association between GR and GWB"

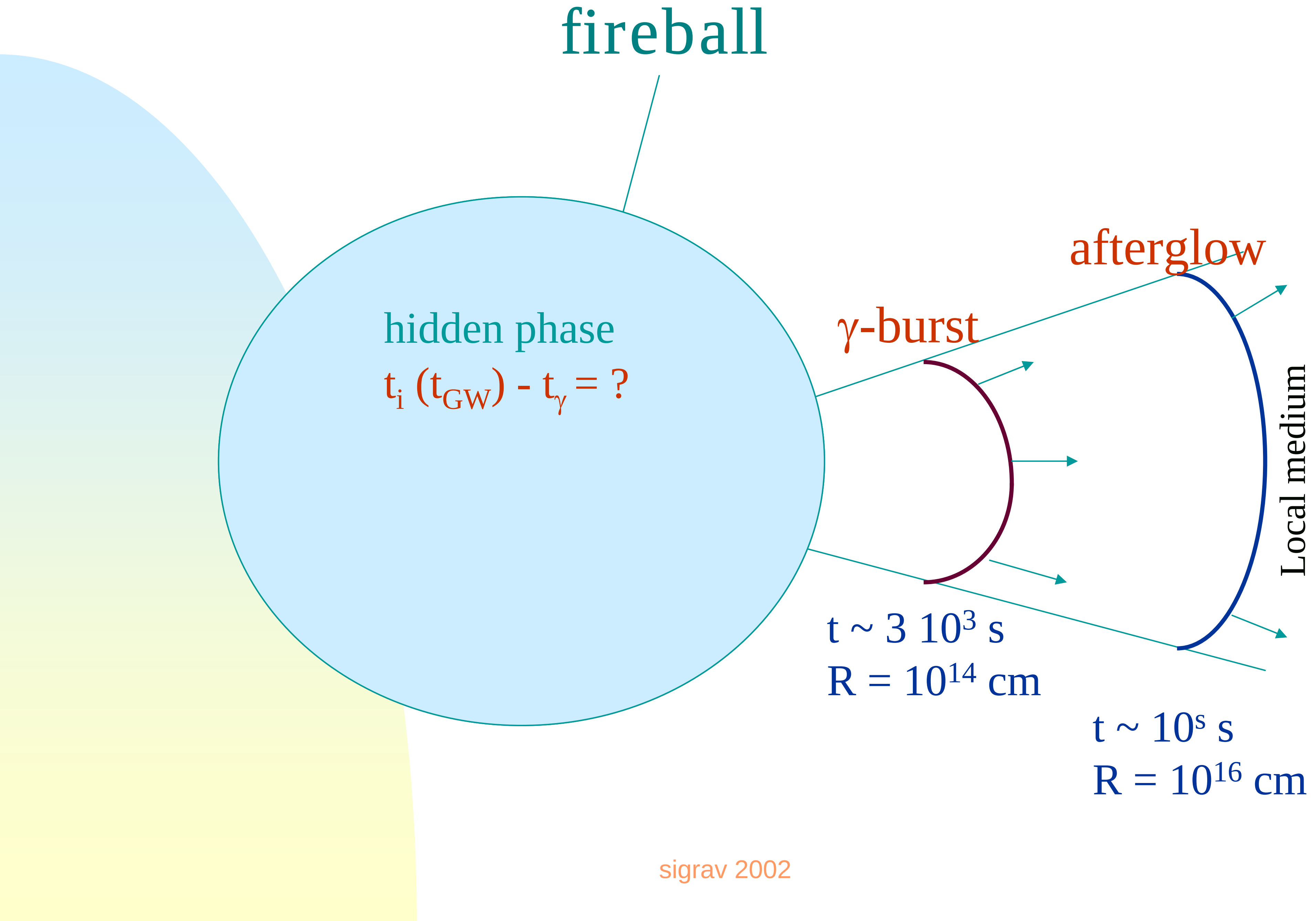
Finn et al.,PRD 60,121101 (1999)

- Cross-correlation of the output of two GW detectors.
- Statistical comparison between on-source set , off-source set.

$$h \leq 9.4\ 10^{-22} \quad \text{for} \quad t_{GRB}-t_{GW} \simeq 500\ s$$

$$h \leq 1.7\ 10^{-22} \quad \text{for} \quad t_{GRB}-t_{GW} \simeq 0.5\ s$$

Expected U.L. for LIGO detector ($S_o=3\times10^{-23}\ Hz^{-1/2}$, Bw=100Hz), with **1000** GRBs, with 95% c.l.



fireball
hidden phase
t_i (t_{GW}) - t_γ = ?
γ-burst
afterglow
Local medium
t ~ 3 10^3 s
R = 10^{14} cm
t ~ 10^s s
R = 10^{16} cm

"Cross-correlation between GW detectors for detecting association with GRBs"

G.Modestino and A. Moleti, PRD **65**,022005 (2002)

- Cumulative cross-correlation technique.
  - Study of the real data background of NAUTILUS x EXPLORER
    - $h^2 \sim [\Delta t/(N_{GRBs}\ B_w)]^{1/2}$
  - Effective also in the case of non-gaussian data set (N_{GRBs}<100).
  - No hypothesis is required about Δt.

Experimental studies

- SEARCH FOR TIME CORRELATION BETWEEN GRBs and DATA FROM TH GRAVITATIONAL WAVE ANTENNA EXPLORER.

Coincidence technique.
No evidence in a time window of ± 1 s , at several delays.

(**ROG Coll.**) Astron. Astrophys. Suppl. Ser. **138**, 603 –604 (1999)

- MEASUREMENTS WITH THE RESONANT GRAVITATIONAL WAVE DETECTOR EXPLORER DURING THE GRB 980425

No anomaly in the background of the GW data detector with the sensitivity of $h>=10^{-18}$

(**ROG Coll.**) Astron. Astrophys. Suppl. Ser. **138** 605-606

- CORRELATION BETWEEN GRBs AND GWs.

Using 120 GRBs, in a 10s time window, an U.L. of $1.5\ 10^{-18}$ was obtained.

(**AURIGA Group**) Phys.Rev. **D 63**, 082002

- SEARCH FOR CORRELATION BETWEEN GRBÕS DETECTED Y BEPPOSAX GRAVITATIONAL WAVE DETECTORS EXPLORER AND NAUTILUS.

Cross-correlation tecnique-
Absence of signal of amplitude of $h>1.2\ 10^{-18}$ within ± 400 s.
$h>6.5\ 10^{-19}$ ± 5 s.

(**ROG Coll.**) astro-ph/0206431

astro-ph/0206431 (sub. to PRD)

Search for correlation between GRB's detected by BeppoSAX and gravitational wave detectors EXPLORER and NAUTILUS

P. Astone[1], M. Bassan[2], P. Bonifazi[3], P. Carelli[4], G. Castellano[5]
E. Coccia[2], C. Cosmelli[6], G. D'Agostini[6], S. D'Antonio[2], V. Fafone[7], G. Federici[1]
F. Frontera[8], C. Guidorzi[9], A. Marini[7], Y. Minenkov[2], I. Modena[2]
G. Modestino[7], A. Moleti[2], E. Montanari[10], G. V. Pallottino[6]
G. Pizzella[11], L. Quintieri[7], A. Rocchi[2], F. Ronga[7], R. Terenzi[12], G. Torrioli[5], M. Visco[13]

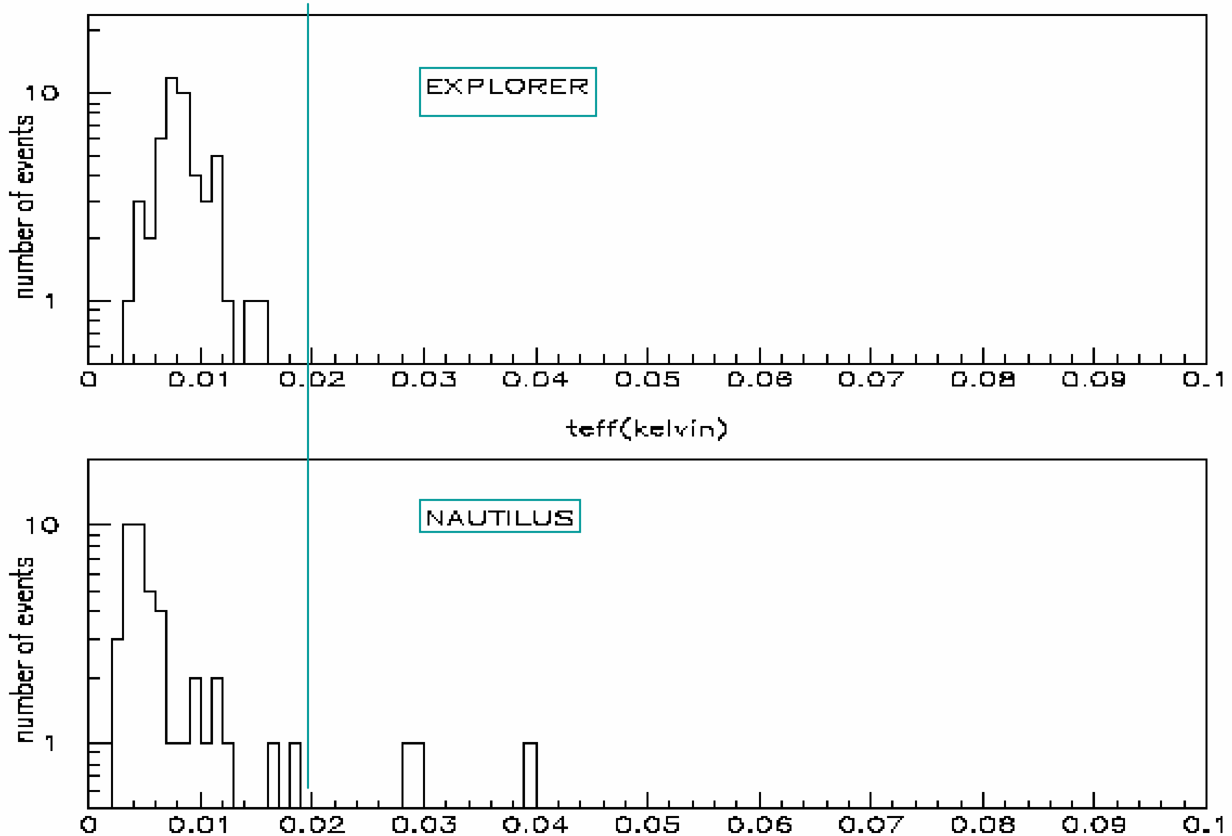
1) *Istituto Nazionale di Fisica Nucleare INFN, Rome*
2) *University of Rome "Tor Vergata" and INFN, Rome 2*
3) *IFSI-CNR and INFN, Rome*
4) *University of L'Aquila and INFN, Rome 2*
5) *IESS-CNR and INFN, Rome*
6) *University of Rome "La Sapienza" and INFN, Rome*
7) *Istituto Nazionale di Fisica Nucleare INFN, Frascati*
8) *University of Ferrara and IASF-CNR, Bologna*
9) *University of Ferrara, Ferrara*
10) *University of Ferrara, Ferrara and ITA "I. Calvi", Finale Emilia, Modena*
11) *University of Rome "Tor Vergata" and INFN, Frascati*
12) *IFSI-CNR and INFN, Rome 2*
13) *IFSI-CNR and INFN, Frascati*

Astone et al. (ROG Coll), astro-ph/0206431.

EXPLORER - NAUTILUS (2001)

Cross-correlation analysis

T_{eff} evaluated within a time window of ± 400s, centered at t_{GRB}

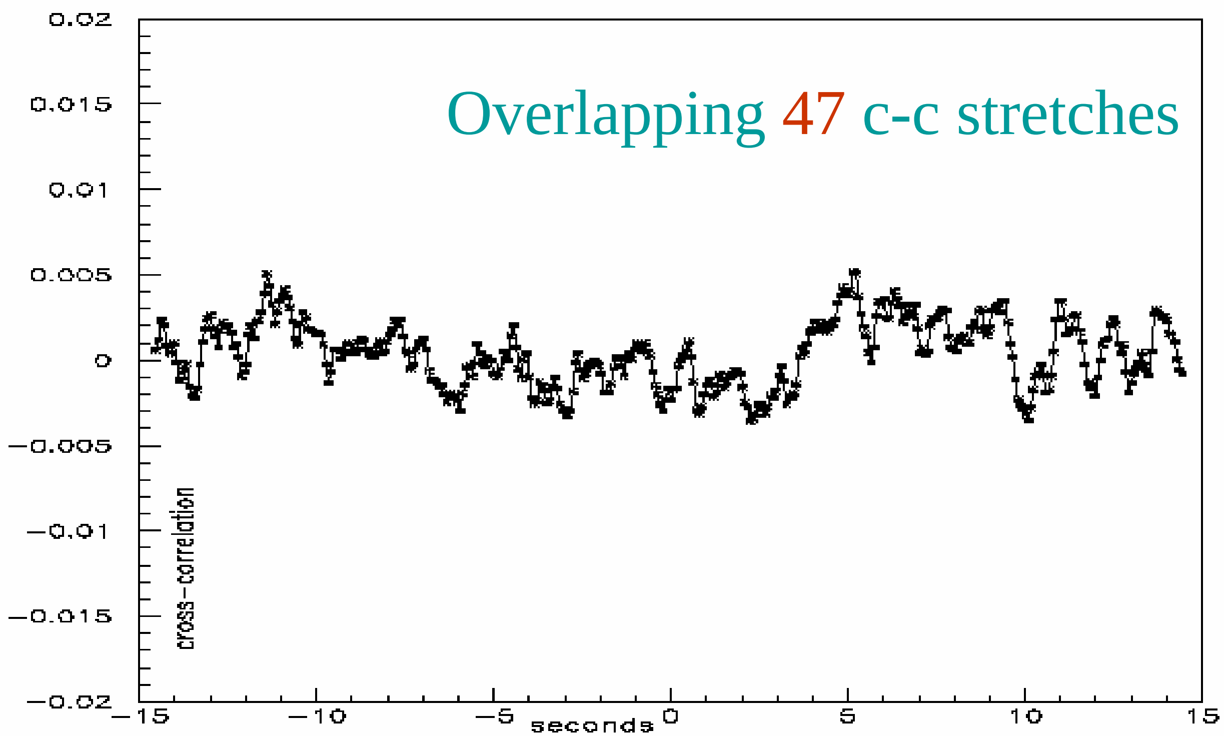


The data with $T_{eff} \leq$ 20 mk are selected.

47 GRB are analyzed

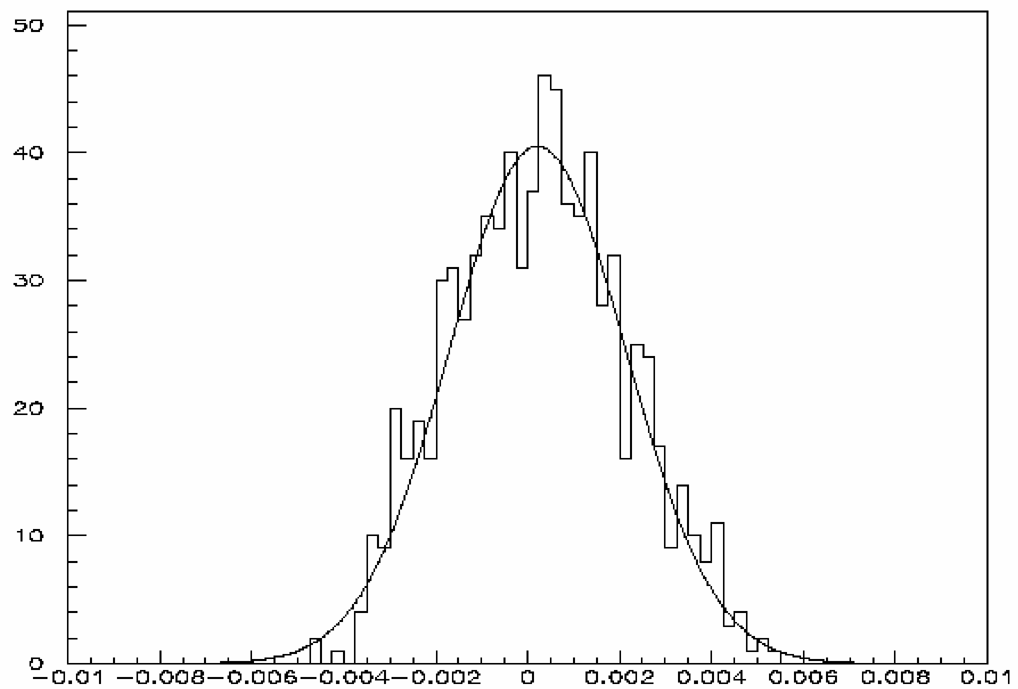
Astone et al. (ROG Coll), astro-ph/0206431.

EXPLORER - NAUTILUS
Cross-correlation result



Astone et al. (ROG Coll), astro-ph/0206431.

Average cross-correlation distribution and gaussian fit.



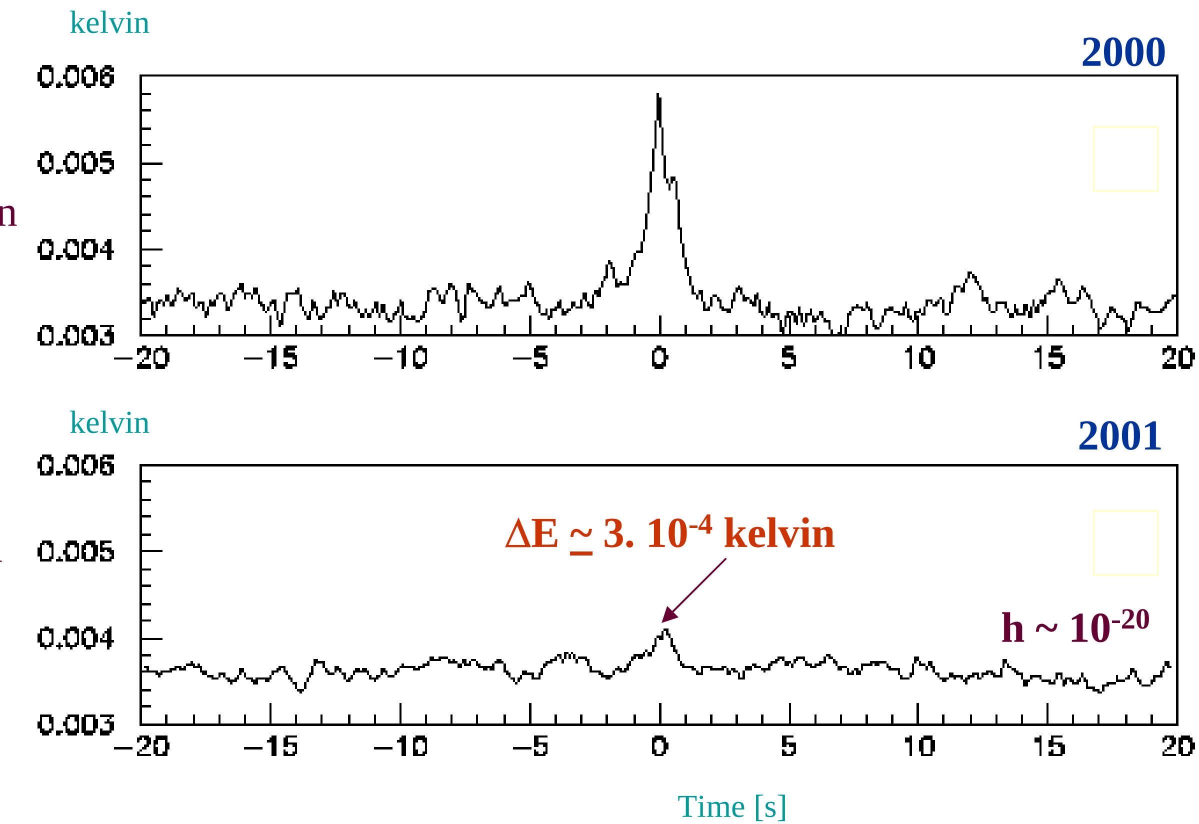
$h \leq 1.2\ 10^{-18}$ (Δt=+400s)

$h \leq 6.5\ 10^{-19}$ (Δt=+5s)

Cosmic-ray showers interacting with NAUTILUS

@ $T_{bar} \simeq 0.1$ kelvin

@ $T_{bar} > 1$ kelvin



Astone et al. (ROG Coll.)
PRD, 84, 14, 2000.

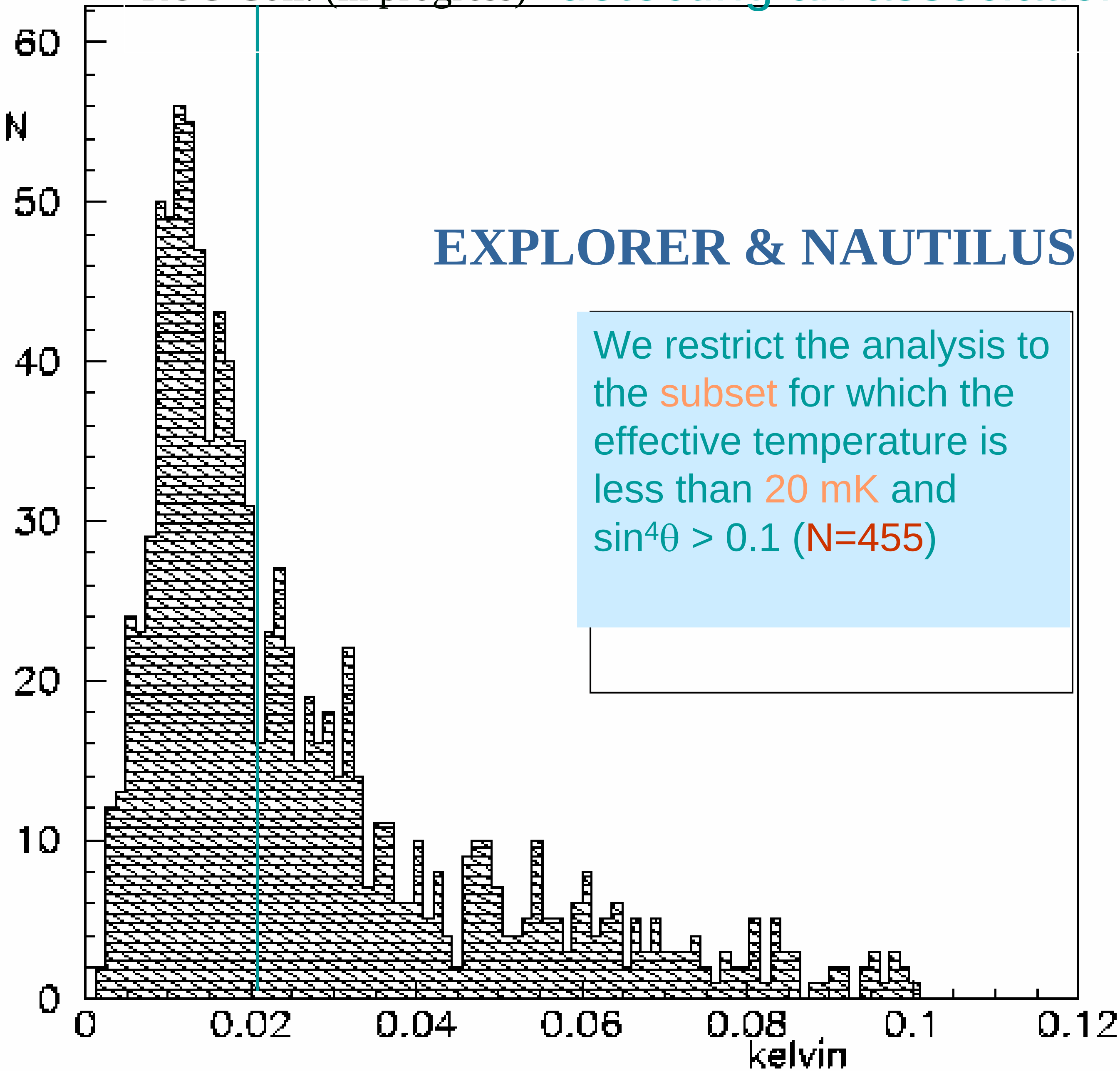
Astone et al. (ROG Coll.)
Phy. Lett. B 499 16 (2001)

Astone et al. (ROG Coll.)
Phys. Lett. B 540 179 (2002)

The results show a good agreement with the thermo-acoustic model

ROG Coll. (in progress)

detecting an association at Δt=0



EXPLORER & NAUTILUS

We restrict the analysis to the subset for which the effective temperature is less than 20 mK and $\sin^4\theta > 0.1$ (N=455)

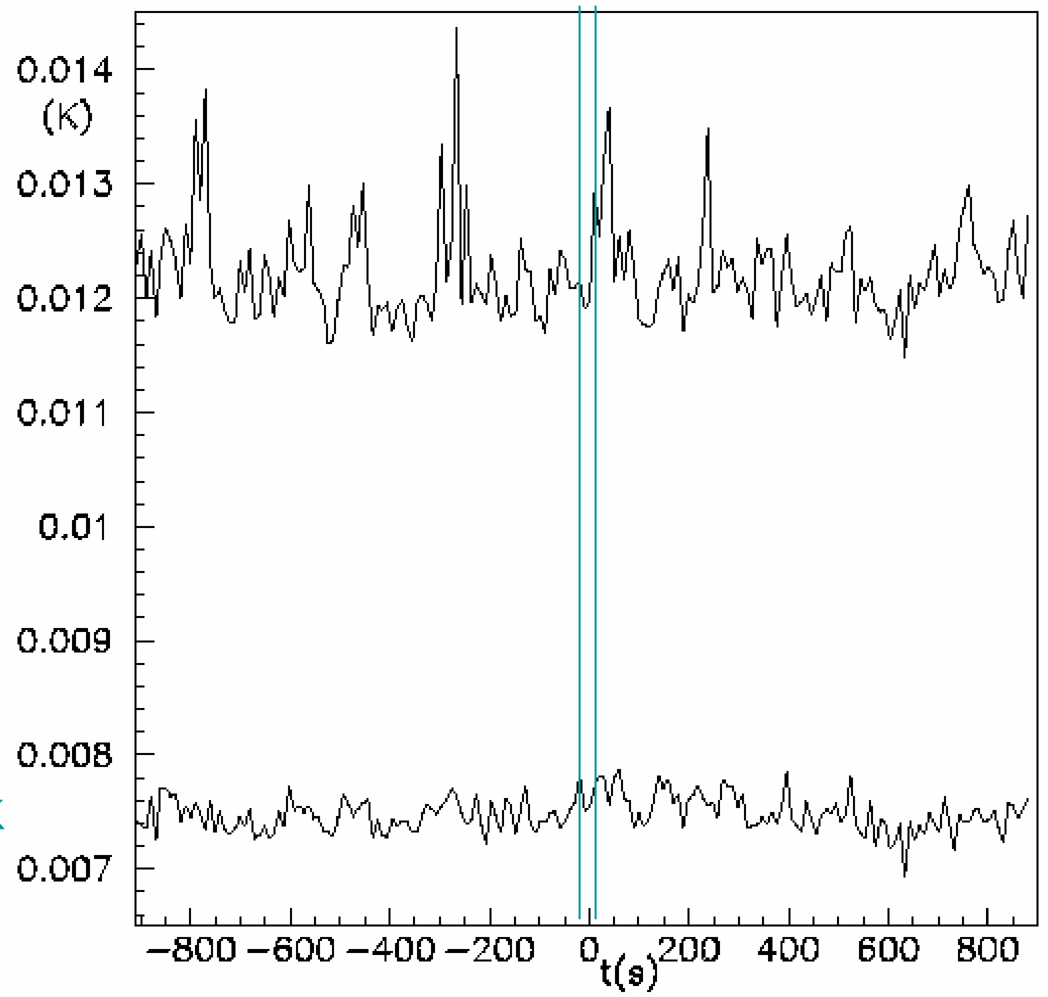
ROG Coll.
(in progress)

GW detector energy as a function of the GW-GRB delay.

(N_{GRB}=455)

Cumulative average
$\pm$5s E(0) $\simeq$ <E>=12mK

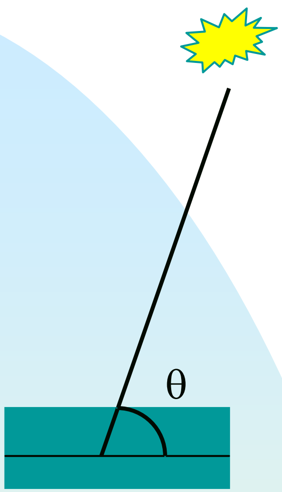
Cumulative median
$\pm$5s E(0) $\simeq$ <E>=7.5mK
σ = 0.4 mK

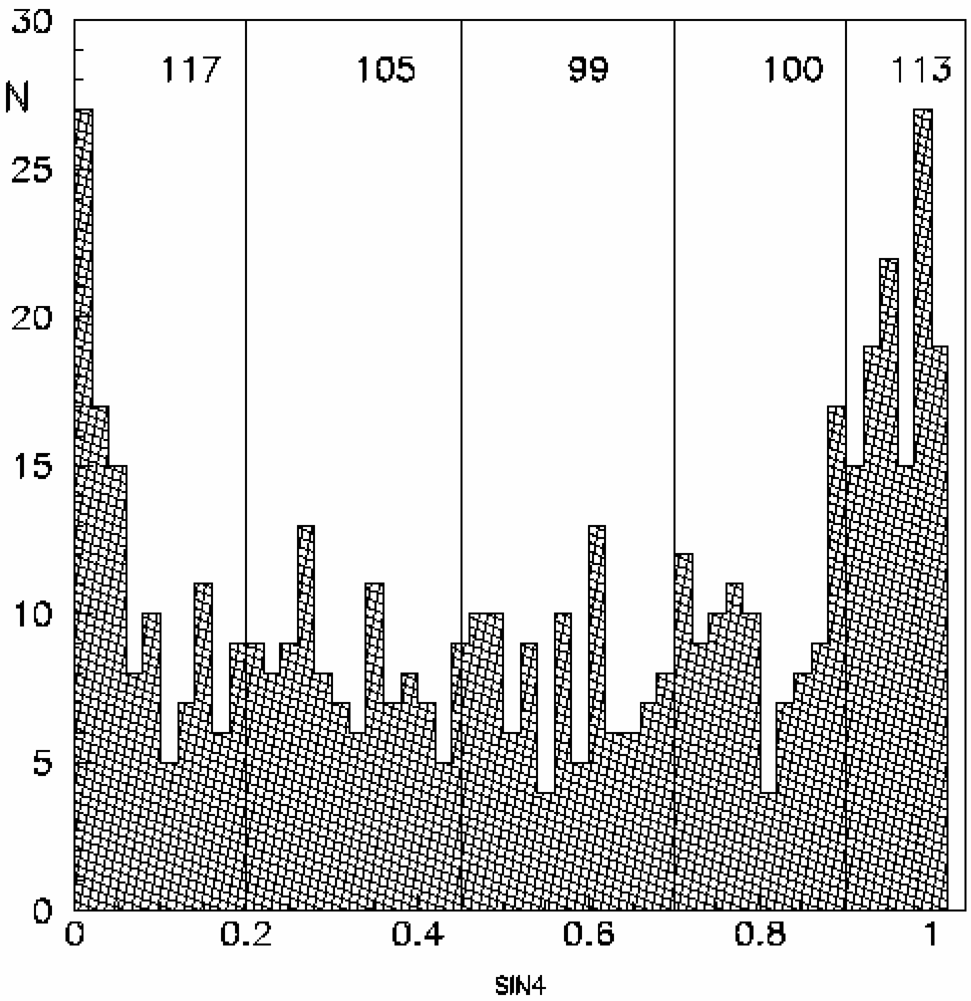


97.5% $h \leq 1.4\ 10^{-19}$

sigrav 2002

to look for a correlation with $\sin^4\theta$.



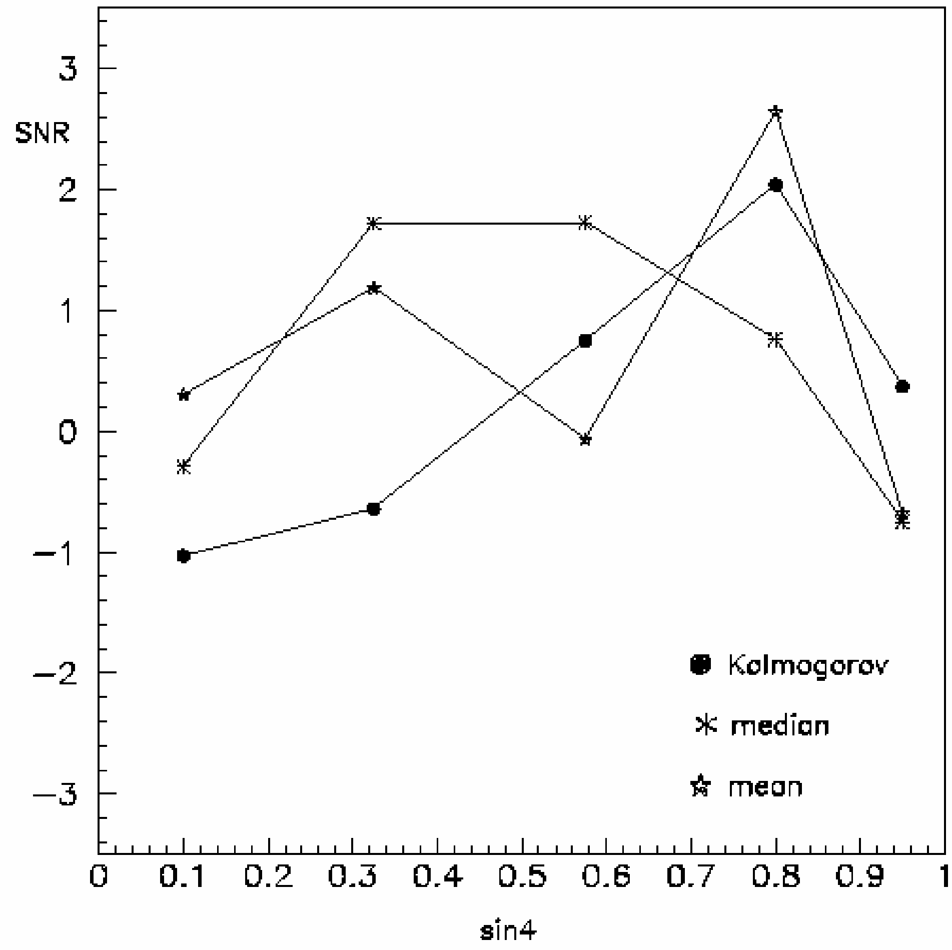


$\sin^4\theta$ correspondingly to the **534** selected GRB arrival times.
The five regions of increasing $\sin^4\theta$, separated by vertical lines, correspond to the data subsets separately analyzed.

ROG Coll. (in progress)

ROG Coll.
In progress

Signal-to-noise ratio for GRB-average, median and Kolmogorov maximum distance evaluated at the arrival time of GRB, for five data subsets of increasing $\sin^4\theta$



Time window ± 15 s around the peak time of GRB.

Interpretation of real GW detector data

1) Cumulative technique:

Combine the signals from each GRB and from different GW detectors, to simulate a single detector of greater amplitude.

Statistically significant:

$S/N \sim (N_{det} \times N_{GRBs})^{1/2}$ BUT…

We need to assume:

$t_{GWB} - t_{GRB} \sim cost$

Interpretation of real GW detector data

2) Cumulative technique:

Cross-correlate the output of **two** GW detectors.

Effective also in the case of non-gaussian noise and unpredictable delay between GWs and GRBs, (model independent).

Conclusions:

Experimental searches about physical correlation are possible.

Analyzing the data of the present GW detectors, interesting ranges are been investigate : $h \sim 10^{-19}$.

The proposed methods are robust and effective also in absence of a specific theoretical model.

The conditions are rapidly improving (better sensitivity, more measurements…)