Coincidences between Gravitational Wave Interferometers & High Energy Neutrino Telescopes

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GW/HE ν Coincidences are...

- ...Possible ?
  - $\Rightarrow$ Common Sources for GW/HE ν
  - $\Rightarrow$ Coincident signals in GW and HE ν
- ...Observable ?
  - $\Rightarrow$ Common Sky Map ?
- ...Detectable ?
  - $\Rightarrow$ Signal Efficiencies
  - $\Rightarrow$ Background Rejection
  - $\Rightarrow$ Accidentals Coincidence Rate :
    $R_{\mathrm{coincidence}} \sim R_{Antares}\, R_{Virgo}\, \Delta t_{\mathrm{coincidence}}$
  - $\Rightarrow$ Setting *e.g.* $R_{\mathrm{coincidence}} \sim 1/yr$ constrains efficiencies

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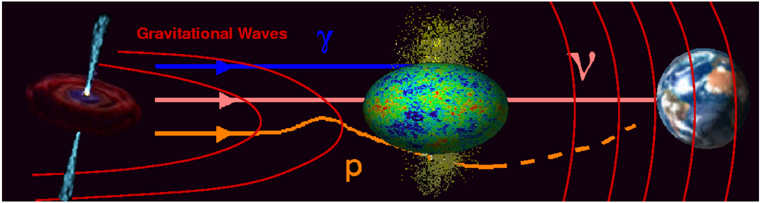
GW/HE ν Coincidences...

Why study GW/HE ν Coincidences ?



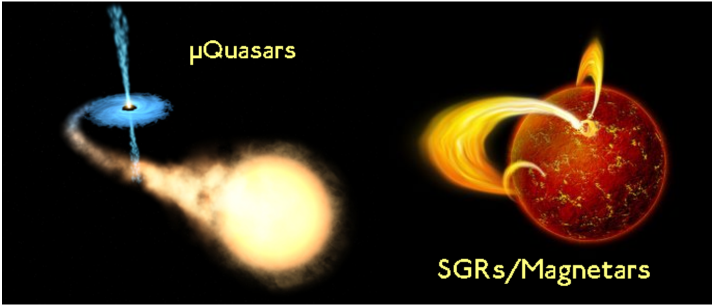
- Sources invisible in electromagnetic channels may emit both GW/ν
- Unique information on internal processes
- Quantum Gravity : $c^2p^2 = E^2 \left[1 + \xi \left(\frac{E}{E_{QG}} \right) + \mathcal{O} \left(\frac{E^2}{E_{QG}^2} \right) + \ldots \right]$

$$\Rightarrow \ |\Delta t_{QG}| \simeq 0.15ms \left(\frac{d}{10\ kpc} \right) \left(\frac{E_\nu^{HE}}{1\ TeV} \right) \left(\frac{10^{19}\ GeV}{E_{QG}} \right) \text{ for } z \ll 1$$

S. Choubey & S. F. King, Phys. Rev. D **67**, 073005 (2003)

GW/HE ν Coincidences...

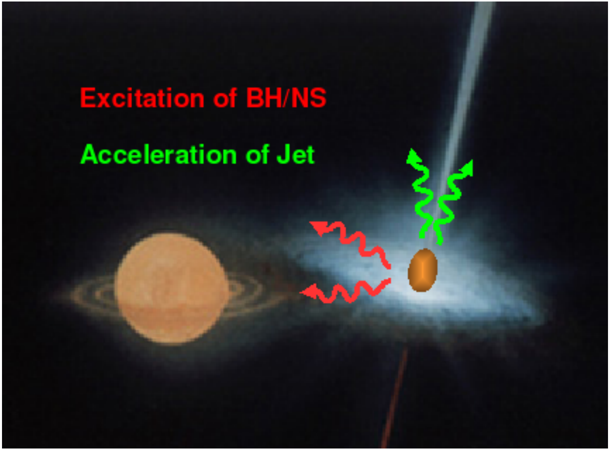
Galactic Sources of GW & ν



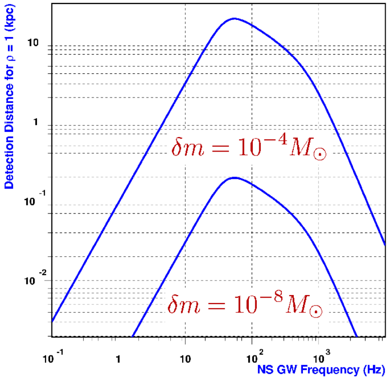
Focus on galactic sources

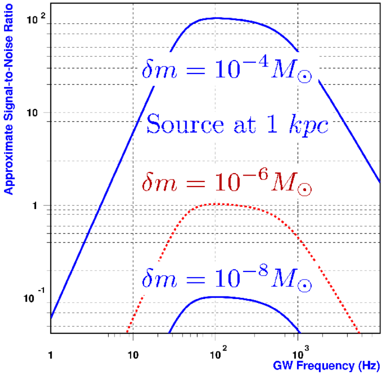
- Only accessible sources for 1[st] detectors *Antares* & *Virgo*?
- Δt_{QG} independent on cosmological models for $z \ll 1$

MicroQuasars : Gravitational Waves (I)



MicroQuasars : Gravitational Waves (II)





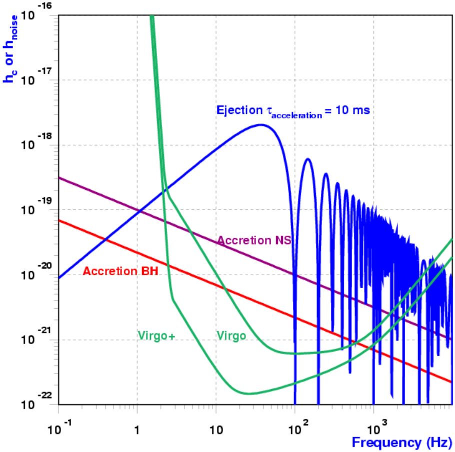
Accretion $\Rightarrow$ ringing

- Limit of detection at 1 kpc

Ejection $\Rightarrow$ acceleration

- *SNR* $\gg 1$ at 1 kpc

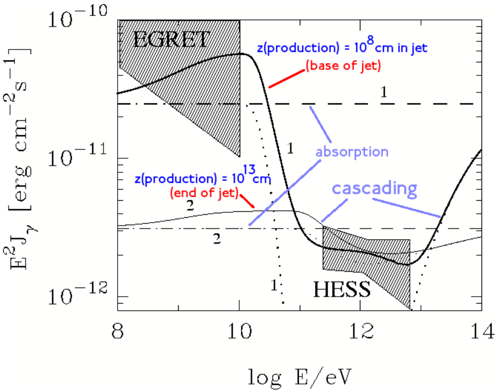
MicroQuasars : Gravitational Waves (III)



- $\delta m \sim 10^{-4} M_\odot$ at 1 kpc
- Accretion less favourable
- Ejection more promising if :
  - $\tau_{\rm acceleration} \lesssim 1$ s - fast !
  - discrete/discontinuous flow

Th. P., A&A, in preparation

MicroQuasars : Neutrinos from LS 5039



- Production of γ/ν at the base of the jet favoured

F. A. Aharonian, L. A. Anchordoqui, D. Khangulyan & T. Montaruli J.Phys.Conf.Ser. **39**, 408-415 (2006)

MicroQuasars : Neutrinos & Flares

Source name	Δt (days)	N_μ
CI Cam	0.6	0.05
XTE J1748-288	20	2.5
Cygnus X-3	3	4.8
LS 5039	persistent	0.2
GRO J1655-40	6	1.8
GRS 1915+105	6	0.5
Circinus X-1	4	0.2
XTE J1550-564	5	0.04
V4641 Sgr	0.3	0.03
V4641 Sgr	0.3	3.9
Scorpius X-1	persistent	0.9
SS433	persistent	252
GS 1354-64	2.8	0.02
GX 339-4	persistent	183.4
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GRO J0422+32	1-20	0.1-2

C. Distefano et al., Astrophys.J. **575**, 378-383 (2002)

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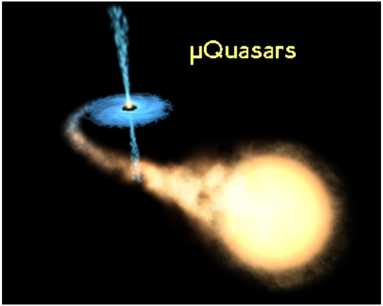
MicroQuasars : summary



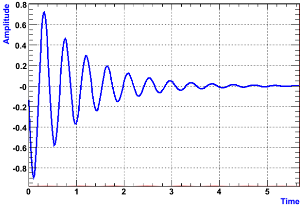
- Accretion GW signal precedes HE ν emission
- HE ν emitted at the onset of acceleration
- Ejection GW signal coincident with HE ν
- Unknown time lag

Soft Gamma Repeaters : Gravitational Waves

Deformation of NS crust $\Rightarrow$ star pulsation

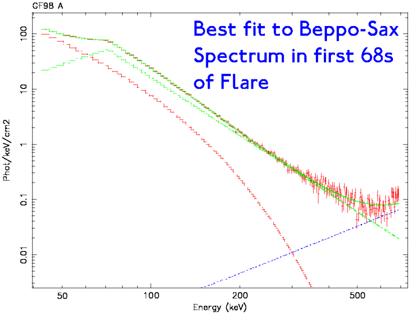
- Depends on Star Model
- Energy released in GW linked to γ Flux

$M/M_\odot$	frequency (kHz)	damping (s)	h_0	d_{max} (kpc)
0.55	1.36	1.30	$8.9\ 10^{-23}$	1.2
...	...	...	...	...
0.57	13.24	1.55	$7.5\ 10^{-23}$	1.4
0.49	17.46	4.67	$3.3\ 10^{-23}$	2.7
1.76	11.91	0.14	$4.6\ 10^{-22}$	0.4



J. A. de Freitas Pacheco, A&A **396**, 397-401 (1998)

Soft Gamma Repeaters : Neutrinos



Neutrino Spectrum (cm^{-2} s^{-1} GeV^{-1})	Upward-going μ's (s^{-1})
$5.90(E/GeV)^{-0.73}$	$2 \cdot 10^{6}$
$8.74 \cdot 10^{-3}(E/GeV)^{-1.47}$	**0.8**
$3.09 \cdot 10^{-4}(E/GeV)^{-1.85}$	$5 \cdot 10^{-4}$
$8.23 \cdot 10^{-5}E^{-2.00}$	$3 \cdot 10^{-5}$

SGR 1806-20 : Dec. 27th, 2004

- Huge flare
- but few predicted events...

F. Halzen, H. Landsman & T. Montaruli arXiv : astro-ph/0503348v1

Soft Gamma Repeaters : summary

- GW emission coincident with γ/HE ν
- Unknown time lag

Orphan Sources... ?

Sources with no electromagnetic counterparts

- *HESS* has discovered a lot of sources not visible before...

Orphan Sources... ?

HESS Sources with no electromagnetic counterparts

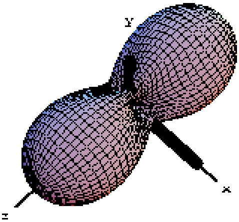
- *HESS* has discovered a lot of sources not visible before...

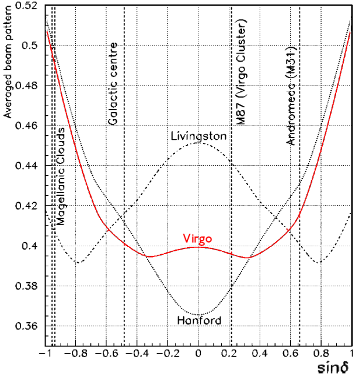
Source Name	$\varnothing$ (°)	N_{src} - $E_\nu > 1$ TeV min-max(mean)	N_{atm}
HESS J1303−631	0.3	0.8-2.3(1.6)	11
HESS J1745−303	0.4	0-18(9)	9.0
HESS J1614−518	0.5	1-10(6)	19
HESS J1837−069	0.2	1.2-4.5(3.3)	5.9
HESS J1634−472	0.2	0.0-3.1(1.7)	9.8
HESS J1708−410	0.1	0.1-1.6(1.1)	7.6

A. Kappes et al., Astron.J. **656**, 870-878 (2007)

GW/HE ν Coincidences...

Virgo Beam Pattern, daily averaged

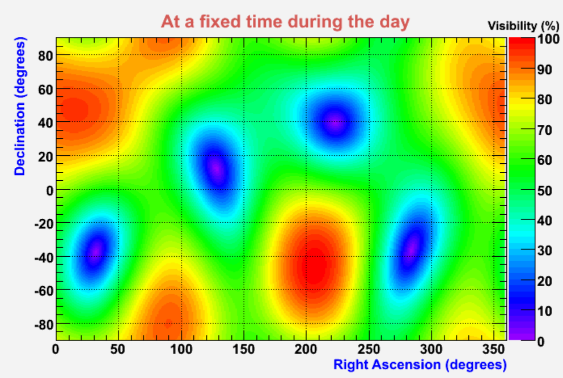




A GW interferometer is an antenna

- Beam Pattern depends on Wave Polarization Ψ and (α, δ)

Virgo Beam Pattern, instantaneous



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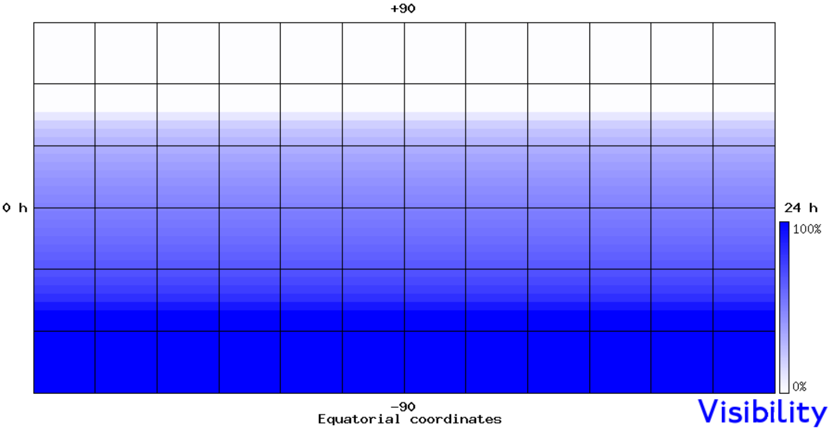
Antares Visibility, daily averaged



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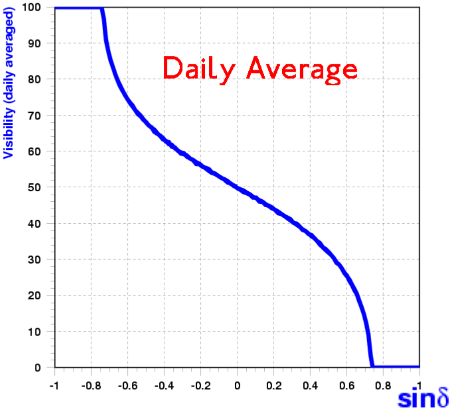

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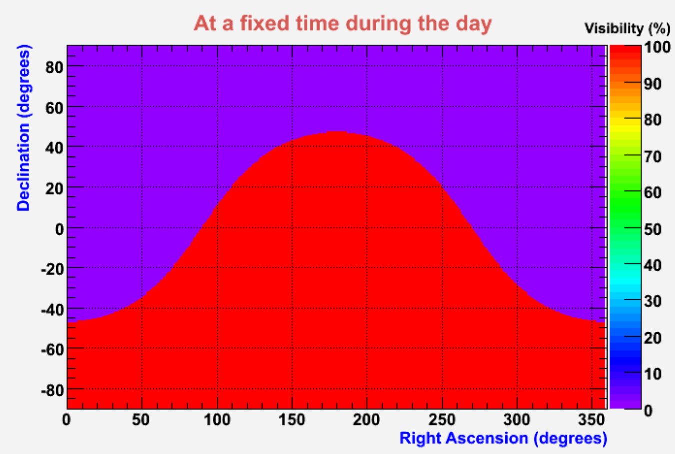
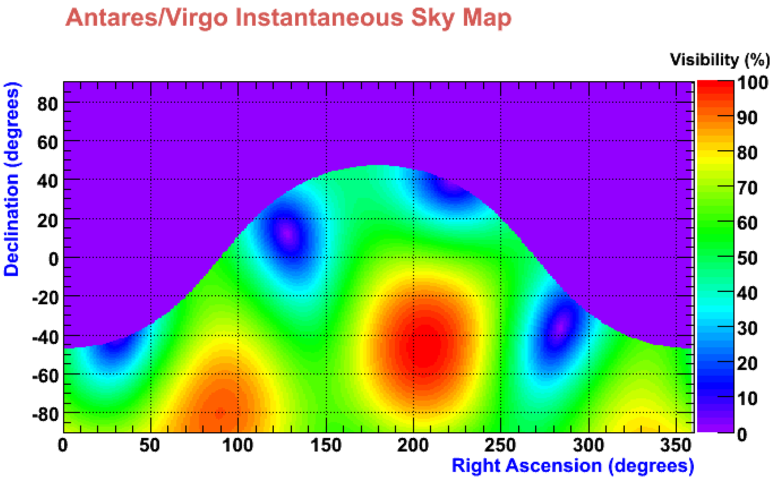


Antares & *Virgo* common Sky



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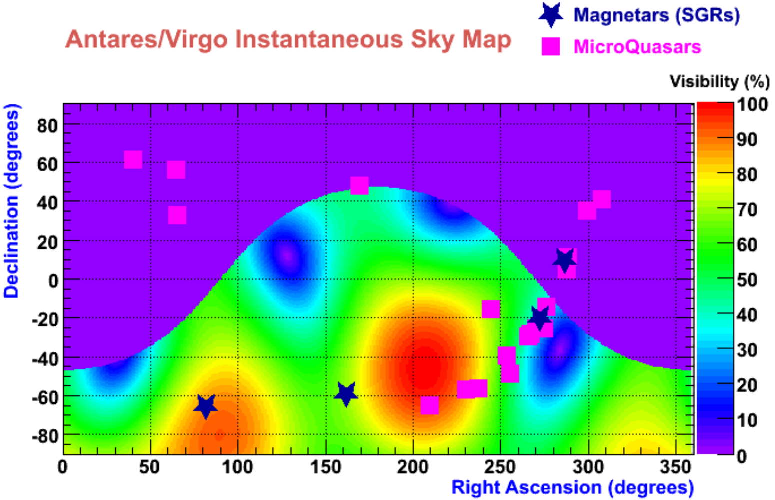

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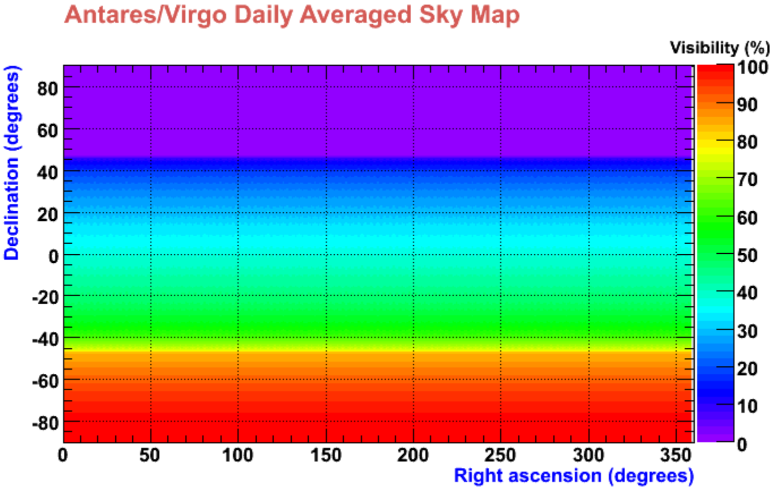

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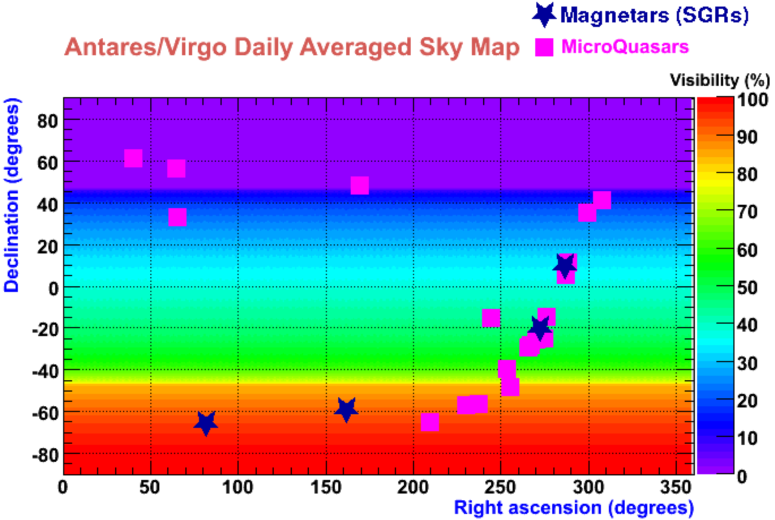


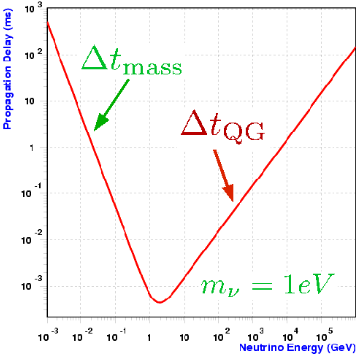
GW/HE ν Coincidences...

Quantum Gravity effects & coincidence window

- $m_{\text{graviton}} = 0$, and $E_{\text{graviton}} \ll 1 \Rightarrow \Delta t_{QG}^{\text{GW}}$ negligible !
- $\delta t_{\text{mass}}^{\nu} \ll 1$ for $E_{\nu} \sim TeV$
- Quantum Gravity : Dispersion
  $c^2 p^2 = E^2 \left[1 + \xi \left(\frac{E}{E_{QG}} \right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2} \right) + \ldots \right]$
- $\xi = -1$ favoured (ν slower than c)
- $z \ll 1 \Rightarrow$ independence from cosmological models
- $\Delta t_{QG}^{\text{GW-}\nu} \simeq 0.15 ms \left(\frac{d}{10\ kpc} \right) \left(\frac{E_{\nu}^{HE}}{1\ TeV} \right) \left(\frac{10^{19}\ GeV}{E_{QG}} \right)$

S. Choubey & S. F. King, Phys. Rev. D **67**, 073005 (2003)

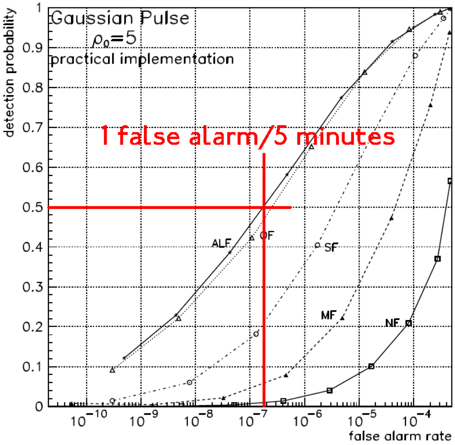
Quantum Gravity effects & coincidence window

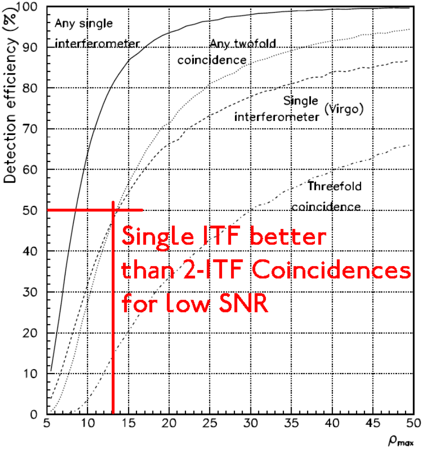


Maximum QG delay for $E_{QG} \sim 10^{19}\,GeV$

- $\Delta t_{QG} \lesssim 1\ s$: $E_\nu \lesssim 1\ PeV$, $d \lesssim 50\ kpc$ (whole Galaxy + LMC)
- $\Delta t_{QG} \lesssim 1\ s$: $E_\nu \lesssim 3\ TeV$, $d \lesssim 20\ Mpc$ (Virgo Cluster)

Virgo Detection : efficiency





N. Arnaud et al. Phys. Rev. D **65**, 042004 (2002)

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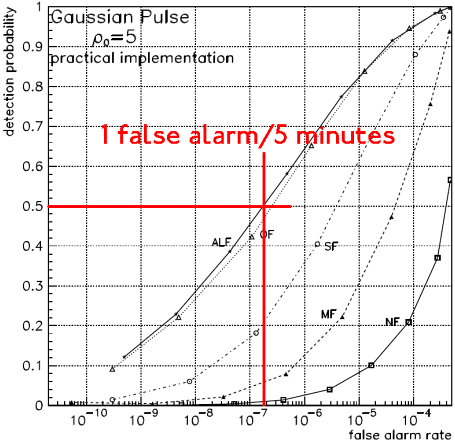

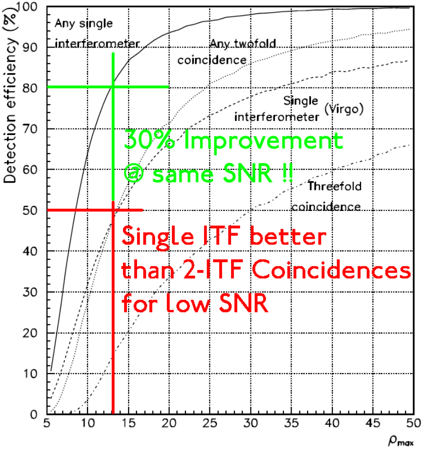

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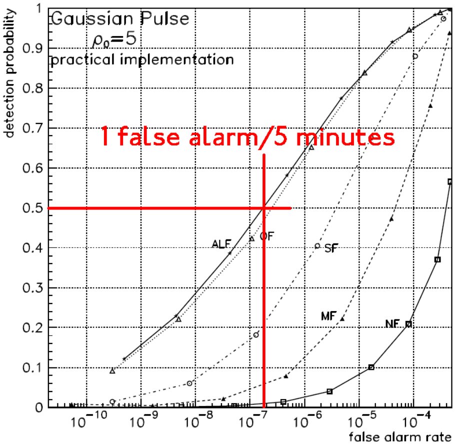
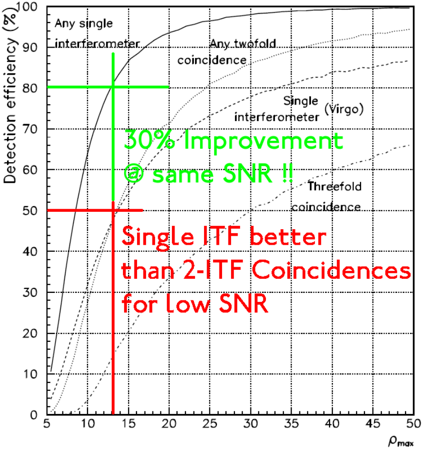
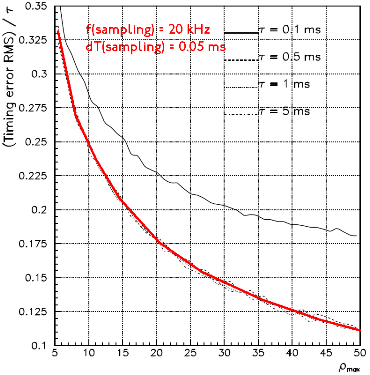




- Case *Any single interferometer*/*Virgo only* $\oplus$ probable

$\Rightarrow$ Directional information not available !

Virgo Detection : Timing



- Sampling at 20 kHz (0.05*ms*)
- For Gaussian Burst, width τ ms :

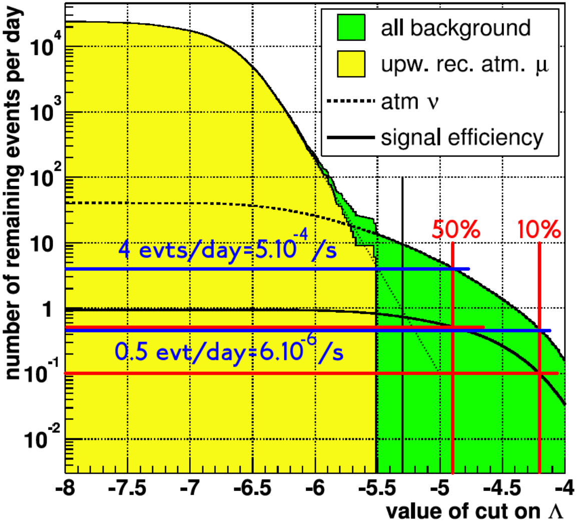
$$\Delta t^{\mathrm{RMS}} \approx \frac{1.5}{\mathrm{SNR}} \left(\frac{\tau}{1 \text{ ms}} \right) \text{ ms}$$

GW Timing

- Timing Resolution $\lesssim$ 1 ms for $\rho > 5$, $\tau \lesssim 3$ ms

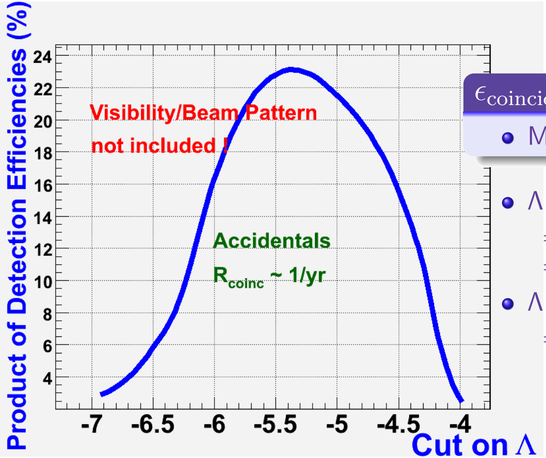
N. Arnaud et al. Phys. Rev. D **65**, 042004 (2002)

Antares Detection : efficiency vs background



- $\Lambda \approx \frac{\log(\mathcal{L})}{N_{DOF}}$
- Standard cut : $\Lambda > -5.3$:
  - $\Rightarrow$ Efficiency $\sim 75\%$
  - $\Rightarrow$ Atm. ν : 10/day
- For lower Λ, bkg explodes
- For higher Λ, ϵ drops

Combined Detection Efficiency : $\Delta t_{\rm coincidence} = 1\ s$

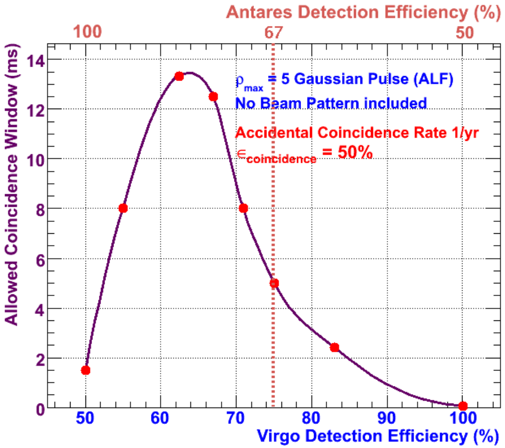


$\epsilon_{\rm coincidences} \sim \epsilon_{Virgo} \times \epsilon_{Antares}$

- Maximum for $\Lambda \sim -5.5$

- Λ low :
  - $\Rightarrow$ *Antares* bkg high
  - $\Rightarrow$ *Virgo* Threshold too high
- Λ high :
  - $\Rightarrow$ *Antares* efficiency too low

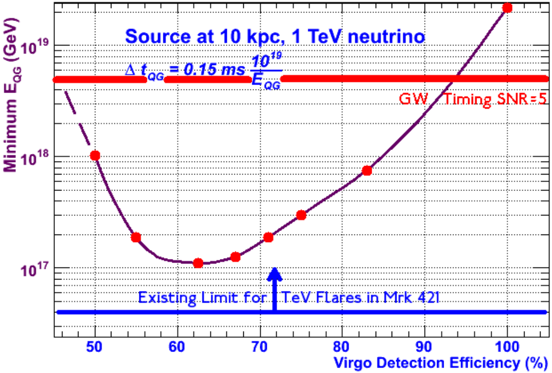
Combined Detection Efficiency : $\epsilon_{\text{coincidence}} = 50\%$



Detection Probability : $\epsilon = 50\%$

- $\Delta t_{\text{max}} \sim$ 15 ms

Possible Scientific Output : Minimum accessible $E_{\rm QG}$



- Limited by GW Timing Resolution
- Here $E_{QG}^{\max} \approx 5 \times 10^{18}\ GeV$

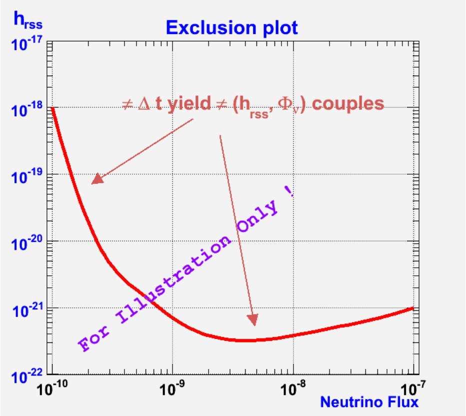
$\Delta t_{QG} \propto E_{QG}^{-1}$

- for $\epsilon_{\rm coincidence} = 50\%$, can go down to $10^{17}\ GeV$!

Possible Scientific Output : h vs $E^2\Phi_\nu$

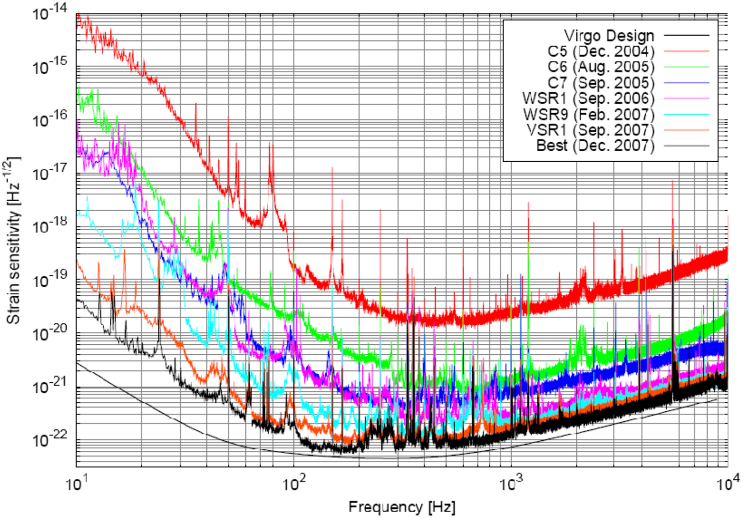
if no coincidence observed

- Exclusion plot $h_{\rm rss} = \sqrt{\int h^2(t)dt}$ vs $E^2\Phi_\nu$



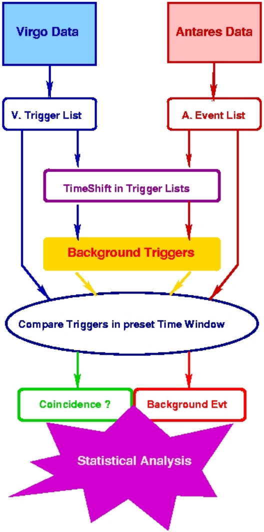
GW/HE ν Coincidences...

Antares & *Virgo* Status



Antares & *Virgo* Status

	Antares	Virgo
September 2006	2 Lines	WSR I-2
October 2006	2 Lines	WSR 3-4
November 2006	2 Lines	WSR 5
December 2006	2 Lines	WSR 6
January 2007	5 Lines	WSR 7
February 2007	5 Lines	WSR 8-9
March 2007	5 Lines	WSR I0
April 2007	5 Lines	
May 2007	5 Lines	VSRI
June 2007	5 Lines	VSRI
July 2007	5 Lines	VSRI
August 2007	5 Lines	VSRI
September 2008	5 Lines	VSRI
October 2007	5 Lines	
November 2007	5 Lines	
December 2007	I0 Lines	



Antares & *Virgo* Coincidences : Conclusions...

- GW/HE ν coincidences are :
  - possible (Galaxy at least)
  - observable : sky maps not $\perp$!
  - détectable (with a bit of luck...)
- for *Antares* & *Virgo* with 5 Lines/VSR coincidences :
  - Accidental coincidence rate : 1/century ?
  - Set $\Delta t \Leftrightarrow$ Set $\epsilon^{\text{no beam pattern}}_{\text{coincidences}}$?
  - Self-consistent analysis for bkg by timeshifting data streams
- 2009 : Full *Antares* /*Virgo* +
  - *Antares* 12 Lines
  - *Virgo* upgrade $\Rightarrow$ improvement by factor 2 above 1 kHz
- *circa* 2015 : KM^3/Advanced *Virgo*
  - KM^3 in the Mediterranean...
  - *Advanced Virgo* : enhanced sensitivity above 20 Hz

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- 2009 : Full *Antares* / *Virgo* +
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  - *Virgo* upgrade $\Rightarrow$ improvement by factor 2 above 1 kHz
- *circa* 2015 : KM^3/Advanced *Virgo*
  - KM^3 in the Mediterranean...
  - *Advanced Virgo* : enhanced sensitivity above 20 Hz

Antares & *Virgo* Coincidences : Conclusions...

- GW/HE ν coincidences are :
  - possible (Galaxy at least)
  - observable : sky maps not $\perp$!
  - détectable (with a bit of luck...)
- for *Antares* & *Virgo* with 5 Lines/VSR coincidences :
  - Accidental coincidence rate : 1/century ?
  - Set Δt $\Leftrightarrow$ Set $\epsilon^{\text{no beam pattern}}_{\text{coincidences}}$?
  - Self-consistent analysis for bkg by timeshifting data streams
- 2009 : Full *Antares* / *Virgo* +
  - *Antares* 12 Lines
  - *Virgo* upgrade $\Rightarrow$ improvement by factor 2 above 1 kHz
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