Gravitational Waves and High Energy Neutrino coincidences : The GWHEN Project

Thierry Pradier

for the GWHEN Group

IPHC (IN2P3) & University of Strasbourg

GWHEN

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- Virgo, APC (Paris) : **E. Chassande-Mottin (Contact)**
- LIGO :
  - Columbia U. (USA) : *I. Bartos*, **S. Márka (Contact)**, Z. Márka
  - Cardiff (UK) : P. Sutton
  - Potsdam (Germany) : I. Di Palma & M.-A. Papa
- IceCube : C. Finley (OKC, Sweden)

GWHEN Coincidences are...

- ...Interesting !
  - ⇒ Scientific motivations
- ...Possible !
  - ⇒ Common Sources for GWHEN, possible coincident transients
- ...Observable !
  - ⇒ Common Sky Map
- ...Detectable !
  - ⇒ Signal Efficiencies vs Background Rejection, case study
- ...Currently underway !
  - ⇒ The GWHEN Group

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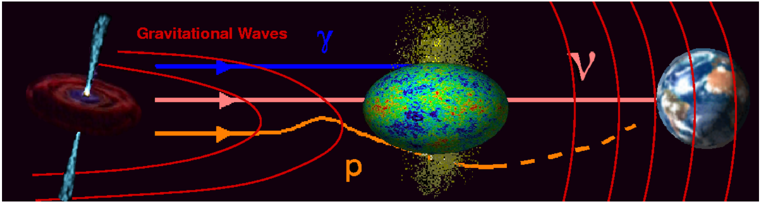
GWHEN Coincidences

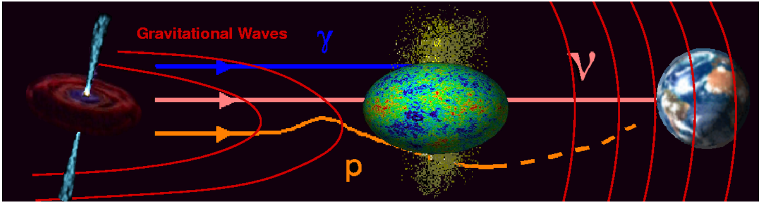


1 - Sources invisible in photons may emit GW and HE ν (GWHEN)

⇒ γ-Telescopes discovered a lot of sources

⇒ *Orphan* Flares also in GWHEN ?

GWHEN Coincidences



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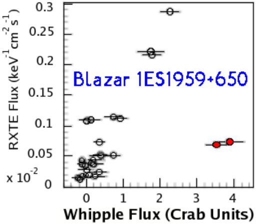
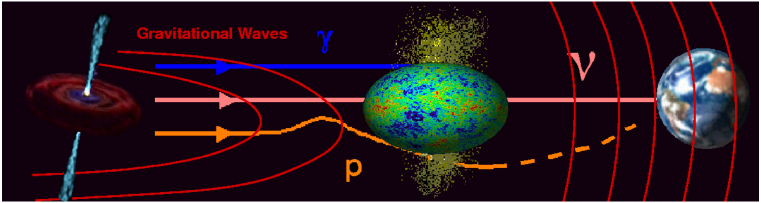


GWHEN Coincidences



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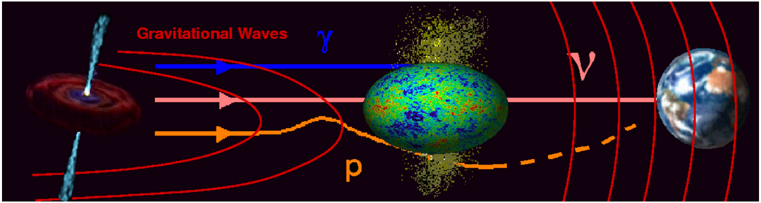
2 - Coincident detection (time+space) *validates* GWHEN detections

GWHEN Coincidences

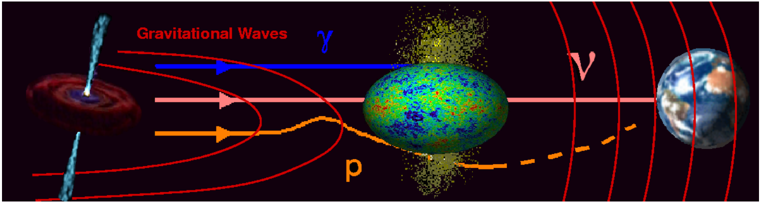


1 - *Sources invisible in photons may emit GWHEN*

2 - *Coincident detection (time+space) validates GWHEN detections*

3 - Unique information on internal processes : accretion, ejection...

GWHEN Coincidences



1 - *Sources invisible in photons may emit GWHEN*

2 - *Coincident detection (time+space) validates GWHEN detections*

3 - *Unique information on internal processes*

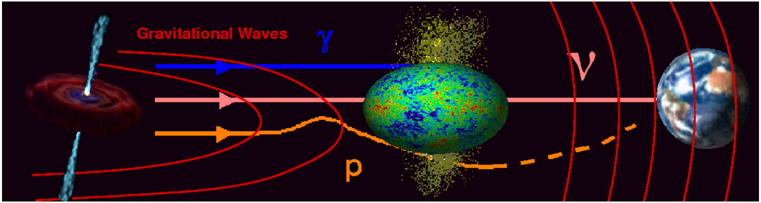
4 - Fundamental Physics :

- Quantum Gravity : $c^2 p^2 = E^2 \left[1 + \xi\left(\frac{E}{E_{QG}}\right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right) + \ldots\right]$

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

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

GWHEN Coincidences



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2 - *Coincident detection (time+space) validates GWHEN detections*

3 - *Unique information on internal processes*

4 - *Fundamental Physics*

see *Th. P.*, NIM A **602-1**, *268-274*

GW Detectors : *Virgo/LIGO/GEO* network

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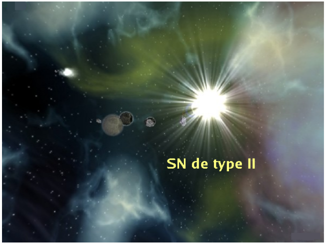
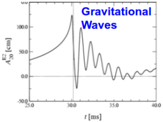
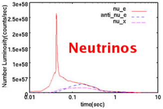
GWHEN Joint Data Taking

- 2007 : *Antares* 5 Lines/*Virgo* VSR1+*LIGO* S5
- 2009 : *Antares* 12 Lines/*Virgo* VSR2+*LIGO* S6
- 2015 : km3 in the Mediterranean/Advanced Interferometers (ITF)

An example of GW-ν Coincidences : Type II SN





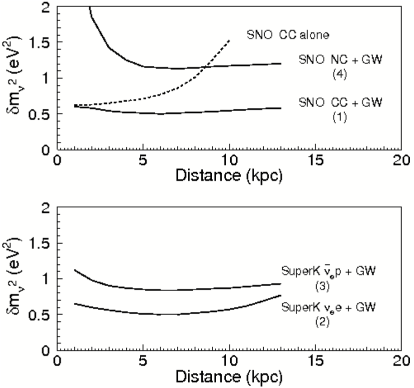


Type II SN

- $m_\nu \neq 0 : \delta t_{\rm propagation} \simeq 5.15 ms \left(\frac{L}{10kpc}\right) \left(\frac{m_\nu c^2}{1eV}\right)^2 \left(\frac{10MeV}{E_\nu}\right)^2$
- $E_\nu^{SN} \sim MeV$, $\delta t_{\rm GW-\nu_e^{flash}} \lesssim 0.5\ ms$

N. Arnaud et al., Phys.Rev. D65 (2002) 033010

An example of GW-ν Coincidences : Type II SN

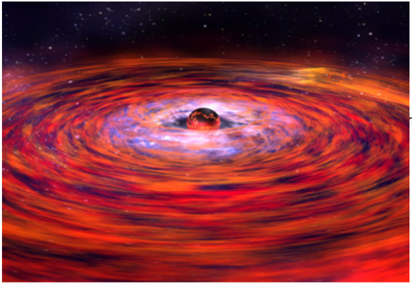


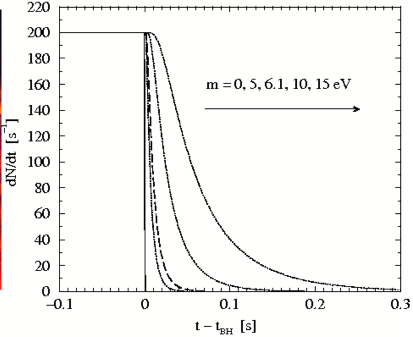
Type II SN

$\Rightarrow$ $\delta m^2 \sim 0.6\ eV^2$

N. Arnaud et al., Phys.Rev. D65 (2002) 033010

An example of GW-ν Coincidences : Type II SN



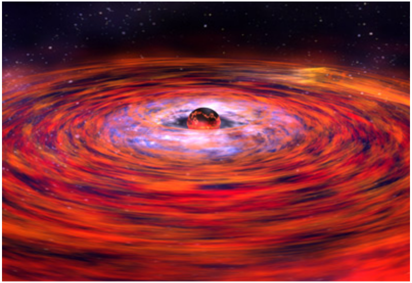


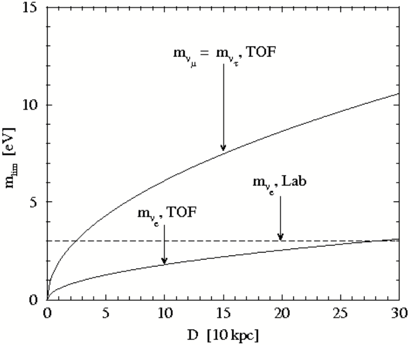
Collapse of NS into BH induced by accretion

- ⇒ Sudden stop of neutrino signal
- ⇒ Strong GW Signal

J. F. Beacom et al., Phys.Rev. D63 (2001) 073011

An example of GW-ν Coincidences : Type II SN



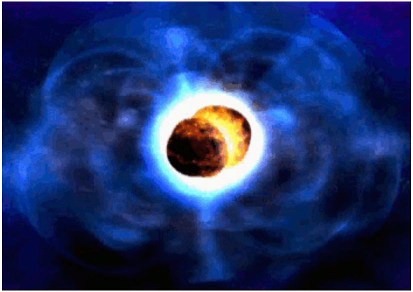


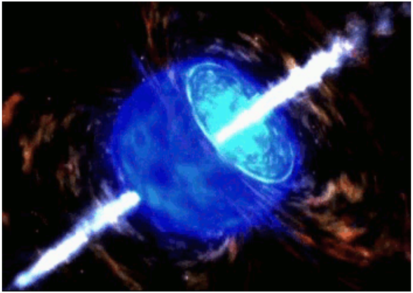
Collapse of NS into BH induced by accretion

⇒ Limits on neutrino absolute mass scale

J. F. Beacom et al., Phys.Rev. D63 (2001) 073011

Gamma-Ray Bursters





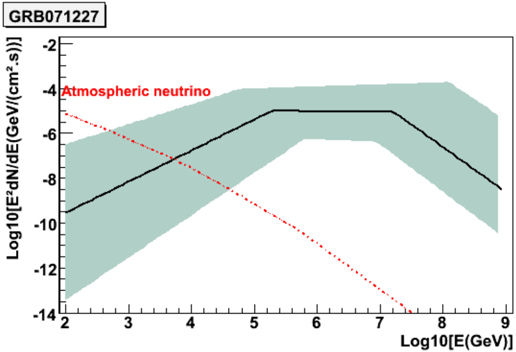
Short GRBs

Binary Mergers

Long GRBs

Collapsars

Gamma-Ray Bursters



Neutrinos from GRBs

E. Waxman & J. Bahcall, Phys.Rev.Lett. 78 (1997) 2292-2295

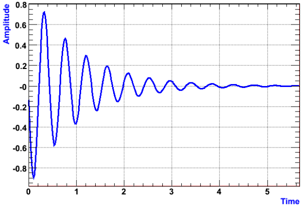
Soft-Gamma Repeaters

GW Signal : NS crust disruption $\Rightarrow$ star pulsation

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

Soft-Gamma Repeaters

$M/M_{\odot}$	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

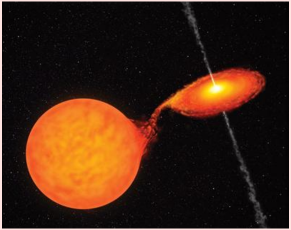
HEN Signal : acceleration of CRs in magnetic field

- Few predicted events, even for SGR 1806-20 huge flare of Dec. 2004

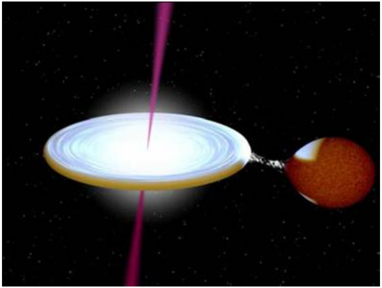
F. Halzen, H. Landsman & T. Montaruli, arXiv : astro-ph/0503348v1

MicroQuasars

MicroQuasars (Galactic) : Stellar-Mass X-Ray Binaries



A model for microquasars : GW



Signals from accretion/ejection :

- Accretion : infall of matter onto NS/BH
- Ejection : acceleration of matter

A model for microquasars : GW

GW Signal from ejection

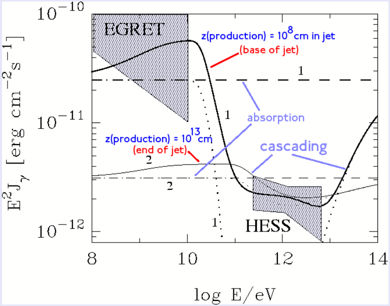
- Blob of matter accelerated during $\tau_{\rm acc}$ and $f_{\rm GW} \sim \tau_{\rm acc}^{-1}$
  - $\tau_{\rm acc}^{\rm min} = \Delta t_{\rm free\text{-}fall} = \frac{2GM_{\rm BH}}{c^3} \sim 0.1$ ms
  - Radio emission observed at 0.1 AU from BH/NS $\Rightarrow \tau_{\rm acc}^{\rm max} \approx 100$ s
- $\Delta h \sim 2 \times 10^{-22} \left(\frac{1\rm kpc}{d}\right)\left(\frac{\delta M}{10^{-6} M_\odot}\right)\left(\frac{\Gamma}{10}\right)$
- SNR $\rho = f(\text{ejected mass } \delta M, \text{jet Lorentz factor } \Gamma)$

Th. P., arXiv:0807.2562

A model for microquasars : HEN

HEN Signal from ejection

- νs emitted once matter accelerated : $\Delta t_{\text{GW-}\nu}$ linked to τ_{acc}
- $\Phi_\nu \propto \delta M \times \Gamma$
- Models favour production of ν near base of jet [LS 5039]



Aharonian et al., J. Phys. Conf. Ser. 39 (2006) 408-415

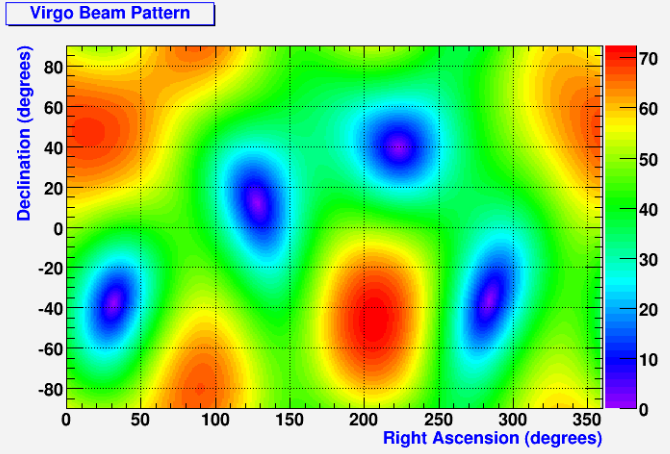
A model for microquasars

Summary, for a blob of mass δm, Lorentz factor Γ

- $h \propto \frac{\Gamma \delta m c^2}{d}$ at frequency $f \sim \tau_{\mathrm{acceleration}}^{-1}$
- $L_\nu \propto \frac{\Gamma \delta m c^2}{\tau_{\mathrm{acceleration}}}$
- Measuring $\Delta t_{\mathrm{GW}\text{-}\nu}$ yields information on τ_{acc}

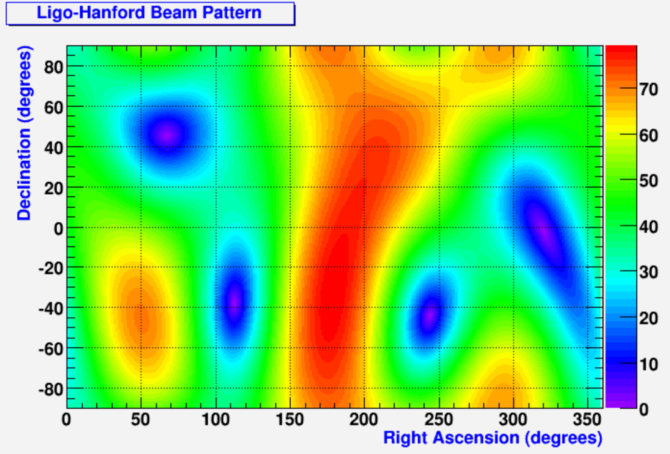
Interferometers' Beam Patterns

Interferometers' Beam Patterns



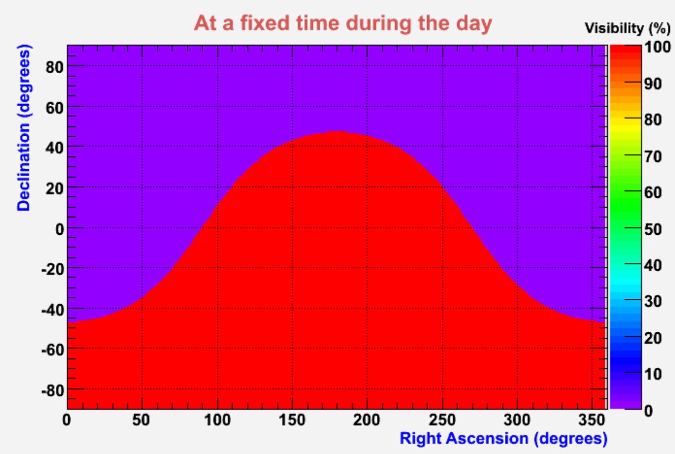
Equatorial Coordinates

Interferometers' Beam Patterns



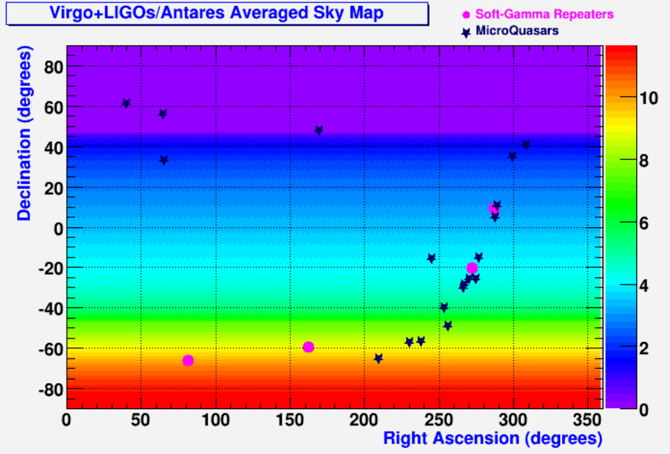
Equatorial Coordinates

Antares Sky Map

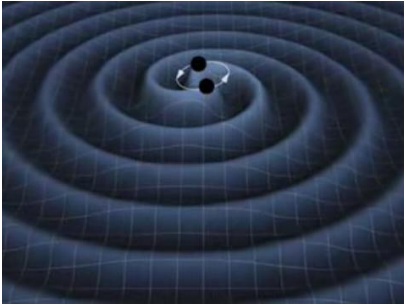


Equatorial Coordinates

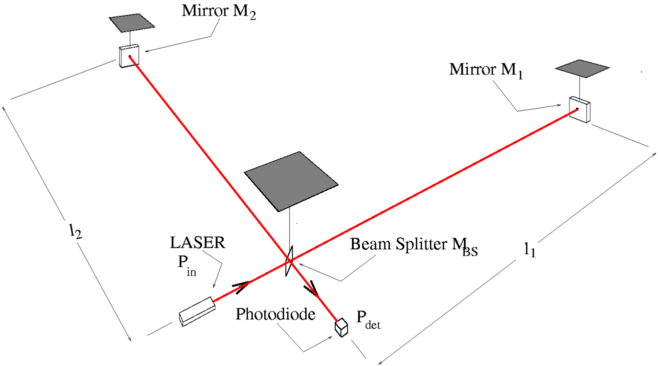
Antares+*LIGO* Hanford+*LIGO* Livingstone



GW Detection



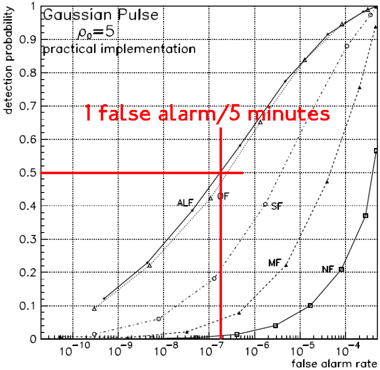
GW Detection : efficiency

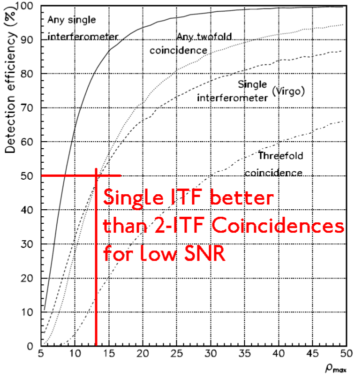


Propagating erturbation of space-time h

- $\frac{\delta L}{L} \propto h$
- $P_{\mathrm{det}} \propto h = f(t)$

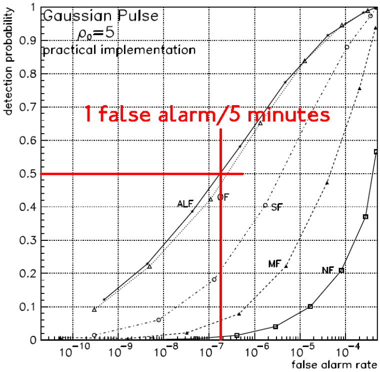
GW Detection : efficiency

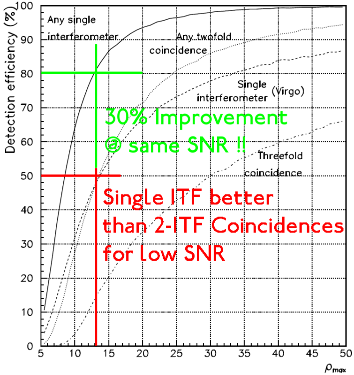




N. Arnaud et al., Phys. Rev. D ***65****, 042004 (2002)*

GW Detection : efficiency

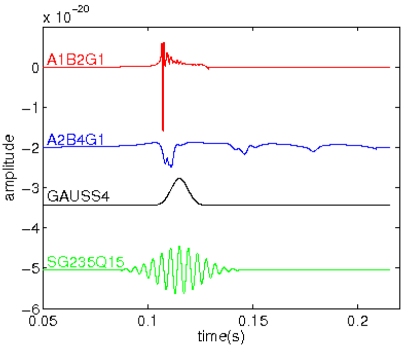


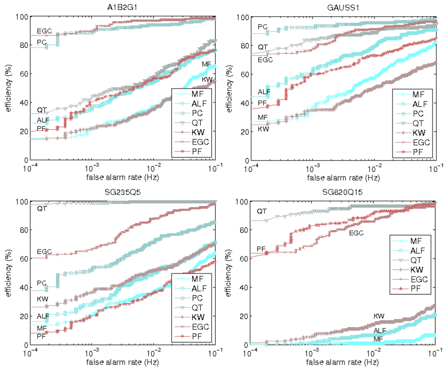


- Case *Any single interferometer only* more probable
  ⇒ Time Coincidences (no direction) possible
- Direction rejects background : Coincidence/Coherent Analysis

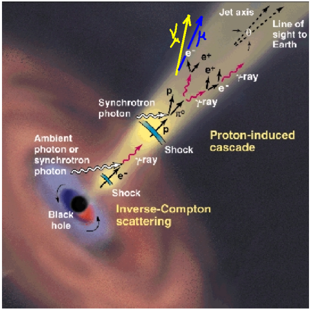
Detection depends on the signal waveform...

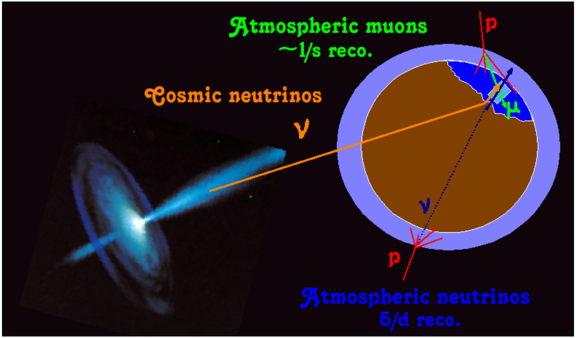
F. Beauville et al., Class.Quant.Grav.25 :045002 (2008)



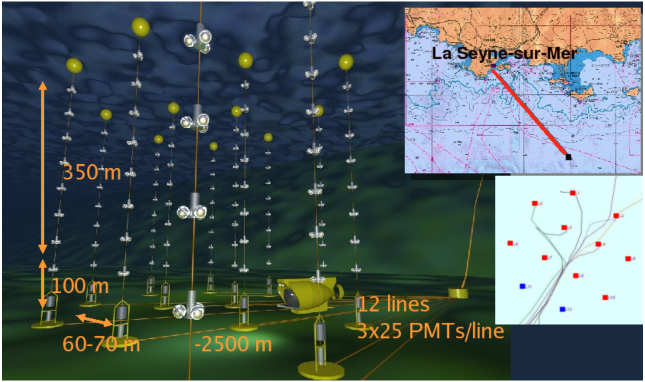


Antares Detection





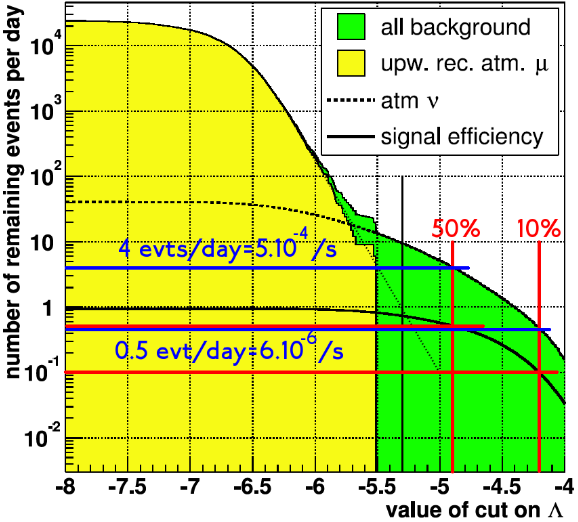
Antares Detection



⇒ 12 Lines in operation since mid-2008 !

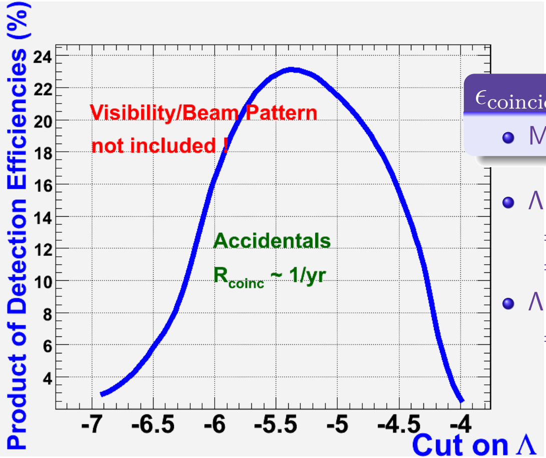
⇒ μ track reconstructed from (t, Q) of hits from Cherenkov light

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

Simple case : time coincidences



$\epsilon_{\text{coincidences}}$ for $\Delta t \sim 1\ s$

- Maximum for $\Lambda \sim -5.5$

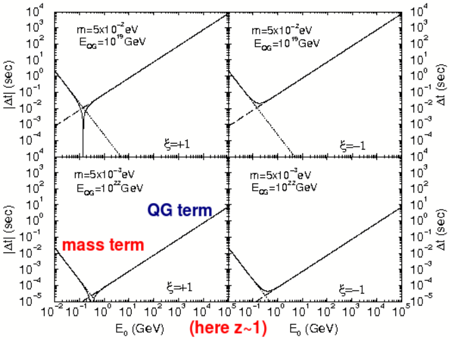
- Λ low :
  - $\Rightarrow$ *Antares* bkg high
  - $\Rightarrow$ *Virgo* Threshold too high
- Λ high :
  - $\Rightarrow$ *Antares* efficiency too low

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
  $c^2 p^2 = E^2 \left[1 + \xi \left(\frac{E}{E_{QG}}\right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right) + \dots\right]$
- $\xi = -1$ favoured (ν slower than c)
- $z \ll 1$
  - $\Rightarrow$ Given fluxes and amplitudes, first signals seen local universe
  - $\Rightarrow$ independence from cosmological models
- $\Delta t_{QG}^{\text{GW-}\nu} \simeq 0.15ms \left(\frac{d}{10\ \ kpc}\right)\left(\frac{E_\nu^{HE}}{1\ \ TeV}\right)\left(\frac{10^{19}\ \ GeV}{E_{QG}}\right)$

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

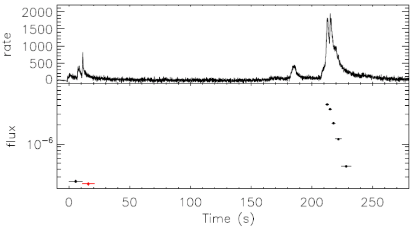
Quantum Gravity effects & coincidence window

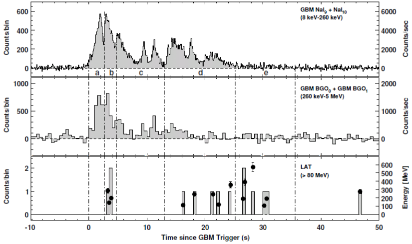


Maximum QG delay for $E_{QG} \sim 10^{19}\,GeV$

- $\Delta t_{QG} \ll$ 100ms for sources in Galaxy and $E_{\nu} \lesssim$ 100 TeV

GRBs : observations and time window





Precursors

$\Rightarrow$ Extend Time Window

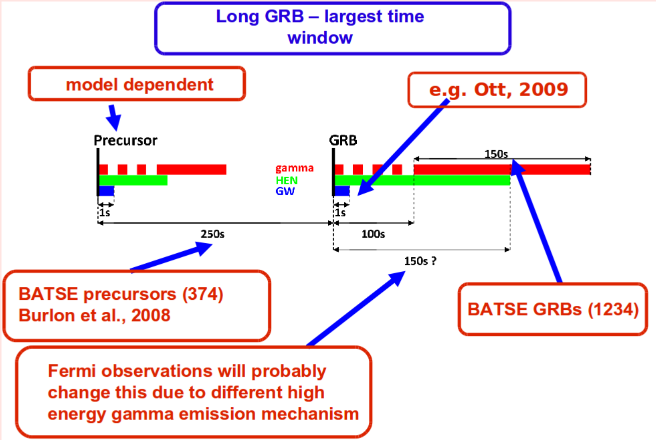
High Energy Emission

- HE γ delayed

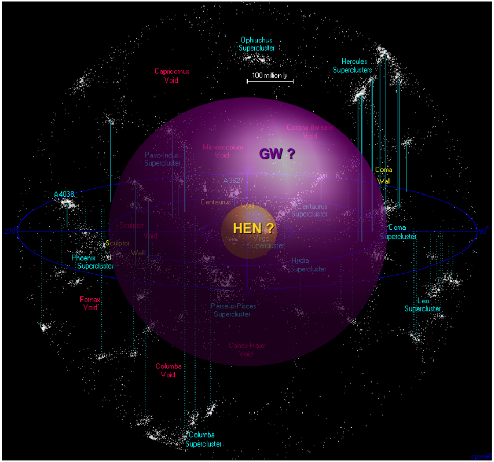
$\Rightarrow$ Preliminary studies show that HEN emission delayed

GRBs : observations and time window

Coincidence Window : $[-250s; +250s]$



The Question of the Horizon :



Conditions for efficient coincidences :

- GWHEN Efficiency limited by *weakest* experiment

The Question of the Horizon : GW

GW Horizon

- Rough estimate of Signal-to-Noise Ratio
  $\rho = \frac{h_c}{h_{\rm RMS}} \approx \frac{1}{\sqrt{fS_h(f)}} \times \frac{1}{d_{\rm GW}} \sqrt{\frac{GE_{\rm GW}}{f\pi^2 c^3}} \Rightarrow d_{\rm GW} \approx \frac{1}{f\rho} \sqrt{\frac{GE_{\rm GW}}{\pi^2 c^3 S_h(f)}}$
- Take $\rho \sim 10, f \sim 250 Hz, S_h(f) \sim 10^{-23}/\sqrt{\rm Hz}$ (Optimal)
- Low Luminosities GRBs $L_{\rm tot} \sim 10^{47}$ erg/s for $\delta t \sim 1$s
- Assume $E_{\rm GW} = \epsilon_{\rm GW} E_{\rm tot}$
- Then $d_{\rm GW} \sim 10$ Mpc $\times \sqrt{\frac{\epsilon_{\rm GW}}{0.01}} \sqrt{\frac{\delta t}{1\ s}}$

The Question of the Horizon : HEN

HEN Horizon

- Luminosity Needed for detection of N_ν events from $N_\nu \propto \Phi_\nu \sigma_\nu R_\mu A_\mu$
- $L_\nu = 4\pi d^2_{\rm HEN}\Phi_\nu \approx 10^{47}{\rm erg/s}\ N_\nu \left(\frac{d_{\rm HEN}}{3\ {\rm Gpc}}\right)^2 \left(\frac{1\ {\rm yr}}{\delta t}\right)$ for $A_\mu \sim 0.1$ km^2
- Requiring $N_\nu = 1$ for a burst $\delta t \sim 100$ s,
  $L_\nu = \epsilon_{\rm HEN} L_{\rm tot} \Rightarrow d^{\rm max}_{\rm HEN} \sim 5$ *Mpc*, scaling as $\sqrt{\delta t}$ and $\sqrt{\epsilon_{\rm HEN}}$

GWHEN Horizon

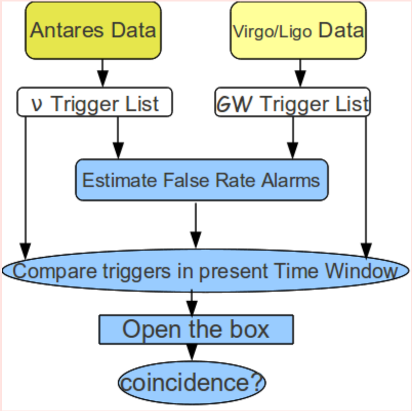
- For Low Luminosities GRBs $d_{\rm GW} \sim d_{\rm HEN} \sim 1 - 100$ Mpc
- Horizons seem equivalent for rough estimates...
- ...But depend on $\epsilon_{\rm GW}, \epsilon_{\rm HEN}, \delta t$...

$\Rightarrow$ Model dependent !

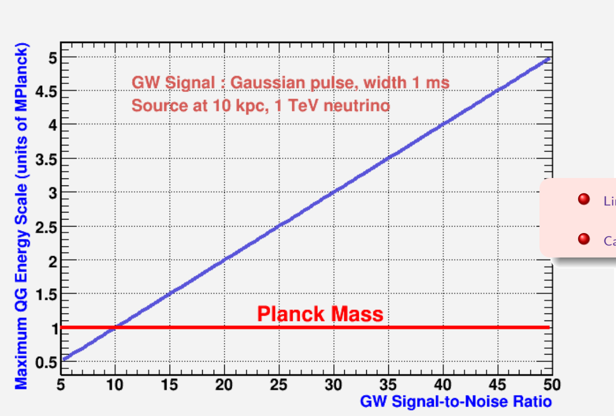
$\Rightarrow$ *Equalization* of Horizons needed for given GWHEN models

A method for coincidences

Coincidence Analysis Method



Maximum accessible E_{QG}



- Limited by GW timing resolution
- Careful : no energy resolution taken into account...

$$\Rightarrow E_{\mathrm{QG}}^{\max} \approx 10^{19} \ GeV \text{ for SNR} \gtrsim 10$$

The GWHEN Group

- Antares :
  - **Contact : Th. P.**
  - B. Baret, *B. Bouhou*, A. Kouchner, L. Moscoso, V. Van Elewyck
- Virgo, APC (Paris) : **E. Chassande-Mottin (Contact)**
- LIGO :
  - **S. Márka (Contact)**
  - Columbia U. (USA) : *I. Bartos*, Z. Márka
  - Cardiff (UK) : P. Sutton
  - Potsdam (Germany) : I. Di Palma & M.-A. Papa
- IceCube : C. Finley (OKC, Sweden)

Collaborative : *Virgo/LIGO* + *Antares*

- MoU for exchange of data signed between *Antares*, *Virgo* and *LIGO*
- Regular Meetings

The GWHEN Group

2010 - Current Analysis : *Antares* 5 Lines + VSR1/S5

- Sub-optimal detectors ⇒ No joint optimization !
- (Null) Results expected after summer 2010...

2010/2012 - Joint Analysis : *Antares* 12 Lines + VSR2/S6

- Optimize Coincident Detection Efficiency

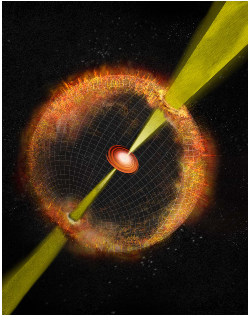
⇒ for specific joint GWHEN emission models...

- Possible First coincident detection ?

Circa 2015 - KM^3 + Advanced Interferometers

- HEN : 1-5 km^3 in the Mediterranean...
- GW : Interferometers with enhanced sensitivity above 20 Hz
- Astrophysics of detected sources ?

The GWHEN Group : perspectives...



What about Quantum Gravity ?

- First coincidences will help understanding the sources !
- An exception : *Jetted* Core-Collapse SN / Short/Long GRBs
  - ⇒ GW signals well modelled - at least timing wrt bounce/merger
  - ⇒ Production of HEN in the jet
  - ⇒ QG studies ok if HEN produced near base of the emitted jet