GWHEN joint analyses

using Antares and LIGO/Virgo data

Thierry Pradier
for the LIGO Scientific Collaboration, Virgo Collaboration and Antares Collaboration

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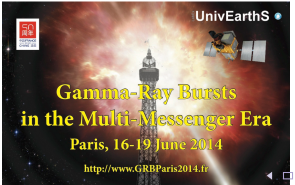

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GWHEN

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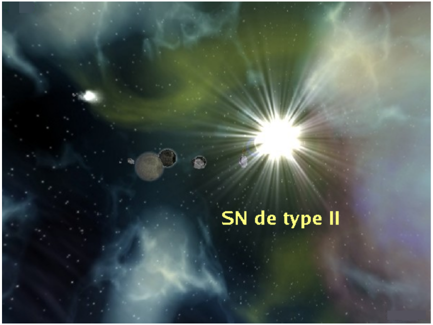
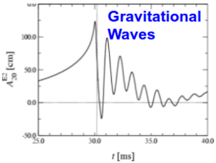
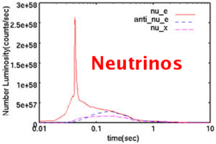
An example of GW-ν Coincidences : Type II SN







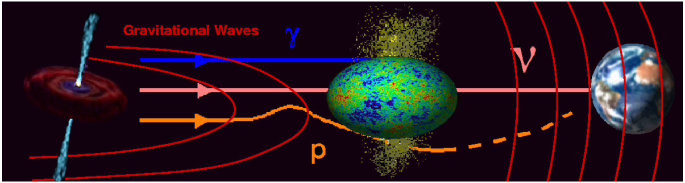
Type II SN

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

  $\Rightarrow$ Limits on ν absolute mass scale from $\Delta t_{GW-\nu}$

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

GWHEN



Gravitational Waves + High Energy Neutrinos (HEN)

1 - Sources invisible in photon ? : *Dark Bursts*

2 - Coincident Detection *validate* both detections

3 - Unique Information on internal processes : accretion-ejection...

4 - Fundamental Physics ? :

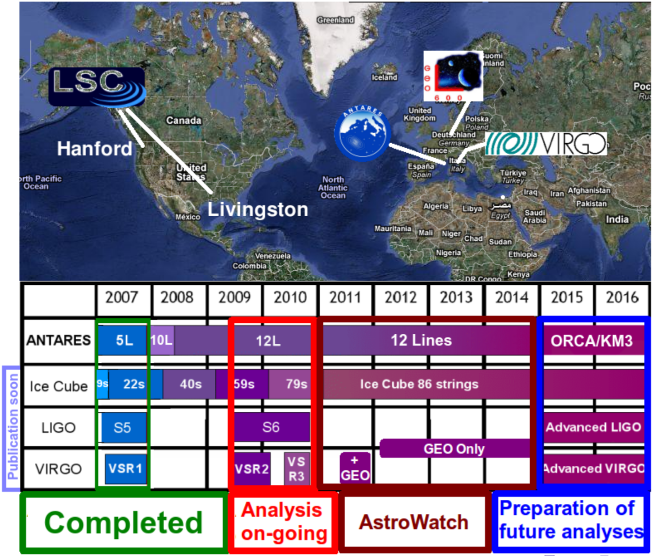
- Quantum Gravity : $c^2p^2 = E^2\left[1 + \xi\left(\frac{E}{E_{QG}}\right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right) + \ldots\right]$

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

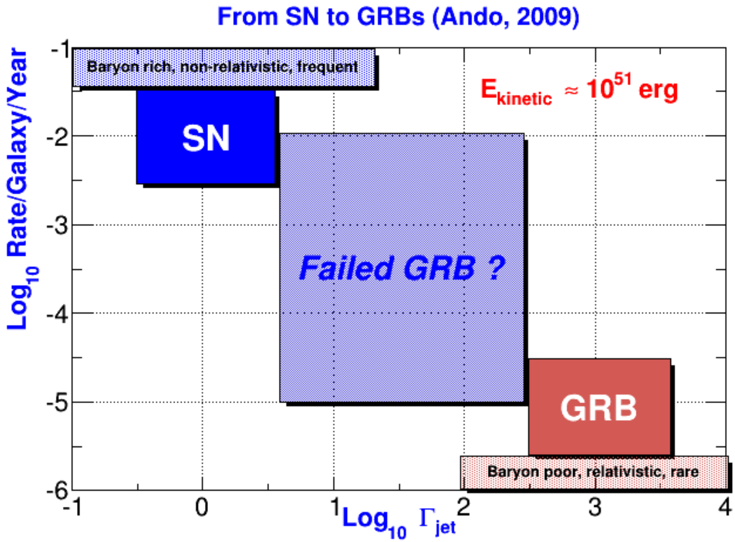
S. Choubey & S. F. King, Phys. Rev. D67 (2003) 073005

Th. P., NIM A 602-1 (2009) 268-274

GW interferometers and HEN Telescopes



« Golden » Targets : Gamma-Ray Bursters (GRBs)



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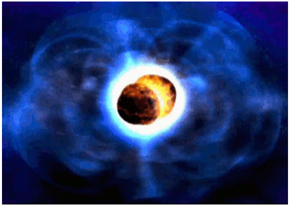
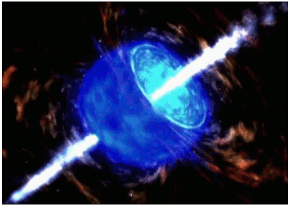
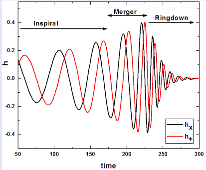




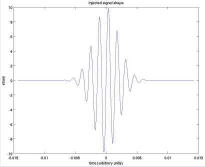
Short GRBs

Binary Mergers : BH or NS



Long GRBs

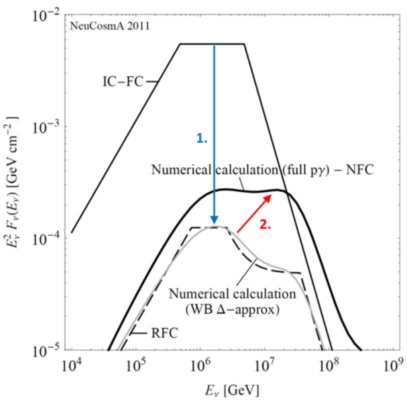
Collapsars - massive star collapse



No Neutrinos ? ▸ IceCube results (2012)

« Golden » Targets : Gamma-Ray Bursters (GRBs)

HEN Spectra from Guetta et al. (2004)...outdated ?



example of GRB080603A:

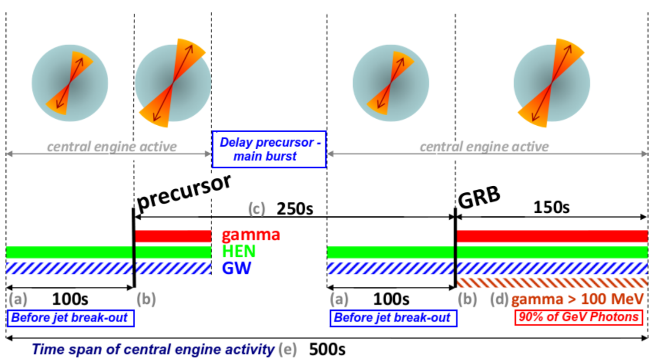
1. Correction to analytic model (IC-FC → RFC)
2. Change due to full numeric calculation

IC-FC: IceCube-Fireball Calculation
RFC: Revised Fireball Calculation
NFC: Numerical Fireball Calculation

Hümmer, Baerwald, Winter, arXiv :1112.1076

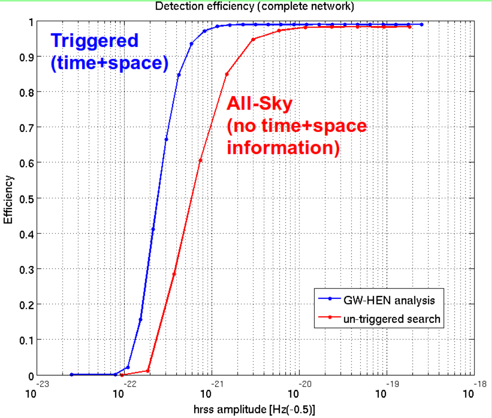
Time Window from long GRB observations

- *Bounding the Time Delay between High-energy Neutrinos and Gravitational-wave Transients from Gamma-ray Bursts*
- B. Baret *et al.*, Astroparticle Physics **35** (2011) 1-7
  $\Rightarrow$ $\Delta T = \pm$500s [arXiv:1101.4669]



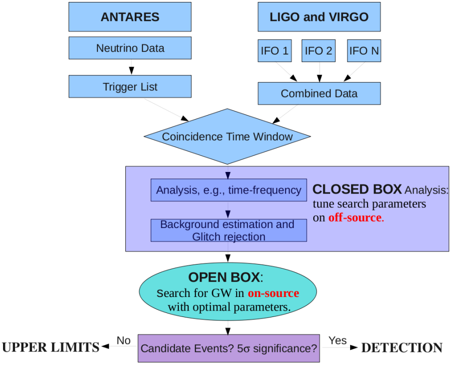
Advantages of a triggered search

A Triggered search (time+space) is more efficient !



- **Smallest detectable signals** (results GWHEN-1)
- **Factor 2.5 (4) improvement** at the 50% (90%) level

1^{st}GWHEN search : joint data



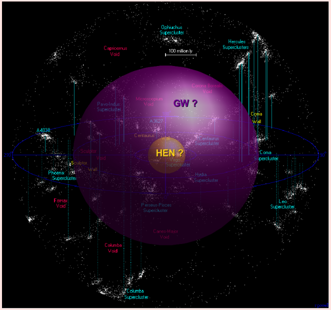
Analysis of 2007 data - Jan 27 - Sept. 30, 2007

- Sub-optimal detectors : no optimization - usual HEN selection
- **Time provided by HEN candidate** - 158 HEN in total

  $\Rightarrow$ 10% at $< E_{\mathrm{HEN}} > \approx 100\,TeV$
- **Position by HEN direction $\pm$ Error Box $= f(E_{\mathrm{HEN}}, \delta)$**

Detection probabilities vs distance

GW and HEN Horizons

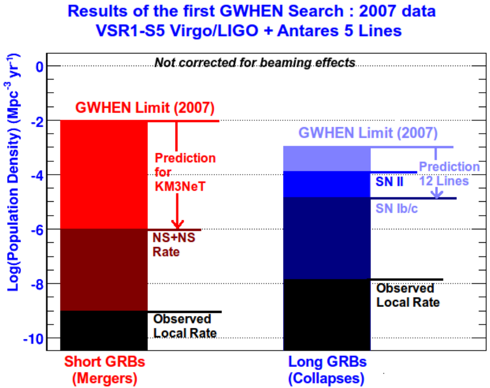


- $P_{\mathrm{HEN}}, P_{\mathrm{GW}}$ vs d $\Rightarrow$ joint analysis' *Horizon*
  $\Rightarrow$ Typically 1-10 Mpc, HEN limited
- From null observation, derive limit on ρ_{GWHEN} at 90% C.L. :

$$\rho_{\mathrm{GWHEN}} \leq \frac{\mathbf{2.3}}{\mathbf{V}_{\mathrm{GWHEN}}\mathbf{T}_{\mathrm{obs}}}$$

GWHEN-1 density limits

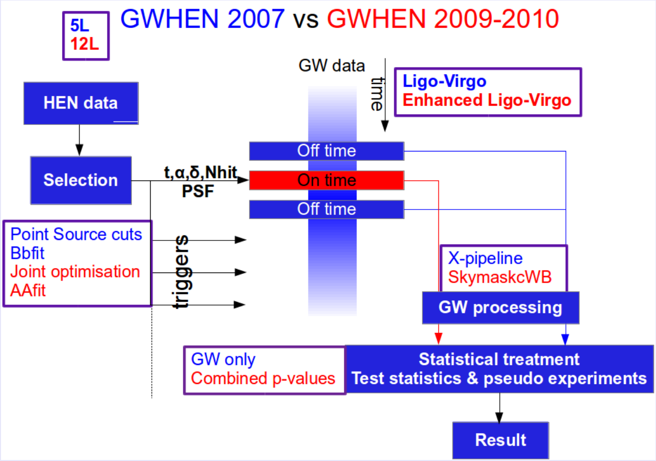
Encouraging results



- First limits on density of Core-Collapses/Mergers with jets
- ArXiV :1205.3018, JCAP 06 (2013) 008

Optimization of the Analysis

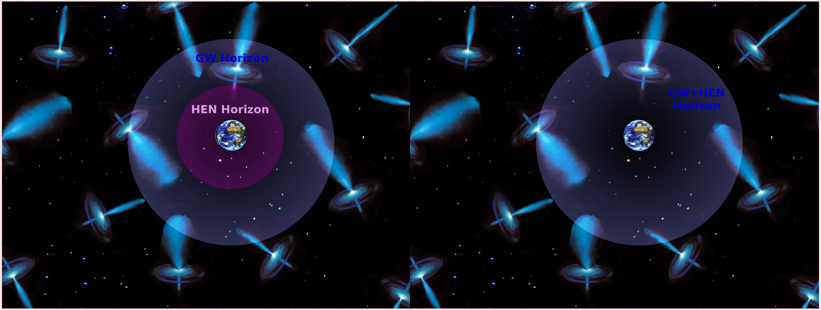
A different strategy



ANTARES 12 lines + VSR2-3/S6 - Jul. 2009, Oct. 2010

- New **GW Software (suitable for joint simulations)**
- New **HEN reconstruction strategy (error boxes : $10^\circ \rightarrow 2^\circ$)**

Maximize the number of detectable sources $\propto \frac{\epsilon_{\mathrm{HEN}}}{\rho_{\mathrm{GW}}}$



HEN and GW inputs

- ANTARES 9 & 12 lines

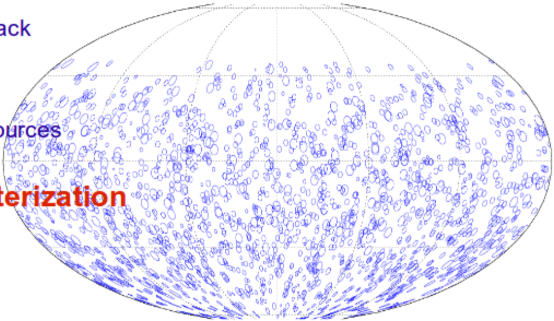
  Jul 7, 2009 to Oct 20, 2010
  ~260 days, 129 days jointly with LV

→ **Preliminary Results**

1986 HEN candidates
~30% with 2-3 IFO

- **HEN selection**
  - Cuts on the quality muon track reconstruction and energy
- **Joint optimization**
  - Maximize # of detectable sources
  - HEN: WB GRB diffuse flux
- **Event by event characterization**
  - Angular error (ASW_{90})
  - Fit of PSF
  - Number of hits (energy)

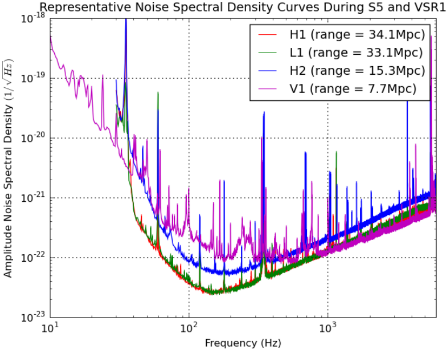
1986 high-energy neutrino candidates, ANTARES 2009/2010

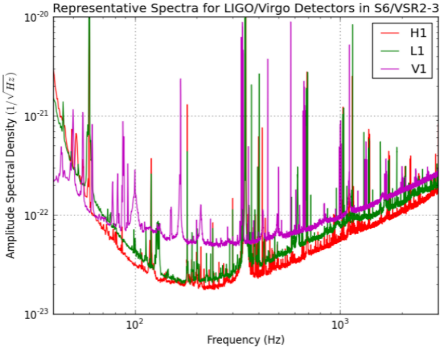


HEN and GW inputs

GW sensitivities and common observation time

- Enhanced sensitivities for low and high $f_{\rm GW}$
- 30% increase in $T_{\rm obs}$

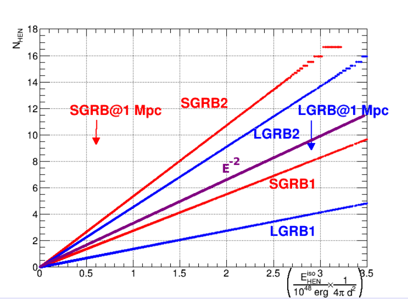




The volume depends on $P_{\rm GW}$ and $P_{\rm HEN}$

$P_{\rm GW}$ and $P_{\rm HEN}$

- $\rho_{\rm GWHEN} \leq \frac{2.3}{V_{\rm GWHEN}\, T_{\rm obs}}$ with $V_{\rm GWHEN} = 2\pi \int_0^\infty P_{\rm GW} P_{\rm HEN}\, r^2 dr$
- $P_{\rm GW}$ vs $h_{\rm rss} = \sqrt{\int (h_+^2(t) + h_\times^2(t))dt} \propto \frac{\sqrt{E^{\rm iso}_{\rm GW}}}{d}$
- $P_{\rm HEN}(N_{\rm HEN} \geq 1) = 1 - e^{-N_{\rm HEN}(E^{\rm iso}_{\rm HEN})} = 1 - \exp^{-k_{\rm model} \frac{E^{\rm iso}_{\rm HEN}}{4\pi d^2}}$

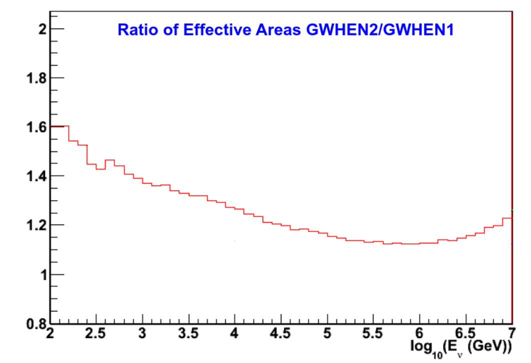


Performances GWHEN-1 vs GWHEN-2

Probed Volume improved by a factor 5

- Better HEN sensitivity ⇒ Improvement of factor 2-3 in N_{HEN}
- Optimization allows to have equivalent HEN and GW horizons

  ⇒ Factor 8 on R_{ul} (/Mpc^3/yr) wrt GWHEN-1



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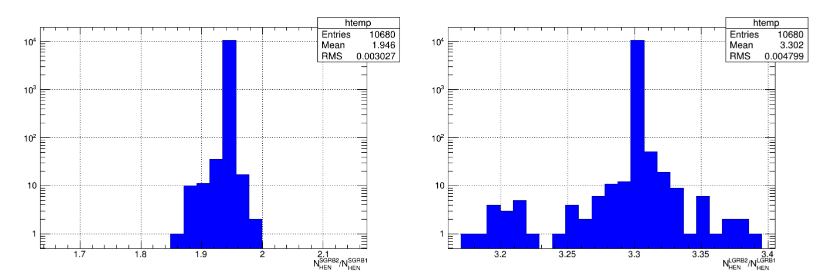
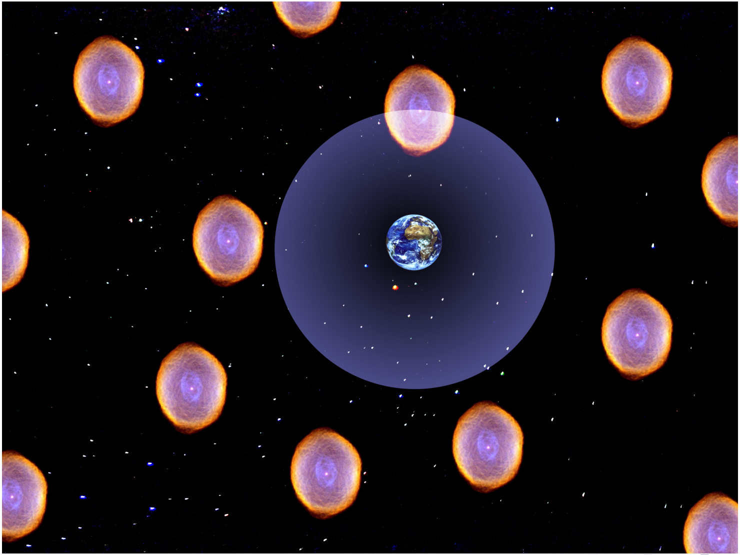
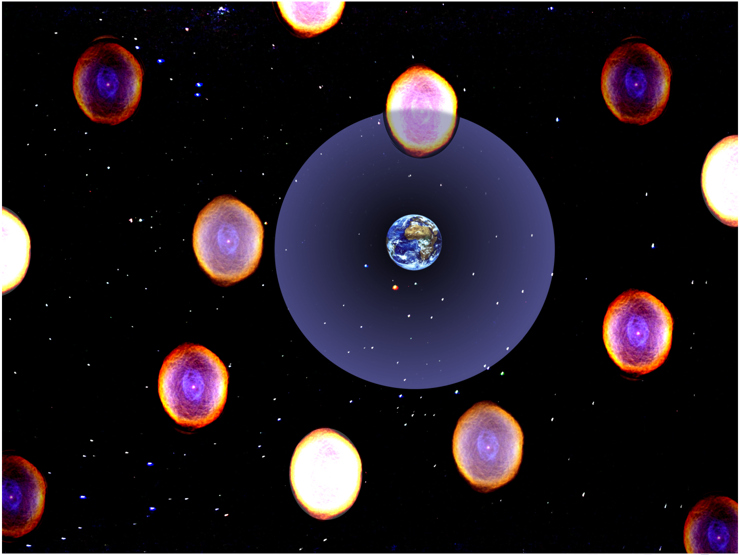


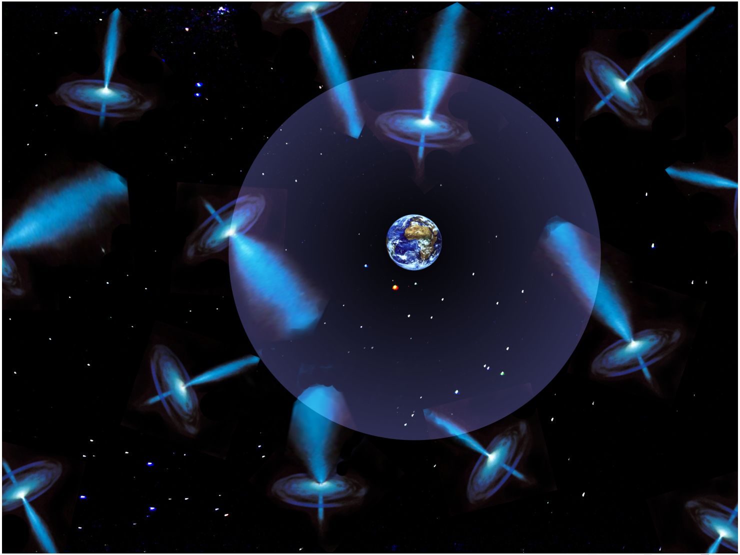
ANTARES 5L : fixed $E_{\mathrm{GW}}^{\mathrm{iso}}$, $E_{\mathrm{HEN}}^{\mathrm{iso}}$ + beaming f_b



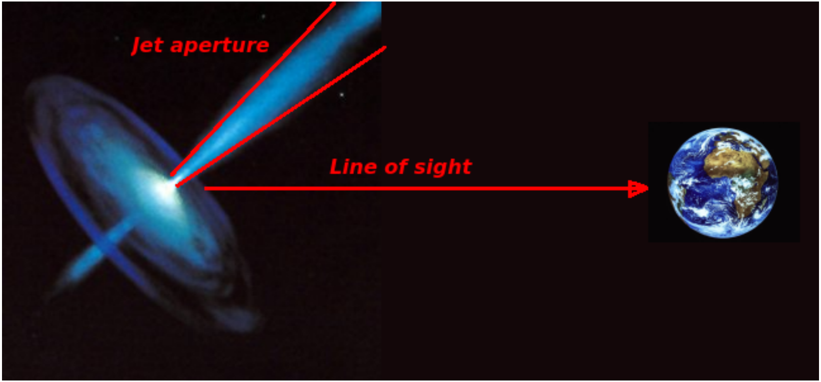
IC22/59/79 : varying $E^{\rm iso}_{\rm GW}$, $E^{\rm iso}_{\rm HEN}$ + beaming f_b



ANTARES 12L : varying E^{iso}_{GW}, E^{iso}_{HEN} + param. of beaming



Jet aperture and line of sight



HEN are beamed

Assume Gaussian profile for HEN emission

- $\Phi_{\mathrm{HEN}}(\theta) \propto e^{-\frac{\theta^2}{2\sigma^2_{\mathrm{HEN}}}}$, with $\theta =$ angle (jet, line of sight)
- For Low-luminosity GRBs, $\sigma_{\mathrm{HEN}} \approx 30^\circ$, beaming factor $f_b \sim 14$
- Normal GRBs, $\sigma_{\mathrm{HEN}} \approx 10^\circ$ (depends on Γ), beaming factor $f_b \sim 100$

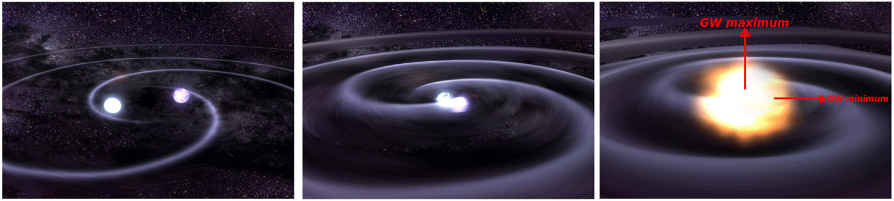
Isotropic equivalent HEN energy $E^{\mathrm{iso}}_{\mathrm{HEN}}$

- ...also convoluted with $e^{-\frac{\theta^2}{2\sigma^2_{\mathrm{HEN}}}}$

  $\Rightarrow$ Maximum for $\theta = 0$, minimum for $\theta = 90^\circ$
- Average on θ : $\langle E^{\mathrm{iso}}_{\mathrm{HEN}} \rangle_\theta \approx \frac{E^{\mathrm{iso}}_{\mathrm{HEN}}}{2\sqrt{\pi}} \left(1 - \frac{1}{2} e^{-\frac{\pi^2}{12\sigma^2_{\mathrm{HEN}}}} \right)$

  $\Rightarrow$ Can be computed for any assumed σ_{HEN}
- Average on σ_{HEN} : $\langle E^{\mathrm{iso}}_{\mathrm{HEN}} \rangle_{\theta, \sigma_{\mathrm{HEN}}} \approx \frac{2\sqrt{\pi}}{15} E^{\mathrm{iso}}_{\mathrm{HEN}}$

GW emission and line of sight



GW beaming

Examples of different GW signals

- **Binary mergers** : $h_+ \propto 1 + \cos^2\theta$, $h_\times \propto \cos\theta$
  - $\Rightarrow$ θ angle between line of sight and axis of rotation
- **Core-Collapse** : no clear pattern ?
  - $\Rightarrow$ For neutrino-driven GW, $h \propto \cos\theta$
- **Bursts with memory from jets** : anti-beaming !

Consider fraction of GW Energy in direction of HEN jet

- For Beamed GW, consider $h \propto 1 + \cos^2\theta$ as typical
  - $\Rightarrow$ Fraction of GW energy $\parallel$ to HEN jet in cone $\pm\sigma_{\rm HEN}$:

$$\eta_{\rm jet} = \frac{2}{3\pi}(3\sigma_{\rm HEN} + \frac{1}{2}\sin 2\sigma_{\rm HEN})$$

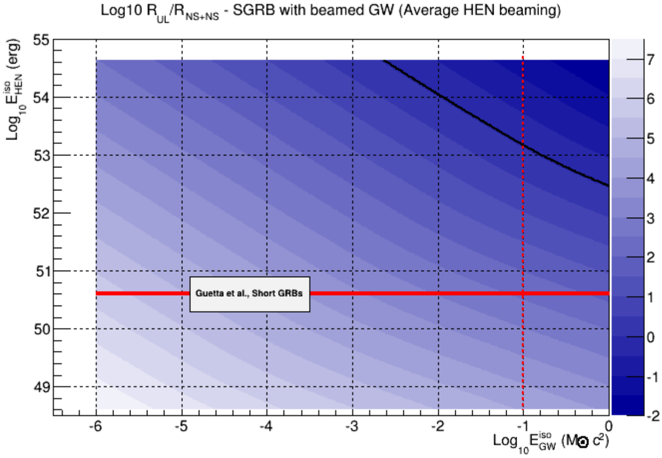
  - $\Rightarrow$ $\langle\eta_{\rm jet}\rangle_{\sigma_{\rm HEN}} \approx 0.6$
- Anti-Beamed GW, consider $h \propto \sin^2\theta$ as typical

$$\eta_{\rm jet} = \frac{2}{\pi}(\sigma_{\rm HEN} - \frac{1}{2}\sin 2\sigma_{\rm HEN})$$

  - $\Rightarrow$ $\langle\eta_{\rm jet}\rangle_{\sigma_{\rm HEN}} \approx 0.3$

Possible results for Short GRBs vs NS+NS rates

With all-sky $P_{\rm GW}$ vs $h_{\rm rss}$ (153 Hz) from Phys. Rev. D 85, 122007 (2012)



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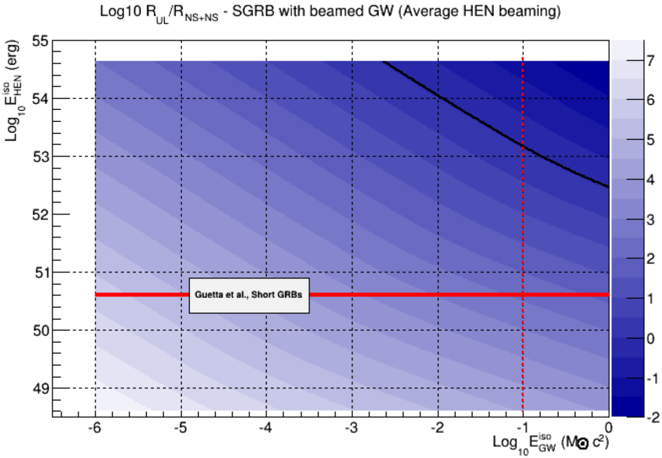
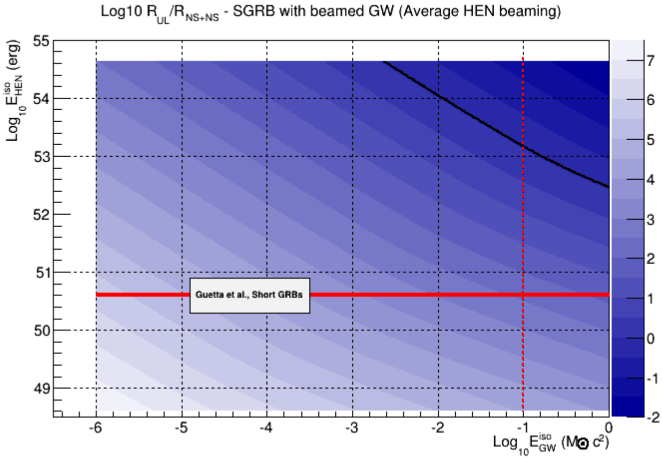


⇒ Constrain **fraction of NS+NS with jets** for ultra-luminous events ?
(Black curve : $R_{\rm UL}/R_{\rm NS+NS} = 1$, with $R_{\rm NS+NS} = 10^{-5}/Mpc^3/yr$)

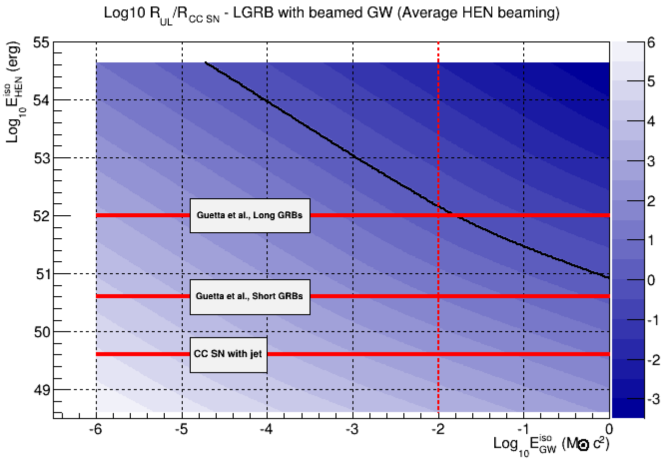
Possible results for Short GRBs vs NS+NS rates



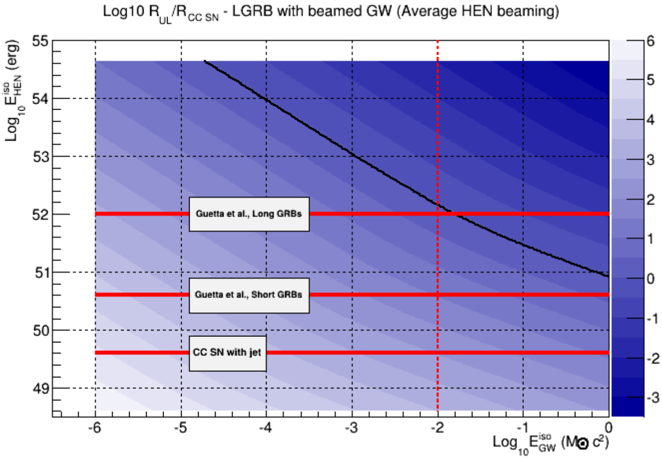
- For Binary Mergers, maximum $E_{\rm GW}^{\rm iso} \approx 10^{-1} M_{\odot} c^2$
- $E_{\gamma}^{\rm iso} \sim 10^{54} erg$ = Naked-Eye GRB !

Possible results for Long GRBs vs CC SN rates

With all-sky P_{GW} vs h_{hrss} (153 Hz) from Phys. Rev. D 85, 122007 (2012)

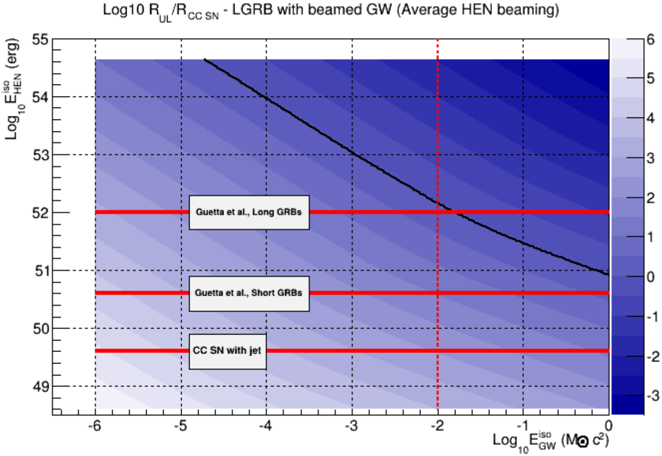


Possible results for Long GRBs vs CC SN rates



⇒ Constrain **fraction of CC SN with jets** with Guetta normalization ?
(Black curve : $R_{\mathrm{UL}}/R_{\mathrm{CC\ SN}} = 1$, with $R_{\mathrm{CC\ SN}} = 5 \times 10^{-4}/Mpc^3/yr$)

Possible results for Long GRBs vs CC SN rates



- But for Core-Collapses, maximum $E_{\mathrm{GW}}^{\mathrm{iso}} \approx 10^{-2} M_{\odot} c^2$

⇒ At limit of physically relevant region with triggered-search P_{GW} ?

Encouraging expected results

A huge improvement wrt GWHEN-1

- Improvement of factor 2-3 in N_{HEN} wrt GWHEN-1
  - ⇒ Factor 8 on R_{ul} (/Mpc^3/yr) wrt GWHEN-1
- Proposal for different GW and HEN beaming parametrization in GWHEN-2, beyond beaming parameter f_b
- **NS+NS rates :**
  - ⇒ Possibility to constrain **fraction of NS+NS mergers with jets** for ultra-luminous events only ?
- **Core-Collapse SN rates :**
  - ⇒ LGRB : possibility to constrain **fraction of CC SN with jet** with typical LGRB parameters (just at the limit $E_{\mathrm{GW}}^{\mathrm{iso}} = 10^{-2} M_{\odot} c^2$)

Encouraging expected results

Improvements

- First, wait for box-opening !
- Under review within LIGO-Virgo
- Include NeuCosmA typical spectrum in the limits

  $\Rightarrow$ Smaller normalization

  $\Rightarrow$ Higher energies

Future

- GWHEN with ANTARES (if extended $\rightarrow$ 2016), KM3NeT(2016-2018) and Advanced LIGO/Virgo

  $\Rightarrow$ Possibly as soon as 2015 (aLIGO) ?

  $\Rightarrow$ 2016-2017 both aLIGO and aVirgo ?