- GWHEN -
Gravitational Waves & High Energy Neutrinos Coincidences

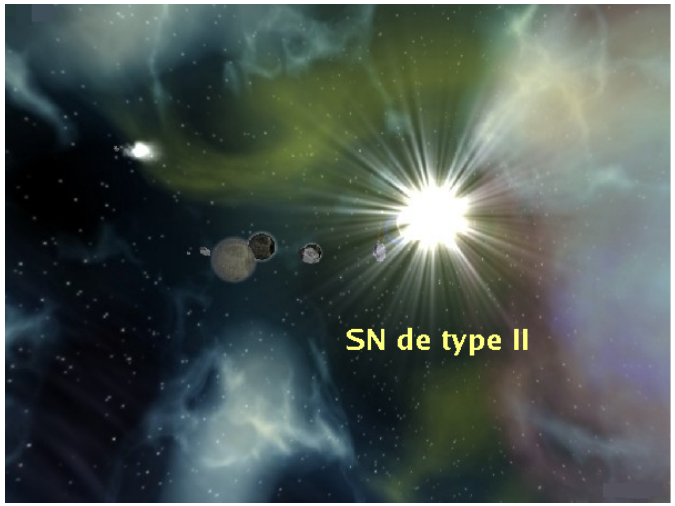
UNIVERSITÉ DE STRASBOURG

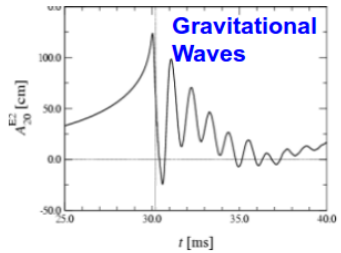
GWHEN

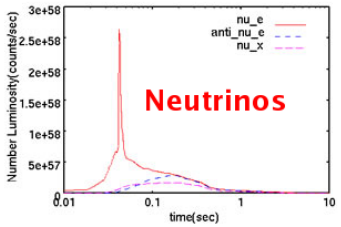
- ANTARES - **Contact : Th. Pradier (IPHC, Strasbourg)**
  - APC (Paris) : B. Baret, *B. Bouhou*, C. Donzaud, A. Kouchner, V. Van Elewyck
  - GRPHE (UHA) to be joining soon : A. Albert
- VIRGO - **Contact : E. Chassande-Mottin (APC, Paris)**
  - **LAL (Orsay) to be joining soon : M.-A. Bizouard, P. Hello, F. Robinet - detection of GW Bursts**
- LIGO - **Contact : S. Márka (Columbia U., USA)**
  - Columbia U. (USA) : *I. Bartos*, Z. Márka
  - Cardiff (UK) : P. Sutton, G. Jones
  - Potsdam (Germany) : I. Di Palma + M.-A. Papa
- IceCube : **C. Finley (OKC, Sweden)**

See arXiv:0807.2562, arXiv:0906.4957

An example of GW-ν Coincidences : Type II SN







Type II SN

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

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

N. Arnaud,...,Th. P. - Phys.Rev. D65 (2002) 033010

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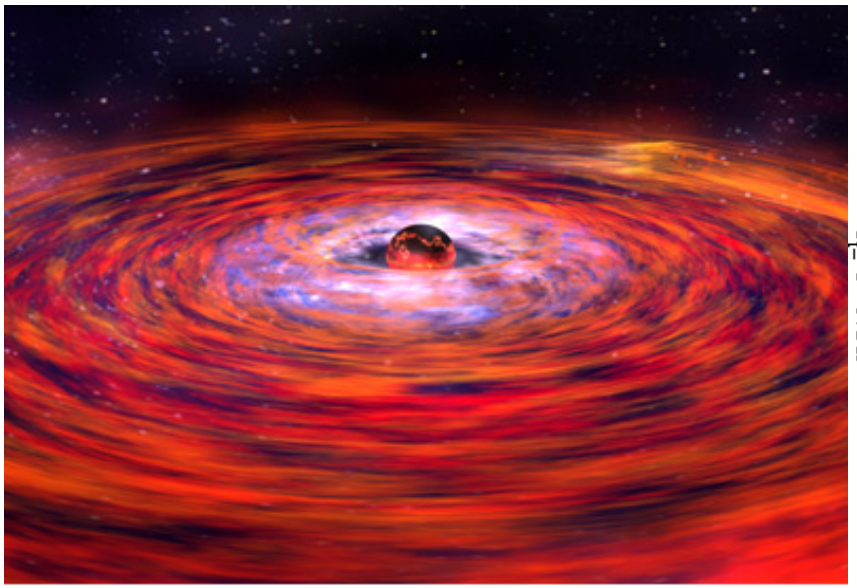
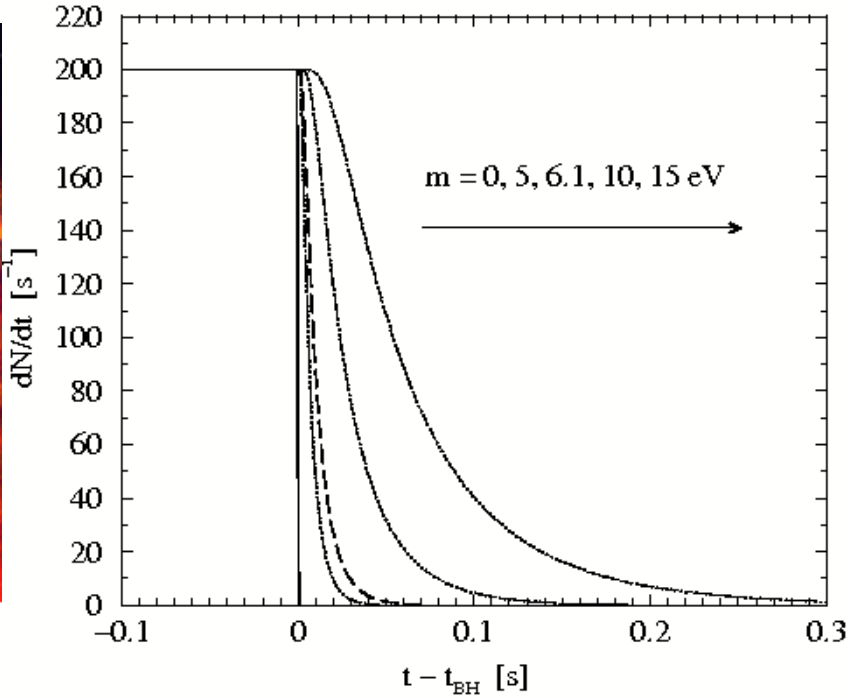




Collapse of NS into BH induced by accretion

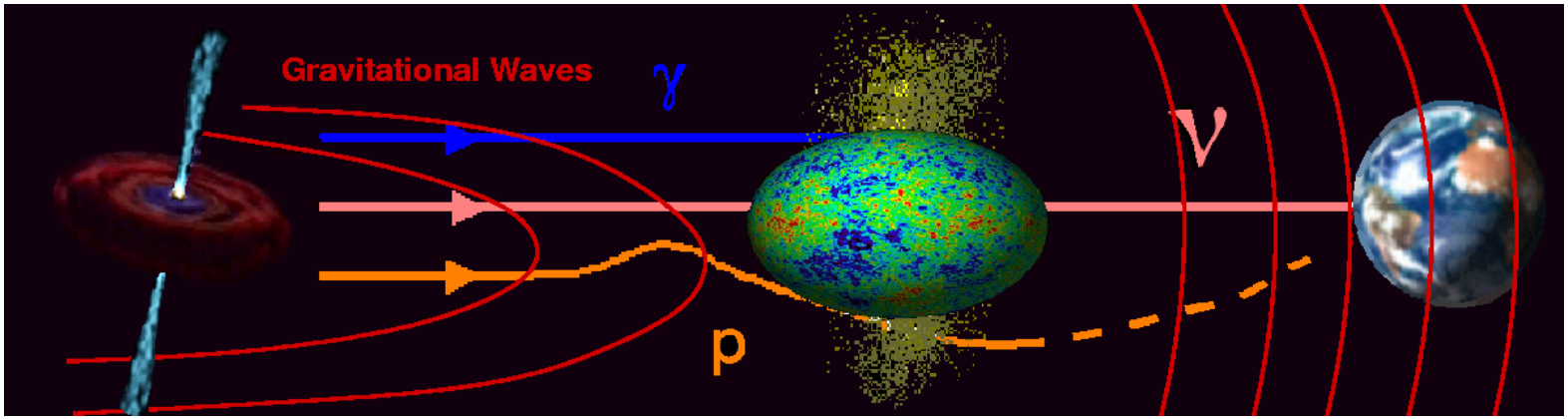
$\Rightarrow$ Sudden stop of neutrino signal

$\Rightarrow$ Strong GW Signal

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

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

GWHEN in 2 words...



High Energy Neutrinos and Gravitational Waves

1 - Coincident Detection (time+space) *validates* detections

2 - Sources invisibles in photons : *Dark Bursts*

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

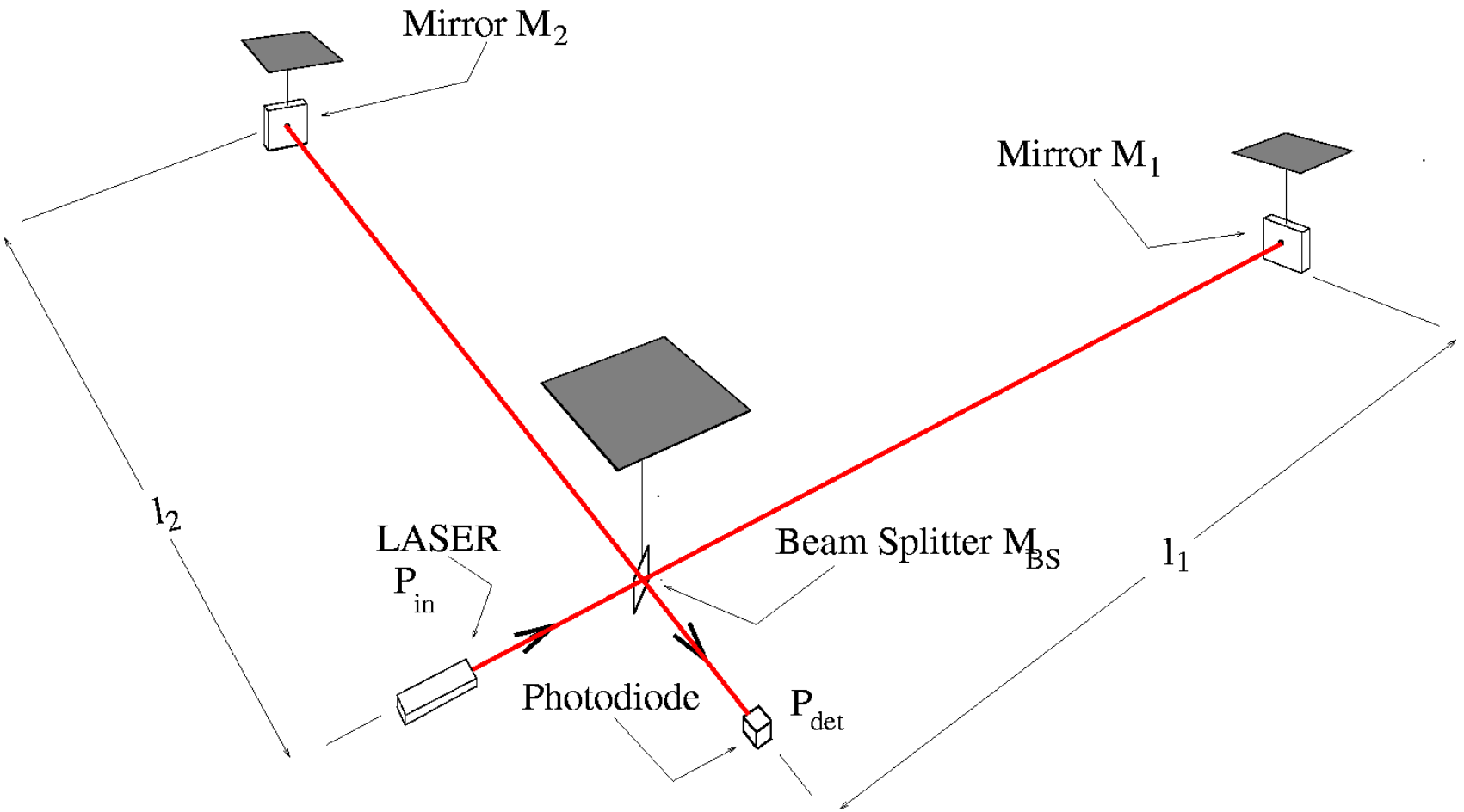
4 - Fundamental Physics :

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

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

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

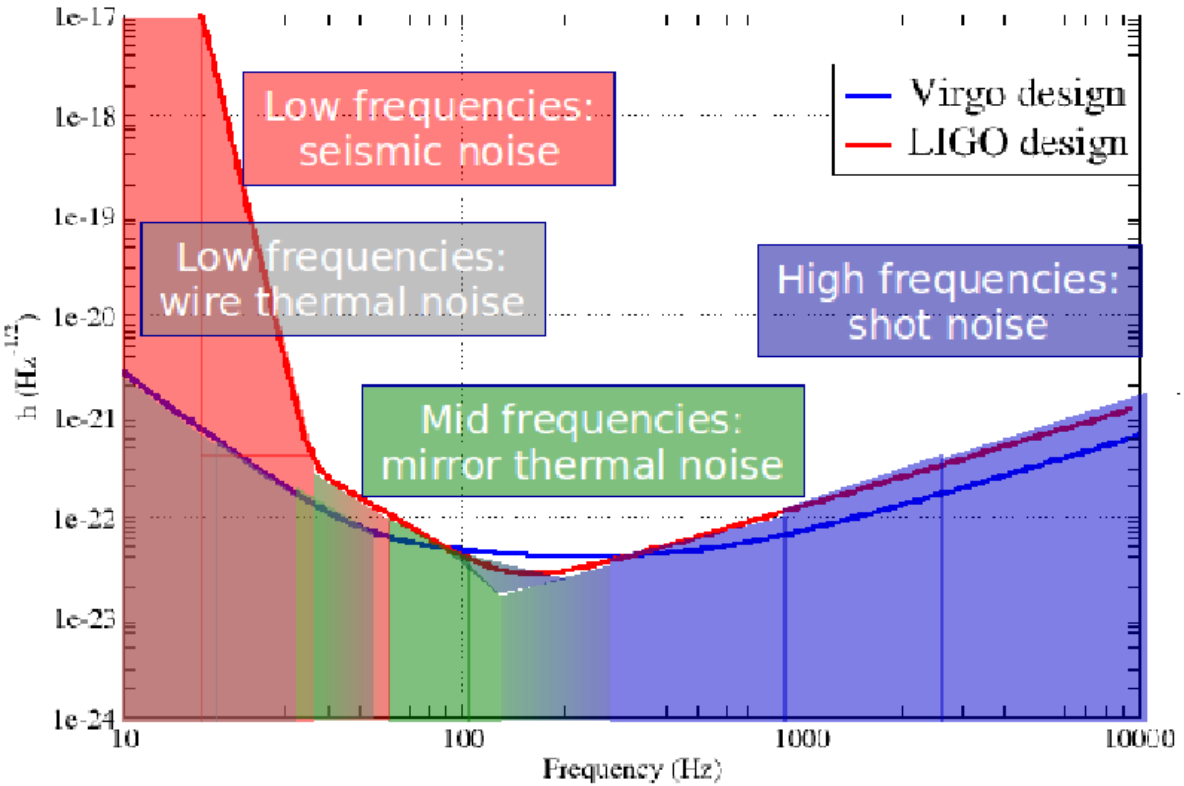
Detecting GW...



Michelson Interferometers

- $L \sim$ km for enhanced sensitivity, with $P_{\rm det} \propto h = f(t)$

Detecting GW...

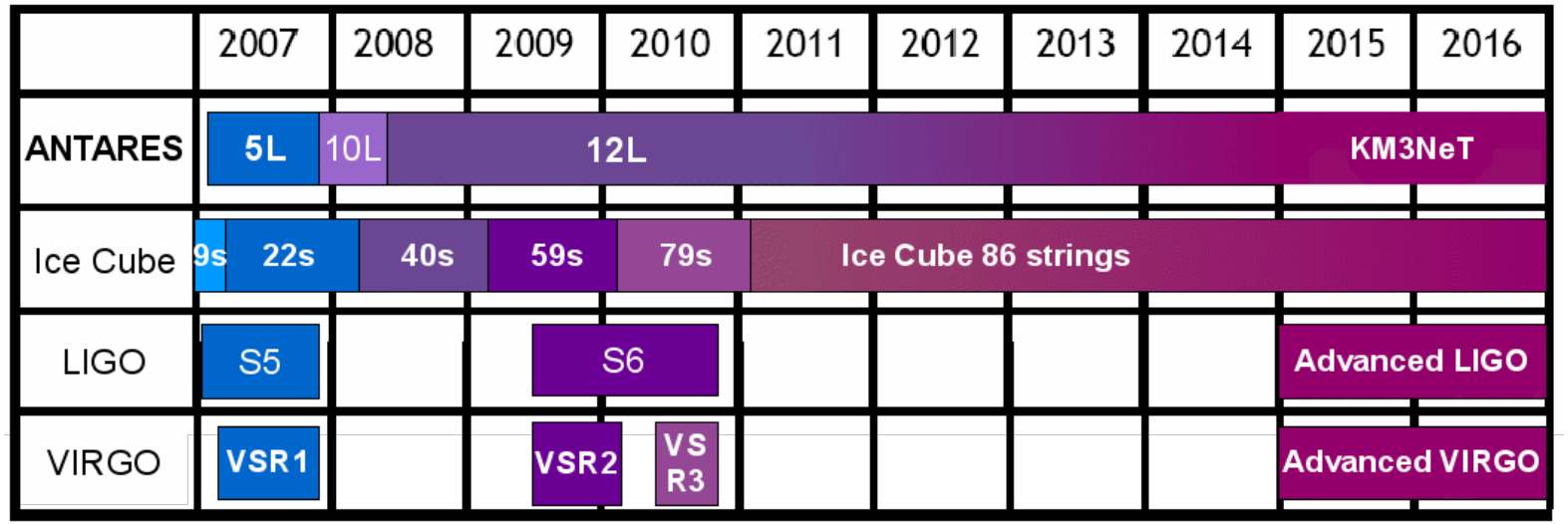


Michelson Interferometers

- $L \sim$ km for enhanced sensitivity, with $P_{\mathrm{det}} \propto h = f(t)$
- Background from seismic noise, photon noise, resonances...

GW Detectors : VIRGO+LIGO

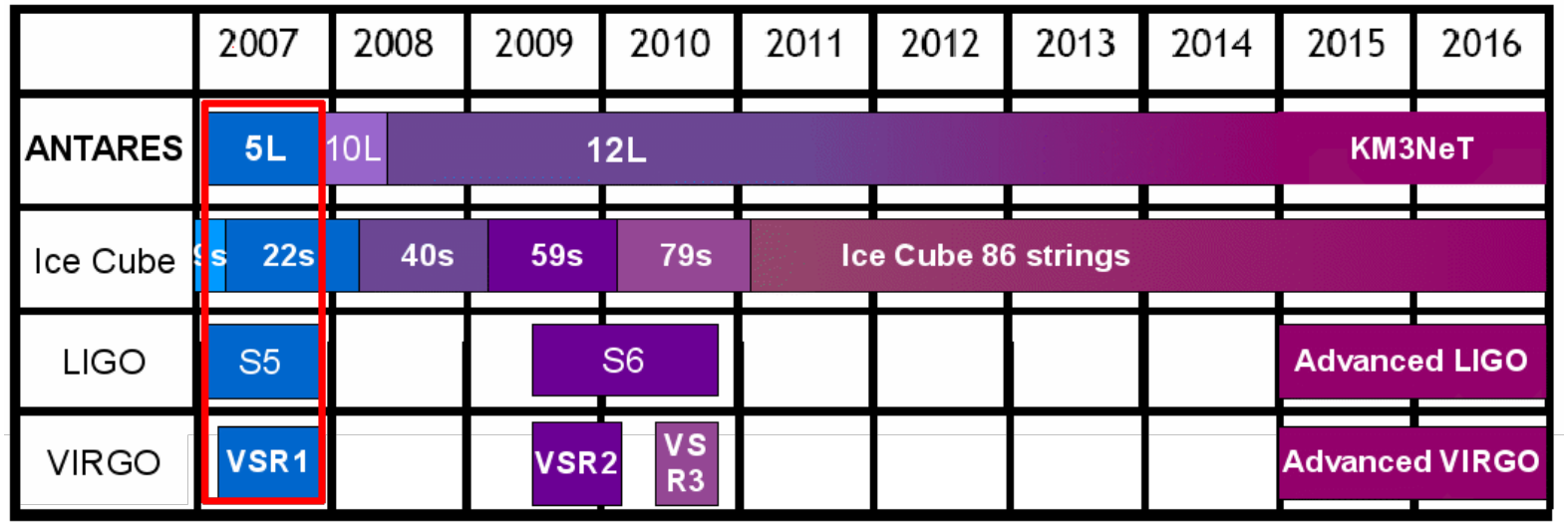
GW interferometers and HEN Telescopes



GWHEN Data for coincidences

- 2007 : ANTARES 5 Lines + VIRGO VSR1+LIGO S5
- 2009-2010 : ANTARES 12 Lines + VIRGO VSR2+LIGO S6
- 2015 : km3 in the Mediterranean + Advanced Interferometers

GW interferometers and HEN Telescopes



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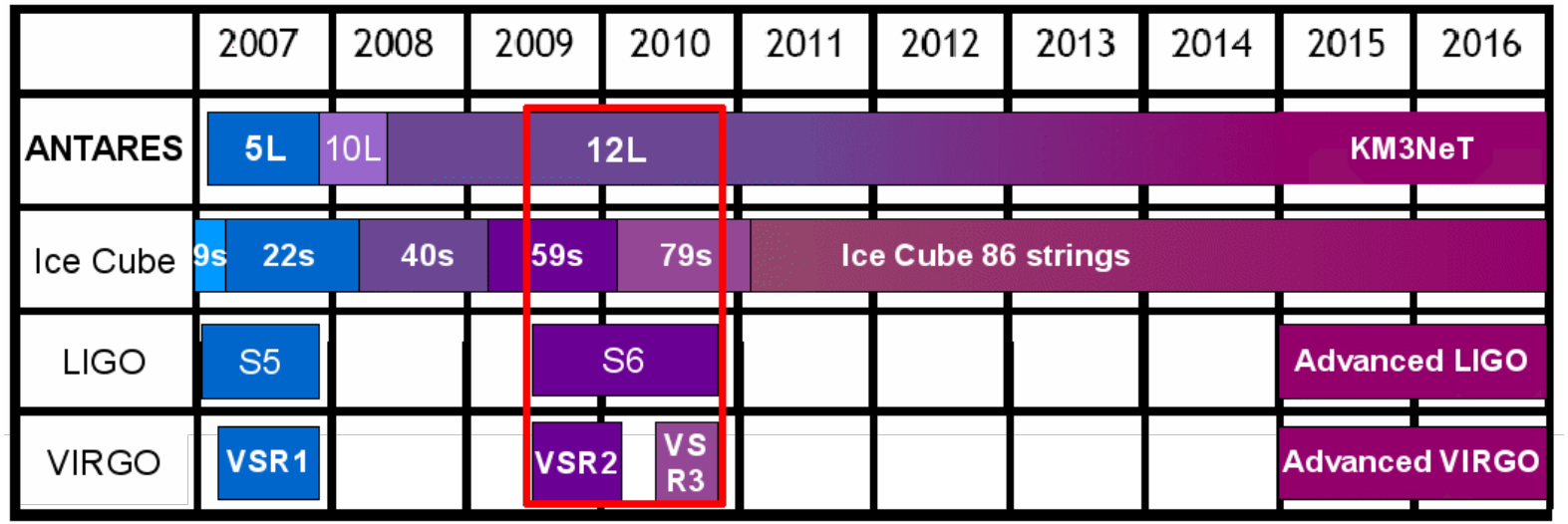

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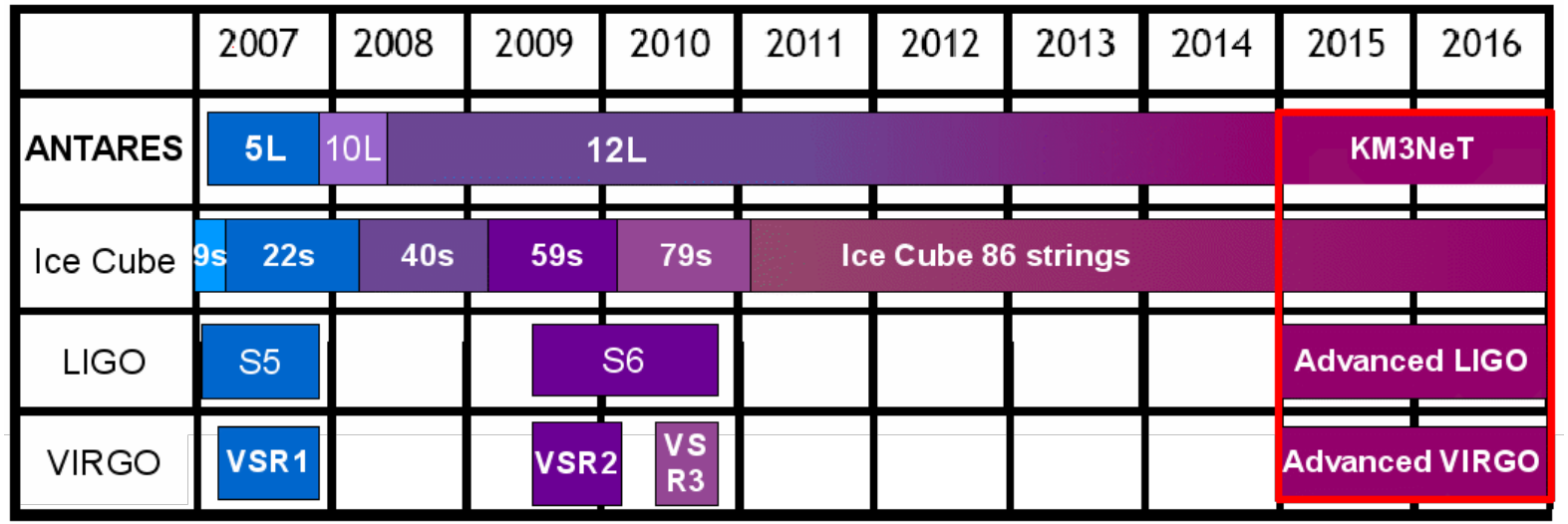

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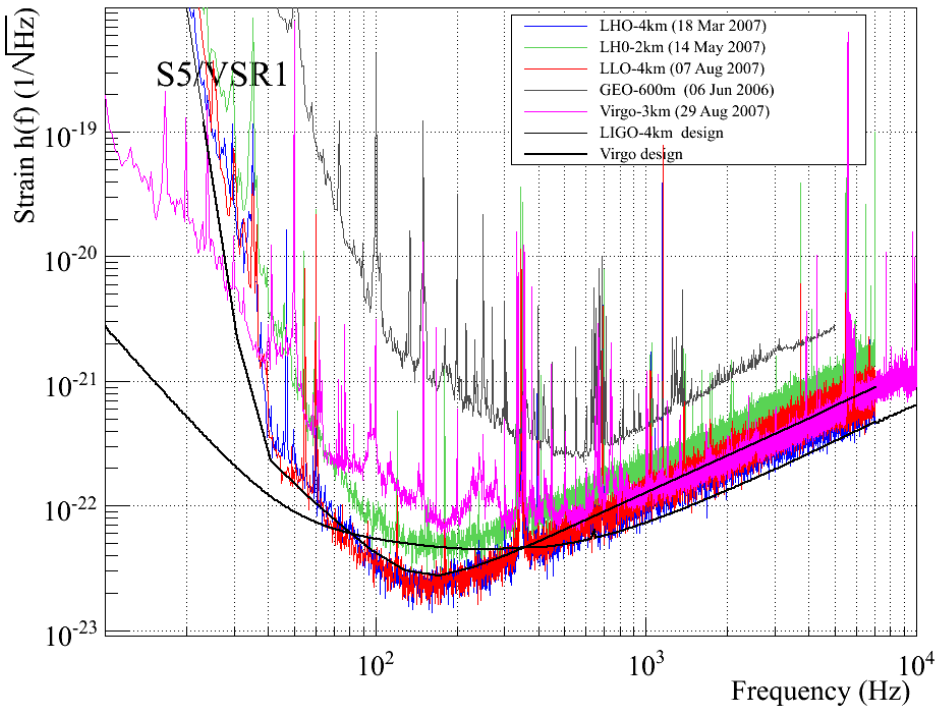
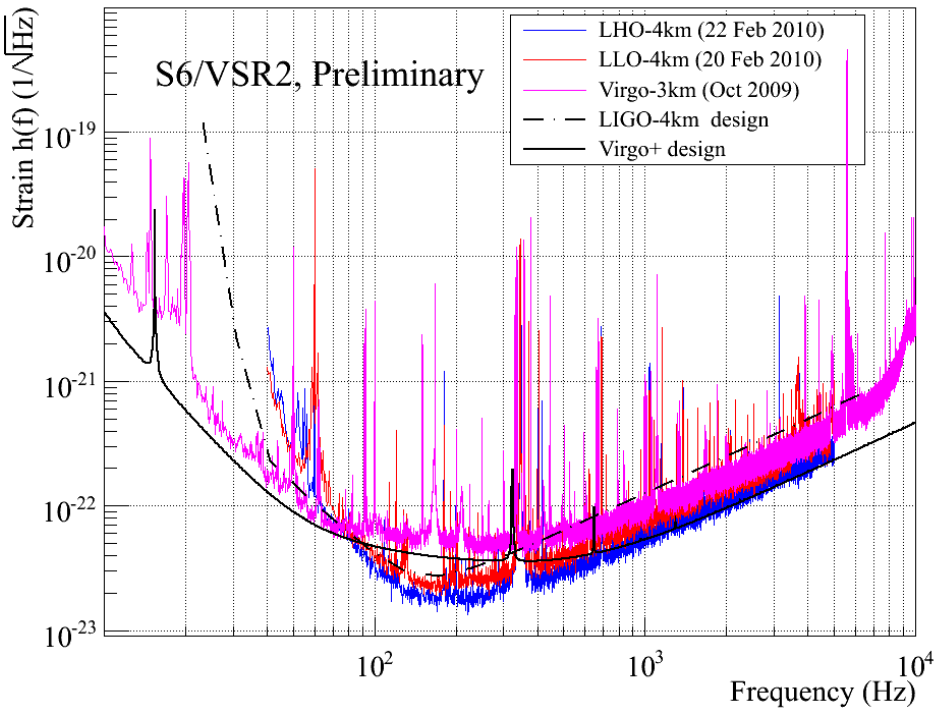




VSR1 - S5 (2007)

VSR2 - S6 (2009)

The GWHEN Group

Proposed independently by :

- Aso *et al.* (LIGO) [Class. Quant. Grav. **25** :114039, 2008]
- Th. P. (ANTARES) [VLVNT 08 proceedings, N.I.M. A **602** :268, 2009]

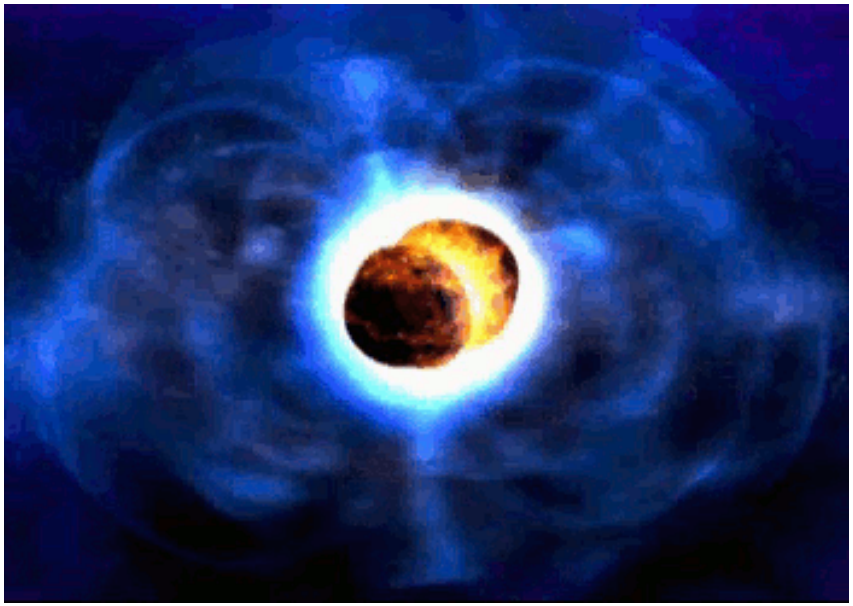
  $\Rightarrow$ **now all authors part of the same GWHEN group**

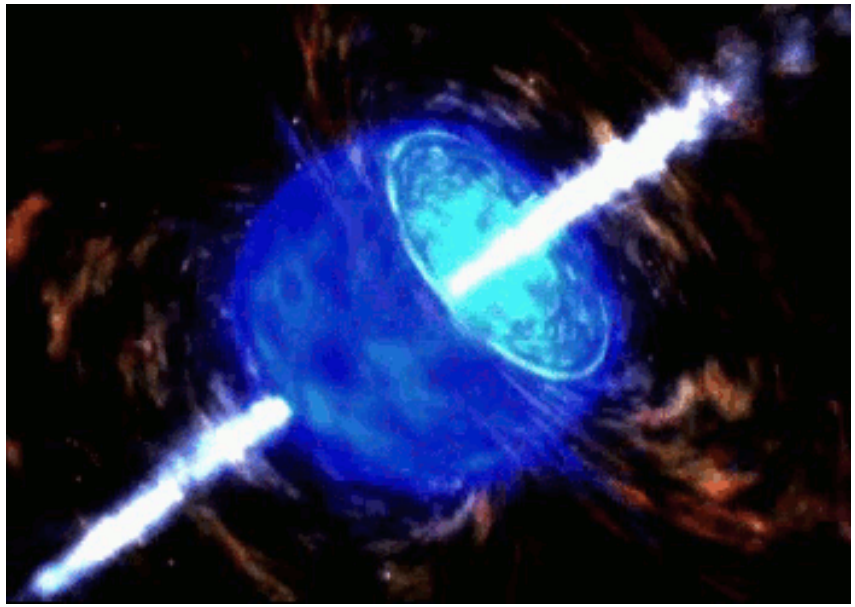
2008 - 2010 : birth of the project

- End of 2008 : MoU ANTARES-VIRGO/LIGO on data exchange
- Common Workshop in 2009 @ APC (GWHEN 2009)
- Joint Working Group : ANTARES+ICECUBE+VIRGO/LIGO

  $\Rightarrow$ Regular Phone Meetings

Gamm-Ray Bursters (GRBs)





Short GRBs

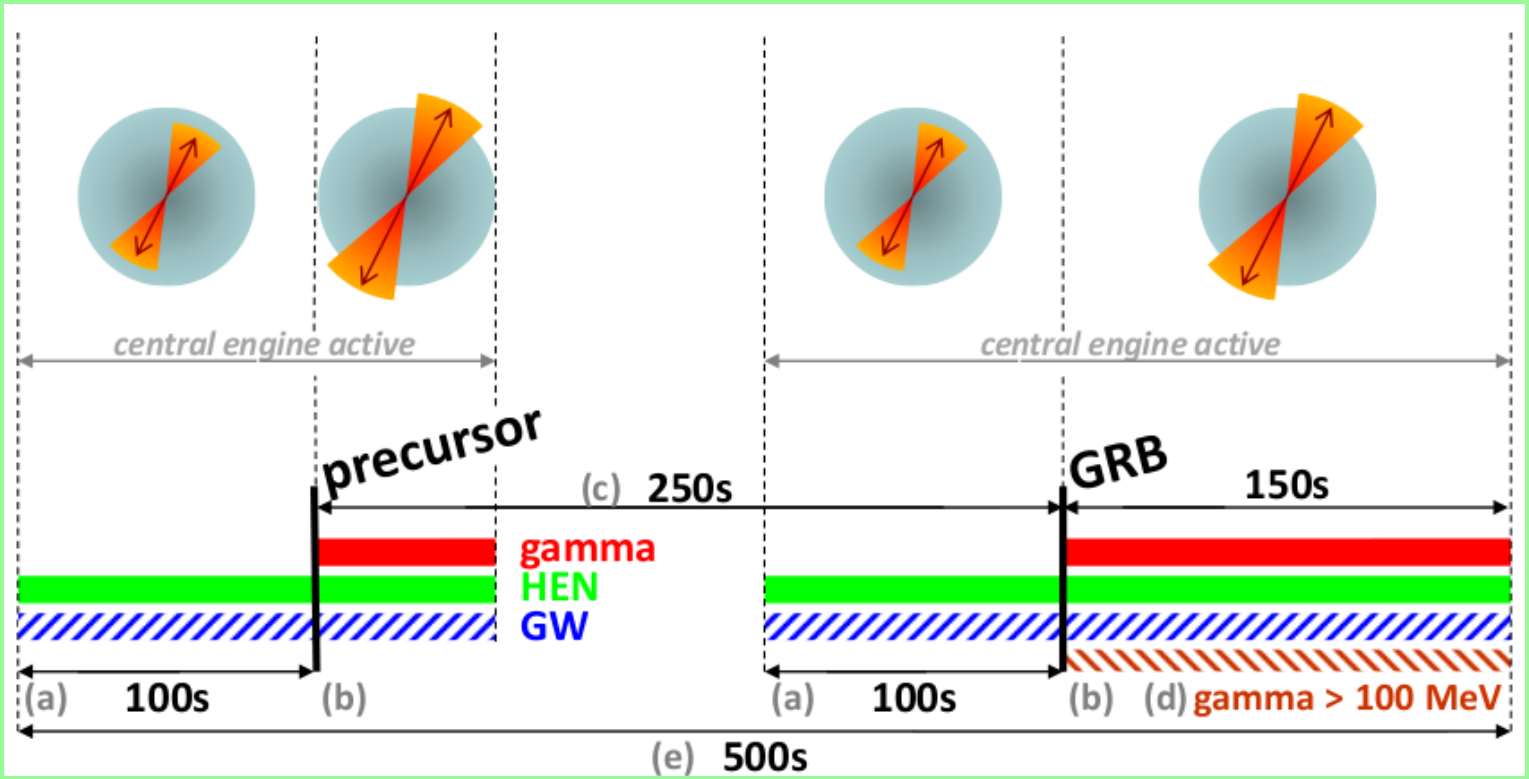
Binary Mergers : BH or NS

Long GRBs

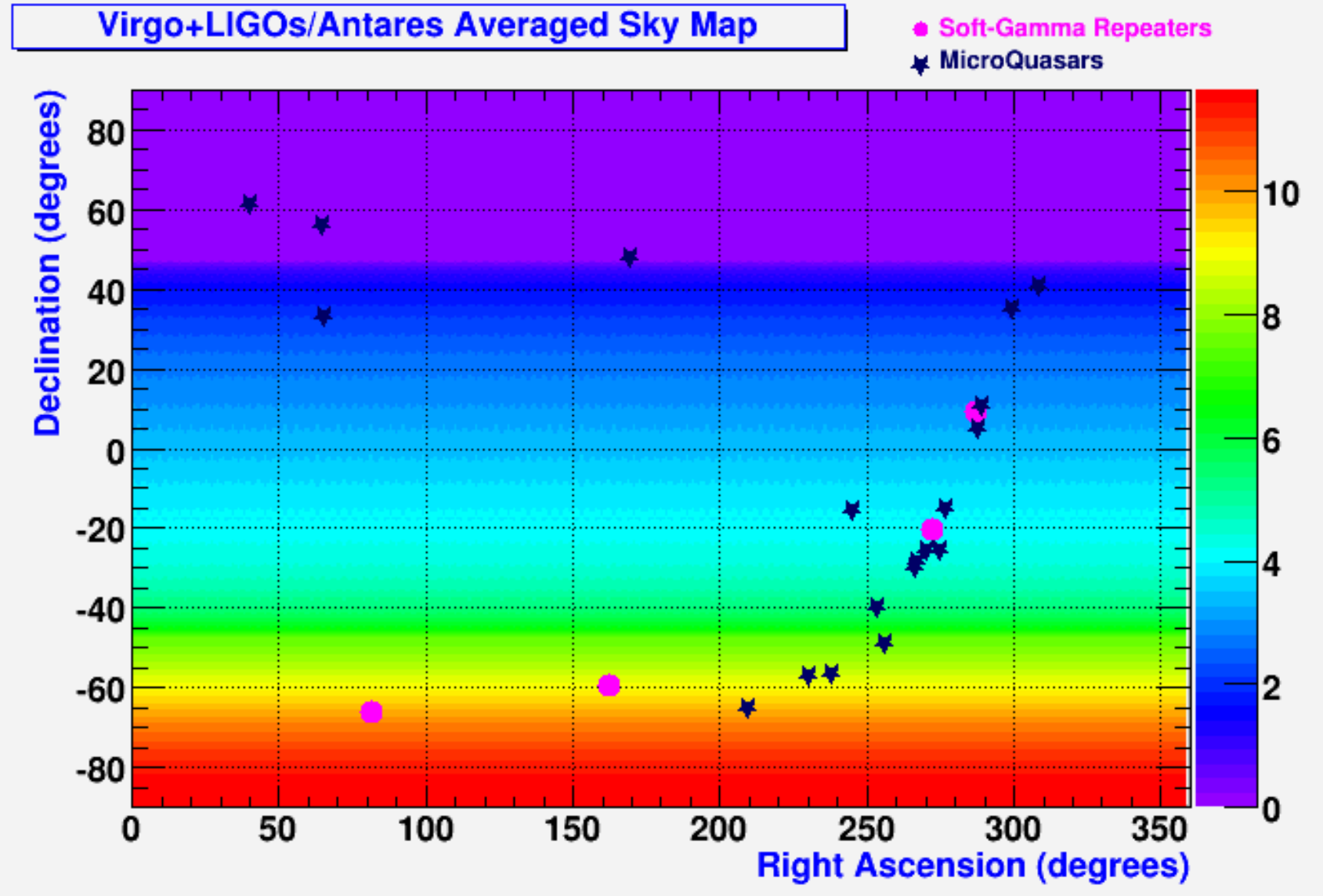
Collapsars - massive star collapse

Time Window for long GRBS

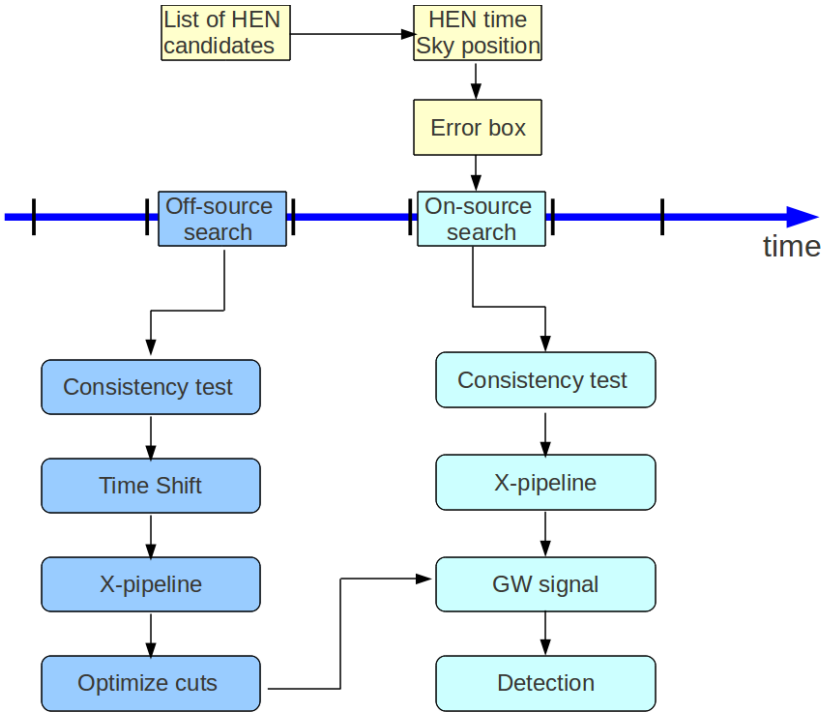
- *Bounding the Time Delay between High-energy Neutrinos and Gravitational-wave Transients from Gamma-ray Bursts*
- GWHEN Group, B. Baret *et al.*, submitted to AstroParticle Physics
  $\Rightarrow$ $\Delta T = \pm 500$**s** [arXiv:1101.4669]

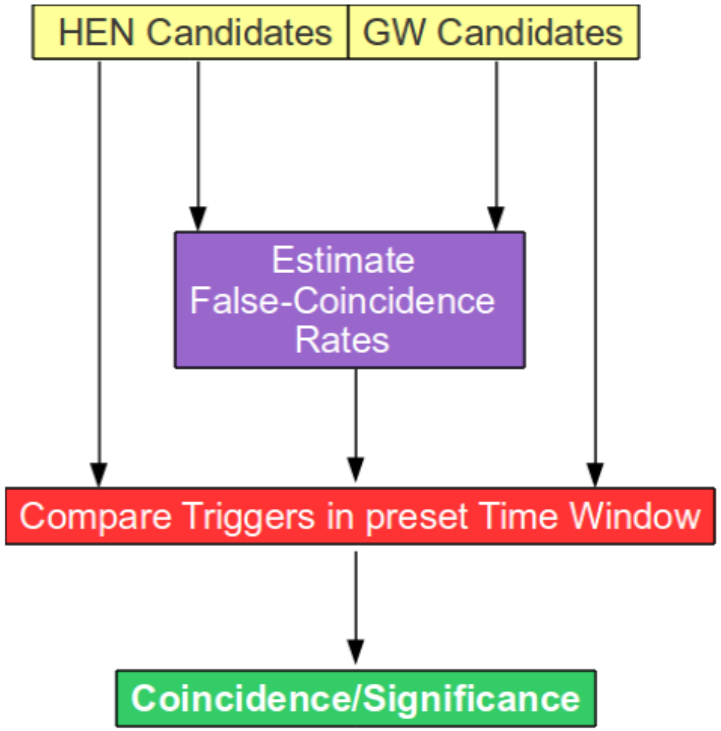


Visbility of some Galactic sources



GWHEN Analysis Strategy





Analysis of 2007 data

- Use of HEN Error Box to look for GW bursts

Analysis of 2009-2010 data

- Symmetrical Analysis

GWHEN with 2007 data

Current Analysis : ANTARES 5L + VSR1/S5 in 2007

- List of HEN candidates (Feb-Sept.'07) → VIRGO/LIGO 08/2010
- GW Bursts Search performed
- Waiting for green light for opening the box...
  - ⇒ **Coincident GW candidates soon to be known...**

HEN List for 5 Line Data : ≈ 220 events

- ∼ 90% events reconstructed with 2/5 Lines
- Only 10% with 3 Lines or more (more energetic ones)
- More than 2 interferometers needed for direction reconstruction :
  - ⇒ ∼ 30% with < 2 interferometers taking data
  - ⇒ ∼ 70% of the original HEN list have analyzable GW counterpart

What if... ?

Target Significance in case of detection

- Depends on False-Coincidence Rate : $f_{\rm coinc} = f_{\rm HEN} \times f_{\rm GW} \times \underbrace{\Delta T}_{1000s}$
- Note : No Solid Angle factor $\frac{\Delta\Omega}{\Omega}$
  - $\Rightarrow$ GW signals only searched for in the HEN Angular Search Window !

$\Rightarrow$ Tuning of $f_{\rm GW}$ to get **Significance** $\gtrsim$ **3**σ if detection

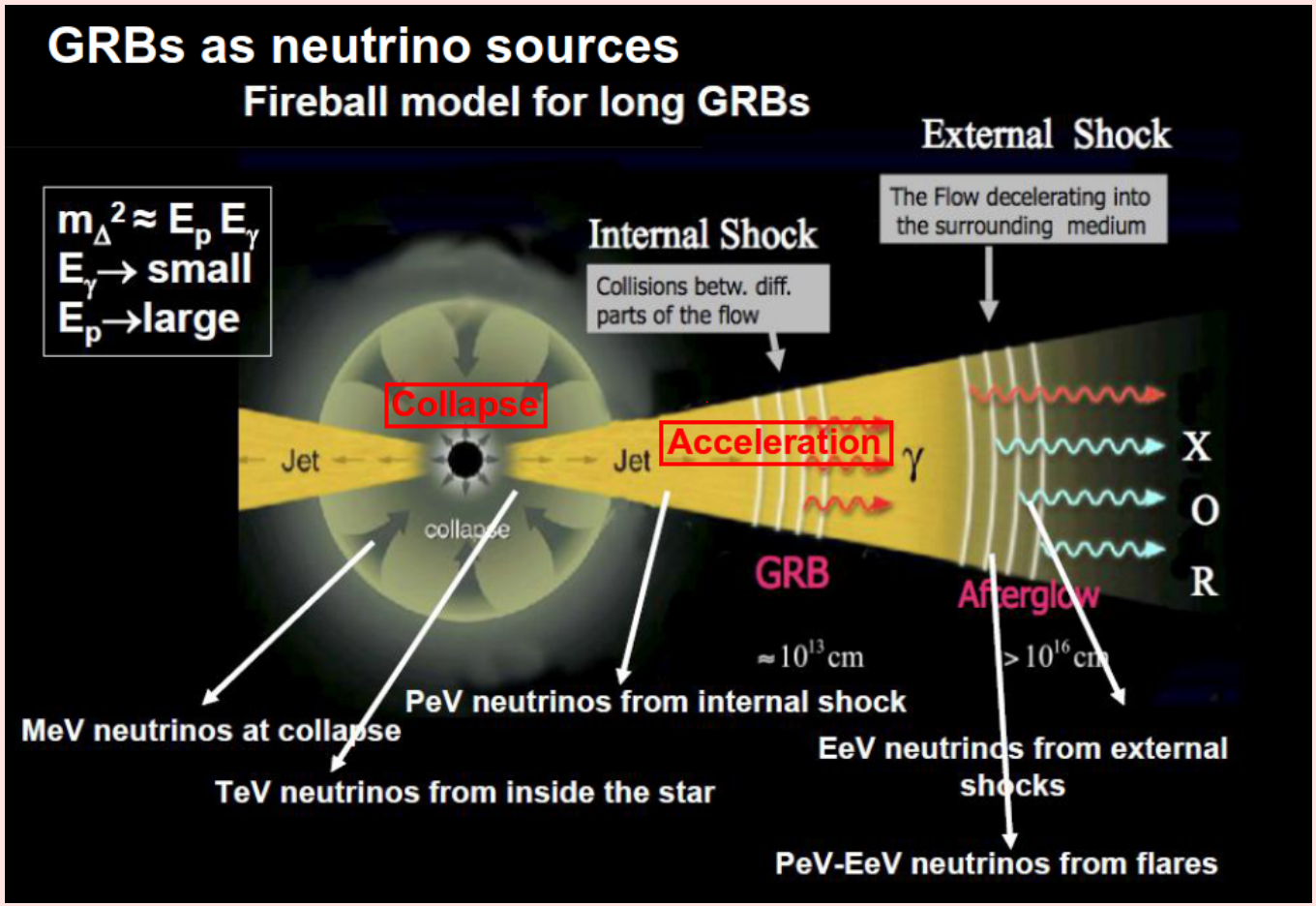
$\Rightarrow$ Choice independent of any models

If no detection...

- Link with GWHEN emission models :
  - No detection $\Rightarrow$ $N_{\rm coinc} \leq 2.44$ **(90% C.L.)**
  - $N_{\rm coinc} = \rho_{\rm GWHEN} \frac{4\pi}{3} d^3_{\rm horizon} T_{\rm observation}$
  - $d_{\rm horizon} = min\left(d^{\rm HEN}_{\rm max}, d^{\rm GW}_{\rm max}\right)$
  - $\Rightarrow$ Exclusion plot $\rho_{\rm GWHEN}$ vs Model Parameters

TeV Neutrinos from mildly relativistic jets

Ando & Beacom Model : *PRL 95 061103 (2005)*



TeV Neutrinos from mildly relativistic jets

GW Collapse Horizon

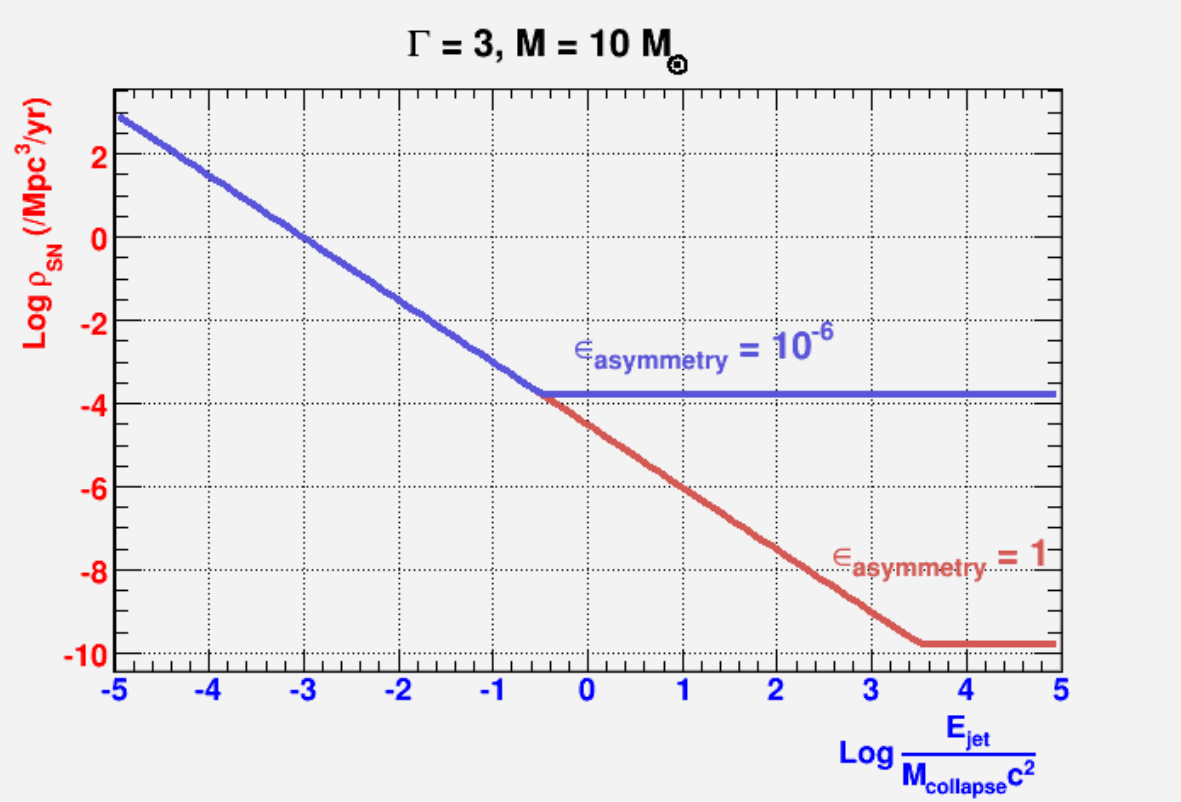
- $h \propto \epsilon_{\rm asym} \frac{M_{\rm collapse} c^2}{d}$

$\Rightarrow d_{\rm max}(GW) \propto \epsilon_{\rm asym} M_{\rm collapse} c^2$

HEN Jet Horizon

- $N_\nu \approx \eta_{\rm baryons} \frac{E_{\rm jet}}{d^2}$

$\Rightarrow d_{\rm max}(HEN) \propto E_{\rm jet}^{1/2}$



Outlook and Conclusions

2007 Data : GW Analysis in coincidence with HEN finished

- Results expected in few days then checks for possible candidates...

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2009-2010 Data : Joint Analysis to be started

- Joint Simulations (consider different GWHEN models)

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2009-2010 Data : Joint Analysis to be started

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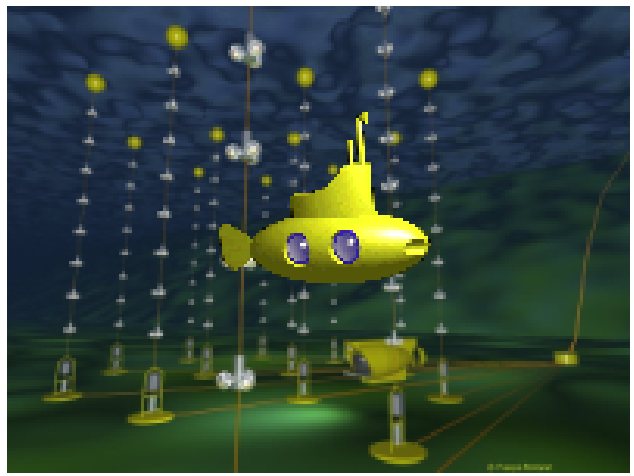
Towards a new joint astronomy...

- Unique way of confirming both GW+HEN detections
- Access to dark sources (failed GRBs)...

Back-Up !



Soft-Gamma Repeaters

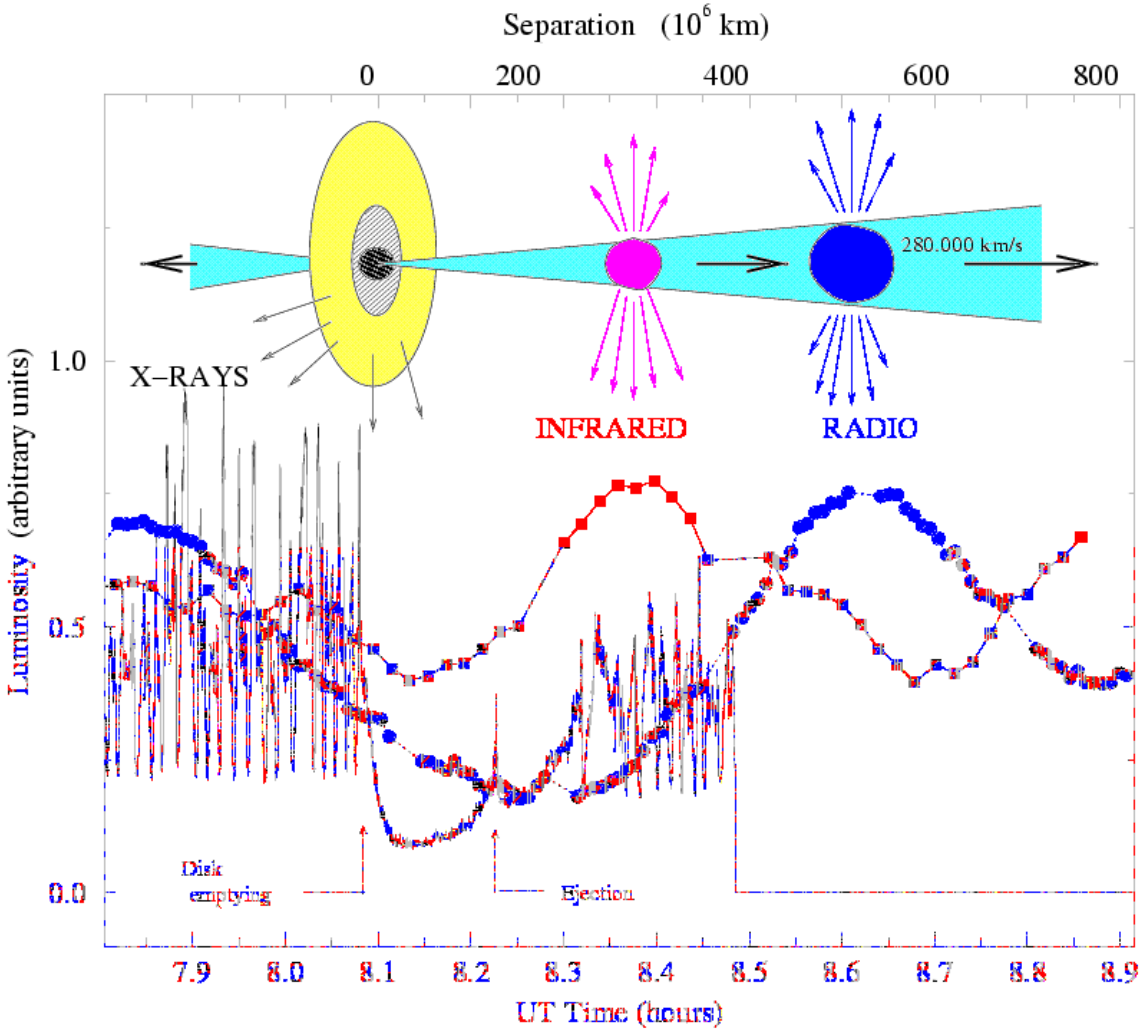
GW Signal : star-quake $\Rightarrow$ pulsation

- Depends on Star Models (EoS)
- Energy liberated in GW linked to γ Flux

HEN Signal : acceleration of CRs in $\vec{B}$

- N_ν detectable, if intense *Flare* (SGR 1806-20 in Dec. 2004)

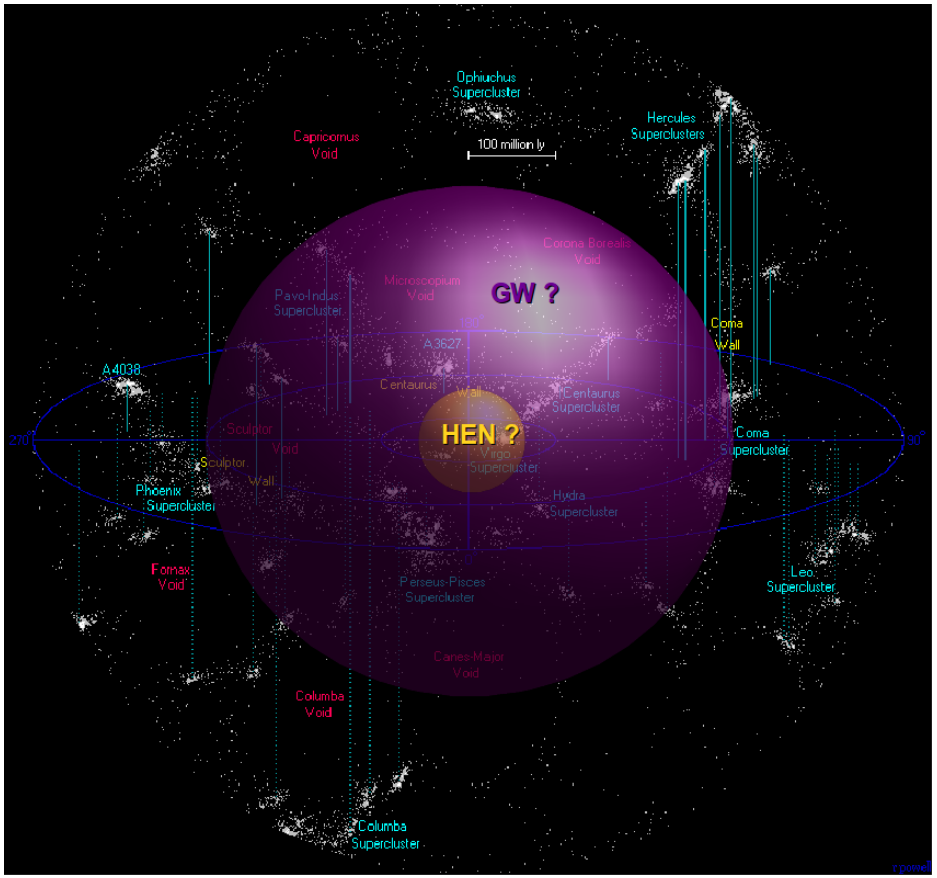
MicroQuasar Outbursts



Accretion/Ejection

- Accretion : infall of matter onto BH/NS
- Ejection : acceleration of matter
  - $\Rightarrow h \propto \frac{\Gamma \delta m c^2}{d}$
  - $\Rightarrow f \sim \tau^{-1}_{\text{acceleration}}$
  - $\Rightarrow L_\nu \propto \frac{\Gamma \delta m c^2}{\tau_{\text{acceleration}}}$
  - $\Rightarrow \Delta t_{\text{GW-}\nu} \Rightarrow \tau_{\text{acc}}$

Optimization of the Analysis

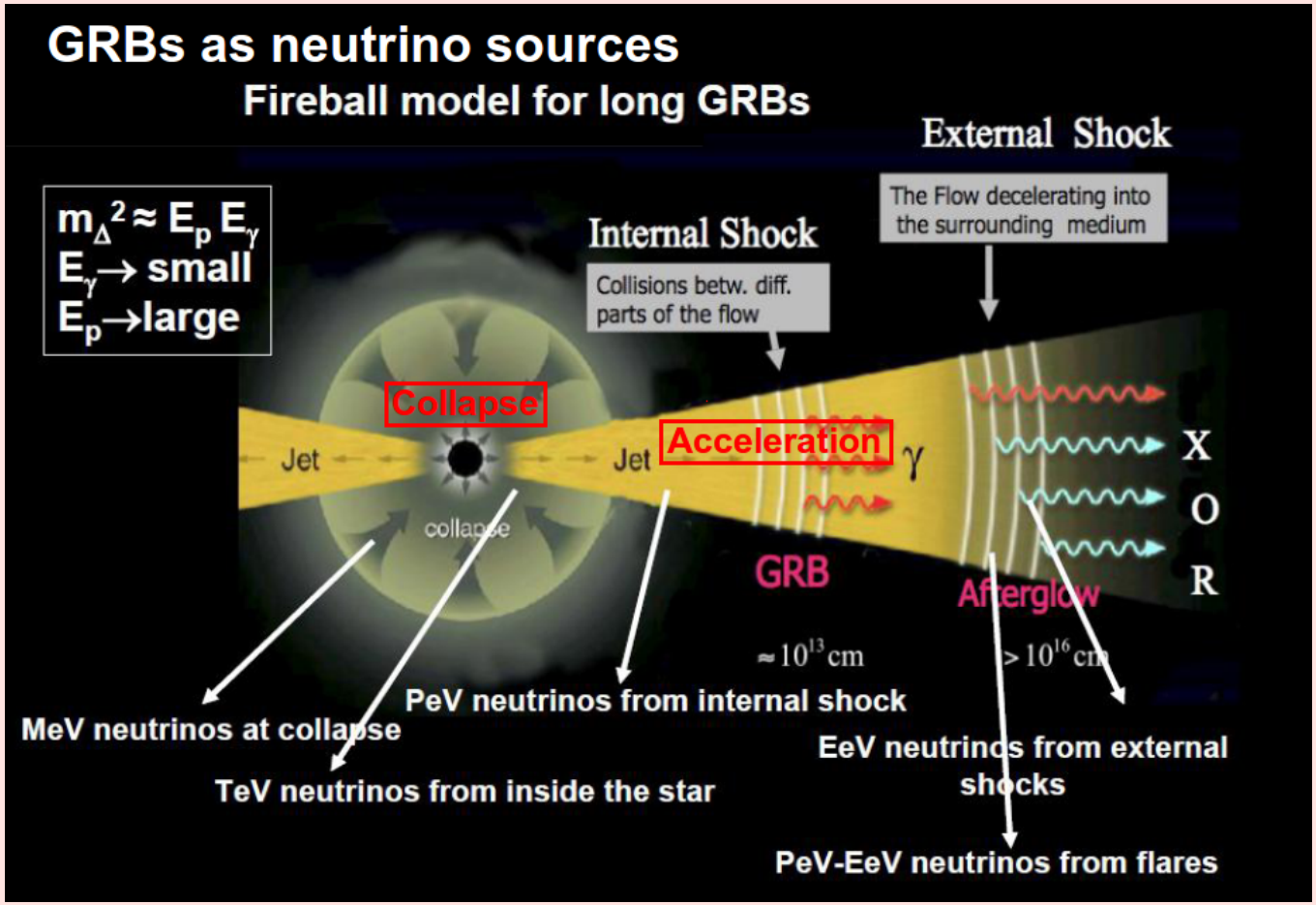


Efficiency limited by *weakest experiment*

⇒ *Equalization/optimization* of Horizons necessary...

⇒ Depends on considered Model : GW frequency, HEN spectral index...

TeV Neutrinos from mildly relativistic jets



TeV Neutrinos from mildly relativistic jets

GRBs

- $\Gamma \approx 100$
- Prompt ν emission (100 TeV)
- Prompt γ emission
- Afterglows (X, V, Radio)

CC SNe (mild jets)

- $\Gamma \approx$ few
- ν emission (100 GeV - TeV)
- No γ emission (choked)
- Afterglows

TeV Neutrinos from mildly relativistic jets

Ando & Beacom Model : *PRL 95 061103 (2005)*

- Low Γ, high baryon density
- $p - p$ collisions $\rightarrow \pi + K \rightarrow \nu$
- Parameters :
  - $E_{\rm jet} \approx 3 \times 10^{51}$ erg
  - $\Gamma \sim 3$
  - Jet opening angle $1/\Gamma \sim 0.3$ degrees
  - $t_{\rm variability} = t_v \sim 0.1$s
  - Internal shocks at $r_{\rm shock} = 2\Gamma^2 c t_v \approx 5 \times 10^8$ m
  - Jet duration $\Delta t \sim 10$ s

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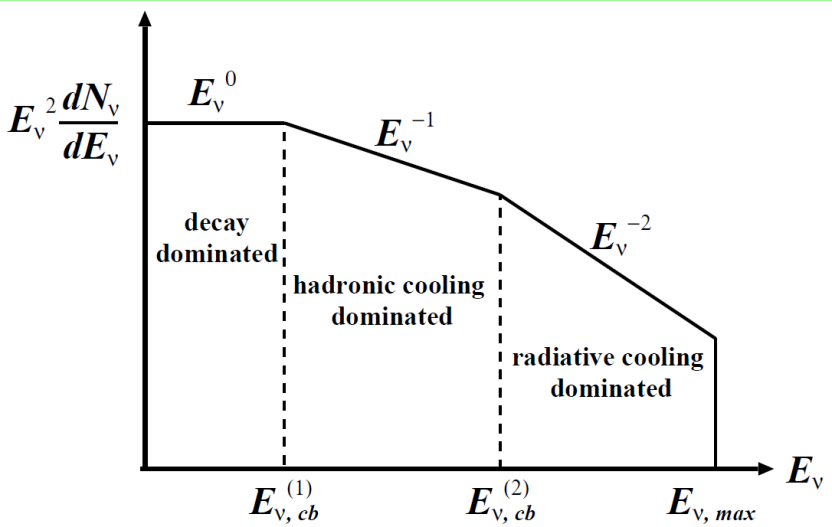

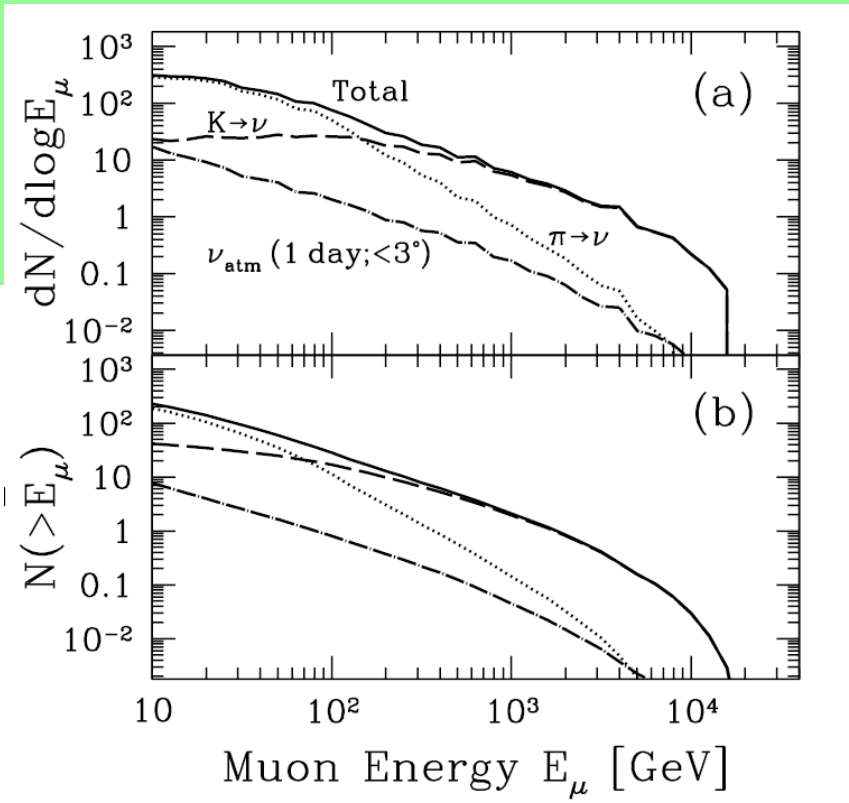

TeV Neutrinos from mildly relativistic jets

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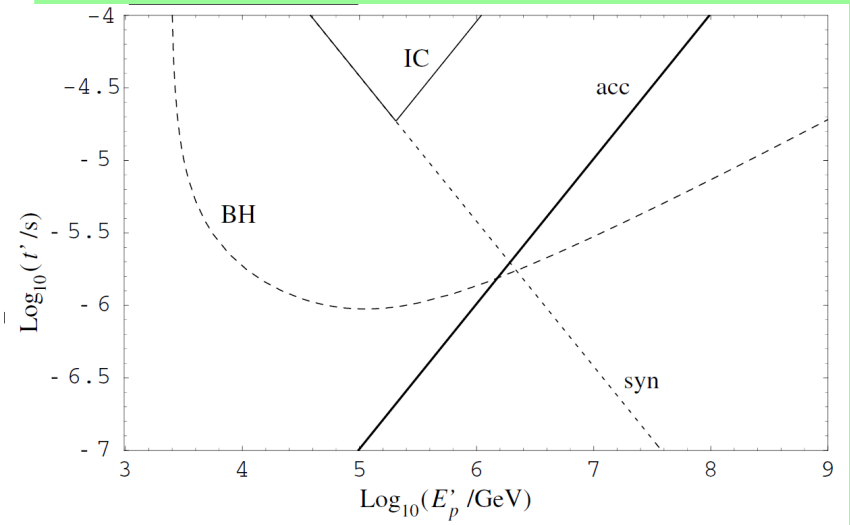


- $\tau_{\mathrm{acc}} > t_v = 0.1s$
- $\tau_{\mathrm{acc}} < \Delta t = 10s$ (jet duration)
  - $\Rightarrow$ $f_{\mathrm{GW}} \in [0.1Hz - 10kHz]$
  - $\Rightarrow$ ok for VIRGO/LIGO

Collapse and Acceleration

Collapse Horizon

- $h \propto \epsilon_{\mathrm{asym}} \frac{M_{\mathrm{collapse}} c^2}{d}$
- $d_{\mathrm{max}}(GW) \propto \epsilon_{\mathrm{asym}} M_{\mathrm{collapse}} c^2$

Acceleration Horizon

- $h \propto \frac{\Gamma E_{\mathrm{jet}}}{d}$
- $d_{\mathrm{max}}(GW) \propto \Gamma E_{\mathrm{jet}}$

HEN Horizon

- $N_\nu \propto \frac{\Gamma E_{\mathrm{jet}}}{d^2}$
- $d_{\mathrm{max}}(HEN) \propto \Gamma^{1/2} E_{\mathrm{jet}}^{1/2}$

GW+HEN Horizon determined by weakest experiment

- $d_{\mathrm{horizon}} = min\left(d_{\mathrm{max}}(HEN), d_{\mathrm{max}}(GW)\right)$
- function of :
  - $\Rightarrow$ Collapse : $\left(\epsilon_{\mathrm{asym}}, \frac{E_{\mathrm{jet}}}{M_{\mathrm{collapse}} c^2}\right)$
  - $\Rightarrow$ Acceleration : $(\Gamma, E_{\mathrm{jet}})$

Collapse and Acceleration

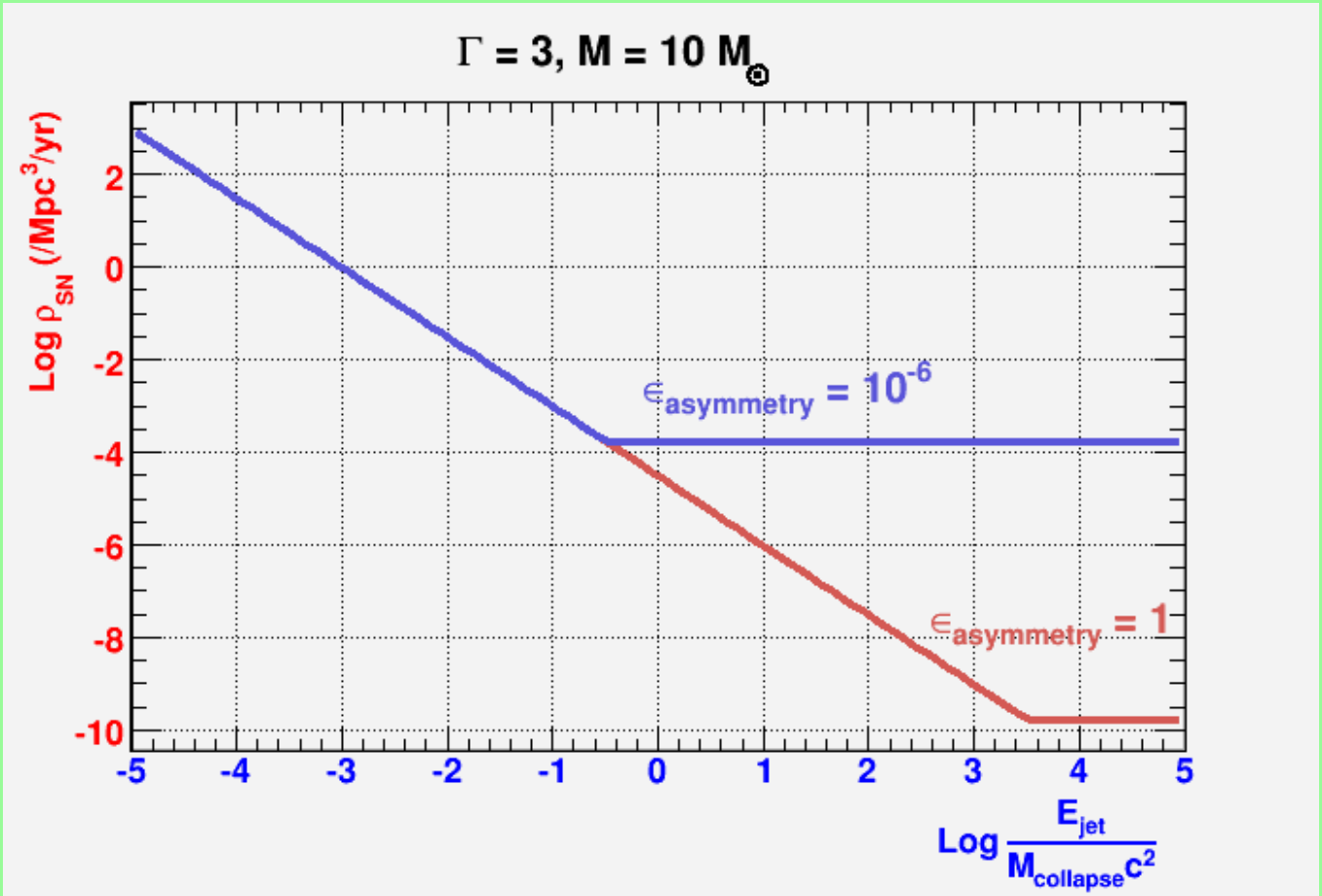
...and limits if no detection after time $T_{\mathrm{observation}}$

- No detection $\Rightarrow$ $N_{\mathbf{coinc}} \leq 2.44$ **(90% C.L.)**
- $N_{\mathrm{coinc}} = \rho_{\mathrm{SN}} \frac{4\pi}{3} d^3_{\mathrm{horizon}} T_{\mathrm{observation}}$

$$\Rightarrow \rho_{\mathbf{SN}} \leq \frac{2.44}{\frac{4\pi}{3} d^3_{\mathbf{horizon}} T_{\mathbf{observation}}}$$

With 1 year of concomittant data...

GW Signal from Collapse



- Normalization : with *canonical* param., detection up to 10 Mpc...

With 1 year of concomittant data...

The need for an equalization of horizons...