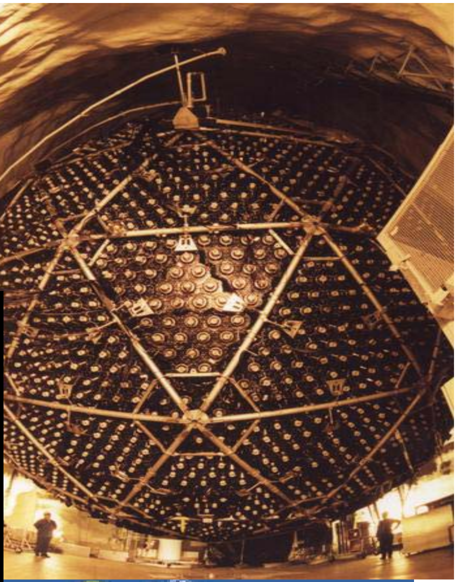
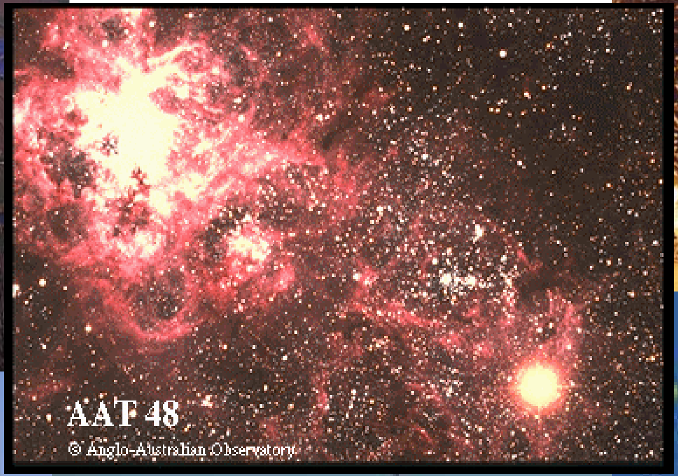
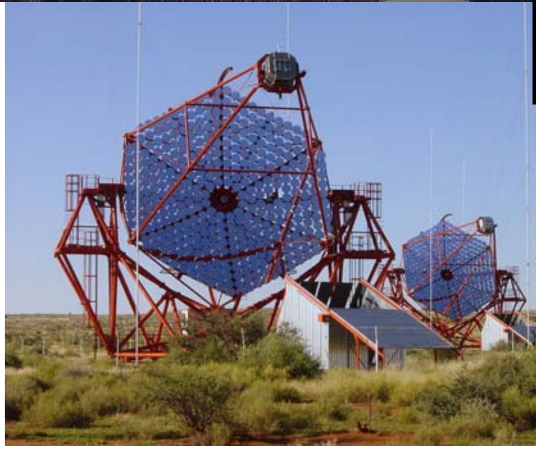
# Multi-messenger Astronomy

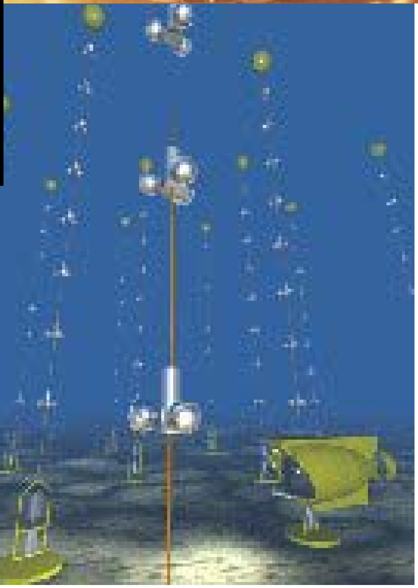
Michel DAVIER

LAL-Orsay









# General Remarks

- A vast subject and a very active field
- Multi-messengers:

  photons (radio, IR, visible, X- and $\gamma$-rays)

  protons and nuclei

  neutrinos

  a new comer: gravitational waves
- The Universe looks very different with different probes
- However: important to observe the same events

- Very selective review (focus on interplay)

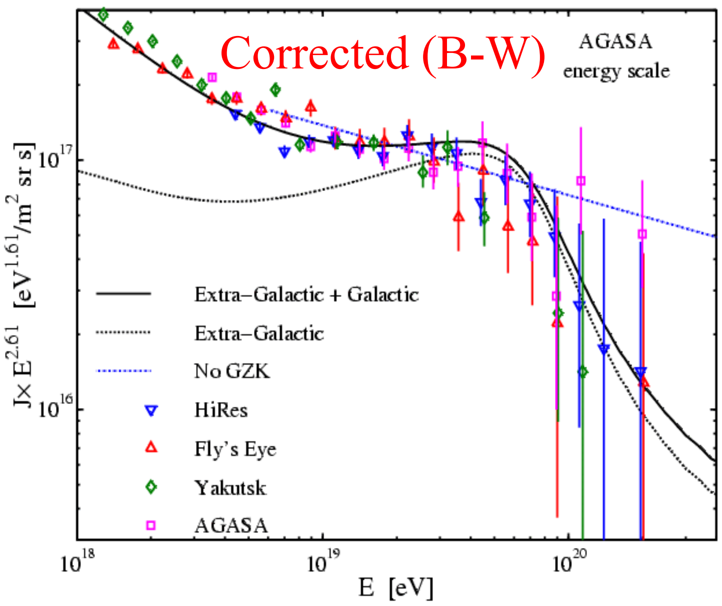
# Outline

- UHE Cosmic Rays
- $\gamma$-ray Bursts
- Investigating Dark Matter with $\gamma$-rays
- GW signals : the next galactic SN
  (a generic case)

# UHE Cosmic Rays

- Energy spectrum extends to ~ $10^{20}$ eV
- Shoulder ~ 5. $10^{19}$ eV
- Big questions:
  - Where are the accelerators ? How do they work?
  - Is the GZK cutoff seen ?

AGASA, Fly's Eye, Yakutsk, HiRes
Problem: energy scale



proton interactions with CMB photons
energy loss distance much reduced

| | |
|---|---|
| 10 Mpc | $10^{20}$ eV |
| 1 Gpc | 0.5 $10^{20}$ eV |

evidence for GZK? (Bahcall-Waxman 03)

Auger expt should settle this point
expect ~ 30 evts/yr above $10^{20}$ eV

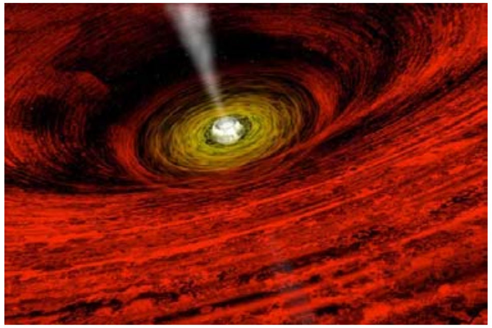
# **GRB** : Facts and Interpretation

- Short variable γ-ray bursts 0.01 – 100 s 0.1 – 1 MeV
- Isotropic distribution (BATSE)
- X-ray afterglow (BeppoSAX) ⇒ optical and radio afterglows
- Beautiful exemple of multi-wavelength approach (same messenger!)

⇒ Sources at cosmological distances

⇒ Enormous energy release ~ $10^{53}$ erg + beaming

- Strong support for fireball model (review Piran 00)



- energy source: accretion on a newly formed compact object
- relativistic plasma jet flow
- electron acceleration by shocks
- γ-rays from synchrotron radiation
- afterglows when jet impacts on surrounding medium
- still many open questions

# **GRB** : Connections

- can UHE Cosmic Rays be explained by GRB's ?

Waxman 95, Pietri 95
Milgrom-Usov 95

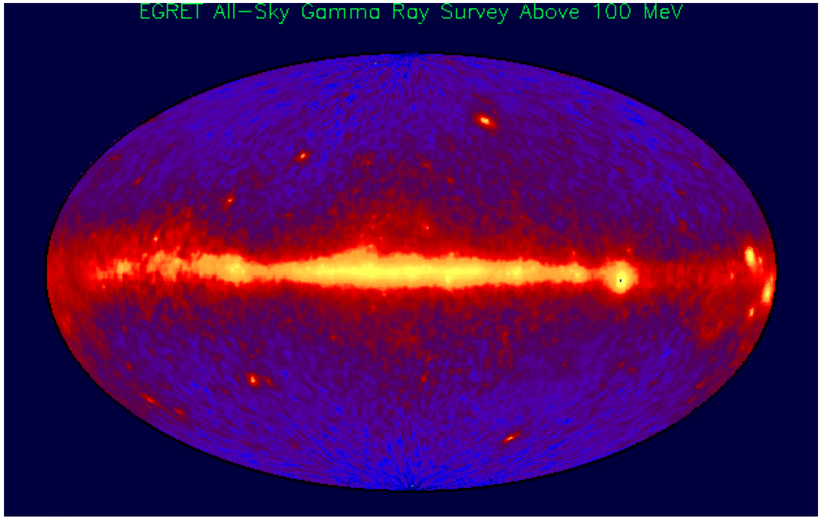
  - relativistic plasma jet can also accelerate protons to ~$10^{20}$ eV
  - constraints on jet similar for p acceleration and $\gamma$ emission (although indep.)
  - energy generation rates similar

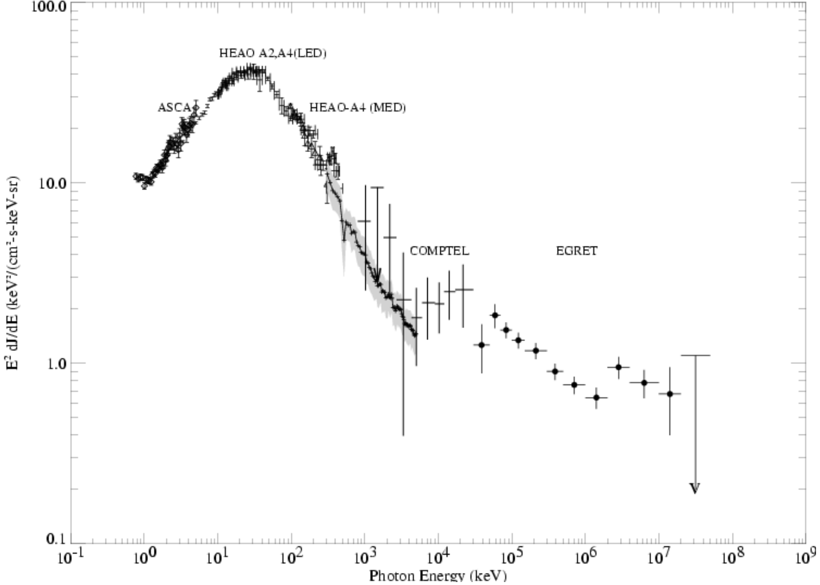
- HE neutrinos are expected
  - accelerated p interact with fireball photons and produce pions
  - $\nu_\mu$ from charged $\pi$ $\Rightarrow \nu_\mu , \nu_\tau$ on Earth $\sim E_\nu^{-2}$
  - expect 20 evts/yr in a 1 km3 detector up to $10^{16}$ eV (Waxman-Bahcall 01)
  - correlated in time and direction with GRB

- central engine also emits GW (compact object, relativistic motion)
  - scenarios to get BH+accretion disk : NS-NS, NS-BH mergers, failed SN
  - 'canonical' GW sources (inspiral → merger, collapse)
  - LIGO-Virgo only sensitive to 30 Mpc, advanced LIGO-Virgo to 400 Mpc
  - BH ringdown has a distinct signature (normal modes, damped sine GW)

# γ-ray signatures of Dark Matter (1)

## Extragalactic γ-ray background and heavy DM





Space Telescopes: EGRET → GLAST
30 MeV – 10 GeV

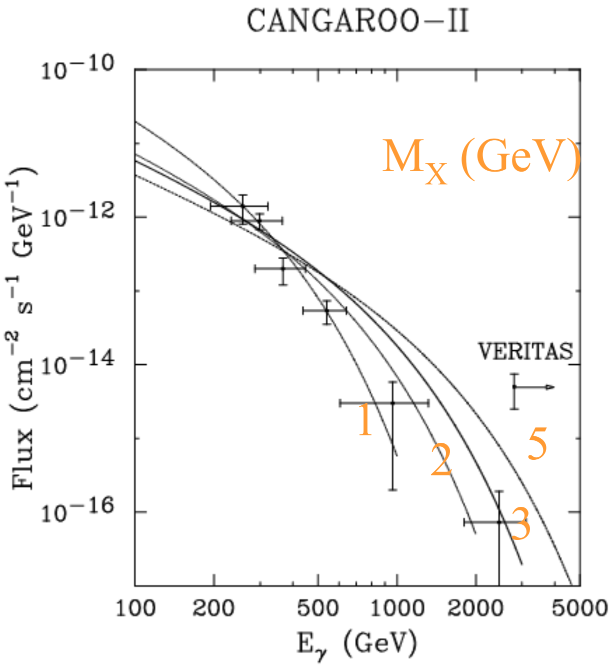
extragalactic component difficult to determine (isotropy not enough, need model of Galactic background, not firmly establihed) Strong 04
superposition of all unresolved sources (AGN)

? could the HE component result from self-annihilating DM particles (such as SUSY LSP)
Elsässer-Mannheim 04 : possibly substantial contribution if mass = 0.5 – 1 TeV, very sensitive to the DM distribution in the Universe

more conventional models work (Strong 04a)

# $\gamma$-ray signatures of Dark Matter (2)

## TeV photons from the Galactic center and heavy DM



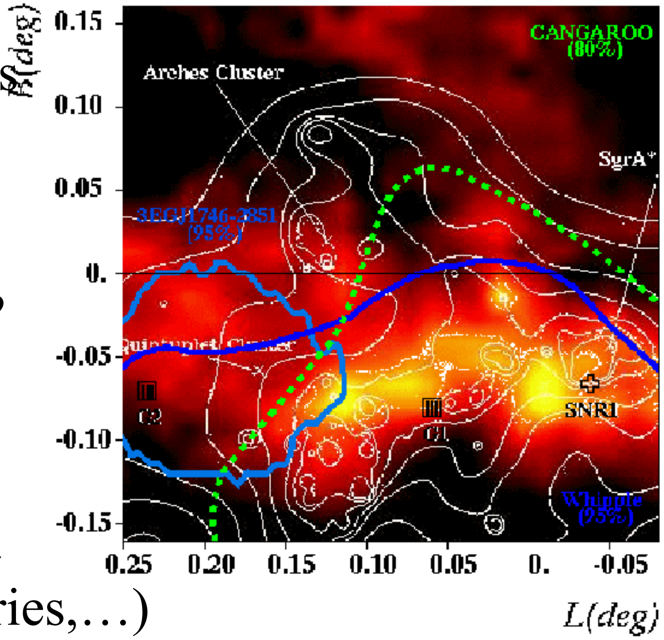
Atmospheric Cerenkov Telescopes: 200 GeV – 10 TeV
Whipple, CAT, HEGRA, VERITAS, CANGAROO II, HESS, MAGIC…

Spectrum from Galactic center: inconsistency between CANGAROO and VERITAS (quid est veritas?)

Center ($10^6$ $M_\odot$ BH) or nearby sources ?

complex region

complementary informations from X-rays and radio



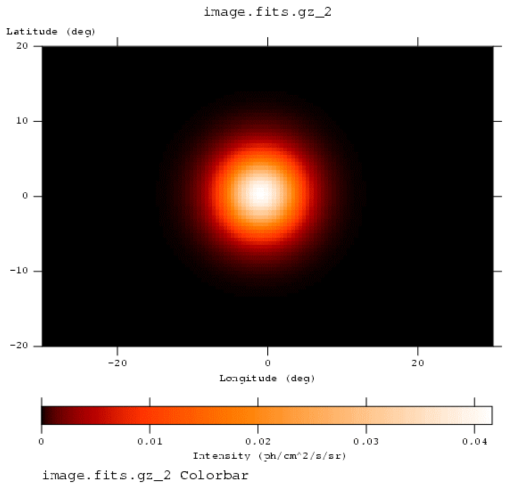
Hooper 04: self-annihilating heavy DM

$X X \rightarrow$ hadrons, $\pi^0 \rightarrow \gamma\gamma$ lines from $X X \rightarrow \gamma\gamma$, $\gamma Z$ ?

?
- need large cross sections and high densities
- very cuspy halo or spike at Galactic center
- $M_X$ : 1 TeV or 5 TeV ? waiting for HESS data
- different interpretations (SN remnants, X-ray binaries,…)

# $\gamma$-ray signatures of Dark Matter (3)

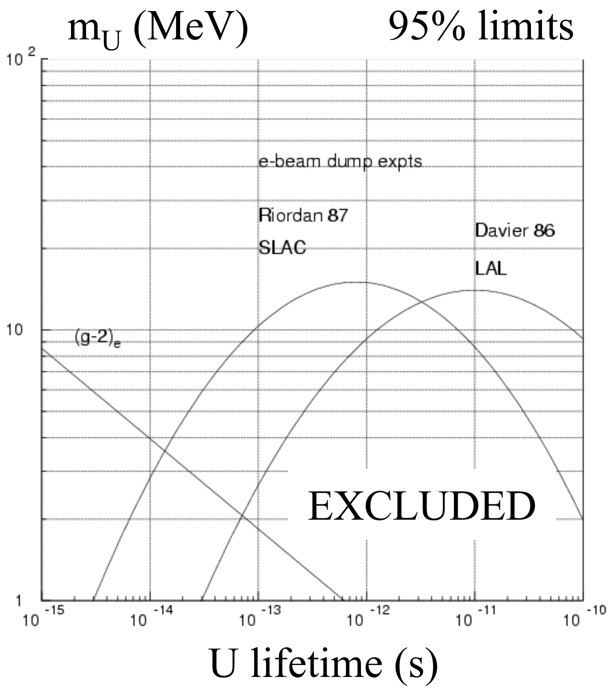
## 511 keV line from the Galactic bulge and light DM



Clear observation by SPI/INTEGRAL of a signal from $e^+e^-$ annihilation at rest in an angular range compatible with the galactic bulge, inconsistent with a single point source

What is the source of positrons ?

'standard' explanation: SN Ia with $\beta^+$ radioactivity of produced nuclei, but rate appears to be too small (Schanne 04)



Cassé 04, Fayet 04 : light DM particles

$\varphi$ spin ½ or 0 $m_\varphi \sim O(1\text{ MeV})$

coupled to a light vector boson U

$m_U \sim$ 1– 100 MeV (lower range favoured)

$\varphi\ \bar{\varphi} \rightarrow U \rightarrow e^+\ e^-$

astrophysical tests proposed

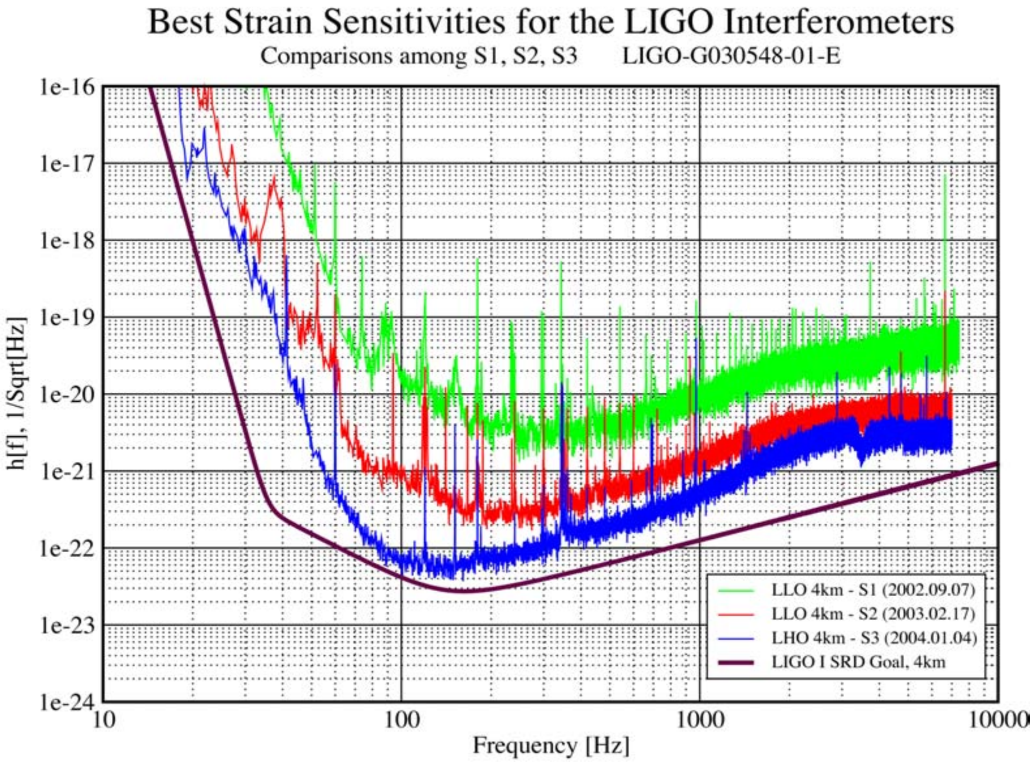
severely constrained by particle physics

# Gravity Wave Detectors

GW : quadrupolar deformation of space-time metrics

amplitude $h = \Delta L / L$ ⇒ interferometric detection well suited

Large interferometric antennas coming into operation:
TAMA (Japan), LIGO-Hanford/Livingston (US),
GEO (Germany-UK), Virgo (France-Italy)


Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1, S2, S3 LIGO-G030548-01-E

LIGO close to nominal sensitivity
Science runs started
S1 (Sept 2002)
S2 (Feb 2003)
S3 (Jan 2004)

Virgo completed and being commissioned
data taking in 2005

# Chronology of stellar collapse

- Core collapse $p\ e^- \rightarrow n\ \nu_e$ neutronization
- supernuclear densities: ‘$\nu$ sphere inside core ($\nu$ trapped)
- Shock wave bounce propagating from deep inside core

$\Rightarrow$ GW burst within a few ms

within < 1 ms shock wave passes through $\nu$ sphere

$\Rightarrow$ initial $\nu_e$ burst (flash) a few ms

- High T $e^+\ e^- \rightarrow \nu_i\ \overline{\nu}_i$ all $\nu$ types ( $e$ , $\mu$ , $\tau$ )

shock turns on release of $\nu_e$ and $\nu_i\ \nu_i$ pairs

$\Rightarrow$ main $\nu$ burst 1-10 s long

- Accretion and explosion ($\nu$ heating of shocked envelope)

$\Rightarrow$ optical signal delayed by a few hrs

# Simulation of neutrino burst

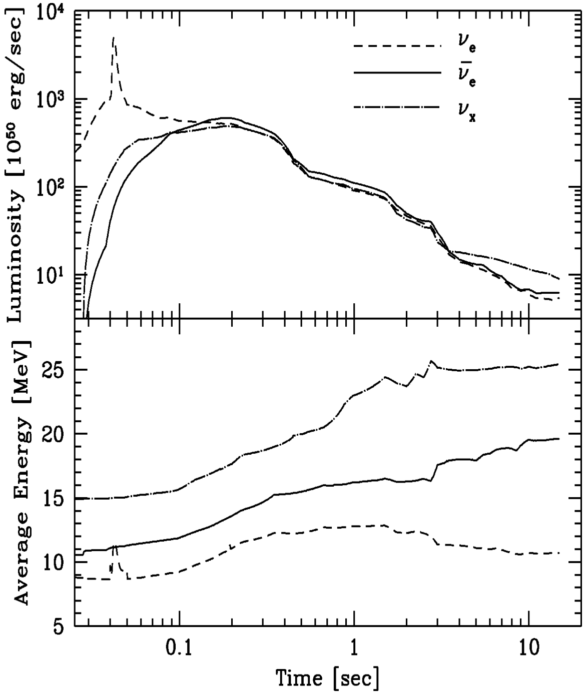
- Model-independent properties

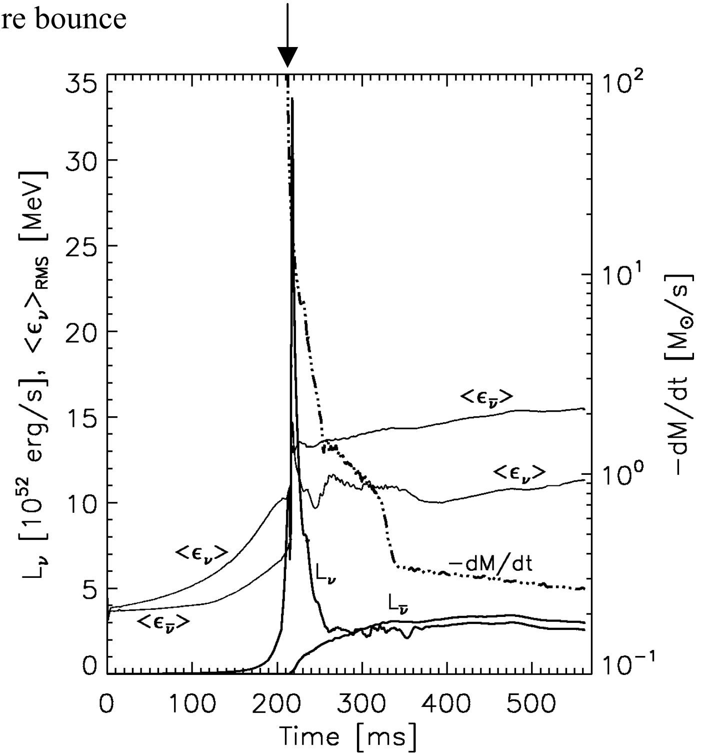
  99% of initial binding energy into ν's (1–2 % in early flash)

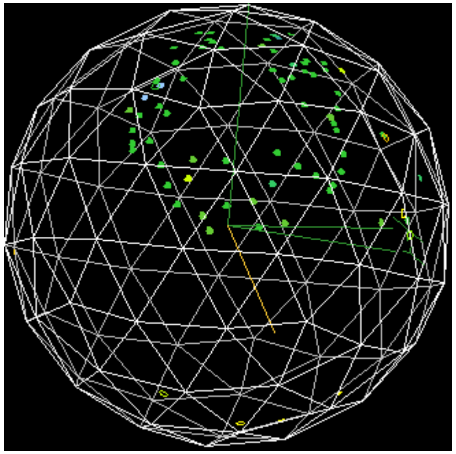
  about 3 $10^{53}$ erg released $<E_\nu> =$ 10 – 20 MeV

- Detailed numerical simulations

  Mayle, Wilson, Barrows, Mezzacappa, Janka, …..




core bounce



# Neutrino detection

best operating detectors are water Cerenkov :

SuperK (32 kt) SNO(1 kt heavy water)

- **SuperK** e± detection

| | | |
|---|---|---|
| $\nu\ e^- \rightarrow \nu\ e^-$ | directional | $E_e$ flat $0 \rightarrow E_\nu$ |
| $\bar{\nu}_e\ p \rightarrow e^+ n$ | non directional | $E_e = E_\nu - 1.77$ MeV |

- **SNO** e± and neutron (delayed) detection

| | | |
|---|---|---|
| $\nu_e\ d \rightarrow e^-\ p\ p$ | non directional | $E_e = E_\nu - 1.44$ MeV |
| $\bar{\nu}_e\ d \rightarrow e^+\ n\ n$ | | 4.03 |
| $\nu_i\ d \rightarrow \nu_i\ p\ n$ | unique | |

# Neutrino event rate (SN at 10 kpc)

| | SuperK | SNO | LVD |
|---|---|---|---|
| $\nu_e$ | 91 | 132 | 3 |
| $\bar{\nu}_e$ | 4300 | 442 | 135 |
| $\nu_\mu$ , $\nu_\tau$ | (40) | 207 | (7) |
| $\nu_e$ flash | 12 | 9 | 0.4 |
| all | 4430 | 781 | 146 |

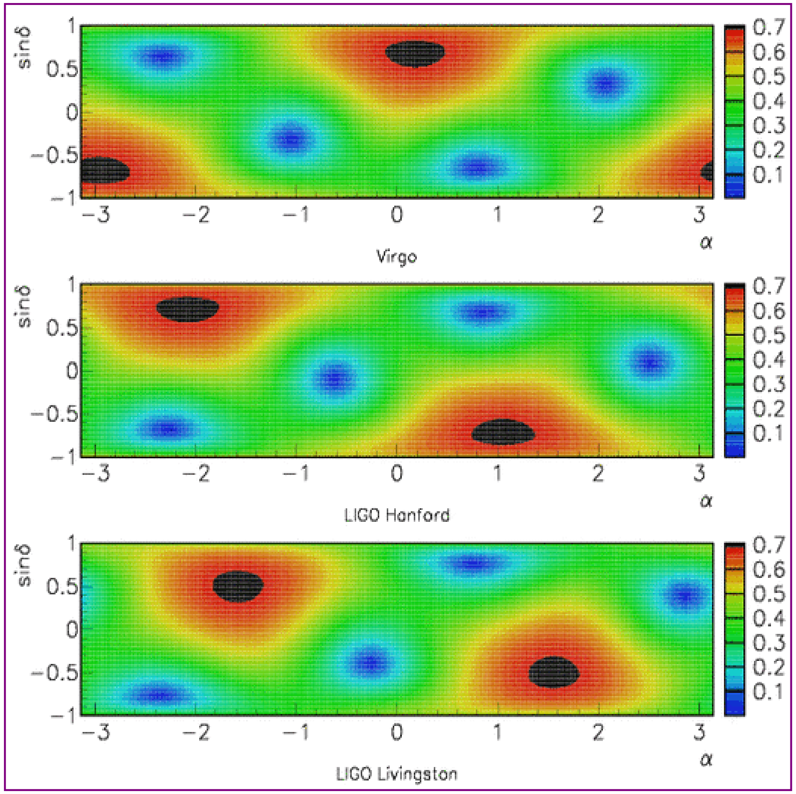
# Supernova GW detection

## (1) Expected amplitude (simulations Zwerger-Müller 97)

LIGO-Virgo

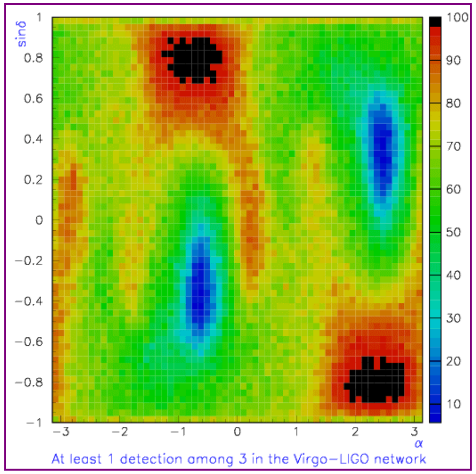
$d_{mean}$ ~ 30 kpc threshold SNR = 5 ⇒ detection limited to our Galaxy

## (2) Antenna patterns

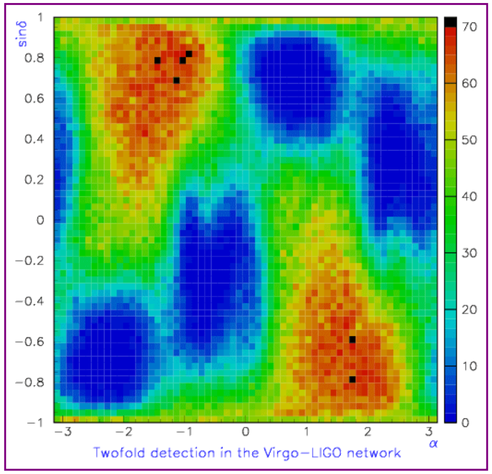


- Sky maps averaged over GW source polarization angle
- 2 LIGO interferometers mostly parallel
- Virgo nearly orthogonal to LIGO

Virgo-LIGO 1/3 2/3



At least 1 detection among 3 in the Virgo−LIGO network



Twofold detection in the Virgo−LIGO network

# The next Galactic SN : GW-ν coincidence strategy (1)

Arnaud 03

- **ν detectors**
  - several running detectors covering the Galaxy with an efficiency of 100%
  - false alarm rate negligible if at least 2 in coincidence
  - direction to ≈ 5 $^{\circ}$ ( best precision from delayed optical observation)
  - SNEWS network : alarm to astronomers + GW detectors within 30'
- **GW interferometers**
  - relatively low threshold barely covers Galaxy, but false rate too high (assuming gaussian stationary noise, not realistic, so even worse)
  - not suitable for sending alarms
  - very important to react on ν alarms (discovery of GW from SN collapse)
  - at least 2 antennas with complementary beam patterns needed for sky coverage, at least 3 to perform coincidences at reasonable efficiency

# GW-ν coincidence strategy (2)

**loose coincidence strategy**: correlate GW signals in **several** antennas without directional information (time window ± 50 ms, maximum time delay between antennas)

**tight coincidence strategy**: knowing source direction (from ν or optical), time window can be reduced to ≈ 10 ms

**coherent analysis** : knowing source direction, outputs of all interferometers can be summed with weights ∝ beam pattern functions, only one threshold on sum, tight coincidence applied with neutrinos

Two goals:

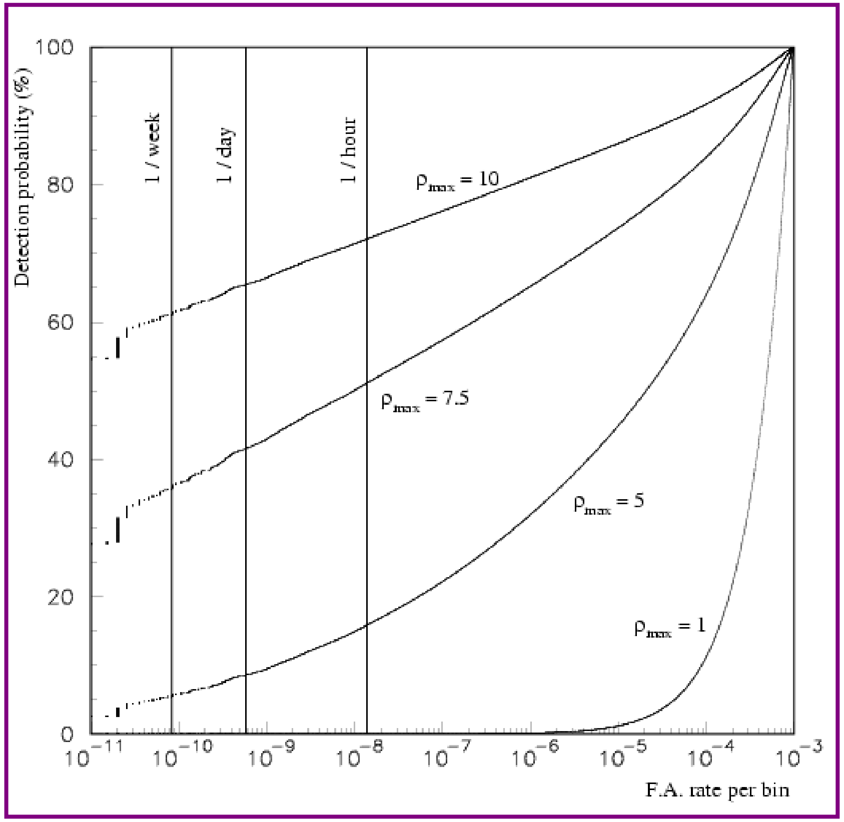
- claim the discovery of GW emission in the SN collapse : require $10^{-4}$ accidental coincidence probability in 10 ms window

- study GW signal in coincidence with neutrinos : $10^{-2}$ enough

# GW-ν coincidence strategy (3)

**LIGO – Virgo network** Arnaud 03

Detection Probability in Coherent Analysis



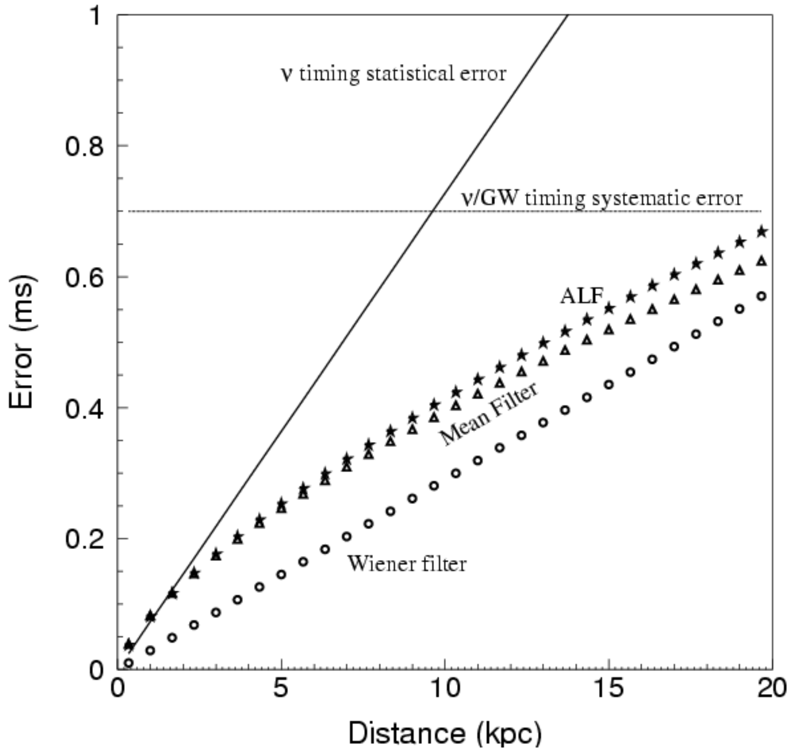
False Alarm rate in sampling bin (20 kHz)

| | Accidental coincidence in 10 ms | |
|---|---|---|
| Efficiency (%) | $10^{-4}$ | $10^{-2}$ |
| Coincidence 2/3 | 55 | 66 |
| OR 1/3 | 71 | 85 |
| Coherent | 80 | 91 |

⇒ Coherent analysis provides best efficiency for SN GW confirmation

# GW/neutrino timing

- SYST: GW peak time / bounce (0.1 ± 0.4) ms Zweiger-Muller 97
- SYST: $\nu_e$ flash / bounce (3.5 ± 0.5) ms simulations
- STAT: GW peak time accuracy < 0.5 ms depends on filtering algorithm
- STAT: $\nu_e$ flash accuracy = $\sigma_{flash} / \sqrt{N_{events}}$ with $\sigma_{flash} = (2.3 \pm 0.3)$ ms



Arnaud 02, 03

to reduce systematic uncertainty
joint simulations needed

# GW/neutrino delay

Pakvasa 72, Fargion 81, Arnaud 02

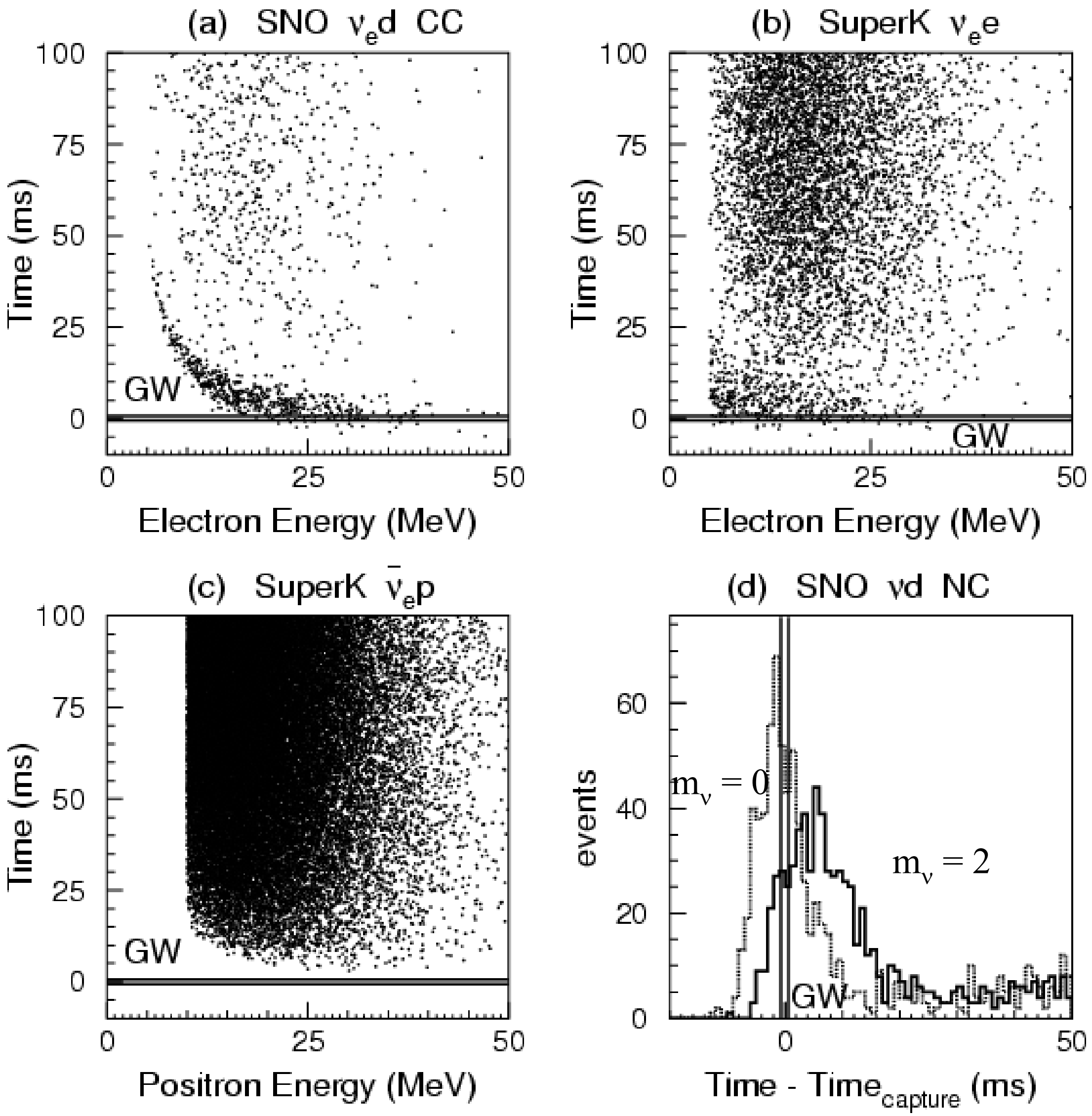
timing between the GW peak and the $\nu_e$ flash

$$\Delta t_{\nu,\,GW} = \Delta t_{prop} + \Delta t_{\nu,bounce} + \Delta t_{GW,\,bounce}$$

$$\begin{aligned}\Delta t_{prop} &= (L / 2)\,(m_\nu / E_\nu)^2 \\ &= 5.2\text{ ms}\;\; (L / 10\text{ kpc})\;\; (m_\nu / 1\text{ eV})^2\;\; (10\text{ MeV} / E_\nu)^2\end{aligned}$$

- yields $\delta m_\nu^2 \propto \Delta t / L \approx$ constant
- accuracy of $\approx$ 1 ms gives sensitivity to neutrino masses < 1 eV
- direct and absolute measurement
- if $\nu_e$ mass obtained from other exp. to a precision < 0.5 eV, then GW/$\nu_e$ timing provides unique information on bounce dynamics

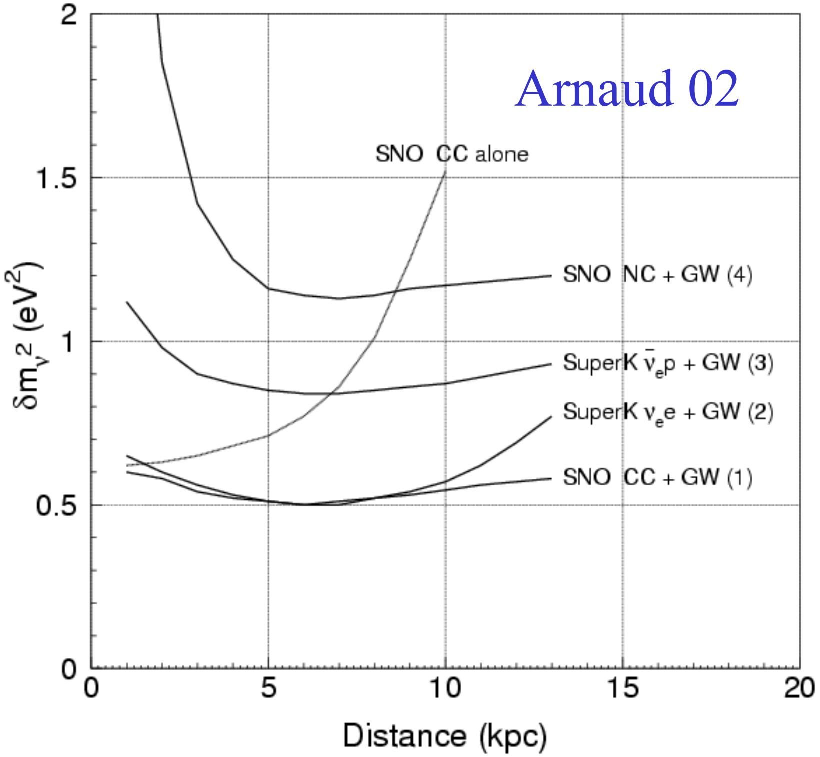
# Simulating the experiment



SN collapse at 10 kpc
statistics x100
$m_\nu$ = 2 eV

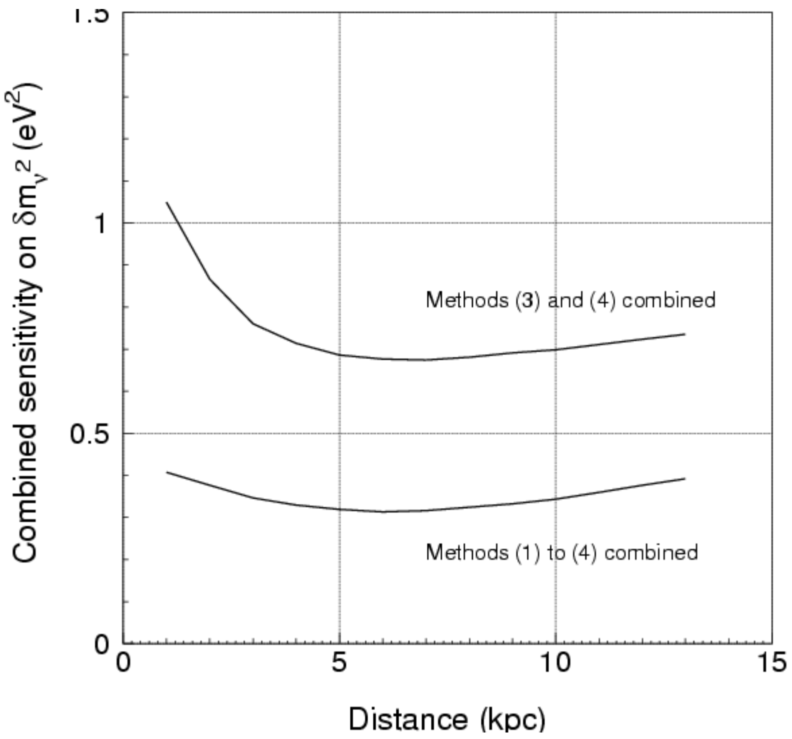
Arnaud 02

# Expected results



- methods (1,2) with $P_e = 0.5$
- method (4) when $P_e = 0$
- method (3) whatever $P_e$

- results take into account neutrino oscillations (Dighe 00)
- relevant parameter: $\nu_e$ survival probability $P_e$ ($\theta_{13}$)



# Supernova physics (1)

neutrino detection : time and energy spectra for $\nu_e$ and $\bar{\nu}_e$
time spectrum for $\nu_{\mu,\tau}$
luminosity (distance)

GW detection : timing (bounce)
amplitude

timing of neutrino pulses / bounce to better than 1 ms
if $\nu$ mass known or $< 0.5$ eV

learn about size of neutrinosphere (core opacity) and shock wave propagation velocity

# Supernova physics (2)

an interesting possibility : inner core collapse + accretion from outer mantle
$\Rightarrow$ delayed Back Hole formation $\approx$ 0.5 s

abrupt cutoff in neutrino time spectrum $\approx$ 0.5 ms

could be used as a timing signal

to observe late neutrinos, but mass sensitivity limited to 1.8 eV
(Beacom 2000)

to search for BH ringdown signal in GW antennas : could run with relatively low threshold thanks to excellent timing, matched filtering (damped sines)

observations of a sharp cutoff in the neutrino time spectrum
and a synchronized GW ringdown signal would constitute
a smoking gun evidence for BH

# Conclusions (1)

- Complementary information on astrophysical phenomena is vital
- So far only used extensively with EM signals from radio to γ-rays (ex. GRBs)
- SN 1987a : extra-solar ν signal for the first time
- Study of the most violent events (collapses, mergers) will benefit enormously from the availability of γ, UHE cosmic rays, ν and GW detectors available and under construction
- Multiwavelength approach to cover a broad range of phenomena:

| | | |
|---|---|---|
| EM | to-day's astrophysics | |
| ν | from 5 MeV to 1000 TeV | |
| GW | Ligo-Virgo 10 Hz – 10 kHz | LISA 0.1 – 100 mHz |

- Rates are small : need for large instruments
- Important to narrow the range of astrophysical interpretations

# Conclusions (2)

- A single Galactic SN event seen in coincidence in GW and ν detectors would bring unique information.
- Sky coverage requires OR-ing several antennas with complementary beam patterns.
- LIGO-Virgo network will be 80% efficient to discover GW emission by a SN seen by ν detectors with an accidental coincidence probability of $10^{-4}$ .
- Precise GW/ν timing can be achieved at better than 1 ms.
- Absolute neutrino masses can be investigated below the present lower limit of 2 eV down to 0.6 – 0.8 eV in a direct way.
- When ν masses are known from other methods or found to be smaller than 0.5 eV, relative GW/ν timing provides a new tool to investigate SN physics.
- If the SN eventually collapses into a BH, a GW/ν coincidence analysis can prove the BH formation.