Multi-messenger astronomy
M. Davier

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Multi-messenger Astronomy

Michel DAVIER
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General Remarks

• A vast subject and a very active field
• Multi-messengers:
  - photons (radio, IR, visible, X- and γ-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 $\sim 10^{20} \text{ eV}$
- Shoulder $\sim 5 \times 10^{19} \text{ eV}$
- 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

$10 \text{ Mpc} \quad 10^{20} \text{ eV}$
$1 \text{ Gpc} \quad 0.5 \times 10^{20} \text{ eV}$

Evidence for GZK? (Bahcall-Waxman 03)

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

M. Davier                Neutrino 2004
Paris 11-16       June 2004
GRB : Facts and Interpretation

• Short variable $\gamma$-ray bursts  $0.01 - 100$ s  $0.1 - 1$ MeV
• Isotropic distribution (BATSE)
• X-ray afterglow (BeppoSAX)  $\Rightarrow$ optical and radio afterglows
• Beautiful exemple of multi-wavelength approach (same messenger!)
  $\Rightarrow$ Sources at cosmological distances
  $\Rightarrow$ Enormous energy release  $\sim 10^{53}$ 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
  - $\gamma$-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 ?  
  - relativistic plasma jet can also accelerate protons to \( \sim 10^{20} \) 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 km\(^3\) 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 \( \rightarrow \) 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)
\( \gamma \)-ray signatures of Dark Matter (1)
Extragalactic \( \gamma \)-ray background and heavy DM

Space Telescopes: \( \text{EGRET} \rightarrow \text{GLAST} \)
30 MeV – 10 GeV

extragalactic component difficult to determine (isotropy not enough, need model of Galactic background, not firmly established) 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)
\textbf{γ-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

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

? - 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,…)

M. Davier Neutrino 2004
Paris 11-16 June 2004
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 $\frac{1}{2}$ or $0$  \[ m_{\varphi} \sim O(1 \text{ MeV}) \]

coupled to a light vector boson $U$

$\varphi \varphi \rightarrow U \rightarrow e^+ e^-$

astrophysical tests proposed

severely constrained by particle physics
Gravity Wave Detectors

GW: quadrupolar deformation of space-time metrics

amplitude \( h = \Delta L / L \) \( \Rightarrow \) interferometric detection well suited

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

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 \( e^+ \, e^- \rightarrow \nu_i \, \bar{\nu}_i \) 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 $\nu$’s (1–2% in early flash)
  - about 3 $10^{53}$ erg released
  - $\langle E_\nu \rangle = 10 - 20$ MeV

- Detailed numerical simulations
  - Mayle, Wilson, Barrows, Mezzacappa, Janka, …..
Neutrino detection

The best operating detectors are water Cerenkov:
- SuperK (32 kt)
- SNO (1 kt heavy water)

**SuperK**

- **$e^\pm$ detection**
  - $\nu_e e^- \rightarrow \nu_e e^-$ 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**

- **$e^\pm$ 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)

<table>
<thead>
<tr>
<th></th>
<th>SuperK</th>
<th>SNO</th>
<th>LVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>91</td>
<td>132</td>
<td>3</td>
</tr>
<tr>
<td>$\overline{\nu}_e$</td>
<td>4300</td>
<td>442</td>
<td>135</td>
</tr>
<tr>
<td>$\nu_\mu$, $\nu_\tau$</td>
<td>(40)</td>
<td>207</td>
<td>(7)</td>
</tr>
<tr>
<td>$\nu_e$ flash</td>
<td>12</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>all</td>
<td>4430</td>
<td>781</td>
<td>146</td>
</tr>
</tbody>
</table>
Supernova GW detection

(1) Expected amplitude (simulations Zwerger-Müller 97)  
\[ d_{\text{mean}} \sim 30 \text{ kpc} \quad \text{threshold SNR} = 5 \]  
\[ \Rightarrow \text{detection limited to our Galaxy} \]

(2) Antenna patterns

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

\[ \text{Virgo-LIGO} \quad 1/3 \quad 2/3 \]
The next Galactic SN: GW-ν coincidence strategy (1)

• 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° (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-\nu coincidence strategy (2)

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

**tight coincidence strategy**: knowing source direction (from \( \nu \) or optical), time window can be reduced to \( \approx 10 \text{ ms} \)

**coherent analysis**: knowing source direction, outputs of all interferometers can be summed with weights \( \propto \) 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

Accidental coincidence in 10 ms

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>$10^{-4}$</th>
<th>$10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coincidence 2/3</td>
<td>55</td>
<td>66</td>
</tr>
<tr>
<td>OR 1/3</td>
<td>71</td>
<td>85</td>
</tr>
<tr>
<td>Coherent</td>
<td>80</td>
<td>91</td>
</tr>
</tbody>
</table>

⇒ Coherent analysis provides best efficiency for SN GW confirmation

M. Davier  Neutrino 2004  
Paris 11-16  June 2004
GW/neutrino timing

- **SYST:** GW peak time / bounce \((0.1 \pm 0.4)\) ms Zweiger-Muller 97
- **SYST:** \(\nu_e\) flash / bounce \((3.5 \pm 0.5)\) ms simulations
- **STAT:** GW peak time accuracy < 0.5 ms depends on filtering algorithm
- **STAT:** \(\nu_e\) flash accuracy = \(\sigma_{\text{flash}} / \sqrt{N_{\text{events}}}\) with \(\sigma_{\text{flash}} = (2.3 \pm 0.3)\) ms Arnaud 02, 03

\[
\sigma_{\text{flash}} = (2.3 \pm 0.3)\text{ ms}
\]

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

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

$$\Delta t_{\text{prop}} = \frac{(L/2)}{(m_{\nu}/E_{\nu})^2} = 5.2 \text{ ms} \ (L/10 \text{ kpc}) \ (m_{\nu}/1 \text{ eV})^2 \ (10 \text{ MeV}/E_{\nu})^2$$

• yields $\delta m_{\nu}^2 \propto \Delta t / L \approx \text{constant}$
• 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
\(m_\nu = 2 \text{ eV}\)

Arnaud 02

M. Davier Neutrino 2004
Paris 11-16 June 2004
Expected results

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

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

⇒ delayed Back Hole formation ≈ 0.5 s

abrupt cutoff in neutrino time spectrum ≈ 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 $\gamma$-rays (ex. GRBs)
• SN 1987a : extra-solar $\nu$ signal for the first time
• Study of the most violent events (collapses, mergers) will benefit enormously from the availability of $\gamma$, UHE cosmic rays, $\nu$ and GW detectors available and under construction
• Multiwavelength approach to cover a broad range of phenomena:
  EM  to-day’s astrophysics
  $\nu$  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.