Externally Triggered GW Searches and Tests of Alternate Gravity Models

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Search Strategy Using External Triggers:

Look for gravitational wave signals associated with different astrophysical observations and extract information based on it.

Possible Sources:

• Gamma-ray bursts (GRBs) -- NS-NS (BH) mergers
• Soft gamma-ray repeaters (SGRs)
• Optical transients (Supernovae)
• Neutrino triggers
• …
Information from External Observations

- **Correlation in time:** Search within an astrophysically motivated trigger time window
- **Correlation in direction:** Search only the relevant portion of the sky or veto candidates not consistent with expected $\Delta t$
- **Correlation in frequency:** Frequency-band specific analysis of data set
- **Source Properties:** Host galaxy, distance...

- Confident detection of GWs.
- Better background rejection $\Rightarrow$ Higher sensitivity to GW signals.
- More information about the source/engine.
- Measurements made possible through coincident detection.
Gamma-ray bursts (GRBs)

Short-duration GRBs (less than ~2 s)
  • coalescing compact binaries
    e.g. neutron star—black hole merger
  • SGR flares

Long-duration GRBs
  => Supernovae

Soft Gamma Repeaters (SGRs)

Possibly highly magnetized neutron stars
  • emit short duration X- and gamma-ray bursts at irregular intervals
  • occasional giant flares (e.g. SGR1806-20, Dec 27, 2004)
    up to 15% of GRBs can be accounted for SGR flares
  • might be accompanied by catastrophic non-radial motion in stellar matter
    => Galactic SGRs may produce Gws
  • several hundred SGRs were observed during S5
Other Sources

Low Mass X-ray Binaries
Low mass star + compact object (neutron star or a black hole)
GW production => by r-modes inside the neutron star are driven by accretion

Pulsar Glitches
Disruption of neutron star's crust should excite oscillatory modes
=> might lead to emission of bursts of GWs

Neutrinos
Several astrophysical phenomena => both GWs and neutrinos
Core-collapse supernovae, binary mergers ...
Negligible absorption => travel cosmological distances
No deflection by magnetic fields => tracing back feasible
Weakly interacting => can escape from dense object
Testing Alternate GR Models with GW Observation

**Strong Field Tests**

LISA and other space observatories

- Inspiral of stellar compact objects into massive BH
  - => extreme-mass-ratio inspirals (EMRIs)

- GW s emitted by cosmological binaries

  - Chern-Simons mod gr, Brans-Dicke, Massive Graviton theories

  - DGP, Einstein-Aether Theories,

**Weak Field Tests**

Relativistic but only small corrections to Newtonian

- Not many tests exist in this regime => negligible effects...

*All tests* => *assuming coincidence in galactic distances*

  => *looking at the data within a narrow time window around the EM trigger*

What about dark matter? So what about it?
Why do we need Dark Matter?

- The missing mass problem  Zwicky (1933)
- The rotation curves of spiral galaxies  Rubin, Ford, Thonnard 1970’s
- Weak lensing to probe DM in galactic clusters  1990’s
- Bullet Cluster, WMAP power spectrum etc…  2000’s

**Rotation Curves**

*Tully–Fisher reln*: \( V^4 = \text{const} \sim L \sim M \)

\[
\Rightarrow V^2 = \text{const} \sim \sqrt{GM}
\]

*Newtonian* \(\Rightarrow \frac{GMm}{r^2} = \frac{mV^2}{r} \Rightarrow V^2 = \frac{GM}{r}\)

\[
\therefore \text{Classical theory doesn’t work!}
\]
Possible Solutions

I. Dark Matter

Isothermal Halo:

\[ \rho(r) = \frac{\rho(0)}{1 + \left(\frac{r}{a}\right)^2} \quad \text{where } a \Rightarrow \text{core radius} \]

\[ M = \rho \cdot V \Rightarrow M \sim r \quad \text{when } r \gg a \]

\[ V^2 = \frac{GM}{r} \Rightarrow \text{constant} \]

• plausible candidates: axions, wimps, sterile neutrinos…

• none yet observed for 20 years!
II. Modified Gravity Models

• **MOND, Milgrom (1983)** ➔ *designed to explain rot. curves*

\[ F = m \mu \left( \frac{a}{a_0} \right) a \]

\[ \text{where} \quad \mu(x) = \begin{cases} x & x \ll 1 \\ 1 & \text{otherwise} \end{cases} \]

\[ F = m \frac{a^2}{a_0} \Rightarrow m \frac{V^4}{a_0 r^2} = \frac{GMm}{r^2} \]

\[ \therefore V^4 = a_0 GM \quad \text{where} \quad a_0 \sim 10^{-10} m s^2 \]

• *can't explain gravitational lensing and many other cosmological events, other problems…*

• **Question**: Can we make a compare the two ?

  • *without having a (complete) relativistic formulation, no real comparison*

• **Question**: What can we do about it ?
No-Go Theorem *

Assumptions:

• gravitation force is carried by the metric, and the source is usual $T_{\mu \nu}$
• the theory of gravitation is generally covariant.
• MOND force is realized in weak field perturbation theory.
• the theory of gravitation is absolutely stable.
• E&M couples conformally to gravity

• $E_{\mu \nu} = \frac{8 \pi G}{c^2} T_{\mu \nu}$

$E_{\mu \nu}$ is not necessarily $G_{\mu \nu}$, can involve higher derivatives, nonlocal functional of $g_{\mu \nu}$

• Generally covariant $\Rightarrow g^{\rho \nu} E_{\mu ; \nu} = 0$

• $g_{\mu \nu} = \eta_{\mu \nu} + h_{\mu \nu}$

• • MOND $\Rightarrow$ significant only for small $a$, deriv. of the metric.

• • General covariance $\Rightarrow$ can choose flat metric a single point

• • Weak field limit $\Rightarrow$ small gradient $\Rightarrow$ expand around $\eta_{\mu \nu}$

$T - F$ reln $\Rightarrow V_{\infty}^2 \sqrt{a_0 G M} \quad \therefore \quad h_{\mu \nu}$ should scale like $\sqrt{G M}$

Static, spherically symmetric geometries

\[ ds^2 = -B(r) \, dt^2 + A(r) \, dr^2 + r^2 \, d\Omega^2 \]

- Geodesic \( \rightarrow \) motion along a circle

\[ \chi^\mu = \begin{pmatrix} ct \\ r = R \\ \theta = \frac{\pi}{2} \\ \varphi \end{pmatrix} \]

geodesic equations:

\[ \ddot{\chi}^\mu + \Gamma^\mu_{\rho \sigma} \, \dot{\chi}^\rho \, \dot{\chi}^\sigma = 0 \]

\( \mu = t \), \( \mu = \theta \) gives tautologies

\( \mu = \varphi \Rightarrow \dot{\varphi} = \text{const} \)

\( \mu = r \Rightarrow \ddot{\chi}^r + \Gamma^r_{tt} \, (c \, \dot{t})^2 + \Gamma^r_{\varphi \varphi} \, (\dot{\varphi})^2 = 0 \)

\[ \Rightarrow \quad \frac{B'}{2A} \, c^2 \, \dot{t}^2 = \frac{r}{A} \, \dot{\varphi}^2 \quad \Rightarrow \quad \text{A factors out!} \]

\[ \therefore \quad \left( \frac{d \varphi}{dt} \right)^2 = \frac{B'}{2r} \, c^2 \]
The first three assumptions have led us:

\[ T_{\mu\nu} \sim M \text{ at least one comp.} \quad E_{\mu\nu}[\eta + h] \sim h^2 \]

- **Question:** Which components?

- **All components?**

\[ T_{\mu\nu} = - \frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g_{\mu\nu}} \quad H \sim h^3 \quad \Rightarrow \text{unstable} \]

- **The theory of gravitation is absolutely stable.**

- **Some components, but which (should obey gen. coord. inv.)?**

**Thm:** A sym. 2\(^{rd}\) rank tensor field contains two distinguished subsets:

i) divergence ii) trace

- can’t be div. zero to all orders \( g^{\rho\nu} E_{\mu\rho;\nu} = 0 \)

- **Answer:** The trace
Result:

\[ T - F \text{ relation imposes } g^{\mu \nu} E_{\mu \nu} [\eta + h] \sim O(h^2) \]

\[ \therefore \text{ Linearized field equations are traceless} \]

• But that’s bad news!

• traceless metric field equations \( \rightarrow \) conformal invariance

• E&M couples conformally to gravity

\[
L = -\frac{1}{4} F_{\mu \nu} F_{\rho \sigma} g^{\mu \rho} g^{\nu \sigma} \sqrt{-g} \quad g_{\mu \nu} \Rightarrow \Omega^2 \ g_{\mu \nu}
\]

• photons are unaware of MOND

Conclusion:

No-Go theorem: If all the assumptions are correct MOND can’t give enough lensing.

Question: Which assumption is incorrect?
**Question:** Which assumption is incorrect?

- **Answer:** 1\textsuperscript{st} one → Multiple metric formulations (e.g. TeVeS)

  **TeVeS**  
  Bekenstein (2004)

  - gravitational waves and matter follow different metrics: \( g_{\alpha \beta} \) and \( \gamma_{\alpha \beta} \)
  
    \[
    \gamma_{\alpha \beta} = e^{-2\phi}(g_{\alpha \beta} + A_\alpha A_\beta) + e^{2\phi} A_\alpha A_\beta
    \]

  - non-relativistic MOND limit \( \checkmark \)
  - post Newtonian parameters \( \checkmark \)
  - structure formation \( \checkmark \)

  **TeVeS is just one example of the class of models that we are considering!**

**Dark Matter Emulators:** All the alternate gravity models which give both the gravitational lensing and the rotation curves right to agree with DM+GR without dark matter.
Static, spherically symmetric geometries

\[ ds^2 = -B(r)\, dt^2 + A(r)\, dr^2 + r^2\, d\Omega^2 \]

- Geodesic \( \rightarrow \) motion along a circle

\[
\chi^\mu = \begin{pmatrix} ct \\ r = R \\ \theta = \frac{\pi}{2} \\ \varphi \end{pmatrix}
\]

geodesic equations: \( \ddot{\chi}^\mu + \Gamma^\mu_{\rho\sigma} \, \dot{\chi}^\rho \, \dot{\chi}^\sigma = 0 \)

\( \mu = t, \mu = \theta \) gives tautologies

\( \mu = \varphi \Rightarrow \dot{\varphi} = \text{const} \)

\[ \mu = r \Rightarrow \ddot{\chi}^r + \Gamma^r_{tt} \, (ct)^2 + \Gamma^r_{\varphi\varphi} \, (\dot{\varphi})^2 = 0 \]

\[ \Rightarrow \frac{B'}{2A} \, c^2 \, \dot{t}^2 = \frac{r}{A} \, \dot{\varphi}^2 \]

\[ \therefore \left( \frac{d\varphi}{dt} \right)^2 = \frac{B'}{2r} \, c^2 \]

\( \cdot \) A factors out!
How to mimic DM?

\[ G_{rr} \propto T_{rr} = 0 \quad \text{for DM fixes } A(r) \; ; \quad G_{tt} = \frac{8\pi G}{c^2} \rho \quad \text{fixes } B(r) \text{as well} \]

\[
\begin{align*}
  ds^2 &= -\left[1 - \frac{2GM}{c^2 r} + \frac{2V_\infty^2}{c^2} \ln\left(\frac{r}{r_s}\right)\right]c^2 dt^2 + \left(1 + \frac{2GM}{c^2 r} + \frac{2V_\infty^2}{c^2}\right)dr^2 + r^2 d\Omega^2 \\
  ds^2 &= -c^2 dt^2 + d\tilde{x} \cdot d\tilde{x} + \frac{2GM}{c^2 r} (c^2 dt^2 + dr^2) + \frac{2V_\infty^2}{c^2} \left(\ln\left(\frac{r}{r_s}\right)c^2 dt^2 + dr^2\right) \\
  &= -c^2 dt^2 + d\tilde{x} \cdot d\tilde{x} + \varepsilon' (c^2 dt^2 + dr^2) + \varepsilon \left(\ln\left(\frac{r}{r_s}\right)c^2 dt^2 + dr^2\right) \\
  &= \eta_{\mu\nu} dx^\mu dx^\nu + \Delta' g_{\mu\nu} dx^\mu dx^\nu + \Delta g_{\mu\nu} dx^\mu dx^\nu \\
\end{align*}
\]

\[
\text{where } \varepsilon \equiv \frac{2V_\infty}{c^2} \quad , \quad \varepsilon' \equiv \frac{2GM}{c^2 r}
\]
Time Lag Calculation

Geodesic Equations: \[ \ddot{\chi}^\mu + \Gamma^\mu_{\rho\sigma} \chi^\rho \chi^\sigma = 0 \]

For isothermal halo model:

\[ \Delta t = \frac{\epsilon \Delta x}{c} \left[ 1 + \frac{\alpha}{2} \ln \left( \frac{r_L}{r_S} \right) - \sqrt{\beta - \alpha^2} \tan^{-1} \left( \frac{\sqrt{\beta - \alpha^2}}{\beta + \alpha} \right) \right] \]

\[ \alpha \equiv \frac{\vec{x}_L \cdot \Delta \vec{x}}{\Delta x^2} \quad \text{and} \quad \beta \equiv \frac{r_L^2}{\Delta x^2} \]

\[ r_S = 8.0 \, \text{kpc} \quad , \quad r_L = 50.9 \, \text{kpc} \quad , \quad \Delta x = 51.4 \, \text{kpc} \]

\[ \Rightarrow \quad \alpha = -0.9775 \quad , \quad \beta = 0.9793 \]

\[ \Delta t \bigg|_{SN1987a} = -78 \, \text{days} \]

Conclusion:

Neutrinos from 1987A should arrive 78 days later than the gravitational waves and one can calculate the time lag for a source in MW galaxy analytically for isothermal halo model.
Time Lag Calculations (SN1987A, GRB 070201, Sco-X1)

- SN’s: Potential sources of gravitational waves
- GRB 070201: short hard gamma-ray burst
  ➔ mergers of two neutron stars or a neutron star and a black hole.
- Sco-X1 (2.8 kpc)
  ➔ one of the brightest Low Mass X-ray Binaries (LMXBs).

- Calculations were done using isothermal halo model, NFW and Moore99 and the effect of choosing different halo models was investigated.

- The time lags can only be calculated numerically for NFW and Moore profiles unlike simple isothermal halo model.

- One would naturally expect the neutrinos/photons to arrive later than the gravitational waves.

Conclusion:

Gravitational Waves should have arrived 2 years earlier than the optical pulse and 2 months for 1987A and five days for Sco-X1.
GRB 070201 – Sky Location

R.A. = 11.089 deg,
Dec = 42.308 deg

\[ D_{\text{M31}} \approx 770 \text{ kpc} \]

Possible progenitors for short GRBs:

• NS/NS or NS/BH mergers
  Emits strong gravitational waves

• SGR
  May emit GW but weaker

\[ E_{\text{iso}} \approx 10^{45} \text{ ergs} \]

if at M31 distance

(more similar to SGR than GRB energy)
Exercise matched filtering techniques for inspiral waveform search.

No plausible gravitational waves identified.

Exclude compact binary progenitor with masses

\[ 1 \, M_\odot < m_1 < 3 \, M_\odot \text{ and } 1 \, M_\odot < m_2 < 40 \, M_\odot \] with \( D < 3.5 \, \text{Mpc} \) at 90% CL.

Exclude any compact binary progenitor in our simulation space at the distance of M31 at > 99% confidence level.


Why did we choose this GRB?
• Shapiro Delays for GRB 070201 from the Isothermal Profiles of the Milky Way ($\Delta t_{MW}$) and Andromeda ($\Delta t_{M31}$) at the central value of the angular position and at the four vertices of the error box. In all cases the distance to the burst was taken to be 780 kpc.

<table>
<thead>
<tr>
<th>Profile</th>
<th>GRB 070201</th>
<th>SN 1987a</th>
<th>Sco–X1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal</td>
<td>742 days</td>
<td>78.2 days</td>
<td>4.98 days</td>
</tr>
<tr>
<td>NFW</td>
<td>804 days</td>
<td>74.8 days</td>
<td>4.88 days</td>
</tr>
<tr>
<td>Moore</td>
<td>811 days</td>
<td>74.5 days</td>
<td>4.97 days</td>
</tr>
</tbody>
</table>

• The time delays for three dark matter profiles.

<table>
<thead>
<tr>
<th>R. Ascension</th>
<th>Declination</th>
<th>$\Delta t_{MW}$</th>
<th>$\Delta t_{M31}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>00h 44m 32s</td>
<td>42° 14’ 21”</td>
<td>407 dy</td>
<td>335 dy</td>
</tr>
<tr>
<td>00h 46m 18s</td>
<td>41° 56’ 42”</td>
<td>407 dy</td>
<td>337 dy</td>
</tr>
<tr>
<td>00h 41m 51s</td>
<td>42° 52’ 08”</td>
<td>407 dy</td>
<td>322 dy</td>
</tr>
<tr>
<td>00h 42m 47s</td>
<td>42° 31’ 41”</td>
<td>407 dy</td>
<td>330 dy</td>
</tr>
<tr>
<td>00h 47m 14s</td>
<td>41° 35’ 35”</td>
<td>407 dy</td>
<td>338 dy</td>
</tr>
</tbody>
</table>
• The time delay as a function of radial distance from Earth

• Time lag as a function of the angle of a source located at 400 Mpc.
Any uncertainty in the calculation?

The time lag depends almost linearly on the total dark matter of the galaxy that we consider.

=> Investigate other simulations for DM profiles of MW and M31

<table>
<thead>
<tr>
<th>Data Set</th>
<th>( \rho (GeV/cm^3) )</th>
<th>( M_{\text{vir}} (M_\odot) )</th>
<th>( \Delta t (\text{days}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW – Klypin [39]</td>
<td>0.185</td>
<td>( 1.0 \times 10^{12} )</td>
<td>426</td>
</tr>
<tr>
<td>MW – Ascasibar [41]</td>
<td>0.347</td>
<td>( 1.0 \times 10^{12} )</td>
<td>421</td>
</tr>
<tr>
<td>M31 – Klypin [39]</td>
<td>0.188</td>
<td>( 1.6 \times 10^{12} )</td>
<td>634</td>
</tr>
<tr>
<td>M31 – Tempel [42]</td>
<td>0.661</td>
<td>( 1.0 \times 10^{12} )</td>
<td>383</td>
</tr>
</tbody>
</table>

The mass of M31 is much bigger in Klypin et al.

=> huge increase in the time lag (as expected)

What is going on with the DM numerical simulation people?
Different! Mass estimates of MW and M31

<table>
<thead>
<tr>
<th>M31</th>
<th>$M_{\text{tot}}(10^{12}M_\odot)$</th>
<th>Milky Way</th>
<th>$M_{\text{tot}}(10^{12}M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corteau [43]</td>
<td>$1.33^{+0.18}_{-0.18}$</td>
<td>Xue [48]</td>
<td>$1.0^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>Evans [44]</td>
<td>$1.23^{+1.8}_{-0.6}$</td>
<td>Smith [49]</td>
<td>$1.42^{+1.14}_{-0.54}$</td>
</tr>
<tr>
<td>Fardal [45]</td>
<td>$0.74^{+0.12}_{-0.12}$</td>
<td>Wilkinson [50]</td>
<td>$1.9^{+3.6}_{-1.7}$</td>
</tr>
<tr>
<td>Seigar [46]</td>
<td>$0.73^{+0.02}_{-0.02}$</td>
<td>Sakamoto [51]</td>
<td>$1.8^{+0.4}_{-0.7}$</td>
</tr>
<tr>
<td>Ibata [47]</td>
<td>$0.75^{+0.25}_{-0.13}$</td>
<td>Battaglia [52]</td>
<td>$1.5^{+0.2}_{-0.2}$</td>
</tr>
</tbody>
</table>

TABLE II: Different mass estimates of the Milky Way and the Andromeda with the corresponding error bars.

a very long road ahead...
Observational Prospects for future SN’s

Neutrinos

• We have already detected neutrinos from 1987A with Kamiokande-II and Irvine-Michigan-Brookhaven detectors.

• Super-Kamiokande, Sudbury Neutrino Observatory (SNO+), Kam-LAND and LVD (Italy)

Gravitational Waves

• amount of GW from SN → oblateness of it from spherical symmetry

• Current detectors → can’t detect sun-like stars

• Advanced LIGO certainly will (SN 1987A type explosions)

• LIGO should have observed GRB 070201 bh ns or bh bh mergers.

• Same calculation can be done for SGR 1806-20 (6 to 15 kpc range) was not observed by LIGO or other detectors

Other possibilities

• Light can also be used instead of neutrinos

• will get the effect but not the precision.
CONCLUSIONS

• Externally triggered GW search is a very powerful method for observation.

• Possible sources: GRBs, Soft Gamma Repeaters, Neutrinos, Low Mass X-Ray Binaries ...

• GW Observation => decisive tests for alternate gravity models.

• Modifying GR to do away with dark matter => multiple metric formalisms (to explain T-F Reln. & Weak lensing).

• This gives rise to, even at this stage, a doable test of them.

• If MOND is correct neutrinos from SN 1987A should arrive 2 months after the gravitational waves and almost 2 years for GRB 070201.

• Huge uncertainty in mass of MW and M31 Numerical simulations estimates. => we need to wait for some time...
• Not being able to reveal any coincident GW and EM pulse
  => MOND is right? Obviously premature to proclaim
  But if plausible sources continue to produce null results? Maybe...

• Not fair to compare a non-rel model with DM

• Problems with TeVeS (one of the first proposed formulations)?
  - Sure! bullet cluster, third peak in the power spectrum...
    but what about the Dark (Matter) side?
    (just seen the numerical side...)

• Komatsu et al. (just released the WMAP-7 Year Results arXiv:1001.4538)
  “It is concluded that the existence of 1E0657-56 (Bullet Cluster) is incompatible with the prediction of a LCDM model”
Some Useful References

• “Decadal Survey Whitepaper: Coordinated Science in the Gravitational and EM Skies” Bloom et al., arXiv:0902.1527

• “Finding and Using Counterparts of GW Sources”, Phinney et al., arXiv:0903.0098

• “Multimessenger astronomy with the Einstein Telescope” Marka et al., arXiv:1004.1964

• “Reduced time delay for gravitational waves with dark matter emulators” Desai et al., arXiv:0804.3804

• “Constraining the mass of the graviton using coalescing black-hole binaries” Keppel et al., arXiv:1004.0284

• “Parametrized tests of post-Newtonian theory using Advanced LIGO and ET” Mishra et al., arXiv:1005.0304

• “A Useful guide for gravitational wave observers to test modified gravity models” E.O. Kahya, arXiv:1001.0725