Galactic Shapiro delay for Gravitational waves

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Based on : **arXiv:0705.0153** E.O. Kahya and R.P. Woodard,

*** arXiv:0801.1984**, **arXiv:1001.0725** E.O. Kahya

*** arXiv:0801.3804** S. Desai, E.O. Kahya and R.P. Woodard

*** arXiv:1510.08228, arXiv:1602.04779** S. Desai, E.O. Kahya

Summary

Idea: Using Shap Delay to test GR + DM

Why do we need DM?

Possible solutions to missing mass problem

  DM vs MOND

General class of relativistic multiple metric formulations of MOND

Weak field tests of GR + DM & DM Alternatives

Shapiro delay calculations for various sources

Conclusions

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

$$Tully - Fisher\ reln: V^4 = const \sim L \sim M$$

$$\Rightarrow V^2 = const \sim \sqrt{GM}$$

$$Newtonian \Rightarrow \frac{GMm}{r^2} = \frac{mV^2}{r} \Rightarrow V^2 = \frac{GM}{r}$$

- *Classical theory doesn't work !*

Rotation Curves

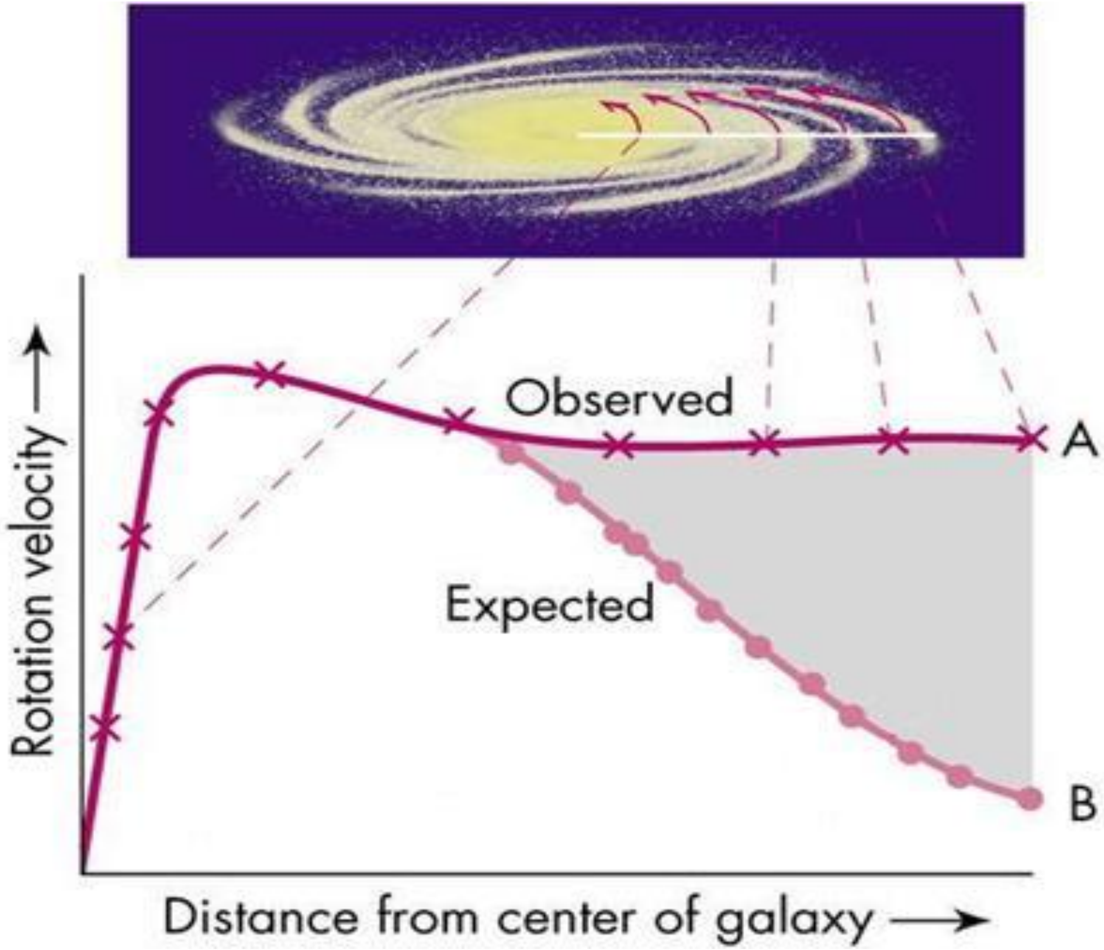


Figure: Rotation curve of a galaxy.

Expected: Velocity that is inverse to the square of the distance.

Actual: Measurements find that the rotation curve is almost flat.

Real Data

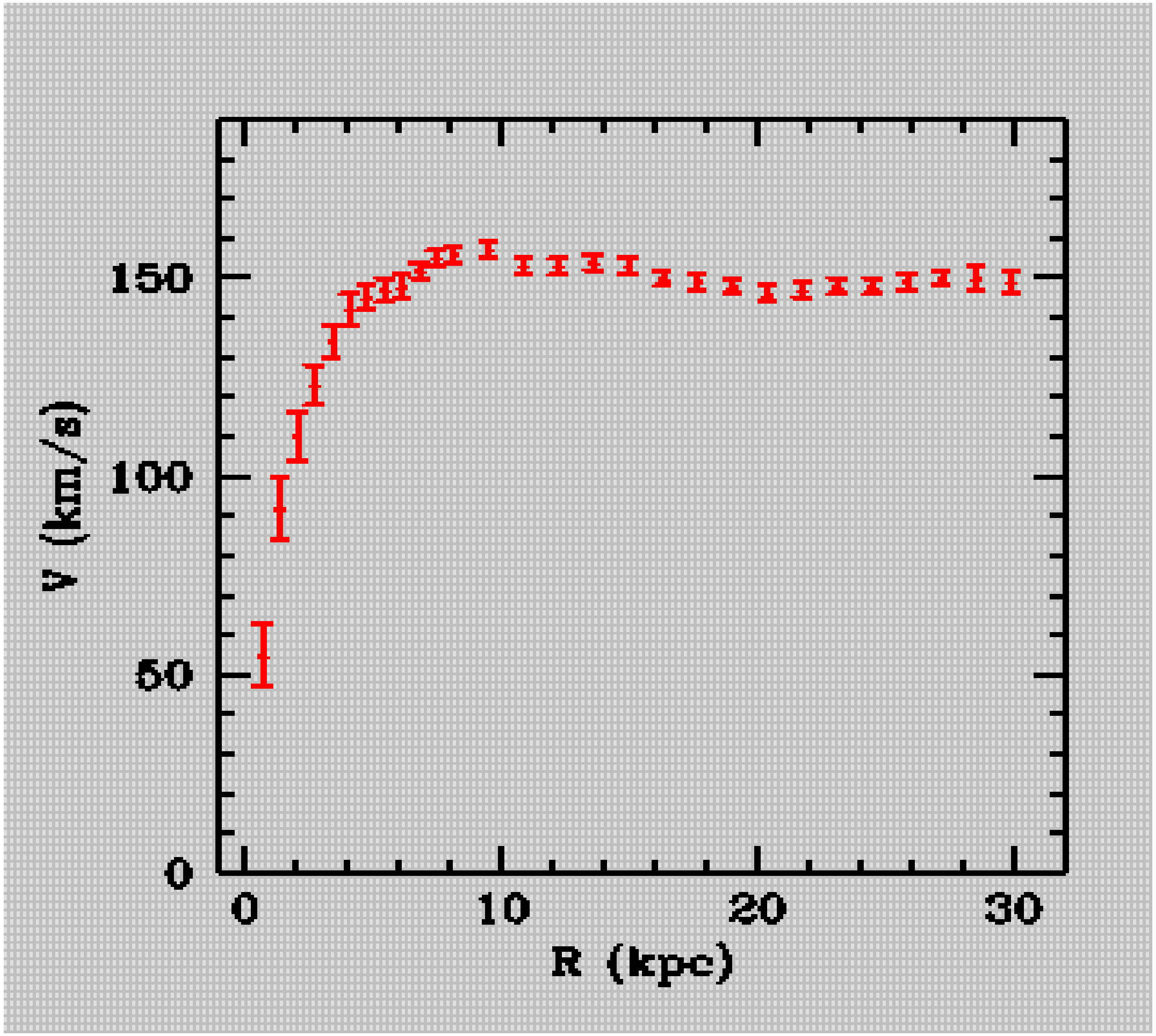
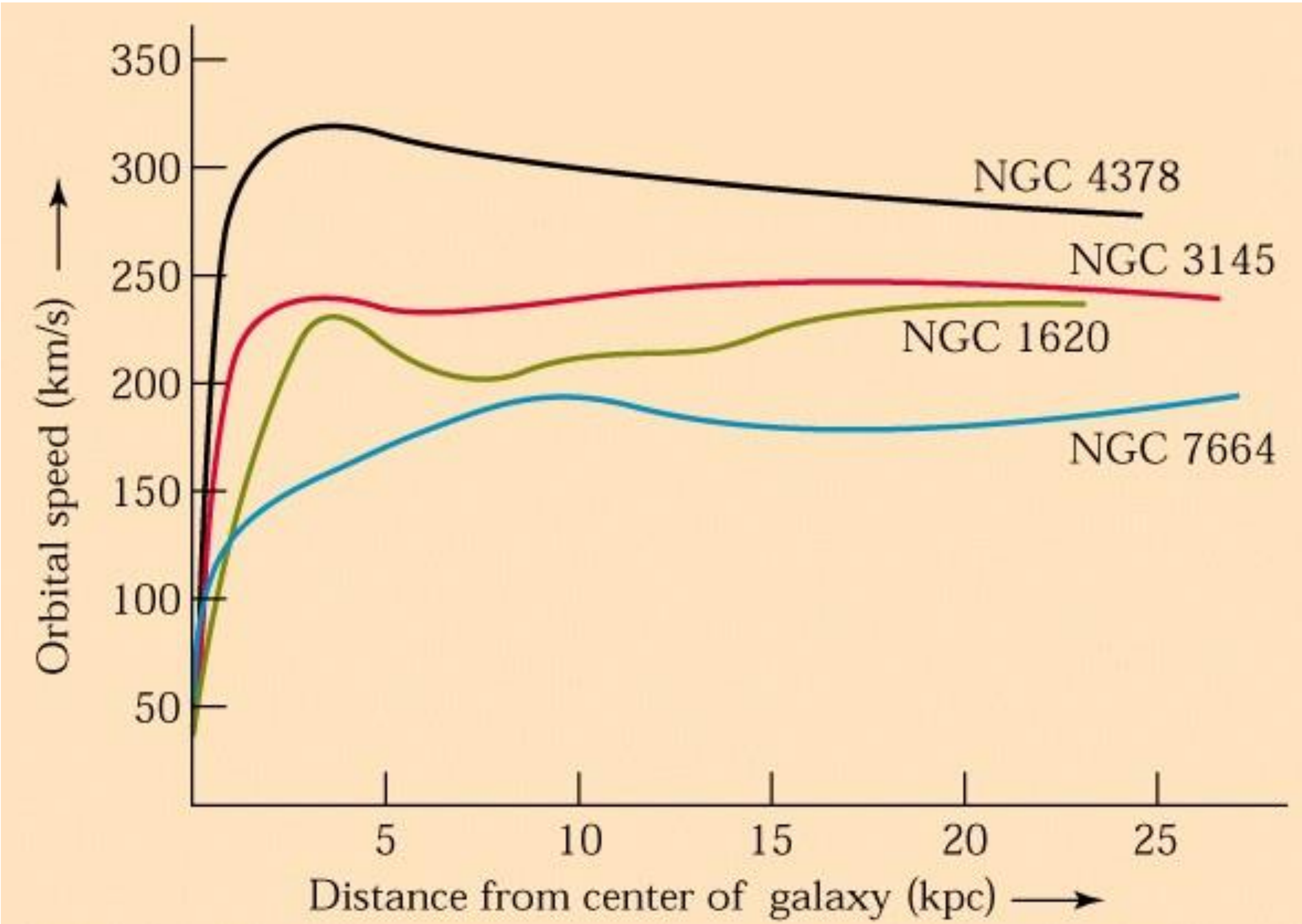


Figure: *The rotation curve for the galaxy NGC3198 from Begeman 1989*

more…



350
300
250
200
150
100
50
Orbital speed (km/s)
5
10
15
20
25
Distance from center of galaxy (kpc)
NGC 4378
NGC 3145
NGC 1620
NGC 7664

Possible Solutions

I. Dark Matter

Isothermal Halo:

$$\rho(r) = \frac{\rho(0)}{1 + \left(\frac{r}{a}\right)^2}$$

where a => core radius

$$M = \rho V \Rightarrow M \sim r \quad when \quad r \gg a$$

$$V^2 = \frac{GM}{r} \Rightarrow constant$$

- *plausible candidates: axions, wimps, sterile neutrinos…*
- *none yet observed for 30 years !*

II. Modified Gravity Models

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

$$F = m\,\mu\left(\frac{a}{a_0}\right) a \quad where \quad \mu(x) = \begin{cases} x & x \ll 1 \\ 1 & otherwise \end{cases}$$

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

$$V^4 = a_o GM \qquad where \;\; a_0 \sim 10^{-10} m/s^2$$

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

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

• *naively => without having a (complete) relativ. formulation, no real comparison*

• *TeVeS, bimetric MOND ? Multiple metrics? Why do we have 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*

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

Question: *Which assumption is incorrect ?*

- ***A Possible answer** : 1st one ➔ Multiple metric formulations*

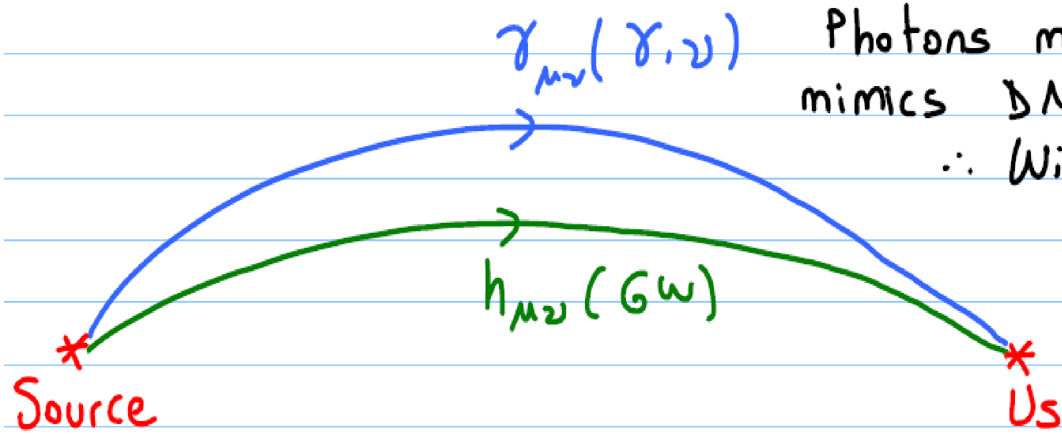
The class of models that we are considering:

***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.*

** Soussa, Woodard (2003) astro-ph/0307358*

IDEA: Two metrics → $\gamma_{\mu\nu}$: γ's ν's follow (Constructed to mimic DM observations)

→ $g_{\mu\nu}$: GW follow (No DM)



Photons move in a geometry that mimics DM (Extra matter)

∴ Will arrive later

(If these models are right)

∴ Arrival times will be different (Shapiro delays)

Q: How big is the difference? (μs or observable)

Basic Glossary: Multimessenger Approaches

"Multi-messenger astrophysics": connecting different kinds of observations of the same astrophysical event or system

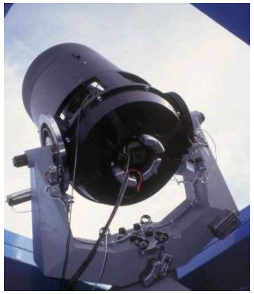
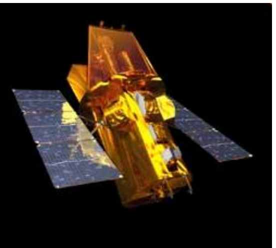


Image courtesy ROTSE collaboration

"Looc-Up" strategy:

GW —Flow of trigger information→ **Telescopes, Satellites or other external entities**

"ExtTrig" strategy:



Telescopes, Satellites or other external entities —Flow of trigger information→ **GW**

Search Strategy for GWs Using External Triggers:

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

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 Δt
- **Correlation in frequency:** Frequency-band specific analysis of data set
- **Source Properties**: Host galaxy, distance...

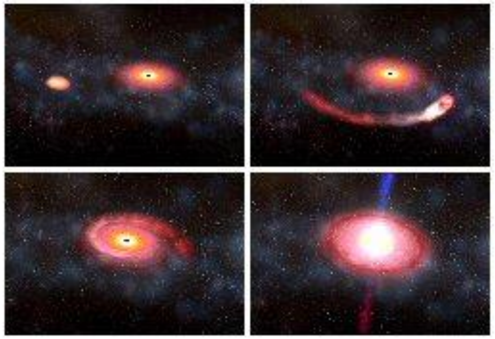
✓ Confident detection of GWs.

✓ Better background rejection => Higher sensitivity to GW signals.

✓ More information about the source/engine.

✓ Measurements made possible through coincident detection.

Possible Sources: Gamma-ray bursts (GRBs)



The black hole first stretches the neutron star into a crescent, swallowing it, and then gulping up crumbs of the broken star in the minutes and hours that followed.

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?

Static, spherically symmetric geometries

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

- *Geodesic ➔ motion along a circle*

$$\chi^\mu = \begin{bmatrix} ct \\ r = R \\ \theta = \frac{\pi}{2} \\ \phi \end{bmatrix}$$

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

$$\mu = t, \mu = \theta \;\; gives \;\; tautologies$$

$$\mu = \phi \Rightarrow \dot{\phi} = const$$

$$\mu = r \Rightarrow \ddot{\chi}^r + \Gamma^r_{tt}\left(c\dot{t}\right)^2 + \Gamma^r_{\phi\phi}\left(\dot{\phi}\right)^2 = 0 \qquad \Rightarrow \frac{B'}{2A}c^2\dot{t}^2 = \frac{r}{A}\dot{\phi}^2$$

$$\left[\frac{d\phi}{dt}\right]^2 = \frac{B'}{2r}c^2$$

- *A factors out !*

How to mimic DM?

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

$$ds^2 = -\left[1 - \frac{2GM}{c^2 r} + \frac{2V_\infty^2}{c^2}\ln\left(\frac{r}{r_S}\right)\right] c^2 dt^2 + \left[1 + \frac{2GM}{c^2 r} + \frac{2V_\infty^2}{c^2}\right] dr^2 + r^2 d\Omega^2$$

$$= -c^2 dt^2 + d\vec{x}\cdot d\vec{x} + \frac{2GM}{c^2 r}\left[c^2 dt^2 + dr^2\right] + \frac{2V_\infty^2}{c^2}\left[\ln\left(\frac{r}{r_S}\right) c^2 dt^2 + dr^2\right]$$

$$= -c^2 dt^2 + d\vec{x}\cdot d\vec{x} + \varepsilon'^{[c^2 dt^2 + dr^2]} + \varepsilon \;\; \left[\ln\left(\frac{r}{r_S}\right) c^2 dt^2 + dr^2\right]$$

$$= \eta_{\mu\nu} dx^\mu dx^\nu + \Delta' g_{\mu\nu} dx^\mu dx^\nu + \Delta g_{\mu\nu} dx^\mu dx^\nu$$

$$where \quad \varepsilon \equiv \frac{2V_\infty}{c^2}, \varepsilon' \equiv \frac{2GM}{c^2 r}$$

Time Lag Calculation

Geodesic Equations: $\ddot{\chi}^{\mu} + \Gamma^{\mu}_{\rho\sigma}\dot{\chi}^{\rho}\dot{\chi}^{\sigma} = 0$

For isothermal halo model:

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

$$\alpha \equiv \frac{\overrightarrow{x_L} \cdot \Delta\vec{x}}{\Delta x^2} \quad \text{and} \quad \beta \equiv \frac{r_L^2}{\Delta x^2}$$

$$r_S = 8.0kpc, r_L = 50.9kpc, \Delta x = 51.4kpc$$
$$\Rightarrow \alpha = -0.9775, \beta = 0.9793$$

$$\Delta t\Big|_{SN1987a} = -78\,days$$

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

  ➔ could have been 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.

Profile	GRB 070201	SN 1987a	Sco–X1
Isothermal	742 days	78.2 days	4.98 days
NFW	804 days	74.8 days	4.88 days
Moore	811 days	74.5 days	4.97 days

- The time delays for three dark matter profiles.

R. Ascension	Declination	$\Delta t_{\rm MW}$	$\Delta t_{\rm M31}$
00h 44m 32s	$42^\circ\, 14'\, 21''$	407 dy	335 dy
00h 46m 18s	$41^\circ\, 56'\, 42''$	407 dy	337 dy
00h 41m 51s	$42^\circ\, 52'\, 08''$	407 dy	322 dy
00h 42m 47s	$42^\circ\, 31'\, 41''$	407 dy	330 dy
00h 47m 14s	$41^\circ\, 35'\, 35''$	407 dy	338 dy

•Shapiro Delays for GRB 070201 from the Isothermal Profiles of the Milky Way (Δt_{MW}) and Andromeda (Δt_{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.

Numerical Integration for the time lag:

The calculation can be performed numerically for arbitrary sources in our galaxy

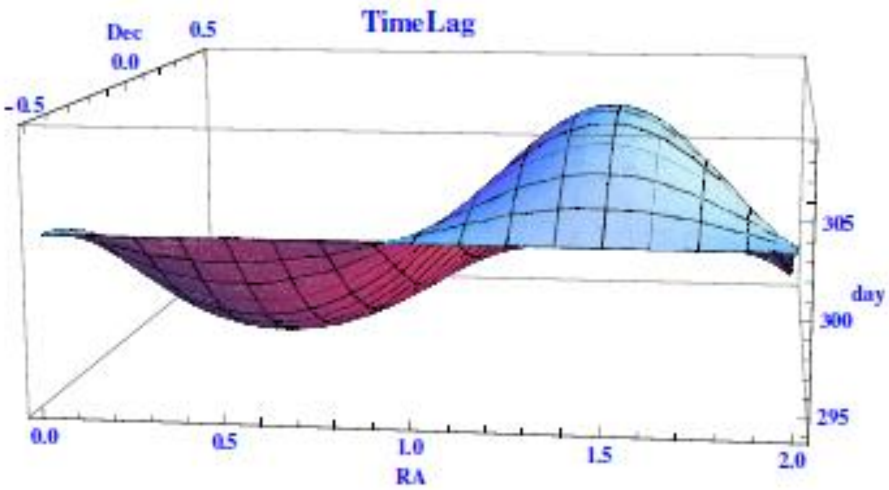


FIG. 2: The angular dependence of Shapiro delays for sources located in Milky Way. The units of RA(Right ascension) and Dec(Declination) is coverted to radians.

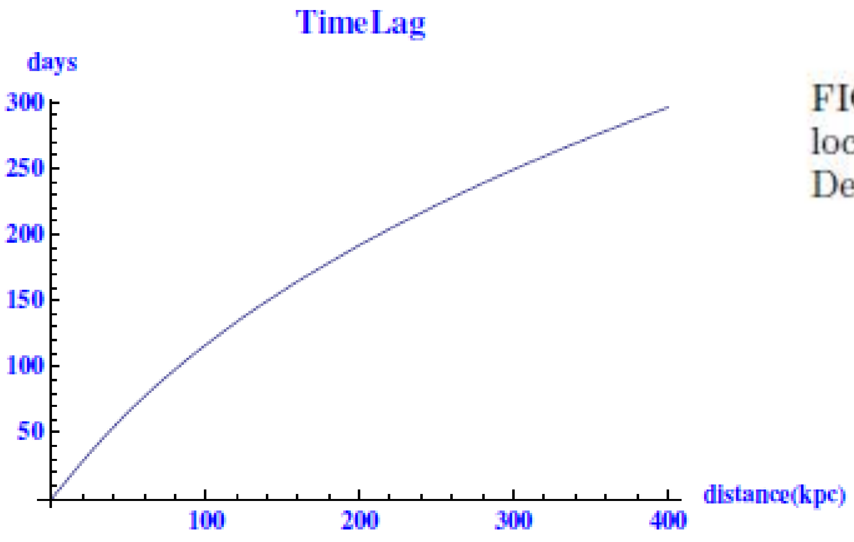


FIG. 1: Shapiro delays for sources located in Milky Way.

=> almost a linear graph

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

Data Set	$\rho(GeV/cm^3)$	$M_{vir}(M_\odot)$	$\Delta t(days)$
MW – Klypin [39]	0.185	1.0×10^{12}	426
MW – Ascasibar [41]	0.347	1.0×10^{12}	421
M31 – Klypin [39]	0.188	1.6×10^{12}	634
M31 – Tempel [42]	0.661	1.0×10^{12}	383

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 simulations?

Different! Mass estimates of MW and M31

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

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

a very long road ahead...

What about sources which are much farther?

GW150914 ➔ arXiv:1602.04779 Shantanu Desai, E.O.K

Distance ~ 400 Mpc => Shapiro delay ~ 1800 days

within a 0.2 second window the near-simultaneous arrival of gravitons

over a freq range ~ 200 Hz

Constrain EEP bwn the gravitons at different freqs.

Freq-dep violations of EEP for gravitons constrained to be O(10^-9)

Shapiro delay calculation becomes much more difficult

Other uncertainties additional to DM profies

Multiple galaxies on GW's way to us

Cosmological effect ➔ arXiv:1601.03636 (Adi Nusser)

an increase on the estimate of Wei et.al. arXiv:1512.07670

All of these taken it account: small fraction of an uncertainty

➔ months of extra time lag ➔GW150914 the uncertainty is very big

Observational Prospects for future

Gravitational Waves

- Already observed : GW150914 & GW151226
  - But they are very far from us and would no give γ BH/BH mergers
  - Huge uncertainty for Shapiro delay calc
- Would be great to have a nearby(in our galaxy) BH+NS merger or a SN explosion.

SN's would be great: 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 MiniBooNE
  - • 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 => 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. And much bigger for GW150914*

- *Huge uncertainty in mass of MW and M31 Numerical simulations estimates.*