Exam for the lecture
"Applied-Multi-Messenger Astronomy 2"
SS 2023

TU-Munich

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1 Introduction

The exam has to be handed-in by e-mail to `martin.wolf@tum.de` latest by September 8 2023 23:59. It can be solved in groups. Please hand-in also possible source code to calculate your solutions (preferably as Jupyter Notebook). An individual oral exam (in person or via video conference) will take place until the end of the summer semester 2023.

2 Dark Matter

2.1 Theory

Assume annihilating dark matter forming a spike structure around a supermassive black hole. The DM profile is given as

$$\rho_\chi(r) = \begin{cases} 0 & (r \leq 2R_{\rm sch}) \\ \rho_{\rm sp}(r) & (2R_{\rm sch} < r < R_{\rm sp}) \\ \rho_{\rm NFW}(r) & (R_{\rm sp} < r \leq R_{\rm vir}) \end{cases} , \tag{1}$$

where

$$\rho_{\rm NFW}(r) \equiv \rho_{\rm s} \left(\frac{r}{r_{\rm s}}\right)^{-1} \left(1 + \frac{r}{r_{\rm s}}\right)^{-2} , \tag{2}$$

$$\rho_{\rm sp}(r) \equiv \rho_{\rm NFW}(R_{\rm sp}) \left(\frac{r}{R_{\rm sp}}\right)^{-\gamma_{\rm sp}} , \tag{3}$$

and r is the distance to the galactic center. The following constants apply:

$$
\begin{aligned}
r_\mathrm{s} &= 24.42 \text{ kpc} && : \text{ Scale radius} \\
\rho_\mathrm{s} &= 0.184 \text{ GeV cm}^{-3} && : \text{ DM density at scale radius} \\
R_\mathrm{sch} &= 3.975 \times 10^{-10} \text{ kpc} && : \text{ Schwarzschild radius of the black hole} \\
R_\mathrm{vir} &= 200 \text{ kpc} && : \text{ Halo's virial radius} \\
R_\mathrm{sp} &\approx 1 \text{ pc} && : \text{ Spike radius (benchmark value)} \\
\gamma_\mathrm{sp} &= \frac{7}{3} && : \text{ Scaling exponent of spike structure}
\end{aligned}
$$

1. State the condition for the dark matter spike profile to be dissolute due to the dissolution effects.

2. Plot the DM density profile as given in equation (1) in the range 10^{-10} kpc $\leq r \leq 200$ kpc.

3. Explain the profile of each region.

2.2 Experiments

Shortly answer the questions below in a qualitative way.

1. What are the main approaches to search for Dark Matter (DM)? What are the main advantages and disadvantages of them?

2. What does "WIMP" stand for?

3. What is the expected velocity distribution of DM particles (WIMPs) at the location of the Earth? What defines the "WIMP wind" and what effects are expected during different seasons?

4. What forms the expected interaction rate of WIMPs in a detector? What generalized processes are possible? What are spin-dependent and spin-independent interactions?

5. What signals can be produced by the interactions of DM particles in the detector? What is the advantage of combining different channels?

6. What is the limitation of current direct DM detectors and how are they addressed? What are the fundamental limits for direct DM detection?

7. What are promising properties of astrophysical objects as sources for indirect DM detection? Name a few potential source types for indirect DM search.

8. An excess of gamma rays has been observed at the Galactic Center. Speculate on its potential explanations. What makes it promising with respect to DM, but controversial?

9. Why is searching for mono-energetic line signatures a very promising way to find DM? What are the main limitations?
10. Comment on the expected effects of anti-matter cosmic rays. Name recent results that can be interpreted as Dark Matter indication.

3 Gravitational Waves

3.1 Theory

Shortly answer the questions below.

1. Are GWs polarized?
2. What is the lowest multipole of GWs?
3. What are the signatures indicating GW emission in the first indirect detection of GWs, *i.e.* pulsar-neutron and pulsar-pulsar binary systems?
4. Explain the detection principle of GWs, with a sketch of an interferometer. Why are two-arm-interferometers used? (Hint: Rate of change in return time formula.) Why are cavities used?
5. Sketch the typical signal shape of GWs in a characteristic strain vs. frequency plot.
6. What is the predicted source of gravitational waves in the lower frequency range (1–10^{-5} Hz)?
7. To what source classes belong all the so far detected GW events?
8. List the sources of noise in GW detection and shortly explain how to handle them. (Two are enough.)

3.2 Matched Filtering in Action

Download the **GW150914 H1** data. To down-sample and cut-off the data, you may need the following functions:

```
strain = highpass(strain, 15.0)
strain = resample_to_delta_t(strain, 1.0/2048)
cut_off_data = strain.crop(2, 2)
```

Filter the data with the time series equivalent of 1 / PSD. Then generate a signal template with the following parameters:

```
get_td_waveform(
    approximant="SEOBNRv4_opt",
    mass1=36,
    mass2=36,
    delta_t=cut_off_data.delta_t,
    f_lower=20)
```

Calculate the signal-to-noise time series for our template. All necessary function for this task could be imported from PyCBC[1] library.

4 Gamma-Rays

4.1 Theory

Shortly answer the following questions.

1. What information bring gamma rays to us?
2. What physical processes enable the detection of gamma rays?
3. How to detect gamma rays using ground-based instruments?
4. Why is fast variability in transient objects (like blazars) important?
5. Which mechanism allows multi-TeV electrons to produce TeV gamma rays?
6. Which mechanism allows ultra-high energy protons (say above 10^{18} eV) to produce TeV gamma rays?
7. Why (in principle) can't we detect on Earth TeV gamma rays from a cosmic source that is located at a redshift 2?
8. Which astrophysical object provided was the first significant (more than 3 sigma) association between a high-energy neutrino (from IceCube) and a gamma ray source (e.g. detected with Fermi-LAT and MAGIC)?
9. What was the first significant detection of a Gamma Ray Burst (GRB) with a ground-based gamma-ray instrument?
10. What is the brightest GRB of all times (BOAT)?
11. Can GRBs be a source of Gravitational Waves that can be measured with current instrumentation?

4.2 Fermi-LAT Analysis

Conduct a Fermi-LAT analysis of the blazar Mrk 421 (4FGL J1104.4+3812). Choose from the following time ranges (in UTC):

1. 1st of January 2012 00:00:00 to 31st of December 2012 00:00:00
2. 30th of October 2015 00:00:00 to 30th of September 2016 00:00:00
3. 22nd of February 2013 00:00:00 to 17th of January 2014 00:00:00

[1] https://github.com/gwastro/pycbc

4. 8th of April 2022 00:00:00 to 15th of April 2023 00:00:00
5. 20th of July 2017 00:00:00 to 16th of August 2018 00:00:00
6. 4th of January 2018 00:00:00 to 12th of February 2019 00:00:00

where the time range number matches the equation `ceil(your-month-of-birth / 2)`. Use a region of interest (roi) radius of 15°, an energy range from 0.1 to 100 GeV, a src_roiwidth of 5° bigger than the roi radius, the zmax recommended for the energy range 0.3–1 GeV, the most up-to-date diffuse background models and the 3rd data release of the 4th Source Catalog of Fermi.

Conduct all the necessary steps to produce a test statistics (TS) map of the roi, calculate the TS of Mrk 421 in the given time range and its spectral parameters. For the fit, delete all sources with a TS < 3 or number of predicted counts < 1 excluding the diffuse background sources. Then free the normalization of close sources within 3 degrees of the roi center and all bright sources with TS > 9, free all parameters of the diffuse background components and all spectral parameters of Mrk 421.

4.3 Correlation Analysis

Compute the DCF between the radio (OVRO) light-curve and the high-energy (HE) gamma-ray (Fermi-LAT) light curve of Mrk 501 (given in the Figure1.fits file from the tutorial 2023-07-07) for the following time lags τ with a $\delta\tau$ = 14 days and produce a figure showing the DCF including uncertainties vs. τ. Choose from the following τ bins (in days):

1. τ = [-266, -252, -238, -224, -210, -196, -182, -168, -154, -140, -126, -112, -98, -84, -70, -56, -42, -28, -14, 0, 14, 28, 42, 56, 70, 84, 98, 112, 126, 140, 154, 168, 182, 196, 210, 224, 238, 252, 266]
2. τ = [-252, -224, -196, -168, -140, -112, -84, -56, -28, 0, 28, 56, 84, 112, 140, 168, 196, 224, 252]
3. τ = [-154, -147, -140, -133, -126, -119, -112, -105, -98, -91, -84, -77, -70, -63, -56, -49, -42, -35, -28, -21, -14, -7, 0, 7, 14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, 98, 105, 112, 119, 126, 133, 140, 147, 154]
4. τ = [-205.3, -196.0, -186.7, -177.3, -168.0, -158.7, -149.3, -140.0, -130.7, -121.3, -112.0, -102.7, -93.3, -84.0, -74.7, -65.3, -56.0, -46.7, -37.3, -28.0, -18.7, -9.3, 0.0, 9.3, 18.7, 28.0, 37.3, 46.7, 56.0, 65.3, 74.7, 84.0, 93.3, 102.7, 112.0, 121.3, 130.7, 140.0, 149.3, 158.7, 168.0, 177.3, 186.7, 196.0, 205.3]
5. τ = [-233.3, -221.7, -210.0, -198.3, -186.7, -175.0, -163.3, -151.7, -140.0, -128.3, -116.7, -105.0, -93.3, -81.7, -70.0, -58.3, -46.7, -35.0, -23.3, -11.7, 0.0, 11.7, 23.3, 35.0, 46.7, 58.3, 70.0, 81.7, 93.3, 105.0, 116.7, 128.3, 140.0, 151.7, 163.3, 175.0, 186.7, 198.3, 210.0, 221.7, 233.3]

6. τ = [-238.5, -228.1, -217.8, -207.4, -197.0, -186.7, -176.3, -165.9, -155.6, -145.2, -134.8, -124.4, -114.1, -103.7, -93.3, -83.0, -72.6, -62.2, -51.9, -41.5, -31.1, -20.7, -10.4, 0.0, 10.4, 20.7, 31.1, 41.5, 51.9, 62.2, 72.6, 83.0, 93.3, 103.7, 114.1, 124.4, 134.8, 145.2, 155.6, 165.9, 176.3, 186.7, 197.0, 207.4, 217.8, 228.1, 238.5]

where the τ bins number matches the equation
`ceil(your-month-of-birth / 2)`.