Microlensing: MACHOs and Modified Gravity

Usyd/UNSW HEP and Cosmology meeting

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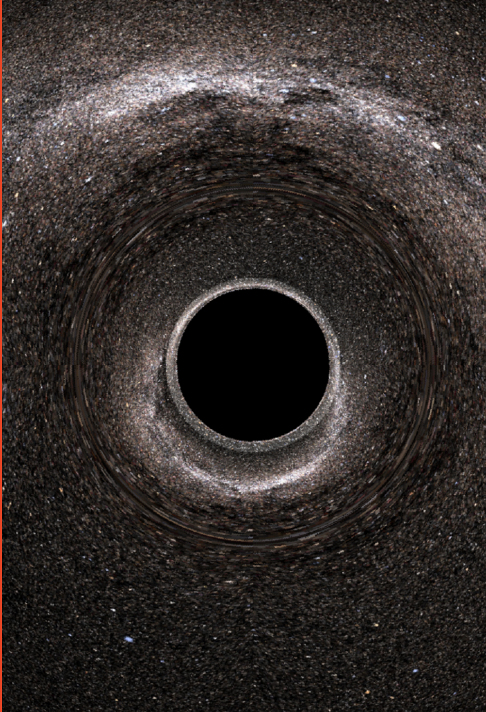
THE UNIVERSITY OF SYDNEY



Talk Outline

MACHOs: Motivation

- MAssive Compact Halo Objects
- Black holes (BHs) definitely[1] exist
  - LIGO BHs (30 $M_\odot$) don't have clear astrophysical origin
  - Primordial Black Holes? (PBHs)
- Hope?
  - Haven't seen any *other* DM yet (except for inside one mountain in Italy)
  - If they're very small- they'd have to be nearby!
- Constraints have more wiggle room than people realize

[1] OK, probably, but probably definitely

MACHO Constraints

- Microlensing: MACHOs pass in front of distant stars, increasing brightness
- Microlensing timescale depends on mass, distance, etc
  - SMC and LMC are commonly used, also M31
  - ≈ 100 days for $1M_\odot$
  - $\approx$ years for $> 10M_\odot$
- Uncertainties:
  - Halo model: local DM density, DM speed, halo shape
  - MACHO power spectrum: "monochromatic" usually assumed

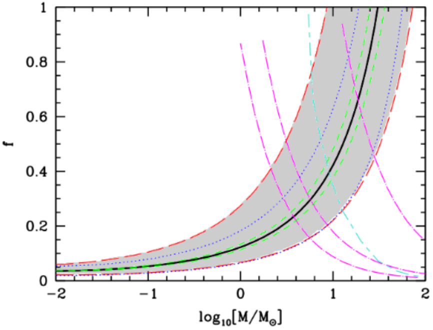


Figure 1: DM fraction f as function of MACHO mass M. (Green 2017)

Astrophysical Constraints

- Dwarf galaxy mass segregation constraint
- Tightest star cluster
  - Dynamical heating puffs up stellar systems in dwarf galaxies
- CMB constraints
  - Screw with ionization history $\Rightarrow$ CMB anisotropies
- Ali-Haïmoud, Kovetz, and Kamionkowski 2017 claim these don't apply to LIGO mass PBHs

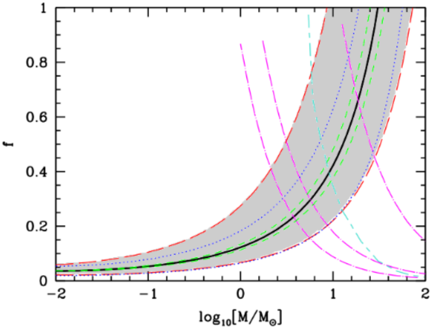


Figure 2: DM fraction f as function of MACHO mass M. (Green 2017)

Binary Formation Constraints

- LIGO binary merger rates are consistent with 100% DM
  - *If* binaries form in galaxy halos
- PBH Binaries might decouple from Hubble flow in early universe
  - $\Rightarrow$ Orders of magnitude more events than LIGO sees

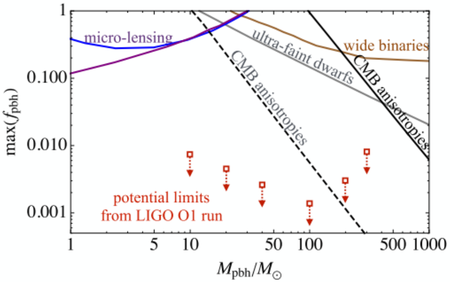


Figure 3: DM fraction f as function of MACHO mass M. (Ali-Haïmoud, Kovetz, and Kamionkowski 2017)

Microlensing in Detail

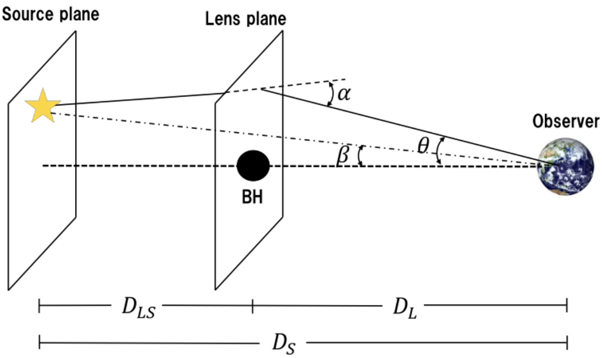


Figure 4: Microlensing geometry in the thin lens approximation. Sasaki et al. 2018

Finding the Photon Metric

Begin with some gravity theory:

$$A = \int d^4x \sqrt{-g} \left[f(\text{invariants}) + \mathcal{L}_{matter} \right] \tag{1}$$

Roughly comparing kinetic energy and potential energy of gravitating bodies,

$$v^2 \approx \frac{GM}{r} \tag{2}$$

If one is interested in Post-Newtonian (PN) corrections to body dynamics, we can expand in this parameter:

$$g_{00} = 1 + g_{00}^{(2)} + \mathcal{O}(4), \qquad g_{0i} = \mathcal{O}(3), \qquad g_{ij} = -\delta_{ij} + g_{ij}^{(2)} + \mathcal{O}(4) \tag{3}$$

Finding the Photon Metric

Assuming some extra symmetry, we can define

$$g_{ij}^{(2)} \equiv 2\Psi\delta_{ij}, \qquad g_{00}^{(2)} \equiv 2\Phi \tag{4}$$

So to lowest order, the invariant is

$$ds^2 = (1+2\Phi)dt^2 - (1-2\Psi)\delta_{ij}dx^i dx^j \tag{5}$$

Finally we should write this in Schwarzschild-like coordinates:

$$r^2 = x^i x^i \left[1 - 2\Psi(\sqrt{x^i x^i})\right] \tag{6}$$

Then expanding to lowest order in $r_s/r = 2GM/r$, you will finally find, with some suitable redefinitions,

$$ds^2 = 0 = \left(1 - \frac{r_s}{r}\Xi(r)\right)dt^2 - \left(1 + \frac{r_s}{r}\Delta(r)\right)dr^2 - r^2 d\Omega. \tag{7}$$

Deflection Angle

Our photon metric is symmetric in time and rotation, so we have two constants of motion

$\Rightarrow$ differential equation for $r_\pm$

Then the deflection angle is just

$$\alpha \equiv -\pi + \int_0^{\phi_{fin}} d\phi = -\pi + 2 \int_{r_0}^{\infty} \frac{\dot{\phi}}{\dot{r}_+} dr \tag{8}$$

We have the condition $\dot{r}_\pm|_{r_0} = 0$, where r_0 is impact parameter, allowing us to remove the constants of motion and find:

$$\alpha = -\pi + 2 \int_{r_0}^{\infty} dr \frac{\sqrt{1 + \frac{r_s}{r} \Delta(r)}}{r \sqrt{\frac{1 - \frac{r_s}{r} \Xi(r_0) r^2}{1 - \frac{r_s}{r} \Xi(r) r_0^2} - 1}} \tag{9}$$

Have fun solving this! I know some tricks so if you want help, you know where to find me...

Microlensing in Detail

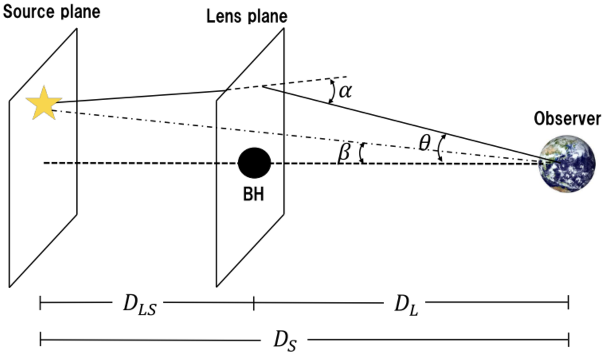


Figure 5: Microlensing geometry in the thin lens approximation. Sasaki et al. 2018

Einstein Radius

If you're a particle physicist, you can probably figure out a way to make your gravity theory into extra (maybe massive) modes. In which case, your answer to the above integral is likely:

$$\alpha = 2\frac{r_g}{r_0}\left(1 + a + be^{-m_g r_0}\right), \tag{10}$$

From the geometry,

$$\beta = \theta - \alpha D_L/D_S, \qquad \theta = r_0/D_L \tag{11}$$

$$\Rightarrow \quad 0 = \theta^2 - \theta_E^2\left(1 + a + be^{-m_g \theta D_L}\right) - \beta\theta, \qquad \theta_E = \sqrt{\frac{2r_s D_{LS}}{D_L D_S}} \tag{12}$$

When $m_g << r_0$, and the sources are aligned, this is easy to solve, and we have our (modified) Einstein Radius:

$$R_E^{new} \approx R_E\sqrt{1 + a + b}, \qquad R_E = \theta_E D_L. \tag{13}$$

Event Rate

- For microlensing, the Einstein Radius is unresolvable
  - But, the source gets brighter for the time it takes the lens to move past the source
  - Larger Einstein Radius ⇒ longer increase in brightness

The total number of expected microlensing events is

$$N_{exp} = N_{stars}\ \Gamma(m)\ t_{obs}\ \epsilon(m) \tag{14}$$

If a choice of f, m predict $>$3 events, and none are seen, we can reject them with 95% confidence. (Griest 1991)

Event Rate

The microlensing event rate Γ depends on the halo model and Einstein Radius (Griest 1991):

$$\Gamma = \sqrt{\pi}\ \rho_0\ v_c\ f\ \frac{M_\odot}{m}\ u_T \int_0^{D_S} \frac{dD_L\ R_E^{new}}{\left(A + B\frac{D_L}{D_S} + \frac{D_L^2}{D_S^2}\right)} \quad (15)$$

- $R_E^{new} \propto R_E = \sqrt{2r_s\frac{D_L(D_s - D_L)}{D_S}}$
  - Peaks at $D_L = \frac{1}{2}D_S$
- ρ_0: Local DM density
- v_c: Sun's circular velocity
- f: MACHO DM fraction
- u_T: slightly corrects Einstein Radius for the microlensing tube an experiment can actually see
- denominator in integral: accounts for Earth's position and a halo model with a Galactic core

Modifications of Gravity

- $R_E^{new} < R_E \Rightarrow \Gamma^{new} < \Gamma$
  - $\Rightarrow$ One can proportionately lift the constraints on f
  - In Bekenstein and Sanders 1994, they predicted any scalar-tensor gravity theory would decrease lensing
- For $m = 1M_\odot$ MACHOs, the impact parameter r_0 is about 1 Au, at $D_L = \frac{1}{2}D_S$
  - Need significant modification on this scale
  - Must still comply with constraints, eg solar system bounds, LIGO bounds, etc.

Modifications of Gravity

We looked at two particular modifications so far:

- Quadratic Gravity: $f(invariants) = R + \beta R^2 + \gamma R^{\mu\nu} R_{\mu\nu}$
  - Does in fact decrease the Einstein Radius
  - But- its short range and well constrained by binary inspirals (Kim, Kobakhidze, and Picker 2019)
    - (Don't believe referees 1 and 3...)
- Bimetric Gravity: Two coupled metrics
  - Generalization of ghost-free massive gravity- originally the Fierz-Pauli theory
  - Veinshtein screening mechanism
  - Mixing angle parameter opens up constraints

Bimetric Gravity

- Bimetric gravity is still young- not a lot of consensus yet, even on basic calculations
- Deflection angle was calculated in Platscher et al. 2018
  - $\alpha_{bimetric}/\alpha_{GR} = \gamma + \frac{3}{4}\beta e^{-m_g r}$
  - $m_g r << 1$ for usual microlensing regime
  - $\gamma + \frac{3}{4}\beta > 1$
  - ... So gravity is *stronger* instead
- Need very large impact parameter to make gravity weaker
  - Larger distance to source (eg M31, but this seems to be insufficient still)
  - Or, *larger mass lenses*
  - Need to argue astrophysical constraints don't apply
    - Maybe!
    - Cosmological bounds are much more complicated though...

Future Work + End

- Instead of modifying gravity, can add an extra $U(1)$ to charge BHs
  - A lot less messy than bimetric cosmology...
- Abandon all hope and look at axions instead

Thanks for listening!