Constraining standard and nonstandard particle properties using astrophysical data

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Outline

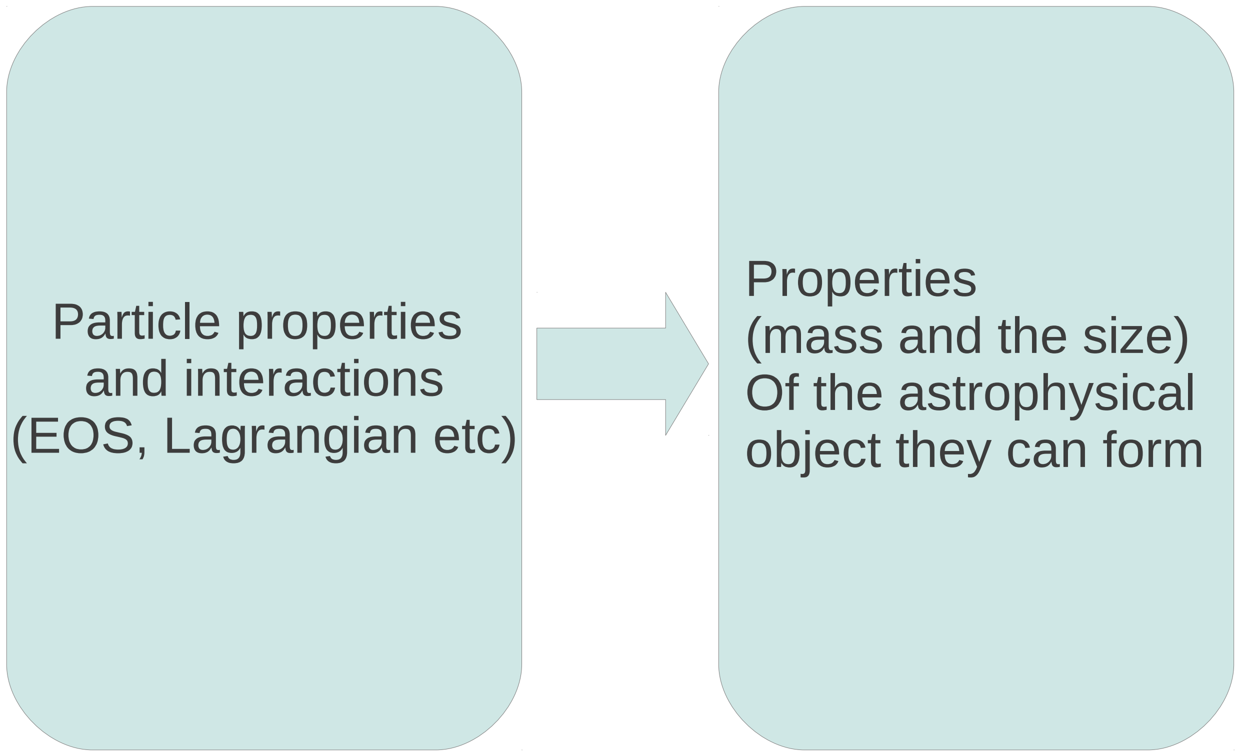
- Bounds extracted from the observation of astrophyiscal objects
- Bounds extracted from the no-observation of astrophyiscal objects

We live in a cavern...

The writing of god (by Jorge Luis Borges)

The story is narrated by a Mayan priest named Tzinacan, who is tortured by Pedro de Alvarado (who burned the pyramid Qaholom where the protagonist was a magician) and incarcerated, with a jaguar in the adjacent cell. Tzinacan searches for a divine script that will provide him omnipotence, and he hopes to see it in the patterns of the animal's fur.

Motivation



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Self-gravitating system made of fermions

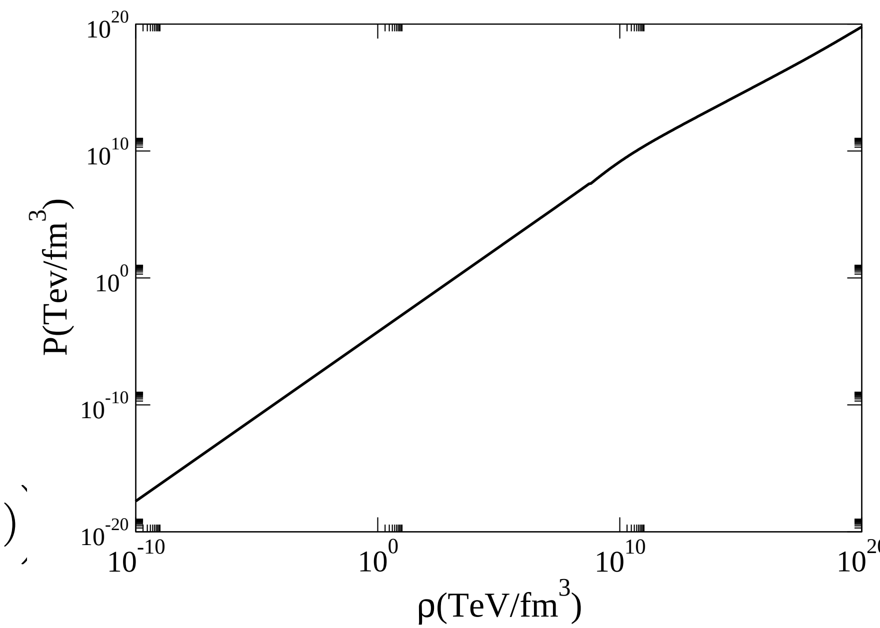
The equation of state for a free gas of fermions at zero temperature can be directly computed

$$\rho = \frac{1}{\pi^2}\int_0^{k_F} k^2\sqrt{m_F^2+k^2}dk$$

$$= \frac{m_f^4}{8\pi^2}\left((2z^3+z)(1+z^2)^{1/2}-\sinh^{-1}(z)\right)$$

$$p = \frac{1}{3\pi^2}\int_0^{k_F}\frac{k^4}{\sqrt{m_F^2+k^2}}$$

$$= \frac{m_f^4}{24\pi^2}\left((2z^3-3z)(1+z^2)^{1/2}+3\sinh^{-1}(z)\right)$$



Dark compact objects

Solve the TOV equations for such EOS:

- Normalized variables $M' = Mm_f^2/m_p^3$, $r' = rm_f^2/m_p$, $p' = p/m_f^4$ and $\rho' = \rho/m_f^4$.
- The equations

$$\frac{dM'}{dr'} = 4\pi r'^2 \rho'$$

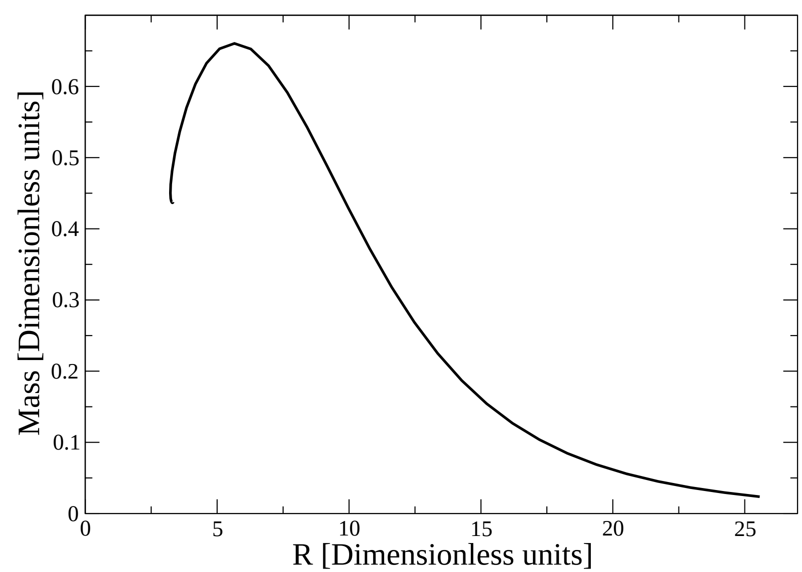
$$\frac{dp'}{dr'} = -\frac{M'\rho'}{r'^2}\left(1+\frac{p'}{\rho'}\right)\left(1+\frac{4\pi r'^3\rho'}{M'}\right)\left(1-\frac{2M'}{r'}\right)^{-1}$$

The maximum mass for a compact star made of fermionic matter

$$M = 1.6 M'_{max}\left(\frac{GeV}{m_f}\right)^2 M_\odot$$

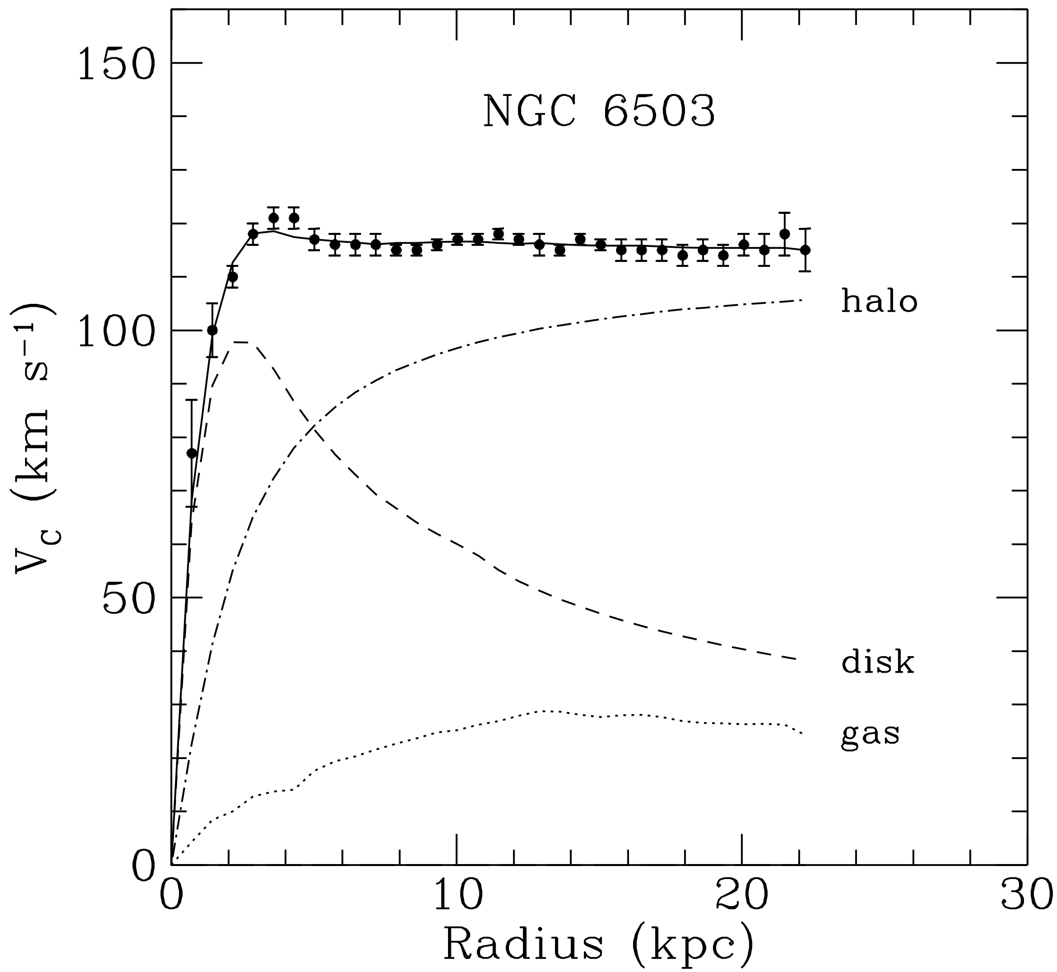
and the minimum radius

$$R_{min} = 8.115\mathrm{Km}\left(\frac{\mathrm{GeV}}{\mathrm{m_f}}\right)^2$$



DM as motivation

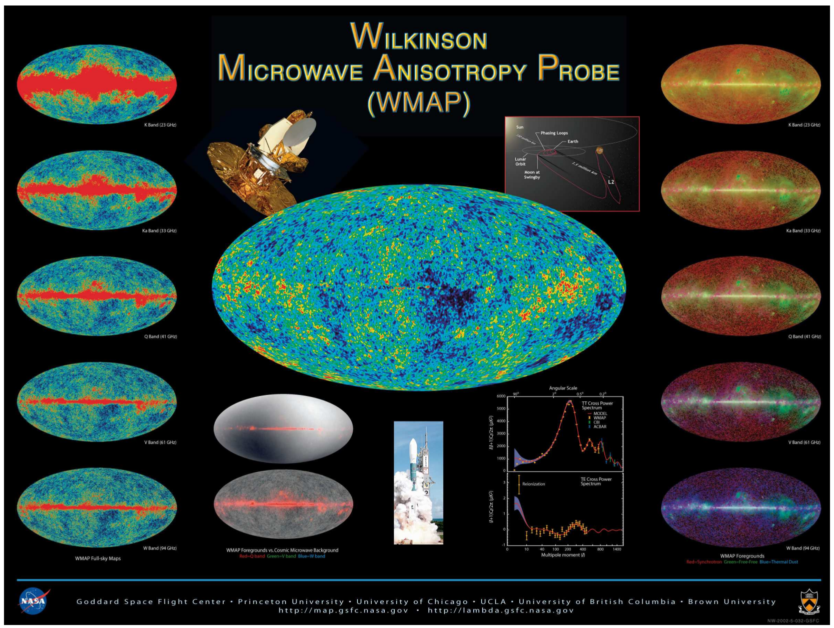
The most convincent and direct evidence of the existence for dark matter at the galactic scale comes from the *rotational curve velocity*, namely the graph of circular velocities of stars and gas as a function of their distance from the galactic center.

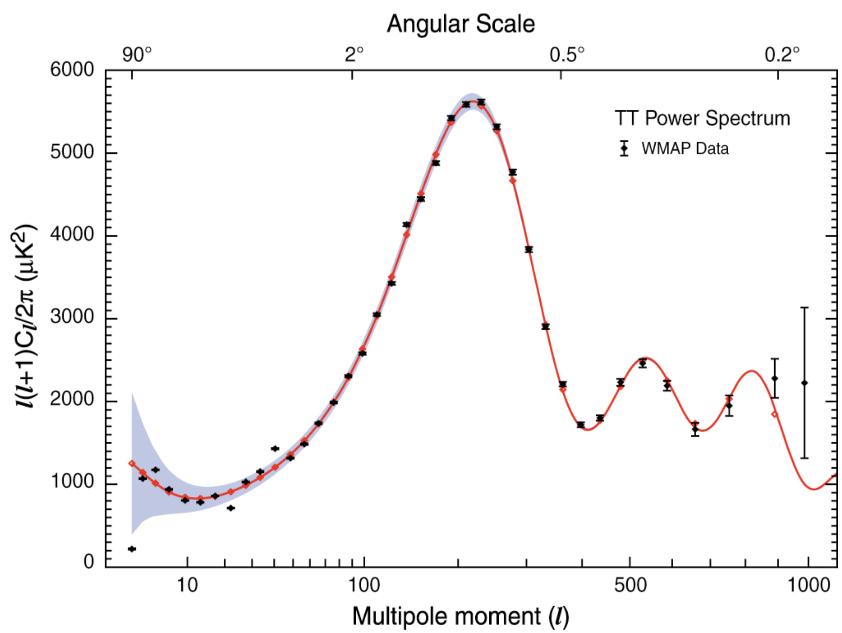


DM as motivation

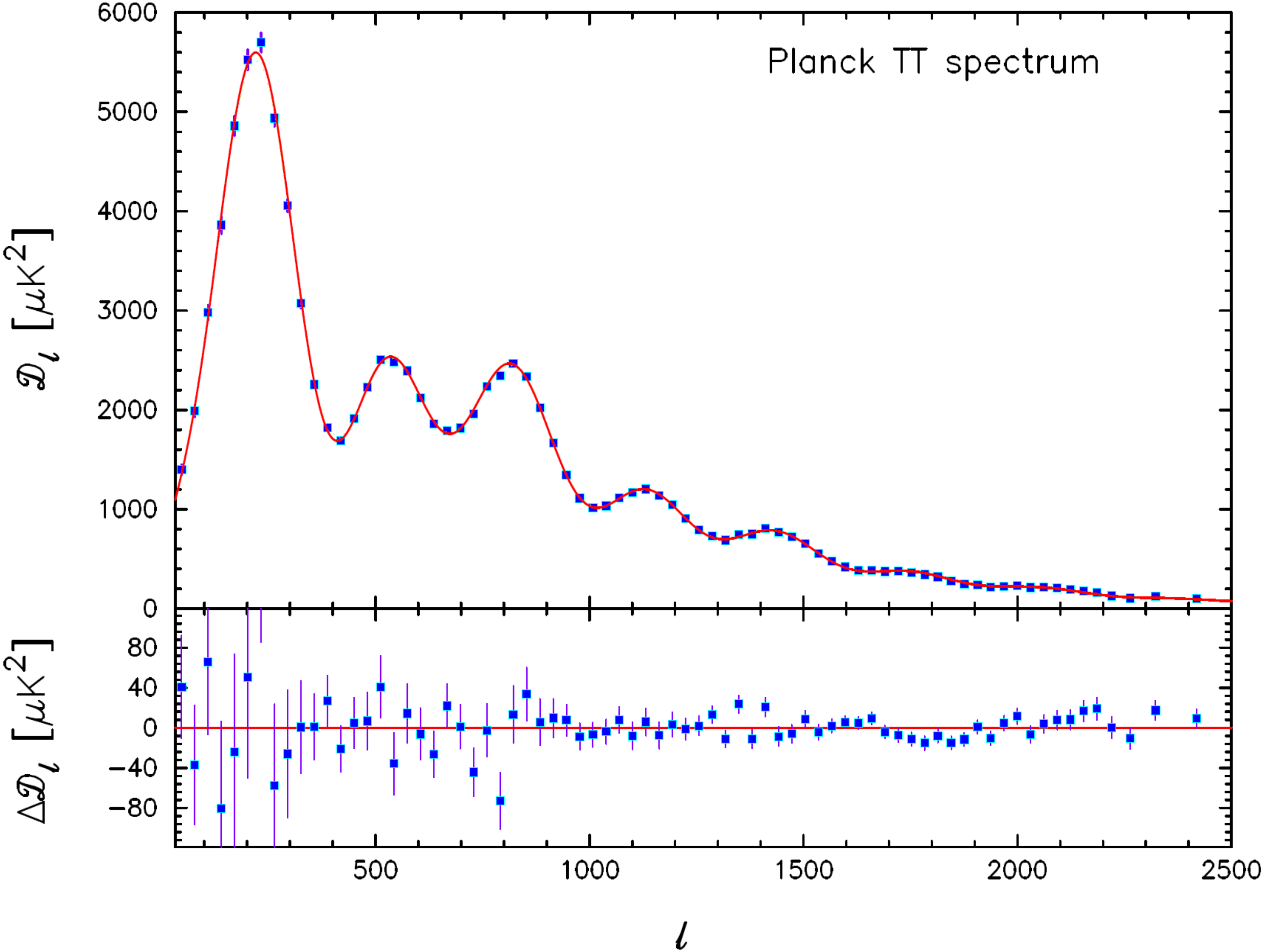
- Furthremore, at galactic scales:
  - *Weak modulation of strong lensing* around individual massive elliptical galaxies. This provides evidence for substructure on scales of $\sim 10^6 \mathrm{M}_\odot$
  - *Weak gravitational lensing* of distant galaxies by foreground structure
  - The *velocity dispersions of dwarf spheroidal galaxies* which imply mass–to–light ratios larger than those observed in our “local” neighborhood.
  - The *velocity dispersions of spiral galaxy satellites* which suggest the existence of dark halos around spiral galaxies, similar to our own, extending at galactocentric radii $\gtrsim 200$ kpc, i.e. well behind the optical disc. This applies in particular to the Milky Way, where both dwarf galaxy satellites and globular clusters probe the outer rotation curve.

DM as motivation (WMAP)





Planck mision results [Planck results XVI. Arxiv 1303.5076]



DM as motivation

- Starting from a cosmological model with a fixed number of parameters, the best-fit parameters are determined from the peak of the N-dimensional likelihood surface.
  - From the combined analysis of Planck + WMAP:
    $\Omega_b h^2 = 0.02206 \pm 0.00028 \quad , \Omega_M h^2 = 0.1174 \pm 0.0030$
  - Including BAO
    $\Omega_b h^2 = 0.02220 \pm 0.00025 \quad \Omega_M h^2 = 0.1161 \pm 0.0028$

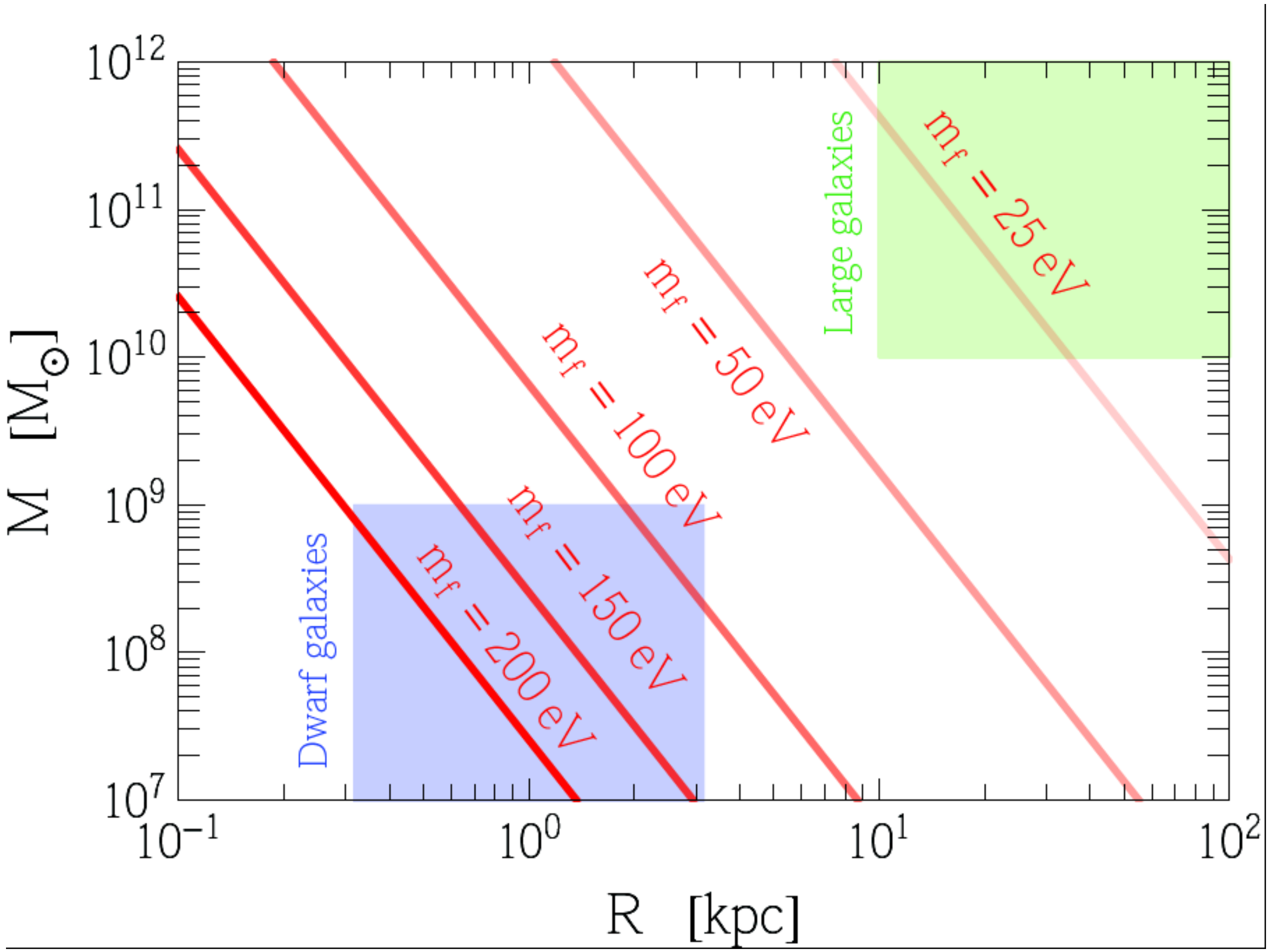
Conclusive evidence in favor of the existence of dark matter

The big problem

- What is Dark Matter?

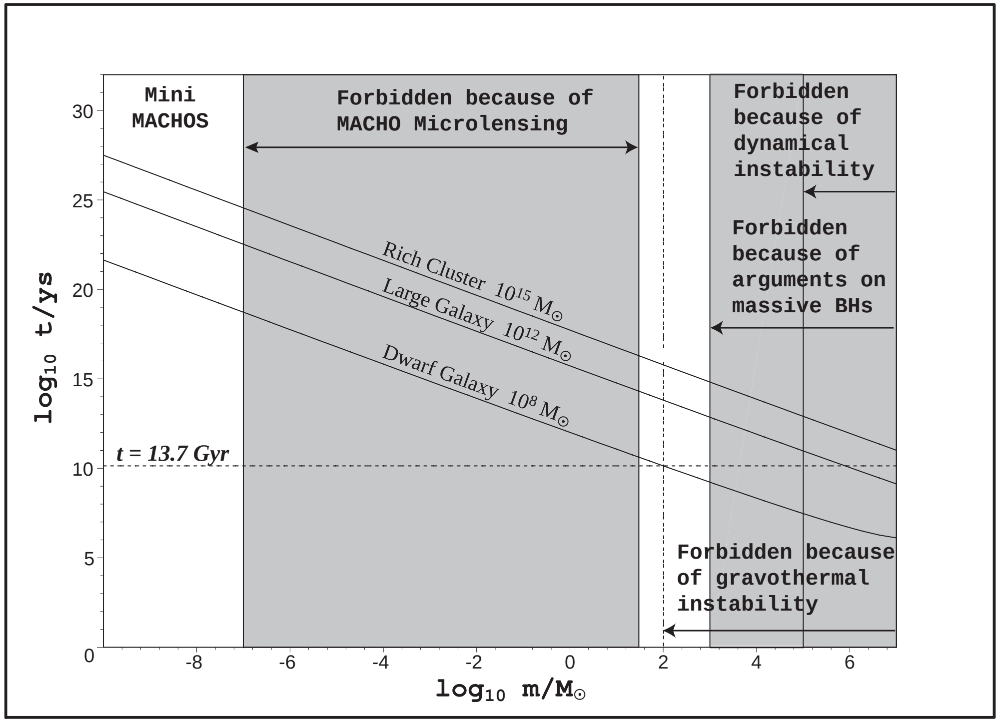
Remember the selfgravitating fermions...

Suppose it is a fermion with no self interaction to Very light DM candidate



[Domcke and Urbano, JCAP 1501 (2015) 01, 002]

Galactic halo as an ensemble of DM mini-MACHOS



X. Hernandez, T. Matos, R. A. Sussman and Y. Verbin,

"Scalar field mini-MACHOs: A new explanation for galactic dark matter," Phys. Rev. D **70***, 043537 (2004)*

- Clumpy neutralino dark matter $M_{\text{neutralino star}} \sim 10^{-7} M_\odot$. J. Ren, X. Li, H. Shen, Commun.Theor.Phys. **49** (2008) 212-216
- Axions may form such scalar field mini-MACHOS. $M_{\text{axion star}} < 10^{-15} M_\odot$ J. Barranco, A. Bernal, Phys. Rev. D **83** (2011) 043525

Formation of dark matter clumps:

- **Neutralino clumps**: At the phase transition from a quark-gluon plasma to a hadron gas, the spectrum of density perturbations may develop peaks and dips produced by the growth of hadronic bubbles. $\rightarrow$ Kinematically decoupled CDM falls into the gravitational potential wells provided from those peaks leading the formation of dark matter clumps with masses $< 10^{-10} M_{\odot}$. [Schmid PRD **59** (1999) 043517]
- **Axion minicluster**:The evolution of the axion field at the QCD transition epoch may produce gravitationally bound miniclusters of axions Such minicluster, due to collisional $2a \rightarrow 2a$ process, it may relax to a selfgravitating system. [Kolb and Tkachev PRL **71** (1993) 3051-3054]

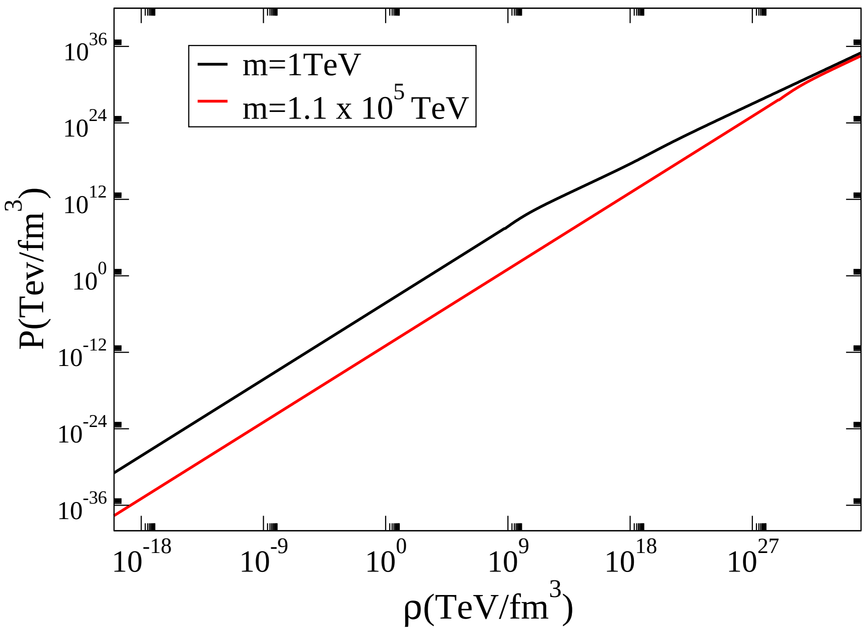
Limits from femtolensing

- The maximum mass for a compact star made of fermionic dark matter

$$M = 1.6 M'_{max} \left(\frac{GeV}{m_f}\right)^2 M_\odot$$

- New constraints on primordial black holes abundance from femtolensing of gamma-ray bursts exclude the range $10^{-17} M_\odot - 10^{-13} M_\odot$ [A. Barnacka, J.F. Glicenstein, R. Moderski Phys.Rev. **D 86** (2012) 043001]
- This imply a limit for the fermionic dark matter:

$$m_f > 1.11 \times 10^5 \text{TeV!!!}$$



Self-gravitating system made of axions

- Axion was originally proposed to solve strong CP problem
- There is a remnant $\gamma - a$ interaction

$$\mathcal{L} = \frac{1}{2}(\partial^{\mu}\phi\partial_{\mu}\phi - m^2\phi^2) - \frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

- Axion properties

$$10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$$

$$10^{-5}\text{eV} \leq m \leq 10^{-3}\text{eV}$$

At late times in the evolution of the universe, the energy density potential is:

$$V(\phi) = m^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right],,$$

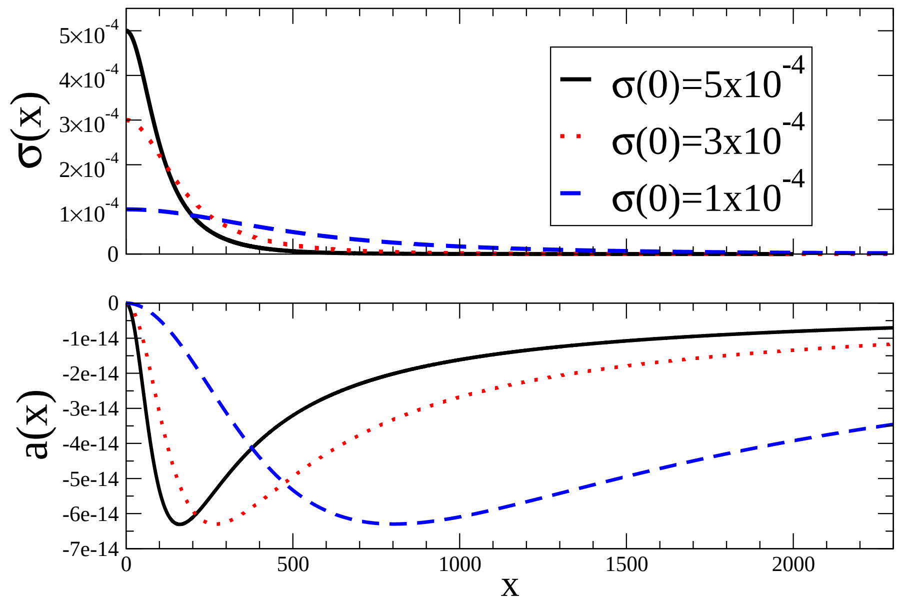
Axion star

$$R = \frac{f_a}{\sqrt{m}}\sigma\,, \quad r = \frac{m_p}{f_a}\sqrt{\frac{m}{4\pi}}x\,, \quad \alpha = \frac{4\pi f_a^2}{m_p^2 m}$$

$$A(x) = 1 - a(x)$$

$$\begin{aligned}
a' + \frac{a(1+a)}{x} + (1-a)^2 x\left[\left(\frac{1}{B}+1\right)m^2\sigma^2 - \frac{m\sigma^4}{4} + \alpha\frac{\sigma'^2}{(1-a)} + \frac{\sigma^6}{72}\right] &= 0\,,\\
B' + \frac{aB}{x} - (1-a)Bx\left[\left(\frac{1}{B}-1\right)m^2\sigma^2 + \frac{m\sigma^4}{4} + \alpha\frac{\sigma'^2}{(1-a)} - \frac{\sigma^6}{72}\right] &= 0\,,\\
\sigma'' + \left(\frac{2}{x} + \frac{B'}{2B} + \frac{a'}{2(1-a)}\right)\sigma' + (1-a)\left[\left(\frac{1}{B}-1\right)m^2\sigma + \frac{m\sigma^3}{3} - \frac{\sigma^5}{24}\right] &= 0
\end{aligned}$$

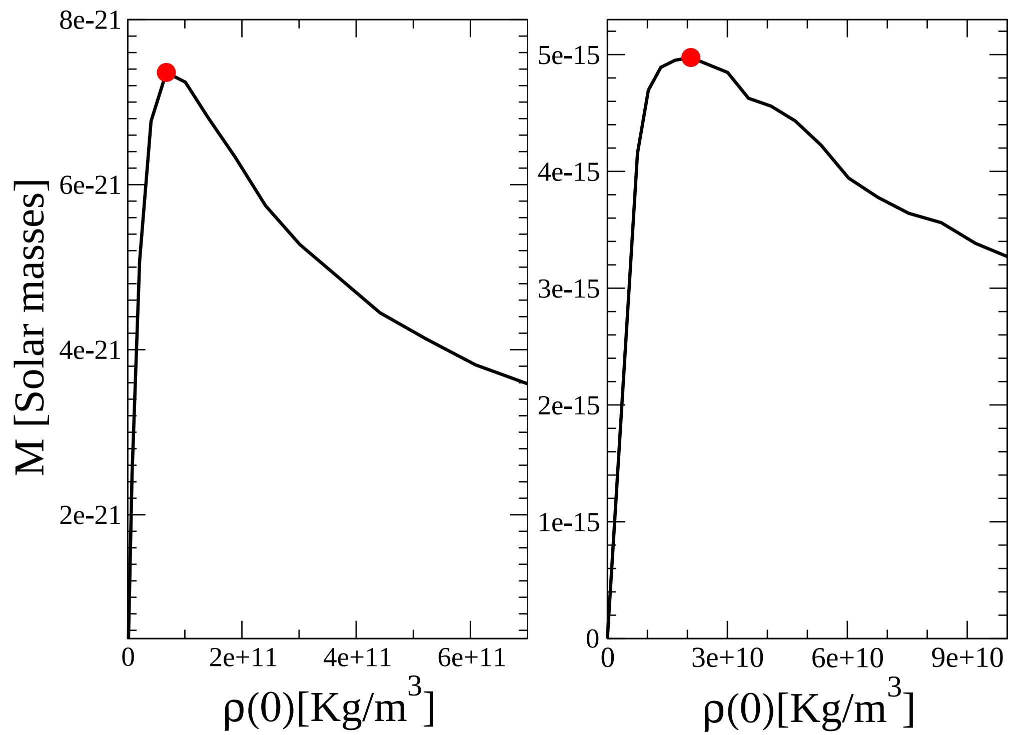
Axion star



$\sigma(0)$	Mass (Kg)	R_{99} (meters)	density ρ (Kg/m^3)
5×10^{-4}	3.90×10^{13}	1.83	6.3×10^{12}
3×10^{-4}	6.48×10^{13}	2.86	2.7×10^{12}
1×10^{-4}	1.94×10^{14}	8.54	3.1×10^{11}

[J. Barranco, A. Bernal, PRD**83**, 043525 (2011)]

Axion star



Axion mass (eV)	$\rho(0)\ \left(\text{Kg}/\text{m}^3\right)$	Mass ($M_\odot$)	R_{99} (meters)
$m_a = 10^{-5}$	2.1×10^{10}	5.0×10^{-15}	119.40
$m_a = 10^{-3}$	6.8×10^{10}	7.4×10^{-21}	0.89

[J. Barranco, A. Carrillo-Monteverde,D. Delepine PRD**87**,(2013) 103011]

Possible γ signal?

- It is possible axion transform to photons in presence of an external magnetic field!
- Strong magnetic fields $\rightarrow$ NS $> 10^8$ Gauss.
- $\sim 10^9$ NS in the galaxy
- Does axion stars collision with Neutron Stars produce a visible effect?
  - Start with

$$\mathcal{L}_{a\gamma\gamma} = \frac{c\alpha}{f_{PQ}\pi} a\vec{E}\cdot\vec{B}$$

  - Obtain “modified” Gauss law:

$$\partial\vec{E} = \frac{-c\alpha}{f_{PQ}\pi}\vec{\partial}\cdot(a\vec{B})$$

  - Energy dissipated in the magnetized conducting media, with averange σ electric conductivity (Ohm’s law)

$$W = \int_{ABS}\sigma E_a^2 d^3x = 4c^2 \times 10^{54}\mathrm{erg/s}\frac{\sigma}{10^{26/s}} \times \frac{M}{10^{-4}M_\odot}\frac{B^2}{(10^8G)^2}$$

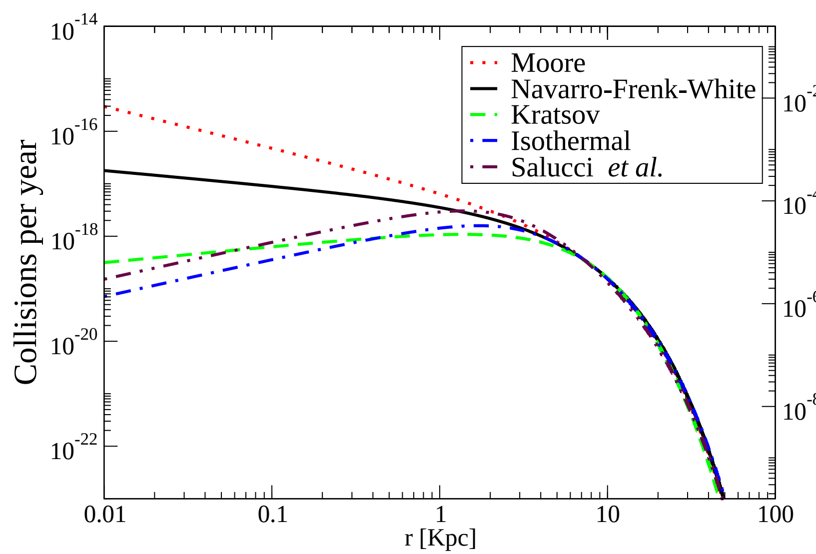
- YES! there could be a signal

can the dark matter halo be a ensemble of axion stars?

The number of collisions per pc^3 per second will be

$$R_c = n_{AS}(r) \times \rho_{NS}(r) \times S \times v \,,$$

n_{AS} is the number of AS per pc^3 and ρ_{NS} is the probability to find a Neutron Star at that point,



- They fulfill the limits from femtolensing
- No significant γ signal from the colission of NS with axion stars

YES

Other interesting problems

- The origin of supermassive black holes (SMBH)) at the center of the galaxies is an open question.
- Most of the numerical and semi-analitycal methods show a lack in time and amount of matter to build SMBH at early times ($z \sim 3$)
- The argument that it is a BH is done because there is not viable alternatives...

Boson stars with self-interaction

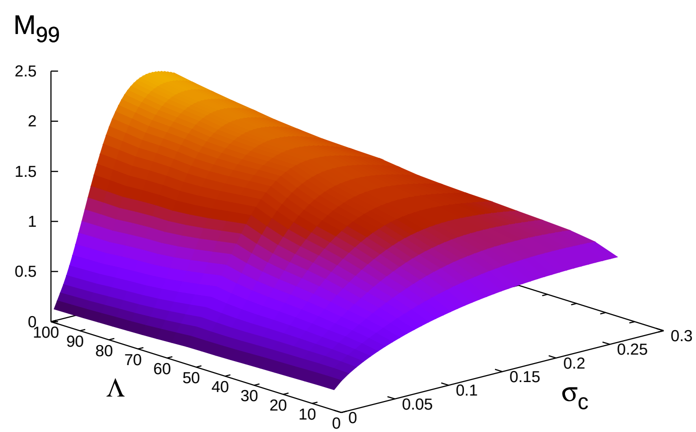
M. Colpi, S. L. Shapiro and I. Wasserman, Phys. Rev. Lett. **57** (1986) 2485.

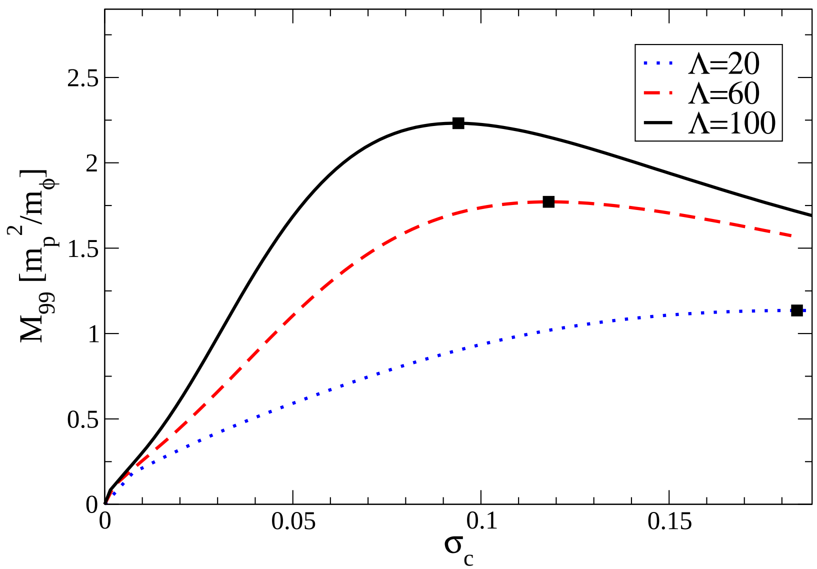
$$T_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \Phi \partial_\nu \Phi^* + \partial_\mu \Phi^* \partial_\nu \Phi\right) - \frac{1}{2} g_{\mu\nu} (g^{\alpha\beta} \partial_\alpha \Phi \partial_\beta \Phi^* + m^2 |\Phi|^2 + \frac{\lambda}{2} |\Phi|^4) \,.$$

$$\Lambda = \frac{\lambda M_p^2}{4\pi m^2}$$

$$\begin{aligned}
\frac{A'}{A^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} + 1\right)\sigma^2 + \frac{\Lambda}{2}\sigma^4 + \frac{\sigma'^2}{A}\right] &= 0\,, \\
\frac{B'}{ABx} - \frac{1}{x^2}\left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} - 1\right)\sigma^2 - \frac{\Lambda}{2}\sigma^4 + \frac{\sigma'^2}{A}\right] &= 0\,, \\
\sigma'' + \left(\frac{1}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right)\sigma' + A\left[\left(\frac{1}{B} - 1\right)\sigma - \Lambda\sigma^3\right] &= 0
\end{aligned}$$

Boson stars with self-interaction

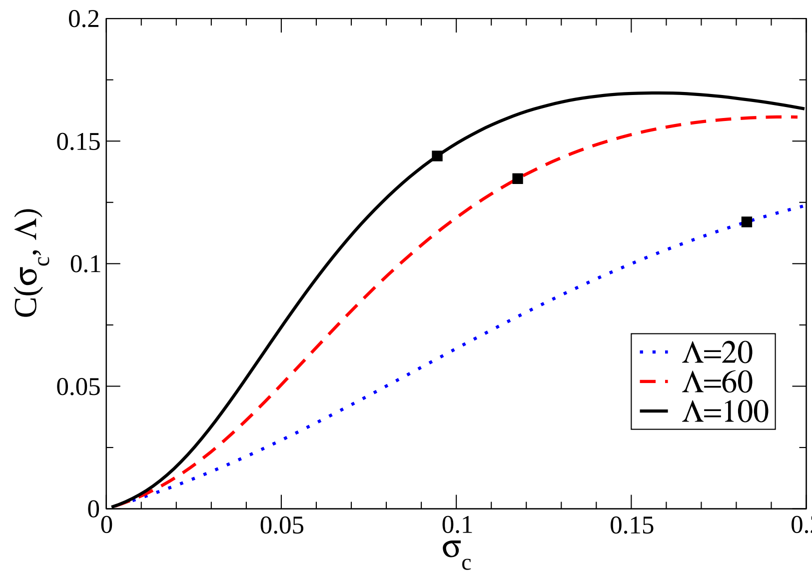


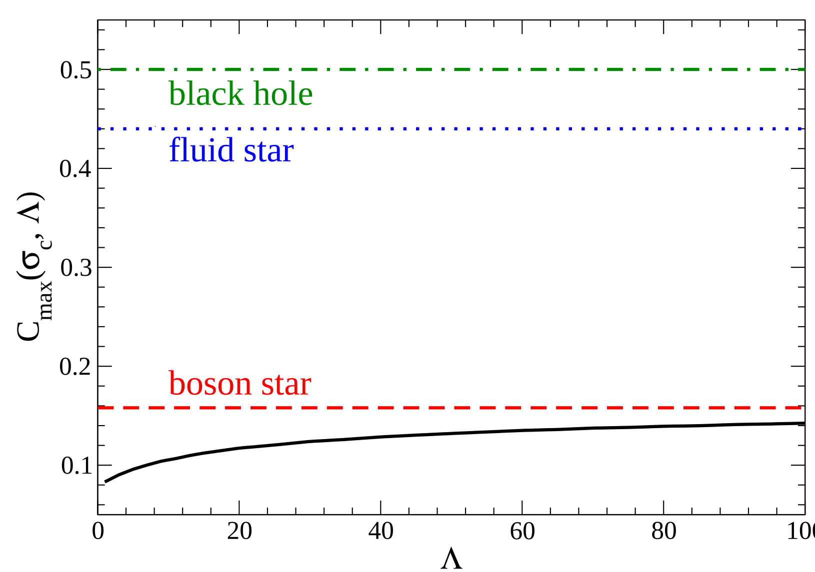


$$M^{max} = \Lambda^{1/2} \frac{m_p^2}{m}$$

Boson stars with self-interaction

$$C(\sigma_c, \Lambda) \equiv \frac{M_{99}(\sigma_c, \Lambda)}{R_{99}} \; ,$$

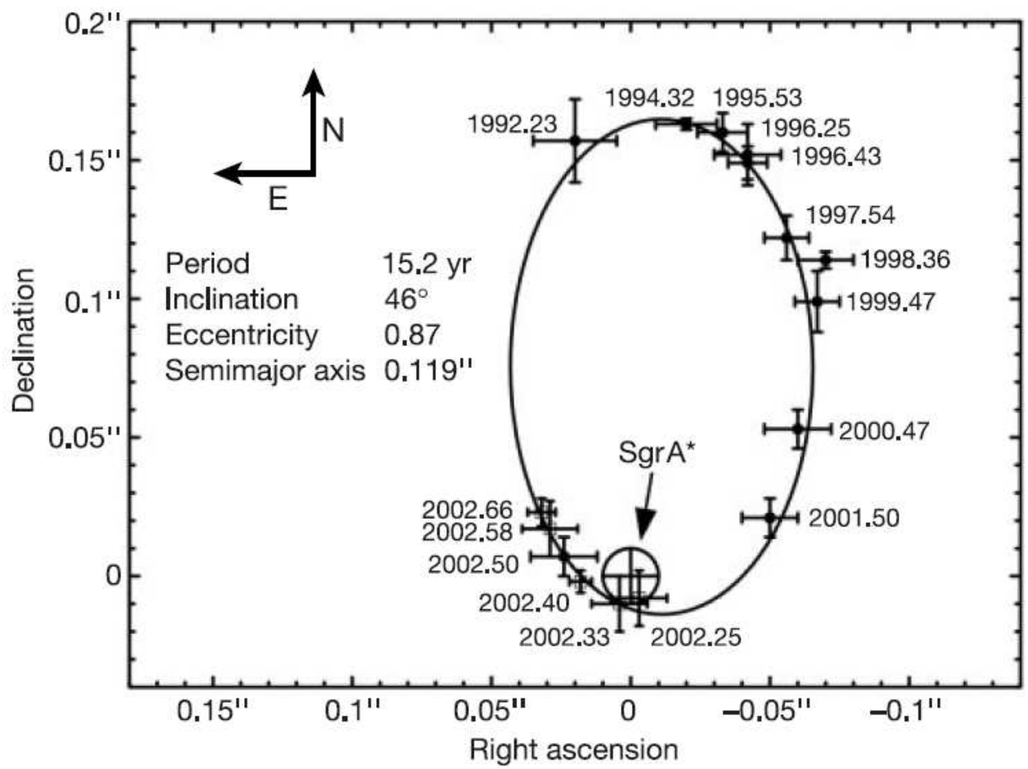




0.0 $< C_{BS}(\sigma_c, \Lambda) <$ 0.158, $M^{max} = \Lambda^{1/2} \frac{m_p^2}{m}$.

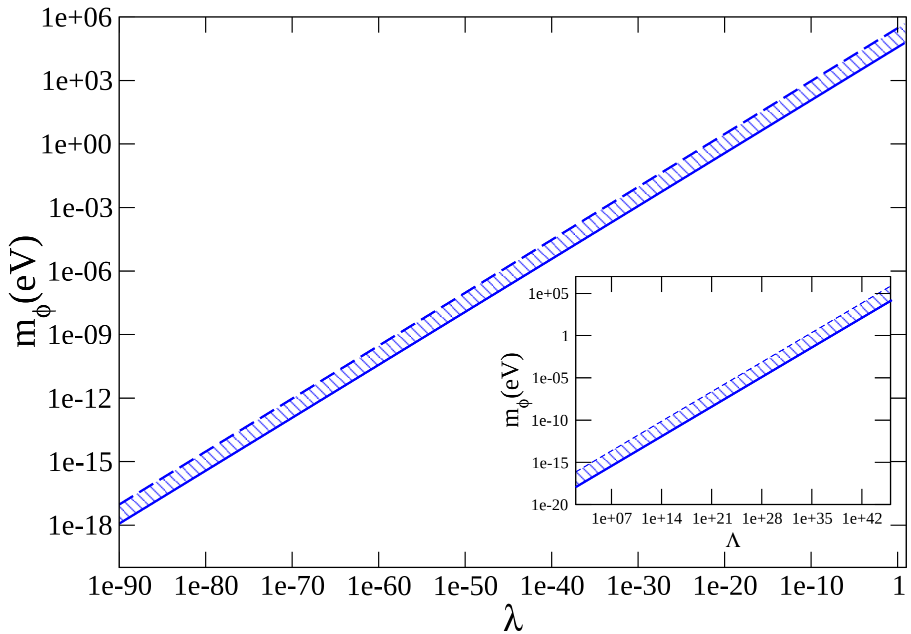
Is there any value of m and λ as to mimic a SMBH?

Can a BS mimic SgrA*?



$$3.32 \times 10^{-4} \simeq C_{\min} \leq C_{\mathsf{BS}} \leq C_{\max} \simeq 0.158 \quad C_{\mathsf{min}} = \frac{M_{\mathsf{Sgr\ A}^*}}{R_{S2}} \simeq \frac{1}{3015}\,.$$

Can a BS mimic SgrA*?

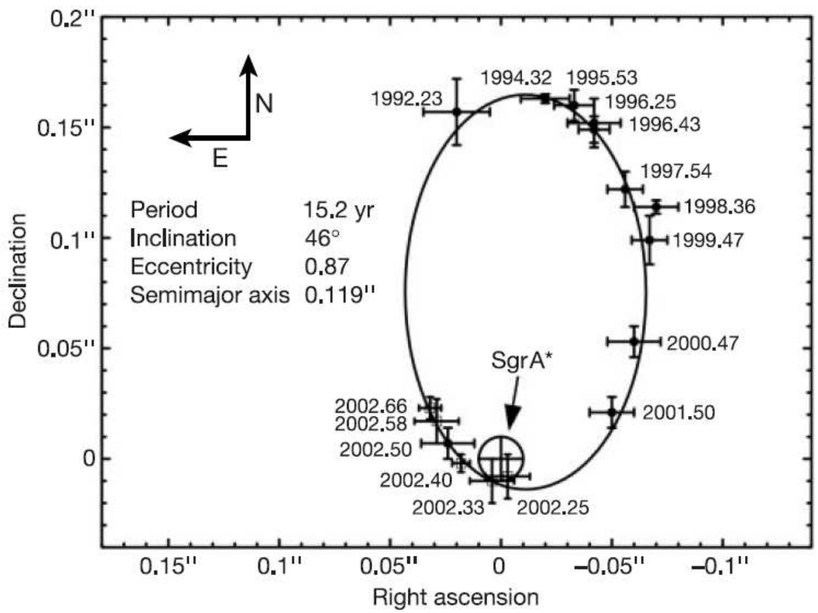


$$m_\phi \geq \frac{M_{\rm min}(\Lambda)}{M_{\rm SgrA^*}} m_P^2 \qquad M_{\rm min}(\Lambda) \equiv C_{\rm min} R(\sigma_c^*)$$

$$m_\phi \leq \frac{M_{\rm max}(\Lambda)}{M_{\rm SgrA^*}}\, m_P^2 \ .$$

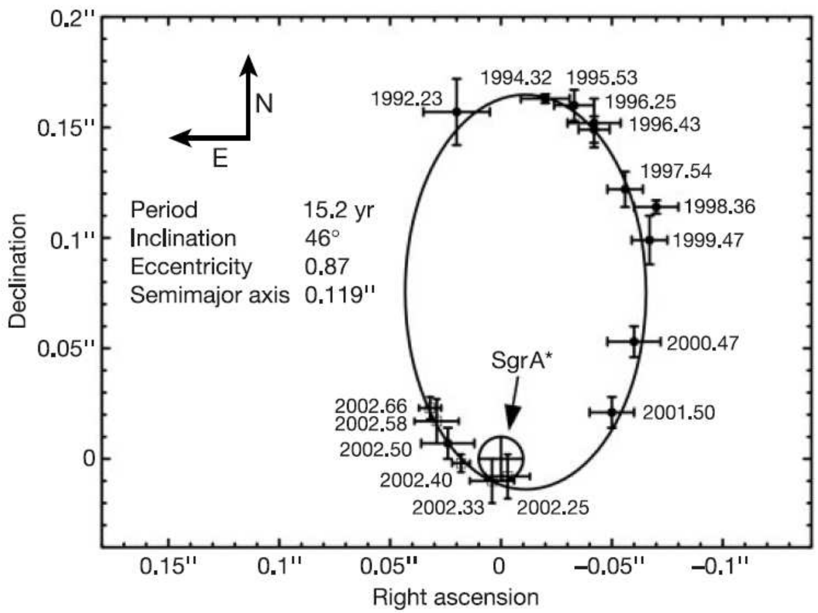
[P. Amaro-Seoane, JB, A. Bernal, L. Rezzolla, JCAP 1011 (2010) 002]

Evidence of SMBH

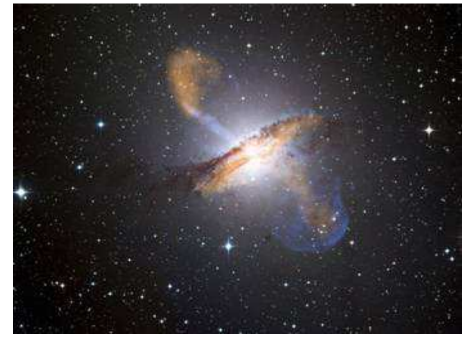


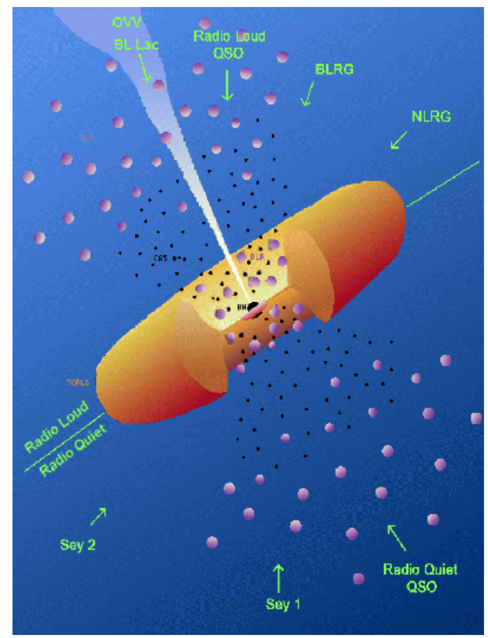
$$M_{BH} = 4.3 \times 10^6 M_\odot$$

Evidence of SMBH



$$M_{BH} = 4.3 \times 10^6 M_\odot$$





$$M_{BH} \sim 10^9 M_\odot$$

SFDM as a viable model for DM

- Another approach: The Scalar Field Dark Matter model (SFDM)
  The Dark Matter is modeled by a scalar field with a ultra-light associated particle. ($m \sim 10^{-23}$eV)
  - At cosmological scales it behaves as cold dark matter
    T. Matos, L.A. Urena-Lopez, Class. Quant. Grav. **17** L75 (2000),

    V. Sahni and L.M. Wang, Phys. Rev D **62**, 103517 (2000).
  - At galactic scales, it does not have its problems: neither a cuspy profile, nor a over-density of satellite galaxies.

    A. Bernal, T. Matos, D. Nuñez, Rev. Mex. A.A. 44, 149 (2008)

    T. Matos, L.A. Urena-Lopez, Phys. Rev. D **63**, 063506 (2001)

Scalar field in a Schwarzschild background

Starting with the Klein-Gordon eqyation

$$(\Box - \mu^2)\phi = 0$$

with

$$\Box := (1/\sqrt{-g})\,\partial_\mu(\sqrt{-g}g^{\mu\nu}\partial_\nu)$$

$$ds^2 = -N(r)dt^2 + \frac{dr^2}{N(r)} + r^2 d\Omega^2 \ , \qquad N(r) := 1 - 2M/r \ ,$$

and

$$\phi(t,r,\theta,\varphi) = \frac{1}{r}\sum_{\ell,m}\psi_{\ell m}(t,r)Y^{\ell m}(\theta,\varphi) \ ,$$

we arrive to:

$$\left[\frac{1}{N(r)}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial r}N(r)\frac{\partial}{\partial r} + \mathcal{U}_\ell(\mu,M;r)\right]\psi_{\ell m} = 0 \ , \qquad \mathcal{U}_\ell(\mu,M;r) := \frac{\ell(\ell+1)}{r^2} + \frac{2M}{r^3} + \mu^2 \ .$$

Scalar field in a Schwarzschild background

We look for stationary solutions:

$$\psi_{\ell m}(t,r) = e^{i\omega_{\ell m} t} u_{\ell m}(r) \ ,$$

$$\left[-N(r)\frac{\partial}{\partial r}\left(N(r)\frac{\partial}{\partial r}\right) + N(r)\,\mathcal{U}_\ell(\mu, M; r)\right] u(r) = \omega^2 u(r) \ , \qquad 2M < r < \infty \ .$$

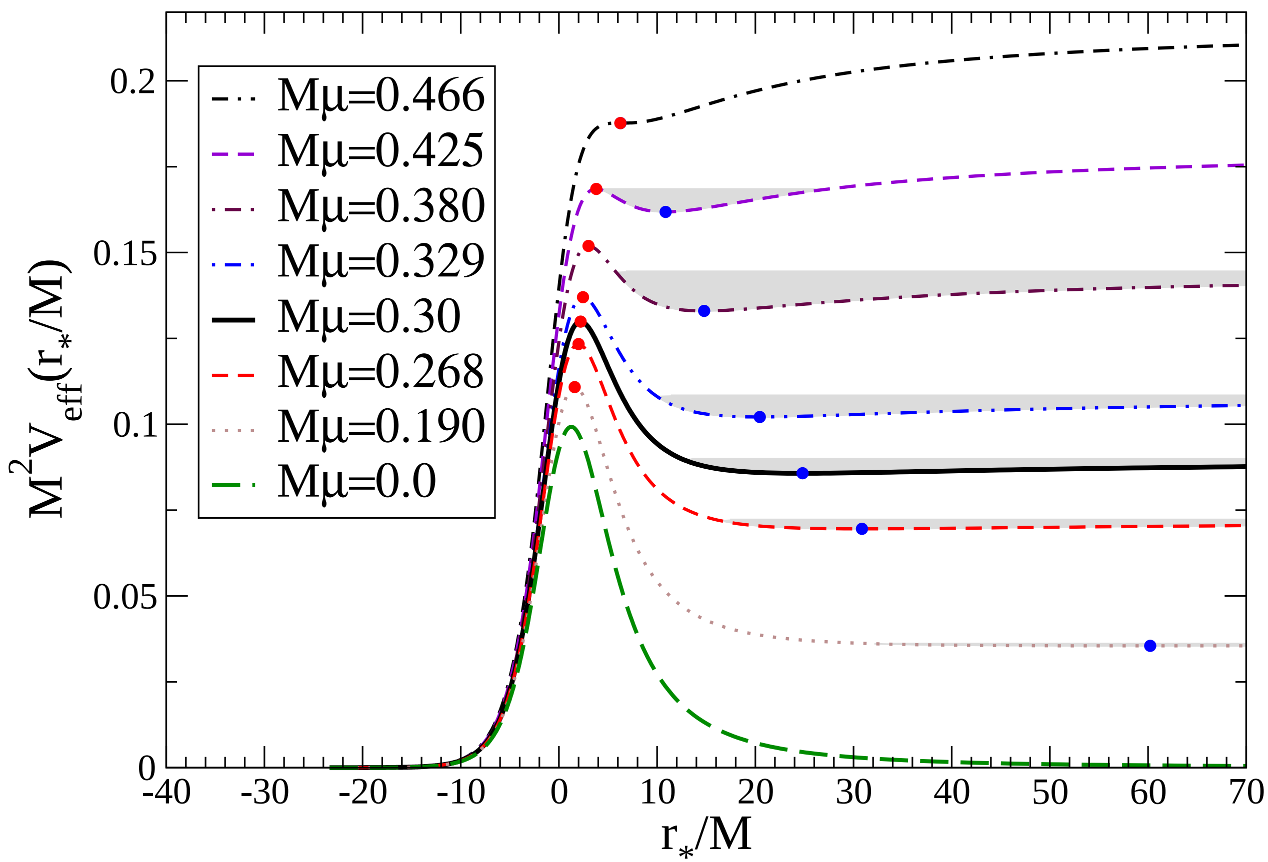
By a change in the coordinates to the Regge-Wheeler coordinates $r^* := r + 2M\ln(r/2M - 1)$, the above equation has the Schrödinger eq. form:

$$\left[-\frac{\partial^2}{\partial r^{*2}} + V_{\text{eff}}(r^*)\right] u(r^*) = \omega^2 u(r^*) \ , \qquad -\infty < r^* < \infty,$$

with an effective potential $V_{\text{eff}}(r^*)$:

$$V_{\text{eff}}(r^*) := N(r)\,\mathcal{U}_\ell(\mu, M; r) \ , \qquad r = r(r^*).$$

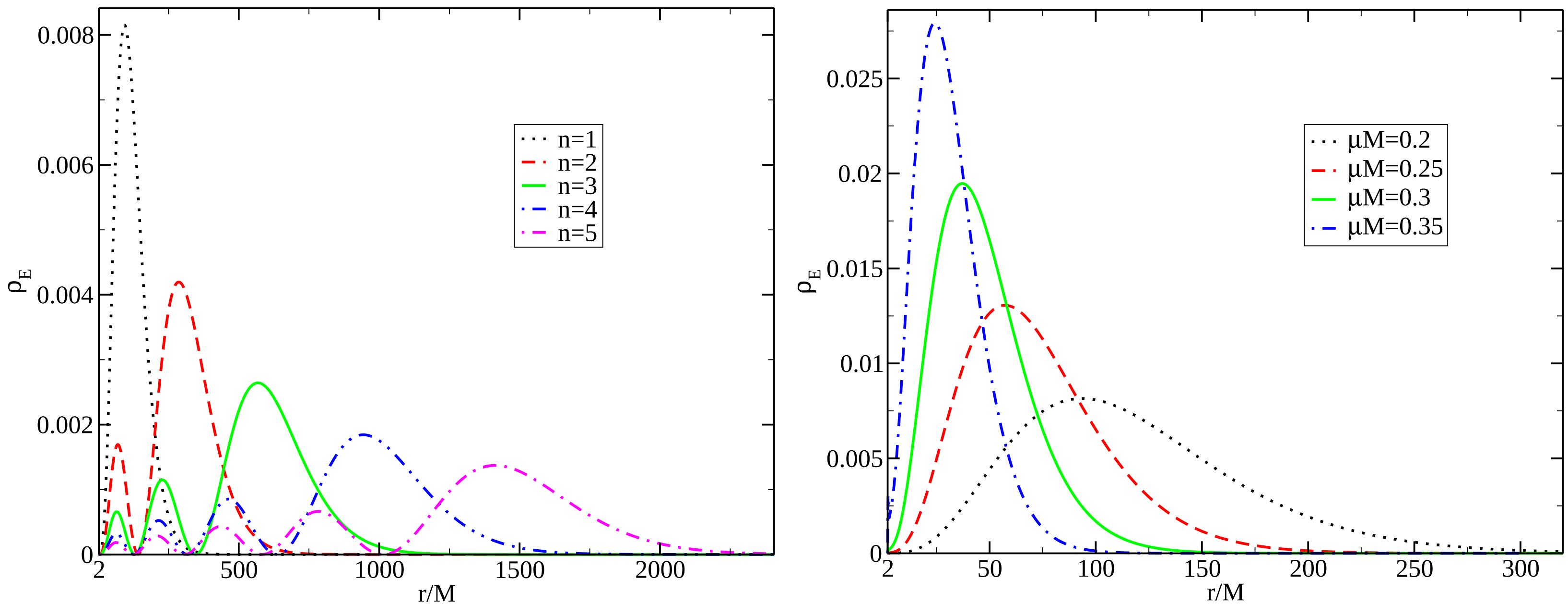
The effective potential:



It has critical points!!!

$$M\mu^2 r^3 - \ell\,(\ell+1)\,r^2 + 3M\,\left(\ell^2+\ell-1\right)r + 8M^2 = 0\ .$$

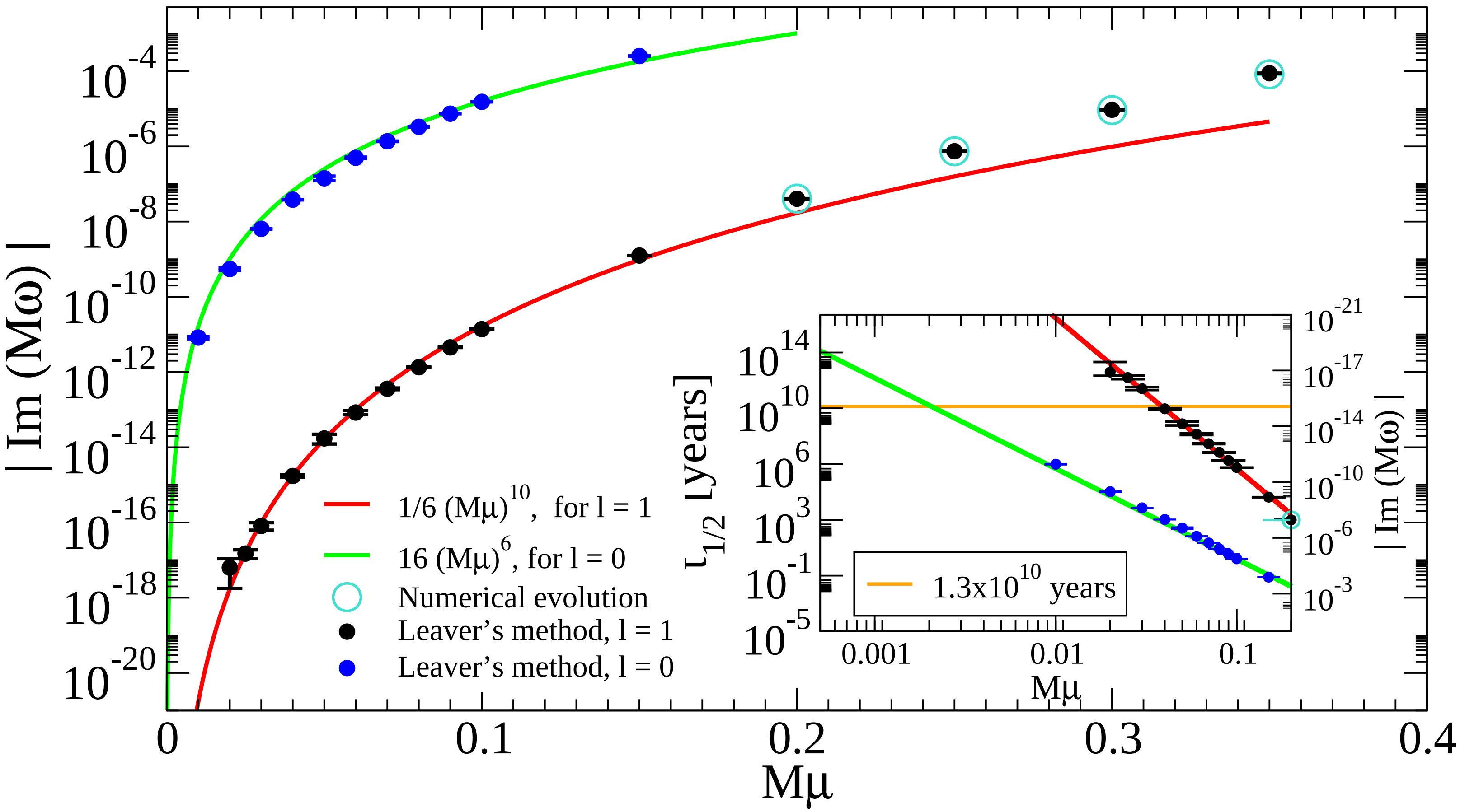
Quasi-resonant modes:



$$\rho_E(r) = \frac{1}{2}\left(\frac{1}{N(r)}\left|\frac{\partial \psi_{\ell m}}{\partial t}\right|^2 + N(r)\left|\frac{\partial \psi_{\ell m}}{\partial r}\right|^2 + \mathcal{U}_\ell(\mu, M; r)|\psi_{\ell m}|^2\right)$$

[Barranco *et al.* Phys.Rev. D84 (2011) 083008]

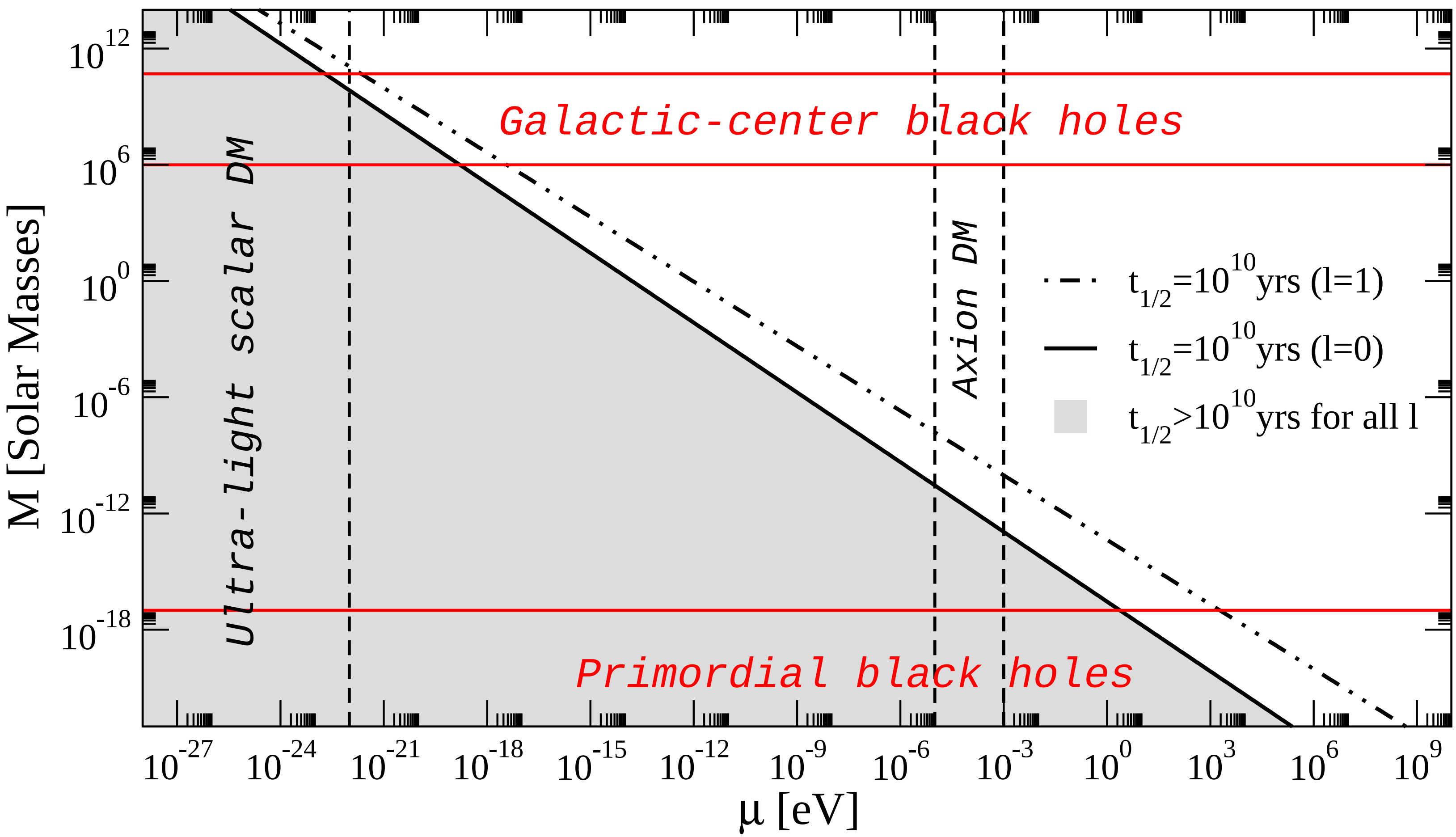
More important!



Schwarzschild black holes can wear scalar wigs

[Barranco *et al.* Phys.Rev.Lett. 109 (2012) 081102]

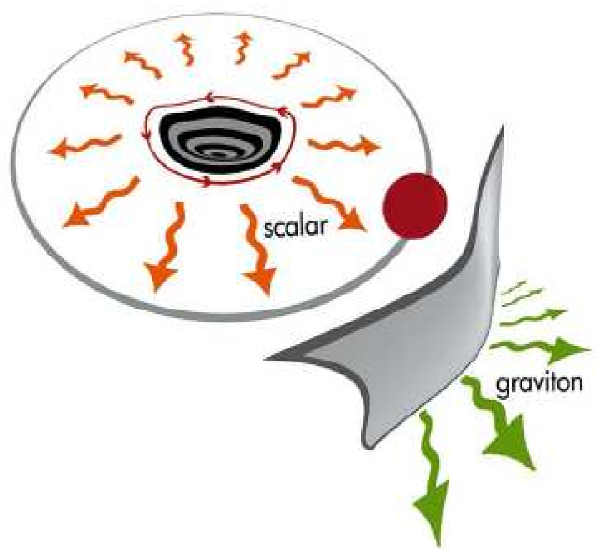
Scalar wigs!



[Barranco *et al.* Phys.Rev.Lett. 109 (2012) 081102]

The black hole bomb

- If the BH is rotating, a bosonic field impinging on a rotating black hole can be amplified through superradiant scattering.
- The scattered wave will then be reflected back and forth between the mass term and the black hole becoming amplified on each reflection.
- The growth of the field is asserted to be exponential and unstable. A black hole bomb



[Press and Teukolsky Nature 238, 211-212 (28 July 1972)]

What about vectorial fields?

The Kerr metric in Boyer-Lindquist coordinates

$$
\begin{aligned}
ds^2_{\rm Kerr} &= -\left(1-\frac{2Mr}{\Sigma}\right)dt^2+\frac{\Sigma}{\Delta}dr^2-\frac{4rM^2}{\Sigma}\tilde{a}\sin^2\vartheta d\varphi dt \\
&+ \Sigma d\vartheta^2+\left[(r^2+M^2\tilde{a}^2)\sin^2\vartheta+\frac{2rM^3}{\Sigma}\tilde{a}^2\sin^4\vartheta\right]d\varphi^2\,,
\end{aligned}
$$

where $\Sigma=r^2+M^2\tilde{a}^2\cos^2\vartheta$, $\Delta=(r-r_+)(r-r_-)$, $r_\pm=M(1\pm\sqrt{1-\tilde{a}^2})$ and M and $J=M^2\tilde{a}$ are the mass and the angular momentum of the BH, respectively.

The Proca equation

(1) $$\nabla_\sigma F^{\sigma\rho}-\mu^2A^\rho=0\,,$$

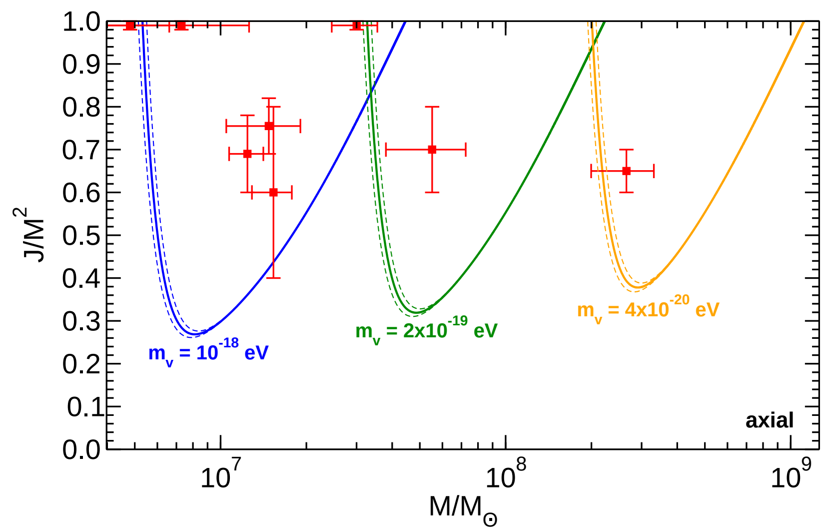
where A_μ is the vector potential, $F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu$ and $m_v=\mu\hbar$ is the mass of the vector field.

The problem: This equation is not separable in the Kerr background.

The strongest limit on photon mass

Nevertheless, Pani *et al.* [Phys.Rev.Lett. 109 (2012) 131102] solved the Proca equation and found:

$$M\omega_I \sim \gamma_{S\ell}\left(\tilde{a}m - 2r_+\mu\right)\left(M\mu\right)^{4\ell+5+2S},$$



It is shown that current supermassive black hole spin estimates provide the tightest upper limits on the mass of the photon $(mv < 4x10^{-20}$ eV.

Conclusions

- If DM is a fermion with no interaction: either
  - it is too light in order to fit the rotational curves of galaxies
  - or it is too heavy in order to evade the microlensing limits
- Axion stars may be an important component of dark matter with some possible observational consequences
- Black holes do not eat everything: They may have wigs, and to avoid the destruction of SMBH, the photon mass should be less than 10^{-20} eV.