ON PRIMORDIAL BLACK HOLES AND DARK MATTER

Michel H.G. Tytgat
Université Libre de Bruxelles
Belgium

CreutzFest 2014
BNL, September 4-5 2014

SAILING IN LONG ISLAND WITH A BIG GUY

4th of August 1996 was DEAD CALM

WHY DARK MATTER?

WHY DARK MATTER?

DARK MATTER

DARK ENERGY

BARYONS

electroweak baryogenesis → finite T QFT

electroweak baryogenesis → CP violation

PHYSICAL REVIEW D VOLUME 52, NUMBER 5 1 SEPTEMBER 1995

Quark masses and chiral symmetry

Michael Creutz*
Physics Department, Brookhaven National Laboratory, Upton, New York, 11973
(Received 10 May 1995)

I discuss the global structure of the strongly interacting gauge theory of quarks and gluons as a function of the quark masses and the CP-violating parameter θ. I concentrate on whether a first order phase transition occurs at $\theta = \pi$. I show why this is expected when multiple flavors have a small degenerate mass. This transition can be removed by sufficient flavor breaking. I speculate on the implications of this structure for Wilson's lattice fermions.

PHYSICAL REVIEW D, VOLUME 61, 114009

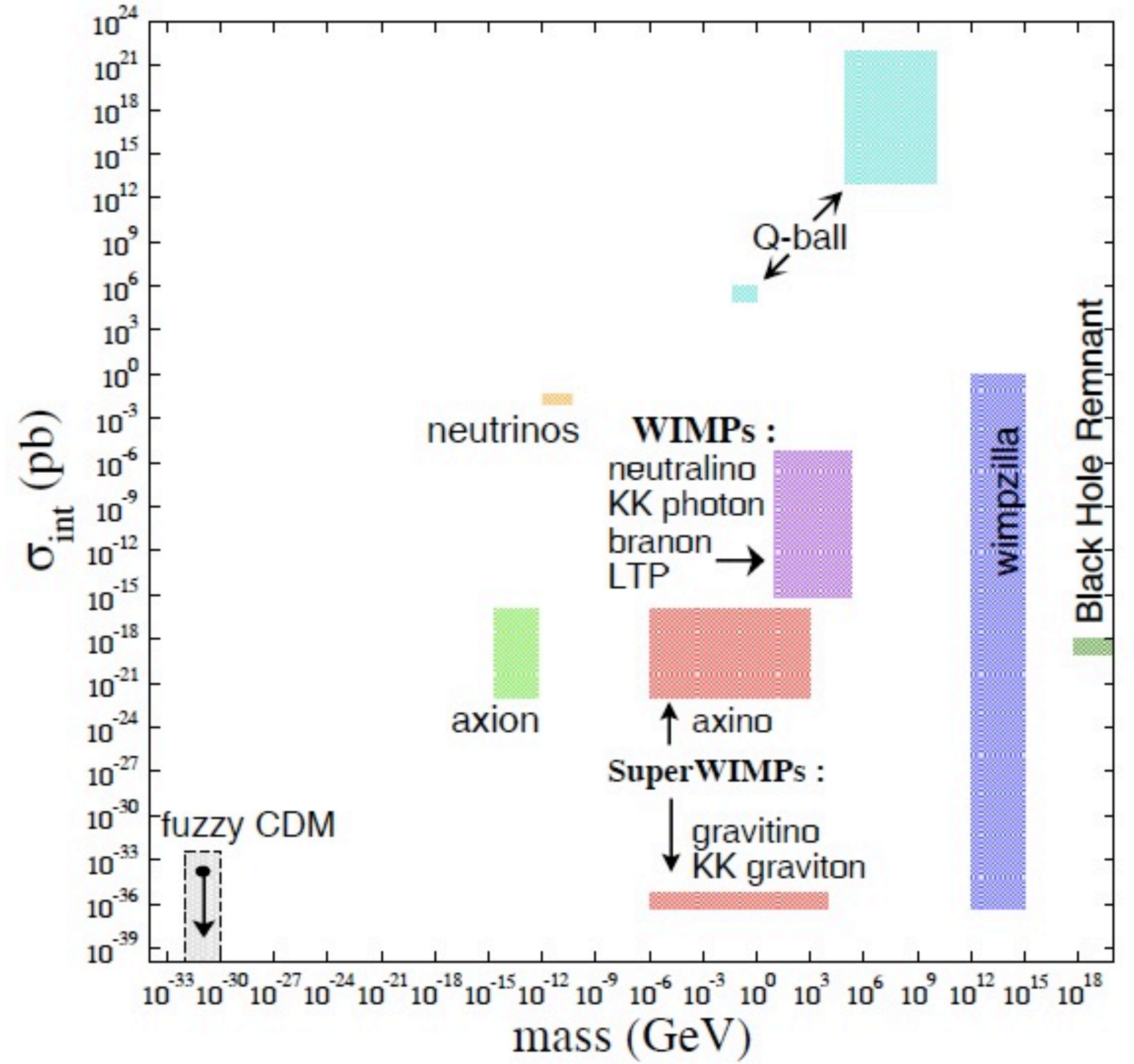
QCD at $\theta \sim \pi$ reexamined: Domain walls and spontaneous CP violation

Michel H. G. Tytgat
Service de Physique Théorique, CP225, Université Libre de Bruxelles, Boulevard du Triomphe, 1050 Bruxelles, Belgium
(Received 1 October 1999; published 8 May 2000)

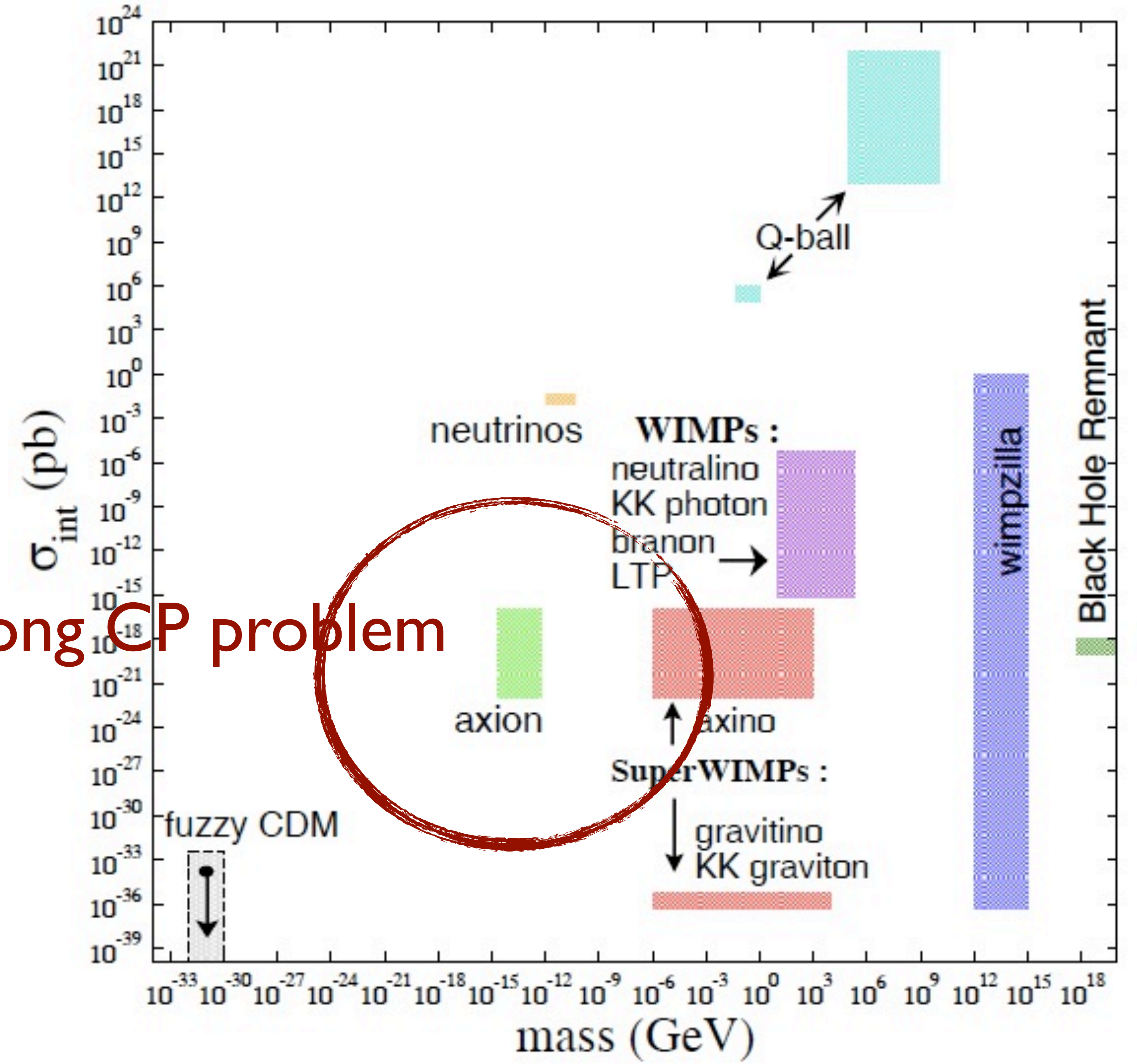
We consider QCD at $\theta \sim \pi$ with two, one and zero light flavors N_f, using the Di Vecchia–Veneziano–Witten effective Lagrangian. For $N_f = 2$, we show that CP is spontaneously broken at $\theta = \pi$ for finite quark mass splittings, $z = m_d/m_u \neq 1$. In the $z - \theta$ plane, there is a line of first order transitions at $\theta = \pi$ with two critical end points, $z_1^* < z < z_2^*$. We compute the tension of the domain walls that relate the two CP violating vacua. For $m_u = m_d$, the tension of the family of equivalent domain walls agrees with the expression derived by Smilga from chiral perturbation theory at next-to-leading order. For $z_1^* < z < z_2^*$, $z \neq 1$, there is only one domain wall and a wall-some sphaleron at $\theta = \pi$. At the critical points, $z = z_{1,2}^*$, the domain wall fades away, CP is restored and the transition becomes of second order. For $N_f = 1$, CP is spontaneously broken only if the number of colors N_c is large and/or if the quark is sufficiently heavy. Taking the heavy quark limit ($\sim N_f = 0$) provides a simple derivation of the multibranch θ dependence of the vacuum energy of large N_c pure Yang-Mills theory. In the large N_c limit, there are many quasistable vacua with a decay rate $\Gamma \sim \exp(-N_c^4)$.

WHY DARK MATTER?

WHICH DARK MATTER?

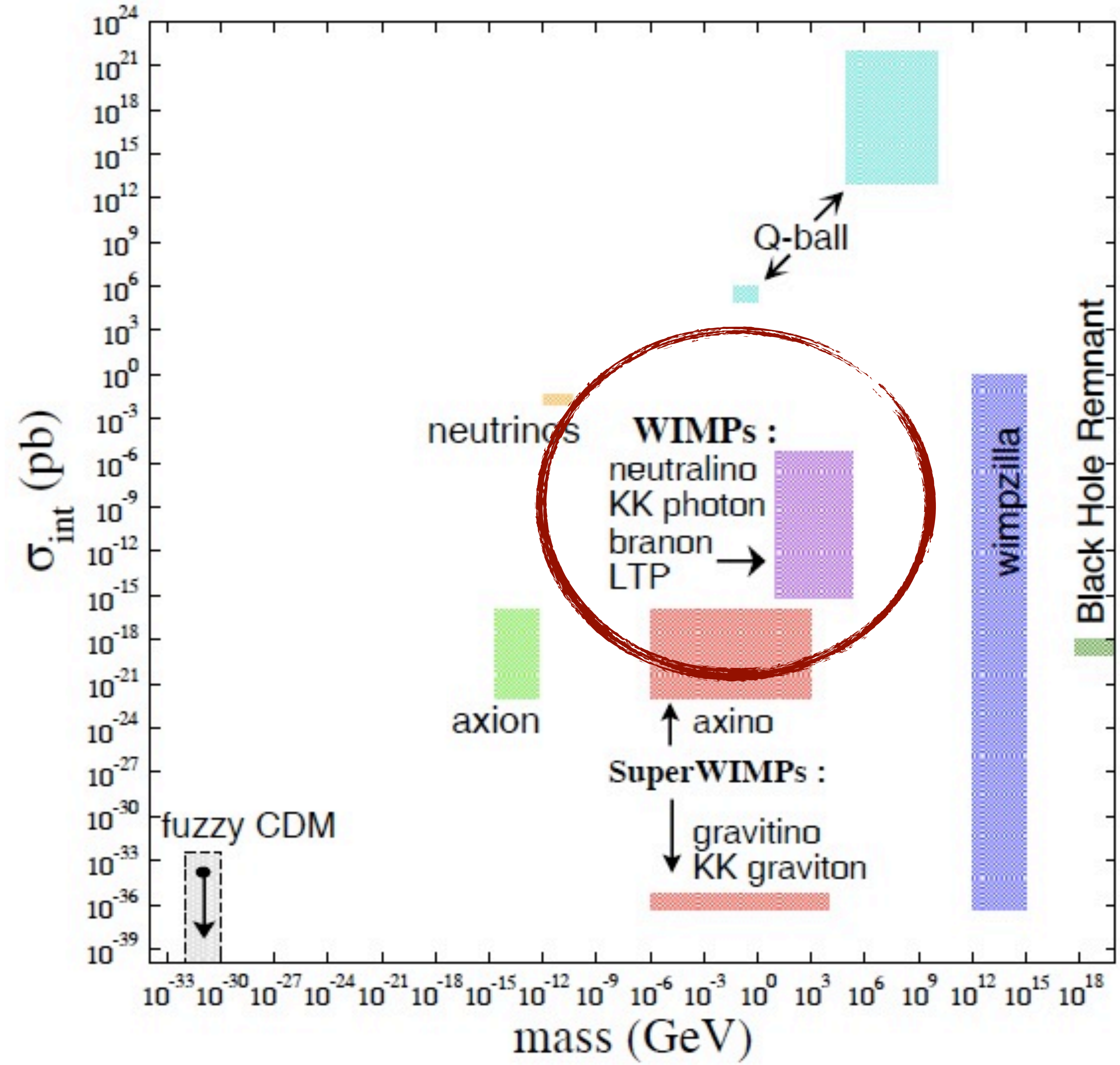


WHICH DARK MATTER?



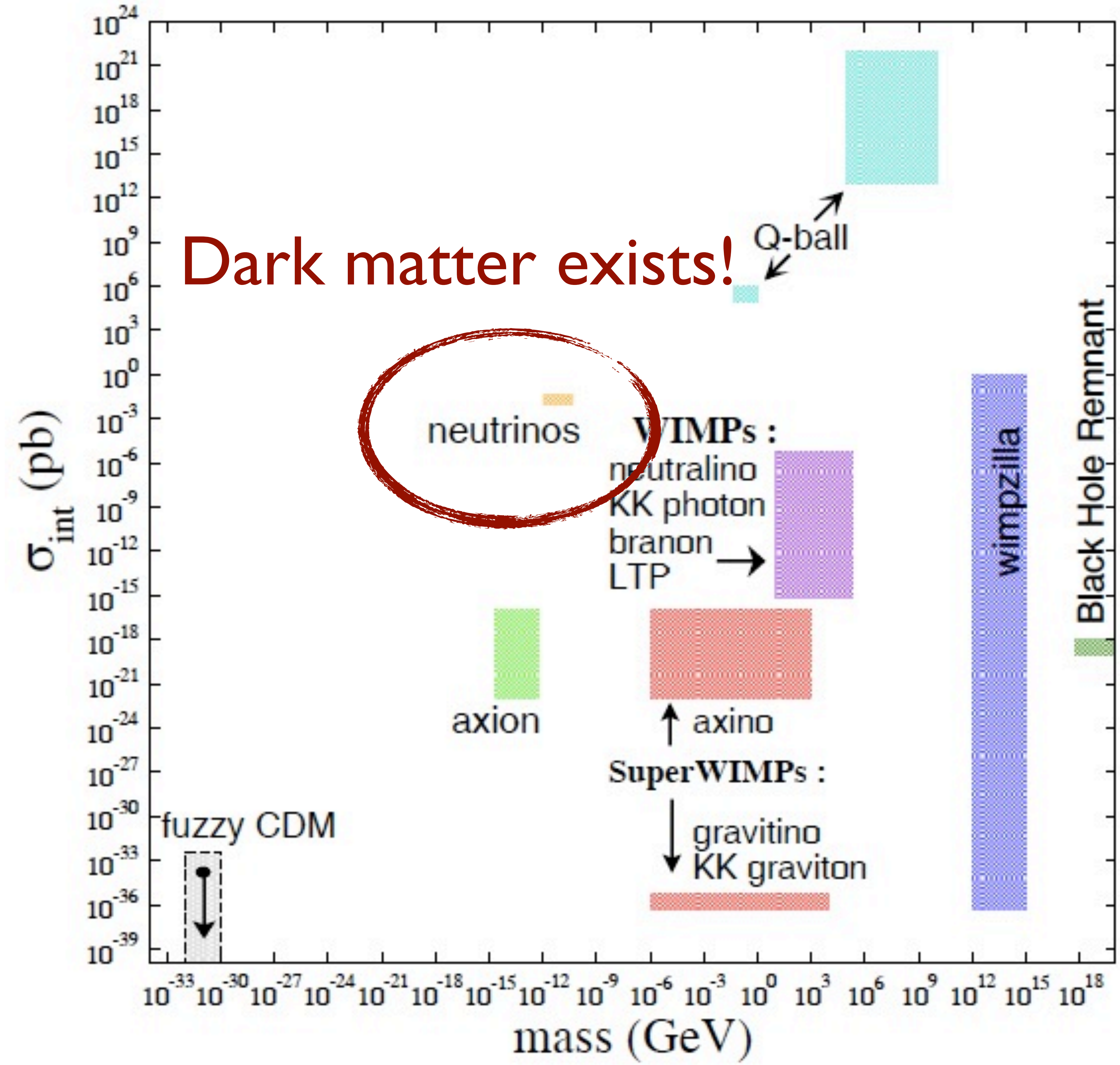
Strong CP problem

WHICH DARK MATTER?



DO YOU THINK IT'S A NEUTRALINO?!
I'D SAY IT'S A GRAVITINO!
NO, A SNEUTRINO!
TO ME, IT LOOKS LIKE A BIT OF SPIT...
FIAMI

WHICH DARK MATTER?



NEUTRON STAR

PHYSICAL REVIEW D VOLUME 57, NUMBER 10 15 MAY 1998

Neutrino ground state in a dense star

Ken Kiers*
High Energy Theory, Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000

Michel H. G. Tytgat†
High Energy Theory, Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000
and Service de Physique Théorique, Université Libre de Bruxelles, CP225 Bd du Triomphe, 1050 Bruxelles, Belgium

(Received 23 December 1997; published 21 April 1998)

It has recently been argued that long range forces due to the exchange of massless neutrinos give rise to a very large self-energy in a dense, finite-ranged, weakly charged medium. Such an effect, if real, would destabilize a neutron star. To address this issue we have studied the related problem of a massless neutrino field in the presence of an external, static electroweak potential of finite range. To be precise, we have computed to one loop the exact vacuum energy for the case of a spherical square well potential of depth α and radius R. For small wells, the vacuum energy is reliably determined by a perturbative expansion in the external potential. For large wells, however, the perturbative expansion breaks down. A manifestation of this breakdown is that the vacuum carries a non-zero neutrino charge. The energy and neutrino charge of the ground state are, to a good approximation for large wells, those of a neutrino condensate with chemical potential $\mu=\alpha$. Our results demonstrate explicitly that long-range forces due to the exchange of massless neutrinos do not threaten the stability of neutron stars. [S0556-2821(98)00710-3]

Long-Range Forces and Neutrino Mass

EPHRAIM FISCHBACH*

Physics Department, Purdue University, West Lafayette, Indiana 47907-1396

Received June 21, 1995; revised August 17, 1995

We explore the limits on neutrino mass which follow from a study of the long-range forces that arise from the exchange of massless or ultra-light neutrinos. Although the 2-body neutrino-exchange force is unobservably small, the many-body force can generate a very large energy density in neutron stars and white dwarfs. We discuss the novel features of neutrino-exchange forces which lead to large many-body effects, and present the formalism that allows these effects to be calculated explicitly in the Standard Model. After considering, and excluding, several possibilities for avoiding the unphysically large contributions from the exchange of massless neutrinos, we develop a formalism to describe the exchange of massive neutrinos. It is shown that the stability of both neutron stars and white dwarfs in the presence of many-body neutrino-exchange forces implies a lower bound, $m \gtrsim 0.4\ \mathrm{eV}/c^2$ on the mass m of any neutrino.

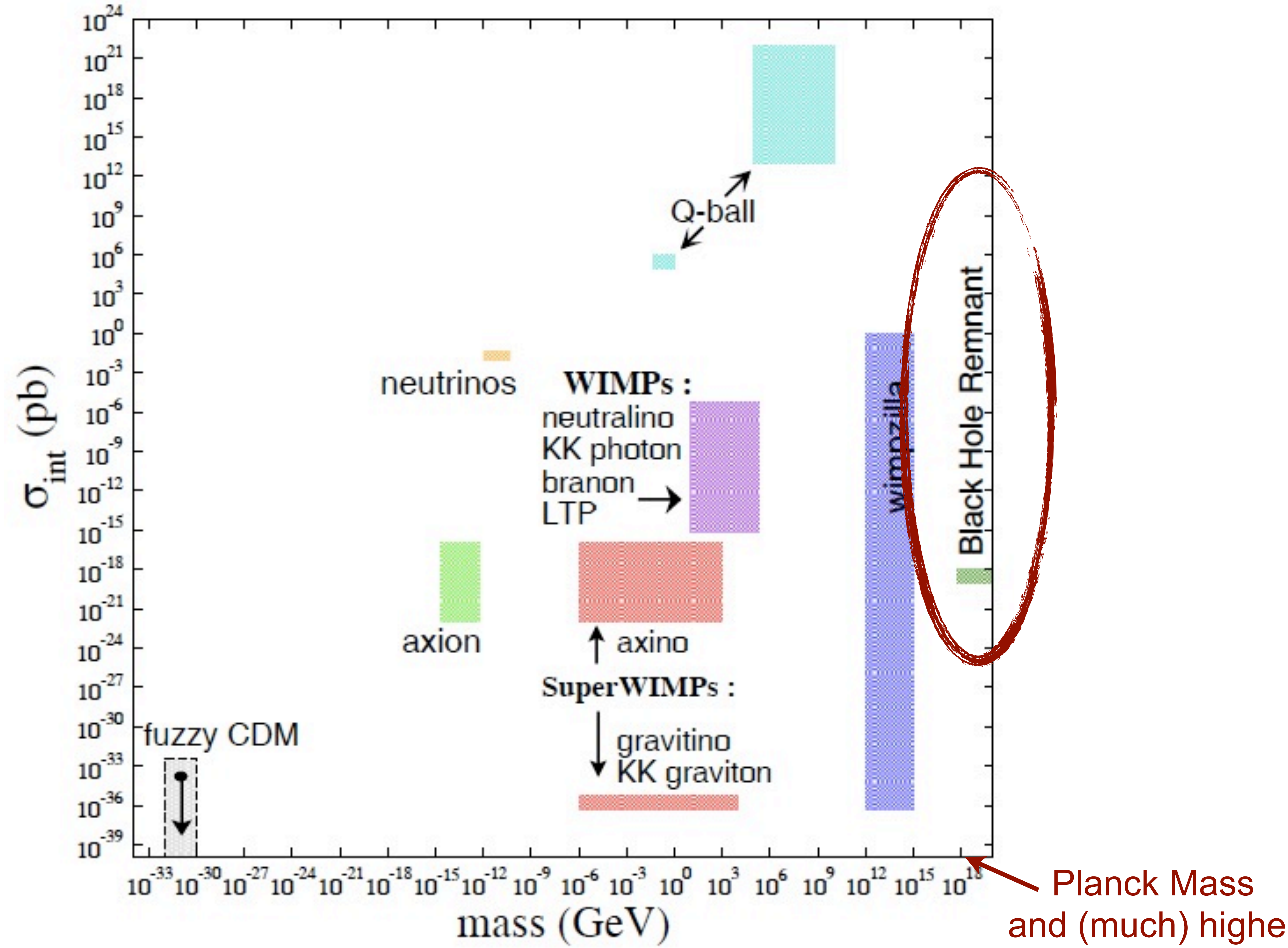
FORMALLY A DIVERGENT SUM

$$\Delta E \sim \sum_{k}^{\mathrm{neut}} \frac{1}{k} \frac{1}{R_{NS}} \left(V_{MSW} R_{NS}\right)^{k}$$

with $V_{MSW} \approx 20\,\mathrm{eV}$ (Mikheyev-Smirnov-Wolfenstein potential)

then $V_{MSW} R_{NS} \sim 10^{12}$ **for a neutron star**

WHICH DARK MATTER?



CONSTRAINTS ON PRIMORDIAL BH

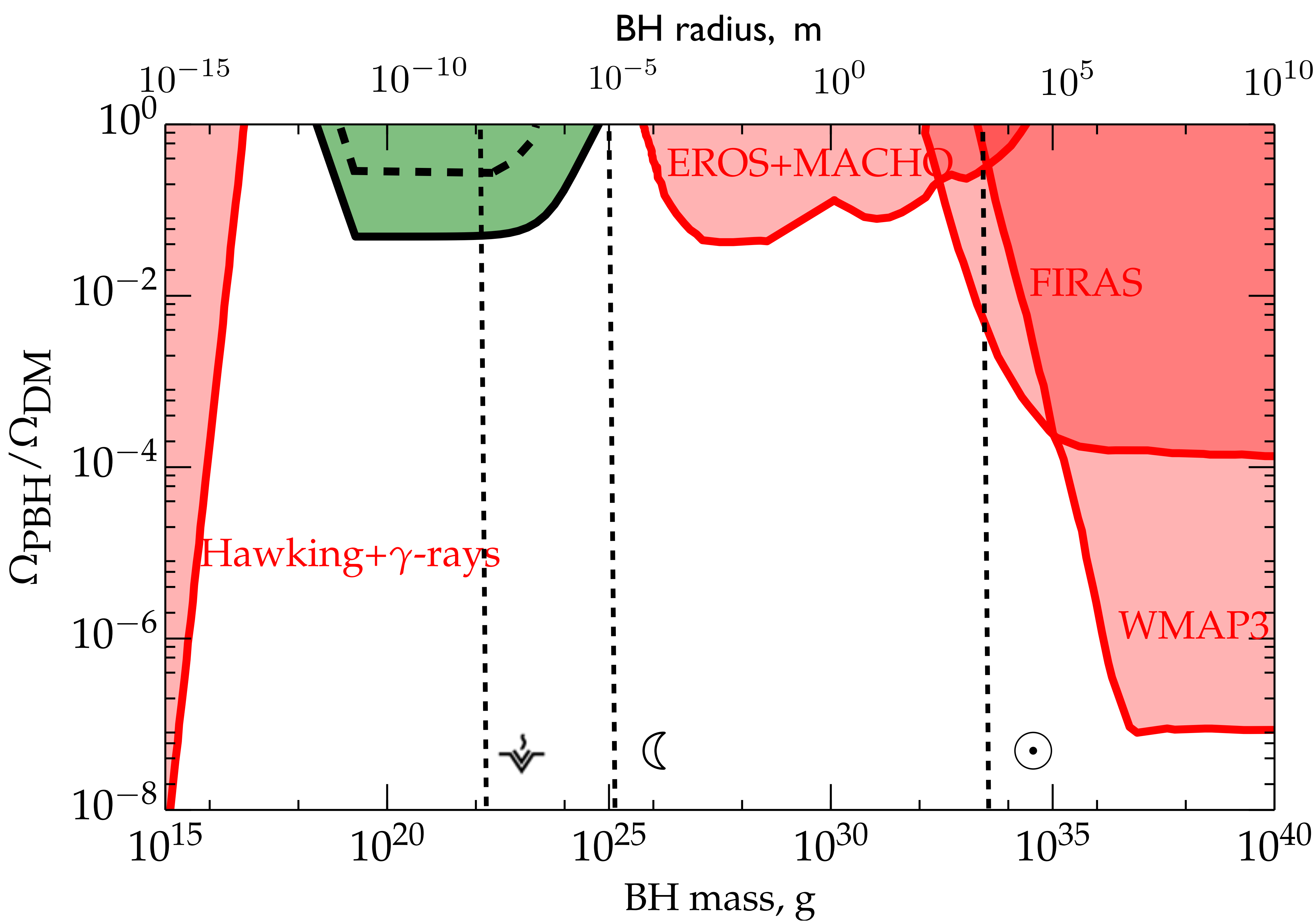


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

CONSTRAINTS ON PRIMORDIAL BH

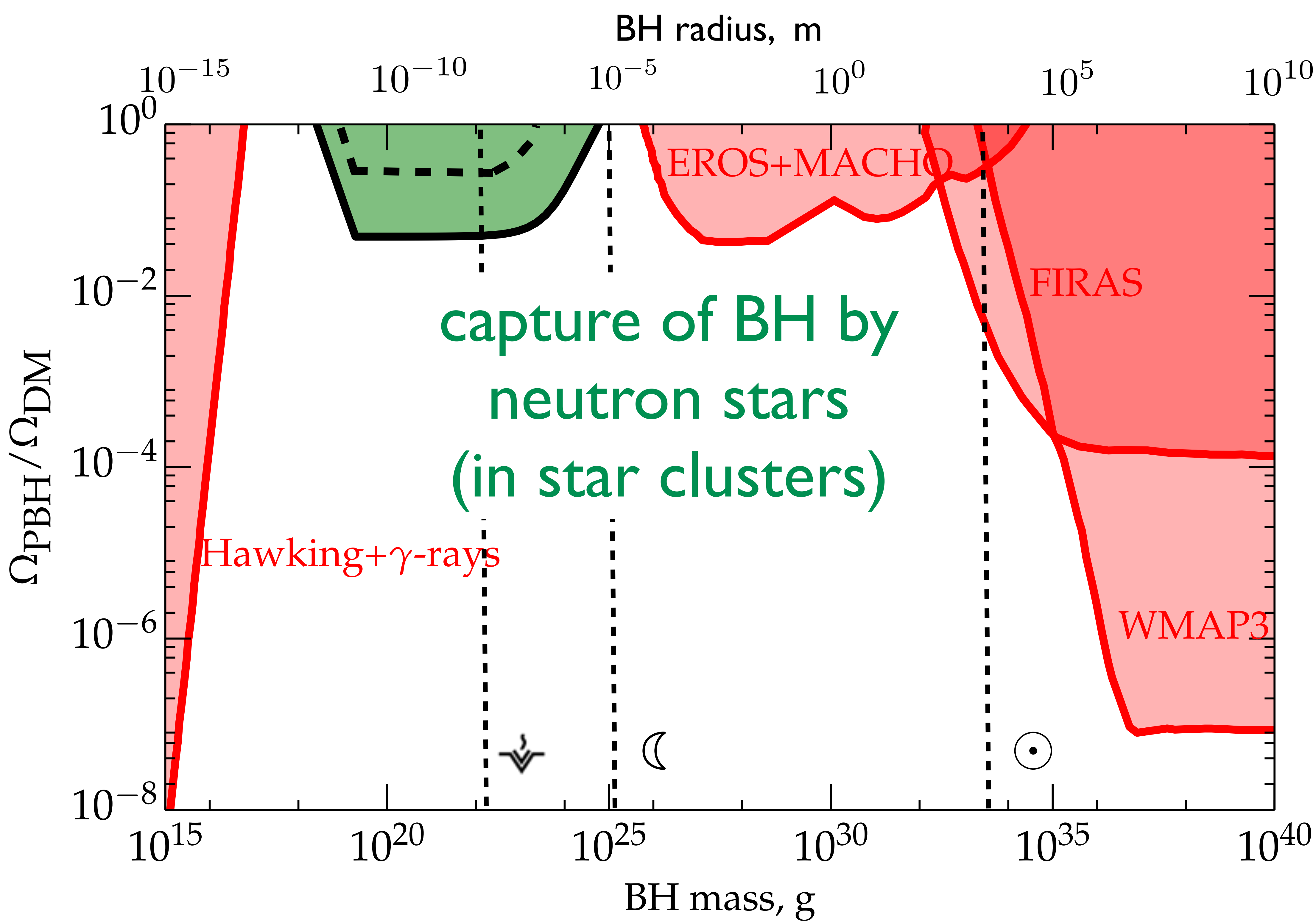
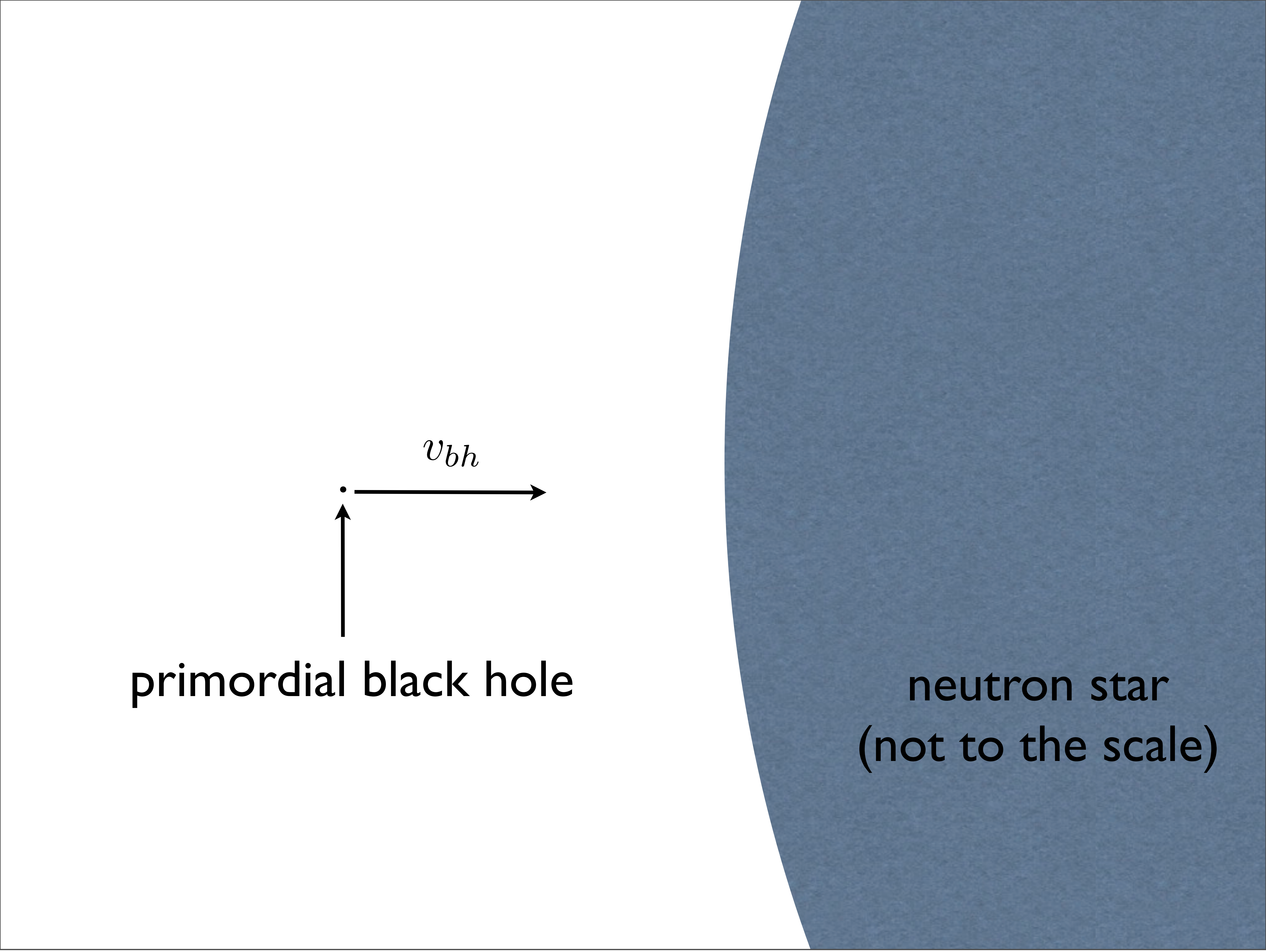
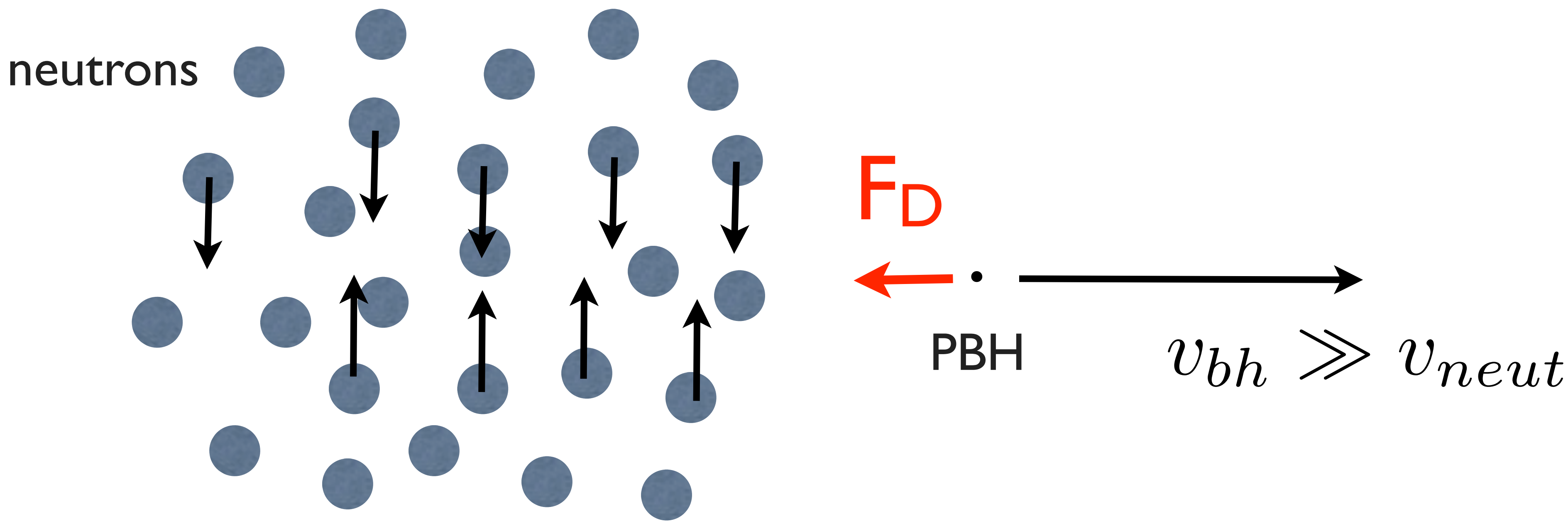


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov


v_{bh}
primordial black hole
neutron star
(not to the scale)

CAPTURE BY DYNAMICAL FRICTION



$$-\frac{dE}{dx} \approx \frac{4\pi G^2 M_{bh}^2 \rho}{v_{bh}^2} \log \frac{b_{max}}{b_{min}} \longrightarrow E_{loss} \sim \frac{G M_{bh}^2}{R_{ns}}$$

S. Chandrasekhar (1947)

CONSTRAINTS ON PRIMORDIAL BH

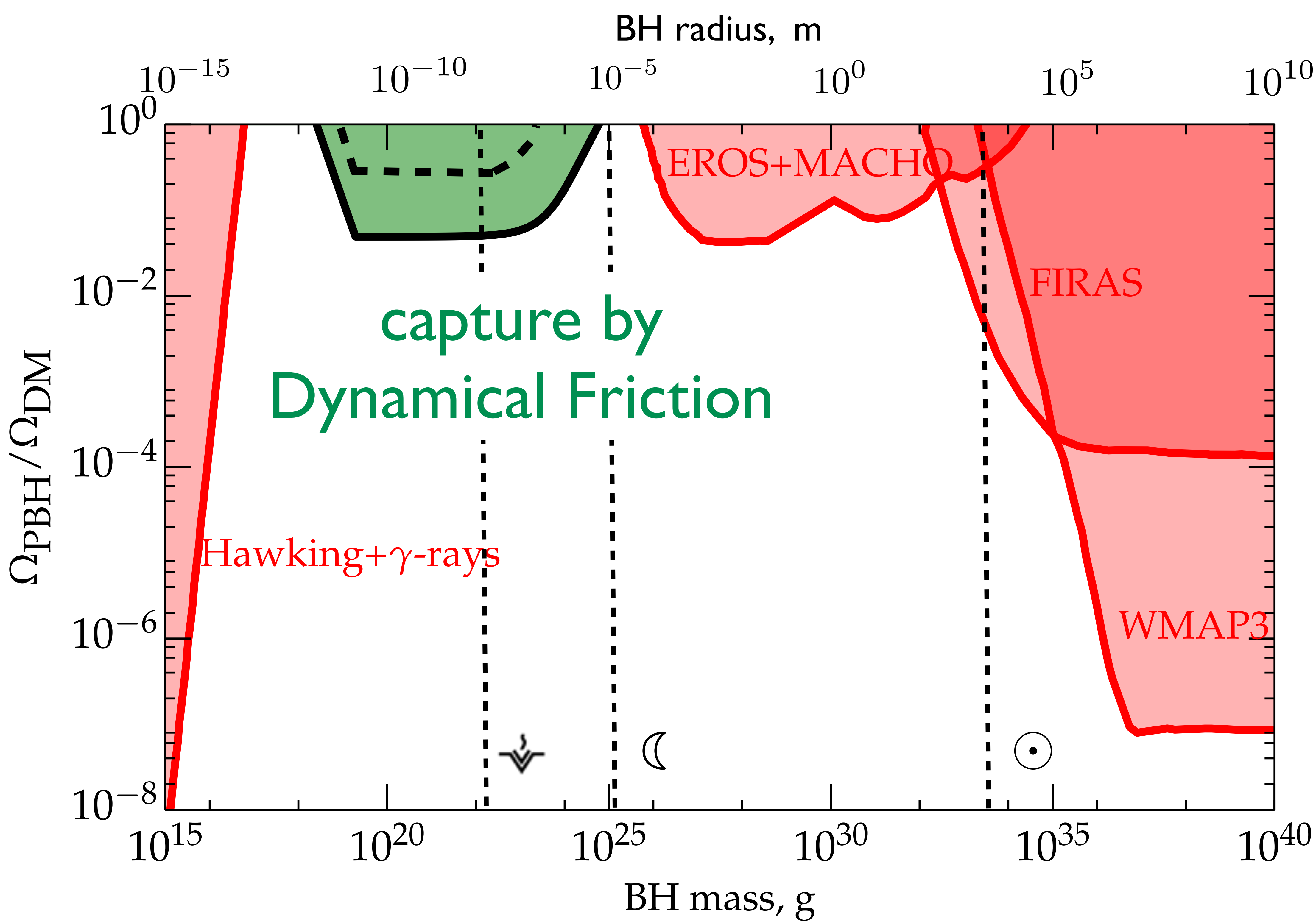


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

Tidal capture of a primordial black hole by a neutron star: implications for constraints on dark matter

Paolo Pani[a,b] **Abraham Loeb**[b]

[a]CENTRA, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal.

[b]Institute for Theory and Computation, Harvard-Smithsonian CfA, 60 Garden Street, Cambridge MA 02138, USA

E-mail: paolo.pani@tecnico.ulisboa.pt, aloeb@cfa.harvard.edu

Abstract. In a close encounter with a neutron star, a primordial black hole can get gravitationally captured by depositing a considerable amount of energy into nonradial stellar modes of very high angular number l. If the neutron-star equation of state is sufficiently stiff, we show that the total energy loss in the point-particle approximation is formally divergent. Various mechanisms – including viscosity, finite-size effects and the elasticity of the crust – can damp high-l modes and regularize the total energy loss. Within a short time, the black hole is trapped inside the star and disrupts it by rapid accretion. Estimating these effects, we predict that the existence of old neutron stars in regions where the dark-matter density $\rho_{\rm DM} \gtrsim 10^2(\sigma/\text{km s}^{-1})\text{GeV cm}^{-3}$ (where σ is the dark-matter velocity dispersion) limits the abundance of primordial black holes in the mass range $10^{17}\text{g} \lesssim m_{\rm PBH} \lesssim 10^{24}\text{g}$, which was previously unconstrained. In combination with existing limits, our results suggest that primordial black holes cannot be the dominant dark matter constituent.

$$E_{\rm loss} \sim \frac{GM_{bh}^2}{R_{ns}} \sum_{l=2}^{l_{max}} \frac{1}{l^n}$$

same as dynamical friction

but sum on modes (spherical harmonics) formally divergent (worse case: n=0 for an incompressible fluid)

Compared to DF, claim an enhancement of O(10^6-10^9)

CONSTRAINTS ON PRIMORDIAL BH

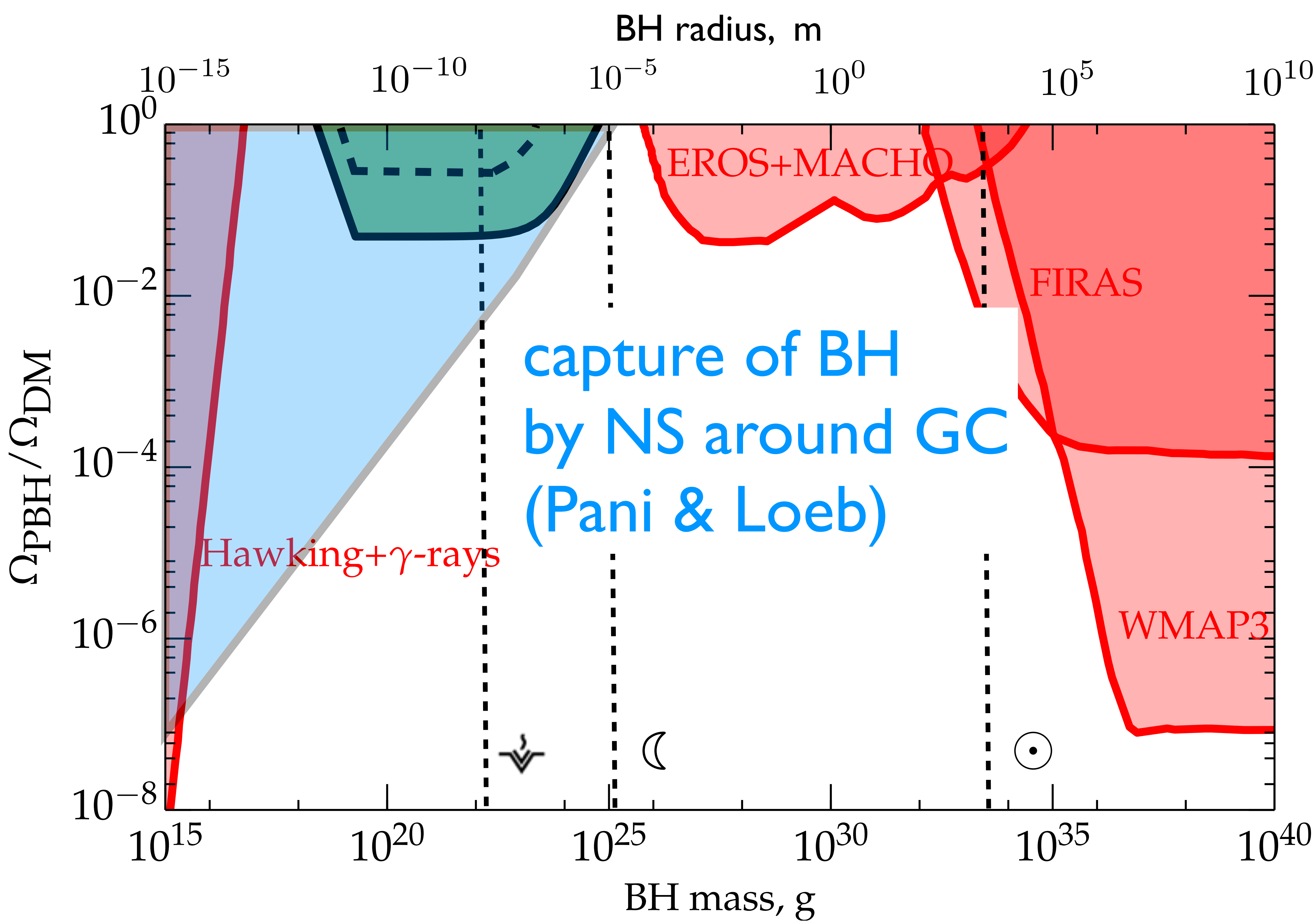


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

Basically excludes Primordial Black Holes as the dominant form of DM

Unfortunately (we think) it’s incorrect

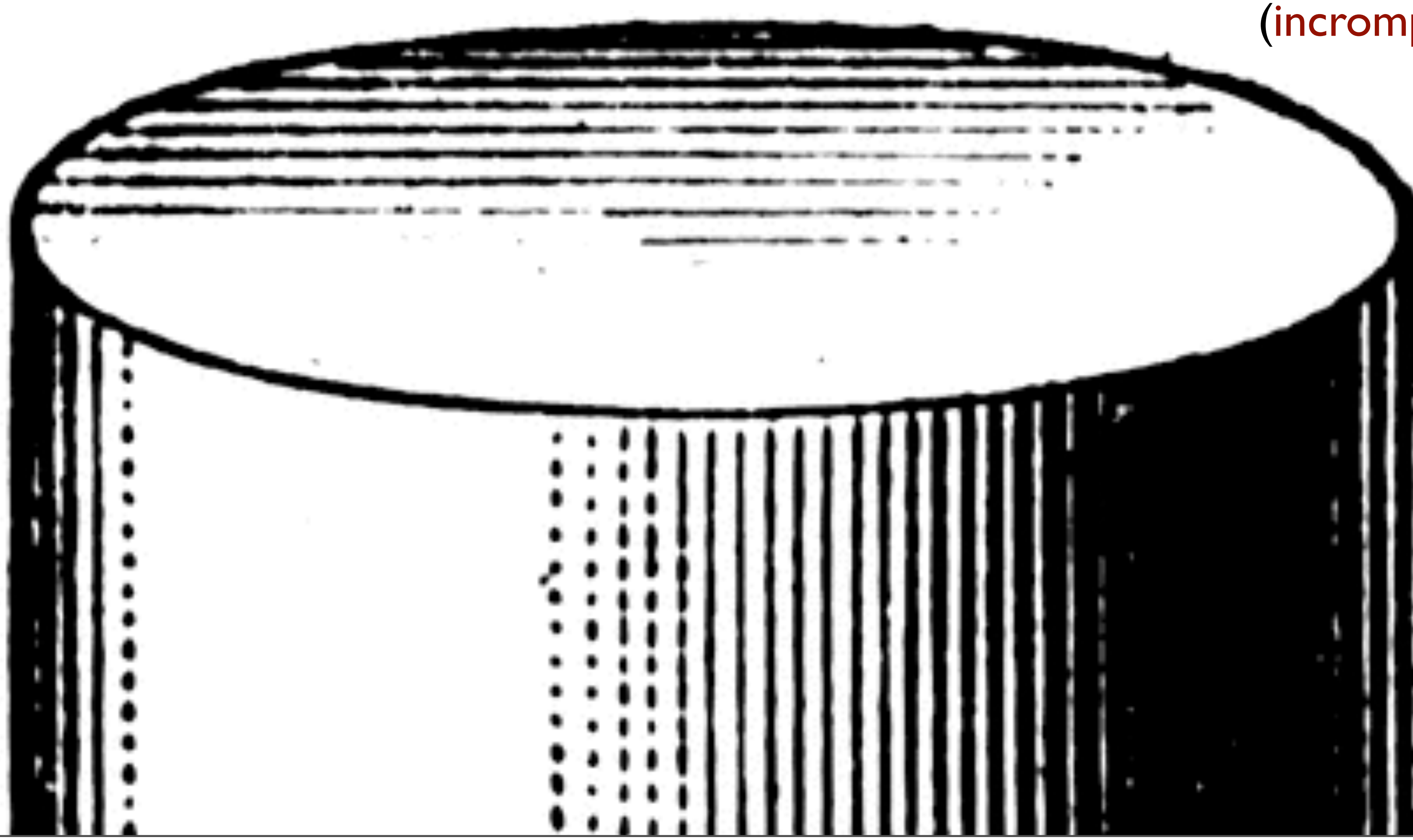
It’s a UV problem, so go planar

primordial black hole $\longrightarrow$ $\cdot$

$\downarrow v_{bh}$

flat ‘neutron star’

(incrompressible fluid)



In this limit the problem may be solved analytically (instead of numerically)

Petr Tinyakov, M.T. (ULB, Brussels)
Guillaume Petillon, Etienne Granet (Ecole Polytechnique, Paris)
arXiv:1409.0469

SURFACE DEFORMATION

$$\eta(t,r) = \frac{GM_{bh}}{g} \int dk \frac{1}{1 + kv_{bh}^2/g} \left[e^{-kv_{bh}|t|} + 2\theta(t) v_{bh} \sqrt{\frac{k}{g}} \sin(\omega_k t) \right] J_0(kr)$$

surface gravity

mode velocity $v_{wave} = \sqrt{\frac{g}{k}}$

SURFACE DEFORMATION

$$\eta(t,r) = \frac{GM_{bh}}{g} \int dk \frac{1}{1 + kv_{bh}^2/g} \left[e^{-kv_{bh}|t|} + 2\theta(t) v_{bh} \sqrt{\frac{k}{g}} \sin(\omega_k t) \right] J_0(kr)$$

surface gravity

mode velocity

$$v_{wave} = \sqrt{\frac{g}{k}}$$

Taken from “From boats to antimatter”, a talk by Mike Creutz (when and where I don’t know)

Water Waves

$v_p \neq v_g$ occurs often, including with water

My favorite example of dimensional analysis: how fast are water waves

v_p might be a function of several things

- λ, wavelength, measured in some units of length, L
- g, gravitational pull, units of acceleration, L/T^2
- ρ, density, units of mass per cubic length, M/L^3

From these construct a velocity, with units of length per time, L/T

- only one combination has the right units $L/T = \sqrt{L \times L/T^2}$

$$v_p \sim \sqrt{\lambda g}$$

SURFACE DEFORMATION

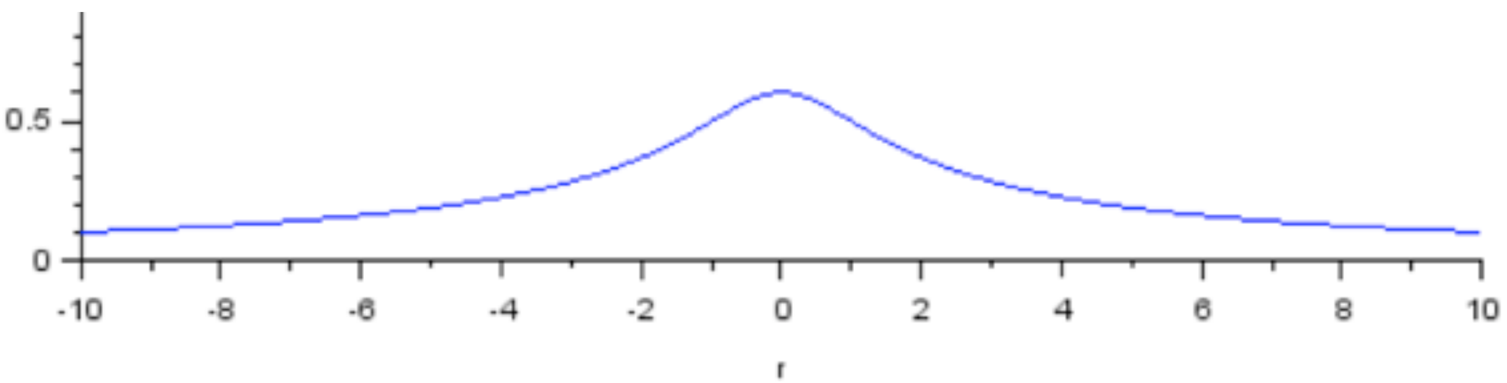
$$\eta(t,r) = \frac{GM_{bh}}{g}\int dk\,\frac{1}{1+kv_{bh}^2/g}\left[e^{-kv_{bh}|t|} + 2\theta(t)\,v_{bh}\sqrt{\frac{k}{g}}\,\sin(\omega_k t)\right] J_0(kr)$$

surface gravity

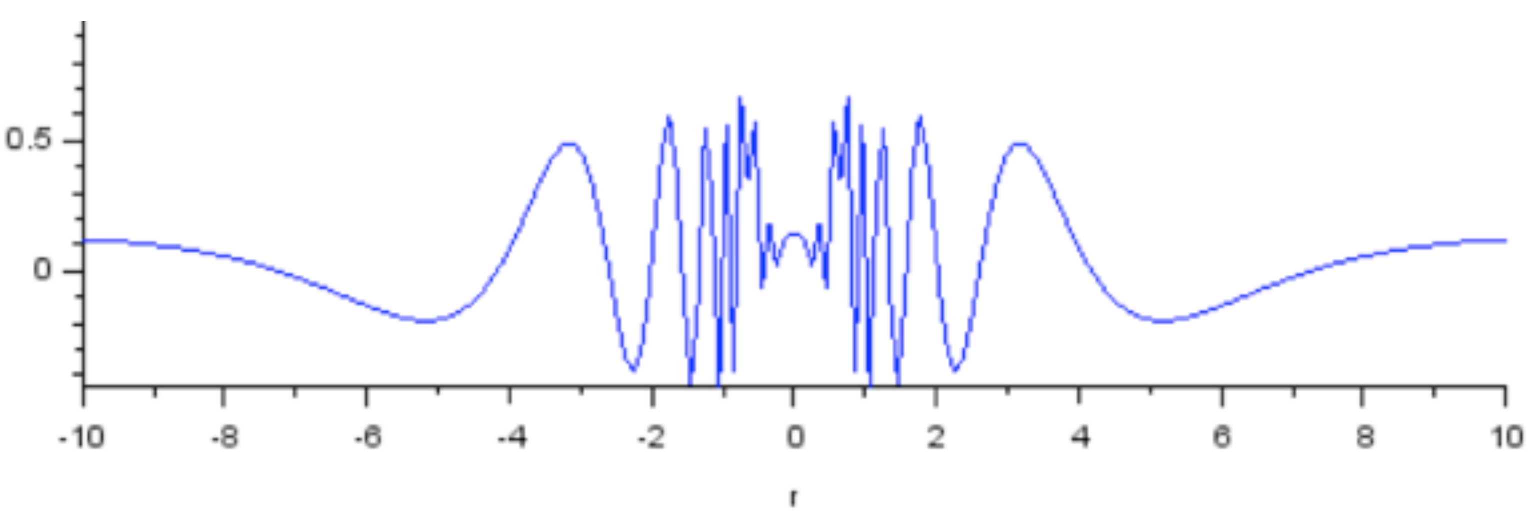
mode velocity $v_{wave} = \sqrt{\frac{g}{k}}$

Production of <u>high-k modes</u> cut off for $v_{bh} > v_{wave}$

$t < 0$



$t > 0$



ENERGY LOSS FROM TIDAL DEFORMATION

$$E_{loss} = \frac{4\pi\rho G M_{BH}^2 v_{BH}^2}{g^2} \int dk \frac{1}{(1 + k v_{bh}^2/g)^2}$$

$$= 4\pi\rho \frac{G^2 M_{bh}^2}{g} \approx \frac{G M_{bh}^2}{R_{ns}}$$

similar to
dynamical friction
(ie nothing new)

SO, WHAT WENT WRONG?

$$\vec{s}(\vec{x},t) = \sum_{l=2}^{\infty} \vec{s}_l(\vec{x}) \int dt' \int_{\mathrm{star}} dV \; \vec{f}_{bh} \cdot \vec{s}_l(\vec{x}')G_l^+(t-t')$$

fluid displacement

long range force

Formal manipulations lead to dropping terms which are actually singular for long range forces

More clearly seen in planar, incompressible fluid limit

$$\vec{s}(\vec{x},t) = \quad GM_{bh}\,\mathrm{Re}\int dk \frac{k}{\omega_k^2}\left(1 - \frac{kv_{bh}}{kv_{bh} - i\omega_k}\right) e^{kz+kv_{bh}t}\left(J_0(kr)\vec{1}_z - J_1(kr)\vec{1}_r\right)$$

boundary term

Pani & Loeb (UV divergent)

CONSTRAINTS ON PRIMORDIAL BH

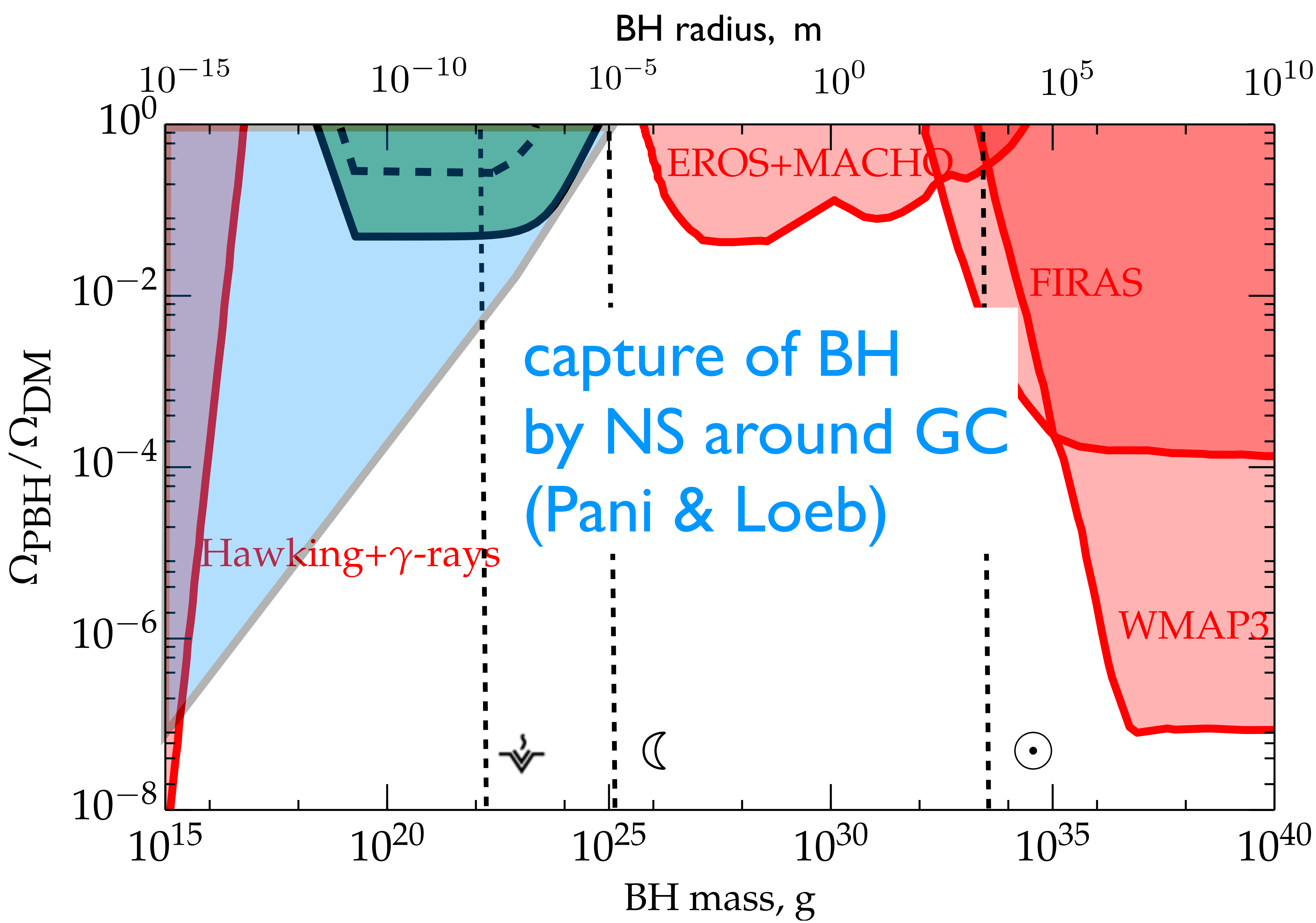


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

CONSTRAINTS ON PRIMORDIAL BH

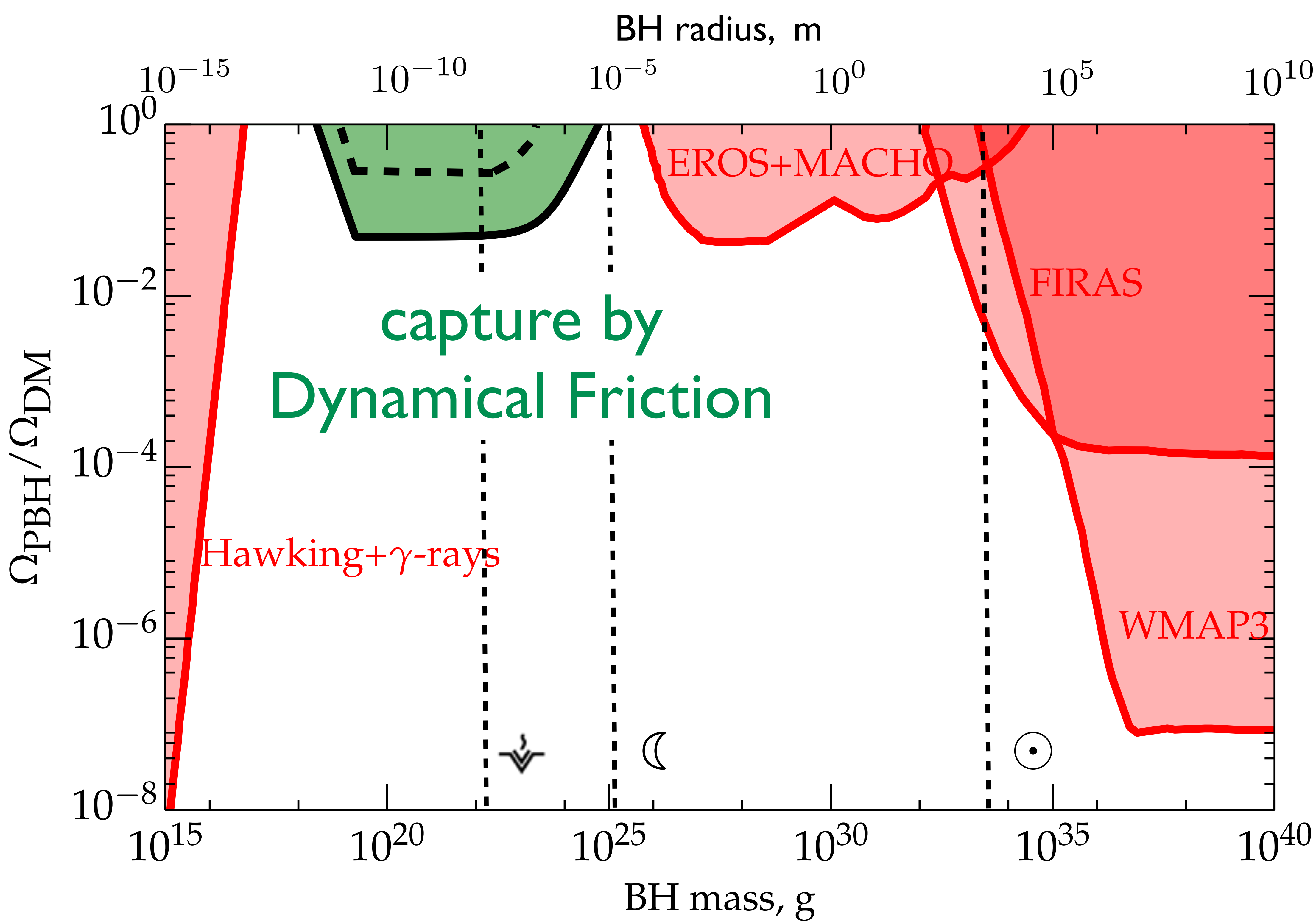


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov


HERGÉ
LES AVENTURES DE TINTIN
COKE EN STOCK

THE IMPORTANT QUESTION

Bon vent Mike!

Long-Range Forces and Neutrino Mass

VOLUME 64, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JANUARY 1990

Bound-Neutrino Sphere and Spontaneous Neutrino-Pair Creation in Cold Neutron Stars

Abraham Loeb
The Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 August 1989)

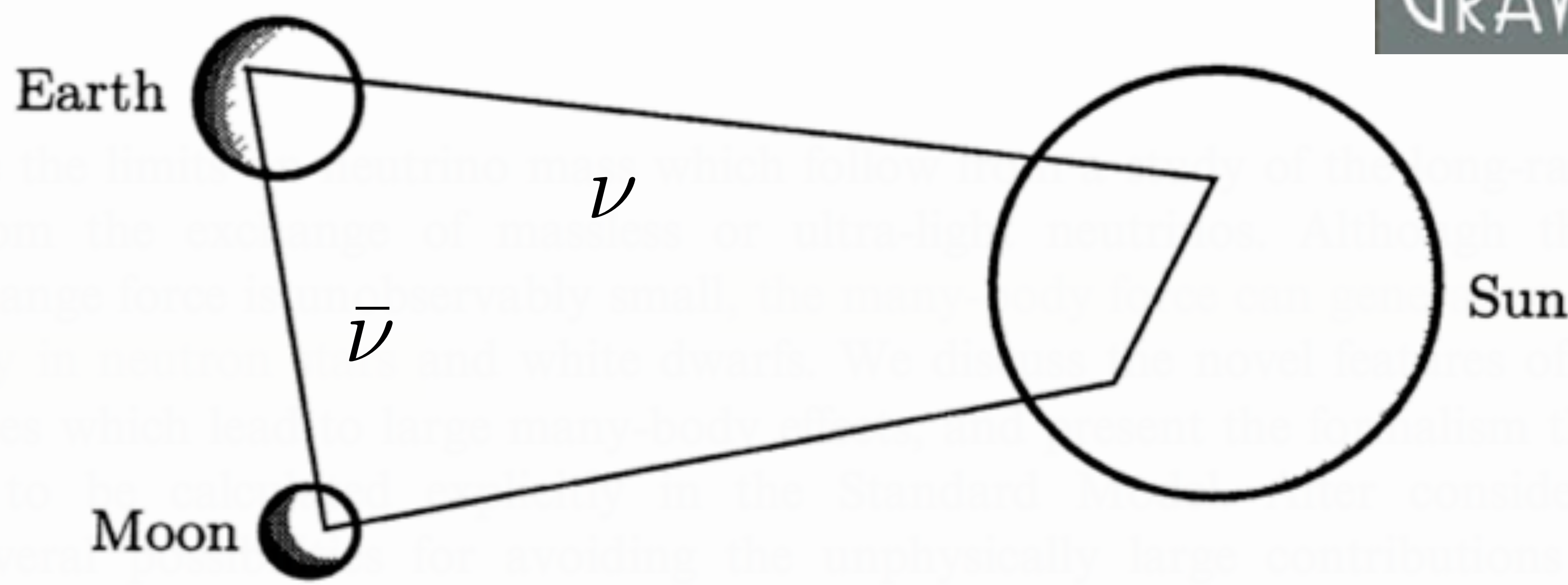
It is shown that neutrinos (massless or massive), produced with kinetic energies below ~ 50 eV in a supernova, have bound orbits in the remnant neutron star. The binding is mediated by a radial weak-interaction force, caused by a gradient in the collective weak potential of the neutrons in the star. This force is also able to create spontaneously neutrino-antineutrino pairs. If the bound-neutrino sphere is not fully degenerate at low momenta, a cold neutron star will shine continuously antineutrinos with energies $\lesssim 50$ eV, as a result of the density gradient in it. In principle, these effects can also be realized at smaller (e.g., solid) densities for sufficiently low neutrino energies.

exchange of massless neutrinos, we develop a formalism to describe the exchange of massive neutrinos. It is shown that the stability of both neutron stars and white dwarfs in the presence of many-body neutrino-exchange forces implies a lower bound, $m \gtrsim 0.4\ \mathrm{eV}/c^2$ on the mass m of any neutrino.

Long-Range Forces and Neutrino Mass

EPHRAIM FISCHBACH*

2.4 The Exchange of Two Neutrinos



neutrinos. It is shown that the stability of both neutron stars and white dwarfs in the presence of many-body neutrino-exchange forces implies a lower bound, $m \gtrsim 0.4\ \mathrm{eV}/c^2$ on the mass m of any neutrino.

Long-Range Forces and Neutrino Mass

VOLUME 64, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JANUARY 1990

Bound-Neutrino Sphere and Spontaneous Neutrino-Pair Creation in Cold Neutron Stars

Abraham Loeb
The Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 August 1989)

It is shown that neutrinos (massless or massive), produced with kinetic energies below ~ 50 eV in a supernova, have bound orbits in the remnant neutron star. The binding is mediated by a radial weak-interaction force, caused by a gradient in the collective weak potential of the neutrons in the star. This force is also able to create spontaneously neutrino-antineutrino pairs. If the bound-neutrino sphere is not fully degenerate at low momenta, a cold neutron star will shine continuously antineutrinos with energies $\lesssim 50$ eV, as a result of the density gradient in it. In principle, these effects can also be realized at smaller (e.g., solid) densities for sufficiently low neutrino energies.

exc[illegible]ve neutrinos. It is shown that the stability of both neutron stars and white dwarfs in the presence of many-body neutrino-exchange forces implies a lower bound, $m \gtrsim 0.4\ \mathrm{eV}/c^2$ on the mass m of any neutrino.