2 FACETS OF DARK MATTER

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WHY DARK MATTER?

WHICH DARK MATTER?

OBSERVATIONS CONSISTENT
WITH DM BEING MADE OF
MASSIVE NON-LUMINOUS OBJECTS

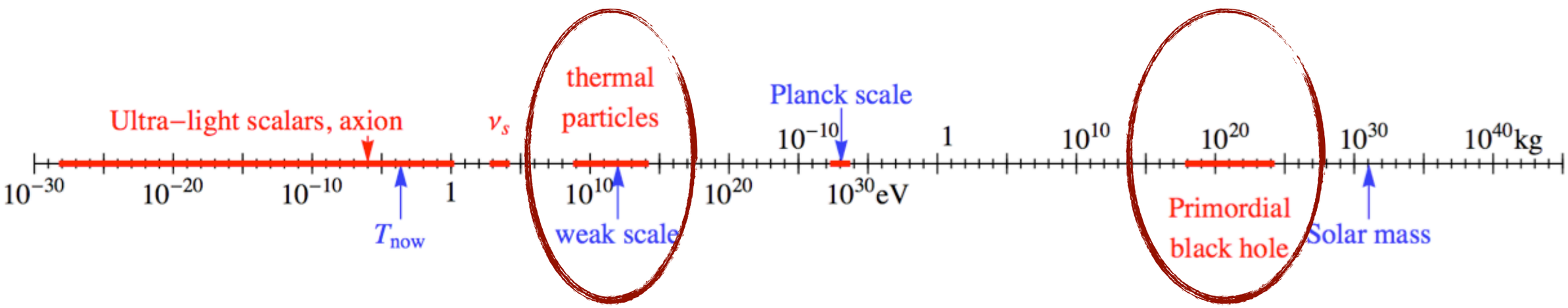
.
ie

A MASSIVE NEUTRAL PARTICLE WOULD DO

but

OTHER POSSIBILITIES ARE STILL "ALIVE AND WELL"

WHICH DARK MATTER?



courtesy of M.Cirelli

ON A SIMPLIFIED WIMP MODEL

ON CONSTRAINTS ON PRIMORDIAL BLACK HOLES AS DM

I. DM AS PRIMORDIAL BLACK HOLES (PBH)

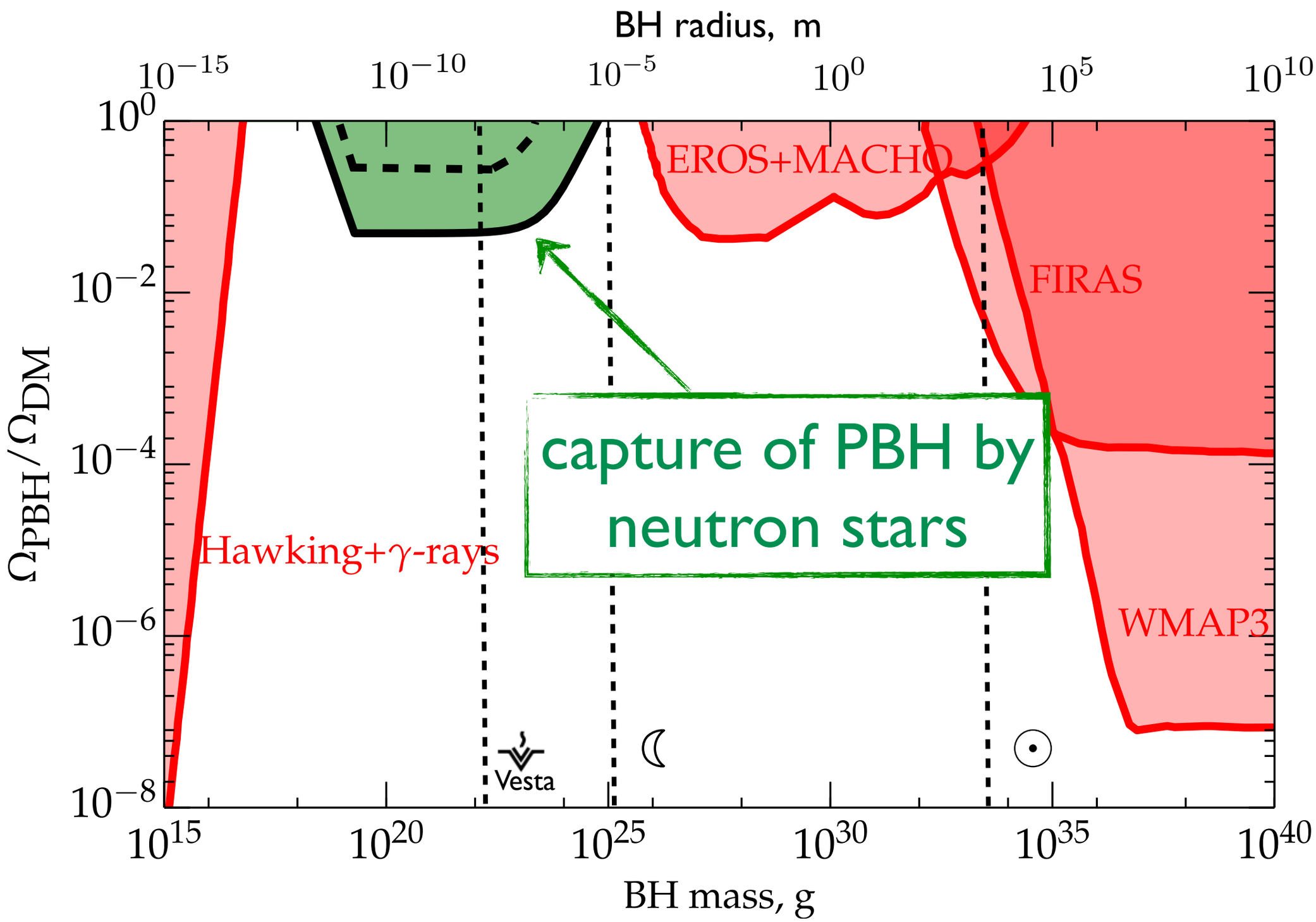
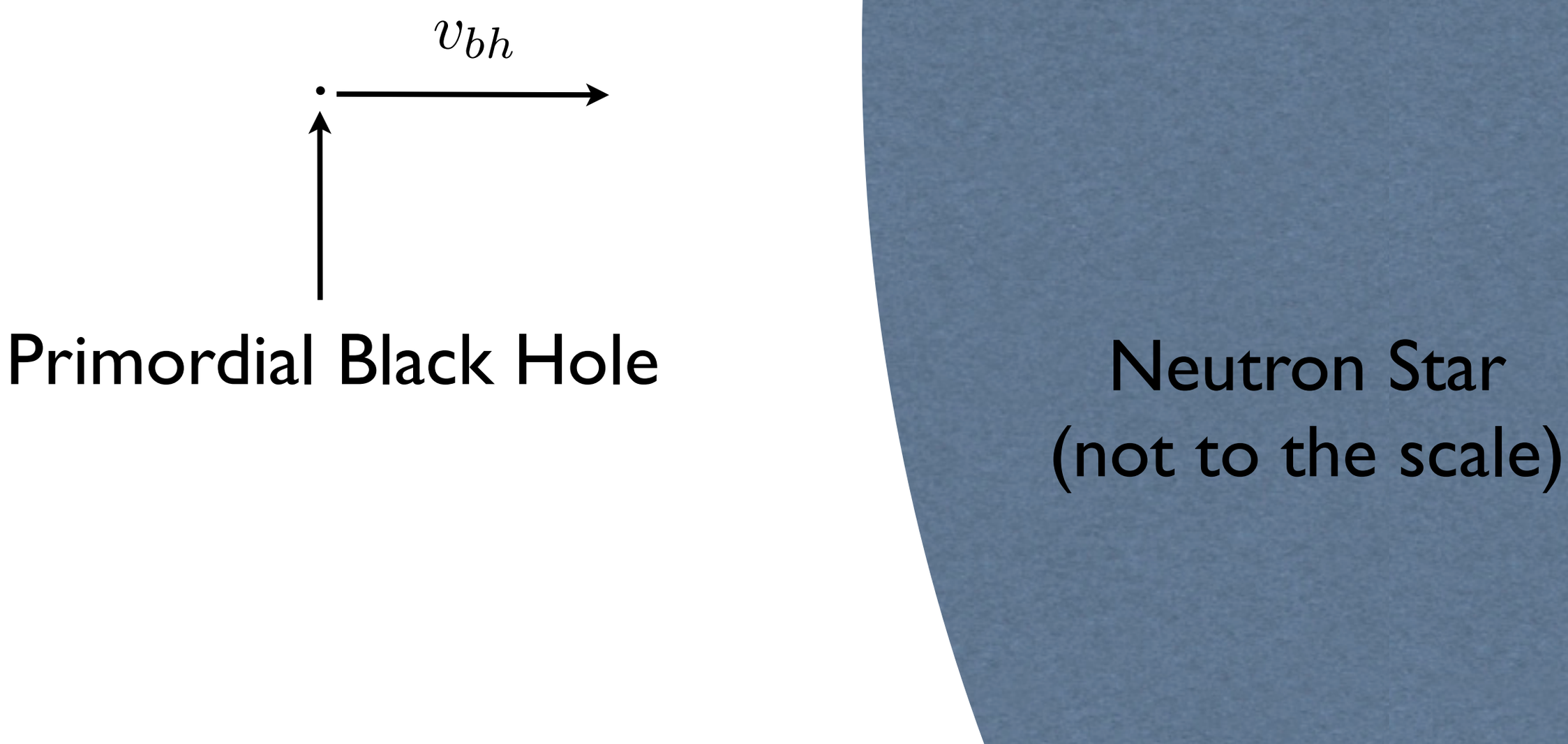
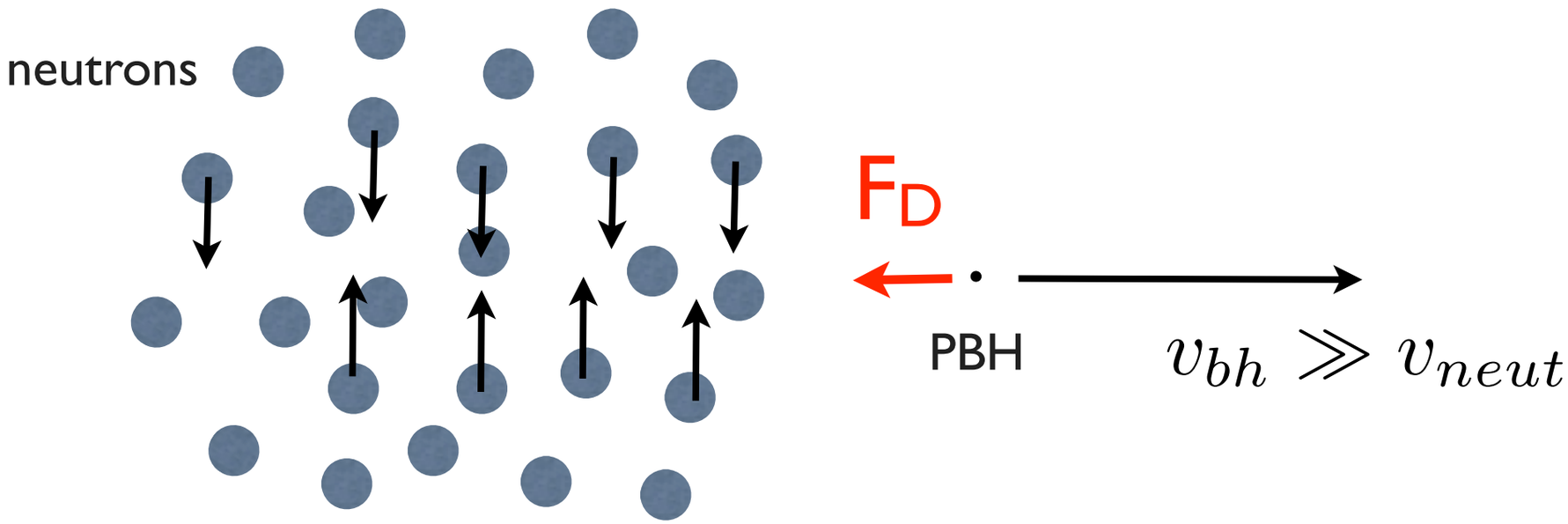


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov


v_{bh}
Primordial Black Hole
Neutron Star
(not to the scale)

PBH 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)

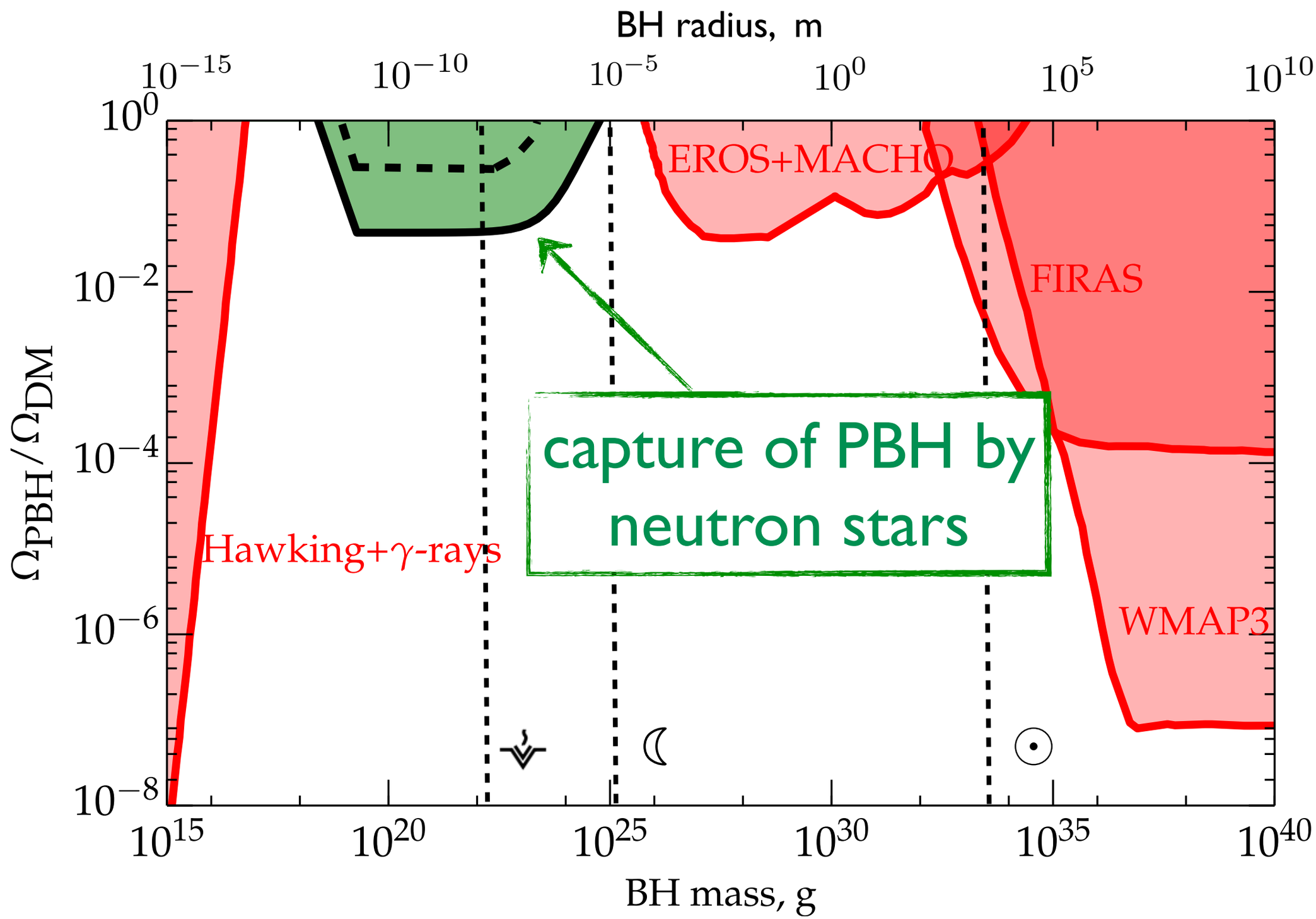


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

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

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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 $\rho_{\rm DM} \gtrsim 10^2(\sigma/{\rm km\ s^{-1}}){\rm GeV\ cm^{-3}}$ (where σ is the dark-matter velocity dispersion) limits the abundance of primordial black holes in the mass range $10^{17}{\rm g} \lesssim m_{\rm PBH} \lesssim 10^{24}{\rm g}$, 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 (DF)

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

Compared to DF, claim an enhancement of $O(10^6\text{-}10^9)$

CONSTRAINTS ON PRIMORDIAL BH

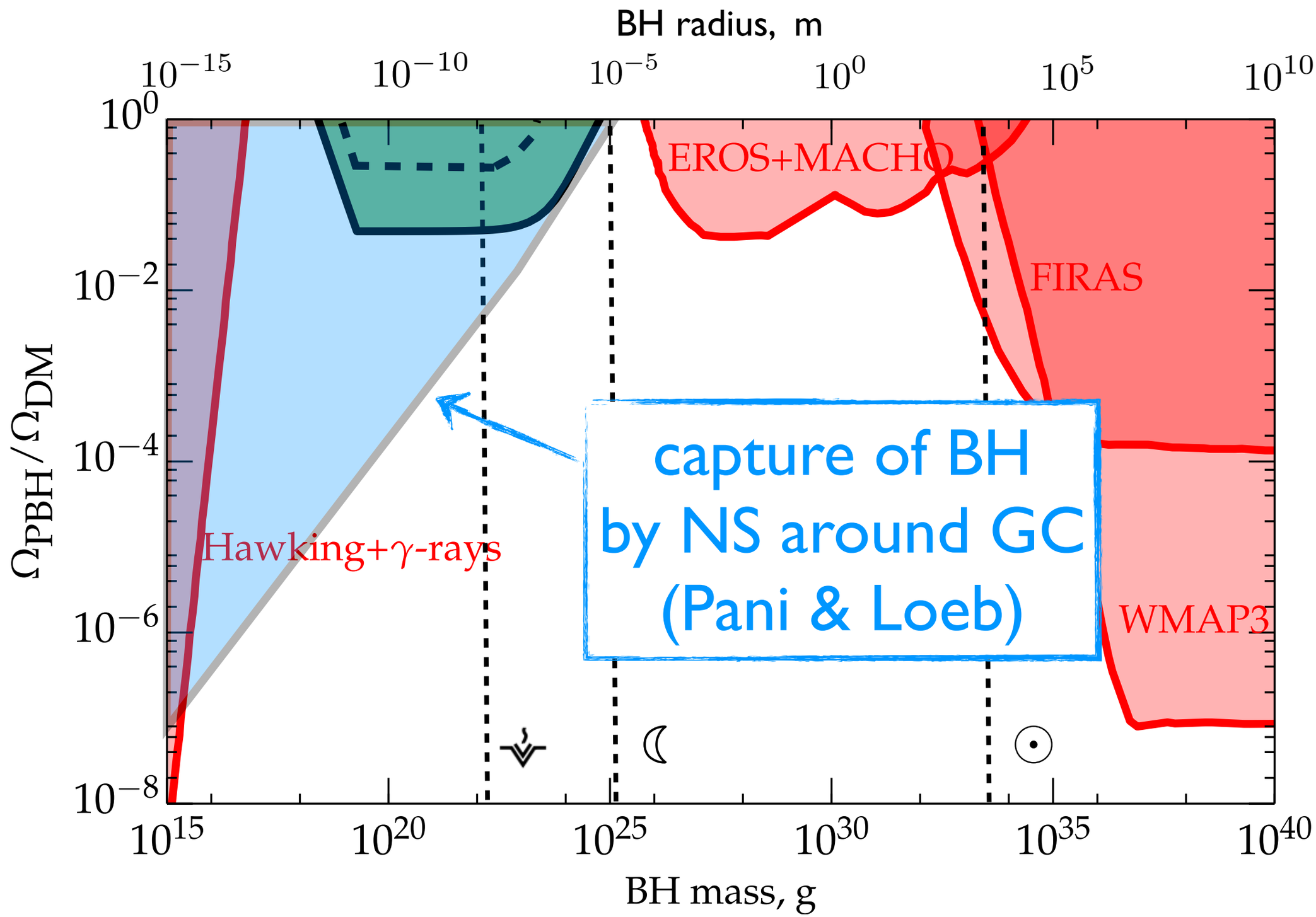


Fig. from 1301.4984
Capela, Pshirkov & Tinyakov

Basically EXCLUDES Primordial Black Holes as the dominant form of DM

Very interesting (actually important)
but unfortunately INCORRECT (we think)

Petr Tinyakov, M.T. (ULB, Brussels)
Guillaume Petillon, Etienne Granet (Ecole Polytechnique, Paris)
Phys.Rev.D90 (2014) 10, 103522, arXiv:1409.0469

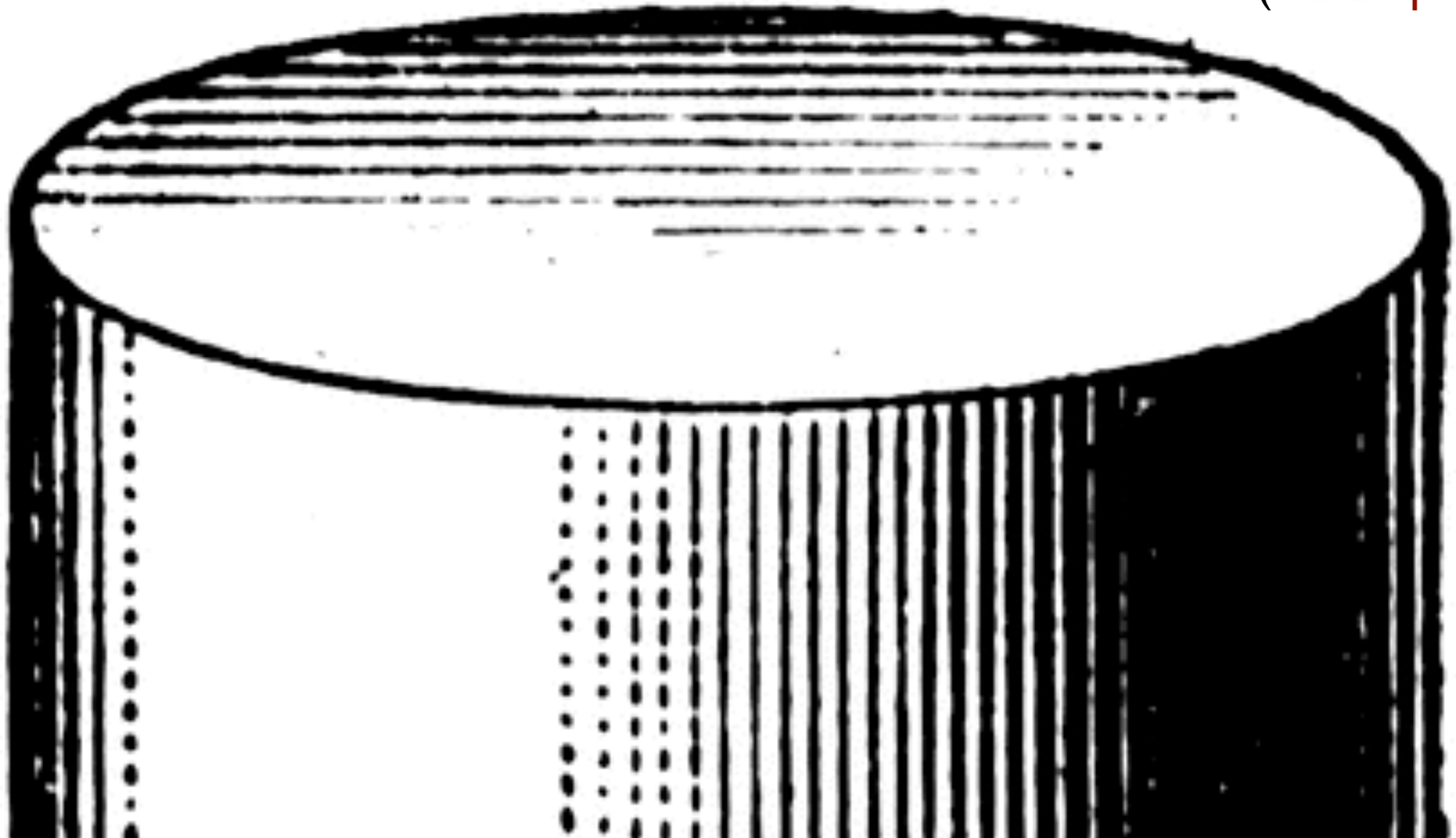
It's a UV problem, so we went planar

primordial black hole $\longrightarrow$ $\cdot$

$\downarrow v_{bh}$

a flat 'neutron star'

(incrompressible fluid)



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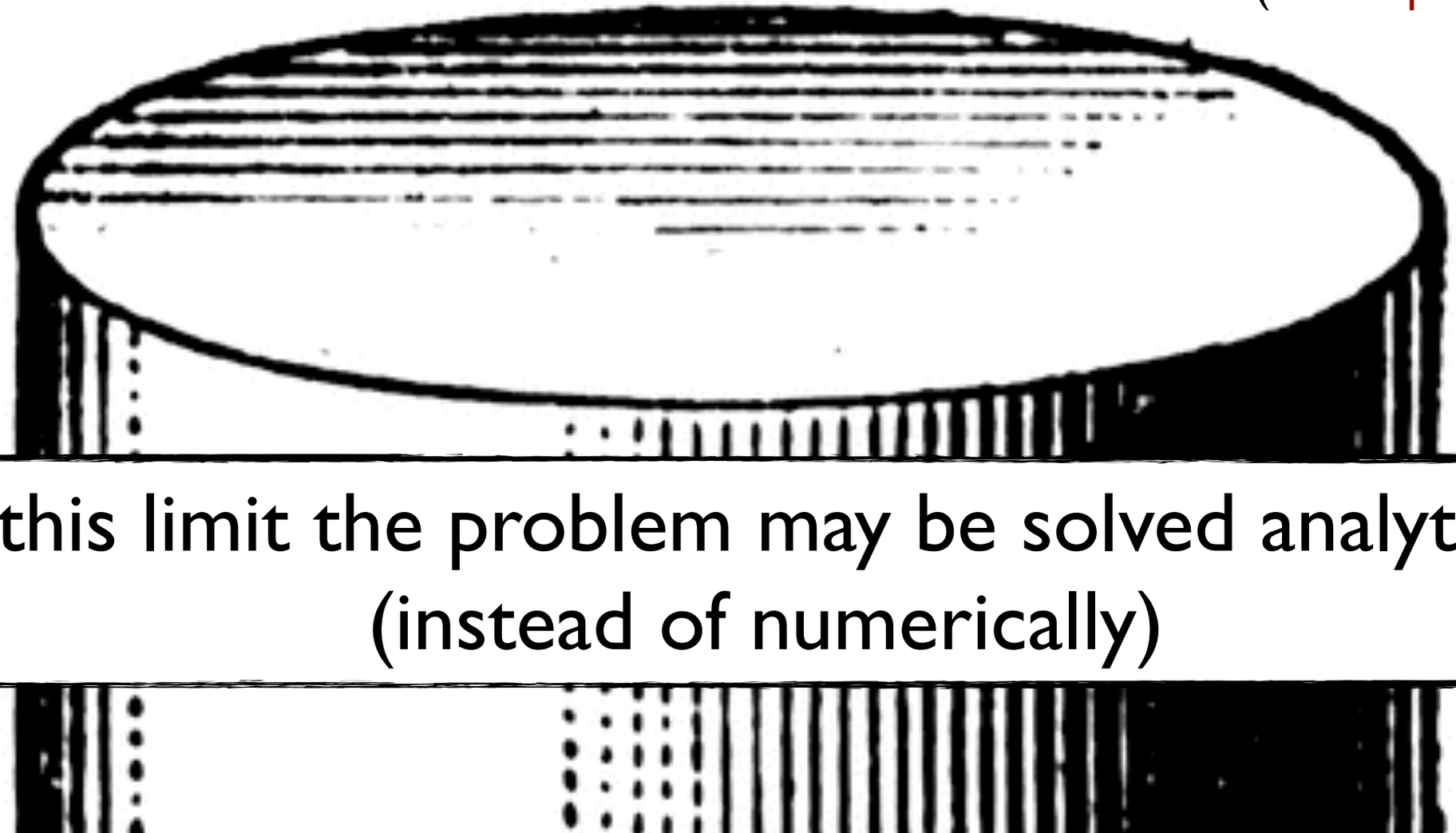


In this limit the problem may be solved analytically (instead of numerically)

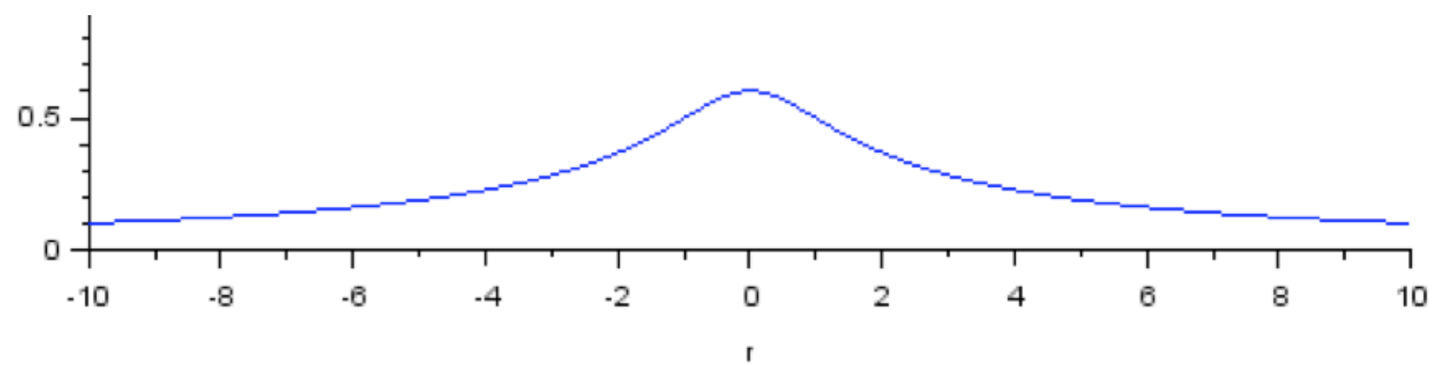
SURFACE DEFORMATION

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

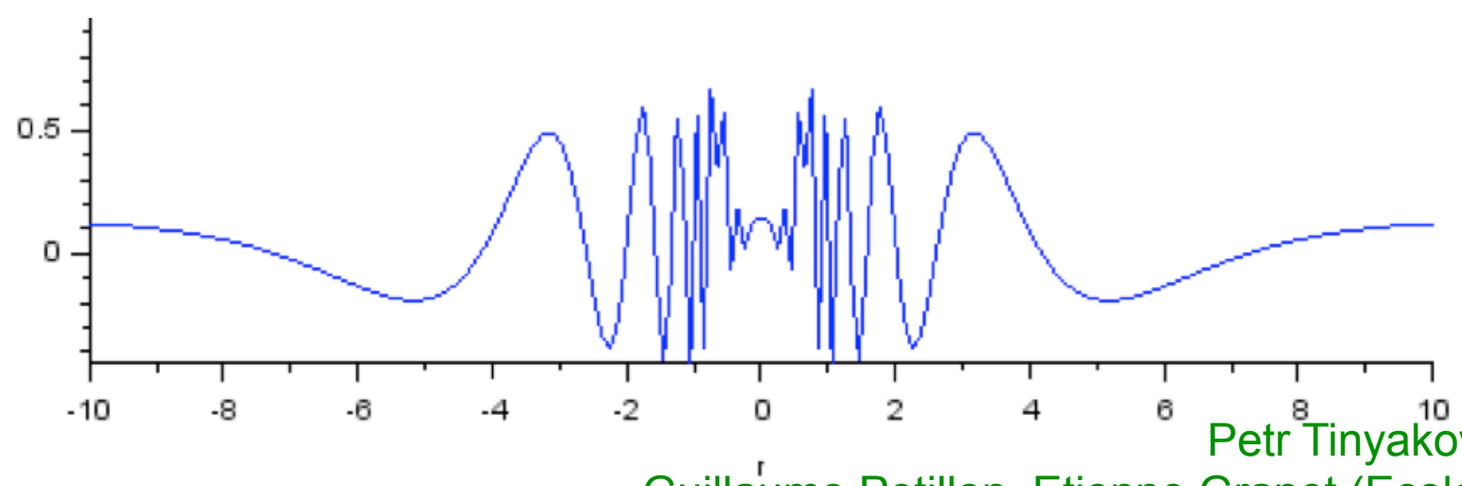
mode velocity $v_{wave} = \sqrt{\frac{g}{k}}$

modes with $v_{\rm wave} \lesssim v_{bh}$ (i.e. high k or high l) are not excited!

$t < 0$



$t > 0$



Petr Tinyakov, M.T. (ULB, Brussels)
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ENERGY LOSS FROM TIDAL DEFORMATION

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

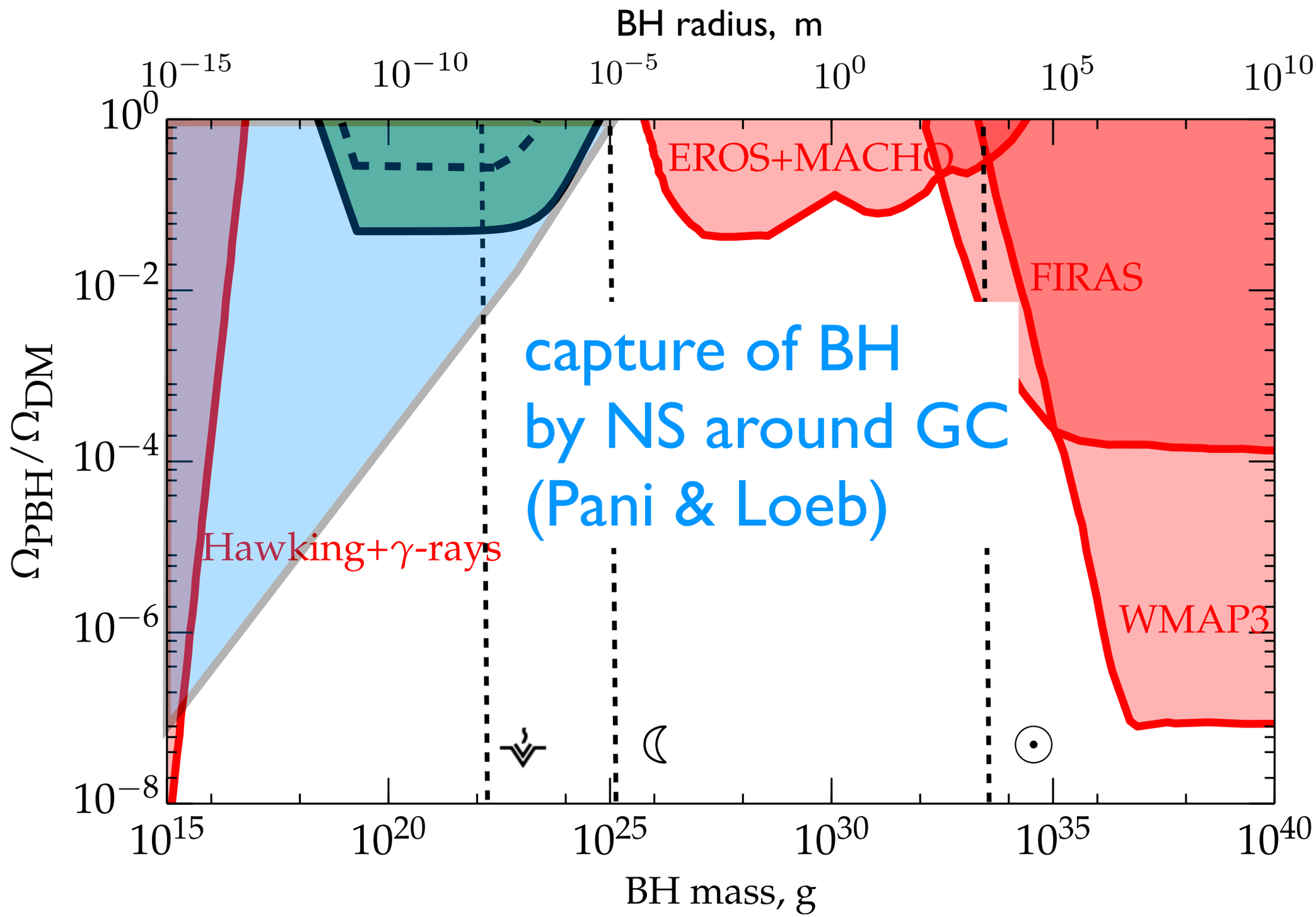
$$= 4\pi\rho \frac{G^2 M_{bh}^2}{g} \approx \frac{G M_{bh}^2}{R_{ns}}$$

SIMILAR TO DYNAMICAL FRICTION

(ie nothing new from tidal deformation)

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

CONSTRAINTS ON PRIMORDIAL BH



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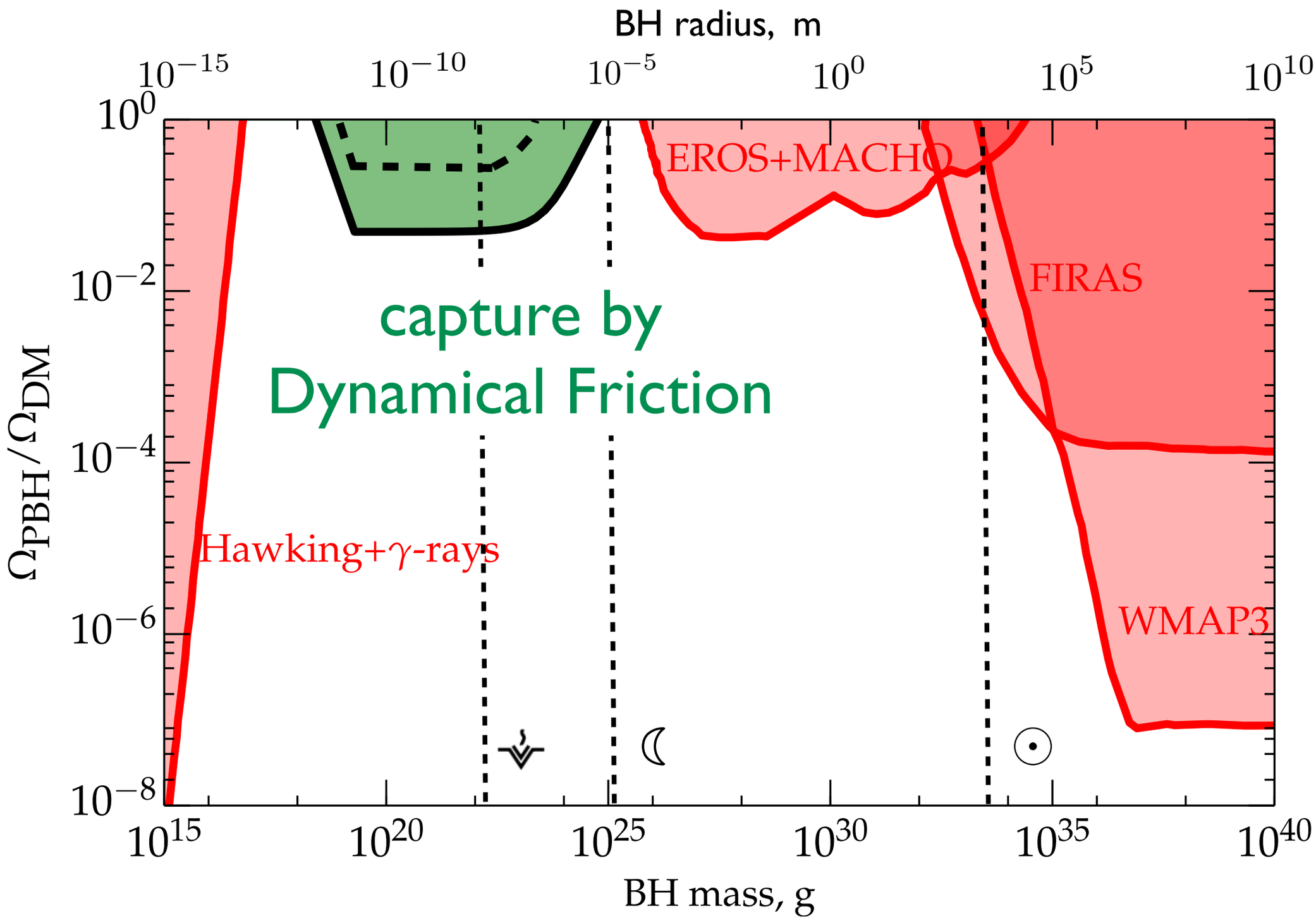

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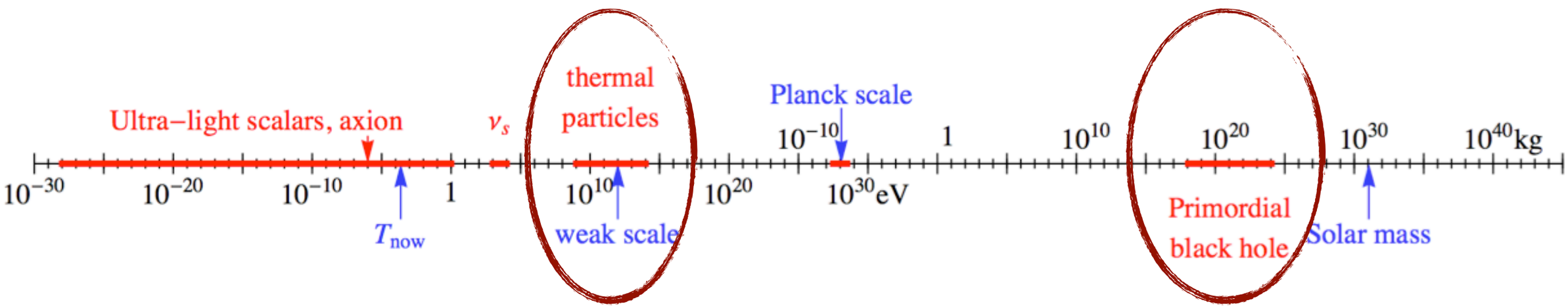
WHICH DARK MATTER?



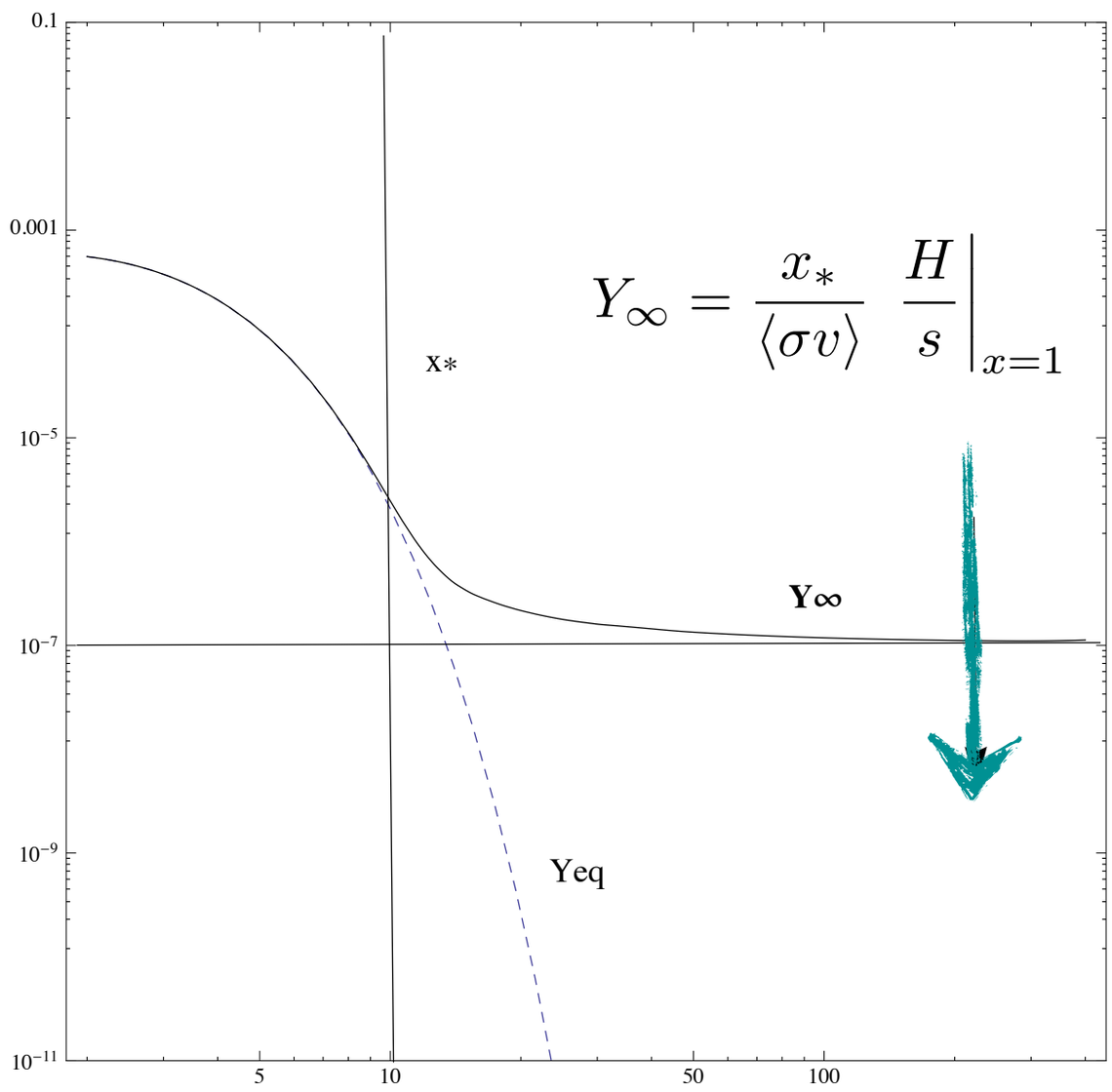
courtesy of M.Cirelli

ON A SIMPLIFIED WIMP MODEL

ON CONSTRAINTS ON PRIMORDIAL BLACK HOLES AS DM

A MASSIVE PARTICLE WITH A WEAK INTERACTION OR WIMP COULD HAVE THE RIGHT ABUNDANCE

$$Y = \frac{n_X}{s}$$



$$Y_\infty = \frac{x_*}{\langle \sigma v \rangle} \left. \frac{H}{s} \right|_{x=1}$$

$$x = \frac{m}{T}$$

relic abundance
from
thermal freeze-out

cosmology requires

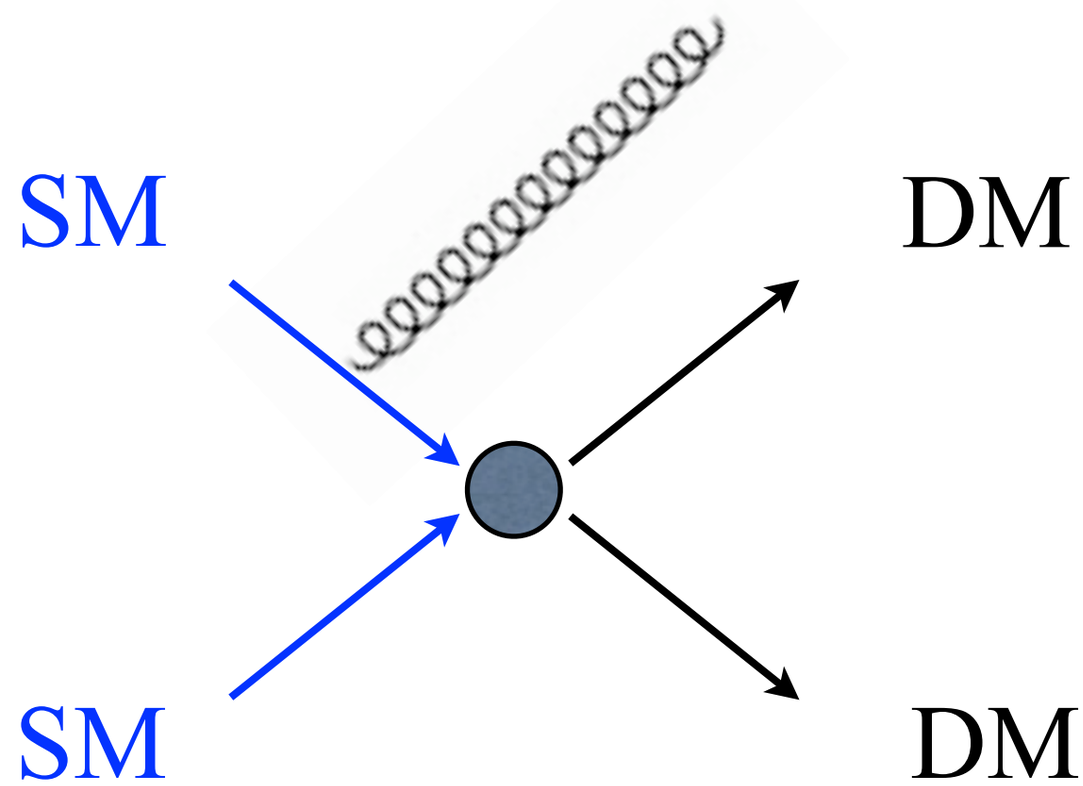
$$\langle \sigma v \rangle \approx 3 \cdot 10^{-26} \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

ie a “weak scale”
cross section

A MASSIVE PARTICLE WITH A WEAK INTERACTION OR WIMP COULD HAVE THE RIGHT ABUNDANCE

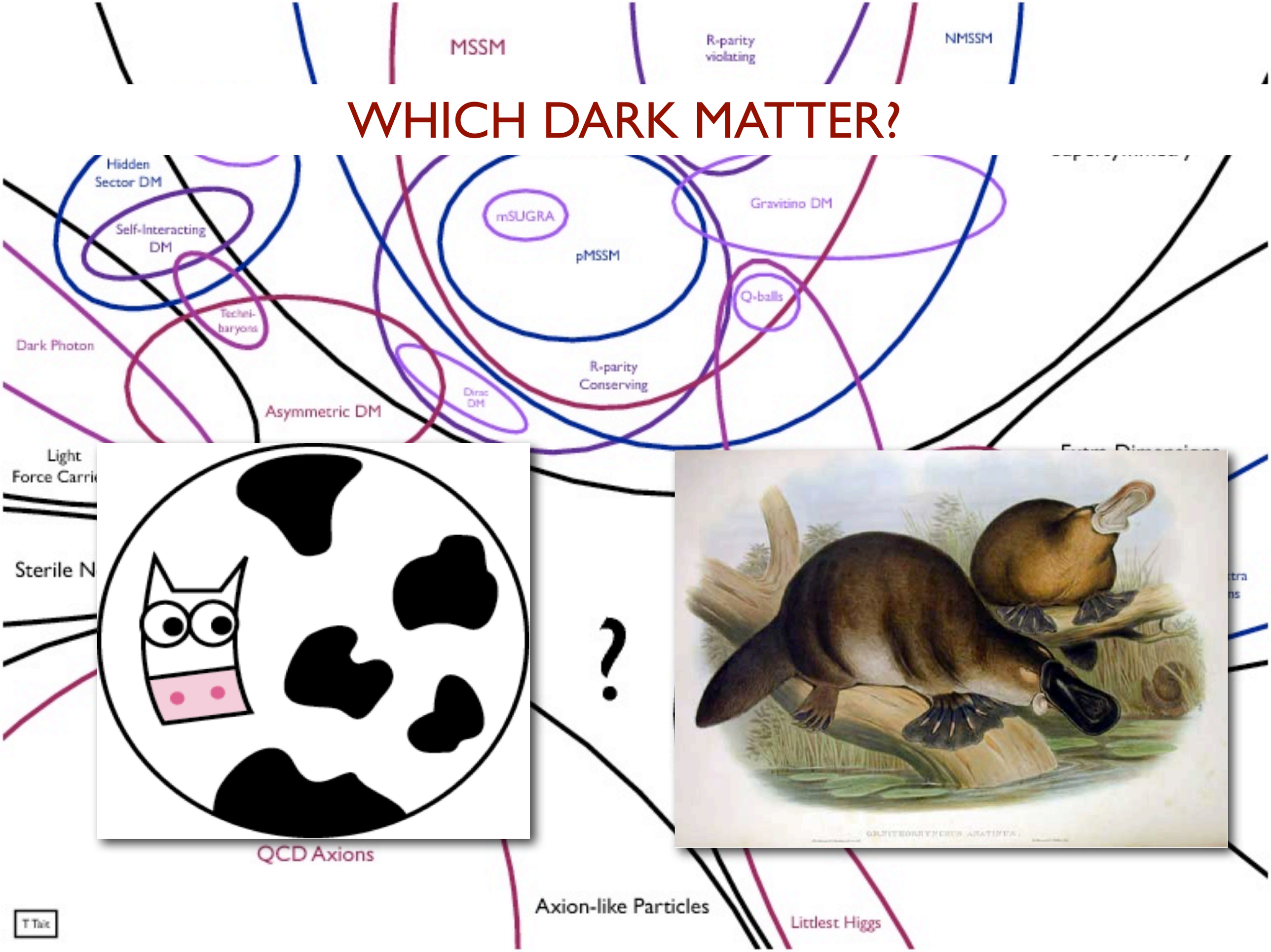
SOME CALL IT A MIRACLE

ULTIMATE TEST OF THE WIMP HYPOTHESIS



DM CREATION AT THE LHC!

WHICH DARK MATTER?



THIS PLETHORA OF DM CANDIDATES

(and, arguably, the absence -so far- of SUSY at the LHC)

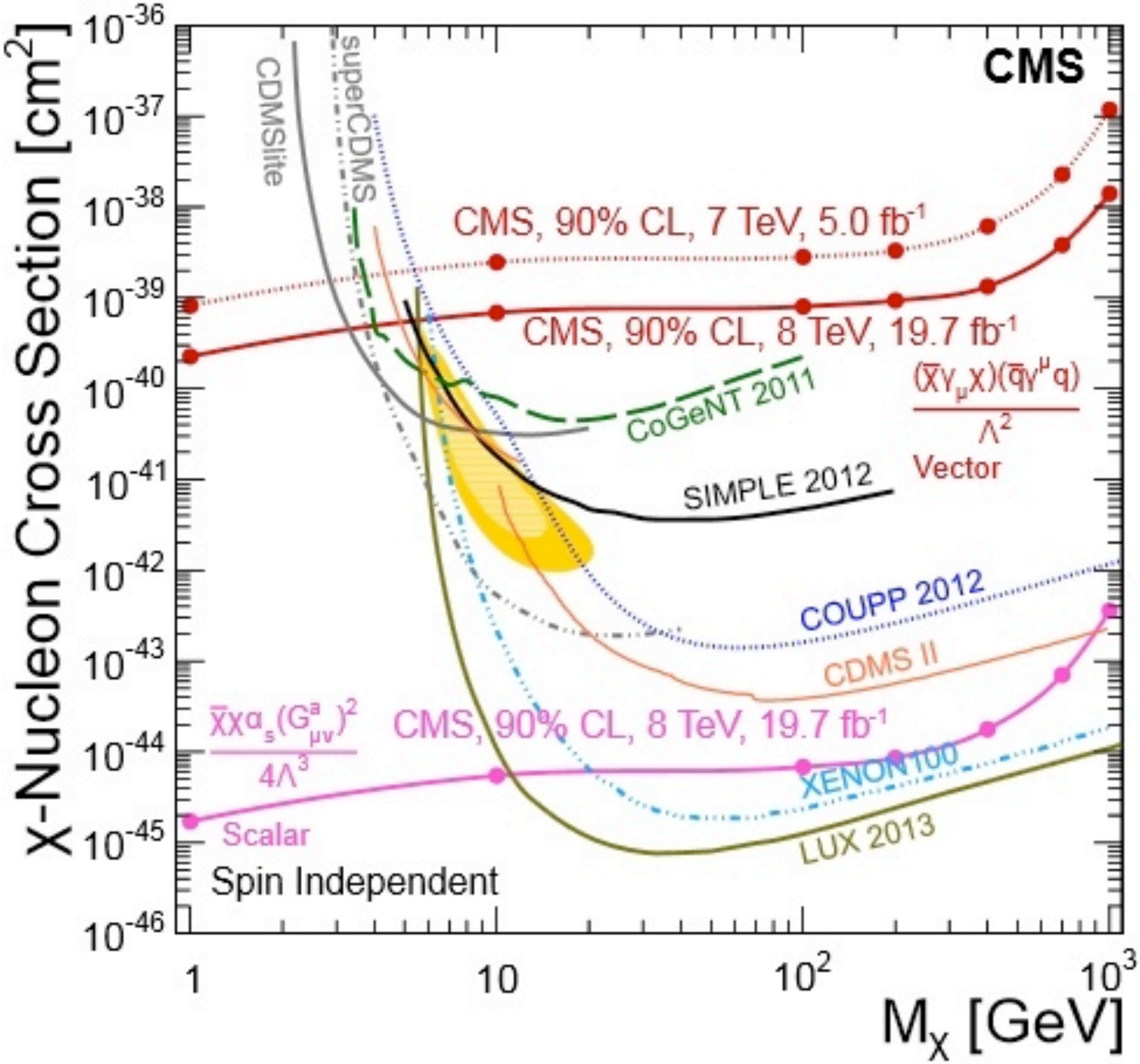
has motivated the use of

EFFECTIVE OPERATORS

ie

A MODEL INDEPENDENT APPROACH

5 orders of magnitude!?



CMS collaboration, arXiv:1408.3583

INTERPRETATION OF RESULTS BASED ON EFFECTIVE OPERATORS REQUIRES CAUTION

* MAYBE PHYSICALLY INCONSISTENT *

* MAY GIVE BIASED CONCLUSIONS *

* LOSS OF SIGNIFICANT INFORMATION *

See also talks by Giorgio Arcadi and Andreas Goudelis

A New Trend (?)

SIMPLIFIED WIMP MODELS

PARAMETERIZE EXPERIMENTAL SIGNATURES
WITH FEW PARAMETERS:
i.e.
MASS OF DM & MEDIATOR + COUPLING(S)

PROVIDE CONSISTENT CORRESPONDENCE BETWEEN
COMPLEMENTARY SEARCHES

BOTH CONFIRMATION
(obviously)
AND REJECTION OF PREDICTIONS ARE INSTRUCTIVE
(may point to a need for more degrees of freedom, etc)

AN INSTANCE OF SIMPLIFIED WIMP

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

real singlet scalar

vector-like charged lepton

SM light lepton

Z_2 symmetry

$S \longrightarrow -S$ S = Dark Matter

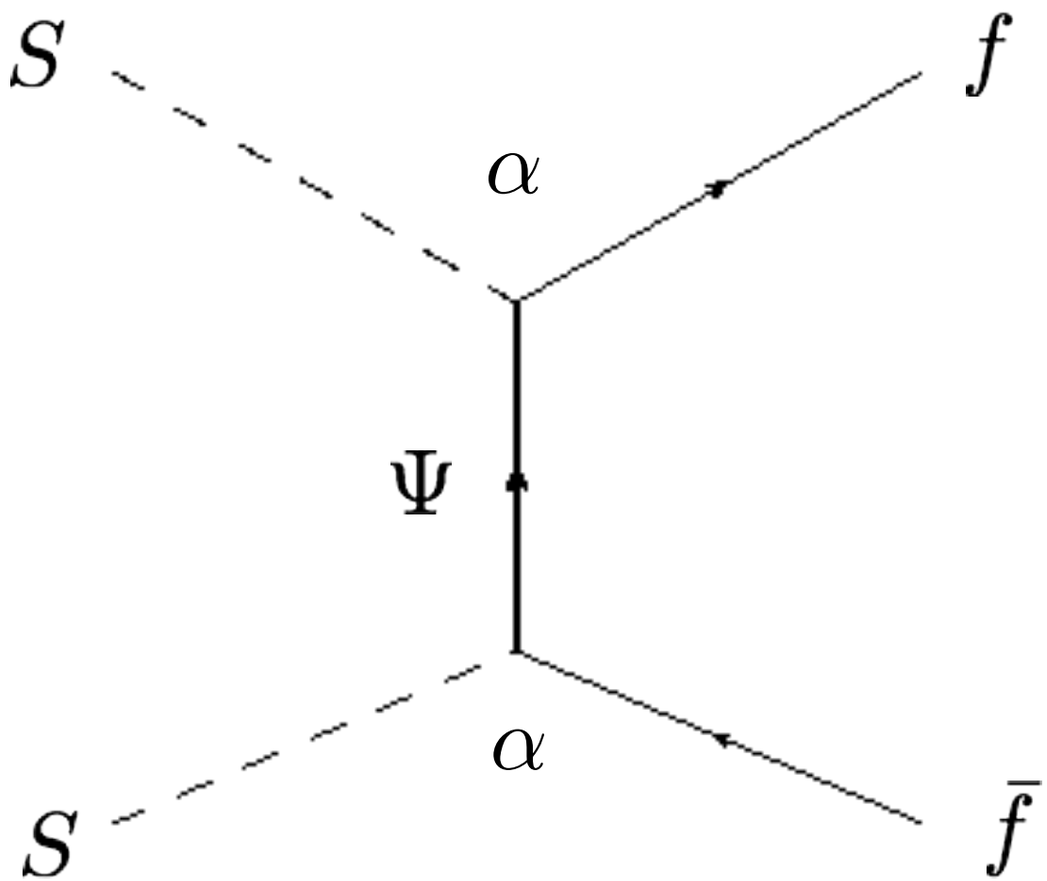
$\Psi \longrightarrow -\Psi$ Ψ = Mediator

→ WE CALL IT THE VECTOR-LIKE PORTAL

following P. Fileviez Perez, M.B. Wise
arXiv:1303.1452

but aka “Effective WIMP” or “Fermionic Portal”

THE VECTOR-LIKE PORTAL



assume 1 coupling (MFV?)
fixing the abundance leaves a 2-dim parameter space
(masses of DM and mediator)

ANNIHILATION CROSS SECTION

$$\sigma v(SS \to l\bar{l}) = \frac{y_l^4}{60\pi} \frac{v^4}{M_S^2} \frac{1}{(1+r^2)^4}$$

$$r = \frac{M_\Psi}{M_S} > 1$$

The annihilation cross section is **d-wave** in chiral limit
(I don't know of another instance. Do you?)

Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

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$$\sigma v(\chi\chi \to l\bar{l}) = \frac{\tilde{y}_l^4}{48\pi}\frac{v^2}{M_\chi^2}\frac{1+r_\chi^4}{(1+r_\chi^2)^4} \qquad r_\chi = \frac{M_{\tilde{\Psi}}}{M_\chi} > 1$$

As is well-known, Majorana annihilation
is **p-wave**

Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

EARLY UNIVERSE $\langle v^2 \rangle \approx 0.3$

GALACTIC CENTRE $v \sim 10^{-3}$

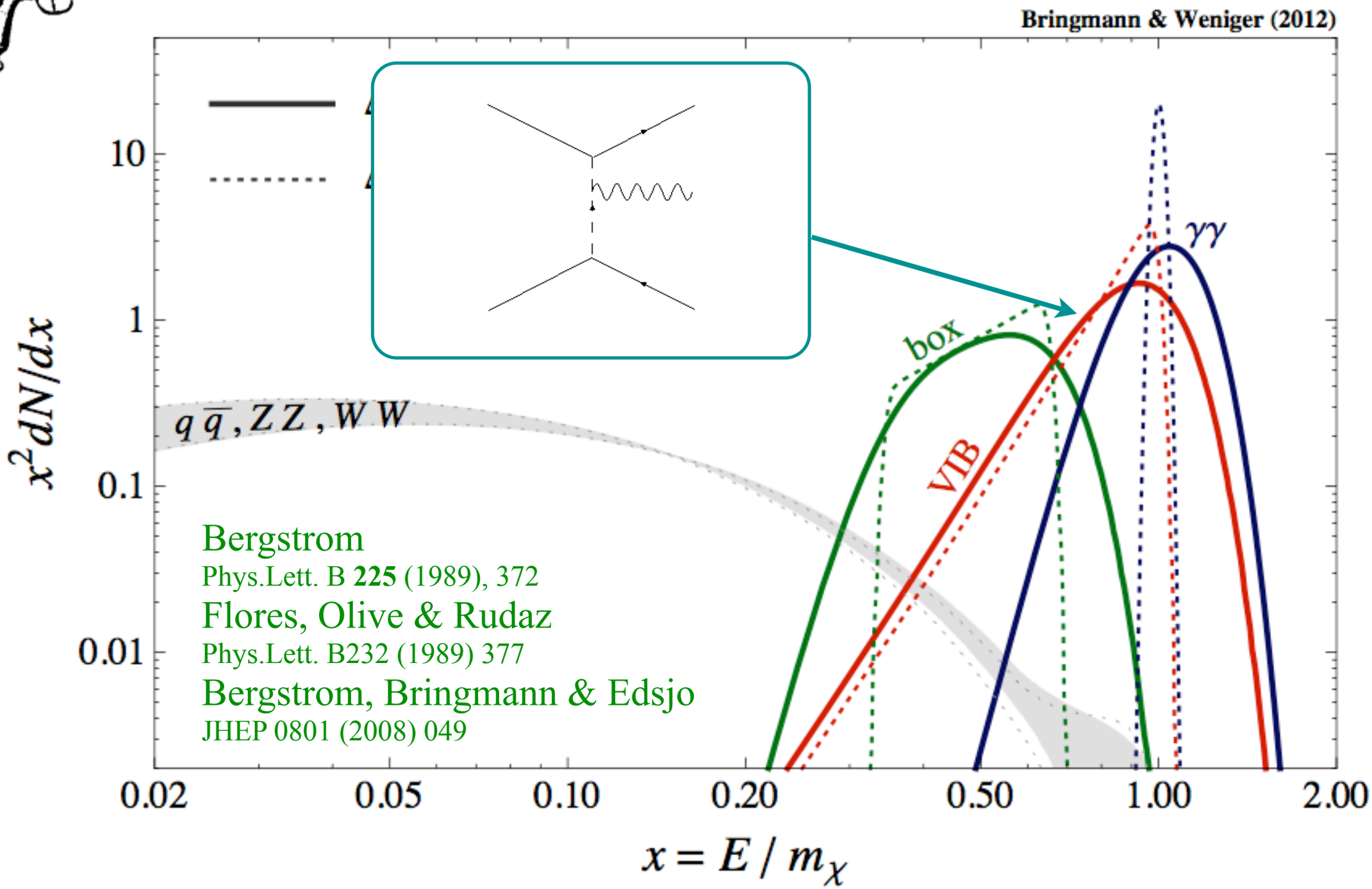
2-BODY DM ANNIHILATION SUPPRESSED AT GC

NO INDIRECT DETECTION?

YES, LOOK FOR RADIATIVE CORRECTIONS!

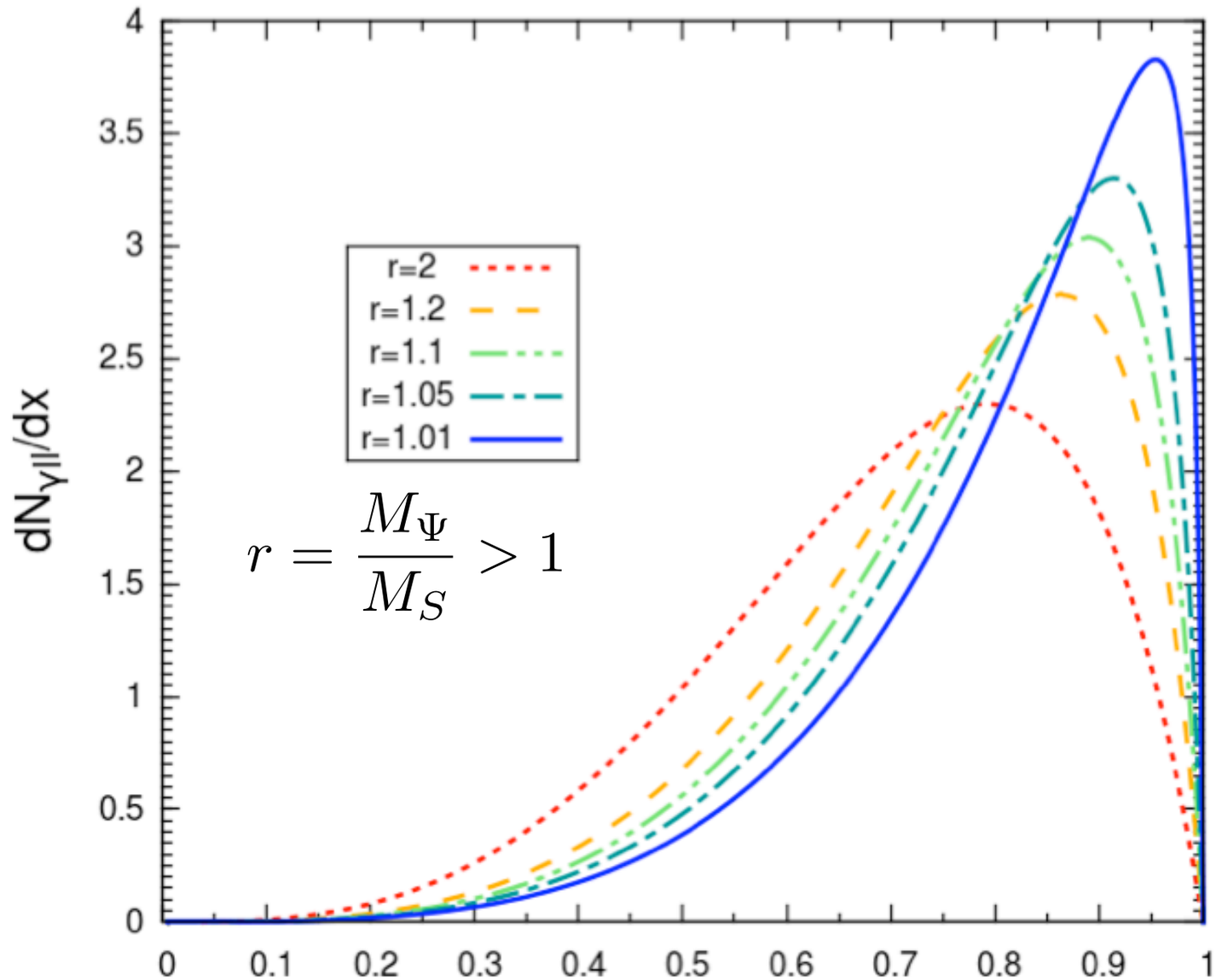
power of α and phase-space suppressed, but s-wave

GAMMA RAY FEATURES
INTERNAL BREMSSTRAHLUNG



INTERNAL BREMSSTRAHLUNG SPECTRUM

(same for scalar and Majorana)



PEAKED AT

$E \sim M_{DM}$

$$x = \frac{E_\gamma}{M_{DM}}$$

Barger, Keung & Marfatia
arXiv:1111.4523

Takashi Toma
arXiv:1307.6181

Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

SAME BUT CROSS SECTION DIFFER BY A FACTOR OF 8

$$\frac{\sigma(SS \to f\bar{f}\gamma)}{\sigma(\chi\chi \to f\bar{f}\gamma)} = \frac{8y_l^4}{g_l^4}$$

VIB ENHANCED

while

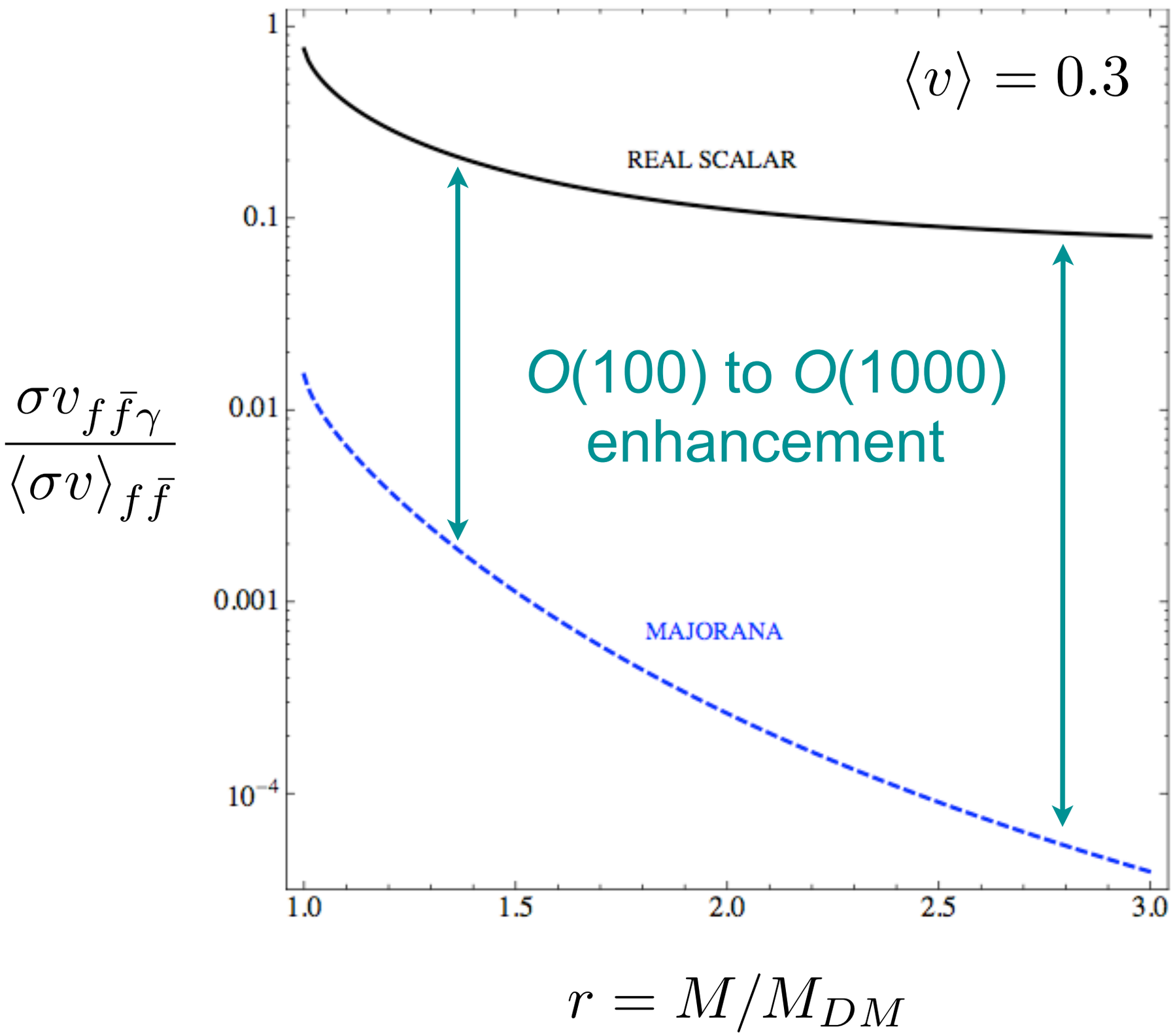
$$\frac{\langle\sigma v\rangle(SS \to f\bar{f})}{\langle\sigma v\rangle(\chi\chi \to f\bar{f})} < 0.16\frac{y_l^4}{g_l^4}$$

2-BODY SUPPRESSED

→ huge enhancement of VIB for scalar DM w.r.t. Majorana DM

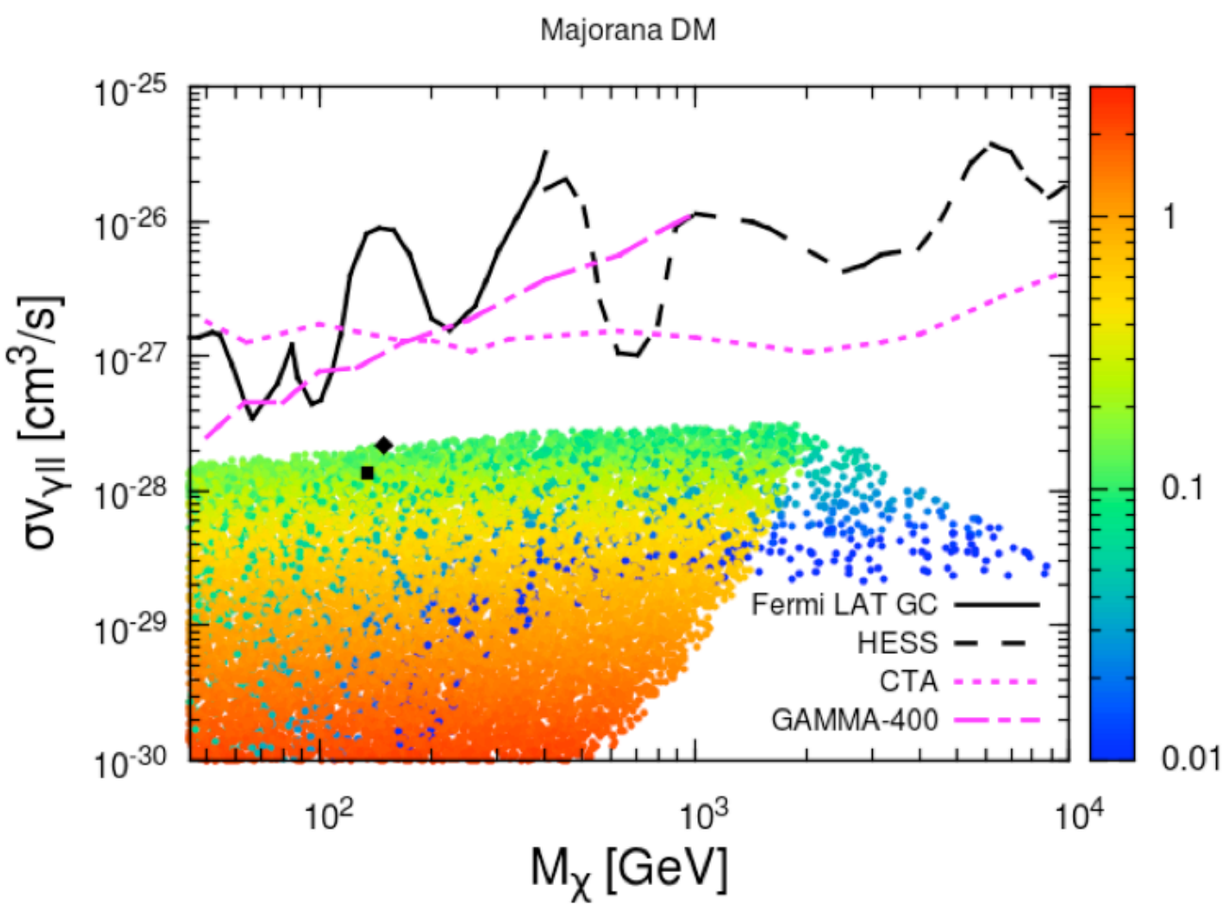
Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

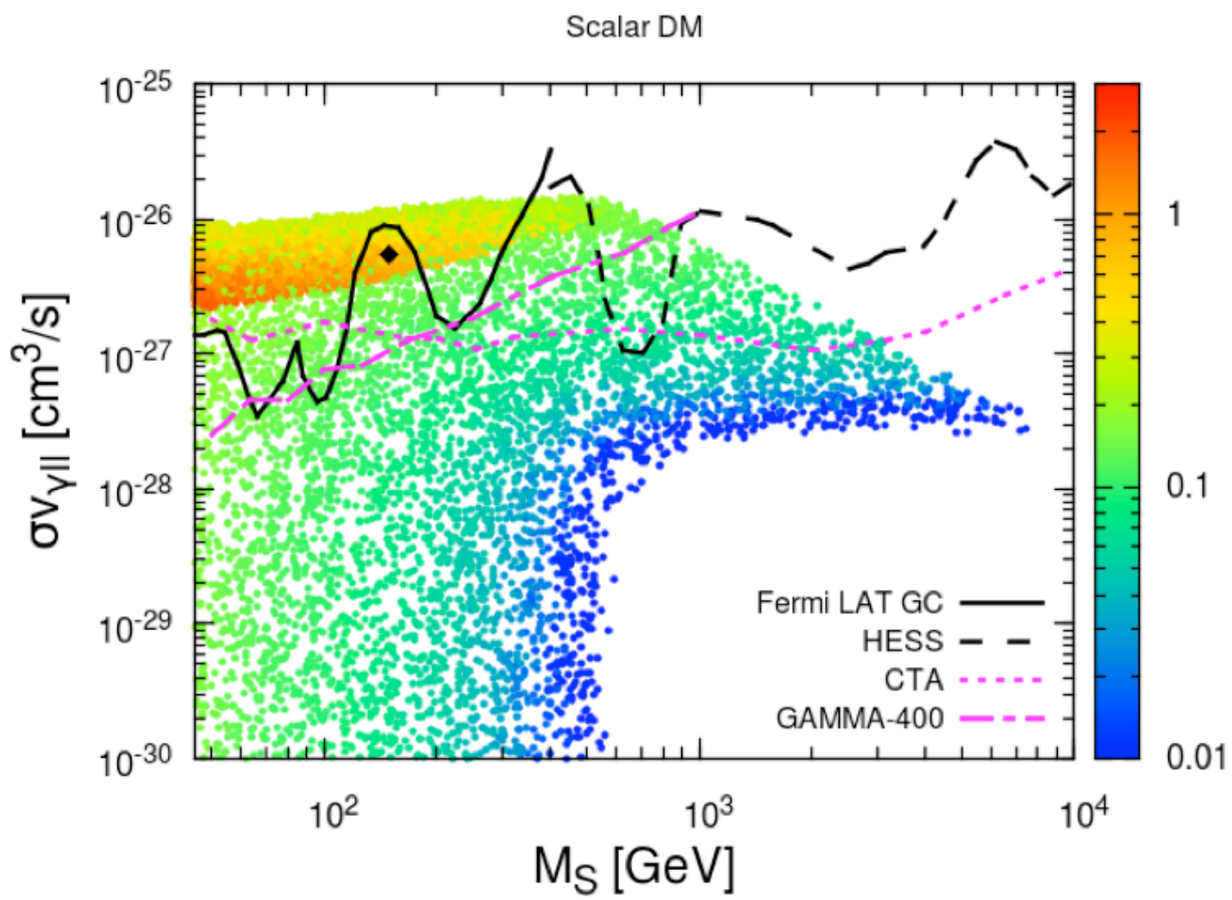
VIB ENHANCEMENT



MAJORANA

SCALAR





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arXiv:1307.6480
See also
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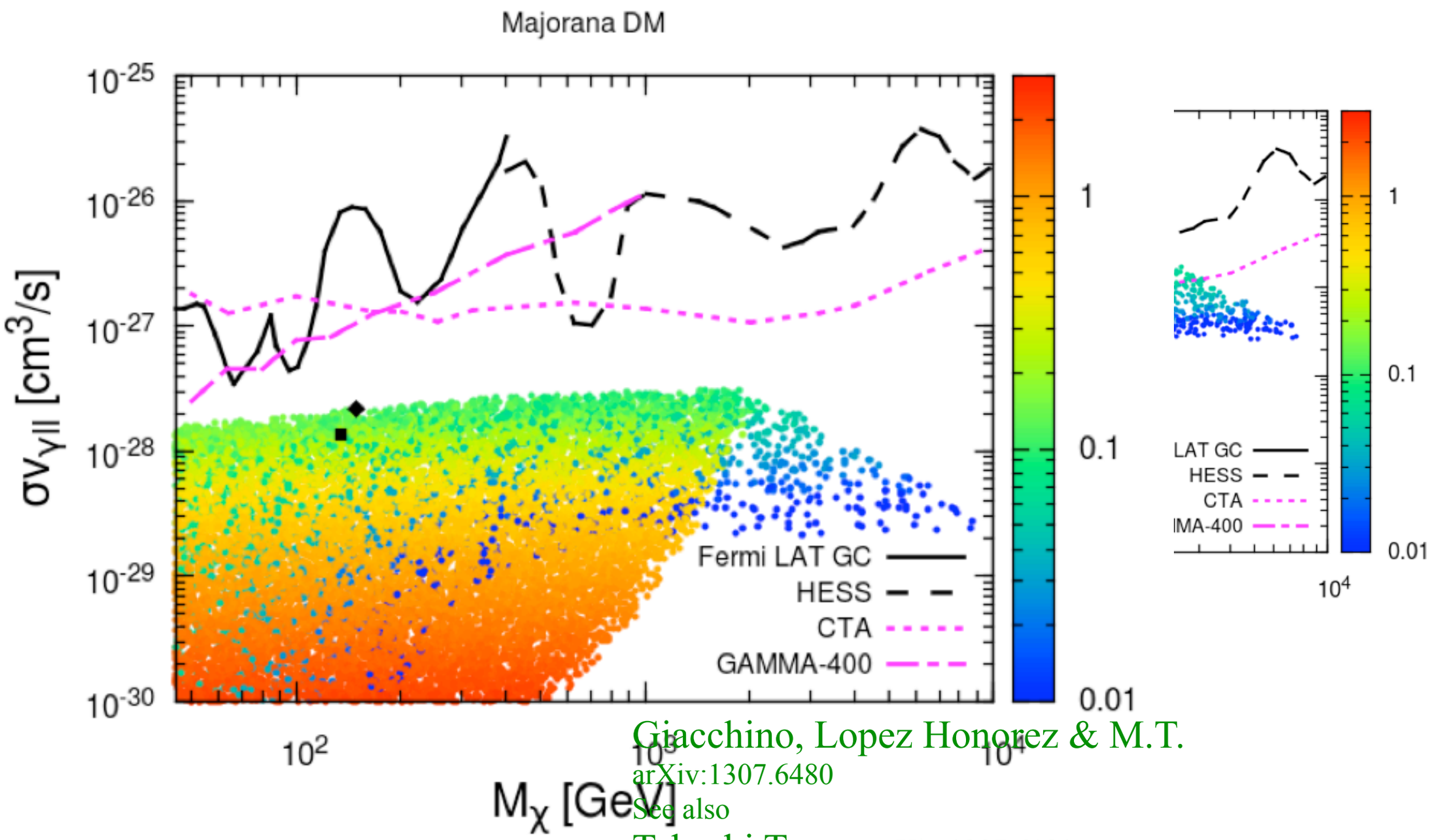
MAJORANA SCALAR



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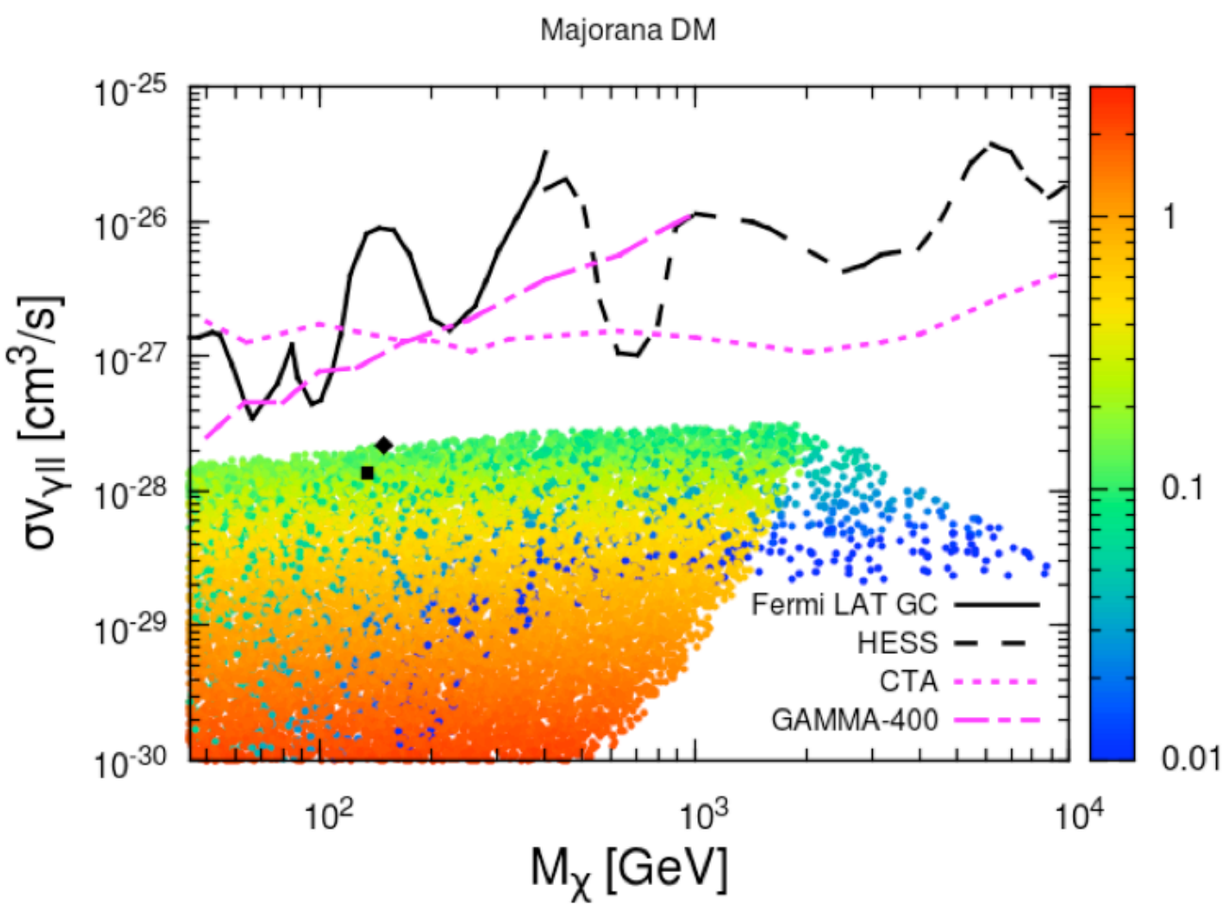

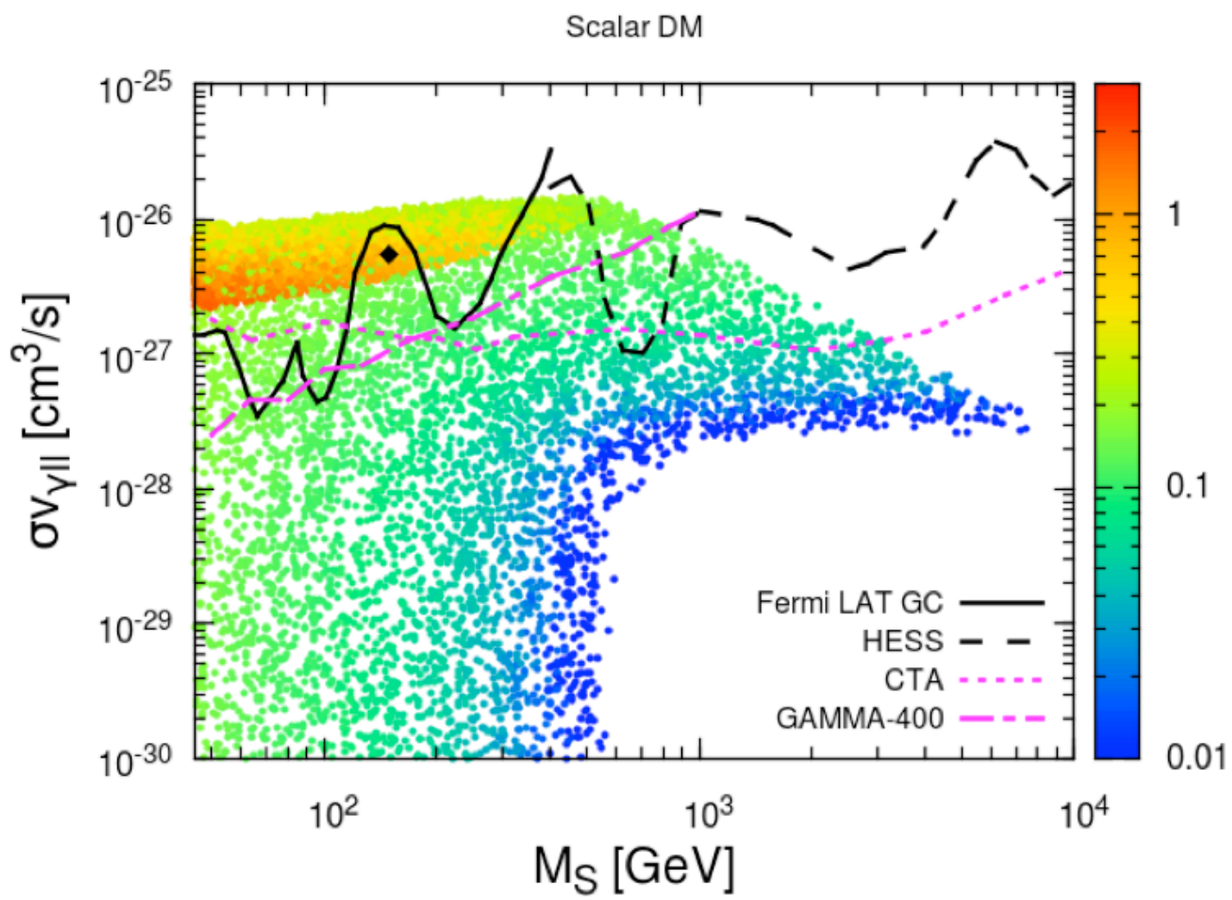

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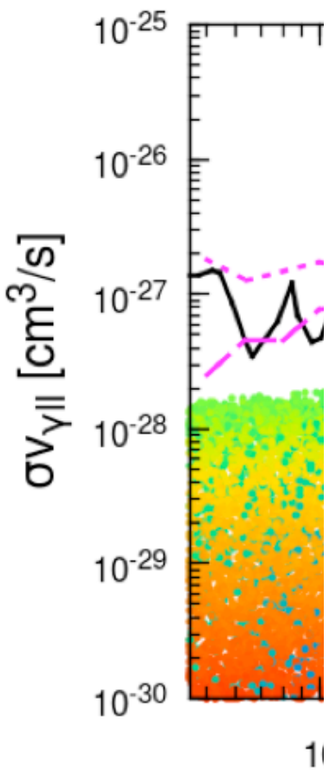

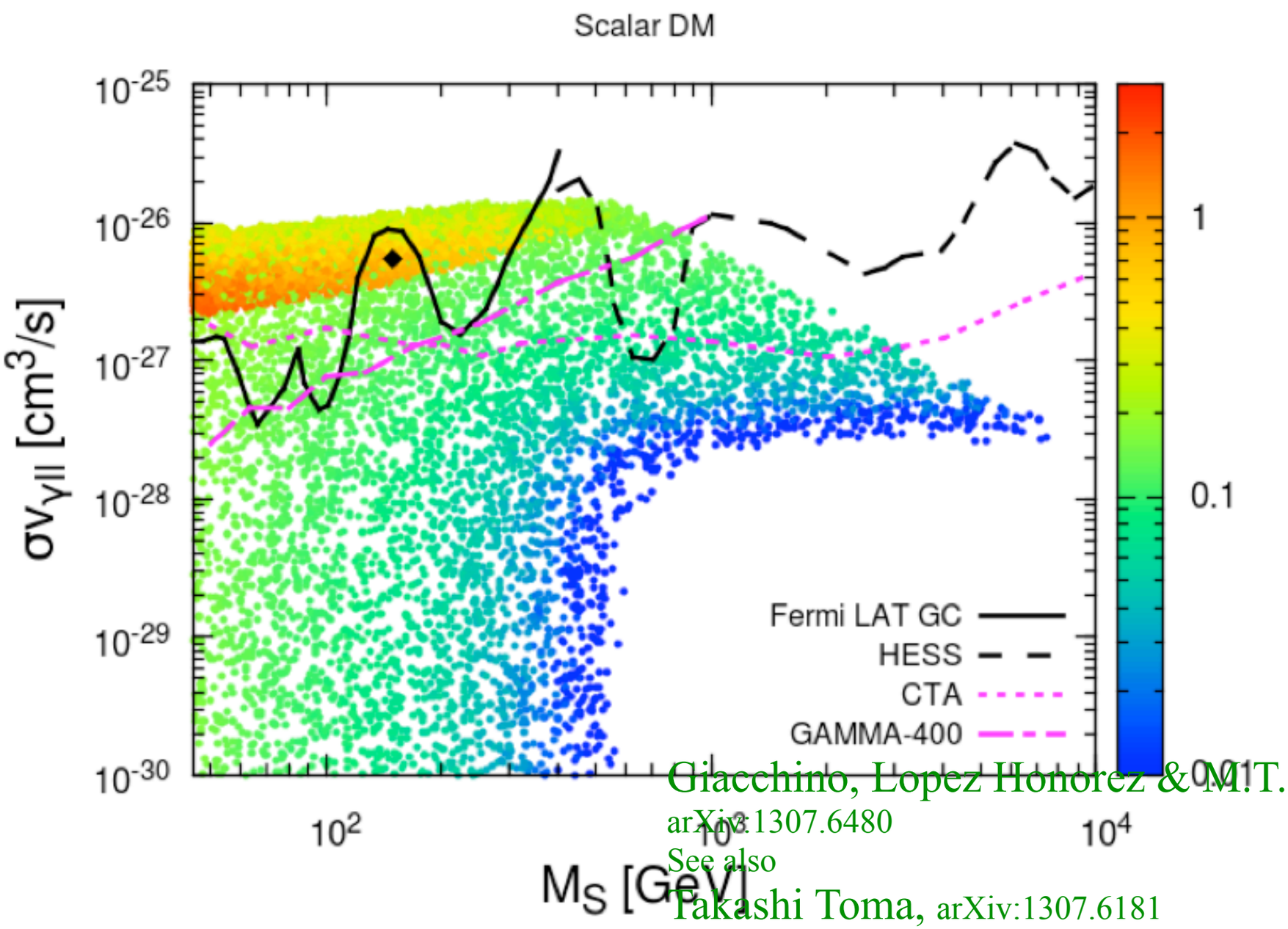

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FINAL WORDS

WE STILL DON'T KNOW WHAT DM IS MADE OF
BUT
WE KNOW MORE AND MORE WHAT IT IS NOT

THE WIMP PARADIGM IS VERY APPEALING
PROVIDED WE FIND DM
(LEPTOGENESIS IS ALSO APPEALING)

IN THAT RESPECT
SIMPLIFIED MODELS ARE USEFUL BECAUSE THEY ARE SENSICAL & INSTRUCTIVE

KEY MESSAGE
NATURE OF THE PORTAL/MEDIATOR IS IMPORTANT

(WE MAY VERY WELL FIND THE MEDIATOR BEFORE DM)

IMPORTANT TO CONSIDER ALTERNATIVES

KEY MESSAGE
PBH ARE STILL ALIVE (BUT HAVE PROBLEMS OF THEIR OWN)
CAN WE COMPLETELY KILL THIS POSSIBILITY?

BACKUP SLIDES

WHAT'S NEXT?
A POSSIBLE EXTENSION

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR WITH VL LEPTONS

$$\mathcal{L} \supset y_q \, S \, \bar{\Psi} q_R + h.c.$$

THE SAME WITH VL QUARKS

$$\frac{\langle \sigma v \rangle_{g\bar{q}q}}{\langle \sigma v \rangle_{\gamma\bar{q}q}} = \frac{N_c^2 - 1}{2N_c} \frac{\alpha_s}{Q^2 \alpha}$$

~ 40 (up-like quarks)

~ 150 (down-like quarks)

$$\langle \sigma v \rangle_{q\bar{q}} \ll \langle \sigma v \rangle_{q\bar{q}g}$$

EVEN IN EARLY UNIVERSE

→ ABUNDANCE FROM (GLUON) BREMSSTRAHLUNG

+ DIRECT DETECTION
+ CONSTRAINTS FROM CR ANTI-PROTONS
+ **LHC constraints**
etc...

Work in progress

SO, WHAT WENT WRONG?

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

fluid displacement

long range force

Formal manipulations lead to dropping seemingly innocuous terms but which are singular for long range forces

Quite hidden, but clearly seen in planar, incompressible fluid limit

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

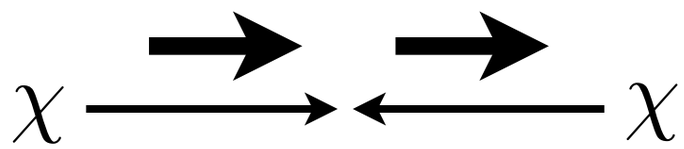
a forgotten boundary term
(UV divergent)

Pani & Loeb kept only this
(UV divergent too)

A DIGRESSION

ANNIHILATION OF MAJORANA DM INTO LIGHT SM FERMIONS

P-WAVE INITIAL STATE



$^3P_1(1^{++})$

FINAL STATE

$\bar{\psi}_f \gamma^k \gamma_5 \psi_f$

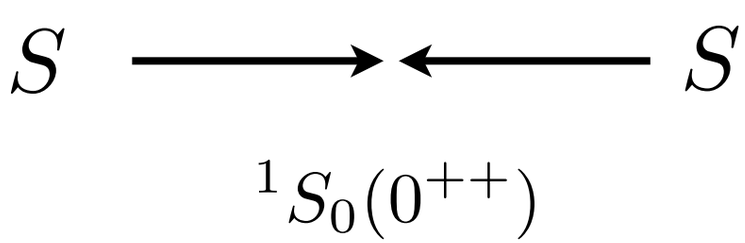
P-WAVE IN CHIRAL LIMIT (remember that $v \sim 10^{-3}$)

$$\sigma v \propto y_f^4 \frac{v^2}{M_\chi^2}$$

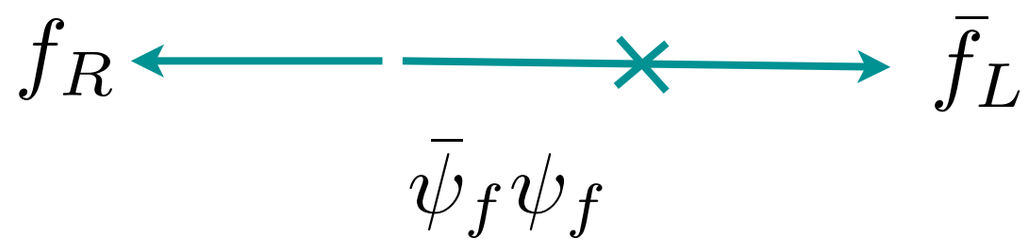
Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

WHY?

S-WAVE INITIAL STATE

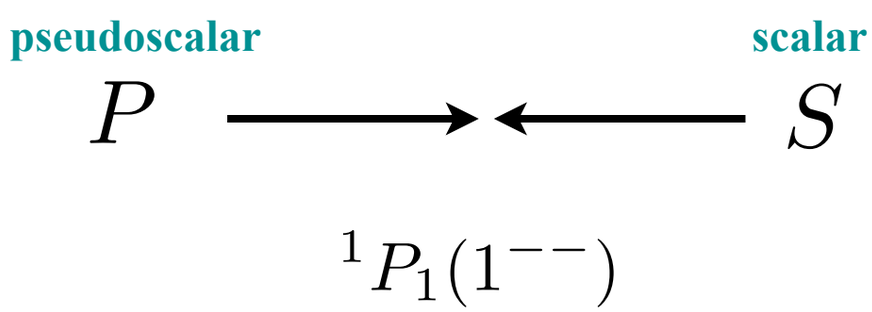


FINAL STATE

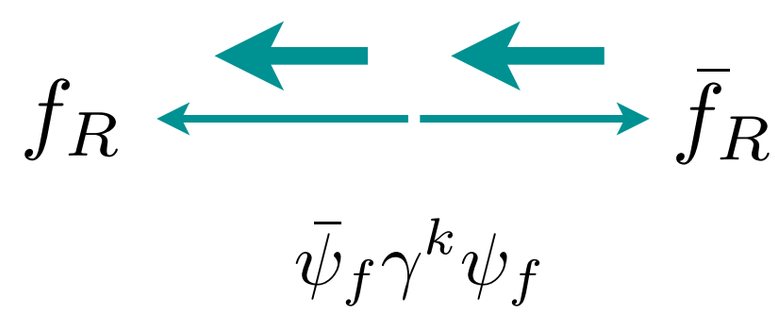


chirally suppressed → $\mathcal{O}_S = m_f \, S^2 \, \bar{\psi}_f \psi_f$

P-WAVE INITIAL STATE



FINAL STATE



a <u>complex scalar</u> could have p-wave annihilation → $\mathcal{O} = P \overleftrightarrow{\partial_\mu} S \; \bar{\psi}_f \gamma^\mu \psi_f$

WHY?

S-WAVE INITIAL STATE

$S \longrightarrow \longleftarrow S$

$^1S_0(0^{++})$

FINAL STATE

$f_R \longleftarrow \times \longrightarrow \bar{f}_L$

$\bar{\psi}_f \psi_f$

chirally suppressed $\longrightarrow$ $\mathcal{O}_S = m_f\, S^2\, \bar{\psi}_f \psi_f$

D-WAVE INITIAL STATE

$S \longrightarrow \longleftarrow S$

$^1D_2(2^{++})$

FINAL STATE

$f_R \longleftrightarrow \bar{f}_R$

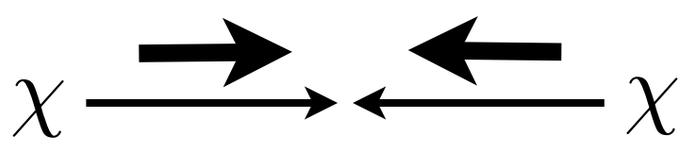
$\Theta^{ij} = \frac{i}{2}\bar{\psi}_f(\gamma^i \overrightarrow{\partial}^j - \gamma^j \overleftarrow{\partial}^i)\psi_f$

d-wave in chiral limit $\longrightarrow$ $\mathcal{O}_T = \partial_\mu S \partial_\nu S\, \Theta^{\mu\nu}_{f_R}$

FERMION STRESS-ENERGY TENSOR

A DIGRESSION
ANNIHILATION OF MAJORANA DM INTO LIGHT SM FERMIONS

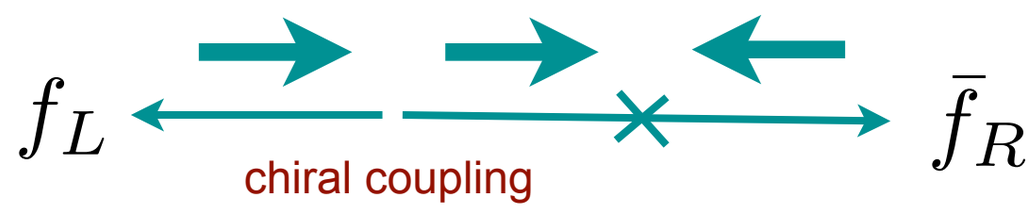
S-WAVE INITIAL STATE



$$^{2S+1}L_J(J^{PC}) = {}^1S_0(0^{-+})$$

$$|S=0\rangle = \frac{1}{2}\left(|\downarrow\rangle|\uparrow\rangle - |\uparrow\rangle|\downarrow\rangle\right)$$

FINAL STATE



$$\bar{\psi}_f \gamma_5 \psi_f$$

S-WAVE ANNIHILATION IS MASS SUPPRESSED

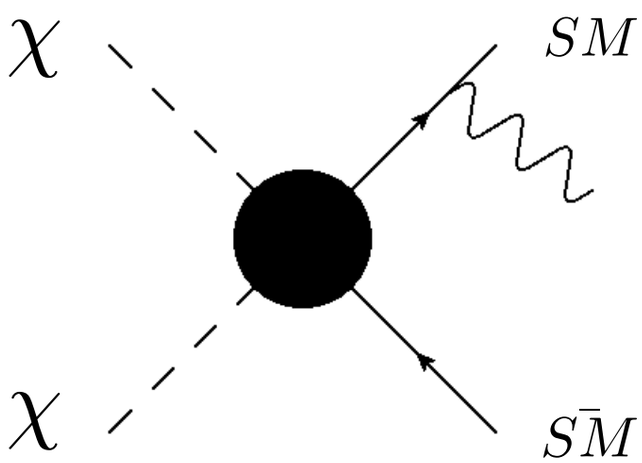
$$\mathcal{O}_{\mathrm{s-wave}} = m_f \bar{\chi}\gamma_5\chi\, \bar{\psi}_f\gamma_5\psi_f$$

$$\sigma v \propto y_f^4 \frac{m_f^2}{M_\chi^4}$$

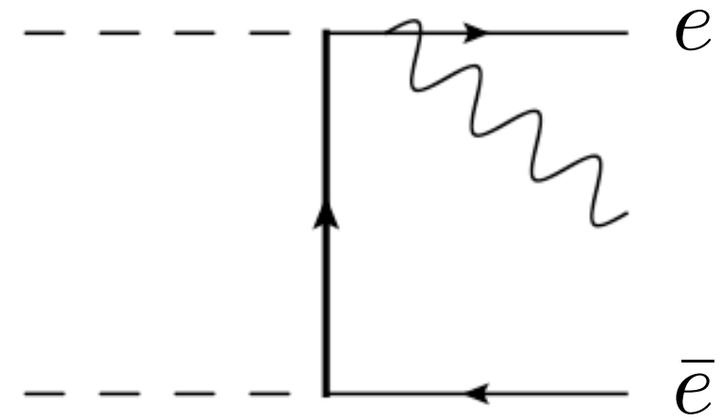
Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

VIRTUAL INTERNAL BREMSSTRAHLUNG (VIB)

annihilation of DM into charged particles



e.g.



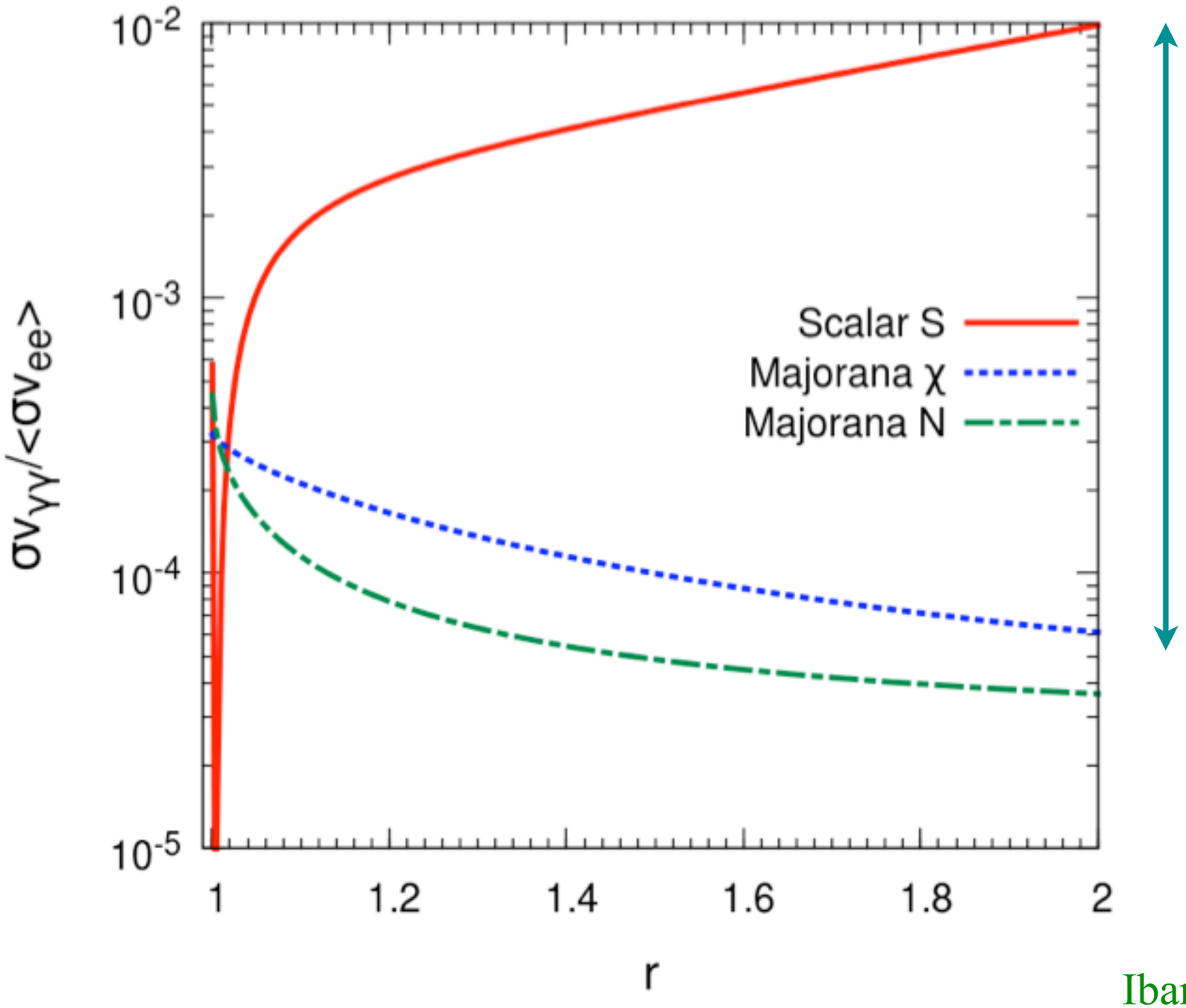
→ Final State Radiation (FSR)

$$\frac{d\sigma(\chi\chi \to X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \sigma(\chi\chi \to X\bar{X})$$

Collinear/soft emission.
Universal (but final state dependent) feature,
encoded in splitting function.

Birkedal, Matchev, Perelstein and Sprey (2005)

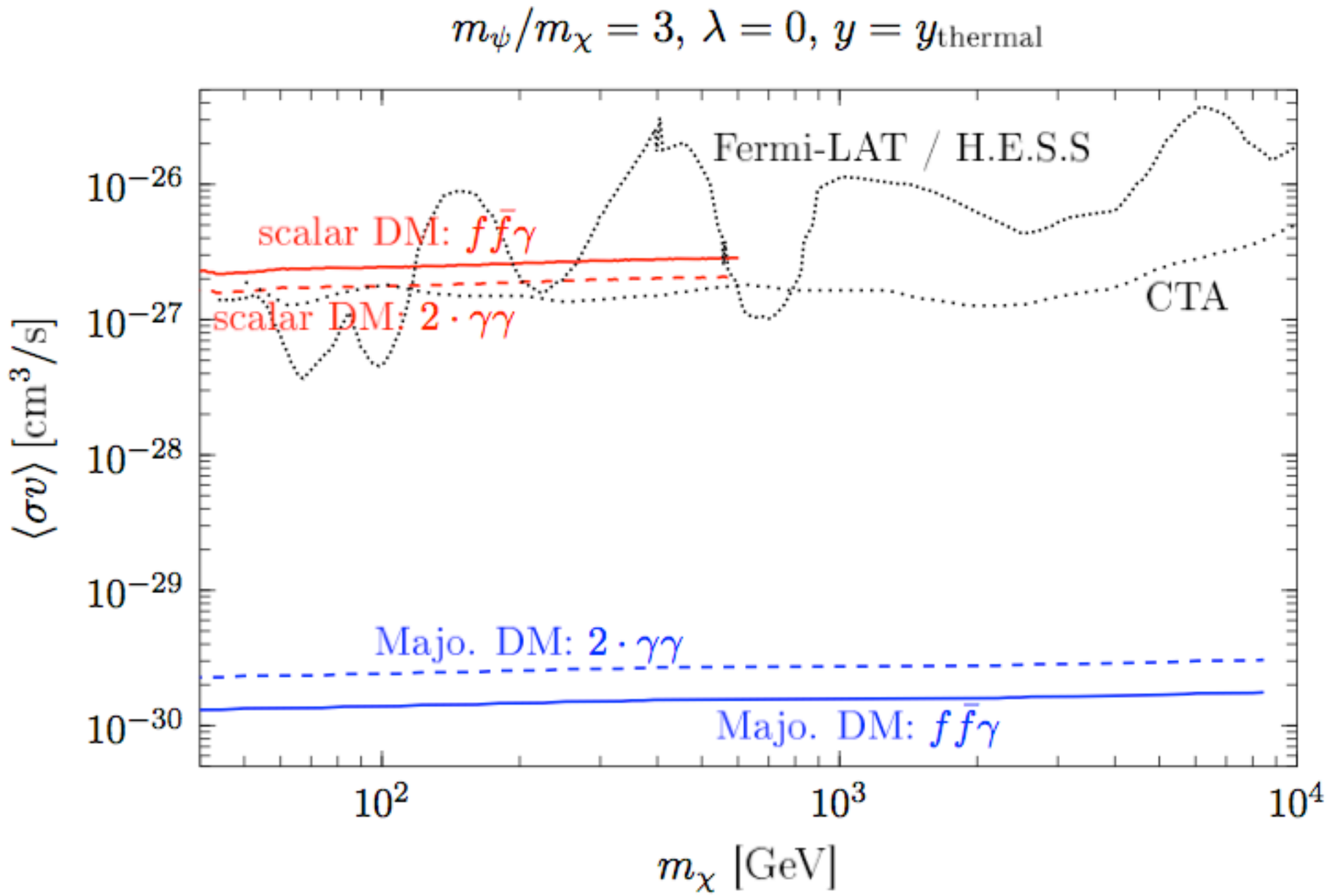
MONOCHROMATIC GAMMA RAYS



O(100) enhancement

$$r = \frac{M_\Psi}{M_S} > 1$$

Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917
Giacchino, Lopez Honorez, M.T.
arXiv:1405.6921



Ibarra, Toma, Totzauer & Wild
arXiv:1405.6917