Indirect probes of Dark Matter

Bradley J. Kavanagh
(IFCA, UC-CSIC, Santander)

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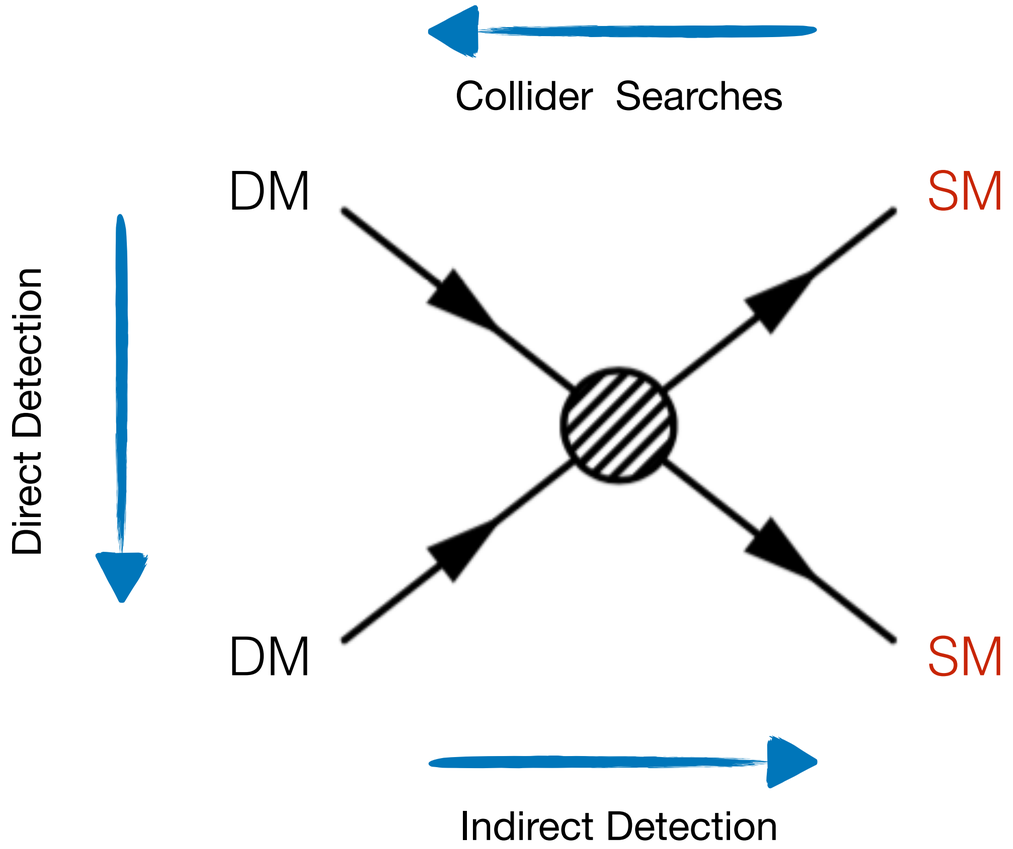
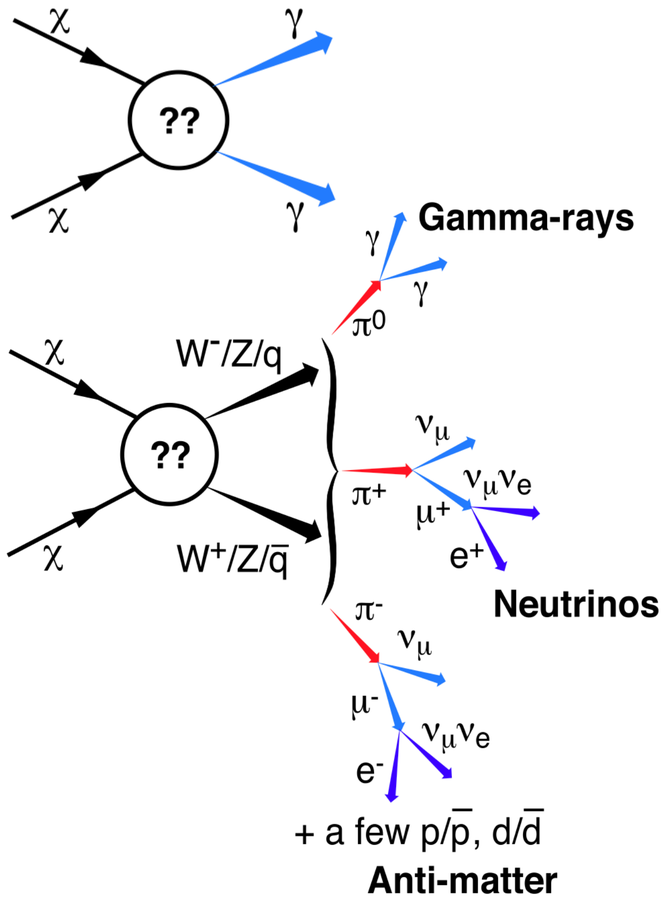
Instituto de Física de Cantabria
Consejo Superior de Investigaciones Científicas
Universidad de Cantabria
Excelencia María de Maeztu

kavanagh@ifca.unican.es
@BradleyKavanagh

Indirect Detection™





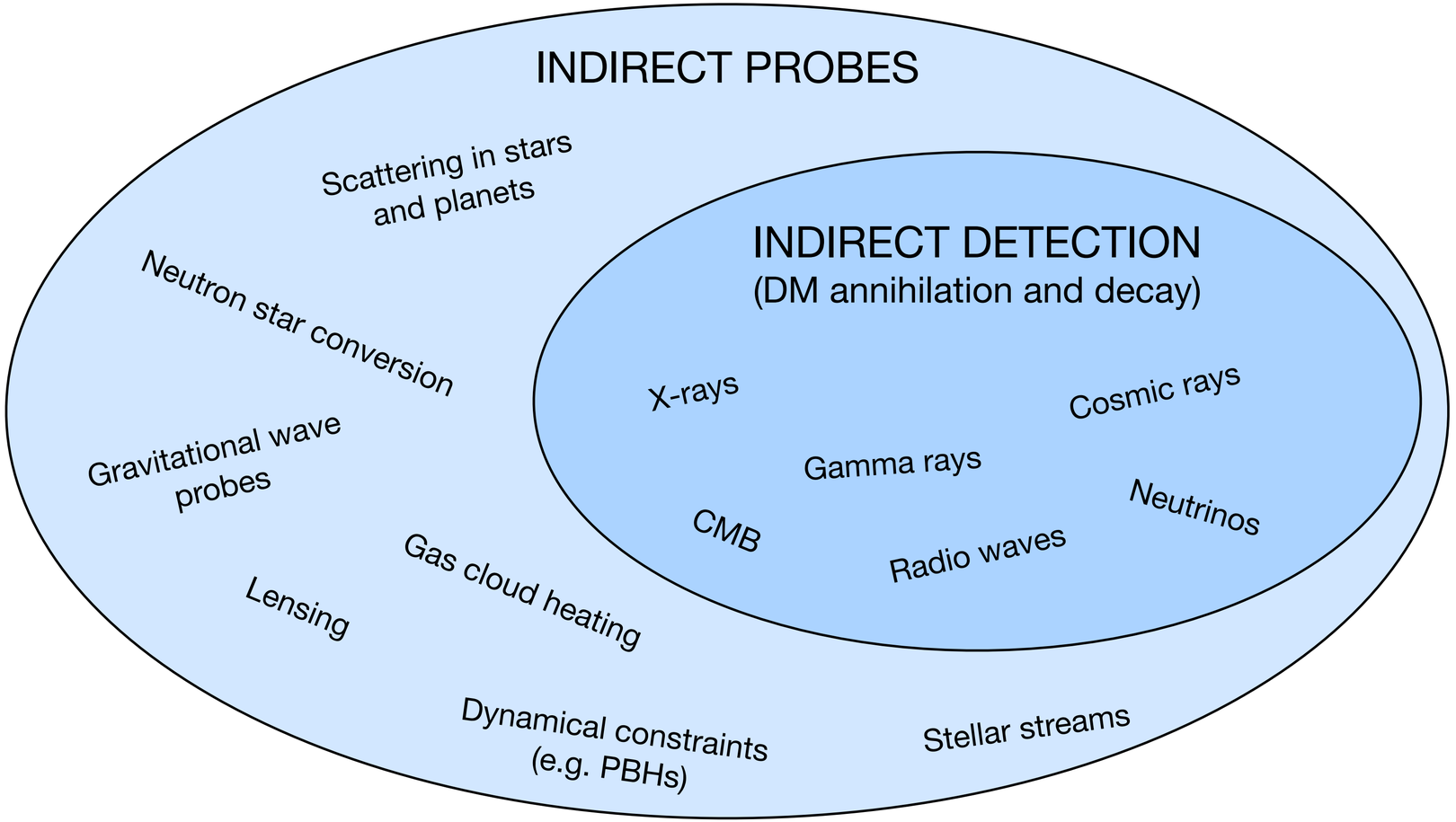
[0806.2911]

What are indirect probes?

Broad definition - *searches for DM in which the interactions (gravitational or otherwise) happen whether we like it or not ('passive probes?')*

Practical definition - *searches for the effects of DM in astrophysical and cosmological systems.*

Cynical definition - *searches for DM in which we have very little experimental control (e.g. over backgrounds, systematics, etc.)*



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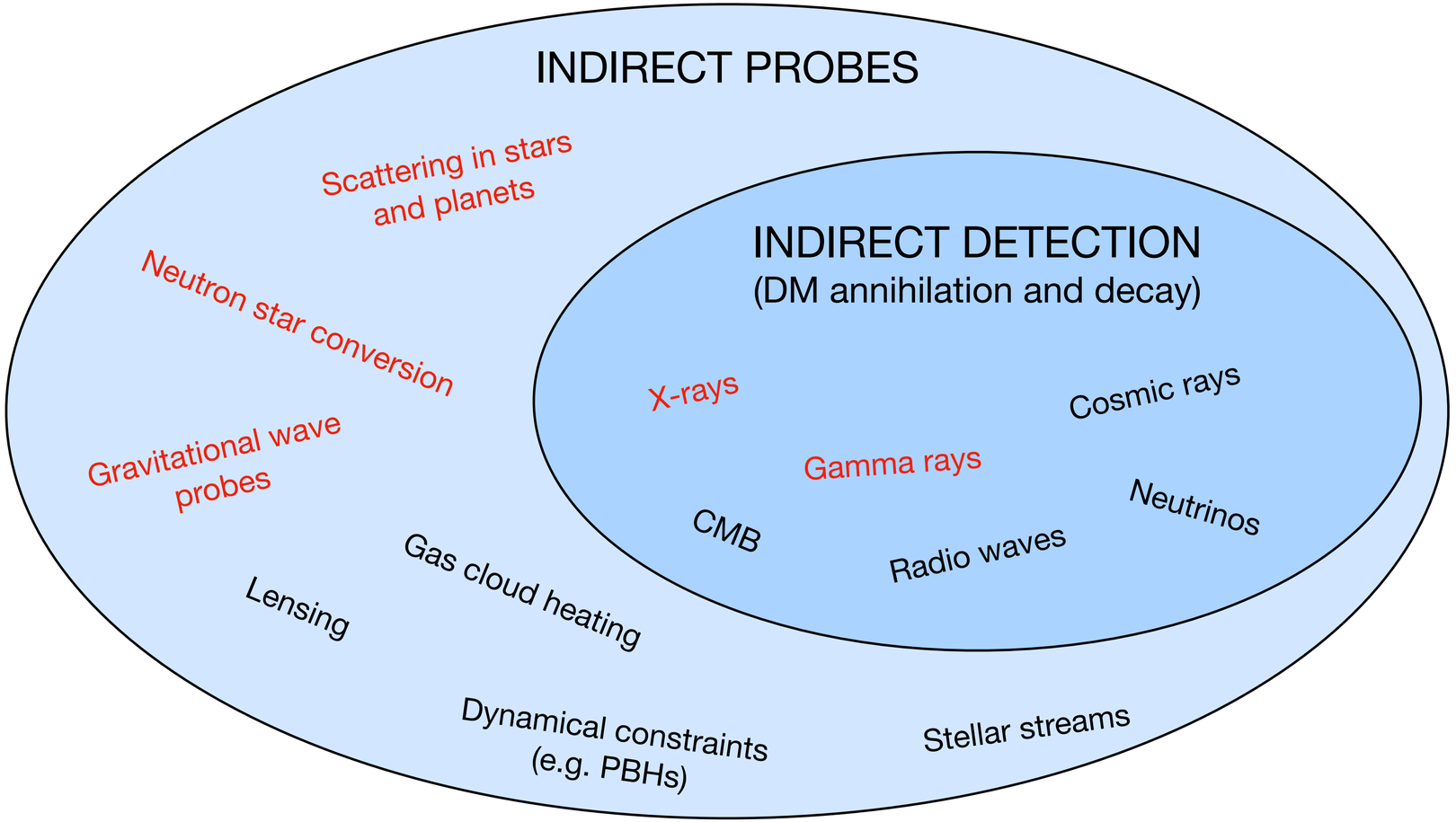
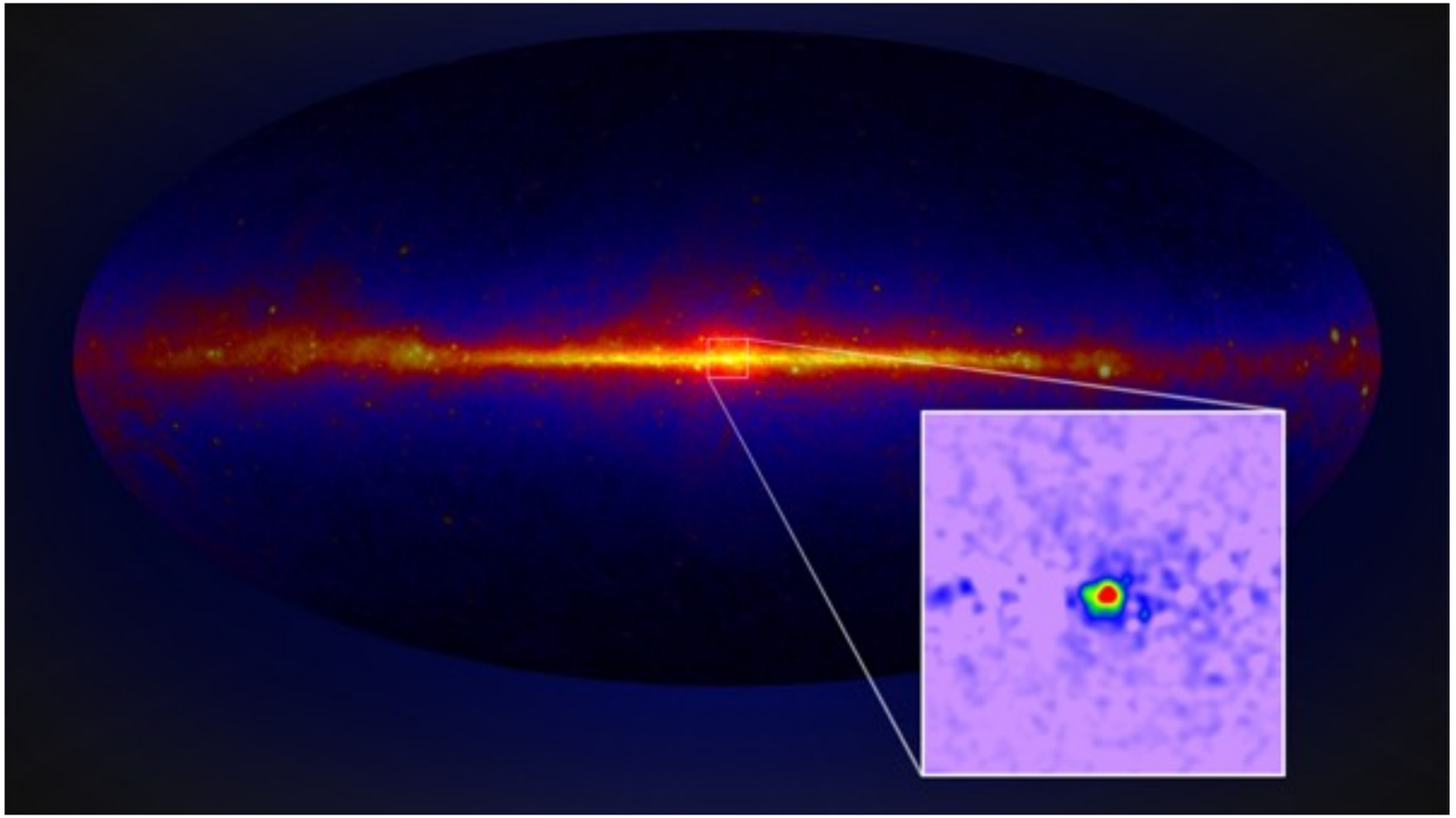
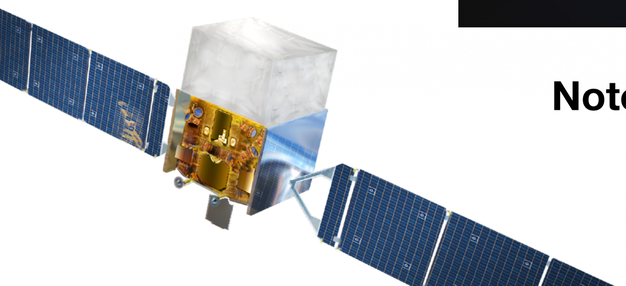


Gamma-rays in the Milky Way



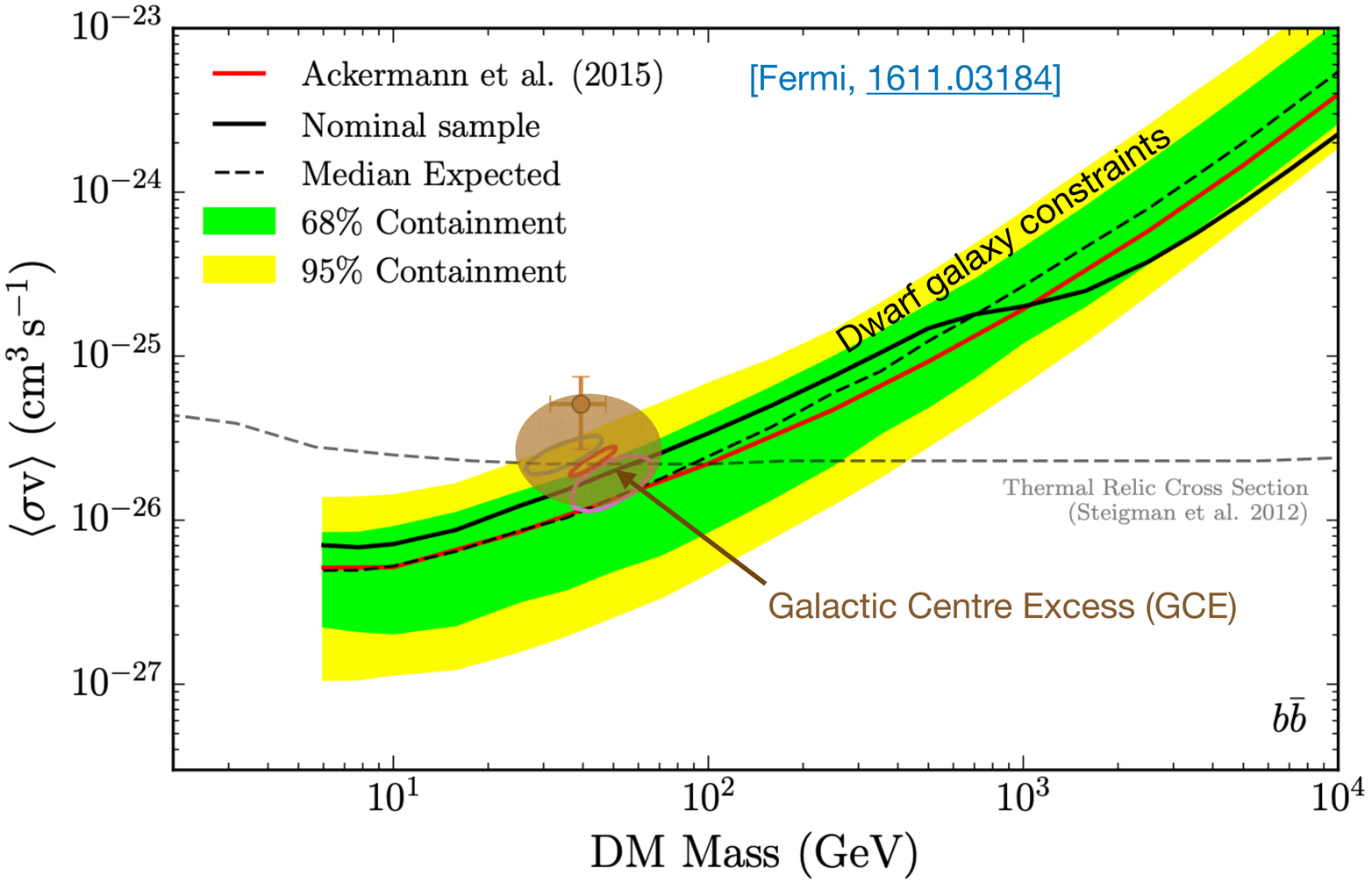
[Credit: NASA/T. Linden, U.Chicago]

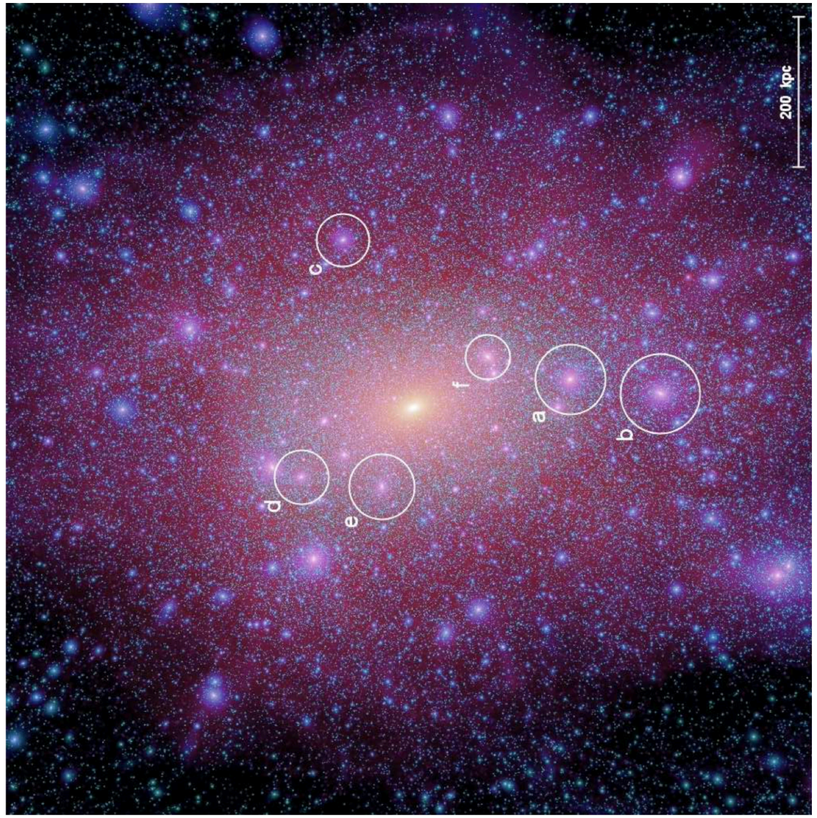


Note: increasing evidence of consistency with point sources. Millisecond pulsars?

[E.g. Macias et al., 1611.06644, 1901.03822 ; Bartels et al., 1711.04778;
But see also Leane & Slatyer, 2002.12370]

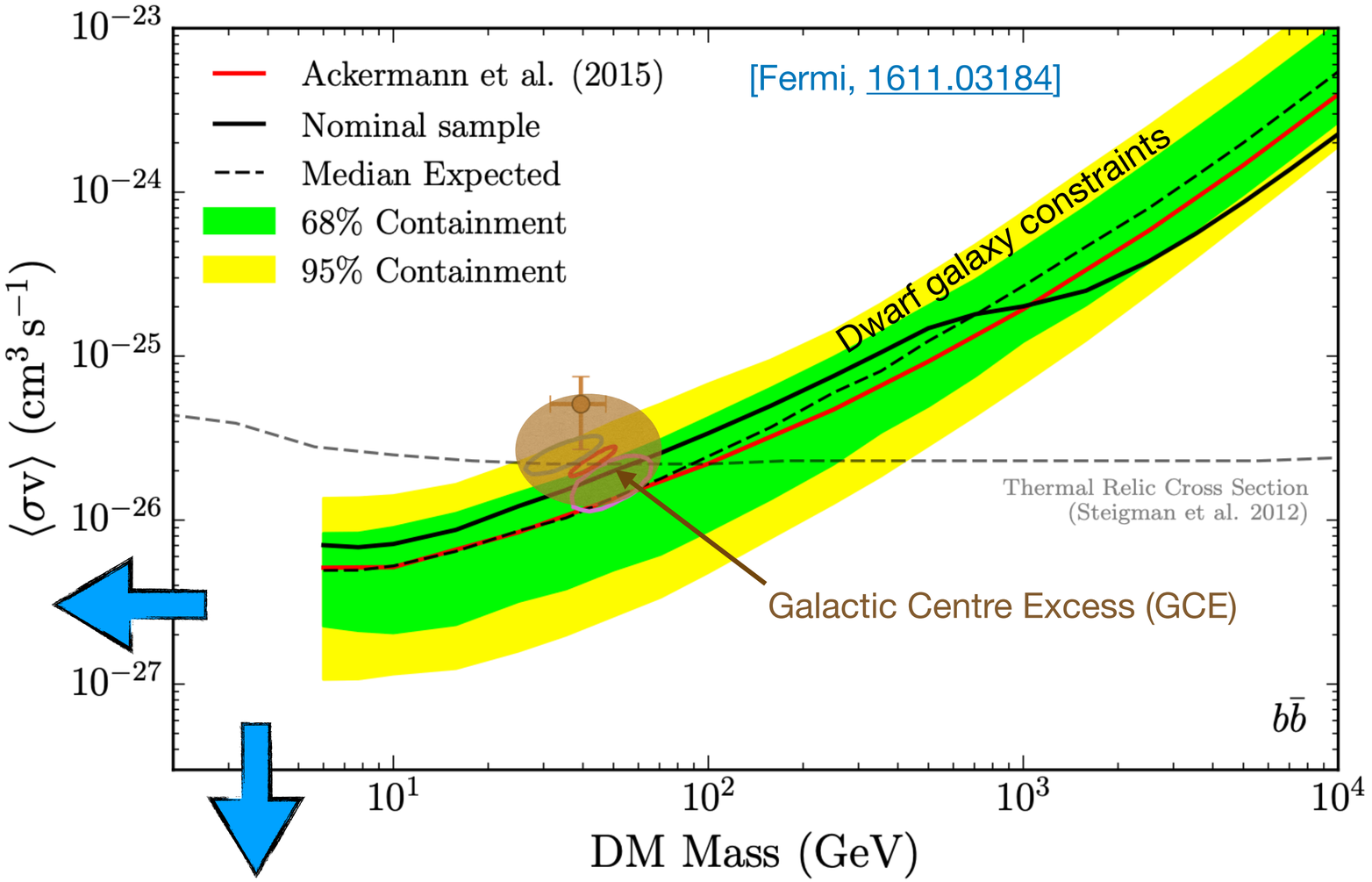
Gamma-ray constraints

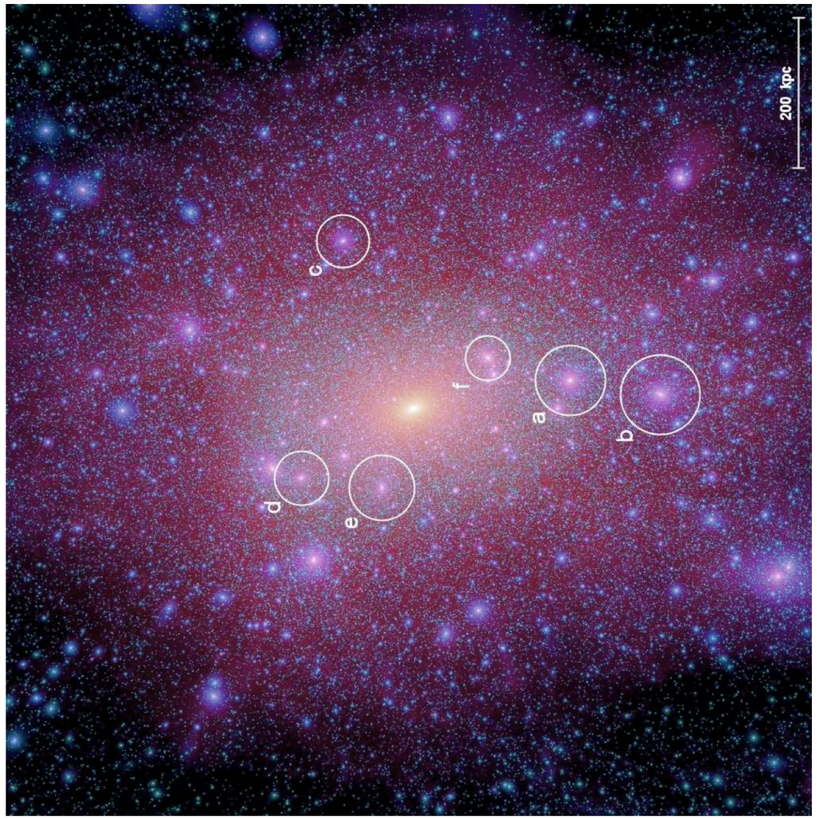




[Aquarius - Springel et al., 0809.0898]

Gamma-ray constraints





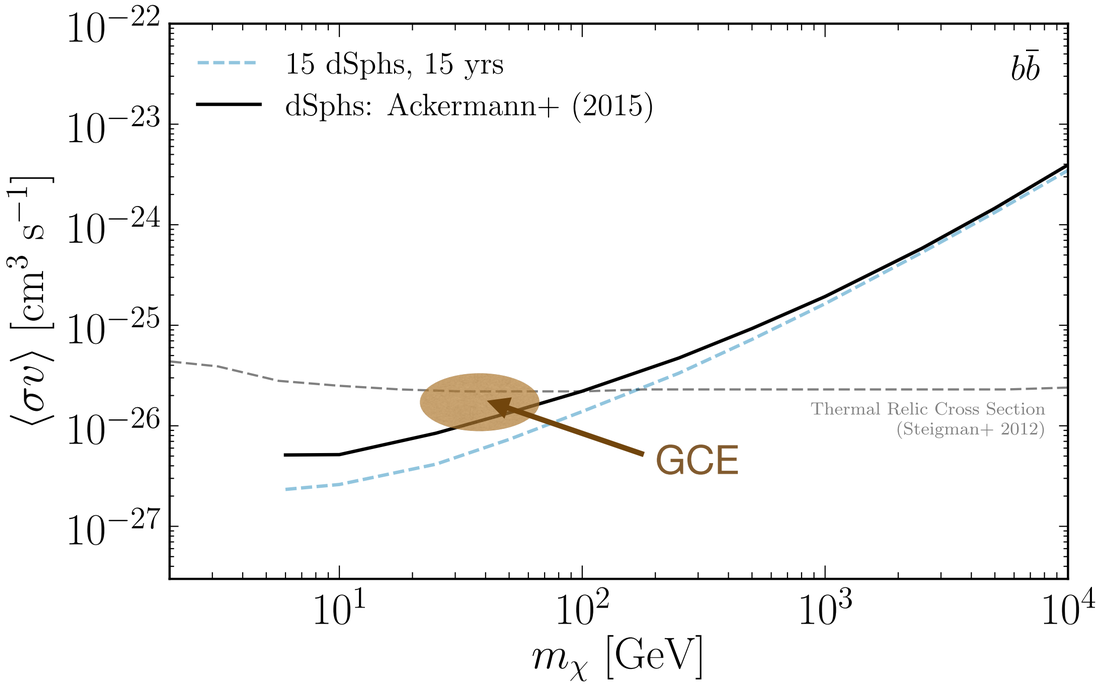
[Aquarius - Springel et al., 0809.0898]

How can we extend the reach of these indirect searches?

Strengthening the constraints

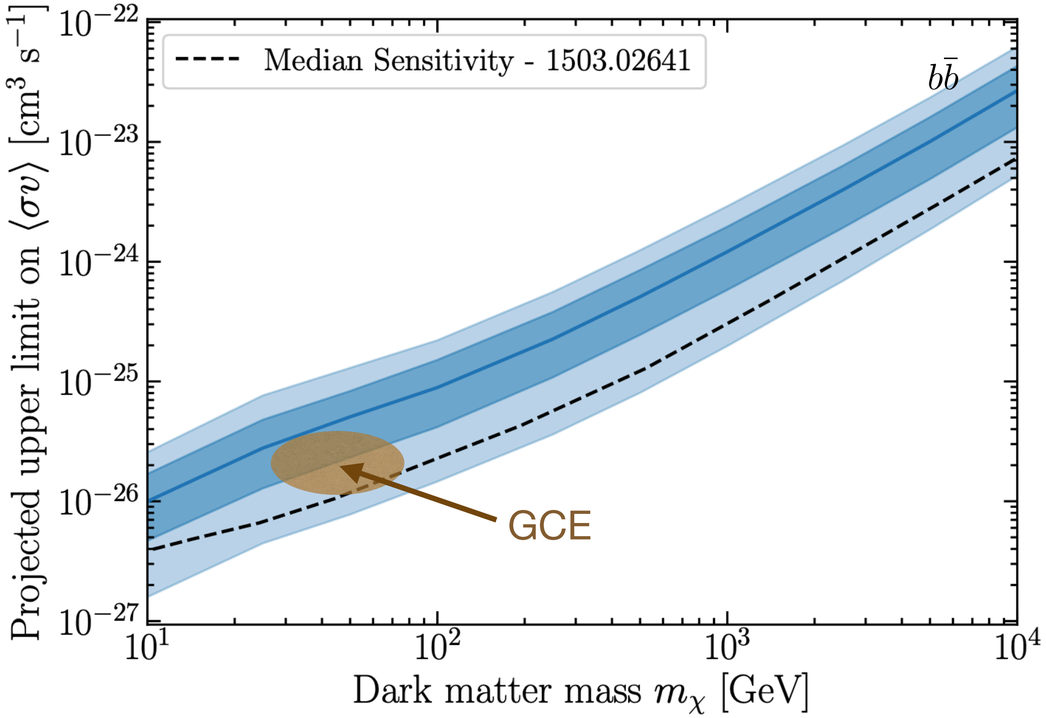
Observe for longer…?

[Fermi-LAT Collaboration, 1605.02016]



Discover more dSphs…?

[Ando, **BJK**, Macias et al., 1905.07128]



But hard to reach much further down in cross section…

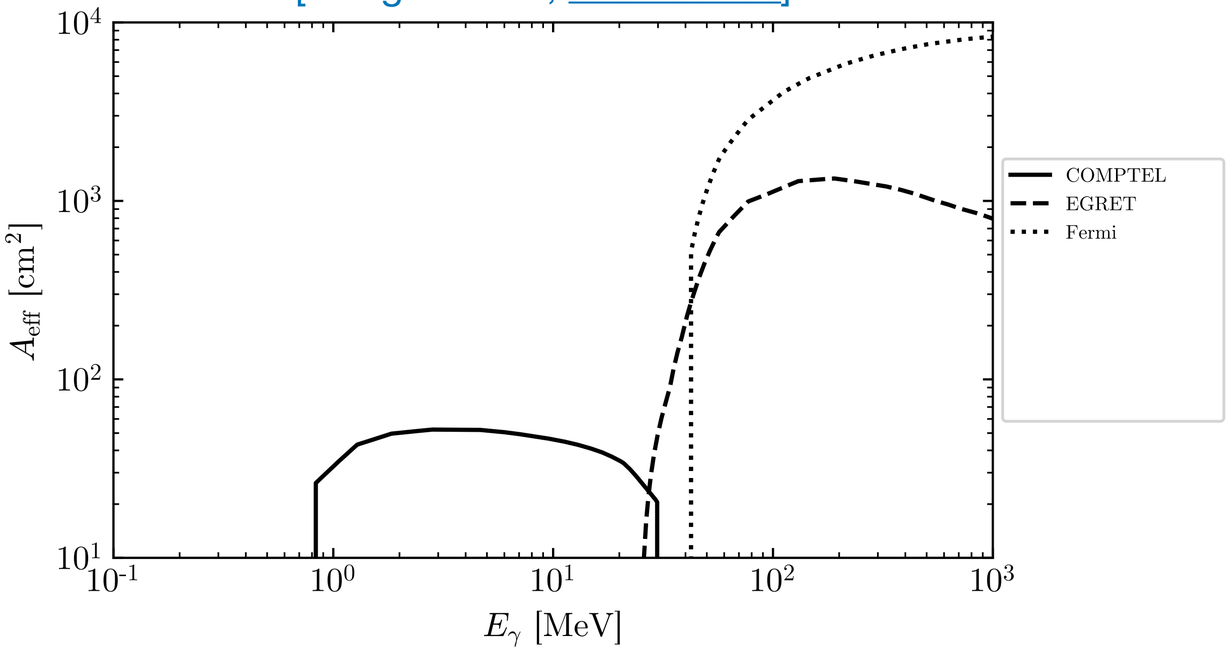
Especially with plenty of modelling uncertainties (e.g. J-factors)…

[e.g. Alvarez et al., 2002.01229; Ando et al., 2002.11956]

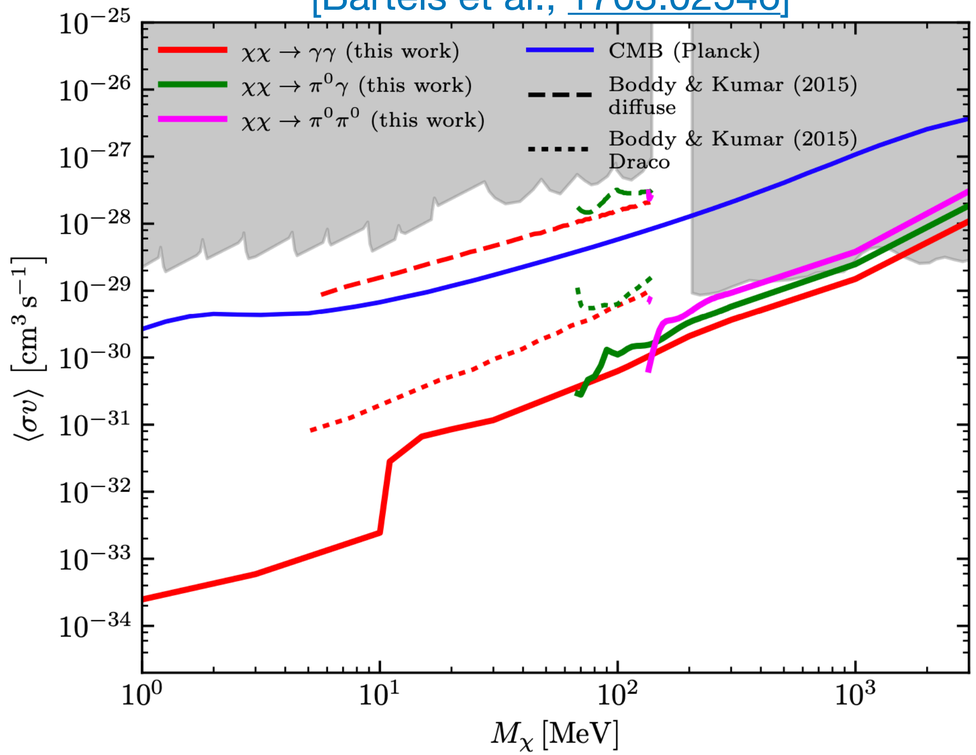
The MeV ‘Gap’

New telescopes and theoretical developments

[Coogan et al., 2104.06168]



[Bartels et al., 1703.02546]



Careful modelling required for MeV-scale DM…

[See also Boddy & Kumar, 1509.03333; Coogan et al., 1907.11846, 2101.10370]

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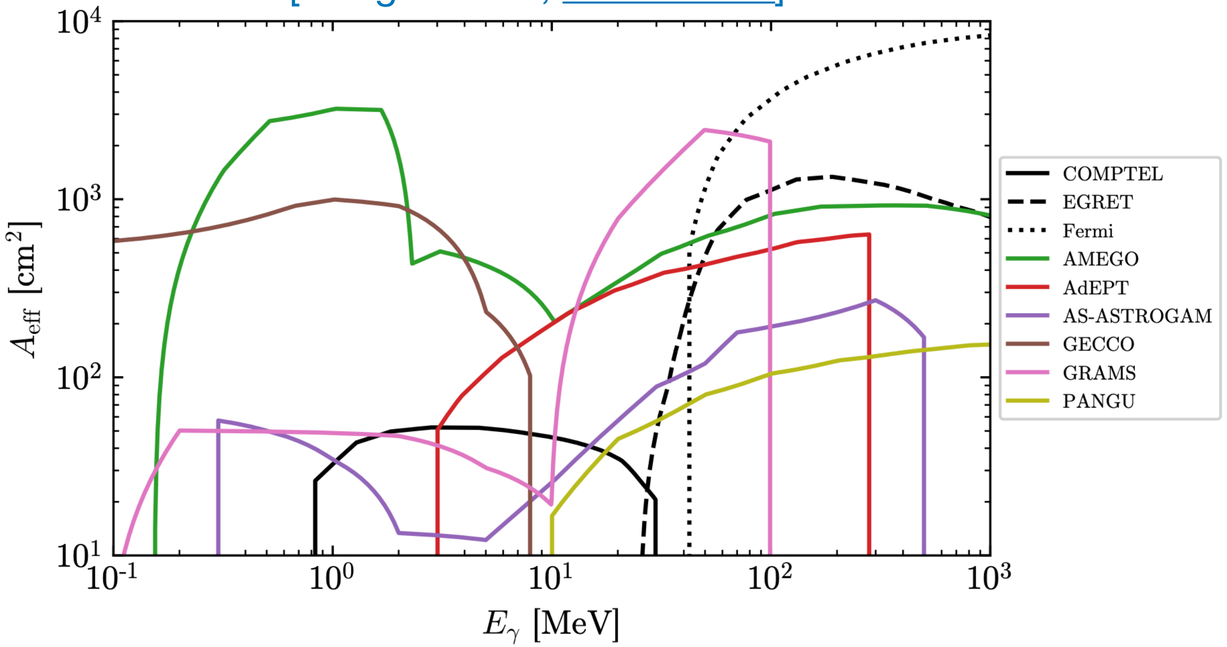

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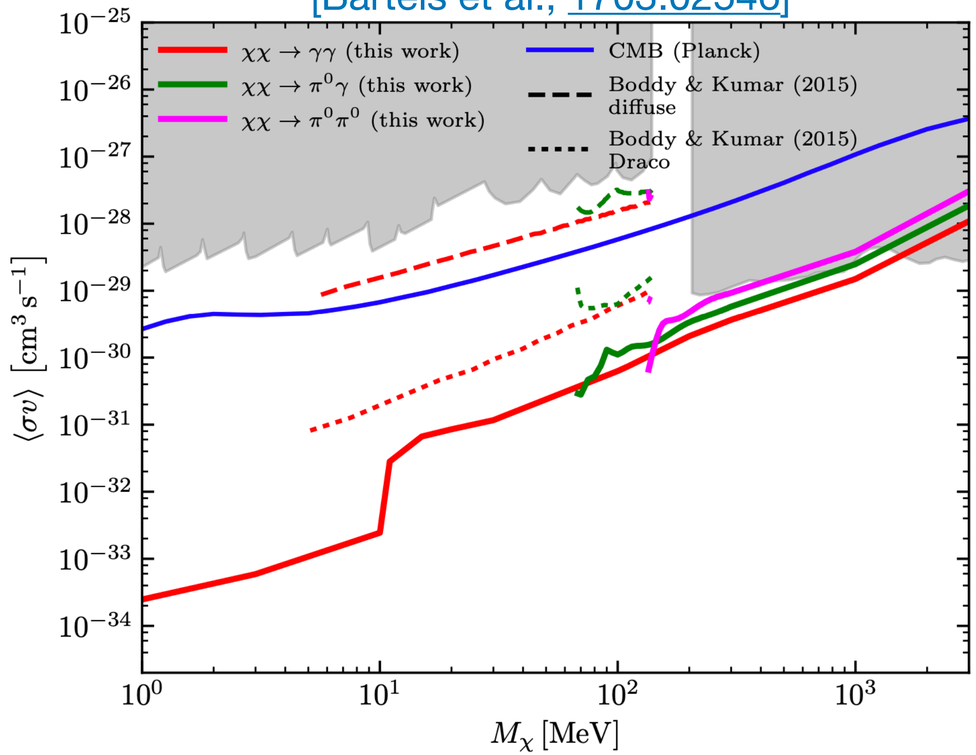

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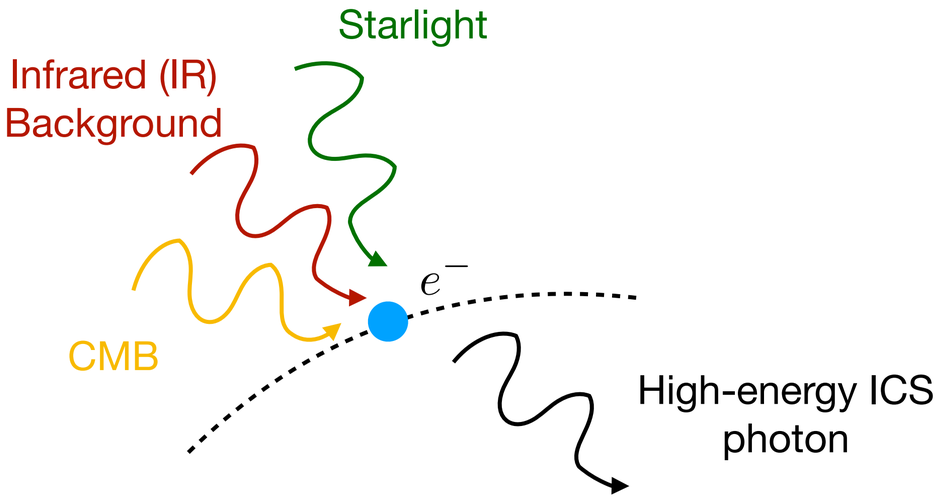
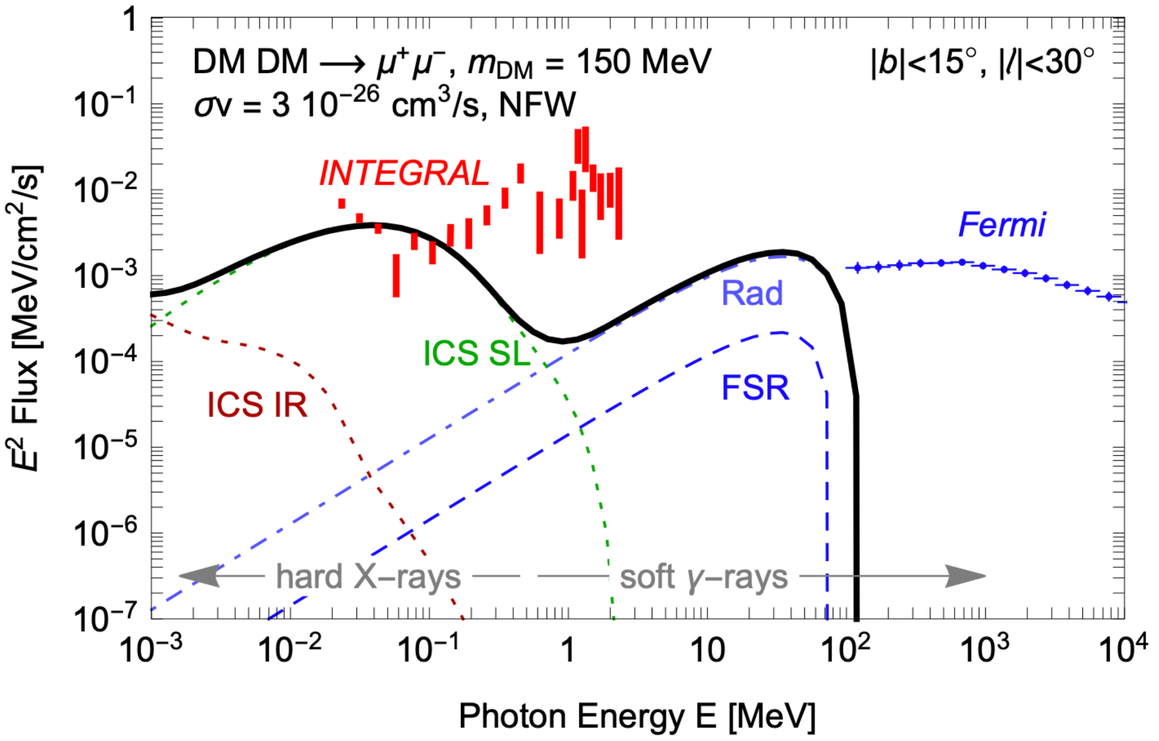
The MeV ‘Gap’

Old telescopes and new approaches

Inverse Compton scattering (ICS)





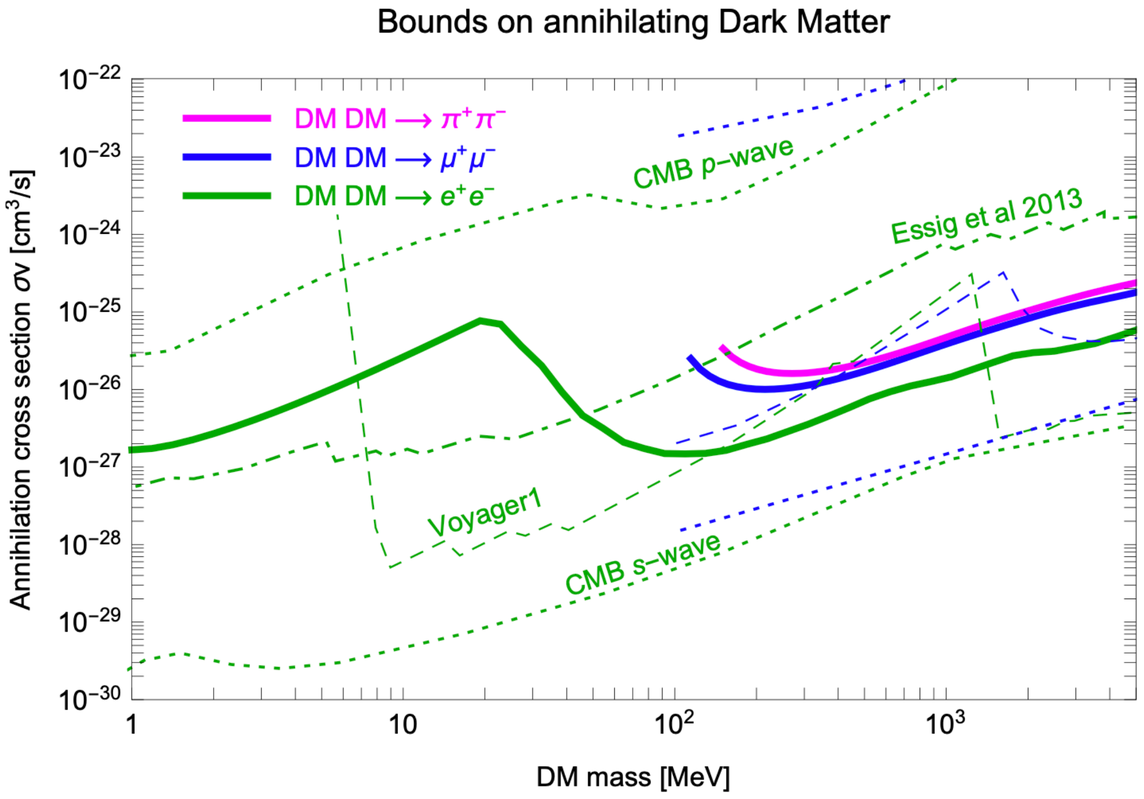
+ final state radiation (“FSR”)
+ radiative decay (“Rad”), for muons

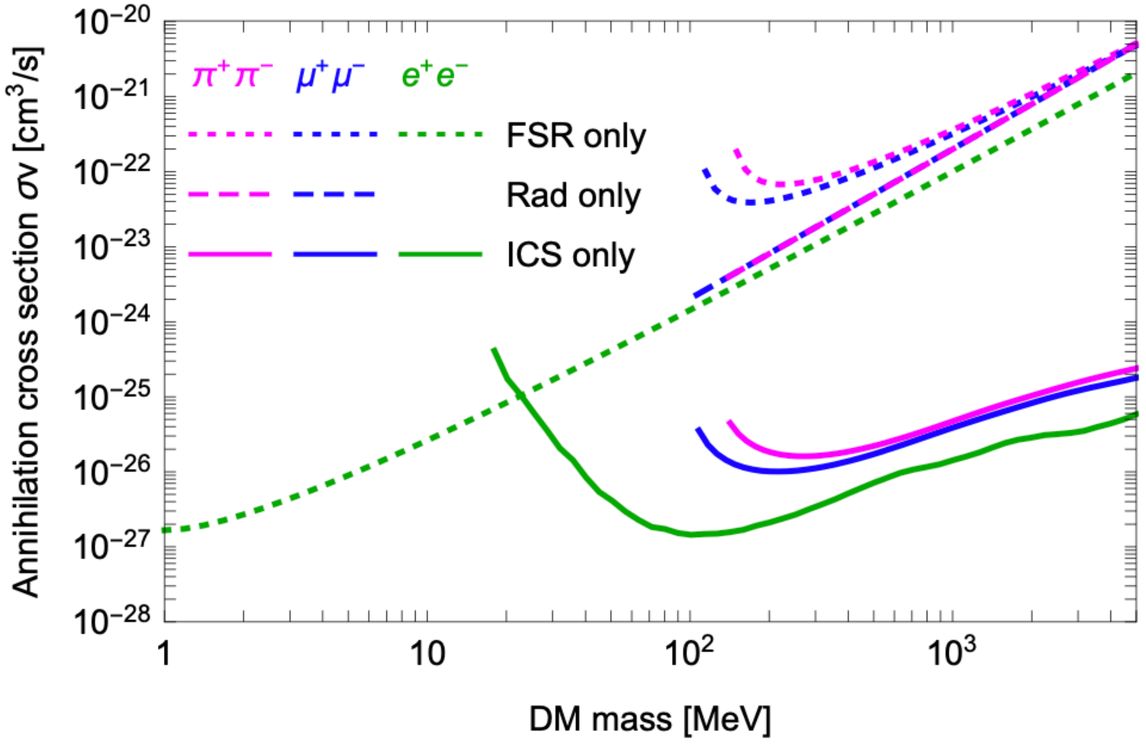
[Cirelli, Fornengo, **BJK** & Pinetti, 2007.11493]
[See also Essig et al., 1309.4091; Boudaud et al., 1612.07698]

The MeV ‘Gap’

Old telescopes and new approaches

Constraints from the INTEGRAL X-ray telescope:





[Cirelli, Fornengo, **BJK** & Pinetti, 2007.11493]

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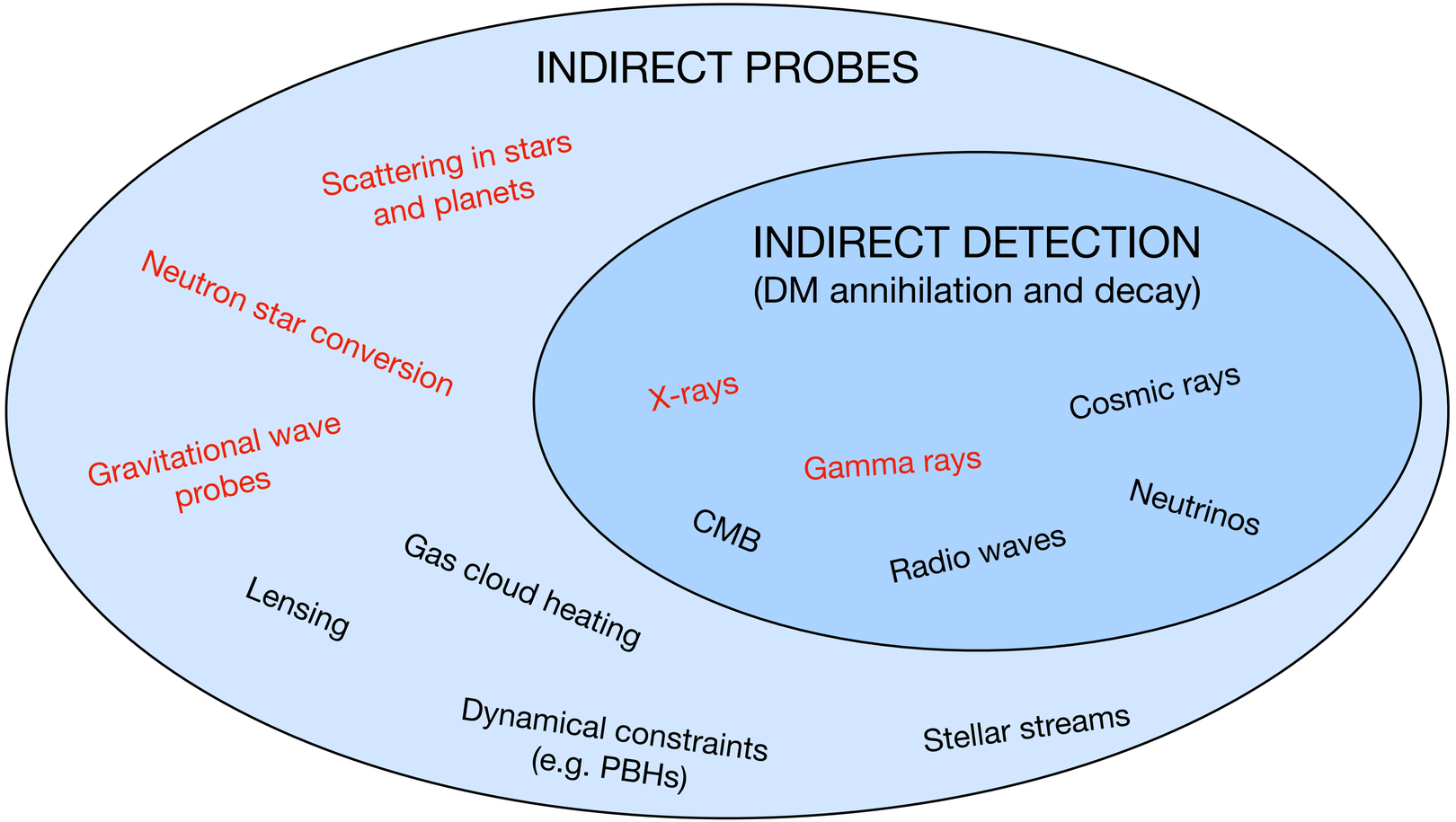
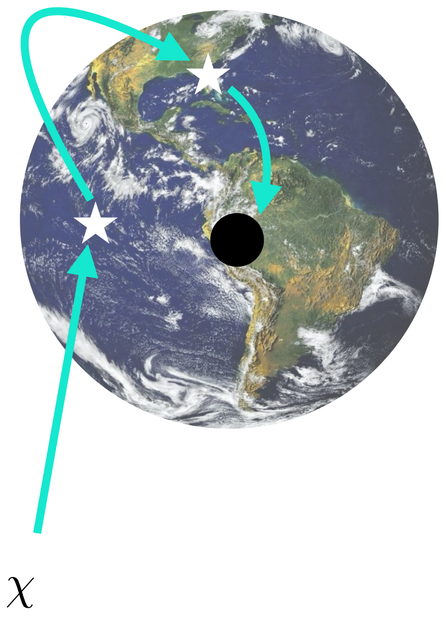
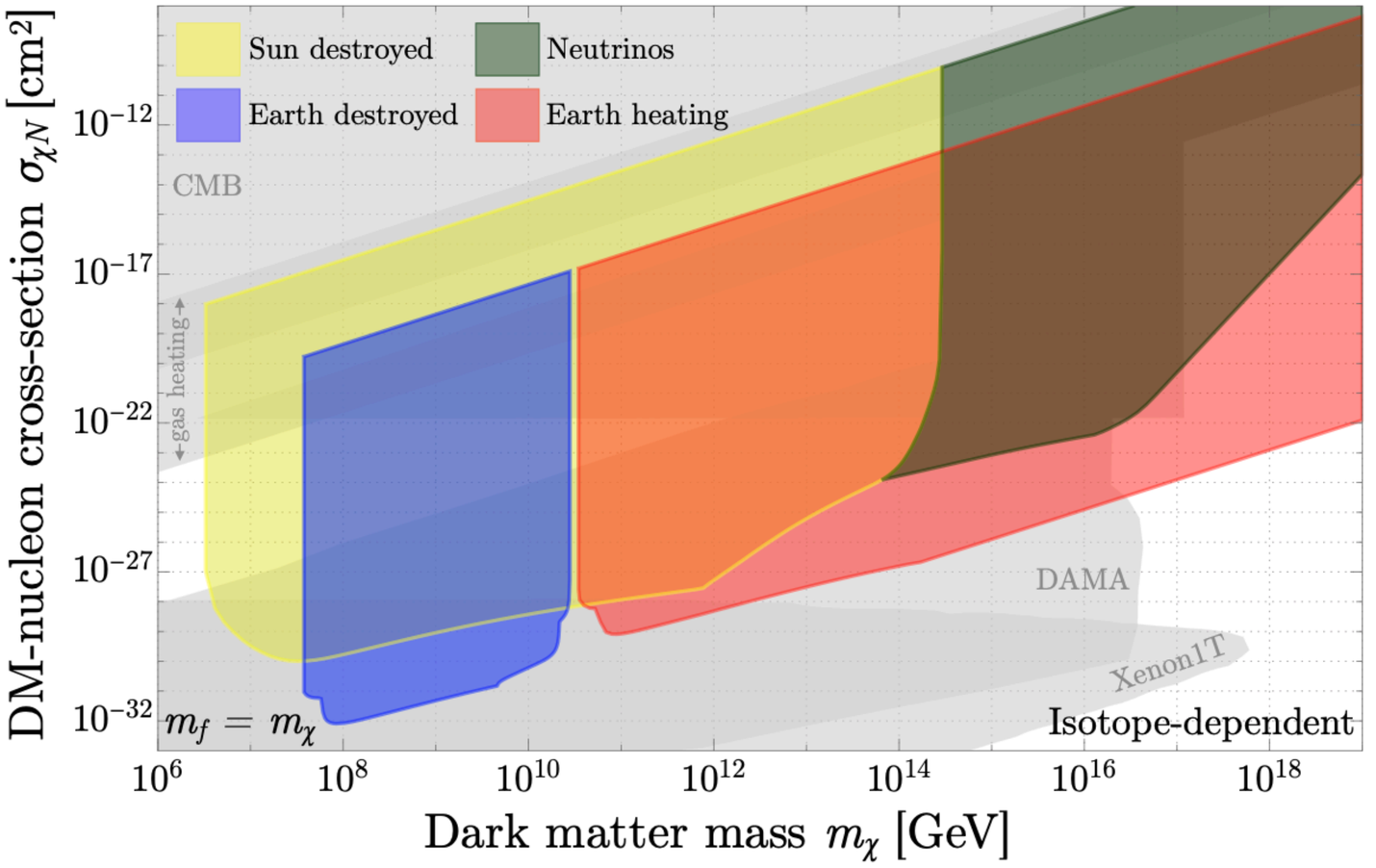


DM Capture in the Earth and Sun





[Acevedo et al., 2012.09176]

Complementary to direct searches for Strongly interacting DM [e.g. **BJK**, 1712.04901; EDELWEISS, 1901.03588]

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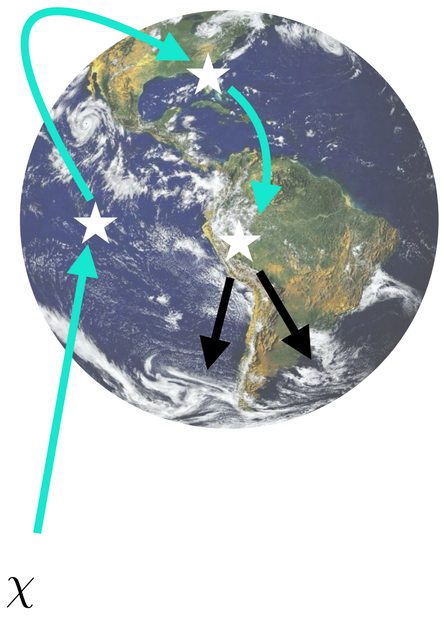

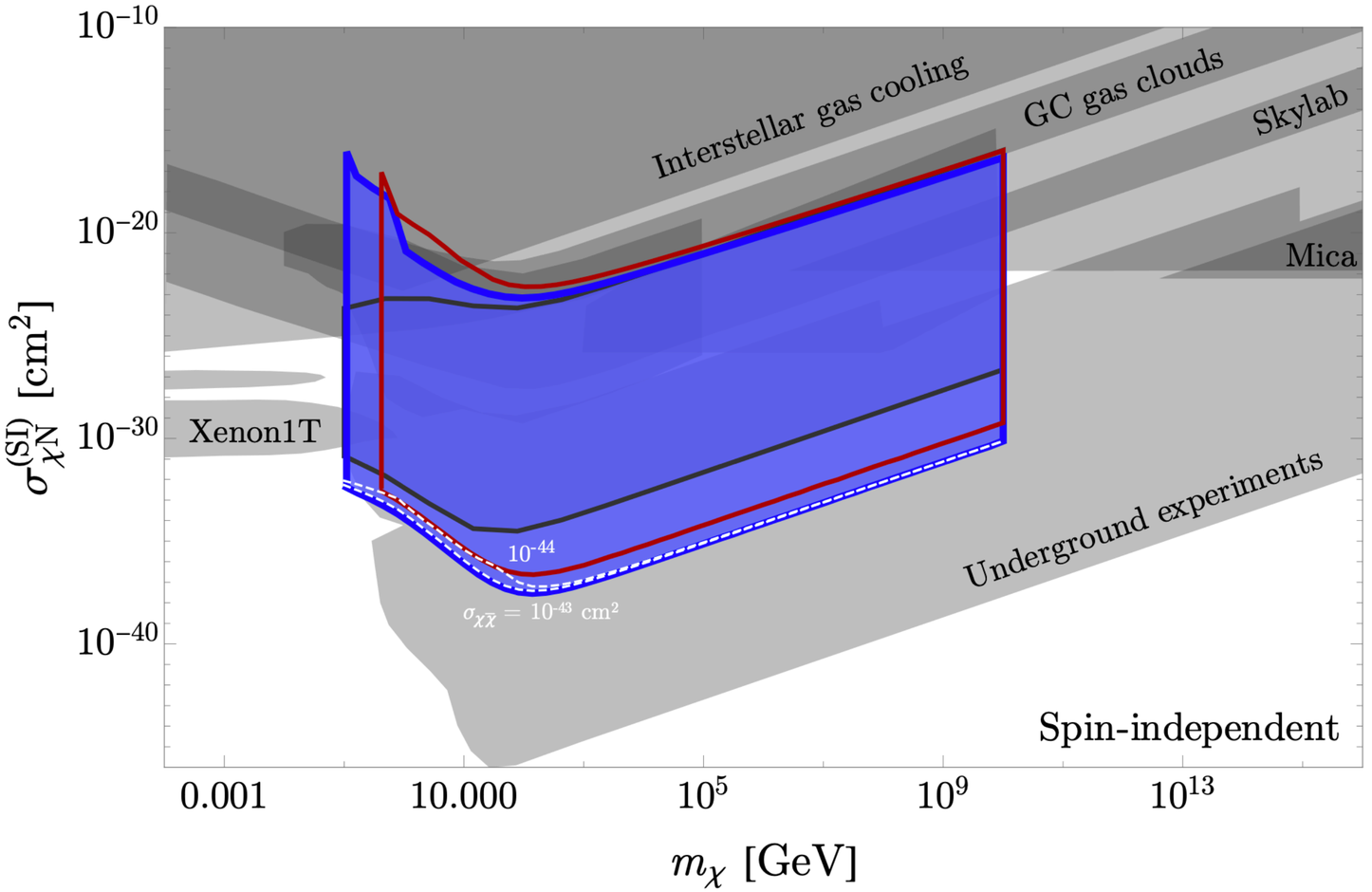

[Bramante et al., 1909.11683]

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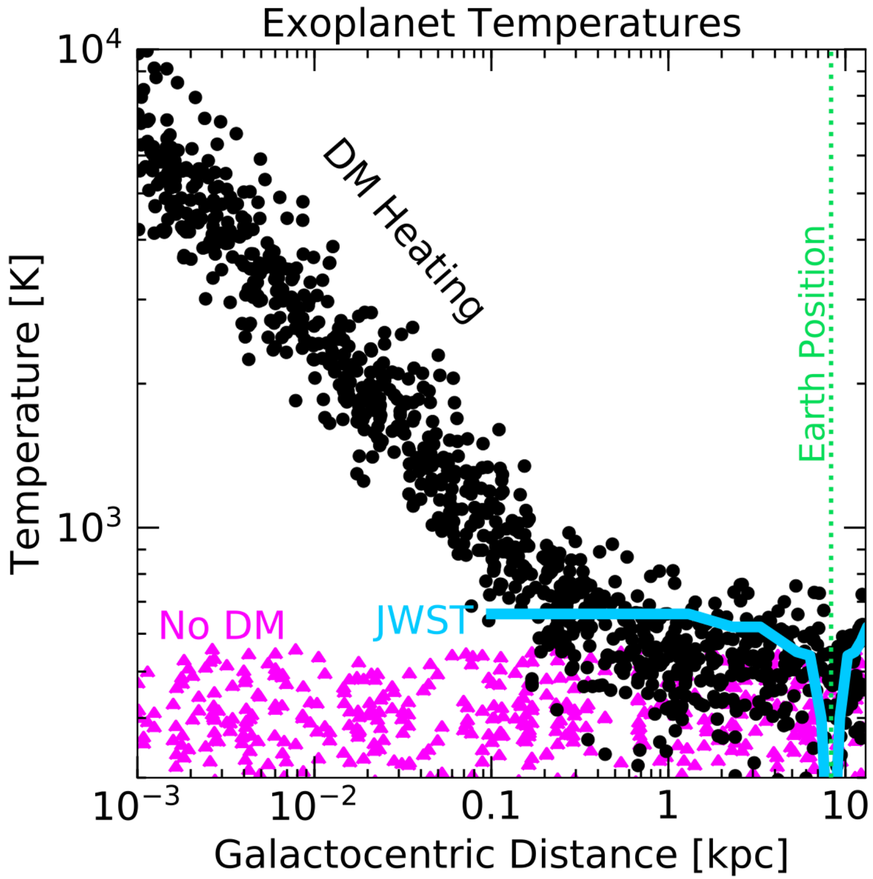
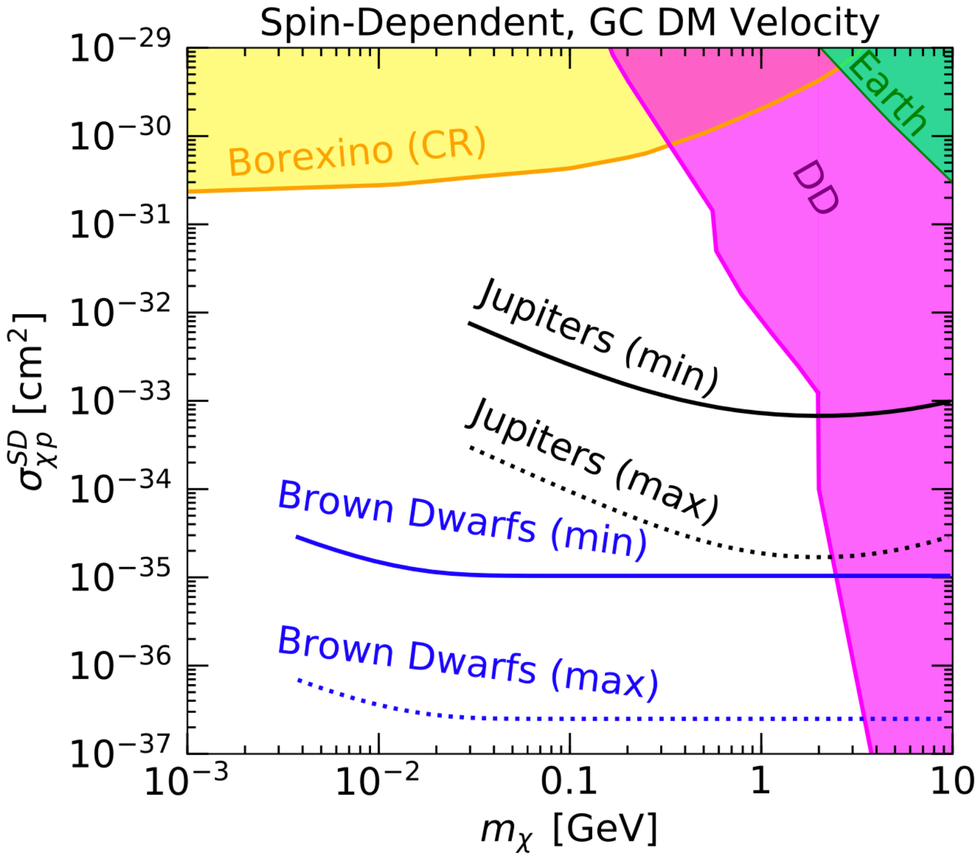
DM Capture in exoplanets



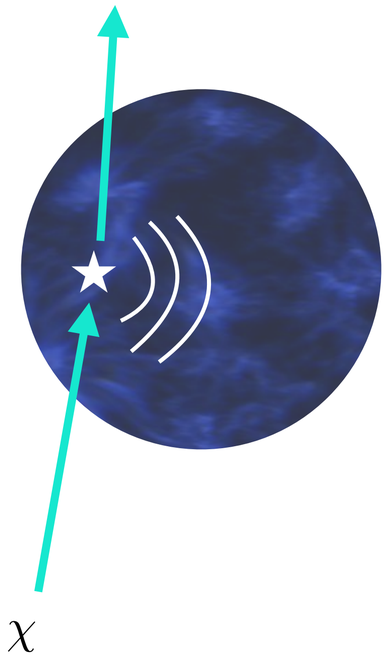
[Leane & Smirnov, 2010.00015]



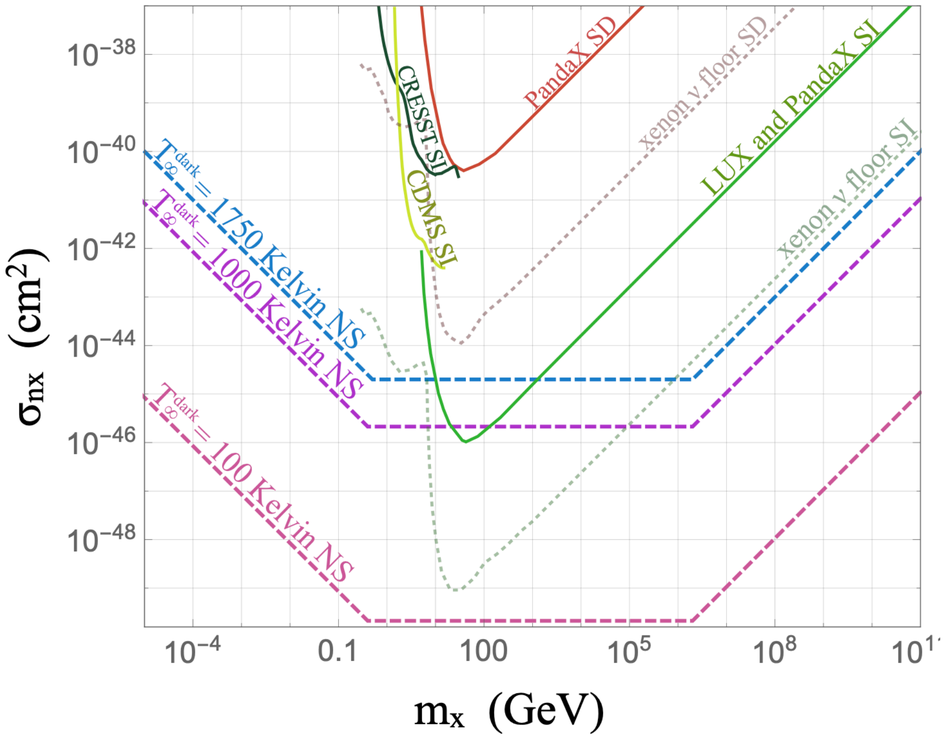
[See also Payel Mukhopadhyay's talk this morning]

[See also Leane et al., 2101.12213; Leane & Linden, 2104.02068]

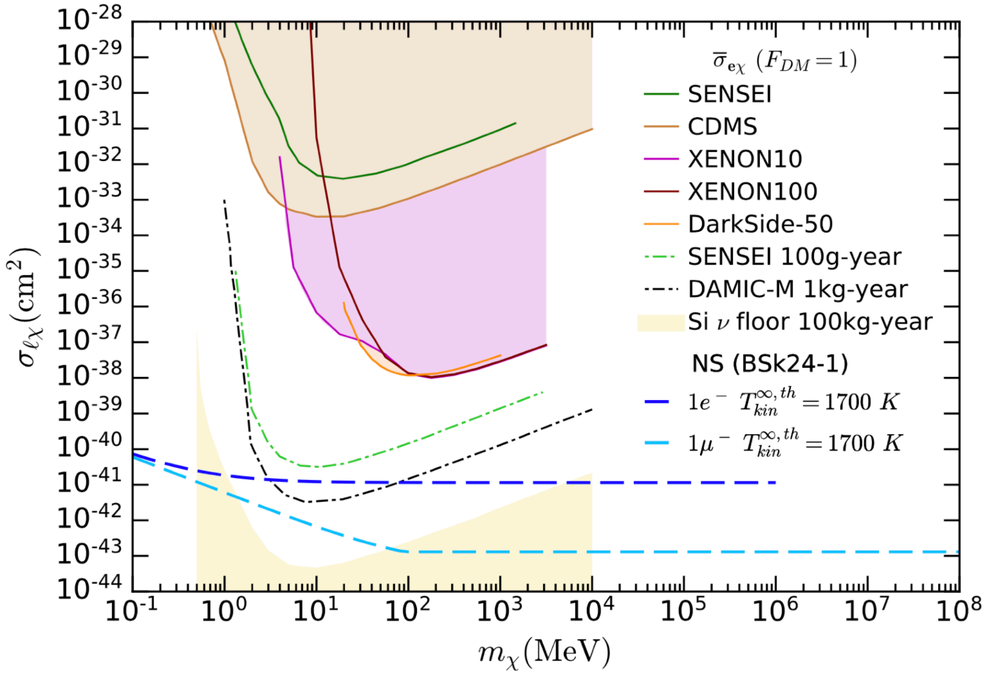
Neutron Star Heating



[Baryakhtar et al., 1704.01577]



[Bell et al., 1904.09803]



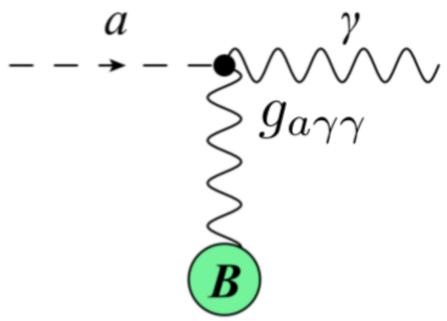
NS and WD capture rate becoming more and more refined, but what are the observational prospects?

[Acevedo et al., 1911.06334; Bell et al., 2004.14888, 2104.14367; Dasgupta et al., 2006.10773]

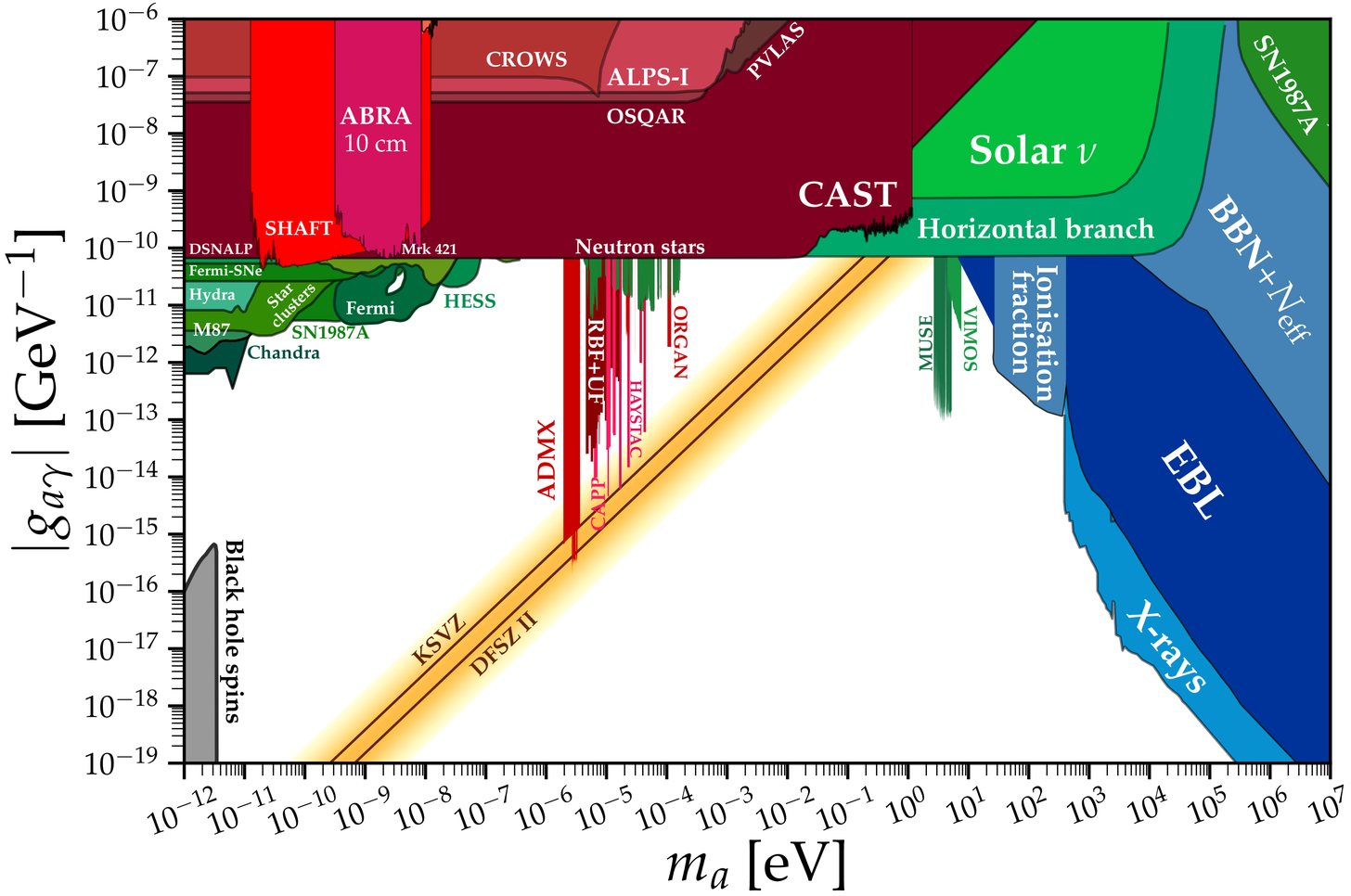
Captured DM may also affect NS equation of state: [Cermeño et al., 1710.06866]

Axions and Neutron Stars

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$



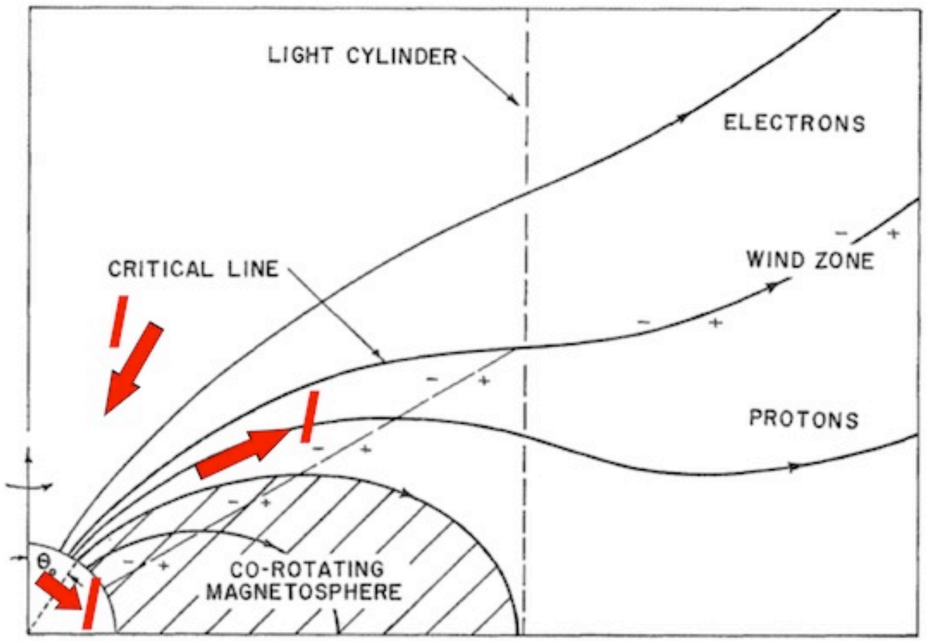
[O'Hare, cajohare.github.io/AxionLimits/]



Axions and Neutron Stars

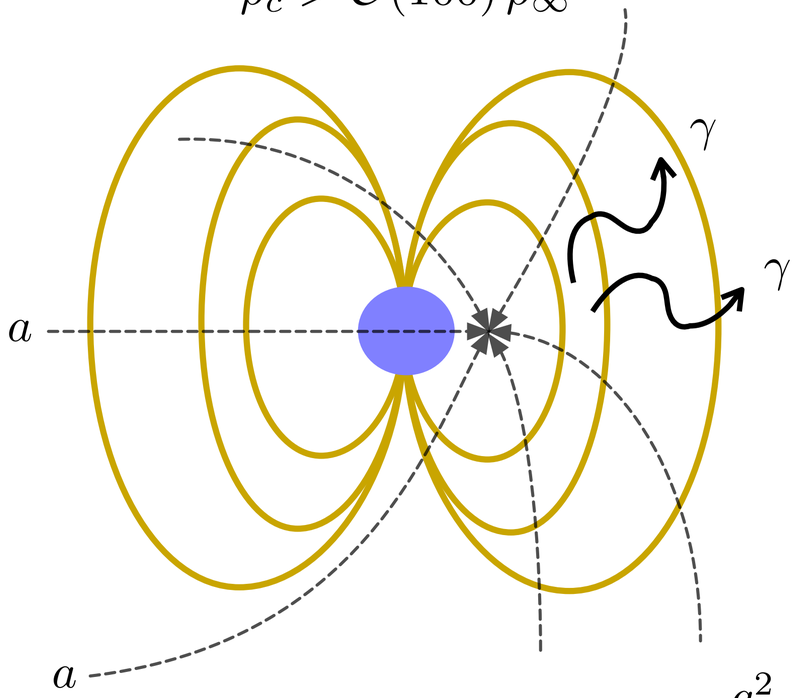
Dense plasma around NS allows ‘resonant’ conversion when axion mass matches plasma mass:

$$\omega_p\left(B_0, P\right) = m_a/2\pi$$



$$B_0 = 10^{12} - 10^{15}\,G$$

$$\rho_c > \mathcal{O}(100)\,\rho_\infty$$



$$p_{a\gamma} \propto \frac{g_{a\gamma\gamma}^2 B\left(r_c\right)^2}{2v_c}$$

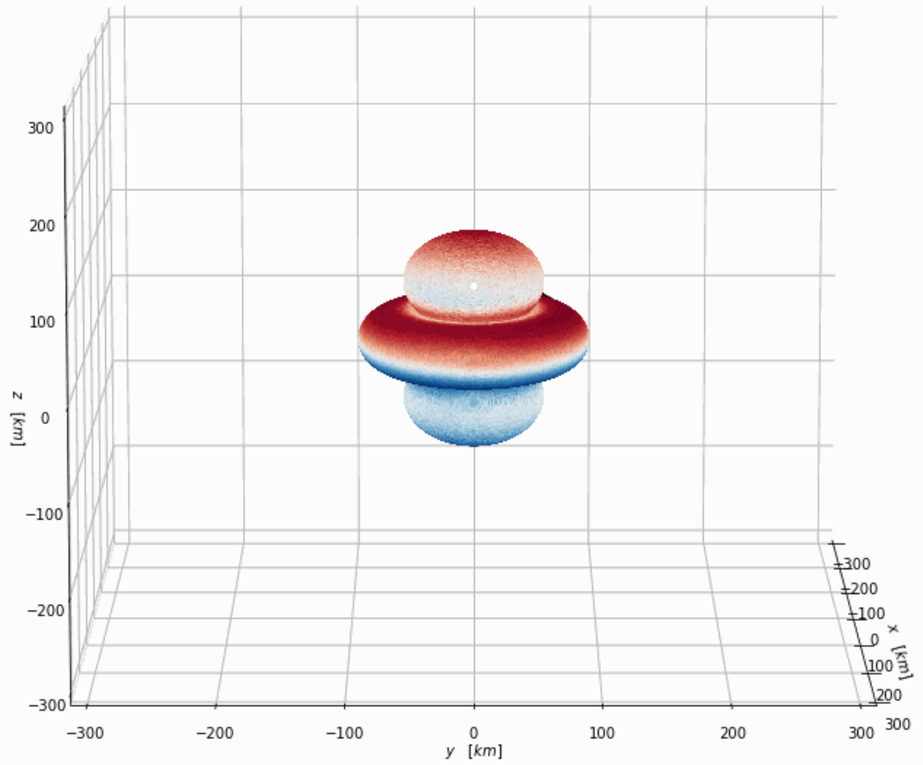
Radio up to X-ray signals, depending on axion mass…

[Huang et al., 1803.08230; Hook et al., 1804.03145; Safdi et al., 1811.01020; Foster et al., 2004.00011]

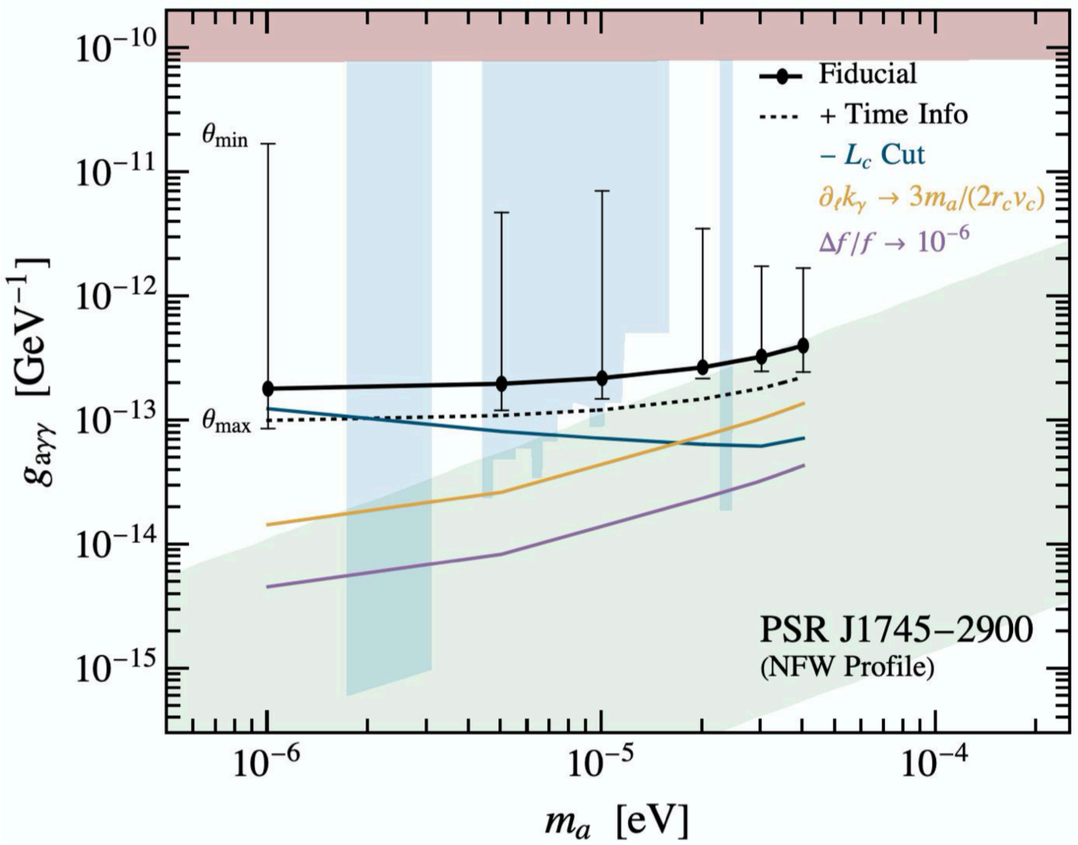
Axions and Neutron Stars

Recent refinements in modeling axions and photons in the NS magnetosphere:

Red - Northern hemisphere



Blue - Southern hemisphere



[Witte et al., 2104.07670]

[See also Battye et al., 1910.11907, 2104.08290; Leroy et al., 1912.08815]

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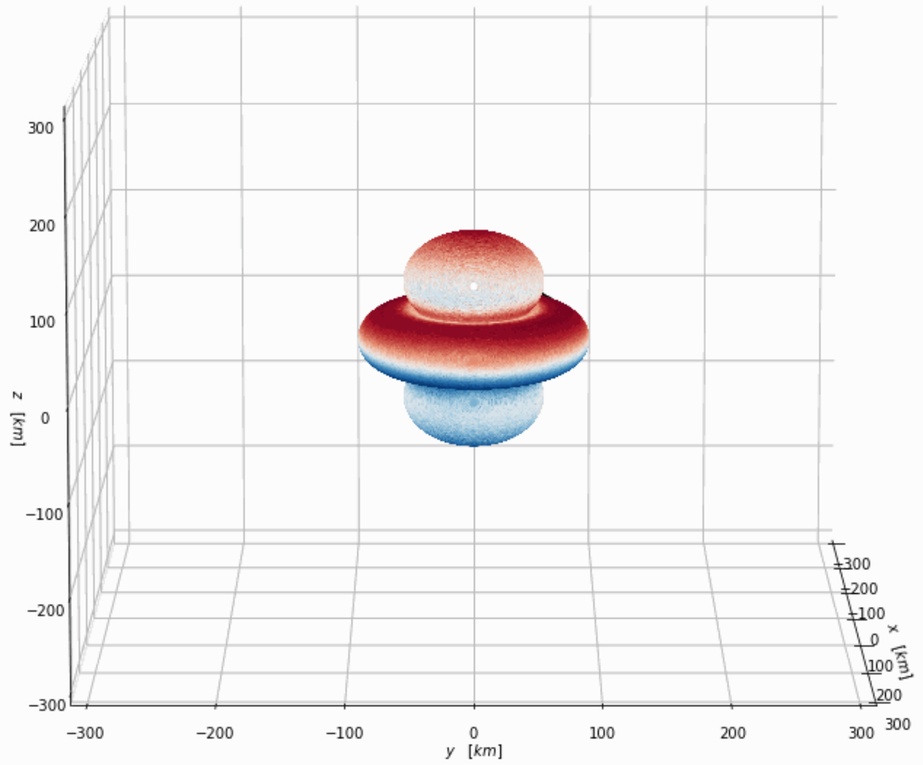

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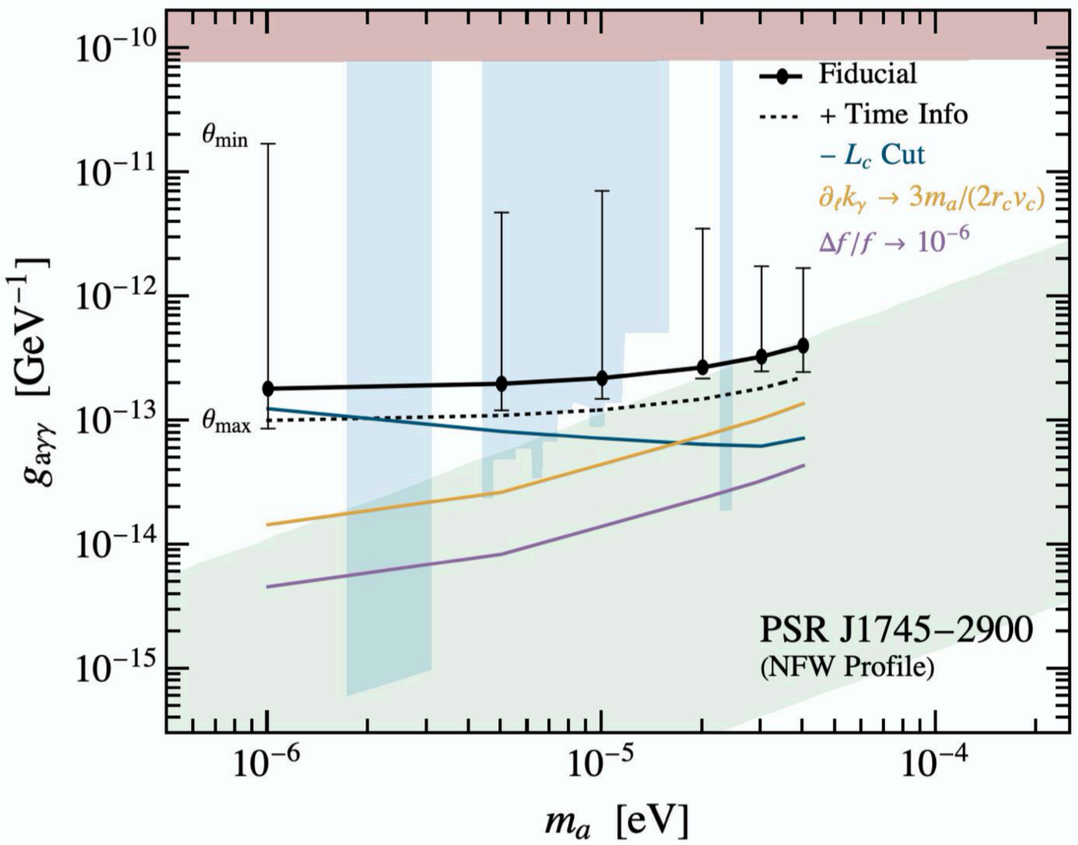
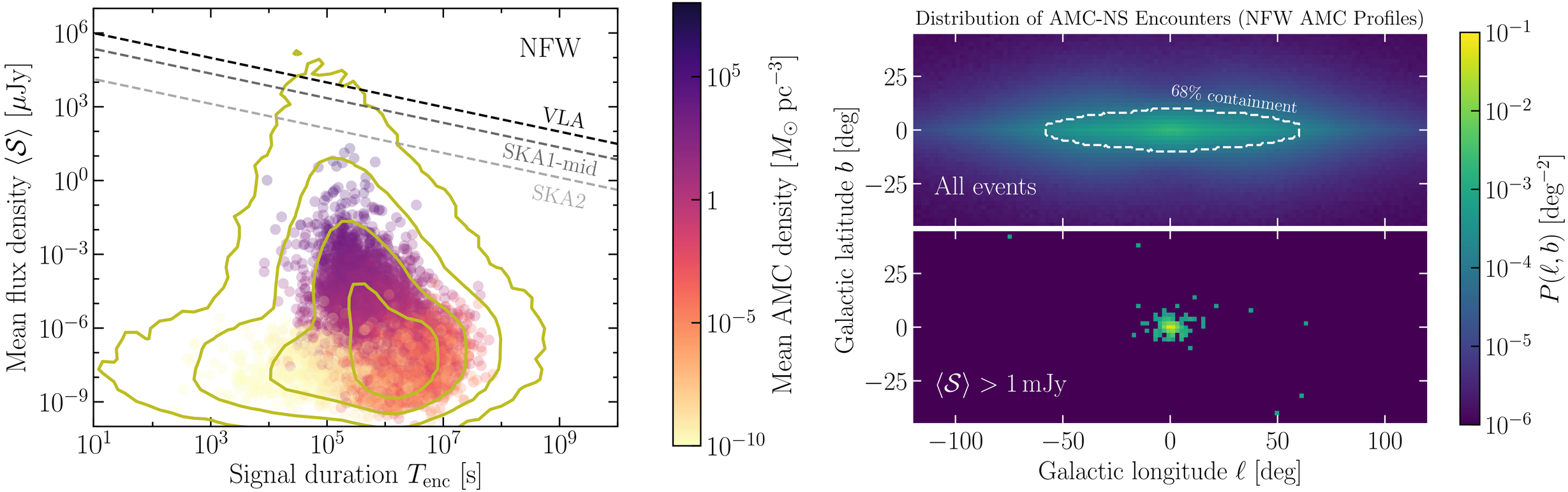


[Witte et al., 2104.07670]

[See also Battye et al., 1910.11907, 2104.08290; Leroy et al., 1912.08815]

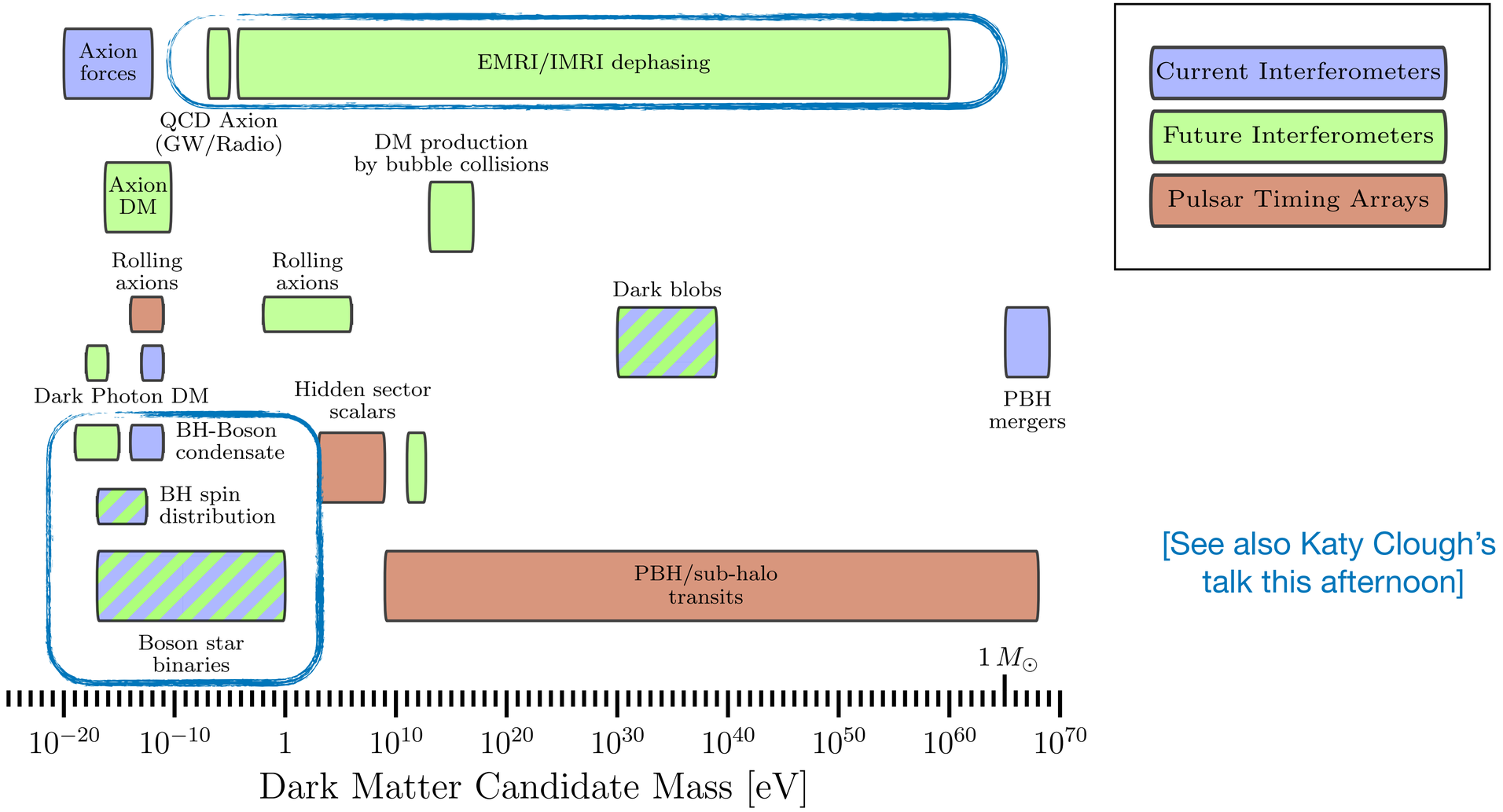
Axion-miniclusters + NSs

Clumps of axion DM ('miniclusters') crossing NSs could lead to bright radio transients towards the GC:
[Hogan & Rees (1988)]



[**BJK**, Edwards, Visinelli & Weniger, 2011.05377; Edwards, **BJK**, Visinelli & Visinelli, 2011.05378]

GW Probes of DM



[See also Katy Clough's talk this afternoon]

[Bertone, Croon, Amin, Boddy, **BJK**, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu, SciPost Phys. Core 3, 007 (2020), 1907.10610]

Gravitational Atoms

Compton wavelength of a light scalar field:

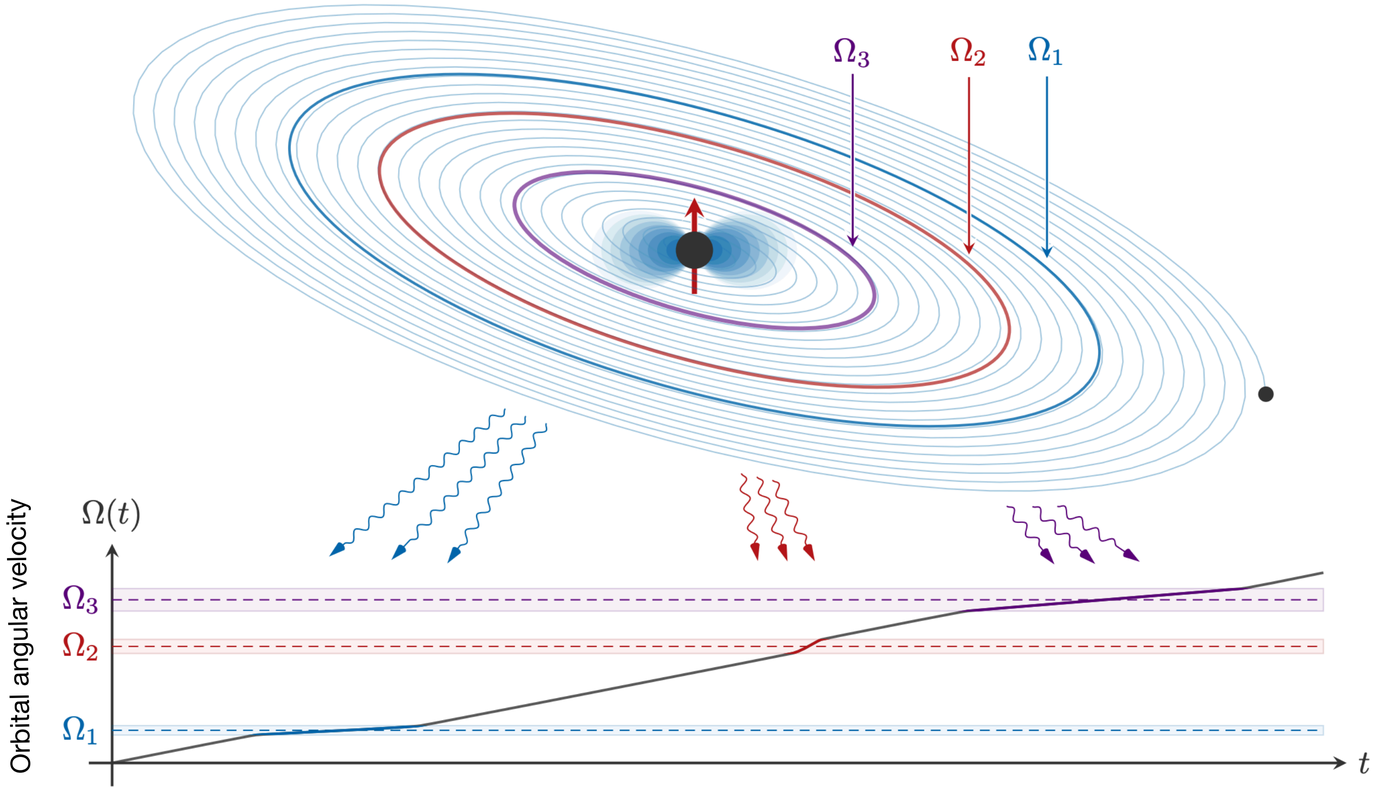
$$\lambda_c \simeq 2\,\mathrm{km}\left(\frac{10^{-10}\,\mathrm{eV}}{\mu}\right)$$

Super-radiance (and growth of a 'gravitational atom') when:

$$r_g \sim GM_{\mathrm{BH}}/c^2 < \lambda_c$$

$$M_{\mathrm{BH}} \in [1, 10^{10}]\, M_\odot$$
$$\rightarrow m_\phi \in [10^{-20}, 10^{-10}]\,\mathrm{eV}$$

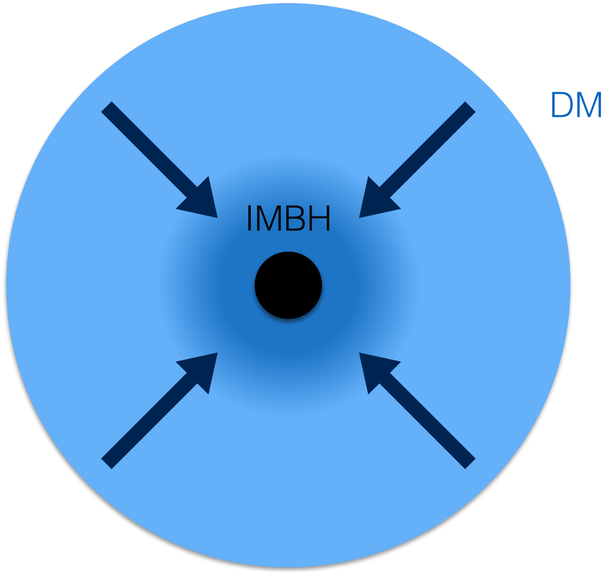
[Chia, 2012.09167]



[Baumann et al., 1804.03208, 1908.10370, 1912.04932]

GW Dephasing from DM

Dense DM spike may form around IMBHs

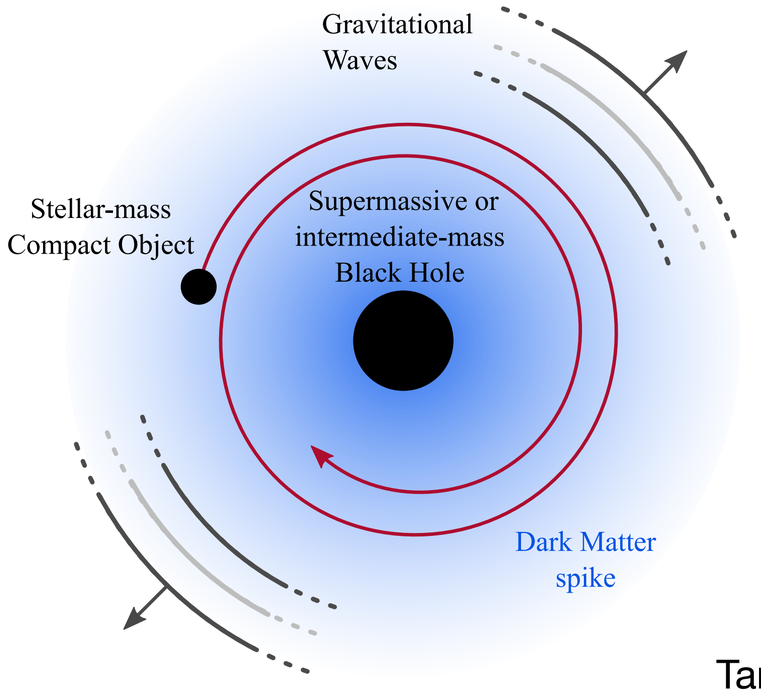


$$\rho_{\rm DM}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

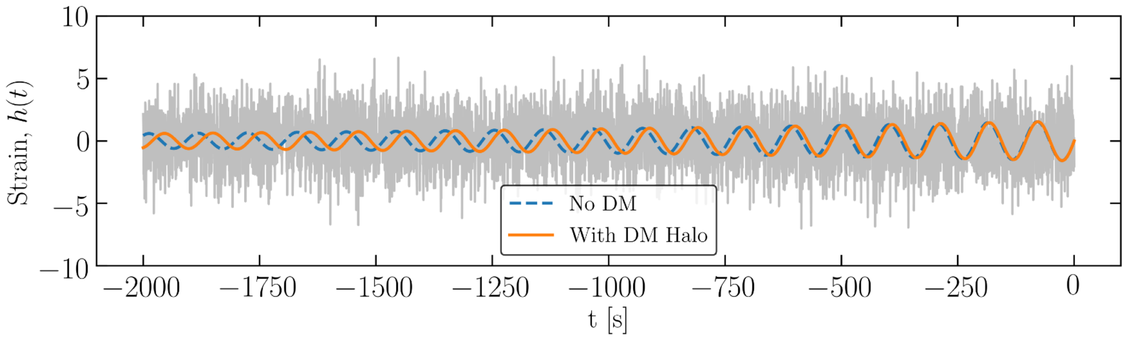
$$\rho_{\rm DM}(r_{\rm isco}) \sim 10^{24}\, M_\odot\, {\rm pc}^{-3}$$

[Gondolo & Silk, astro-ph/9906391]

[Eda et al., 1301.5971, 1408.3534]

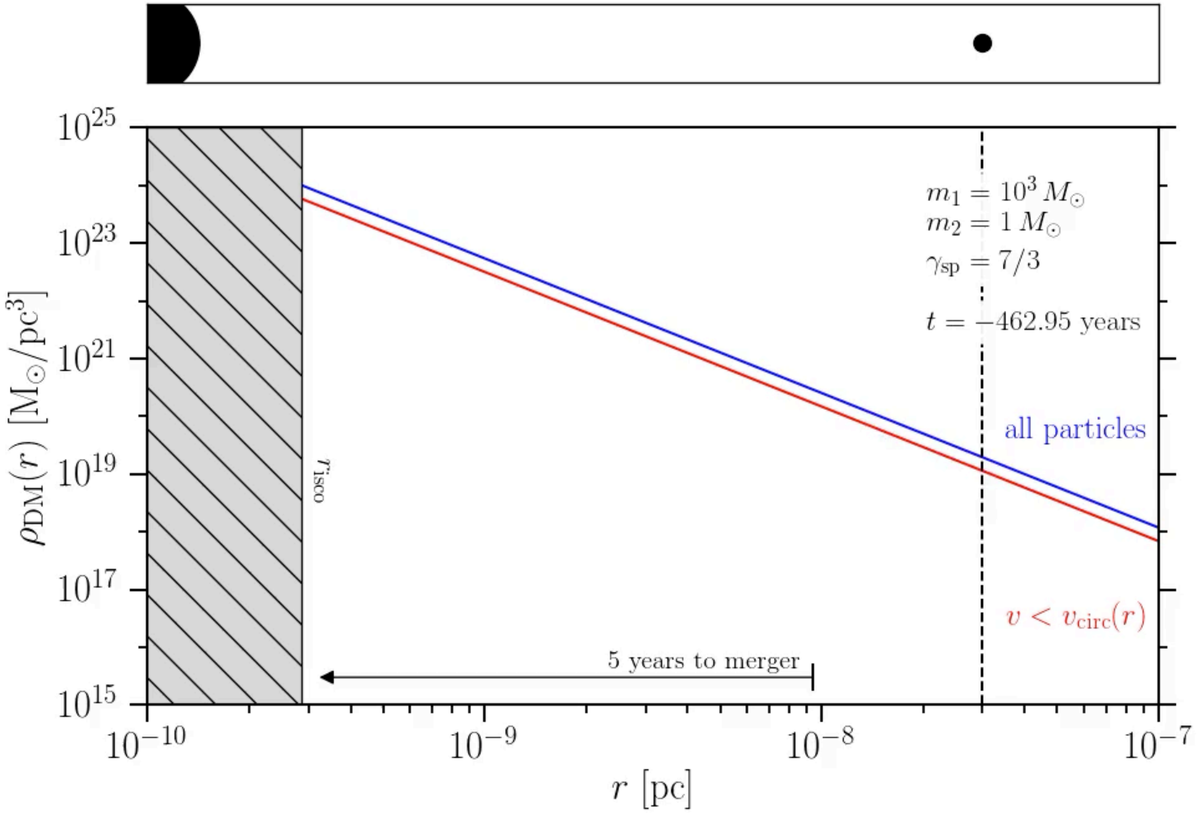


Target with LISA

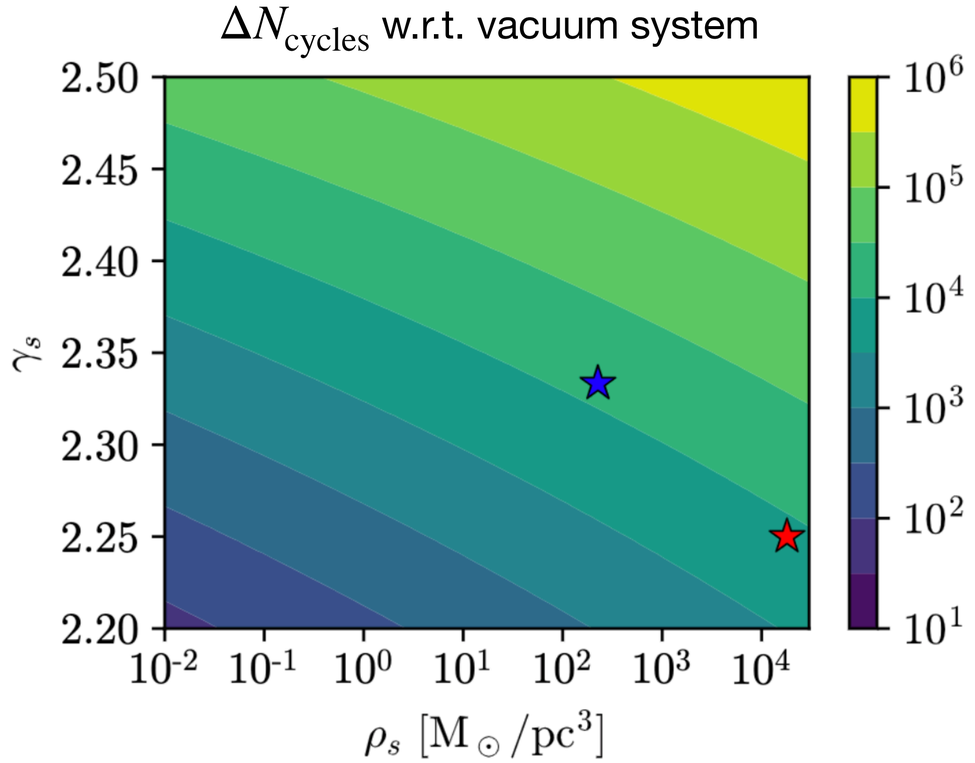


Dark Matter feedback

Need to worry about dynamic response of the DM spike…



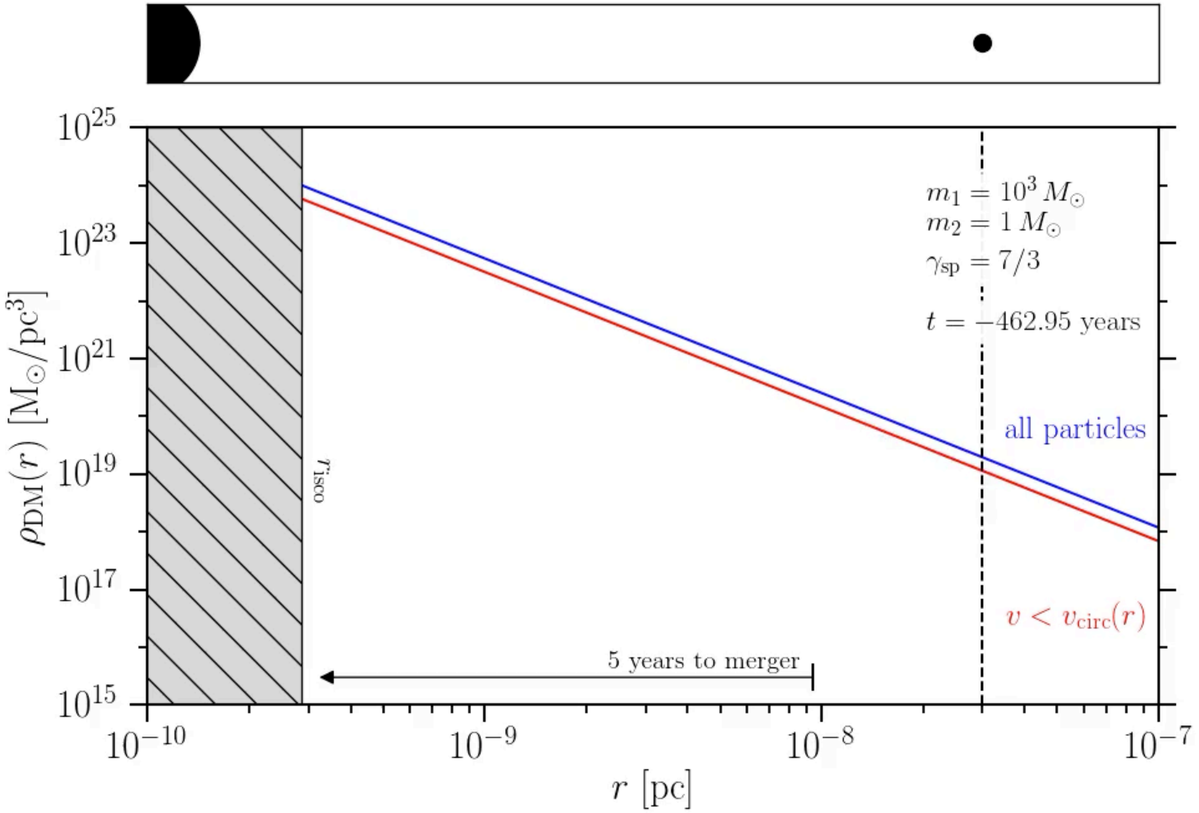
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]



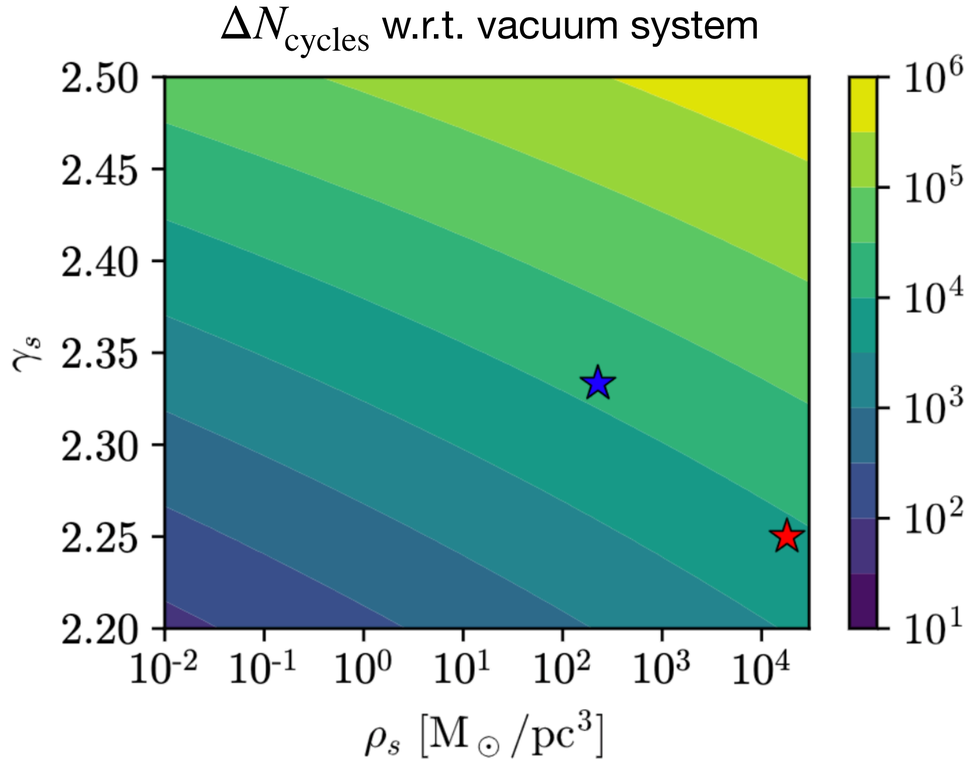
[Coogan, Bertone, Gaggero, **BJK** & Nichols, *in progress*]

Dark Matter feedback

Need to worry about dynamic response of the DM spike…



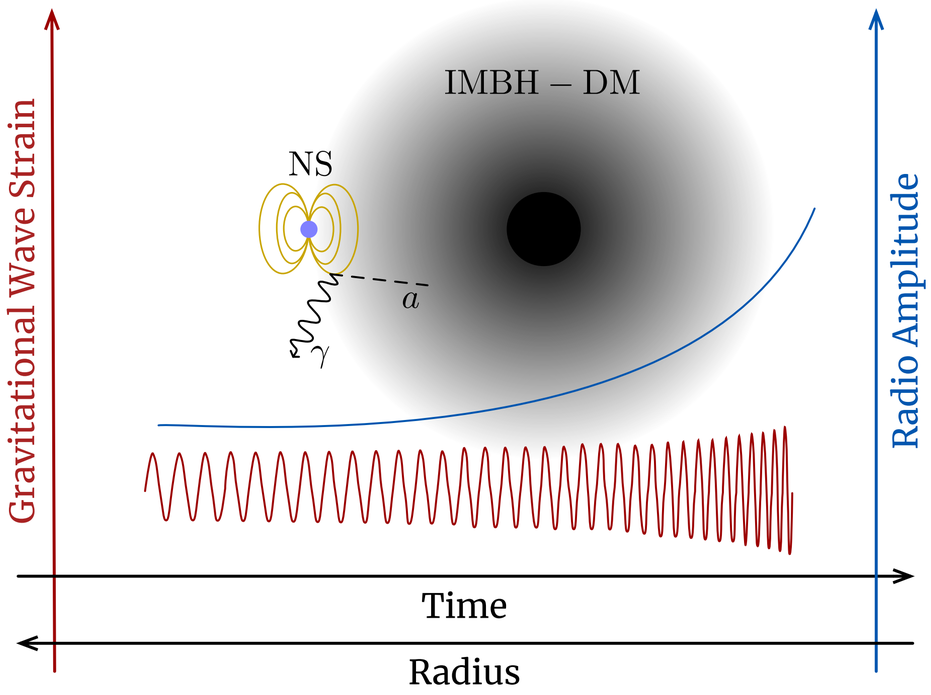
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

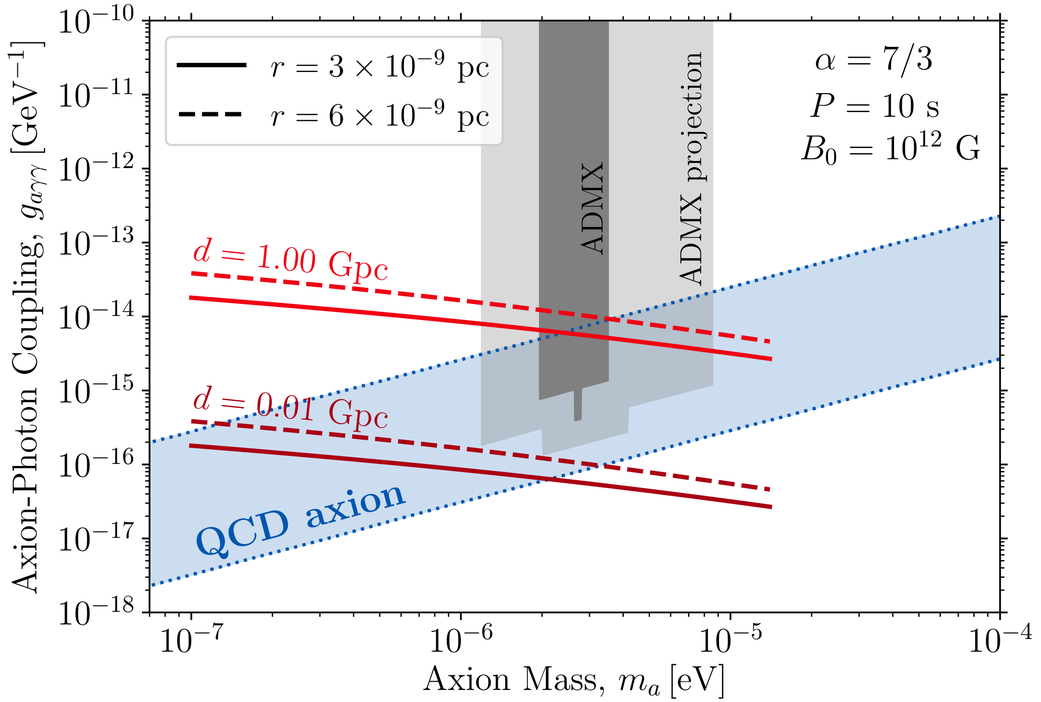


[Coogan, Bertone, Gaggero, **BJK** & Nichols, *in progress*]

Multimessenger: GWs + Radio

Consider an NS, embedded in an axion-DM spike, around an IMBH!





Radio observations with SKA would be able to probe QCD axion DM in the range 10^{-7} - 10^{-5} eV.

[Edwards, Chianese, **BJK**, Nissanke, Weniger, 1905.04686]

Things I couldn't talk about

Some Reviews:

Indirect detection [1604.00014, 2006.00513, 2008.11561]
Galactic Centre Excess [10.1146/annurev-nucl-101916-123029]
Indirect detection with neutrinos [1912.09486]
Indirect detection with cosmic rays [1802.00636]
GW Probes of DM [1907.10610]
Primordial Black Holes as DM [2007.10722]

Some other 'indirect probes':

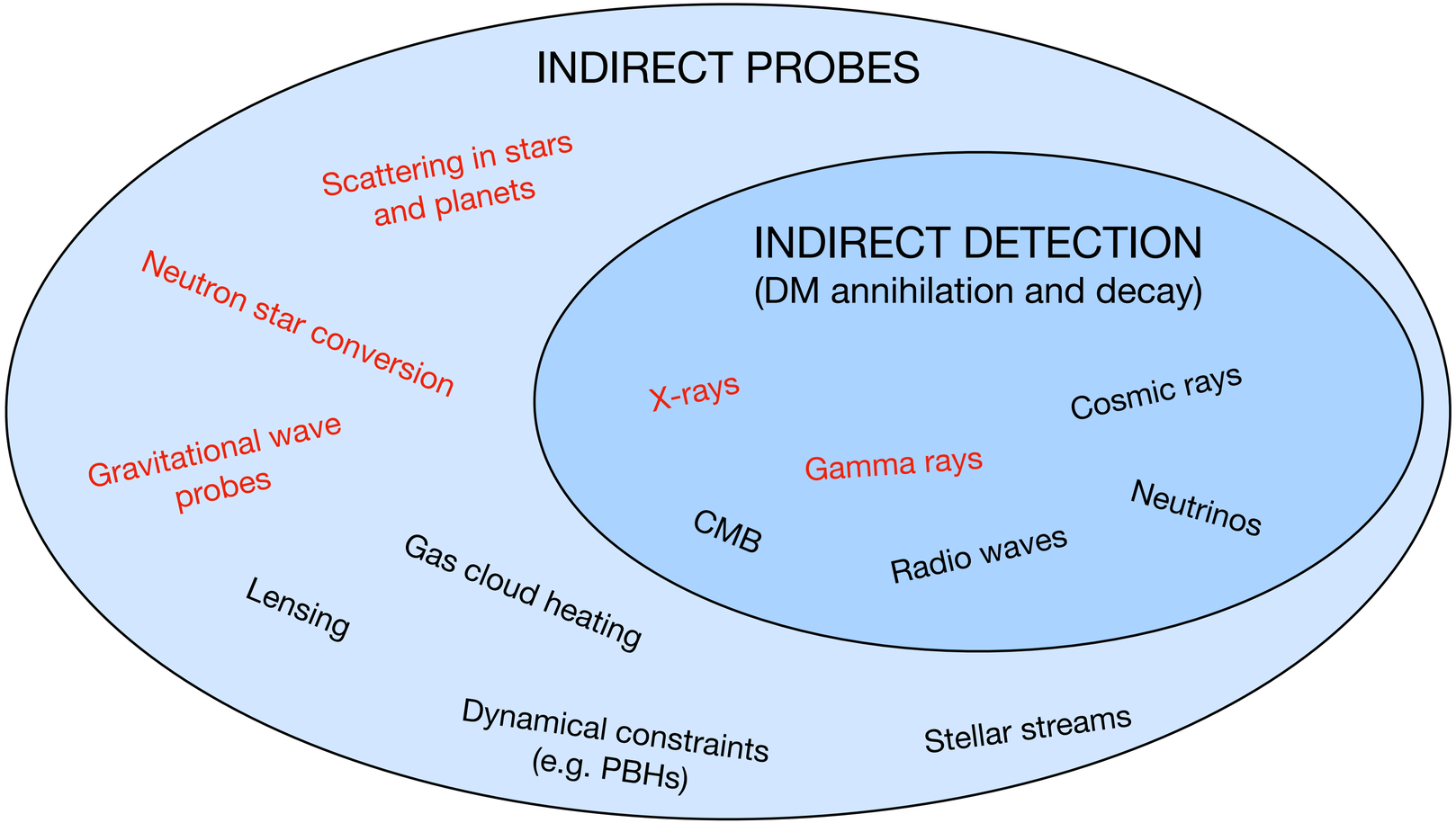
Cosmic rays [Cuoco et al., 1903.01472; Boudaud et al., 1906.07119; Génolini et al., 2103.04108]
Gas cloud heating [Bhoonah et al., 1806.06857, 1812.10919, 2010.07240; Wadekar & Farrar, 1903.12190]
Strong-lensing of substructure [Diaz Rivero & Dvorkin, 1910.00015; Coogan et al., 2010.07032]
Micro-lensing of substructure [Croon et al., 2002.08962, 2007.12697]
Stellar streams [Bonaca et al., 1811.03631; Banik et al., 1911.02662, 1911.02663]
CMB [Slatyer, 1506.03811; Gluscevic & Boddy, 1712.07133; Boddy et al., 1808.00001]
Cosmic birefringence [Fujita et al., 2008.02473]
Stellar structure and evolution [Vincent, 2009.00663; Croon et al., 2009.01213]

What are indirect probes?

Broad definition - *searches for DM in which the interactions (gravitational or otherwise) happen whether we like it or not ('passive probes?')*

Practical definition - *searches for the effects of DM in astrophysical and cosmological systems.*

Cynical definition - *searches for DM in which we have very little experimental control (e.g. over backgrounds, systematics, etc.)*



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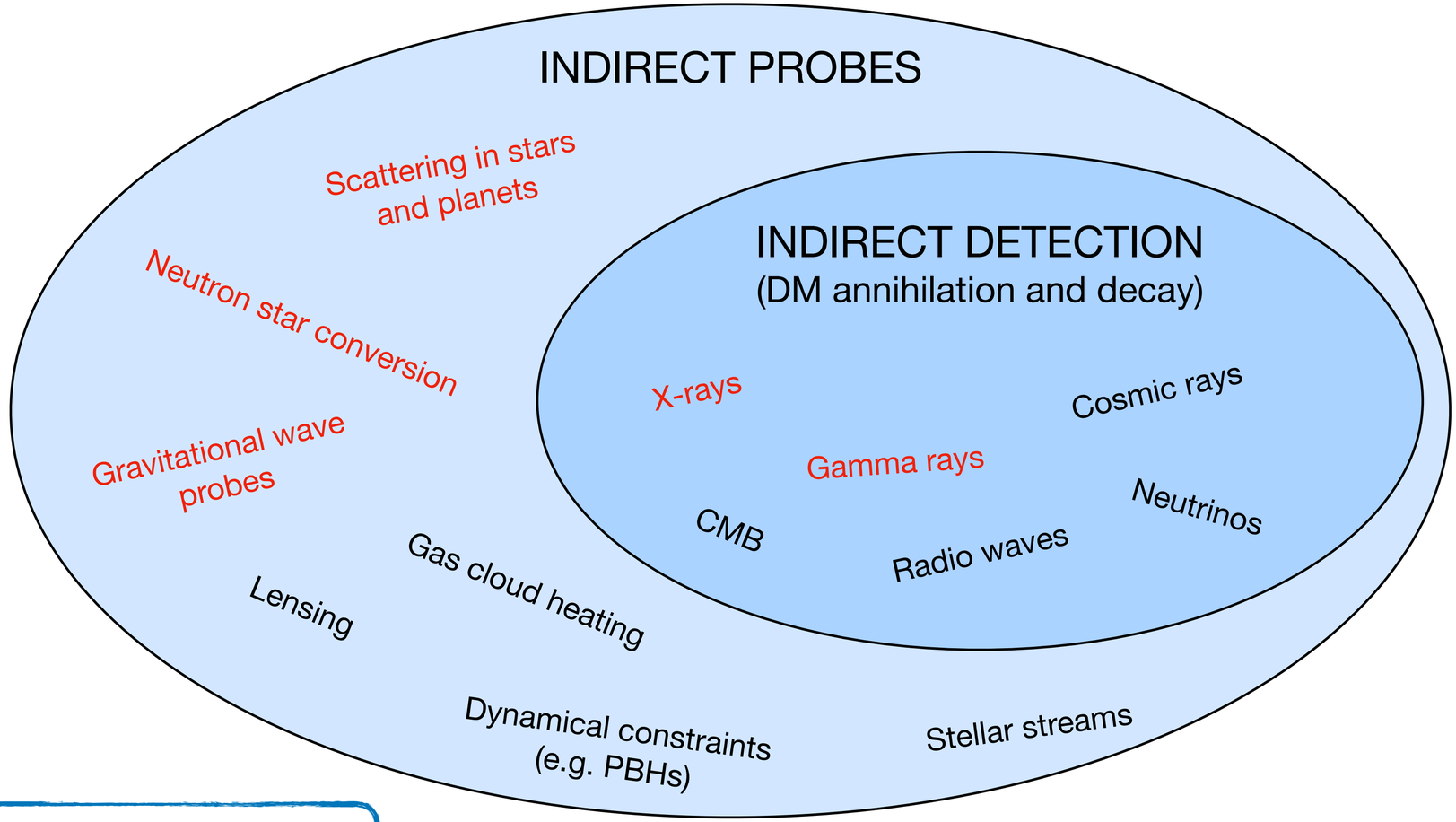
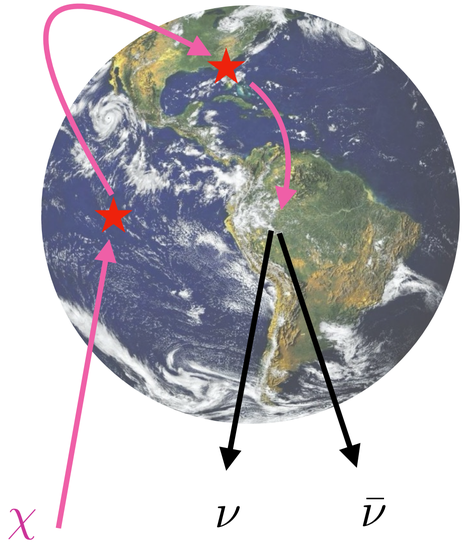
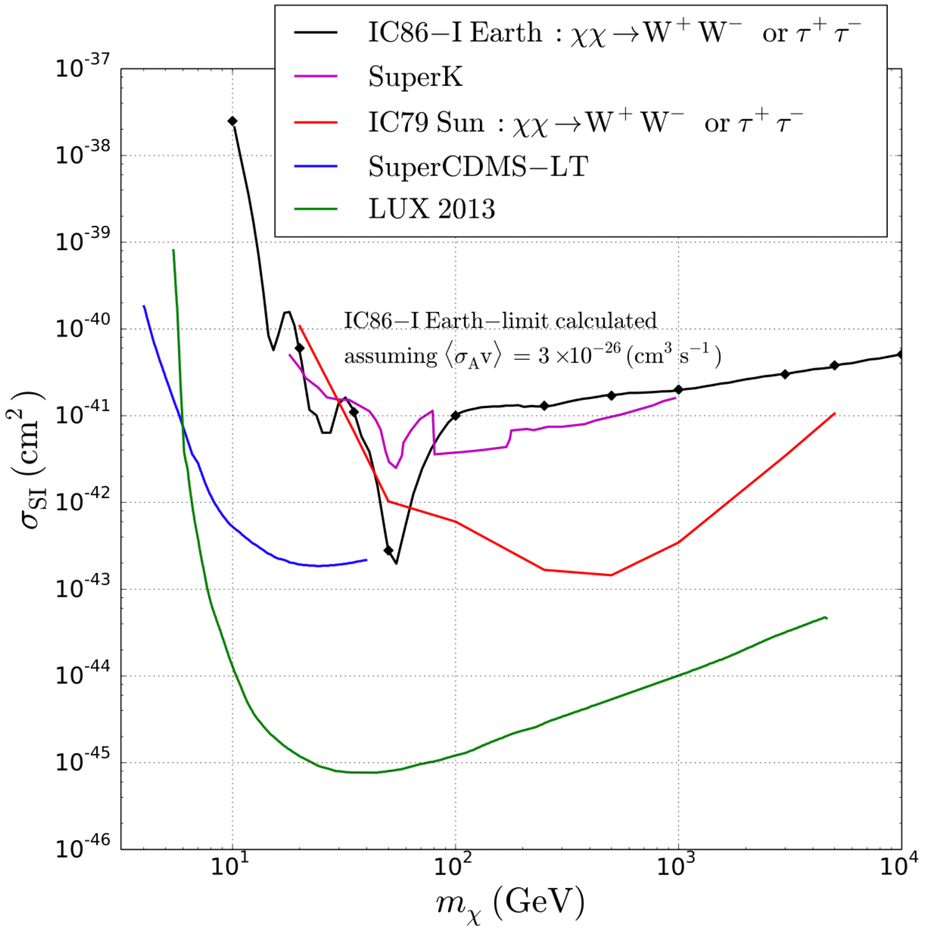


Thank you!

Backup Slides

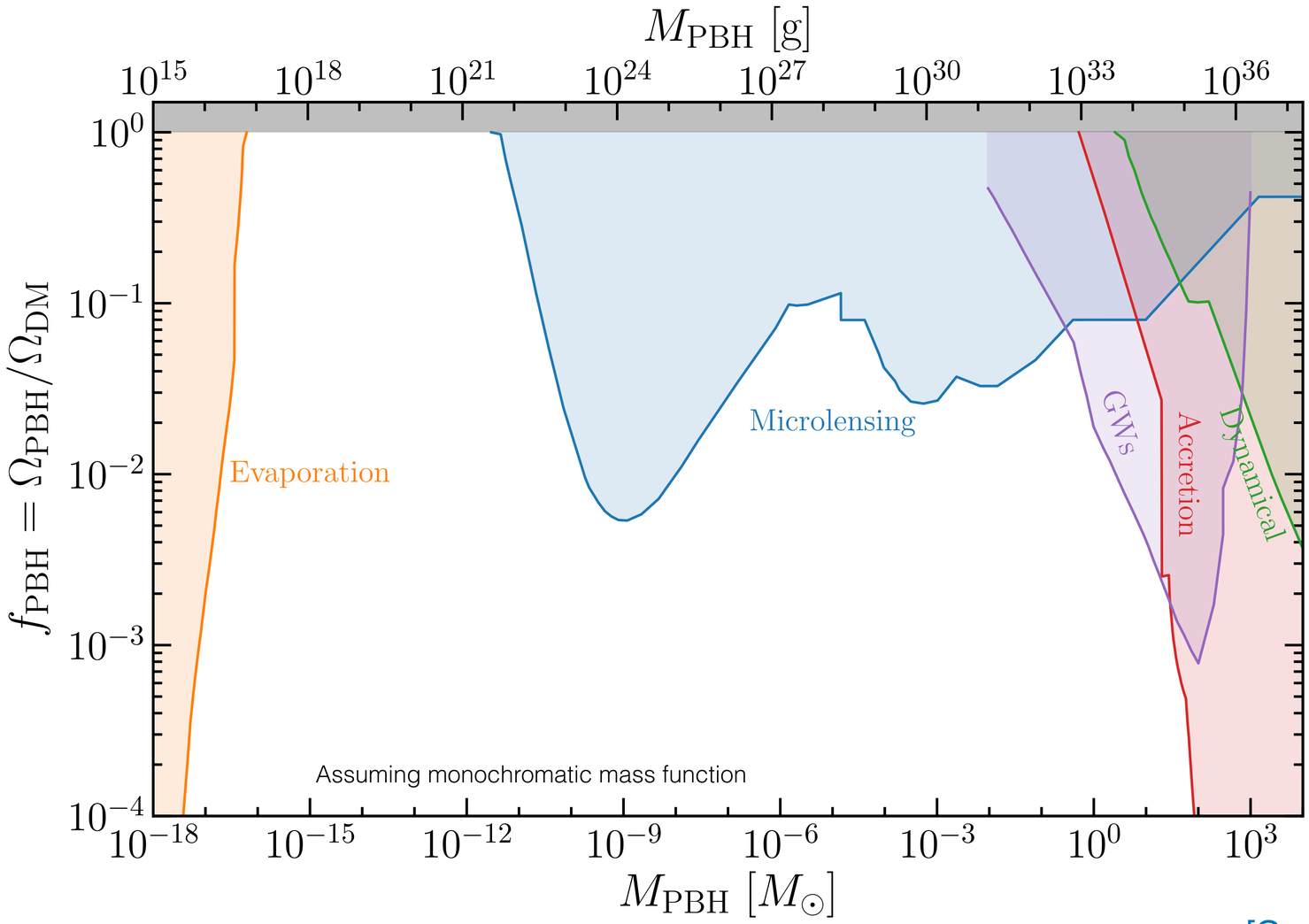
DM Capture in the Earth and Sun





[IceCube, 1609.01492]

Primordial Black Holes



[Green & BJK, 1709.06576]

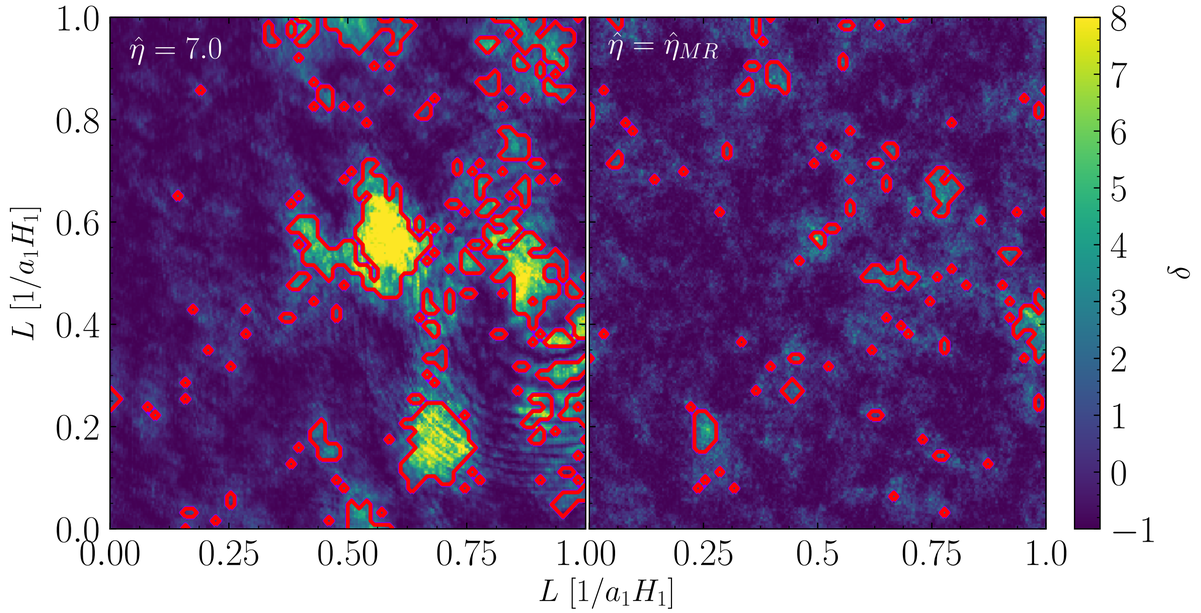
[Other reviews: 1801.05235, 2002.12778, 2006.02838]

[Code online: github.com/bradkav/PBHbounds]

Axion miniclusters

$$\delta = (\rho - \bar{\rho})/\rho$$

Overdensities act as ‘seeds' for bound “axion miniclusters” (**AMCs**)



[Buschmann et al., 1906.00967]

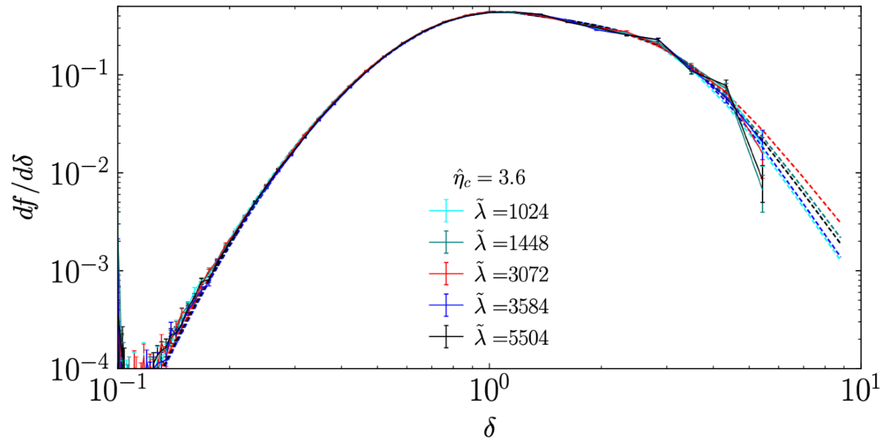
For an overdensity of size $\delta = (\rho - \bar{\rho})/\rho$ the final density is:

$$\rho_{\rm AMC}(\delta) = 140(1+\delta)\delta^3 \rho_{\rm eq}$$

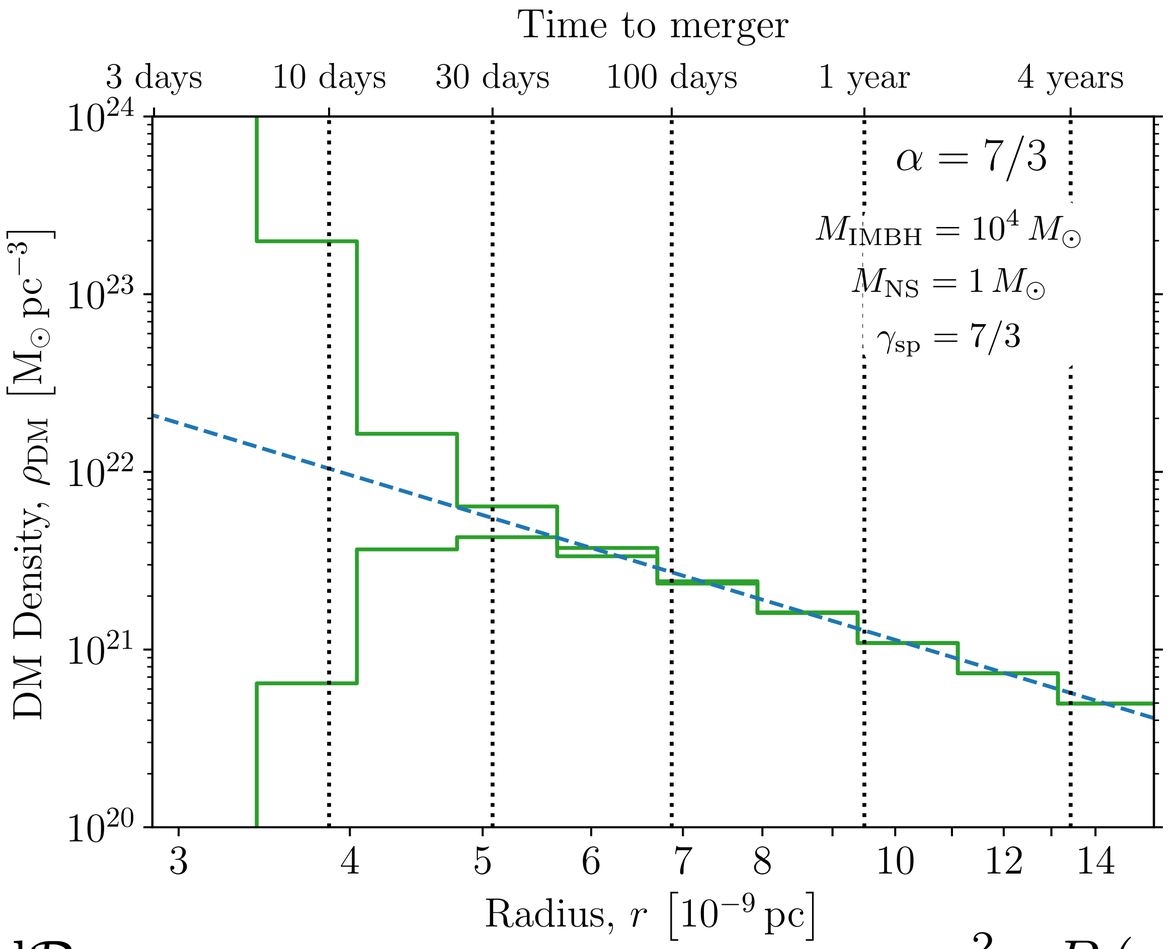
[Kolb & Tkachev, astro-ph/9403011]

Not to be confused with Axion Stars

[Schive et al., 1407.7762, Visinelli et al., 1710.08910]



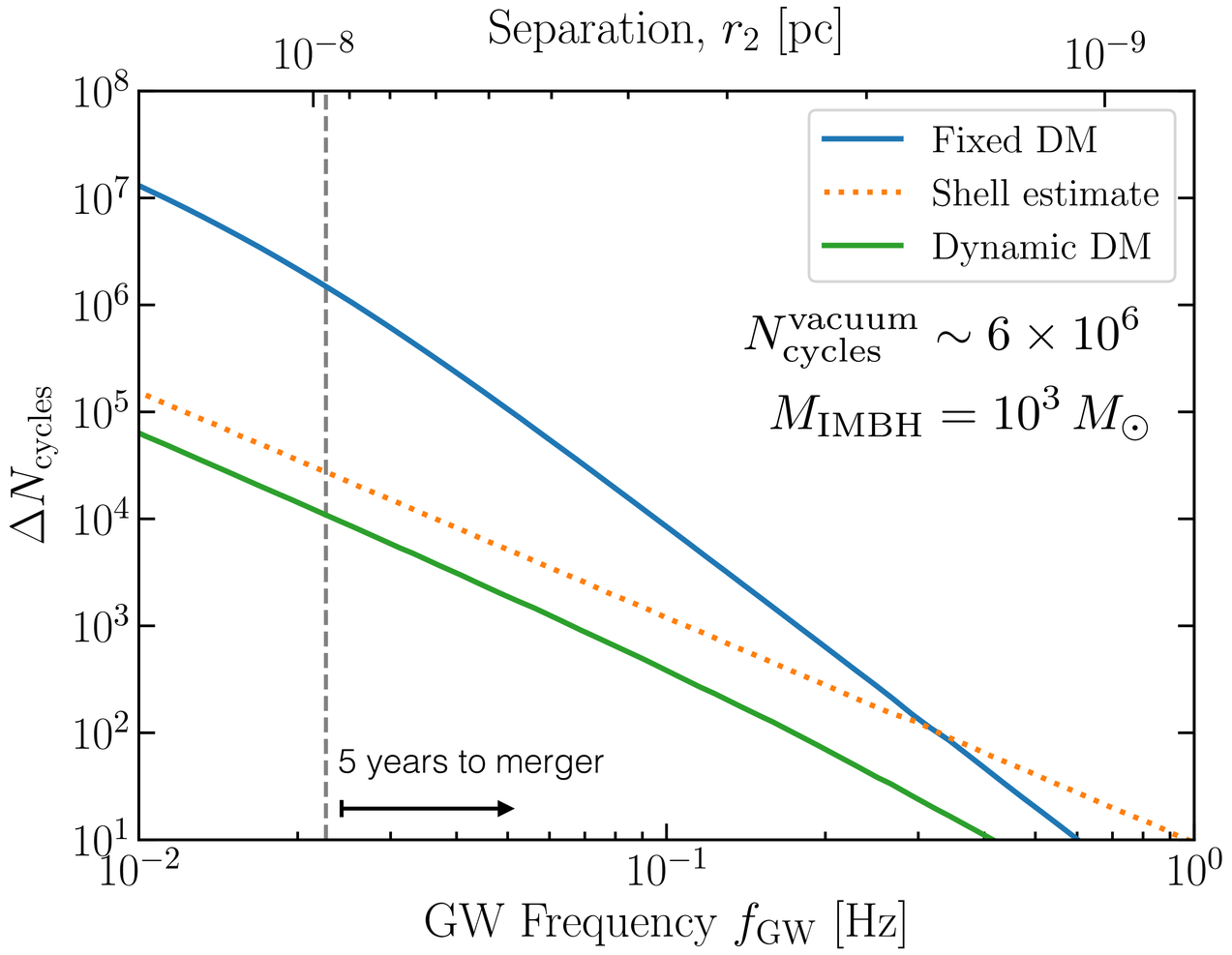
GW+Radio - DM density



$$\frac{{\rm d}\mathcal{P}}{{\rm d}\Omega} \sim 2 \times p_{a\gamma} \rho_{\rm DM}\left(r_c\right) v_c r_c^2 \qquad p_{a\gamma} \propto \frac{g_{a\gamma\gamma}^2 B\left(r_c\right)^2}{2 v_c}$$

[Edwards, Chianese, **BJK**, Nissanke, Weniger, 1905.04686]

DM Dephasing

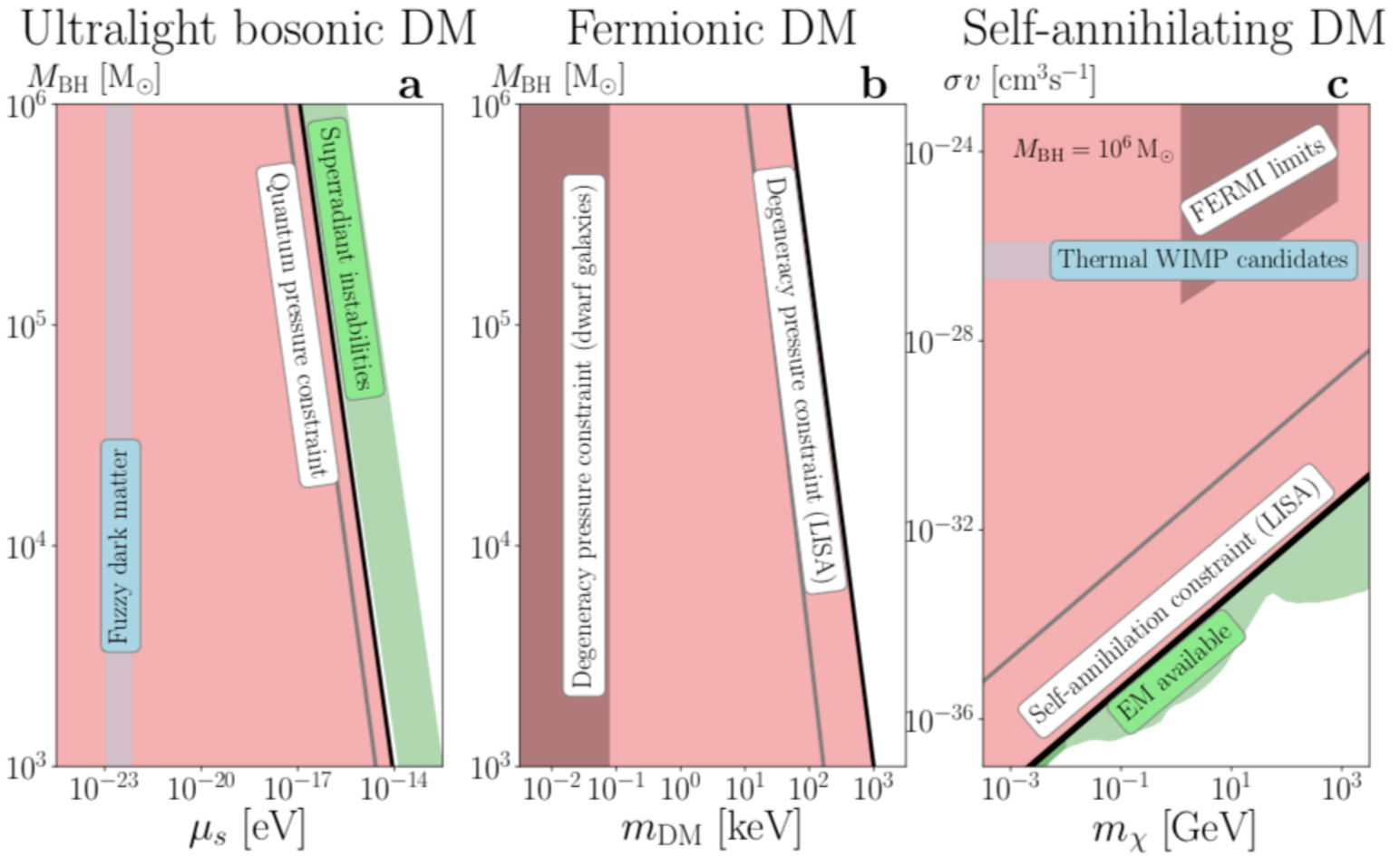


$$\Delta N_{\rm cycles}({\rm static}) \approx 10^6 \;\rightarrow\; \Delta N_{\rm cycles}({\rm dynamic}) \approx 10^4$$

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

Nature of Dark Matter

Red regions would be ruled out by observation of a DM spike! [Hannuksela et al., 1906.11845]



[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]