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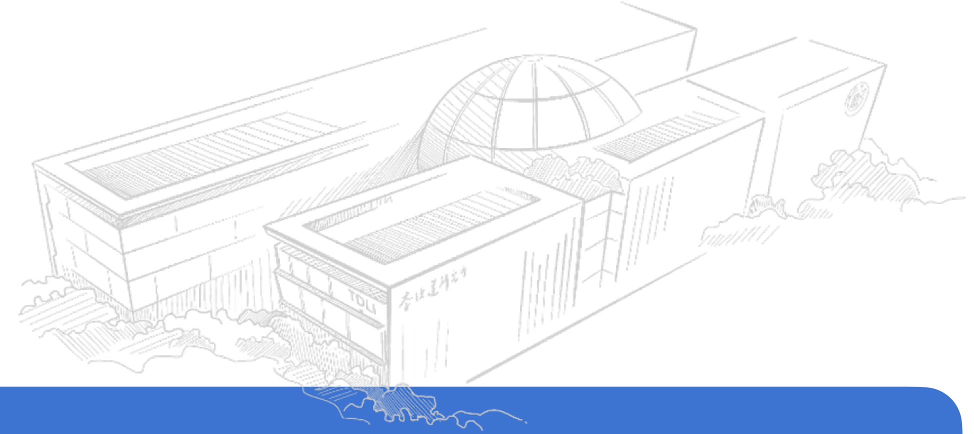


FLASH TDR meeting: Theory challenges

Luca Visinelli
TDLI & Shanghai Jiao Tong University

INFN-LNF, November 26, 2024

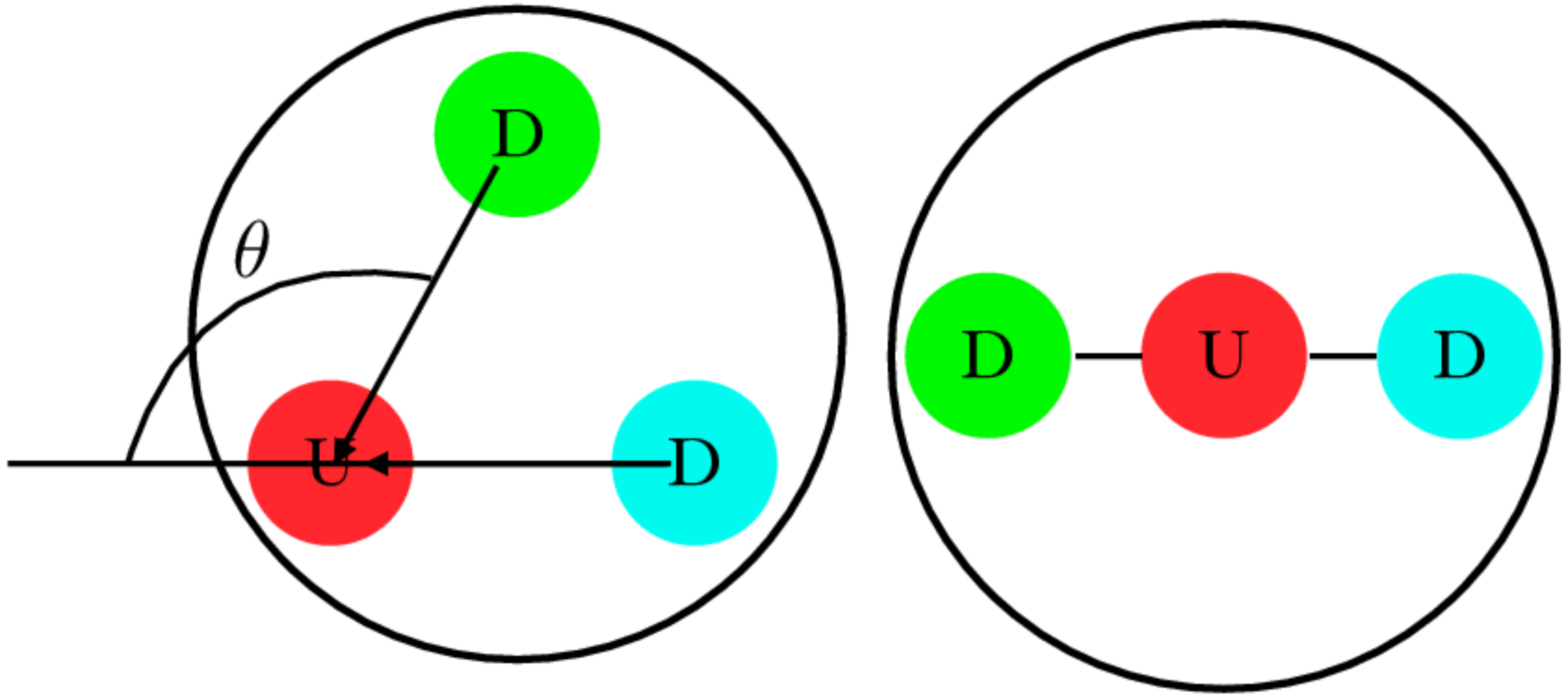
QCD Axion: Theory motivations

The QCD sector of particle physics demands solving the “strong-CP puzzle”

The distribution of quarks in a neutron defines the neutron’s **electric dipole moment**

Experimentally, this is remarkably small

$$|\theta| \lesssim 10^{-10}$$



[Peccei, Quinn, PRL **38** (1977) 1440]
[Weinberg, PRL **40** (1978) 223]
[Wilczek, PRL **40** (1978) 279]

Idea: the quantity θ is not a parameter but a field a (the axion)

$$\mathcal{L}_{\rm QCD} \supset \theta\, \tilde{G}G \longrightarrow \frac{a}{f_a}\, \tilde{G}G$$

G Gluon field

f_a New energy scale

Cold axions as dark matter

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

Cold axions as dark matter

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

Coupling of the axion with the photon

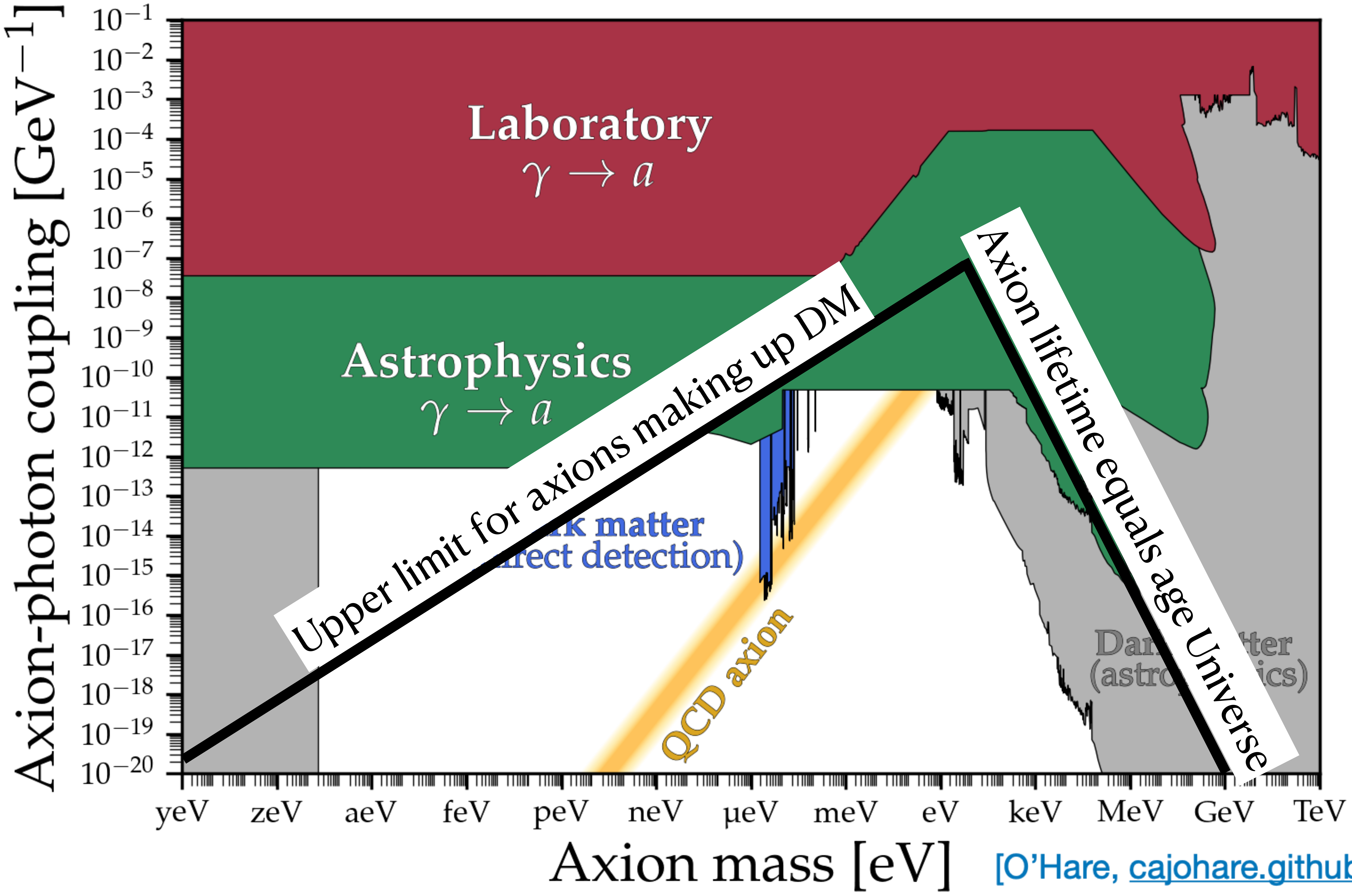
Interactions are set by the **pseudo-scalar nature** of the axion, with Lagrangian:

$$\mathcal{L} \supset \underline{g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}} + g_{af}\,(\nabla a)\cdot\mathbf{S} + g_{\mathrm{EDM}}\, a\, \mathbf{S}\cdot\mathbf{E}$$

Experimentally, how do they look like?

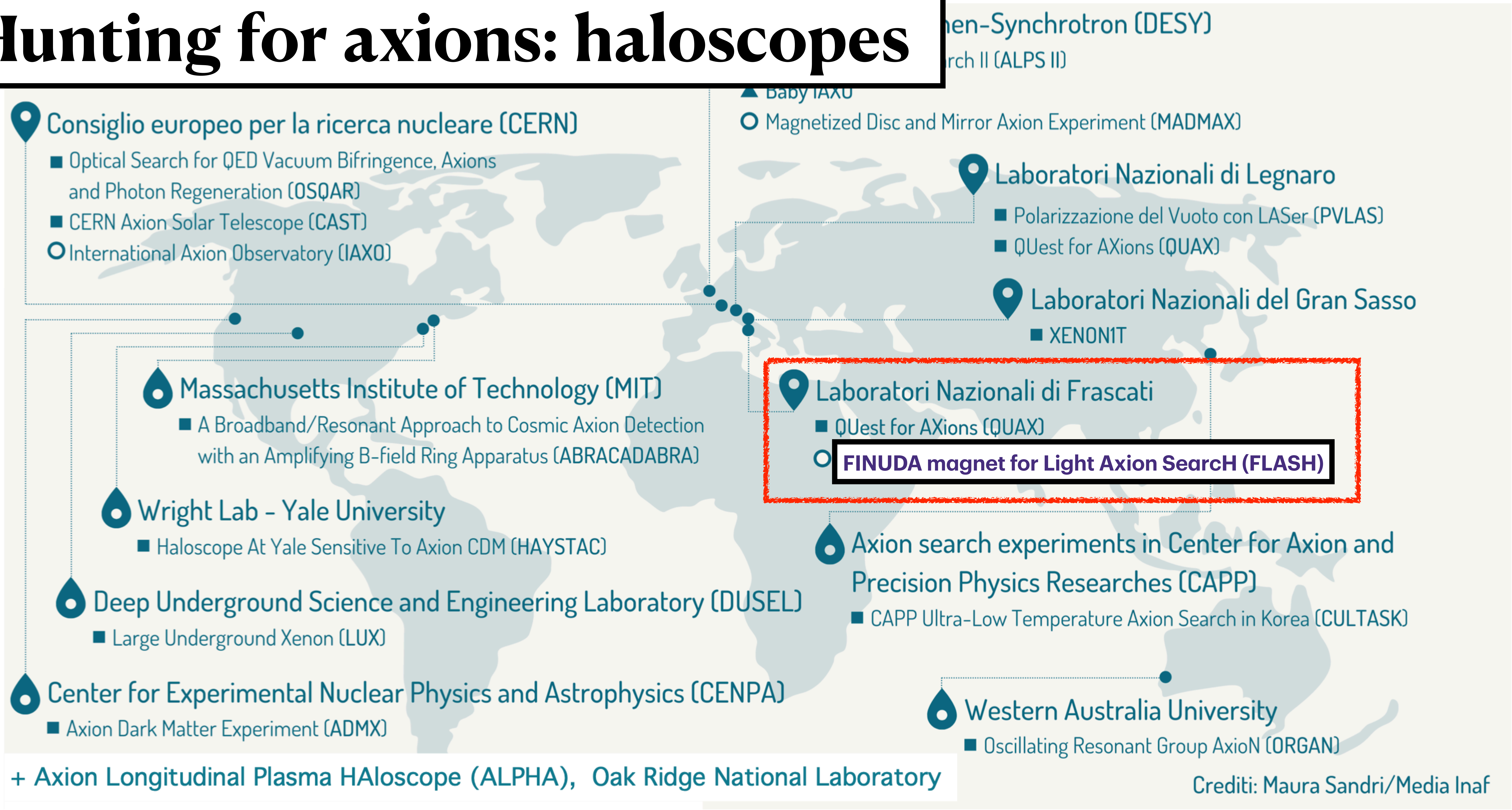
- Via $\mathbf{E}\cdot\mathbf{B}$ coupling (CP-odd) → Additional electric current
- Via coupling to e^- and n spins → Precessions

Coupling of the axion with the photon



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

Hunting for axions: haloscopes



hen-Synchrotron (DESY)
rch II (ALPS II)
▲ Baby IAXO
○ Magnetized Disc and Mirror Axion Experiment (MADMAX)

Consiglio europeo per la ricerca nucleare (CERN)
■ Optical Search for QED Vacuum Bifringence, Axions and Photon Regeneration (OSQAR)
■ CERN Axion Solar Telescope (CAST)
○ International Axion Observatory (IAXO)

Laboratori Nazionali di Legnaro
■ Polarizzazione del Vuoto con LASer (PVLAS)
■ QUest for AXions (QUAX)

Laboratori Nazionali del Gran Sasso
■ XENON1T

Massachusetts Institute of Technology (MIT)
■ A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus (ABRACADABRA)

Laboratori Nazionali di Frascati
■ QUest for AXions (QUAX)
○ **FINUDA magnet for Light Axion SearcH (FLASH)**

Wright Lab - Yale University
■ Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

Axion search experiments in Center for Axion and Precision Physics Researches (CAPP)
■ CAPP Ultra-Low Temperature Axion Search in Korea (CULTASK)

Deep Underground Science and Engineering Laboratory (DUSEL)
■ Large Underground Xenon (LUX)

Center for Experimental Nuclear Physics and Astrophysics (CENPA)
■ Axion Dark Matter Experiment (ADMX)

Western Australia University
■ Oscillating Resonant Group AxioN (ORGAN)

Crediti: Maura Sandri/Media Inaf

+ Axion Longitudinal Plasma HAloscope (ALPHA), Oak Ridge National Laboratory

+ Taiwan Axion Search Experiment with Haloscope (TASEH)

+ Cosmic Axion Spin Precession Experiment (CASPEr), Boston and Mainz

Courtesy of Caterina Braggio

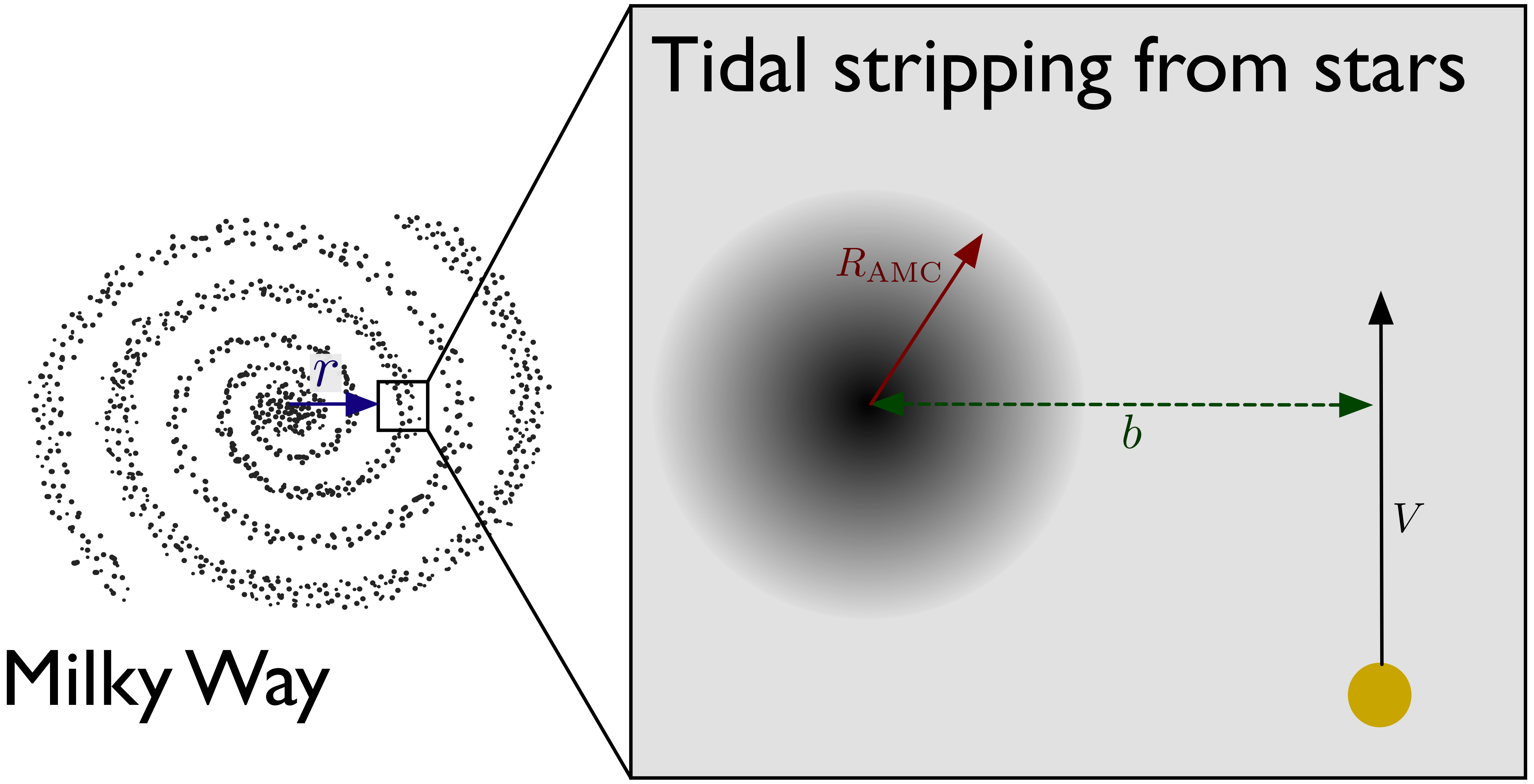
Detecting axion miniclusters in FLASH?

Overdensities produced in the early Universe act as “seeds” for bound axion *miniclusters* (Hogan, Rees 88)

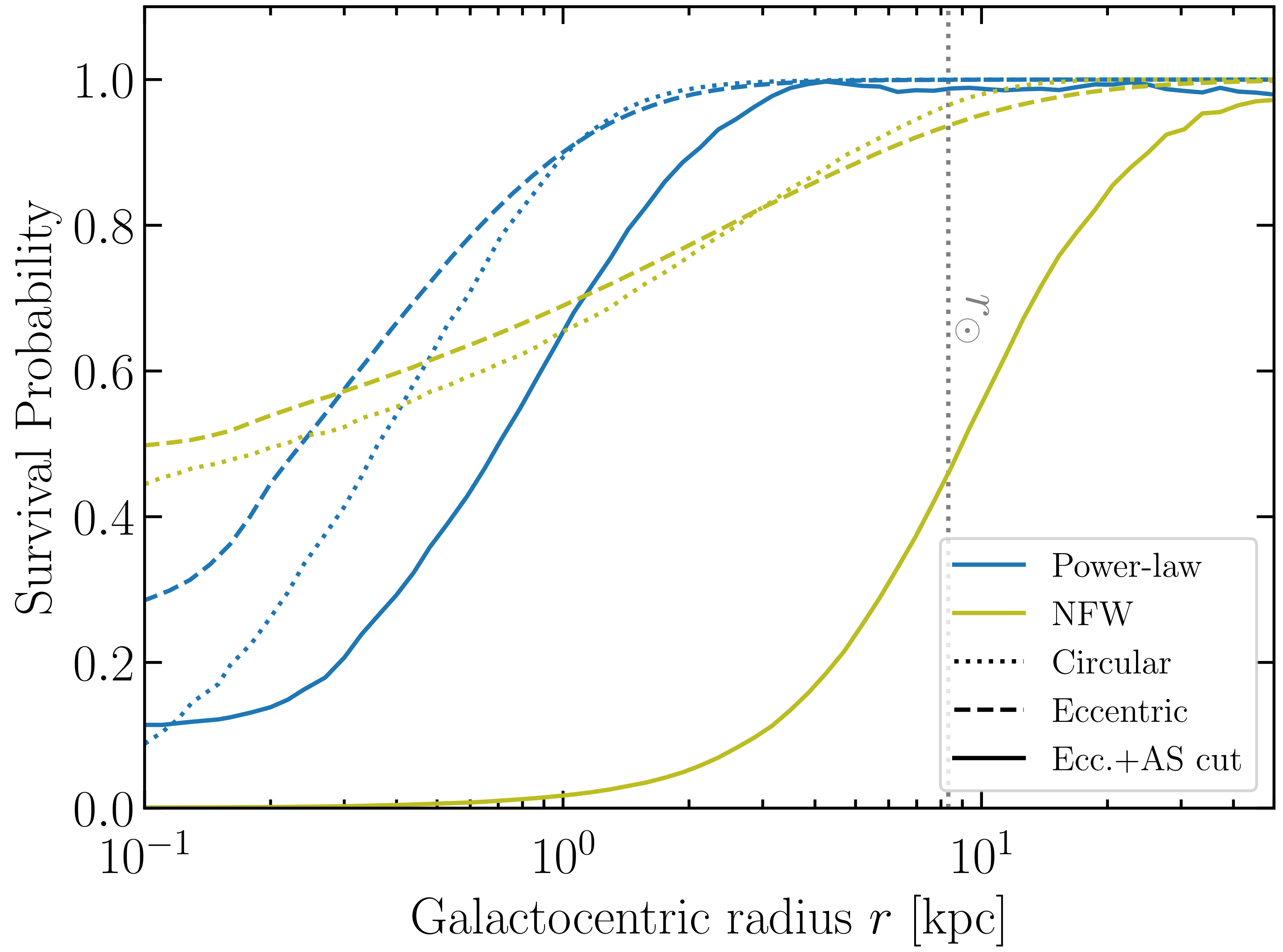
For an overdensity $\delta \equiv 1 - \bar{\rho}/\rho$ the AMC density is $\rho_{\rm amc}(\delta) = 140\,(1+\delta)\delta^3 \rho_{\rm eq}$

Kolb, Tkachev astro-ph/9311037

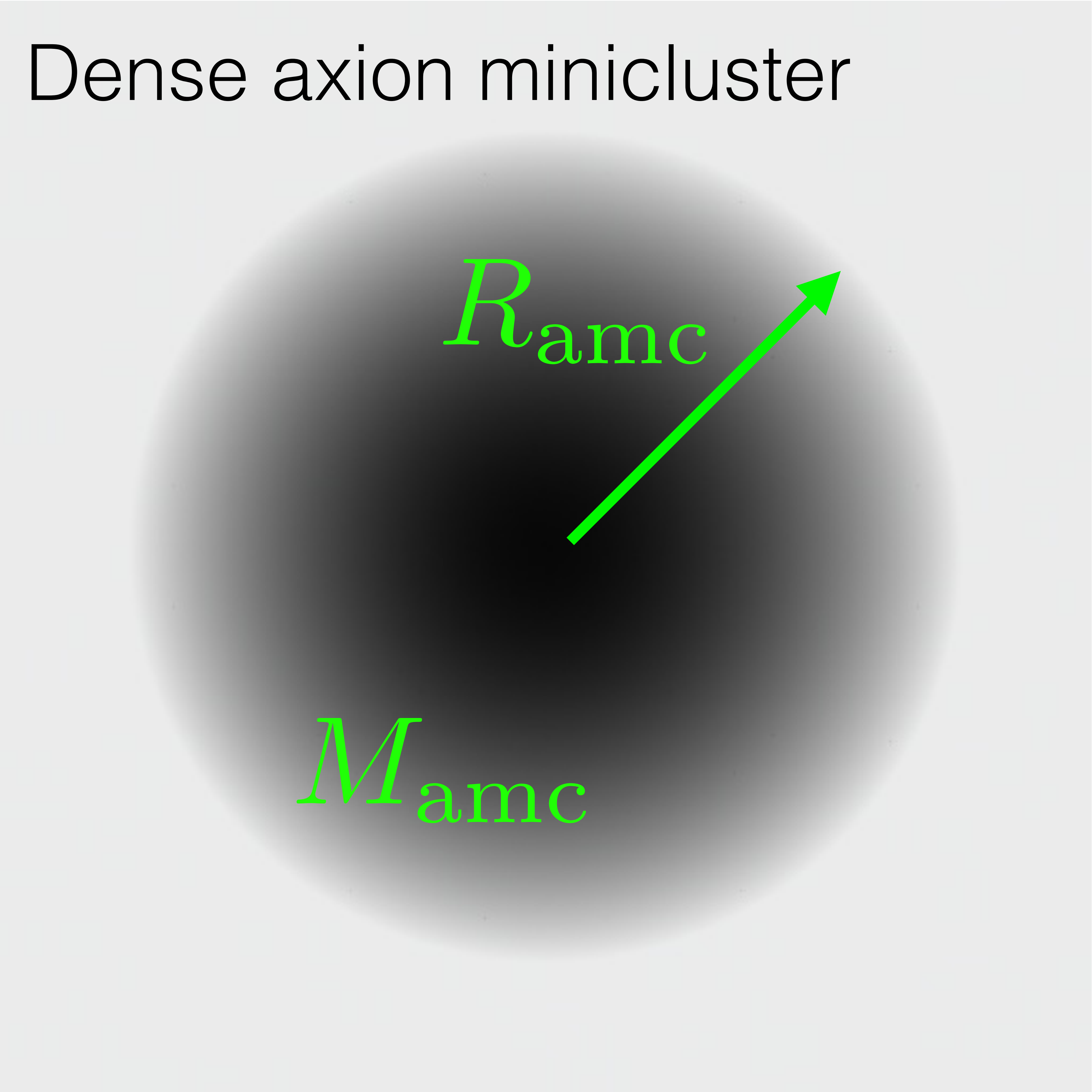
We first assessed the minicluster distribution in the Milky Way Kavanagh, Edwards, **LV**, Weniger 2011.05377


Tidal stripping from stars

Milky Way



Detecting axion miniclusters in FLASH?



Velocity dispersion in the AMC: $\sigma_v^2 = \frac{G\,M_{\rm amc}}{R_{\rm amc}}$

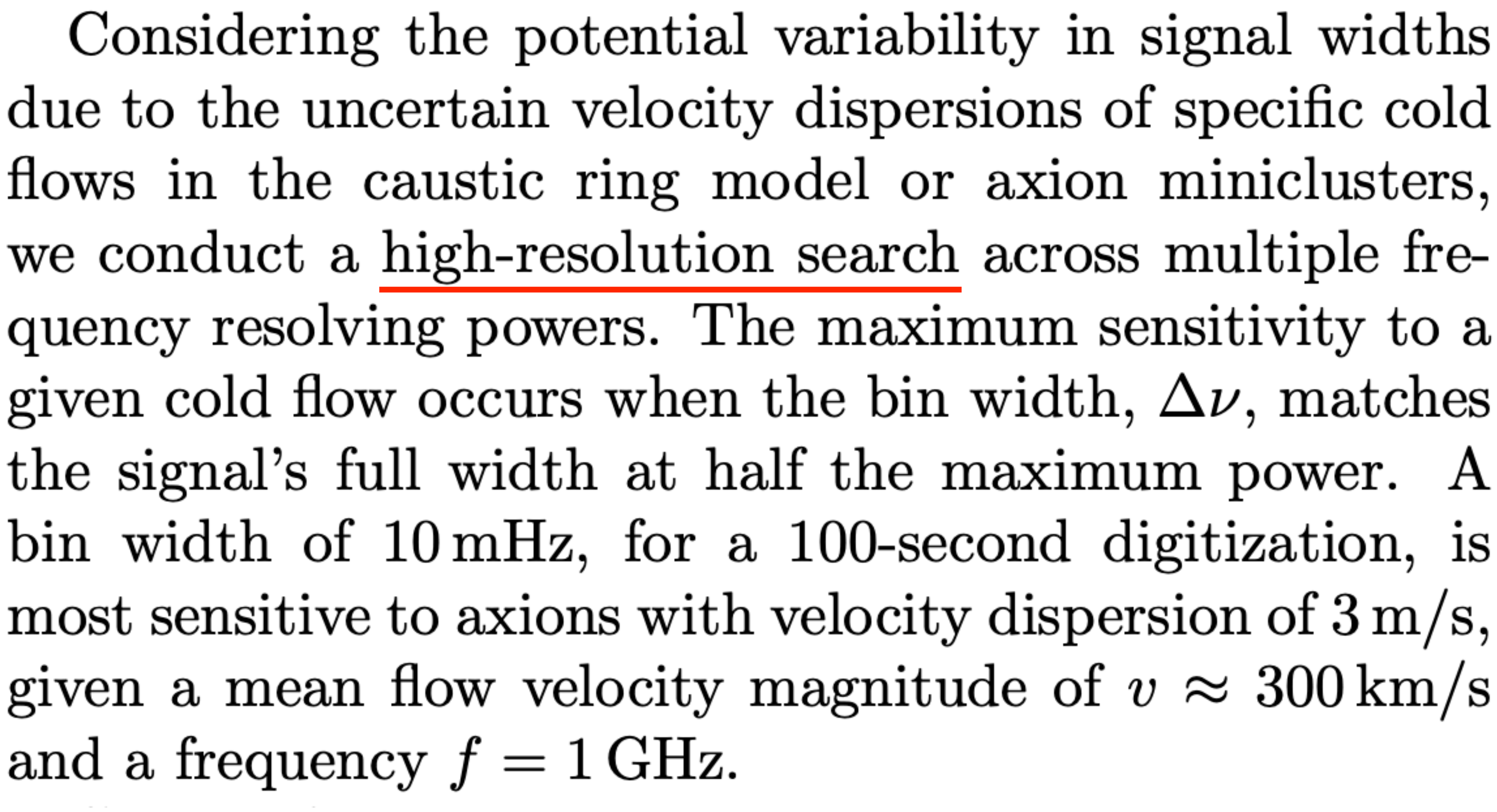
$$\sigma_v \approx 1.4\,{\rm m/s}\left(\frac{M_{\rm amc}}{10^{-10}\,M_\odot}\right)^{1/3}\left(\frac{\delta}{10}\right)^{2/3}$$

This translates into the frequency width:

$$\delta f = f\left(\frac{v\sigma_v}{c^2}\right) \approx 0.23\,{\rm mHz}\left(\frac{f}{100\,{\rm MHz}}\right)\left(\frac{M_{\rm amc}}{10^{-10}\,M_\odot}\right)^{1/3}\left(\frac{\delta}{10}\right)^{2/3}$$

Detecting axion miniclusters in FLASH?

This has been recently sought in ADMX: 2410.09203



Considering the potential variability in signal widths due to the uncertain velocity dispersions of specific cold flows in the caustic ring model or axion miniclusters, we conduct a high-resolution search across multiple frequency resolving powers. The maximum sensitivity to a given cold flow occurs when the bin width, $\Delta\nu$, matches the signal's full width at half the maximum power. A bin width of 10 mHz, for a 100-second digitization, is most sensitive to axions with velocity dispersion of 3 m/s, given a mean flow velocity magnitude of $v \approx 300$ km/s and a frequency $f = 1$ GHz.

Detecting axion miniclusters in FLASH?

Other things to do if we proceed for this!

Some simulations of minicluster dynamics that involve the axion DM in the mass range of FLASH.

This includes assessing the mass distribution of miniclusters for axions with $m_a = 1\,\mu\mathrm{eV}$

The mass distribution includes tidal stripping: my work 2011.05377 + recent work 2402.03236

Power in the cavity: $P(\omega) \propto g_{a\gamma}^2\, \rho_a\, f(\omega)$

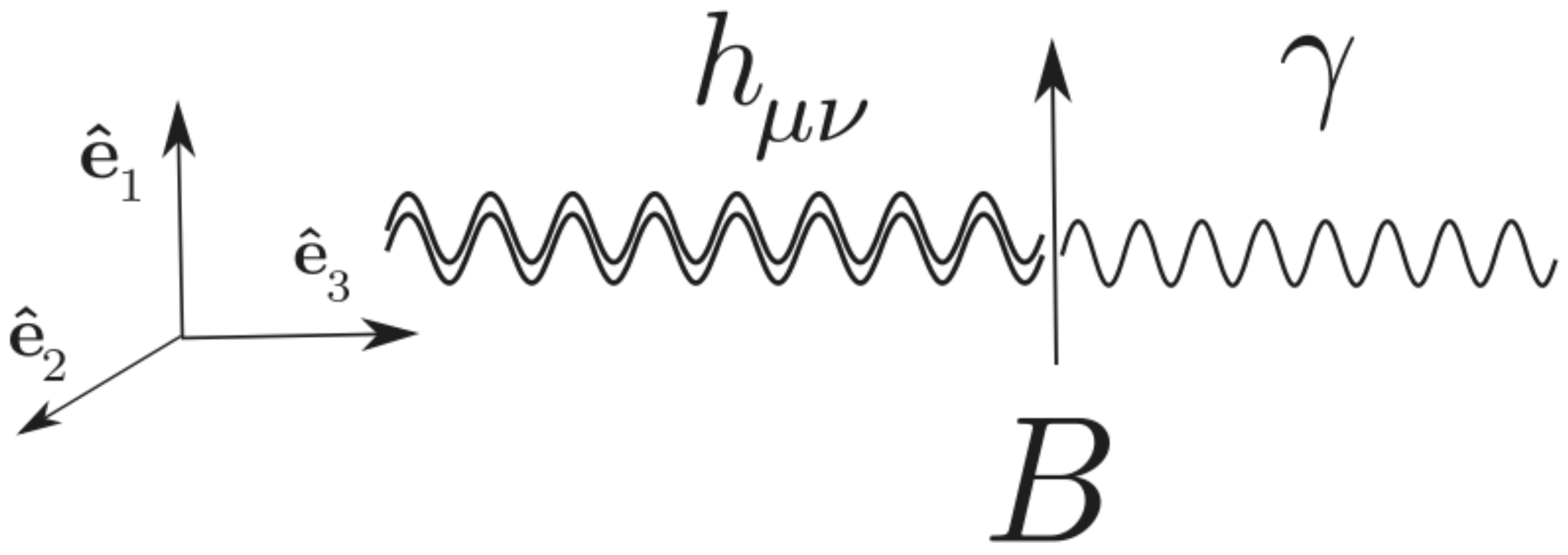
Fourier decomposition at the frequency ω

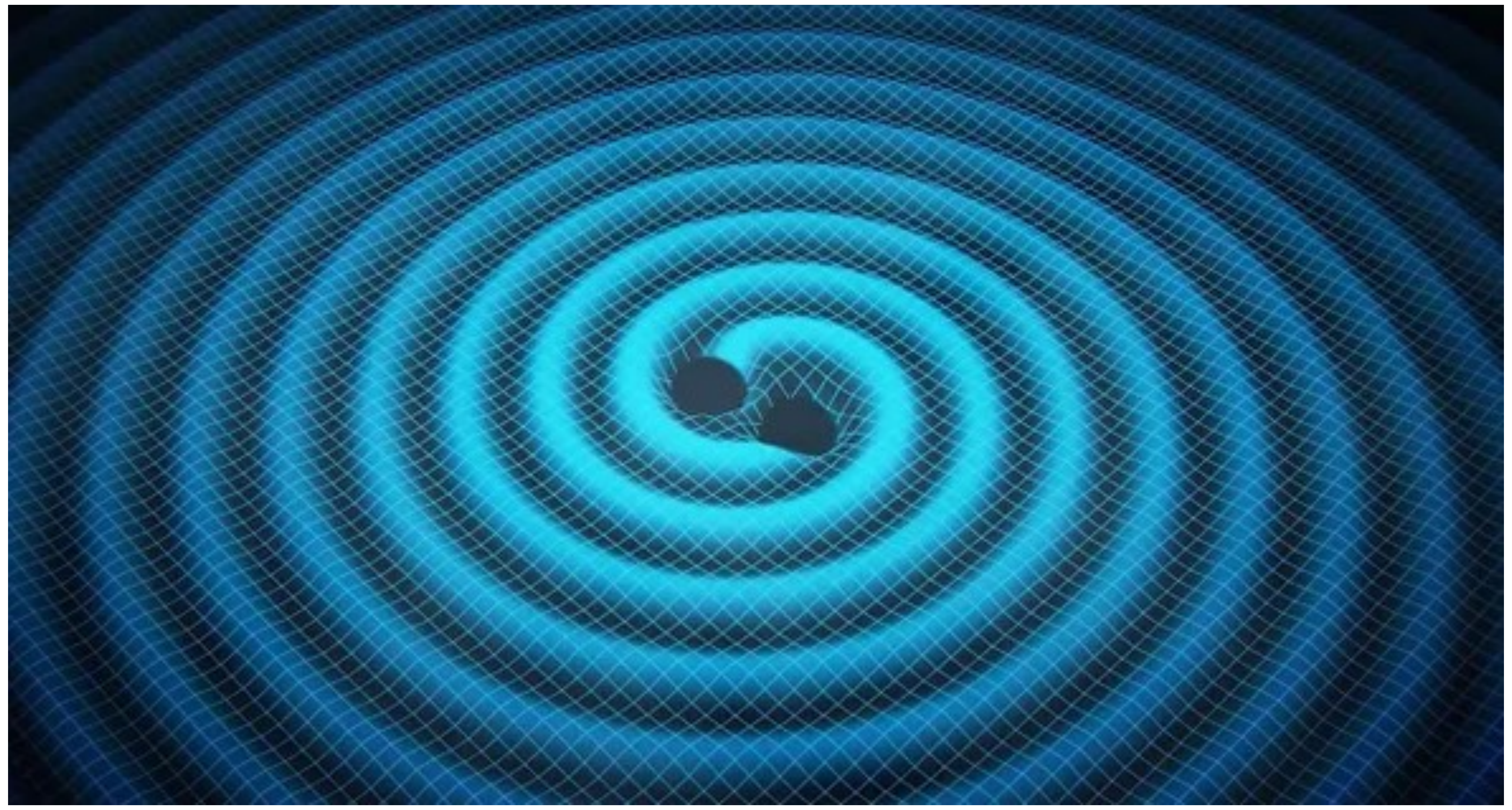
We need to account for the chance of encountering miniclusters and streams: 2212.00560

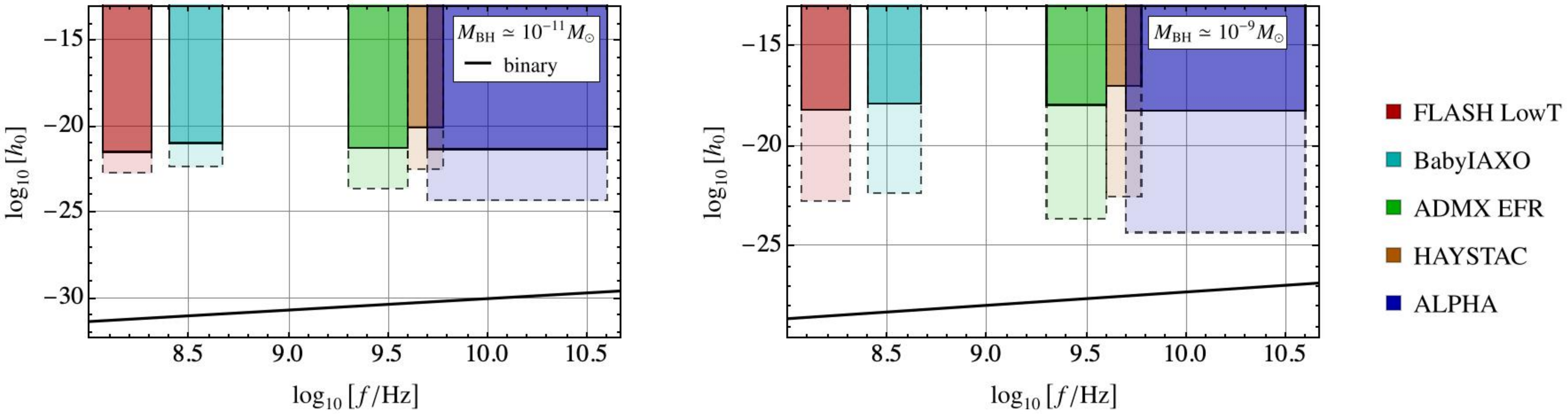
High-frequency gravitational waves

Inverse Gertsenshtein effect (see e.g. Camilo Garcia work)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad h_0 \sim |h_{\mu\nu}|$$





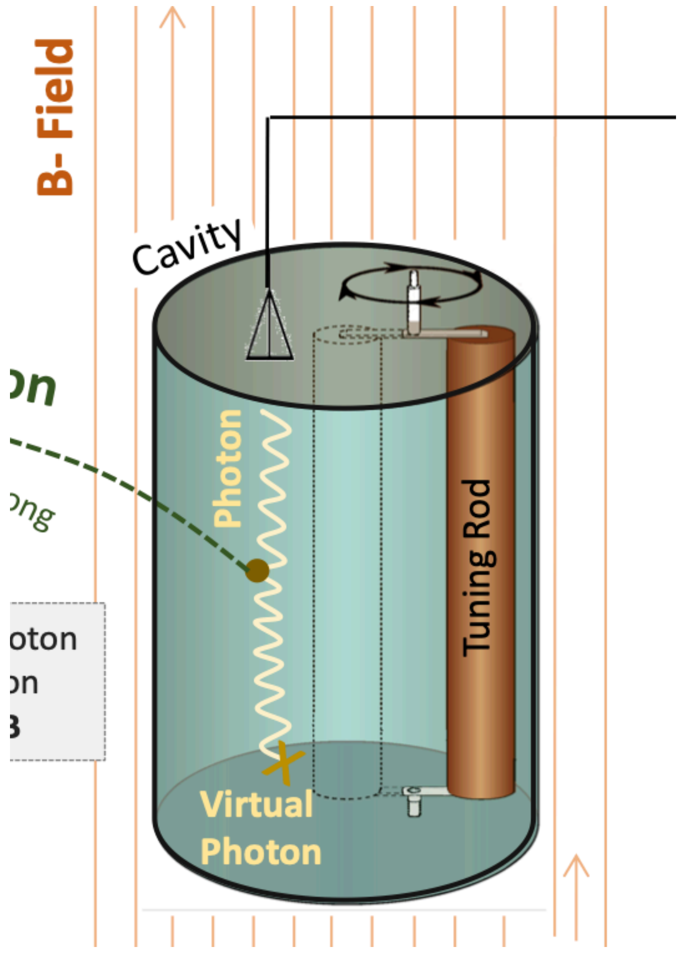


Gatti, **LV**, Zantedeschi 2403.18610, PRD

Work with
Michael Zantedeschi
(postdoc @TDLI)

High-frequency gravitational waves

Vs.

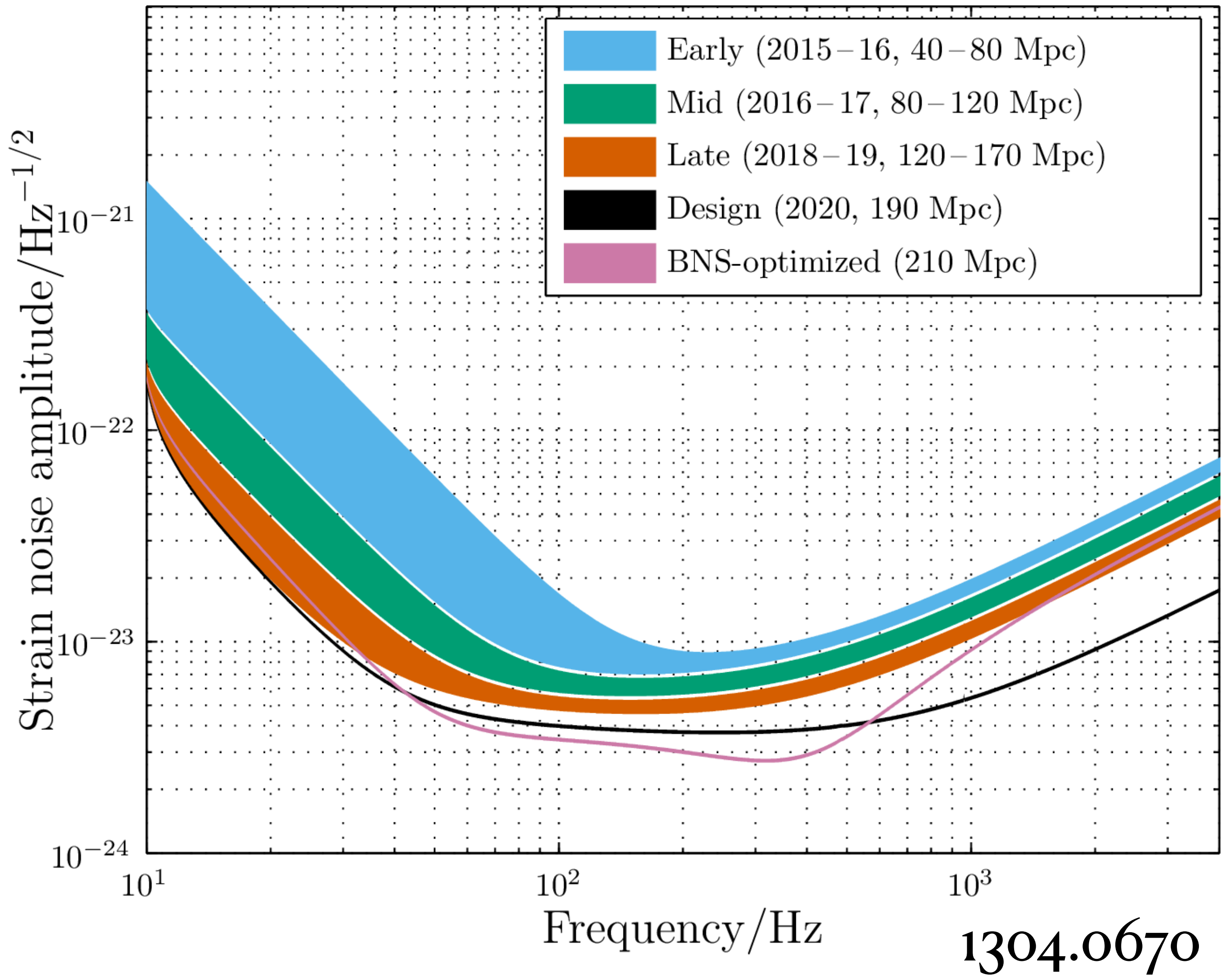


Cavities resonate at much higher frequencies than those in LIGO/VIRGO/KAGRA

Gatti, **LV**, Zantedeschi
2403.18610

LVK $f \sim$ (10-1000) Hz: Solar-mass BHs

Cavity $f \sim$ (0.1-10) GHz: Primordial BHs



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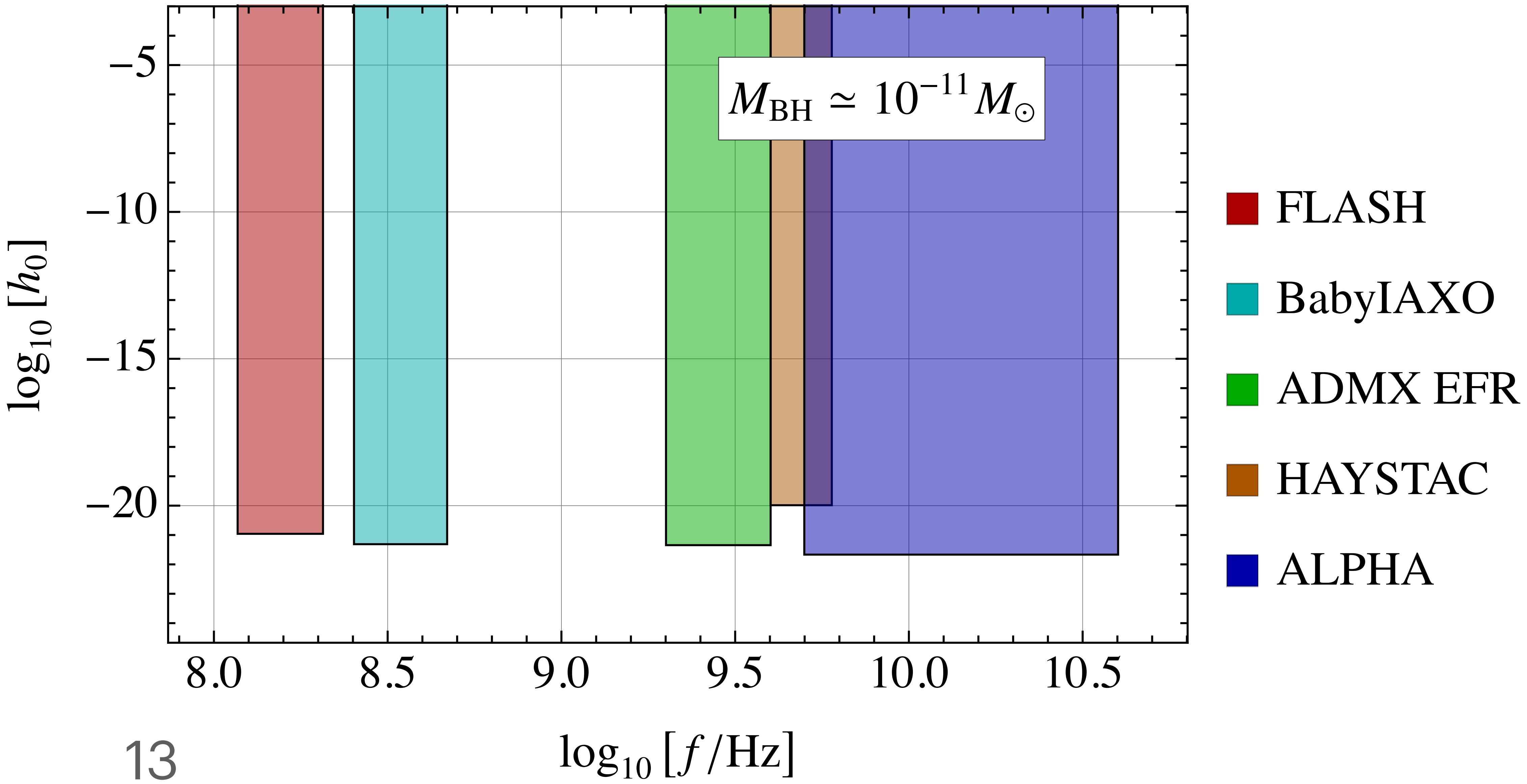


High-frequency gravitational waves

Open theory questions, see for more: Gatti, **LV**, Zantedeschi 2403.18610

- How precisely can we infer the signal geometry using a single cavity?

- Multiple cavities help distinguishing between spin-0, spin-1, or spin-2 (pseudo-)fields and provide noise reduction

- Further work needed to characterize coherent versus stochastic signals, as well as continuous versus transient signals.

- Nevertheless, any potential detection would unequivocally point to new physics of astrophysical origin.

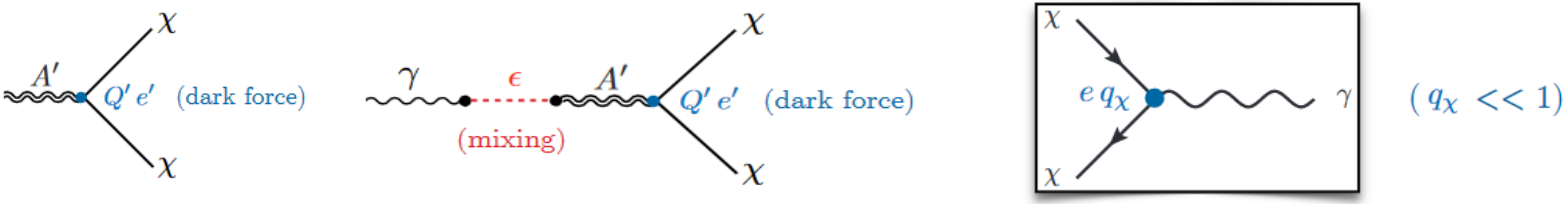
Millicharged particles

Intriguing opportunity not discussed so far in the CDR

The visible universe is governed by a rich spectrum of forces and particles.

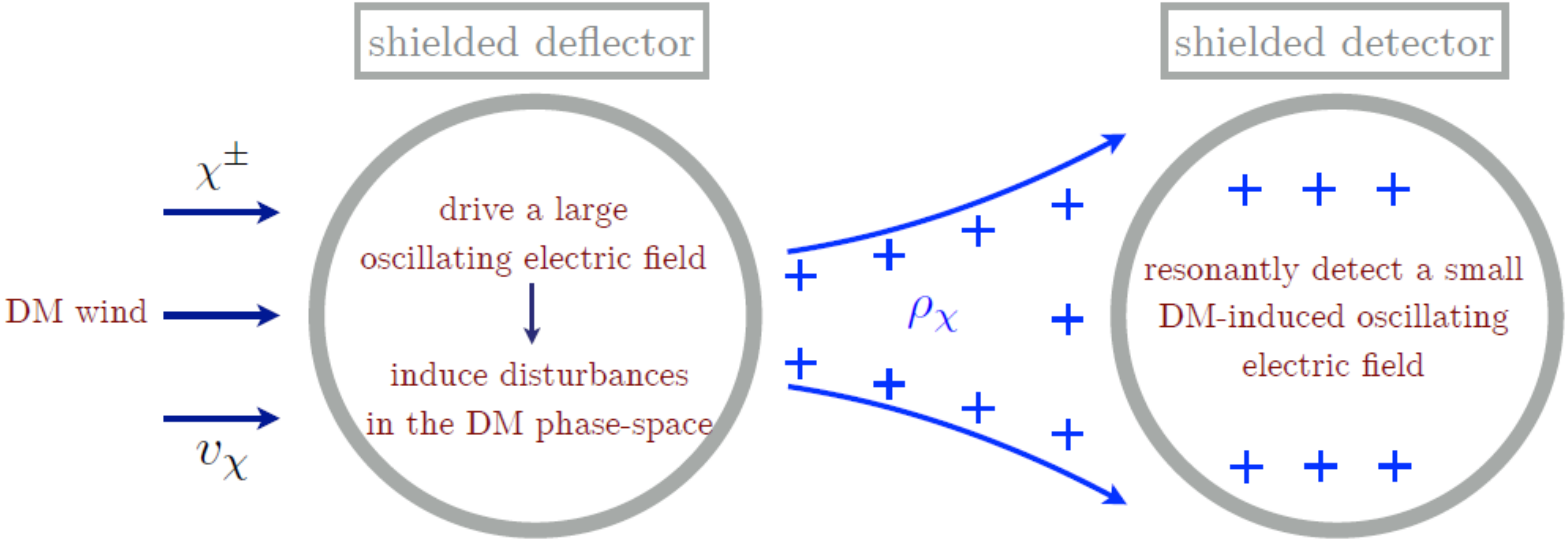
What particle physics governs most of the matter in the universe?

Generic to expect that dark matter couples to new long-ranged forces.



$$\Longrightarrow \; q_\chi \sim \epsilon\, Q'\, e'/e \quad \text{(effective DM charge)}$$

Millicharged particles



Goal

Induce and measure disturbances of the dark matter "fluid,"

Berlin+ 1908.06982

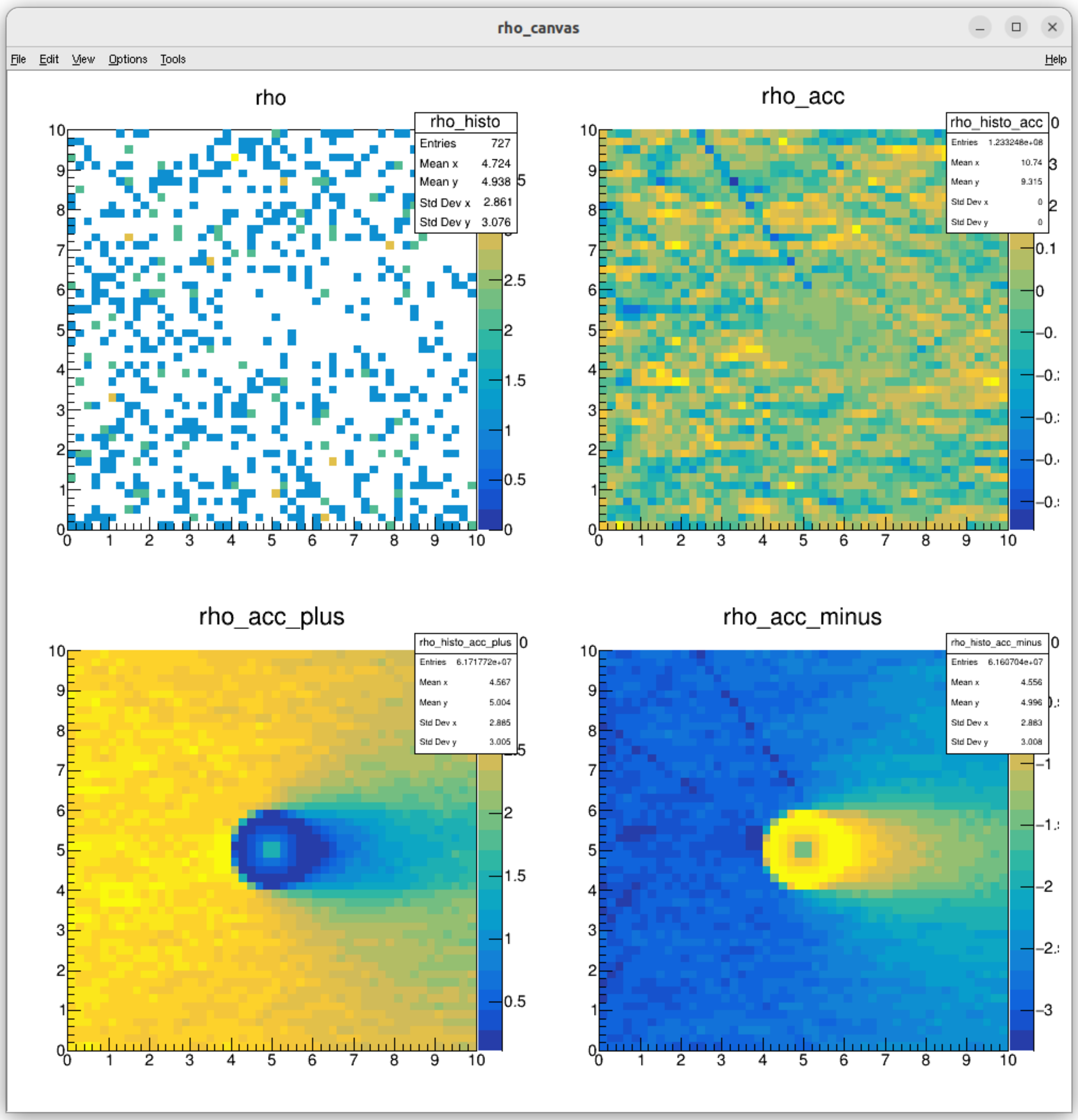
Millicharged particles

- ❑ Tool (python/root) to simulate the deflection and detection phases

- ❑ Tool tested for spherical electric field

- ❑ Tool ready for more realistic setup (discussing with D. Alesini per la configurazione finale)

F. Mescia, G. Grilli di Cortona, F. La Valle (RM1 laureando) & M.Navydenov



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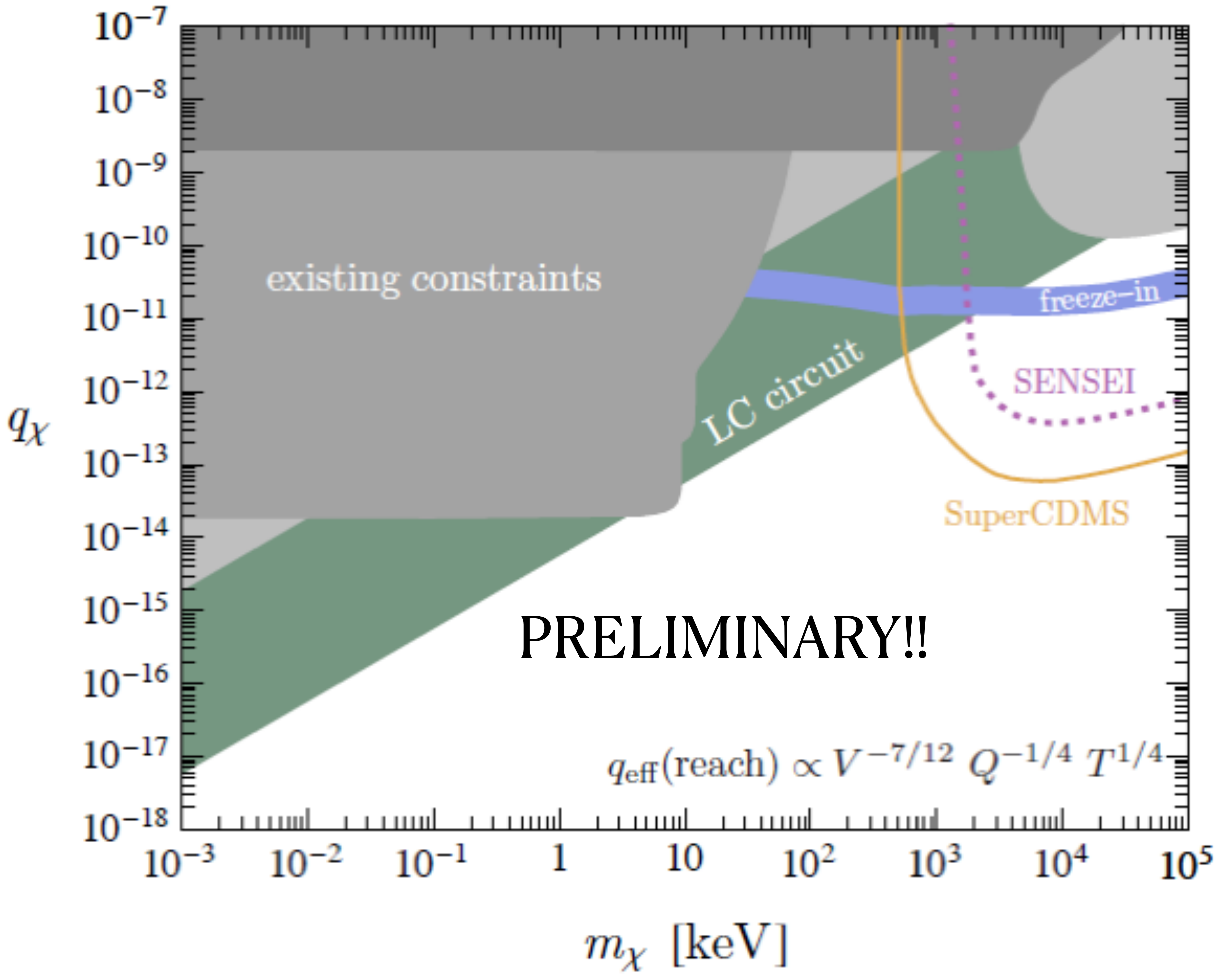

Summary

Ideal theory focus for 2025:

- Impact of dark matter substructures on direct detection.
- Motivations for GW searches at the GHz
- Millicharged particles
- Refining the computations for axions and dark photons in cavities

Introductory slides and other ideas can be found in the kick-off meeting: https://agenda.infn.it/event/41365/

Please refer to the CDR publication: 2309.00351

Thanks to my collaborators: Claudio Gatti, Enrico Nardi, Federico Mescia, Michael Zantedeschi
+ the whole FLASH staff