New Opportunities for Direct Dark Matter Detection

Dark Photon and Beyond

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Dark Matter
Light bosons
QCD Axions
Axion-like Particles
Fuzzy Dark Matter
Neutrinos
Standard Model ν
Sterile neutrinos
Weak Scale
Super-symmetry
Extra-dimensions
Little Higgs
Effective Field Theory
Simplified Models
Other Particle
WIMPzilla
Self-interacting
Superfluid
Macroscopic
Macros
MaCHOs
Primordial BHs
Modified Gravity
MOG
TeVeS
MoND
Emergent Gravity

T. Tait

Direct DM Detection

- **Direct DM detection:** detection of energy deposit in experiments from Milky Way halo DM passing through the Earth

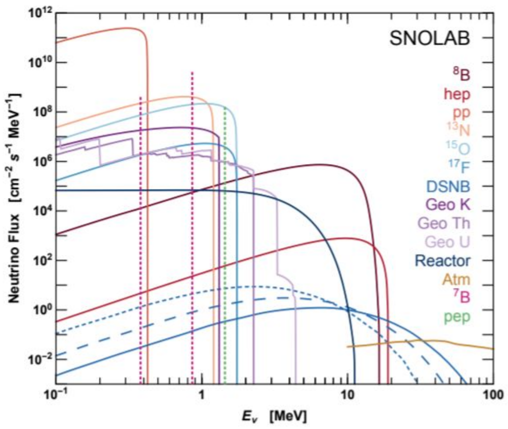
- Conventional searches focus on nuclear recoils due to electroweak-scale WIMPs within large (~ton-scale) experiments

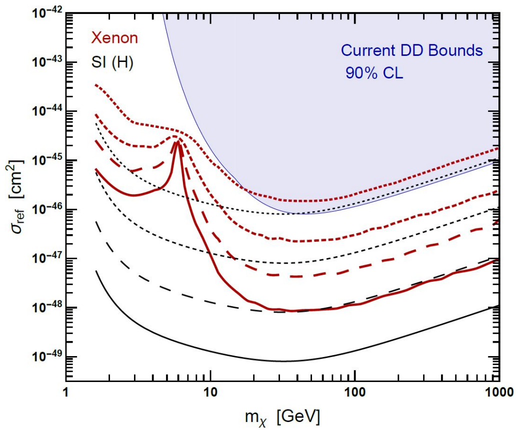
- Great efforts, but no convincing signs of DM → probe further with new experiments

*** *exciting new anomalies (e.g. XENON1T) keep theorists on the edge*

DM-Neutrino Telescopes

- Eventually will encounter irreducible neutrino-background: **"neutrino floor"**





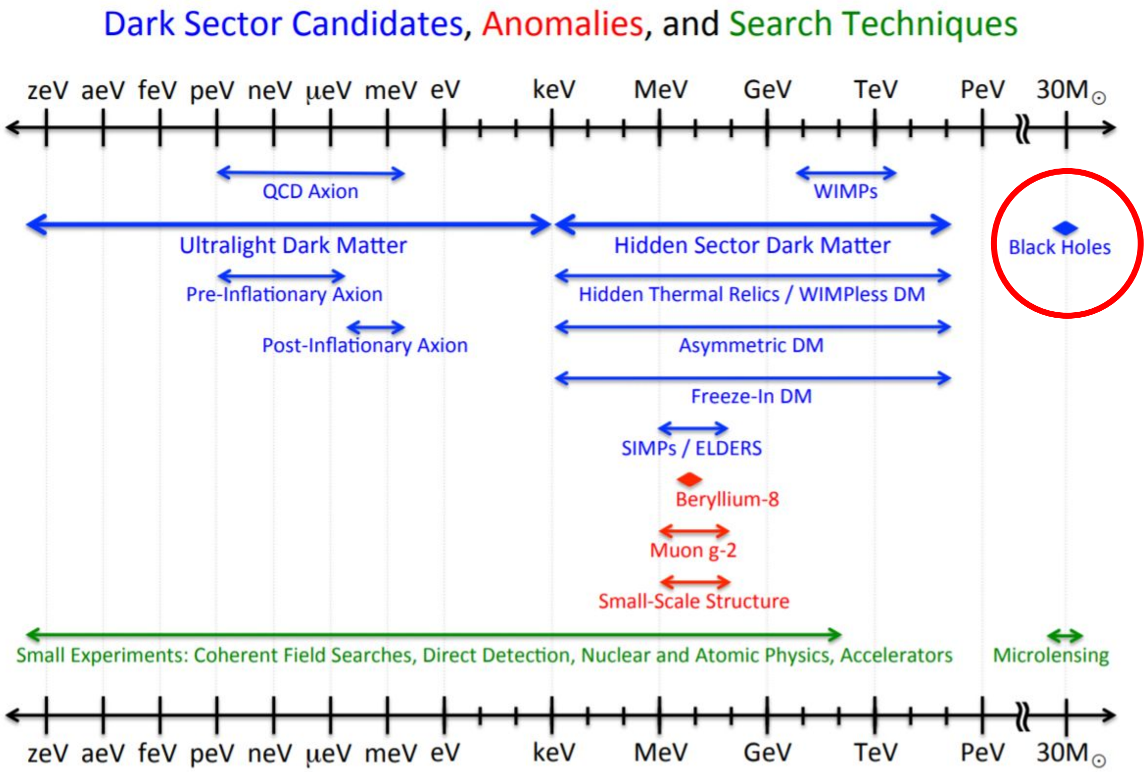
[Gelmini, **VT**, Witte, JCAP, 2018]

- A curse for DM searches, but an opportunity for neutrino physics !
  → large DM experiments as ***"effective neutrino telescopes"***

- Complementary studies to dedicated neutrino observatories
  (pre-)supernova neutrinos, solar & atmospheric neutrinos, geo-neutrinos, etc.

[Raj, **VT**, Witte, PRD, 2019] [Gelmini, **VT**, Witte, PRD, 2018]

The Vast DM Parameter Space



*** *novel limits on PBH in LIGO-range from dwarf galaxy heating*

[Lu, **VT**, Gelmini, Hayashi, Inoue, Kusenko, 2020]

US Cosmic Visions Report (2017)

- Without convincing signs and large theory uncertainty → **important to search broadly**

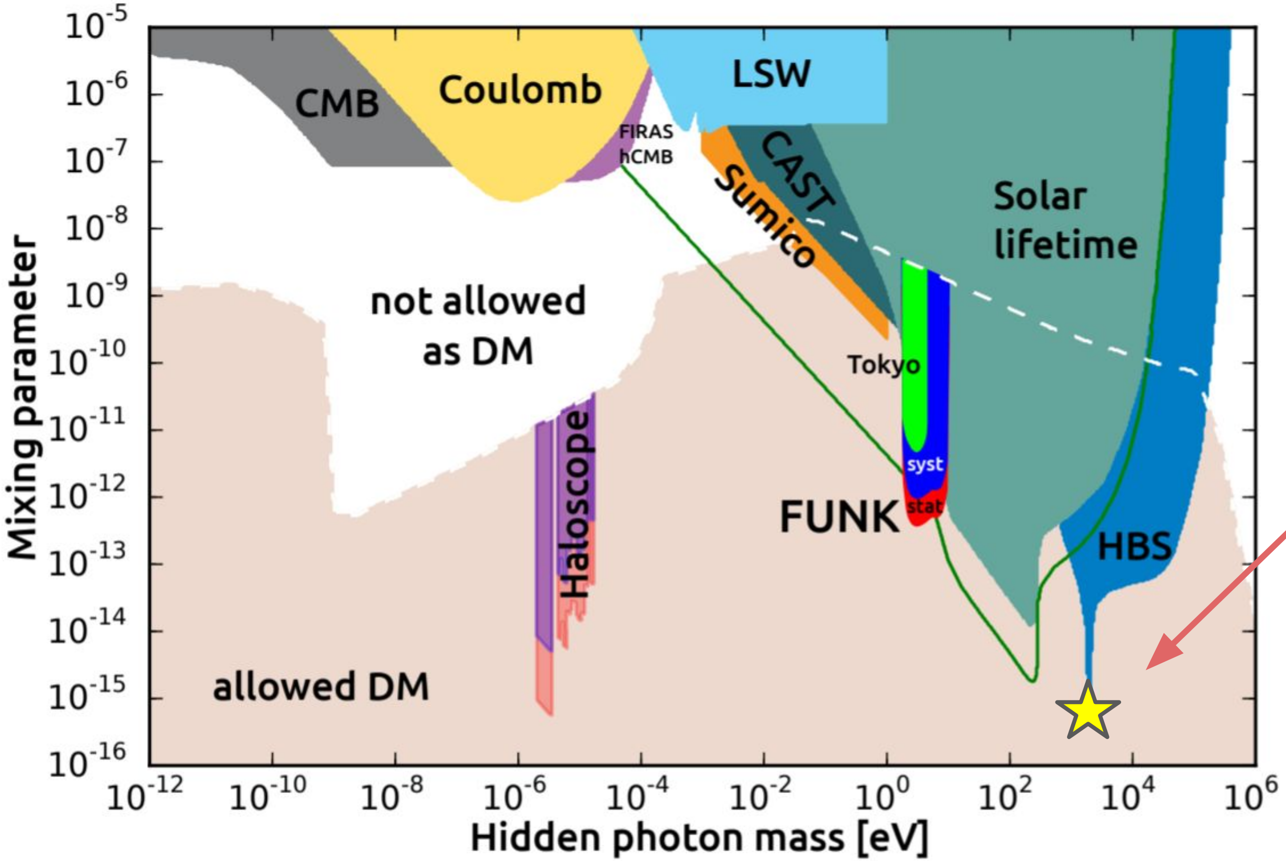
Dark Photon, New Opportunities

Dark (Hidden) Photon DM

- **Dark photon:** vector boson of additional dark sector U(1) local symmetry
- Appears in minimal SM extensions, well motivated from top-down constructions
- Kinetically mixes with SM photon [Holdom, 1986]
- Mass from Higgs or Stueckelberg mechanism
- Considering very small mass, behaves as coherent classical field
- Abundance set by early Universe formation (mis-alignment, inflation fluctuations, decays…)
  [Nelson, Scholtz, 2011; Graham+, 2016; Arias+ 2012; others]
- Present direction of DP vector field random or aligned

**** DP DM can fit to XENON1T excess* [An+, 2020; Alonso-Alvarez+, 2020; others]

Dark Photon Status

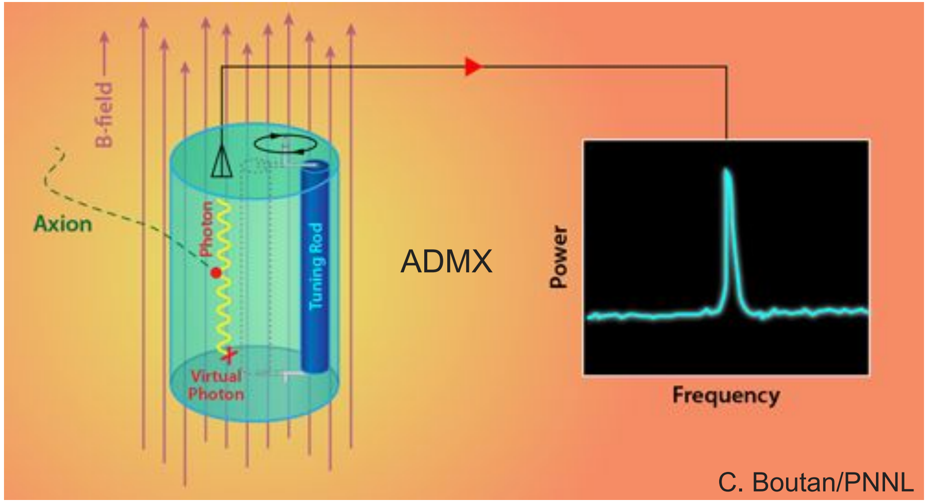


XENON1T excess fit

FUNK Collaboration (2017)

Conventional Haloscopes

- Cavity haloscopes [Sikivie, 1983; others] searching for photons from axion conversion also well equipped for DP searches (for DP searches don't need external B-field [Arias+, 2012])



- Conversion enhanced at cavity resonance mode → **limited by cavity geometry**

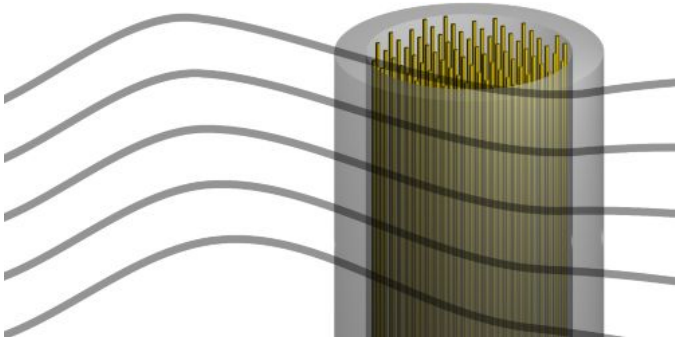
**** other proposals include dish antennas, dielectric haloscopes (MADMAX) ...*

In-Medium Effects

- Many proposals to detect light DM (e.g. superconductors) are based on small band-gap materials, above which quasi-particle production (e.g. phonons, magnons) is efficient
- Near the quasi-particle production resonance, in-medium effects suppress interactions
- **Exploit:** if manage to stay on resonance → dramatically enhance interactions

Tunable Plasma Haloscope

- Tunable plasma haloscope utilizing axion-plasmon coupling recently proposed [Lawson+, 2019]
- Based on wire metamaterials [Pendry+, 1998]: structure of thin wires behaves like metal, changing wire spacing changes “wire metal” properties (e.g. plasma frequency)
- Axion couples to plasmon within the “wire metal”, can “tune” frequency to always stay on resonance → exploit in-medium effects
- Resonance frequency not limited by geometry as in cavity haloscopes



A. Millar/Stockholm U.

DP DM in Plasma Haloscope

- Tunable plasma haloscopes also great as DP DM detectors via DP-plasmon conversion

  *** *DP-plasmon conversion well studied for astrophysical media* [Raffelt, Redondo, Pospelov, others]

- Kinetic mixing of DP **(X)** and SM photon **(A)** [Holdom, 1986]

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\sin\alpha}{2}F^{\mu\nu}X_{\mu\nu} + eJ^{\mu}_{\mathrm{EM}}A_{\mu} + \frac{m_X^2\cos^2\alpha}{2}X^{\mu}X_{\mu}$$

- Add in-medium effects (polarization tensor): $J^{\mu}_{\mathrm{ind}} = -\Pi^{\mu\nu}A_{\nu}$

[Gelmini, Millar, **VT**, Vitagliano, 2020]

DP DM in Plasma Haloscope

- Macroscopic description based on modified Maxwell equations (wave equation, E & B fields)

- Can match with microscopic description of thermal field theory (use optical theorem to relate DP absorption with DP self-energy that includes in-medium effects)

- Resulting output power:

$$P_{\rm out} = 1.1 \times 10^{-22}\,{\rm W} \left(\frac{\kappa}{0.5}\right)\left(\frac{\mathcal{G}}{1}\right)\left(\frac{\chi}{10^{-15}}\right)^2\left(\frac{Q}{100}\right) \times \left(\frac{V_d}{0.8\,{\rm m}^3}\right)\left(\frac{\nu}{10\,{\rm GHz}}\right)\left(\frac{\rho}{0.45\,{\rm GeV/cm}^3}\right).$$

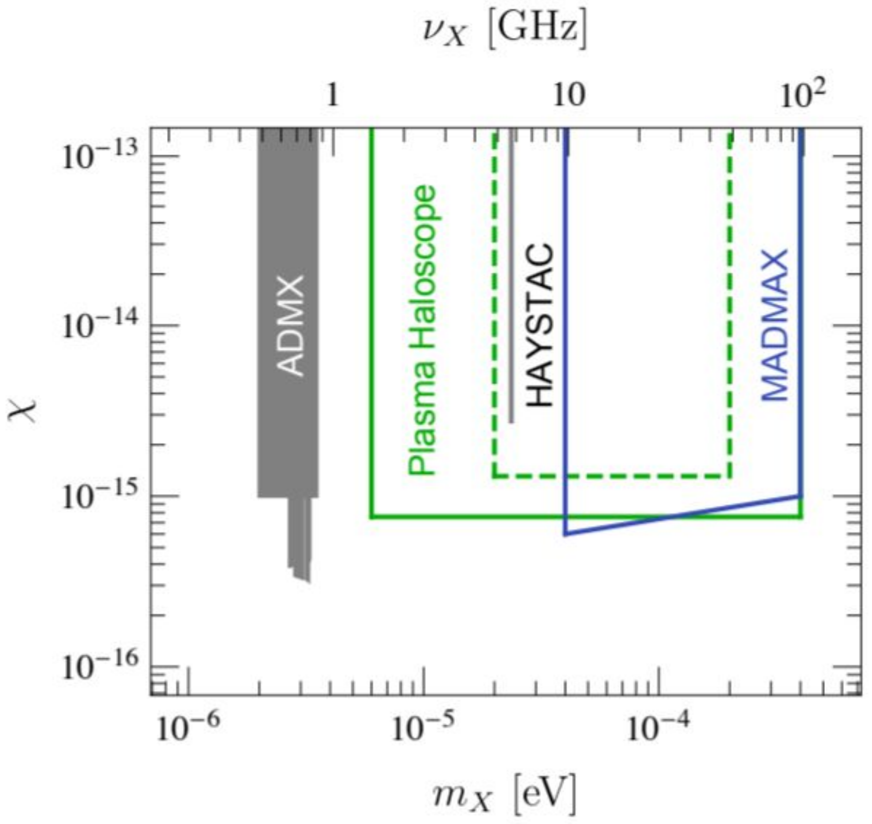
- Relate output power to readout signal/noise ratio (radiometer):

$$\frac{S}{N} = \frac{P}{T_{\rm sys}}\sqrt{\frac{\Delta t}{\Delta\nu_{\rm DP}}}$$

[Gelmini, Millar, **VT**, Vitagliano, 2020]

Dark Photon in Plasma Haloscope

- Do not need B-field for DP
  → tunable plasma haloscope design less restrictive and can probe even larger DM parameter space than for axions !

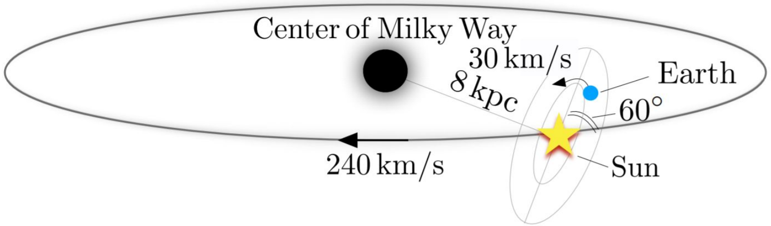


[Gelmini, Millar, **VT**, Vitagliano, 2020]

DP Signal Modulation

- Earth motion w.r.t. Galaxy induces signal annual (& smaller daily) **modulation** in detector

- If DP DM is clumped
  → amplitude erratically modulated



- If DP vector field is aligned,
  Earth's rotation induces modulation in anisotropic detectors
  → another distinction with axions

- Observing modulation is key to confirming detected signal is DM
  → could shed light on production mechanism

[Gelmini, Millar, **VT**, Vitagliano, 2020]

What about scalars?

Scalar In-Medium Effects

- Scalars are simplest extension of SM, many expected from top-down theories, can contribute to DM

- While previously neglected, in analogy to DP, scalar-plasmon mixing also possible and hence in-medium effects will affect direct detection proposals

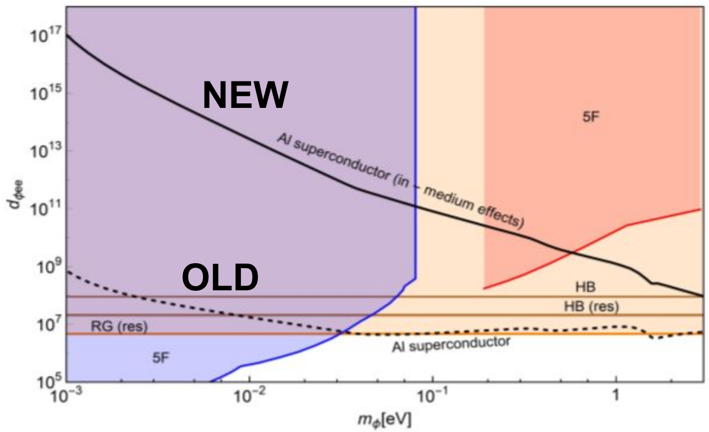
**** scalar in-medium effects noted for astrophysical sources* [Hardy, Lasenby, 2016]

[Gelmini, **VT**, Vitagliano, 2020]

Scalar In-Medium Effects

- Signal rates suggested in proposals for light DM detection could be significantly suppressed

- Example: semiconductors
  [Hotchberg, Lin, Zurek, 2016]



- Mitigating in-medium effects
  - be far from resonance (e.g. boosted DM)
  - exploit the resonance, *tunable plasma haloscopes*

[Gelmini, **VT**, Vitagliano, 2020]

Conclusions

- Many new ideas for direct DM detection, without established observation and significant theory uncertainty important to broadly explore parameter space

- Large DM experiments → "effective neutrino telescopes"

- Light bosonic DM is well motivated
  → newly proposed tunable plasma haloscopes address limitations of other proposals and excellent DP detectors

- Previously neglected scalar in-medium effects could significantly impact signal rates in experiments
  → highlights proposals like tunable plasma haloscopes as highly effective