

Extreme Astrophysical Laboratories for New Physics:

From Black Holes to Quantum Sensors

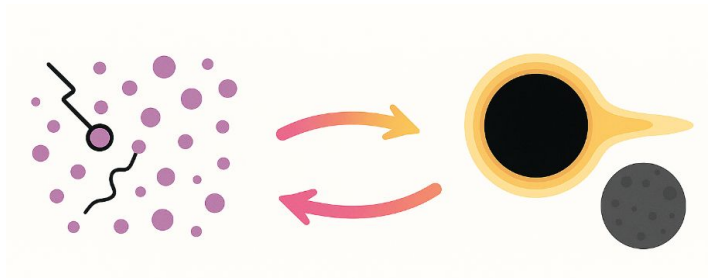
Volodymyr Takhistov

QUP & Theory Center, KEK / SOKENDAI / Kavli IPMU, U. Tokyo



Bridging Macroscopic and Microscopic Worlds

- Fundamental physics can leave distinct and amplified imprints in extreme astrophysical systems
- Macroscopic objects like black holes, dark stars, axion structures and others can serve as unique laboratories
- Multimessenger signals provide diverse probes across scales
- New observables, including with quantum sensing, open novel detection channels

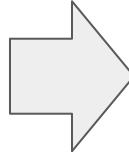


From Extreme Environments to New Observables

- Can exploit amplification in nature, signal structure and new degrees of freedom to gain insights into new physics regimes

Source / Environment

- astrophysical amplification
- structured signal emission

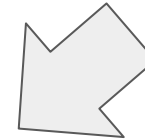


Messenger / Propagation

- spectra / timing
- coherence/interference
- signal distortions

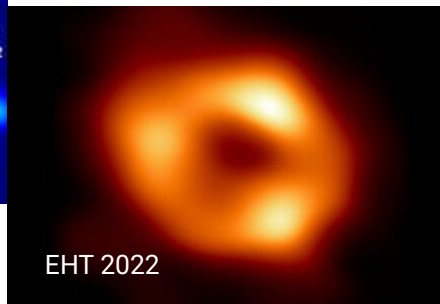
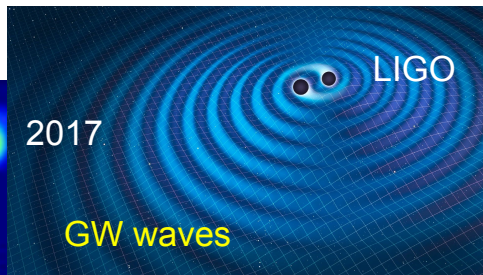
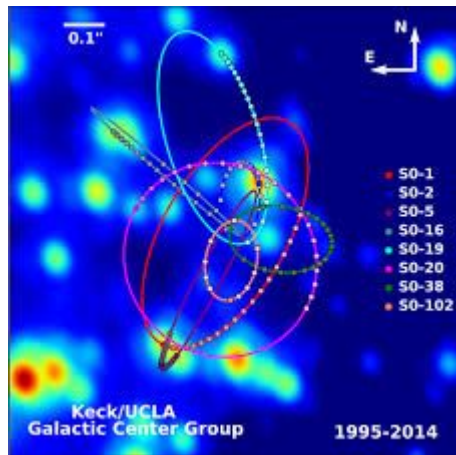
Observables / Detector / Analysis

- correlations
- internal states
- signal topology
- detector configuration

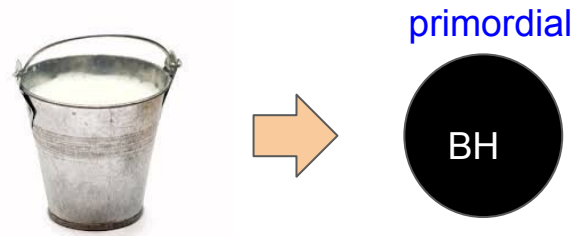


Black Holes **Exist, Can Form in Early Universe**

- Black holes not just theoretical objects. Observed astrophysical laboratories, besides astrophysical pathways can also originate from the early Universe (many mechanisms....)



In early Universe, can roughly take scoop of large overdensity and make BH



Zel'dovich, Novikov, Hawking, Carr ...
~ 50 years ago

PBHs as dark matter (DM)

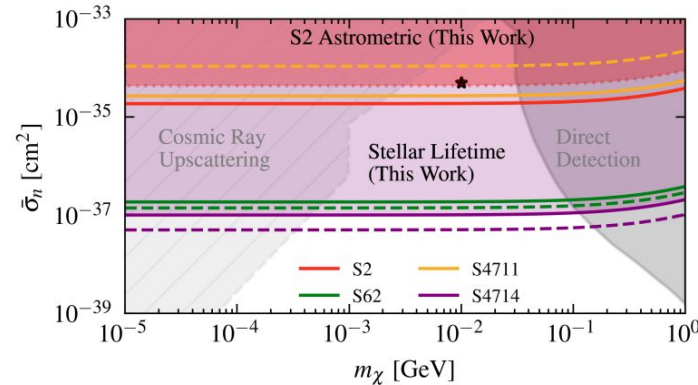
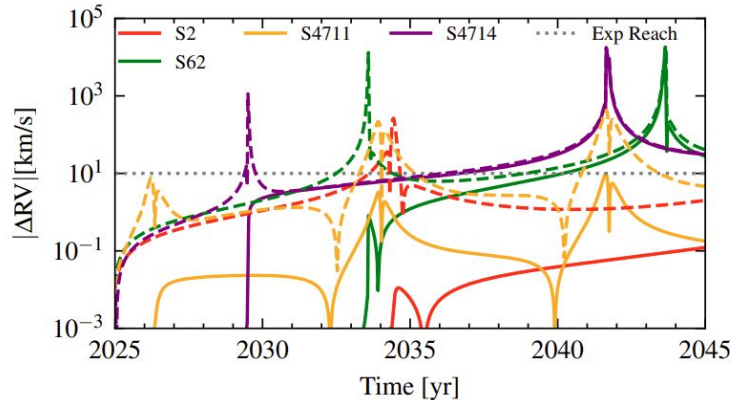
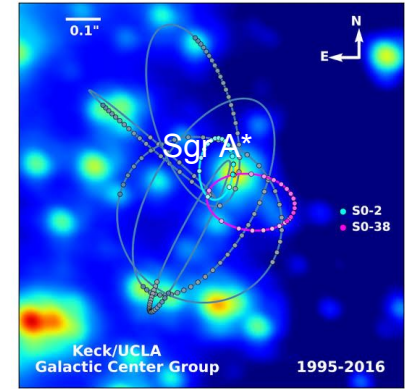
– possibility within standard gravitational physics

Many Weak Interactions Can Create Macroscopic Effects

- **Amplification I:** accumulation of many weak interactions
→ many DM particle scatterings can affect dynamics of stars
- Create new force on stars in DM-rich environment such as Galactic Center near supermassive black hole (SMBH) Sgr A*
- *Observables:* modified stellar orbits, decay of orbits over time

can be stronger than gravity

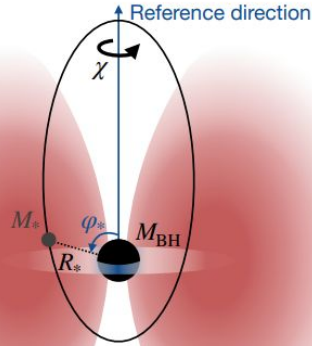
$$\mathbf{F}_{\text{scat}} = \pi R_s^2 \frac{\rho_\chi}{m_\chi} v_s \int \langle \mathbf{p}_{\text{SM}} \rangle f(\mathbf{v}_\chi) d^3 \mathbf{v}_\chi$$



** considering DM overdensity spike*

[Gustafson, Shoemaker, Takhistov, 2510.07387 (2025)]

Growth Around Compact Objects: Superradiance



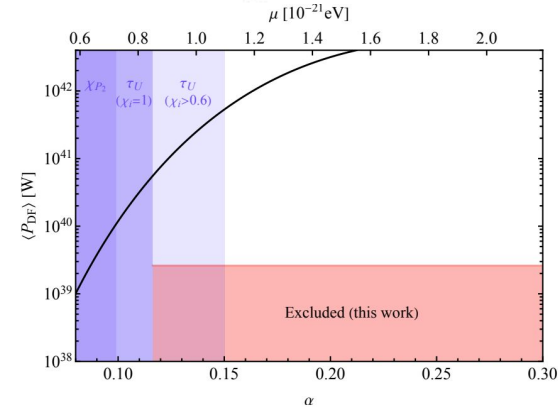
- **Amplification II:** coherent growth around compact objects
- Spinning BHs can amplify boson superradiance [Zel'dovich, 1971; Press, Teukolsky, 1972] $r_c \sim r_S$
→ formation of long-lived bound “gravitational atom” states
- Dynamical friction from boson clouds in SMBH binaries can enhance orbital decay beyond GW emission

$$\langle P_{\text{GW}} \rangle = -\frac{32m_r^2 M_t^3}{5a^5} (1-e^2)^{-7/2} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4 \right) \text{ vs. } P_{\text{DF}} = \frac{4\pi q^2 M_{\text{BH}}^2}{v} \rho_{nlm}(x_*, \theta_*) C_\Lambda$$

- **Excellent test site:** OJ287, 120 yr observed SMBH binary
 - Require deviations from GR < 1% [Deb+, ApJL, 2025]

$$\mu \simeq (8.5 - 22) \times 10^{-22} \text{ eV}$$

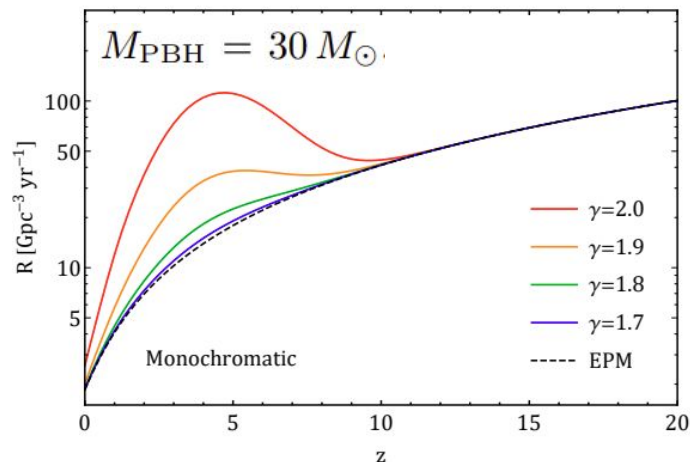
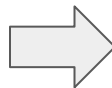
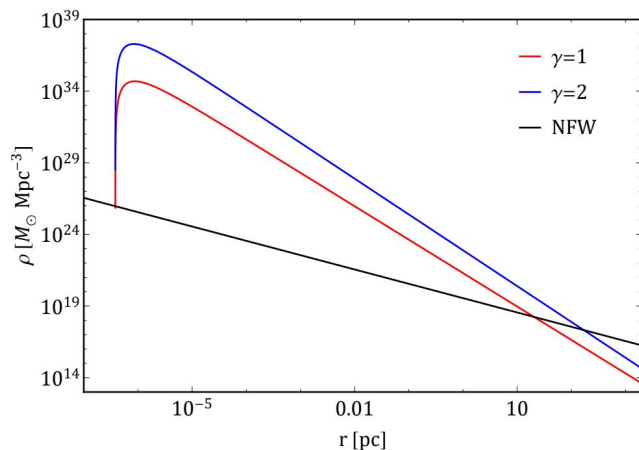
- Superradiant clouds can drive final-parsec evolution
- **New feature: GW turnover** when orbit enters Bohr radius



[Ding, He, VT, Zhu, *Phys.Rev.D* (2025)]

Astrophysical Environments Shape Object Populations

- **Amplification III:** environmental enhancement of populations, can be time dependent
- SMBHs in galaxy centers, many new observations by JWST
- DM dynamics in vicinity expected to be modified → DM overdensity “spikes” [Gondolo, Silk, 1999]
- For PBH DM mergers significantly affected [Nishikawa+, 2017], including distinct redshift evolution



[Ding, He, Takhistov, *Astrophys.J.*, (2024)]

Compact Objects as Dark Matter Detectors

- Compact objects themselves can become “detectors”. **Examples:** complementarity from different considerations - capture, conversion, heating, etc.

PBH capture on stars

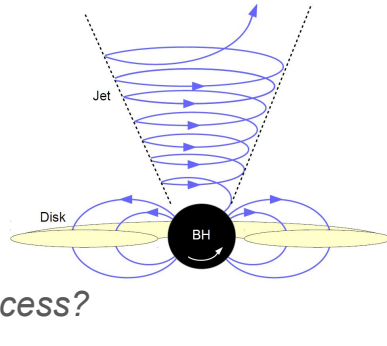
Transmuted
(sub)solar-mass BHs

[Takhistov, *Phys.Lett.B* (2019)]

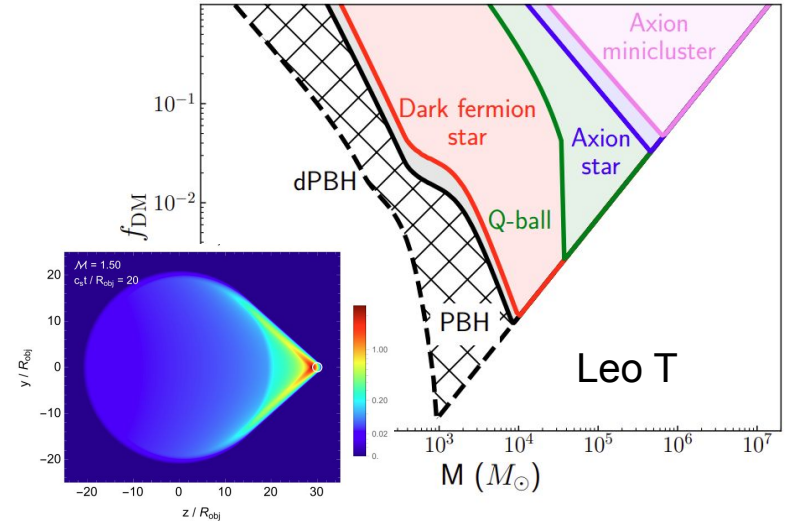
[Takhistov, *Phys.Lett.B*, (2018)]

kilonova, positrons, FRB, *r*-process?

[Takhistov+, *Phys.Rev.Lett.*, (2020)]



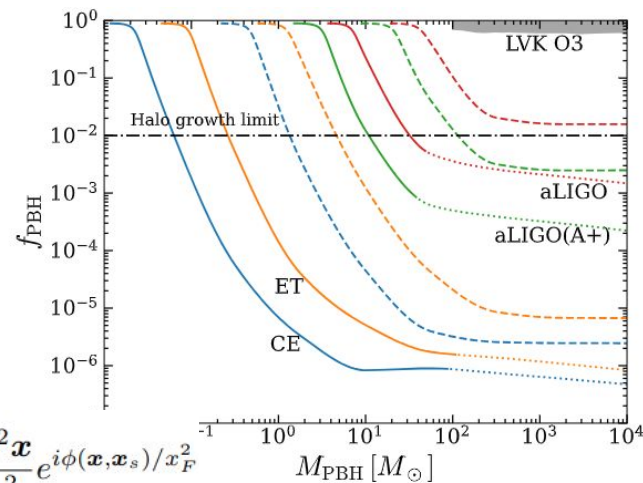
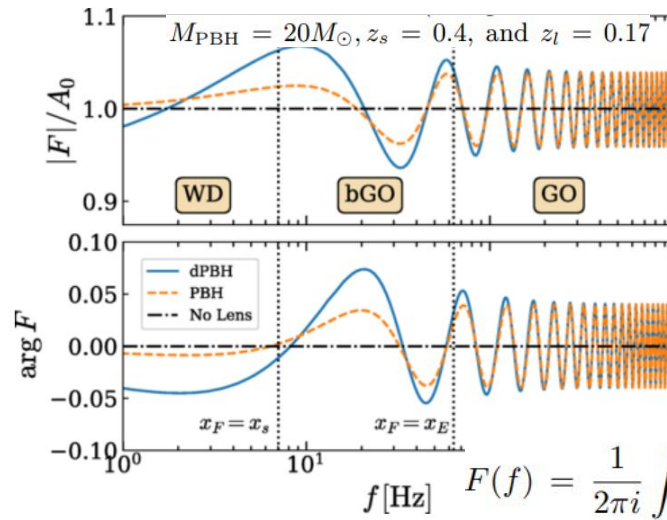
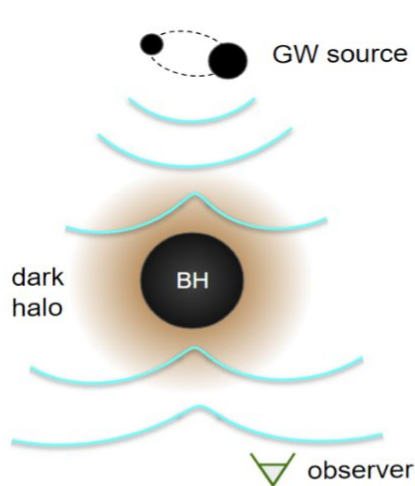
Gas heating by compact objects
(dynamical friction, jets, etc.)



[Lu, Takhistov+, *Astrophys.J.Lett.*, (2020);
Takhistov+, *JCAP*, (2021); Takhistov+, *MNRAS
Lett.*, (2022), Kim, Lu, Takhistov, *JCAP* (2026)]

Patterns in Signals Can Reveal Dark Matter Structure

- Compact objects can harbor hidden structure → signal patterns can reveal
- Gravitational wave lensing effects enable “scanning” over frequencies



- Can break degeneracy of bare PBH vs. DM halo-dressed PBH, single event detection possible
→ ~ **definitive general probe of numerous particle + PBH DM scenarios**

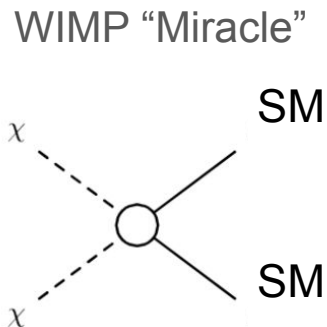
[Choi, Jung, Lu, Takhistov, *Phys.Rev.Lett.* (2024)]

Black Holes as Portals: Gravity Connects Hidden Sectors

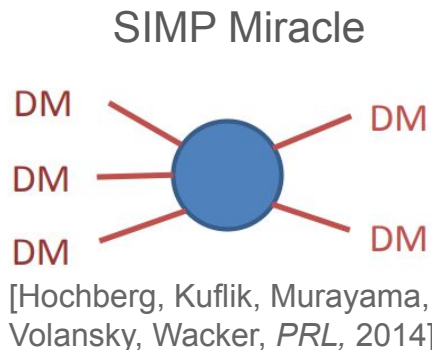
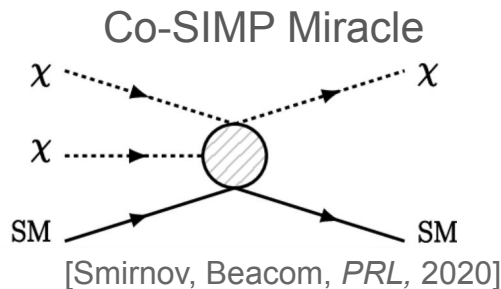
- Black holes enable gravitational connections between hidden sectors

conventional particle DM relies on interactions

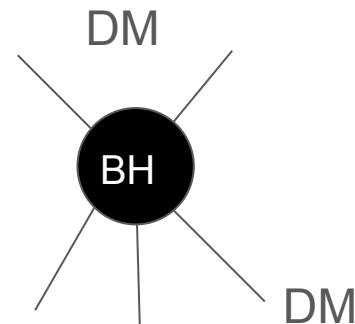
Ex.)



abundance set
by annihilation



unconventional general idea:
Regurgitated DM



BH “scrambles”, re-emits DM with new properties, doesn’t rely on interactions
[Kim, Lu, Marfatia, Takhistov, *PRD Lett.*, (2024)]

**** evaporation dynamics also imprints on gravitational waves** [He, Ma, Sasaki, Takhistov, arXiv:2606.09804 (2026)]

Formation of Objects Can Encode Insights to Microphysics

- Macroscopic compact object properties can lead to potential insights on microphysics
- **Example 1:** QCD strong force tested in limited regimes, in SM confines $\lesssim \text{GeV}$
- Dynamics readily modified in new theories, **high-T transitions** (1st order) are natural w/ scalars

[Ipek, Tait, PRL, 2018]

$$\mathcal{L} \supset -\frac{1}{4} \left(\frac{1}{g_{s0}^2} + \frac{S}{M} \right) G_{\mu\nu}^a G_a^{\mu\nu} + \dots \quad \Lambda(\langle S \rangle) = \Lambda_0 \text{Exp} \left[\frac{24\pi^2}{2N_f - 33} \frac{\langle S \rangle}{M} \right]$$

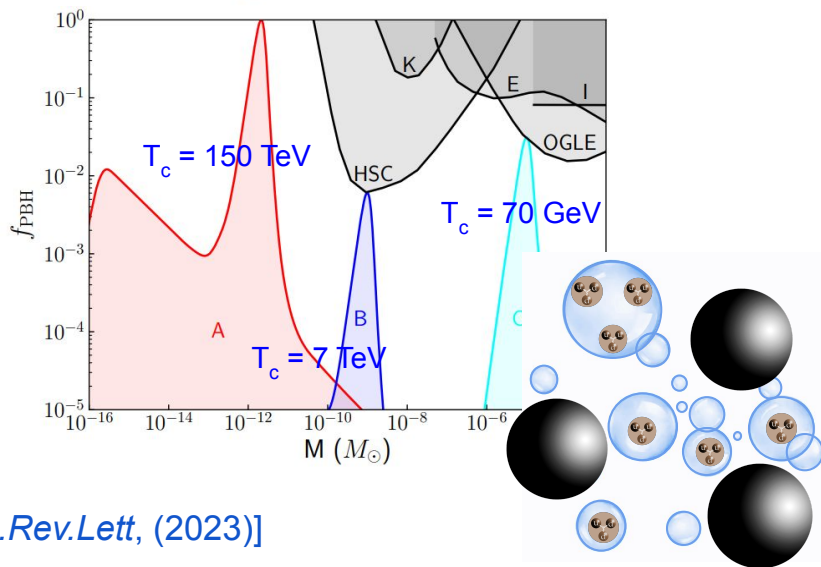
- **How to test?** enhanced collapse $\rightarrow$ PBHs

$$M_H \sim 5 \times 10^{-10} M_\odot \left(\frac{T}{10 \text{ TeV}} \right)^{-2}$$

$\rightarrow$ can be all DM, unlike SM QCD-type PBHs

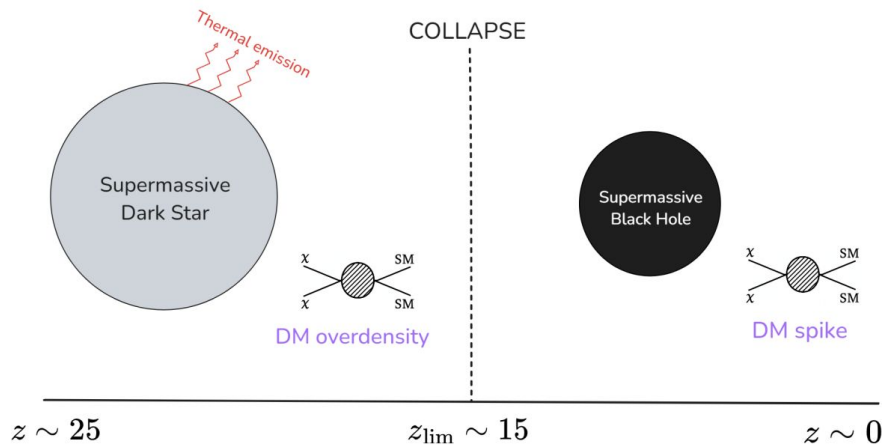
- **Example 2:** PBHs with potential spin from scalar field fragmentation, e.g. oscillons [Cotner, Kusenko, Takhistov, PRD (2018); Cotner, Kusenko, Sasaki, Takhistov, JCAP (2019)]

[Lu, Takhistov, Fuller, *Phys.Rev.Lett*, (2023)]

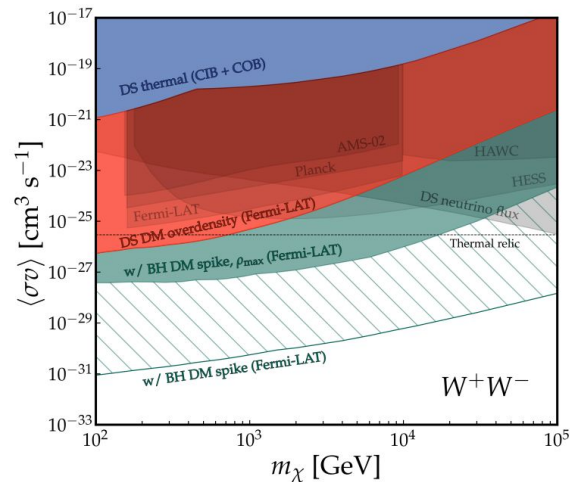


Multimessenger Signals Can Probe DM Origin of First Stars

- Earliest stars could be “dark stars” supported by dark matter heating instead of fusion [Spolyar, Freese, Gondolo, *PRL* (2008)]
- Dark stars can be significantly bigger ($\sim 10^6 M_\odot$) than Population III stars
- Upon collapse $\rightarrow$ early massive seeds for supermassive black holes
- Candidates seen in JWST at redshifts $z \sim 11-14$? [Ilie, Paulin, Freese, *PNAS* (2023)]

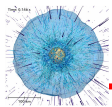


first multimessenger constraints: ν 's, γ 's..



[Schwemberger, Takhistov, *Astrophys.J.Lett*, (2025); Manno, Schwemberger, Takhistov, *JCAP* (accepted) (2026)]

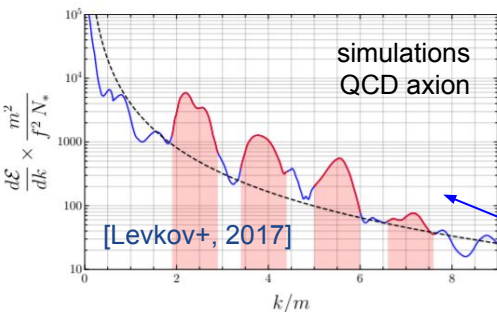
Transients Can Give Unique Insights to Fundamental Physics



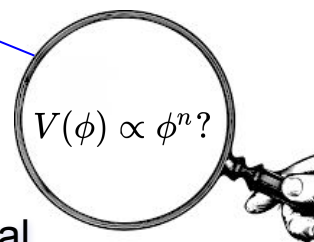
v Burst
v Diff. Back.



Axion/Boson Burst
Axion/Boson Diff. Back.



axion star
explosions
→ *relativistic*
axions

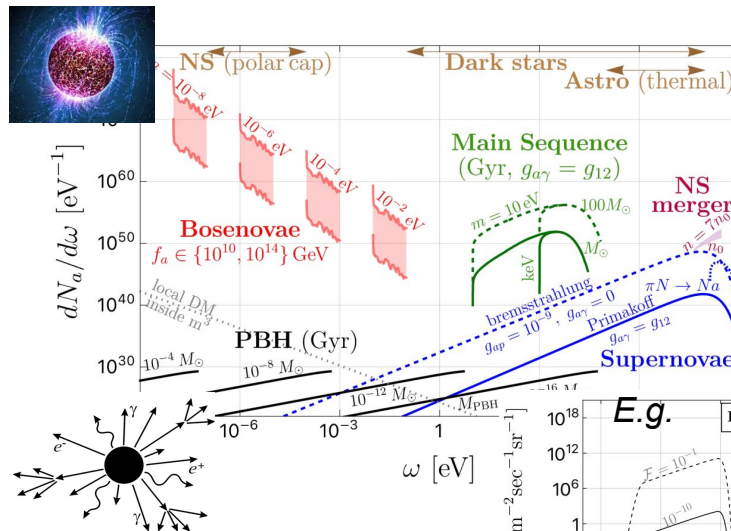


● Spectrum can provide
insights into fundamental
field potential

[Eby, Shirai, Stadnik, Takhistov, *PLB*, (2021)]

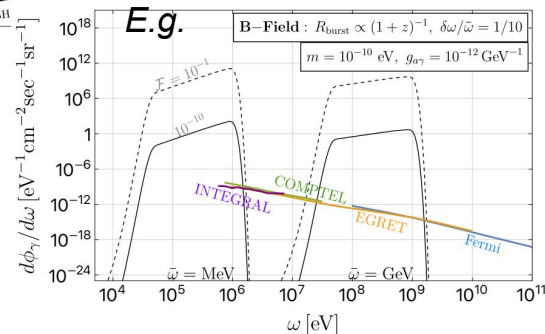
Macroscopic ↔ microscopic connection

many sources can contribute *diffuse axion*
background: astro. vs dark sector

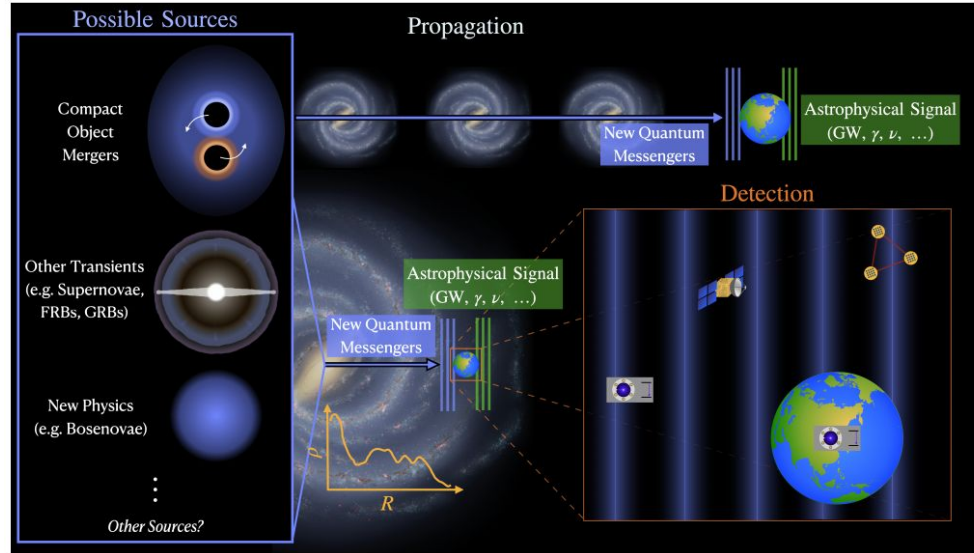
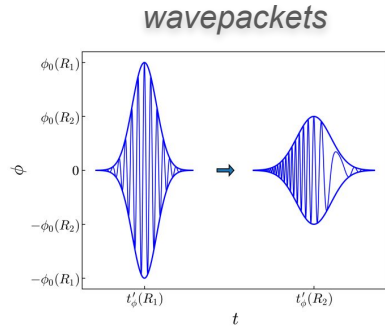


unified
framework

[Eby, Takhistov,
(2024) 2402.00100]



Quantum Sensor Networks as Multimessenger Receivers



sensor network is not just larger effective exposure, can enable: *coincidence, timing, directionality, noise discrimination*

correlate multiple messengers:
GWs, γ , ν , + new ϕ

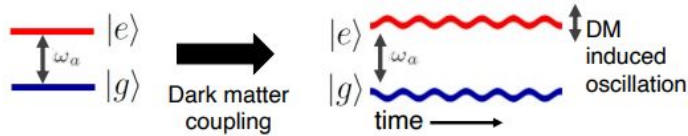
- Framework extends naturally to distributed quantum sensor networks (e.g. GNOME)
- Space and Earth based networks can detect transient and continuous field signals (early phenomenological coincidence analysis [Dailey+, *Nat. Astron.*, 2021])

[Arakawa, Eby, Safronova, Takhistov, Zaheer, *JCAP* (2023); *JCAP* (2025)]

New Multimessenger Astronomy with Quantum Sensors

- Emitted fields can induce fundamental variations

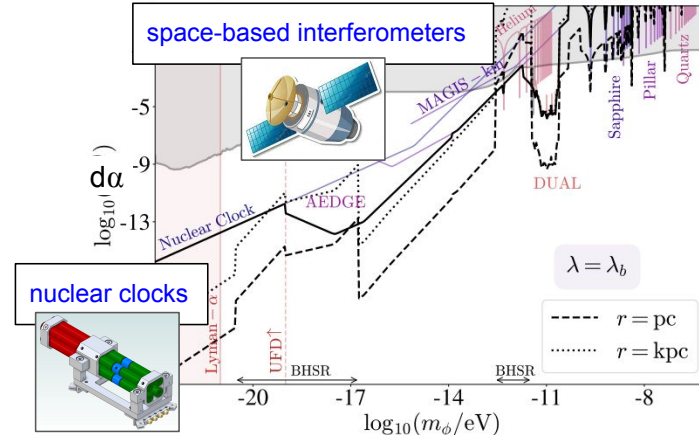
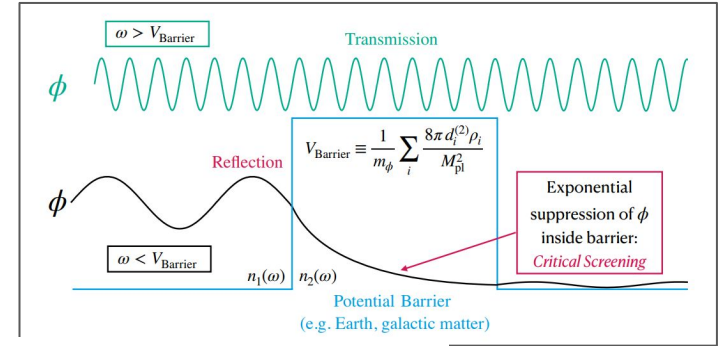
including dark matter



$$\mathcal{L} \supset \kappa \phi \left(\underbrace{d_{m_e} m_e \bar{e} e}_{m_e/m_p} + \underbrace{\frac{d_\alpha}{4} F_{\mu\nu} F^{\mu\nu}}_{\text{fine structure } \alpha} + \underbrace{\frac{d_g \beta_3}{2g_s} G_{\mu\nu}^A G^{A\mu\nu}}_{\text{strong coupling } \alpha_s} \right)$$

- Different operator couplings map onto distinct precision platforms

example



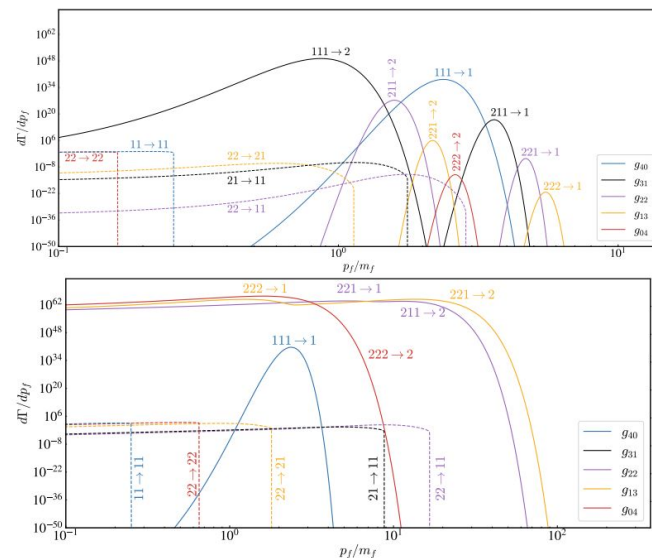
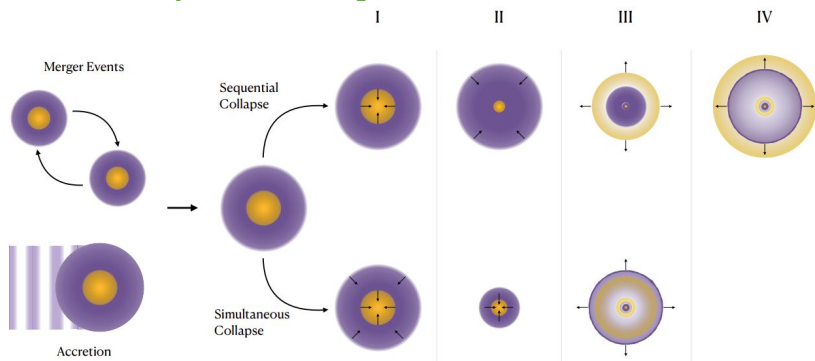
*if environmental screening
→ space can help*

[Arakawa, Eby, Safronova, Takhistov, Zaheer, *JCAP* (2023); *JCAP* (2025)]

Multiple Fields Can Qualitatively Change the Picture

Example: multi-axion bosenovae

- Many theories beyond Standard Model predict multiple axion-like fields
- Multi-axion bosenovae can have multiple bursts that trigger one another, unusual spectra and time-scales are possible
→ can be exploited by network of sensors

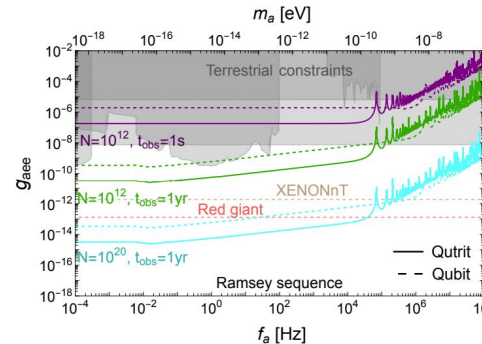
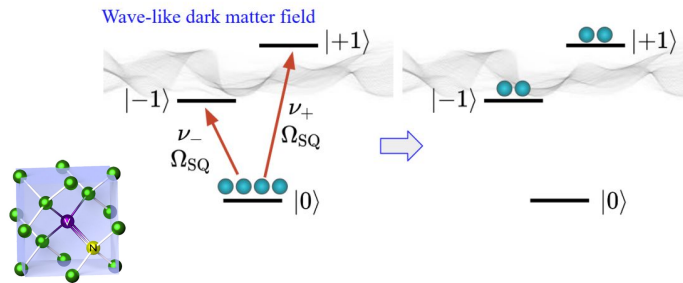


- Complementarity with distinct effects on laboratory searches [de Giorgi, Jaeckel, Monath, Takhistov, JHEP (accepted), (2026)]

[Arakawa, de Giorgi, Takhistov, *in preparation*]

Beyond Qubits: Can Exploit Quantum Structure for New Physics

- Many quantum sensor searches for weak fundamental physics signals are based on 2-state qubits
- Quantum systems often have many levels, established multilevel systems can use 3-state qutrit (qudit) structure to improve sensitivity, access new regimes, discriminate noise
- Case study: NV diamond magnetometry and ultralight DM searches



*Up to an order of magnitude
sensitivity gain possible over
qubit protocols*

- Framework is general and can be applied to other multilevel quantum sensing platforms for fundamental physics searches → quantum states can add new analysis dimensions

[Ma, Takhistov, Mizuochi, Herbschleb, *Phys. Rev. A Lett.* 113 (2026) 6, L060802]

Conclusions

- Microscopic physics is often too weak to see directly, extreme astrophysical systems can amplify weak effects into observable signals and inform us what kind of detectors to consider
- Compact objects provide unique laboratories for dark matter and new fields
- Black holes connect formation, evolution, and hidden-sector physics
- Multimessenger observations and quantum sensors open new detection channels
- Future discoveries may come from exploiting new amplification mechanisms, signal structures, and detector degrees of freedom