The Sound of the Universe: A Resonant Gravitational Instability Driven by Baryon-Dark Matter Relative Drift

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MS+Broderick: arXiv:2604.22665

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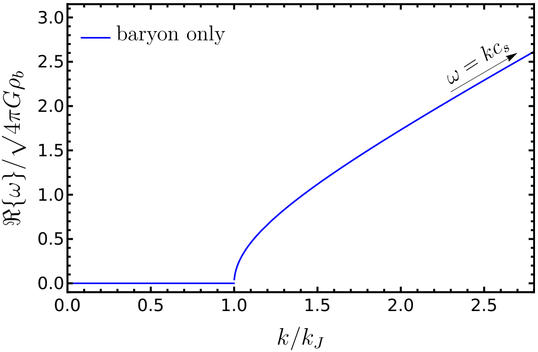
The New Fundamental Mechanism: SBI

"A resonant gravitational instability driven by the relative streaming of baryons and dark matter."



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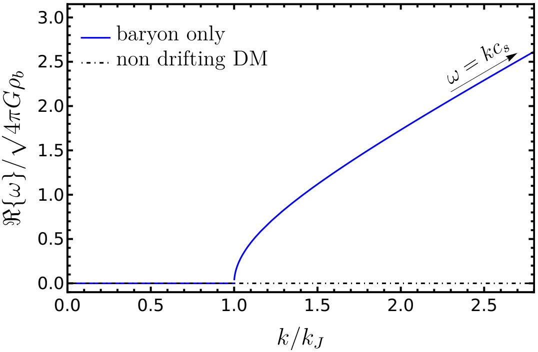

Solar neighborhood: $1/\Omega_{\rm DM} \sim 3 \times 10^8$ yr

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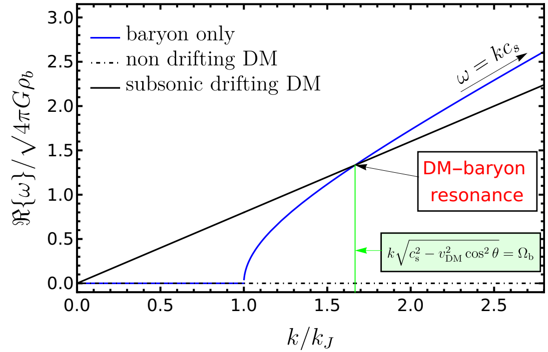

Slope = Projected DM velocity along k-direction. $v_r \equiv v_{\rm DM}\cos\theta/c_s$

Resonance: same ω at the same $k \Rightarrow$ **Shalaby-Broderick instability (SBI)**

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Key Findings – Summary

Relative drift is a direct consequence of the standard ΛCDM model

$\Rightarrow$ **Shalaby-Broderick instability (SBI)**

1. **Resonant instability** when projected drift subsonic ($v_{\rm DM} \cos\theta \leq c_s$).
2. **Stable window** between Jeans scale and resonance (baryon-dominated).
3. **Supersonic suppression –** unifies known effect (Tseliakhovich & Hirata 2010).

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5. **Energy & Momentum exchange** $\rightarrow$ collisionless drag.
6. **Broad impact** from planets to galaxy clusters, growth times $\ll$ ages.
   - A new lens on the interaction of dark and visible matter across all scales.
   - Sound waves in baryons, excited on timescales $\ll$ system ages.
7. **Cosmology** impacting the growth of (baryons) cosmological linear perturbations.

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Using Gravity, Not the Weak Force

...because gravity is coherent, and coherence amplifies.

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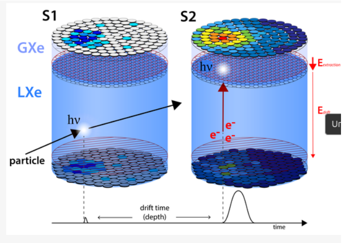
Direct DM Detection: The Standard Paradigm

Traditional searches look for rare, particle-level interactions (WIMP-nucleon scattering).

Example: XENONnT (Aprile et al. PRL 131, 041003; 2023)

- **S1:** Prompt scintillation flash from nuclear recoil.
- **S2:** Secondary flash from ionized electrons.
- Time between flashes ⇒ 3D position.
- Brightness ratio ⇒ DM vs. background discrimination.



Current limit: cross section $< 2.85 \times 10^{-47}$ cm^2 ($m_{\rm DM} = 28$ GeV).

The gold standard. But it relies on the *weak* force.

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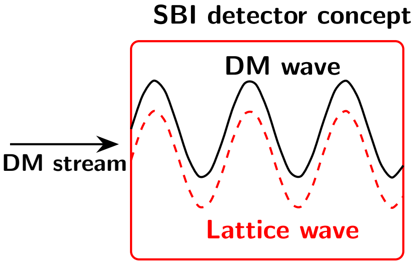
Direct DM Detection: The Idea



Coherent wave-wave resonance

DM stream ↔ lattice vibrations
Same wavelength ⇒ resonant energy transfer

Key Idea: A coherent DM wave resonantly couples to the lattice vibrations of a solid target, driving narrow-band vibrationals oscillations.

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Gravity is Weak — But Coherent

Gravity is weak per nucleon: $\alpha_G = \left(\frac{m_p}{M_{\rm Pl}}\right)^2 \sim 6 \times 10^{-39}$

Weak force per nucleon: $\alpha_W = G_F m_p^2 \sim 10^{-5}$

$$\Rightarrow \frac{\alpha_W}{\alpha_G} \sim 10^{32}$$

Coherent amplification:

$$\alpha_G^{\rm macro} \sim N^2 \alpha_G, \quad N = \frac{M}{m_p}$$

For a 1 kg target:

$$N \sim \frac{10^3 \text{ g}}{1.6 \times 10^{-24} \text{ g}} \sim 6 \times 10^{26}, \quad N^2 \sim 4 \times 10^{53} \Rightarrow \alpha_G^{\rm macro} \sim 10^{15}$$

Conclusion: $m_p \to \text{kg} \Rightarrow \alpha_G \sim 6 \times 10^{-39} \times (\text{kg}/m_p)^2 \sim 10^{15}$
20 orders of magnitude stronger than weak force per nucleon.

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Equivalent Cross-Section

XENONnT-type search:

$$\sigma < 2 \times 10^{-48}\ \text{cm}^2 \quad (m_{\rm DM} = 30\ \text{GeV})$$

SBI detector: Effective cross-section

$$\boxed{\sigma_{\rm eff} \equiv \frac{\Gamma_{\rm res}}{n_{\rm DM}\, v_{\rm rel}}}$$

For lattice density $\rho_{\rm lattice} \sim \text{kg/L}$ and $\rho_{\rm DM} \sim 0.4\ \text{GeV/cm}^3$:

$$\sigma_{\rm eff} \sim 2 \times 10^{-28} \left(\frac{m_{\rm DM}}{\text{eV}}\right)\ \text{cm}^2$$

$m_{\rm DM}$	$\sigma_{\rm eff}$	$\sigma_{\rm eff}/\sigma_{\rm XENONnT}$
1 eV	$\sim 2 \times 10^{-28}\ \text{cm}^2$	$\mathbf{10^{20}}$
1 GeV	$\sim 2 \times 10^{-22}\ \text{cm}^2$	$\mathbf{10^{26}}$

This is a coherent, collective effect — not a particle-level scattering cross-section.

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Example: Tungsten Lattice

Tungsten @ room temperatures

$$\rho_{\rm lattice} = 20 \text{ kg/L}, \quad c_1 = 5.2 \text{ km/s}, \quad \lambda_J \sim 8,000 \text{ km}$$

wavelength	$v_{\rm DM} \cos\theta / c_1$	$T_{\rm res}$	$\lambda_{\rm res}$	$\omega_{\rm res}/\Gamma_{\rm res}$
Long (2e-10 Hz)	$\sim 10^{-7}$	~ 18 yr	$\sim 1.5 \times 10^6 \; c_1$ sec	~ 0.12
Short (0.3 Hz)	~ 0.9999	~ 14 kyr	$\sim 2.2 \times 10^4 \; c_1$ sec	$\sim 1.3 \times 10^{11}$

Challenge: Short wavelengths grow slowly (10^4 yr).
Solution? 'Long' wavelength with reduced c_1: aerogels/metamaterials/cooling to shrink $\lambda_{\rm res}$.

$$c_1 = 0.1 \text{ cm/sec} \Rightarrow \lambda_{\rm res} = 1.5 \text{ m} \;\&\; T_{\rm res} = 18 \text{ yr}$$

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SBI detector: A promising idea for cheap DM direct detection

with a novel, robust mechanism: coherent gravitational resonance **SBI**

Questions I didn't have time to discuss today

1. Impact of lattice impurities/noise (thermal, structural, etc.)
2. Sensitivity needed for seismometer
3. Timescale for growth vs. orientation modulation (earth motion)
4. Other sources, e.g., GeV CRs $\rho_{\rm cr} \sim 10^{-9} {\rm GeV/cm^3}$

A tabletop detector that listens to dark matter's gravitational hum — continuous, coherent, and guaranteed by gravity.
No weak coupling required.
No EM coupling required.

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The Sound of the Universe:

A New Way to Listen to/Detect Dark Matter

- First comprehensive analysis of the resonant gravitational instability from DM–baryon relative drift.
- Short timescales – from tens of kyr (planets) to hundreds of Myr (clusters).
- New observational window into the dark sector.

Thank you for your attention

Full paper: Shalaby & Broderick arXiv:2604.22665

Backup slides

Roadmap: Building the Detector

What would it take to build this?

Step 1: Materials

- Low c_s ($\lesssim 1$ km/s)
- High Q (low damping)
- Candidates: aerogels, foams, metamaterials

Step 2: Design

- Geometry (sphere, cylinder)
- Instrument with accelerometers or interferometry
- Shield from seismic noise

Step 3: Search

- Look for narrow-band peak
- Directional signature (θ dependence)
- Smoking gun: frequency tracks DM stream direction

The Payoff: A tabletop detector that listens to dark matter's gravitational hum — continuous, coherent, and guaranteed by gravity. No weak coupling required.

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Signature in Large-Scale Structure

- Resonant only at $k > k_J$ for $v_{\rm DM} \cos\theta < c_s$
- Jeans scale $k_J = 100/{\rm Mpc}$ $(z > 500)$ — $1000/{\rm Mpc} (z = 0)$
- Relative drift $v_{\rm DM}/c_s = 5$ $(z = 1000)$ — 2 $(z = 0)$

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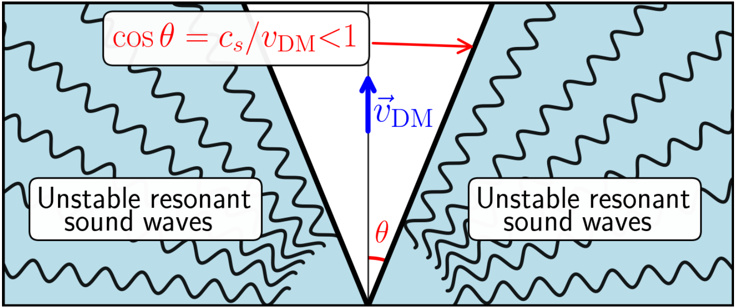

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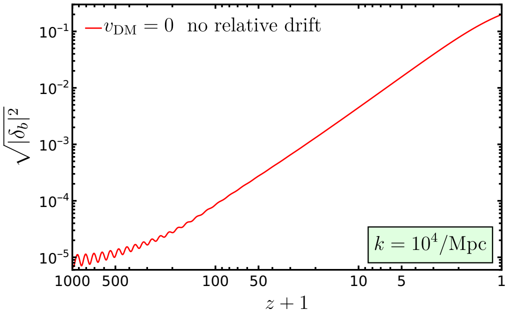
Cosmological Evolution – Baryon Perturbation Growth



Baryon perturbation δ_b at $k = 10^4$ Mpc^{-1}.

- Stable baryon perturbation growth since DM unstable $\rightarrow \delta\Phi \Rightarrow \delta_b$ growth

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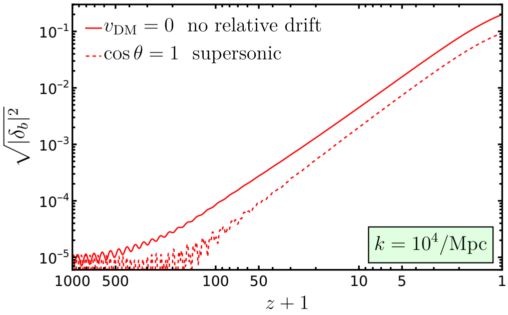

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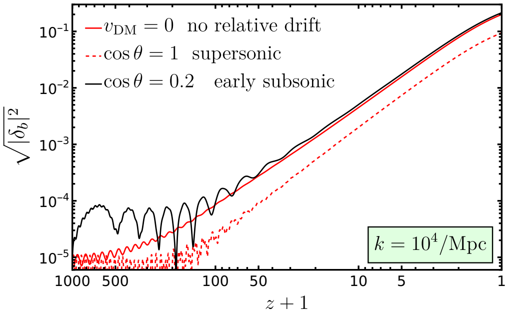

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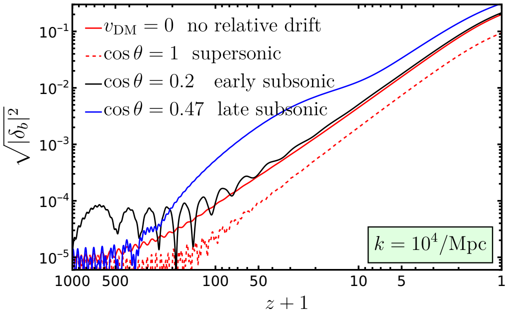

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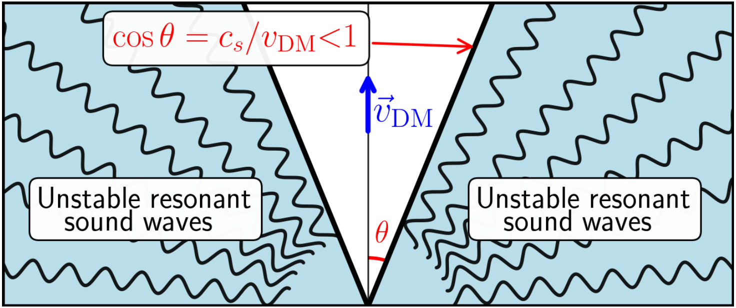
Anisotropy in Large-Scale Structure



The large-scale structure is not isotropic with respect to the primordial DM flow.

- Anisotropy imprinted on 21 cm signal and distribution of early galaxies (or Pop III stars).
- Enhanced backreaction (collisionless drag) + enhanced δ_b $\Rightarrow$ impact Hubble tension.
- Larger baryon perturbation may impact σ_8 tension.

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Astrophysical Systems – Direct Implications

Punchlines: more details in the paper

- **Cooling flow problem in clusters:** DM-ICM drift drives sound waves that heat the intracluster medium, growth time $\sim$ cooling time.
- **Spiral arms in galaxies:** Resonance scale naturally gives multi-armed spirals; constant pitch angle; explains persistence.
- **GMCs:** Driven sound waves $\Rightarrow$ impact star formation inside
- **Seismic signatures:** Predicted vibrations in Continental glaciers, Earth (2 mHz), Moon, Sun (2.5 mHz) – might be hard to detect.

The instability provides a novel, external source of energy injection previously overlooked.

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A New Probe of Dark Matter

- The instability turns the relative motion of DM from a nuisance parameter into a **powerful diagnostic tool**.
- Specific scales and growth rates are sensitive to DM properties:
  - Sound speed (cold / warm / hot)
  - Local density
  - Coherence length (WIMPs vs. ultra-light)
- Opens new observational probes:
  - Seismic measurements in terrestrial bodies (Earth, Moon, ice sheets)
  - Galactic spiral structure (arm number, pitch angle)
  - 21 cm power spectrum anisotropies
  - Pulsar timing array jitter (~ 20 kHz)

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Regimes of Applicability & Future Work

- **Most robust for WIMP-like DM** (coherent over large scales, granularity negligible).
- Ultra-light DM (axions, fuzzy DM) requires separate treatment – granularity may suppress instability.
- Growth must be faster than coherence time and system age – satisfied for most environments in Table 1 (of the paper).
- **Future work:**
    - Quantitative modeling of spiral arms and cluster heating with simulations.
    - Detailed predictions for 21 cm power spectrum.
    - Experimental concepts for seismic detection.

"The sound of the universe is not just a metaphor – it is a potentially observable phenomenon."

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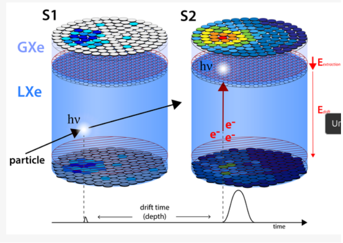
Direct DM detection using SBI

Traditional DM searches look for axion-photon conversion or nuclear recoils.

Example: XENONnT experiment (Aprile et al PRL 131, 041003; 2023)

- S1: A DM particle hits a xenon atom (liquid) ⇒ quick, tiny flash of light.
- S2: DM hit ⇒ loose electrons ⇒ float to the top layer and hit the gas ⇒ second, much brighter flash of light.



* measure the time between the two flashes to determine the loc. of the collision.

* Diff. in the brightness of the two flashes ⇒ DM or background radiation.

No signal ⇒ cross section $< 2.85 \times 10^{-47}$ cm^2 ($m_{\rm DM} = 28$ GeV) (Aprile et al PRL 131, 041003; 2023)

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