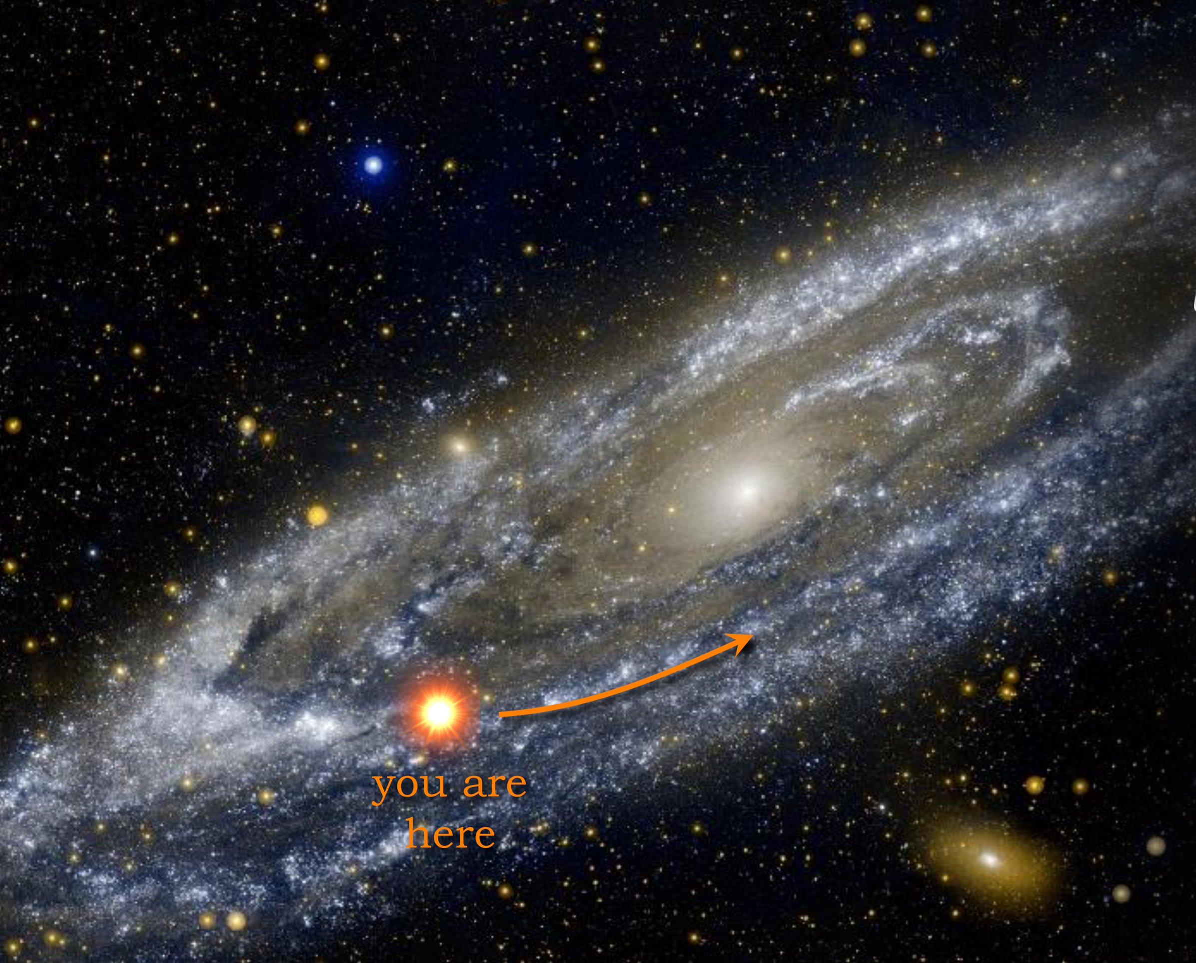
Pushing Experiment to the Planck Mass

Rafael F. Lang
Purdue University
rafael@purdue.edu

Mega Mainz May 2022

Direct Dark Matter Detection



local dark matter mass density is known:

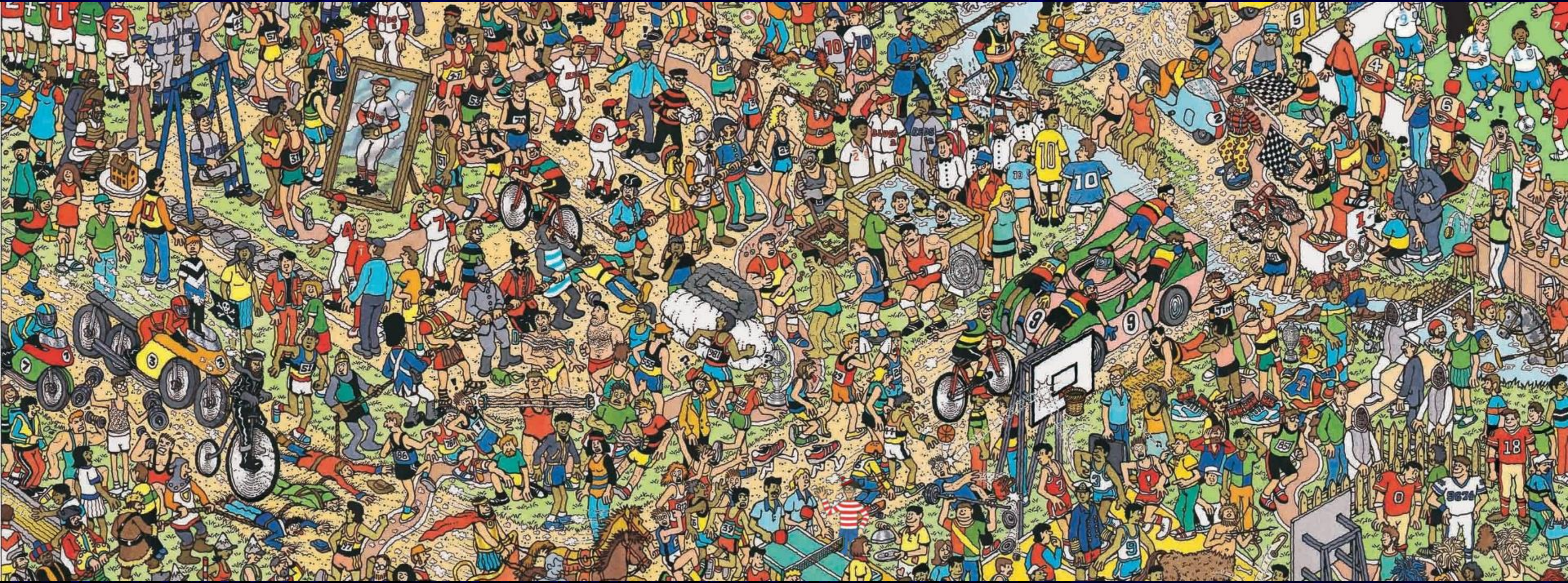
$$\varrho_{\mathrm{DM},\oplus} \approx 0.3\,\mathrm{GeV}/\mathrm{cm}^3$$

aim to detect non-relativistic wind of dark matter quanta (waves or particles)

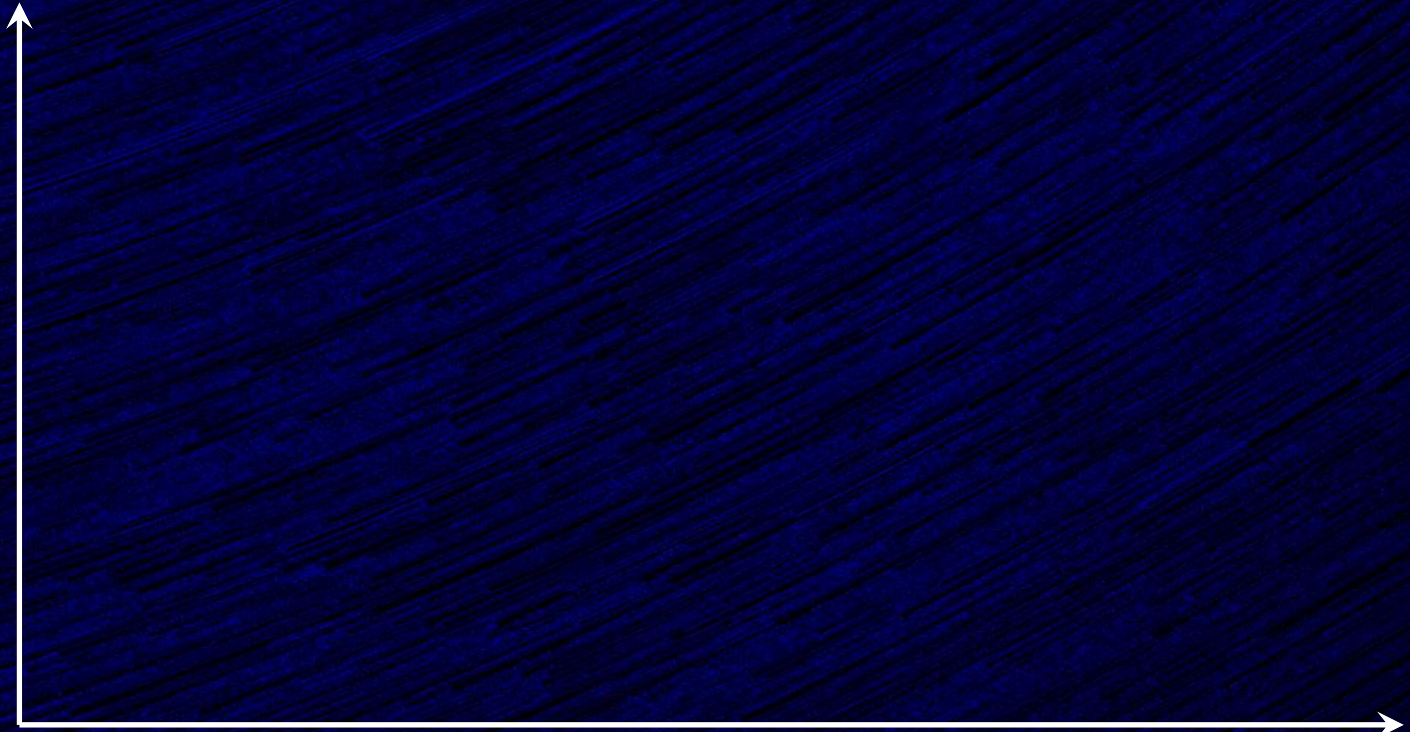
Possible Dark Matter Masses

~90 orders of magnitude

10^{-21}eV eV GeV PeV M_{Planck} kg 10^{50}eV $M_{\text{☽}}$ $M_{\odot}$



Fill Your Prior

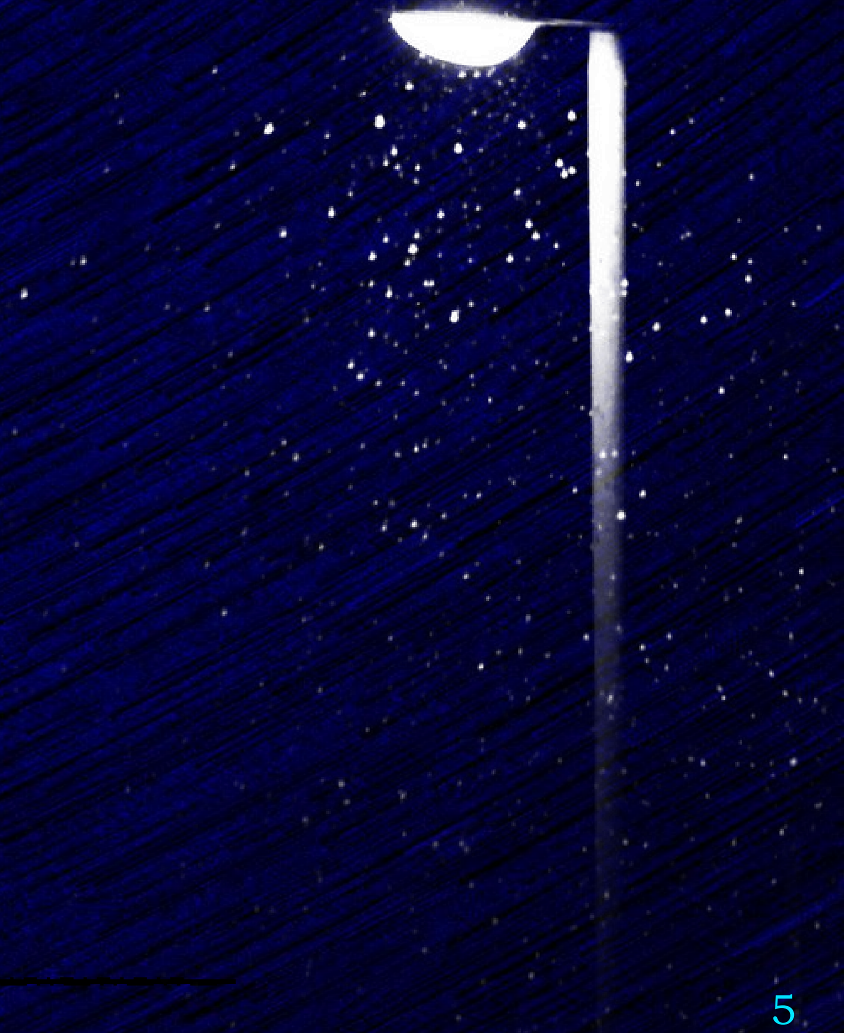


Two Approaches to Experiment

1) Search under the lamppost

Use existing experiment and/or existing data to search in some new corner of parameter space

✓ easy, cheap, quick



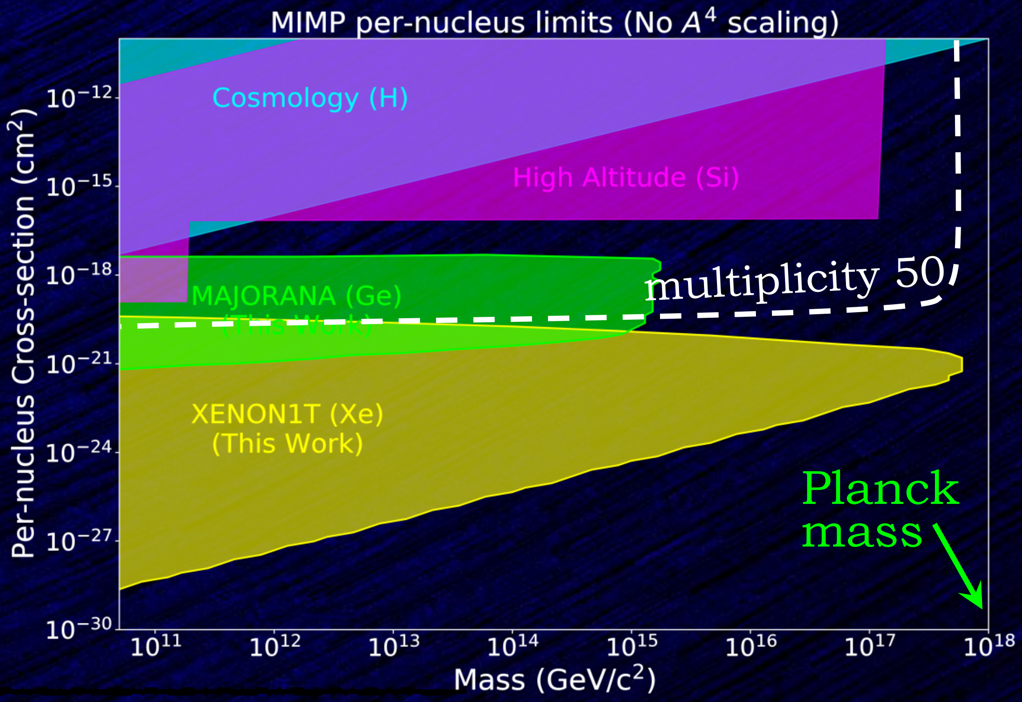
Example: Extrapolate Limits to High Masses

Standard limits almost extrapolate to the Planck scale

Joe, Ben, Nirmal & Rafael 1803.08044

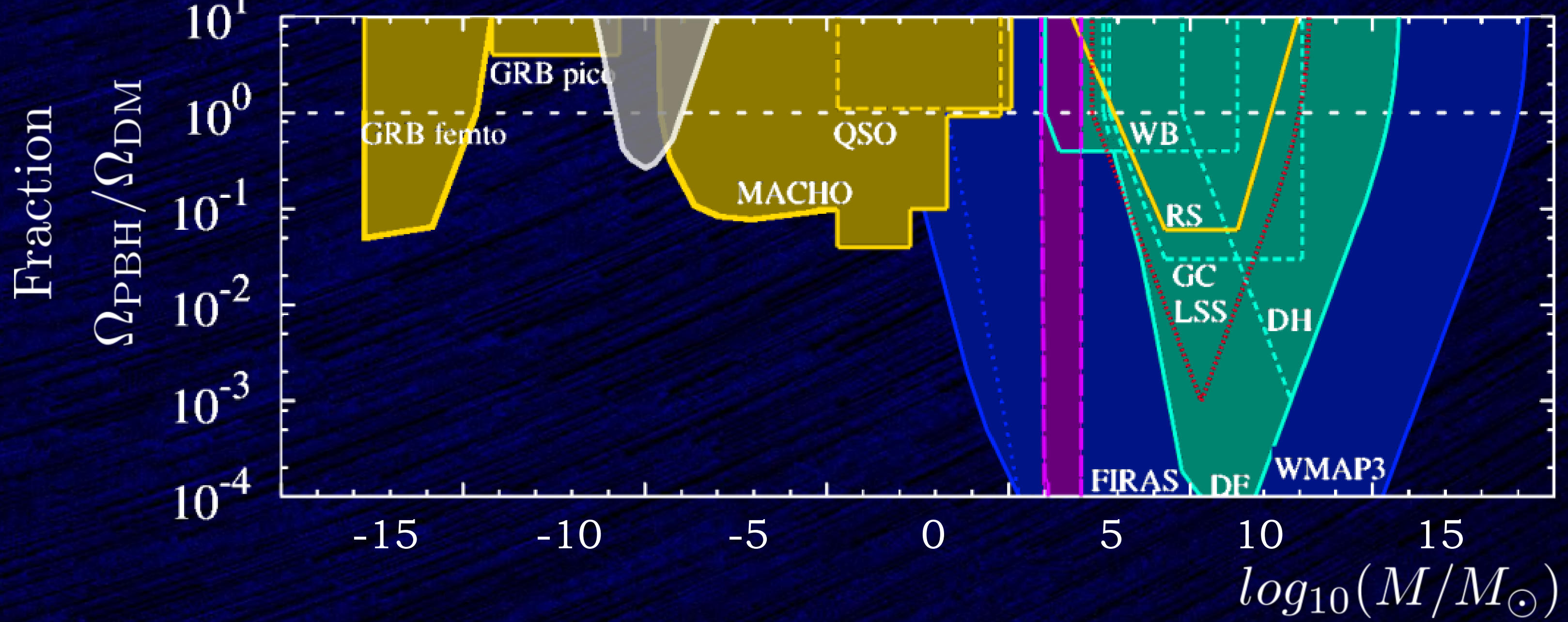
But high cross-section:
signature is tracks

Fully exploit sensitivity:
use dedicated
multi-scatter analysis



Rafael+ 2009.07909

Caveat: Limits Without Sensitivity Really Aren't Limits



Carr+ 0912.5297

Two Approaches

2) Build a Dedicated Experiment

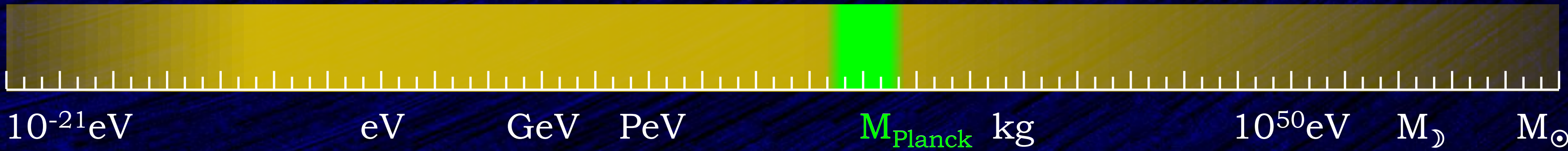
✓ Not easy, not cheap, not quick

Second Approach: Build a Dedicated Experiment

Axions,
Axion-Like Particles
e.g. Primakoff-Effect

WIMPs,
Thermal Relics
e.g. Z-mediation

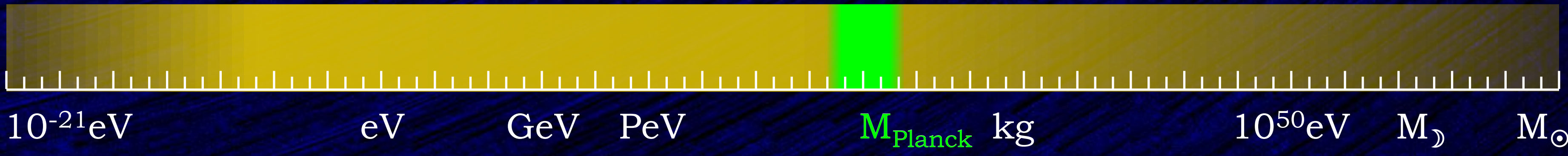
Dark Matter around the Planck Mass



Uniquely motivated

- Primordial Black Holes Hawking-evaporate and leave a quantum-gravity corpse behind MacGibbon 1987, Aharonov+ 1987
- WIMPzillas Kolb+ hep-ph/9810361, 1708.04293, Harigaya+ 1606.00923
- Composite dark matter Krnjaic+ 1406.1171, Hardy+ 1504.05419
- GUT-scale coannihilation Berlin 1704.08256
- Dark quark nuggets Detmold+ 1406.2276, Gresham+ 1707.02316
- Planckian interaction Garny+ 1511.03278
- Extremal black holes Bai+ 1906.04858

Dark Matter around the Planck Mass

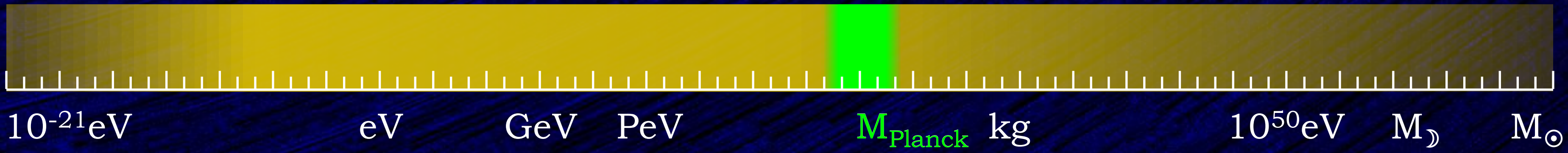


Uniquely motivated
Still accessible in the lab

mass density fixed to ~0.3 GeV/cm^3

at $m_\chi \sim m_{Planck}$, flux ~ 1/m^2/year

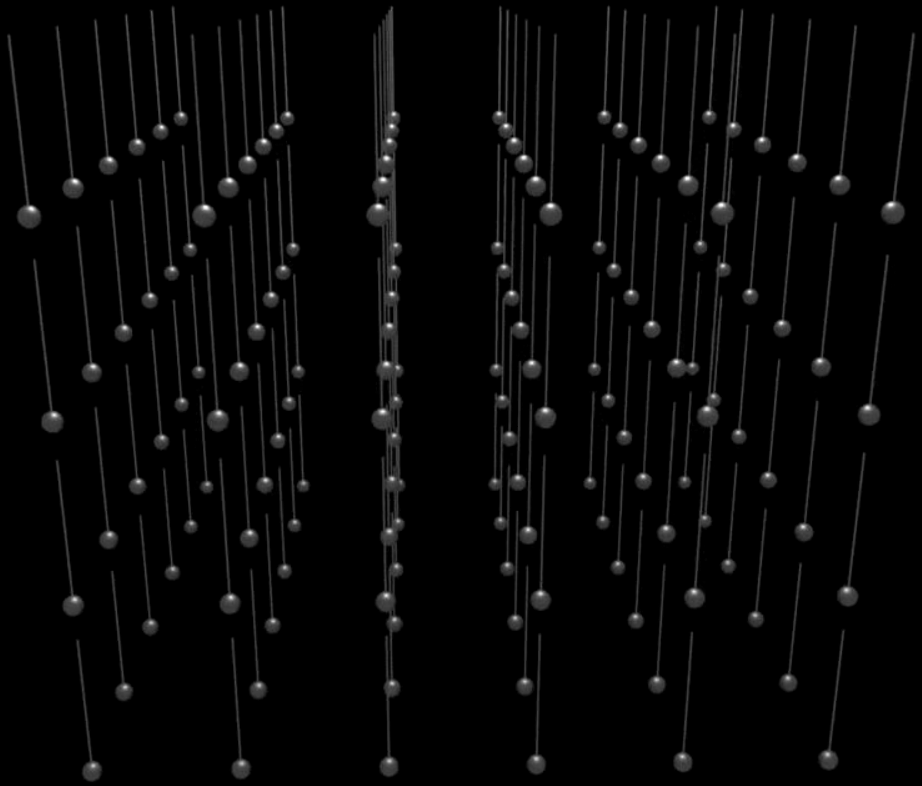
Dark Matter around the Planck Mass



Uniquely motivated
Still accessible in the lab
Gravitational detection possible – though challenging

Carney+ 1903.00492

Windchime Vision



The Windchime Collaboration

PURDUE UNIVERSITY

UNIVERSITY OF MARYLAND

RICE UNIVERSITY

UNIVERSITY OF MINNESOTA

OAK RIDGE National Laboratory

Fermilab

BERKELEY LAB

NIST National Institute of Standards and Technology U.S. Department of Commerce

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U.S. DEPARTMENT OF ENERGY | Office of Science

QUANTUM SCIENCE CENTER

NSF

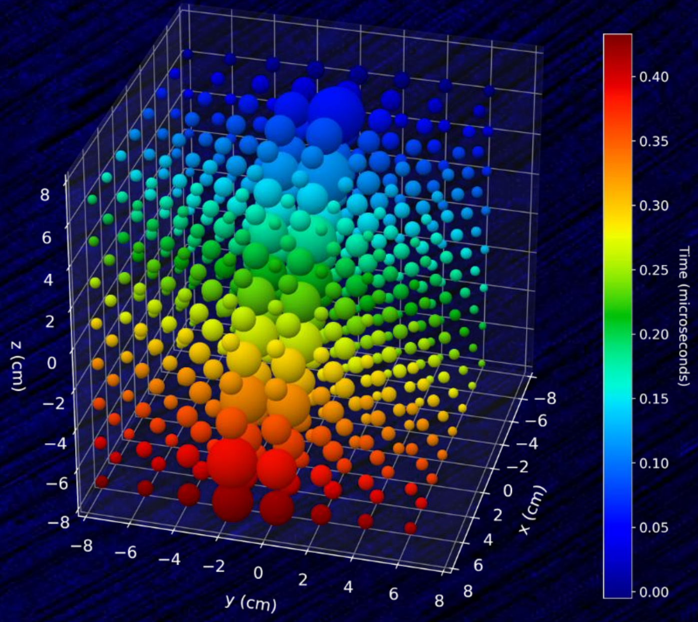
PURDUE UNIVERSITY | Purdue Quantum Science and Engineering Institute

The Windchime Challenge

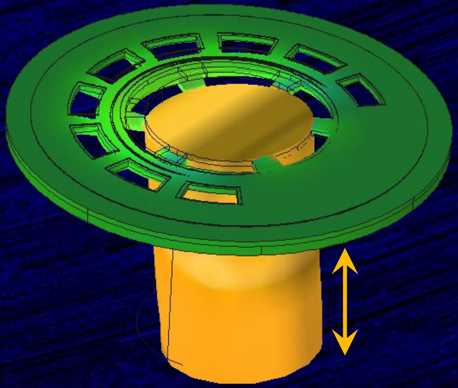
Use array… (~1000^3 channels)

…of fully integrated, ~10mg MEMS accelerometers…

…read out beyond the Standard Quantum Limit using quantum measurement protocols



Silicon MEMS Accelerometers

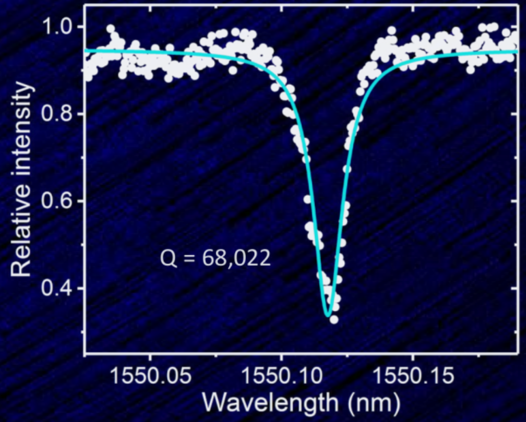


Bao+ 2018

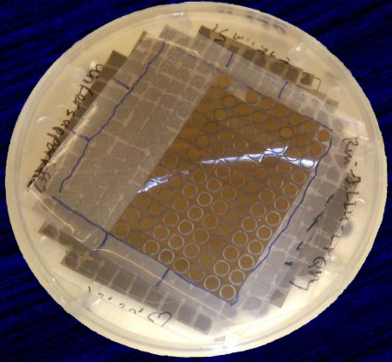
It's mQ/ω that matters

Cervantes+ 1303.1188

Large mass (10 mg) and high Q ($>10^4$) at small noise ($< 1\mu g_n/\sqrt{\text{Hz}}$)



Need full integration on chip, already fab 96/wafer



Redundant read-out:

- piezo-electrics

Dong+ 1903.08479

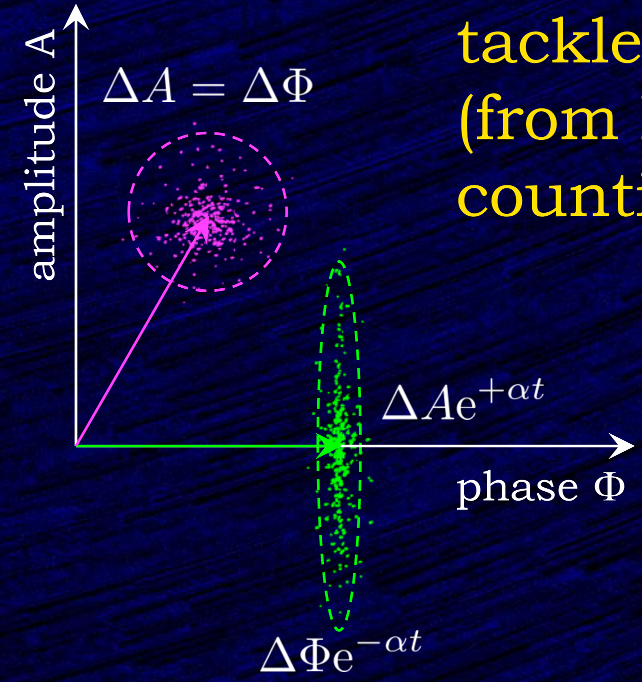
- free-space interferometry

Pooser+ 1912.10550

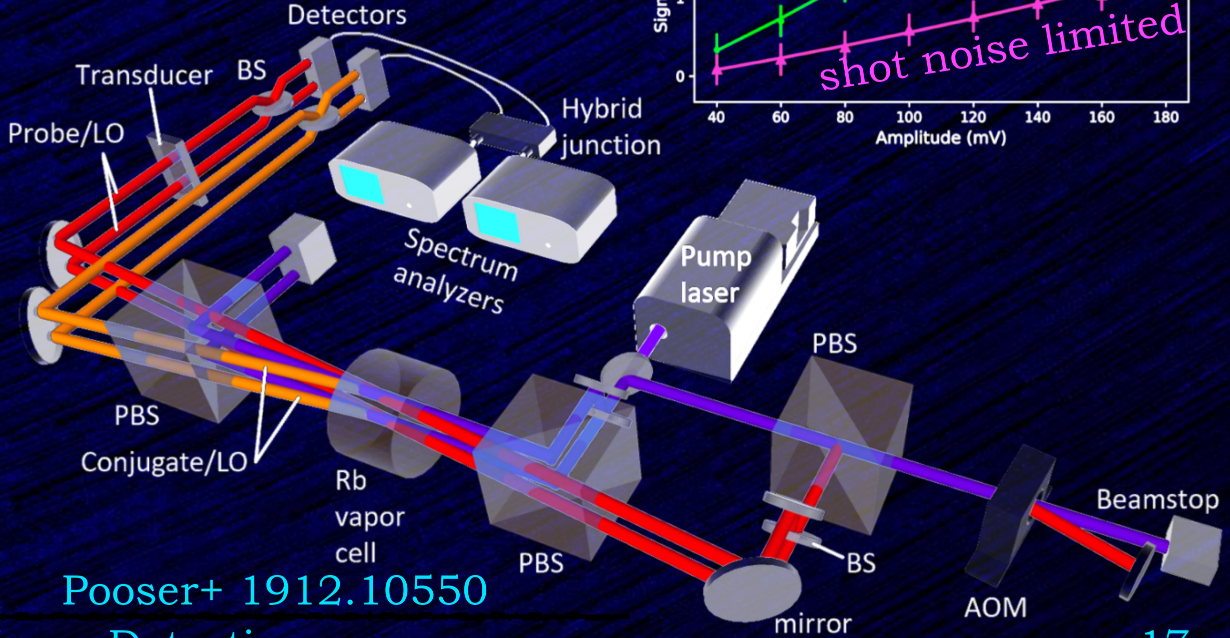
- on-chip photonics

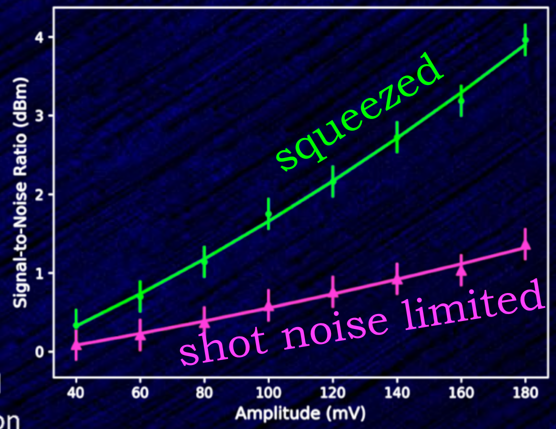
Vaidya+ 1904.07833

Need Quantum Noise Reduction: Squeezing



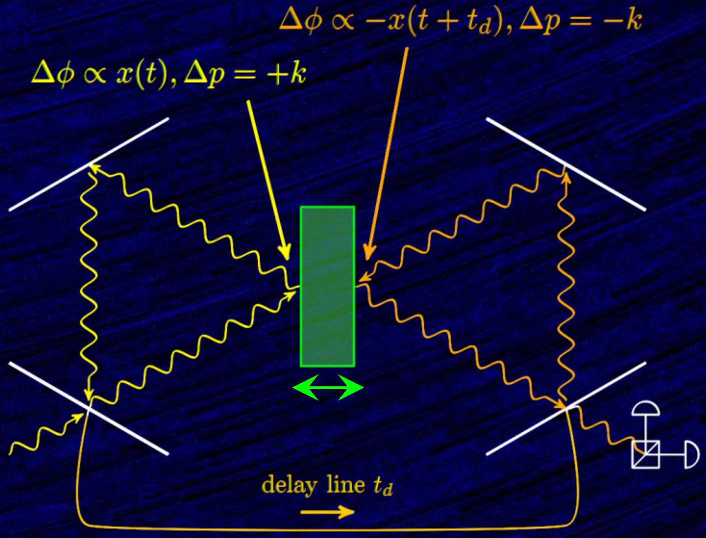
tackle shot noise (from laser photon counting statistics)





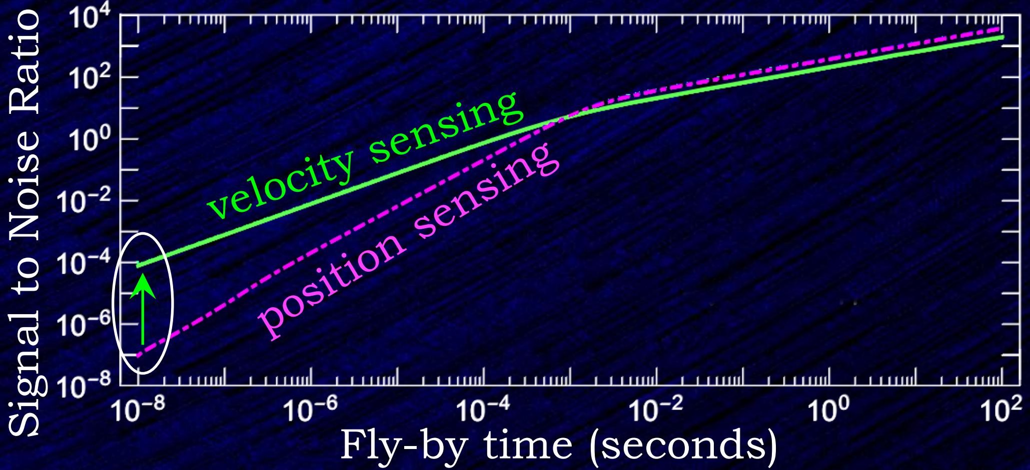
Pooser+ 1912.10550

Need Quantum Noise Reduction: Back-Action Evasion



Passing dark matter gives fast signal:

$$v_\chi \sim 230\,\mathrm{km/s} \;\Rightarrow\; \tau \sim 10^{-8}\,\mathrm{sec}$$



Ghosh+ 1910.11892

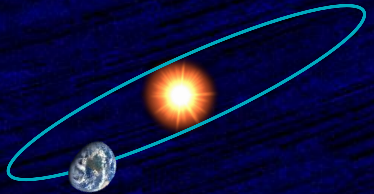
tackle noise from photon momentum transfer

Simulating the Experiment

Dark Matter Halo
- local density
- velocity distribution

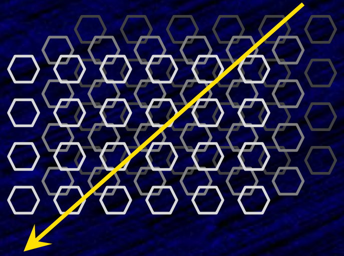
Earth orientation
- seasonal modulation
- directionality

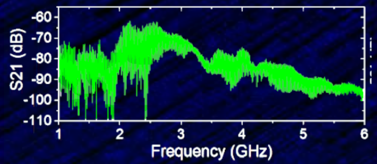
Particle properties



Particle Track

Array layout
Sensor orientation

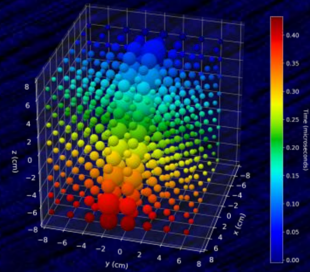




Newtonian acceleration

spectral response

noise spectra, DAQ



simulated data

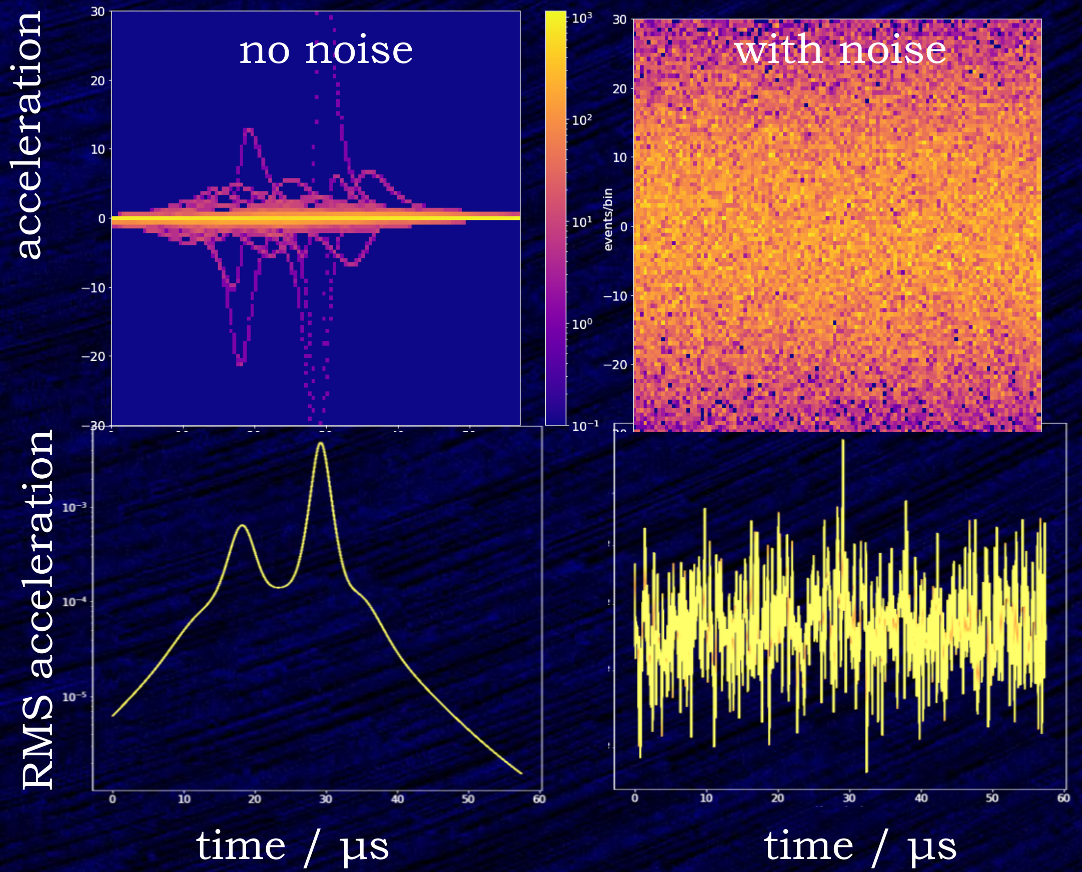
real data

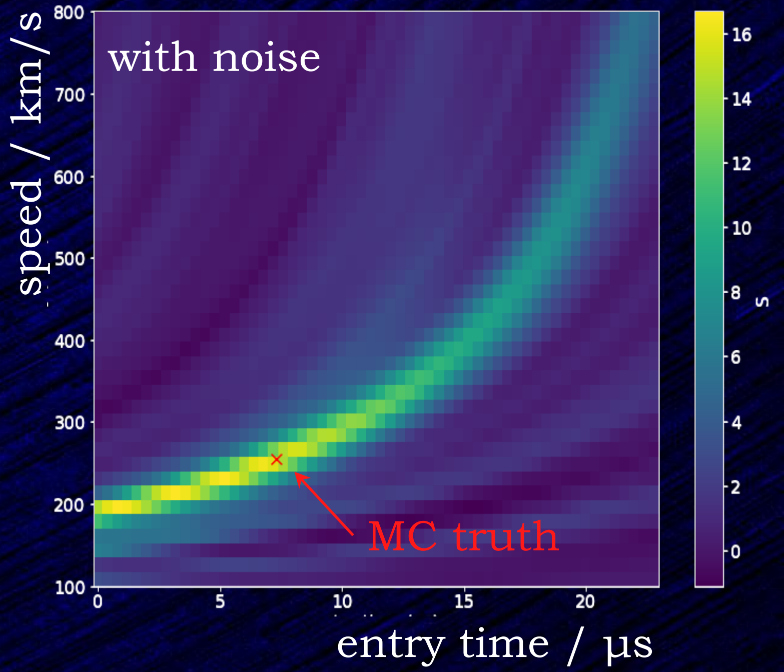
template

fit or parameter scan

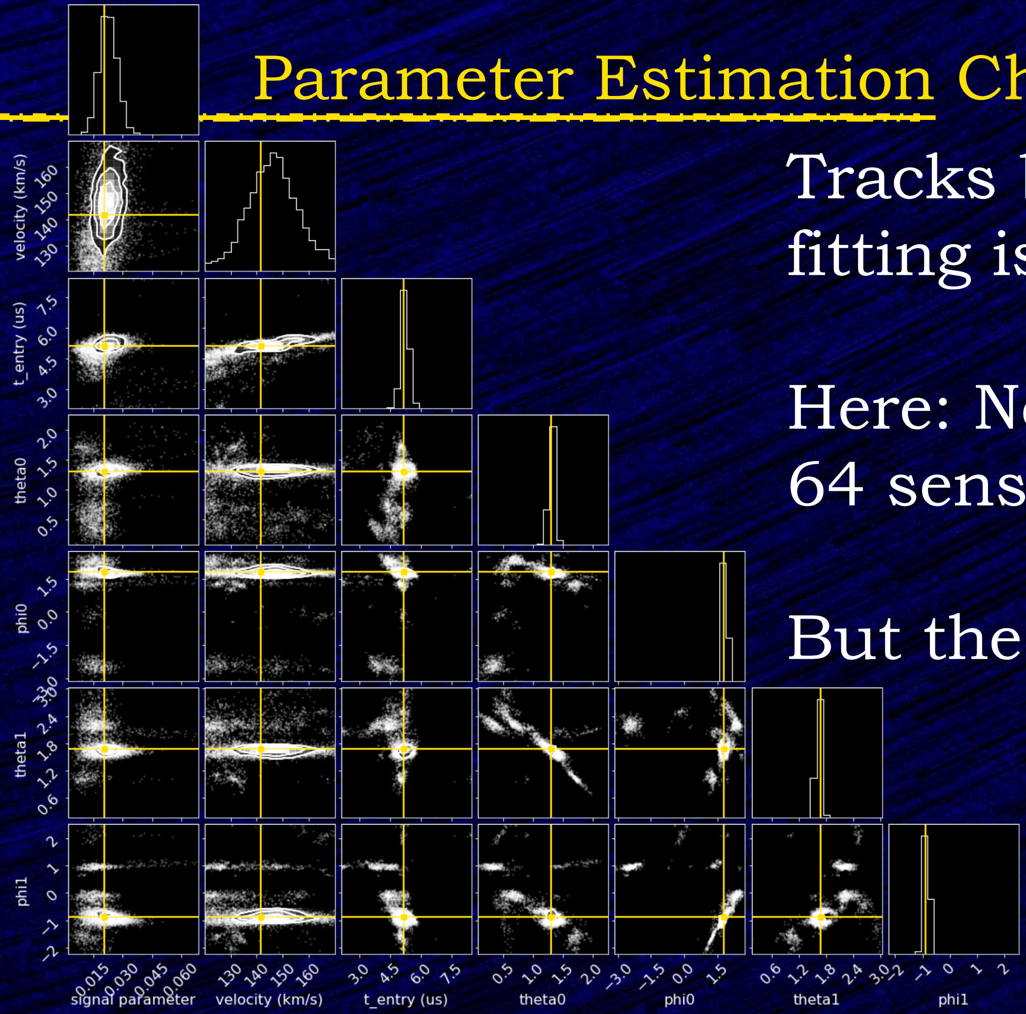
inference

Recovering Tracks from Noisy Data: Radon Transform





Parameter Estimation Challenge



Tracks buried in noise:
fitting is a challenge.

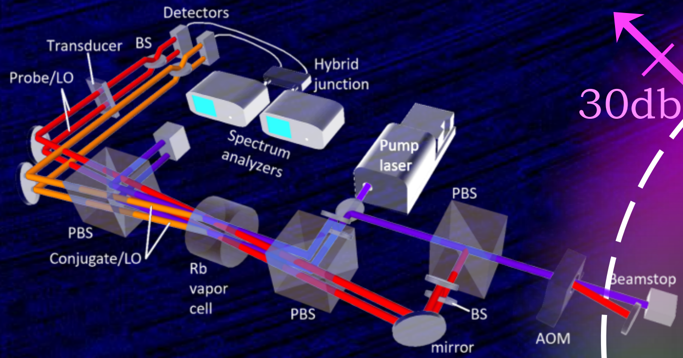
Here: Nested Sampling MCMC
64 sensors: Works.

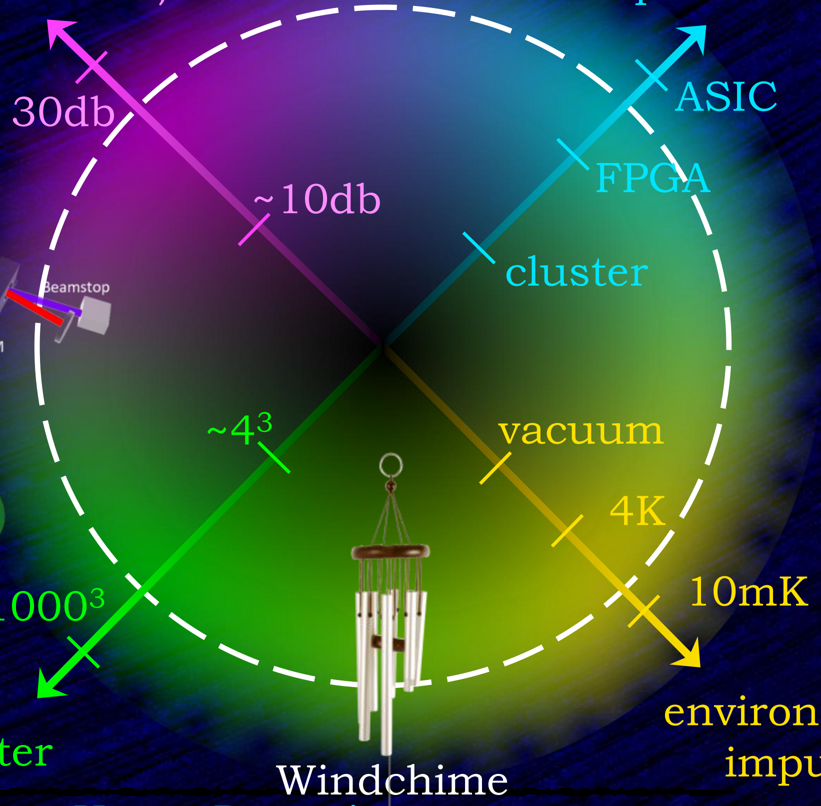
But the trial factor is huge

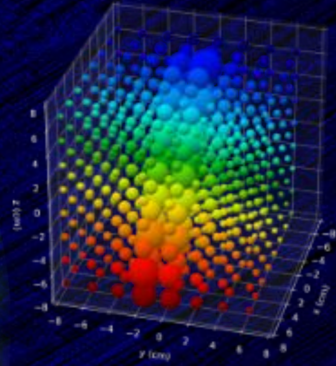
Towards Gravitational Detection of Planck-Mass Dark Matter

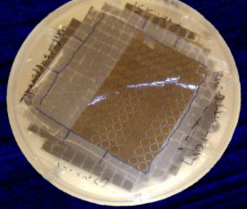
quantum noise suppression:
short signals (particle detection)

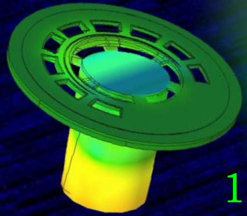
computing:
template fitting, streaming analysis











scale up:
ultralight dark matter

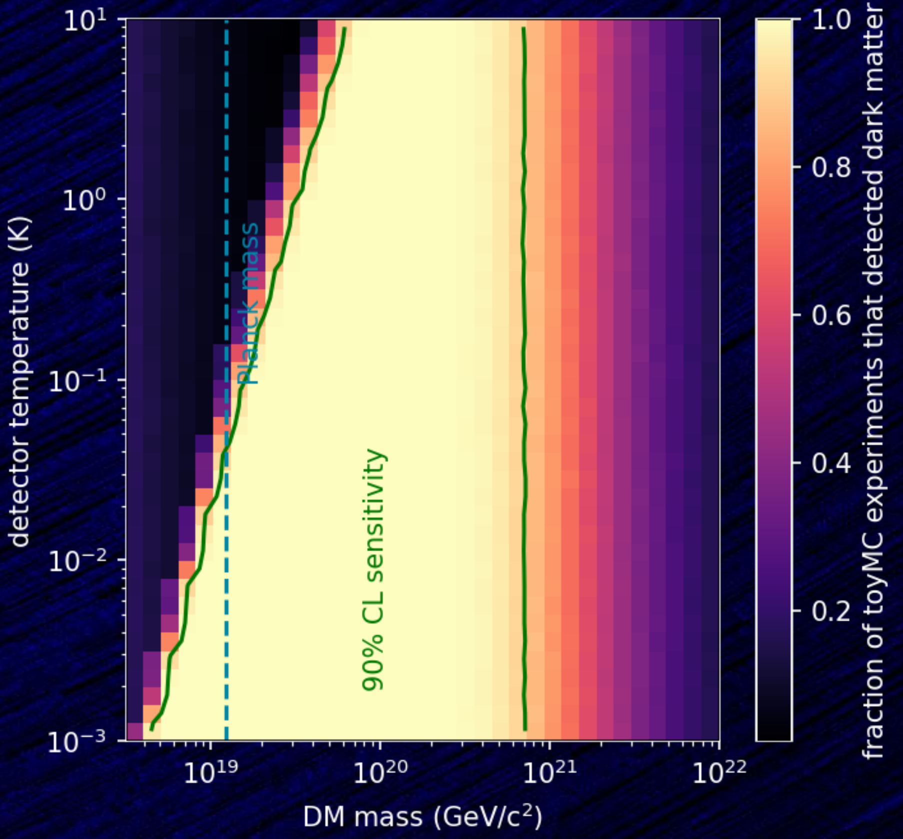
environmental isolation:
impulse metrology

Thermal Noise at kHz Frequencies

Juehang last week:
Circumvent using free-falling sensors!
Go to space!

E.g. small $(11)^3$ * 50g array in space, 10 years:

And yes, we're looking at LISA pathfinder data ☺



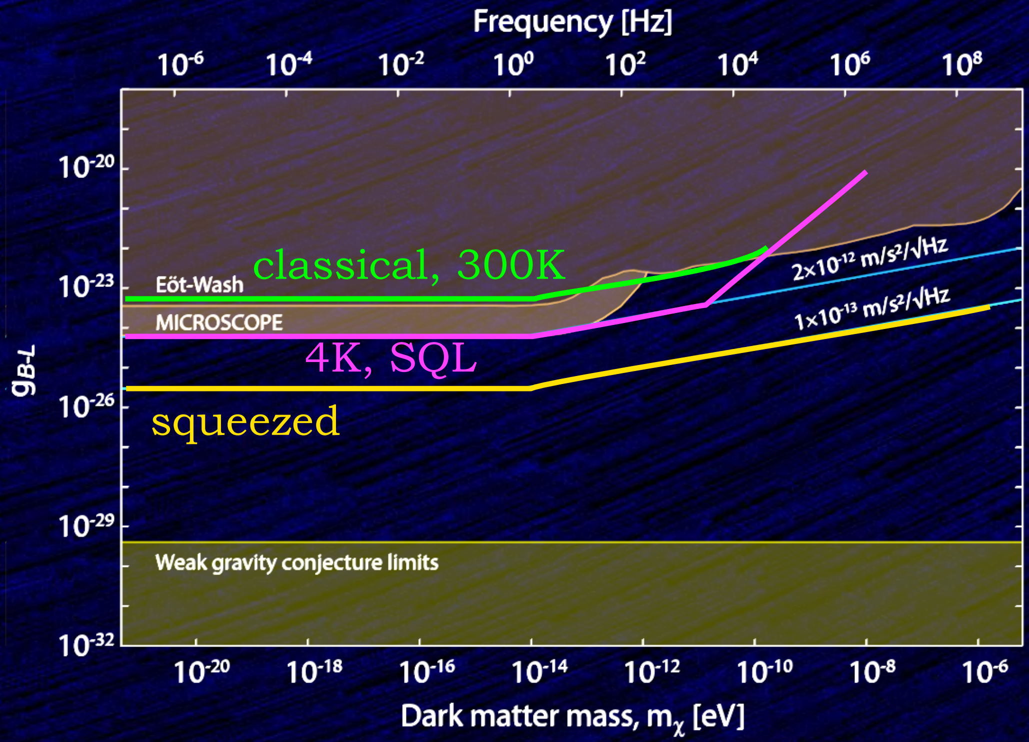
Near-Term Target: Ultralight Dark Matter

Same array also probes wave-like excitations

Graham+ 1512.06165

Carney+ 1908.04797

Manley+ 2007.04899



even existing sensors with classical readout at room temperature interesting

Carney+ 2008.06074

Windchime:
Gravitational detection of dark matter in the lab

Use array of MEMS accelerometers

with quantum-enhanced readout:

- Ultralight dark matter & quantum metrology
- Gravitational detection of Planck-mass dark matter