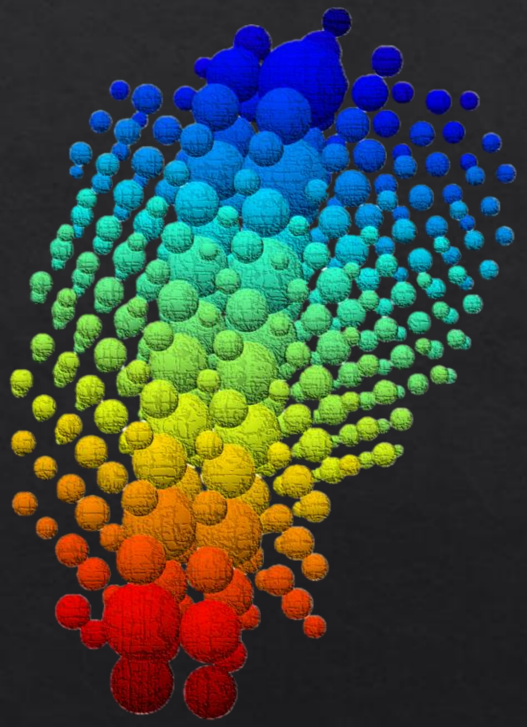
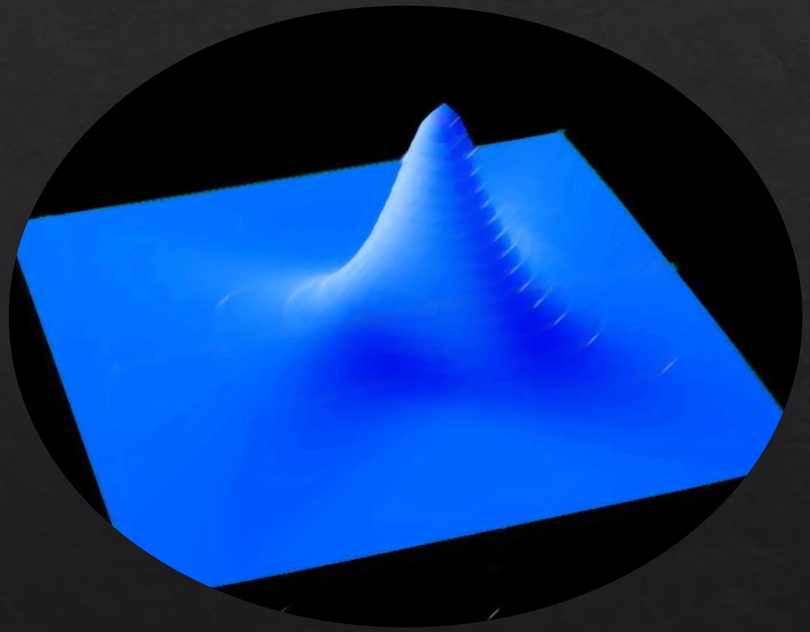
Windchime, Heavy DM Candidates, and QFT in Curved STs

Bahaa Elshimy





Overview

- Experimental Work: *Gravitational Direct Detection of Dark Matter*
- Phenomenology Work: *Heavy Dark Matter Candidates for Direct Detection Techniques*
- Theory Work: *Evolution of Free Scalar Field in Curved Spacetimes*

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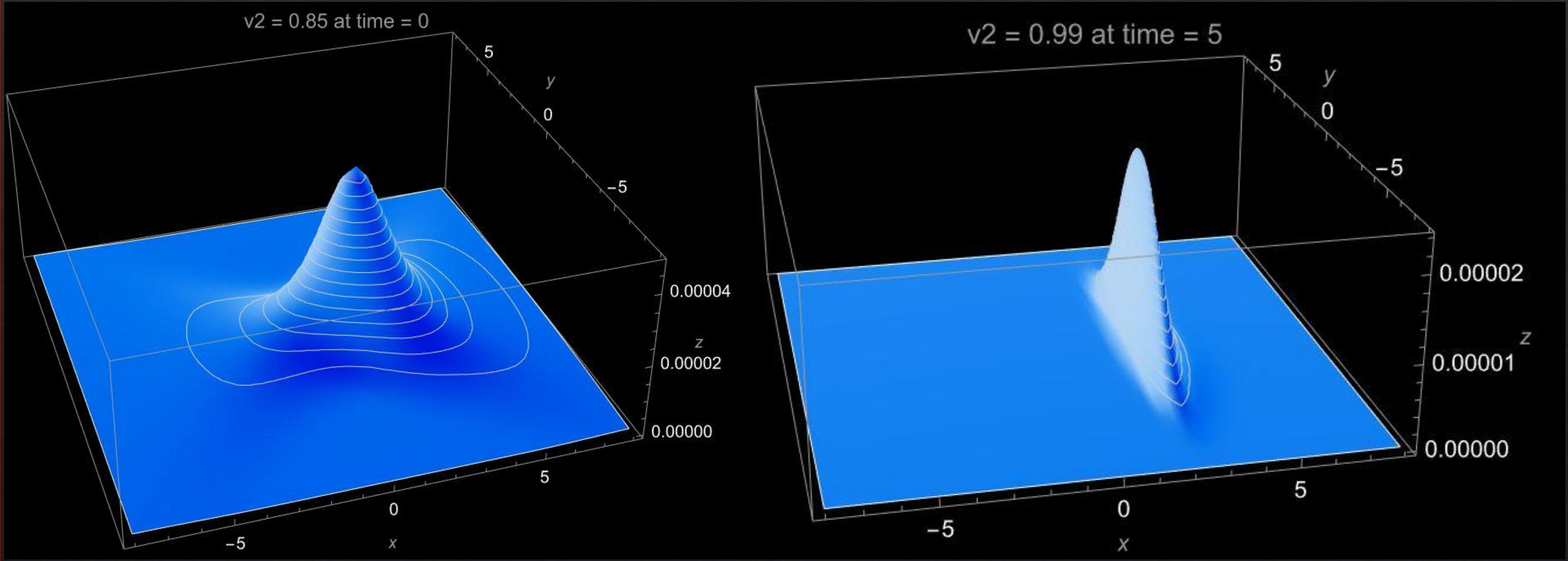
Background

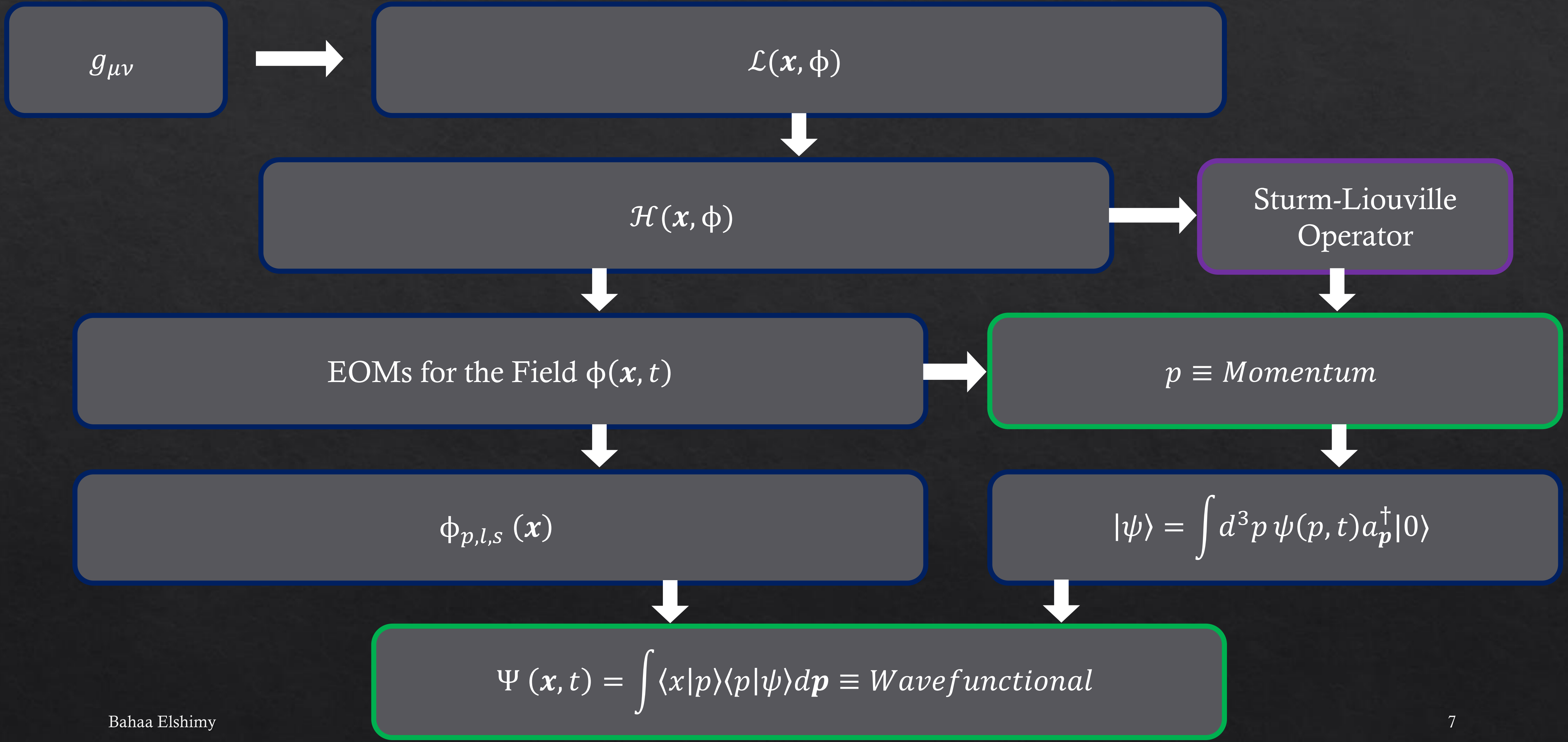
- Standard Approach: Attempt to construct a relativistic quantum theory → QFT with a Flat Background
  - Particles arise naturally as an interpretation of the nonzero components of the Fock space states in the n-fold tensor product space $\overset{n}{\otimes}_s \mathcal{H}$
  - In other words, they are irreducible representations of the associated symmetry group (Poincare)
- Drawback: Relies on the unitary equivalence of the field theory regardless of choice of Hilbert Space
- In curved STs, the machinery can still work, but choice of basis is no longer clear and no longer unique
- Remedy: Reformulate the theory using a symplectic structure and an associated vector space – basically a phase space representation with a symplectic product and a Poisson Bracket

Goal of the Analysis

- Get the energy spectrum of the free particles with different spacetime geometries
  - Analyze what this energy depends on in different regions
- Derive the asymptotic behavior of the scalar fields
  - Determine whether a detector can use information gathered about the evolved state to infer elements of the background geometry via certain behavior observed
- Started with Curvilinear Coordinates, Boosted Frames, & Rindler Coordinates
- Concluded with Static Patch of deSitter Space

WF in Boosted Frame




$g_{\mu\nu}$
$\mathcal{L}(\boldsymbol{x}, \phi)$
$\mathcal{H}(\boldsymbol{x}, \phi)$
Sturm-Liouville Operator
EOMs for the Field $\phi(\boldsymbol{x}, t)$
$p \equiv Momentum$
$\phi_{p,l,s}\,(\boldsymbol{x})$
$|\psi\rangle = \int d^3p\,\psi(p,t)a_{\boldsymbol{p}}^{\dagger}|0\rangle$
$\Psi\,(\boldsymbol{x}, t) = \int \langle x|p\rangle\langle p|\psi\rangle d\boldsymbol{p} \equiv Wavefunctional$

Case 0: Flat Space Spherical Coordinates

$$\mathcal{L}(\boldsymbol{x},\phi) = -\frac{1}{2}\mathrm{r}^2 \sin\theta\,\left(-(\partial_t\phi)^2 + (\partial_r\phi)^2 + \mathrm{m}^2\phi^2\right) - \frac{1}{2}\left(\sin\theta\,(\partial_\theta\phi)^2 + \frac{1}{\sin\theta}\left(\partial_\varphi\phi\right)^2\right)$$

$$\mathcal{H}(\boldsymbol{x},\phi) = \frac{1}{2}\left[\frac{\pi^2}{r^2\sin\theta} + r^2\sin\theta\left((\partial_r\phi)^2 + m^2\phi^2\right) + \sin\theta\,(\partial_\theta\phi)^2 + \frac{1}{\sin\theta}\left(\partial_\varphi\phi\right)^2\right]$$

$$\widehat{D} = \partial_r(r^2\partial_r) - \widehat{L^2} - r^2 m^2$$

$$-\partial_t^2\phi + \frac{1}{r^2}\partial_r(r^2\partial_r\phi) + \frac{1}{r^2\sin\theta}\partial_\theta(\sin\theta\;\partial_\theta\phi) + \frac{1}{r^2\sin^2\theta}\partial_\varphi^2\phi - m^2\phi = 0$$

$$p^2 = \omega_{\boldsymbol{p}}^2 - m^2$$

$$\phi_{p,l,s}(\boldsymbol{x}) = R(r)Y_l^s(\theta,\varphi) = Ae^{is\varphi}j_{\widetilde{k_l}}(pr)P^s_{\widetilde{k_l}}(\cos\theta)$$

$$|\psi\rangle = \psi_0\int d^3p\,\mathrm{e}^{-\mathrm{i}\omega_{\boldsymbol{p}}\mathrm{t}}a_{\boldsymbol{p}}^\dagger|0\rangle$$

$$\Psi(r,\theta,\varphi,t) = \int dp\sum_{l,s} A\; e^{is\varphi}j_{\widetilde{k_l}}(pr)P^s_{\widetilde{k_l}}(\cos\theta)\;\psi_0 e^{-i\omega_p t}$$

Free Scalar Field in deSitter Spacetime

$$\mathcal{L}(\boldsymbol{x},\phi) = -\frac{1}{2}\cos(H\rho)\sin^2(H\rho)\sin\theta\left[-\cos^2(H\rho)(\partial_t\phi)^2 + \left(\partial_\rho\phi\right)^2 + H^2\sin^{-2}(H\rho)\left((\partial_\theta\phi)^2 + \sin^{-2}\theta\left(\partial_\varphi\phi\right)^2\right) - m^2\phi^2\right]$$

$$\mathcal{H}(\boldsymbol{x},\phi) \equiv \dot{\phi}\pi - \mathcal{L} \qquad \pi \equiv \frac{\partial\mathcal{L}}{\partial(\partial_t\phi)} = H^{-2}\cos^{-1}(H\rho)\sin^2(H\rho)\sin\theta\ \dot{\phi}$$

$$D = \partial_r(r^2\partial_r) - \widehat{L}^2 - r^2m^2$$

EOMs

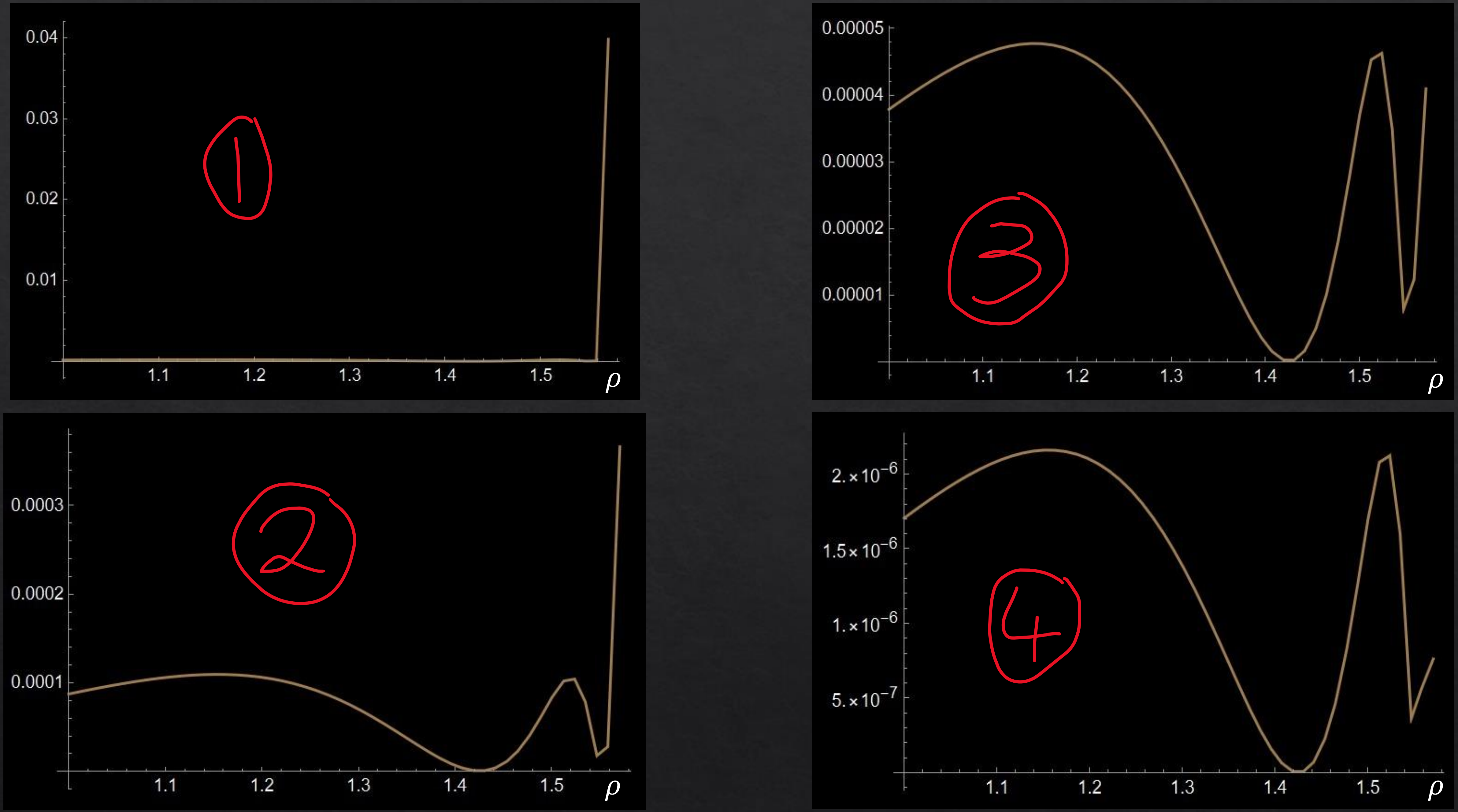
Rescaled Radial Solution with $\frac{m^2}{H^2} \gg 1$

$$\phi_{p,l,s}(r,\theta,\varphi) = A_{l,s}\,Y_l^s(\theta,\varphi)\,N_{pl}\tan^l(H\rho)\cos^n(H\rho)\ {}_2F_1[Args\ \{\rho\}]$$

$|\psi\rangle$

$p^2 = \omega_{\boldsymbol{p}}^2$ at the $\rho \to \frac{\pi}{2H}$ limit

$$\Psi(x,t) = \int \langle x|p\rangle\langle p|\psi\rangle d\boldsymbol{p} = \int \phi_{\boldsymbol{k}}(r,\theta,\varphi,t)\,\psi_0 e^{-i\omega_{\boldsymbol{k}}t}d\boldsymbol{k}$$


1
0.04
0.03
0.02
0.01
1.1
1.2
1.3
1.4
1.5
ρ
3
0.00005
0.00004
0.00003
0.00002
0.00001
1.1
1.2
1.3
1.4
1.5
ρ
2
0.0003
0.0002
0.0001
1.1
1.2
1.3
1.4
1.5
ρ
4
2.×10^-6
1.5×10^-6
1.×10^-6
5.×10^-7
1.1
1.2
1.3
1.4
1.5
ρ

Overview

- Experimental Work: *Gravitational Direct Detection of Dark Matter*
- Phenomenology Work: *Heavy Dark Matter Candidates for Direct Detection Techniques w/ Dr. Carlos Blanco*
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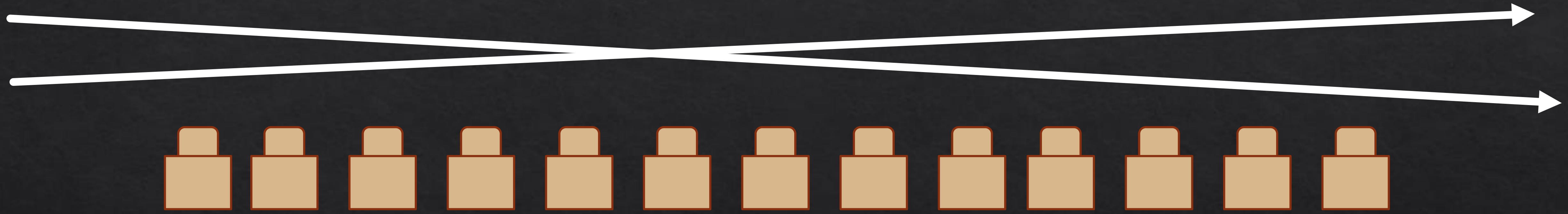
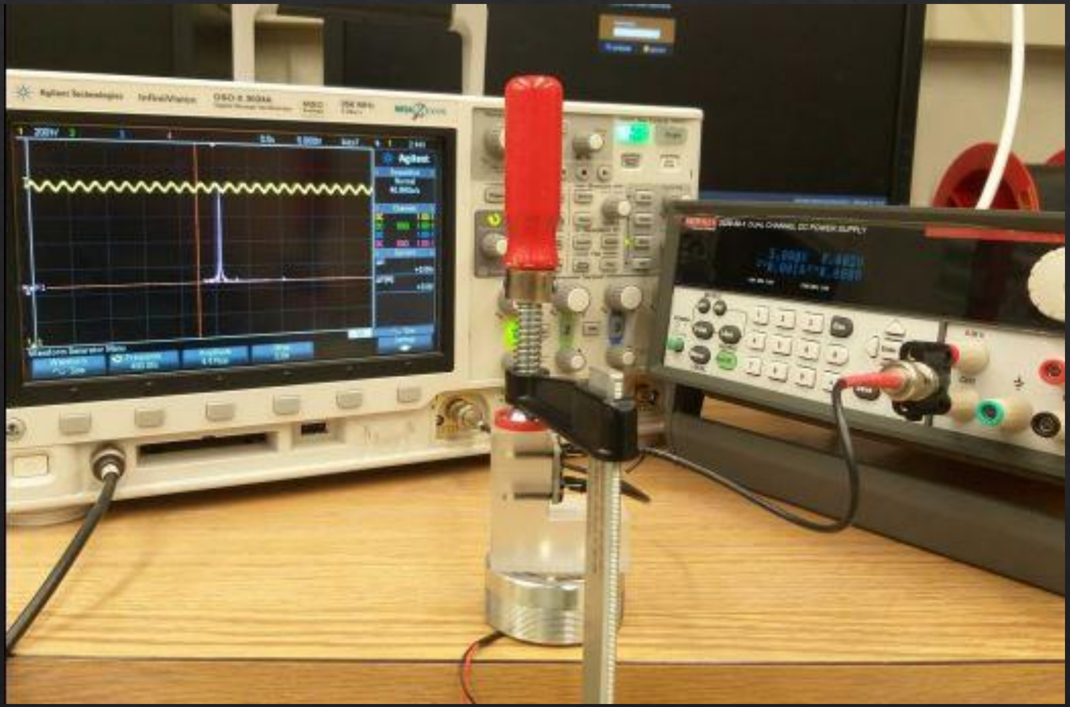
Overview of Gravitational Detection Method

- Long-term Goal: Detect Dark Matter directly using gravitational Interactions
- Uses accelerometers jerked by their interaction with the Dark Matter

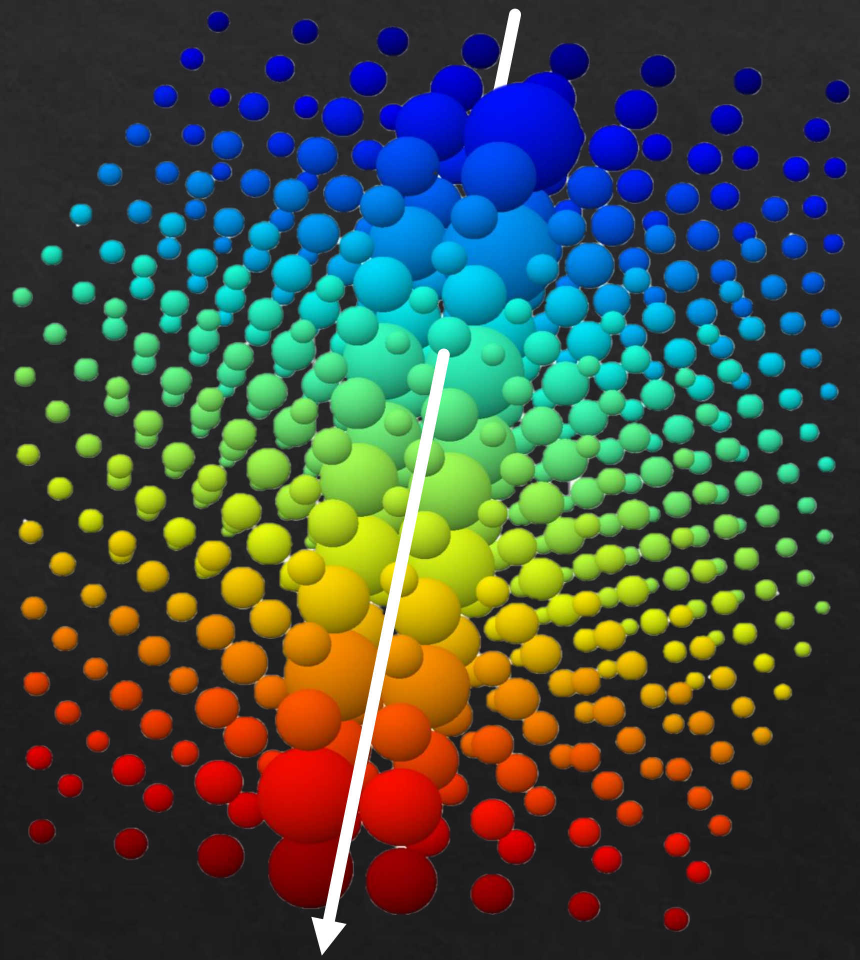


- Current Challenge: Noise
- For a Dark Matter particle detection, it is estimated that some 10^9 sensors *in the path* of the particle are required to have a significant Detection
- Test Statistic: Signal-to-Noise Ratio

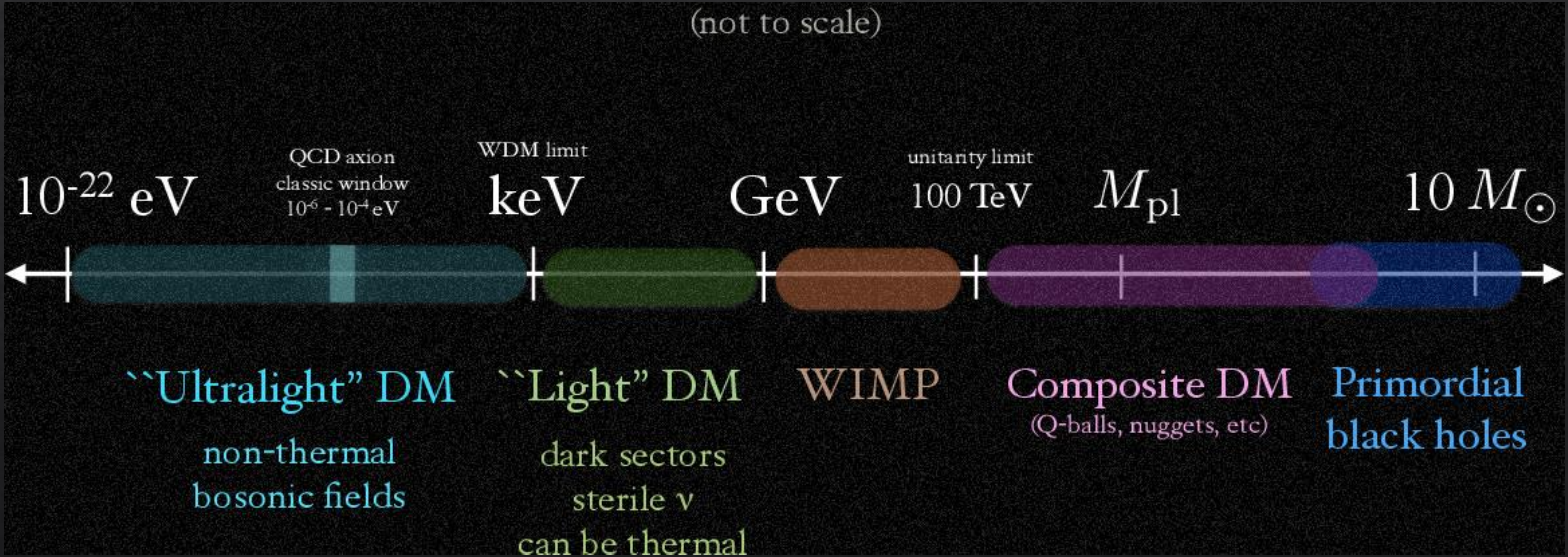
Physical Experiment: Protochime



Virtual Experiment

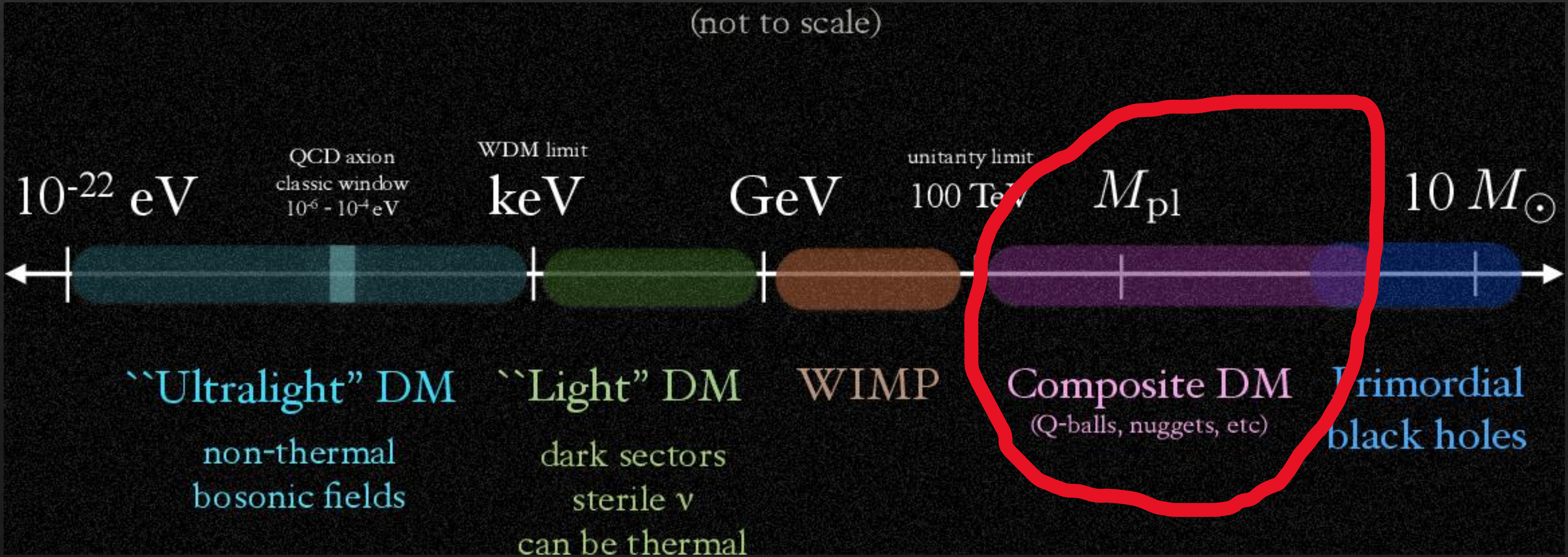


What Kinds of Particles Do We Expect?



https://www.semanticscholar.org/paper/TASI-lectures-on-dark-matter-models-and-direct-Lin/2a5d193da5550a0396c63304fd2b192750f23610

My Focus



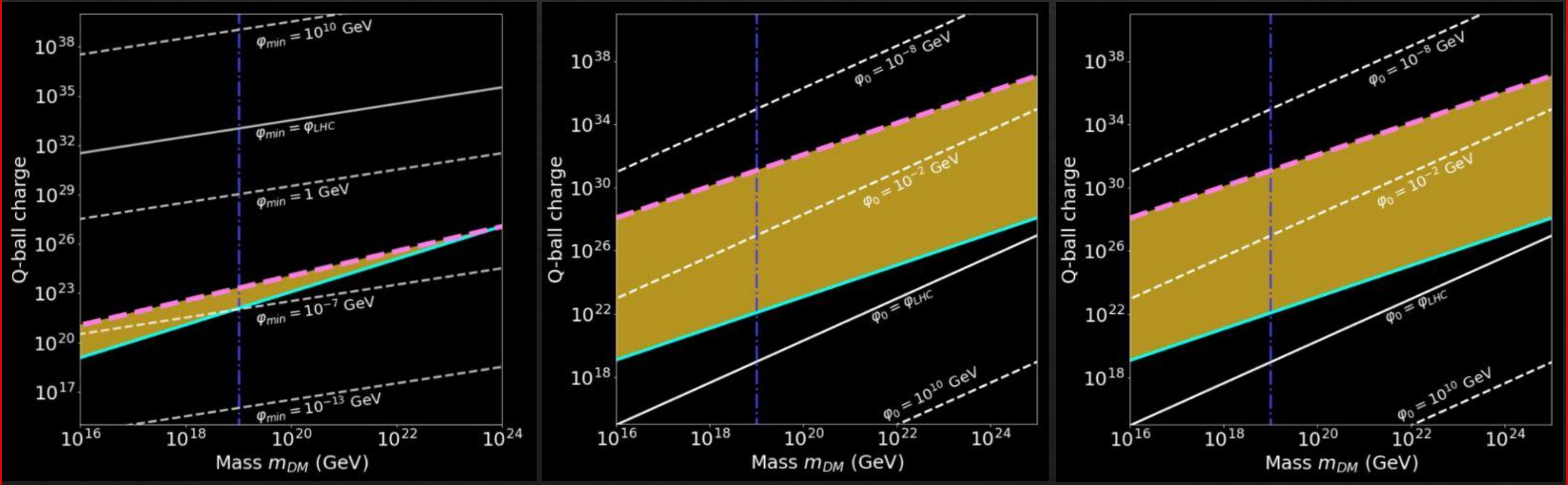
(not to scale)
QCD axion
classic window
10^{-6} - 10^{-4} eV
WDM limit
unitarity limit
10^{-22} eV
keV
GeV
100 Te
M_{pl}
$10\ M_{\odot}$
``Ultralight” DM
non-thermal
bosonic fields
``Light” DM
dark sectors
sterile ν
can be thermal
WIMP
Composite DM
(Q-balls, nuggets, etc)
rimordial
black holes

My Focus

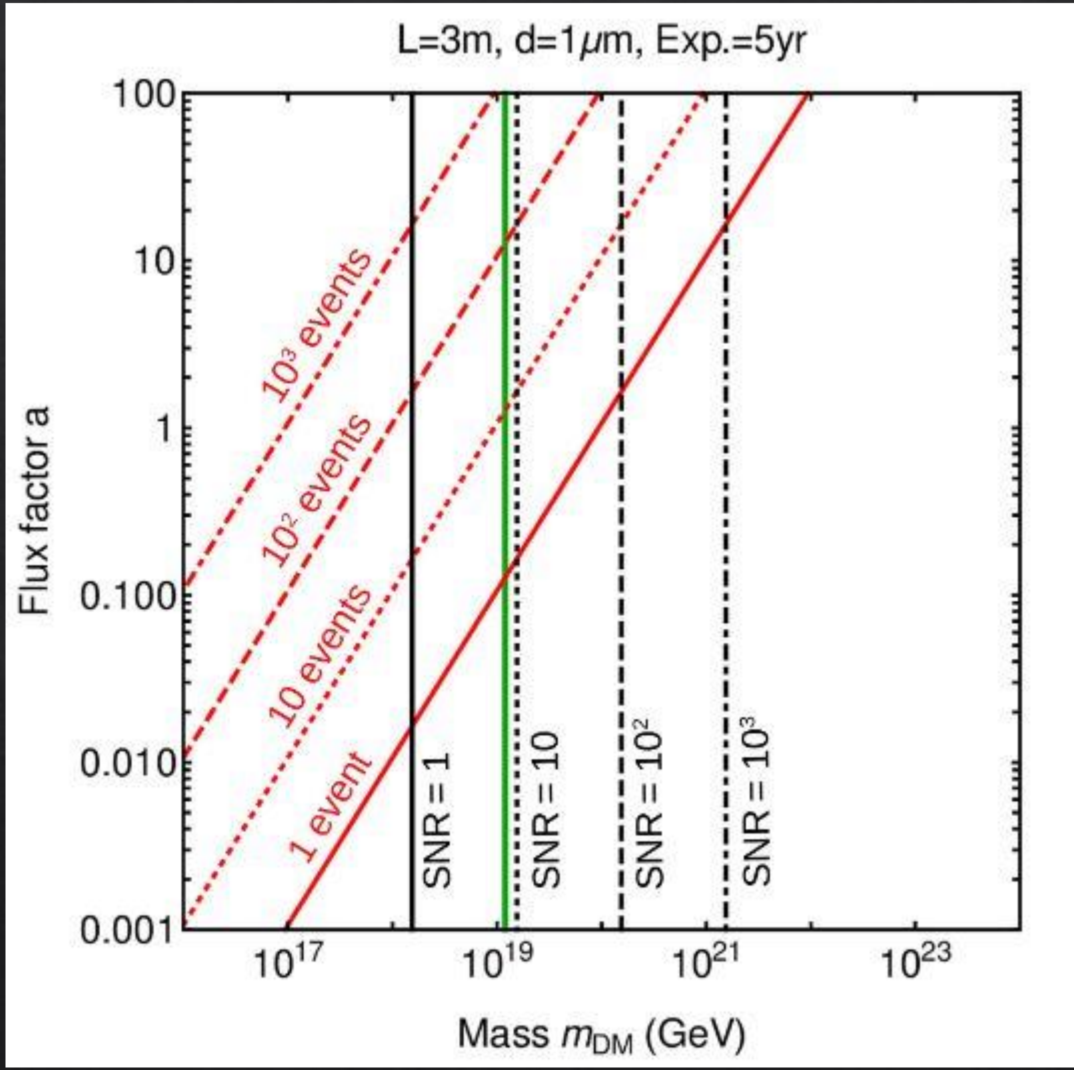
- Composite Dark Matter
  - DM Candidates composed of constituent particles
- Q-Balls – Non-Topological Solitons
  - Soliton solutions that admit a charge and allow for an energetically favorable massive state
- Superheavy Dark Matter Candidates
  - e.g. Extremal and "standard" PBH Relics and Gravitationally Produced particles (such as WIMPZILLAs)
- Flux Factor for a given candidate (mass) observed at a specific exposure and SNR

Q-Balls

- Type I - Thin-walled: The VeV is set close to the φ_0 of the scalar field
- Type II – Thick-walled: Gauge mediated field configuration with a flat potential
- Type III – Thick-walled: Same as Type II but with a logarithmic potential



Multicandidate Flux Factor



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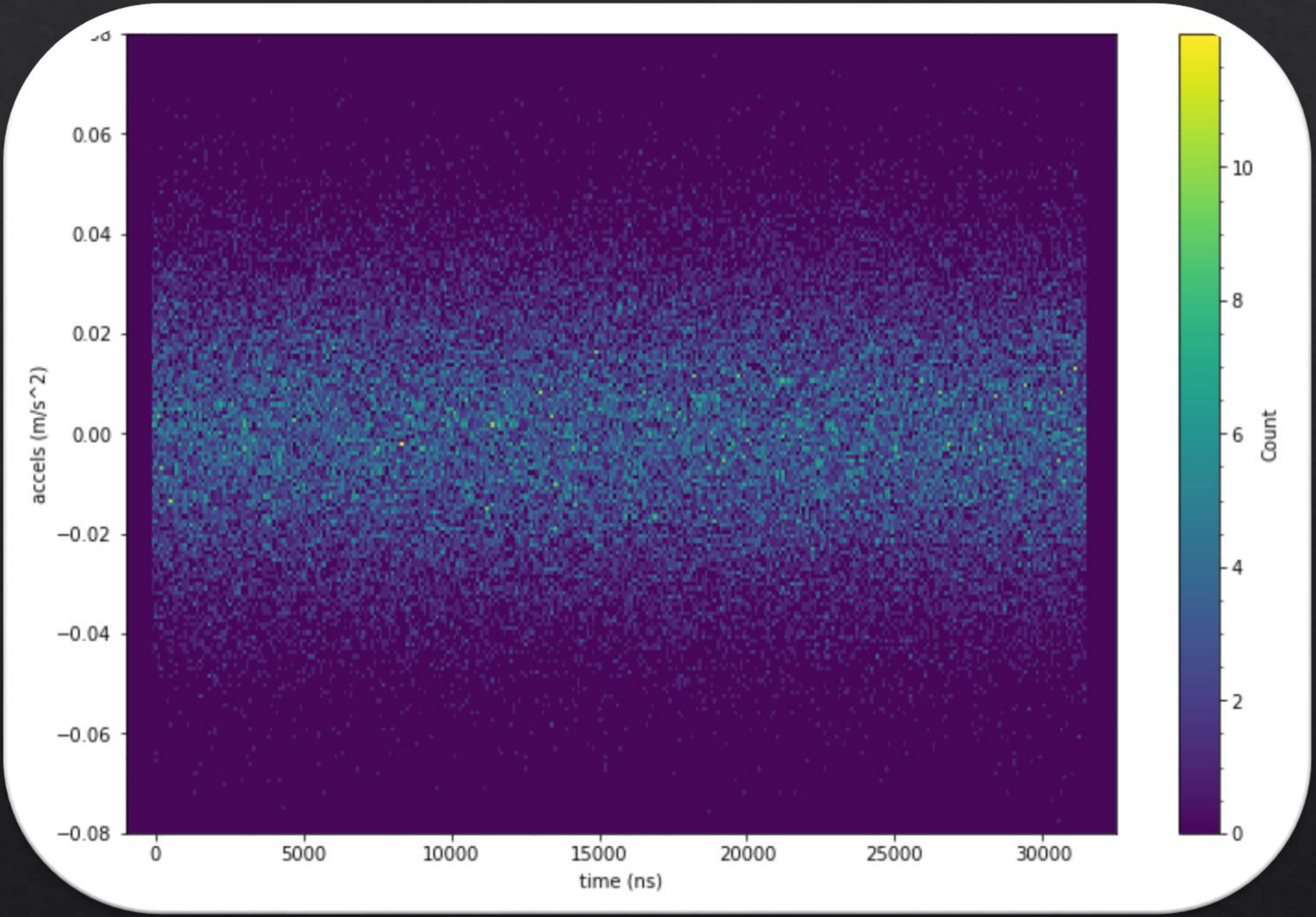
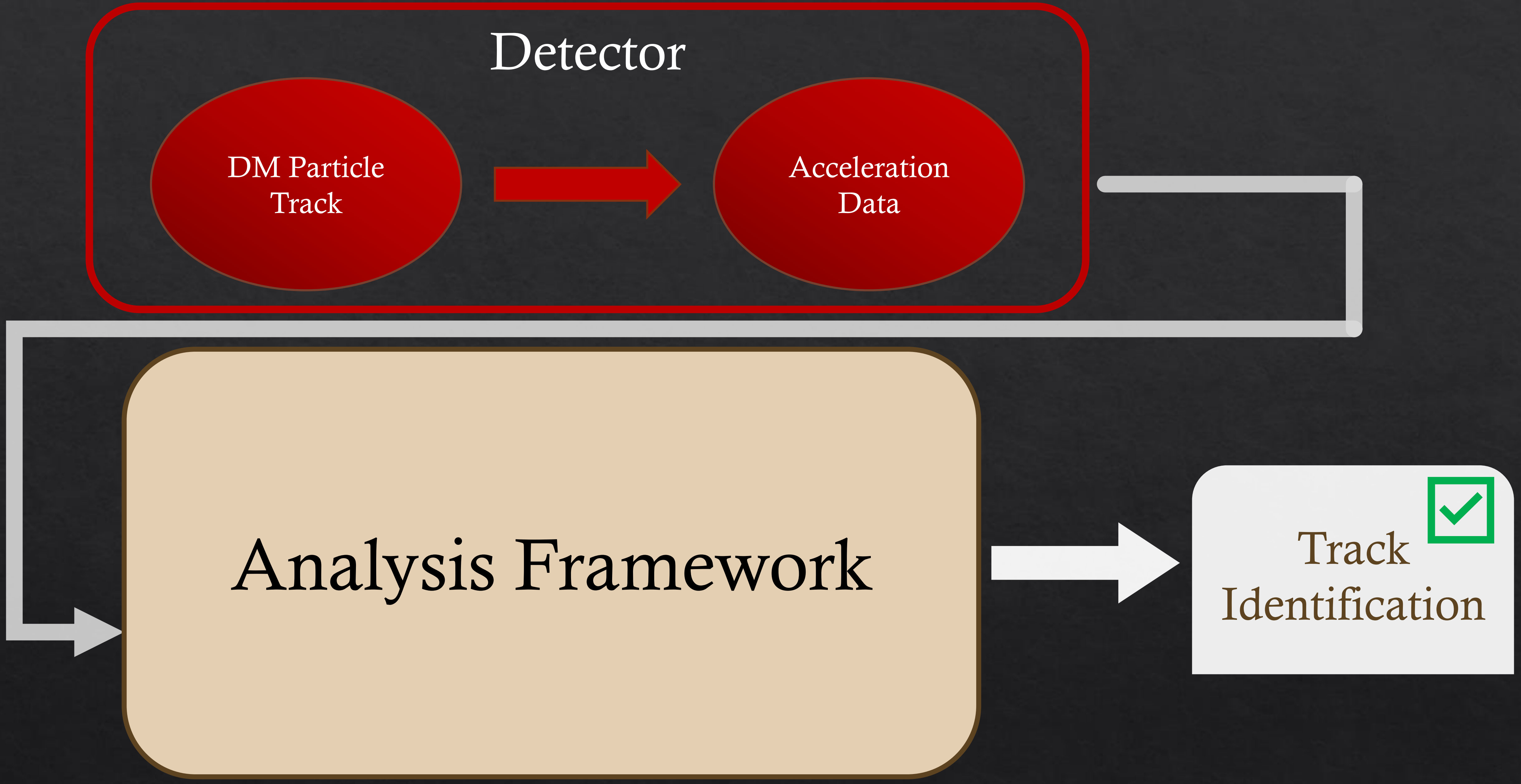
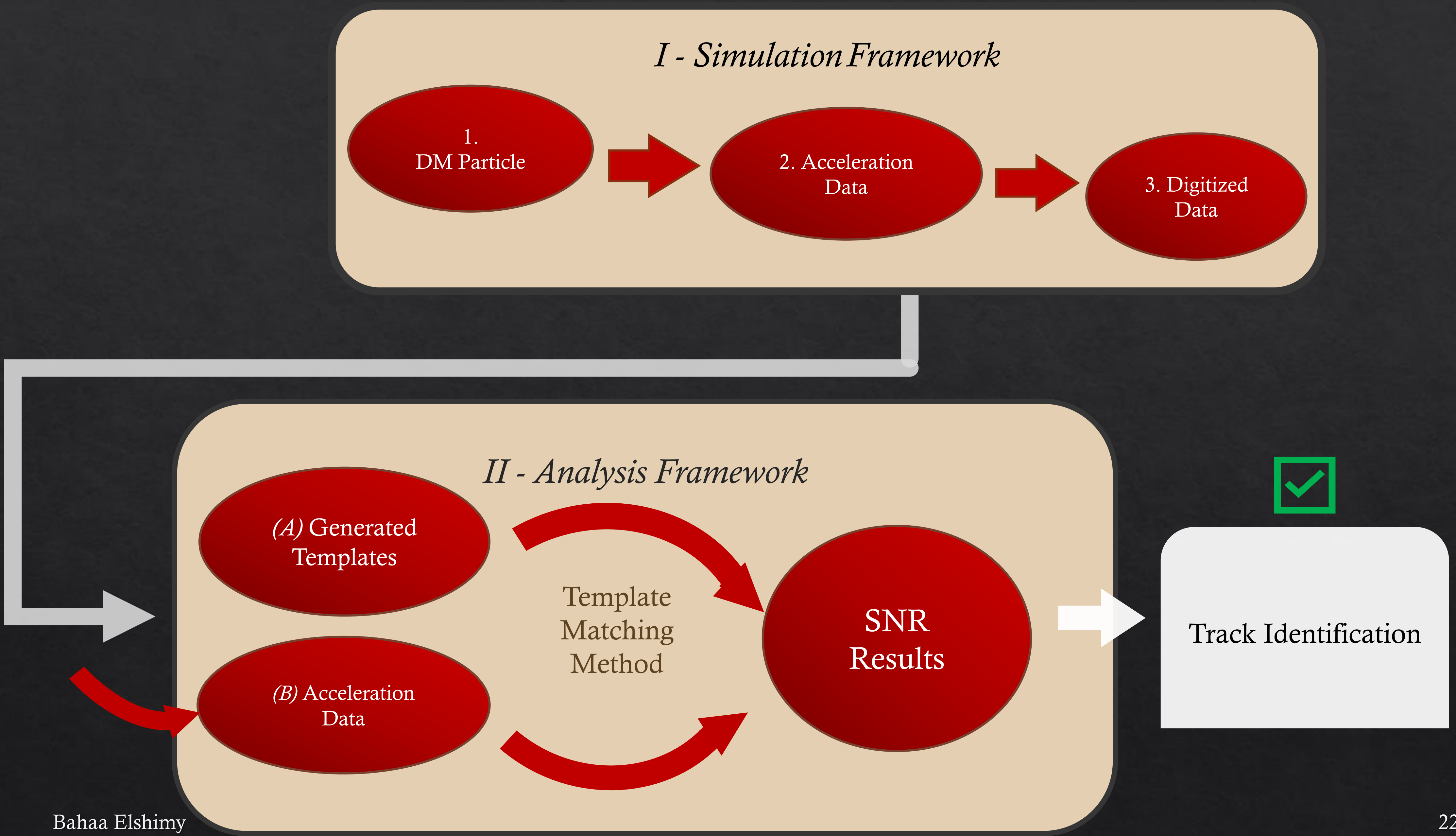
Acceleration Data



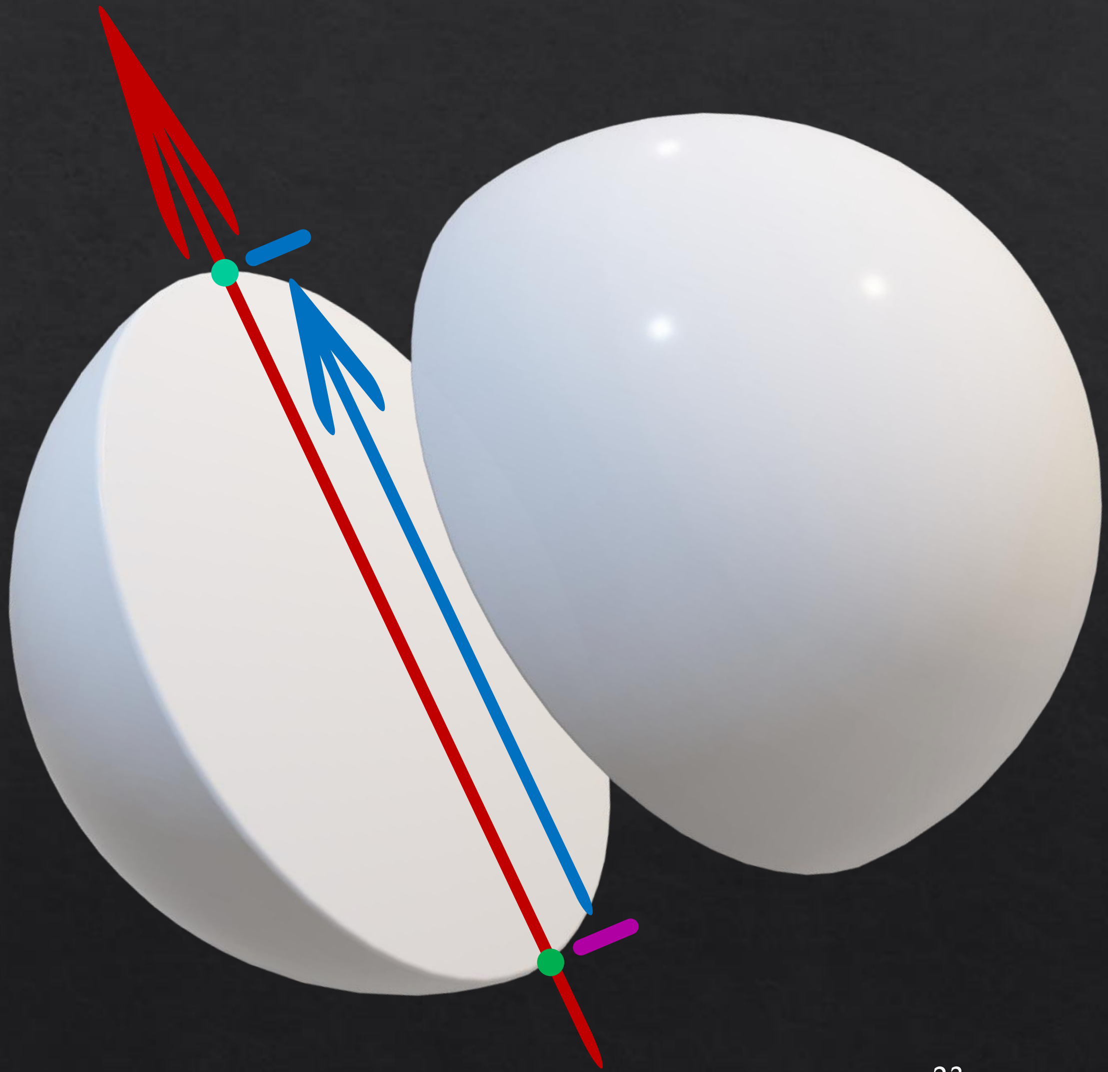


Detector
DM Particle Track
Acceleration Data
Analysis Framework
Track Identification

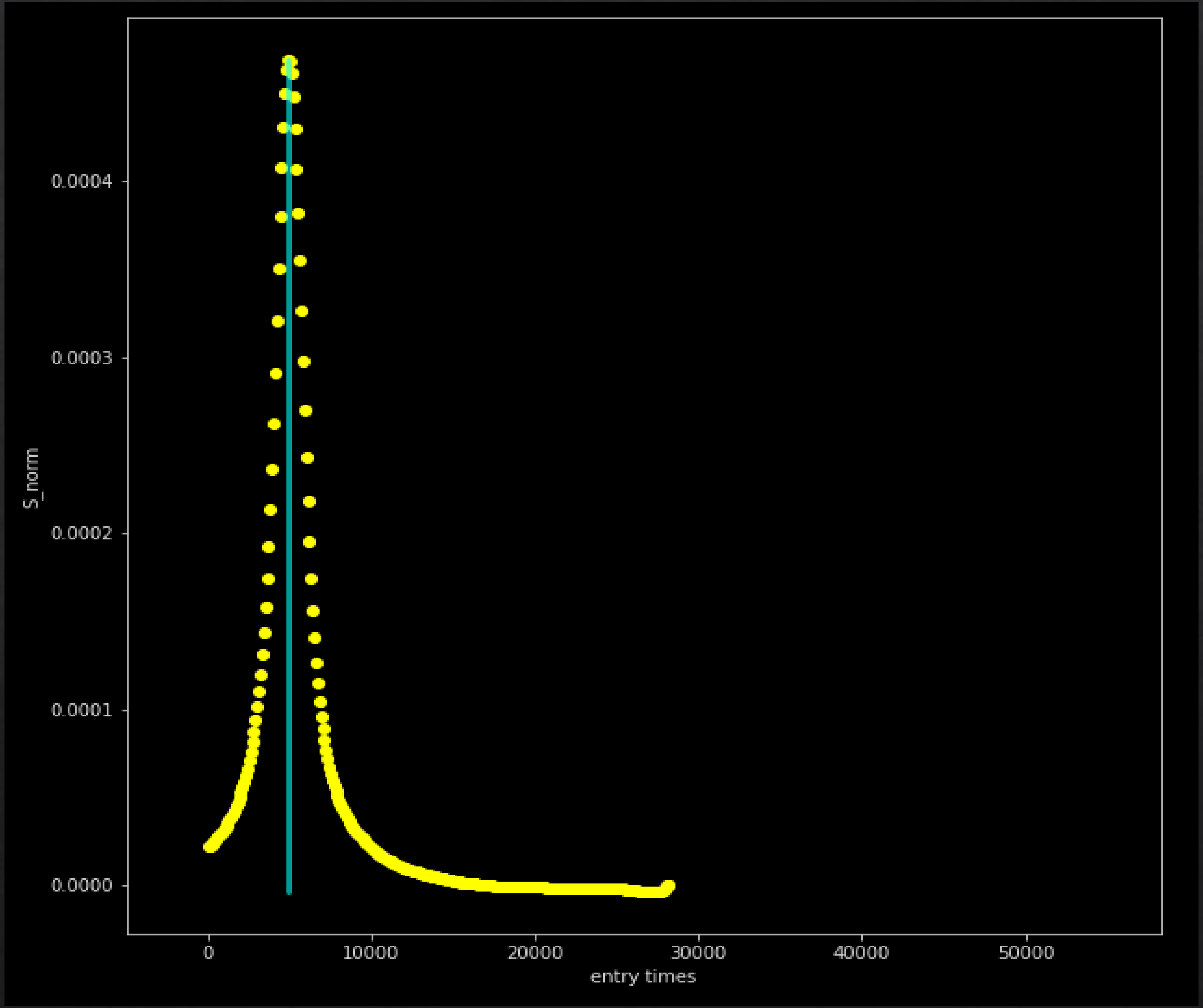

I - Simulation Framework
1. DM Particle
2. Acceleration Data
3. Digitized Data
II - Analysis Framework
(A) Generated Templates
(B) Acceleration Data
Template Matching Method
SNR Results
Track Identification

Template Analysis Parameters

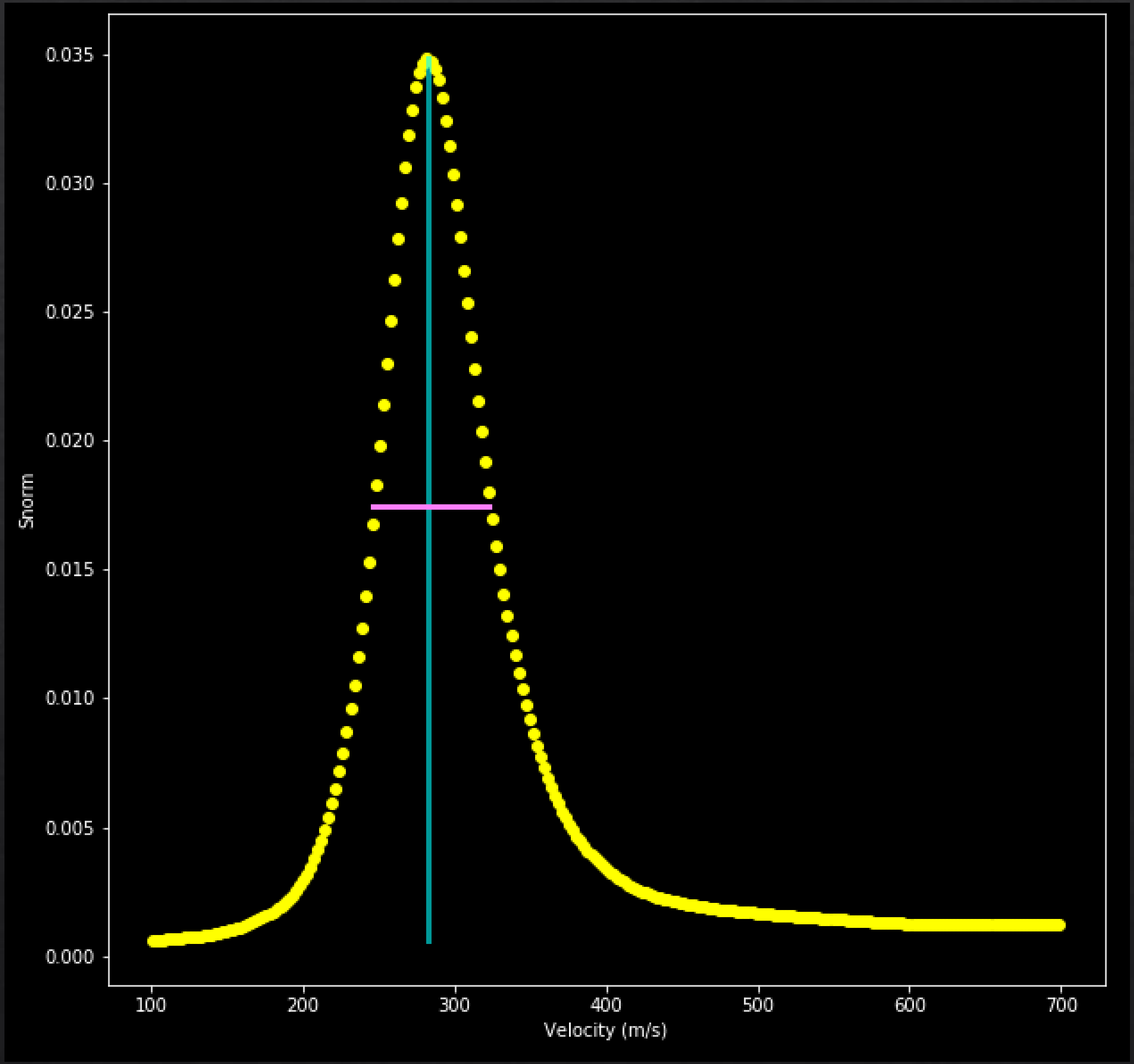
t_{entry} t_{exit} vel θ_0 φ_0 θ_1 φ_1



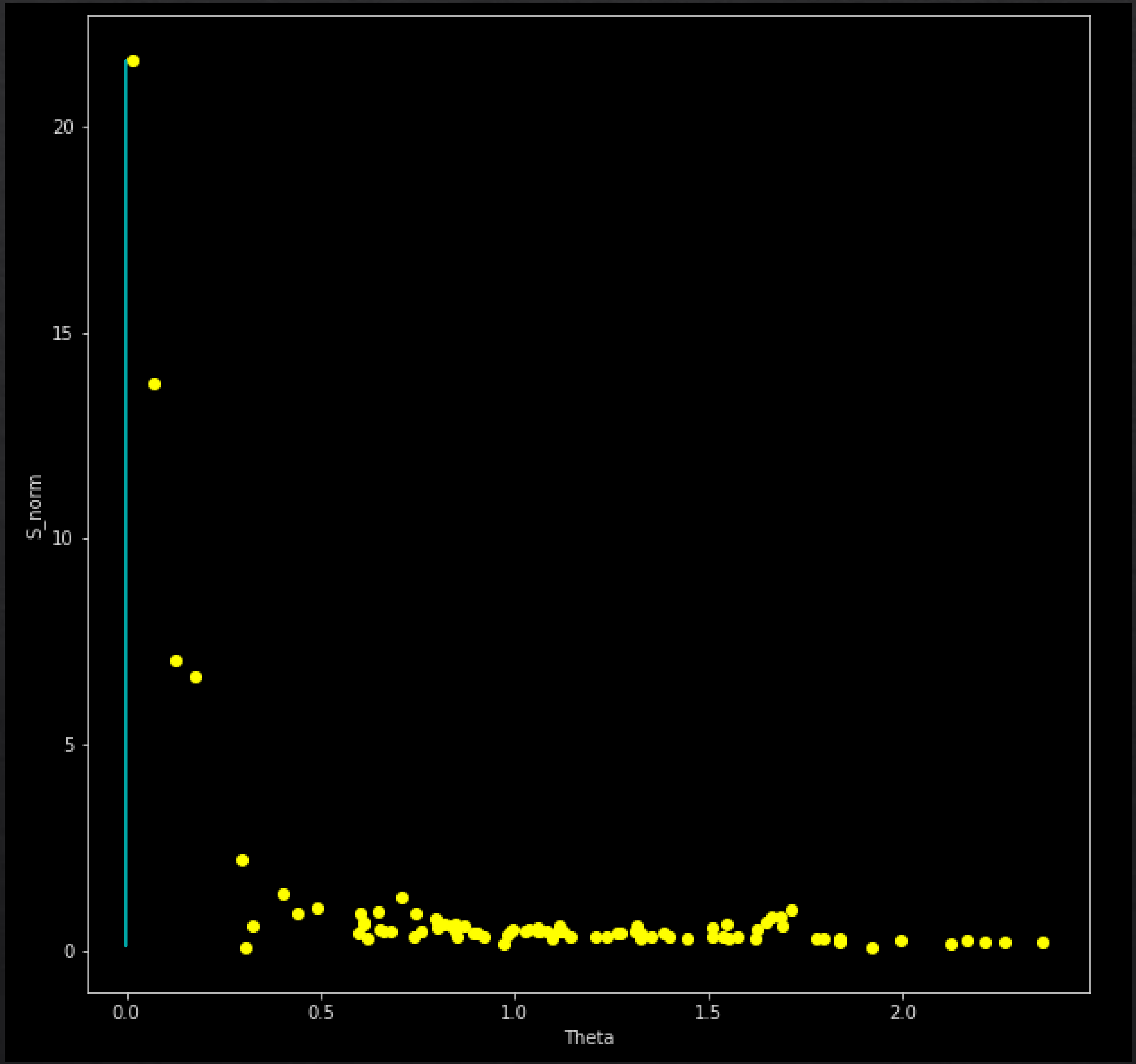
Time Analysis



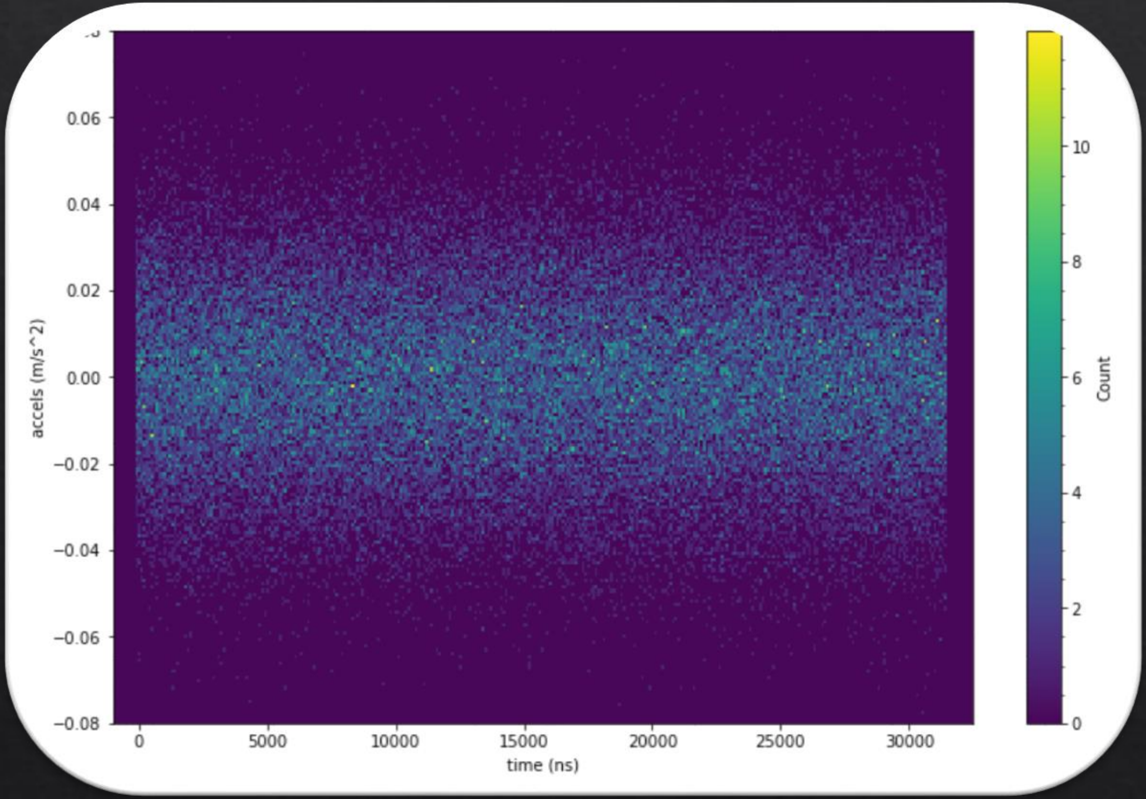
Velocity Analysis

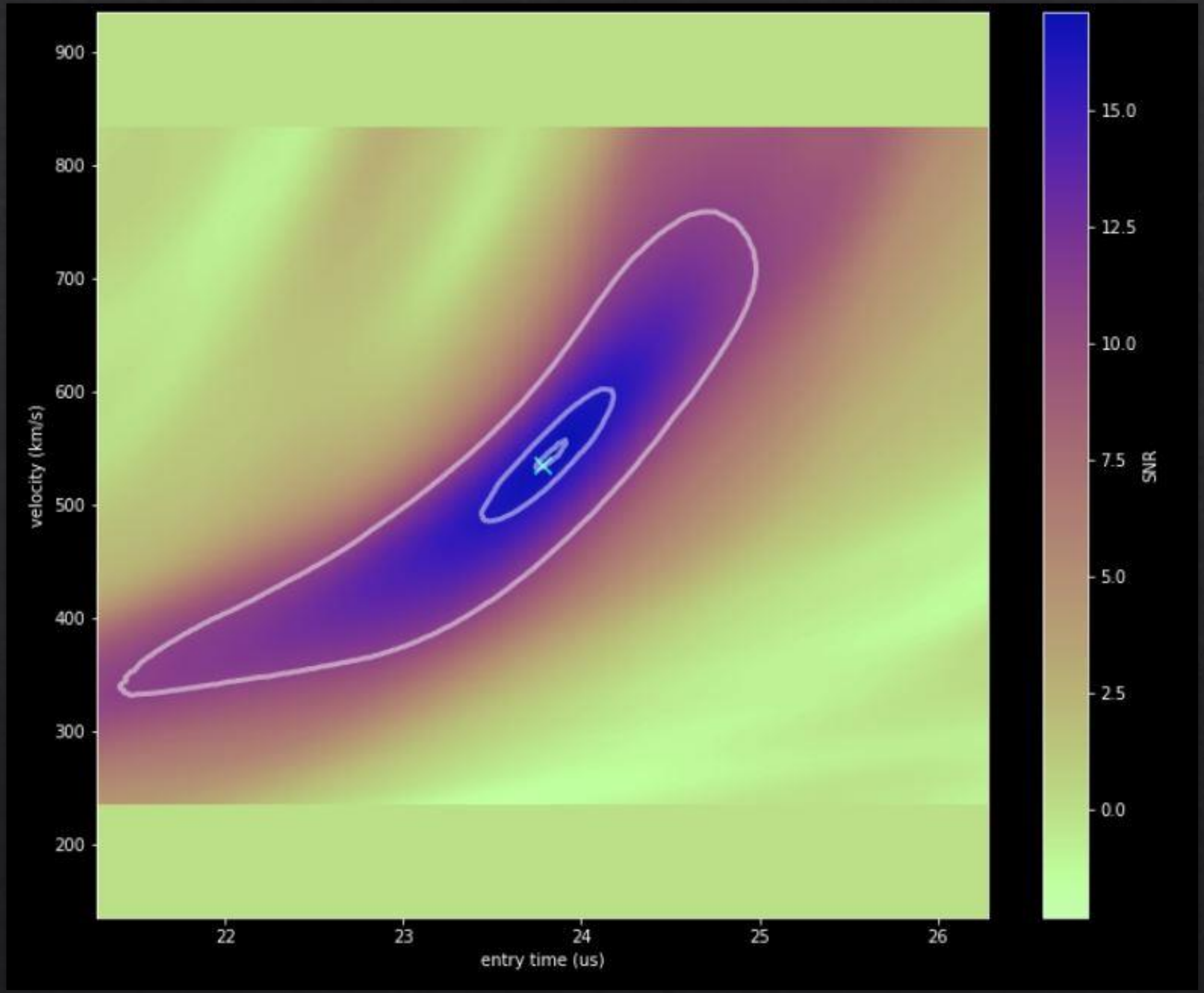


Angular Analysis



Time & Velocity Analysis



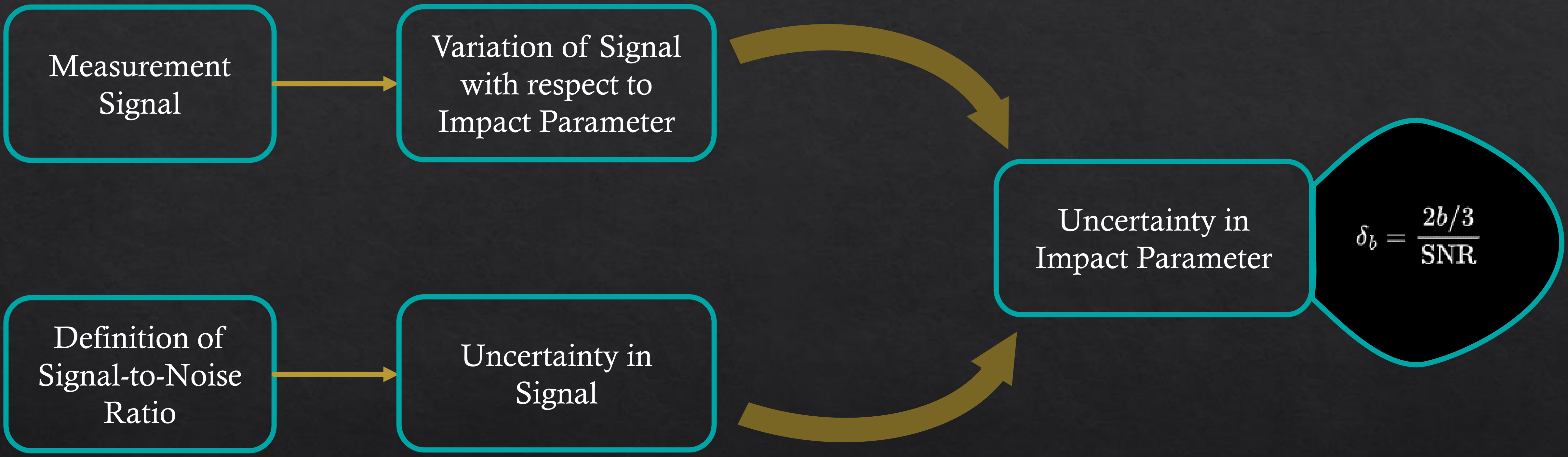


Resolution of the Windchime Detector

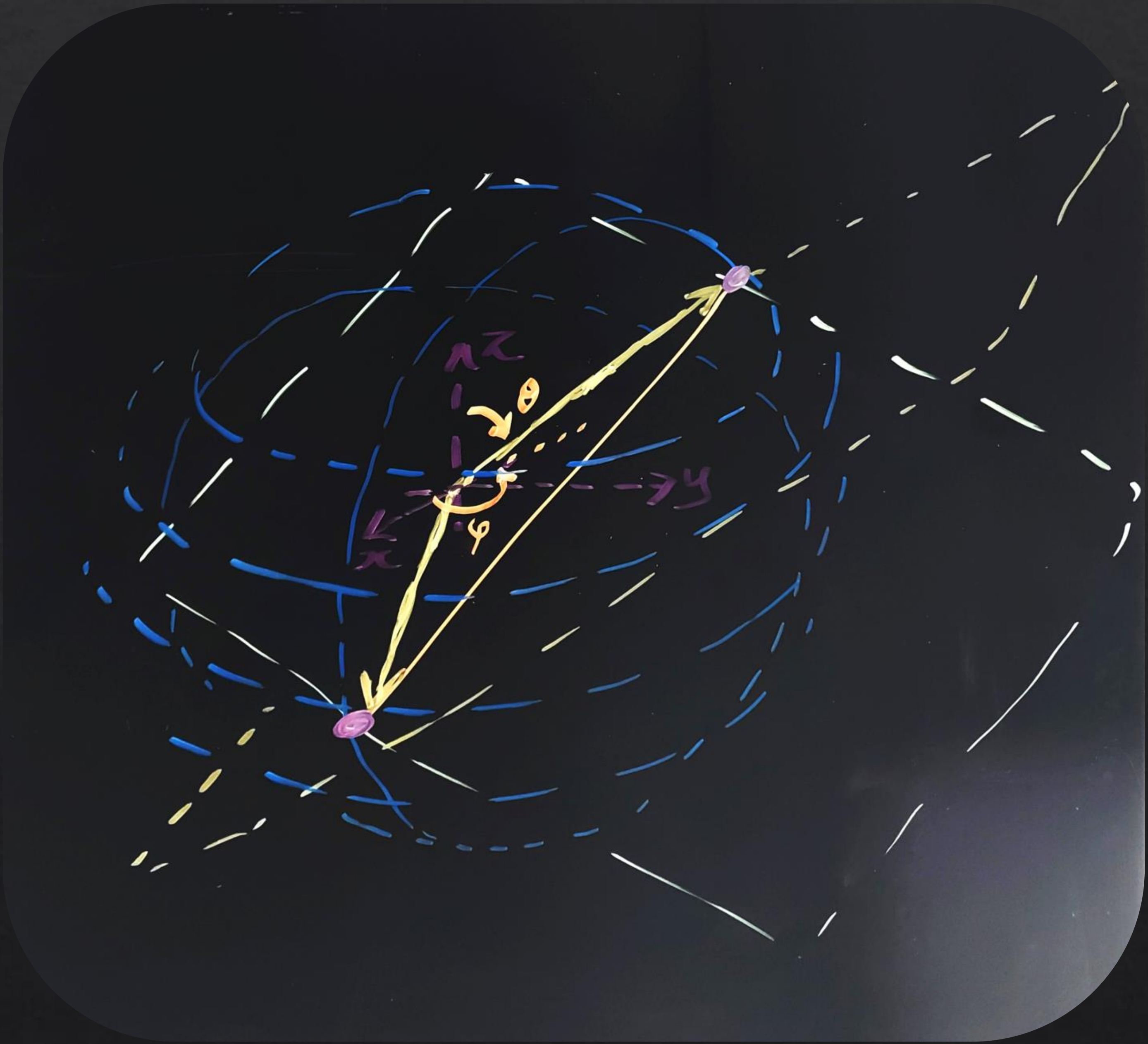
- Capacity to distinguish between different tracks in the detector
  - Smaller Resolution = Better Detector

- Defined through the uncertainty of the track parameters caused by sensor measurement errors
  - Temporal Resolution – Depends on the Exposure Time
  - Spatial Resolution – Depends on the Detector Geometry

Sensor Uncertainty

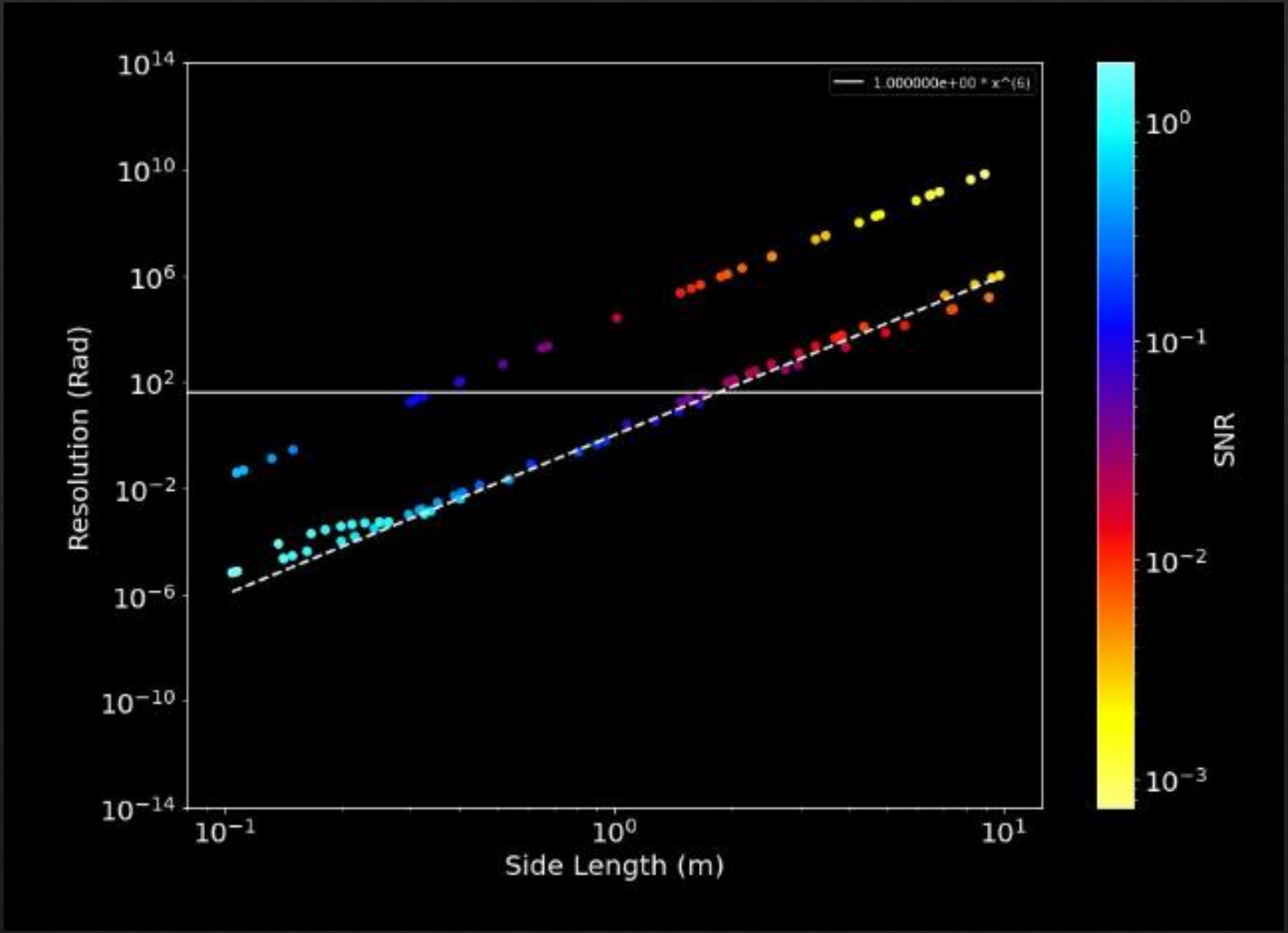


Spatial Resolution Model in 3D



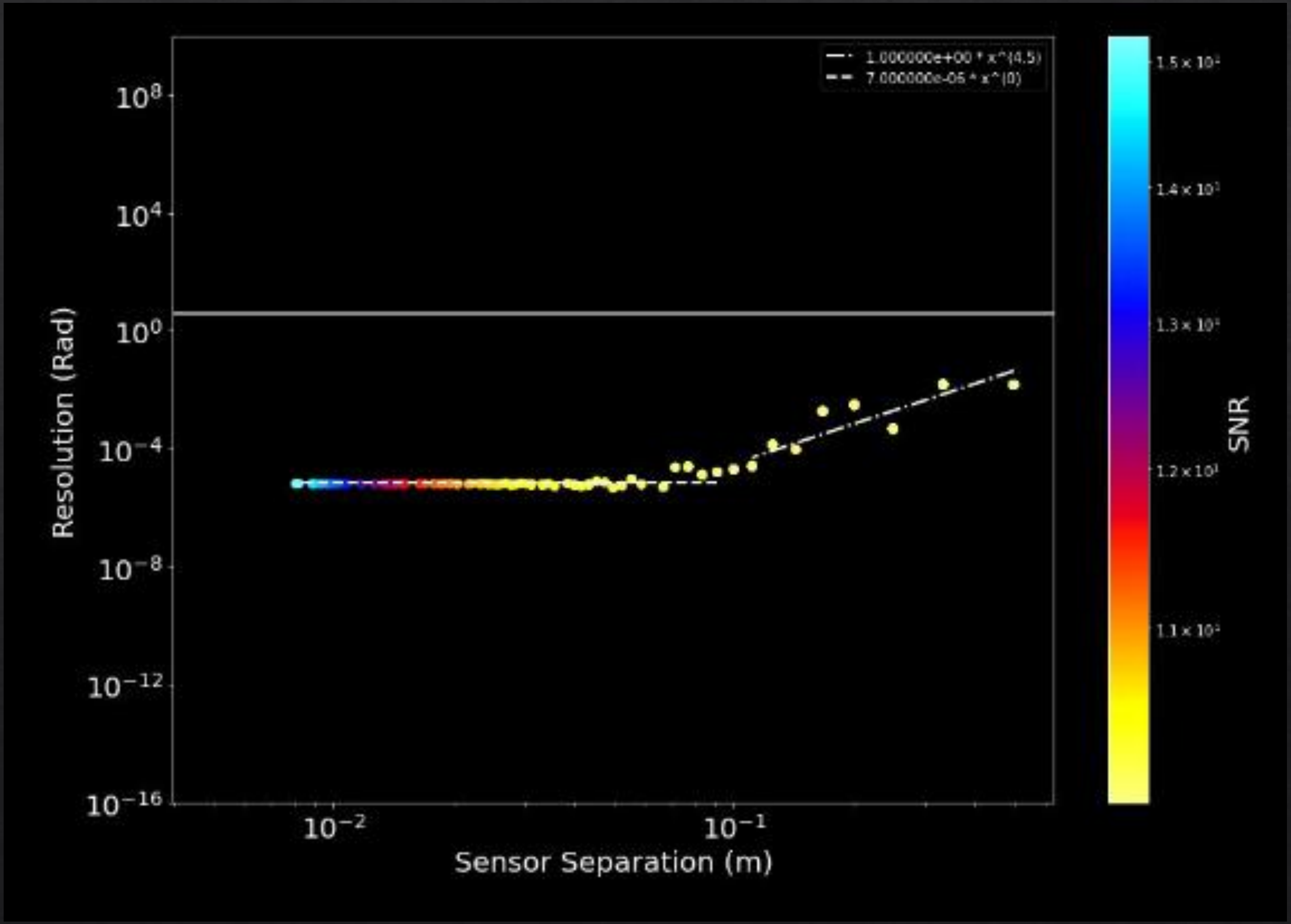
Some of the Results

Constant Number of Sensors 3D Analysis



Some of the Results

Constant SNR and Constant Side Length 2D Analysis



Trial Factor

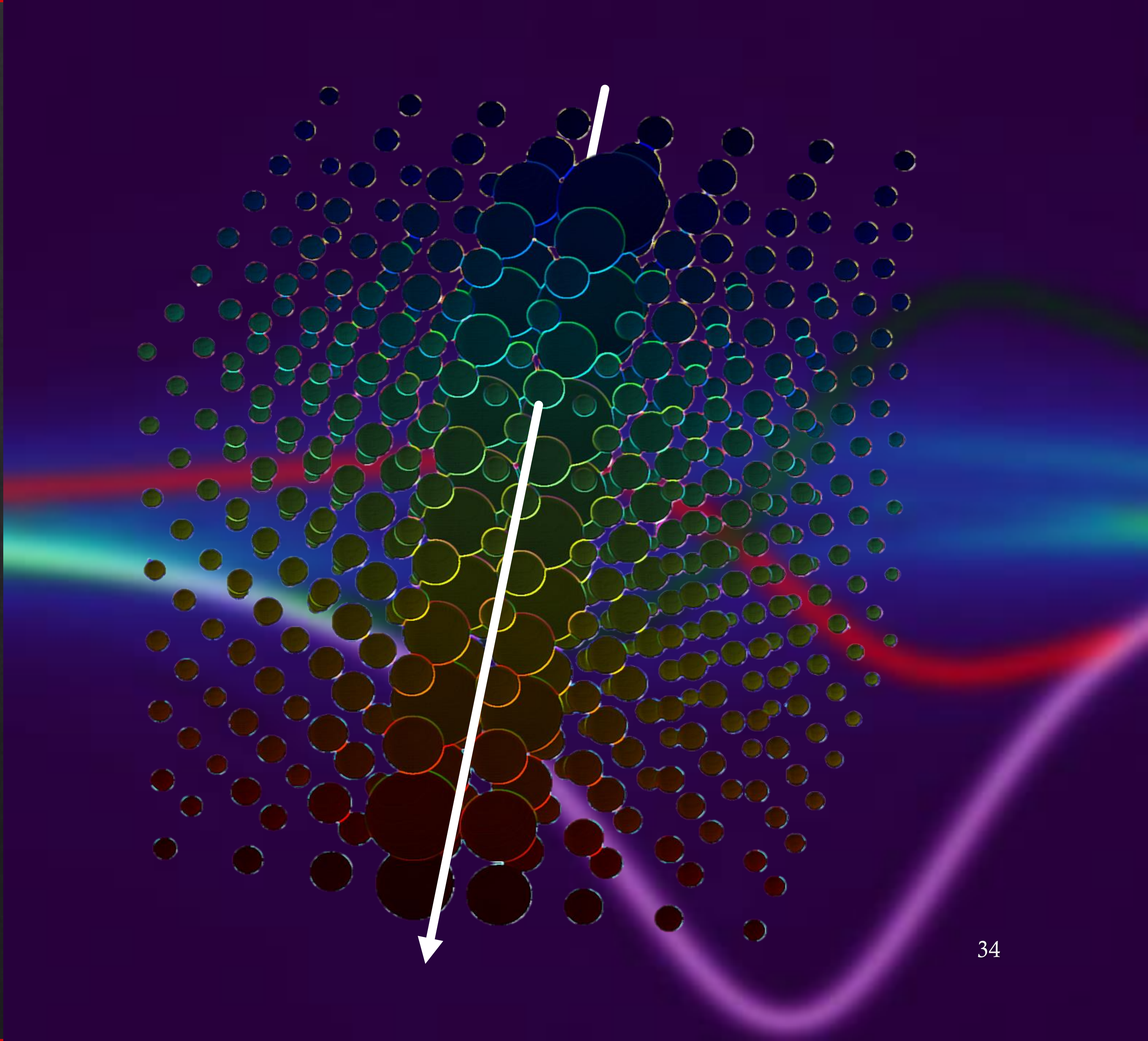
- A measure of how likely it is to have a ***False Positive*** detection purely given the size of the parameter space

Smaller (better) Resolution = Larger Template (parameter) Space = Larger Trial Factor

$$\text{Trial Factor} = \frac{\text{Range Vol}}{\text{Resolution Vol}} \times Z^{\#Dim-1} = \frac{4\pi^4}{\delta_{\theta,entry}\delta_{\theta,exit}\delta_{\varphi,entry}\ \delta_{\varphi,exit}} \times \text{SNR}^3$$

For a specific given detector setup, this takes the detection significance threshold from an ***SNR of 3*** to an ***SNR of 10***

The State of Dark Matter Detection is Going Gravitational!



Thank You!

References

- Gravitational Direct Detection of Dark Matter - https://arxiv.org/pdf/1903.00492.pdf
- Snowmass 2021 White Paper: The Windchime Project - https://arxiv.org/pdf/2203.07242.pdf
- Models of ultra-heavy dark matter visible to macroscopic mechanical sensing arrays - https://arxiv.org/pdf/2112.14784.pdf