Title: Spectral Lines from Relic Quantum Nonequilibrium

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Abstract: <p>In the de Broglie-Bohm pilot-wave formulation of quantum theory, standard quantum probabilities arise spontaneously through a process of dynamical relaxation that is broadly similar to thermal relaxation in classical physics. If we are to regard this process as the cause of the quantum probabilities we observe today, then we must infer a primordial â€˜quantum nonequilibriumâ€™ in the remote past. Such quantum nonequilibrium may have left observable traces today, perhaps in the cosmic microwave background, or in relic particle species that decoupled in the very early universe and that have been sufficiently minimally interacting ever since. The search for the dark matterâ€"that we observe today only through its gravitational interactionsâ€"has provided a compendium of particle species that could at least in
principle carry quantum nonequilibrium. If they did indeed exist, nonequilibrium distributions would not only demonstrate the need to reevaluate the canonical quantum formalism, but also generate new phenomena that lie outside the domain of conventional quantum theory, potentially opening up a large domain for investigation. We will develop a simple, parameter free, quantum field theoretical model of spectral measurement, and use it to demonstrate some of the novel effects that could occur to the profiles of the line spectra of such relic particles. We find for instance, line broadening effects that scale with the resolution of the telescope, the possibility of line narrowing and other effects that could cause multiple bumps to form. We use this discussion to comment on possible implications on the indirect search for dark matter.</p>

Spectral Lines from Relic Quantum Nonequilibrium

Perimeter Institute seminar in Quantum Foundations

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Contents

What is de Broglie-Bohm Theory?

Reinterpret quantum probabilities

Quantum probabilities $\longrightarrow$ ignorance probabilities

$$|\psi|^2 \longrightarrow \rho$$

Possible since $|\psi(x,t)|^2$ is locally conserved:

$$\frac{\partial}{\partial t}|\psi|^2 + \nabla.\left(|\psi|^2\mathbf{v}\right) = 0, \tag{1}$$

where if we write $\psi = |\psi|e^{iS/\hbar}$, then $\mathbf{v} = \nabla S/m$.

Every quantum system has a definite position (or configuration). But then why would we observe ensemble probabilities of $|\psi|^2$?

Classical Probabilities Arise Spontaneously

In classical mechanics

- Entropy given by

$$S = -k \int d\Omega \rho \ln \rho. \qquad (2)$$

- Both probability densities ρ and volumes $d\Omega$ satisfy the Liouville property - they are conserved along trajectories.

Example

Particle in 1D potential,

$$V(x) = x^6 + 4x^3 - 5x^2 - 4x \qquad (3)$$

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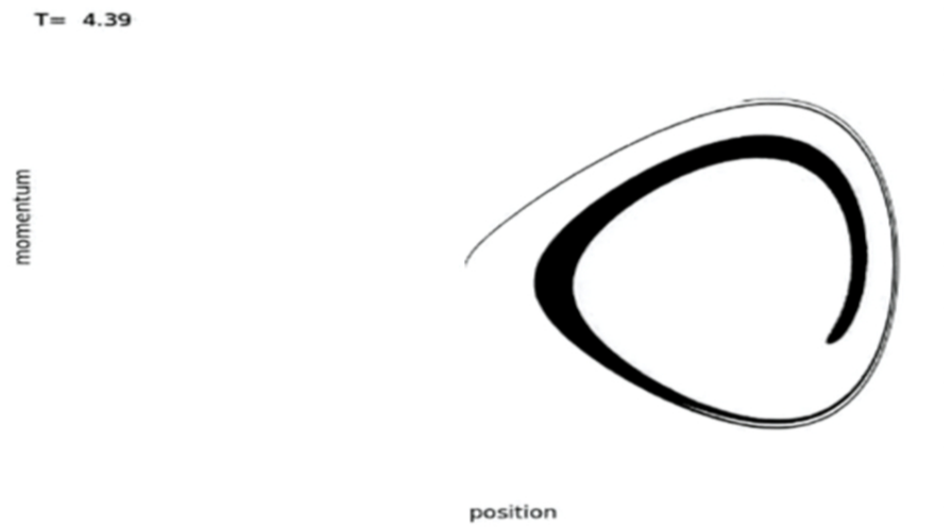


Particle in 1D potential,

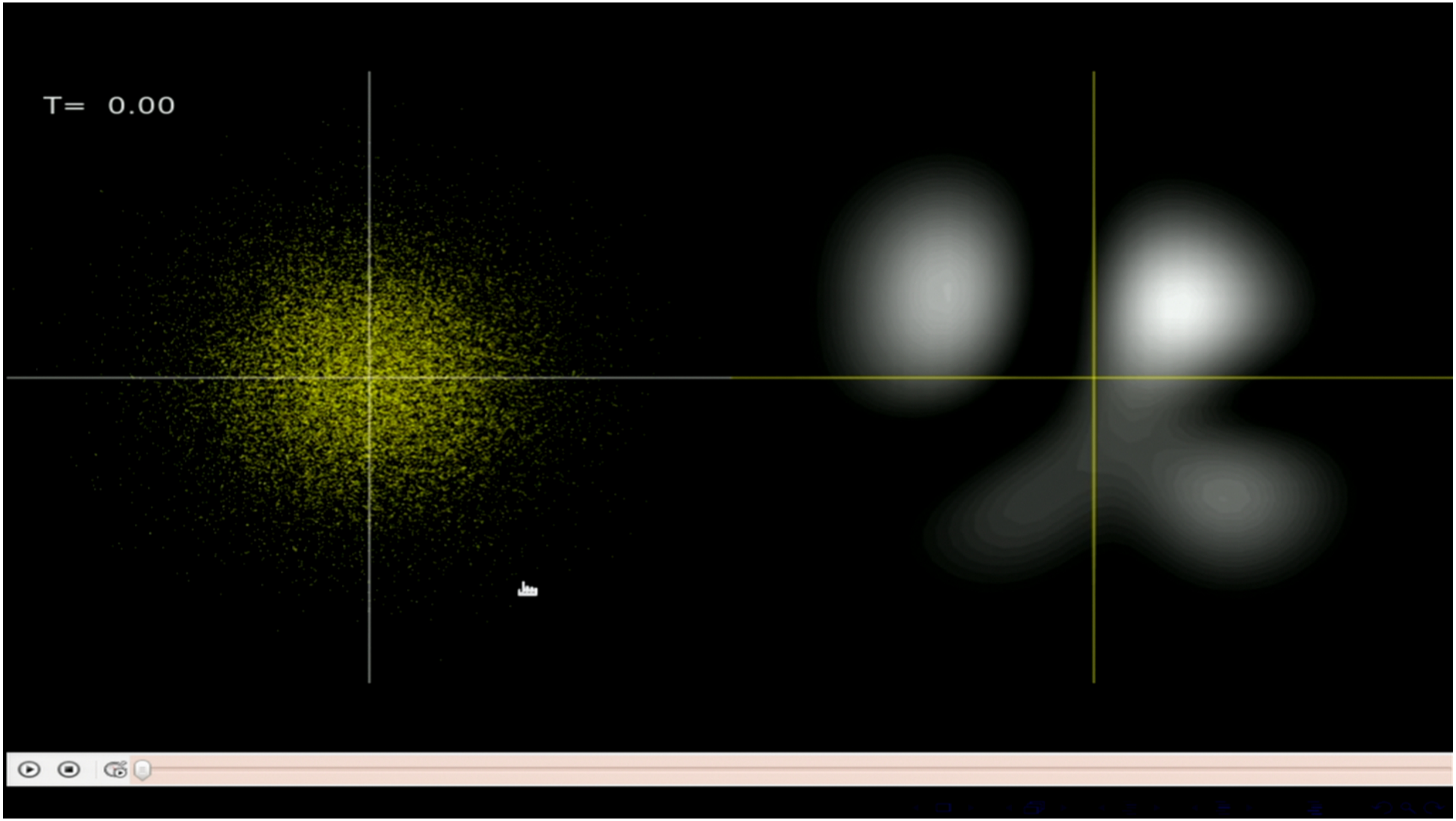
$$V(x) = x^6 + 4x^3 - 5x^2 - 4x \qquad (3)$$

Quantum probabilities Arise Spontaneously

	Classical	Quantum[1]
Liouville property	ρ and $d\Omega$	$f := \rho/|\psi|^2$ and $|\psi|^2 d\Sigma$
Entropy	$S = -k \int \rho \ln \rho \, \mathrm{d}\Omega$	
Maximum Entropy	Uniform distribution	

Example on next slide: 22500 trajectories in a 2D harmonic oscillator

[1] Valentini, A. – Signal-locality, uncertainty, and the subquantum H-theorem. – I Phys. Lett. A, 1991, 156, 5 - 11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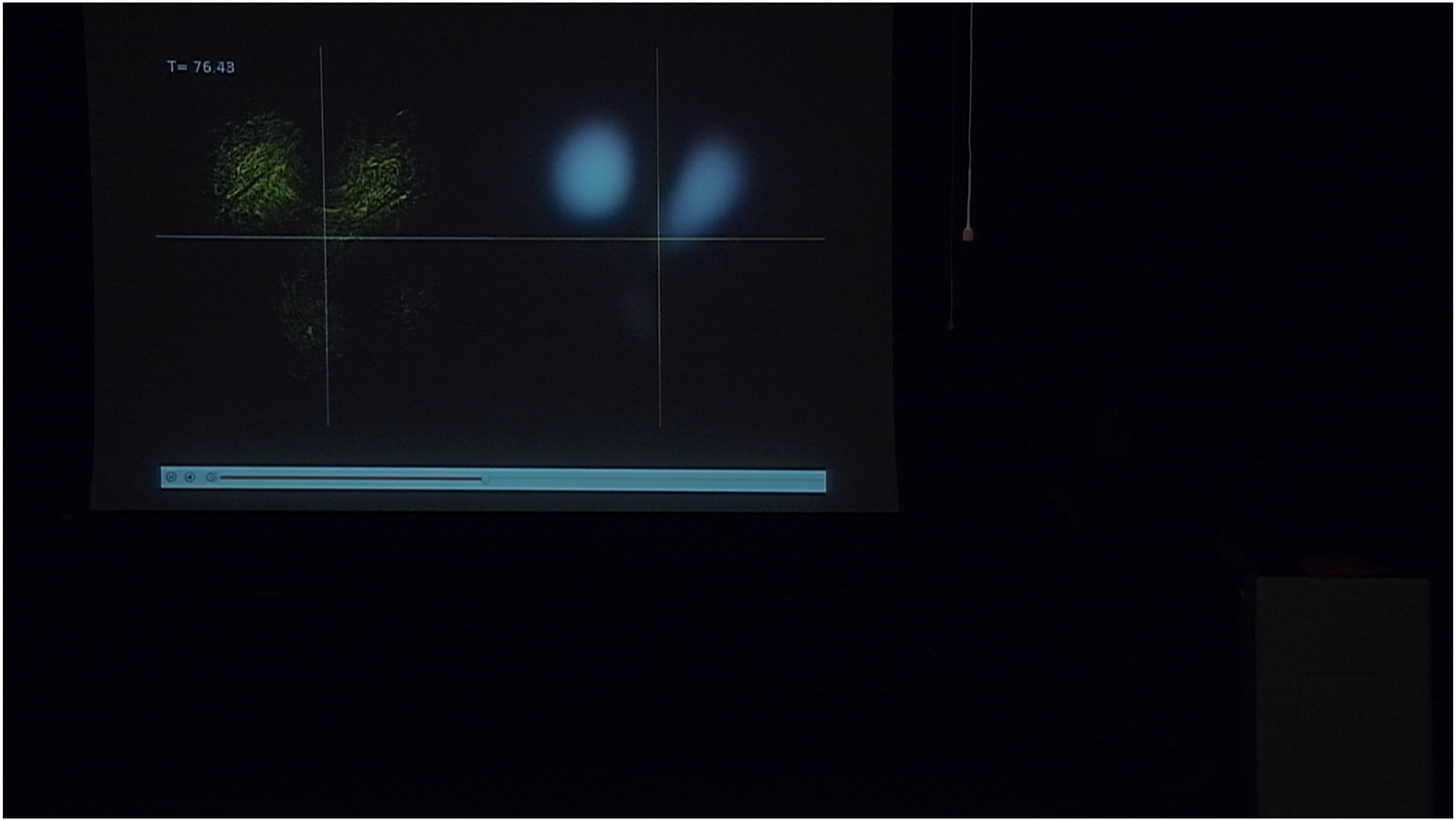
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Could Relic Quantum Nonequilibrium Exist Today?

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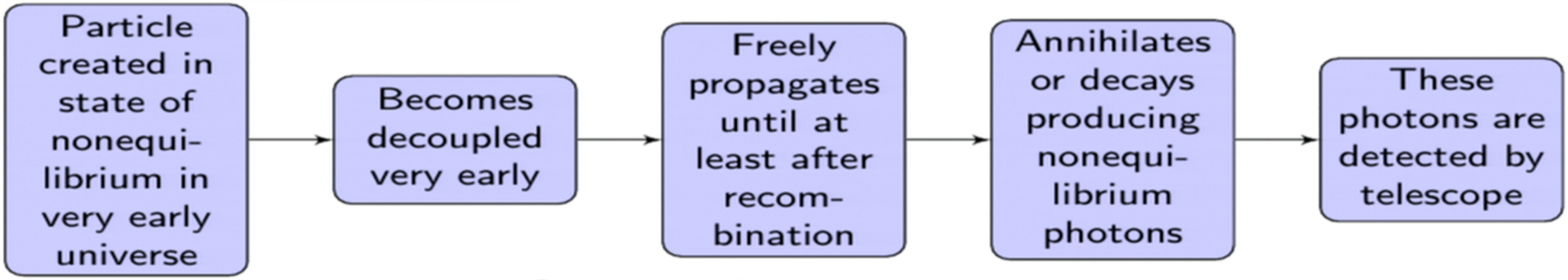
The Basic Scenario



Candidate Particle Species?

- WIMPs
- Neutralinos
- Axions
- Kaluza-Klein DM
- Gravitinos
- Sterile Neutrinos
- SuperWIMPs
- Extended Higgs Sectors
- WIMPzillas

Could Relic Quantum Nonequilibrium Exist Today?

The Basic Scenario

Particle created in state of nonequilibrium in very early universe → Becomes decoupled very early → Freely propagates until at least after recombination → Annihilates or decays producing nonequilibrium photons → These photons are detected by telescope

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Justifications?

Well, we still haven't accounted for $\sim 85\%$ of the matter content of the universe...
Also – the gauge hierarchy problem, the neutrino mass problem, the strong CP problem, the new physics flavor problem...
An illustrative scenario for the gravitino is given in N. G. Underwood and A. Valentini, Phys. Rev. D 92, 063531 (2015).

Take example of γ Ray Telescopes in Search for WIMPs

- The γ photons arrive into telescope one-by-one
- Telescopes measure energy of individual incident photons
- Readings are not perfect, but satisfy the energy dispersion PDF $D(E|E_{\text{true}})$
- Resolution of telescope quantified by spread of this, termed the energy dispersion $\Delta E/E_{\text{true}}$

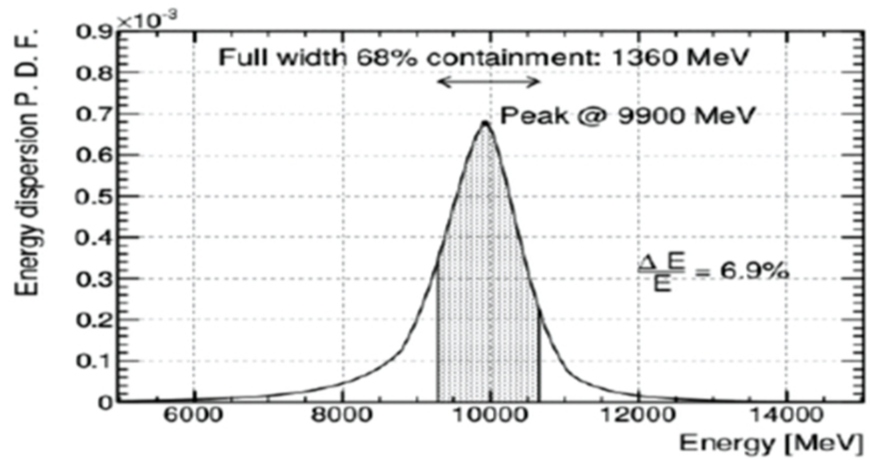
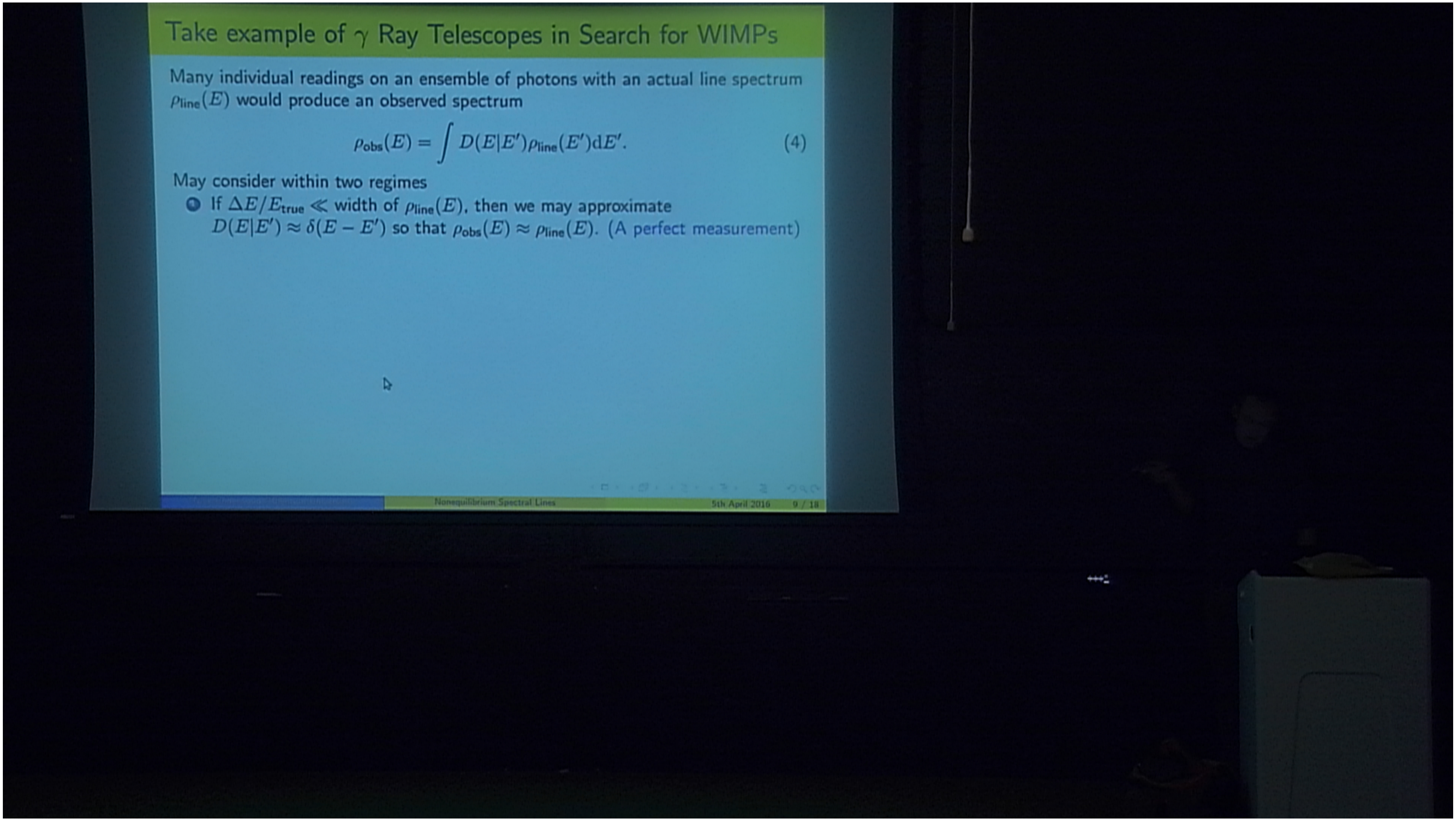


Figure : Example energy dispersion of Fermi LAT (Ackermann et. al. Astrophys. J. Suppl. 2012)

Telescope	Approx. $\Delta E/E$
EGRET	20%
Fermi LAT	10%
DAMPE/GAMMA-400/HERD	1%


Take example of γ Ray Telescopes in Search for WIMPs
Many individual readings on an ensemble of photons with an actual line spectrum $\rho_{\text{line}}(E)$ would produce an observed spectrum
$$\rho_{\text{obs}}(E) = \int D(E|E')\rho_{\text{line}}(E')\mathrm{d}E'. \quad (4)$$
May consider within two regimes
1. If $\Delta E/E_{\text{true}} \ll$ width of $\rho_{\text{line}}(E)$, then we may approximate $D(E|E') \approx \delta(E - E')$ so that $\rho_{\text{obs}}(E) \approx \rho_{\text{line}}(E)$. (A perfect measurement)
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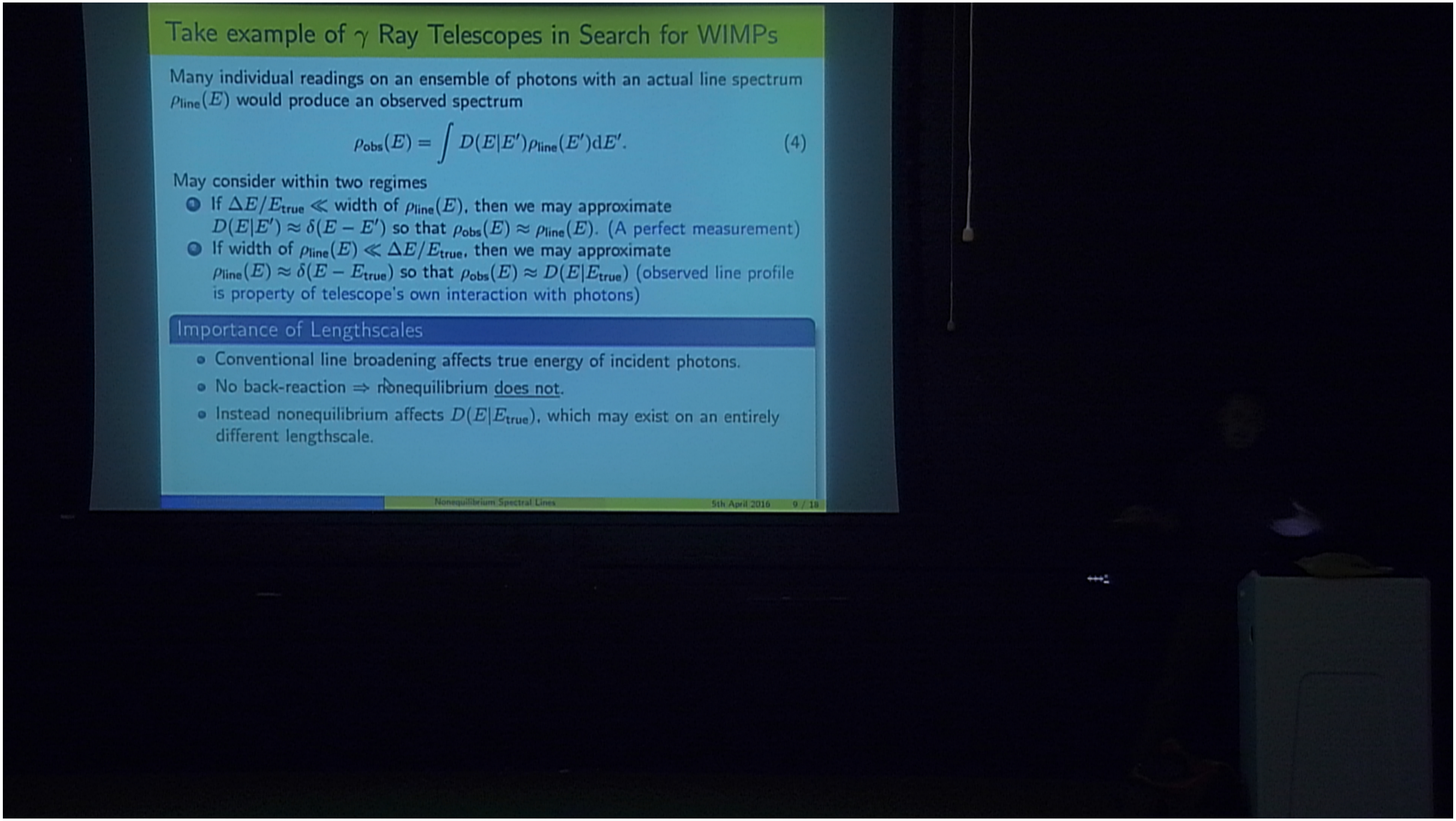
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Importance of Lengthscales
Conventional line broadening affects true energy of incident photons.
No back-reaction ⇒ nonequilibrium does not.
Instead nonequilibrium affects $D(E|E_{\text{true}})$, which may exist on an entirely different lengthscale.
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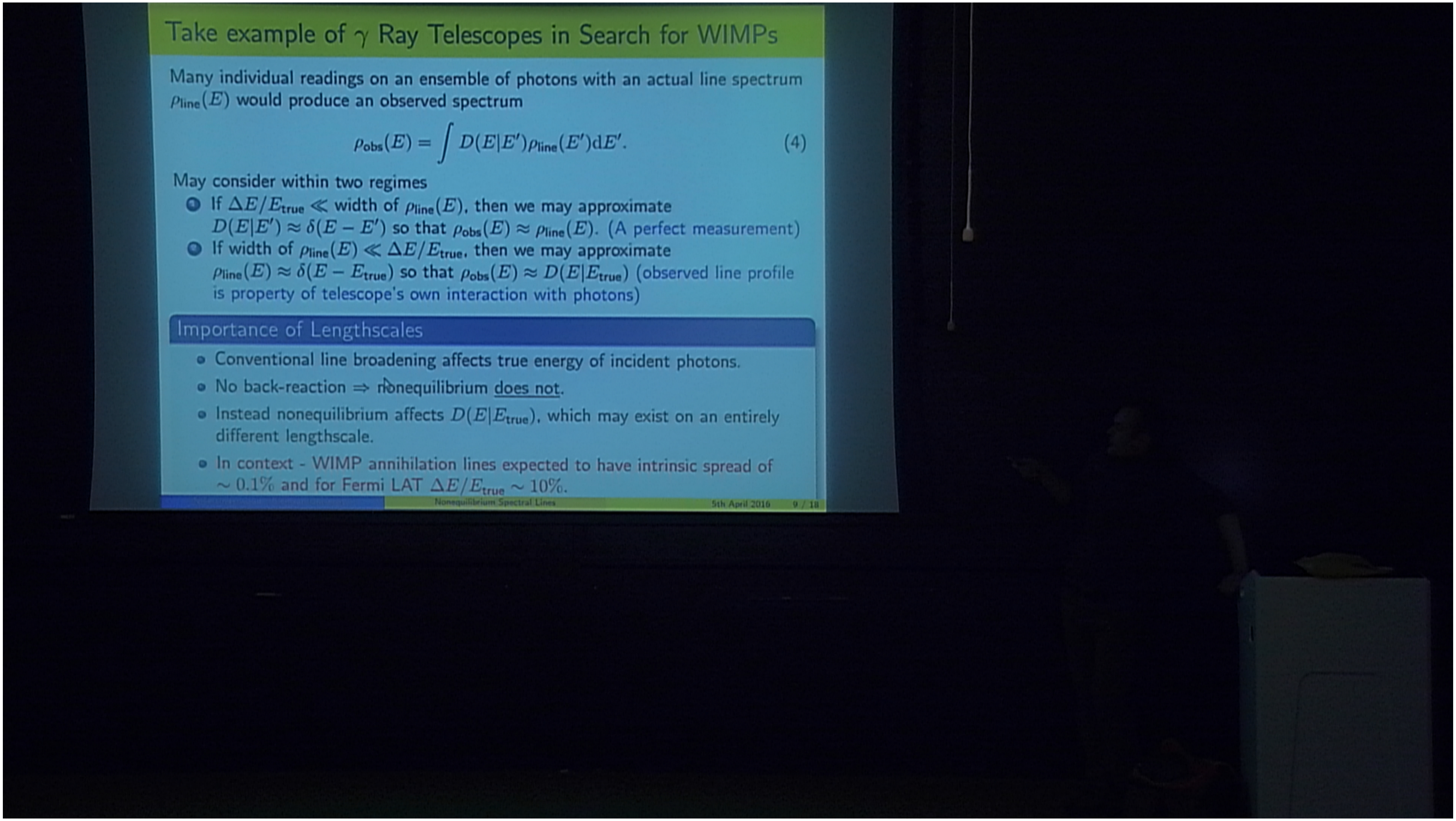
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Importance of Lengthscales
Conventional line broadening affects true energy of incident photons.
No back-reaction $\Rightarrow$ nonequilibrium does not.
Instead nonequilibrium affects $D(E|E_{\text{true}})$, which may exist on an entirely different lengthscale.
In context - WIMP annihilation lines expected to have intrinsic spread of $\sim 0.1\%$ and for Fermi LAT $\Delta E/E_{\text{true}} \sim 10\%$.
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Preliminaries - Measurement in DeBB

In order to measure[2] an observable $\mathcal{A}$ with a discrete nondegenerate spectrum,

1. First, couple the system $\psi(q)$ to a pointer packet $\phi(y)$ with an interaction
$$H_{\text{I}} = g\mathcal{A}p_y. \tag{5}$$
2. Make g large so that the Schrödinger equation is then given by
$$\partial_t \psi = -g\mathcal{A}\partial_y \psi. \tag{6}$$
3. Then, assuming $\psi(q)$ may be expanded in eigenstates of $\mathcal{A}$ as $\psi(q) = \sum_n c_n \psi_n(q)$, the evolution is
$$\psi(q)\phi(y) \rightarrow \sum_n c_n \psi_n(q)\phi(y - ga_n t). \tag{7}$$

[2] Holland, P. R., CUP, Cambridge 1993

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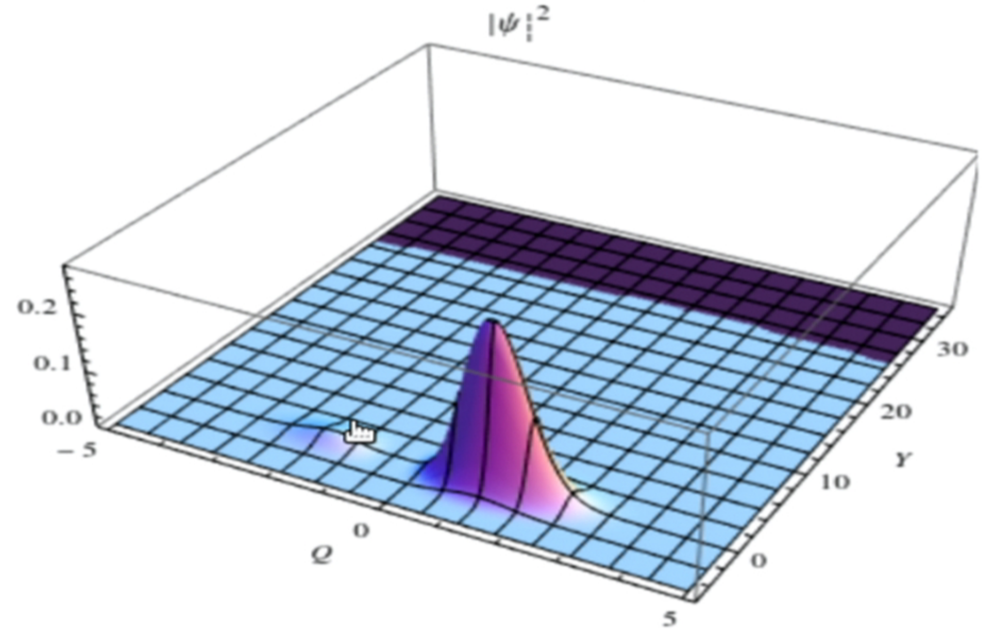
Preliminaries - Measurement in DeBB

- Over time, the different components of $|\psi|^2$ separate in pointer space.
- The conclusion of one such measurement is to find the pointer in the nth region with the nth eigenvalue, at a probability of $|c_n|^2$.
- The discrete spectrum, $|c_n|^2$, may then be reconstructed by repeated measurements over an ensemble.

Example: 1D harmonic oscillator with $c_0 = c_1 = c_2 = 1/\sqrt{3}$.



Recipe for Idealized Spectral Measurement

- This time couple a pointer to the entire (box normalized) electromagnetic field Hamiltonian, $H_{\mathsf{I}} = gH_{\mathsf{EM}}p_y$.
- Treat pointer packet as initially Gaussian of variance σ_y^2.
- Take readings as if $\sigma_y = 0$.
- Perform measurements on individual photons ($n = 1$ number states).
- May show that the energy dispersion PDF is

$$D(E|E_{\mathsf{true}}) = \frac{1}{\sqrt{2\pi}}\frac{gt}{\sigma_y}e^{-\frac{1}{2}\left(\frac{gt}{\sigma_y}\right)^2(E-E_{\mathsf{true}})^2} \quad (8)$$

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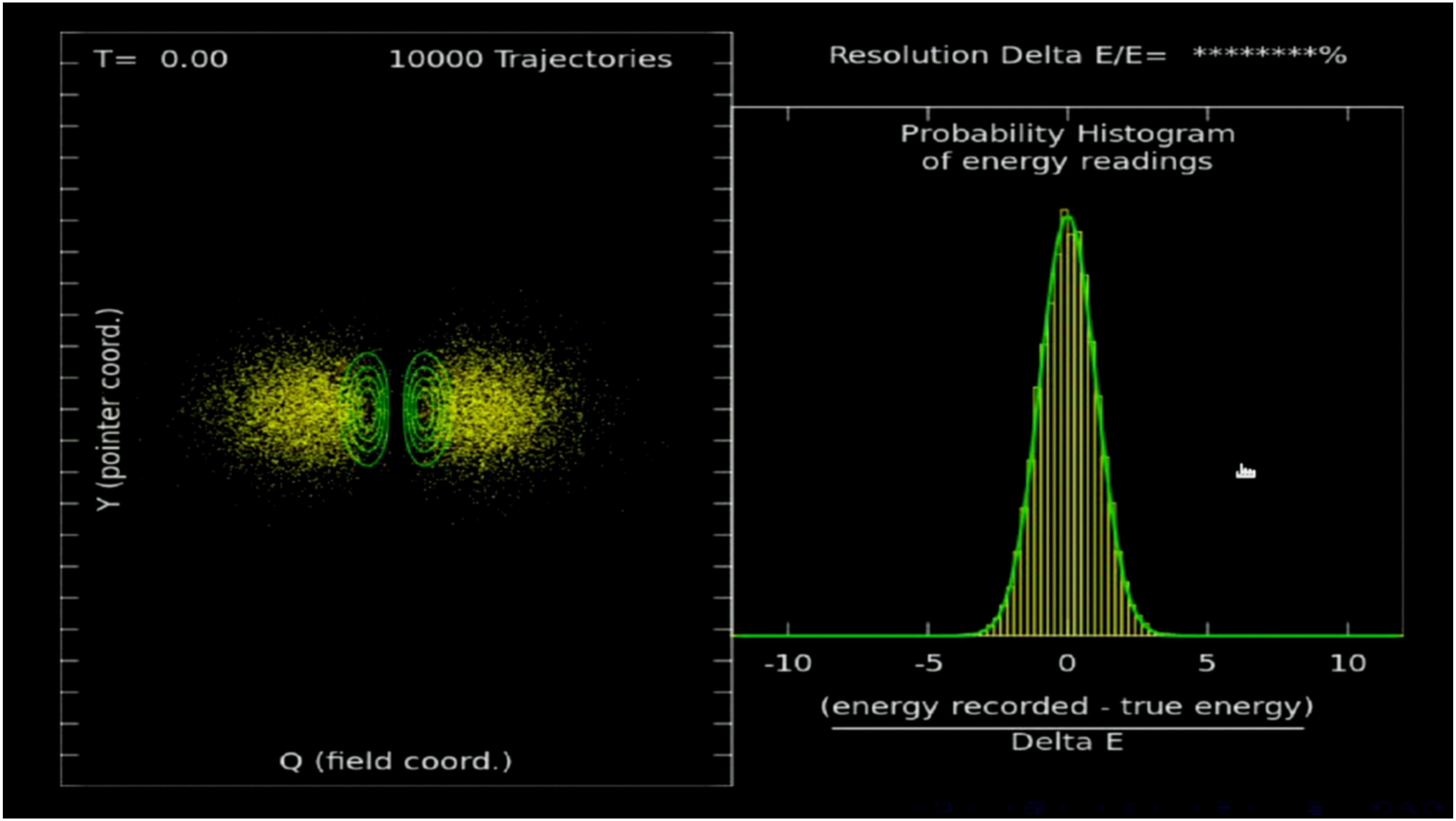
Parameter free!

- The free parameters in the setup (g, σ_y and t) are difficult to interpret.
- But, their combination is simply the resolution of the telescope.
- Define a new time variable

$$T = \frac{gtE_{\text{true}}}{\sigma_y} = \left(\begin{array}{c}\text{energy}\\ \text{dispersion}\end{array}\right)^{-1} \quad (9)$$


T= 0.00
10000 Trajectories
Y (pointer coord.)
Q (field coord.)
Resolution Delta E/E= ********%
Probability Histogram
of energy readings
-10
-5
0
5
10
(energy recorded - true energy)
Delta E

Outlook

"Most recently, the possible observation of a gamma-ray line in the Fermi data from the GC region has sparked considerable interest. .... Moreover, the Fermi team has argued that the line profile is too narrow to match the instrument energy resolution reducing the inferred significance." – Cosmic Frontier Indirect Dark Matter Detection Working Group Summary (US DOE) 2013

"The energy spectrum of this structure is consistent with a single spectral line (at energy 127.0 ± 2.0 GeV with $\chi^2 = 4.48$ for 4 d.o.f.). A pair of lines at 110.8 ± 4.4 GeV and 128.8 ± 2.7 GeV provides a marginally better fit" – Su & Finkbeiner arXiv 1206.1616

"On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. ... However, based on the cluster masses and distances, the line in Perseus is much brighter than expected in this model. This appears to be because of an anomalously bright line at E=3.62 keV in Perseus, possibly an Ar XVII dielectronic recombination line, although its flux would be 30 times the expected value and physically difficult to understand." Bulbul et. al. The Astroph. J. 789 1 2014

The End

Thank you for listening