Challenges for a quantum theory of the Universe:

The clock ambiguity and the Born rule crisis

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Trying to make sense of a wavefunction in which we live ("internal observer'):

➔ I've long been satisfied* with the Everett view

➔ But these two issues give even an Everettian problems:

- Clock Ambiguity: Internal time deeply undermines concreteness of physical laws [AA '94 ,AA & Iglesias '07, '08]

- Born Rule Crisis (BRC): Copies of observer in the multiverse destroy utility of Born rule [Page '09]

*Subject to the need for something like Deutsch-Wallace/Zurek

Clock Ambiguity:

A feature of any time reparameterization invariant theory: Internal time.

Consider a state $\left|\Psi\right\rangle_S$

In superspace S

Identify the clock subspace C with $S = C \otimes R$

"the rest"

Clock Ambiguity:

Now consider bases

$\left\{ \left| t_i \right\rangle_C \right\}$ spanning C ("eigenstates of the clock operator")

$\left\{ \left| j \right\rangle_R \right\}$ spanning R

The direct products states form a basis for the superspace, so one can expand any state in superspace:

$$\left| \Psi \right\rangle_S = \sum_{ij} \alpha_{ij} \left| t_i \right\rangle_C \left| j \right\rangle_R$$

Clock Ambiguity:

$$\left|\Psi\right\rangle_S = \sum_{ij} \alpha_{ij} \left|t_i\right\rangle_C \left|j\right\rangle_R$$

Now define

$$\left|\phi(t_i)\right\rangle_R \equiv \sum_j \alpha_{ij} \left|j\right\rangle_R$$

so that

$$\left|\Psi\right\rangle_S = \sum_{ij} \left|t_i\right\rangle_C \left|\phi(t_i)\right\rangle_R$$

In this formalism

$\left|\phi(t_i)\right\rangle_R$ is "the state of the universe at t_i "

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Full info about state and time evolution contained in α_{ij}

In this formalism

$\left|\phi(t_i)\right\rangle_R$ **is "the state of the universe at t_i "**

Clock Ambiguity:

Can show explicitly that a new choice of $S = C' \otimes R'$ split can lead to

$$\left|\Psi'\right\rangle_S = \sum_{ij} \alpha'_{ij} \left|t_i\right\rangle_C \left|j\right\rangle_R$$

with *any* α'_{ij} and thus any state evolving according to any laws!

Clock Ambiguity:

Example:

➔Build $|\Psi\rangle_S$ out of standard model of electroweak physics (for which a Nobel prize has been awarded) .

➔A different choice of clock would yield same world with O(3) model of electroweak physics being true (and presumable with a Nobel prize awarded to *its* inventors).

Clock Ambiguity:

Comments on the clock ambiguity:

→ No similar issue with lab physics. A cosmological perspective is fundamental to this puzzle.

→ Most clock choices give "garbage"

→ No respect for continuum

→ Well-defined measures & probabilities in superspace (no time) required.

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Either some part of the input assumptions are wrong or we must be able to do physics under these conditions (!)

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For further discussion

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Consider this case now

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or we **must be able to do physics under these conditions (!)**

Clock Ambiguity:

Ideas

The search for "Good Clocks" → successful observers

→Thrive as tiny subsystems

→ Learn and predict behavior of surroundings

The search for “Good Clocks” ➔ successful observers

➔Thrive as t

“Anthropic”, but not about what it takes for “life to exist” (equally valid for automatic data acquisition)

➔ Learn and predict behavior of surroundings

The search for “Good Clocks” ➔ successful observers

➔Thrive as tiny subsystems

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➔Thrive as tiny subsystems ➘

Quasi-separability

➔ Learn and predict behavior of surroundings

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Quasi-separability

Locality

→ Learn and predict behavior of surroundings

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Quasi-separability

Locality

$$H = \int \mathcal{H}(x)\, d^3x$$

→ Learn and predict behavior of surroundings

The search for "Good Clocks" ➔ successful observers

➔Thrive as tiny subsystems

Quasi-separability

Locality

$$H = \int \mathcal{H}(x)\, d^3x$$

Most other "random Hamiltonian" work assumes this

havior of surroundings

The search for "Good Clocks" → successful observers

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Quasi-separability

Locality

Metric

$$H = \int \mathcal{H}(x)\, d^3x$$

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Metric

Gauge Theory?

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The search for "Good Clocks" ➔ successful observers

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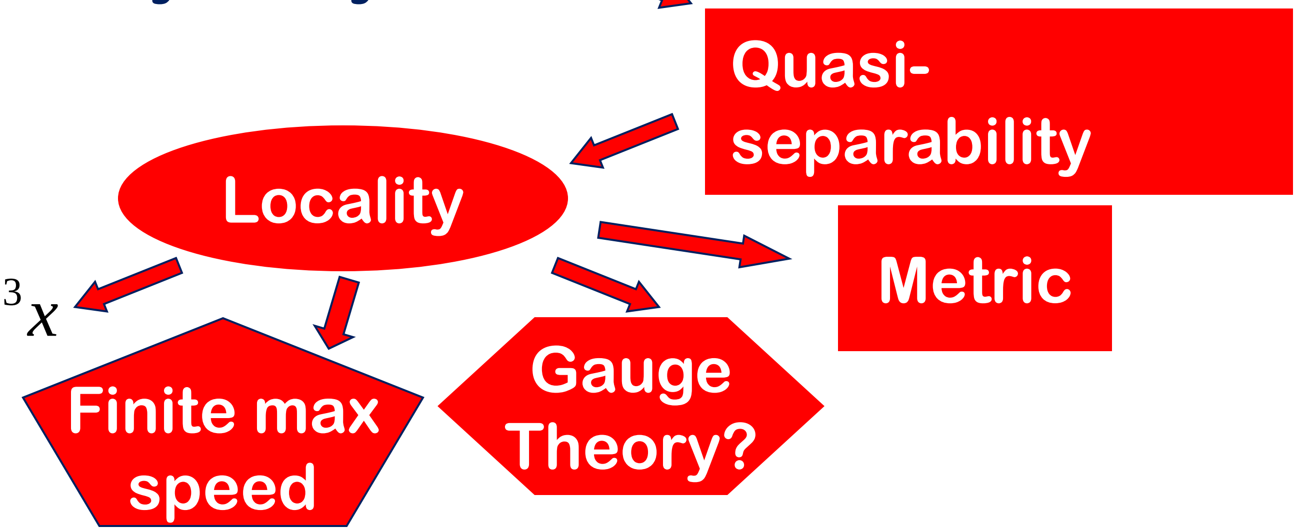

➔ Learn and predict behavior of surroundings

The search for "Good Clocks" → successful observers

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Quasi-separability

Locality

Metric

$$H = \int \mathcal{H}(x)\, d^3x$$

Finite max speed

Gauge Theory?

→ Learn and predict behavior of surroundings

Time independent Hamiltonian

The search for "Good Clocks" → successful observers

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Quasi-separability

Locality

$$H = \int \mathcal{H}(x)\, d^3x$$

Metric

Finite max speed

Gauge Theory?

→ Learn and predict behavior of surroundings

Time independent Hamiltonian

Arrow of time

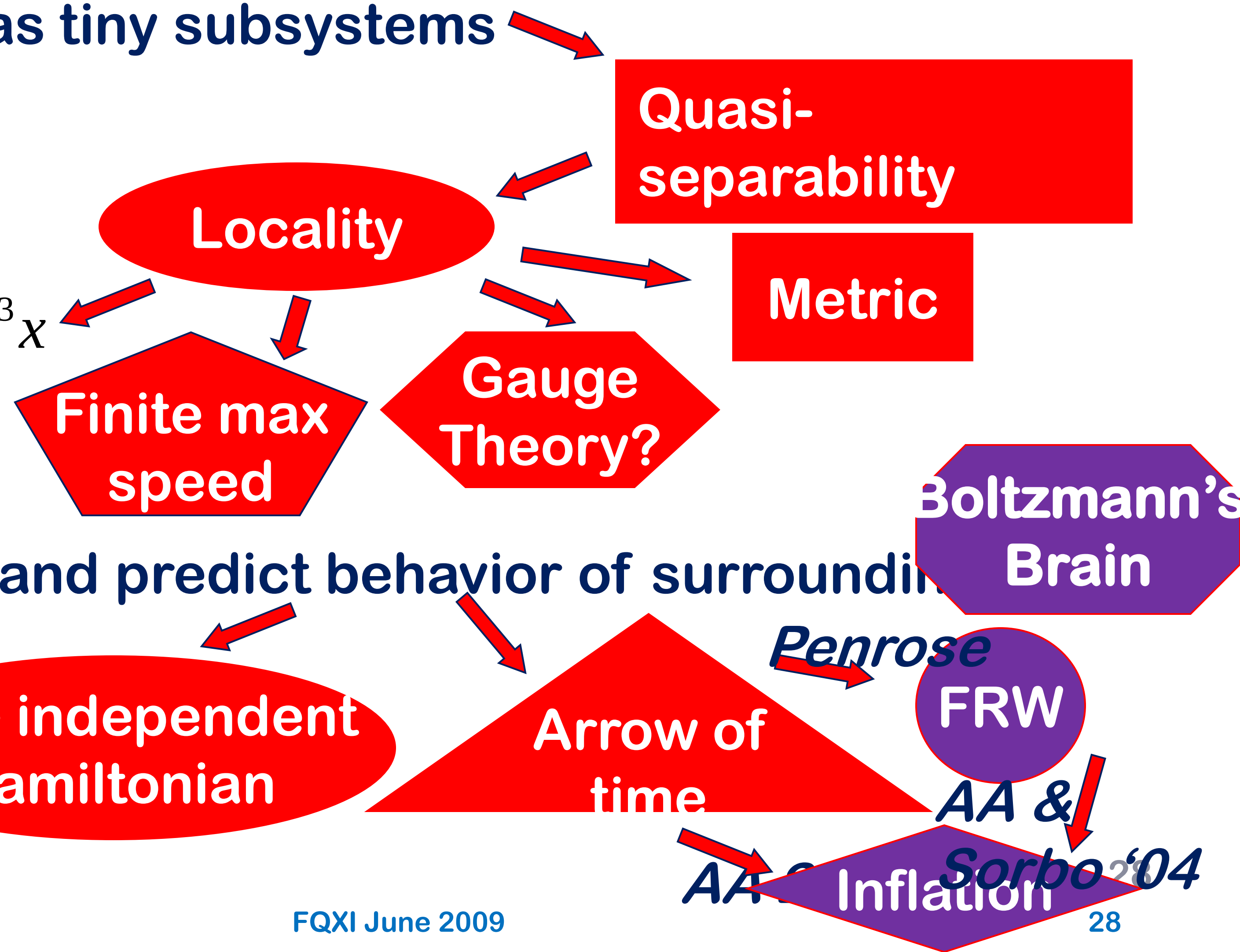
AA 2002

The search for "Good Clocks" ➔ successful observers

➔ Thrive as tiny subsystems

$$H = \int \mathcal{H}(x)\, d^3x$$

➔ Learn and predict behavior of surroundi[ngs]



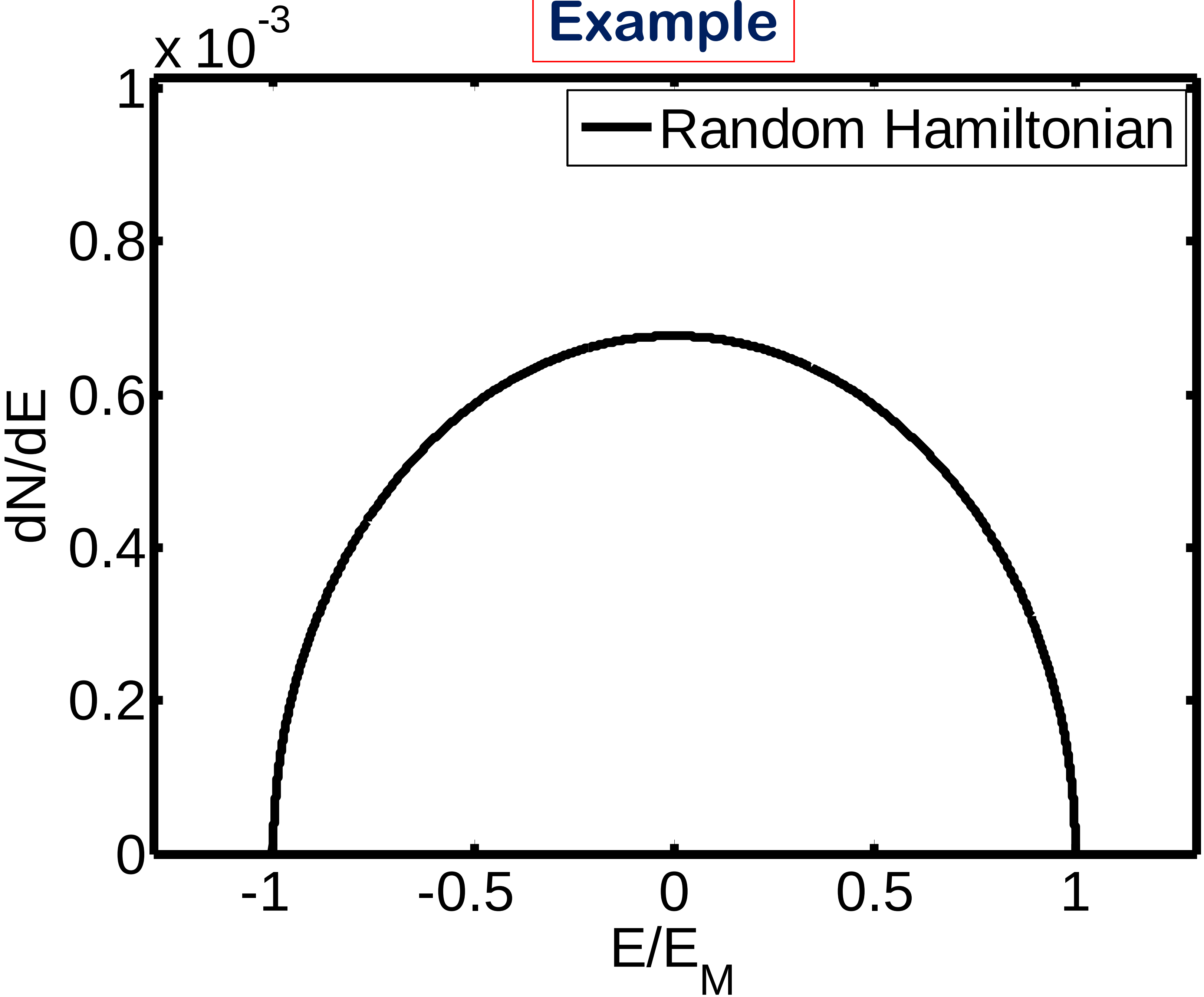
Clock Ambiguity:

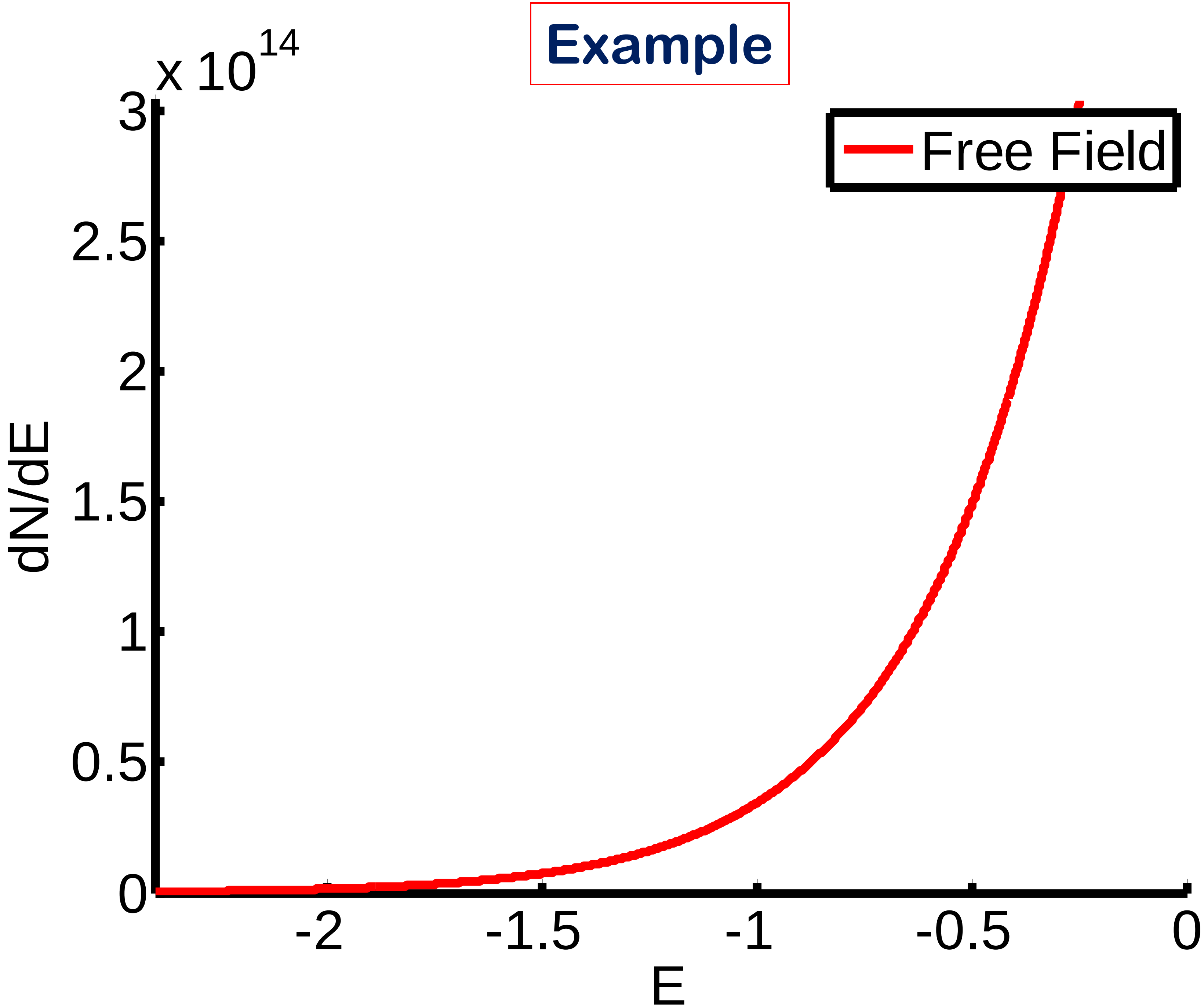
Ideas

Clock Ambiguity:

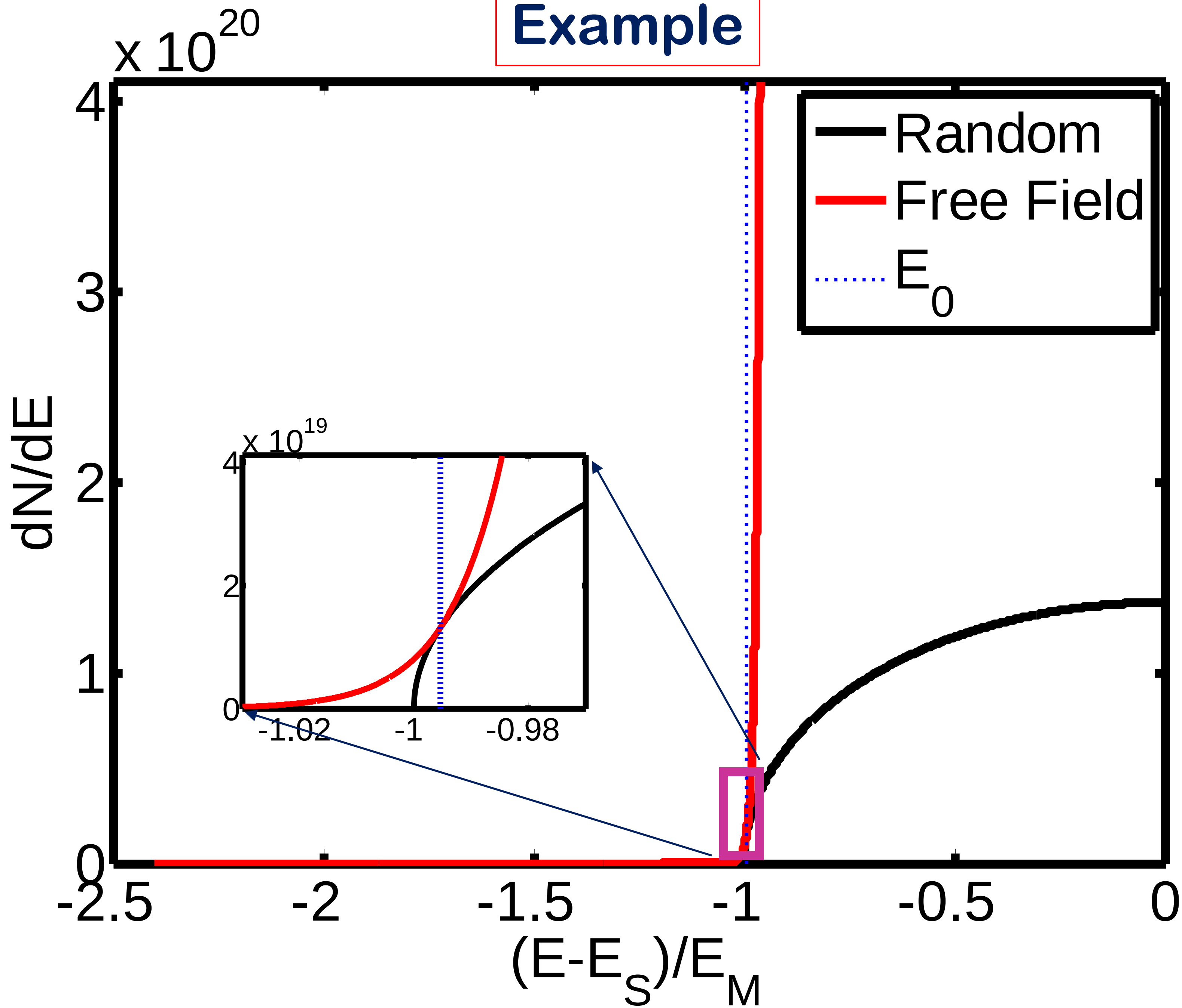
Calculation: Is a random Hamiltonian consistent with a field theory?

Example



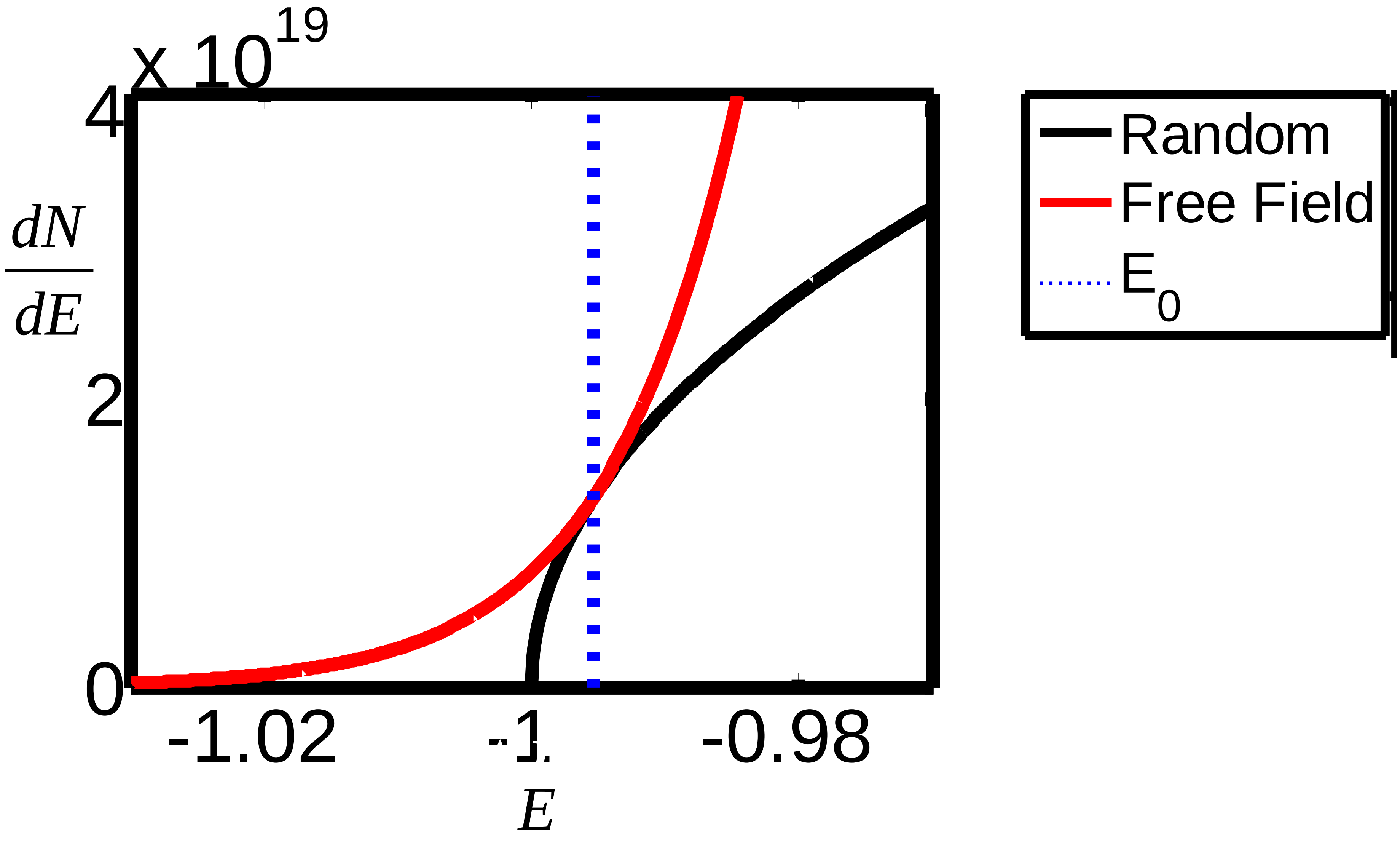

Example
x 10^14
3
2.5
2
1.5
1
0.5
0
dN/dE
-2
-1.5
-1
-0.5
0
E
Free Field

Example



x 10^20
4
3
2
1
0
-2.5
-2
-1.5
-1
-0.5
0
dN/dE
(E-E_S)/E_M
Random
Free Field
E_0
x 10^19
4
2
0
-1.02
-1
-0.98

The term-by-term comparison in pictures



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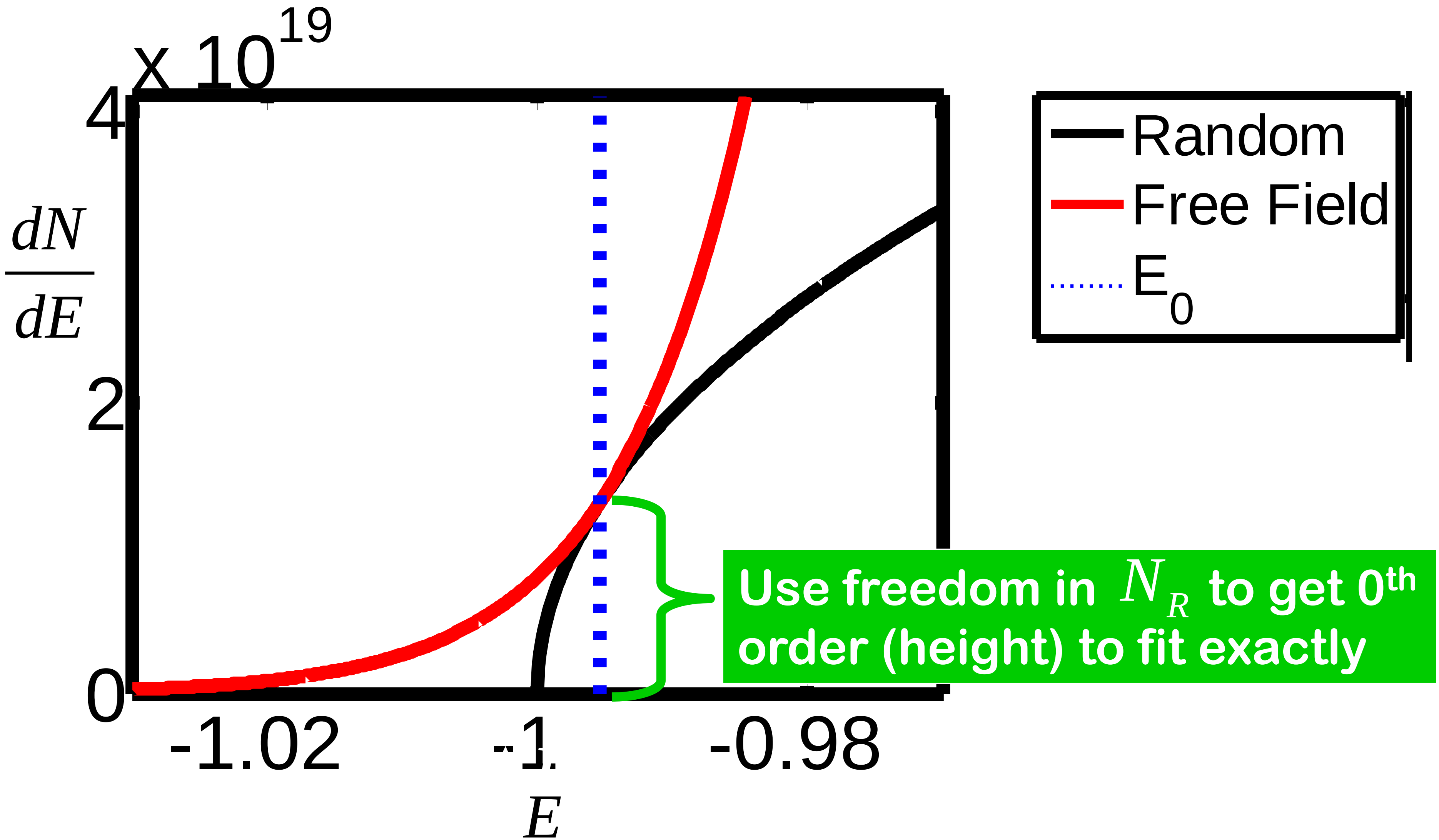

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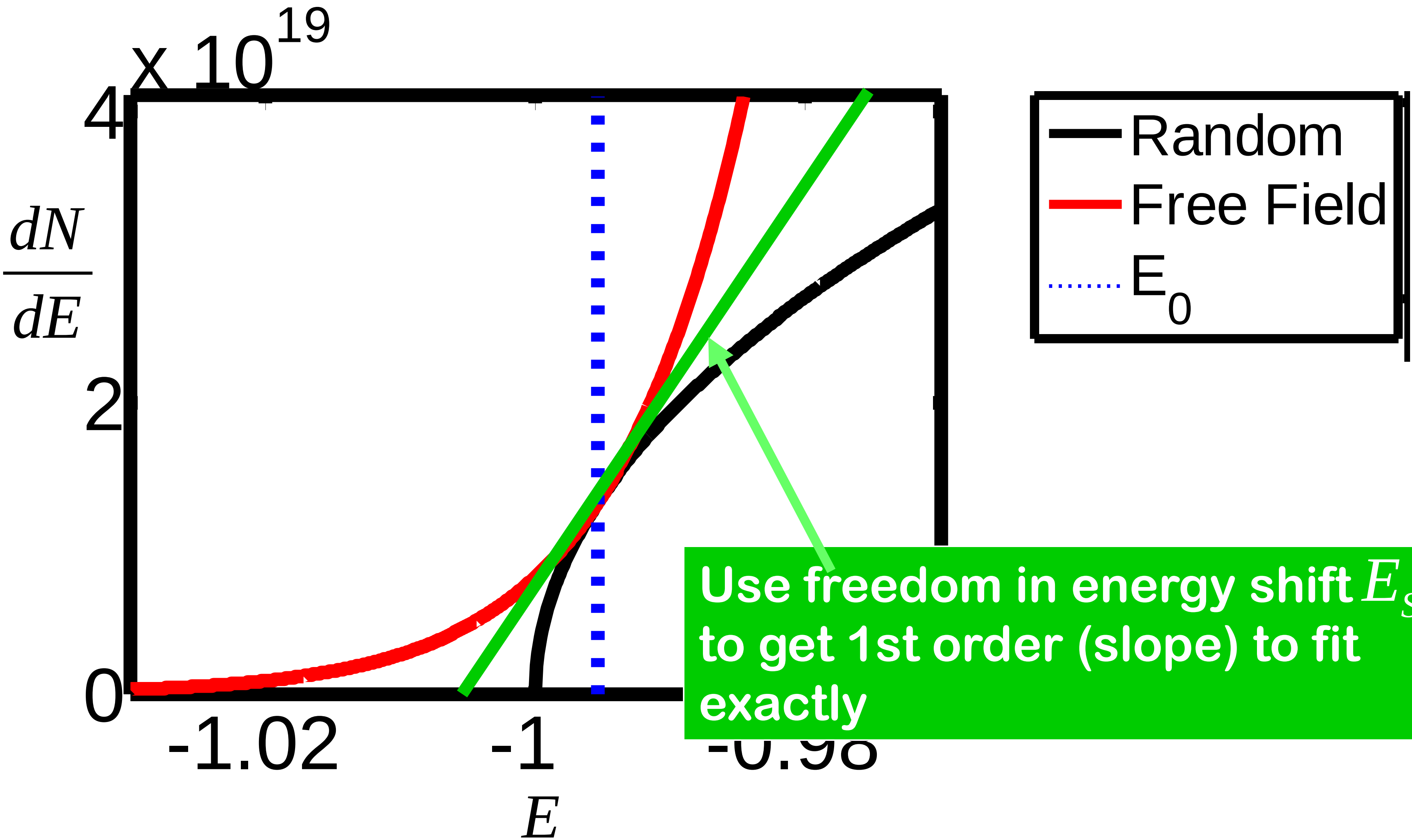
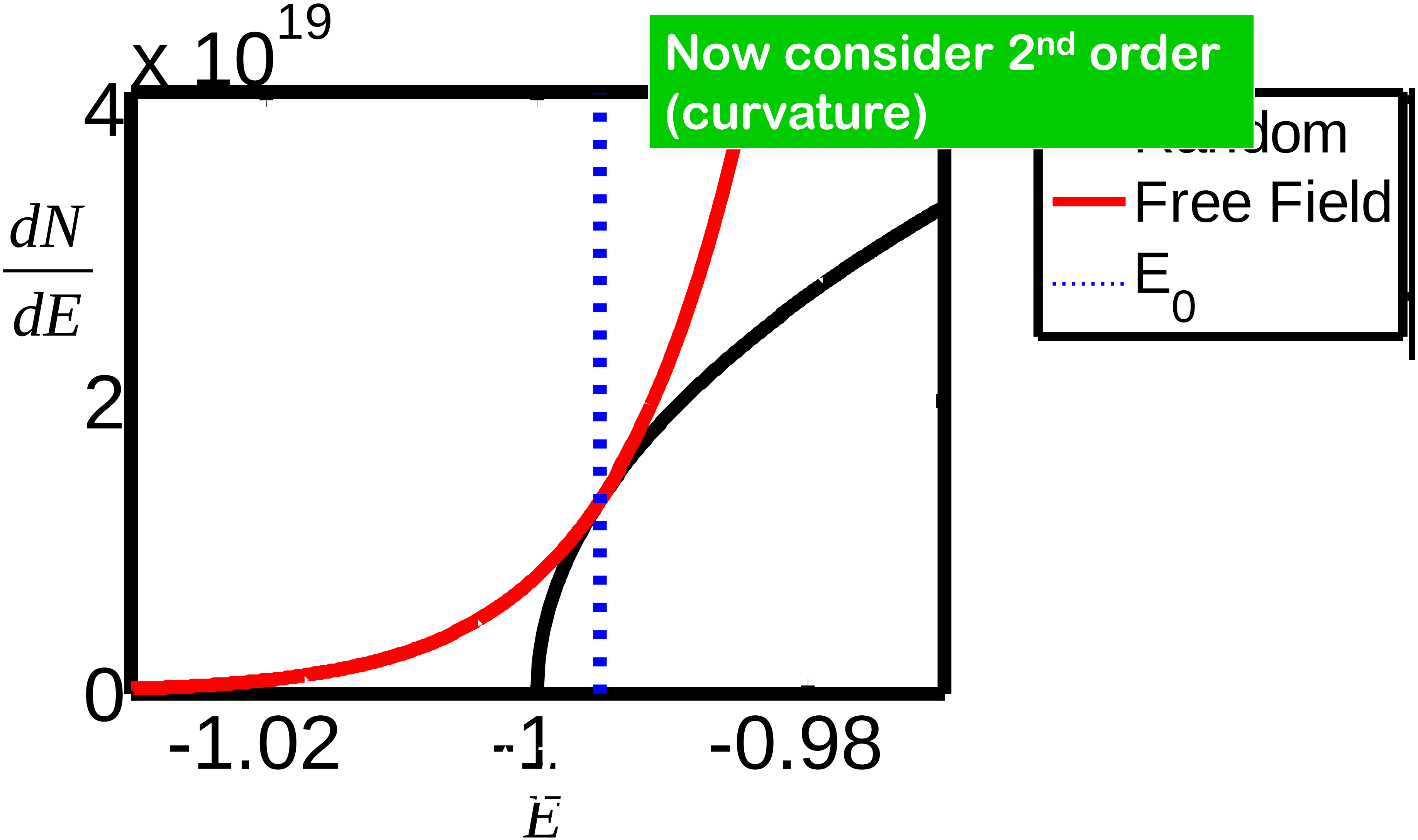


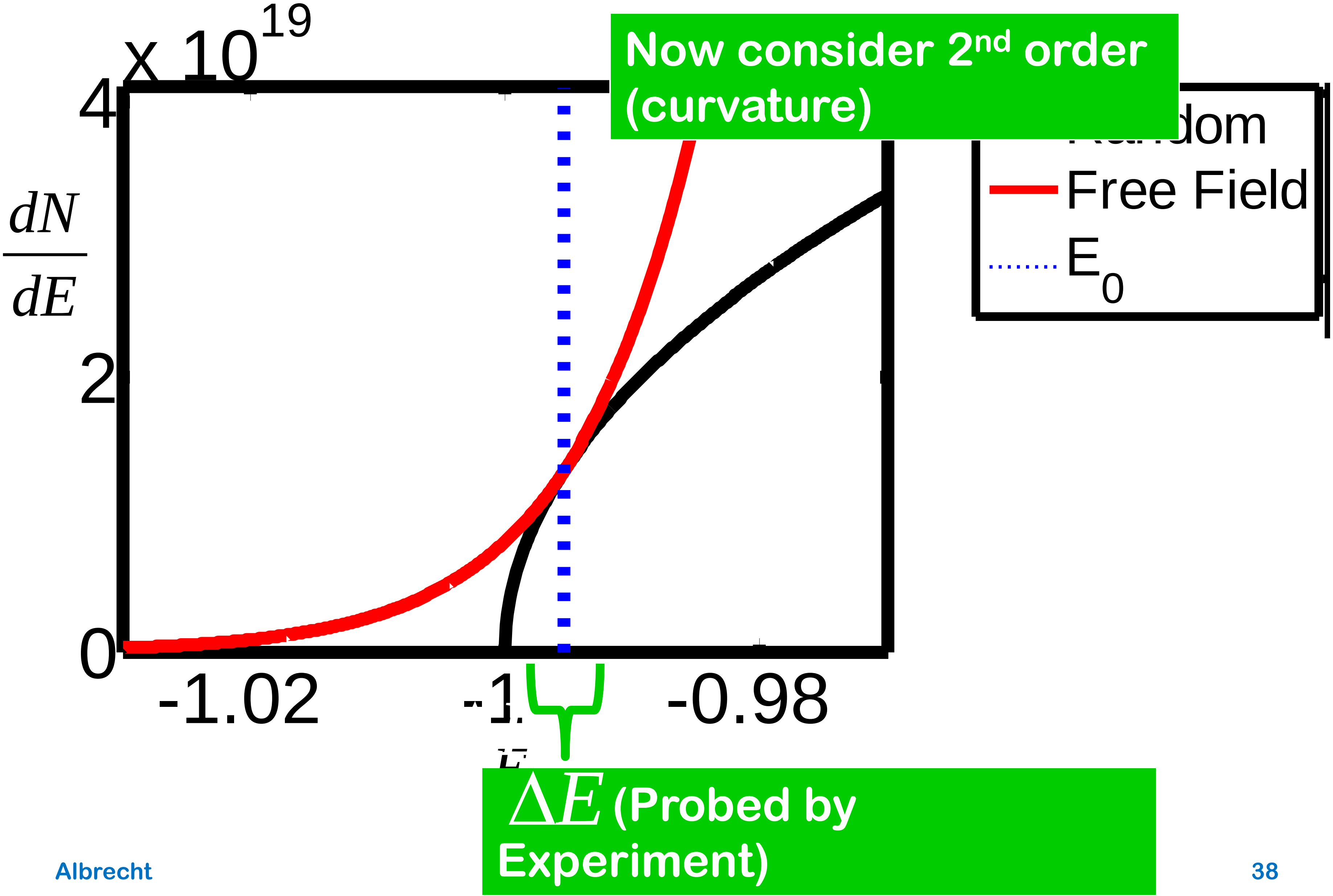
Use freedom in energy shift E_S to get 1st order (slope) to fit exactly

The term-by-term comparison in pictures



Now consider 2nd order (curvature)

The term-by-term comparison in pictures



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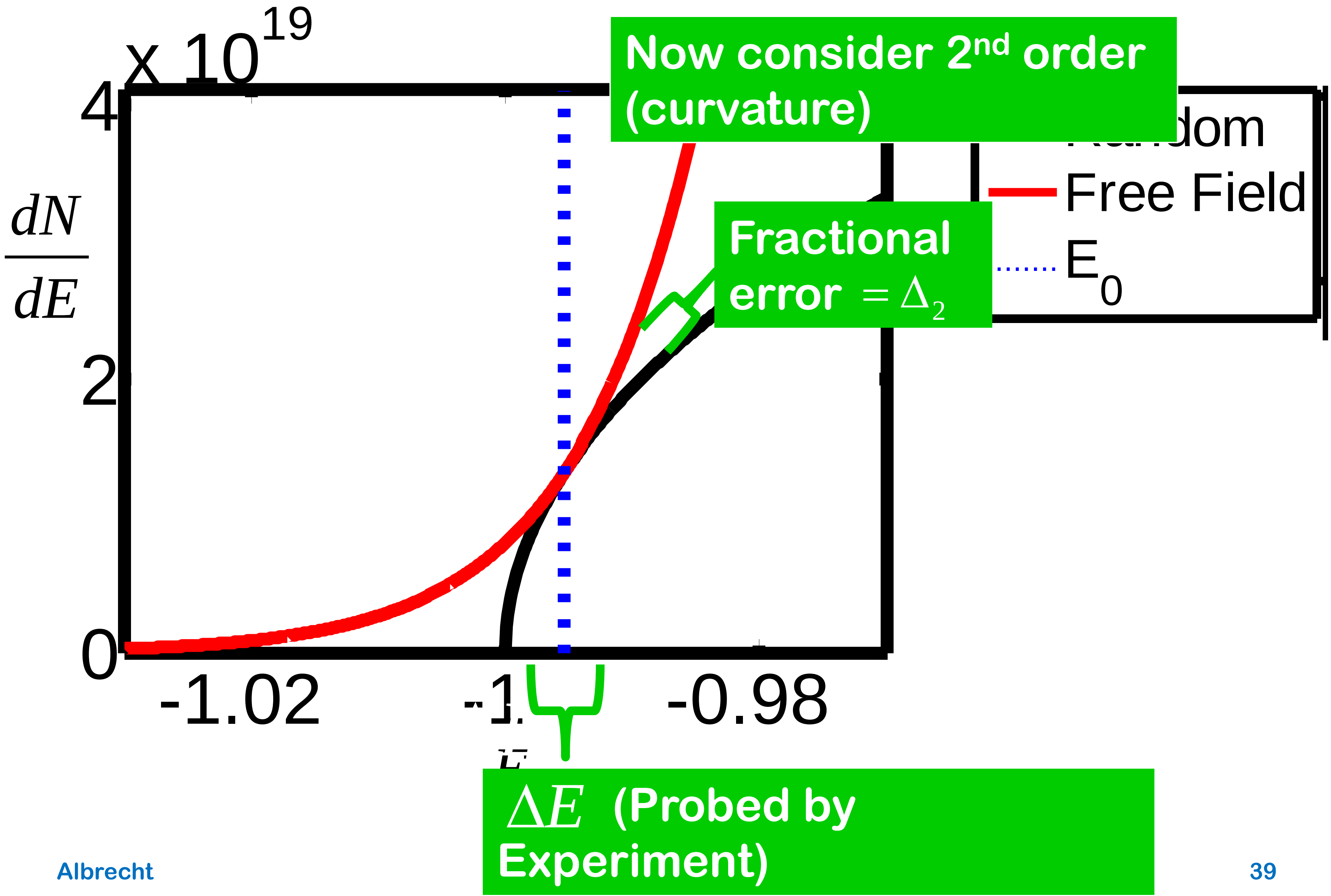


$$E_0 = \rho R_H^3 = 10^{80}\,GeV$$

$$\Delta_2 = \left(\left(\frac{E_0}{\Delta k}\right)^{\alpha} \frac{\Delta E}{E_0}\right)^2$$

α	$\Delta k\,(GeV)$	$\Delta E\,(GeV)$	Δ_2
1/2	10^{-25}	10^{3}	[illegible]
1/2	10^{-25}	10^{11}	$10^{-16.5}$
1/2	10^{-42}	[illegible]	10^{-16}
1/2	[illegible]	[illegible]	10^{-8}
3/4	[illegible]	[illegible]	$10^{1.8}$
3/4	[illegible]	[illegible]	$10^{9.8}$
3/4	[illegible]	[illegible]	$10^{14.5}$
3/4	[illegible]	[illegible]	$10^{22.5}$
1	[illegible]	[illegible]	10^{28}
1	10^{-25}	10^{11}	10^{36}
1	10^{-42}	10^{3}	10^{45}
1	10^{-42}	10^{11}	10^{53}

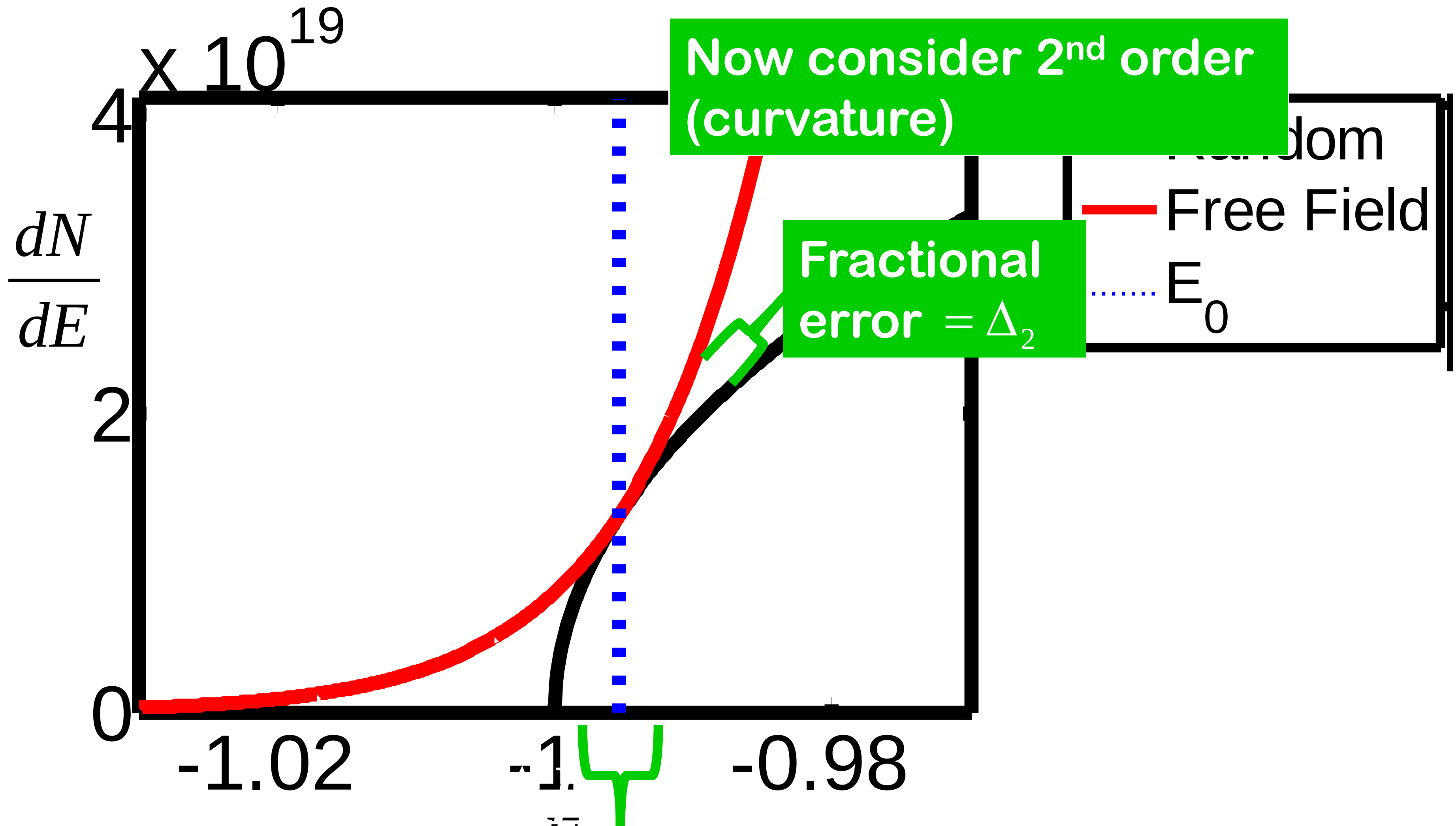
Expansion OK if $\alpha = 1/2$ $(3/4?)$

small (good)

medium (caution/ interesting)

large (bad)

The term-by-term comparison in pictures



Clock Ambiguity:

Conclusions

→ Clock ambiguity threatens "physics as we know it"

→ It may be possible to extract physics despite the clock ambiguity.

→ It seems possible to find field theory (to a sufficient degree) in *any* sufficiently large random Hamiltonian (→ a prediction re optimizing separability)

→ Time dependence of H OK

→ Predictions of gauge theory and gravity possible

→ Perhaps "random" is the most powerful foundation for fundamental physics (as I have long argued it is for "initial conditions").

Born Rule Crisis:

Copies of observer in the multiverse destroy utility of Born rule [Page '09]

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→ Consider two spins, “A” and “B”

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(which must obey $P_i P_j = \delta_{ij}$)

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$$B = \left\{ |1\rangle^B, |2\rangle^B \right\}$$

$$U = A \otimes B$$

$$U = \left\{ |11\rangle, |12\rangle, |21\rangle, |22\rangle \right\}$$

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$$P_i^A = |i\rangle^{A\ A}\langle i| \otimes \mathbf{1}^B = \frac{1}{2}\left[|i1\rangle\langle i1| + |i2\rangle\langle i2|\right]$$

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$$P_i^B = \left|i\right\rangle^{B\ B}\left\langle i\right| \otimes \mathbf{1}^A = \frac{1}{2}\left[\left|1i\right\rangle\left\langle 1i\right| + \left|2i\right\rangle\left\langle 2i\right| \right]$$

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$$\boxed{P_i^I P_j^I = \delta_{ij} P_i^I}$$

Born Rule Crisis:

But: Suppose one says: I want to know the probability of measuring spin =1, but I don't know if I am measuring "A" or "B".

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Think multiverse with multiple copies of "you"

Born Rule Crisis:

~~But: Suppose one says: I want to know the probability of measuring spin =1, but I don't know if I am measuring "A" or "B".~~

There is no suitable set of $\mathcal{P}$'s that can do this, and thus the Born rule can not be used to answer such a question

Born Rule Crisis:

But: Suppose one says:
probability of measuring
know if I am measuring

There is no suit
that can do this
Born rule can n
answer such a q

For example:

$$\tilde{p} \equiv \frac{1}{2}\left[\langle\psi|P_1^A|\psi\rangle + \langle\psi|P_1^B|\psi\rangle\right]$$

Leads to

$$\tilde{P}_i \equiv \frac{1}{2}\left[P_i^A + P_i^B\right]$$

which do not obey

$$\tilde{P}_i\tilde{P}_j = \delta_{ij}\tilde{P}_i$$

Born Rule Crisis:

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know if I am measuring "A" or[…]

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answer such a quest[…]

Relates to:

- spin-statistics
- locality
- properties of wavefunction
- viability of eternal inflation
- total size/duration of universe

Challenges **from** a quantum theory of the Universe:

➔Maybe the laws of physics are random, with predictability from peaks in distributions

➔BRC may severely limit the types of cosmology QM can describe.