Title: A perspective on Quantum Gravity Phenomenology

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Abstract: I discuss the status of Quantum Gravity Phenomenology, focusing separately on the 3 key areas: ability to discover, ability to constrain, and ability to falsify. And I stress the importance of adopting carefully taylored test theories as a remedy to difficulties encountered when comparing experimental evidence to theory evidence.

Effects should be small but could be striking!!!

For example within most approaches to this "QG problem" spacetime ends up being described by a nonclassical ("quantum") geometry, with some nonlocality, and this can indeed lead to striking consequences

- violations of Poincarè/Lorentz symmetry
- violations of CPT symmetry
- some implications for the Equivalence Principle
- absolute limitations on localization in space and time
- decoherence and other effects in which spacetime acts like a medium

Possibility of striking effects has been acknowledge for decades now, but for a long time it was thought that the smallness of the effects would be an unsurmountable difficulty for experimental tests

The difficulties can be traced back to the fact that the energy scale where GR effects can be relevant for QM (microscopic) analyses, which is expected to be the scale that is characteristic of quantumgravity effects, is the huge Planck scale 10^{28}eV (or equivalently the short Planck length 10^{-33}m)

(note however that allowing for large extra dimensions this estimate of the characteristic scale can change significantly)

# of course it is legitimate to try

It was traditionally believed that "Planck-scale effects" could never be tested because $E_P = 10^{28}$ eV is much greater than energies accessible to us (the corresponding "Planck length scale" is much smaller than the distance scales we are able to probe)

BUT this a-priori pessimism is clearly unjustified in light of many examples in the history of physics in which we gained insight on distance scales much shorter than the distance scales at which we conducted the experiments (think for example of grandunification theories tested using low-energy proton-stability experiments)

"Are we at the dawn of QGphenomenology?"
GAC Lect.NotesPhys.541,1 (1999)
GAC Nature408,661-664(2000)

discover

discover

In which sense "proven sensitivity to effects introduced genuinely at the Planck scale"?:

*imagine space is discrete with lattice scale the Planck length, then naturally you end up with

$$p^2 \approx E^2 - m^2 + \eta\, E^4/E_p^{\,2}$$

*then compute the threshold energy requirement for photopion production

$$p + \gamma_{CMBR} \Rightarrow p + \pi$$

with this modified dispersion relation and you'll find (see later) a O(100%) shift of the threshold (and therefore a shift of the GZK scale for the cosmic-ray spectrum)

*So (postponing discussion of whether we "like" this effect)
we do have,
at least in some cases,
a chance to test/falsify/discover
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Some challenges:

*In case of discovery would actually be easier than one might imagine… BUT negative results are not easily translated into meaningful/intelligible constraints on "QG model building"

*difficult to falsify theories: it would require theories that are both falsifiable and manageable, but at present we have theories that are (probably) not falsifiable and/or (probably) unmanageable….
risk of being forever confined to testing "theoretical evidence", i.e. set limits on test theories "inspired" by some "theoretical evidence"

but before worrying about this
let me first mention some opportunities….

gamma-ray bursts (Poincare tests)

GAC+Ellis+Mavromatos+Nanopoulos+Sarkar,Nature(1998)
Schaefer, PhysRevLett(1999)
Biller et al. PhysRevLett(1999)

cosmic rays above GZKlimit
Observations of TeV Blazar photons
(poincare tests)

Kifune, Astr.Journ.Lett.(1999)
Protheroe+Meyer, PhysLettB(2000)
GAC,Nature(2000)
GAC+Piran, PhysRevD(2001)

cascades produced by UHE cosmic rays (poincare tests)

GAC, PhysLettB(2001)
Bertolami, PhysLettB(2002)

Sync rad from the Crab Nebula (poincare tests)

Jacobson+Liberati+Mattingly,Nature(2003)

UHE neutrinos (poincare tests)

Piran, NaturePhysics(2007)
GAC,NaturePhysics(2007)

Ellis+Mavromatos+Nanopoulos+Volkov,GRG (2000)
GAC,IJMPD(2003)
Choubey+King,PRD (2003)

Neutral-kaon studies (decoherence and CPT-symmetry tests)

Ellis+Mavromatos+Nanopoulos+Lopez,PhysRevD(1993)
Huet+Peskin, NuclPhysB(1995)
GAC+Buccella, ModPhysLettA(2001)
Bernabeu+Mavromatos+Papavassiliou, NuclPhysB(1995)

Laser-light and matter interferometers (decoherence)

GAC, Nature (1999)
Ng+VanDam, FoundPhys(2000)
Laemmerzahl et al. PRD(2003)

Various EP tests (mostly GR, but

See, e.g., reviews by Damour (with some Stringy perspective) and Laemmerzahl

discriminate

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Let us consider the example of a modified dispersion relation (for which we have some **"theoretical evidence"** in various approaches to the QG problem)

GAC, Ellis, Mavromatos, Nanopoulos, Gambini, Pullin, Alfaro, Urrutia, Morales-Tecotl

$$p^2 = f(m, E; E_p) \approx E^2 - m^2 + \eta\, E^{2+n}/E_p{}^n \neq E^2 - m^2$$

where $|\lambda_n| \approx E_P{}^{-n}$

and an associated modified speed-energy relationship

$$\Rightarrow v_\gamma = \frac{dE}{dp} \approx 1 - \eta\, E^n/E_p{}^n$$

gamma-ray bursts (Poincare tests) — GAC+Ellis+Mavromatos+Nanopoulos+Sarkar.Nature(1998); Schaefer. PhysRevLett(1999); Biller et al. PhysRevLett(1999)

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WARNING: v=dE/dp requires (I) Heisenberg Principle unmodified (x~d/dp) and (II) Hamiltonian setup (v~[x,E])

[GAC, gr-qc/0212002]

In-vacuo dispersion

GAC+Ellis+Mavromatos+Nanopoulos+Sarkar,Nature393(1998)763
Schaefer, PhysRevLett82(1999)4964

$$v_\gamma = \frac{dE}{dp} \approx 1 - \eta\, E/E_p$$

wavelength-dependent speed for photons

This would mean that two (nearly-)simultaneously-emitted photons would reach the Earth with a relative time-of-arrival difference of

$$\Delta t = T\, \eta\, E/E_p$$

where T is the overall time travelled

gamma-ray bursts:

- travel distances of order 10^{10} light years
- microbursts within a burst have duration 10^{-3} seconds and arrived simultaneously (within available sensitivity) in all BATSE channels
- large ΔE (10 MeV... 100 MeV...possibly a few GeV...)

(N.B.: focusing here on linear effect but quadratic effect within reach applying the same strategy to some UHE neutrino observations)

deformed threshold conditions

Kifune, AJL 518(1999)L21
Kluzniak, AP11(1999)117
Protheroe+Meyer, PhysLettB493(2000)1
GAC, Nature408(2000)661
GAC+Piran, PhysRevD64(2001)036005

example: $\gamma\gamma \rightarrow e^+ e^-$

using $p^2 \approx E^2 - m^2 + \eta\, E^3/E_p$ one may find that the process is only allowed if

$$E - \frac{\eta\, E^3}{\varepsilon E_p} \geq \frac{m_e^2}{\varepsilon}$$

where E is the energy of the hard photon and ε is the energy of the soft photon.
Of course, similar modifications of threshold conditions apply to other processes such as photopion production relevant for the cosmic-ray GZK scale

Any evidence of a threshold anomaly from spectrum of cosmic rays?

Auger (astroph0707.2638) would suggest there isn't

Any evidence of in-vacuo dispersion?

Various "astrodata" indicate that $\eta<10^2$

But MAGIC(astroph0708.2889):....tentative evidence of in-vacuo dispersion just at a QG-reasonable dispersion-relation-deformation scale.......

MAGIC analysis at present tentative (but intriguing/exciting)

Auger still at preliminary stage, but

when cosmic-ray situation stabilizes we will have first facts to constrain QG model building!! Careful use of test theories needed for a satisfactory characterization of these constraints

SOME ABILITY TO DISCRIMINATE MODELS

just an exercise: what if indeed no GZK anomaly but in-vacuo dispersion?

Modified-threshold analysis essentially (see my next talk) requires preferred frame

No preferred frame (and no threshold effects) if:

"Doubly special relativity" GAC, grqc0012051/IJMPD11,35
(a certain type of deformation GAC,hepth0012238/PLB510,255
of Poincaré symmetry)

- LS is "deformed" if the rotation/boost transformations are characeterized by two scales (a short length scale "●" in addition to the familiar high velocity scale "c") BUT there is no preferred class of inertial observers

- Transition from SR to deformedSR exactly of same type as transition from GalileoR to SR
(introduction of a relativistic invariant: 0 invariants in GalileoR, 1 invariant in SR, 2 invariants in deformedSR)

- allows, for example, to state "objectively" (valid for all inertial observers) the existence of a minimum wavelength of Planck-length size

falsify?

falsify?

On the necessity to build more robust links between theory and phenomenology
actual derivations, rather than heuristics.....
theory predicitons, rather than theoretical evidence....:
the kappa-Minkowski case study

$$[x_j, t] = i\lambda x_j \qquad [x_j, x_m] = 0$$

- **Translation generators in kappa-Minkowski:**

$$P_\mu\left(e^{ikx} e^{ik_0 t}\right) = k_\mu\left(e^{ikx} e^{ik_0 t}\right)$$

"classical action"

then

$$P_\mu\left(e^{ikx} e^{ik_0 t} e^{iKx} e^{iK_0 t}\right) = P_\mu\left(e^{i(k+e^{\lambda k_0}K)x} e^{i(k_0-K_0)t}\right)$$

Baker Campbell Hausdorff

$$= \left(k_\mu + e^{-\lambda k_0} K_\mu\right)\left(e^{ikx} e^{ik_0 t} e^{iKx} e^{iK_0 t}\right)$$

$$= \left[P_\mu\left(e^{ikx} e^{ik_0 t}\right)\right]\left(e^{iKx} e^{iK_0 t}\right) + \left[e^{-\lambda P_0}\left(e^{ikx} e^{ik_0 t}\right)\right] P_\mu\left(e^{iKx} e^{iK_0 t}\right)$$

Nontrivial coproduct!!

- **Rotation generators in kappa-Minkowski:**

$$R_j\left(e^{ikx}e^{iEt}\right)=i\varepsilon_{jlm}(x_l P_m - x_m P_l)\left(e^{ikx}e^{iEt}\right)$$

then

$$R_j\left(e^{ikx}e^{iEt}e^{iKx}e^{i\Omega t}\right)=R_j\left(e^{i(k-e^{\lambda E}K)x}e^{i(E+\Omega)t}\right)$$

$$=\left[R_j\left(e^{ikx}e^{iEt}\right)\right]\left(e^{iKx}e^{i\Omega t}\right)+\left(e^{ikx}e^{iEt}\right)R_j\left(e^{iKx}e^{i\Omega t}\right)$$

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Rotations are really classical in k-M

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Modified action needed for consistency with Hopf algebra structure….
IF one adopted unmodified (classical) action then the would-be coproduct requires operators external to the algebra…
Modification of boosts was expected since commutators involve a length scale…
With this modified action the coproduct is OK (can be expressed in terms of P,R,N)
Note that:

$$\left[N_j,P_l\right]=-i\lambda P_lP_j+i\delta_{jl}\left(\frac{\lambda}{2}P_mP_m+\frac{(1-e^{2\lambda P_0})}{2\lambda}\right)$$

and the "mass Casimir" for these deformed transformations is

$$\cosh(\lambda m)=\cosh(\lambda E)-\frac{\lambda^2}{2}e^{\lambda E}P^2$$

Agostini+Arzano+Gubitosi+Marciano'+Mercati+Pranzetti+Tacchi+GAC

Noether analysis goes through easily (!!) if we simply insist that Leibnitz rule be valid for "d"

hep-th/0611221, hep-th/0707.1863, hep-th/0709.2063, hep-th/0709.4600

$$d(fg) = (df)g + f(dg)$$

For example in the time-to-the-right Weyl-map conventions this takes the form

$$df(x) = i\varepsilon_\mu P_\mu f(x)$$

if the noncommutative transformation parameters have the following properties

$$[\varepsilon_0, x_\mu] = 0; [\varepsilon_j, x_l] = 0; [\varepsilon_j, x_0] = i\lambda\varepsilon_j$$

$$Q_\mu = \int d^3x J_{0\mu} = \int d^4p \frac{e^{3\lambda p_0}}{2} p_\mu \tilde{\Phi}(p_0, \vec{p}) \tilde{\Phi}(-p_0, -e^{\lambda p_0}\vec{p}) \frac{p_0}{|p_0|} \delta(C_\lambda(p_\mu))$$

For phenomenology:

- example of the path from "theoretical evidence" to "predictions"

- challenge to test the "no-pure-boost principle" that arises by generalizing

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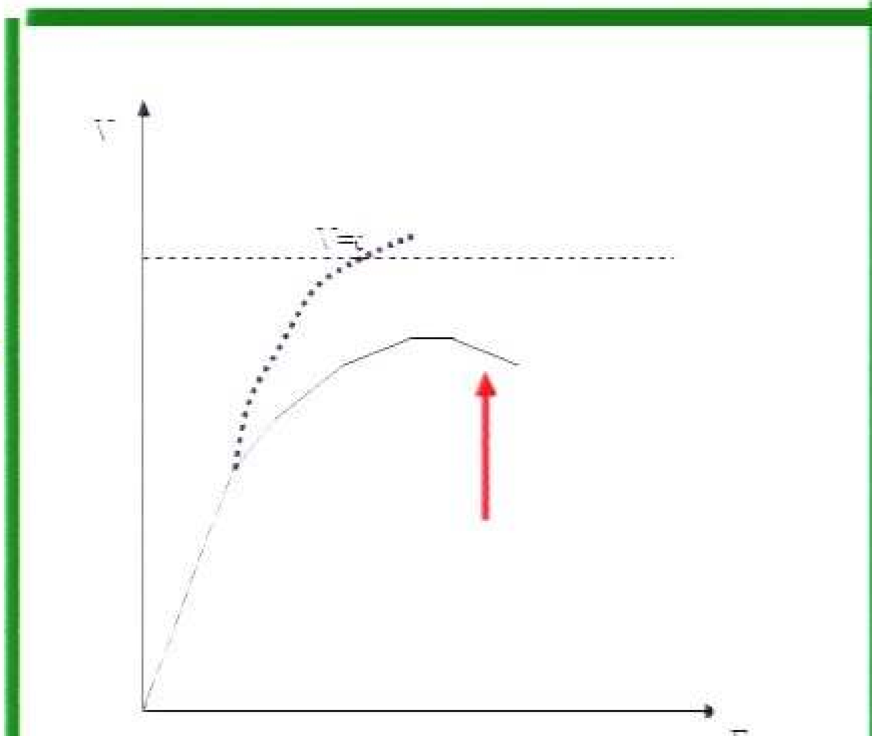
Now on low-energy/high-quality being better than higher-energy/lower-quality (if system is able to amplify small "leading-order effects" we must worry about amplification of next-to-leading effects)

An example: synchrotron radiation from the Crab Nebula

The key point here concerns the high-energy part of the synchrotron-radiation spectrum, which comes from electrons with energies as high as 10^{15}eV

$$p^2 = f(m,E;E_p) \approx E^2 - m^2 + \eta E^3/E_p + \text{"higher order"}$$



Another example (to prefer low-energy/high-quality with respect to high-energy/low-quality): "disappearance in electron-positron pairs" of the multi-TeV photons emitted by Blazars discussed in the context of

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Tentative evidence of some disappearance of these multi-TeV photons can be used to set limits on on parameters of disprel

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$$= E^2 + \eta E^3/E_p + i\xi E^5/E_p^3 + \ldots$$

GAC+Urrutia, in preparation

and for $\xi \simeq 1$ (considering a Blazar at a distance of, say, 100Mpc) this absorption can compensate for the "lost absorption" due to the real correction term

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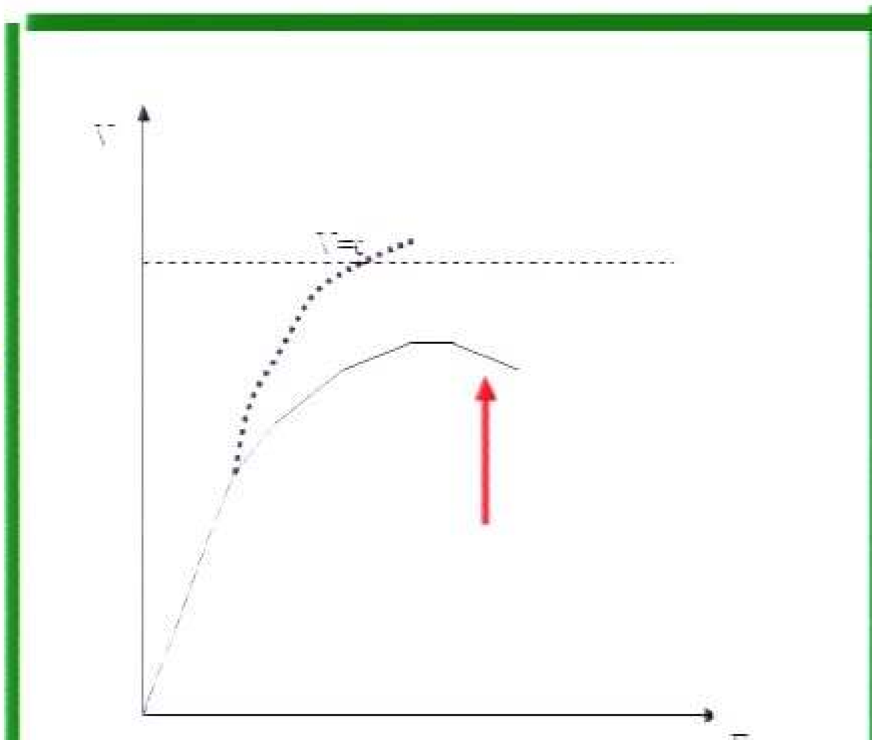
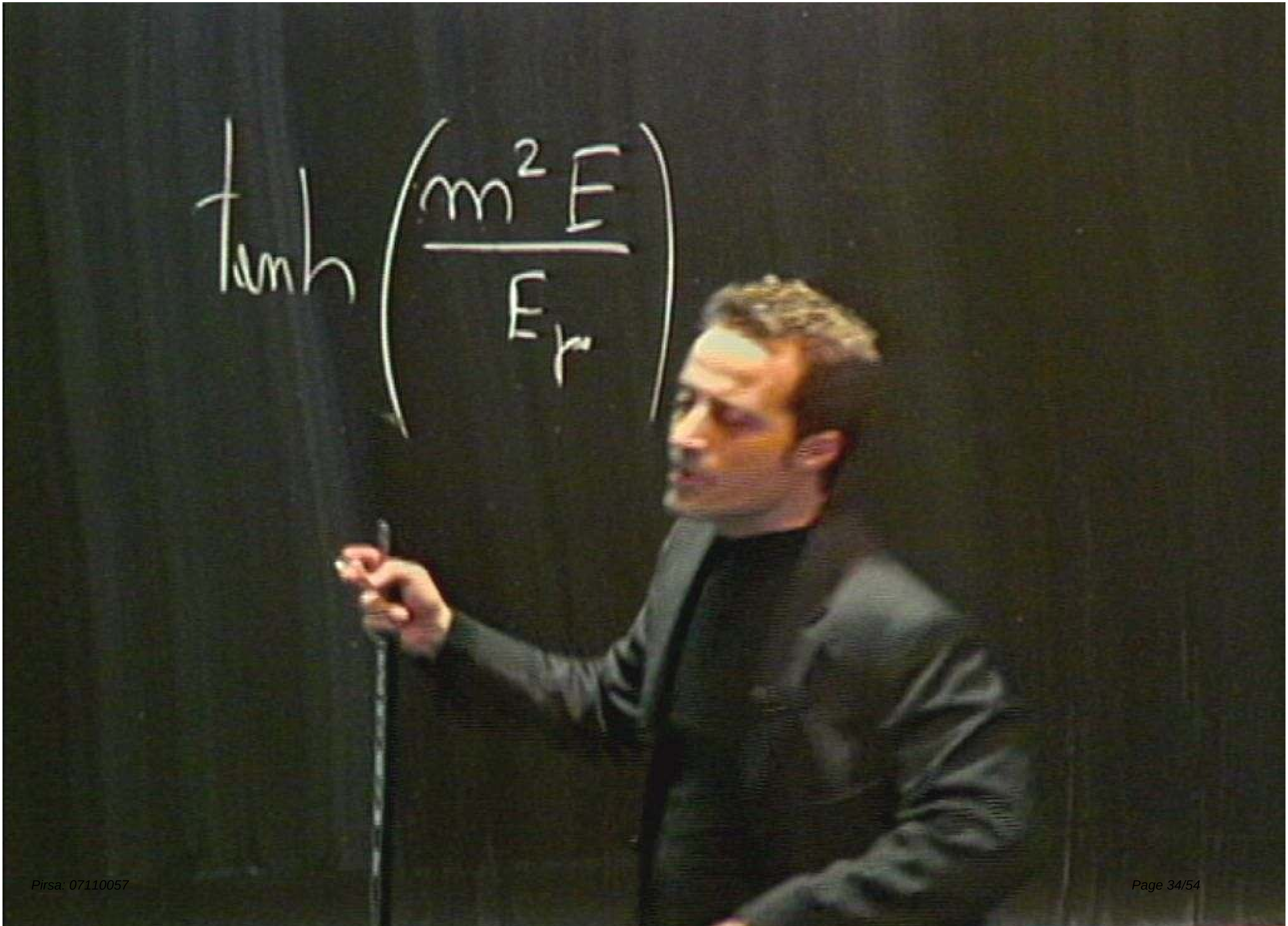
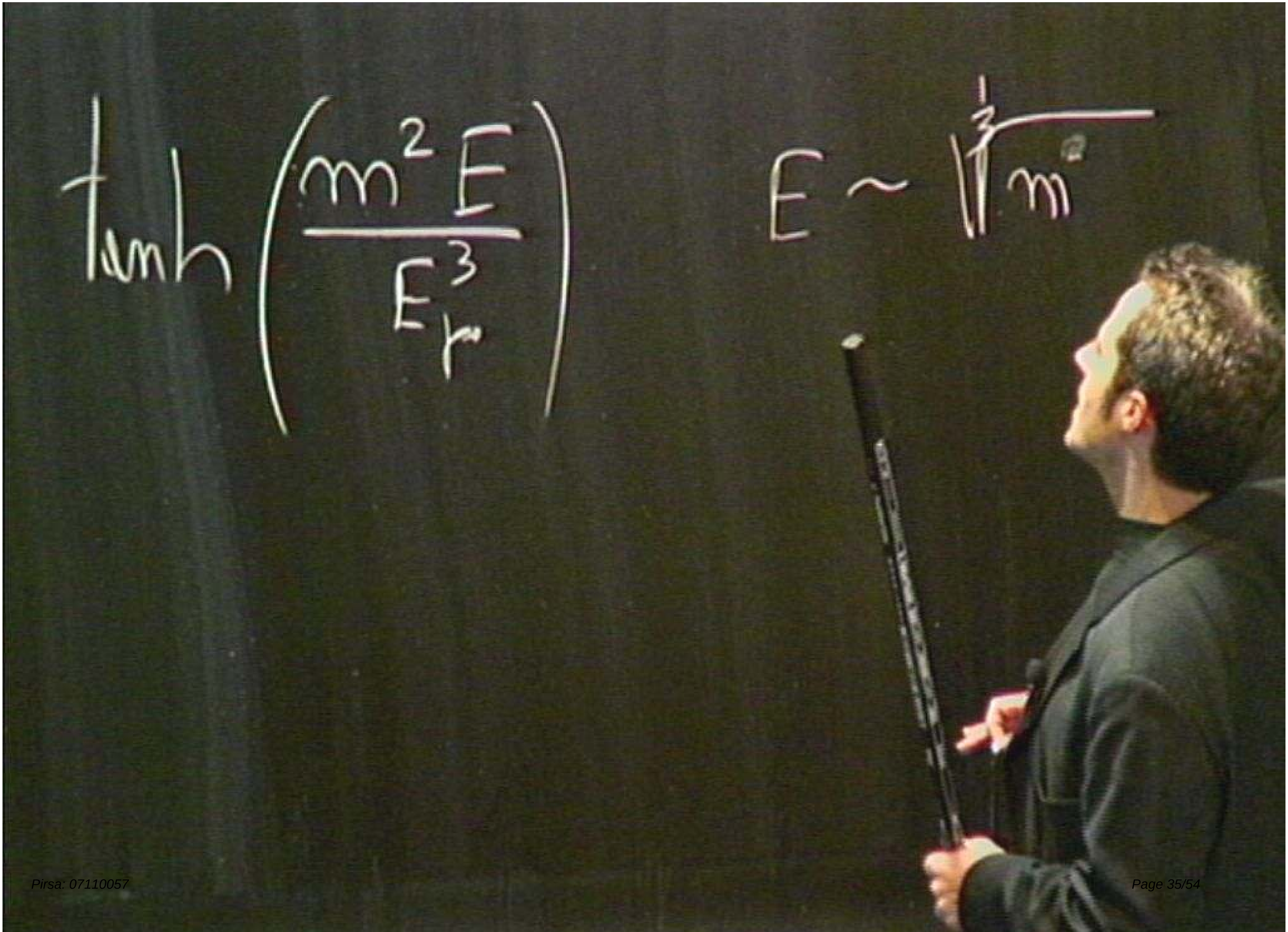
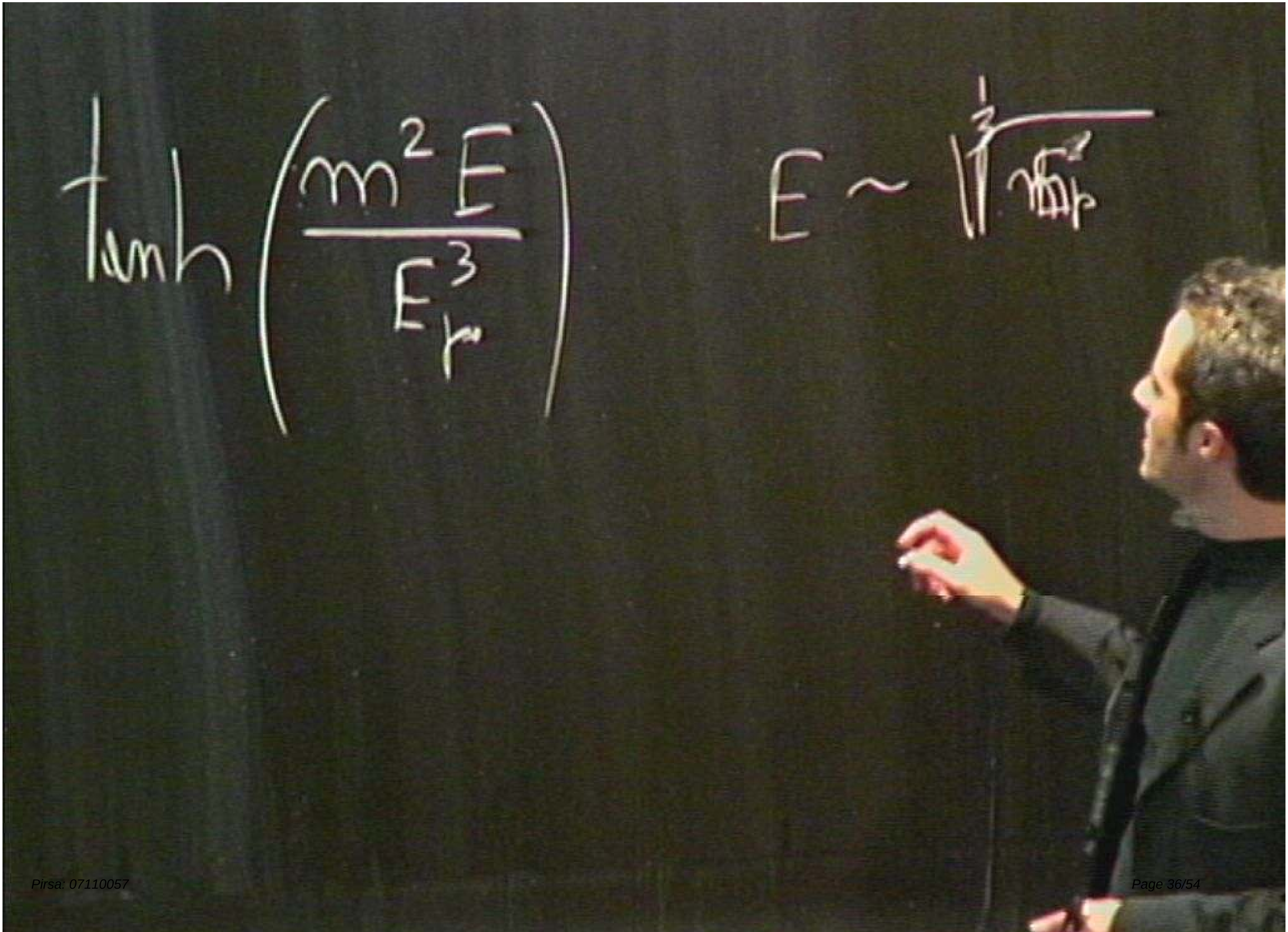



tanh
m2 E
E


tanh (m²E / E³pl)
E ~ ∛m²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$$p^2 = E^2 - m^2 + \eta\, E^3/E_p + \text{"higher order"}$$

Tentative evidence of some disappearance of these multi-TeV photons can be used to set limits on on parameters of disprel

But consider the following example (for photons)

$$p^2 = E^2 + \eta\, E^3/E_p + \text{"higher order"}$$
$$= E^2 + \eta E^3/E_p + i\xi E^5/E_p^3 + \ldots$$

GAC+Urrutia, in preparation

and for $\xi \simeq 1$ (considering a Blazar at a distance of, say, 100Mpc) this absorption can compensate for the "lost absorption" due to the real correction term

ankle!!!!!

test theories!!!!!

the short version:

*sensitivity to effects introduced genuinely at the Planck scale is possible!!

*but it won't be fun to do difficult experimental tests of merely "theoretical evidence" (no fault of phenomenologist....inadequacy of the formal-theory work)

*ability to discriminate between different types of effects introduced genuinely at the Planck scale shown!!

*falsifiability for less ambitious models motivated by the QGproblem might be shown soon!!

*discovery not as difficult as one could imagine, but tranlating negative exp results into meaningful constraints is in some cases rather challenging

Another example (to prefer low-energy/high-quality with respect to high-energy/low-quality): "disappearance in electron-positron pairs" of the multi-TeV photons emitted by Blazars discussed in the context of

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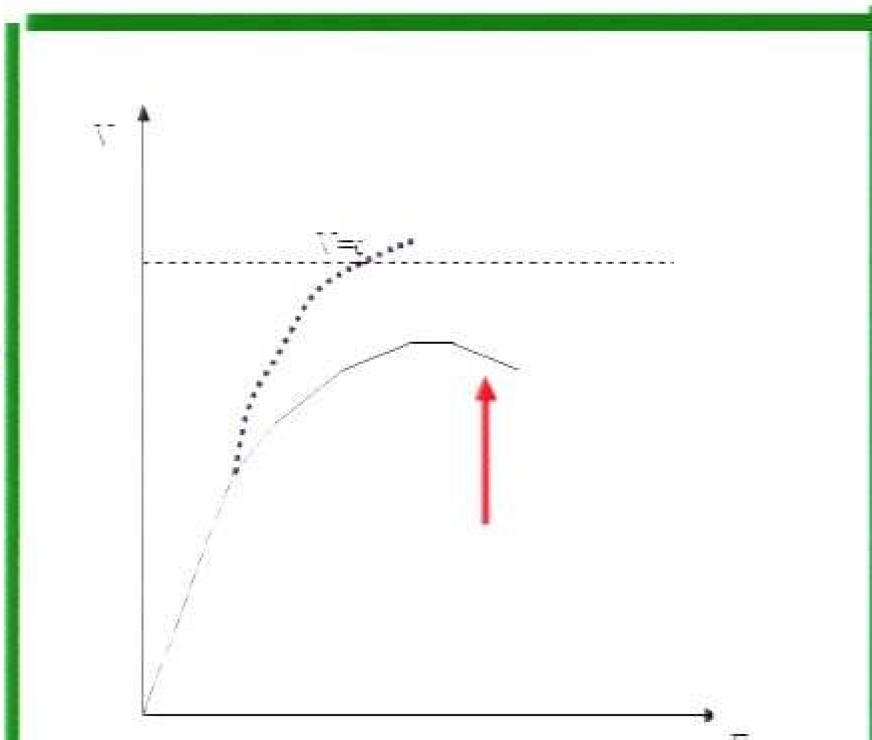
ankle!!!!!
test theories!!!!!

Now on low-energy/high-quality being better than higher-energy/lower-quality (if system is able to amplify small "leading-order effects" we must worry about amplification of next-to-leading effects)

An example: synchrotron radiation from the Crab Nebula

The key point here concerns the high-energy part of the synchrotron-radiation spectrum, which comes from electrons with energies as high as 10^{15}eV

$$p^2 = f(m,E;E_p) \approx E^2 - m^2 + \eta E^3/E_p + \text{"higher order"}$$



SOME ABILITY TO DISCRIMINATE MODELS

just an exercise: what if indeed no GZK anomaly but in-vacuo dispersion?

Modified-threshold analysis essentially (see my next talk) requires preferred frame

No preferred frame (and no threshold effects) if:

"Doubly special relativity" GAC, grqc0012051/IJMPD11,35
(a certain type of deformation GAC,hepth0012238/PLB510,255
of Poincaré symmetry)

- LS is "deformed" if the rotation/boost transformations are characeterized by two scales (a short length scale "●" in addition to the familiar high velocity scale "c") BUT there is no preferred class of inertial observers

- Transition from SR to deformedSR exactly of same type as transition from GalileoR to SR
(introduction of a relativistic invariant: 0 invariants in GalileoR,
1 invariant in SR, 2 invariants in deformedSR)

- allows, for example, to state "objectively" (valid for all inertial observers) the existence of a minimum wavelength of Planck-length size

discriminate

Let us consider the example of a modified dispersion relation (for which we have some "**theoretical evidence**" in various approaches to the QG problem)

GAC, Ellis, Mavromatos, Nanopoulos, Gambini, Pullin, Alfaro, Urrutia, Morales-Tecotl

$$p^2 = f(m,E;E_p) \approx E^2 - m^2 + \eta\, E^{2+n}/E_p{}^n \neq E^2 - m^2$$

where $|\lambda_n| \approx E_P{}^{-n}$

and an associated modified speed-energy relationship

$$\Rightarrow v_\gamma = \frac{dE}{dp} \approx 1 - \eta\, E^n/E_p{}^n$$

WARNING: v=dE/dp requires (I) Heisenberg Principle unmodified (x~d/dp) and (II) Hamiltonian setup (v~[x,E])

[GAC, gr-qc/0212002]

falsify?

On the necessity to build more robust links between theory and phenomenology
actual derivations, rather than heuristics.....
theory predicitons, rather than theoretical evidence....:
the kappa-Minkowski case study

$$[x_j, t] = i\lambda x_j \qquad [x_j, x_m] = 0$$

- **Translation generators in kappa-Minkowski:**

$$P_\mu\left(e^{ikx} e^{ik_0 t}\right) = k_\mu\left(e^{ikx} e^{ik_0 t}\right)$$

"classical action"

then

$$P_\mu\left(e^{ikx} e^{ik_0 t} e^{iKx} e^{iK_0 t}\right) = P_\mu\left(e^{i(k+e^{\lambda k_0}K)x} e^{i(k_0-K_0)t}\right)$$

Baker Campbell Hausdorff

$$= \left(k_\mu + e^{-\lambda k_0} K_\mu\right)\left(e^{ikx} e^{ik_0 t} e^{iKx} e^{iK_0 t}\right)$$

$$= \left[P_\mu\left(e^{ikx} e^{ik_0 t}\right)\right]\left(e^{iKx} e^{iK_0 t}\right) + \left[e^{-\lambda P_0}\left(e^{ikx} e^{ik_0 t}\right)\right] P_\mu\left(e^{iKx} e^{iK_0 t}\right)$$

Nontrivial coproduct!!

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