

Title: Recent and Local Variations and Unified Models

Date: Jul 17, 2008 03:50 PM

URL: <http://pirsa.org/08070029>

Abstract: Precision tests of Local Position Invariance (LPI) involve many different methods in atomic, nuclear and gravitational physics, astrophysics and cosmology, and many different epochs and environments. We present some methods for comparing or combining different methods, either in a model-independent way or within simple scalar field models of variation. We focus on which methods are most sensitive to cosmologically recent time variation, and also on tests of spatial variation within the Solar System.

## RECENT & LOCAL VARIATIONS $\rightarrow$ UNIFIED MODELS

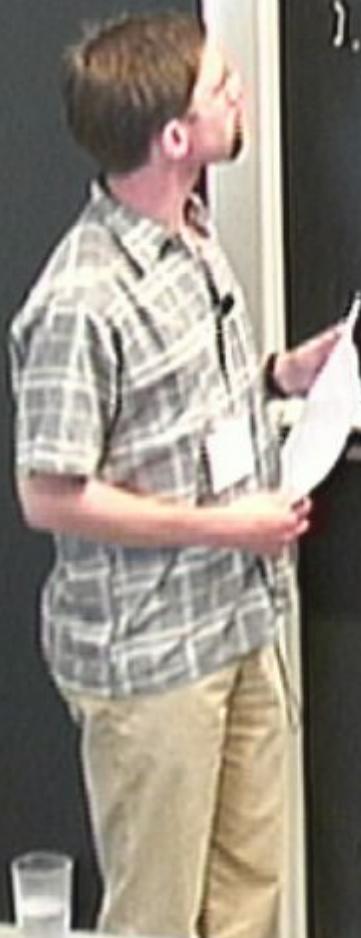
T.D. 0905.05/8 (PL + GR)

hep-ph/0608067

T.D. S. Den. C. Wettenich 0807.229

PLAN

$$J.K. = \frac{\Delta h_i G_i}{\Delta u} : G_i \in \{H, S, T, Y_0, \chi\}$$



## RECENT & LOCAL VARIATIONS $\rightarrow$ UNIFIED MODELS

T.D. 0905.05/8 (PL + GR)

hep-ph/0602067

T.D. S. Stein, C. Wetterich 0807.229

PLAN

$$J.K. = \frac{\Delta h_i G_i}{\Delta u} \propto e^{\omega_i H_i} \propto T_i^{-1} \propto \frac{1}{u_i}$$



## RECENT & LOCAL VARIATIONS $\rightarrow$ UNIFIED MODELS

T.D. 0905.05/8 (PL + GMR)

Kep-ph/0608067

T.D. S. Sten, C. Wetterich 0807.221

PLAN

$$J.K. = \frac{\Delta h_i G_i}{\Delta u} ; \quad G_i = \omega, H, J_T, \eta_i, \frac{m_i}{\lambda}$$



## RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0905.05/8 (PL+GME)

hep-ph/0602067

T.D. S. Stein,C. Wetterich 0807.229

PLAN

$$J.K. = \frac{\Delta h_i G_i}{\Delta u} ; \quad G_i \in \omega, H, J_T, \eta_+, \eta_-$$



# RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0905, 0318 (PRC-70 come)  
hep-ph/0608067

T.D. S.Stan, C.Wetterich 0807.???

PLAN

$$J.k. = \frac{\Delta \ln G}{\Delta U}; G_i = \alpha, \mu, j_P, q^n, \frac{\kappa_L}{\lambda}$$

# RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0905.0318 (PRL to come)  
kap-ph/0608067

T.D. S.Stan,C.Wettrich 0807.???

PLAN

$$J.k_i = \frac{\Delta k_i G_i}{\Delta u} ; \quad G_i = \alpha, \mu, j_p, g_{\mu}, \frac{e_L}{\lambda}$$

# RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0905.0318 (PRD-10 CONFER)  
hep-ph/0608067

T.D. S. Stan, C. Wettenich 0807.???

PLAN

$$J.K. = \frac{\Delta \ln G}{\Delta U}; G_i = \alpha, \mu, j_P, g^{\mu\nu}, \frac{r_F}{r}$$



# RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0805.0318 (PRD 70(2004))

hep-ph/0608067

T.D. S.Stan, C.Wetterich 0807.????

## PLAN

$$J. k_c = \frac{\Delta \ln G}{\Delta u}; \quad G_1 \approx \alpha, \mu, \beta, g_{\mu}, \frac{m_e}{\Lambda}$$

Motivation  $\rightarrow$  light scalar

NON-universal coupling



# RECENT & LOCAL VARIATIONS & UNIFIED MODELS

T.D. 0805.0318 (PRD 70 Game)

hep-ph/0608067

T.D. S. Stein, C. Wettenrich 0807.???

PLAN

$$J. k_i = \frac{\Delta \ln G_i}{\Delta u}; \quad G_i \approx \alpha, \mu, s_T, g_u, \frac{m_f}{\Lambda}$$

Motivate  $\rightarrow$  light scalar

NON-universal coupling  
Gravitational bounds



# RECENT & LOCAL VARIATIONS $\Rightarrow$ UNIFIED MODELS

T.D. 0805.03/8 (PRL TO CME)

hep-ph/0608067

T.D. S.Stan, C.Wetterich 0807.???

## PLAN

$$J, k = \frac{\Delta \ln G_i}{\Delta U} ; \quad G_i = \alpha, m, g_F, g_B, \frac{m_F}{m_B}$$

isolate  $v$   $\rightarrow$  light scalar

NON-UNIVERSAL coupling

Gravitational bounds  $\rightarrow |k_i| < 10^{-8} \dots 10^{-9}$

# RECENT & LOCAL VARIATIONS $\Rightarrow$ UNIFIED MODELS

T.D. 0905.03/8 (PRL TO CME)

hep-ph/0608067

T.D. S.Stan, C.Wetterich 0807.???

PLAN

$$J, k_i = \frac{\Delta \ln G_i}{\Delta u}; G_i = \alpha, m, j_T, g_{\mu}, \kappa_F$$

Motivate  $\rightarrow$  light scalar

NON-universal coupling

Gravitational bounds  $\rightarrow |k_i| < 10^{-6} \dots 10^{-7}$

## 2. GUTs

Speaker's name: [redacted]



2. GUTs

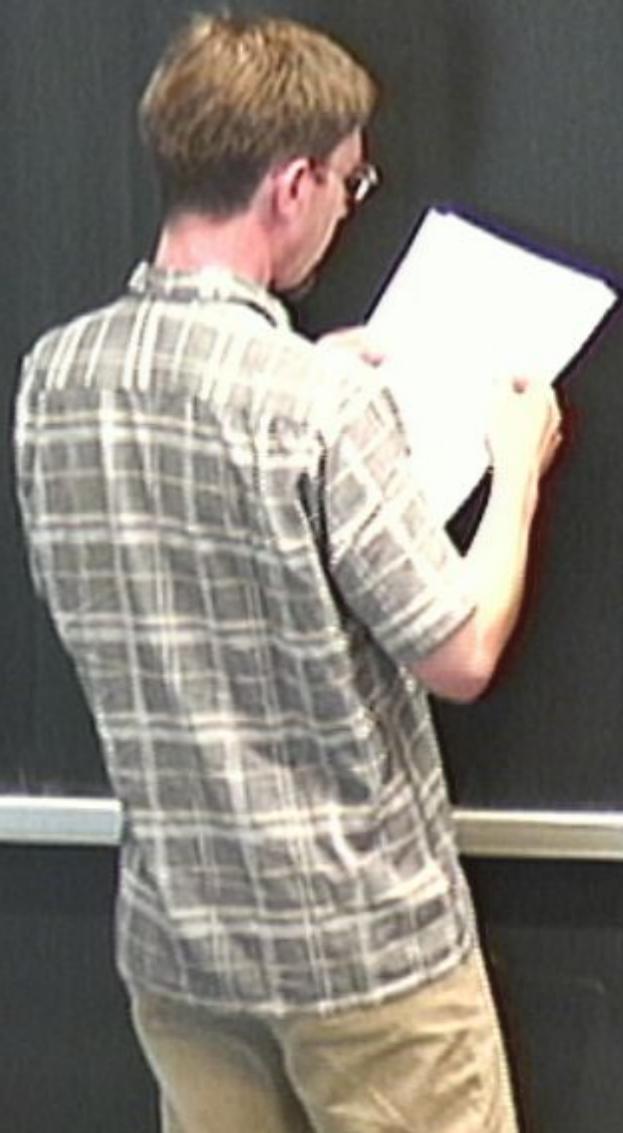
$$\Delta \ln G_i = \frac{d_i}{dx}$$



2. GUTS

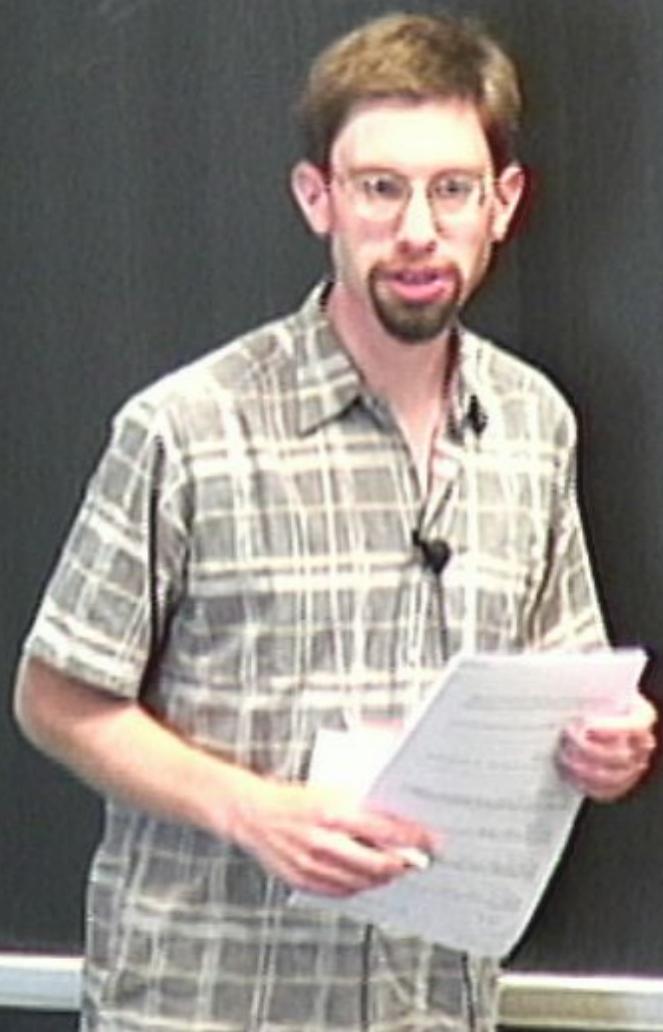
$$\Delta \ln G_T = \frac{d\ln G_T}{dx} \Delta \ln x \quad (\Rightarrow)$$

=



2. GUTS

$$\Delta \ln G_i = \frac{d_i}{dx} \Delta \ln x (\varphi)$$
$$= d_i \beta x \Delta \varphi$$



## 2. GUTs

$$\Delta \ln G_i = \frac{d_i}{\beta x} \Delta \ln x \quad (\rightarrow)$$
$$= d_i \beta x \Delta \varphi$$

$d_i \Rightarrow$  constants



2. GUTs

$$\Delta \ln G_i = \frac{d_i}{\beta x} \Delta \ln x \quad (\rightarrow)$$
$$= d_i \beta x \Delta \varphi$$

$d_i \Rightarrow$  constants

Combine observations

2. GUTs

$$\Delta \ln G_i = \frac{d_i}{\alpha} \Delta \ln \alpha \quad (\rightarrow)$$
$$= d_i \beta \times \Delta \varphi$$

$d_i \Rightarrow$  constants

Combine observations

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha}$$

2. GUTS

$$\Delta \ln G_i = \frac{d_i}{\Delta x} \Delta \ln \alpha_x (\tau) \\ = d_i \beta_x \Delta \varphi$$

$d_i \Rightarrow$  constants

Combine observations

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha}$$

$$\frac{g'}{g}$$

Who can detect variation first?

$$z < 0.8$$

2. GUTs

$$\Delta \ln G_i = \frac{d_i}{\alpha} \Delta \ln \alpha_i (\Rightarrow)$$
$$= d_i \beta \times \Delta \varphi$$

$d_i \Rightarrow$  constants

Combine observations

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha}$$

$$\frac{g'}{g}$$

Who can detect Variation first?

Meteorite  $R_{\text{Os}} - Os > 0.8$

2. GUTs

$$\Delta \ln G_i = \frac{d_i}{\ln \alpha} \Delta \ln \alpha_i (\beta) \\ = d_i \beta \times \Delta \varphi$$

$d_i \Rightarrow$  constants

Combine observations

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha}$$
$$\frac{g'}{g}$$

Who can detect variation first?

Meteorite  $R_{\text{Fe}} - O_S \geq 0.8$

3. WEP  $\Rightarrow$  recent

Variation

$$\frac{G_i}{G_r}$$

$\Delta \ln \kappa (\tau)$

$\propto \Delta \varphi$



$\Delta \ln \alpha_x (\approx)$

3. WEP  $\Rightarrow$  recent

Variation  $\frac{G_i}{G_i}$

"Speed limit"  $\dot{\varphi} \leq \dot{\varphi}_{\max}$



$$\Delta \ln G_i = \frac{d \epsilon}{\Delta x} \Delta \ln x_i \quad (?)$$

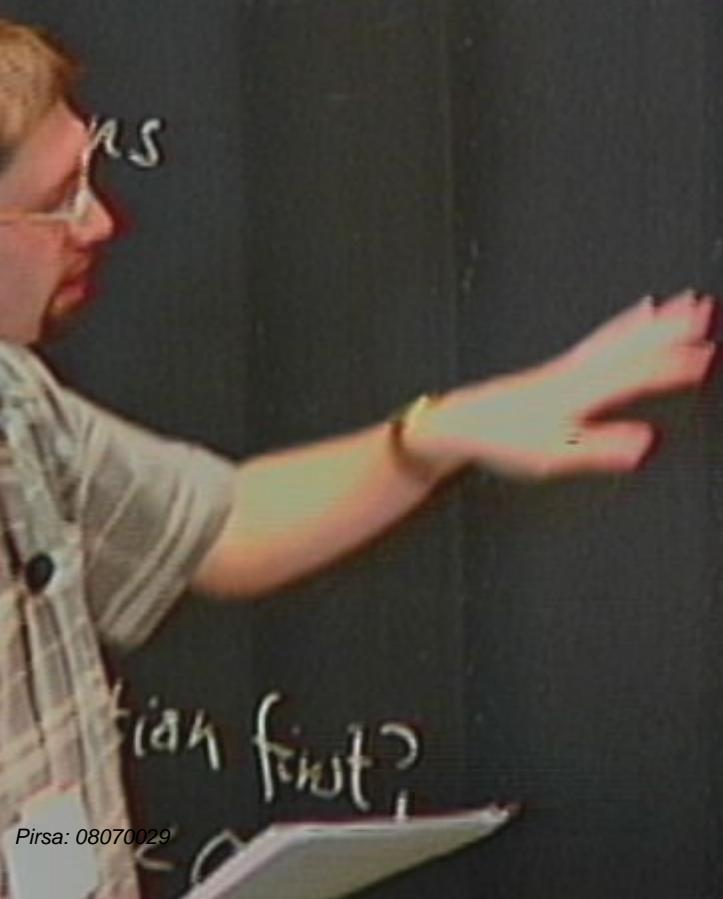
$$= d_i \beta_x \Delta \varphi$$

3. WEP  $\Rightarrow$  recent  
Variation

$\frac{G_i}{G_i \text{ to}}$

"Speed limit"  $\dot{\varphi} \leq \dot{\varphi}_{\max}$

$\Rightarrow$  strong bounds on



2. GUTs

$$\Delta \ln G_i = \frac{d_i}{dx} \Delta \ln x, (r) \\ = d_i \beta x \Delta \varphi$$

$d_i \Rightarrow$  constraints

Combine ob. & constraints

$$\frac{\Delta \ln g}{\Delta \ln a}$$

$$\frac{g'}{g}$$

What can we do?

Met

What?

0.8

3. WEP  $\Rightarrow$  recent

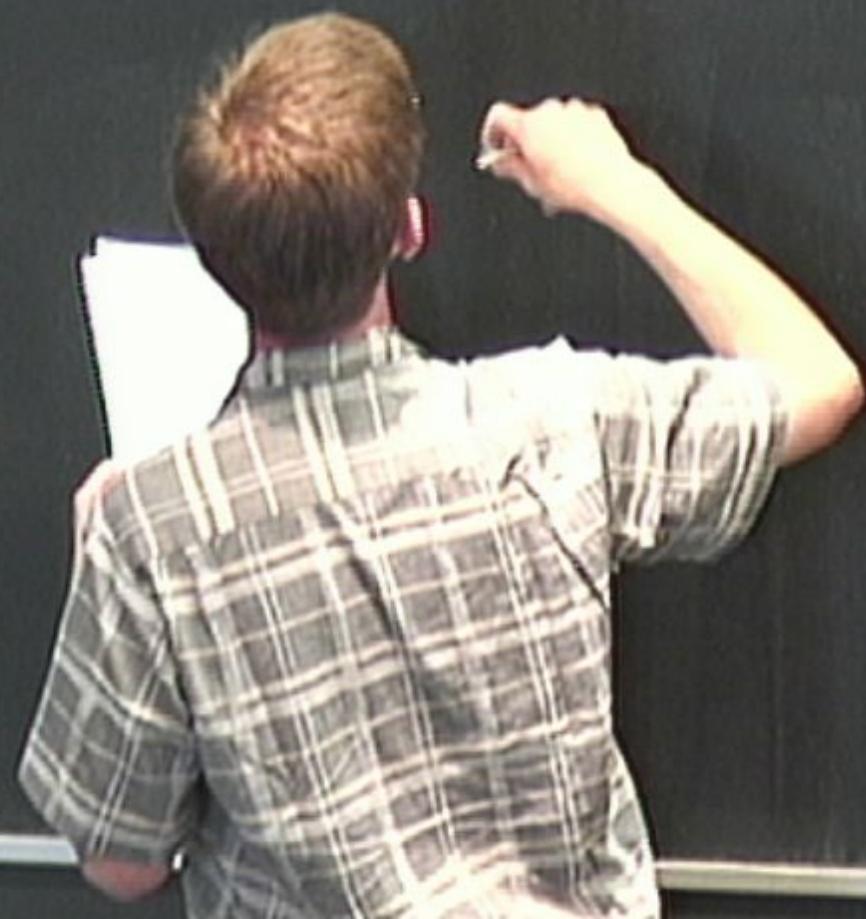
Variation

$$\frac{G_s}{G_0} |_{t_0}$$

"Speed limit"  $\dot{\varphi} \leq \dot{\varphi}_{max}$

$\Rightarrow$  strong bounds on  $\dot{\varphi}$  at

$$\nabla^2 U = \frac{f}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G}$$



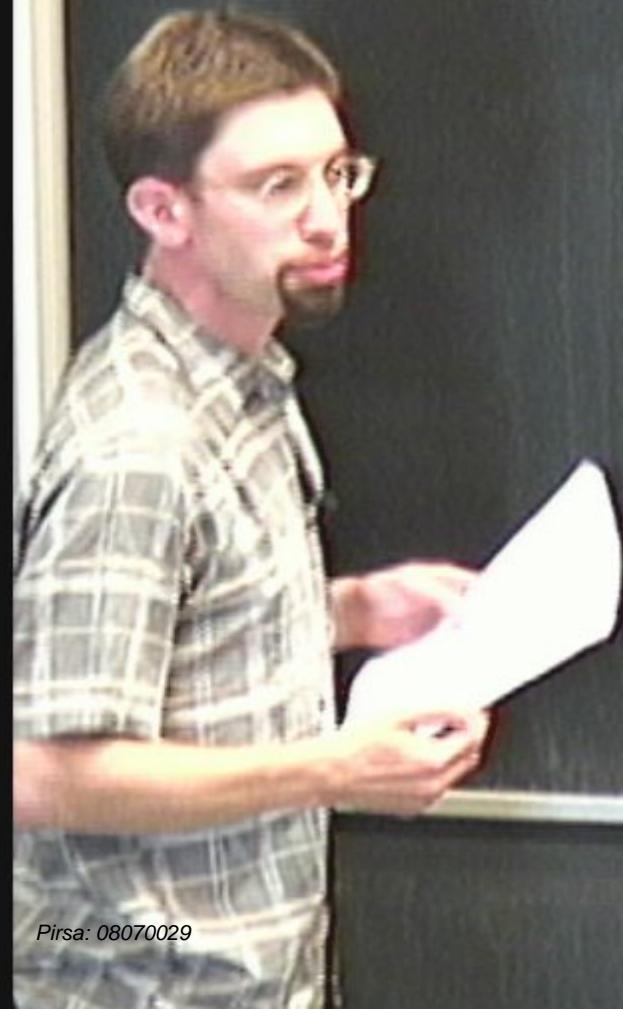
$$\nabla^2 U - \frac{f}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1$$



$$\nabla^2 U = \frac{e}{2M_{Pl}^2} \quad M_{Pl}^2 = \frac{1}{\text{常数}} \equiv 1 \quad \varphi \equiv \frac{\phi}{M_{Pl}}$$

$$\nabla^2 U = \frac{f}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\Psi}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi), V''(\varphi)$  to be neglected



$$\nabla^2 U = \frac{f}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\Psi}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi) \approx V''(\varphi)$  to be neglected

$$L_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{PL}} \right)$$

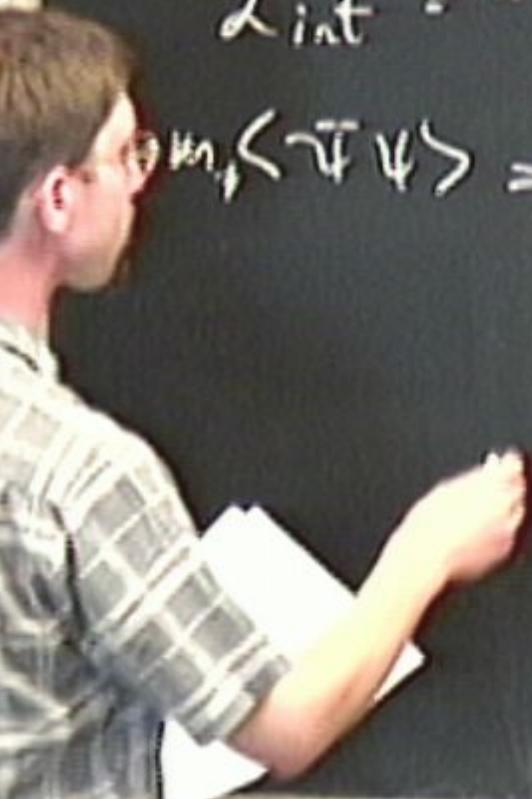


$$\nabla^2 U = \frac{\rho}{2M_{Pl}^2} \quad M_{Pl}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\psi}{M_{Pl}}$$

"Light" scalar  $\Rightarrow V(\varphi) \sim (\varphi)$  to be neglected

$$L_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{Pl}} \right)$$

$$\langle \bar{\psi} \psi \rangle = \bar{\rho}_{(t)} + \delta \rho(t, x)$$



$$\nabla^2 U = \frac{\rho}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\Psi}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi)$ ,  $V''(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{PL}} \right)$$

$$m_\Psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_{(t)} + \delta \rho(t, x)$$

$$\bar{\rho}_0 + \delta \rho(x)$$



$$\nabla^2 U = \frac{\rho}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{q}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi), V'(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{PL}} \right)$$

$$m_\Psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\begin{aligned} \square \dot{\varphi} + 3H\dot{\varphi} &= -V'(\varphi) - c_\Psi \rho(x, t) \\ \ddot{\varphi}(t) + 3H\dot{\varphi} &\sim -V'(\varphi) - \bar{\rho}(t) \end{aligned}$$

$$\nabla^2 U = \frac{\rho}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\psi}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi), V'(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{PL}} \right)$$

$$m_\psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\square \dot{\varphi} + 3H\dot{\varphi} = -V'(\varphi) - C_\Psi \rho(x, t)$$

$$\ddot{\varphi}(t) + 5H\dot{\varphi} = -V'(\varphi) - \bar{\rho}(t)$$



$$\nabla^2 u = \frac{f}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{u}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi) \approx V'(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\psi(\varphi) \bar{\psi} \psi \quad m_\psi = m_{\psi_0} \left( 1 + \frac{C_\psi \varphi}{M_{PL}} \right)$$

$$m, \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\square \dot{\varphi} \rightarrow iH \dot{\varphi} = -V'(\varphi) - C_\psi \bar{\rho}(x, t)$$

$$\ddot{\varphi}(t) + 3H\dot{\varphi} \sim -V'(\varphi) - \bar{\rho}(t)$$

$$\nabla^2 \varphi \sim C_\psi [\bar{\rho}(x) - \bar{\rho}(x_0)] \quad \Delta \varphi \Big|_{x_0}^{x_1} \propto C_V \Delta u \Big|_{x_0}^{x_1}$$

$$\nabla^2 U = \frac{f}{2M_{Pl}^2} \quad M_{Pl}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\psi}{M_{Pl}}$$

"Light" scalar  $\Rightarrow V(\varphi), V'(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{Pl}} \right)$$

$$m_\Psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\square \dot{\varphi} + 3H\dot{\varphi} = -V'(\varphi) - c_\Psi \bar{\rho}(x, t)$$

$$+ 3H\dot{\varphi} \sim -V'(\varphi) - \bar{\rho}(t)$$

$$\nabla^2 \varphi = c_\Psi [\bar{\rho}(x) - \bar{\rho}(t)] \quad \Delta \varphi \Big|_{x_i}^{x_e} \propto c_\Psi \Delta u \Big|_{x_i}^{x_e}$$

$$\nabla^2 U = \frac{\rho}{2M_{Pl}^2} \quad M_{Pl}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi \equiv \frac{\phi}{M_{Pl}}$$

"Light" scalar  $\Rightarrow V(\varphi), V'(\varphi)$  to be neglected

$$\mathcal{L}_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{Pl}} \right)$$

$$m_\Psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\square \phi \rightarrow H \dot{\phi} = -V'(\varphi) - c_\Psi \rho(x, t)$$

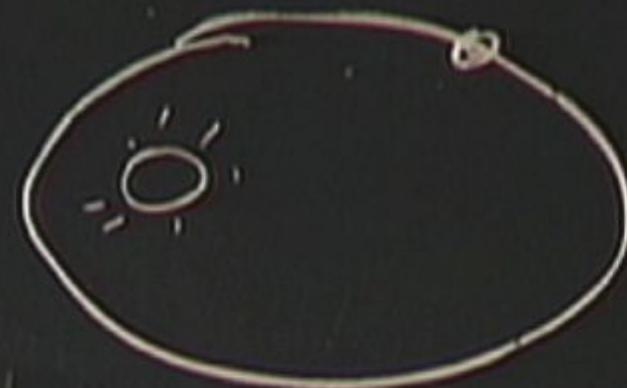
$$\ddot{\phi}(t) + H \dot{\phi} \approx -V'(\varphi) - \bar{\rho}(t)$$

$$\nabla^2 \varphi \cdot c_\Psi [\rho(x) - \bar{\rho}(t)] \quad \Delta \varphi \Big|_{x_i}^{x_e} \propto c_\Psi \Delta u \Big|_{x_i}^{x_e}$$

$$\frac{c_s}{M_{Pl}} = 1 \quad \varphi \equiv \frac{c_s}{M_{Pl}}$$

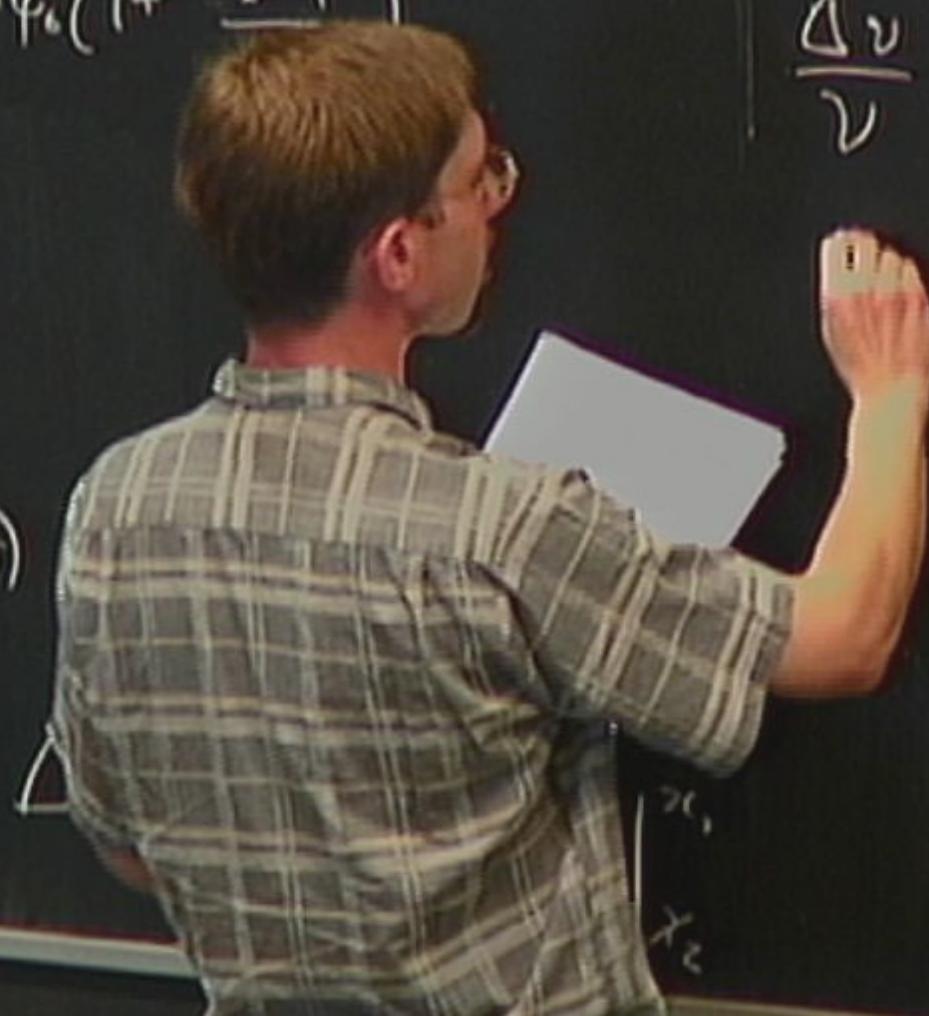
$V''(\varphi)$  to be neglected

$$\Psi = m_\Psi e \left( 1 + \frac{c_\Psi}{M_{Pl}} \varphi \right)$$



$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta G}{G}$$

$$EP(x,t)$$



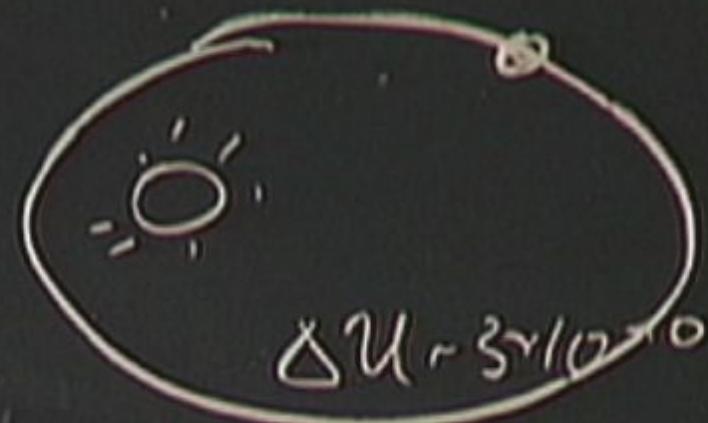
$$= \frac{1}{\sqrt{2} G} = 1 \quad \varphi = \frac{\varphi}{M_{Pl}}$$

(1)  $V''(\varphi)$  to be neglected

$$m_\Psi = m_{\Psi_0} \left( 1 + \frac{C_\Psi \varphi}{\Lambda} \right)$$

(2)

Barrow Shaw



$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta G}{G}$$

$$\sim 10^{-16}$$

$$k_i \Rightarrow f_{e_0} \times 10^{-7}$$

$$PL = \frac{M_{\text{Pl}}}{M_{\text{Pl}}} = 1 \quad \varphi \equiv \frac{\varphi}{M_{\text{Pl}}}$$

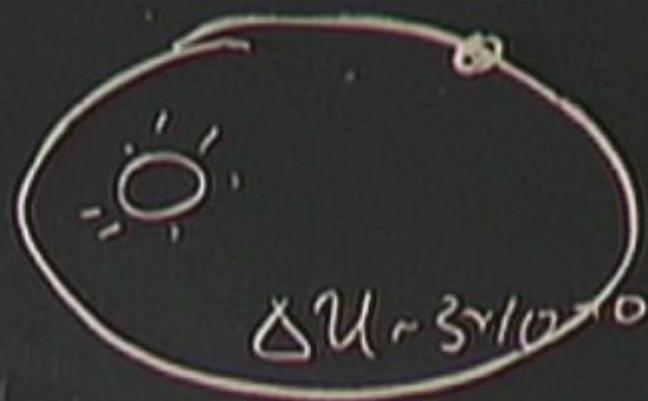
$V'(\varphi)$   $V''(\varphi)$  to be neglected

$$\dot{\varphi}^2 m_\Psi^2 = m_{\Psi_0}^2 \left( 1 + \frac{C_\Psi \varphi}{M_{\text{Pl}}} \right)$$

$(t, x)$

$C_\Psi P(x, t)$

$$\Delta \varphi \Big|_{x_1}^{x_2} \propto C_V \Delta U \Big|_{x_1}^{x_2}$$



$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta G}{G} \sim 10^{-16}$$

$$k_i \rightarrow \text{few} \times 10^{-7}$$

Barrow/Shaw  
fit Rosjan band et al

$$\frac{1}{M_{PL}} \ll 1 \quad \varphi \equiv \frac{\Psi}{M_{PL}}$$

far  $\Rightarrow V(\varphi) \approx V'(\varphi)$  to be neglected

$$m_\Psi \approx m_{\Psi_0} \left( 1 + \frac{c_\Psi \varphi}{M_{PL}} \right)$$

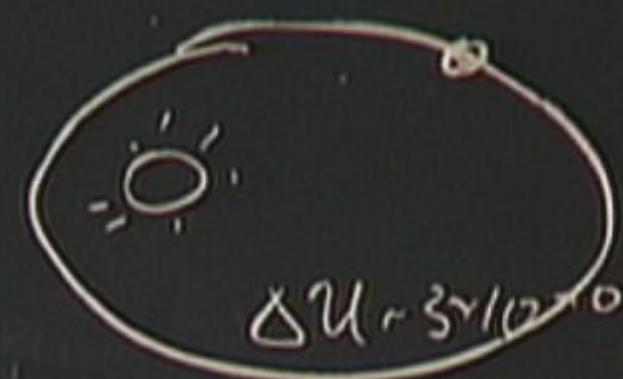
$$\bar{\rho}_t + \delta\rho(t, x)$$

$$\bar{\rho}_0 + \delta\rho(x)$$

$$= -V'(\varphi) - c_\varphi$$

$$-V'(\varphi) - \bar{\rho}(t)$$

$$c_\varphi [\rho(x) - \bar{\rho}]$$



$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta G}{G} \\ \sim 10^{-16}$$

$$k_i \rightarrow f_{\text{nu}} \times 10^{-7}$$

Barrow Shaw  
fit Rosenband et al  
 $k_\alpha = (5.4 \pm 5.1) \times 10^{-8}$

$$C_{\mu\nu} \propto \frac{1}{x^2}$$

$$=\frac{1}{2\pi G} \equiv 1 \quad \varphi = \frac{\varphi}{M_{Pl}}$$

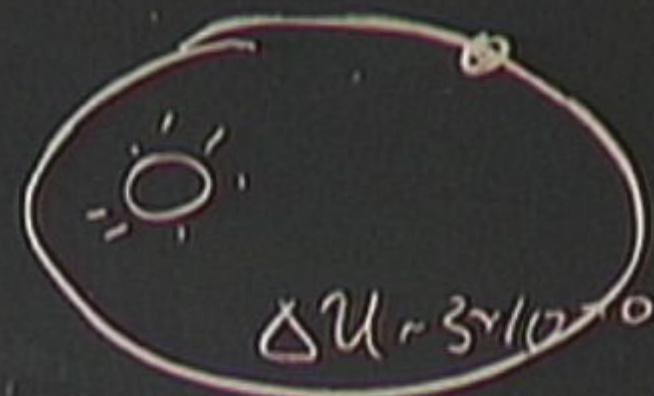
( $\varphi$ )  $V'(\varphi)$  to be neglected

$$m_\Psi = m_{\Psi_0} \left( 1 + \frac{C_\Psi \varphi}{M_{Pl}} \right)$$

$x)$

$C_\Psi P(x,t)$

$$[t_0] \quad \Delta\varphi \Big|_{x_i}^x \propto C_\Psi \Delta U \Big|_{x_i}^x$$



$$\begin{aligned} \frac{\Delta v}{v} &\sim O(1) \frac{\Delta \varphi}{G} \\ &\sim 10^{-6} \end{aligned}$$

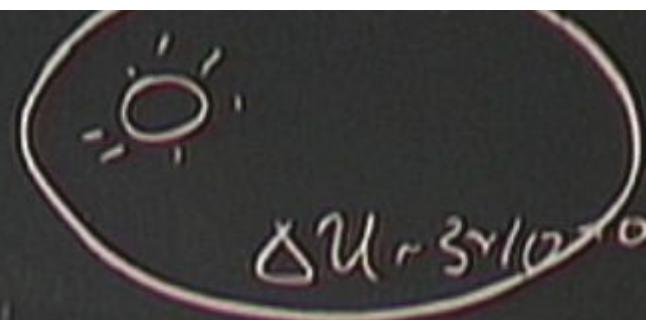
$$k_i \rightarrow \text{few} \times 10^{-7}$$

Barrow Shaw  
fit Rosenbandet  $k_\alpha = (-54 \pm 5.1)$

$$\begin{array}{ll} k_\mu & 10^{-8} \\ \text{few} \times 10^{-6} & k_\alpha \end{array}$$

$\varphi$ )  $V''(\varphi)$  to be neglected

$M_{PL}$



$$m_\Psi = m_{\Psi_0} \left( 1 + \frac{C_\Psi \epsilon}{M_{PL}} \right)$$

x)

$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta \epsilon}{G}$$

$$\sim 10^{-16}$$

$$k_i \rightarrow \text{few} \times 10^{-7}$$

$C_V P(x, t)$

Barrow Shaw fit Rosenband et al  $k_\alpha = (54 \pm 5.1) 10^{-8}$

$$[t_0] \quad \Delta \varphi \Big|_{x_1}^x \propto C_V \Delta U \Big|_{x_2}^x \Bigg| \frac{k_\mu}{k_\alpha} \text{ few} \times 10^{-6}$$

$$k_q \rightarrow \frac{m_1}{\lambda_{QCD}} \quad m_1 = \frac{m_u + m_d}{2}$$

$$\nabla^2 U = \frac{\rho}{2M_{PL}^2} \quad M_{PL}^2 = \frac{1}{8\pi G} \equiv 1 \quad \varphi = \frac{\psi}{M_{PL}}$$

"Light" scalar  $\Rightarrow V(\varphi), V''(\varphi)$  to be neglected

$$L_{int} = -m_\Psi(\varphi) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left(1 + \frac{c_\Psi \varphi}{M_{PL}}\right)$$

$$m_\Psi \langle \bar{\psi} \psi \rangle = \bar{\rho}_0 + \delta \rho(t, x)$$

$$\square \dot{\varphi} + 3H\dot{\varphi} = -V'(\varphi) - c_\Psi \rho(x, t)$$

$$\ddot{\varphi}(t) + 5H\dot{\varphi} = -V''(\varphi) - \bar{\rho}(t)$$

$$\nabla^2 \varphi \cdot c_\Psi [\rho(x) - \bar{\rho}(t)] \quad \Delta \varphi \Big|_{x_i} \propto c_V \Delta U \Big|_{x_i} \Bigg| \frac{k_\mu}{k_\varphi} \text{ few} \times 10^{-4} \quad 10^{-5}$$

$$k_\varphi \rightarrow \frac{m_\varphi}{\Lambda_{\text{cusp}}} \quad m_\varphi = \frac{M_{\text{Planck}}}{2}$$

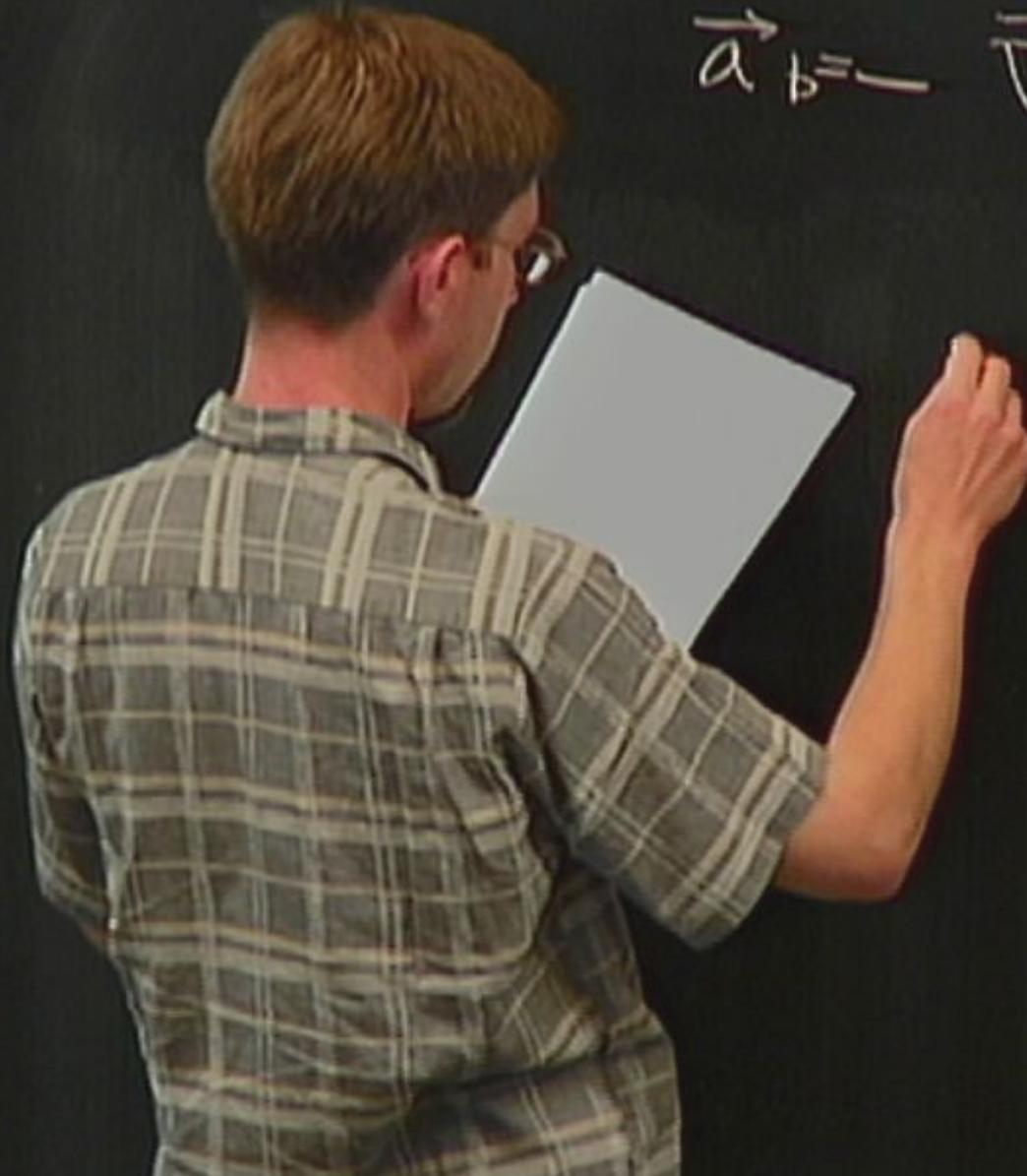


$$\frac{\Delta v}{v} \sim O(1) \frac{\Delta G}{G} \sim 10^{-16}$$

$$k_\varphi \rightarrow \text{few} \times 10^{-7}$$

Barrow Shaw  
fit Rosat bandet al  $k_\alpha = (-5.1 \pm 5.1) \times 10^{-8}$

$$M_b(\vec{x}) \Rightarrow \text{acceleration}$$
$$\vec{a}_b = -\vec{\nabla}_b$$



$$M_b(\vec{x}) \Rightarrow \text{acceleration}$$
$$\vec{a}_b = -\frac{\vec{\nabla} M_b}{M_b}$$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = -\frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

CAUTION

Keep at least one meter away  
from the center of the beam  
if a deviation in angle  
from vertical exceeds 10°.

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = -\frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b + \vec{a}_{b'}$$

$$\Leftrightarrow \vec{\nabla}_{G_i \neq 0}$$



$M_b(x) \Rightarrow$  acceleration

$$\vec{a}_b = -\frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow M_b \neq M_{b'}$$

$$\int m d\tau$$

$$\vec{a}_b \neq \vec{a}_{b'} \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = \frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$M_b(\vec{x}) \rightarrow \text{acceleration} \\ \vec{a}_b = -\vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m_0}{m}\right)^2 g_{\mu\nu}$$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = -\frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m}{m_0}\right)^2 g_{\mu\nu}$$



$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = \frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m}{m_0}\right)^2 g_{\mu\nu}$$

Geodesics of  $\vec{g}'_{\mu\nu}$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = \frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m}{m_0}\right)^2 g_{\mu\nu}$$

Geodesics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{00} = -\vec{\nabla} - \frac{\vec{\nabla} M}{m}$$

$M_b(x) \Rightarrow$  acceleration

$$\vec{a}_b = -\vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_b'}{\partial \ln a_i} \Rightarrow \vec{a}_b = \vec{a}_b'$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla}_{G_i + C}$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m}{m_0}\right)^2 g_{\mu\nu}$$

Geodesics of  $g'_{\mu\nu}$

$$\vec{\ddot{x}} = -\frac{1}{2} \vec{\nabla} g'_{00} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$$\frac{M_b}{M_b} = \text{const}$$



$M_b(x) \Rightarrow$  acceleration

$$\vec{a}_b = -\vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_b'}{\partial \ln a_i} \Rightarrow \vec{a}_b = \vec{a}_b'$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla}_{G_i + \phi}$$

$$m = m_0 \left(1 + \frac{\Delta h_i}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m}{m_0}\right)^2 g_{\mu\nu}$$

Geodesics of  $g'_{\mu\nu}$

$$\vec{\ddot{x}} = -\frac{1}{2} \vec{\nabla} g'_{00} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$$\frac{M_b}{M_b'} = \text{const}$$

$M_b(\vec{x}) \rightarrow \text{acceleration}$

$$\vec{a}_b = \frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta m}{m_0}\right) \quad g'_{\mu\nu} = \left(\frac{m_0}{m}\right)^2 g_{\mu\nu}$$

Geodesics of  $g'_{\mu\nu}$

$$\vec{\ddot{x}} = -\frac{1}{2} \vec{\nabla} g'_{\alpha\alpha} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$\frac{M_b}{M_b'} \neq \text{const} \Rightarrow \text{cannot define } g'_{\mu\nu} \text{ universally}$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = \vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} \neq \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int_M \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i \neq 0$$

$$m = m_0 \left(1 + \frac{\Delta k_0}{k_0}\right) \quad g'_{\mu\nu} = \left(\frac{m_0}{k_0}\right)^2 g_{\mu\nu}$$

Geodesics of  $g'_{\mu\nu}$

$$\vec{\ddot{x}} = -\frac{1}{2} \vec{\nabla} g'_{\alpha\beta} = -\vec{\nabla} - \vec{\nabla} \frac{M}{M}$$

$\frac{M_b}{M_b'} \neq \text{const} \Rightarrow$  cannot define  $g'_{\mu\nu}$  universally

$M_b(x) \Rightarrow$  acceleration

$$\vec{a}_b = \frac{\vec{\nabla} M_b}{M_b}$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b + \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} dx^\mu dx^\nu} dt \leftrightarrow \vec{\nabla}_c$$

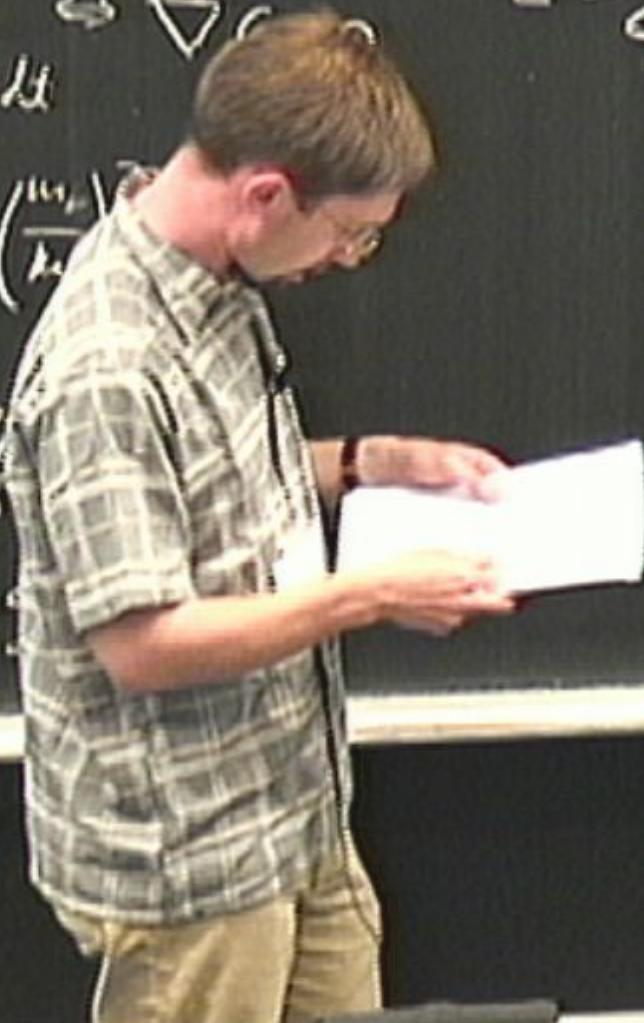
$$m = m_0 \left(1 + \frac{\Delta \mu}{\mu_0}\right) \quad g'_{\mu\nu} = \left(\frac{\mu_0}{\mu}\right)$$

geodetics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{\mu\nu} = -\vec{\nabla} - \vec{\nabla}_M$$

$$\frac{M_b}{M_b'} + \text{const} \Rightarrow \text{cannot define}$$

$$\begin{aligned} \eta &\equiv \frac{\alpha_b \cdot \alpha_{b'}}{g} \\ &= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{M_b}{M_{b'}} \right) \cdot \hat{g} \\ &= -\sum_i \frac{\partial \ln \left( \frac{M_b}{M_{b'}} \right)}{\partial G_i} \end{aligned}$$



$$\eta \equiv \frac{\alpha_b - \alpha_{b'}}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{m_b}{m_{b'}} \right) \cdot \hat{\vec{g}}$$

$$= - \sum_i \frac{\partial \ln \left( \frac{m_b}{m_{b'}} \right)}{\partial G_i} \frac{1}{g} \vec{\nabla} (\ln G_i) \cdot \hat{\vec{g}}$$



$$\eta = \frac{\alpha_b - \alpha_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{m_b}{m_{b'}} \right) \cdot \hat{\vec{g}}$$

$$= -\sum_i \frac{\partial \ln \left( \frac{m_b}{m_{b'}} \right)}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} \ln G_i - \hat{\vec{g}}$$

$$\vec{\nabla} \ln G_i = k_i \vec{\nabla} u = k_i \vec{g}$$

$$\eta \equiv \frac{a_b - a_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{m_b}{m_{b'}} \right) \cdot \hat{\vec{g}}$$

$$= -\sum_i \frac{\partial \ln \left( \frac{m_b}{m_{b'}} \right)}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} (\ln G_i \cdot \hat{\vec{g}})$$

$$\vec{\nabla} \ln G_i = k \cdot \vec{\nabla} u = k_i \vec{g}$$

$$\eta = \sum_i \lambda^{b-b'}_i k_i$$

$$M_b(\vec{x}) \Rightarrow \text{acceleration}$$

$$\vec{\alpha}_b = \vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{\alpha}_b + \vec{\alpha}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} d\mu \Leftrightarrow \vec{\nabla}_{G_i+0}$$

$$m = m_0 \left(1 + \frac{\Delta k_i}{k_{i_0}}\right) \quad g'_{\mu\nu} = \left(\frac{m_{i_0}}{k_{i_0}}\right)^2 g_{\mu\nu}$$

geodesics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{\mu\nu} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$$\frac{M_b}{M_{b'}} \neq \text{const} \Rightarrow \text{cannot}$$

$$\eta = \frac{\alpha_b - \alpha_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{M_b}{M_{b'}} \right) \cdot \hat{g}$$

$$= -\sum_i \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} \ln G_i \cdot \hat{g}$$

$$\vec{\nabla} \ln G_i = k \cdot \vec{\nabla} u = k \cdot \vec{g}$$

$$\eta = \sum_i \lambda_i^{b-b'} k_i \cdot \lambda_i^b \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i}$$



$M_b(\vec{x}) \Rightarrow$  acceleration  
 $\vec{a}_b = \vec{\nabla} M_b$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b \neq \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla}_{G_i+0}$$

$$m = m_0 \left(1 + \frac{\Delta k_i}{k_i}\right) \quad g'_{\mu\nu} = \left(\frac{m_i}{k_i}\right)^2 g_{\mu\nu}$$

geodesics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{\mu\nu} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$\frac{M_b}{M_b'} \neq \text{const} \Rightarrow$  cannot define  $g'_{\mu\nu}$  universally

$$\eta = \frac{a_b - a_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{M_b}{M_{b'}} \right) \cdot \hat{g}$$

$$< -\sum_i \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} \ln G_i \cdot \hat{g}$$

$$\vec{\nabla} \ln G_i = k \cdot \vec{\nabla} u = k \cdot \vec{g}$$

$$\eta = \sum_i \lambda_i^{b-b'} k_i \cdot \lambda_i^{b'} \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i}$$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = \vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b + \vec{a}_{b'}$$

$$\int m dt = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla}_{G_i+0}$$

$$m = m_0 \left(1 + \frac{\Delta k_i}{k_i}\right) g'_{\mu\nu} = \left(\frac{m_i}{k_i}\right)^2 g_{\mu\nu}$$

geodesics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{\mu\nu} = -\vec{\nabla} - \vec{\nabla} \frac{M}{m}$$

$$\frac{M_b}{M_b'} \neq \text{const} \Rightarrow \text{cannot define}$$

$$\eta = \frac{a_b - a_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{M_b}{M_b'} \right) \cdot \hat{g}$$

$$= -\sum_i \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} \ln G_i.$$

$$\vec{\nabla} \ln G_i = k_i \vec{\nabla} u = k_i \vec{g}$$

$$\eta = \sum_i \lambda^{b-b'}_i k_i \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i}$$

$$2 \ln \left[ \frac{M_b/A_{b' \text{kin}}}{M_b'/A_{b' \text{kin}}} \right]$$

$M_b(\vec{x}) \Rightarrow$  acceleration

$$\vec{a}_b = -\vec{\nabla} M_b$$

$$\frac{\partial \ln M_b}{\partial \ln G_i} + \frac{\partial \ln M_{b'}}{\partial \ln G_i} \Rightarrow \vec{a}_b + \vec{a}_{b'}$$

$$\int m d\tau = \int m \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu} dt \Leftrightarrow \vec{\nabla} G_i + 0$$

$$m = m_0 \left(1 + \frac{\Delta k_i}{k_i}\right) g'_{\mu\nu} \circ \left(\frac{m}{k_i}\right)^2 g_{\mu\nu}$$

Geodetics of  $g'_{\mu\nu}$

$$\vec{x} = -\frac{1}{2} \vec{\nabla} g'_{\mu\nu} = -\vec{\nabla} - \vec{\nabla}_M$$

$$\frac{M_b}{M_{b'}} \neq \text{const} \Rightarrow \text{cannot define } g'_{\mu\nu} \text{ universally}$$

$$\eta \equiv \frac{a_b - a_{b'}}{g}$$

$$= -\frac{1}{g} \vec{\nabla} \ln \left( \frac{M_b}{M_{b'}} \right) \cdot \hat{j}$$

$$= -\sum_i \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i} \frac{1}{g} \vec{\nabla} \ln G_i \cdot \hat{j}$$

$$\vec{\nabla} \ln G_i = k_i \vec{\nabla} u = k_i \vec{g}$$

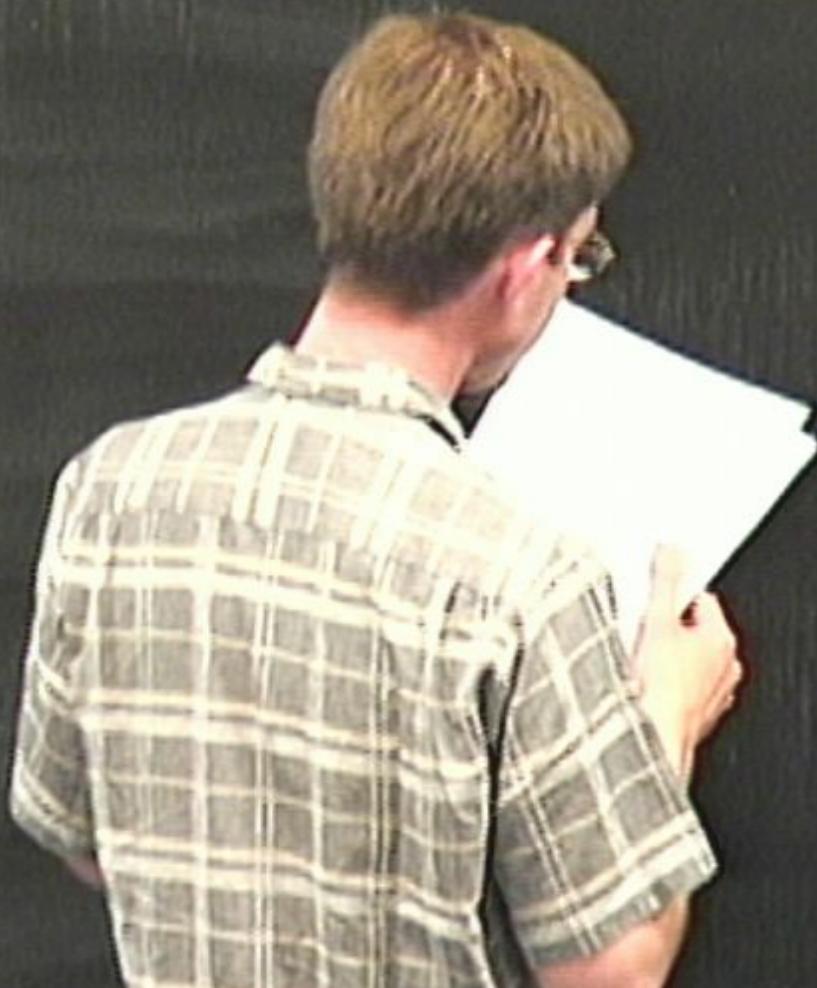
$$\eta = \sum_i \lambda_i^{b-b'} k_i \lambda_i^u \frac{\partial \ln (M_b/M_{b'})}{\partial \ln G_i}$$

$$\partial \ln \left[ \frac{M_b/A_{b'NN}}{M_{b'}/A_{b'NN}} \right] \quad m_N = \frac{m_p + m}{2}$$

$$\frac{M_b}{A_{MN}} = 1 - \left( f_p \cdot \frac{1}{2} \right) \frac{\delta_{IN}}{A_{MN}} + f_g \frac{\delta_{IN}}{A_{MN}} + \frac{z^2}{A_{MN}} \frac{\alpha_0}{A_{MN}}$$



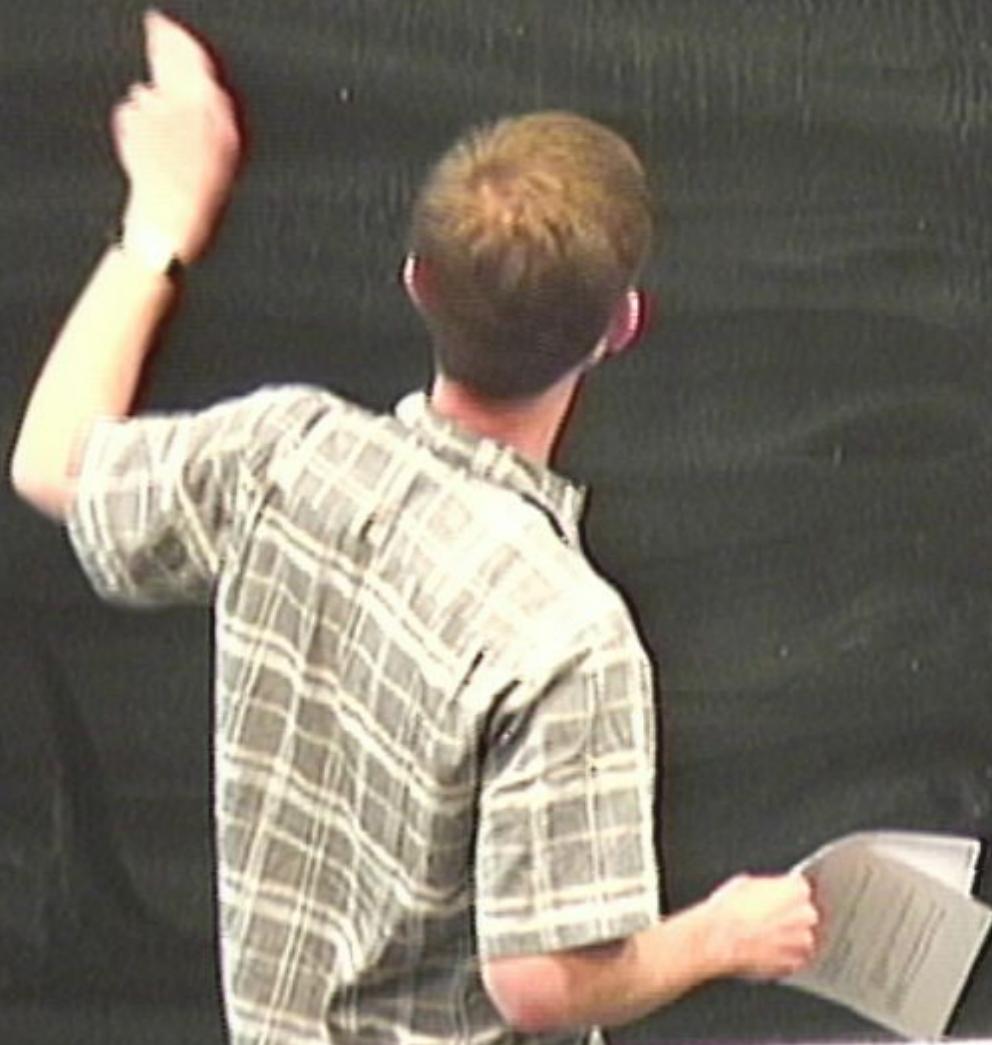
$$\frac{M_b}{A_{MN}} = 1 - \left(f_p \cdot \frac{1}{2}\right) \frac{f_N}{m_N} + f_p \frac{m_e}{m_N} + \frac{\epsilon^2}{A^{MN}} \frac{a_c}{m_N}$$
$$\frac{a_c}{m_N} \sim 10^{-3}$$
$$= \text{const} \times a$$



$$\frac{M_b}{A_{MN}} = 1 - \left(f_p \cdot \frac{1}{2}\right) \frac{\delta_N}{MN} + f_g \frac{m_e}{MN} + \frac{z^2}{A_{MN}} \frac{a_c}{MN} - \frac{a_v}{MN}$$

$\frac{a_c}{MN} \sim 10^{-3}$

$= \text{const} \cdot \alpha$



$$\frac{M_b}{A_{MN}} = 1 - \left( f_g \cdot \frac{1}{2} \right) \frac{\delta_{MN}}{E_{MN}} + f_g \frac{f_{ce}}{E_{MN}} + \frac{r^2}{A^2} \frac{a_c}{E_{MN}} - \frac{q_v}{E_{MN}} + A^{-1} \frac{q_1}{E_{MN}} + \dots$$

$\frac{a_c}{E_{MN}} \sim 1D^{-3}$   
 $a_c = a$



$$\frac{M_b}{A_{MN}} = 1 - \left( f_g \cdot \frac{1}{2} \right) \frac{\delta_{MN}}{A_{MN}} + f_g \frac{a_e}{MN} + \frac{r^2}{A^2} \frac{a_e}{MN} - \frac{a_v}{MN} + A^{-1} \frac{a_1}{MN} + \dots$$

$\frac{a_e}{MN} \sim 10^{-3}$   
 $a_e \sim a$

$$\frac{a_v}{MN} \sim \frac{a_1}{MN} \sim 0.017$$



$$\frac{M_b}{A \cdot u_N} = 1 - \left( f_p \cdot \frac{1}{2} \right) \frac{\delta_N}{u_N} + f_T \frac{a_e}{u_N} + \frac{\gamma^2}{A^2} \frac{a_e}{u_N} - \frac{a_V}{u_N} + A^{-1} \frac{a_L}{u_N} + \dots$$

$$\frac{\delta_N}{u_N} = \frac{u_A - u_P}{u_N} \approx 1.3 \cdot 10^{-3}$$

$$\frac{a_e}{u_N} \approx 10^{-3}$$

$\approx \text{constant}$

$$\frac{a_V}{u_N} \approx \frac{a_L}{u_N} \approx 0.017$$



$$\frac{M_b}{A_{MN}} = 1 - \left(f_p - \frac{1}{2}\right) \frac{\delta_N}{\kappa_{MN}} + f_p \frac{\kappa_e}{\kappa_{MN}} + \frac{2^L}{A^{48}} \frac{a_c}{\kappa_{MN}}$$
$$f_p = \frac{2}{A}$$
$$\frac{\delta_N}{\kappa_{MN}} \approx 1.3 \cdot 10^{-3}$$
$$\frac{a_c}{\kappa_{MN}} \sim 10^{-3}$$
$$= \text{const} = \alpha$$

$$\frac{M_b}{A_{MN}} = 1 - \left( f_p \cdot \frac{1}{2} \right) \frac{\delta_N}{MN} + f_p \frac{a_e}{MN} + \frac{\pi^2}{A^2} \frac{a_e}{MN} - \frac{a_y}{MN} + A^{-1} \frac{a_1}{MN} + \dots$$

$$f_p = \frac{2}{\pi} \quad \frac{\delta_N}{MN} = \frac{m_p - m_f}{MN} \approx 1.3 \cdot 10^{-3}$$

$$\frac{a_e}{MN} \sim 10^{-3}$$

scand-a

$$\frac{a_y}{MN} \sim \frac{a_e}{MN} \sim 0.017$$



$$\frac{M_b}{A_{MN}} = 1 - \left( f_p - \frac{1}{2} \right) \frac{f_N}{m_N} + f_R \frac{m_e}{m_N} + \frac{\gamma^2}{A^{9/5}} \frac{\alpha_c}{m_N}$$

$$f_p = \frac{\gamma^2}{A} \quad \frac{\delta_N}{m_N} = \frac{m_R - m_p}{m_N} \sim 1.3 \times 10^{-3} \quad \frac{\alpha_c}{m_N} \sim 10^{-3}$$

$\gamma = \text{const} \times \alpha$

$$\Delta \ln \frac{M_b}{M_b'} = - \frac{\delta_i}{\ln \frac{\delta_N - m_e}{m_N}} + \frac{d}{\ln \frac{m_R - m_p}{m_N}}$$

$$\left[ f_p \right]_b' \quad \left[ A^{-1/3} \right]_b'$$

$$\frac{M_b}{A_{MN}} = 1 - \left(f_p \cdot \frac{1}{2}\right) \frac{f_N}{m_N} + f_p \frac{m_e}{m_N} + \frac{\gamma^2}{A^{95}} \frac{a_c}{m_N}$$

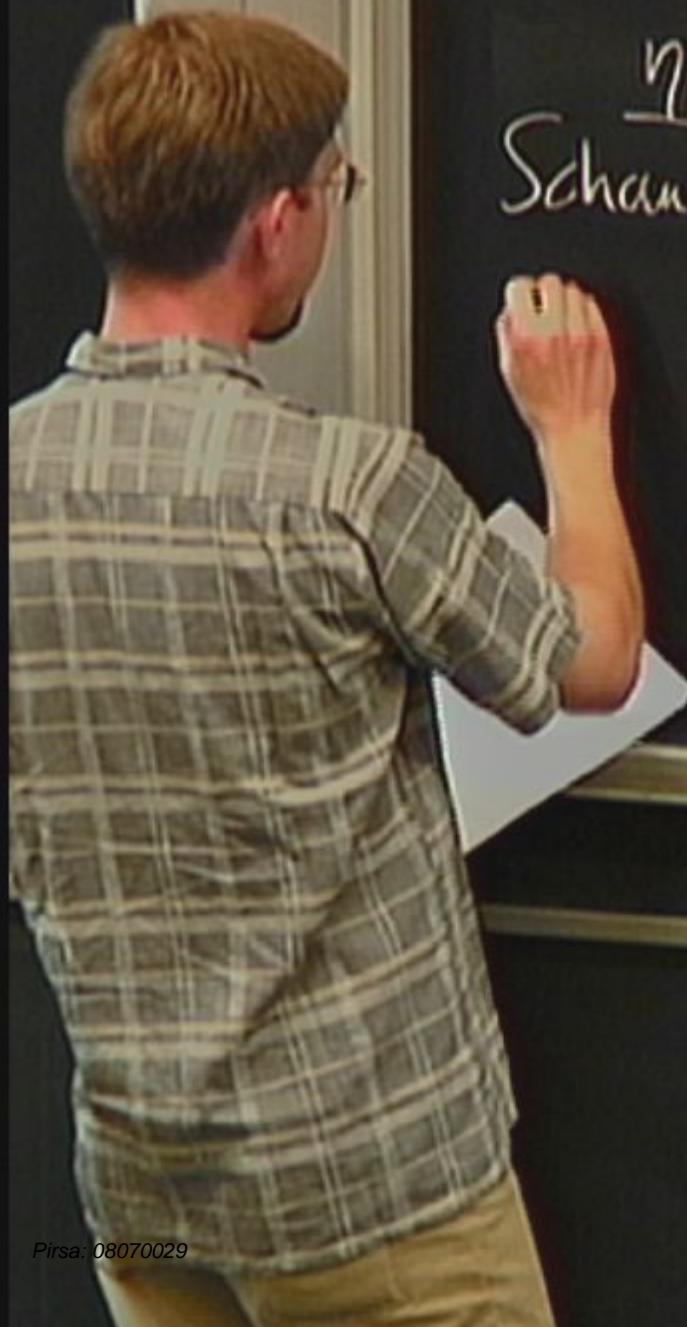
$$f_p = \frac{\gamma^2}{A} \quad \frac{\delta_N}{m_N} = \frac{m_R - m_p}{m_N} \sim 1.3 \times 10^{-3} \quad \frac{a_c}{m_N} \sim 10^{-3}$$

$= \text{const} \times \alpha$

$$\Delta b^{AA} = - \frac{\delta_{N-m_e}}{m_N} \Delta \ln \frac{\delta_{N-m_e}}{m_N} \left[ f_p \right]_b^b + \frac{a_s}{m_N} \Delta \ln \frac{a_s}{m_N} \left[ A^{-\frac{1}{3}} \right]_b^b$$

$$T^{1/b} = \frac{m_N - \Delta m}{m_N} \left[ f_P \right]_b,$$
$$\eta \text{ values} + \frac{\alpha_s}{m_N} \Delta \ln \frac{\alpha_s}{m_N} \left[ A^{-1} S \right]_b,$$

Schaefer 08 Be-Ti  $(0.3 \pm 1.8) \times 10^{-13}$



$$\frac{M_b}{A_{MN}} = 1 - \left(f_p \cdot \frac{1}{2}\right) \frac{\delta_{N,M}}{m_N} - f_p \frac{m_c}{m_N} + \frac{\gamma^2}{\Lambda^4} \frac{a_c}{m_N} - \frac{a_V}{m_N} + A^{-\frac{1}{2}} \frac{a_S}{m_N} + \dots$$

$$f_p = \frac{2}{\Lambda} \quad \frac{\delta_N}{m_N} = \frac{m_c - m_p}{m_N} \sim 1.3 \cdot 10^{-3}$$

$$\frac{a_c}{m_N} \sim 10^{-3}$$

constant

$$\frac{a_V}{m_N} \sim \frac{a_S}{m_N} \sim 0.017$$

$$\Delta \ln \frac{M_b}{m_b} = - \frac{\delta_{N,M}}{m_N} \Delta \ln \frac{\delta_{N,M}}{m_N} \left[f_p\right]_b^b + \frac{a_c}{m_N} \Delta \ln \left[\frac{\gamma(\gamma-1)}{\Lambda^4 s}\right]_b^b$$

$$+ \frac{a_S}{m_N} \Delta \ln \left[A^{-\frac{1}{2}}\right]_b^b$$

$k_\infty \propto k_{as} \Rightarrow \frac{a_S}{m_N}$

Schwarzschild '08 Be-Ti  $(0.3 \pm 1.8) \cdot 10^{-3}$

Bar



$$\frac{M_b}{A_{MN}} = 1 - (f_p \cdot \frac{1}{2}) \frac{\delta_N}{m_N} + f_p \frac{m_c}{m_N} + \frac{r^2}{A^2} \frac{a_c}{m_N} - \frac{a_V}{m_N} + A^{-1} \frac{a_L}{m_N} + \dots$$

$$f_p = \frac{2}{A} \quad \frac{\delta_N}{m_N} = \frac{m_B - m_P}{m_N} \sim 1.3 \cdot 10^{-3}$$

$$\frac{a_c}{m_N} \sim 10^{-3}$$

constant

$$\frac{a_V}{m_N} \sim \frac{a_S}{m_N} \sim 0.017$$

$$\Delta \ln \frac{M_b}{m_N} = - \frac{\delta_N \cdot m_c}{m_N} \Delta \ln \frac{\delta_N \cdot m_c}{m_N} \left[ f_p \right]_{b'}^b + \frac{a_c}{m_N} \Delta \ln \left[ \frac{r(r-1)}{A^2 s} \right]_{b'}^b$$

$$\eta \text{ values} + \frac{a_S}{m_N} \Delta \ln \frac{a_S}{m_N} \left[ A^{-1} s \right]_{b'}^b$$

$$K_{Qn} \propto k_{as} \Rightarrow \frac{a_S}{m_N}$$

$$\Rightarrow \frac{\delta_N \cdot m_c}{m_N}$$

Snijders '08 Be-Ti  $(0.3 \pm 1.8) \cdot 10^{-3}$

Y9 Fe-SiO<sub>2</sub>  $(0.5 \pm 7.1) \cdot 10^{-3}$

Jansky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$

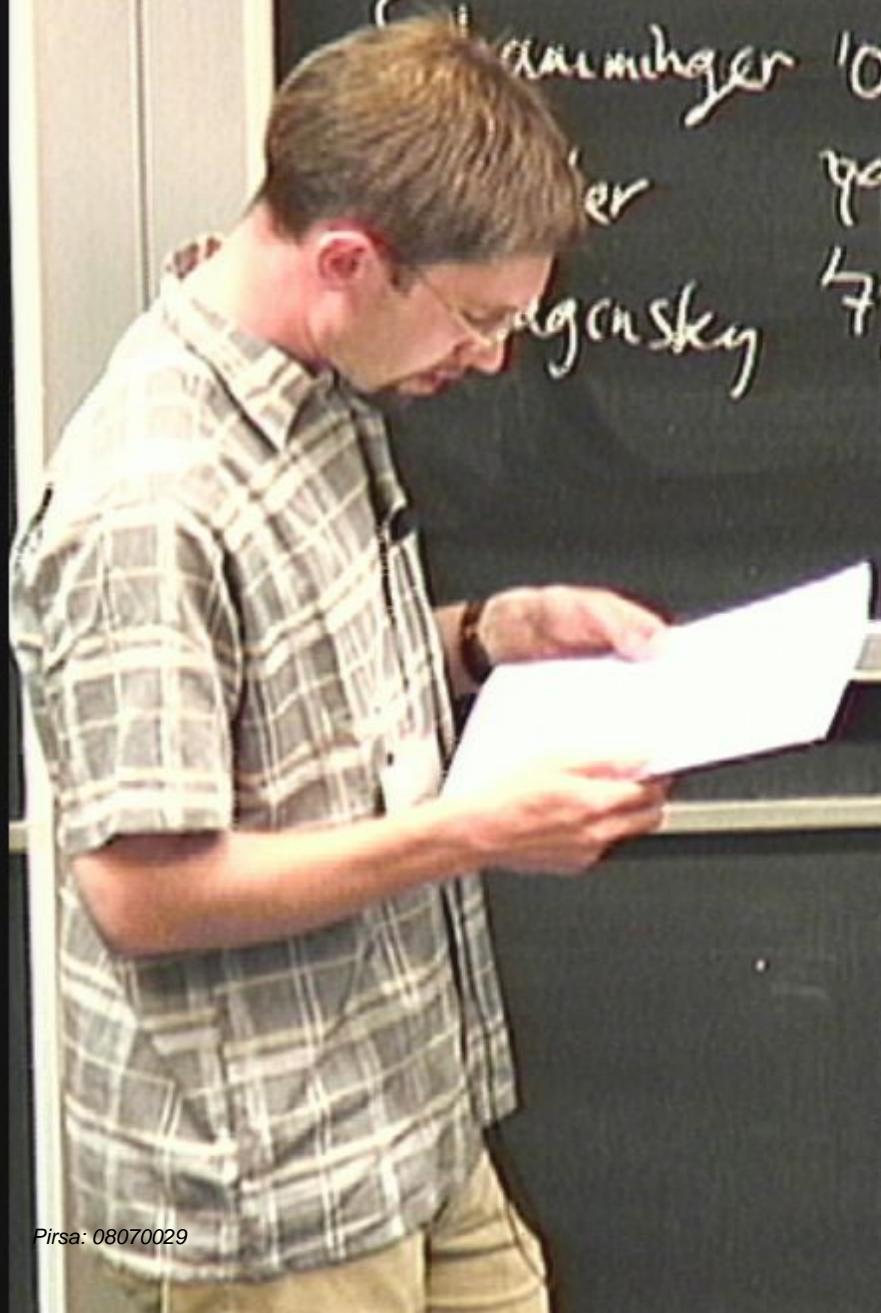


$$\eta \text{ values} + \frac{\alpha_s}{m_N} \Delta \ln \frac{\alpha_s}{m_N} \left[ A^{-1}s \right]_{b'} K_{Qn}$$

raamhager '08 Be-Tl.  $(0.3 \pm 1.8) \cdot 10^{-13}$

er '99 Fe-SiO<sub>2</sub>  $(0.5 \pm 7.1) \cdot 10^{-13}$

agansky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$



$$\frac{M_b}{A_{MN}} = 1 - \left(f_p \cdot \frac{1}{2}\right) \frac{\delta_N}{m_N} + f_p \frac{m_c}{m_N} + \frac{z^2}{A^{1/3}} \frac{a_c}{m_N} - \frac{a_V}{m_N} + A^{-1} \frac{a_S}{m_N}$$

$$f_p = \frac{2}{A} \quad \frac{\delta_N}{m_N} = \frac{m_p - m_p}{m_N} \sim 1.3 \cdot 10^{-3} \quad \frac{a_c}{m_N} \sim 10^{-3} \quad \frac{a_V}{m_N} \sim \frac{a_S}{m_N} \sim 0.017$$

$$\Delta \ln \frac{M_b}{M_b'} = - \frac{\delta_N \cdot a_c}{m_N} \Delta \ln \frac{\delta_N \cdot m_c}{m_N} [f_p]_{b'}^b + \frac{a_c}{m_N} \Delta \ln a \left[ \frac{z(p-1)}{A^{1/3}} \right]_{b'}^b$$

$$\eta \text{ values} + \frac{a_S}{m_N} \Delta \ln \frac{a_S}{m_N} [A^{-1/3}]_{b'}^b \quad k_{Qn}^k \propto k_{as} \Rightarrow \frac{a_S}{m_N} \\ \Rightarrow \frac{\delta_N \cdot m_c}{m_N}$$

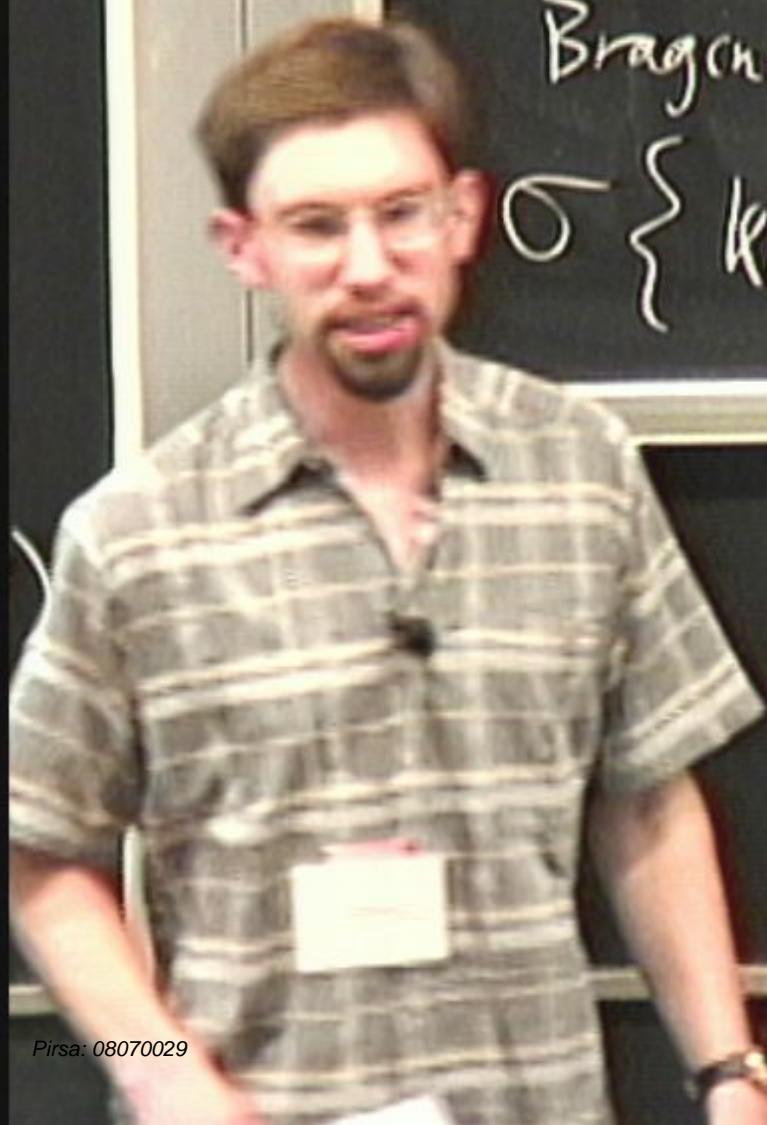
Schammlinger '08 Be-Ti  $(0.3 \pm 1.8) \cdot 10^{-13}$

Baybler '99 Te-SiO<sub>2</sub>  $(0.5 \pm 7.1) \cdot 10^{-13}$

Braginsky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$

$$\sigma \{ k_{Qn}, k_\alpha, k_{as} \} = \{ 38, 2.3, 1.03 \} \cdot 10^{-9}$$

Schaefferger '08 Be-Ti  $(0.3 \pm 1.8) \cdot 10^{-13}$   
Bäbler 99 Fe-SiO<sub>2</sub>  $(0.5 \pm 1.1) \cdot 10^{-13}$   
Braginsky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$   
 $\sigma \{ k_{\alpha_1}, k_{\alpha_2}, k_{\alpha_3} \} = \{ 38, 23, 1.0 \} \cdot 10^{-9}$



Schauflinger '08 Be-Ti  $(0.3 \pm 1.8) \cdot 10^{-13}$   
Bäbler 99 Fe-SiO<sub>2</sub>  $(0.5 \pm 1.1) \cdot 10^{-13}$   
Braginsky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$

$$\sigma \{ k_{\alpha\gamma}, k_\alpha, k_{\alpha\beta} \} = \{ 38, 2.3, 1.0 \} \cdot 10^{-9}$$

$\gamma$  values       $\mu_N$        $\mu_N C$        $J_b$        $K_{Qn}$

Schaeffinger '08 Be-T.  $(0.3 \pm 1.8) \cdot 10^{-13}$   
Baybker '99 Te-SiO<sub>2</sub>  $(0.5 \pm 7.1) \cdot 10^{-13}$   
Braginsky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$

$\sigma \{ k_{\alpha}, k_{\alpha}, k_{\alpha} \} = \{ 38, 2.3, 1.0 \} \cdot 10^{-9}$

$$k_q \Rightarrow \frac{mc}{\lambda_{\text{abcd}}}$$



Schumannger '08 Be-T.  $(0.3 \pm 1.8) \cdot 10^{-13}$   
 Baybier '99 Te-SiO<sub>2</sub>  $(0.5 \pm 1.1) \cdot 10^{-13}$   
 Braginsky '72 Pt-Al  $(0.3 \pm 0.4) \cdot 10^{-12}$   
 $\sigma \{ k_{\text{Co}}, k_{\alpha}, k_{\text{as}} \} = \{ 38, 2.3, 1.0 \} \cdot 10^{-9}$

$$k_2 \rightarrow \frac{m_e}{\Lambda_{\text{QCD}}}$$

estimated

$$\frac{\Delta \ln \alpha_s / m_N}{\Delta \ln m_N / \Lambda} \sim -1$$

$$k_q \Rightarrow \frac{m_\pi}{\Lambda_{QCD}}$$

estimated

$$\frac{\Delta \ln \alpha_s / m_\pi}{\Delta \ln m_\pi / \Lambda} \sim -1$$

$$\sigma \{ k'_\delta \}$$

135  
0

Schauflinger '08	Be-Ti	$(0.3 \pm 1.8) 10^{-13}$	$K_{Qn}$
Bayblier '99	Fe-SiO <sub>2</sub>	$(0.5 \pm 7.1) 10^{-13}$	
Braginskij '72	Pt-Al	$(0.3 \pm 0.4) 10^{-12}$	
$\sigma \{ k_{\phi_n}, k_\alpha, k_{as} \}$		$\{ 38, 2.3, 1.0 \} 10^{-9}$	

$$k_2 \Rightarrow \frac{m_e}{\lambda_{\text{ac}, \phi}}$$

estimated  $\frac{\Delta \ln a_s / m_n}{\Delta \ln \phi / \lambda} \hat{-} 1$

$$\sigma \{ k'_{\delta f}, k'_\alpha, k'_2 \} = \{ 14, 1.7, 1 \} 10^{-1}$$

$$k_2 \Rightarrow \frac{m_e}{\Lambda_{QCD}}$$

estimated  $\frac{\Delta k^{\text{asym}}}{\Delta k^{\text{min}}/\Delta} \sim -1$

$$\{k'_f, k'_\alpha, k'_q\} = \{14, 1.7, 1\} 10^{-1}$$

$$k'_f \equiv k'_q - 0.25 k_e$$



$$k_2 \Rightarrow \frac{n_a}{\Lambda_{QCD}}$$

estimated  $\frac{\Delta k_{as/mn}}{\Delta k_{mn}/\Delta} \sim -1$

$$\{k'_{sf}, k'_\alpha, k'_q\} = \{14, 1.7, 1\} 10^{-1}$$

$$\equiv k'_{sf} e^{-0.25 K_e} \frac{n_a}{\Lambda}$$



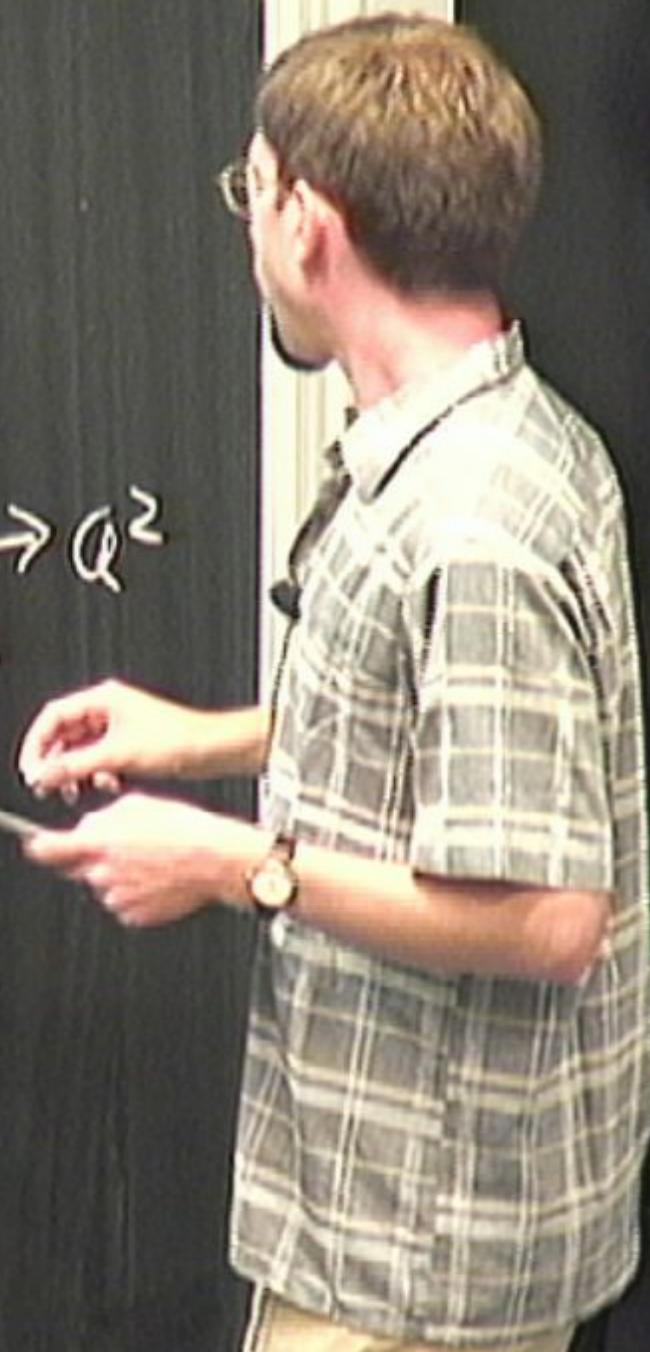
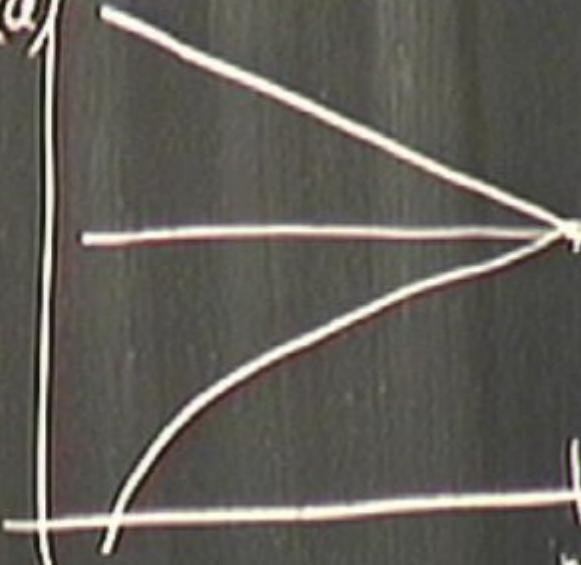
$$k_2 \Rightarrow \frac{m_a}{\lambda_{GCD}}$$

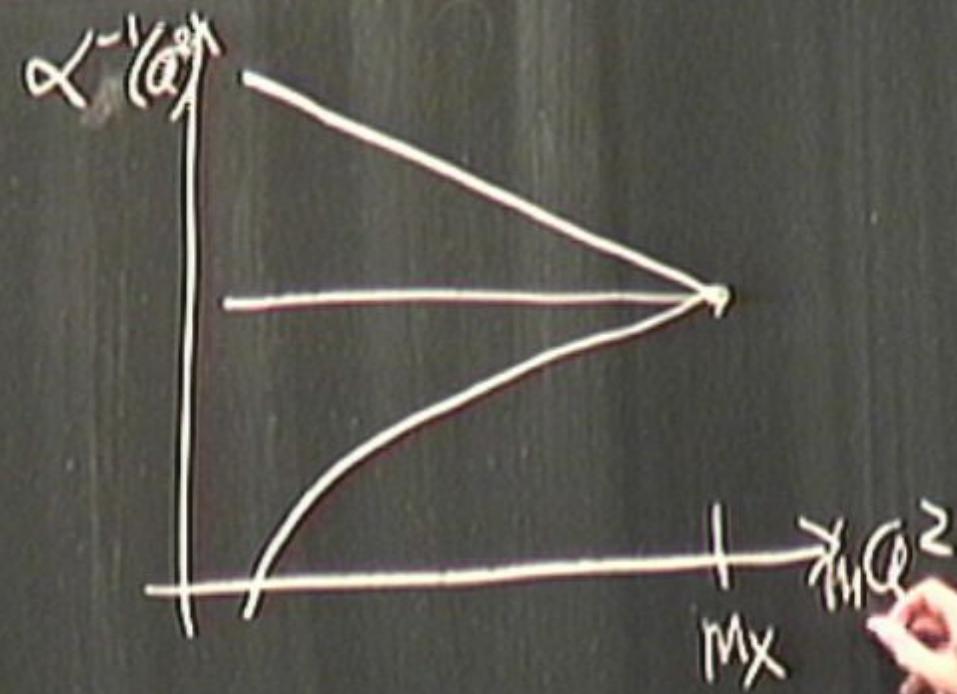
estimated  $\frac{\Delta \ln \alpha_s / m_n}{\Delta \ln m_n / \Lambda} \sim -1$

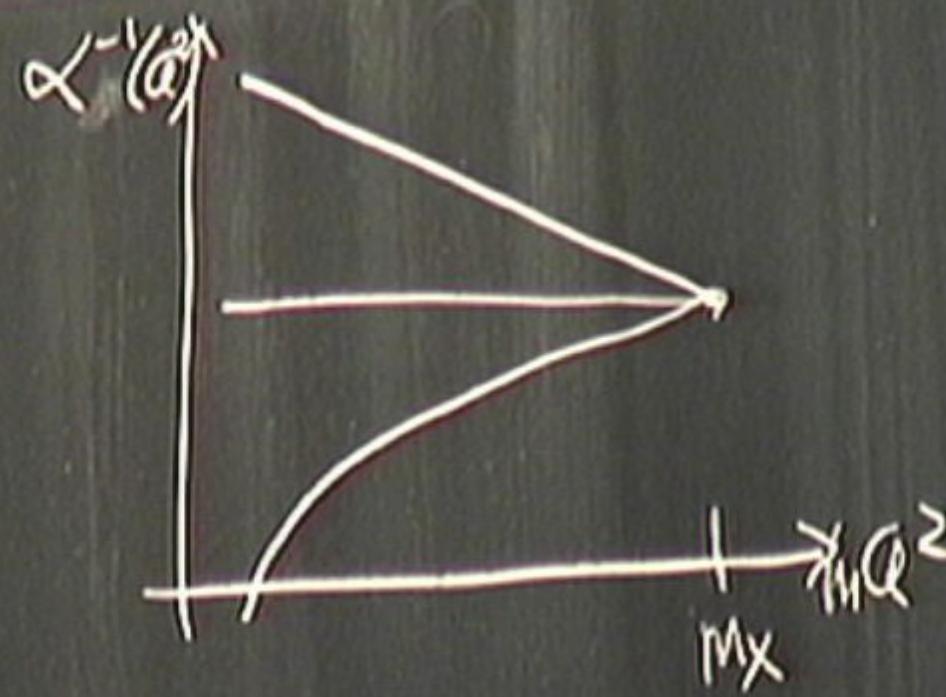
$$\{k'_f, k'_d, k'_q\} = \{14, 1.7, 1\} 10^{-1}$$

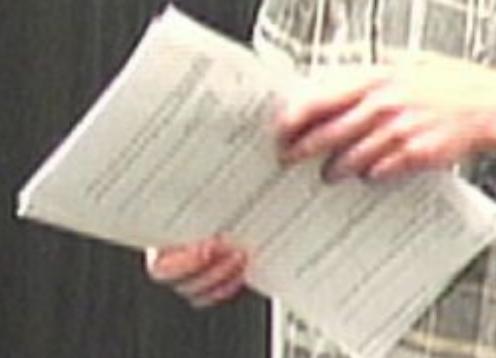
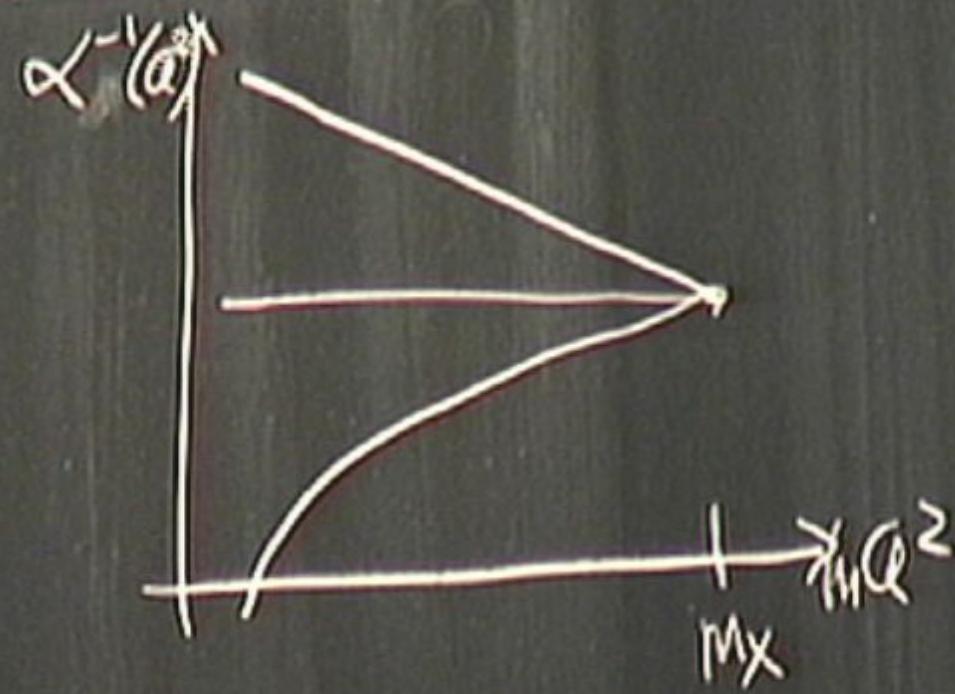
$$k'_f \equiv k'_q - 0.25 k_e$$

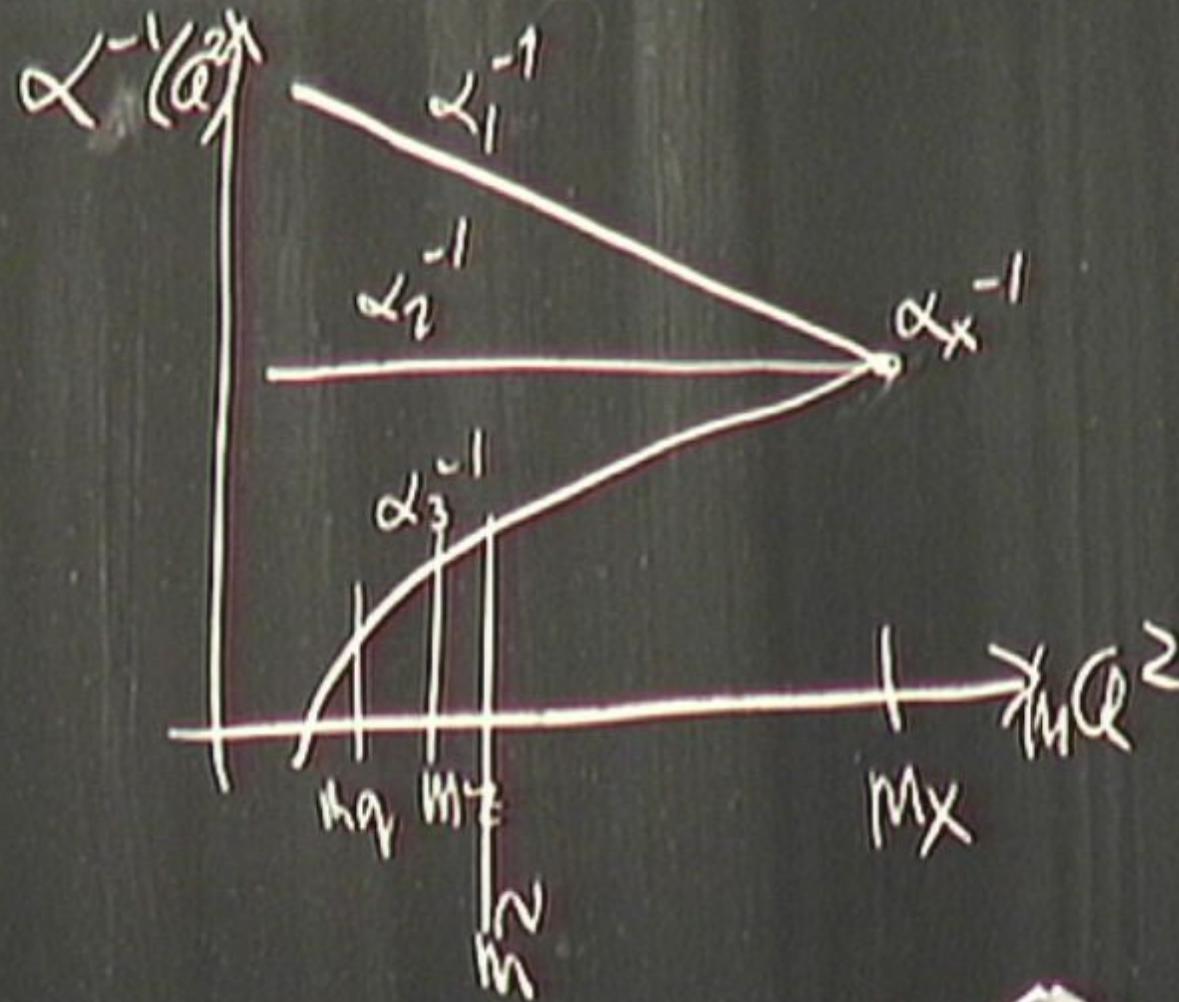
$\underbrace{\frac{m_d - m_u}{\Lambda}}_{na} \quad \underbrace{\frac{na}{\pi}}$

$\alpha^{-1}(Q)$ 









$\mathcal{L}_X$  $\frac{m_X}{m_P}$ 

$$\Delta \ln \lambda_x(z)$$

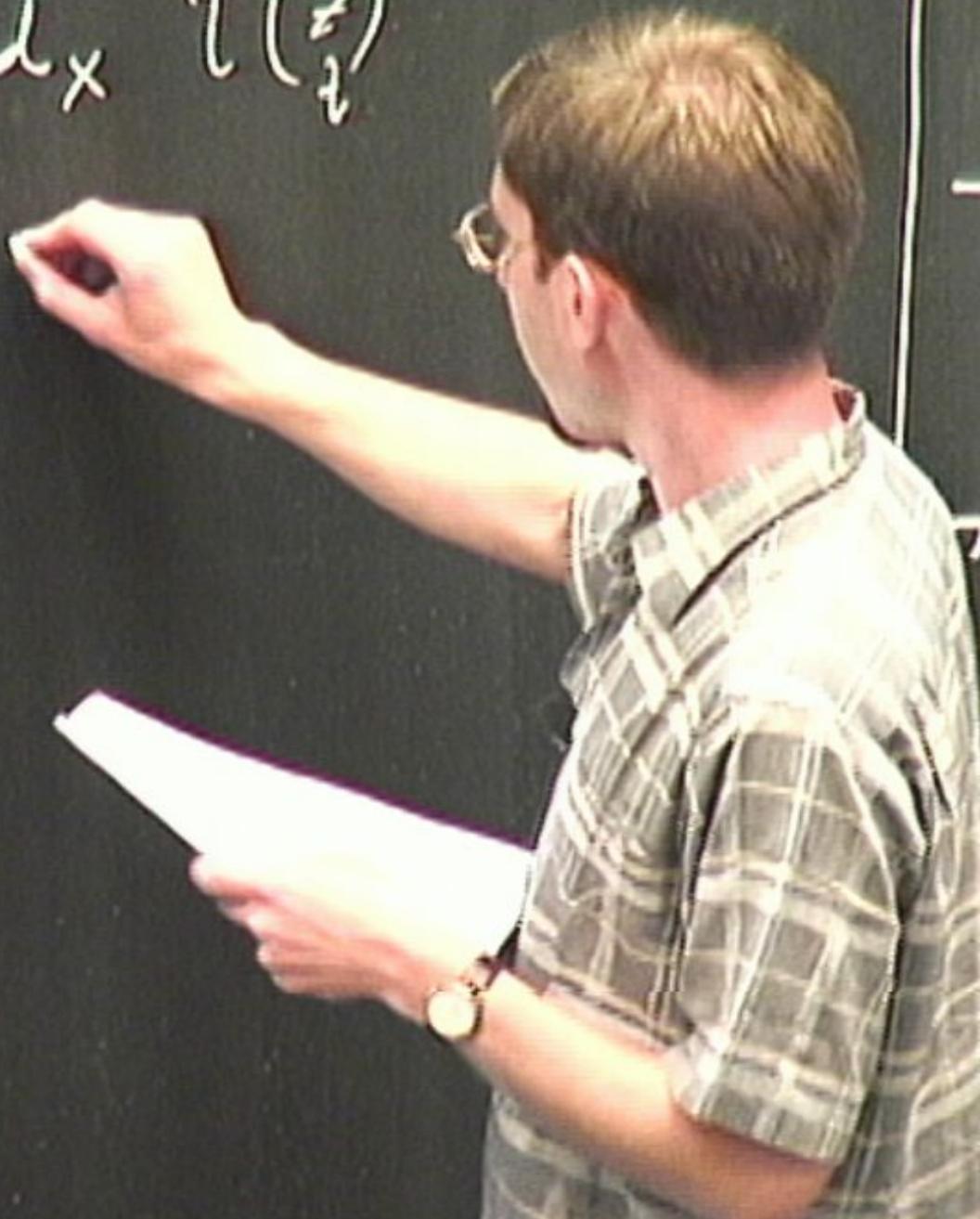
$$\mathcal{L}(\alpha^2)$$

$$\mathcal{L}_1^{-1}$$

$$\mathcal{L}_2^{-1}$$

$$\mathcal{L}_3^{-1}$$

$$m_2 \quad m_3 \quad m_2$$



$$\mathcal{L}_X$$

$$\frac{m_x}{m_p}$$

$$\frac{\langle \phi \rangle}{m_p}$$

$$\frac{\Delta n}{\lambda_X} \approx \left(\frac{?}{?}\right)$$

$$\frac{\Delta n}{\lambda_m} \approx$$

$$\mathcal{L}'(a) \approx$$

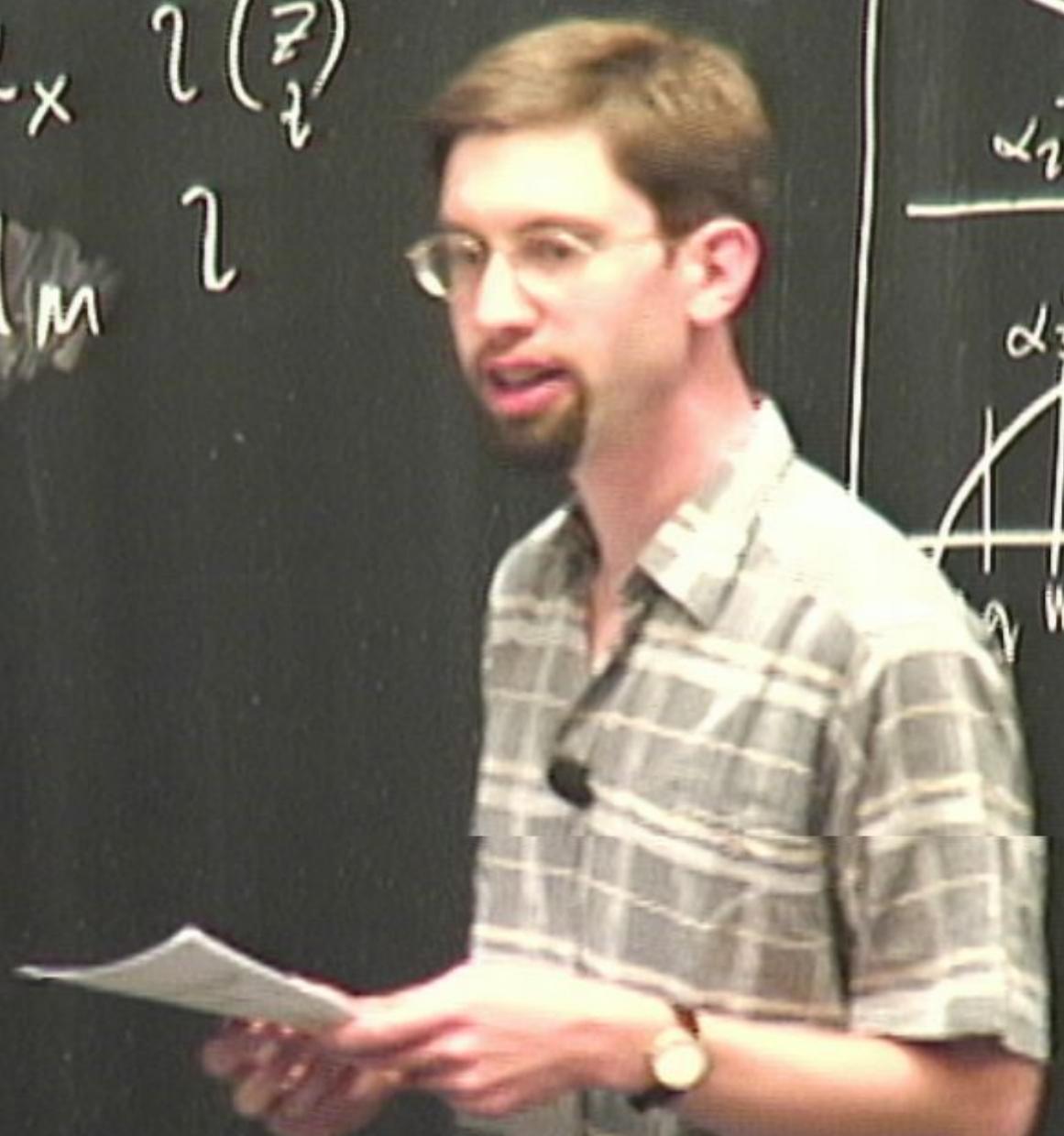
$$\alpha_1^{-1}$$

$$\alpha_2^{-1}$$

$$\alpha_3^{-1}$$

$$m_1^{-1}$$

$$m_2^{-1}$$



GUT

"Scenario"

{ $d_k, d_m, d_H, d_S$ }

$\alpha_x$

$$\frac{m_x}{m_p}$$

$$\frac{\langle \phi \rangle}{m_x} \hat{n}$$

$$\Delta^m_x \ i\left(\frac{z}{r}\right)$$

$d_m$

$d_H$

$d_S$

$i$

$i$

# GUT

"Scenario"

$$\{d_x, d_m, d_n, d_s\}$$

↓  
↓

$$\begin{array}{lll} \frac{\Delta n}{d_x} & \nu(\text{?}) \\ \frac{m_x}{m_p} & d_m & \nu \\ \frac{\langle \phi \rangle}{m_x} & d_n & \nu \\ \frac{\tilde{m}}{m_x} & d_s & \nu \end{array}$$



GUT

$\mathcal{L}_X$

$d_X \sim \mathcal{L}(?)$

"Scenario"

$\{d_k, d_m, d_h, d_s\}$



$$\frac{m_x}{m_p}$$

$$\langle \phi \rangle$$

$$\frac{m_x}{\tilde{m}}$$

$$\frac{\tilde{m}}{m_x}$$

$d_m \sim$

$d_h \sim$

$d_s \sim$

Der  $\Delta \ln \left\{ \frac{\Delta}{m_x}, \frac{m_e}{\pi}, \frac{m_\eta}{\pi} \right\}$

GUT

$\alpha_X$

$\alpha_X \sim \mathcal{U}(?)$

"Scenario"

$\{\alpha_k, \alpha_m, \alpha_h, \alpha_s\}$

$\downarrow$

$$\frac{m_X}{m_P}$$

$$\langle \phi \rangle$$

$$\frac{m_X}{\tilde{m}}$$

$$\frac{\tilde{m}}{m_X}$$

$\alpha_m \sim$

$\alpha_h \sim$

$\alpha_s \sim$

Derive  $\Delta \ln \left\{ \frac{\Lambda}{m_X}, \frac{m_e}{\pi}, \frac{m_\mu}{\pi} \right\}$

GUT

"Scenario"

$$\{d_x, d_m, d_h, d_s\}$$

$$\text{Derive } \Delta \ln \left\{ \frac{\Delta}{m_x} \cdot \frac{m_e}{\pi} \cdot \frac{m_q}{\pi} \right\}$$

Classical  $\Delta t = 1 \rightarrow 5 \text{ y}$   $\Delta G_{G/Q} / Q_i$   $10^{-16 \dots 17}$

Spectral  $\Delta t \sim 10^{10} \text{ y}$   $10^{-5} - 10^{-6}$

$\lambda_x$

$$\frac{m_x}{m_p}$$

$$\frac{\langle \phi \rangle}{m_x}$$

$$\frac{\tilde{n}}{m_x}$$

$\lambda_x \sim ?$

$d_m \sim$

$d_h \sim$

$d_s \sim$

GUTI

"Scenario"

$$\{d_x, d_m, d_h, d_s\}$$

↓  
1

$\alpha_x$

$$\frac{m_x}{m_p}$$

$$\frac{\langle \phi \rangle}{m_x}$$

$$\tilde{n}$$

$$\frac{m_x}{m_x}$$

$\lambda_x \sim (z)$

$d_m \sim$

$d_h \sim$

$d_s \sim$

Derive  $\Delta \ln \left\{ \sum \frac{m_e}{m_x} \frac{1}{\pi} \frac{1}{\pi} \right\}$

Clocks  $\Delta t = 1 \rightarrow 5 \text{ y}$   $\Delta G_L / Q_i$   $10^{-16 \dots 17}$

Spectra  $\Delta t \sim 10^{10} \text{ y}$   $10^{-5} - 10^{-6}$

GUT

$\lambda_X$

$\lambda_X \sim l(z)$

"Scenario"

$\{\lambda_X, d_m, d_H, d_S\}$

$\downarrow$

$$\frac{m_X}{m_P}$$

$$\langle \phi \rangle$$

$$\frac{m_X}{\tilde{m}}$$

$$\frac{m_X}{m_X}$$

$d_m \sim$

$d_H \sim$

$d_S \sim$

Derive  $\Delta \ln \left\{ \Lambda \frac{m_e}{\pi} \frac{m_q}{\pi} \right\}$

Clocks  $\Delta t = 1 \rightarrow 5 \text{ y}$   $\Delta G_F / Q_i$   $10^{-16 \dots 17}$

Spectra  $\Delta t \sim 10^{10} \text{ y}$   $10^{-5} - 10^{-6}$

Oklo\*

GUT

$\alpha_x$

$\alpha_x \gamma (?)$

"Scenario"

$\{\alpha_x, \alpha_m, \alpha_n, \alpha_s\}$

$\downarrow$

$\frac{m_x}{m_p}$

$\frac{\langle \phi \rangle}{m_x}$

$\frac{n}{m_x}$

$d_m \gamma$

$d_n \gamma$

$d_s \gamma$

Derive  $\Delta \ln \left\{ \frac{1}{m_x}, \frac{m_e}{\pi}, \frac{h_q}{\pi} \right\}$

Clocks  $\Delta t = 1 \rightarrow 5 y$   $\Delta G_F/Q$   $10^{-16 \dots 17}$

Spectra  $\Delta t \sim 10^{10} y$   $10^{-5} - 10^{-6}$

Oklo\*  $\Delta t \sim 2 \cdot 10^9 y$   $10^{-7 \dots 8}$

Meteorite ( $\alpha$ , Qn,  $\frac{\alpha A}{Mn}$ )

$10^{-6}$



Meteorite ( $\alpha, Q_n, \frac{\alpha A}{M_N}$ )

$$\Delta t = 4.5 \cdot 10^{-9}$$

$$\frac{\Delta G}{G_{\text{ref}}} \sim 10^{-6}$$



Meteorite ( $\alpha, Q_n, \frac{\alpha A}{m_n}$ )

$$\Delta t = 4.5 \cdot 10^{-9}$$

$$\frac{\Delta G_i}{G_i} \sim 10^{-6}$$

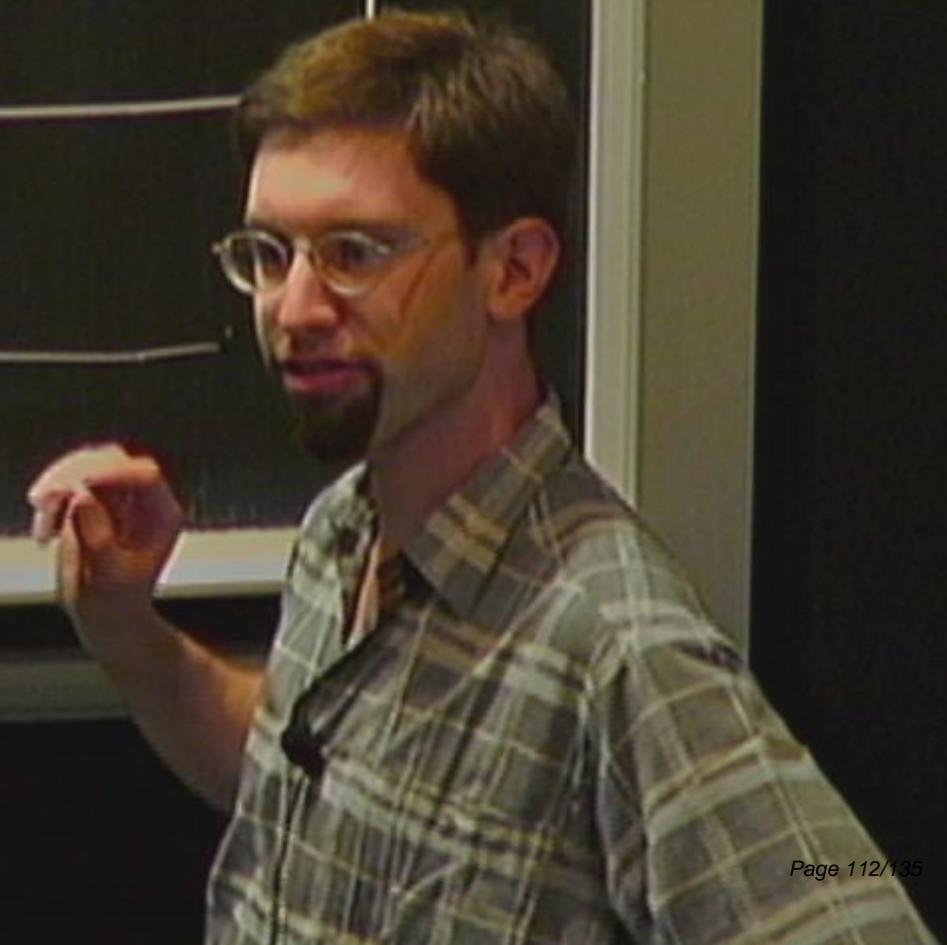
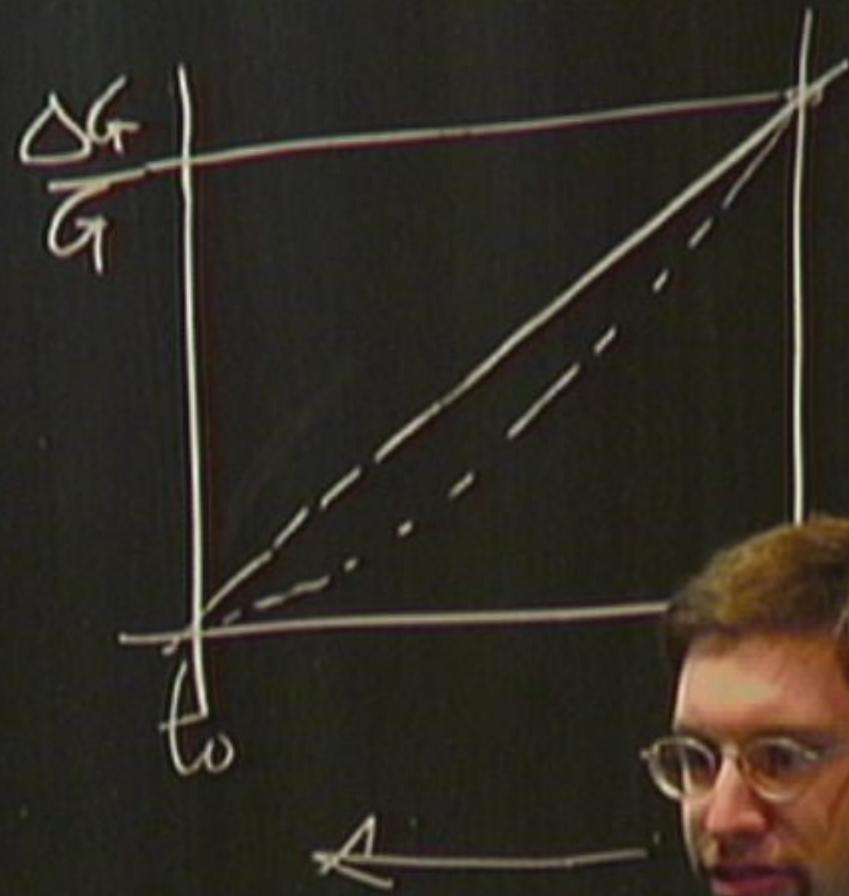
WEP  $t_{\text{now}}$   $\dot{\varphi} \leq \dot{\varphi}_{\text{max}} \approx 5 \times 10^{-11}$

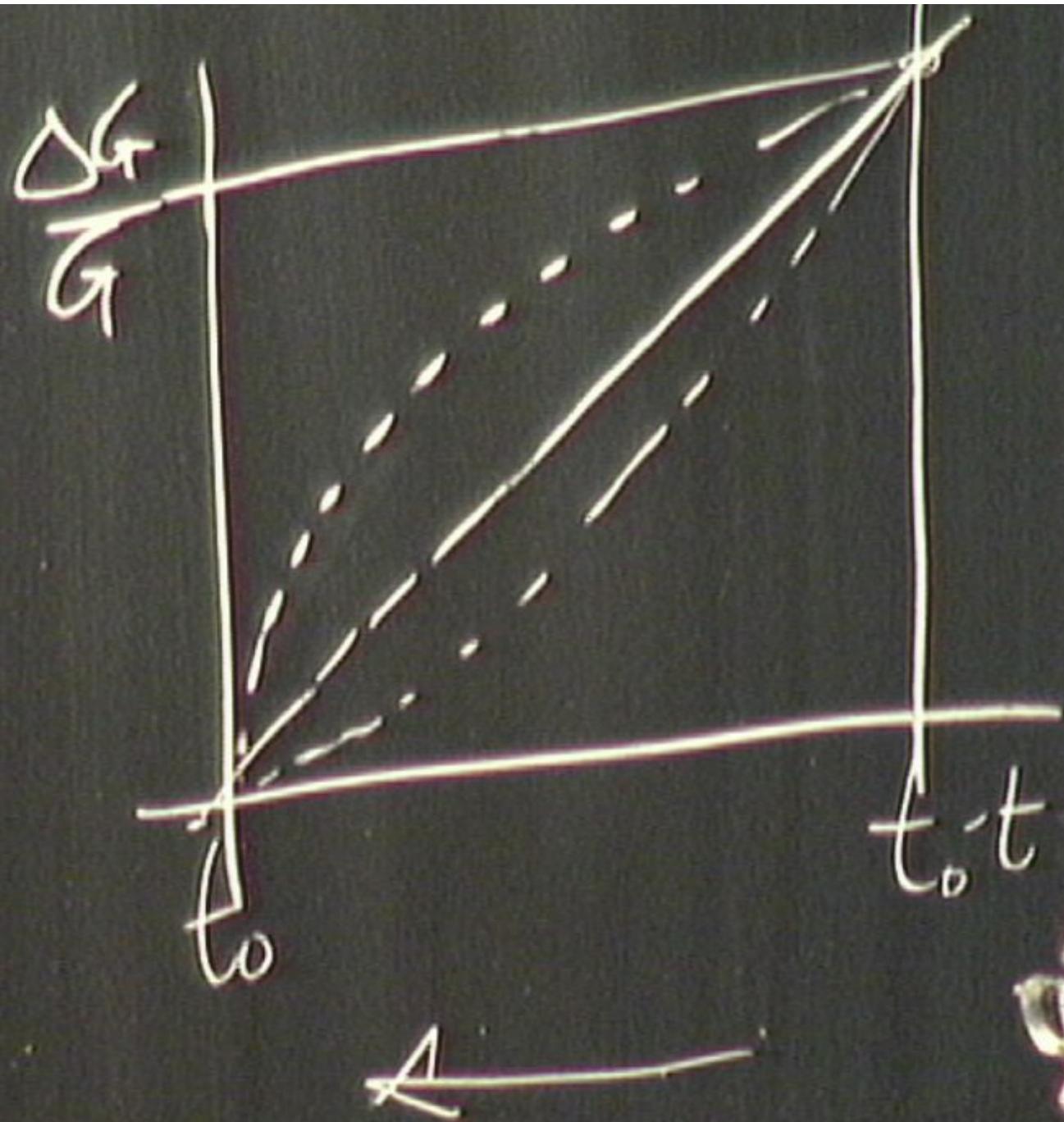
Meteorite ( $\alpha, Q_n, \frac{\alpha A}{m_n}$ )

$$\Delta t = 4.5 \cdot 10^{-9}$$

$$\frac{\Delta G}{G_i} : \sim 10^{-6}$$

WEP  $t_{\text{now}}$   $\dot{\varphi} \leq \dot{\varphi}_{\max} \approx 5 \times 10^{-10} / \text{y}$





Scenario	$X$	Clocks	WEP	Oklo	Meteorite	Astro
$\alpha$ only	$\alpha$	0.13 ( $\alpha$ )	12	0.033	0.32	0.44 ( $y$ )
2	$\alpha_X$	0.074 ( $\mu$ )	0.014	0.039	0.015	0.013 ( $\text{NH}_3$ )
2S	$\alpha_X$	0.12 ( $\mu$ )	0.023	0.064	0.026	0.022 ( $\text{NH}_3$ )
3	$\langle \phi \rangle / M_X$	2.6 ( $\mu$ )	0.67	18	0.53	0.47 ( $\text{NH}_3$ )
4	$\langle \phi \rangle / M_X$	6.2 ( $\mu$ )	0.71	2.6	1.2	1.1 ( $\text{NH}_3$ )
5, $\tilde{\gamma} = 42$	$\alpha_X$	0.32 ( $\alpha$ )	0.025	0.035	0.069	0.075 ( $\text{NH}_3$ )
6, $\tilde{\gamma} = 70$	$\alpha_X$	0.21 ( $\alpha$ )	0.016	0.023	0.049	0.054 ( $\text{NH}_3$ )
6, $\tilde{\gamma} = 25$	$\alpha_X$	0.25 ( $\mu$ )	0.022	0.040	0.056	0.044 ( $\text{NH}_3$ )

Table 4: Competing bounds on recent time variations in unified scenarios. For each scenario we give  $1\sigma$  uncertainties of bounds on  $d(\ln X)/dt$  in units  $10^{-15} \text{y}^{-1}$ , where  $X$  is the appropriate fundamental parameter. The column “Clocks” indicates whether  $\alpha$  or  $\mu$  gives the stronger bound, the column “Astro” indicates which measurements of astrophysical spectra are currently most sensitive.

At present these methods give null results up to redshifts about 0.8, but if a nonzero time variation exists, we can determine for each unified scenario which

" $\alpha$  only"

"Scenario 2"

$$d_x = 1 \quad d_{11} = d_S = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha}$$

" $\alpha$  only"

"Scenario 2"

$$d_x = 1 \quad d_u = d_s = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$



" $\alpha$  only"

"Scenario 2"

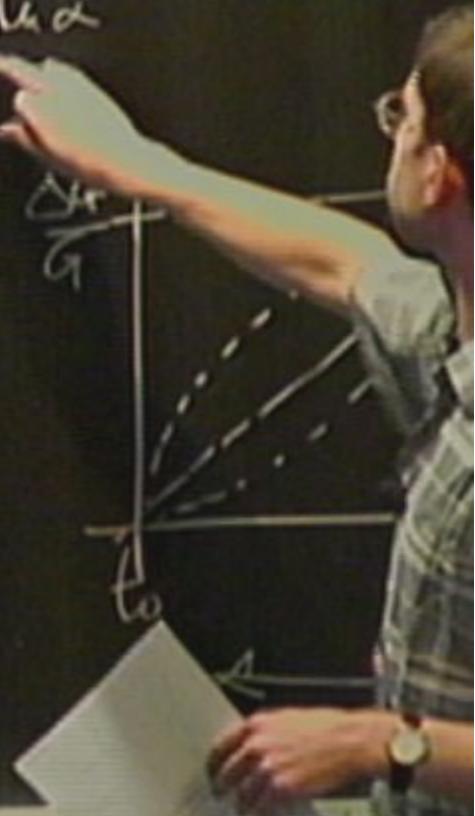
"Scenario 3"

$$dx = 1 \quad dh = ds = 0$$

$$dx = 0 \quad dh = 1 \quad ds = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 300$$



" $\alpha$  only"

"Scenario 2"

"Scenario 3"

" .. 4 "

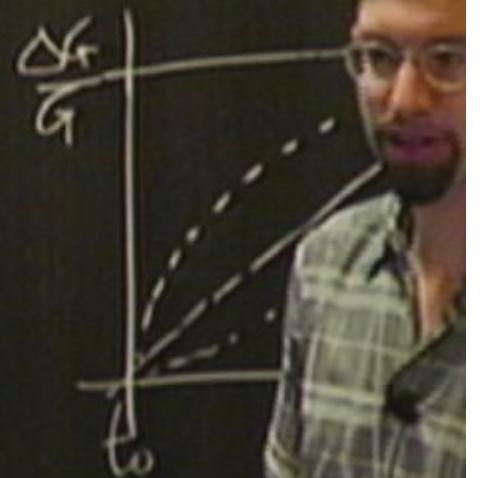
$$dx = 1 \quad d_{H^+} = ds = 0$$

$$dx = 0 \quad d_{H^+} = 1 \quad ds = 0$$

$$dx = 0 \quad d_{H^+} = 1 \quad ds = 1$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 300$$



" $\alpha$  only"

"Scenario 2"

$$d_x = 1 \quad d_{H} = d_S = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

"Scenario 3"

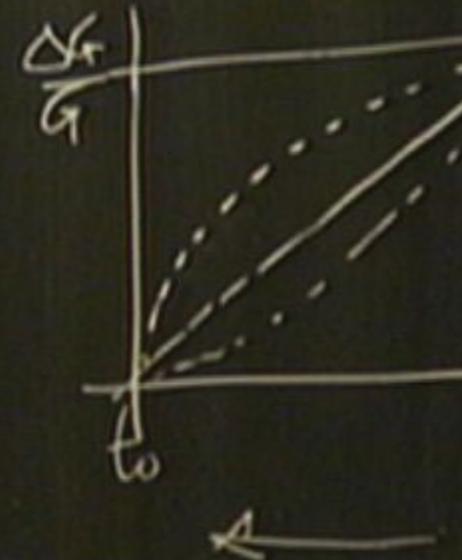
$$d_x = 0 \quad d_H = 1 \quad d_S = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 300$$

".. 4"

$$d_x = 0 \quad d_H = 1 \quad d_S = 1$$

$$\approx 21$$



" $\alpha$  only"

"Scenario 2"  $d_x = 1$   $d_{\mu} = d_S = 0$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

"Scenario 3"

$d_x = 0$   $d_{\mu} = 1$   $d_S = 0$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -300$$

".. 4"

$d_x = 0$   $d_{\mu} = 1$   $d_S = 1$

$$\approx -21$$

"Scenario 5"

$d_x = 1$   $d_{\mu} = \tilde{f} d_x$   $d_S = 0$

$$\tilde{f} = 42$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -6$$



Scenario	$X$	Clocks	WEP	Oklo	Meteorite	Astro
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4	$\langle \phi \rangle / M_X$	6.2 ( $\mu$ )	0.71	2.6	1.2	1.1 (NH <sub>3</sub> )
5, $\tilde{\gamma} = 42$	$\alpha_X$	0.32 ( $\alpha$ )	0.025	0.035	0.069	0.075 (NH <sub>3</sub> )
6, $\tilde{\gamma} = 70$	$\alpha_X$	0.21 ( $\alpha$ )	0.016	0.023	0.049	0.054 (NH <sub>3</sub> )
6, $\tilde{\gamma} = 25$	$\alpha_X$	0.25 ( $\mu$ )	0.022	0.040	0.056	0.044 (NH <sub>3</sub> )

Table 4: Competing bounds on recent time variations in unified scenarios. For each scenario we give  $1\sigma$  uncertainties of bounds on  $d(\ln X)/dt$  in units  $10^{-15} \text{y}^{-1}$ , where  $X$  is the appropriate fundamental parameter. The column “Clocks” indicates whether  $\alpha$  or  $\mu$  gives the stronger bound, the column “Astro” indicates which measurements of astrophysical spectra are currently most sensitive.

At present these methods give null results up to redshifts about 0.8, but if a nonzero time variation exists, we can determine for each unified scenario which

" $\alpha$  only"

"Scenario 2"  $d_x = 1 \quad d_u = d_s = 0$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

"Scenario 3"  $d_x = 0 \quad d_u = 1 \quad d_s = 0$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 300$$

".. 4"  $d_x = 0 \quad d_u = 1 \quad d_s = 1$

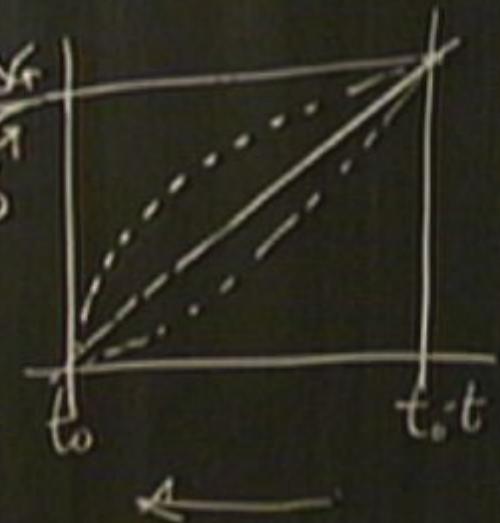
$$\approx -21$$

"Scenario 5"  $d_x = 1 \quad d_u = \tilde{f} d_x \quad d_s = 0$

$$\tilde{f} = 42 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -6$$

"Scenario 6"  $d_v = 1 \quad d_u = d_s = 70$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 1$$



" $\alpha$  only"

"Scenario 2"

$$dx = 1 \quad du = ds = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$$

"Scenario 3"

$$dx = 0 \quad du = 1 \quad ds = 0$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 300$$

"... 4"

$$dx = 0 \quad du = 1 \quad ds = 1$$

$$\approx -21$$

"Scenario 5"

$$dx = 1 \quad du = \sqrt{dx} \quad ds = 0$$

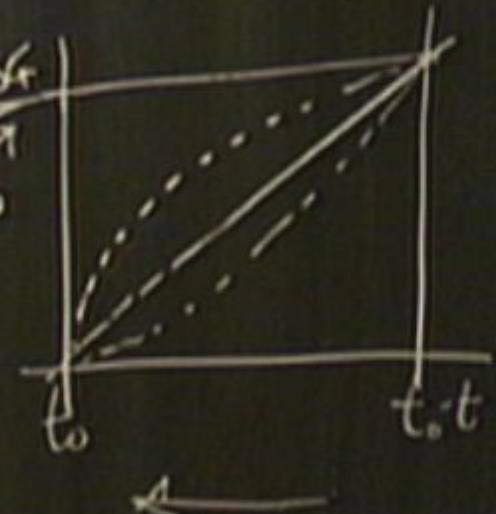
$$\frac{\Delta r}{G}$$

$$\sqrt{r} = 42 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -6$$

"Scenario 6"

$$dr = 1 \quad du = ds = 70$$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 10 - 4$$



" $\alpha$  only"

"Scenario 2"  $d_x = 1 \quad d_u = d_s = 0 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx 27$

"Scenario 3"  $d_x = 0 \quad d_u = 1 \quad d_s = 0 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -300$

" .. 4 "  $d_x = 0 \quad d_u = 1 \quad d_s = 1 \quad \approx -21$

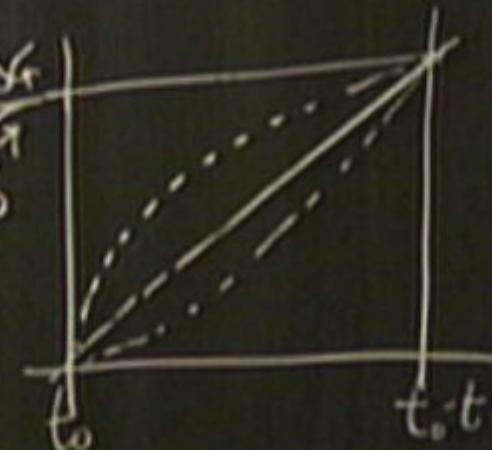
"Scenario 5"  $d_x = 1 \quad d_u = \tilde{g} d_x \quad d_s = 0$

$$\tilde{g} = 42 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -6$$

"Scenario 6"  $d_v = 1 \quad d_u = d_s = 70$

$$\frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -4$$

$d_u = d_s = 25 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx +8$



Scenario	$X$	Clocks	WEP	Oklo	Meteorite	Astro
$\alpha$ only	$\alpha$	0.13 ( $\alpha$ )	12	0.033	0.32	0.44 ( $y$ )
2	$\alpha_X$	0.074 ( $\mu$ )	0.014	0.039	0.015	0.013 (NH <sub>3</sub> )
2S	$\alpha_X$	0.12 ( $\mu$ )	0.023	0.064	0.026	0.022 (NH <sub>3</sub> )
3	$\langle \phi \rangle / M_X$	2.6 ( $\mu$ )	0.67	18	0.53	0.47 (NH <sub>3</sub> )
4	$\langle \phi \rangle / M_X$	6.2 ( $\mu$ )	0.71	2.6	1.2	1.1 (NH <sub>3</sub> )
5, $\tilde{\gamma} = 42$	$\alpha_X$	0.32 ( $\alpha$ )	0.025	0.035	0.069	0.075 (NH <sub>3</sub> )
6, $\tilde{\gamma} = 70$	$\alpha_X$	0.21 ( $\alpha$ )	0.016	0.023	0.049	0.054 (NH <sub>3</sub> )
6, $\tilde{\gamma} = 25$	$\alpha_X$	0.25 ( $\mu$ )	0.022	0.040	0.056	0.044 (NH <sub>3</sub> )

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At present these methods give null results up to redshifts about 0.8, but if a nonzero time variation exists, we can determine for each unified scenario which

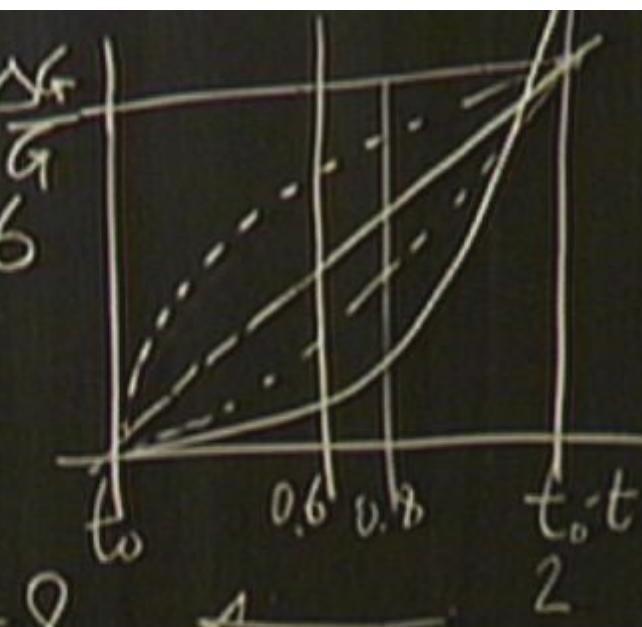
$$dx = 1 \quad du = 5dx \quad ds = 0$$

$$y = 42 \quad \frac{\Delta \ln \mu}{\Delta \ln \alpha} \approx -6$$

$$dv = 1 \quad du = ds = 70$$

$$\frac{\Delta \ln \mu}{\Gamma} \approx -4$$

$$du = ds = \frac{m}{t \ln \alpha} \approx +8$$



$$m_{\pi}(0) \bar{\psi} \psi \quad m_\Psi = m_{\Psi_0} \left( 1 + \frac{C_\Psi \varphi}{M_{PL}} \right)$$

$$\left( 1 + \frac{C_1 \varphi}{M_{PL}} + \frac{C_2 \varphi^2}{M_{PL}^2} + \dots \right)$$

$\rho(x)$

$$\dot{\rho}(x) = C_\Psi \rho(x, t)$$

$\dot{\rho}(t)$

Barrow/Sh  
fit Rosa

$$\Delta \varphi \Big|_{x_c}^{x_i} \propto C_\Psi \Delta u \Big|_{x_c}^{x_i}$$

$$m_{\Psi}(\varphi) \bar{v} \psi \quad m_{\Psi} = m_{\Psi_0} \left( 1 + \frac{c_1(\varphi - \varphi_0)}{M_{PL}} \right)$$

$$\left( 1 + \frac{c_1 \varphi}{M_{PL}} + \frac{c_2 \varphi^2}{M_{PL}^2} + \dots \right)$$

$$= \bar{\rho}_{(t)} +$$

$$\bar{\rho}_0 +$$

$\varphi$

$$C_{\Psi} P(x, t)$$

$$(\psi_0)$$

$$\Delta \varphi \Big|_{x_c}^{x_i} \propto C_{\Psi} \Delta u \Big|_{x_c}^{x_i}$$

Barrow Sh  
fit Rosa

Scenario 6

$$d_3 = 1 \quad d_4 = d_5 = -$$

NONSUSY  $\hat{g} \simeq 35$   $\frac{\langle \phi \rangle}{D^m \Delta} \approx 0$

Scenario 6

$$d_x = l \quad d_M = d$$

NONSUSY  $\tilde{g} \simeq 35 \frac{\langle \phi \rangle}{D^m \Delta} \approx 0$

$$d_M = d$$

"Scenario 6"  $d_4 = 1$   $d_4 = \frac{f_L}{d_5} = 70$   $\frac{\Delta m^2}{\Delta m_\alpha} \approx -6$

NONNSY  $\hat{f} \approx 35$   $\frac{\langle \phi \rangle}{D_m \Lambda} \approx 0$

SUSY  $\hat{f} \approx 50$   $\frac{1}{D_m \Lambda} \approx 0$   $d_4 = d_5$

$\cdot 1-4$

$$\frac{\Delta m^2}{\Delta m_\alpha} \approx +8$$

### Scenarios

NON-SUSY  $\hat{\gamma} \simeq 35$   $\frac{D_m \langle \phi \rangle}{\Delta} \approx 0$

SUSY  $\hat{\gamma} \simeq 50$   $\frac{D_m \Delta \tau}{\Delta \omega}$

Conditions

NON-SUSY

$$\hat{f} \approx 35 \quad \frac{\partial m}{\partial \Delta} \approx 0$$

SUSY

$$\hat{f} \approx 50 \quad \frac{\partial m}{\partial \Delta} \approx 0$$

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