Title: Looking for The Origin of Neutrinos Masses: from neV to YeV

Date: Apr 29, 2011 01:00 PM

URL: http://pirsa.org/11040061

Abstract: After quickly reviewing what we have learned about neutrinos during the past decade, I present an overview of different mechanisms responsible for non-zero neutrino masses, also discussing the possibility of experimentally deciding which one, if any, is correct.

Looking for The Origin of Neutrino Masses: from neV to YeV

André de Gouvêa

Northwestern University

Particle Physics Seminar – Perimeter Institute

Outline

1. Quick Reminder: Evidence for Neutrino Masses;
2. What We Are Trying to Understand;
3. Why Are Neutrino Masses Small?;
4. Example – the Seesaw Mechanism: Three Avenues Toward Tiny Neutrino Masses, with Consequences;
5. A Fourth Avenue: Neutrino Masses from "Indirect" $\Delta L = 2$ New Physics (Loops);
6. How Do We Learn More, and Concluding Remarks.

For those of who were curious (but not curious enough to Google it):

1 YeV (yotta electron-Volt)$= 10^{24}$ eV $= 10^{15}$ GeV.

[Maltoni and Schwetz, arXiv: 0812.3161]

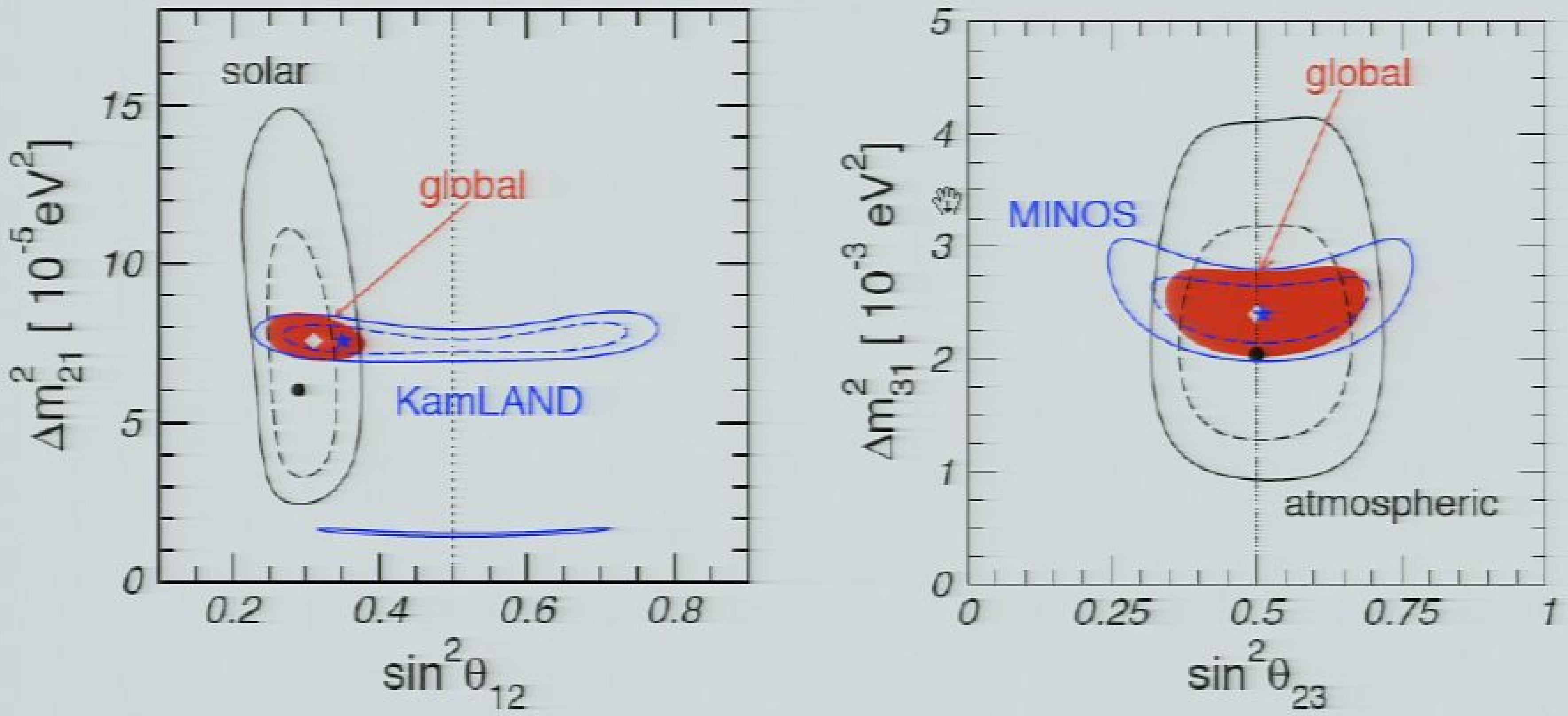


Figure 1: Determination of the leading "solar" and "atmospheric" oscillation parameters [1]. We show allowed regions at 90% and 99.73% CL (2 dof) for solar and KamLAND (left), and atmospheric and MINOS (right), as well as the 99.73% CL regions for the respective combined analyses.

Outline

1. Quick Reminder: Evidence for Neutrino Masses;
2. What We Are Trying to Understand;
3. Why Are Neutrino Masses Small?;
4. Example – the Seesaw Mechanism: Three Avenues Toward Tiny Neutrino Masses, with Consequences;
5. A Fourth Avenue: Neutrino Masses from "Indirect" $\Delta L = 2$ New Physics (Loops);
6. How Do We Learn More, and Concluding Remarks.

For those of who were curious (but not curious enough to Google it):

$$1 \text{ YeV (yotta electron-Volt)} = 10^{24} \text{ eV} = 10^{15} \text{ GeV}.$$

Very Quick Reminder: ν Flavor Oscillations

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments ["indisputable"];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments ["indisputable"];
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor neutrinos ["indisputable"];
- $\nu_\mu \to \nu_{\rm other}$ from accelerator experiments ["indisputable"].

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.

[Maltoni and Schwetz, arXiv: 0812.3161]

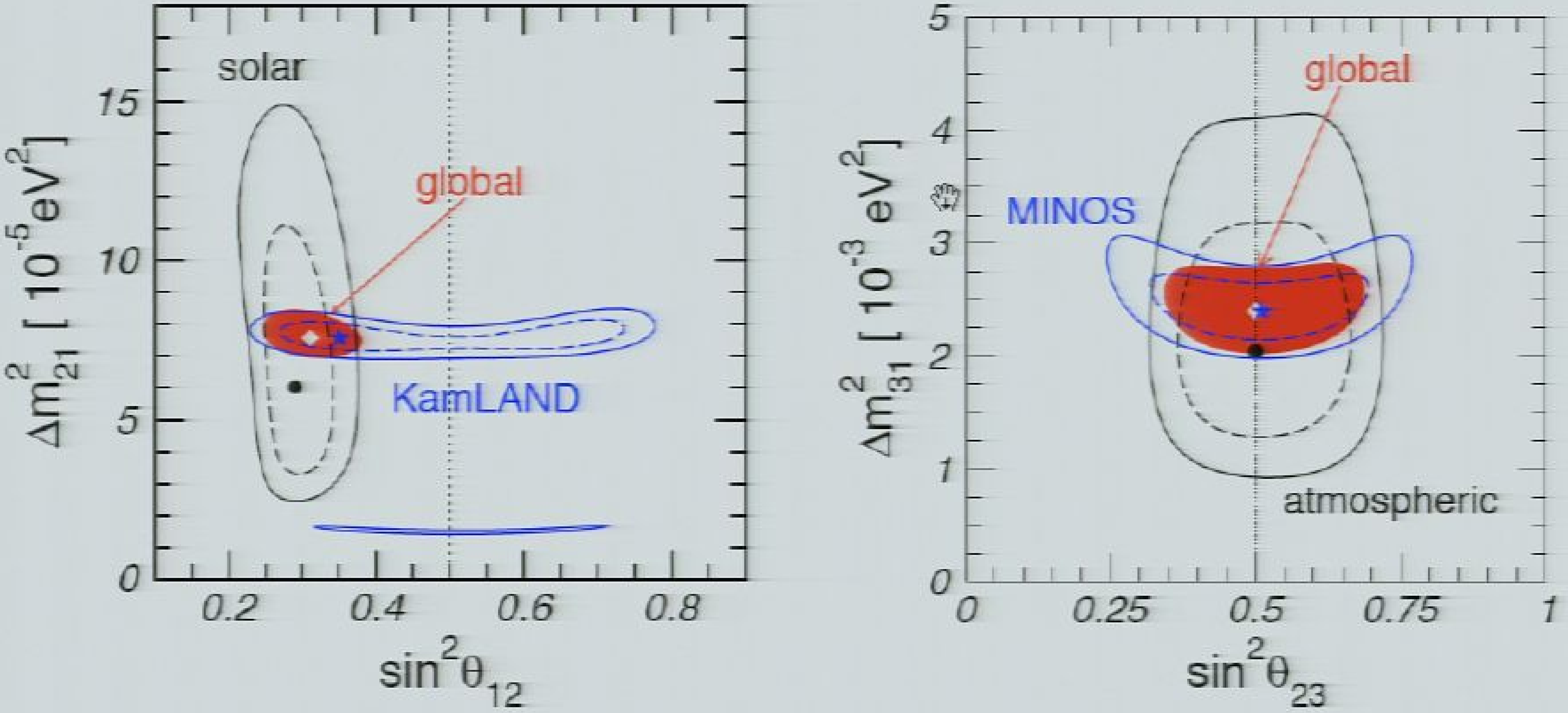


Figure 1: Determination of the leading "solar" and "atmospheric" oscillation parameters [1]. We show allowed regions at 90% and 99.73% CL (2 dof) for solar and KamLAND (left), and atmospheric and MINOS (right), as well as the 99.73% CL regions for the respective combined analyses.

We often assume two-flavor mixing. Of course, there are three neutrinos…

Phenomenological Understanding of Neutrino Masses & Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ $\Delta m_{31}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m_{31}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[for a detailed discussion see AdG, Jenkins, arXiv:0804.3627]

Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

parameter	best fit $\pm 1\sigma$	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]

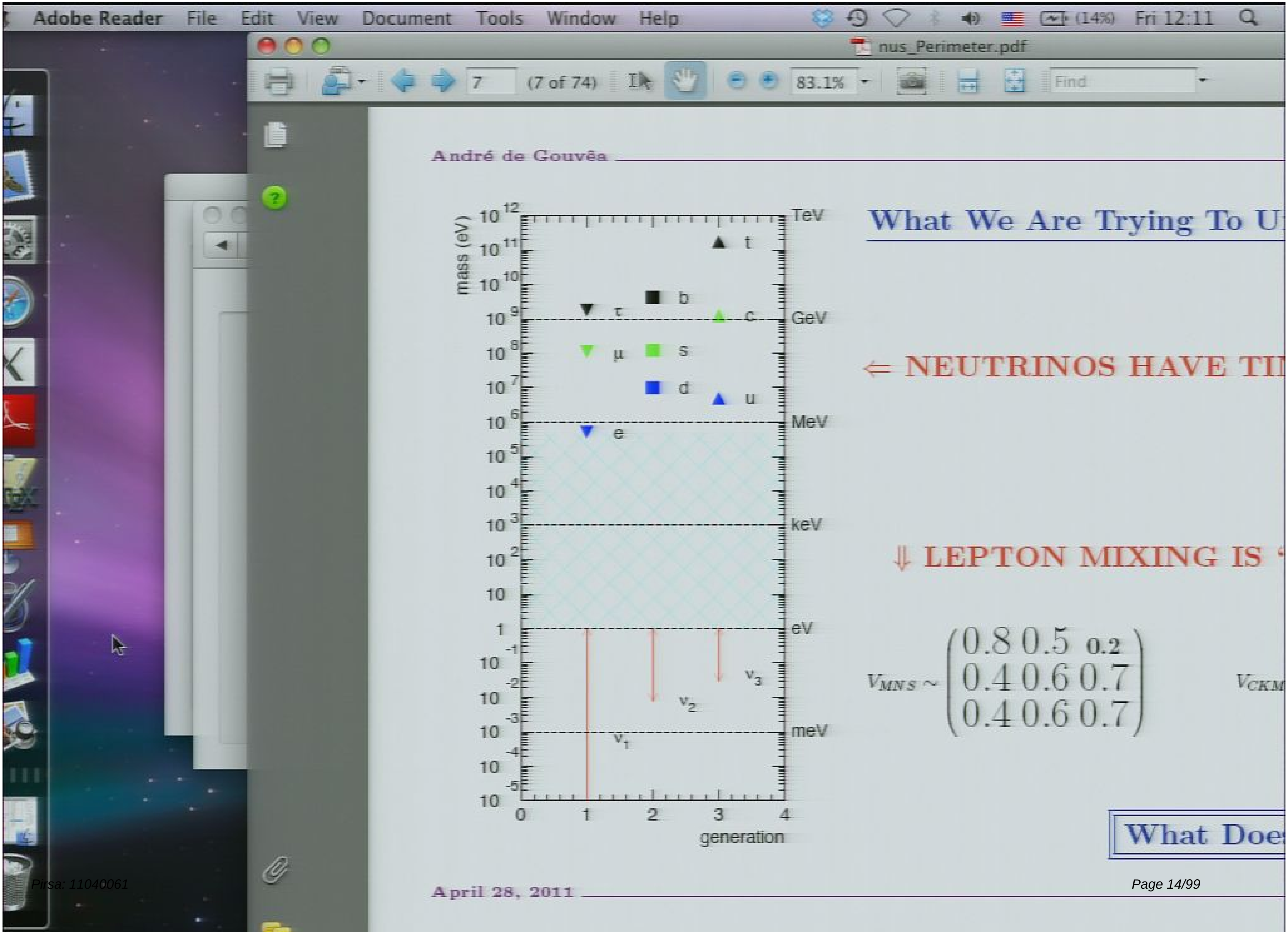
Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]



André de Gouvêa

What We Are Trying To U

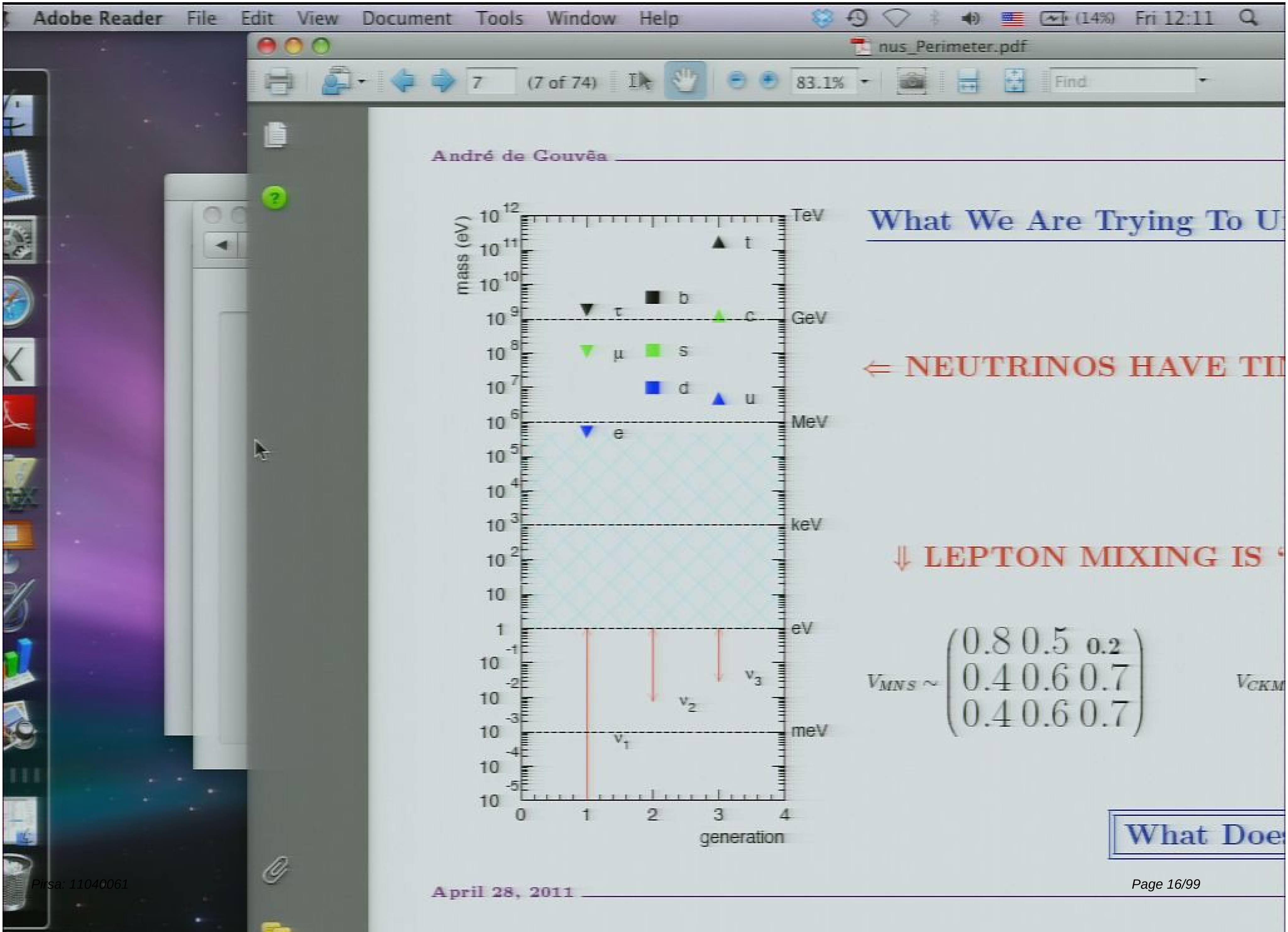
⇐ NEUTRINOS HAVE TI

⇓ LEPTON MIXING IS

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM}$$

What Doe

April 28, 2011



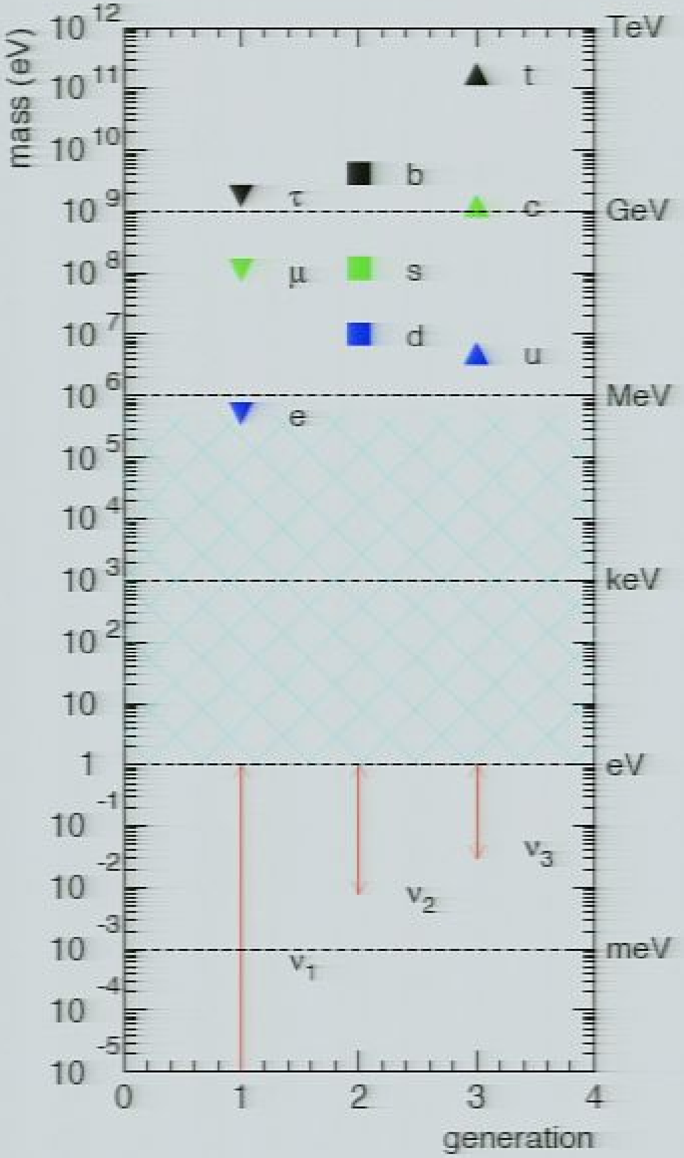
What We Are Trying To U

⇐ NEUTRINOS HAVE TI

⇓ LEPTON MIXING IS "

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM}$$

What Doe



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS “WEIRD” ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

parameter	best fit ±1σ	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
$\Delta m^2_{31}\ [10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]

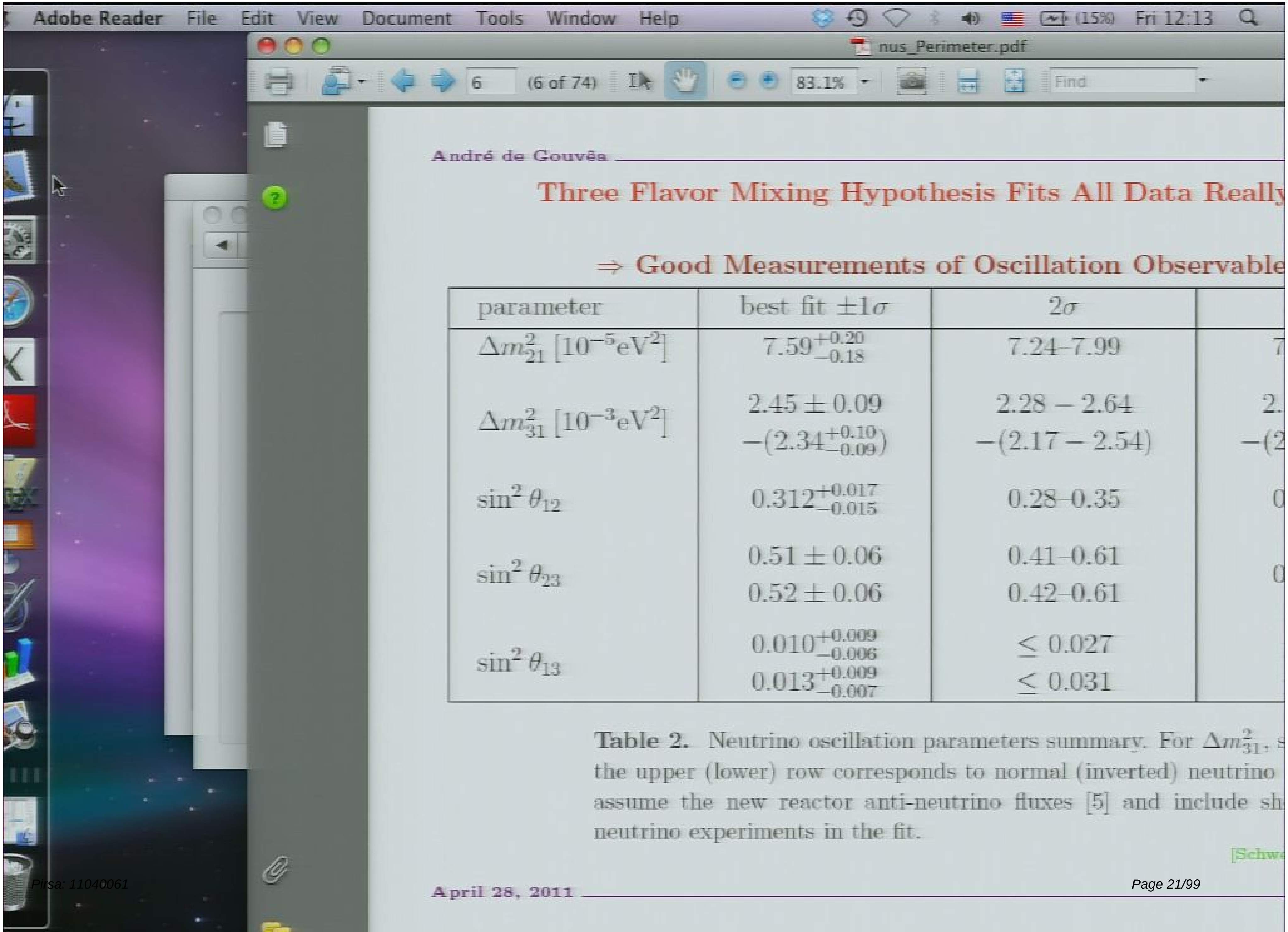
Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

parameter	best fit ±1σ	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]



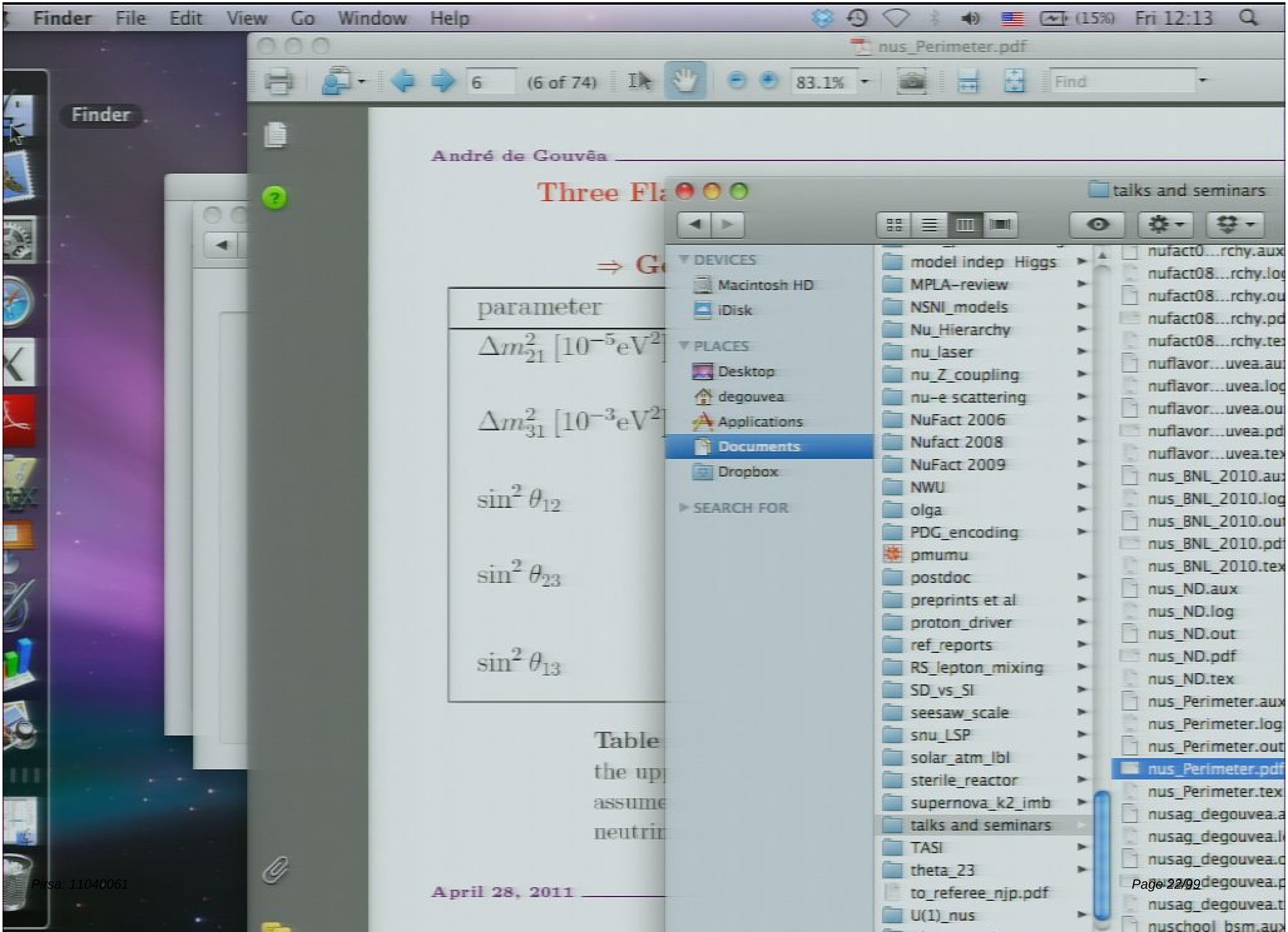
Three Flavor Mixing Hypothesis Fits All Data Really

⇒ Good Measurements of Oscillation Observable

parameter	best fit ±1σ	2σ	
$\Delta m^2_{21}\ [10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7
$\Delta m^2_{31}\ [10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	2. −(2
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, s the upper (lower) row corresponds to normal (inverted) neutrino assume the new reactor anti-neutrino fluxes [5] and include sh neutrino experiments in the fit.

[Schw



André de Gouvêa

Three Fl

⇒ G

parameter
Δm^2_{21} [10^{-5}eV^2]
Δm^2_{31} [10^{-3}eV^2]
$\sin^2\theta_{12}$
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$

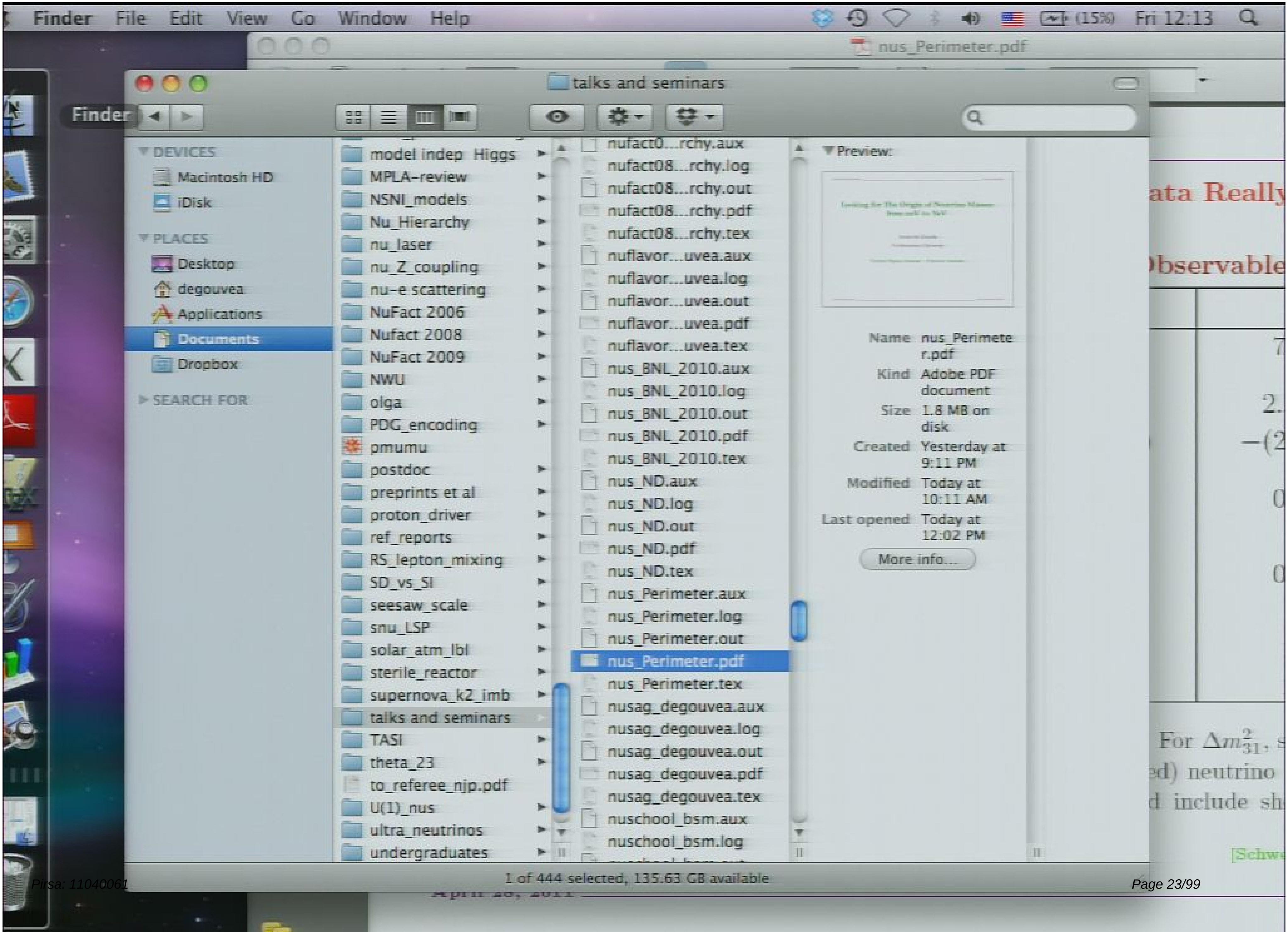
Table

the up

assume

neutrin

April 28, 2011

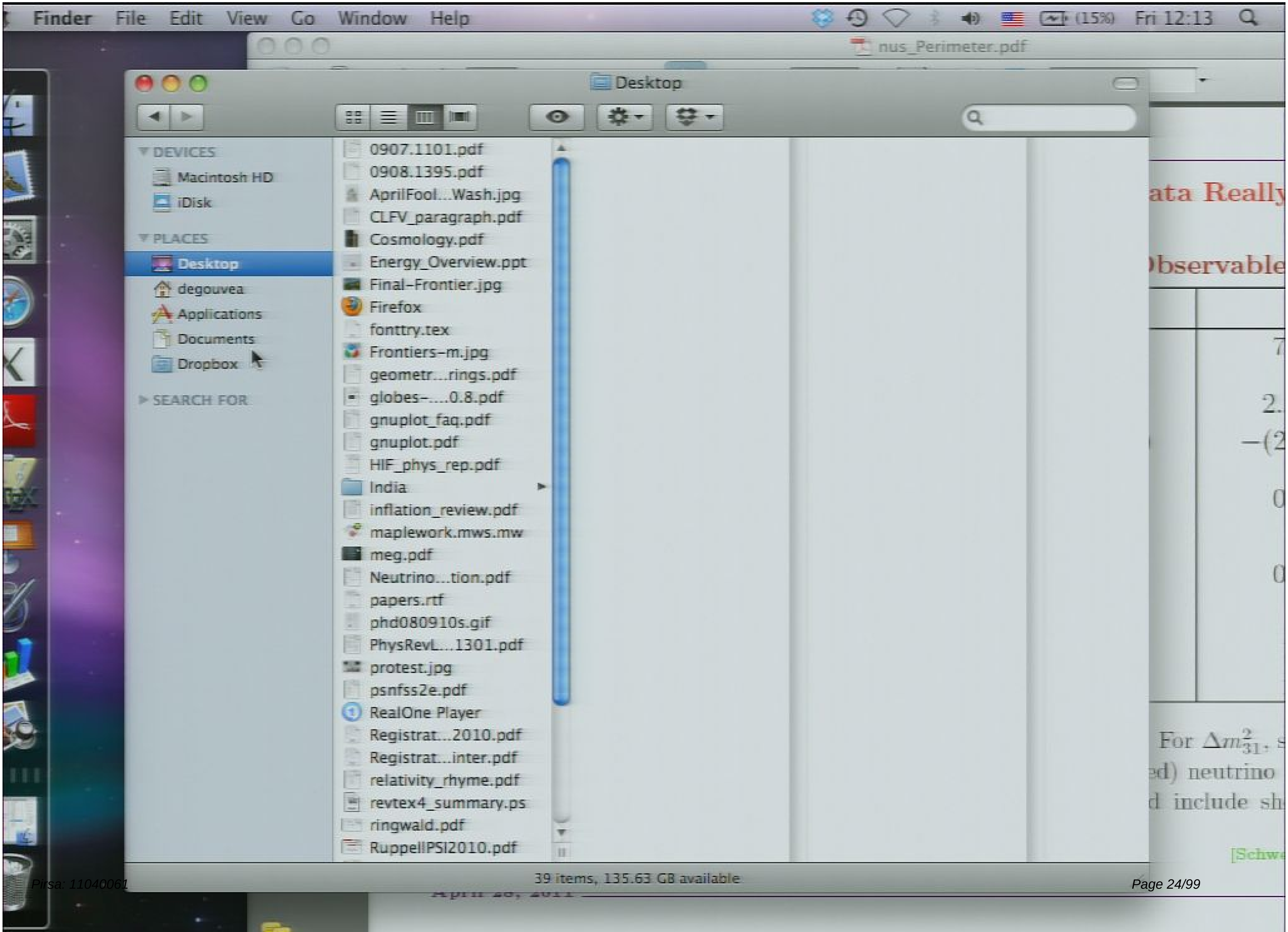


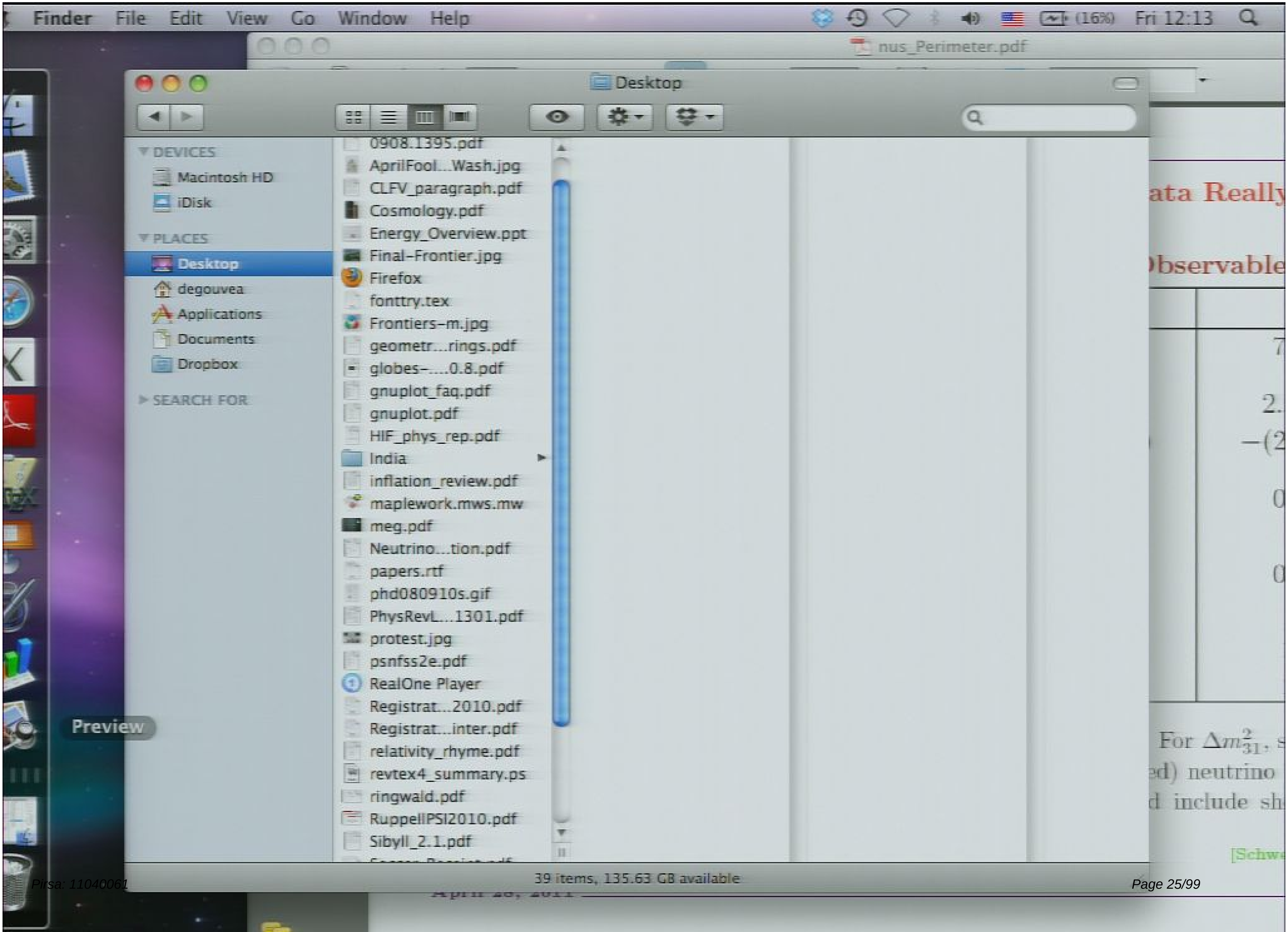
model indep Higgs
MPLA-review
NSNI_models
Nu_Hierarchy
nu_laser
nu_Z_coupling
nu-e scattering
NuFact 2006
Nufact 2008
NuFact 2009
NWU
olga
PDG_encoding
pmumu
postdoc
preprints et al
proton_driver
ref_reports
RS_lepton_mixing
SD_vs_SI
seesaw_scale
snu_LSP
solar_atm_lbl
sterile_reactor
supernova_k2_imb
talks and seminars
TASI
theta_23
to_referee_njp.pdf
U(1)_nus
ultra_neutrinos
undergraduates

nufact0...rchy.aux
nufact08...rchy.log
nufact08...rchy.out
nufact08...rchy.pdf
nufact08...rchy.tex
nuflavor...uvea.aux
nuflavor...uvea.log
nuflavor...uvea.out
nuflavor...uvea.pdf
nuflavor...uvea.tex
nus_BNL_2010.aux
nus_BNL_2010.log
nus_BNL_2010.out
nus_BNL_2010.pdf
nus_BNL_2010.tex
nus_ND.aux
nus_ND.log
nus_ND.out
nus_ND.pdf
nus_ND.tex
nus_Perimeter.aux
nus_Perimeter.log
nus_Perimeter.out
nus_Perimeter.pdf
nus_Perimeter.tex
nusag_degouvea.aux
nusag_degouvea.log
nusag_degouvea.out
nusag_degouvea.pdf
nusag_degouvea.tex
nuschool_bsm.aux
nuschool_bsm.log

Name	nus_Perimeter.pdf
Kind	Adobe PDF document
Size	1.8 MB on disk
Created	Yesterday at 9:11 PM
Modified	Today at 10:11 AM
Last opened	Today at 12:02 PM

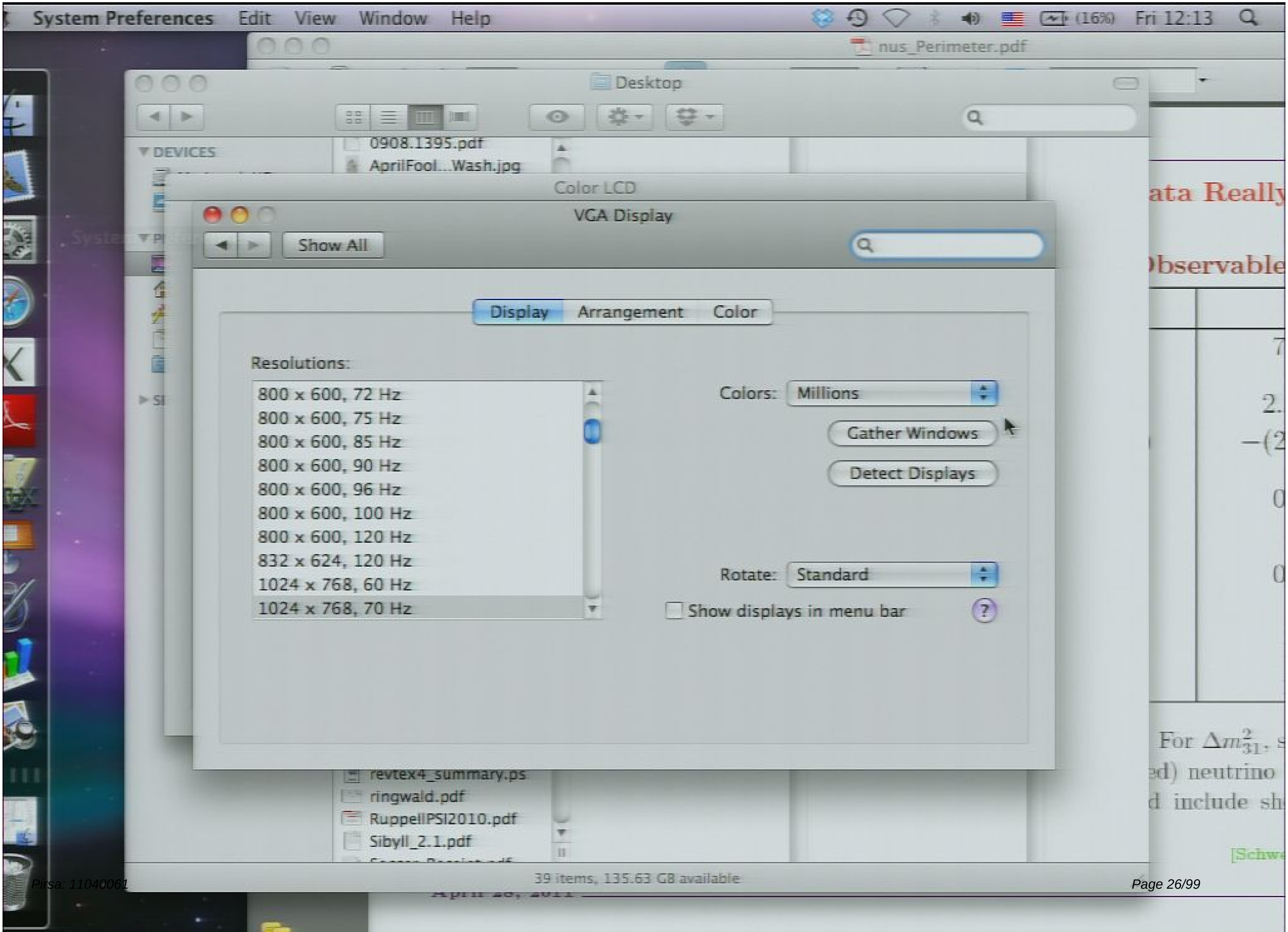
1 of 444 selected, 135.63 GB available


Finder File Edit View Go Window Help
(15%) Fri 12:13
nus_Perimeter.pdf
Desktop
DEVICES
Macintosh HD
iDisk
PLACES
Desktop
degouvea
Applications
Documents
Dropbox
SEARCH FOR
0907.1101.pdf
0908.1395.pdf
AprilFool...Wash.jpg
CLFV_paragraph.pdf
Cosmology.pdf
Energy_Overview.ppt
Final-Frontier.jpg
Firefox
fonttry.tex
Frontiers-m.jpg
geometr...rings.pdf
globes-....0.8.pdf
gnuplot_faq.pdf
gnuplot.pdf
HIF_phys_rep.pdf
India
inflation_review.pdf
maplework.mws.mw
meg.pdf
Neutrino...tion.pdf
papers.rtf
phd080910s.gif
PhysRevL...1301.pdf
protest.jpg
psnfss2e.pdf
RealOne Player
Registrat...2010.pdf
Registrat...inter.pdf
relativity_rhyme.pdf
revtex4_summary.ps
ringwald.pdf
RuppelPSI2010.pdf
39 items, 135.63 GB available
ata Really
Observable
For Δm^2_{31},
ed) neutrino
d include sh
[Schwe
April 28, 2011



0908.1395.pdf
AprilFool...Wash.jpg
CLFV_paragraph.pdf
Cosmology.pdf
Energy_Overview.ppt
Final-Frontier.jpg
Firefox
fonttry.tex
Frontiers-m.jpg
geometr...rings.pdf
globes-....0.8.pdf
gnuplot_faq.pdf
gnuplot.pdf
HIF_phys_rep.pdf
India
inflation_review.pdf
maplework.mws.mw
meg.pdf
Neutrino...tion.pdf
papers.rtf
phd080910s.gif
PhysRevL...1301.pdf
protest.jpg
psnfss2e.pdf
RealOne Player
Registrat...2010.pdf
Registrat...inter.pdf
relativity_rhyme.pdf
revtex4_summary.ps
ringwald.pdf
RuppelIPSI2010.pdf
Sibyll_2.1.pdf

39 items, 135.63 GB available

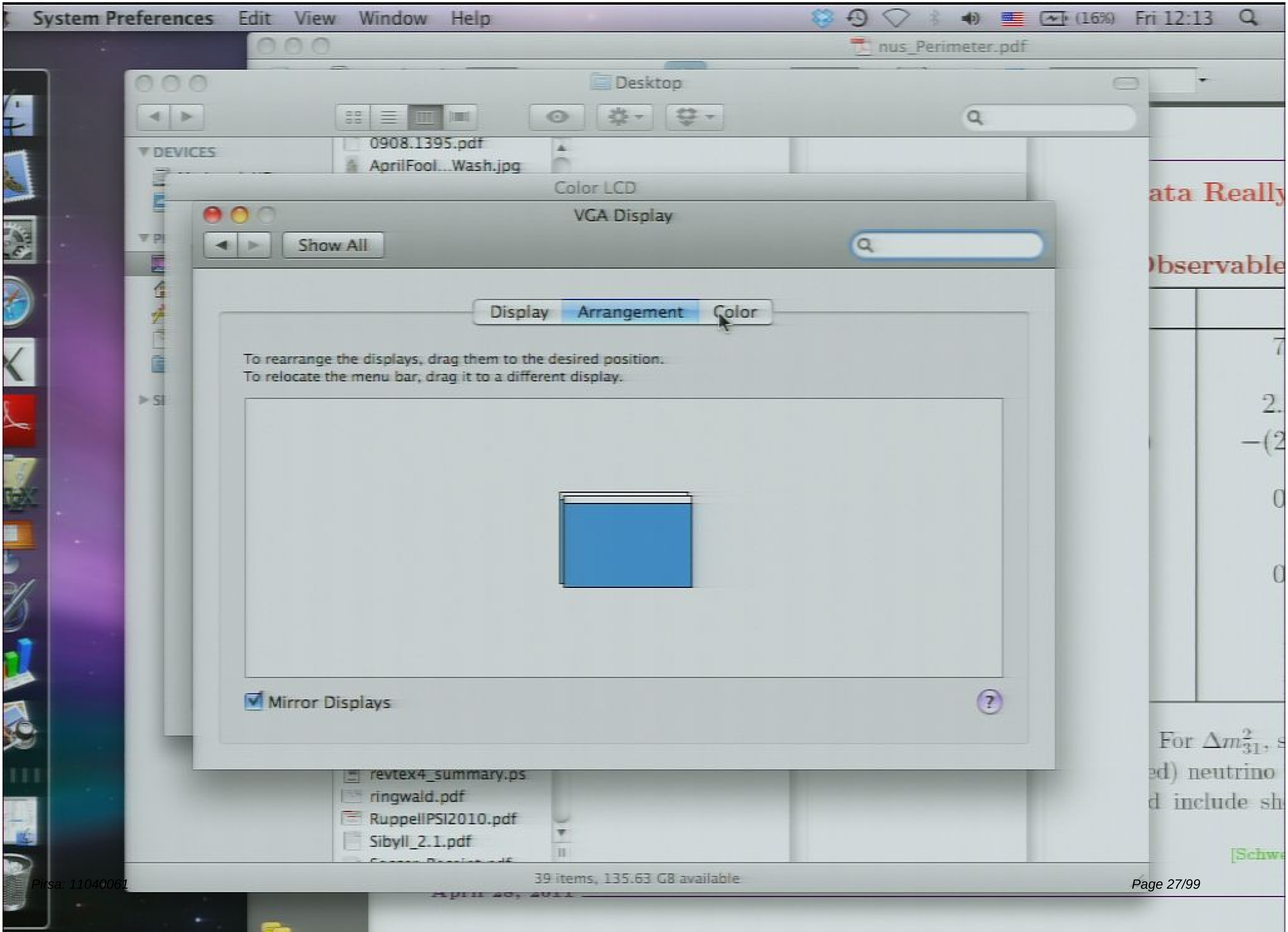


Resolutions:
800 x 600, 72 Hz
800 x 600, 75 Hz
800 x 600, 85 Hz
800 x 600, 90 Hz
800 x 600, 96 Hz
800 x 600, 100 Hz
800 x 600, 120 Hz
832 x 624, 120 Hz
1024 x 768, 60 Hz
1024 x 768, 70 Hz

Colors: Millions

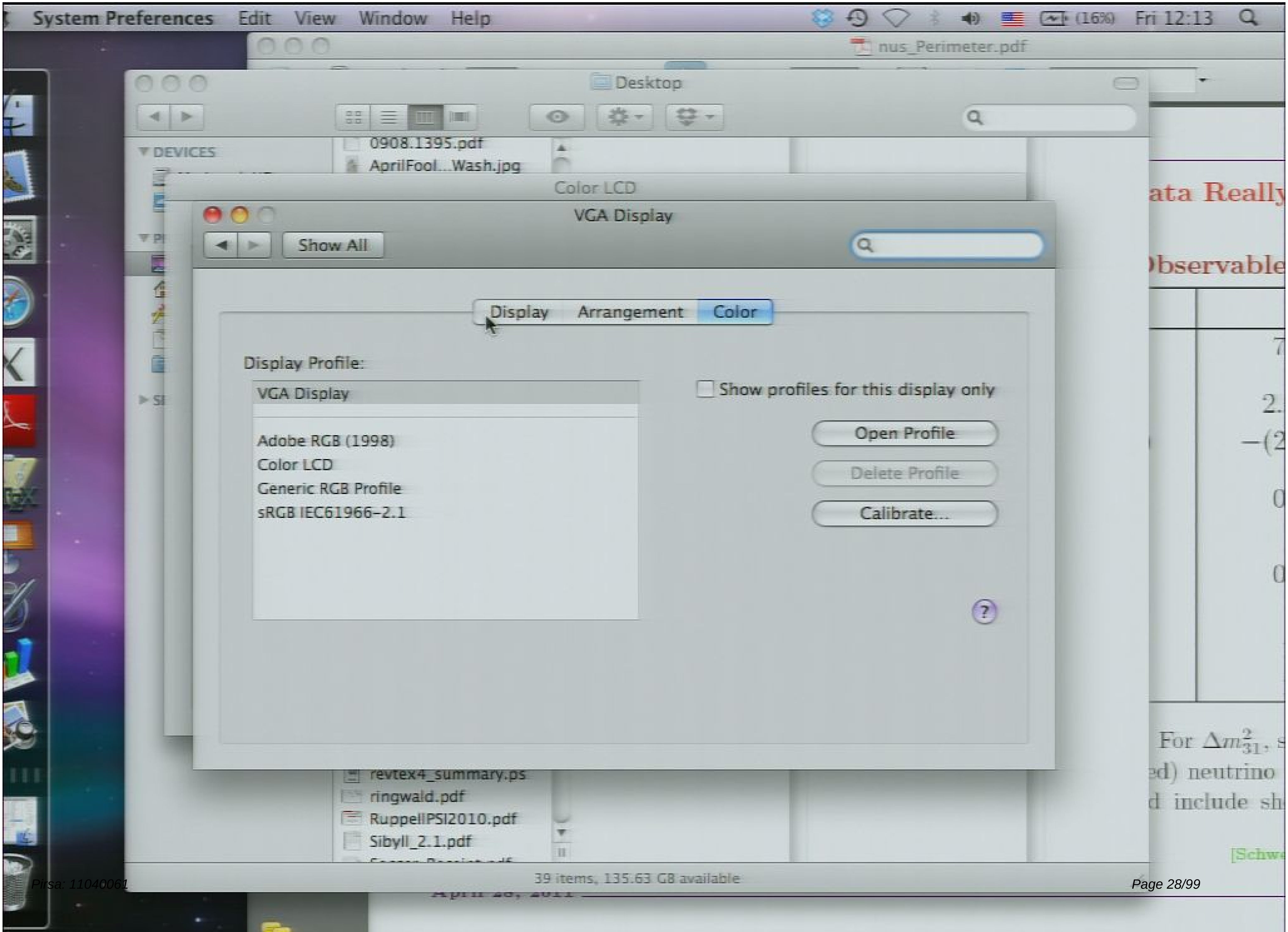
Rotate: Standard

☐ Show displays in menu bar



To rearrange the displays, drag them to the desired position.
To relocate the menu bar, drag it to a different display.

☑ Mirror Displays

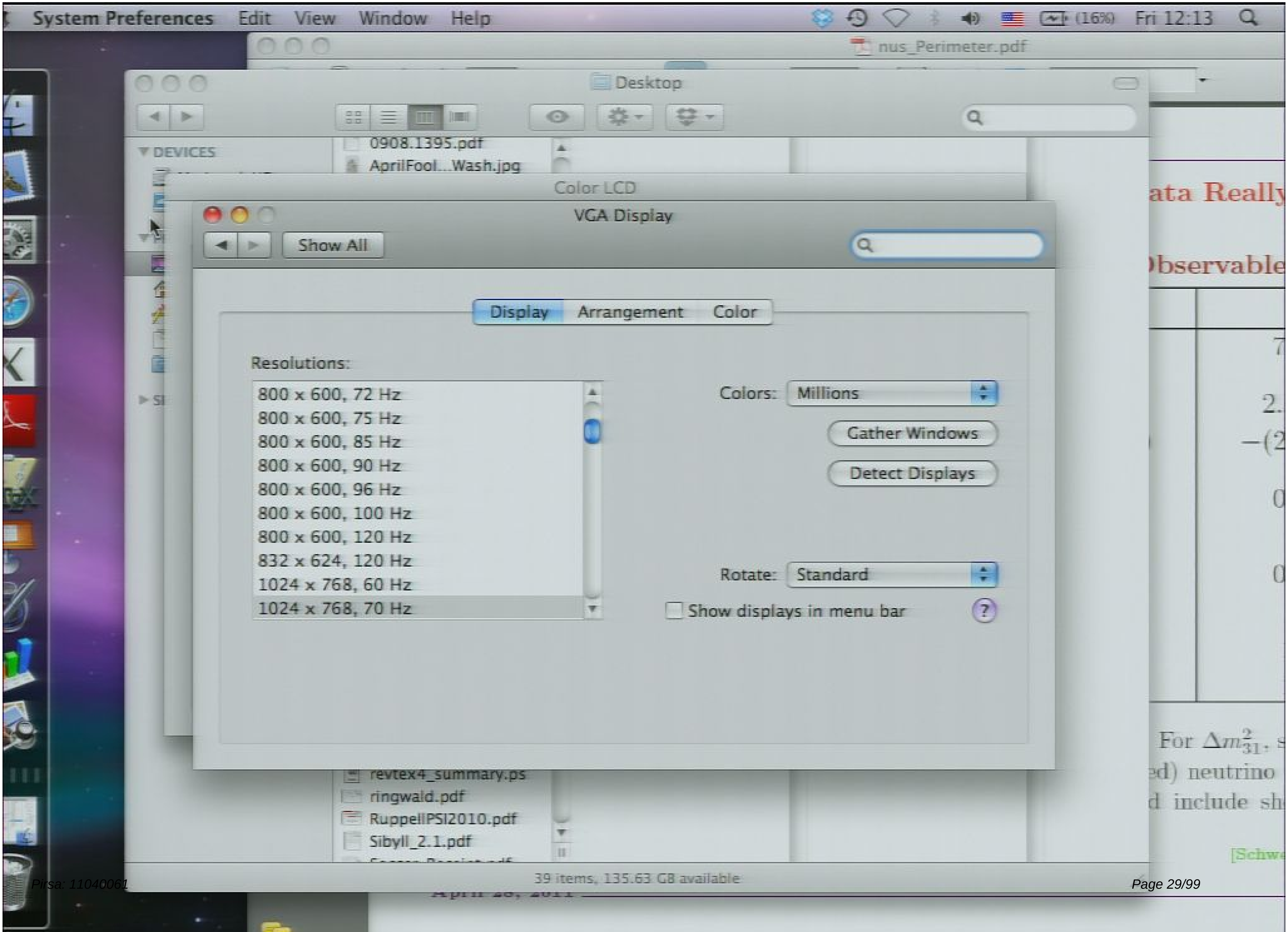


Display Profile:

VGA Display

Adobe RGB (1998)
Color LCD
Generic RGB Profile
sRGB IEC61966-2.1

☐ Show profiles for this display only



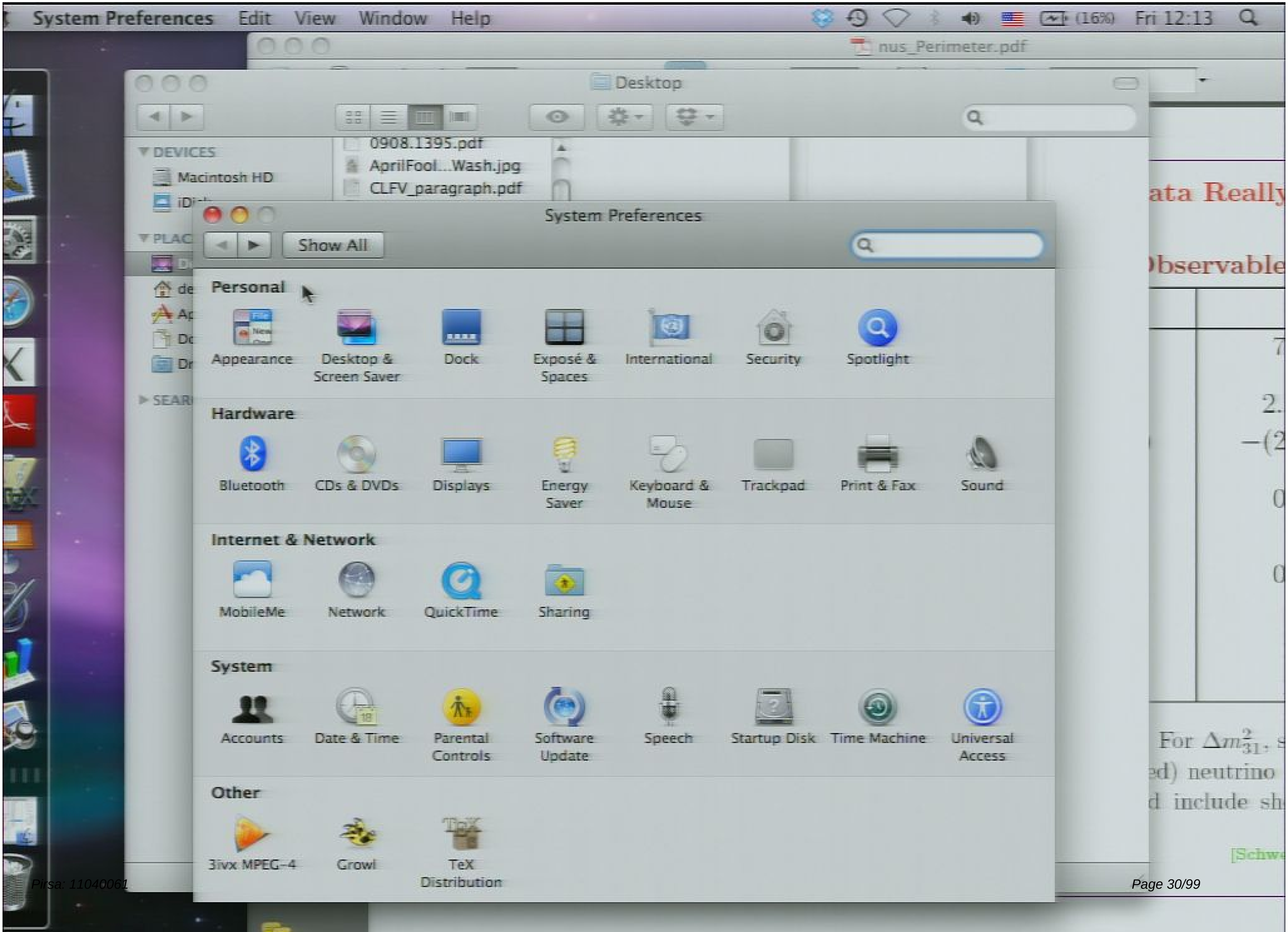
Resolutions:

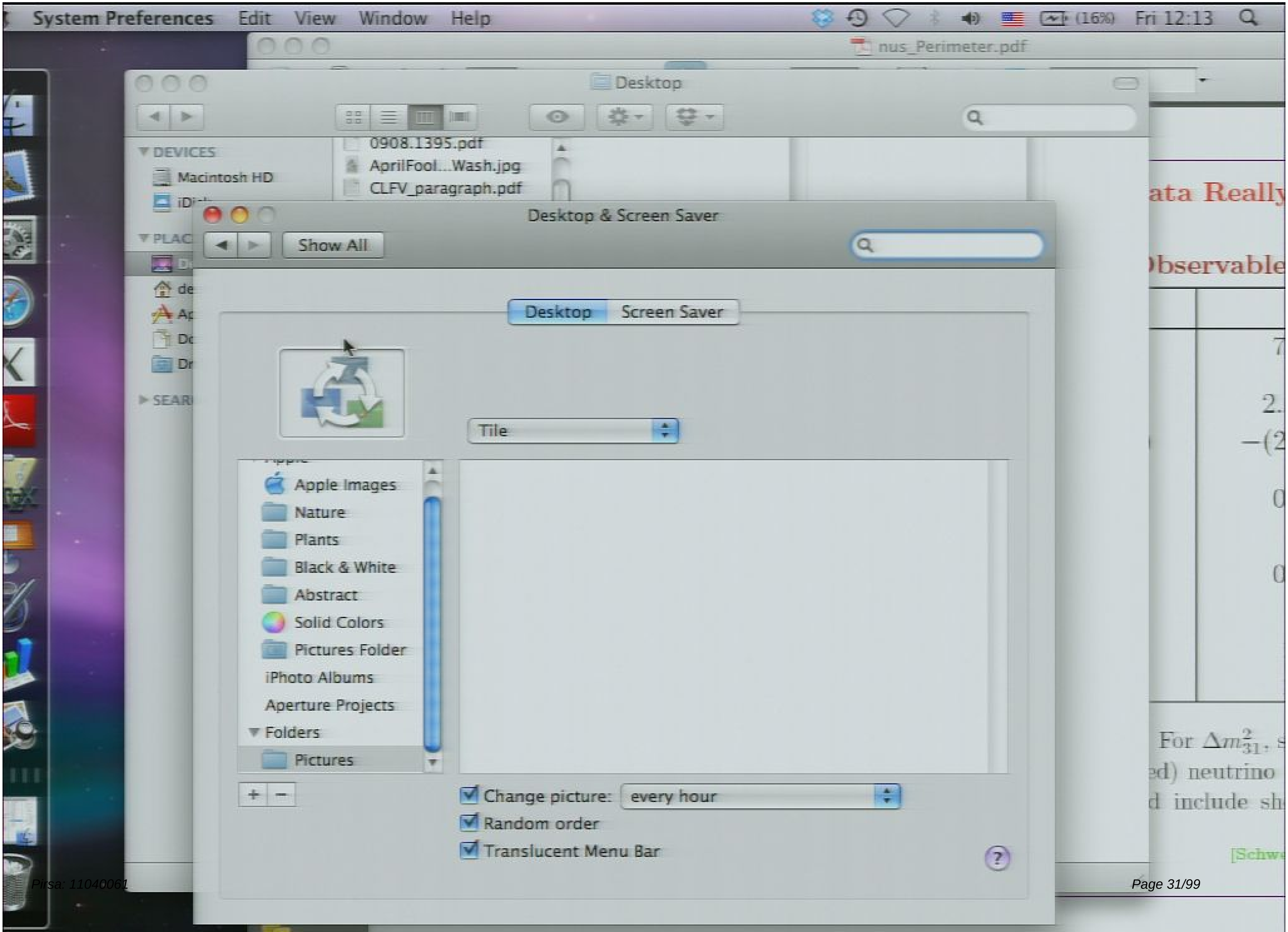
- 800 x 600, 72 Hz
- 800 x 600, 75 Hz
- 800 x 600, 85 Hz
- 800 x 600, 90 Hz
- 800 x 600, 96 Hz
- 800 x 600, 100 Hz
- 800 x 600, 120 Hz
- 832 x 624, 120 Hz
- 1024 x 768, 60 Hz
- 1024 x 768, 70 Hz

Colors: Millions

Rotate: Standard

☐ Show displays in menu bar


System Preferences
Edit
View
Window
Help
(16%)
Fri 12:13
nus_Perimeter.pdf
Desktop
DEVICES
Macintosh HD
0908.1395.pdf
AprilFool...Wash.jpg
CLFV_paragraph.pdf
System Preferences
Show All
Personal
Appearance
Desktop & Screen Saver
Dock
Exposé & Spaces
International
Security
Spotlight
Hardware
Bluetooth
CDs & DVDs
Displays
Energy Saver
Keyboard & Mouse
Trackpad
Print & Fax
Sound
Internet & Network
MobileMe
Network
QuickTime
Sharing
System
Accounts
Date & Time
Parental Controls
Software Update
Speech
Startup Disk
Time Machine
Universal Access
Other
3ivx MPEG-4
Growl
TeX Distribution
ata Really
Observable
For Δm^2_{31},
ed) neutrino
d include sh

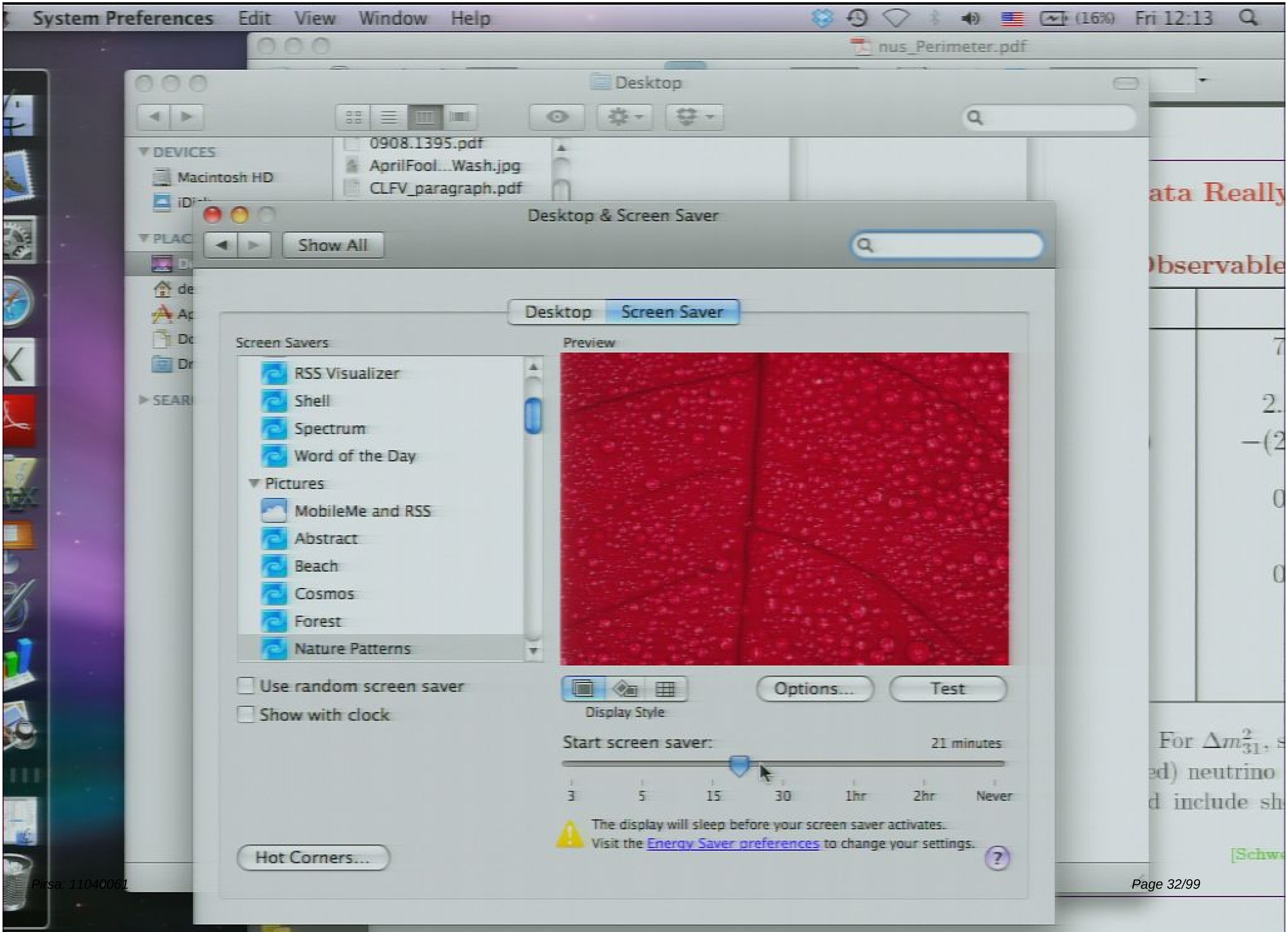


Tile

☑ Change picture: every hour

☑ Random order

☑ Translucent Menu Bar

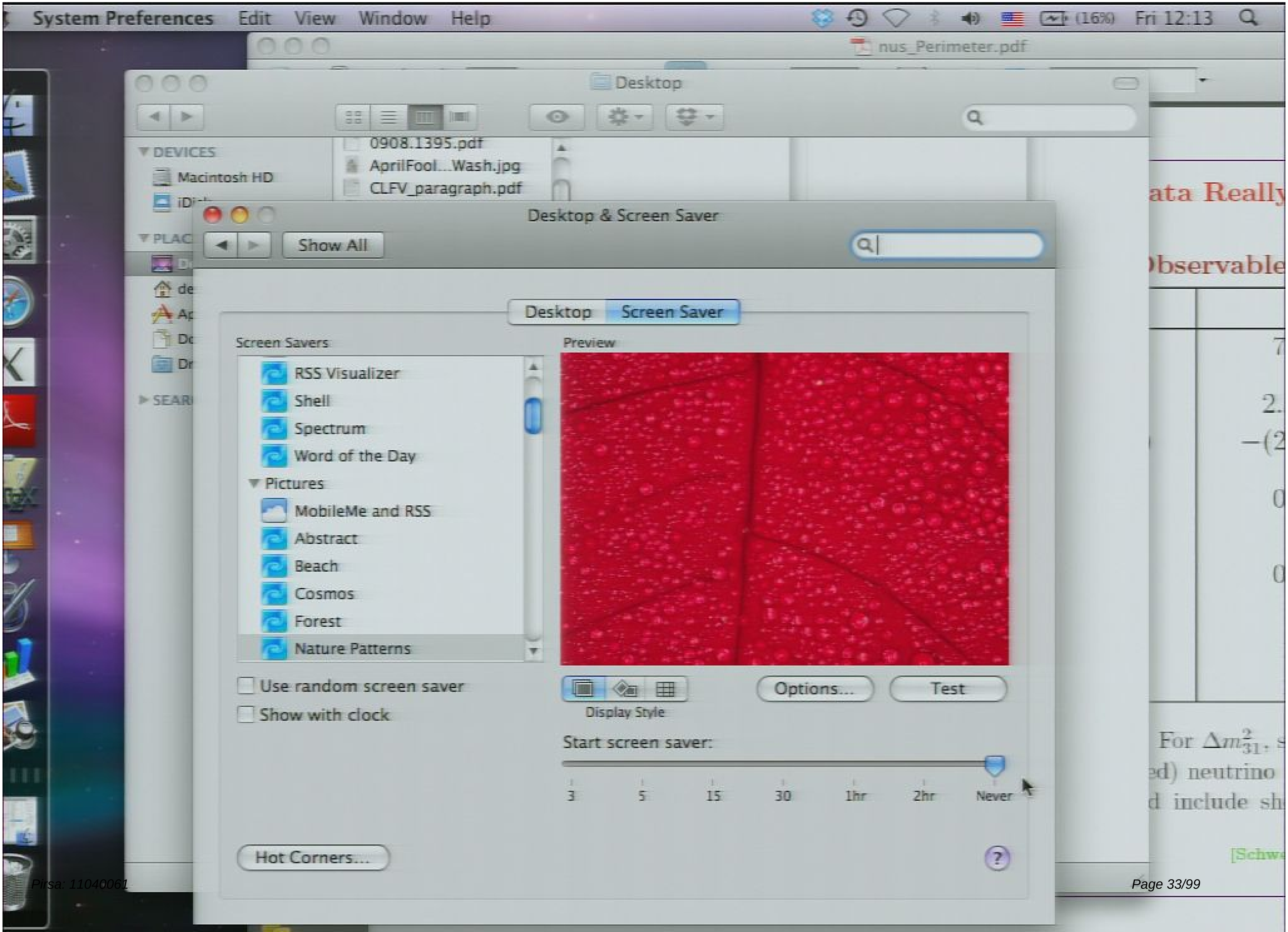


☐ Use random screen saver

☐ Show with clock

Start screen saver: 21 minutes

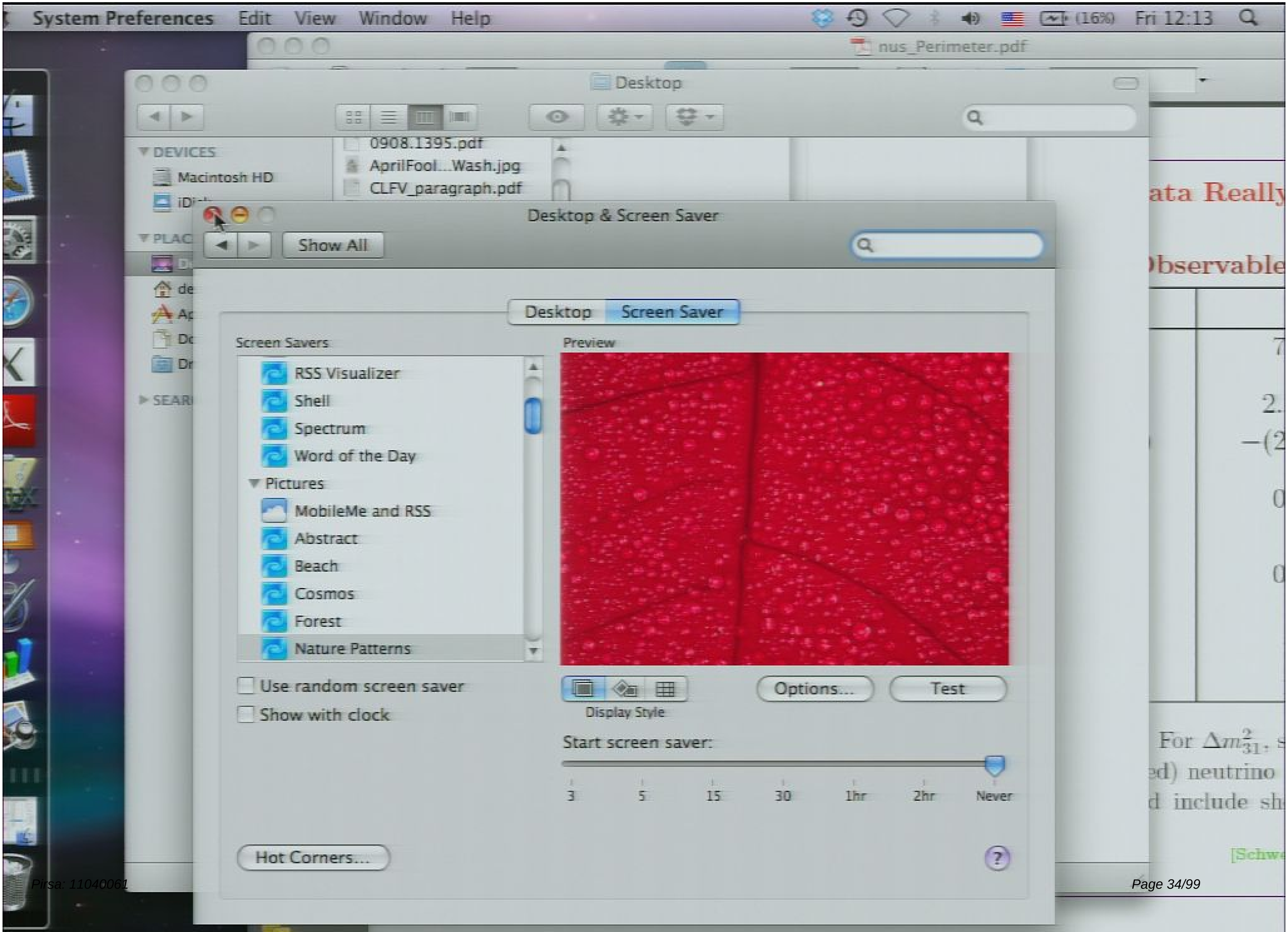
The display will sleep before your screen saver activates.
Visit the Energy Saver preferences to change your settings.



☐ Use random screen saver

☐ Show with clock

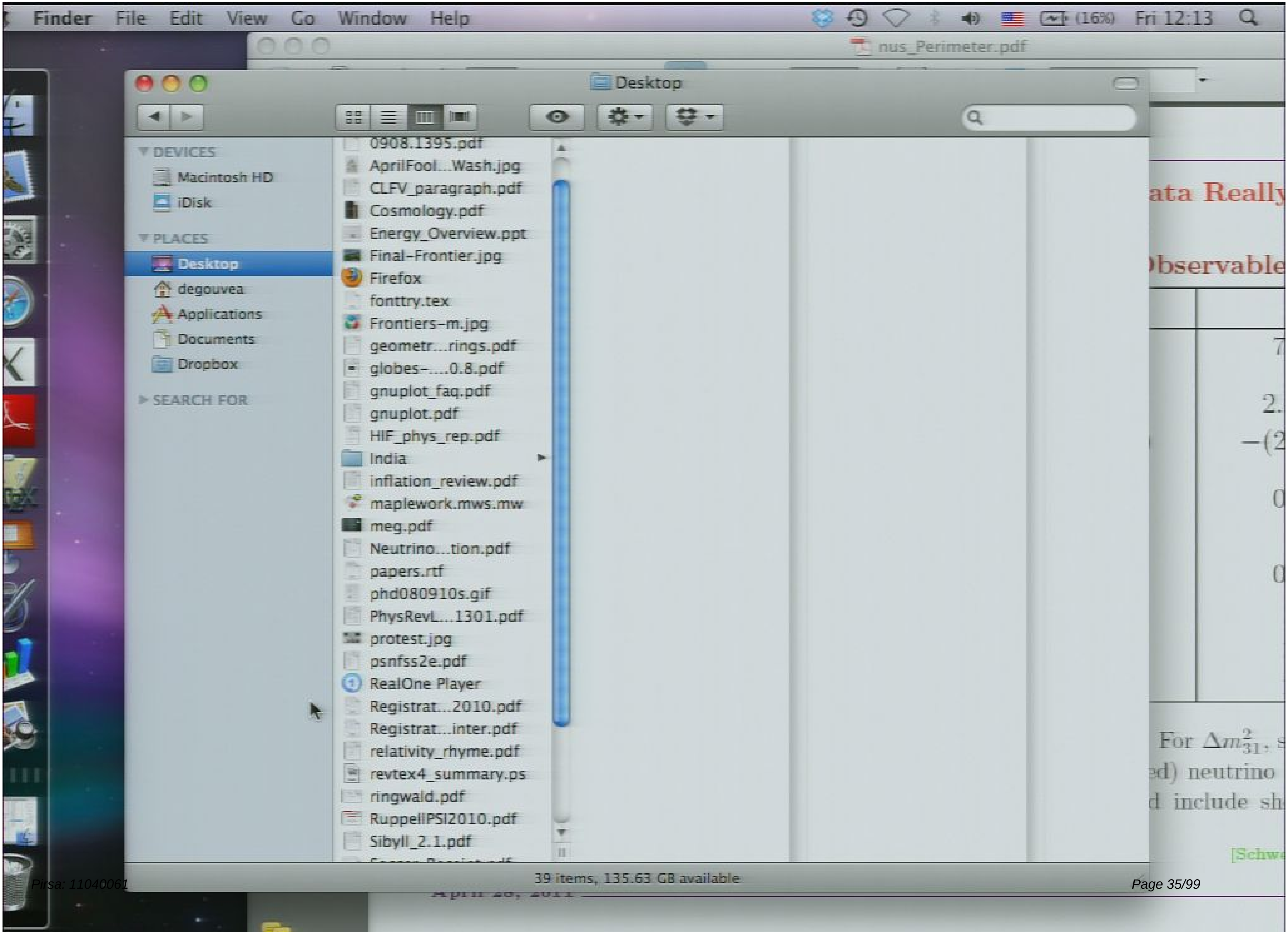
Start screen saver: Never



☐ Use random screen saver

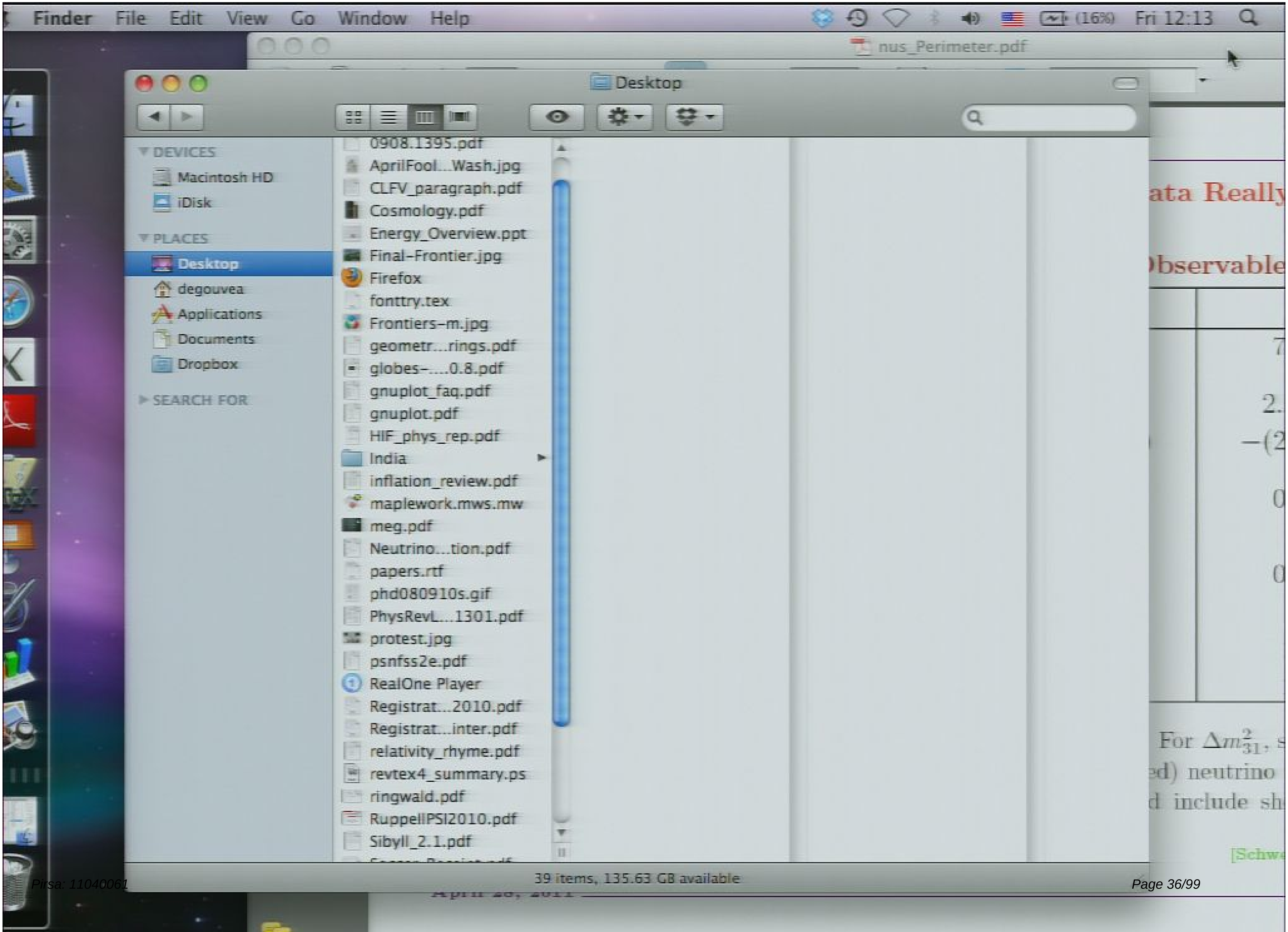
☐ Show with clock

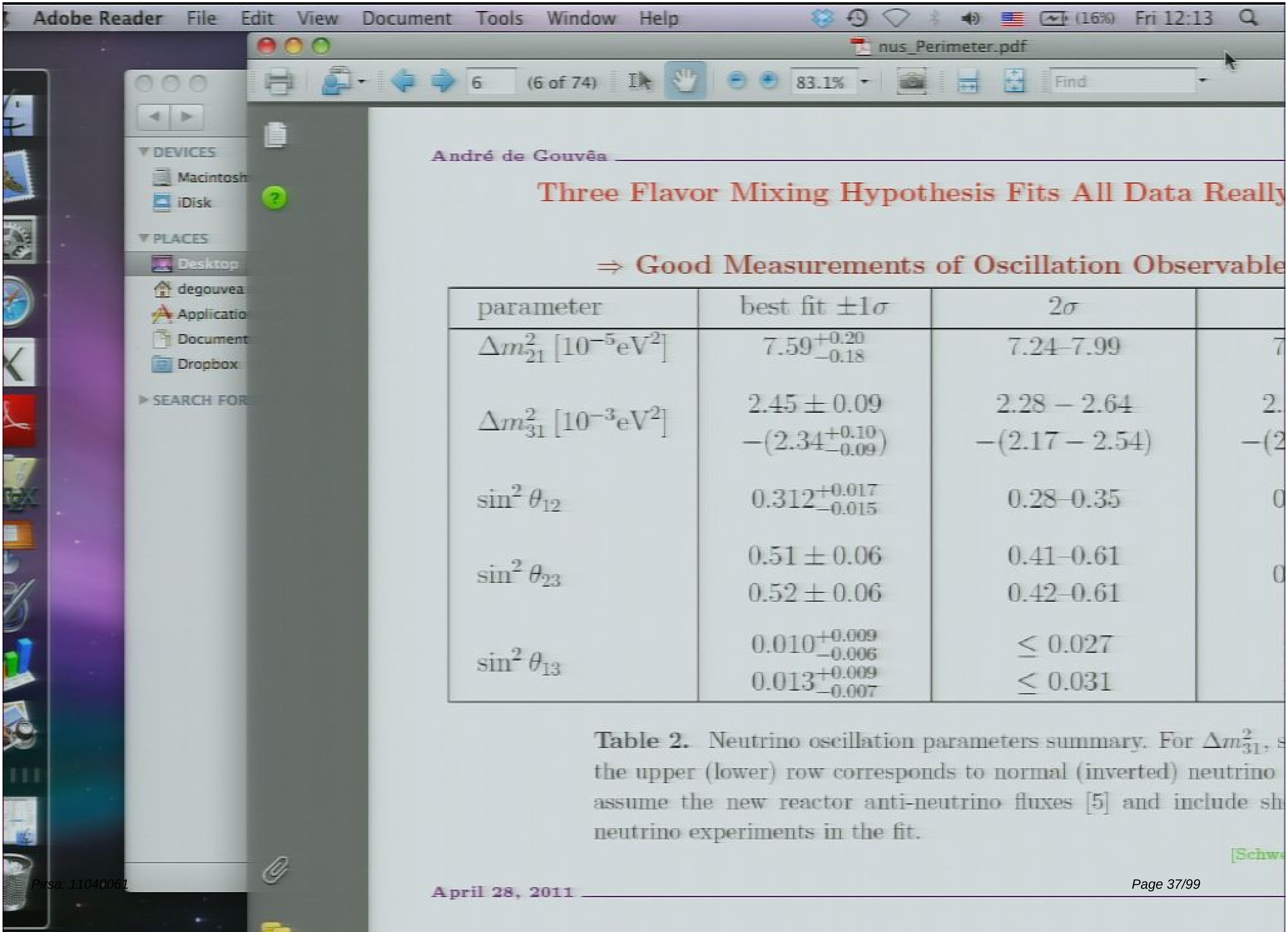
Start screen saver: Never



0908.1395.pdf
AprilFool...Wash.jpg
CLFV_paragraph.pdf
Cosmology.pdf
Energy_Overview.ppt
Final-Frontier.jpg
Firefox
fonttry.tex
Frontiers-m.jpg
geometr...rings.pdf
globes-....0.8.pdf
gnuplot_faq.pdf
gnuplot.pdf
HIF_phys_rep.pdf
India
inflation_review.pdf
maplework.mws.mw
meg.pdf
Neutrino...tion.pdf
papers.rtf
phd080910s.gif
PhysRevL...1301.pdf
protest.jpg
psnfss2e.pdf
RealOne Player
Registrat...2010.pdf
Registrat...inter.pdf
relativity_rhyme.pdf
revtex4_summary.ps
ringwald.pdf
RuppelIPSI2010.pdf
Sibyll_2.1.pdf

39 items, 135.63 GB available


Finder File Edit View Go Window Help
(16%) Fri 12:13
nus_Perimeter.pdf
Desktop
DEVICES
Macintosh HD
iDisk
PLACES
Desktop
degouvea
Applications
Documents
Dropbox
SEARCH FOR
0908.1395.pdf
AprilFool...Wash.jpg
CLFV_paragraph.pdf
Cosmology.pdf
Energy_Overview.ppt
Final-Frontier.jpg
Firefox
fonttry.tex
Frontiers-m.jpg
geometr...rings.pdf
globes-....0.8.pdf
gnuplot_faq.pdf
gnuplot.pdf
HIF_phys_rep.pdf
India
inflation_review.pdf
maplework.mws.mw
meg.pdf
Neutrino...tion.pdf
papers.rtf
phd080910s.gif
PhysRevL...1301.pdf
protest.jpg
psnfss2e.pdf
RealOne Player
Registrat...2010.pdf
Registrat...inter.pdf
relativity_rhyme.pdf
revtex4_summary.ps
ringwald.pdf
RuppelIPSI2010.pdf
Sibyll_2.1.pdf
39 items, 135.63 GB available
ata Really
bservable
For Δm^2_{31},
ed) neutrino
d include sh
[Schwe



André de Gouvêa

Three Flavor Mixing Hypothesis Fits All Data Really

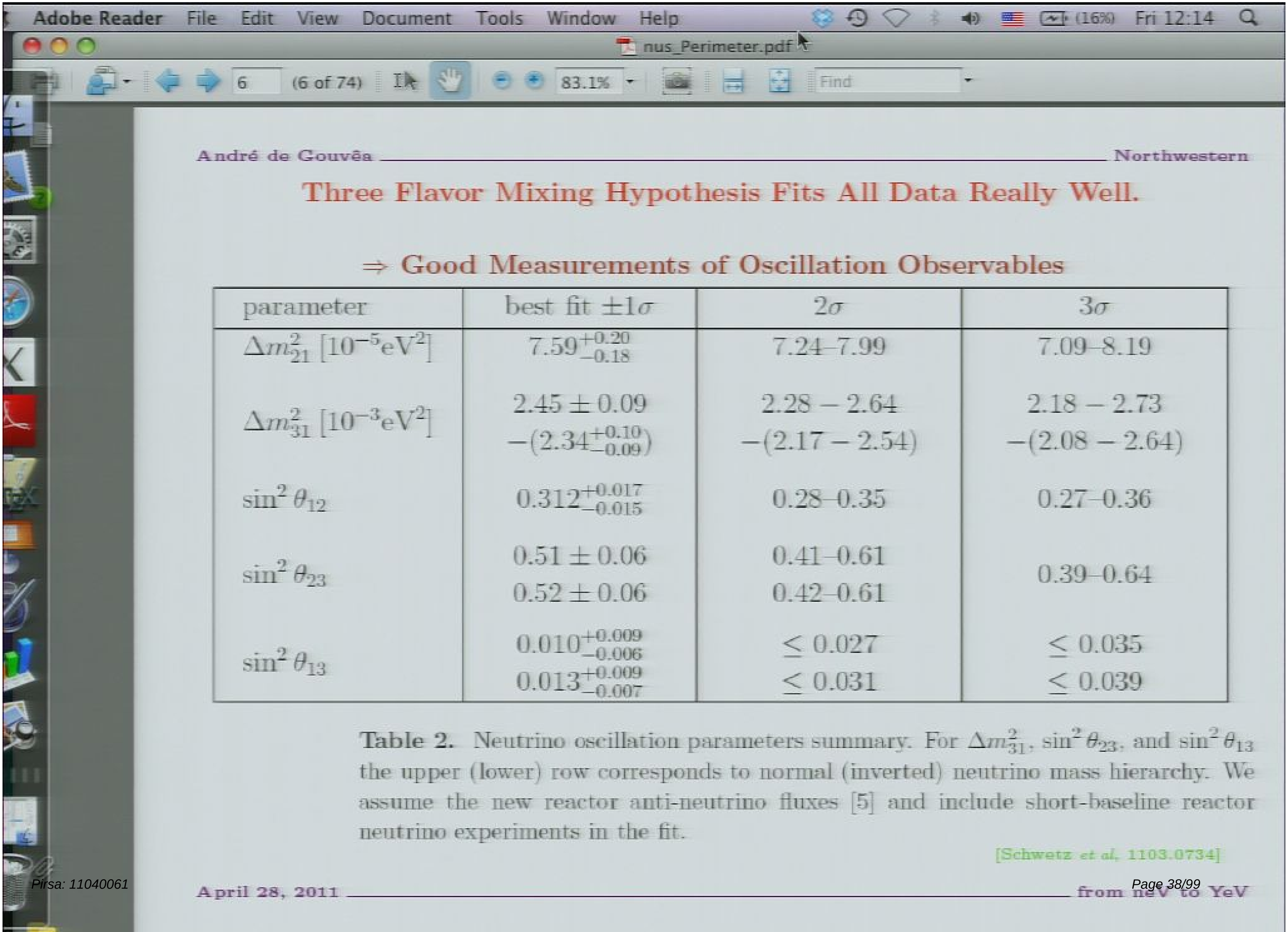
⇒ Good Measurements of Oscillation Observable

parameter	best fit ±1σ	2σ	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	2. −(2
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, s
the upper (lower) row corresponds to normal (inverted) neutrino
assume the new reactor anti-neutrino fluxes [5] and include sh
neutrino experiments in the fit.

[Schw

April 28, 2011



Three Flavor Mixing Hypothesis Fits All Data Really Well.

⇒ Good Measurements of Oscillation Observables

parameter	best fit ±1σ	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]

Three Flavor Mixing Hypothesis Fits All Data Really Well.

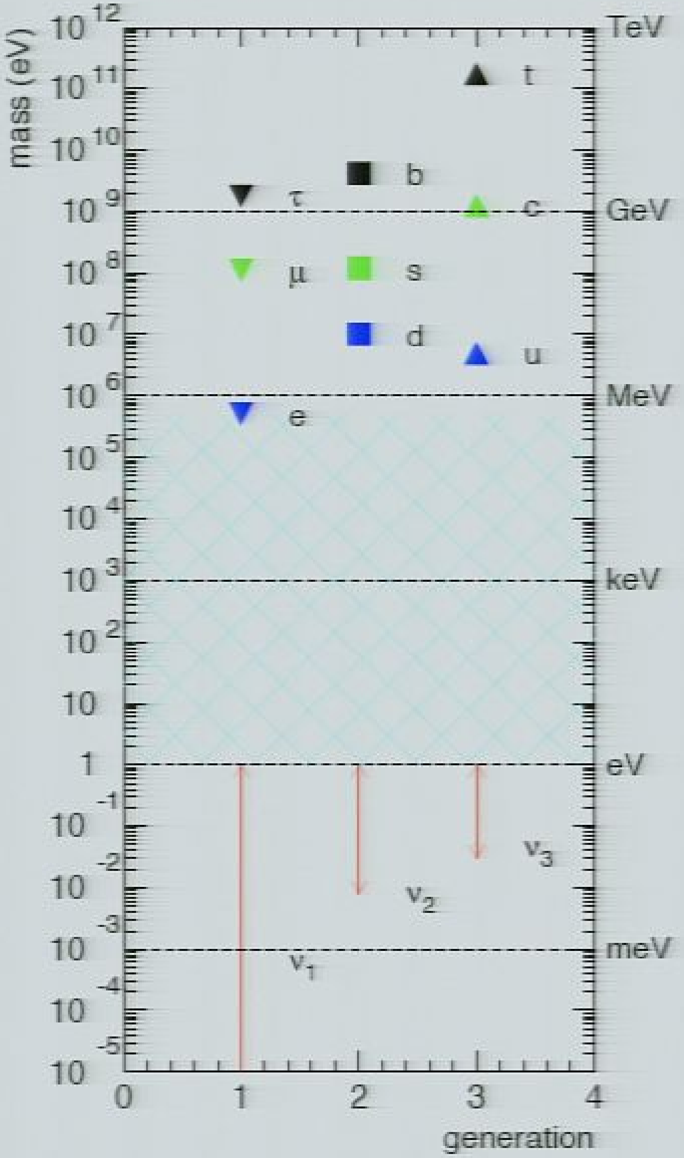
⇒ Good Measurements of Oscillation Observables

parameter	best fit ±1σ	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

[Schwetz *et al*, 1103.0734]

What We Are Trying To Understand:



⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Who Cares About Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

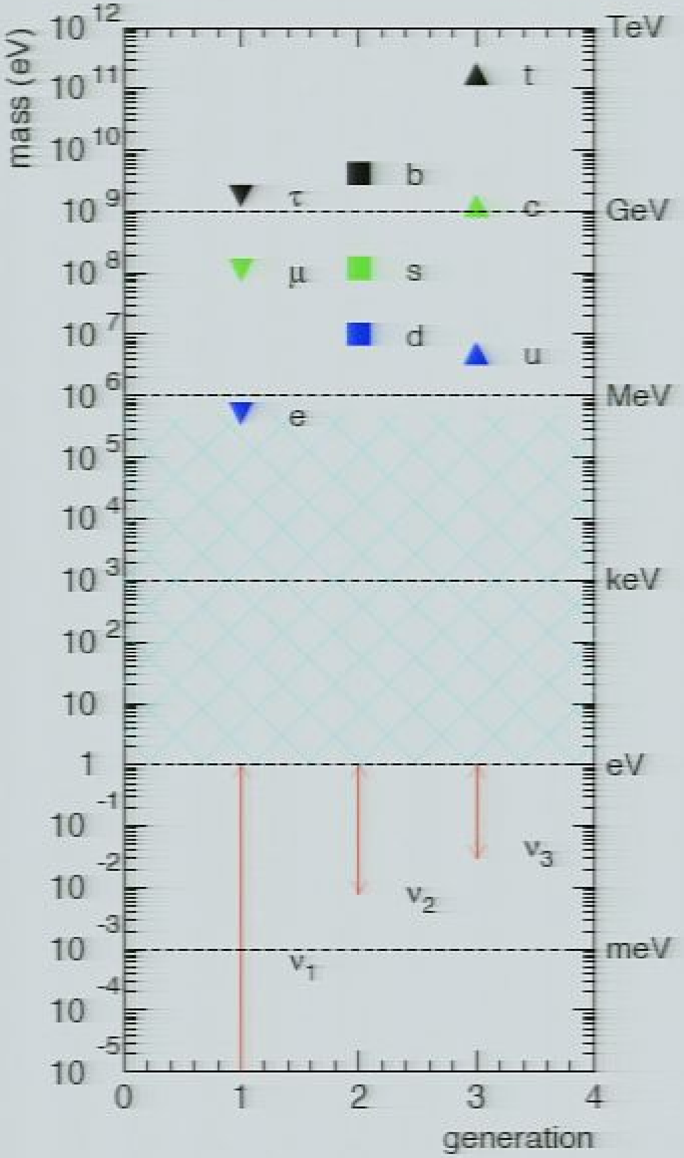
The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

---

* There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of "palpability" (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs *or* not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this "particle physics?").



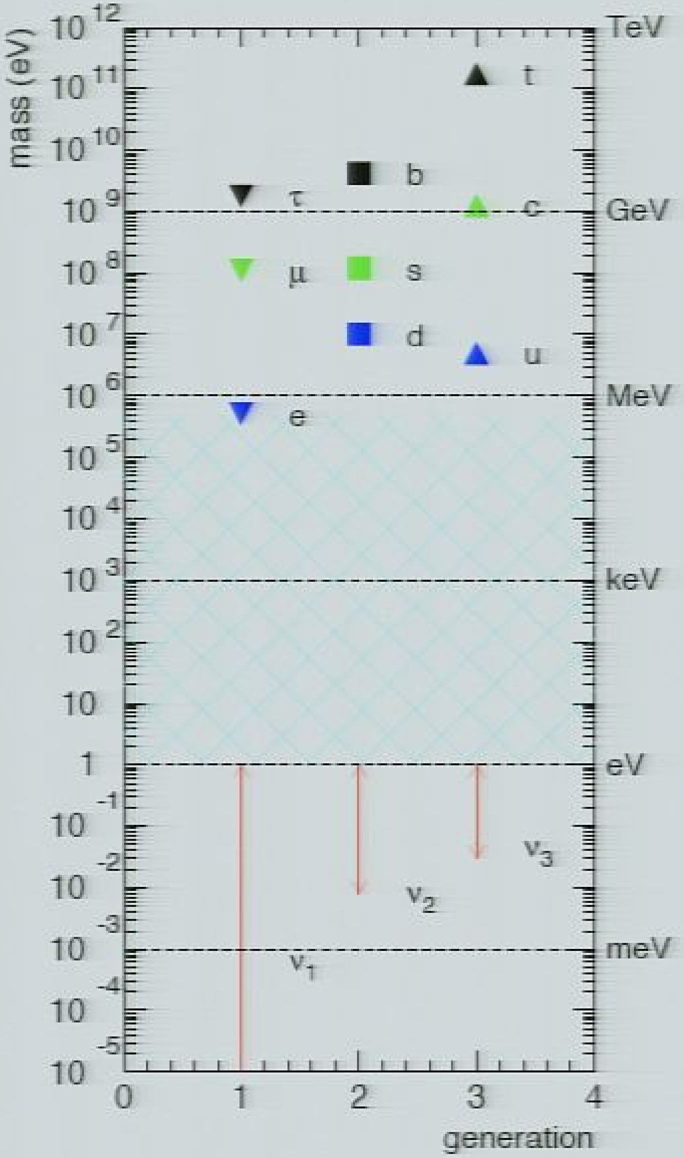
What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS “WEIRD” ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Who Cares About Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

---

[*] There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of "palpability" (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs *or* not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this "particle physics?").

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$\Updownarrow$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Candidate νSM: The One I'll Concentrate On

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^i H L^j H}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB: } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above *at most* Λ/y.
- Define $y_{\max} \equiv 1 \Rightarrow$ data require $\Lambda \sim 10^{14}$ GeV.

What else is this "good for"? Depends on the ultraviolet completion!

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$\Updownarrow$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Candidate νSM: The One I'll Concentrate On

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^iHL^jH}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB: } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above *at most* Λ/y.
- Define $y_{\max} \equiv 1 \Rightarrow$ data require $\Lambda \sim 10^{14}$ GeV.

What else is this "good for"? Depends on the ultraviolet completion!

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

---

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

Candidate νSM: The One I'll Concentrate On

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^iHL^jH}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB: } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above *at most* Λ/y.
- Define $y_{\max} \equiv 1 \Rightarrow$ data require $\Lambda \sim 10^{14}$ GeV.

What else is this "good for"? Depends on the ultraviolet completion!

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

---

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$).

Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

What We Know About M:

- $M = 0$: the six neutrinos “fuse” into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \ \Rightarrow \ \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$).

Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

What We Know About M:

- $M=0$: the six neutrinos "fuse" into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \Rightarrow \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

Why are Neutrino Masses Small in the $M \neq 0$ Case?

If $\mu \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

High-Energy Seesaw: Brief Comments

- This is everyone's favorite scenario.
- Upper bound for M (e.g. Maltoni, Niczyporuk, Willenbrock, hep-ph/0006358):

$$M < 7.6 \times 10^{15}\ \mathrm{GeV} \times \left(\frac{0.1\ \mathrm{eV}}{m_\nu}\right).$$

- Hierarchy problem hint (e.g., Casas, Espinosa, Hidalgo, hep-ph/0410298):

$$M < 10^7\ \mathrm{GeV}.$$

- Physics "too" heavy! No observable consequence other than leptogenesis. From thermal leptogenesis $M > 10^9$ GeV. Will we ever convince ourselves that this is correct? (e.g., Buckley, Murayama, hep-ph/0606088)

Low-Energy Seesaw [AdG PRD72,033005)]

The other end of the M spectrum ($M < 100$ GeV). What do we get?

- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light? [For a possible alternative see Canetti, Shaposhnikov, arXiv: 1006.0133 and reference therein.]
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos ⇒ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

More Details, assuming three right-handed neutrinos N:

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

M is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in $(\lambda v)M^{-1}$, the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1} (\lambda v)^t,$$

where m_a is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of M.

6×6 mixing matrix U $[U^t m_\nu U = \text{diag}(m_1, m_2, m_3, m_4, m_5, m_6)]$ is

$$U = \begin{pmatrix} V & \Theta \\ -\Theta^\dagger V & 1_{n\times n} \end{pmatrix},$$

where V is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \text{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

$$\Theta = (\lambda v)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V \sqrt{\text{diag}(m_1, m_2, m_3)} R^\dagger M^{-1/2},$$

where R is a complex orthogonal matrix $RR^t = 1$.

More Details, assuming three right-handed neutrinos N:

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

M is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in $(\lambda v)M^{-1}$, the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1} (\lambda v)^t,$$

where m_a is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of M.

6×6 mixing matrix U $[U^t m_\nu U = \text{diag}(m_1, m_2, m_3, m_4, m_5, m_6)]$ is

$$U = \begin{pmatrix} V & \Theta \\ -\Theta^\dagger V & 1_{n\times n} \end{pmatrix},$$

where V is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \text{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

$$\Theta = (\lambda v)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V\sqrt{\text{diag}(m_1, m_2, m_3)}R^\dagger M^{-1/2},$$

where R is a complex orthogonal matrix $RR^t = 1$.

More Details, assuming three right-handed neutrinos N:

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

M is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in $(\lambda v)M^{-1}$, the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1} (\lambda v)^t,$$

where m_a is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of M.

6×6 mixing matrix U $[U^t m_\nu U = \mathrm{diag}(m_1, m_2, m_3, m_4, m_5, m_6)]$ is

$$U = \begin{pmatrix} V & \Theta \\ -\Theta^\dagger V & 1_{n\times n} \end{pmatrix},$$

where V is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \mathrm{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

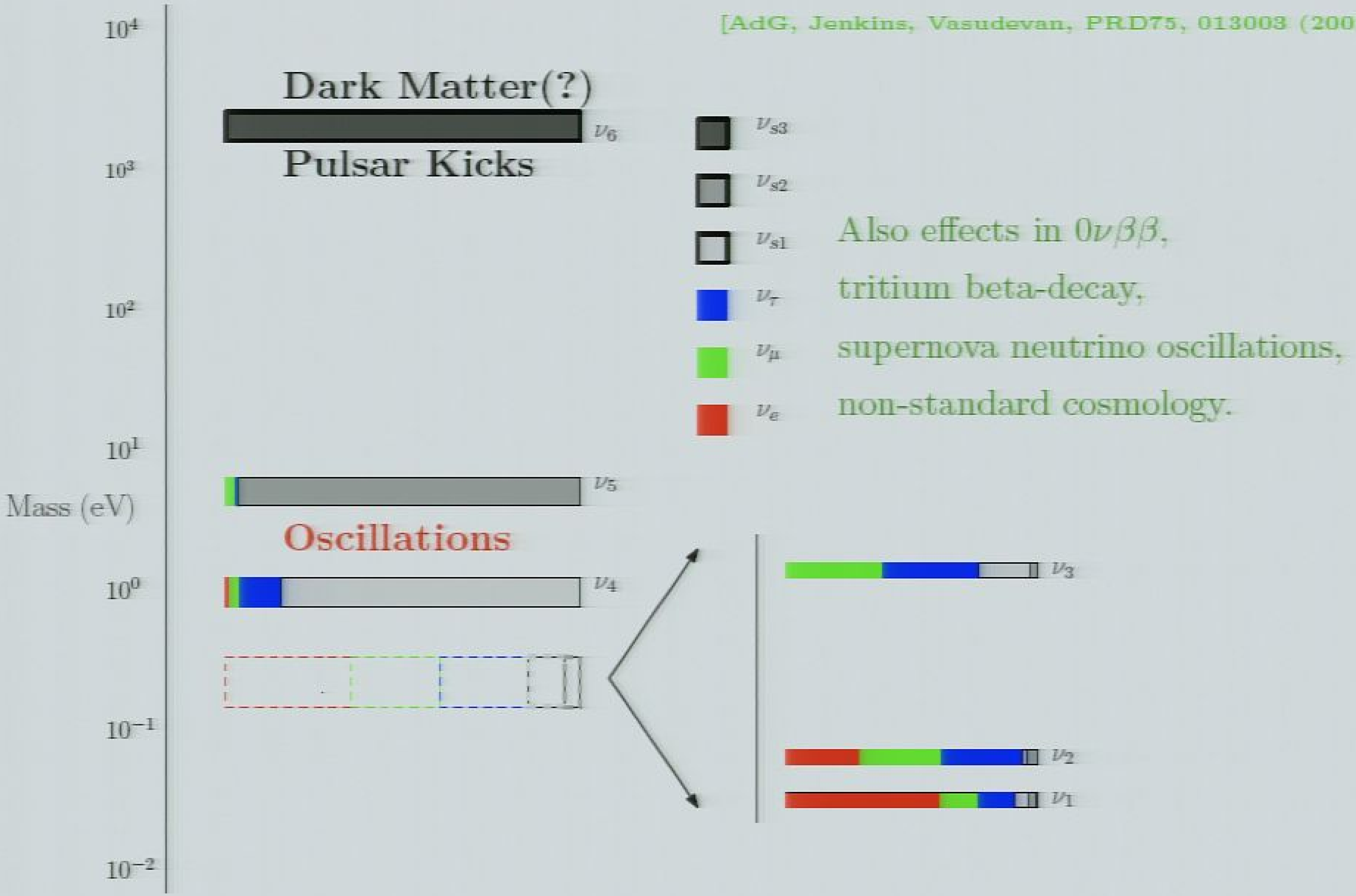
$$\Theta = (\lambda v)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V \sqrt{\mathrm{diag}(m_1, m_2, m_3)} R^\dagger M^{-1/2},$$

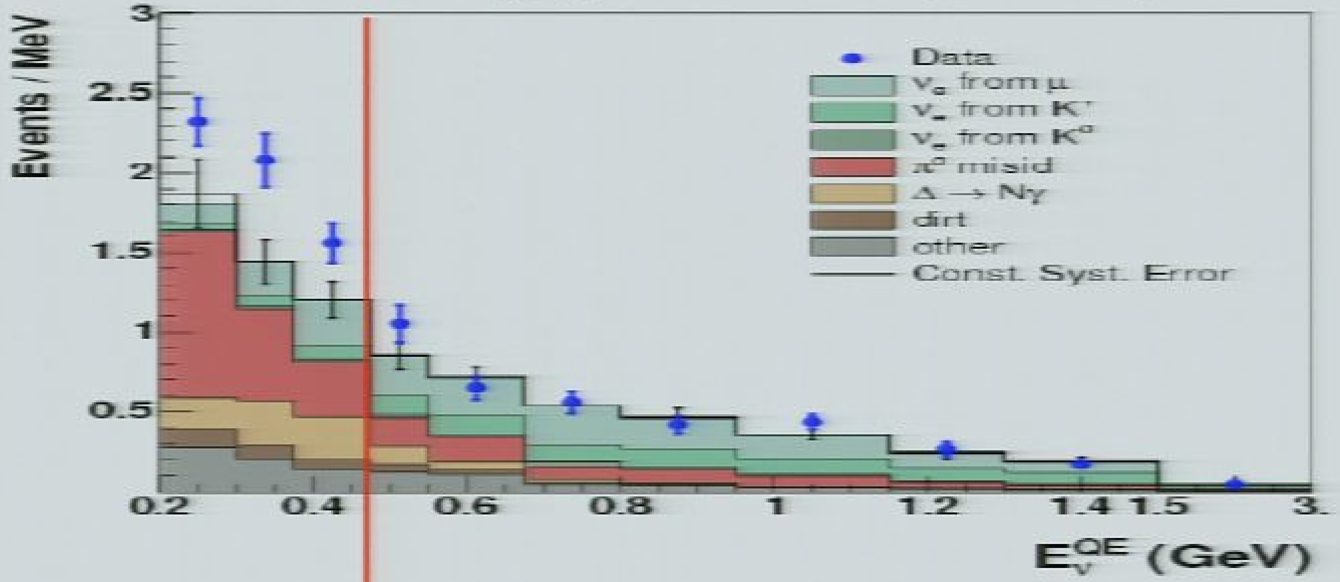
where R is a complex orthogonal matrix $RR^t = 1$.

[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]

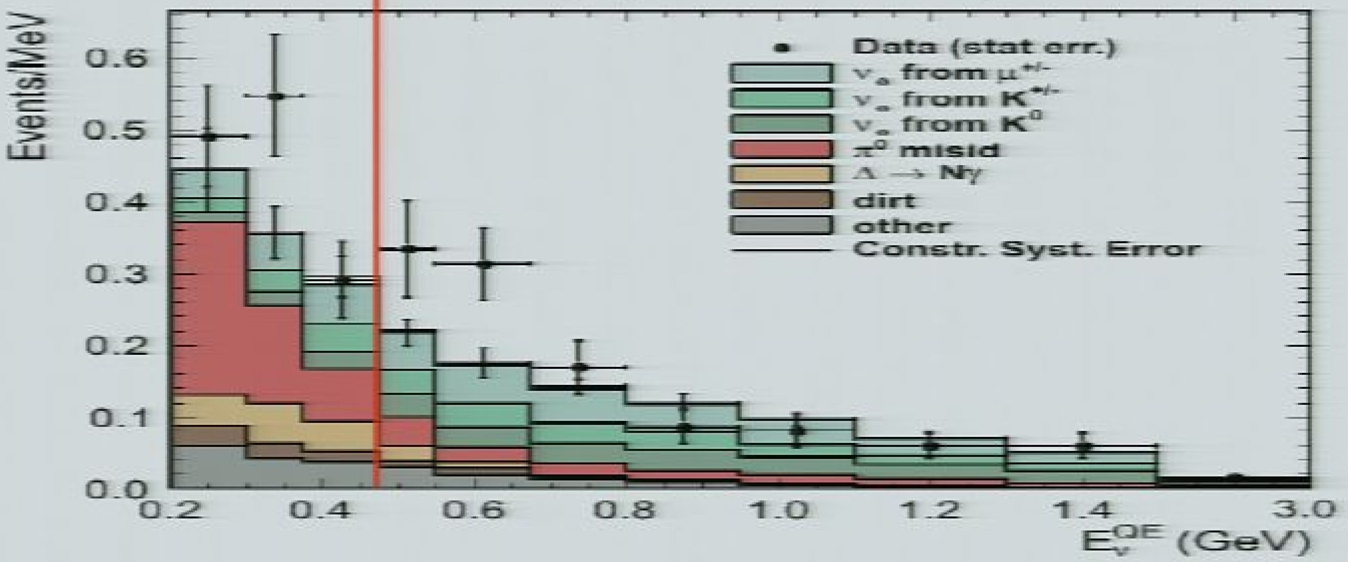


Also effects in $0\nu\beta\beta$,
tritium beta-decay,
supernova neutrino oscillations,
non-standard cosmology.

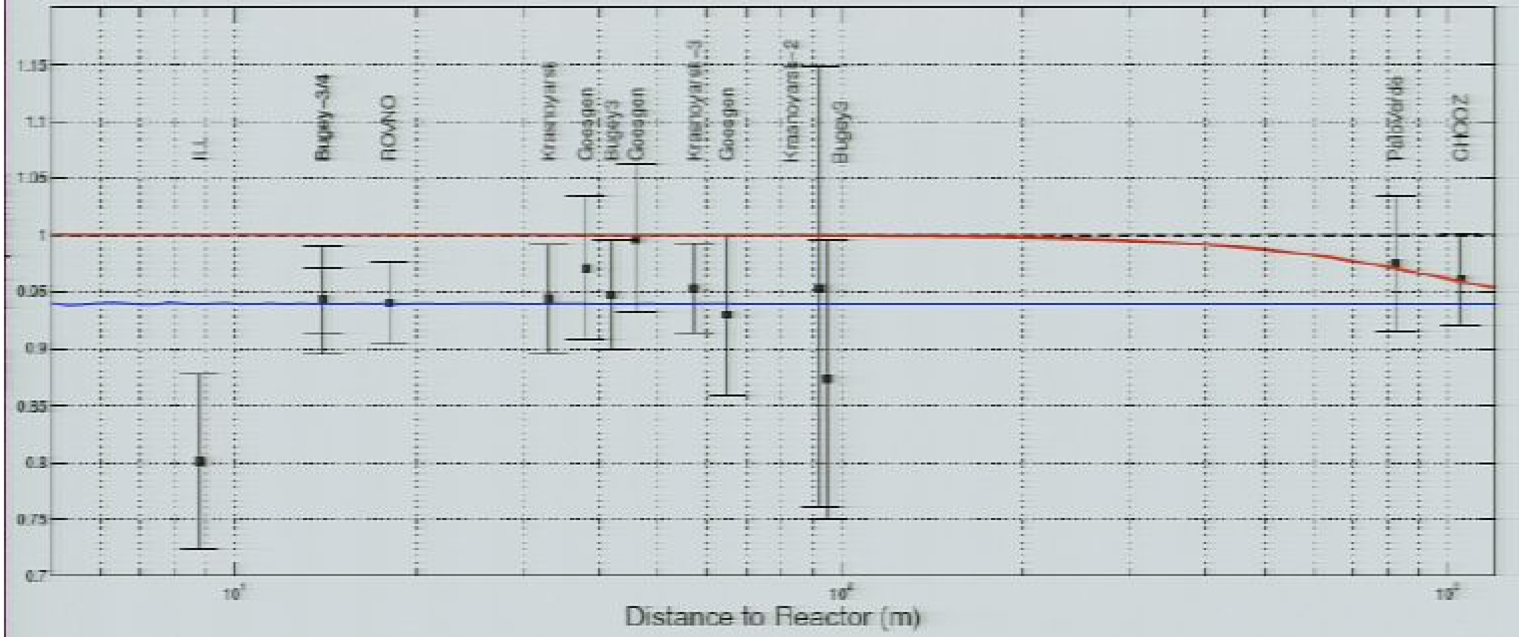
Neutrino ν_e Appearance Results (6.5E20POT)

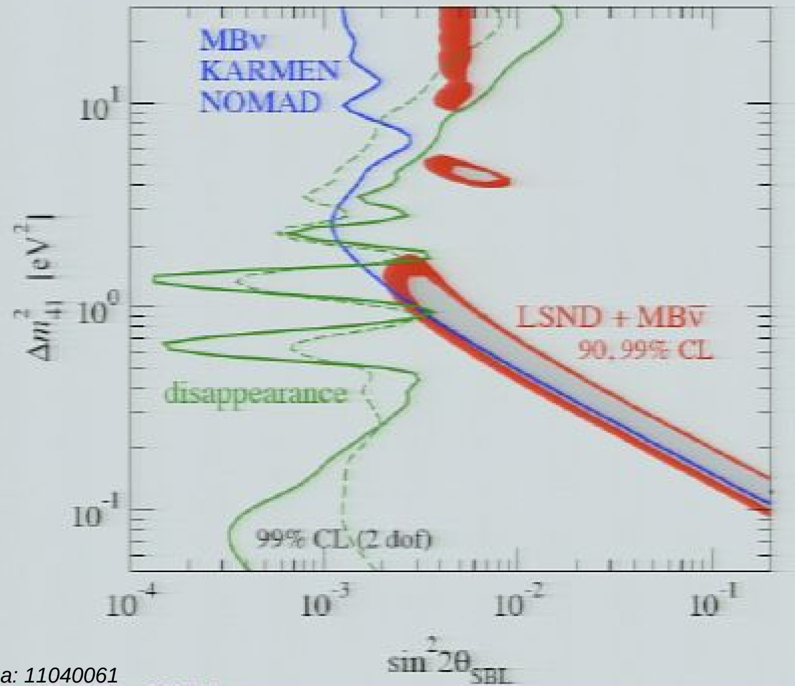


Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)



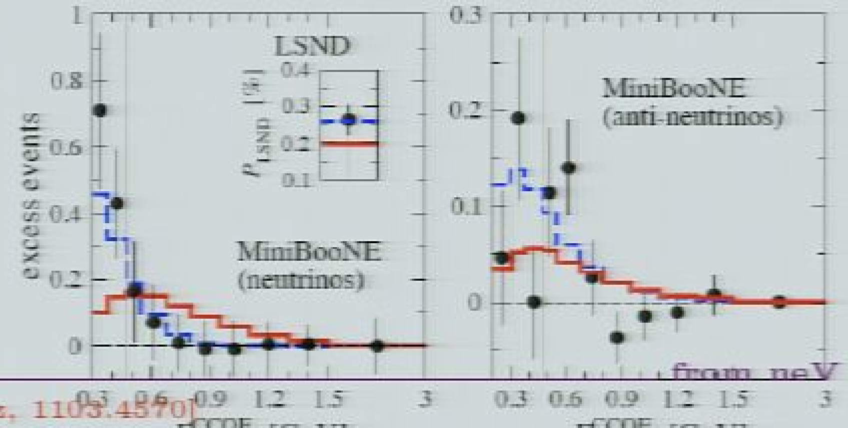
More Room For New Neutrinos?





	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).



[Kopp, Maltoni, Schwetz, 1103.4570]

igure 3: Global constraints on sterile neutrinos in the 3+1

[Kopp,Maltoni,Schwetz, 1103.4570]

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\rm PG,3+2}$/dof	25.1/5	19.9/5	19.9/4	14.7/4
$\rm PG_{3+2}$	10^{-4}	0.13%	5×10^{-4}	0.53%
$\chi^2_{\rm PG,1+3+1}$/dof	19.6/5	16.0/5	14.4/4	10.6/4
$\rm PG_{1+3+1}$	0.14%	0.7%	0.6%	3%

Table III: Compatibility of data sets [23] for 3+2 and 1+3+1 oscillations using old and new reactor fluxes.

data, although in this case the fit is slightly worse than a fit to appearance data only (dashed histograms). Note that MiniBooNE observes an event excess in the lower part of the spectrum. This excess can be explained if only appearance data are considered, but not in the global analysis including disappearance searches [8]. Therefore, we follow [19] and assume an alternative explanation for this excess, e.g. [25]. In Tab. III we show the compatibility of the LSND/MiniBooNE($\bar{\nu}$) signal with the rest of the data, as well as the compatibility of appearance and disappearance searches using the PG test from [23].

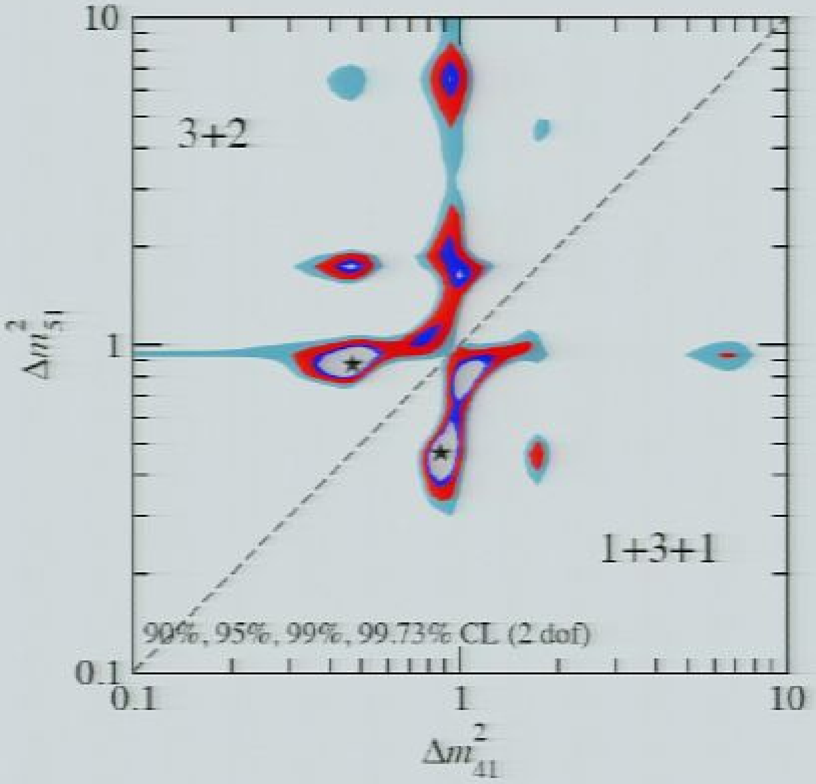
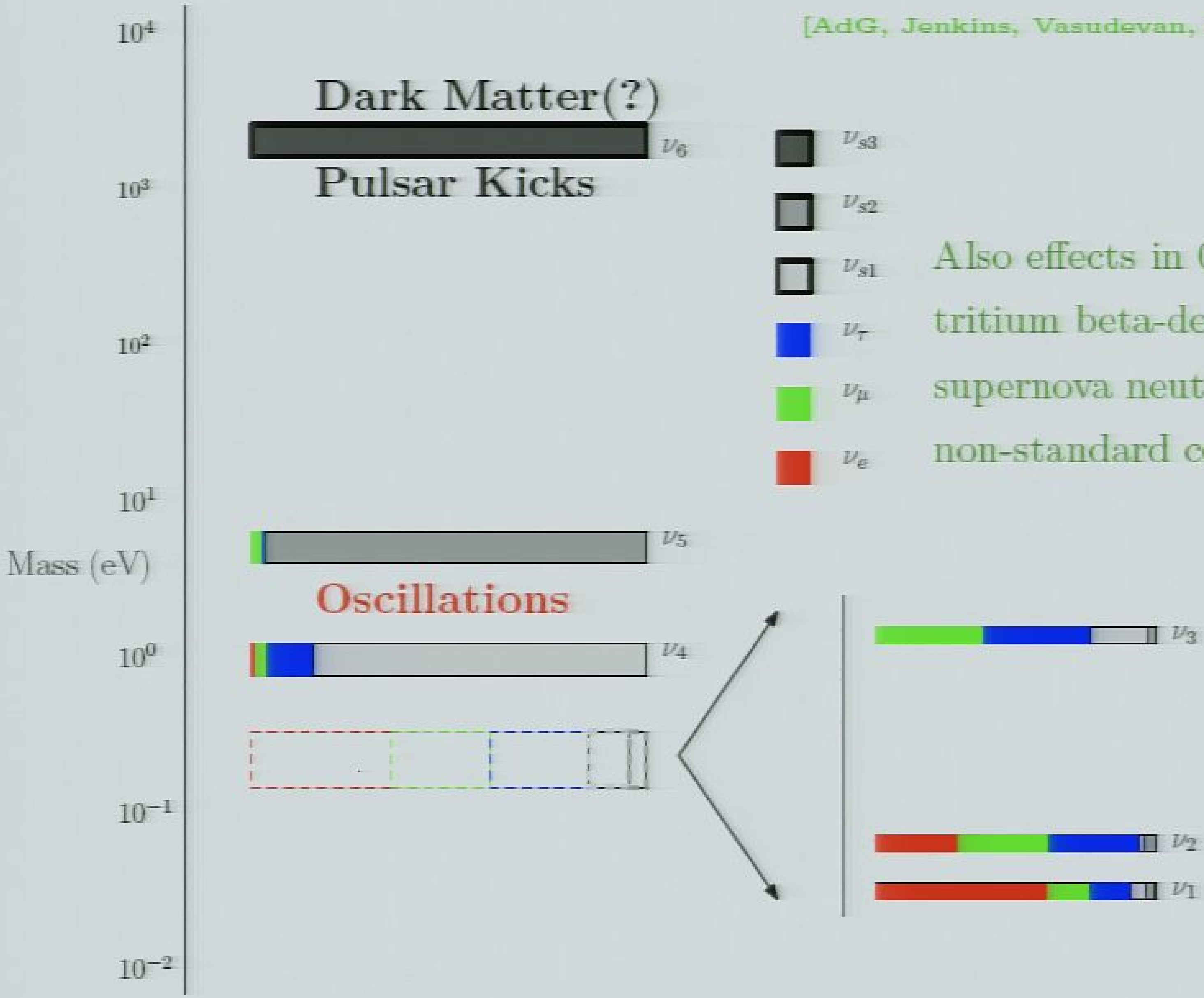


Figure 5: The globally preferred regions for the neutrino mass squared differences Δm^2_{41} and Δm^2_{51} in the 3+2 (upper left) and 1+3+1 (lower right) scenarios.

[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]



Also effects in $0\nu\beta\beta$,

tritium beta-decay,

supernova neutrino oscillations,

non-standard cosmology.

[Kopp,Maltoni,Schwetz, 1103.4570]

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\rm PG,3+2}$/dof	25.1/5	19.9/5	19.9/4	14.7/4
$\rm PG_{3+2}$	10^{-4}	0.13%	5×10^{-4}	0.53%
$\chi^2_{\rm PG,1+3+1}$/dof	19.6/5	16.0/5	14.4/4	10.6/4
$\rm PG_{1+3+1}$	0.14%	0.7%	0.6%	3%

Table III: Compatibility of data sets [23] for 3+2 and 1+3+1 oscillations using old and new reactor fluxes.

data, although in this case the fit is slightly worse than a fit to appearance data only (dashed histograms). Note that MiniBooNE observes an event excess in the lower part of the spectrum. This excess can be explained if only appearance data are considered, but not in the global analysis including disappearance searches [8]. Therefore, we follow [19] and assume an alternative explanation for this excess, e.g. [25]. In Tab. III we show the compatibility of the LSND/MiniBooNE($\bar{\nu}$) signal with the rest of the data, as well as the compatibility of appearance and disappearance searches using the PG test from [23].

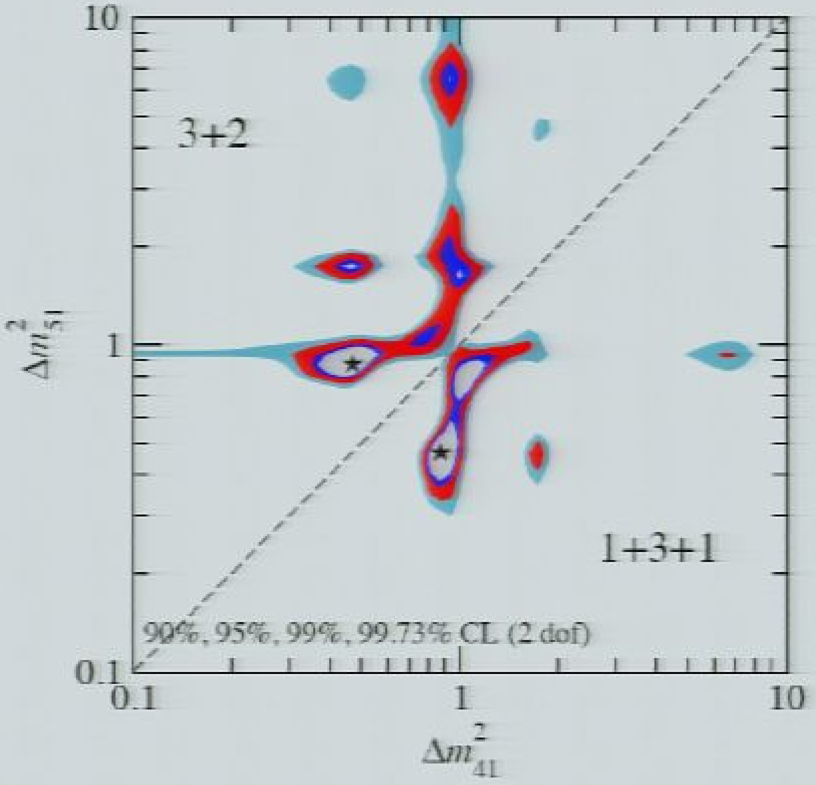
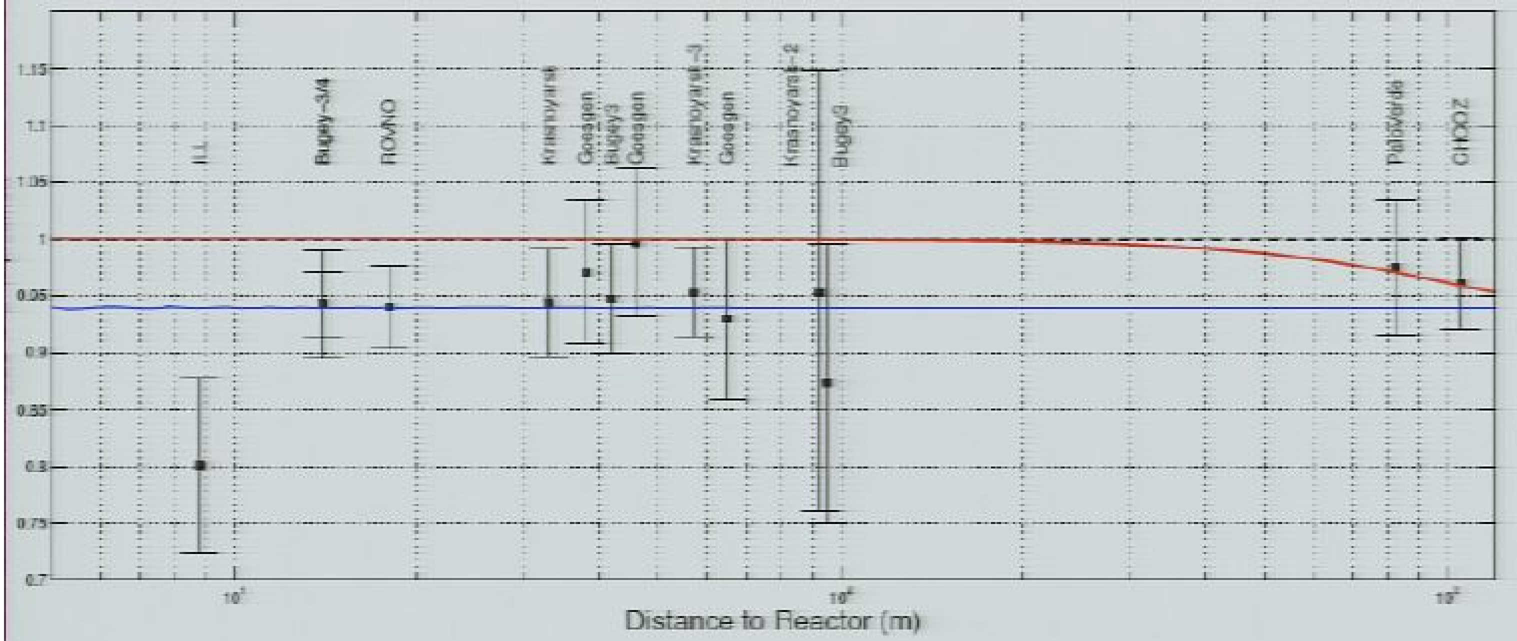
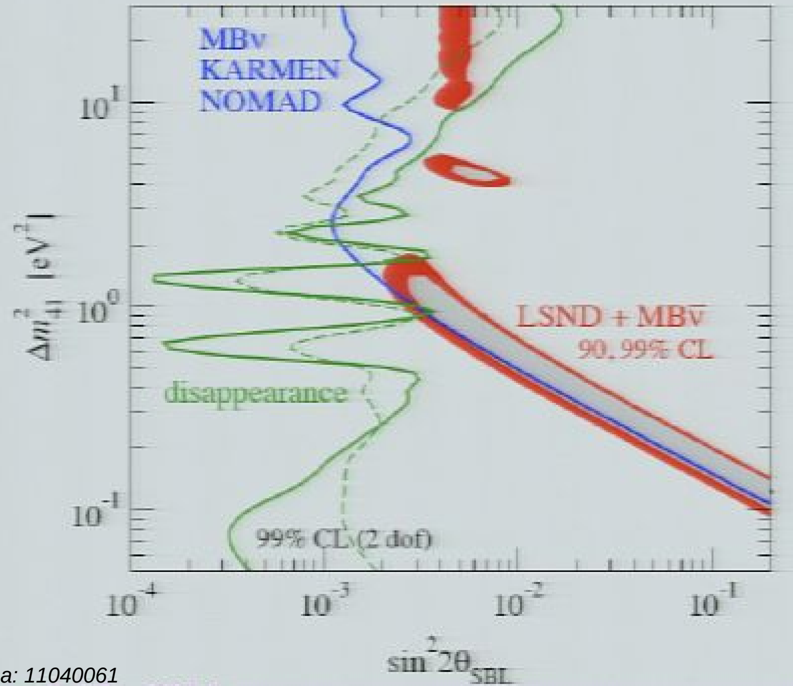


Figure 5: The globally preferred regions for the neutrino mass squared differences Δm^2_{41} and Δm^2_{51} in the 3+2 (upper left) and 1+3+1 (lower right) scenarios.

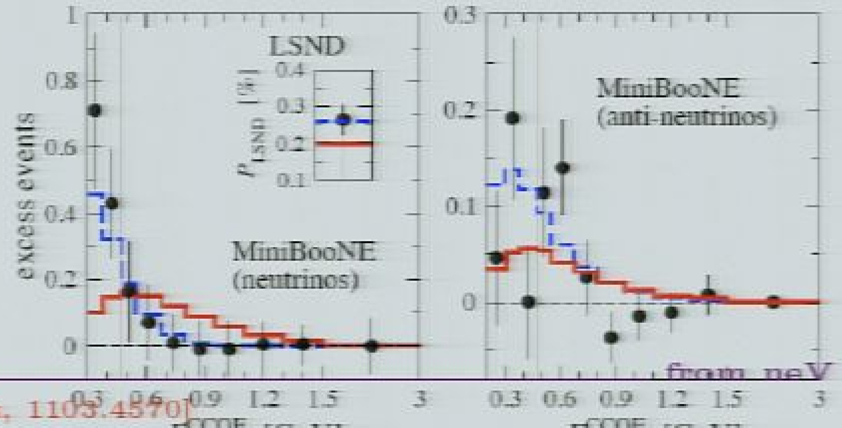
More Room For New Neutrinos?





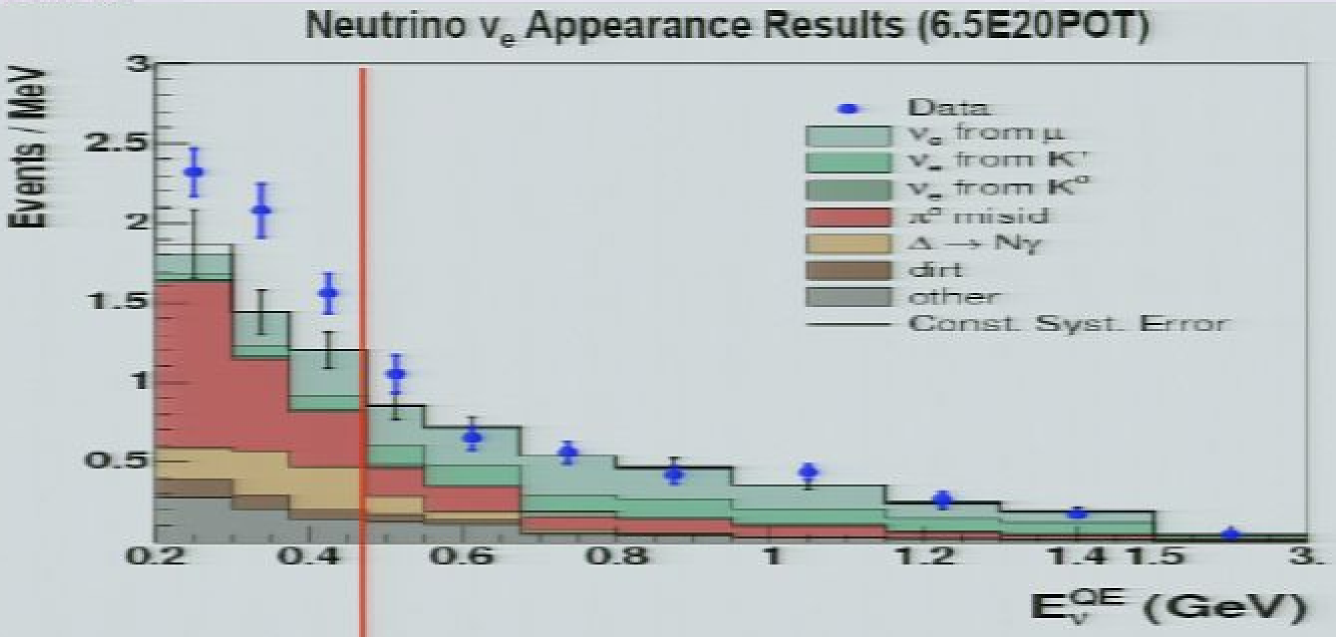
	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

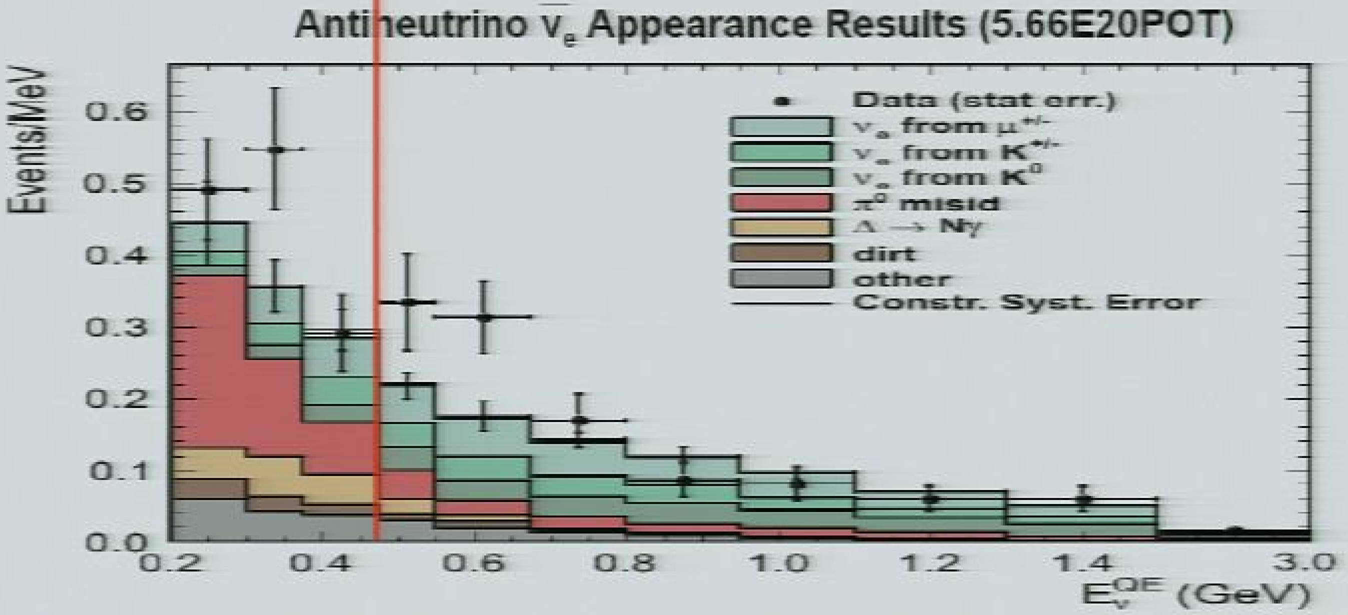
Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).



[Kopp, Maltoni, Schwetz, 1103.4570]

igure 3: Global constraints on sterile neutrinos in the 3+1


Neutrino ν_e Appearance Results (6.5E20POT)
Events / MeV
3
2.5
2
1.5
1
0.5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.5
3.
E_ν^{QE} (GeV)
Data
ν_e from μ
ν_e from K^+
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Const. Syst. Error


Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)
Events/MeV
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
3.0
E_ν^{QE} (GeV)
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error

Predictions: Neutrinoless Double-Beta Decay

The exchange of Majorana neutrinos mediates lepton-number violating neutrinoless double-beta decay, $0\nu\beta\beta$: $Z \to (Z+2)e^-e^-$.

For light enough neutrinos, the amplitude for $0\nu\beta\beta$ is proportional to the effective neutrino mass

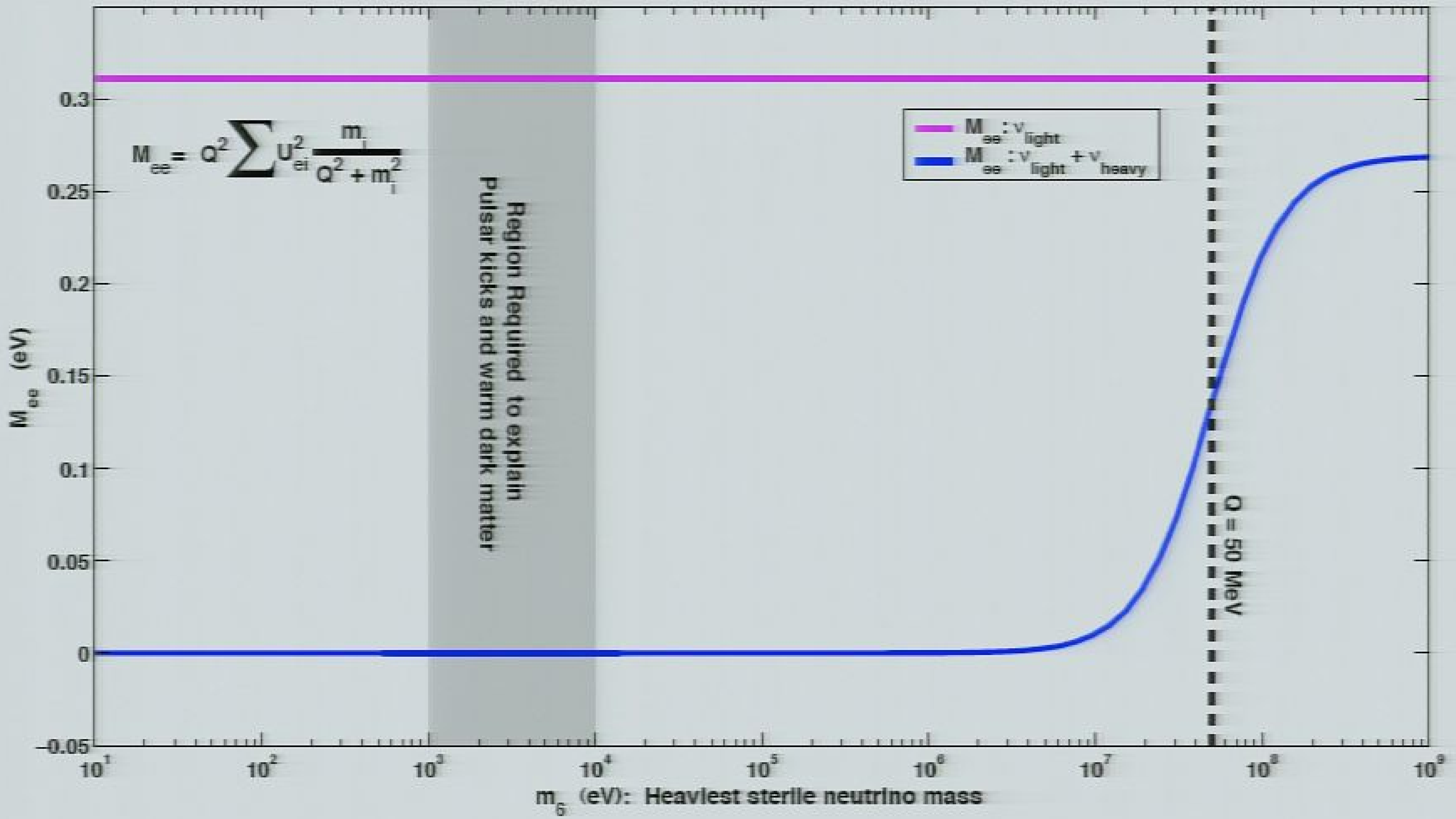
$$m_{ee} = \left|\sum_{i=1}^{6} U_{ei}^2 m_i\right| \sim \left|\sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{i=1}^{3} \vartheta_{ei}^2 M_i\right|.$$

However, upon further examination, $m_{ee} = 0$ in the eV-seesaw. **The contribution of light and heavy neutrinos exactly cancels!** This seems to remain true to a good approximation as long as $M_i \ll 1$ MeV.

$$\left[\ \mathcal{M} = \begin{pmatrix} 0 & \mu^T \\ \mu & M \end{pmatrix} \ \to \ m_{ee} \text{ is identically zero!}\ \right]$$

(lack of) sensitivity in $0\nu\beta\beta$ due to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



Predictions: Neutrinoless Double-Beta Decay

The exchange of Majorana neutrinos mediates lepton-number violating neutrinoless double-beta decay, $0\nu\beta\beta$: $Z \to (Z+2)e^- e^-$.

For light enough neutrinos, the amplitude for $0\nu\beta\beta$ is proportional to the effective neutrino mass

$$m_{ee} = \left|\sum_{i=1}^{6} U_{ei}^2 m_i\right| \sim \left|\sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{i=1}^{3} \vartheta_{ei}^2 M_i\right| .$$

However, upon further examination, $m_{ee} = 0$ in the eV-seesaw. **The contribution of light and heavy neutrinos exactly cancels!** This seems to remain true to a good approximation as long as $M_i \ll 1$ MeV.

$$\left[\mathcal{M} = \begin{pmatrix} 0 & \mu^{\mathrm{T}} \\ \mu & M \end{pmatrix} \rightarrow m_{ee} \text{ is identically zero!} \right]$$

Predictions: Tritium beta-decay

Heavy neutrinos participate in tritium β-decay. Their contribution can be parameterized by

$$m_\beta^2 = \sum_{i=1}^{6} |U_{ei}|^2 m_i^2 \simeq \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 + \sum_{i=1}^{3} |U_{ei}|^2 m_i M_i,$$

as long as M_i is not too heavy (above tens of eV). For example, in the case of a 3+2 solution to the LSND anomaly, the heaviest sterile state (with mass M_1) contributes the most: $m_\beta^2 \simeq 0.7~\text{eV}^2 \left(\frac{|U_{e1}|^2}{0.7}\right)\left(\frac{m_1}{0.1~\text{eV}}\right)\left(\frac{M_1}{10~\text{eV}}\right)$.

NOTE: next generation experiment (KATRIN) will be sensitive to $O(10^{-1})$ eV^2.

On Early Universe Cosmology / Astrophysics

A combination of the SM of particle physics plus the "concordance cosmological model" severely constrain light, sterile neutrinos with significant active-sterile mixing. Taken at face value, not only is the eV-seesaw ruled out, but so are all oscillation solutions to the LSND anomaly.

Hence, **eV-seesaw → nonstandard particle physics and cosmology**.

On the other hand…

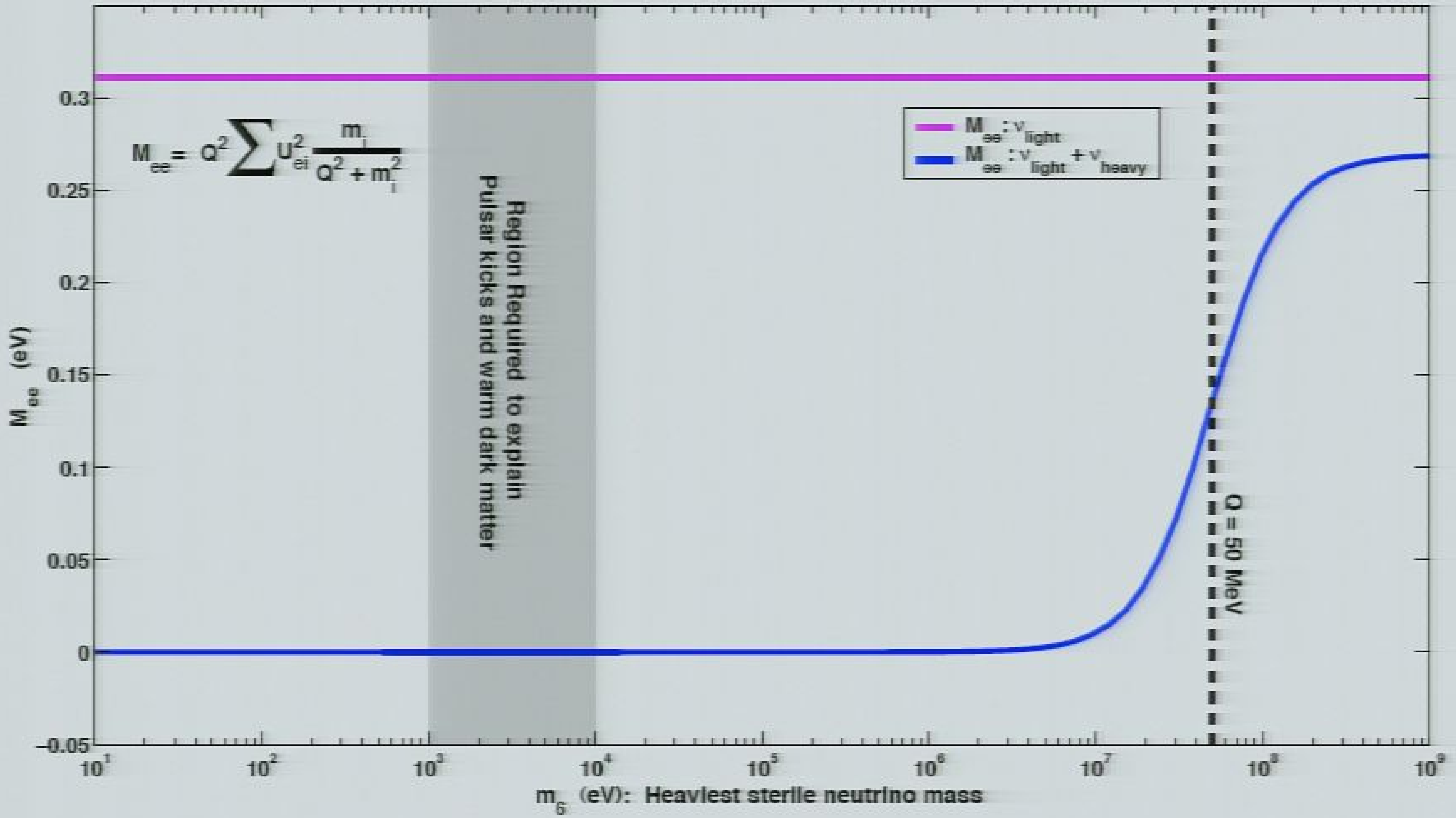
- Right-handed neutrinos may make good warm dark matter particles.

  Asaka, Blanchet, Shaposhnikov, hep-ph/0503065.

- Sterile neutrinos are known to help out with r-process nucleosynthesis in supernovae, …
- …and may help explain the peculiar peculiar velocities of pulsars.

(lack of) sensitivity in $0\nu\beta\beta$ due to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



On Early Universe Cosmology / Astrophysics

A combination of the SM of particle physics plus the "concordance cosmological model" severely constrain light, sterile neutrinos with significant active-sterile mixing. Taken at face value, not only is the eV-seesaw ruled out, but so are all oscillation solutions to the LSND anomaly.

Hence, **eV-seesaw → nonstandard particle physics and cosmology**.

On the other hand. . .

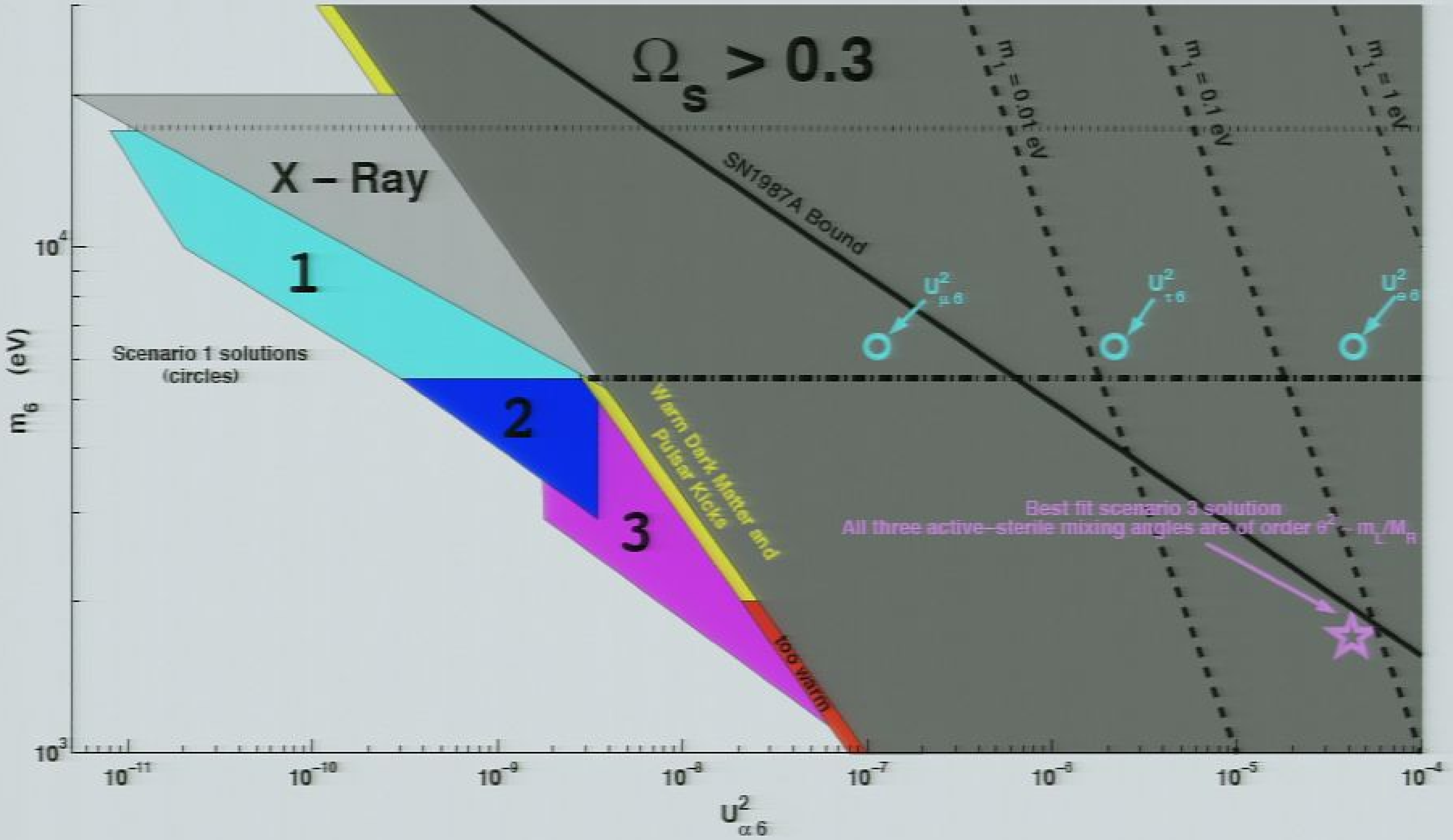
- Right-handed neutrinos may make good warm dark matter particles.

Asaka, Blanchet, Shaposhnikov, hep-ph/0503065.

- Sterile neutrinos are known to help out with r-process nucleosynthesis in supernovae, . . .
- . . . and may help explain the peculiar peculiar velocities of pulsars.

On Astrophysical / Cosmological Bounds

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



What if 1 GeV$< M <$1 TeV?

Naively, one expects

$$\Theta \sim \sqrt{\frac{m_a}{M}} < 10^{-5}\sqrt{\frac{1\text{ GeV}}{M}},$$

such that, for $M = 1$ GeV and above, sterile neutrino effects are mostly negligible.

However,

$$\Theta = V\sqrt{\text{diag}(m_1, m_2, m_3)}R^{\dagger}M^{-1/2},$$

and the magnitude of the entries of R can be arbitrarily large [$\cos(ix) = \cosh x \gg 1$ if $x > 1$].

This is true as long as

- $\lambda v \ll M$ (seesaw approximation holds)
- $\lambda < 4\pi$ (theory is "well-defined")

This implies that, in principle, Θ is a quasi-free parameter – independent from light neutrino masses and mixing – as long as $\Theta \ll 1$ and $M < 1$ TeV.

What Does $R \gg 1$ Mean?

It is illustrative to consider the case of one active neutrino of mass m_3 and two sterile ones, and further assume that $M_1 = M_2 = M$. In this case,

$$\begin{aligned} \Theta &= \sqrt{\frac{m_3}{M}} \begin{pmatrix} \cos\zeta & \sin\zeta \end{pmatrix}, \\ \lambda v &= \sqrt{m_3 M} \begin{pmatrix} \cos\zeta^* & \sin\zeta^* \end{pmatrix} \equiv \begin{pmatrix} \lambda_1 & \lambda_2 \end{pmatrix}. \end{aligned}$$

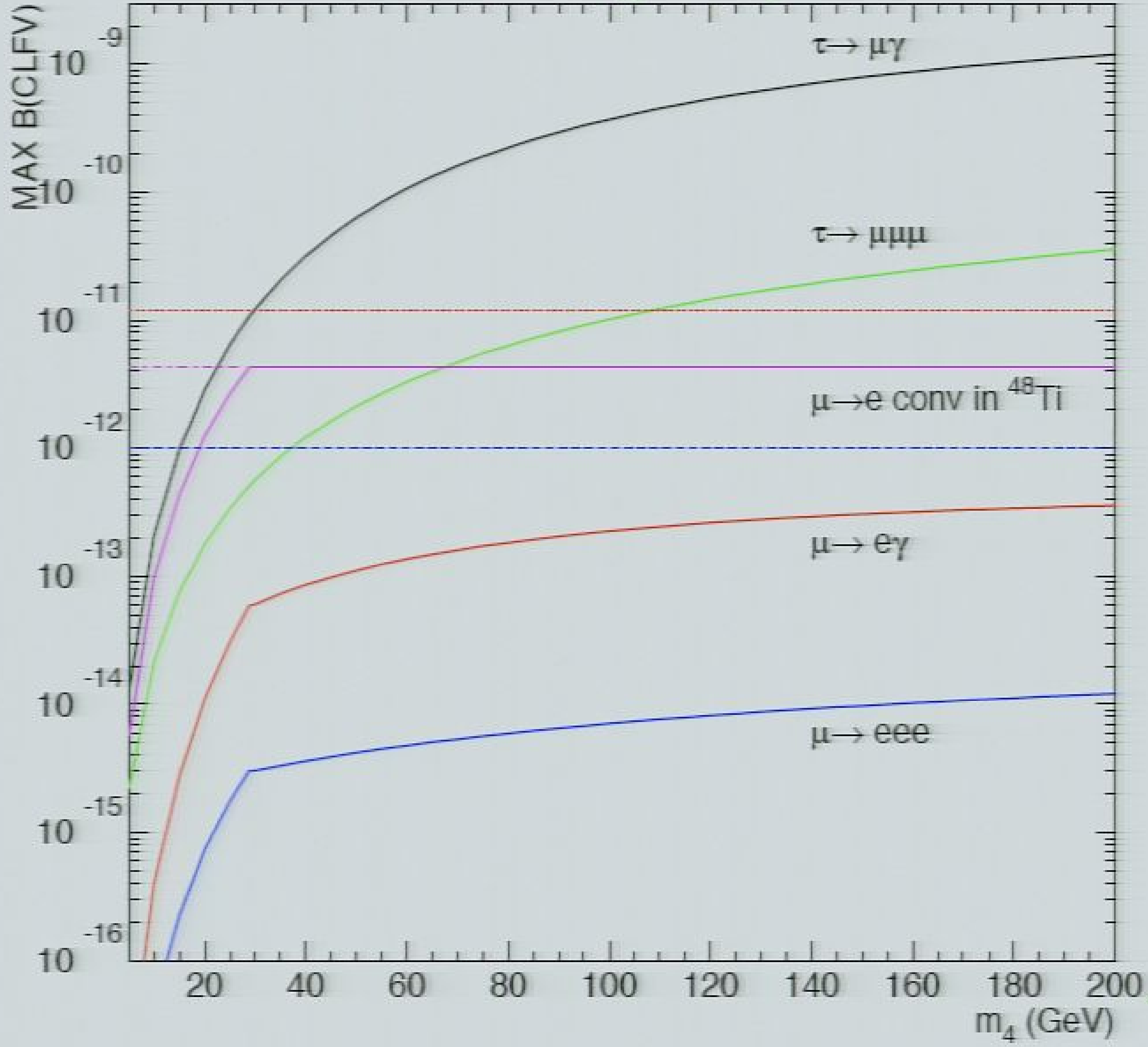
If ζ has a large imaginary part $\Rightarrow \Theta$ is (exponentially) larger than $(m_3/M)^{1/2}$, λ_i neutrino Yukawa couplings are much larger than $\sqrt{m_3 M}/v$

The reason for this is a strong cancellation between the contribution of the two different Yukawa couplings to the active neutrino mass
$\Rightarrow$ $m_3 = \lambda_1^2 v^2/M + \lambda_2^2 v^2/M$.

For example: $m_3 = 0.1$ eV, $M = 100$ GeV, $\zeta = 14i \Rightarrow \lambda_1 \sim 0.244, \lambda_2 \sim -0.244i$, while $|y_1| - |y_2| \sim 3.38 \times 10^{-13}$.

NOTE: cancellation may be consequence of a symmetry (say, lepton number). See, for example, the "inverse seesaw" Mohapatra and Valle, PRD34, 1642 (1986).

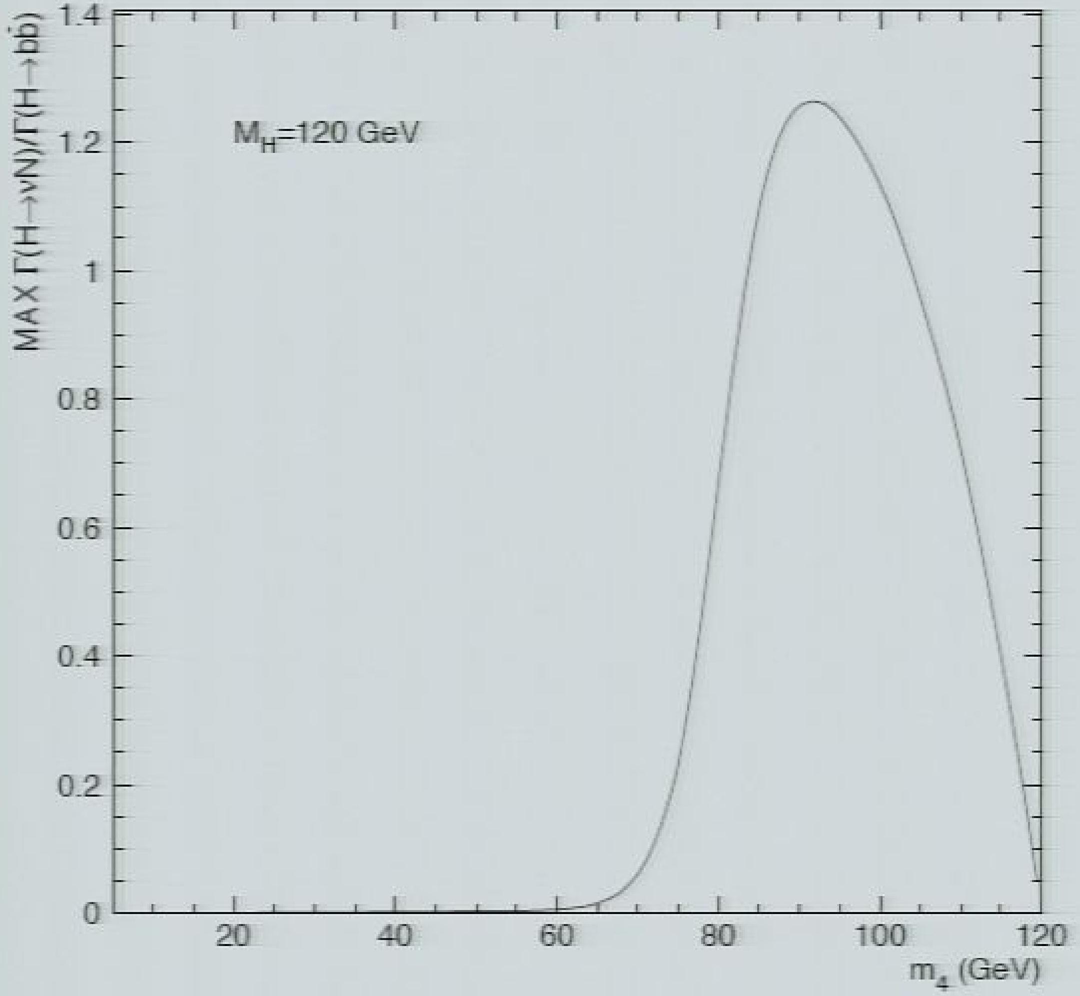
Constraints From Charged Lepton Flavor Violation



arXiv:0706.1732 [hep-ph]

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless…

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

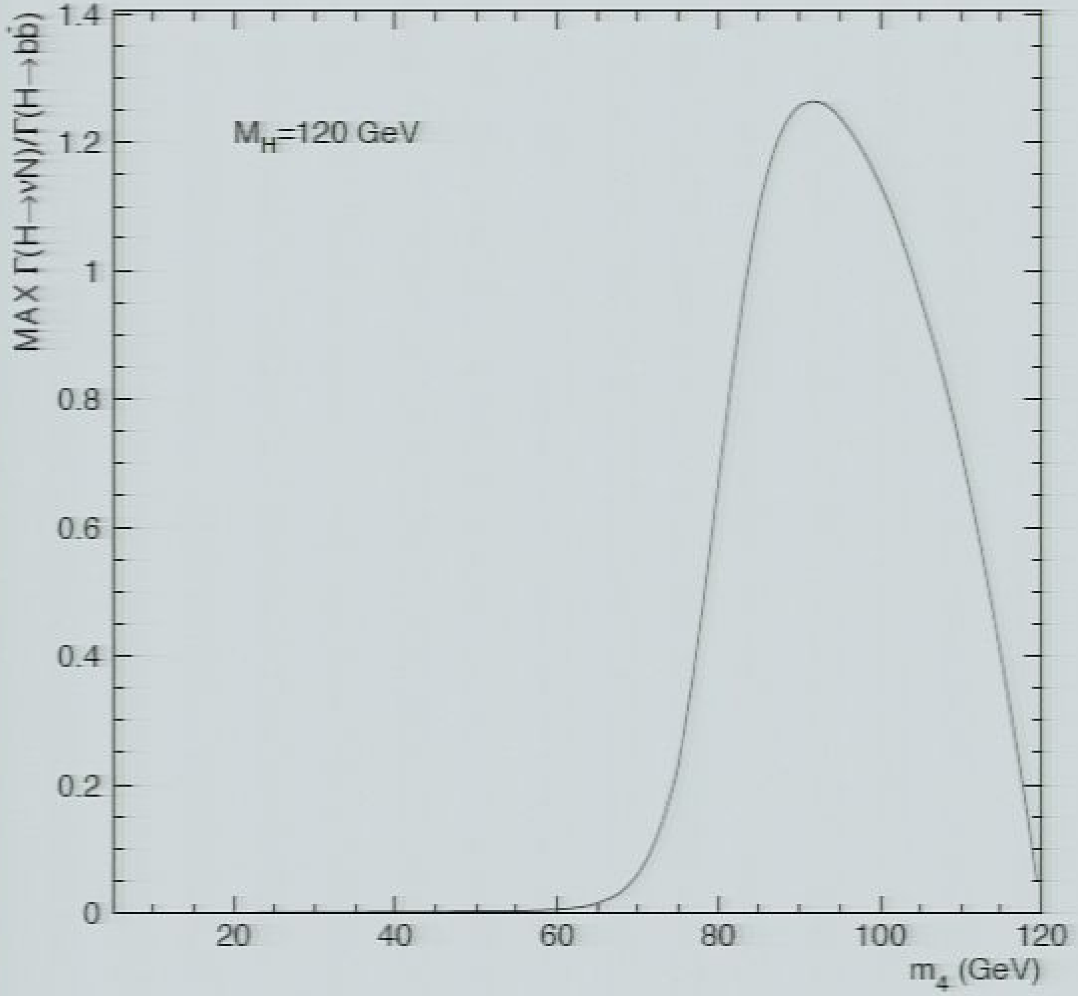
$\Leftarrow$ $H \to \nu N$ as likely as $H \to b\bar{b}$!

$\Big($NOTE: $N \to \ell q' \bar{q}$ or $\ell \ell' \nu$ (prompt)
"Weird" Higgs decay signature! $\Big)$

[+ Lepton Number Violation at Colliders?]

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless…

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

$\Leftarrow$ $H \to \nu N$ as likely as $H \to b\bar{b}$!

$\big($NOTE: $N \to \ell q'\bar{q}$ or $\ell\ell'\nu$ (prompt)

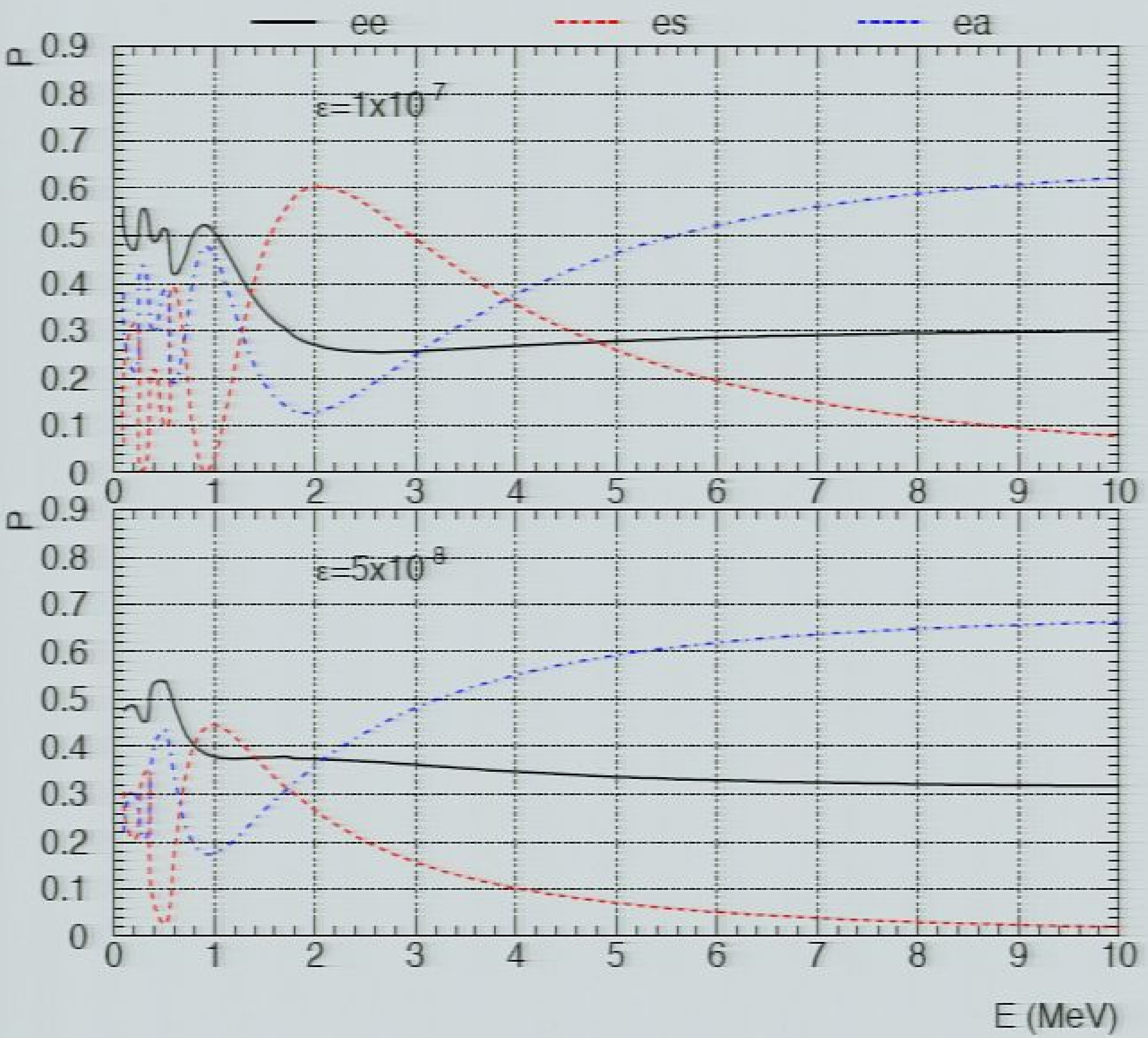
"Weird" Higgs decay signature! $\big)$

[+ Lepton Number Violation at Colliders?]

Going All the Way: What Happens When $M \ll \mu$?

In this case, the six Weyl fermions pair up into three quasi-degenerate states ("quasi-Dirac fermions").

These states are fifty–fifty active–sterile mixtures. In the limit $M \to 0$, we end up with Dirac neutrinos, which are clearly allowed by all the data.

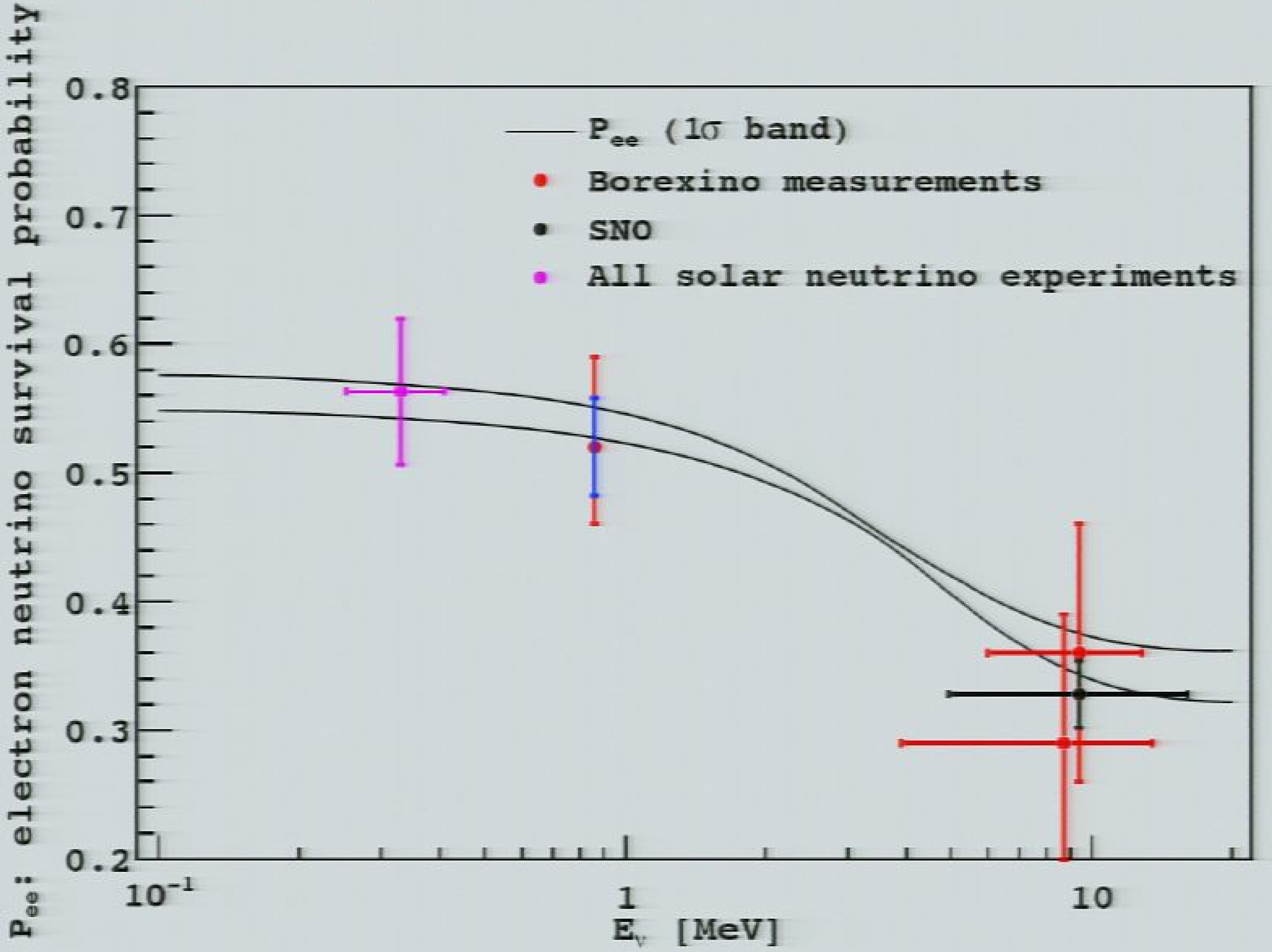


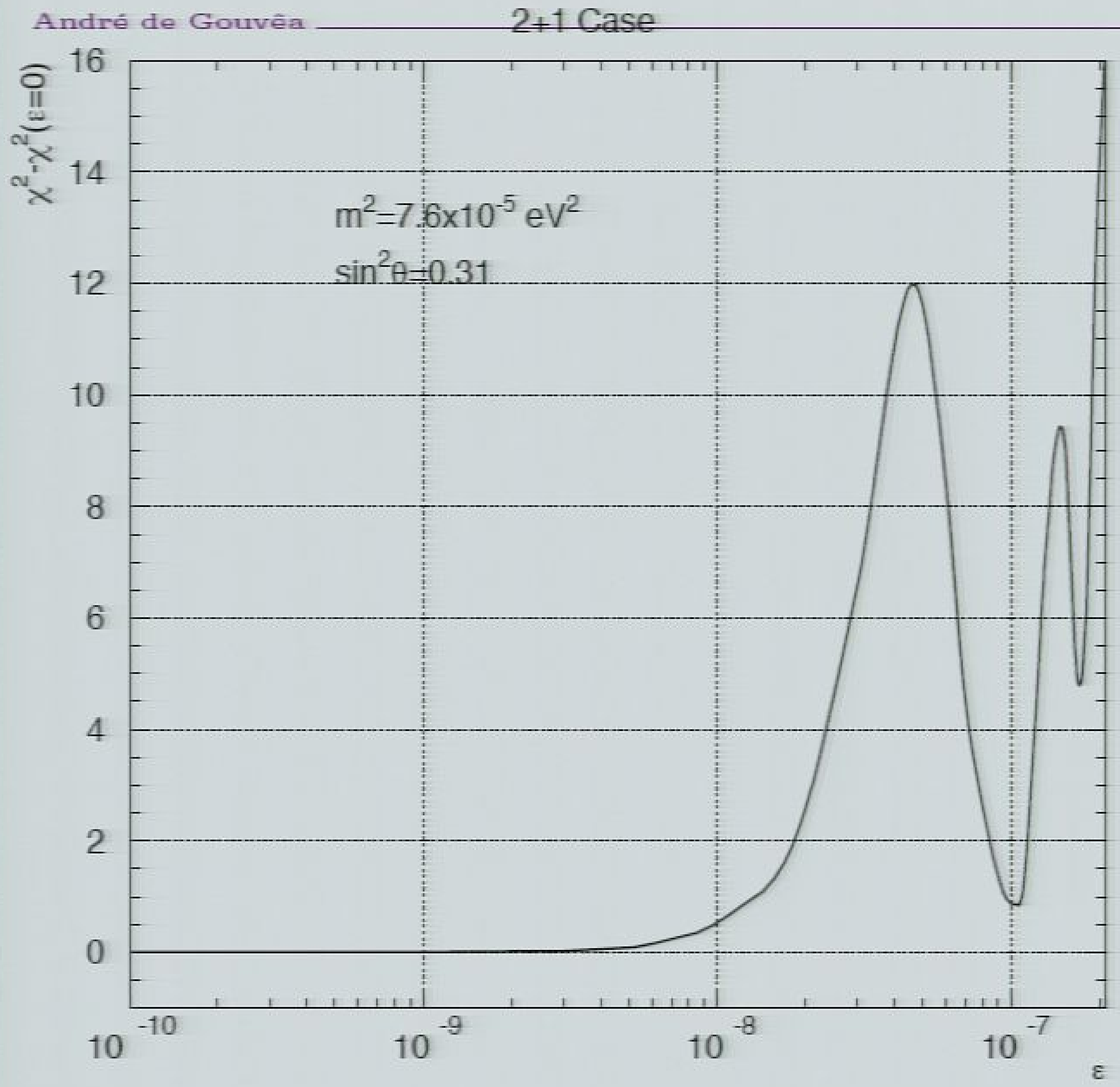
Quasi-Sterile Neutrinos

- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
- maximal mixing!
- Effects in Solar νs

[AdG, Huang, Jenkins, arXiv:0906.1611]

(Almost) All We Know About Solar Neutrinos



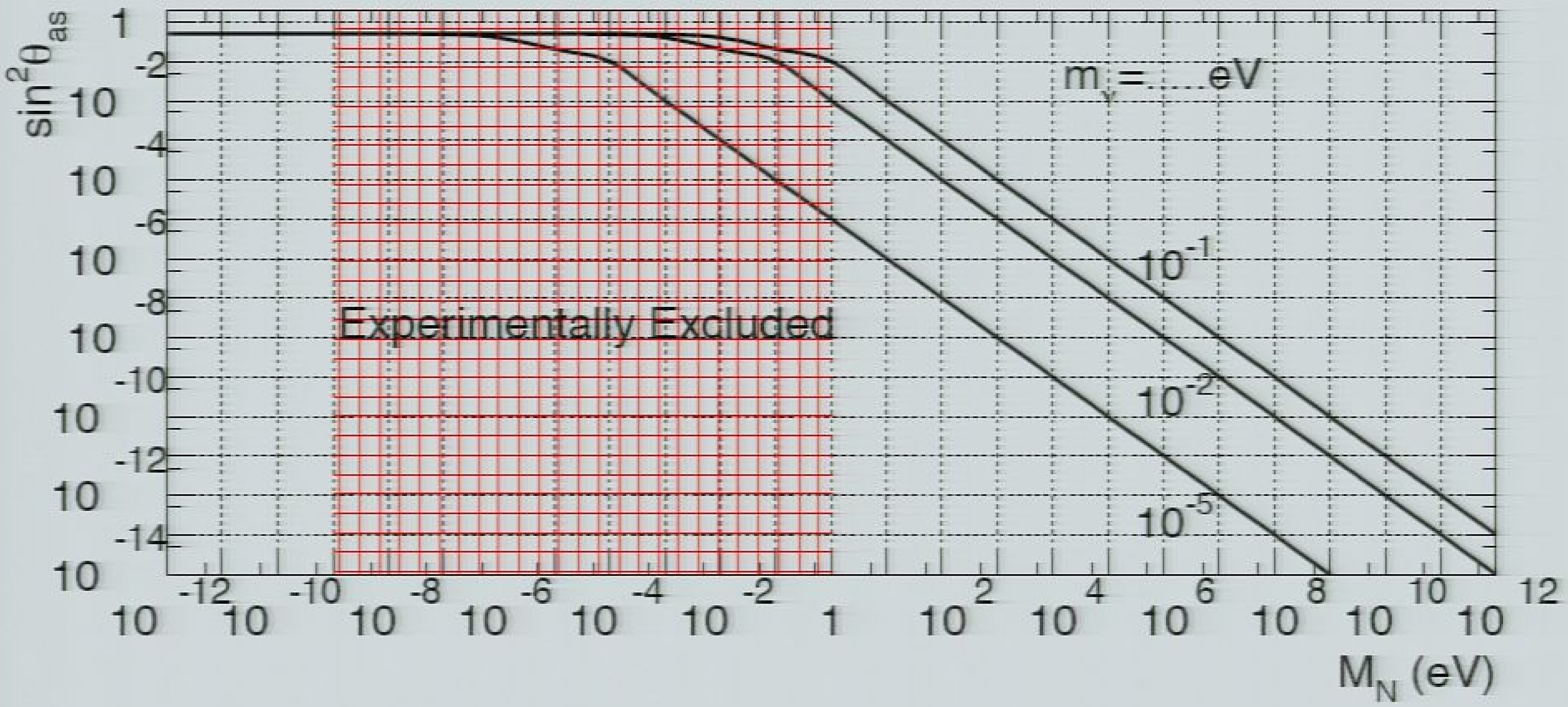


[AdG, Huang, Jenkins, arXiv:0906.1611]

Quasi-Sterile Neutrinos

- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
- maximal mixing!
- Effects in Solar νs

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

Fourth Avenue: Higher Order Neutrino Masses from $\Delta L = 2$ Physics.

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, in general, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

For example:

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee model – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen, *et al.* 0706.1964 – neutrino masses at two loops;
- etc

[arXiv:0708.1344 [hep-ph]]

Order-One Coupled, Weak Scale Physics

Can Also Explain Naturally Small

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;
  ($\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc)
- searches for lepton number violation;
  (neutrinoless double beta decay, etc)
- neutrino oscillation experiments;
  (Daya Bay, NOνA, etc)
- searches for fermion electric/magnetic dipole moments
  (electron edm, muon $g-2$, etc);

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;

  ($\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc)
- searches for lepton number violation;

  (neutrinoless double beta decay, etc)
- neutrino oscillation experiments;

  (Daya Bay, NOνA, etc)
- searches for fermion electric/magnetic dipole moments

  (electron edm, muon $g-2$, etc);

- precision studies of neutrino – matter interactions;

  (Minerνa, NuSOnG, etc)

- collider experiments:

  (LHC, etc)

  - *Can* we "see" the physics responsible for neutrino masses at the LHC? – YES!
    Must we see it? – NO, but we won't find out until we try!
  - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

CONCLUSIONS

1. we have a very successful parametrization of the neutrino sector, but we still don't understand where neutrino masses (and lepton mixing) come from;
2. neutrino masses are very small – we don't know why, but we think it means something important;
3. we need a minimal νSM Lagrangian. In order to decide which one is "correct" we must uncover the faith of baryon number minus lepton number ($0\nu\beta\beta$ is the best bet? Likely, but not guaranteed).

4. We know very little about the new physics uncovered by neutrino oscillations.
   - It could be renormalizable → "boring" Dirac neutrinos
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV → high energy seesaw. How can we ever convince ourselves that this is correct?
   - It could be due to very light new physics → low energy seesaw. Prediction: new light propagating degrees of freedom – sterile neutrinos
   - It could be due to new physics at the TeV scale → either weakly coupled, or via a more subtle lepton number breaking sector. Predictions: charged lepton flavor violation, collider signatures!
5. We need more experimental data in order to decide what is really going on!

Backup Slides . . .

4. We know very little about the new physics uncovered by neutrino oscillations.
   - It could be renormalizable → "boring" Dirac neutrinos
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV → high energy seesaw. How can we ever convince ourselves that this is correct?
   - It could be due to very light new physics → low energy seesaw. Prediction: new light propagating degrees of freedom – sterile neutrinos
   - It could be due to new physics at the TeV scale → either weakly coupled, or via a more subtle lepton number breaking sector. Predictions: charged lepton flavor violation, collider signatures!
5. We need more experimental data in order to decide what is really going on!