

Georg Raffelt, Max-Planck-Institut für Physik, München

# Neutrino Physics in Heaven



New Views of the Universe, 9-13 Dec 2005, Chicago  
Kavli Institute Inaugural Symposium in Honor of David Schramm



# 75 Jahre Neutrino

## 4. Dezember 1930: Postulat des Neutrinos

Physikalisches Institut der  
Eidgenössische Technische Hochschule  
Zürich

Offener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen  
Zürich, 4. Dezember 1930

Liebe Radioaktive Damen und Herren,

wie der Überbringer dieser Zeilen, den ich huldvollst  
anzuhören bitte, Ihnen des näheren auseinandersetzen wird,  
bin ich angesichts der 'falschen' Statistik der N- und Li  
6-Kerne, sowie des kontinuierlichen  $\beta$ -Spektrums auf einen  
verzweifelten Ausweg verfallen, um den 'Wechselsatz' der  
Statistik und den Energiesatz zu retten. Nämlich die  
Möglichkeit, es könnten elektrisch neutrale Teilchen, die  
ich Neutronen nenne will, in den Kernen existieren, welche  
den Spin 1/2 tragen und das Ausschließungsprinzip befolgen  
und sich von Lichtquanten außerdem noch dadurch unterscheiden,  
daß sie nicht mit Lichtgeschwindigkeit laufen.  
Die Masse der Neutronen müsste von derselben Größenordnung  
wie die Elektronenmasse sein und jedenfalls nicht größer  
als 0,01 Protonenmasse.  
Das kontinuierliche  $\beta$ -Spektrum wäre dann verständlich unter  
der Annahme, daß beim  $\beta$ -Zerfall mit dem Elektron jeweils  
noch ein Neutron emittiert wird, derart, daß die Summe der  
Energien von Neutron und Elektron konstant ist ...

Ich traue mich vorläufig aber nicht, etwas über diese Idee  
zu publizieren, und wende mich erst vertrauensvoll an Euch,  
liebe Radioaktive, mit der Frage, wie es um den experimentellen  
Nachweis eines solchen Neutrons stände, wenn dieses  
ebensolches oder etwas 10mal größeres Durchdringungsvermögen  
besitzen würde wie ein  $\gamma$ -Strahl.

Ich gebe zu, daß mein Ausweg vielleicht von vornherein  
wenig wahrscheinlich erscheinen mag die Neutronen, wenn  
sie existieren, wohl längst gesehen hätte. Aber nur wer  
wagt gewinnt, und der Ernst der Situation beim kontinuierlichen  
 $\beta$ -Spektrum wird durch einen Ausspruch meines verehrten  
Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich  
in Brüssel gesagt hat: 'O, daran soll man am besten gar  
nicht denken, so wie an die neuen Steuern.' Darum soll man  
jeden Weg zur Rettung ernstlich diskutieren.

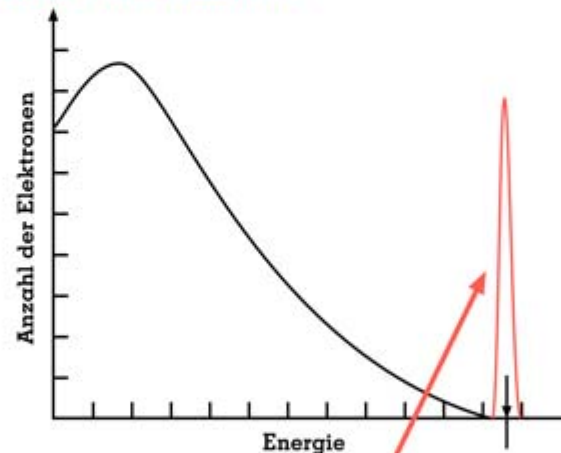
Also, liebe Radioaktive, prüfet und richtet.

Leider kann ich nicht persönlich in Tübingen erscheinen,  
da ich infolge eines in der Nacht vom 6. zum 7. Dez. in  
Zürich stattfindenden Balles hier unabkömmlich bin.

Mit vielen Grüßen an Euch,  
Euer untertänigster Diener,

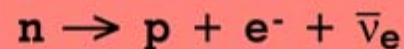
W. Pauli

Um das Energiespektrum von Elektronen aus dem  $\beta$ -Zerfall zu erklären, nimmt Pauli an, dass ein drittes, unsichtbares Teilchen emittiert wird. In seinem berühmten Brief vom 4.12.1930 („Liebe Radioaktive Damen und Herren“) präsentiert er diese Idee der Fachwelt.



Erwartung für zwei Teilchen  
im Endzustand

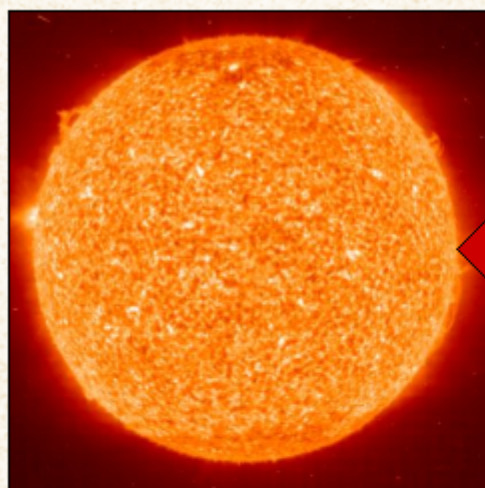
Es sind aber drei!



Wolfgang Pauli



# Sun Glasses for Neutrinos?



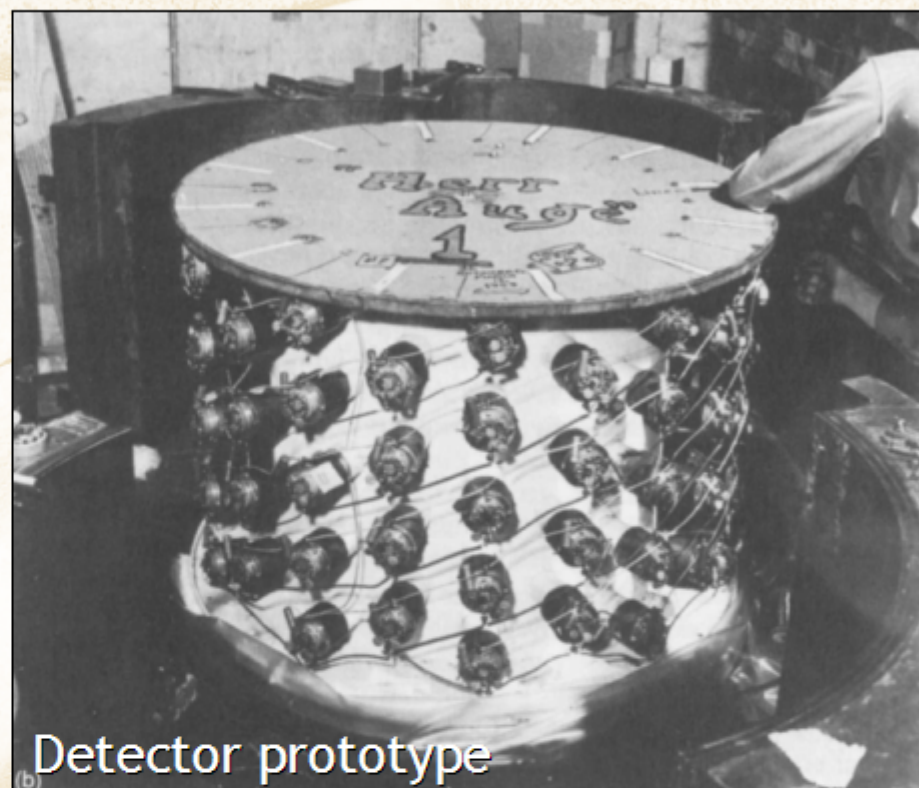
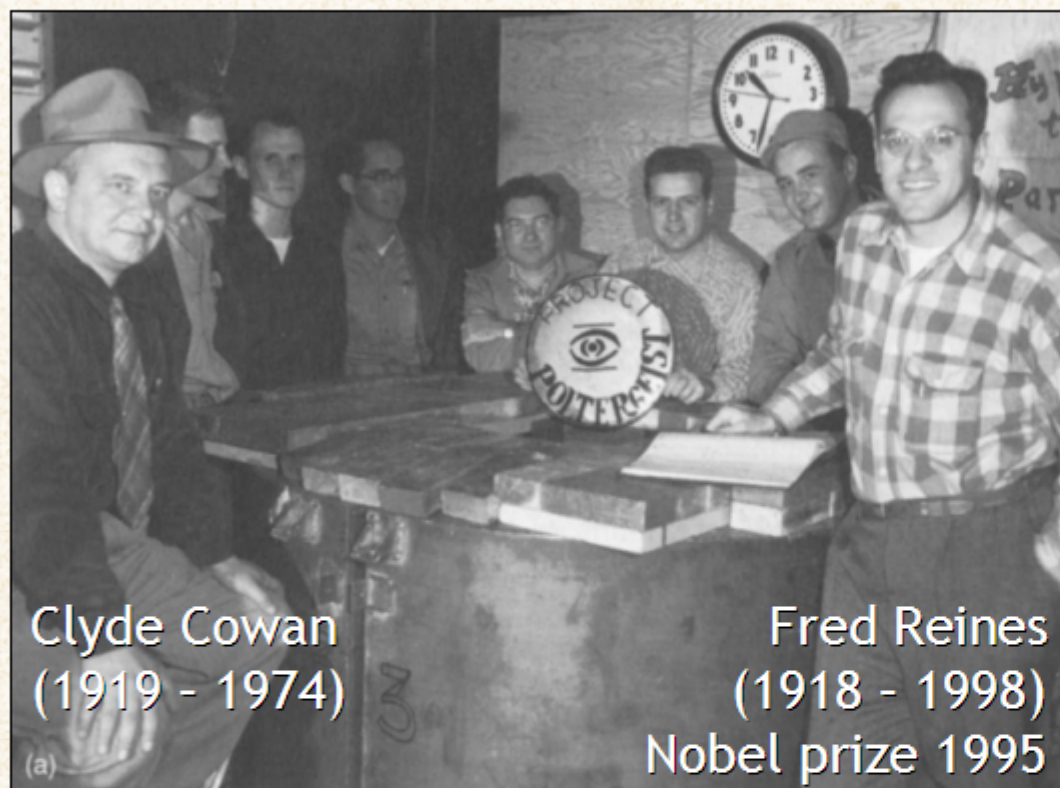
**1000 light years of lead  
needed to shield solar  
neutrinos**

**Bethe & Peierls 1934:  
“... this evidently means  
that one will never be able  
to observe a neutrino.”**

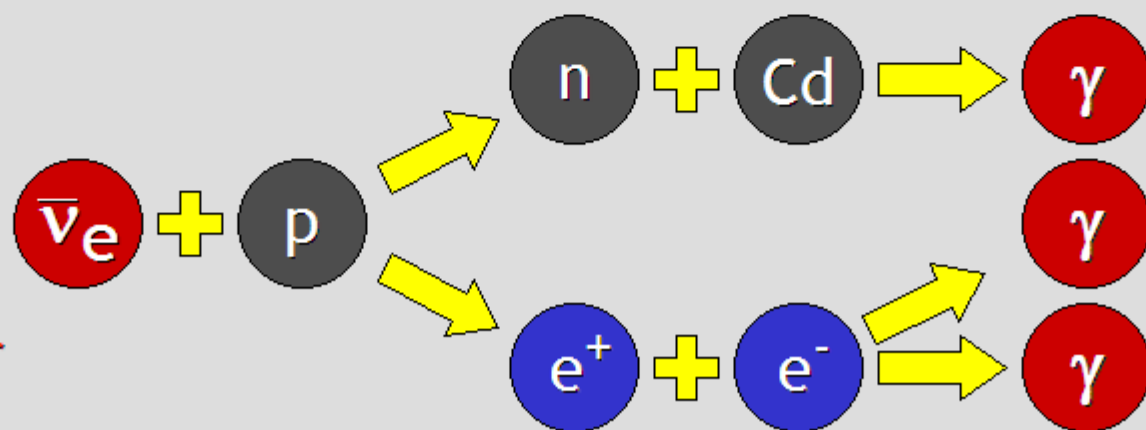




# First Detection (1954 - 1956)



Anti-Electron  
Neutrinos  
from  
Hanford  
Nuclear Reactor



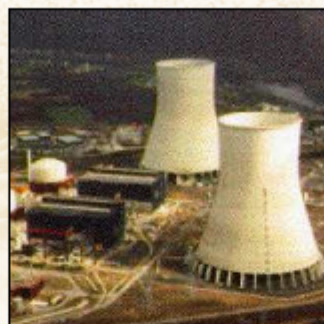
3 Gammas  
in coincidence



# Where do Neutrinos Appear in Nature?



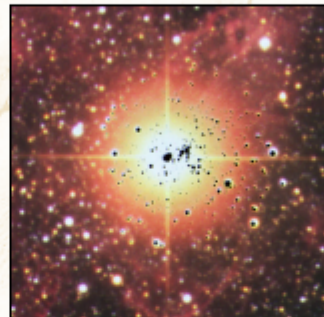
Nuclear Reactors



Sun



Particle Accelerators

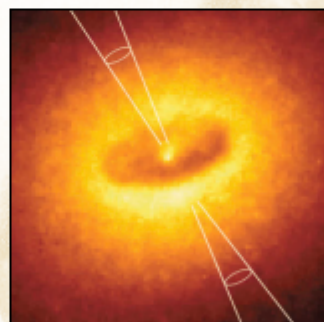
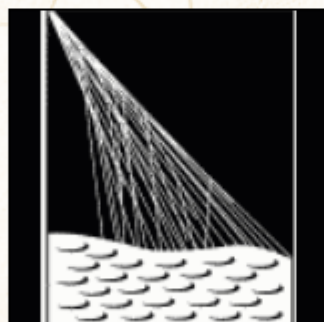


Supernovae  
(Stellar Collapse)

SN 1987A ✓



Earth Atmosphere  
(Cosmic Rays)

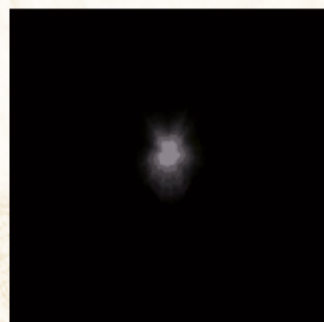


Astrophysical  
Accelerators

Soon ?



Earth Crust  
(Natural  
Radioactivity)



Cosmic Big Bang  
(Today  $330 \nu/\text{cm}^3$ )

Indirect Evidence



A detailed black and white illustration of a hand holding a pen, set against a background of a textured surface. The hand is rendered with fine lines and shading, showing the texture of the skin and the grip on the pen. The pen is a simple, cylindrical object with a small ring near the tip. The text 'Supernova Neutrinos' is overlaid in a bold, yellow, sans-serif font, centered over the hand and pen. The overall composition is a classic 'hand holding a pen' motif, often used to represent a signature or a mark of authority.

# Supernova Neutrinos



# Sanduleak -69 202



Tarantula Nebula

Large Magellanic Cloud  
Distance 50 kpc  
(160.000 light years)





**Sanduleak -69 202**



**Supernova 1987A**

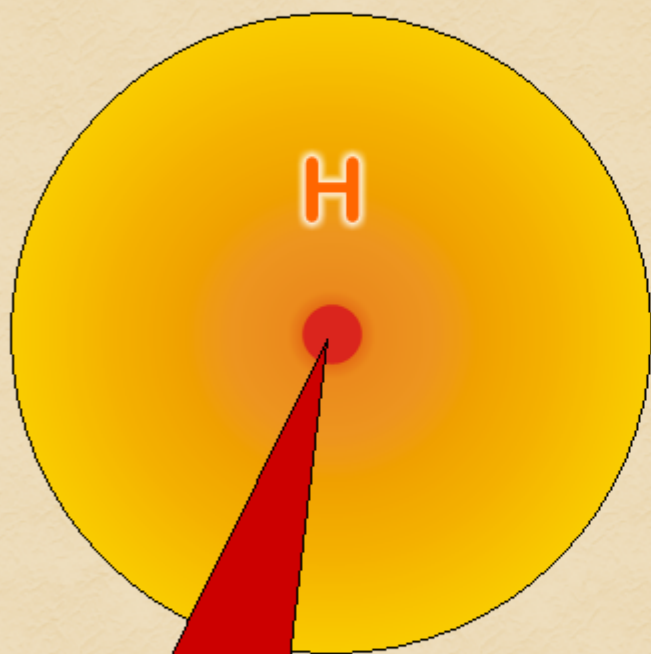
**23 February 1987**





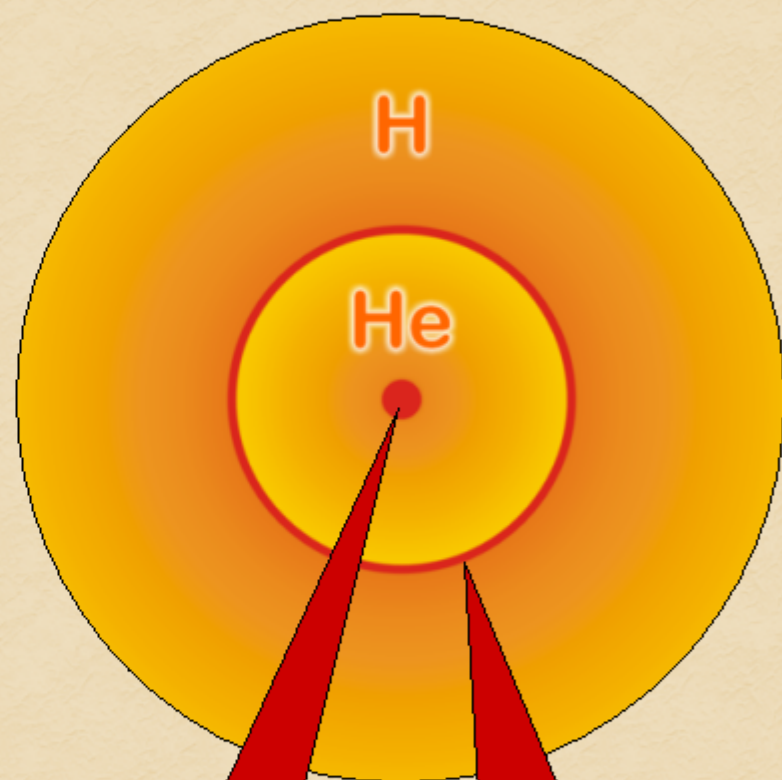
# Stellar Collapse and Supernova Explosion

Main-sequence star



Hydrogen Burning

Helium-burning star



Helium  
Burning

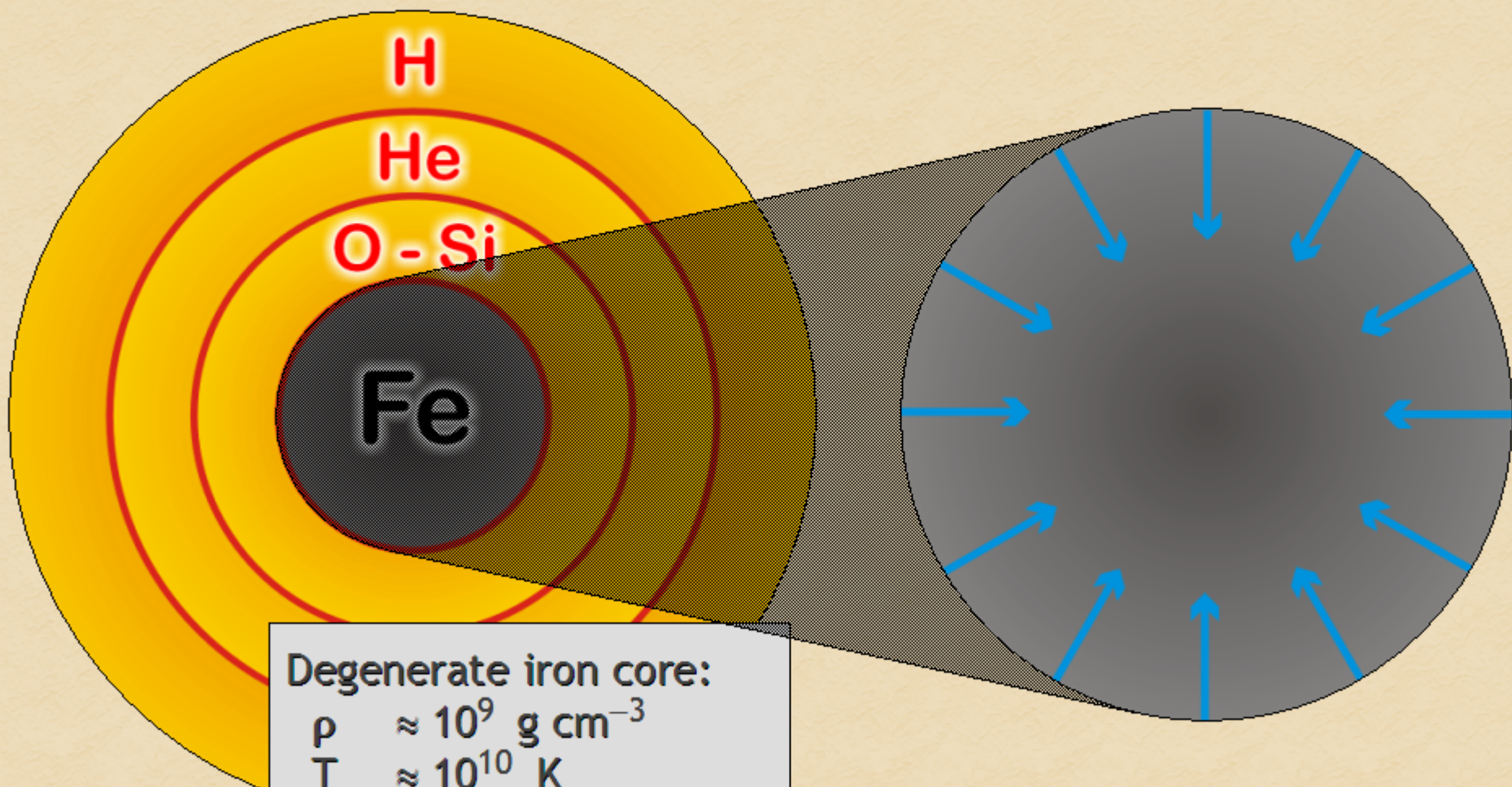
Hydrogen  
Burning



# Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

$$\rho \approx 10^9 \text{ g cm}^{-3}$$

$$T \approx 10^{10} \text{ K}$$

$$M_{\text{Fe}} \approx 1.5 M_{\text{sun}}$$

$$R_{\text{Fe}} \approx 8000 \text{ km}$$



# Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Explosion

~ 50 km

Neutrino  
Cooling

Proto-Neutron Star

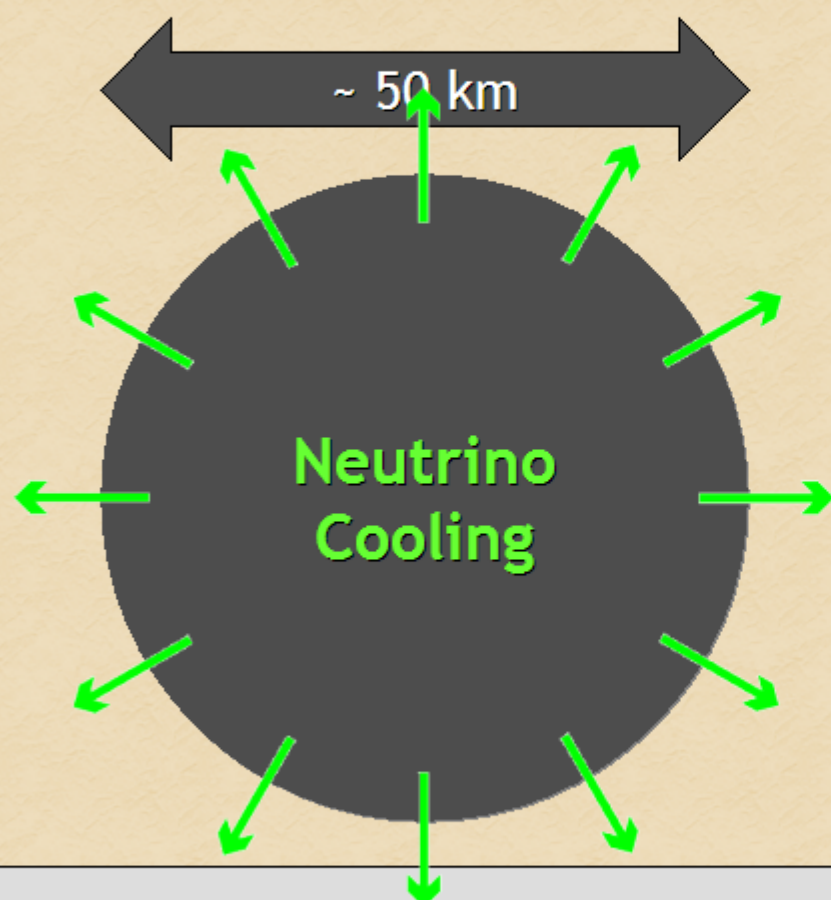
$$\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$$

$$T \approx 30 \text{ MeV}$$



# Stellar Collapse and Supernova Explosion

## Newborn Neutron Star



### Proto-Neutron Star

$$\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$$
$$T \approx 30 \text{ MeV}$$

### Gravitational binding energy

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\text{SUN}} c^2$$

### This shows up as

- 99% Neutrinos
- 1% Kinetic energy of explosion  
(1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

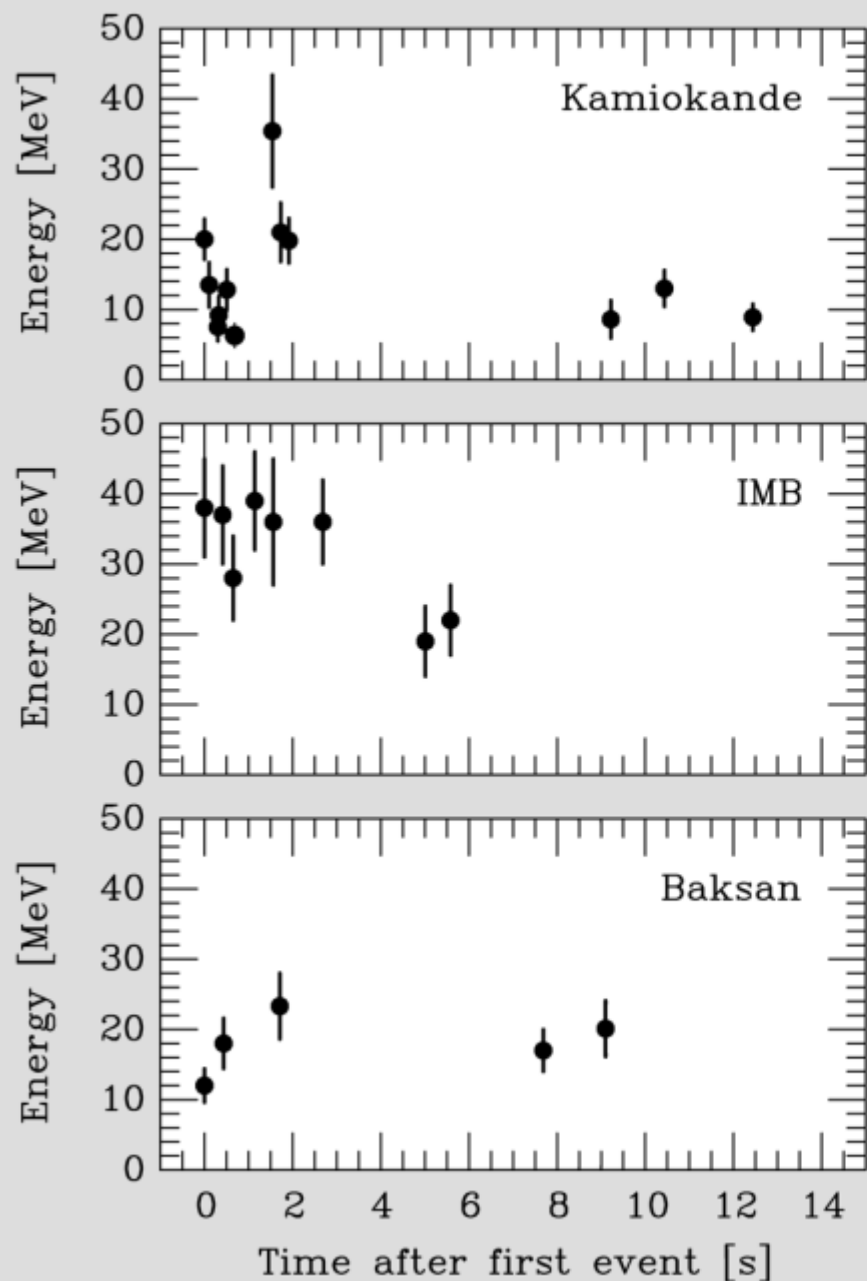
### Neutrino luminosity

$$L_\nu \approx 3 \times 10^{53} \text{ erg} / 3 \text{ sec}$$
$$\approx 3 \times 10^{19} L_{\text{SUN}}$$

While it lasts, outshines the entire visible universe



# Neutrino Signal of Supernova 1987A



Kamiokande (Japan)  
Water Cherenkov detector  
Clock uncertainty  $\pm 1$  min

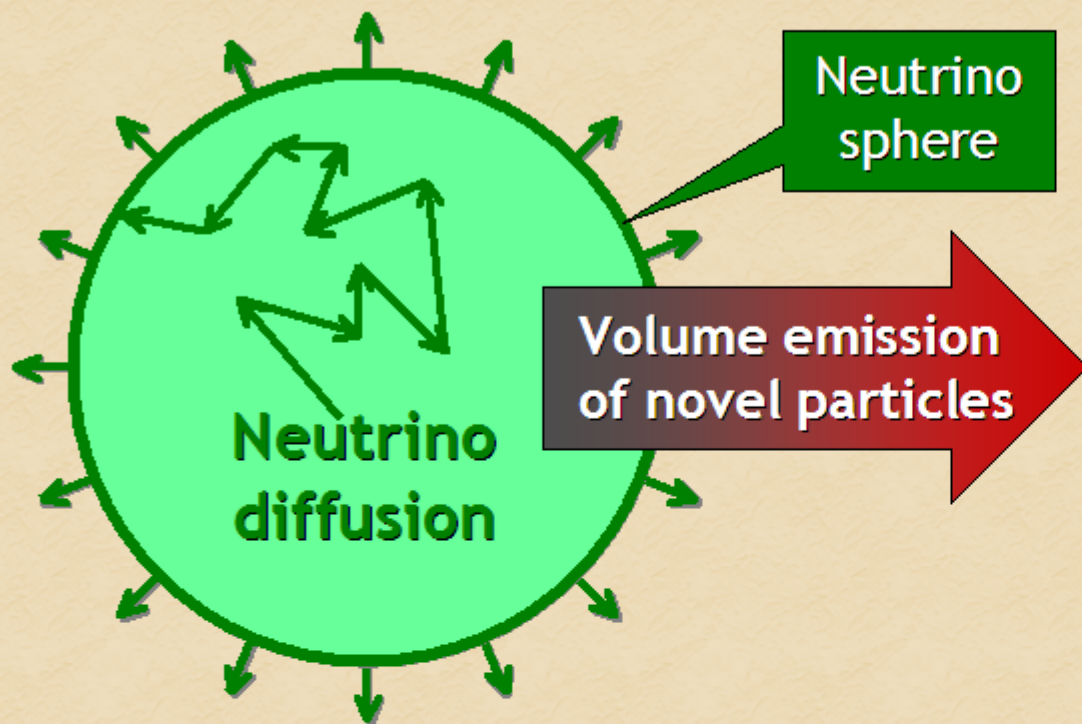
Irvine-Michigan-Brookhaven (US)  
Water Cherenkov detector  
Clock uncertainty  $\pm 50$  ms

Baksan Scintillator Telescope  
(Soviet Union)  
Clock uncertainty  $+2/-54$  s

Within clock uncertainties,  
signals are contemporaneous



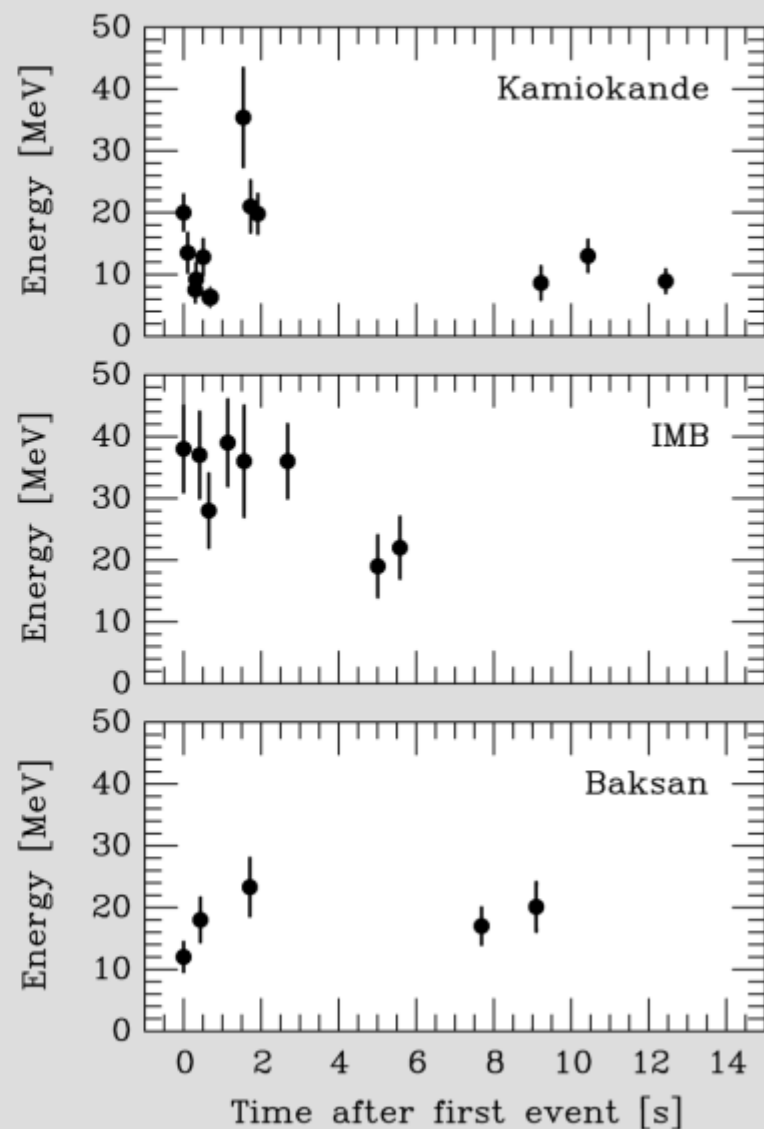
# The Energy-Loss Argument



Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.  
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

## SN 1987A neutrino signal





# David Schramm put me to work ...

David Schramm  
(Editor Physics Reports)

“Why don't you write a  
review on astrophysical  
particle limits?”





# David Schramm put me to work ...

PHYSICS REPORTS (Review Section of Physics Letters) 198, Nos. 1 & 2 (1990) 1-113. North-Holland

## ASTROPHYSICAL METHODS TO CONSTRAIN AXIONS AND OTHER NOVEL PARTICLE PHENOMENA

Georg G. RAFFELT

Max-Planck-Institut für Physik, Postfach 401212, 8000 München 40, Germany

Editor: D.N. Schramm

Received March 1990

### Contents:

1. Introduction	3	7. Axions from the Sun	60
1.1. Prologue	3	7.1. Energy loss and energy transfer in the Sun; first constraints	60
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2.1. Generic features of the Peccei-Quinn mechanism	10	8. Red giants and horizontal branch stars	63
2.2. The most common axion models	15	8.1. The general agenda	64
2.3. Fine points of axion properties	17	8.2. The evolution of low-mass stars	65
3. Axion cosmology	22	8.3. Suppression of the helium flash by particle emission	68
3.1. Inflationary scenario	23	8.4. Reduction of the helium burning phase	71
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3.4. Decaying axions and a glow of the night sky	26	9.1. White dwarfs: theoretical and observed properties	77
3.5. Experimental search for galactic axions	27	9.2. Cooling theory for white dwarfs	79
4. Emission rates from stellar plasmas	28	9.3. Neutrino losses included	81
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4.2. Absorption rates	29	10. Cooling of nascent and young neutron stars	82
4.3. Many-body effects in stellar plasmas	30	10.1. Birth and cooling of neutron stars	82
4.4. Compton process	39	10.2. Supernova explosions and new particle physics	87
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4.9. Primakoff effect and axion-photon mixing	49	10.7. Axion bounds from Einstein observations	97
4.10. Plasmon decay rate	54	10.8. What if neutron stars are strange quark stars?	98
5. Energy transfer	55	11. Summary of axion and neutrino bounds	98
5.1. Radiative transfer by massive bosons	56	11.1. Neutrinos	98
5.2. Opacity contribution of massive pseudoscalars	56	11.2. Axions	100
6. Exotic energy loss of low-mass stars; analytic treatment	57	References	104
6.1. The equations of stellar structure	57		
6.2. Homologous changes	58		

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David Schramm  
(Editor University of  
Chicago Press)

“Why don't you turn the  
review into a book?”





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## Stars as Laboratories

## for Fundamental Physics

THE ASTROPHYSICS OF NEUTRINOS, AXIONS, AND  
OTHER WEAKLY INTERACTING PARTICLES

Georg G. Raffelt

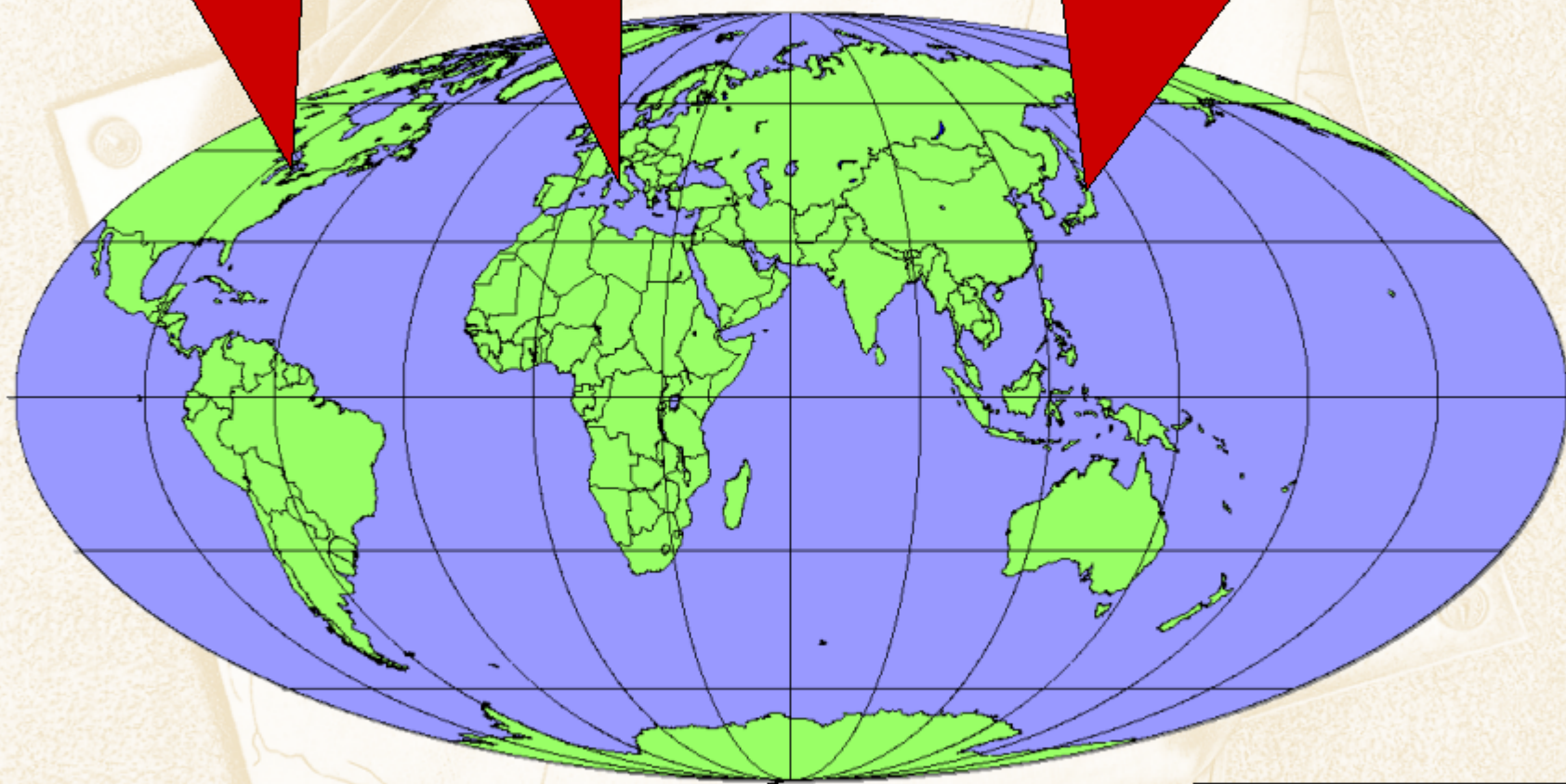


# Large Detectors for Supernova Neutrinos

SNO (800)  
MiniBooNE (190)

LVD (400)  
Borexino (80)

Super-Kamiokande ( $10^4$ )  
Kamland (330)

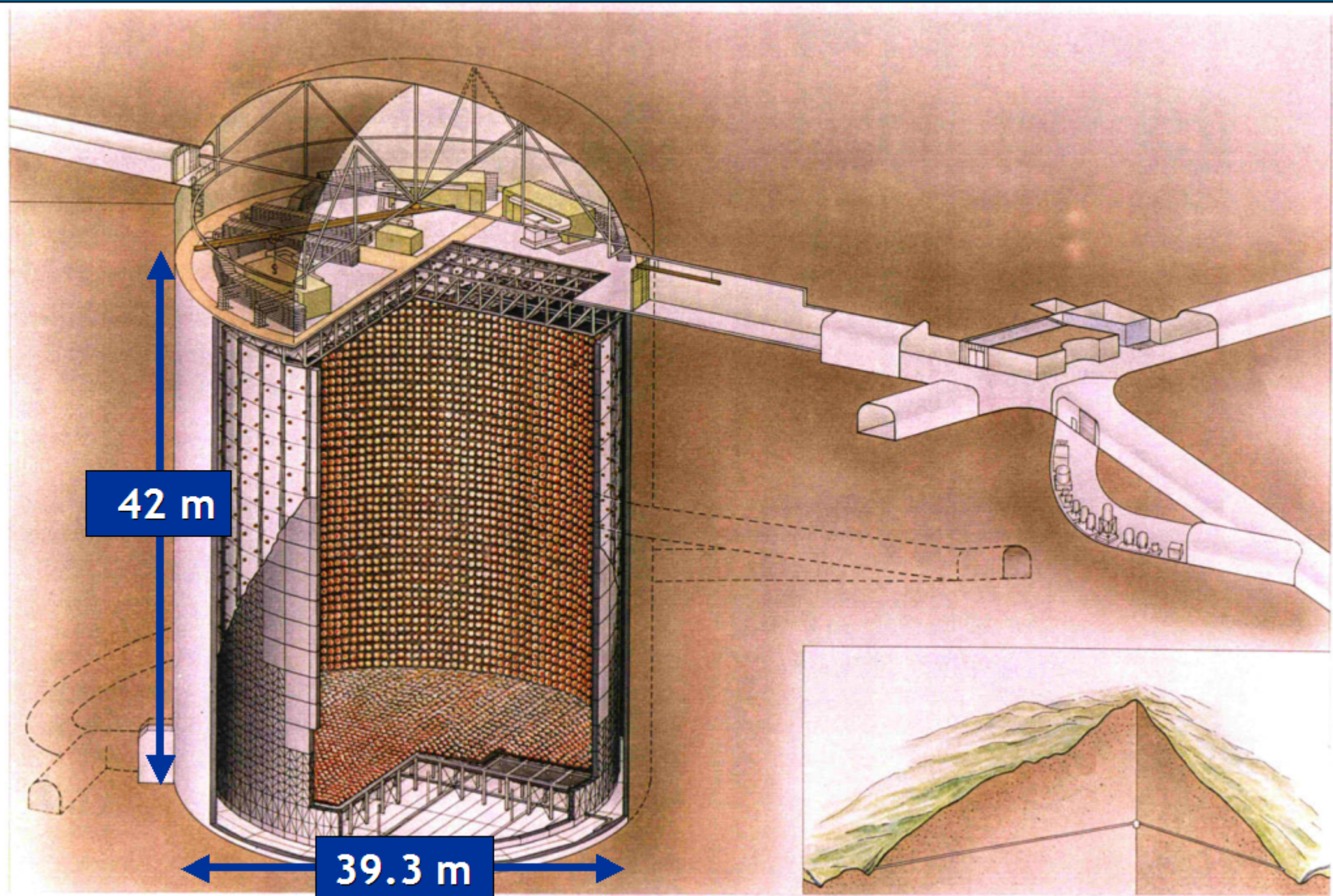


Amanda  
IceCube

In brackets events  
for a "fiducial SN"  
at distance 10 kpc

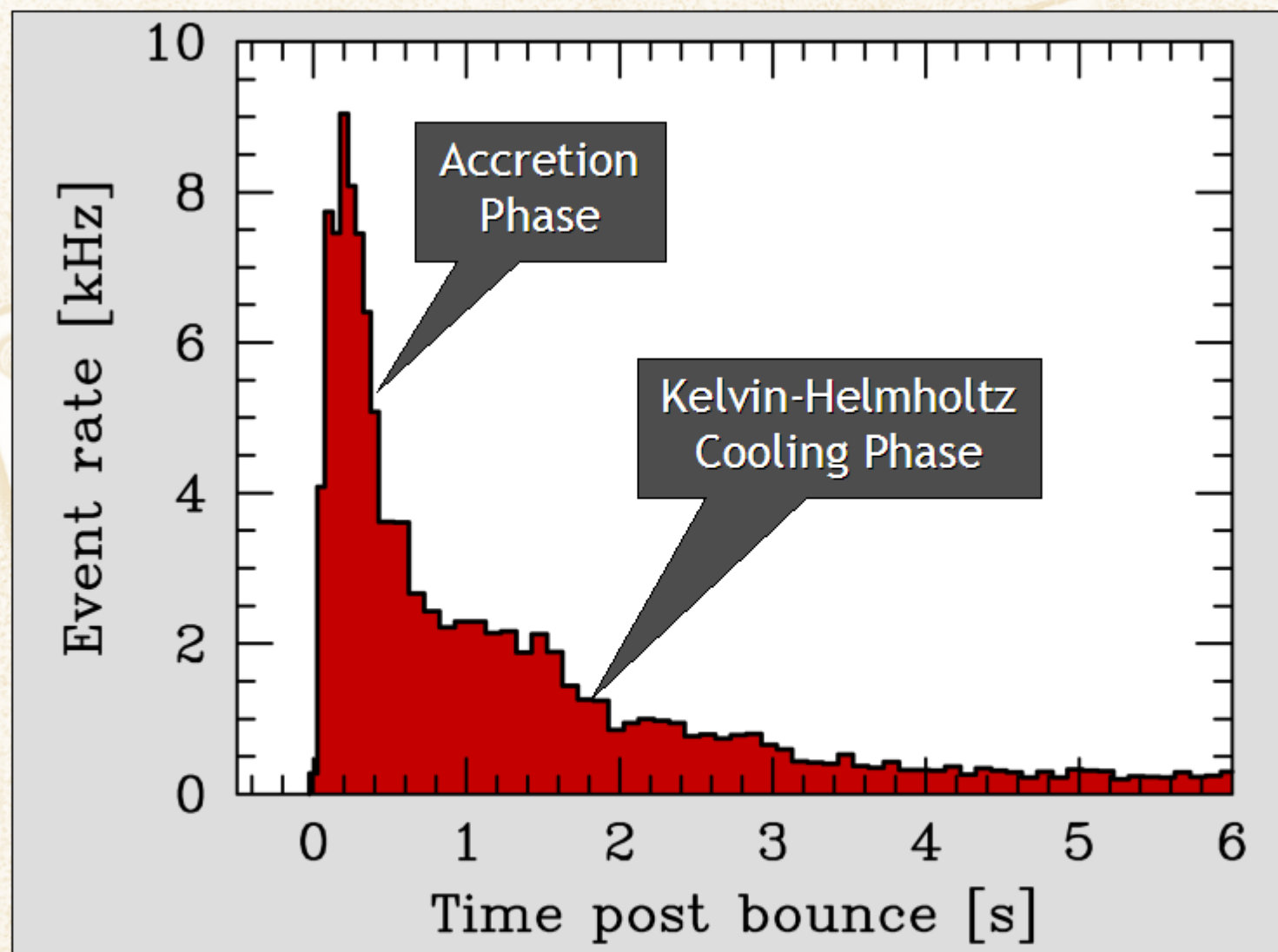


# Super-Kamiokande Neutrino Detector





# Simulated Supernova Signal at Super-Kamiokande



Simulation for Super-Kamiokande SN signal at 10 kpc,  
based on a numerical Livermore model  
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]



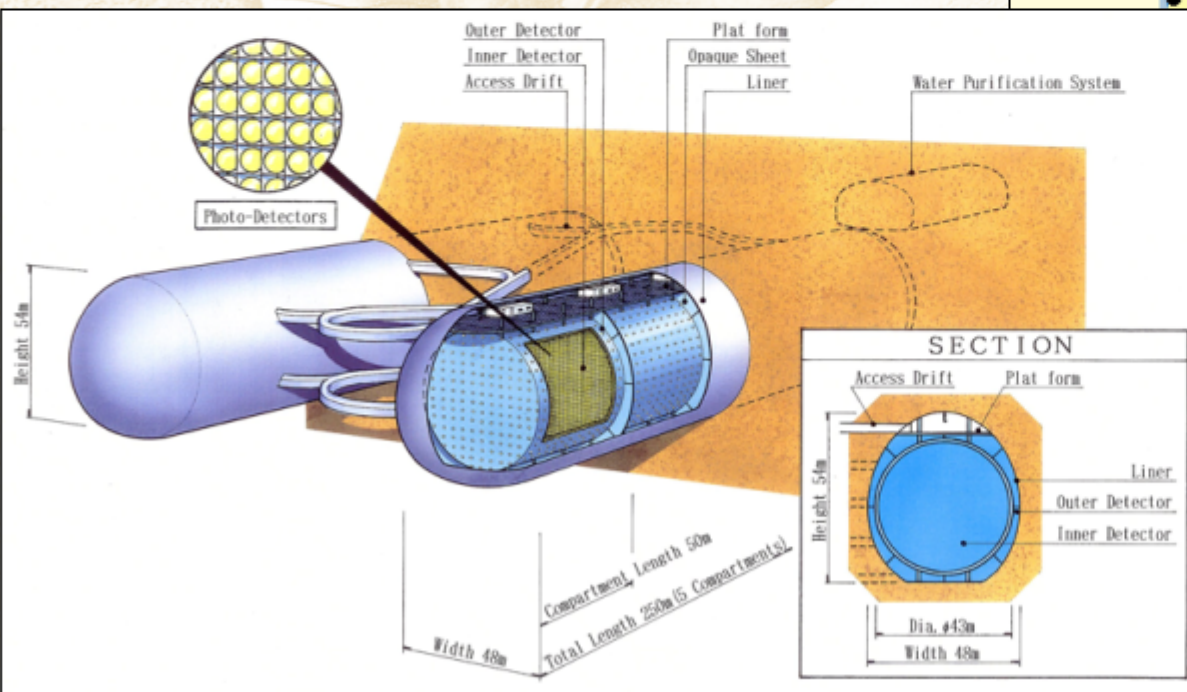
# The Future: A Megatonne Detector?

Megatonne detector motivated by

- Long baseline neutrino oscillations
  - Proton decay
  - Atmospheric neutrinos
  - Solar neutrinos
  - Supernova neutrinos
- ( $\sim 10^5$  events for SN at 10 kpc)

## 1. Overview of the experiment

(expect to start in 2007)



Similar discussions in

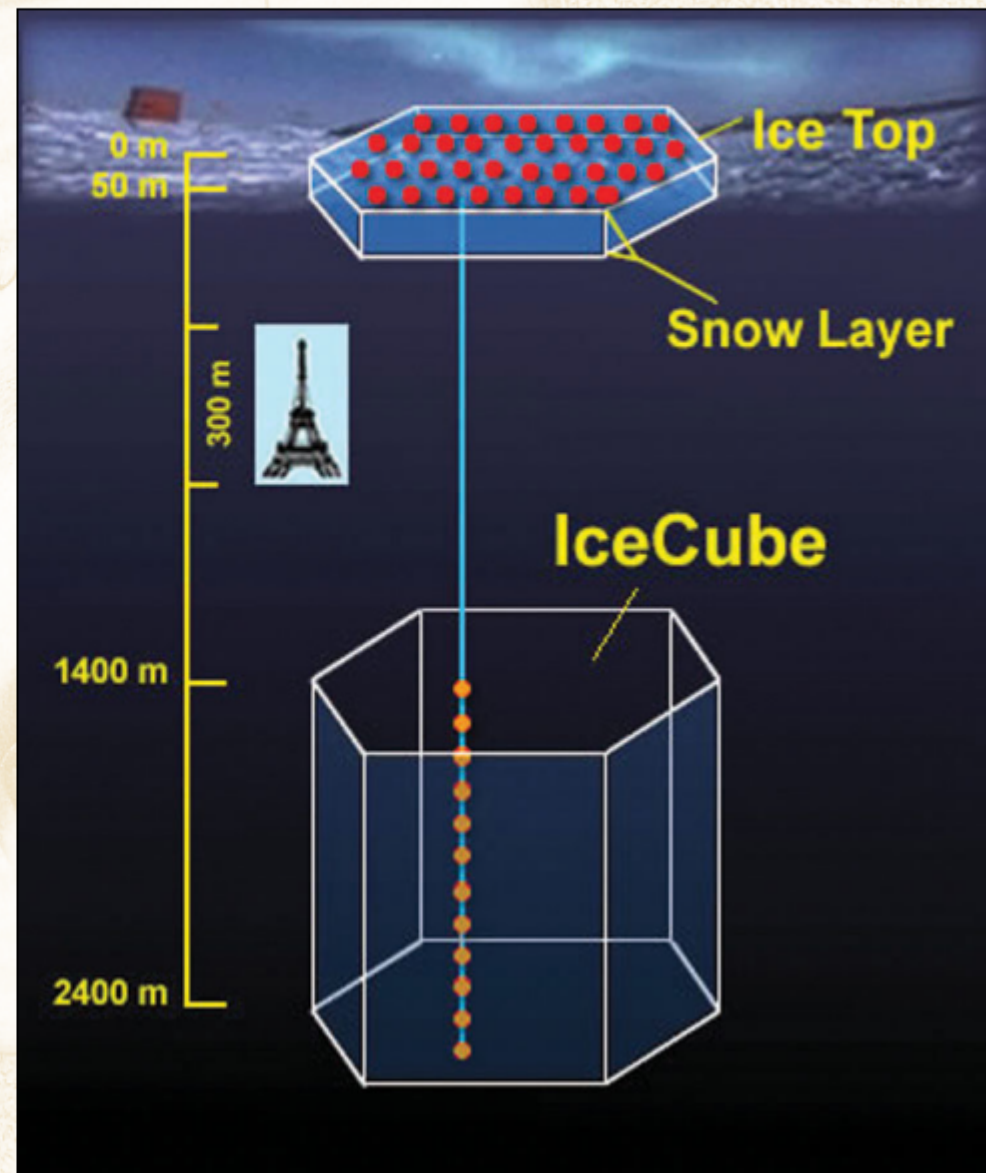
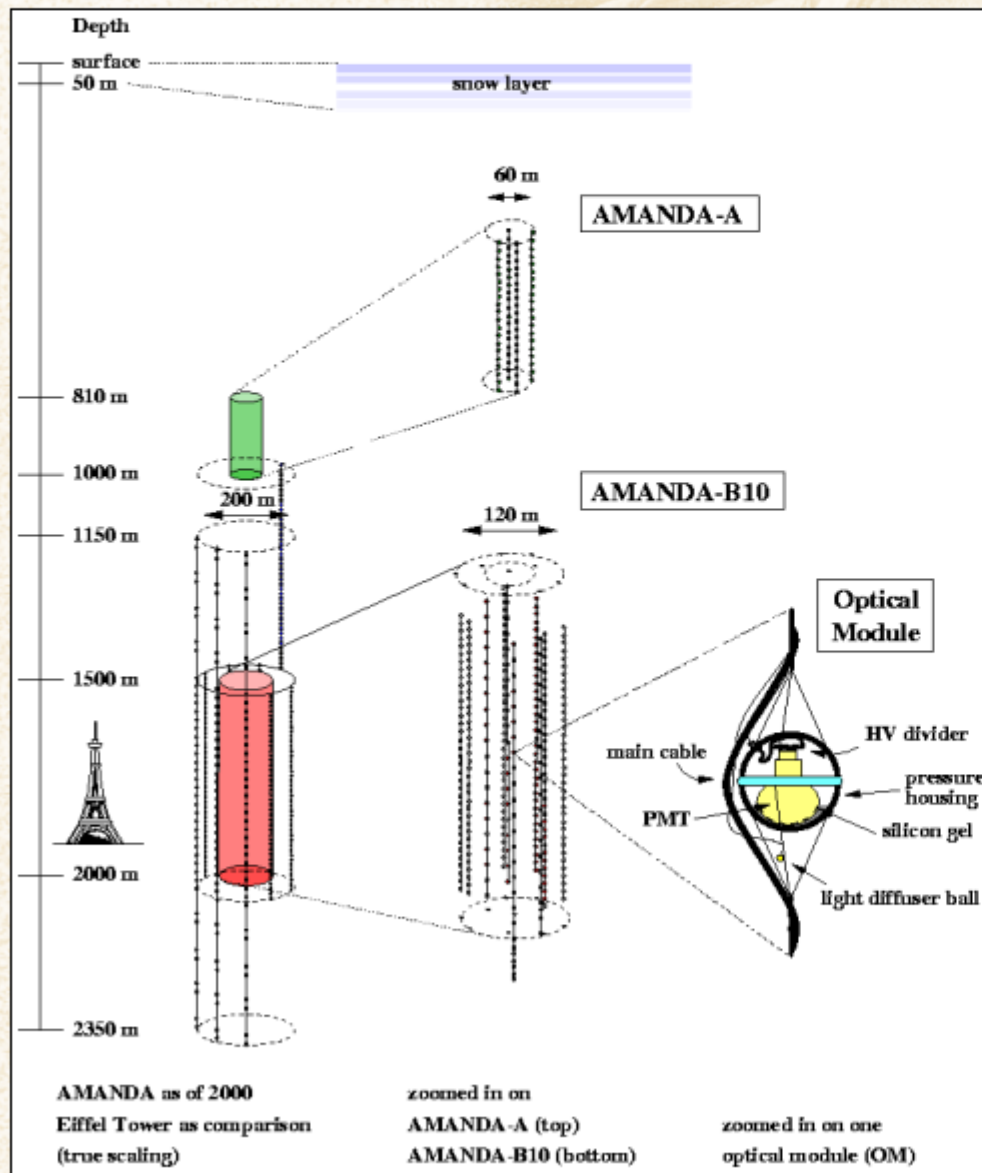
- US (UNO project)
- Europe (MEMPHYS project)



# Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km<sup>3</sup>, 800 PMTs)

Future IceCube (1 km<sup>3</sup>, 4800 PMTs)



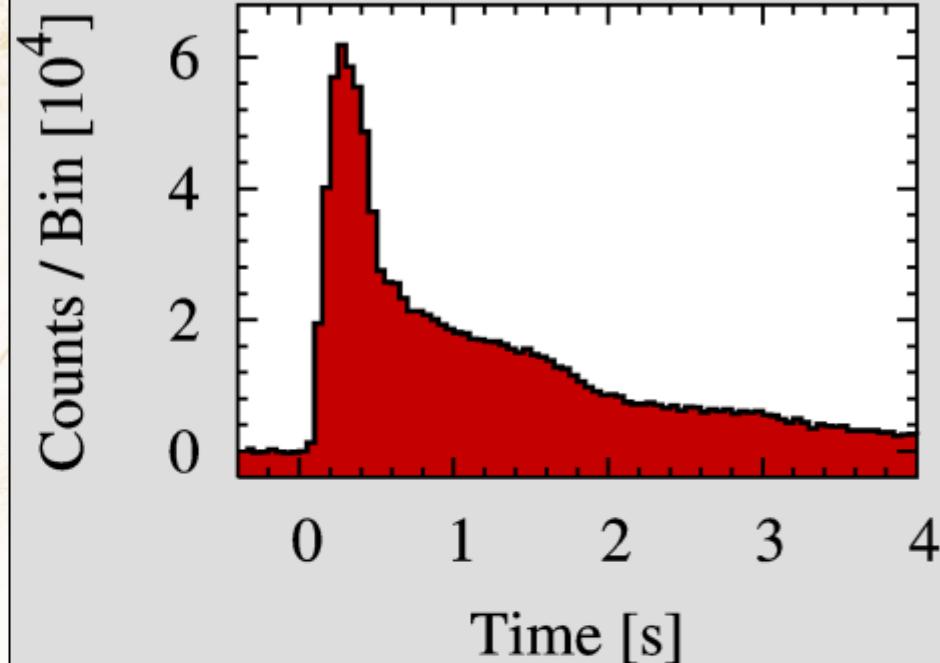
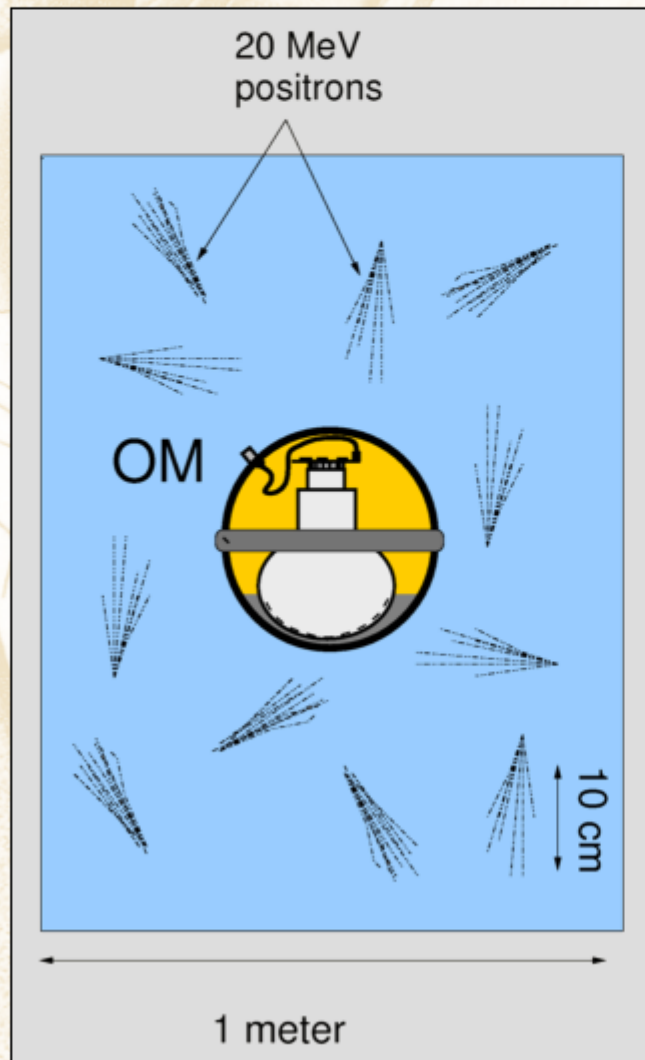


# IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as “correlated noise”.

~ 300  
Cherenkov  
photons  
per OM  
from a SN  
at 10 kpc

Noise  
per OM  
< 500 Hz



IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]



# Three-Flavor Neutrino Parameters

Atmospheric/K2K  
 $37^\circ < \theta_{23} < 54^\circ$

CHOOZ  
 $\theta_{13} < 11^\circ$

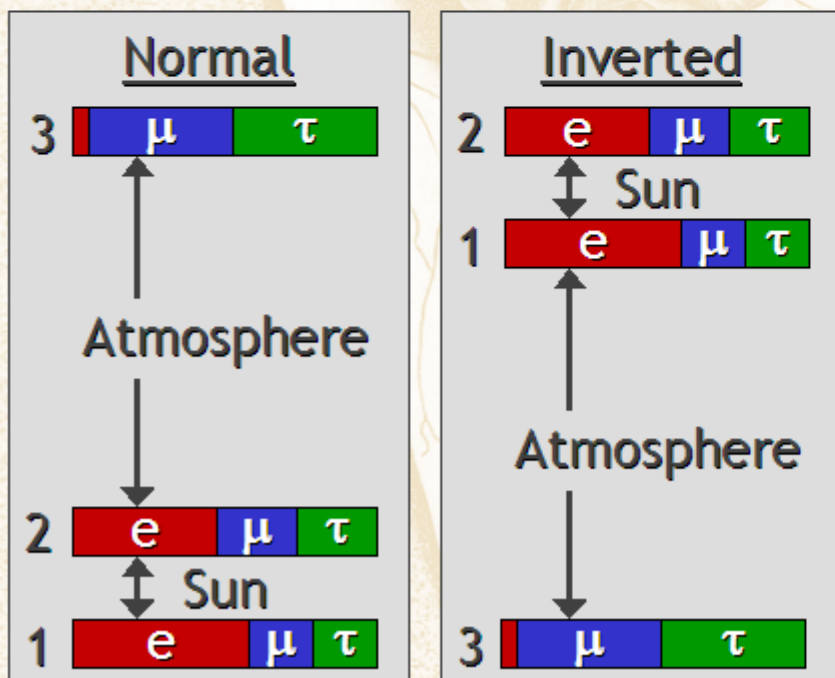
Solar/KamLAND  
 $30^\circ < \theta_{12} < 36^\circ$

$2\sigma$  ranges  
 hep-ph/0405172

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & C_{23} & S_{23} \\ & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & & e^{-i\delta} S_{13} \\ & 1 & \\ -e^{i\delta} S_{13} & & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} \\ -S_{12} & C_{12} \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$C_{12} = \cos \theta_{12}$  etc.,  $\delta$  CP-violating phase

Solar  
 75–92  
 Atmospheric  
 1400–3000  
 $\Delta m^2 / \text{meV}^2$



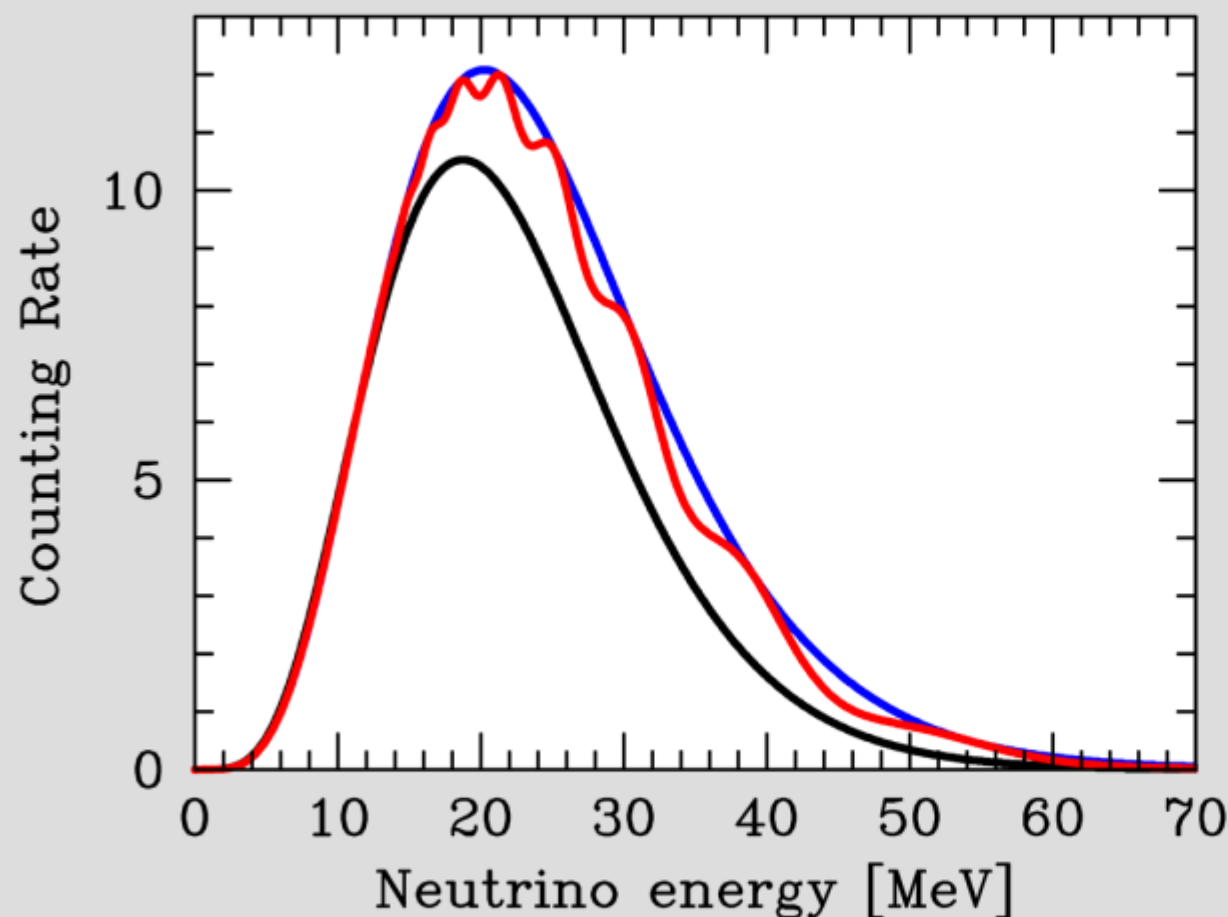
## Tasks and Open Questions

- Precision for  $\theta_{12}$  and  $\theta_{23}$
- How large is  $\theta_{13}$ ?
- CP-violating phase  $\delta$ ?
- Mass ordering?  
 (normal vs inverted)
- Absolute masses?  
 (hierarchical vs degenerate)
- Dirac or Majorana?



# Oscillation of Supernova Anti-Neutrinos

Measured  $\bar{\nu}_e$  spectrum at a detector like Super-Kamiokande



Assumed flux parameters

Flux ratio  $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15 \text{ MeV}$

$\langle E(\bar{\nu}_x) \rangle = 18 \text{ MeV}$

Mixing parameters

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

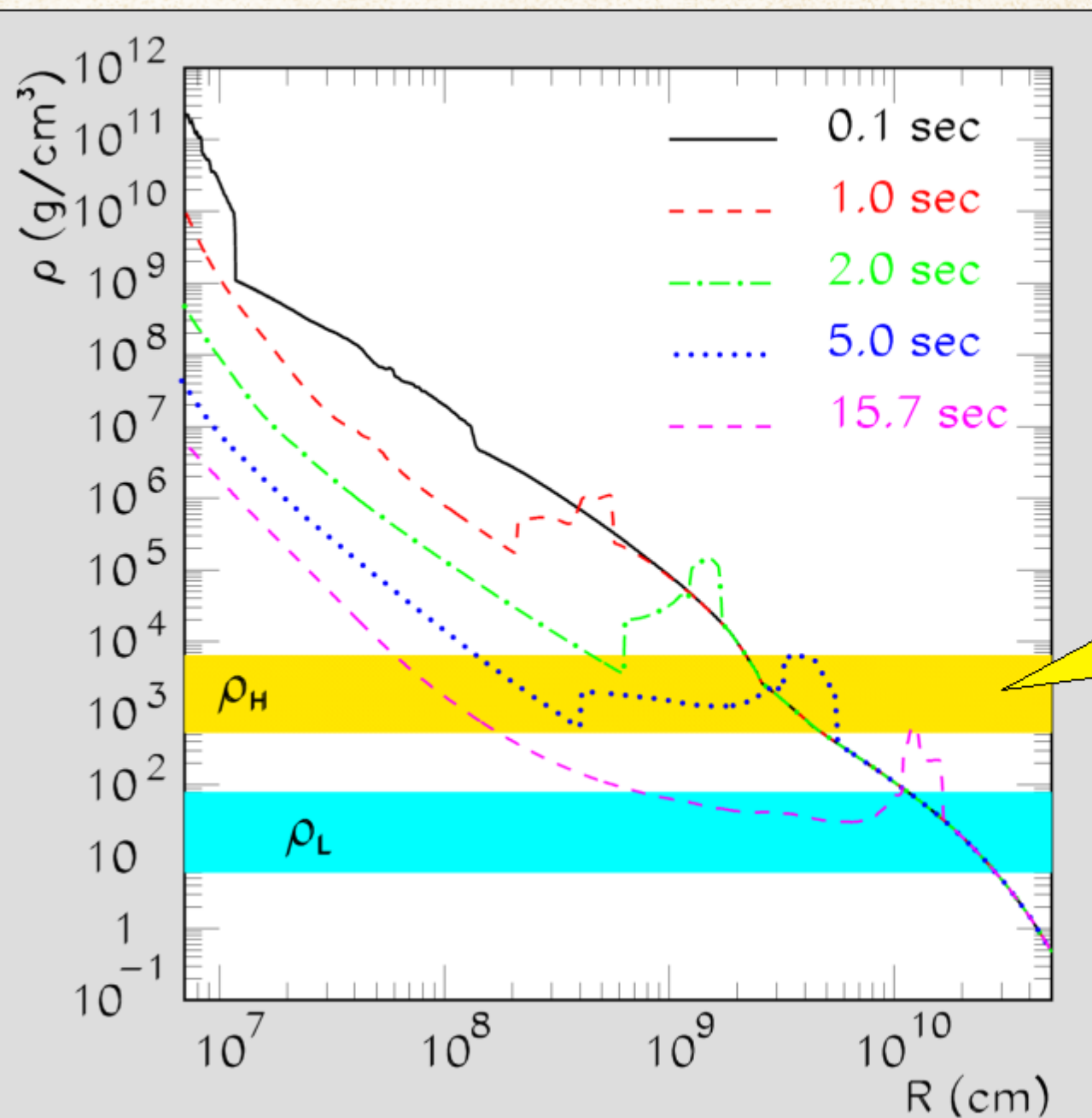
Oscillations in SN envelope

**Earth effects included**

$\Pi$ (Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs),  
hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172



# Supernova Shock Propagation and Neutrino Oscillations



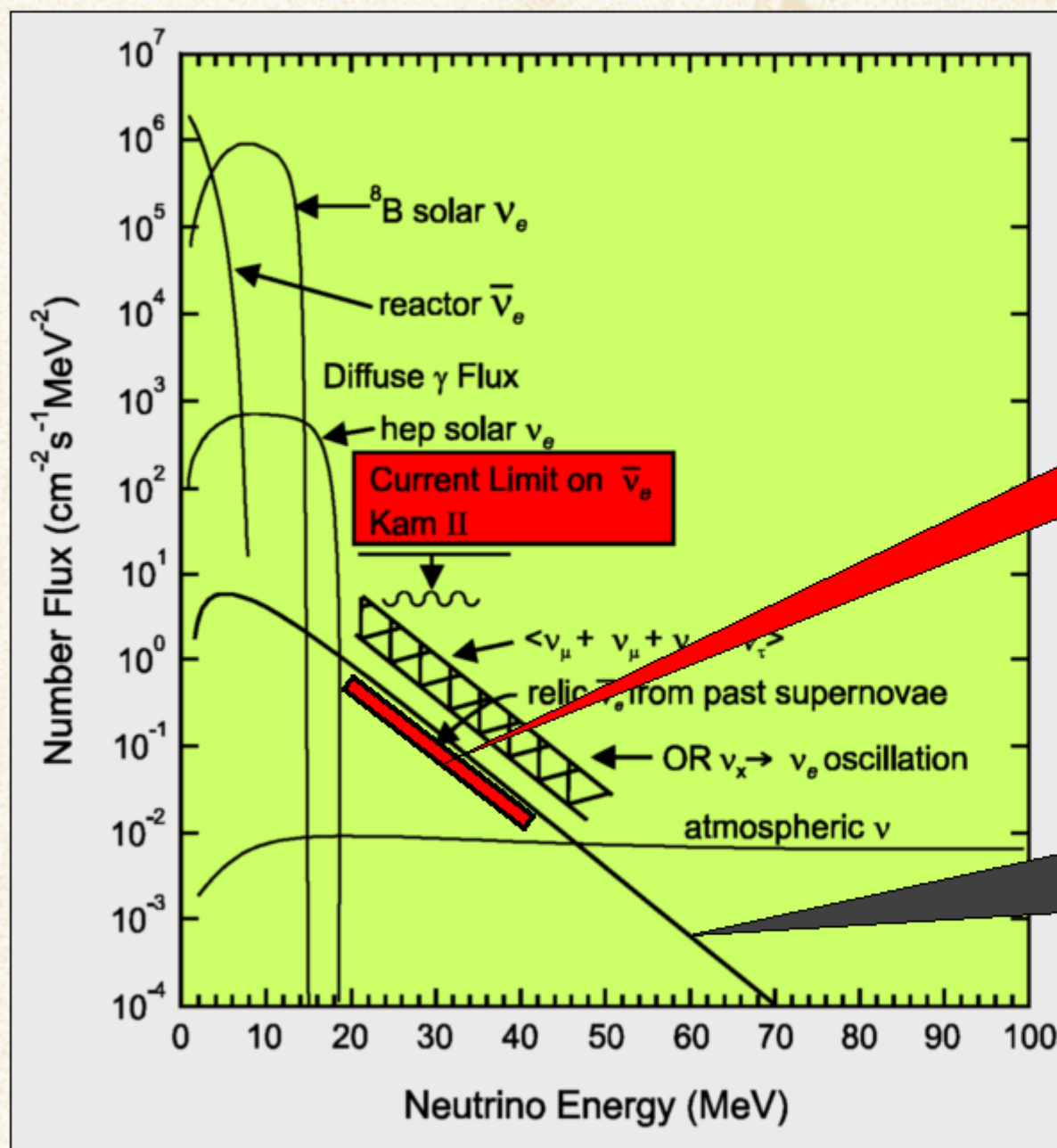
Schirato & Fuller:  
Connection between  
supernova shocks,  
flavor transformation,  
and the neutrino signal  
[astro-ph/0205390]

Resonance  
density for  
 $\Delta m_{\text{atm}}^2$

R. Tomàs, M. Kachelriess,  
G. Raffelt, A. Dighe,  
H.-T. Janka & L. Scheck:  
Neutrino signatures of  
supernova forward and  
reverse shock propagation  
[astro-ph/0407132]



# Experimental Limits on Relic Supernova Neutrinos



Super-K upper limit  
 $29 \text{ cm}^{-2} \text{ s}^{-1}$  for  
Kaplinghat et al. spectrum  
[hep-ex/0209028]

Upper-limit flux of  
Kaplinghat et al.,  
astro-ph/9912391  
Integrated  $54 \text{ cm}^{-2} \text{ s}^{-1}$

Cline, astro-ph/0103138

# Improved Sensitivity with Neutron Tagging

J.Beacom and M.Vagins, hep-ph/0309300 [Phys. Rev. Lett., 93:171101, 2004]

Super-Kamiokande limited by

- Solar neutrinos for  $E_\nu < 18\text{--}19\text{ MeV}$
- Sub-Cherenkov muons from atm nus  
 $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

Solution:

Neutron tagging  $\bar{\nu}_e + p \rightarrow e^+ + n$

Water: Neutron capture on protons  
2.2 MeV gammas, invisible in SK

Add gadolinium to SK:

- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1% (100 tons of Gd  $\text{Cl}_3$ )  
achieves  $> 90\%$  tagging efficiency

SN relic nus: A few events per year  
in SK with no background at all

**Gadolinium**  
**Antineutrino**  
**Detector**  
**Zealously**  
**Outperforming**  
**Old**  
**Kamiokande,**  
**Super!**



# Diffuse Supernova Neutrino Background in GADZOOKS!

Beacom & Vagins, hep-ph/0309300  
[Phys. Rev. Lett., 93:171101, 2004]

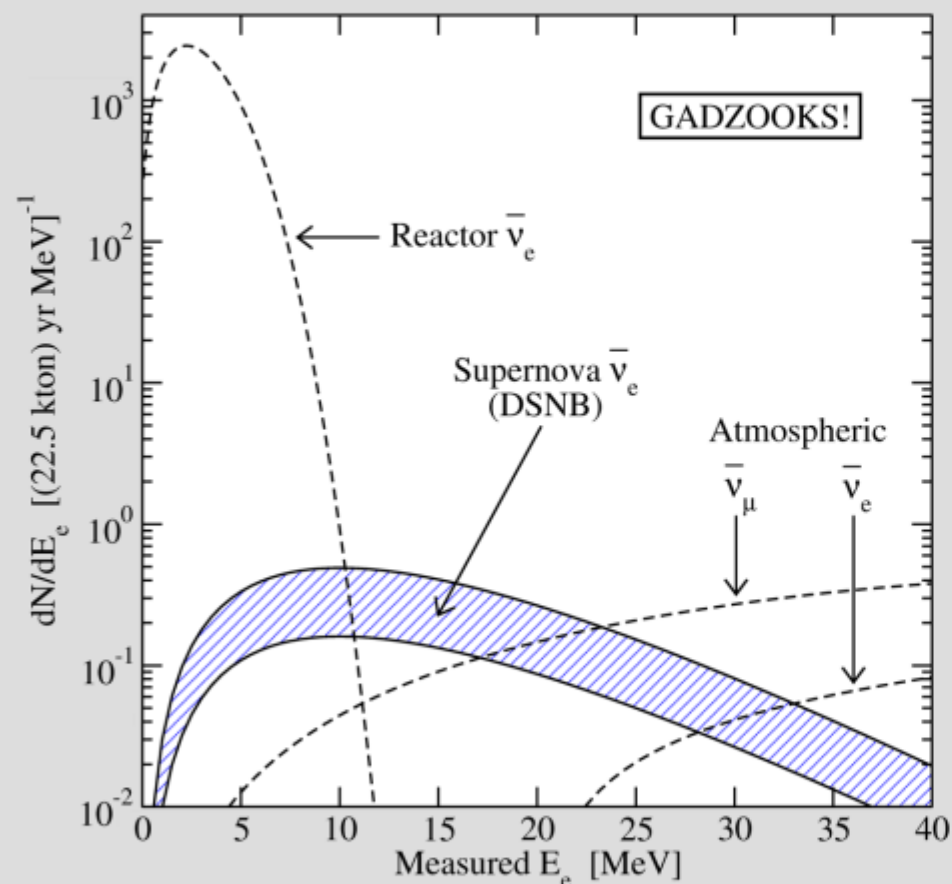


FIG. 1: Spectra of low-energy  $\bar{\nu}_e + p \rightarrow e^+ + n$  coincidence events and the sub-Cherenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.



Pushing the boundaries of neutrino astronomy to cosmological distances

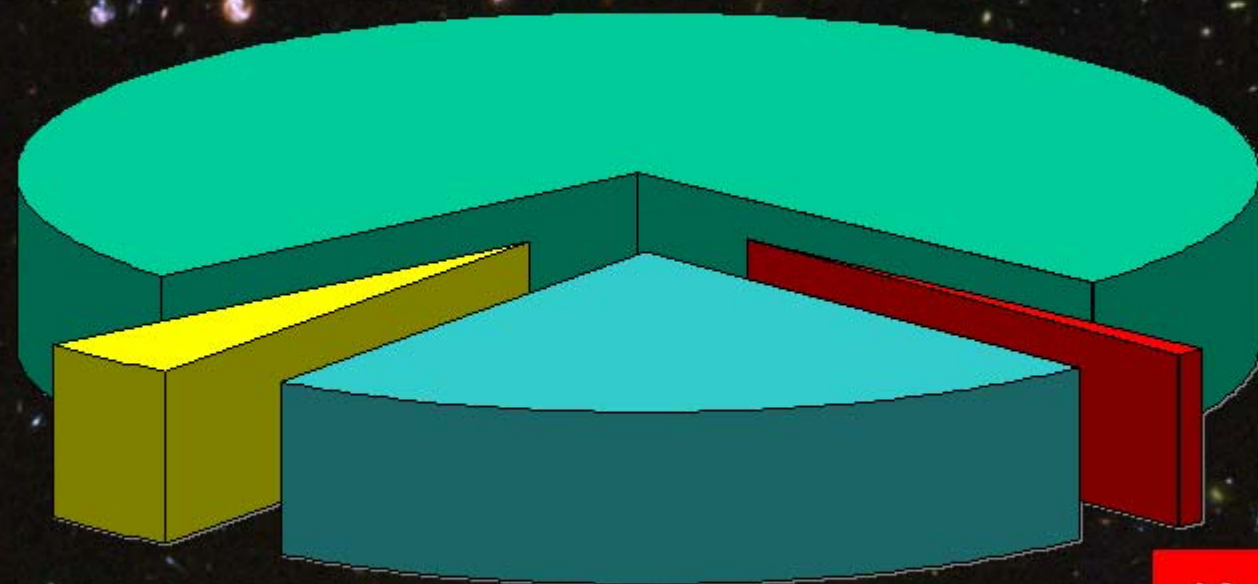




# Neutrino Dark Matter



**Dark Energy 73%**  
**(Cosmological Constant)**



**Normal Matter 4%**  
**(of this about 10%  
luminous)**

**Dark  
Matter 23%**

**Neutrinos  
0.1-2%**



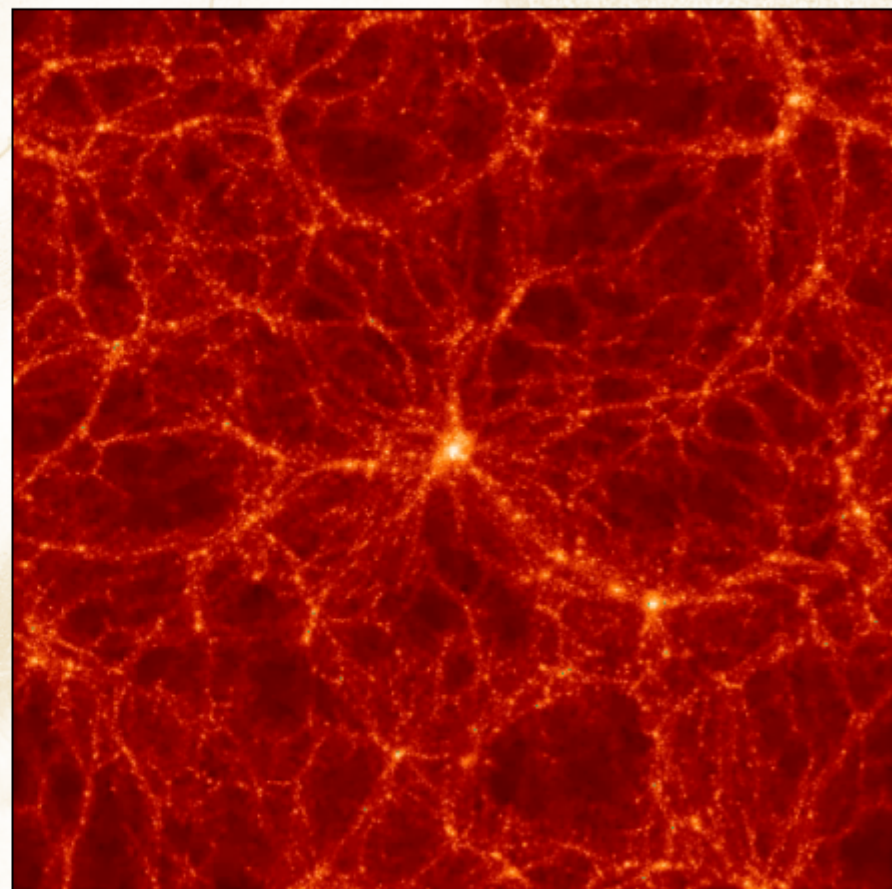
# Formation of Structure

Smooth



Structured

Structure forms by  
gravitational instability  
of primordial  
density fluctuations





# Formation of Structure

Smooth

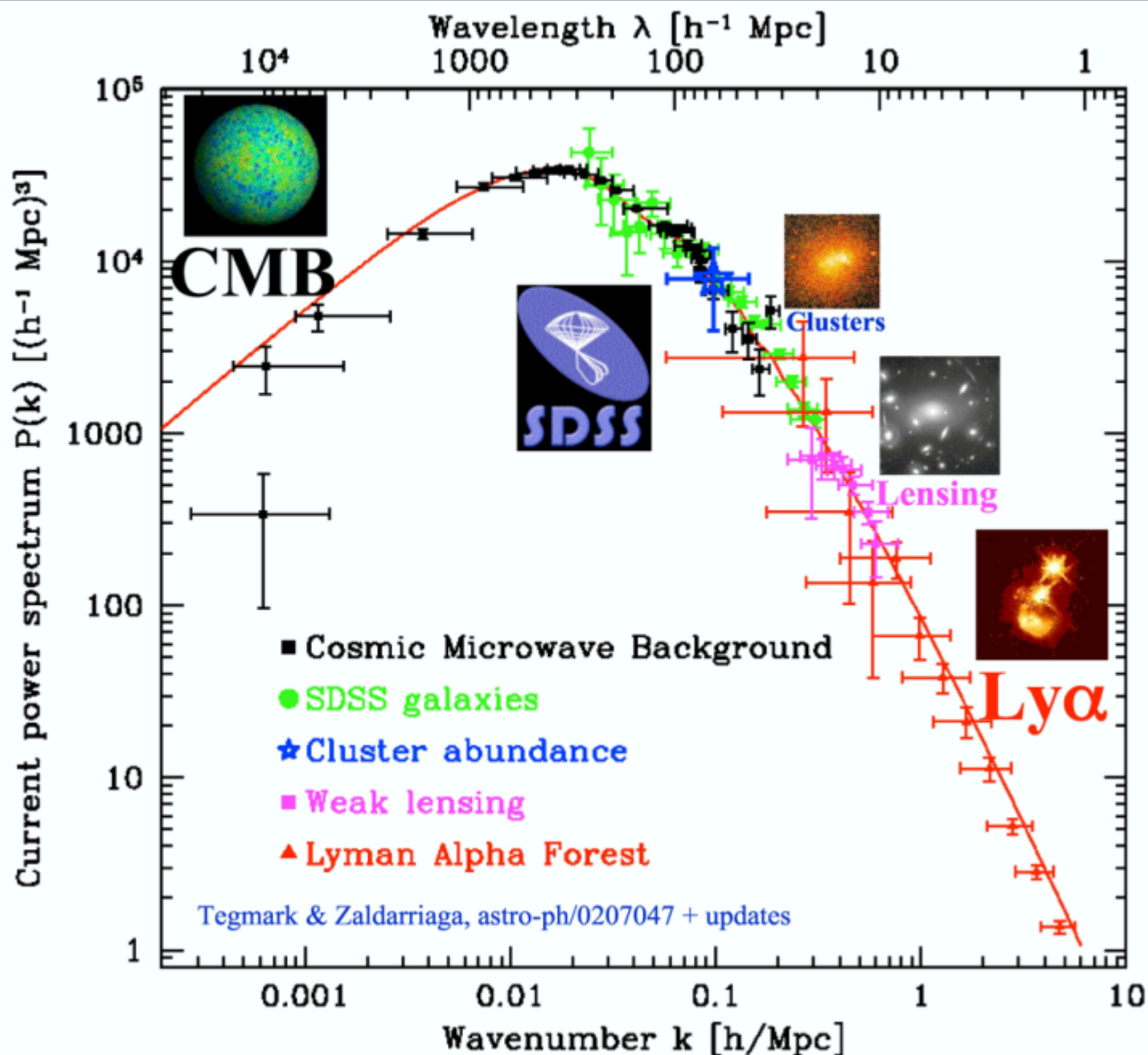


Structured

Structure forms by  
gravitational instability  
of primordial  
density fluctuations

A fraction of hot dark matter  
suppresses small-scale structure

# Power Spectrum of Cosmic Density Fluctuations

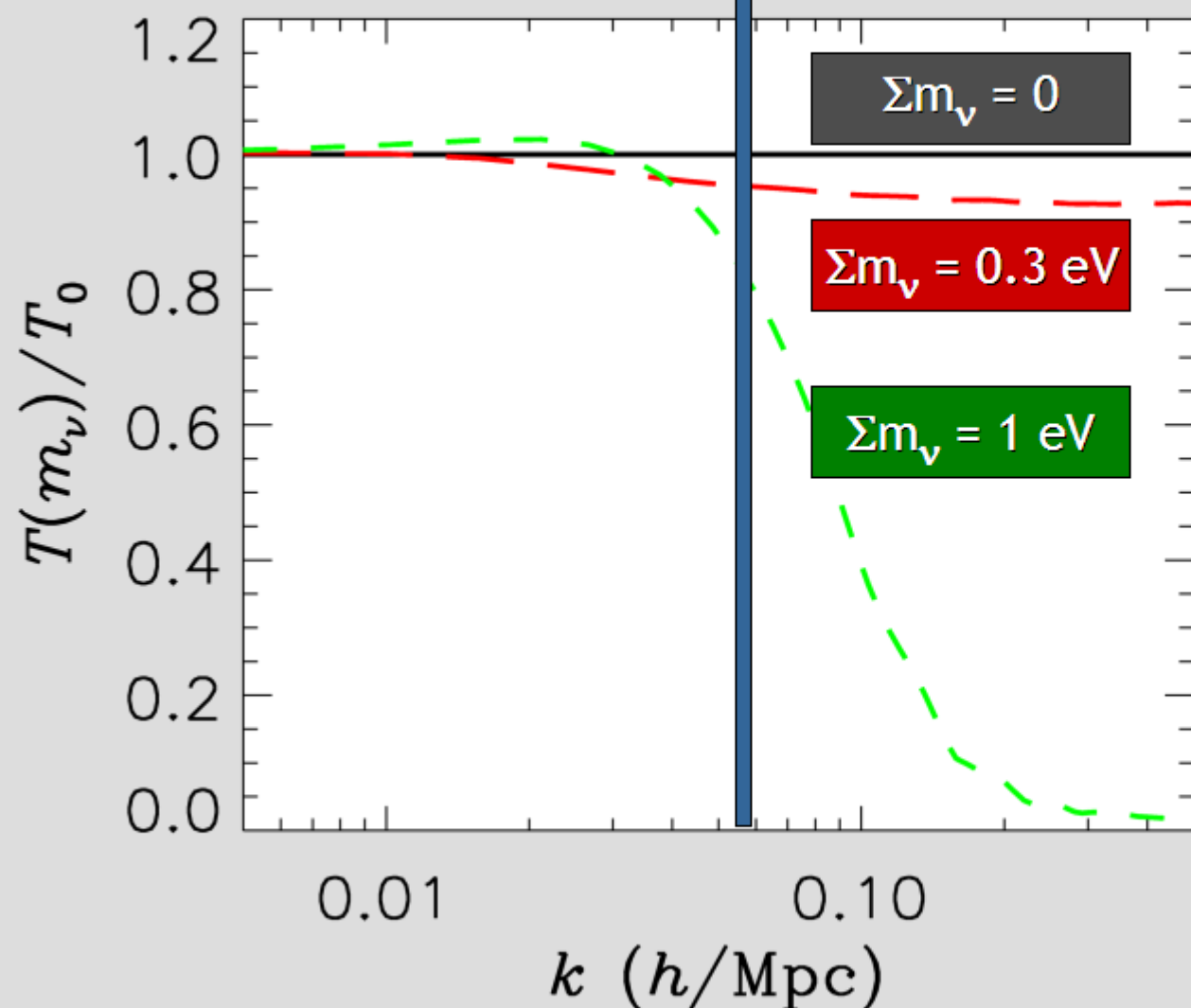


Max Tegmark  
 Univ. of Pennsylvania  
 max@physics.upenn.edu  
 TAUP 2003  
 September 5, 2003



# Neutrino Free Streaming - Transfer Function

Power suppression for  $\lambda_{\text{FS}} \lesssim 100 \text{ Mpc}/h$



Transfer function

$$P(k) = T(k) P_0(k)$$

Effect of neutrino free streaming on small scales

$$T(k) \approx 1 - 8\Omega_\nu/\Omega_M$$

valid for

$$8\Omega_\nu/\Omega_M \ll 1$$

Hannestad, Neutrinos in Cosmology, hep-ph/0404239

# Recent Cosmological Limits on Neutrino Masses

	$\Sigma m_\nu / \text{eV}$ (limit 95%CL)	Data / Priors
Ichikawa, Fukugita, Kawasaki 2004 [astro-ph/0409768]	2.0	WMAP
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, HST, $\sigma_8$
Barger et al. 2003 [hep-ph/0312065]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP, SDSS, SN Ia gold sample, Ly- $\alpha$ data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly- $\alpha$ data from SDSS sample



# Sensitivity Forecasts for Future LSS Observations

Lesgourgues, Pastor  
& Perotto,  
hep-ph/0403296

Planck & SDSS

$\Sigma m_\nu > 0.21$  eV detectable  
at  $2\sigma$

Ideal CMB & 40 x SDSS

$\Sigma m_\nu > 0.13$  eV detectable  
at  $2\sigma$

Abazajian & Dodelson  
astro-ph/0212216

Future weak lensing  
survey 4000 deg<sup>2</sup>

$\sigma(m_\nu) \sim 0.1$  eV

Kaplinghat, Knox & Song,  
astro-ph/0303344

CMB lensing

$\sigma(m_\nu) \sim 0.15$  eV (Planck)  
 $\sigma(m_\nu) \sim 0.044$  eV (CMBpol)

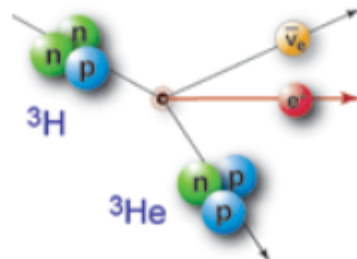
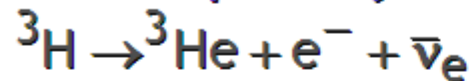
Wang, Haiman, Hu,  
Khoury & May,  
astro-ph/0505390

Weak-lensing selected  
sample of  $> 10^5$  clusters

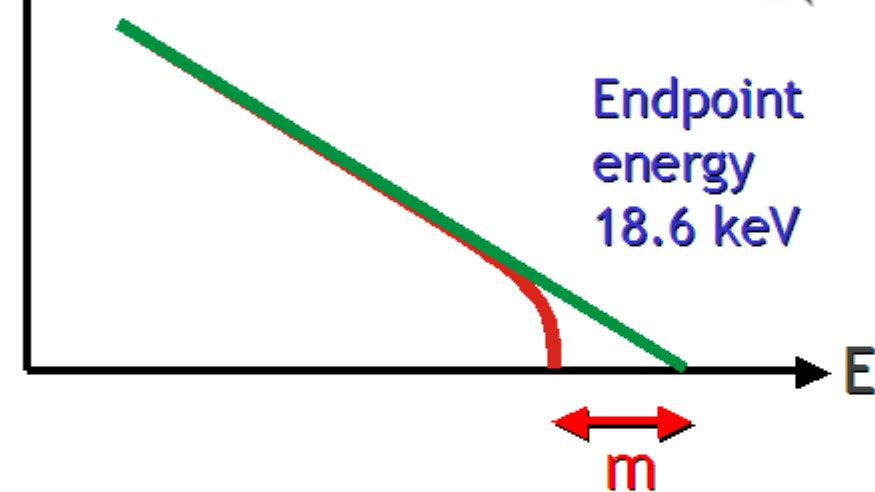
$\sigma(m_\nu) \sim 0.03$  eV

# “Weighing” Neutrinos with KATRIN

Tritium  $\beta$ -decay



Electron spectrum



- Sensitive to **common mass scale  $m$**  for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk  
 **$m < 2.2 \text{ eV}$  (95% CL)**
- KATRIN can reach **0.2 eV**
- Under construction
- Data taking foreseen to begin in 2007



WGTS

DPS

CPS

Pre-Spectrometer

Main Spectrometer

Detector

<http://www-ik.fzk.de/katrin/>



# Extending the Mass Bound to Other Low-Mass Particles

Assume a generic hot dark matter particle that was in thermal equilibrium at some cosmological epoch

- Internal particle degrees of freedom (e.g. spin states)  $g_X$
- Mass  $m_X$
- Effective number of thermal degrees of freedom at freeze-out  $g_*$

Contribution to cosmic mass density

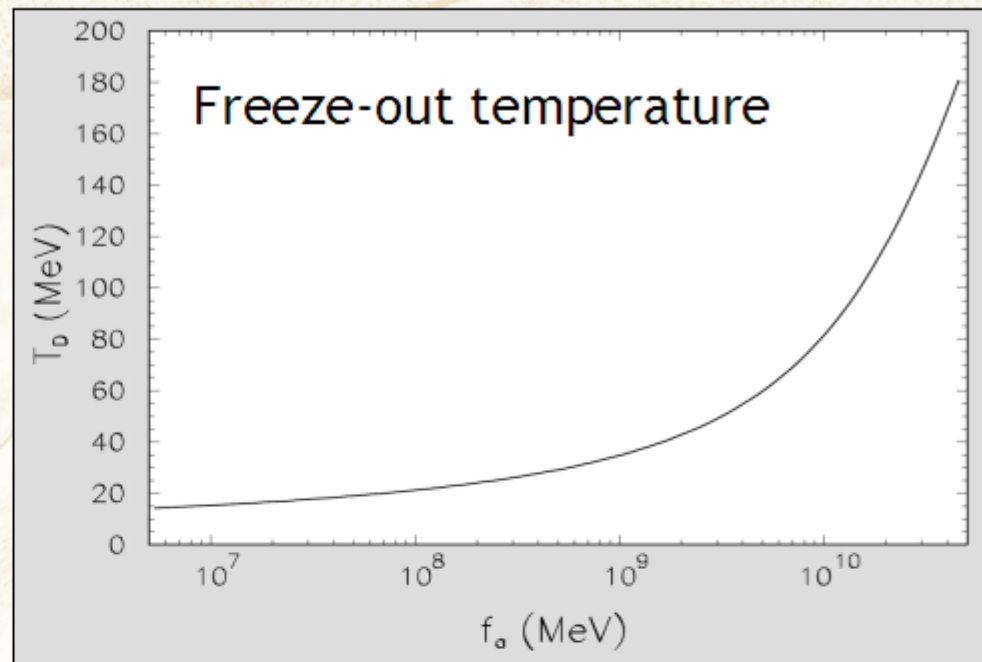
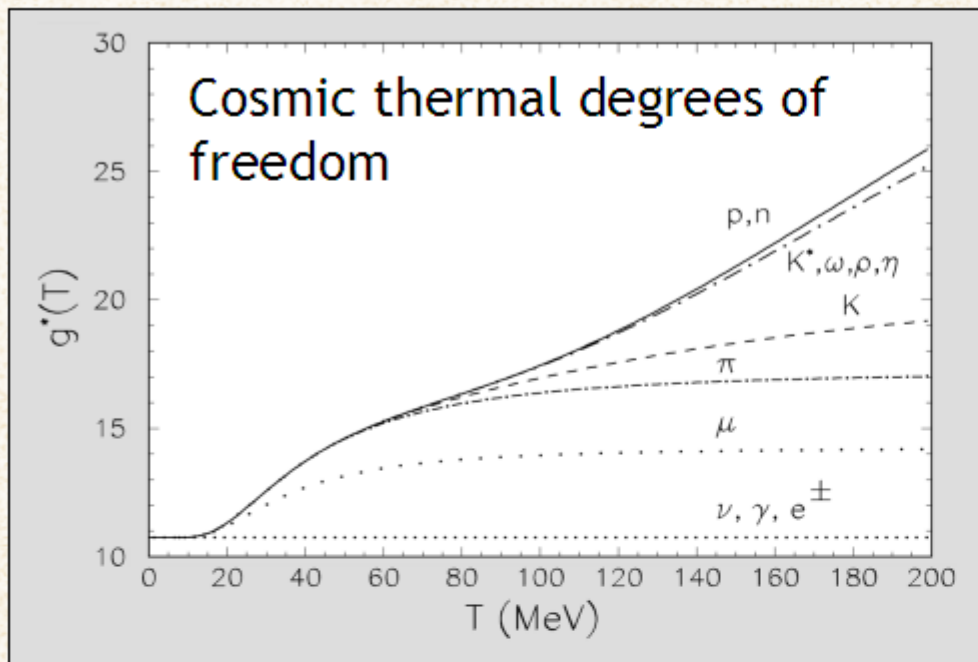
$$\Omega_X h^2 = \frac{m_X g_X}{183 \text{ eV}} \frac{10.75}{g_*} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

Free-streaming length

$$\lambda_{\text{FS}} \approx \frac{20 \text{ Mpc}}{\Omega_X h^2} \left( \frac{T_X}{T_\nu} \right)^4 \left[ 1 + \log \left( 3.9 \frac{\Omega_X}{\Omega_m} \frac{T_\nu^2}{T_X^2} \right) \right]$$

Perform maximum likelihood analysis for different choices of  $g_X$  and  $g_*$  to derive cosmological limit on  $m_X$

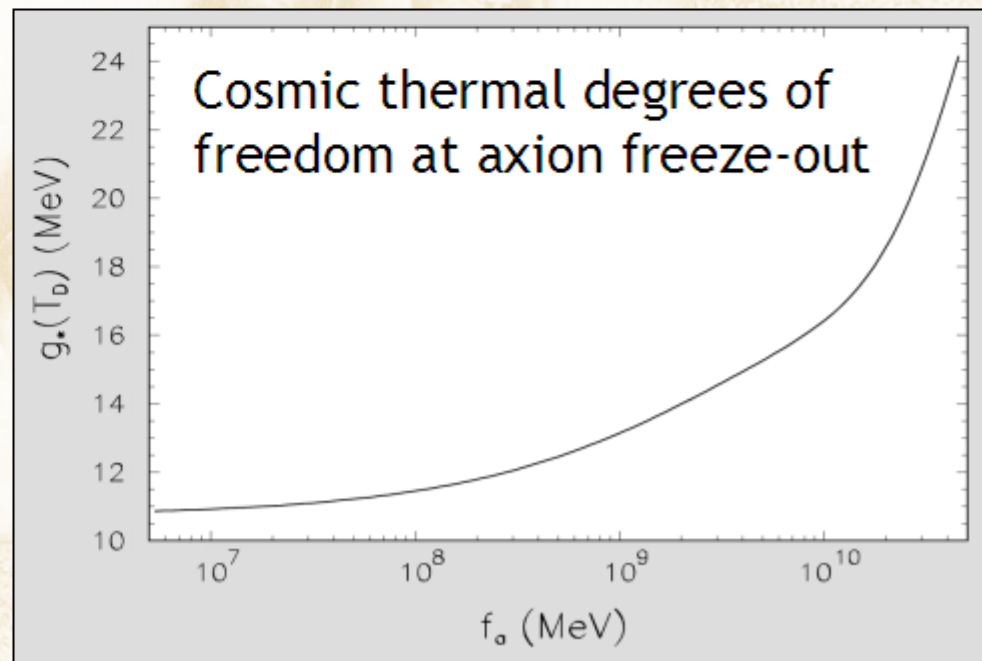
# Axion Freeze-Out



$$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi} (\pi^0 \pi^+ \partial_\mu \pi^- + \pi^0 \pi^- \partial_\mu \pi^+ - 2\pi^+ \pi^- \partial_\mu \pi^0) \partial^\mu a$$

$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

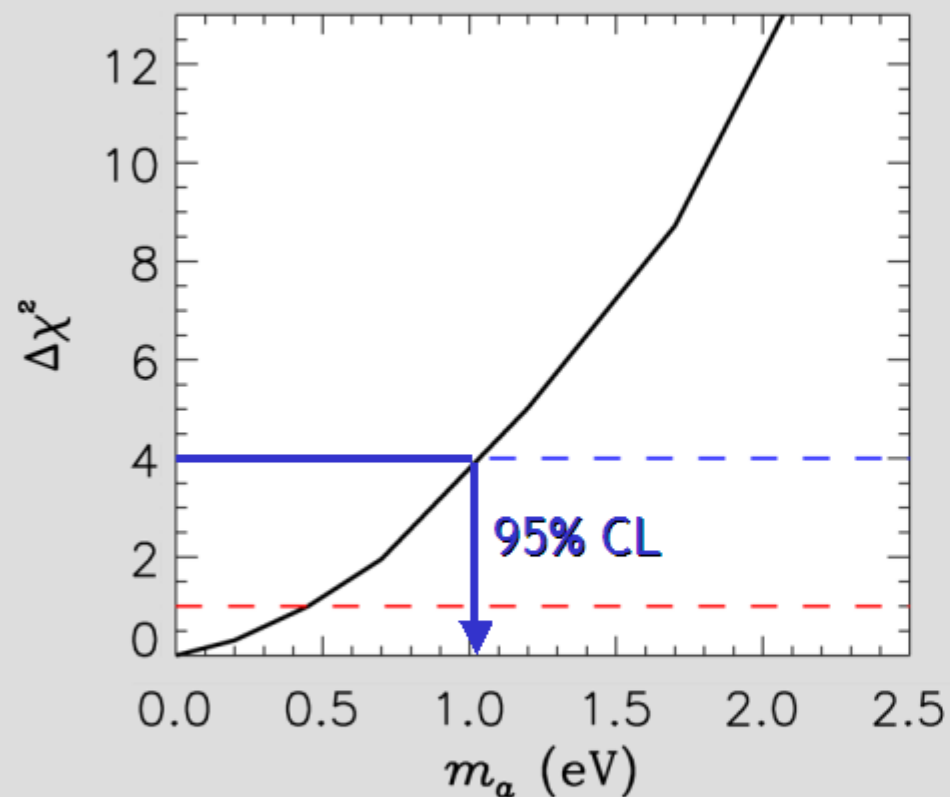
Chang & Choi, PLB 316 (1993) 51





# Mass Limits on Hot Dark Matter Axions and Neutrinos

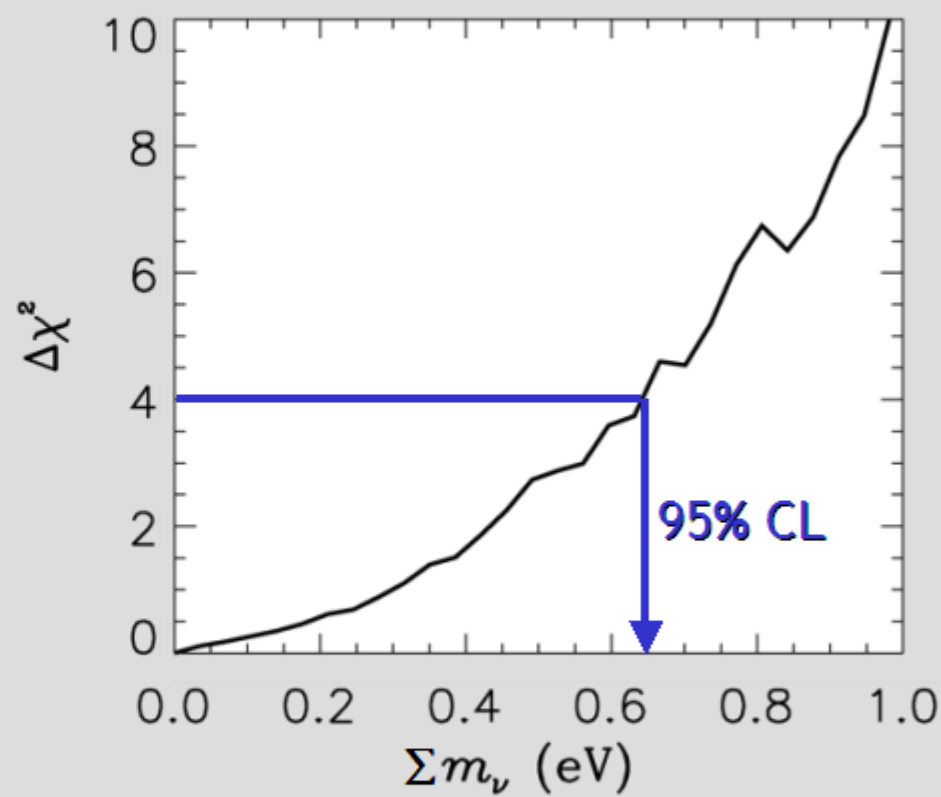
Hannestad, Mirizzi & Raffelt  
hep-ph/0504059



Axions

$$m_a < 1.05 \text{ eV (95% CL)}$$

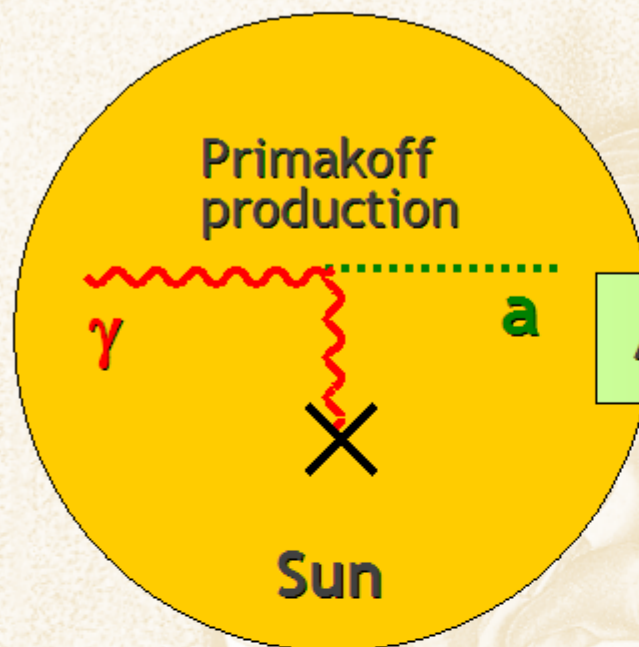
Hannestad, astro-ph/0409108  
(Seesaw proceedings, Paris, 2004)



Neutrinos

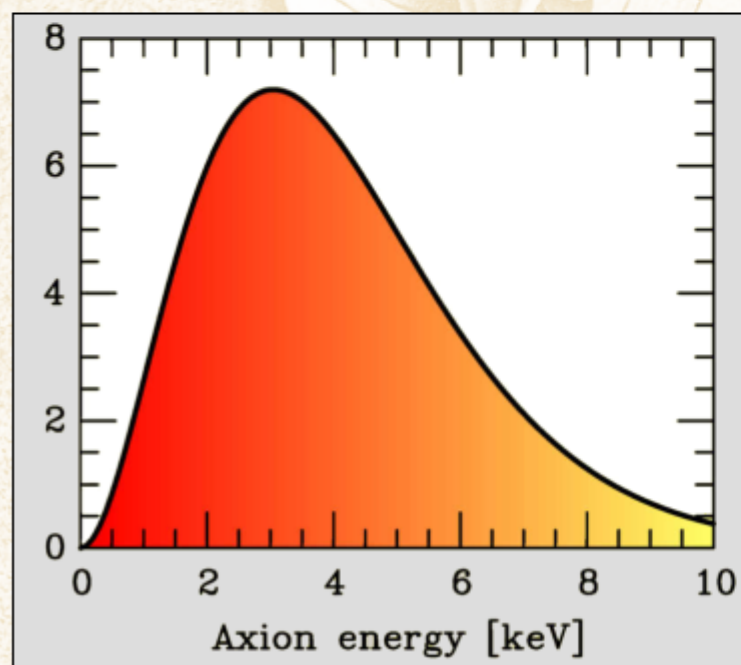
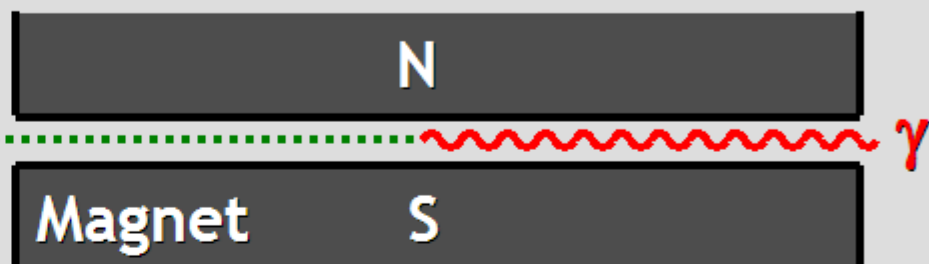
$$\Sigma m_\nu < 0.65 \text{ eV (95% CL)}$$

# Search for Solar Axions



## Axion Helioscope (Sikivie 1983)

### Axion-Photon-Oscillation



- Tokyo Axion Helioscope (Results since 1998)
- CERN Axion Solar Telescope (CAST) (Result since 2003)

### Alternative technique:

#### Bragg conversion in crystal

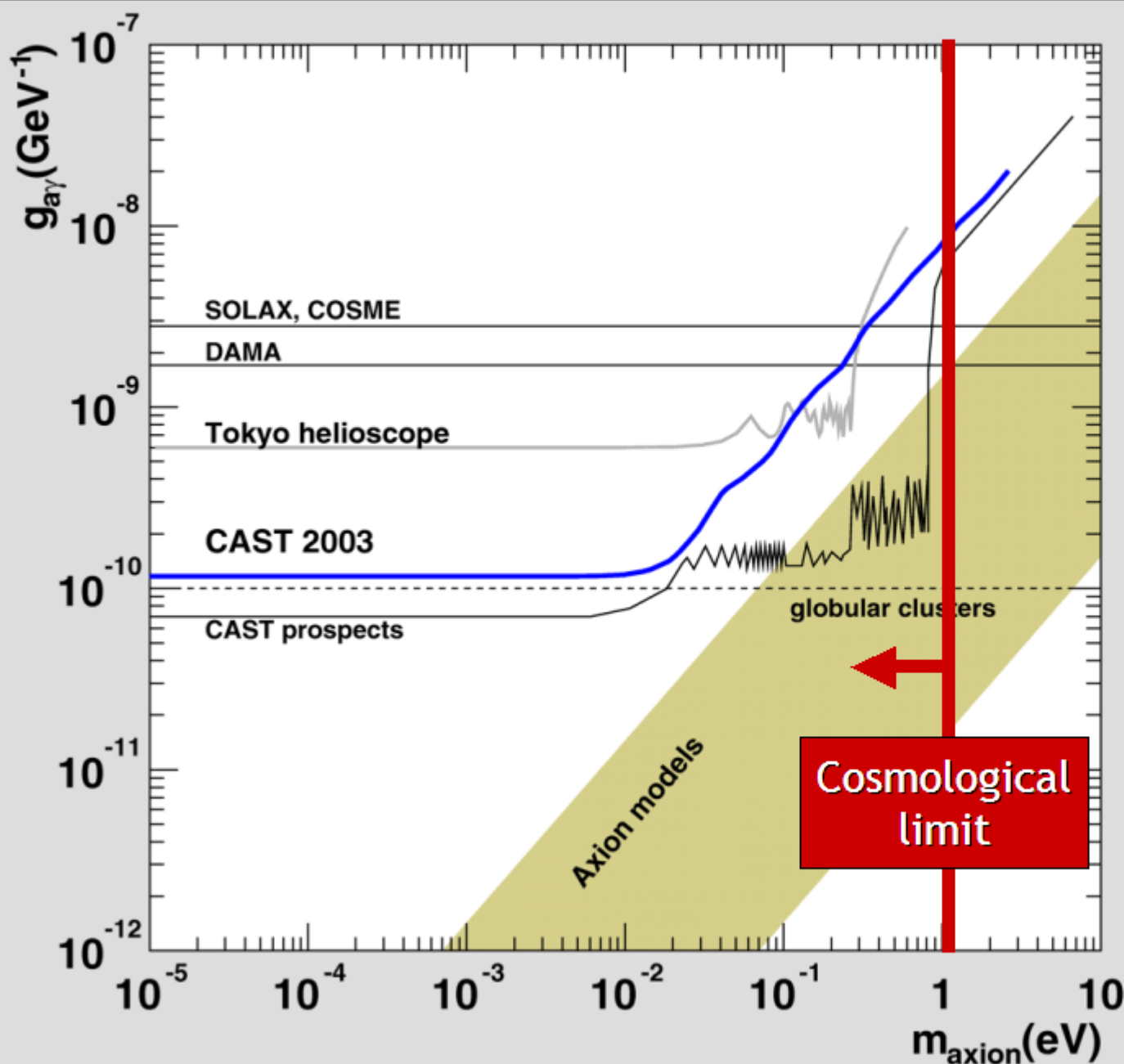
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)



# CAST Movies



# Results and Prospects of the CAST Experiment



CAST Collaboration:  
First results from the  
CERN Axion Solar  
Telescope (CAST)  
PRL, in press (2005)  
(hep-ex/0411033)

CAST Phase II and  
future cosmological  
sensitivity probably  
connect



# The Standard Model of Elementary Particles

quarks

u UP	c CHARM	t TOP
d DOWN	s STRANGE	b BOTTOM
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino
e	$\mu$ muon	$\tau$ tau

EM force $\gamma$ photon
STRONG force g gluon
WEAK force W W boson
WEAK force Z Z boson

force carriers

Dark Energy 73%  
(Cosmological Constant)

Leptogenesis

Ordinary Matter 4%  
(of this only about 10% luminous)

Dark Matter 23%

Neutrinos 0.1–2%







