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 β-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 β-Spektrum wäre dann verständlich unter der Annahme, daß beim β-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 γ-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 β-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.

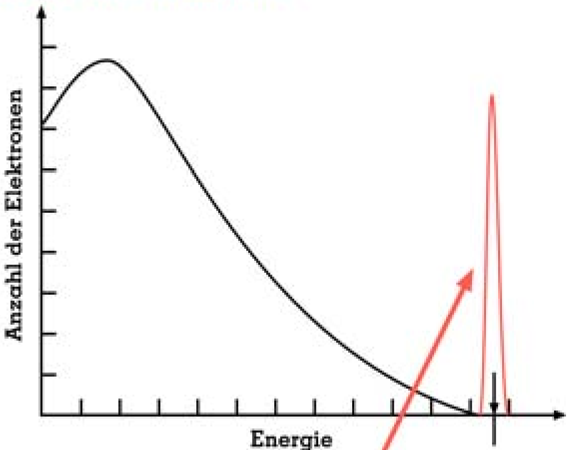
Also, liebe Radioaktive, prüfet und richtet.

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 β-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.

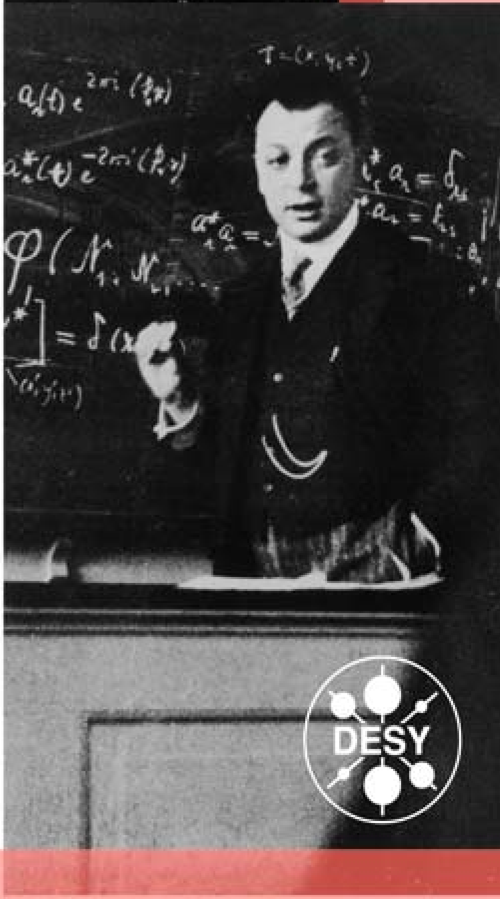


Erwartung für zwei Teilchen im Endzustand

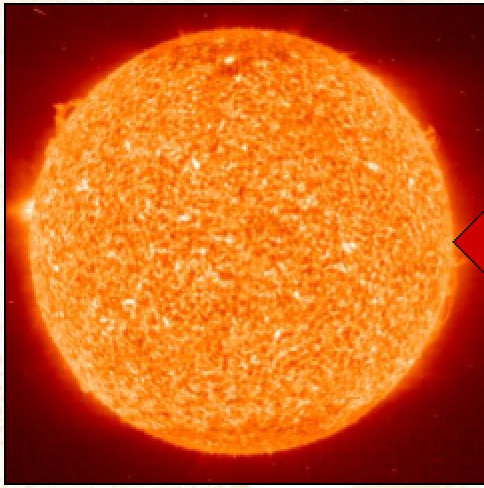
Es sind aber drei!

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

Wolfgang Pauli



Sun Glasses for Neutrinos?

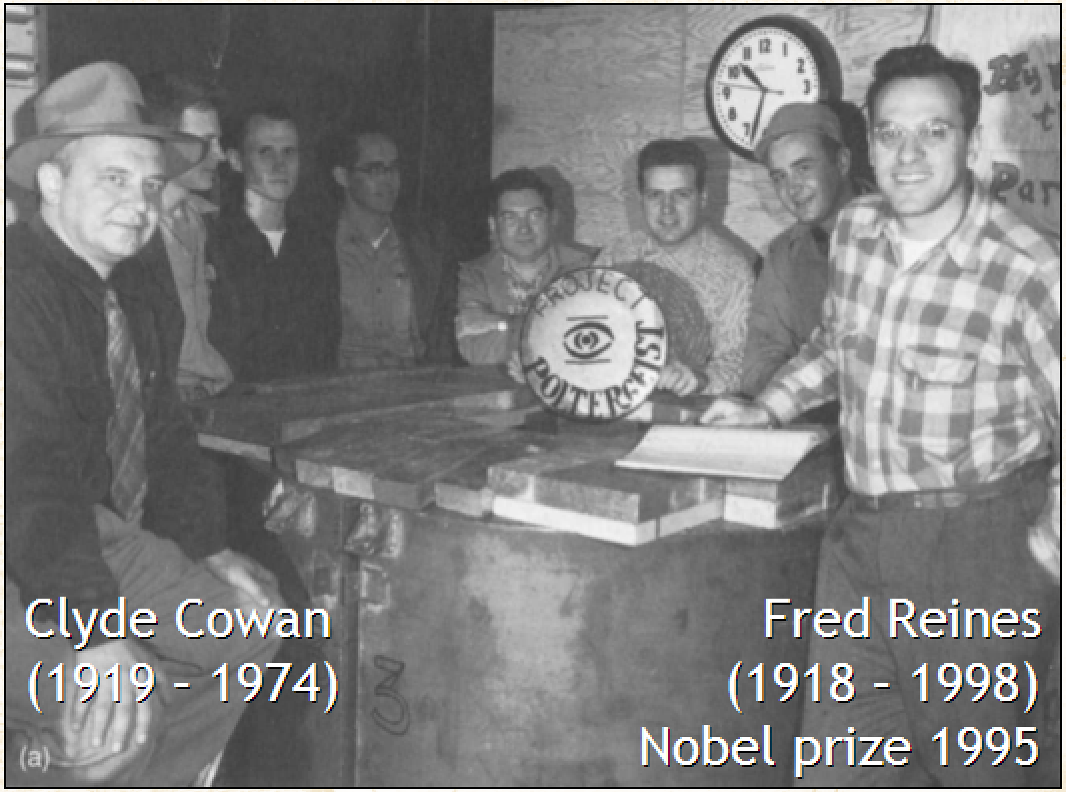


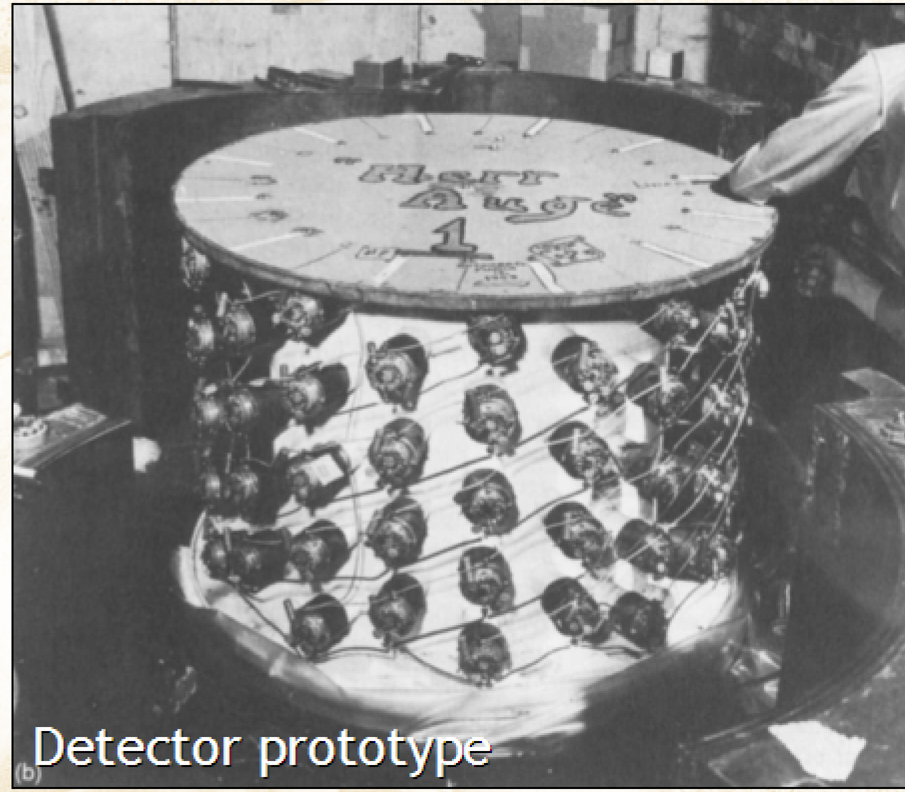
8.3 light minutes

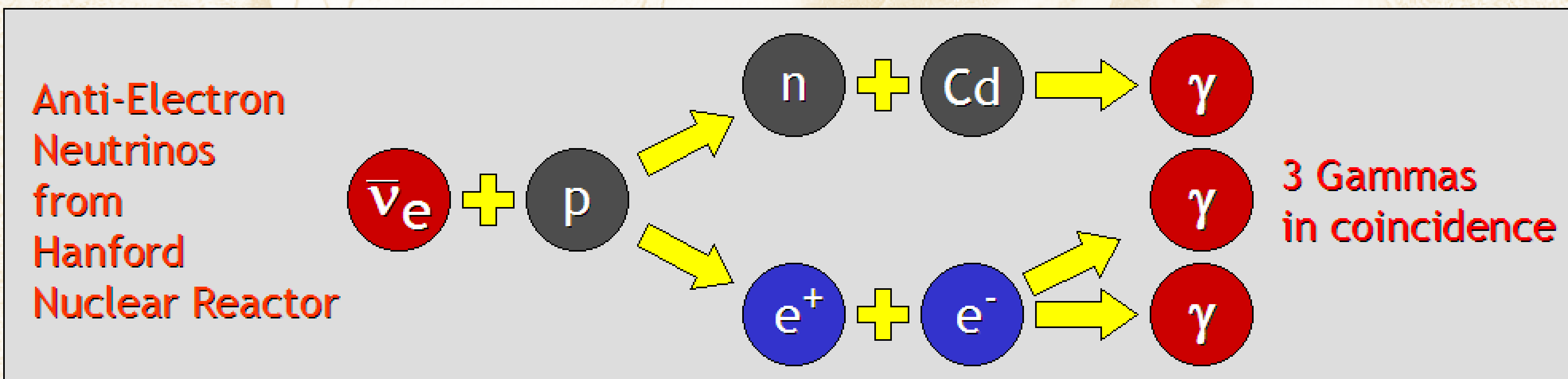
1000 light years of lead needed to shield solar neutrinos

Bethe & Peierls 1934:
"… this evidently means that one will never be able to observe a neutrino."

First Detection (1954 - 1956)

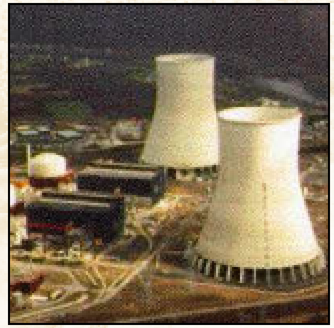


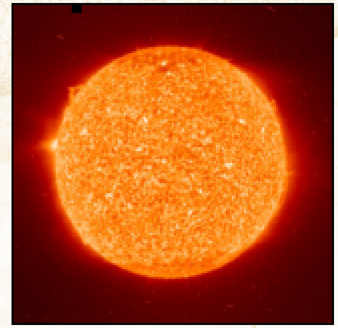




Where do Neutrinos Appear in Nature?

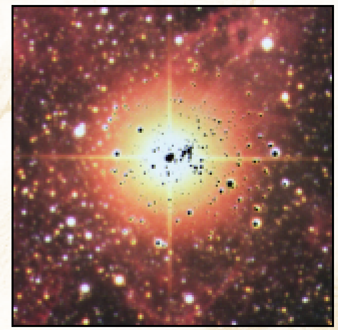
✔ Nuclear Reactors





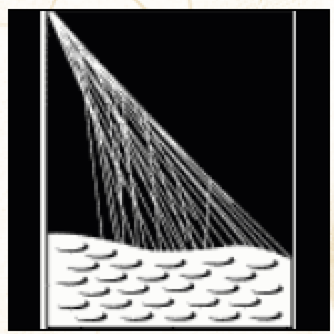
Sun ✔

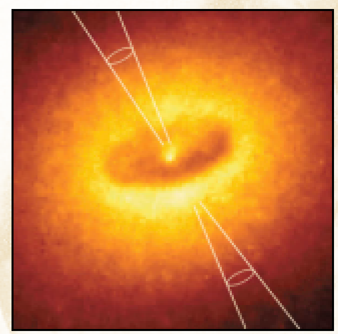
✔ Particle Accelerators



Supernovae
(Stellar Collapse)
SN 1987A ✔

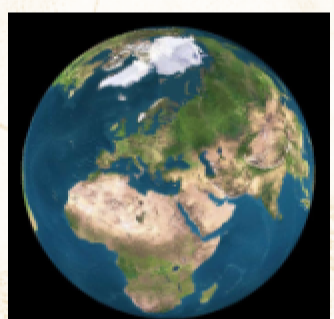
✔ Earth Atmosphere
(Cosmic Rays)

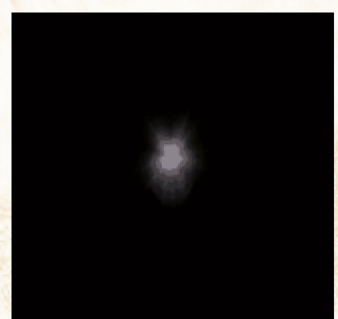




Astrophysical
Accelerators Soon ?

✔ Earth Crust
(Natural
Radioactivity)





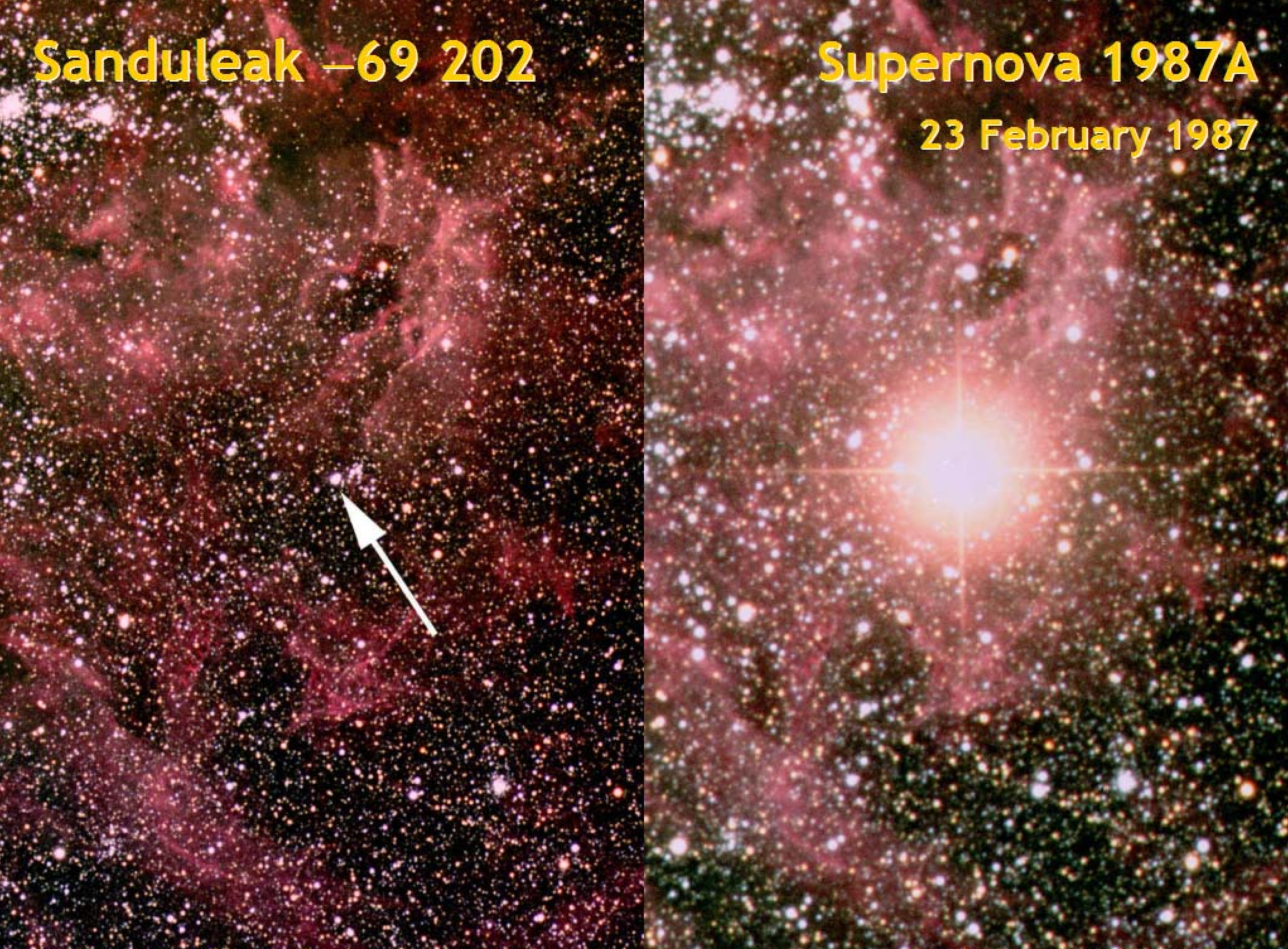
Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Supernova Neutrinos


Sanduleak −69 202

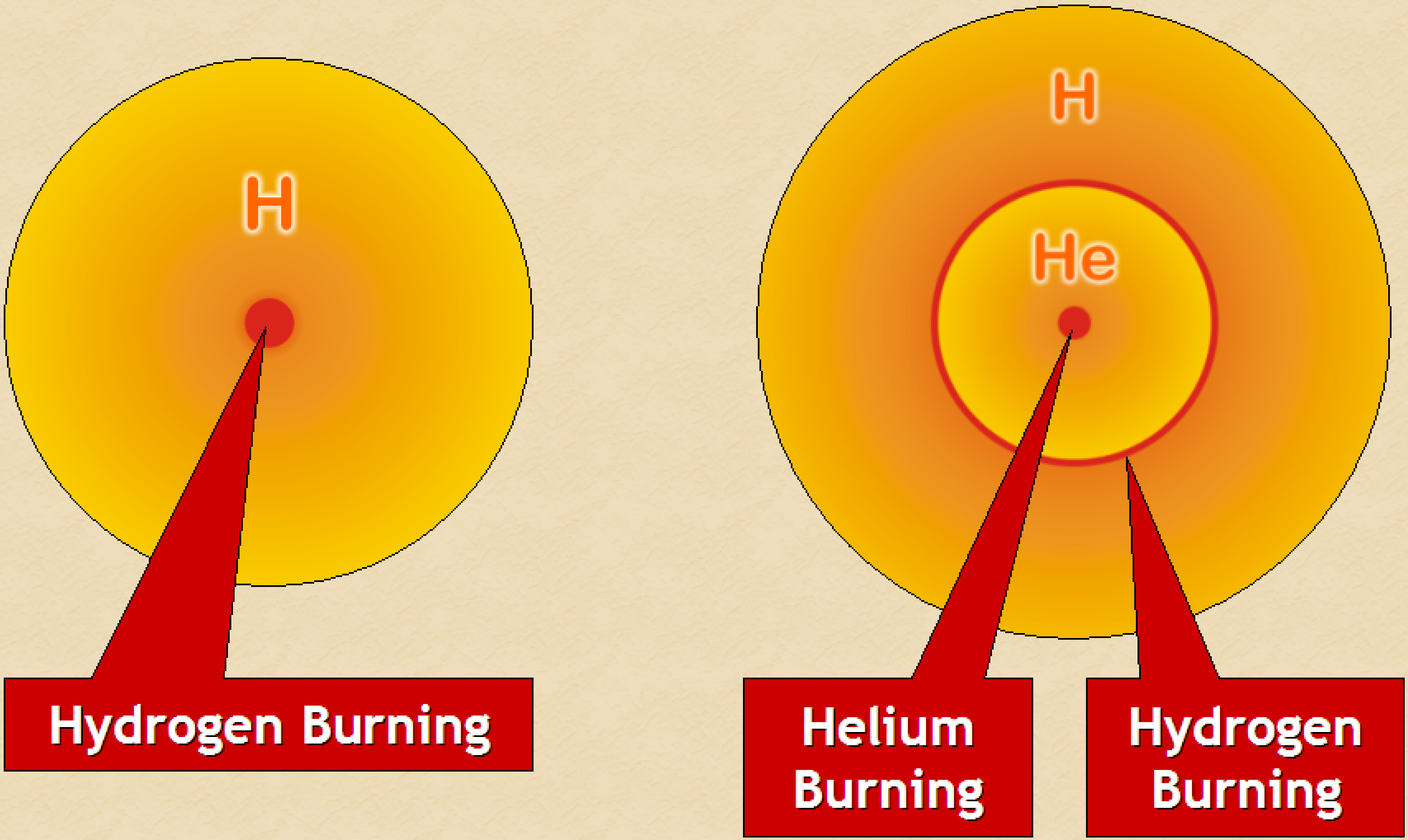

Tarantula Nebula


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak −69 202
Supernova 1987A
23 February 1987

Stellar Collapse and Supernova Explosion

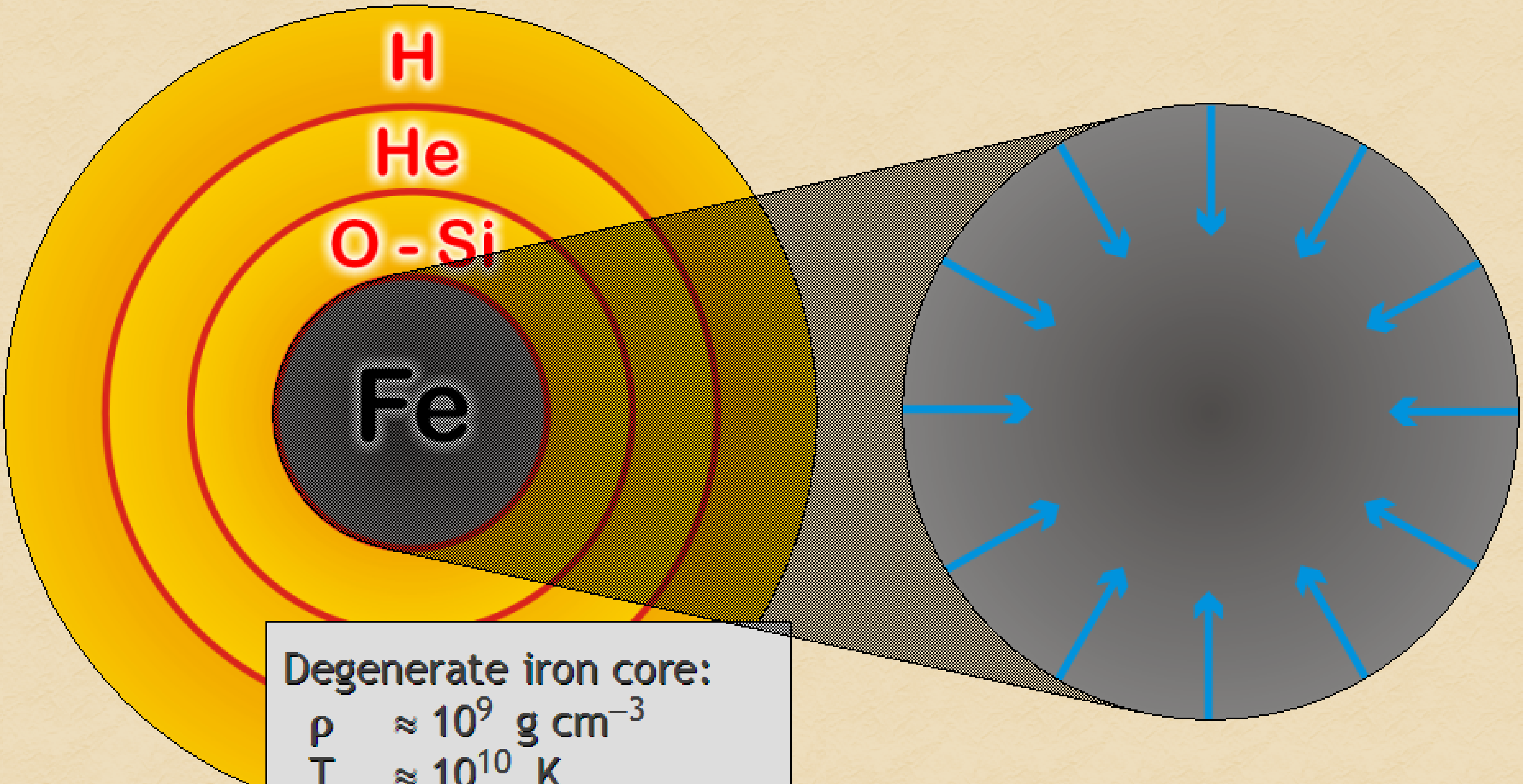
Main-sequence star | **Helium-burning star**



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

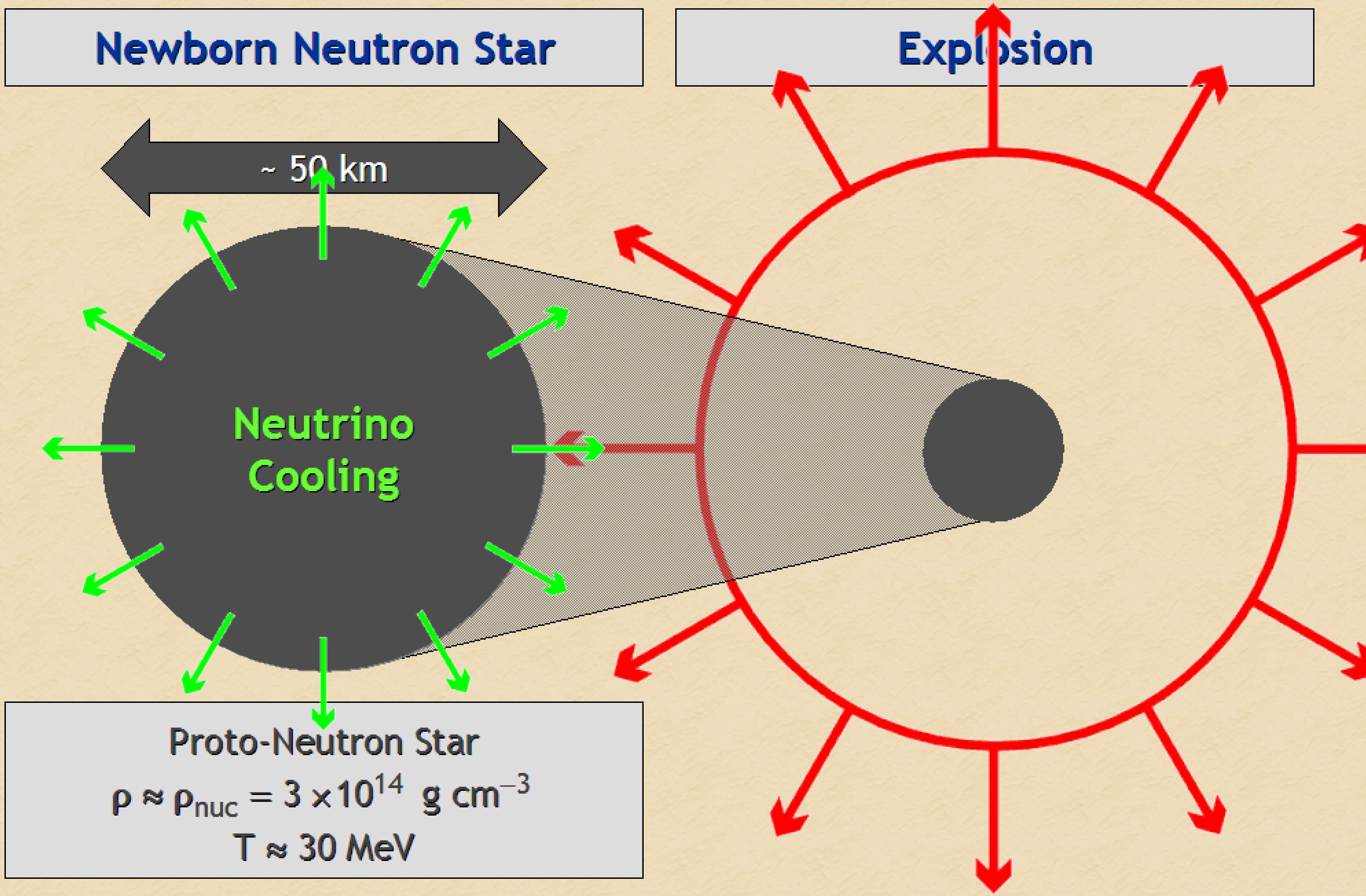
$\rho \approx 10^{9}\ \mathrm{g\ cm^{-3}}$

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

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

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

Stellar Collapse and Supernova Explosion



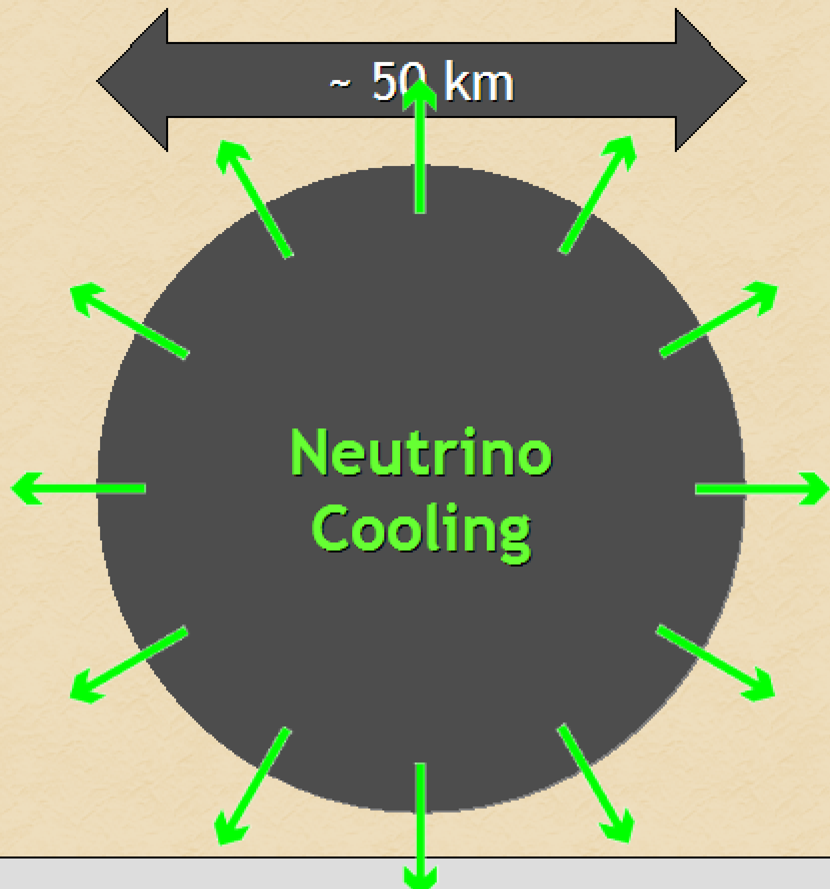
Proto-Neutron Star

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

$T \approx 30$ MeV

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

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

Gravitational binding energy

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

This shows up as

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

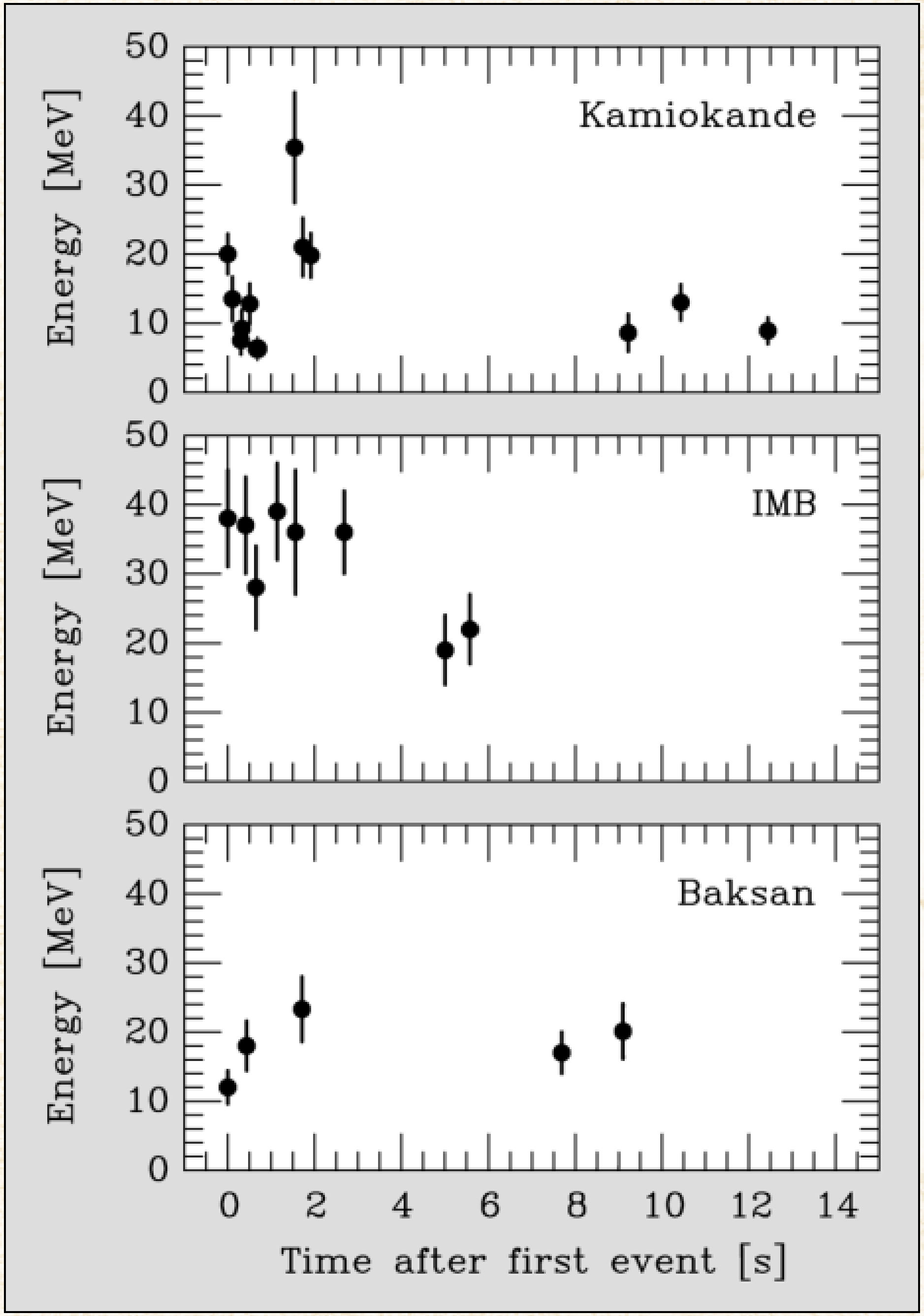
Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



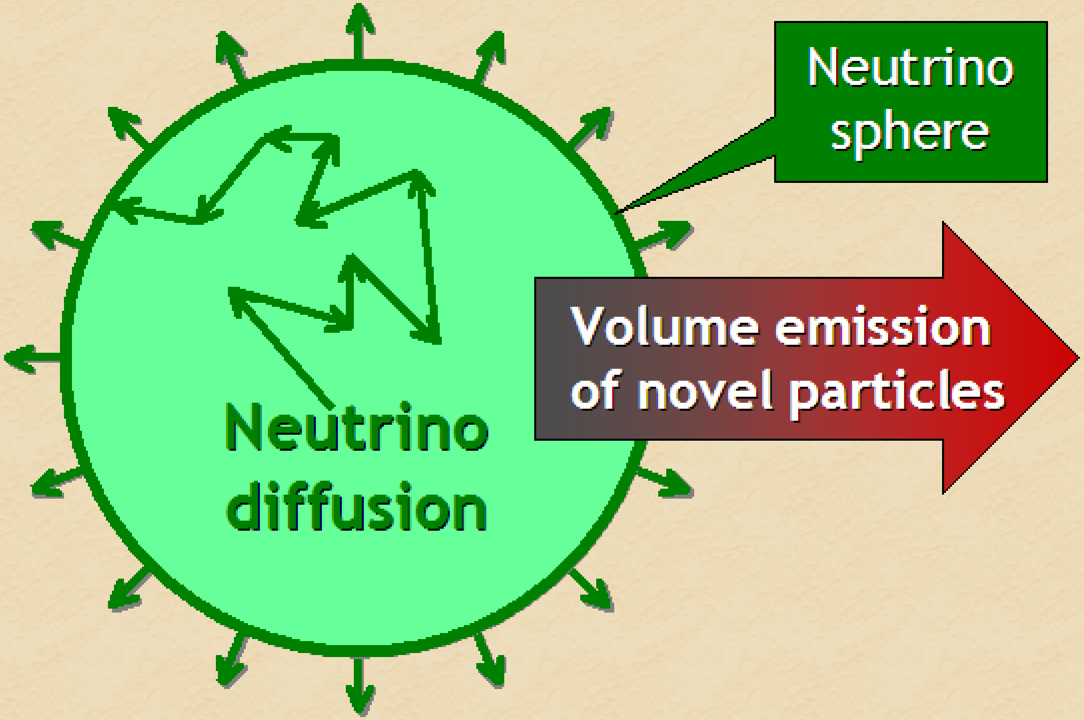
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

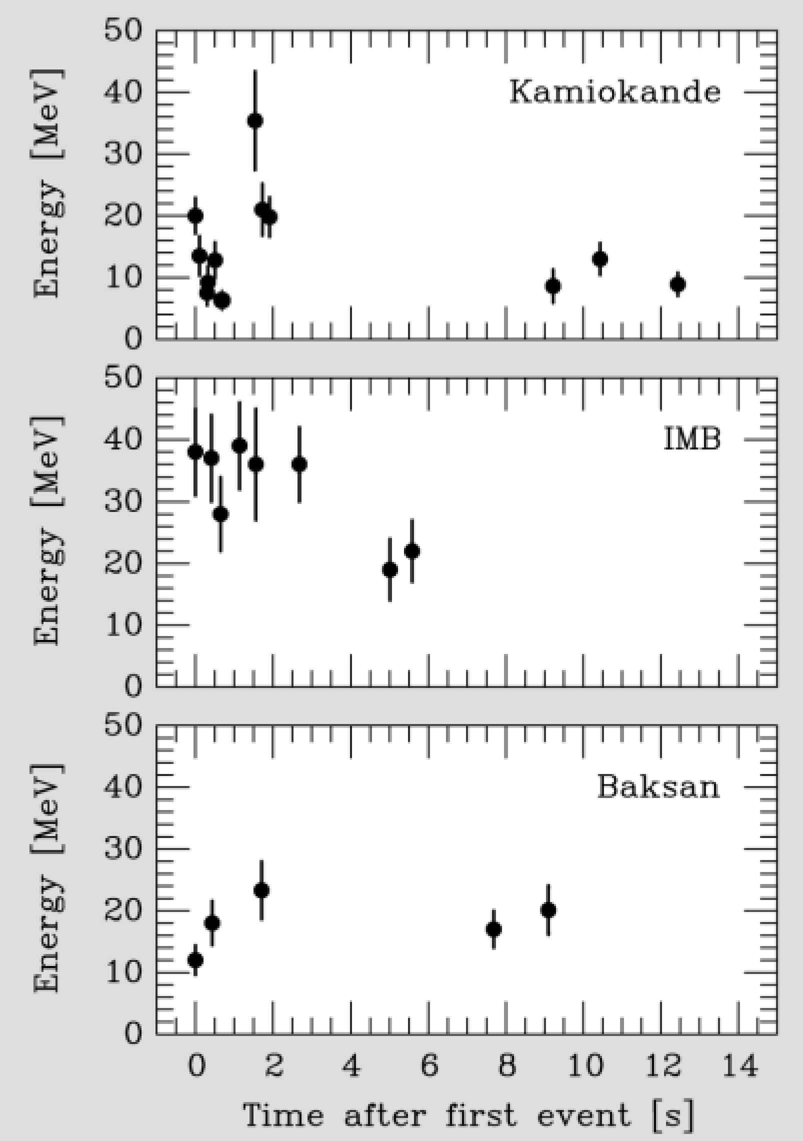
Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

The Energy-Loss Argument



SN 1987A neutrino signal



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

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

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Single issue price Dfl. 85.00, postage included.

David Schramm
(Editor University of Chicago Press)

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

David Schramm put me to work …

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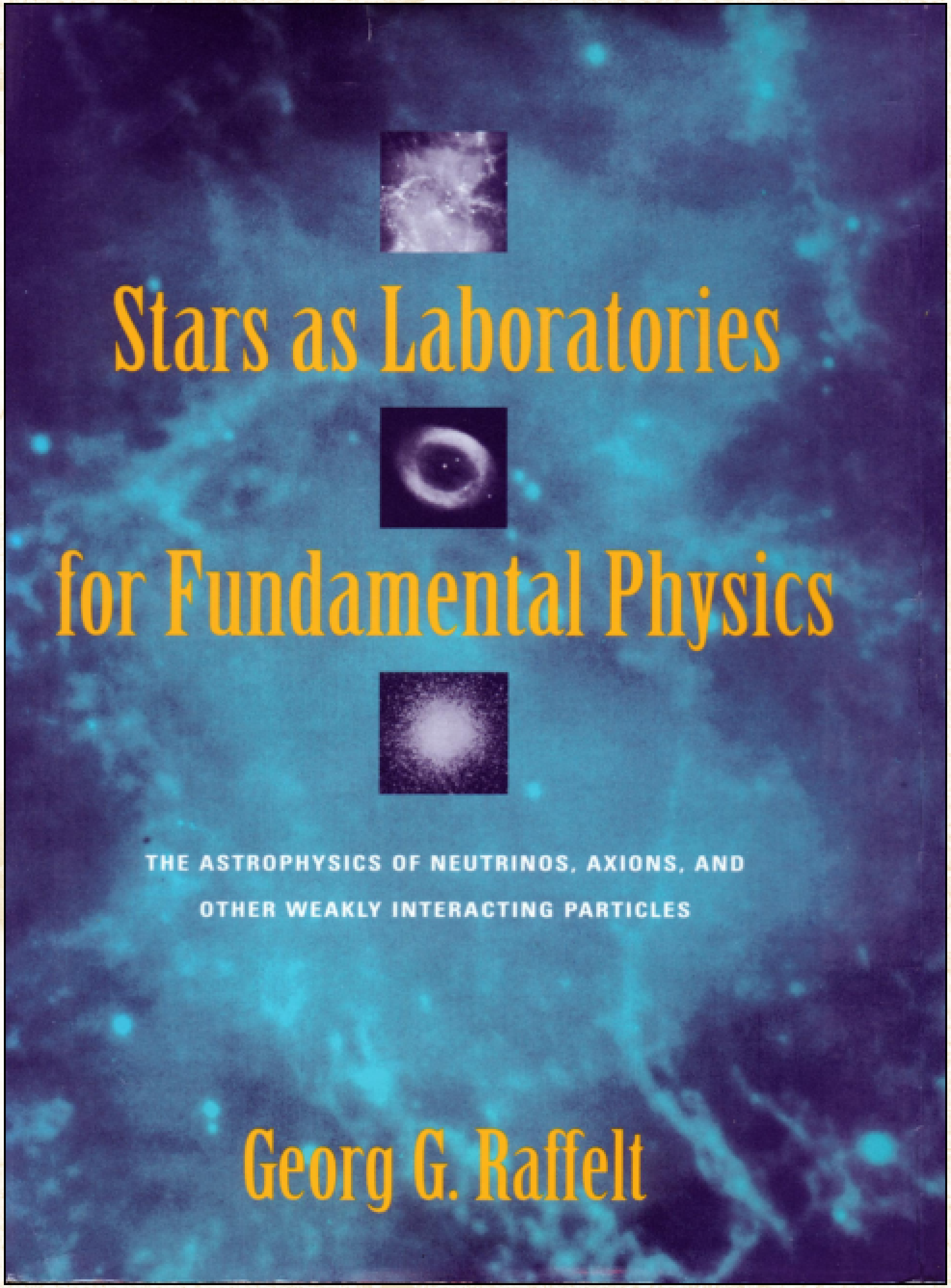
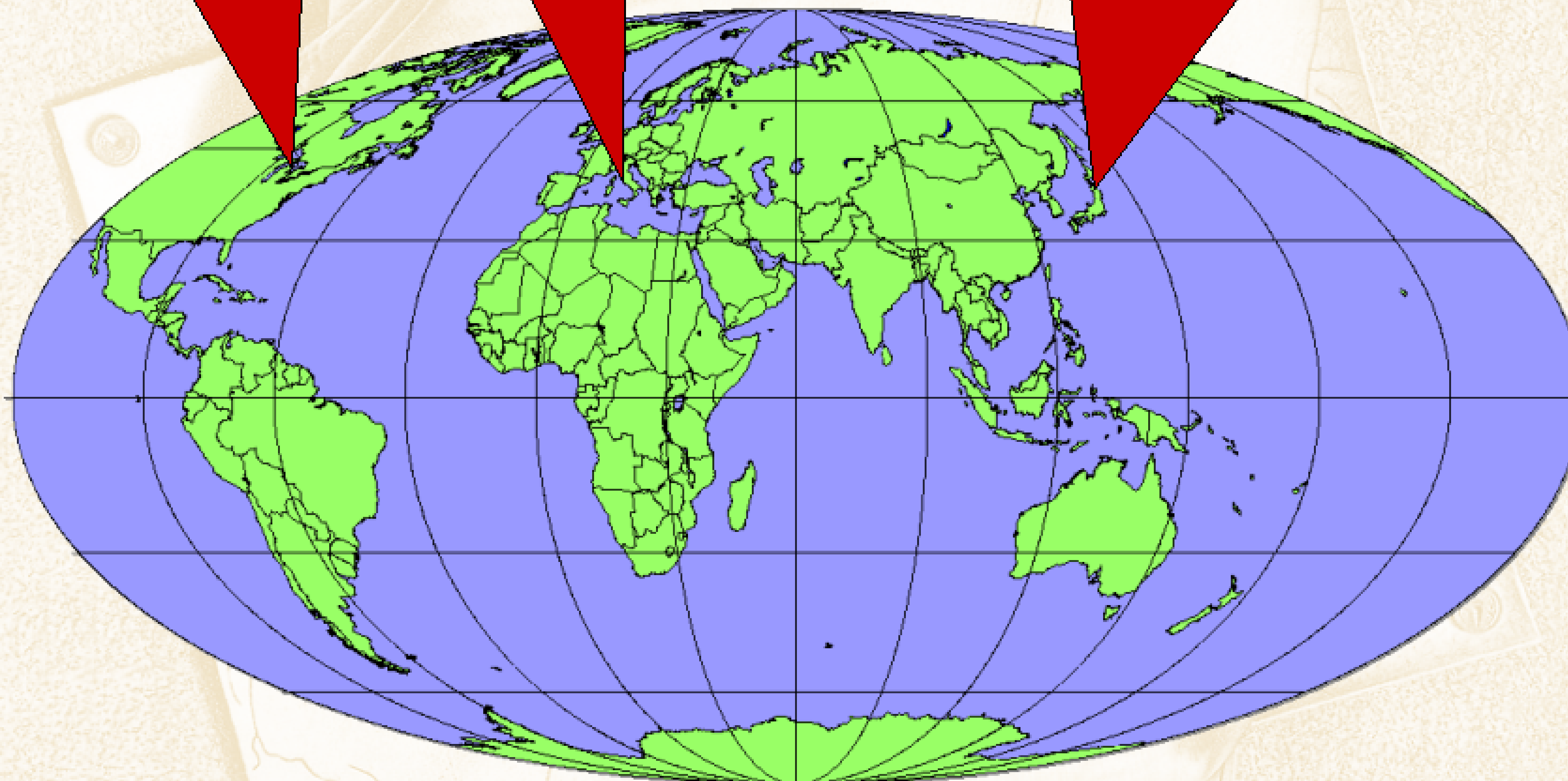


Large Detectors for Supernova Neutrinos

SNO (800)
MiniBooNE (190)

LVD (400)
Borexino (80)

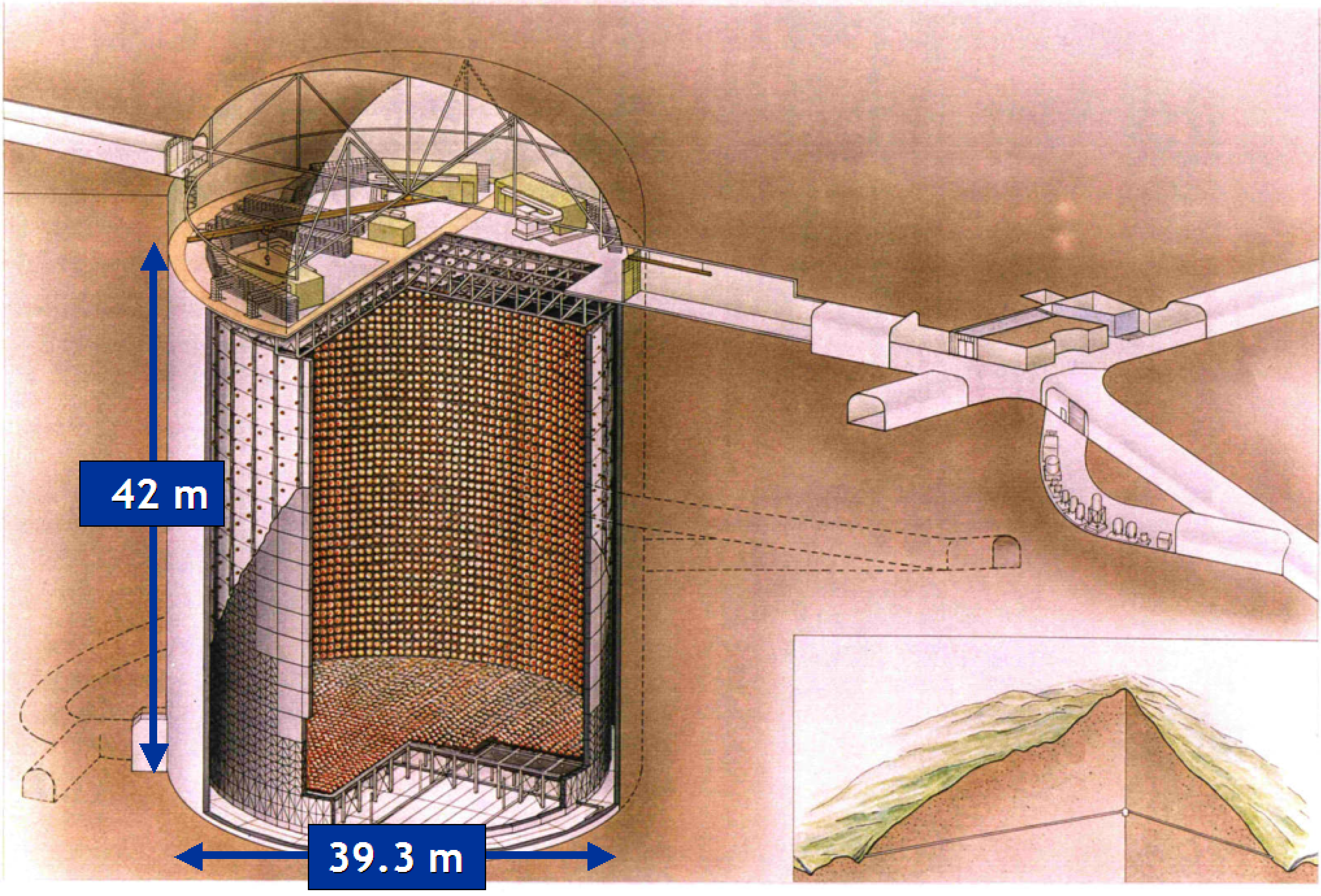
Super-Kamiokande (10^4)
Kamland (330)



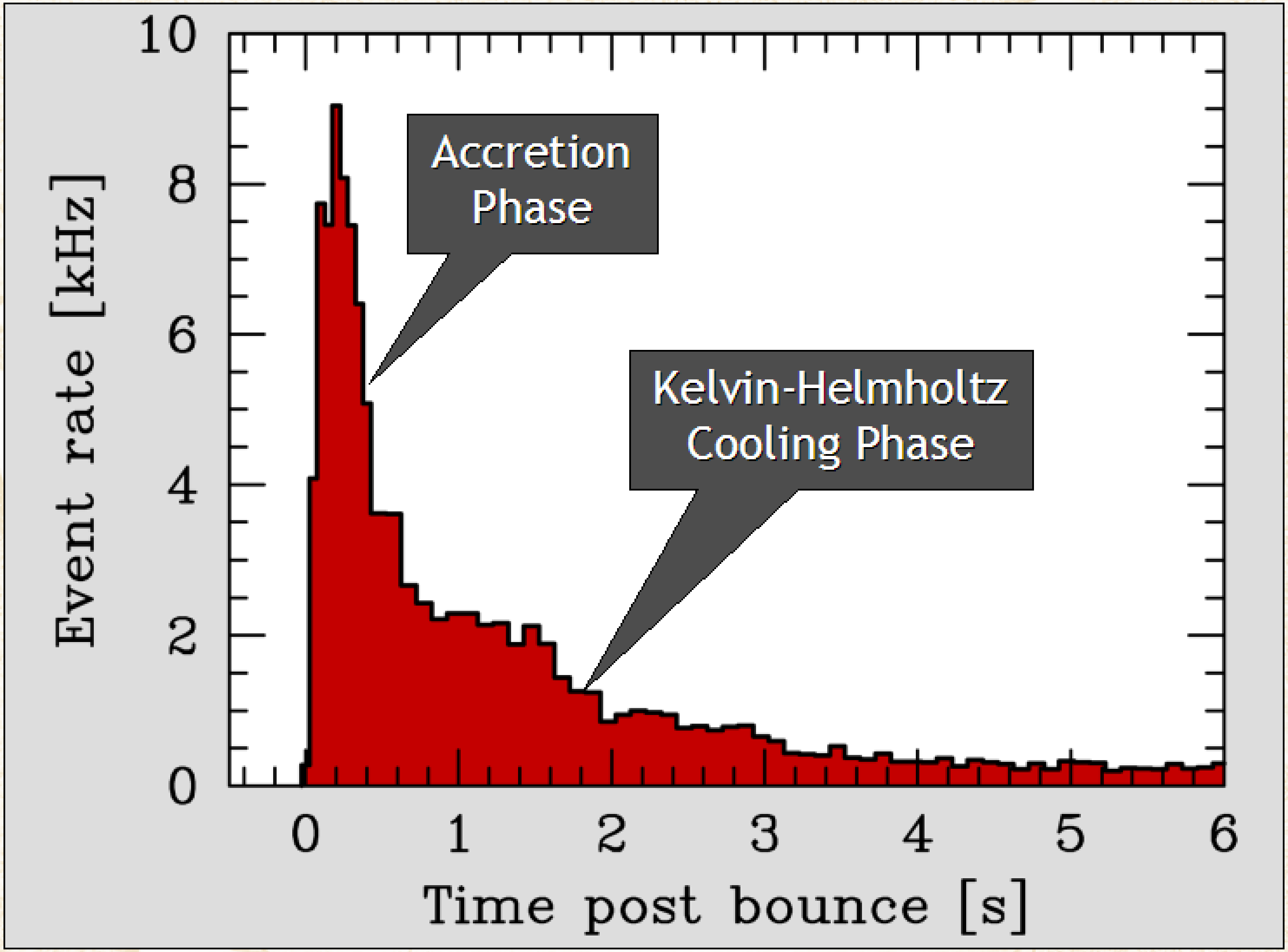
Amanda
IceCube

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

Super-Kamiokande Neutrino Detector



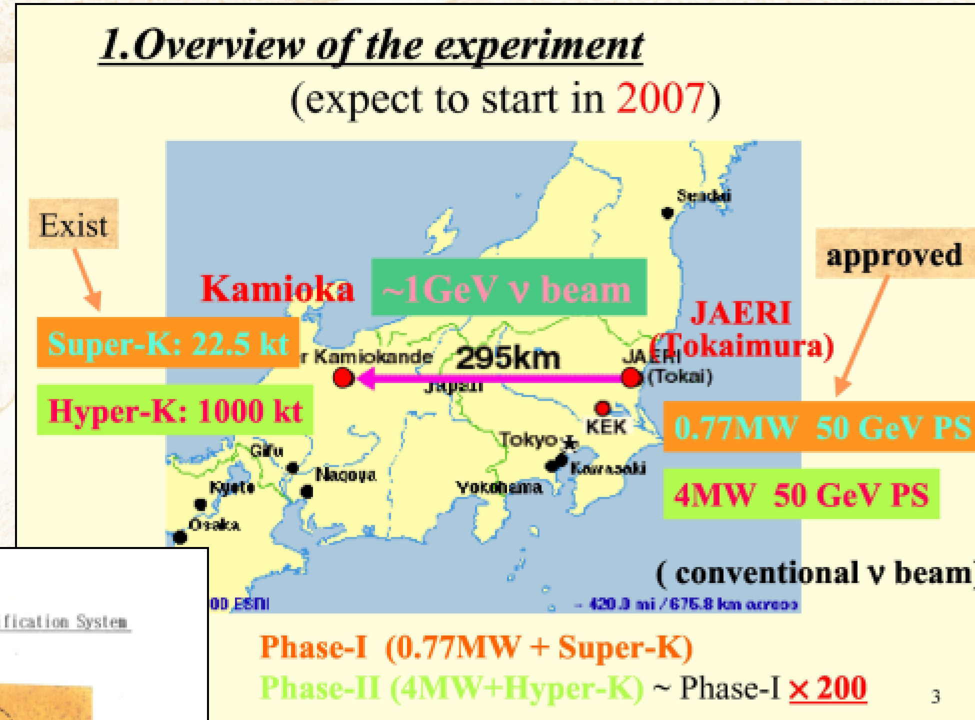
Simulated Supernova Signal at Super-Kamiokande

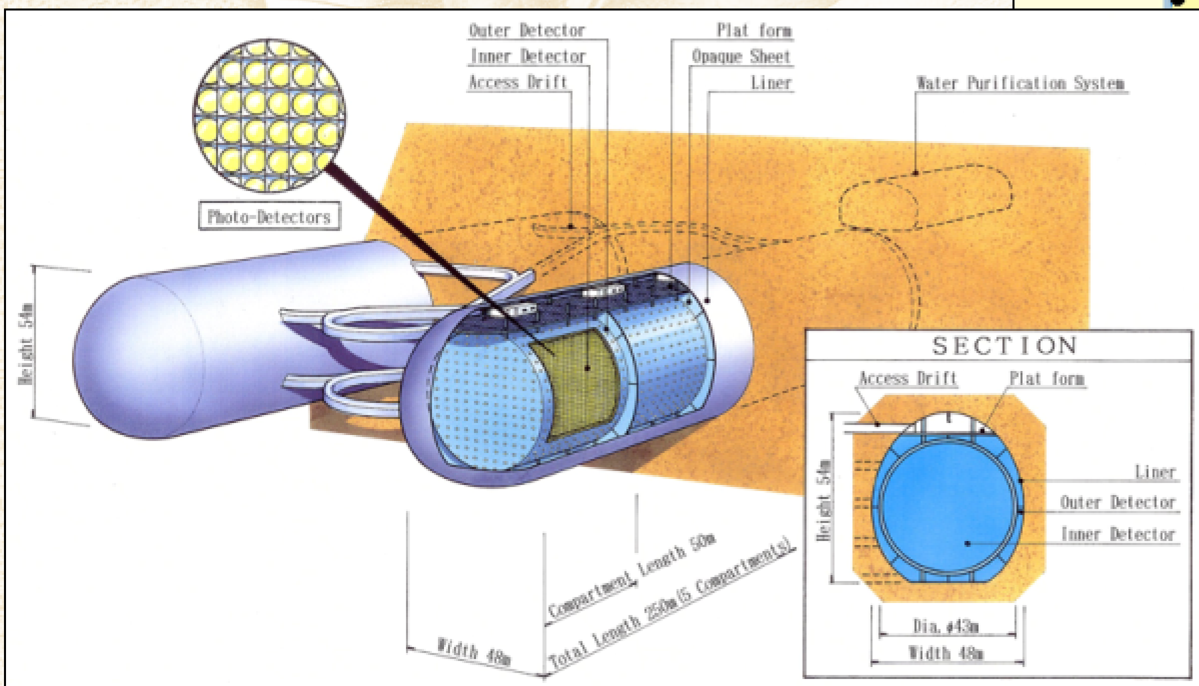


Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

The Future: A Megatonne Detector?

Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)

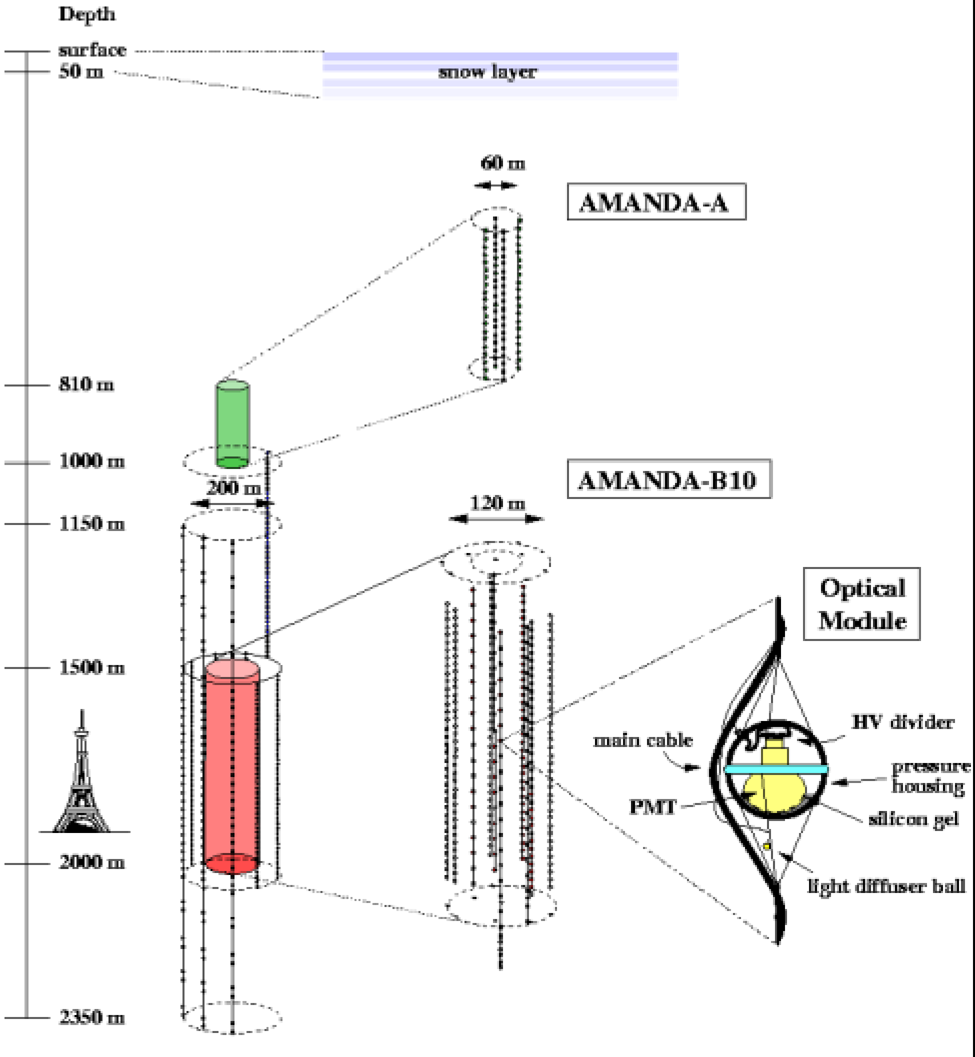




Similar discussions in
- US (UNO project)
- Europe (MEMPHYS project)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)

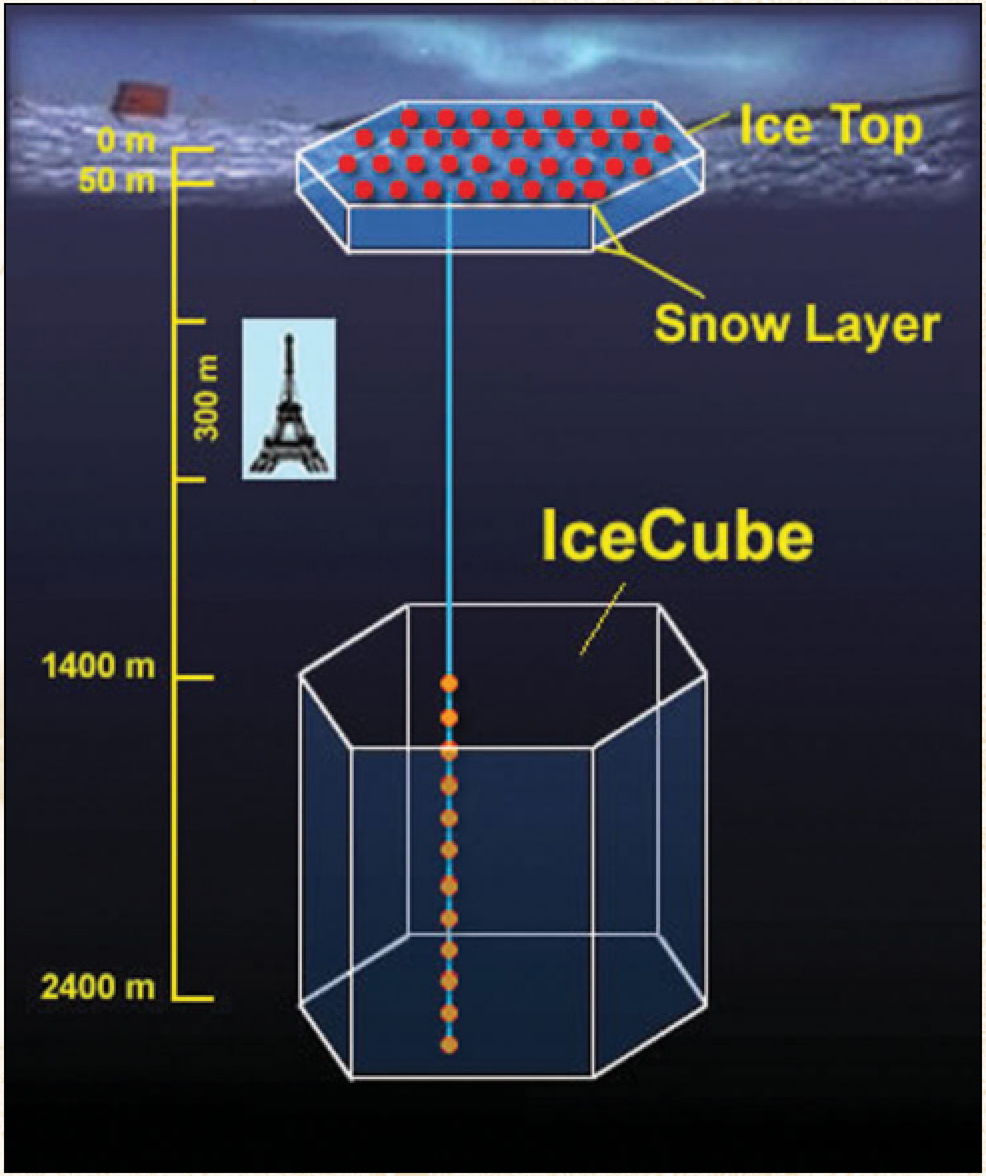


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Future IceCube (1 km^3, 4800 PMTs)

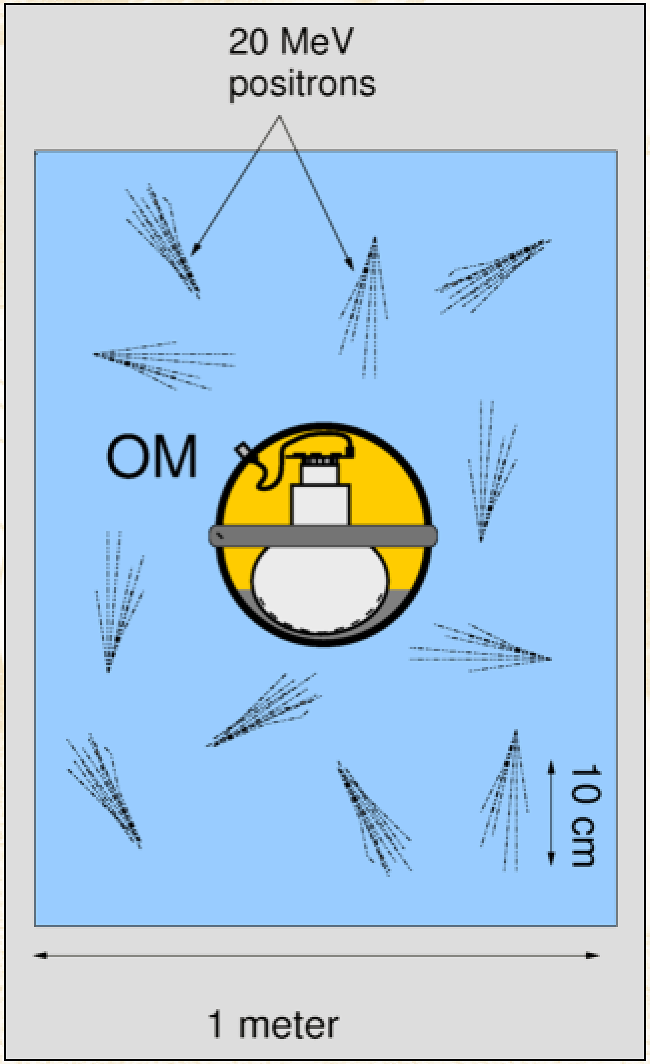


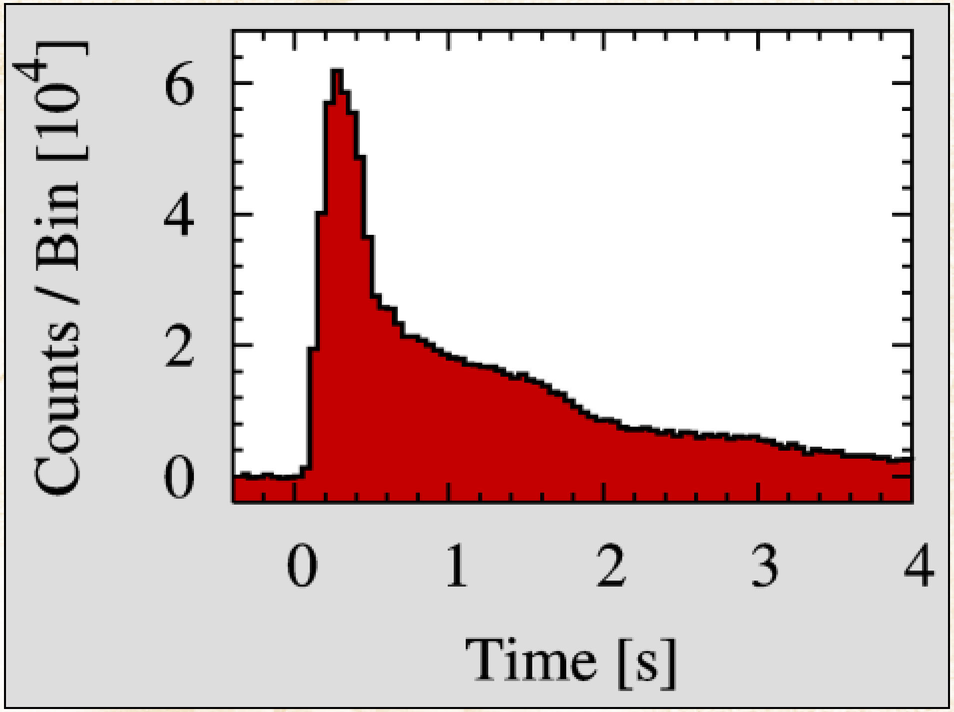
IceCube as a Supernova Neutrino Detector

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	CHOOZ	Solar/KamLAND	2σ ranges
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	hep-ph/0405172

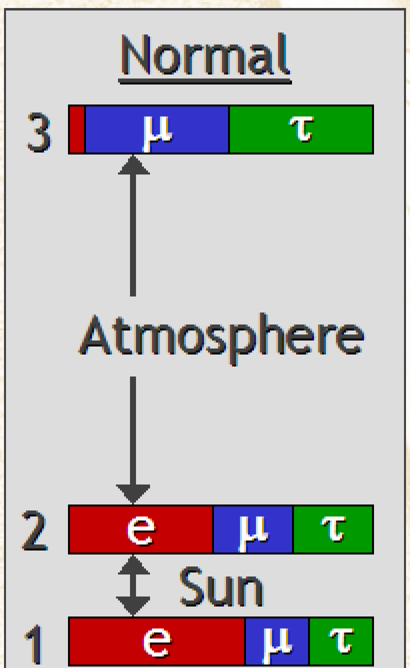
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\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

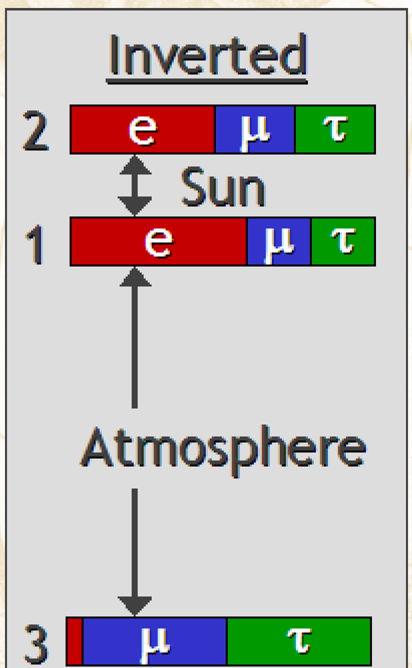
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar
75–92

Atmospheric
1400–3000

$\Delta m^2/\mathrm{meV}^2$



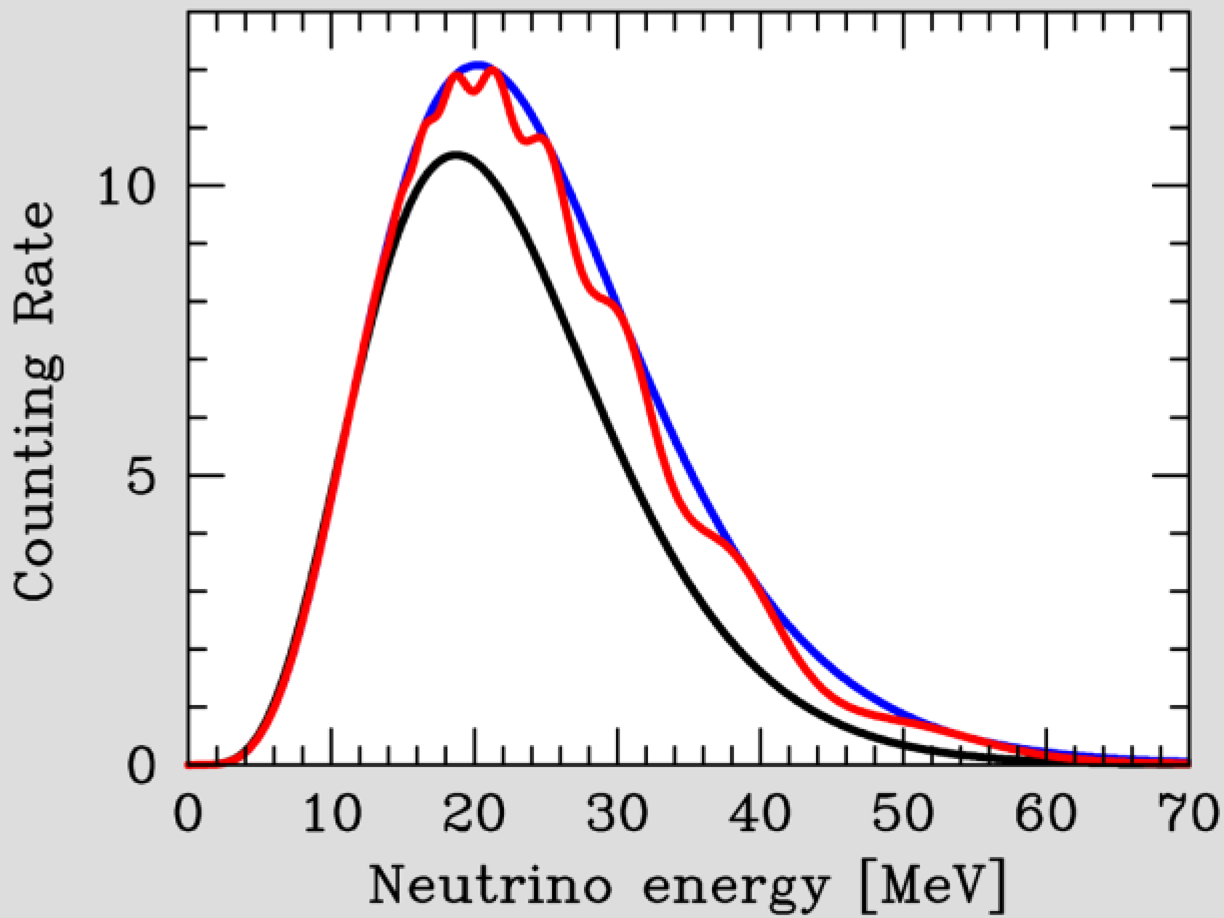


Tasks and Open Questions

- Precision for θ_{12} and θ_{23}
- How large is θ_{13}?
- CP-violating phase δ?
- 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 $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

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

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

Mixing parameters

$\Delta m^2_{\mathrm{sun}} = 60\,\mathrm{meV}^2$

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

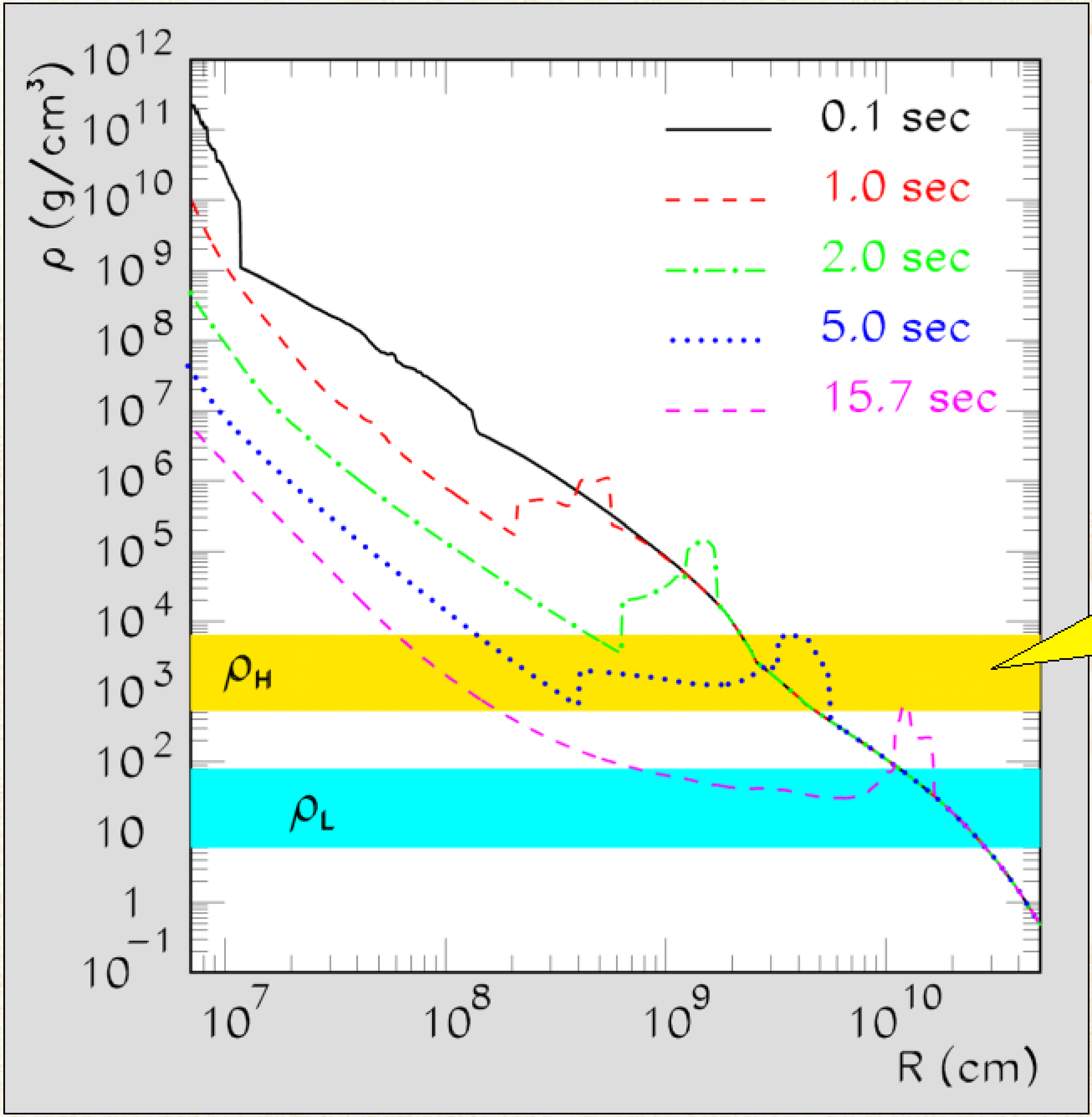
No oscillations

Oscillations in SN envelope

Earth effects included

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

Supernova Shock Propagation and Neutrino Oscillations

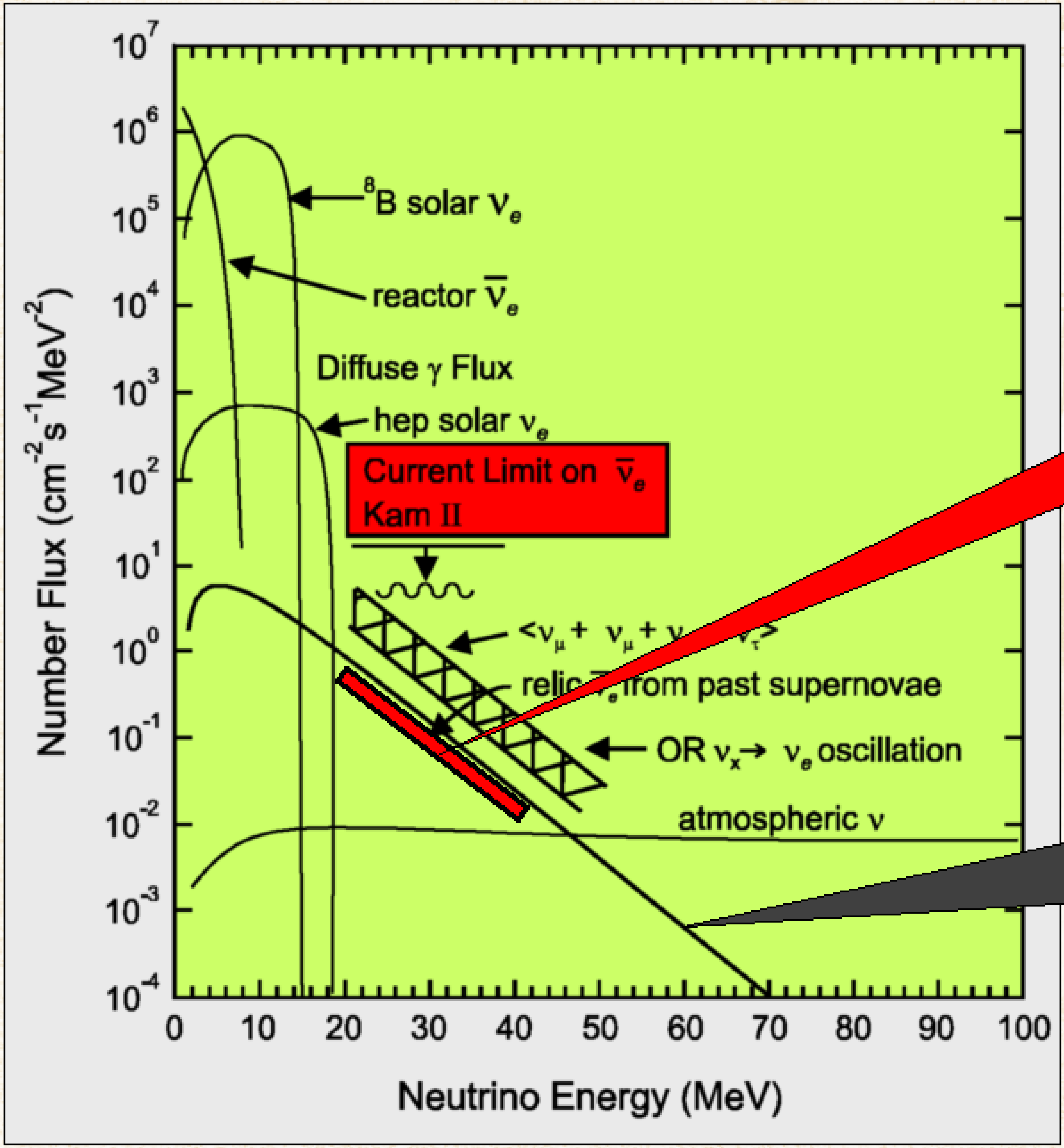


Schirato & Fuller:
Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

Resonance density for Δm^2_{atm}

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 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated 54 cm^{-2} 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 $E_\nu < 18$–19 MeV
- Sub-Cherenkov muons from atm nus
  $\mu \to e + \nu_e + \bar{\nu}_\mu$

Solution:
Neutron tagging $\bar{\nu}_e + p \to e^+ + n$

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 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]

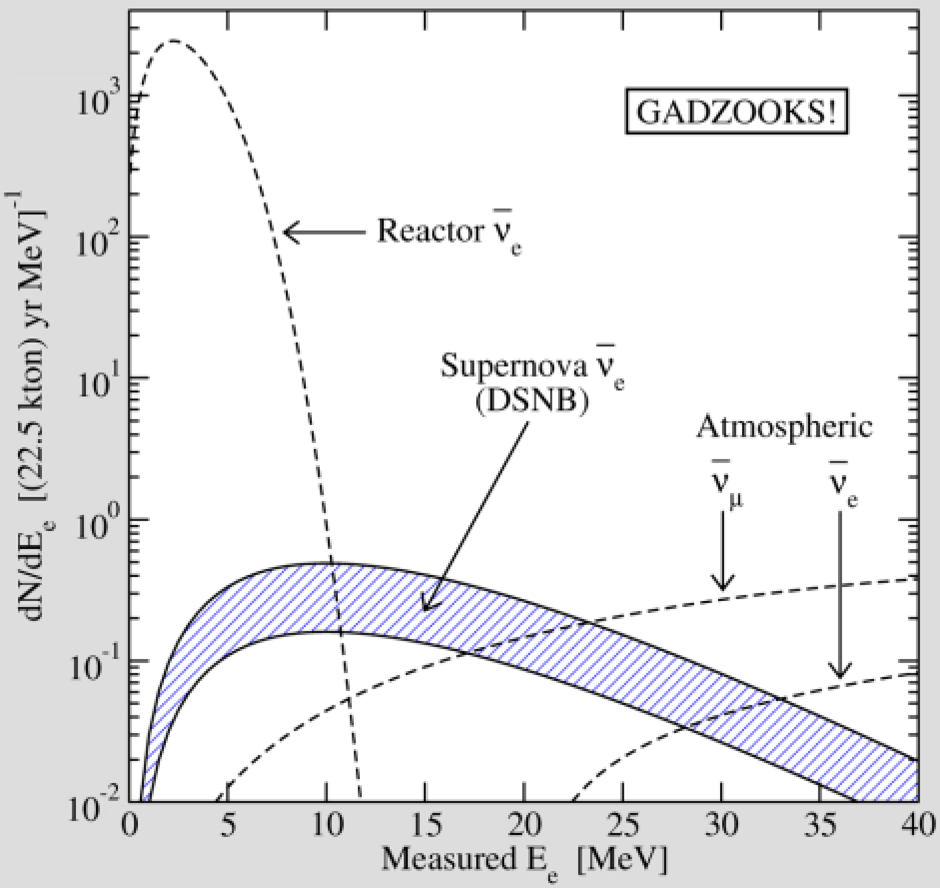
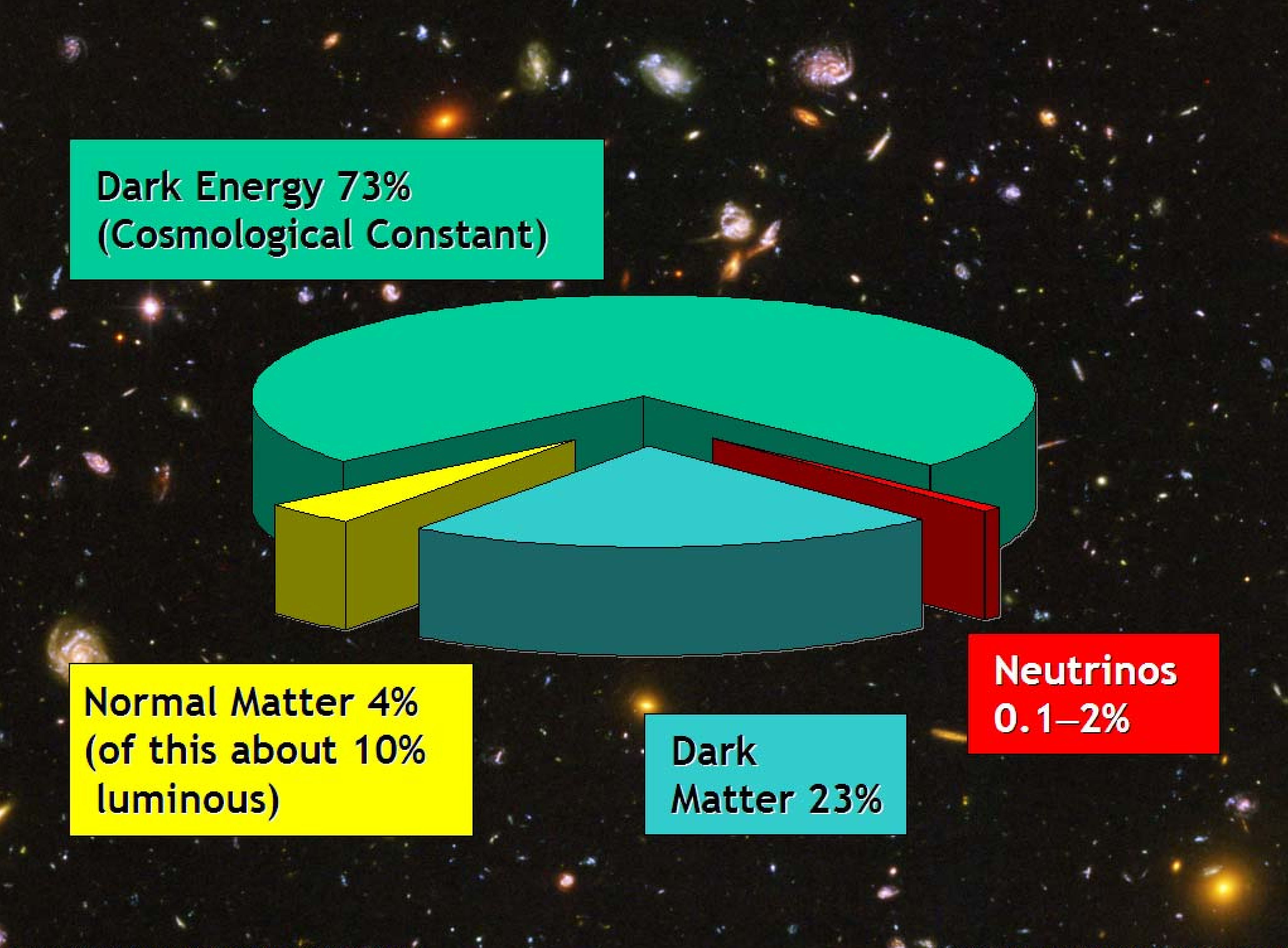


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

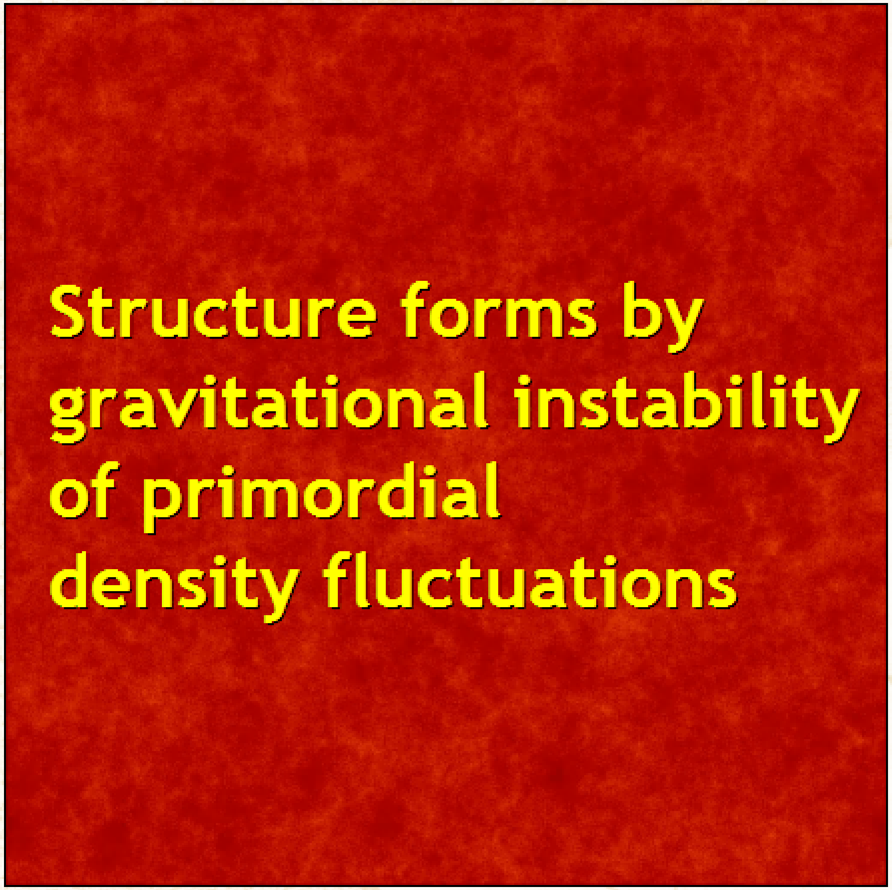
Pushing the boundaries of neutrino astronomy to cosmological distances

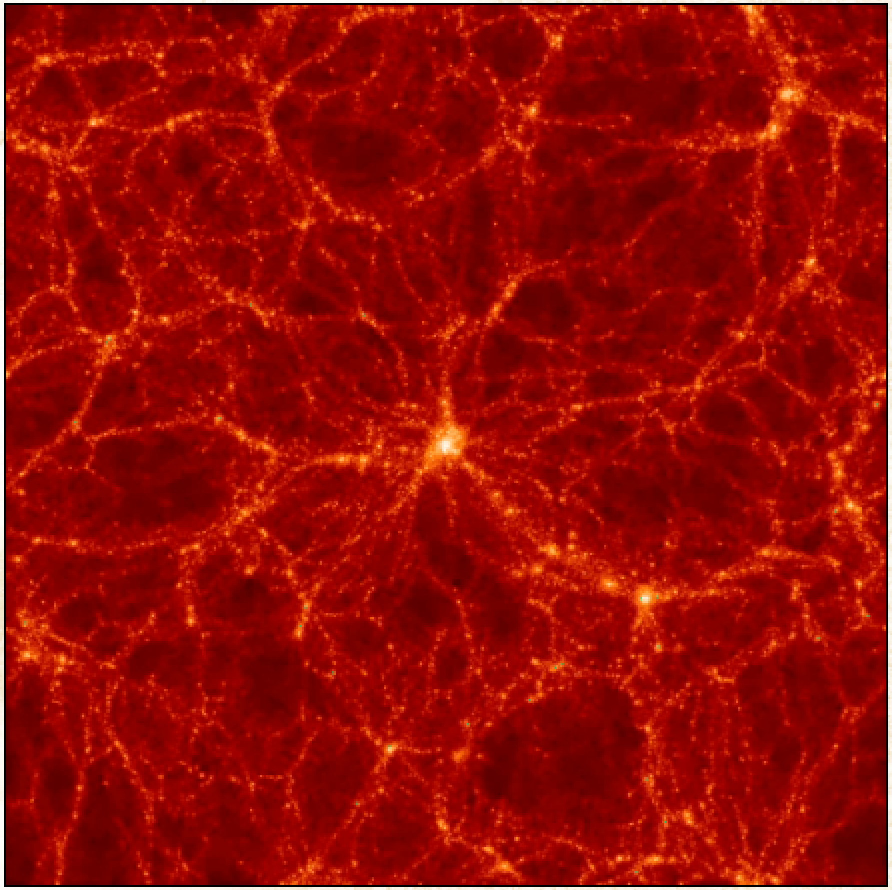

Neutrino
Dark Matter


Dark Energy 73%
(Cosmological Constant)
Normal Matter 4%
(of this about 10%
luminous)
Dark
Matter 23%
Neutrinos
0.1–2%

Formation of Structure

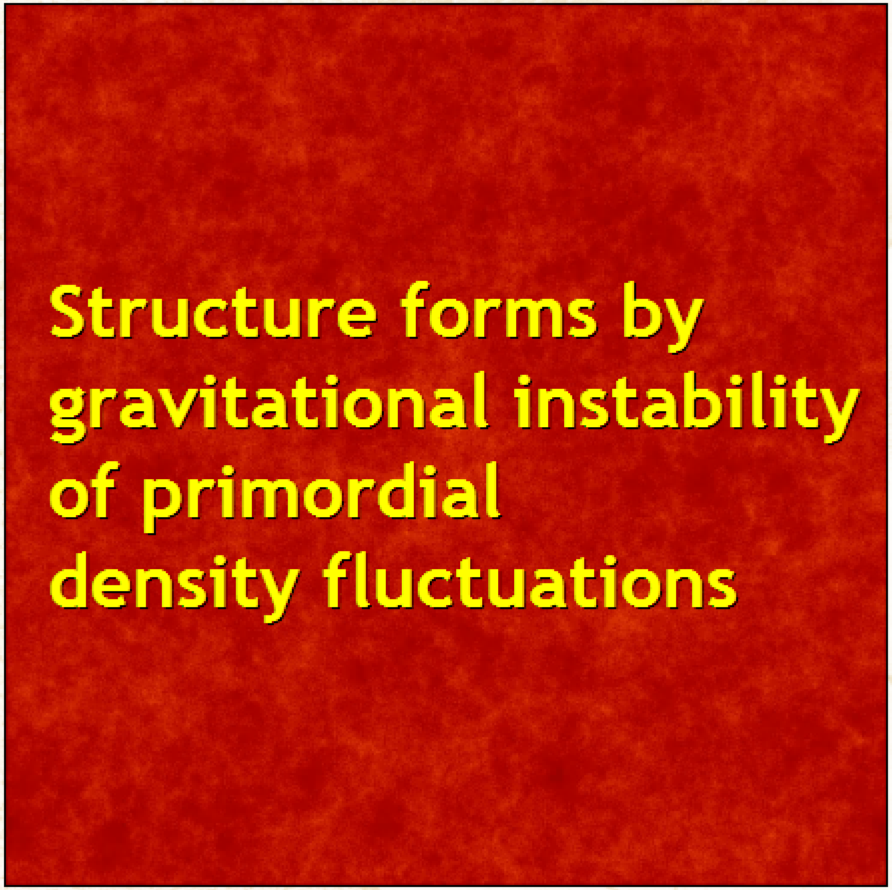
Smooth → **Structured**

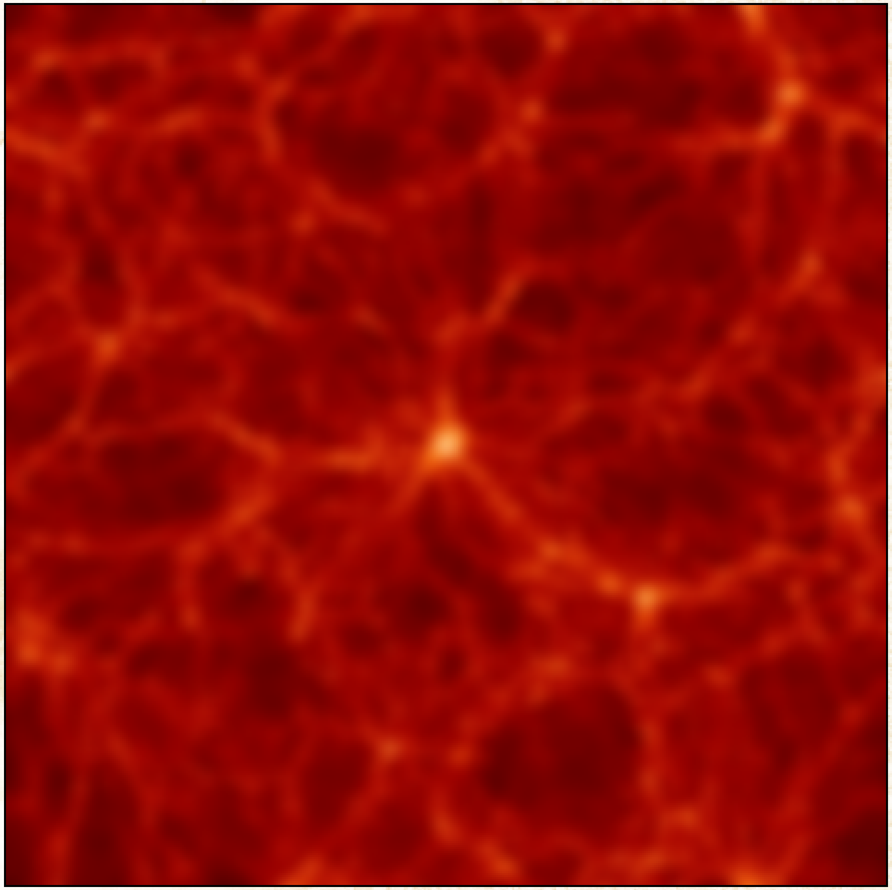




Formation of Structure

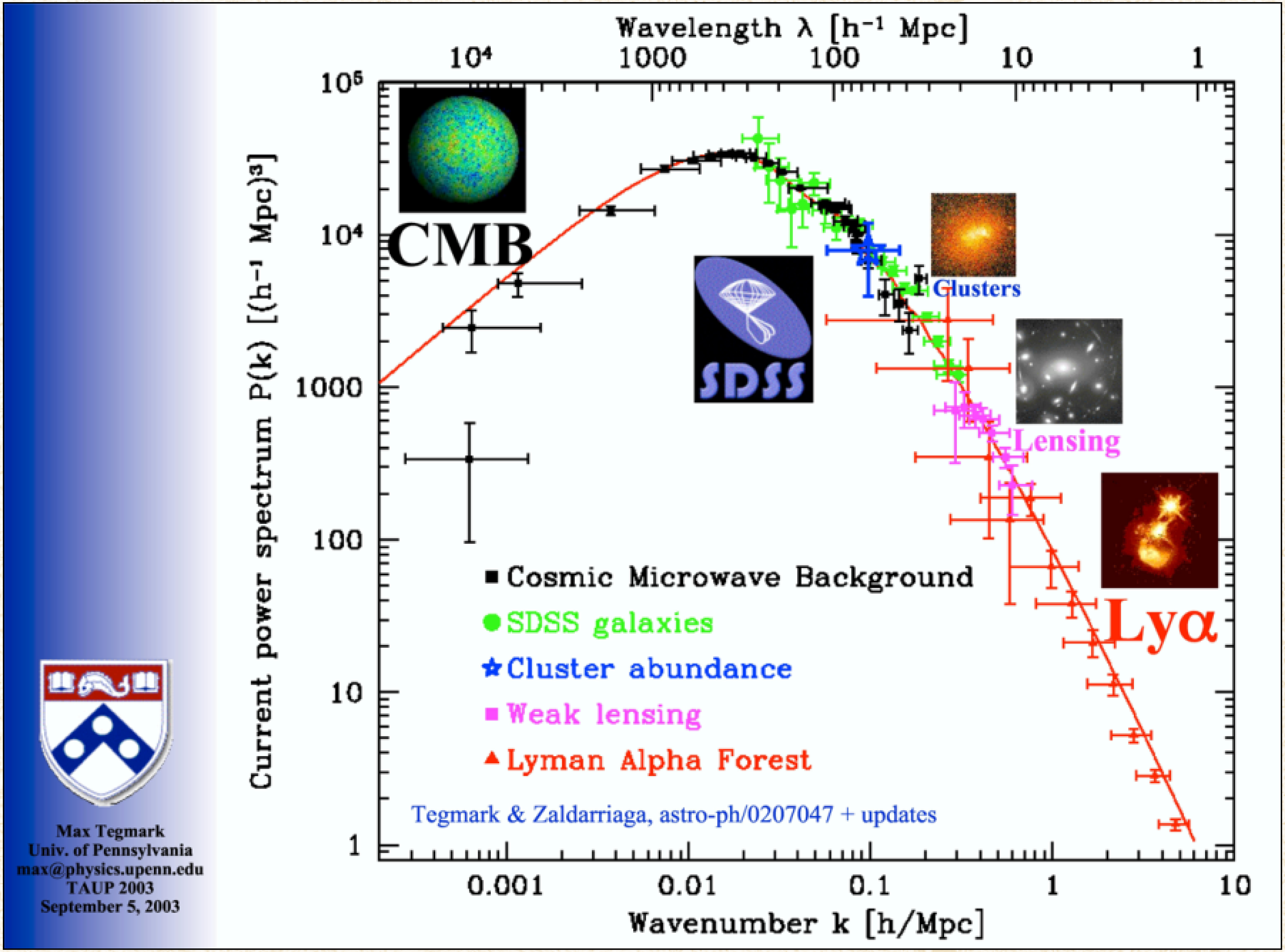
Smooth	→	Structured



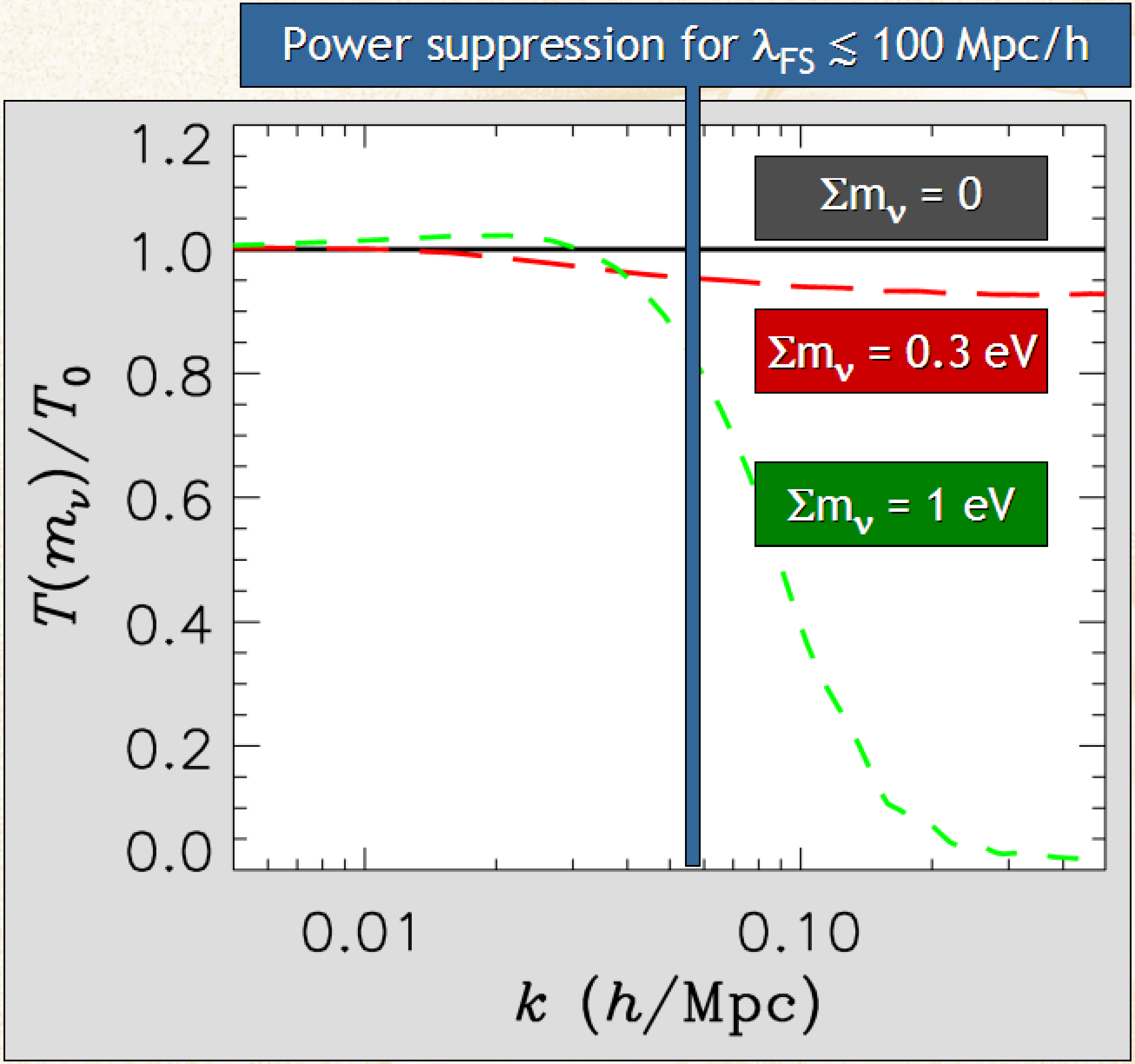


A fraction of hot dark matter suppresses small-scale structure

Power Spectrum of Cosmic Density Fluctuations



Neutrino Free Streaming - Transfer Function



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

	Σm_ν/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, σ_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-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

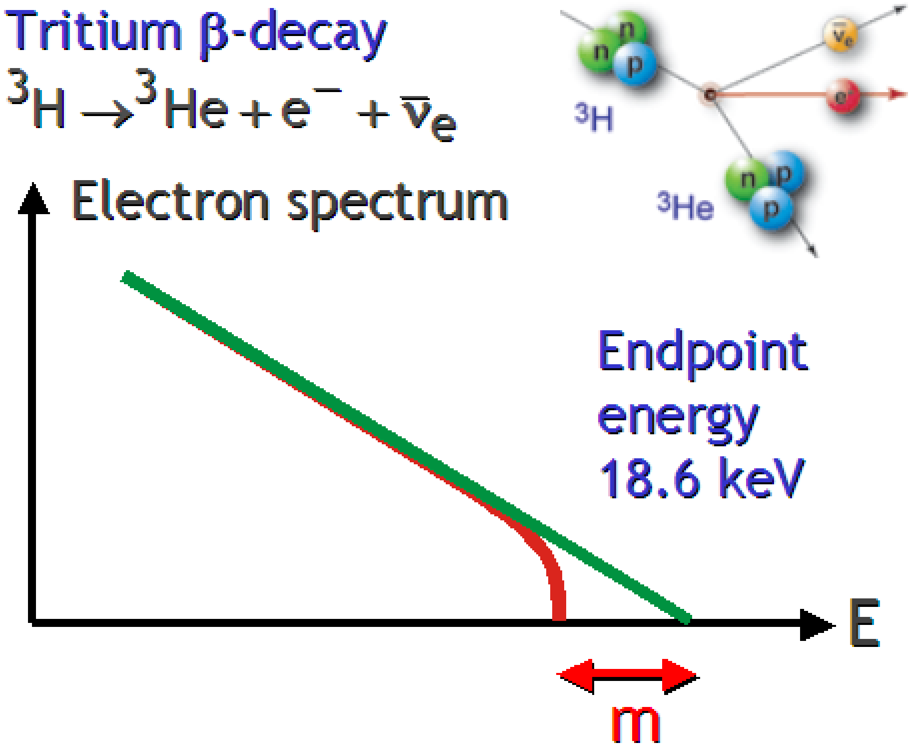
Sensitivity Forecasts for Future LSS Observations

Lesgourgues, Pastor & Perotto, hep-ph/0403296	Planck & SDSS	Σm_ν > 0.21 eV detectable at 2σ
	Ideal CMB & 40 x SDSS	Σm_ν > 0.13 eV detectable at 2σ
Abazajian & Dodelson astro-ph/0212216	Future weak lensing survey 4000 deg^2	$\sigma(m_\nu)$ ~ 0.1 eV
Kaplinghat, Knox & Song, astro-ph/0303344	CMB lensing	$\sigma(m_\nu)$ ~ 0.15 eV (Planck) $\sigma(m_\nu)$ ~ 0.044 eV (CMBpol)
Wang, Haiman, Hu, Khoury & May, astro-ph/0505390	Weak-lensing selected sample of > 10^5 clusters	$\sigma(m_\nu)$ ~ 0.03 eV

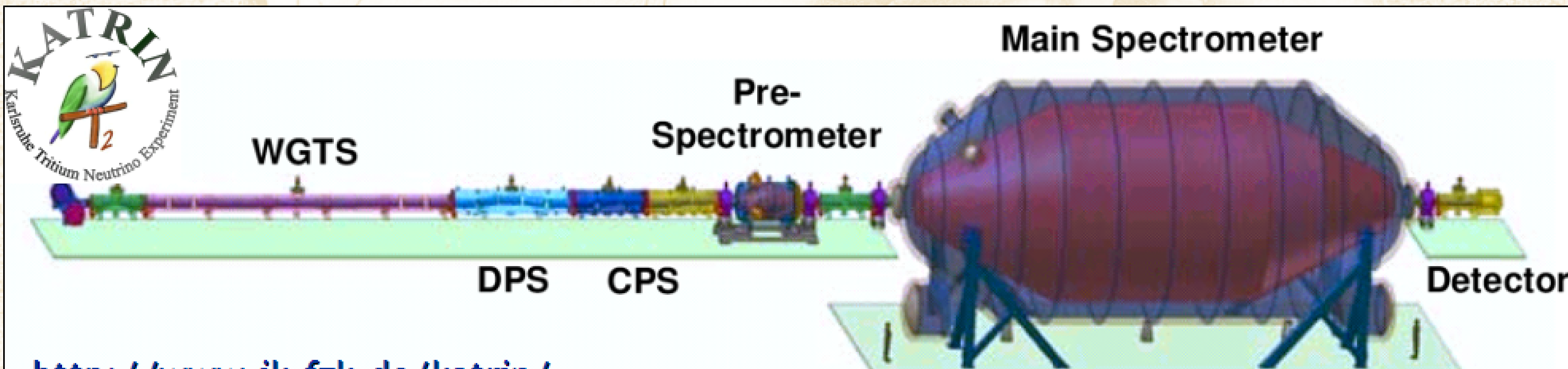
"Weighing" Neutrinos with KATRIN

Tritium β-decay

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$



- 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 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking foreseen to begin in 2007



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

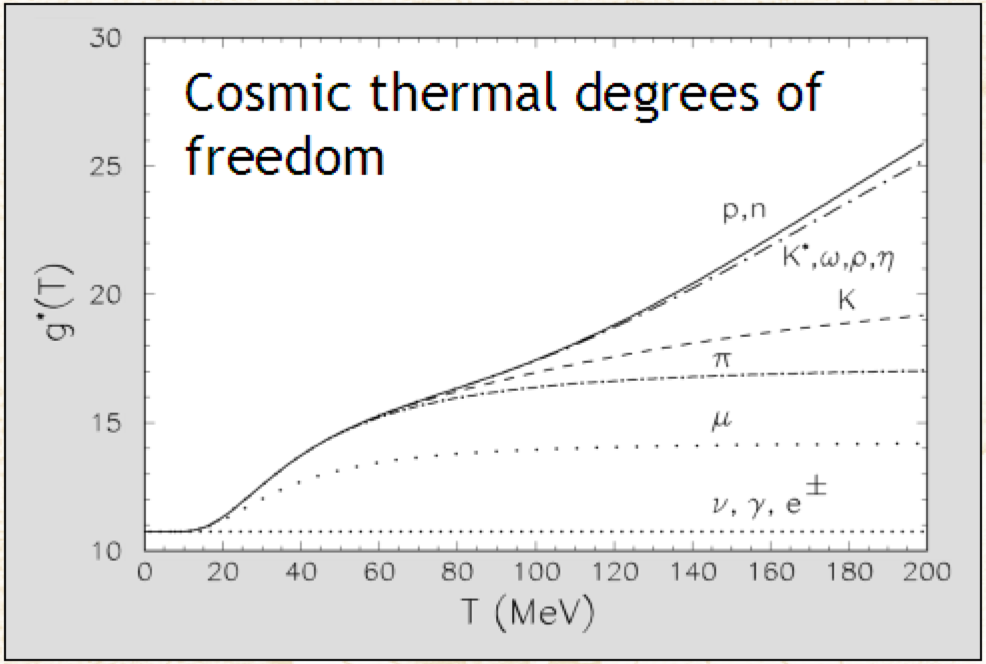
$$\Omega_X h^2 = \frac{m_X g_X}{183\ \mathrm{eV}} \frac{10.75}{g_{*X}} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

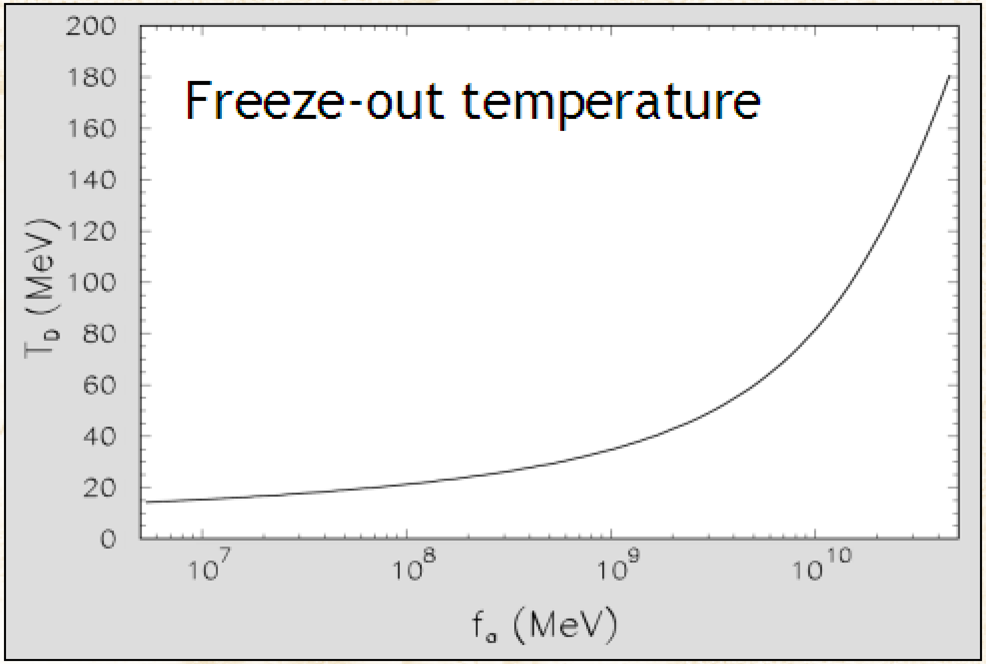
Free-streaming length

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

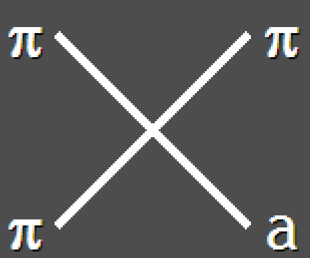
Perform maximum likelihood analysis for different choices of g_X and g_* to derive cosmological limit on m_X

Axion Freeze-Out



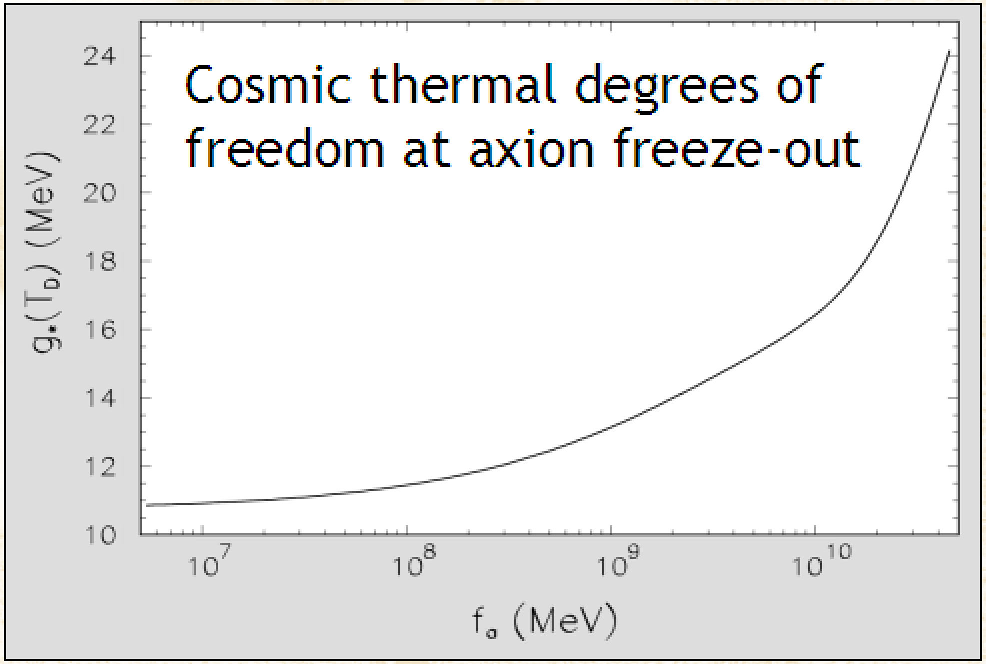


$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\partial^\mu a$$



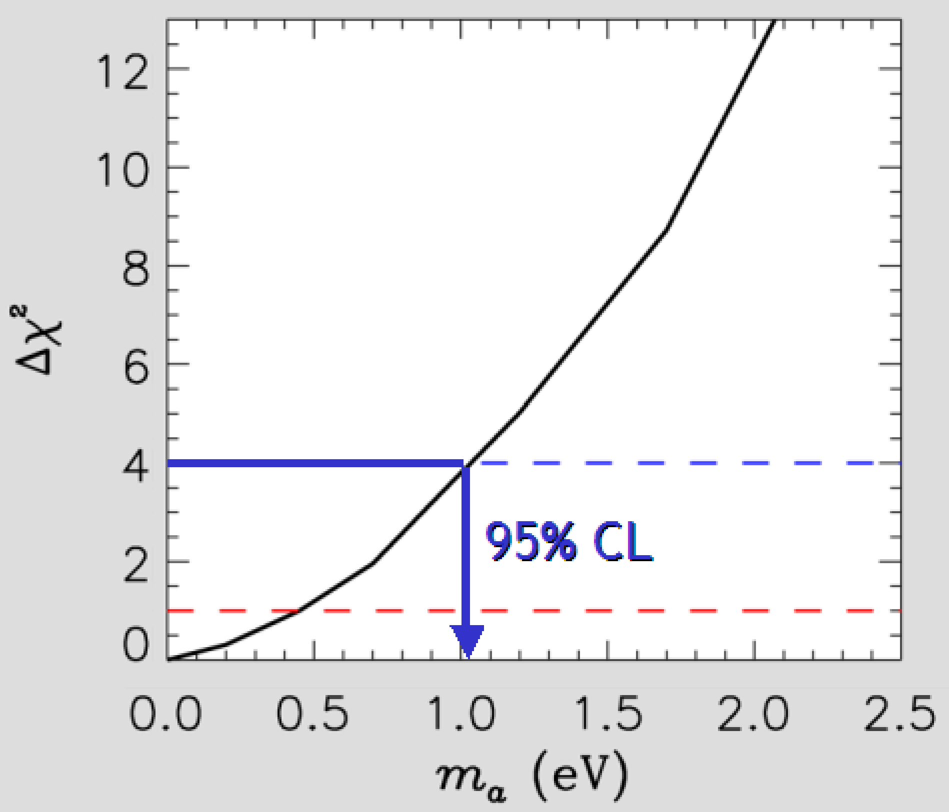
$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51



Mass Limits on Hot Dark Matter Axions and Neutrinos

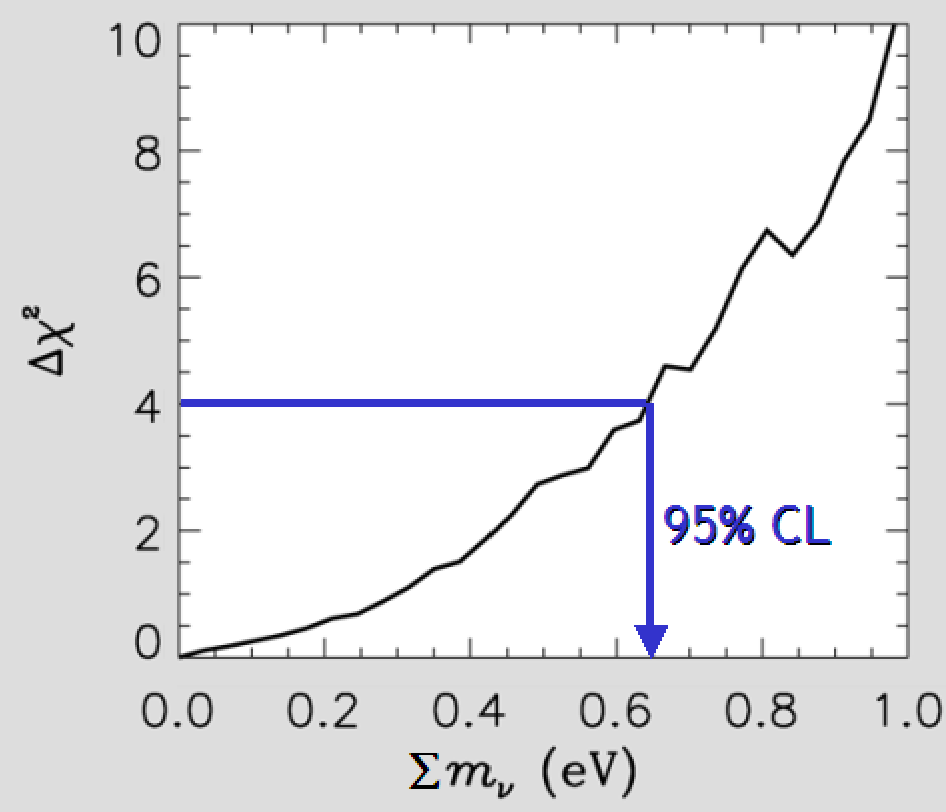
Hannestad, Mirizzi & Raffelt
hep-ph/0504059



Axions

$m_a < 1.05$ eV (95% CL)

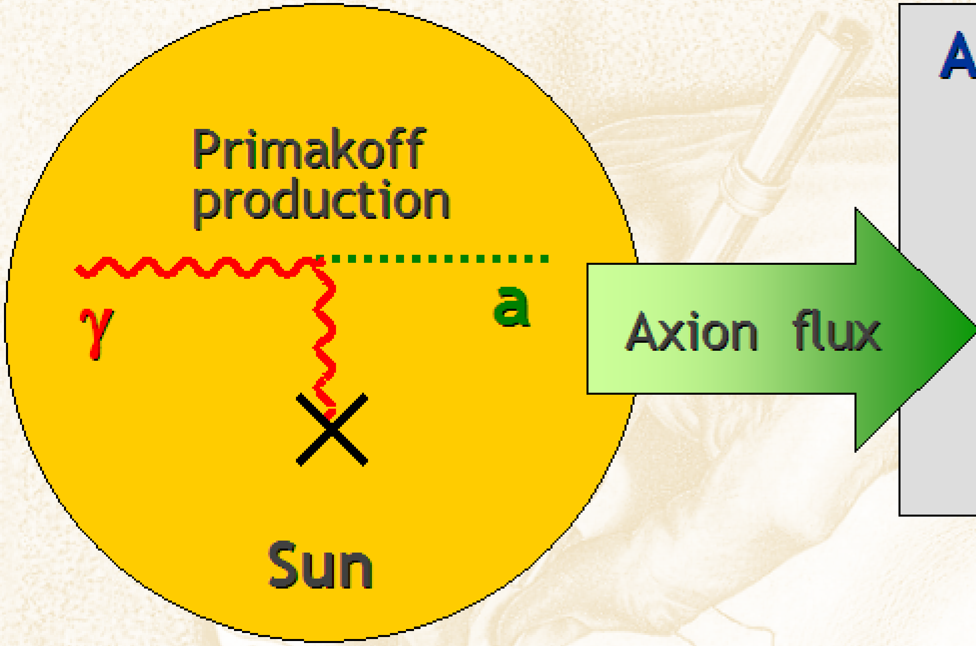
Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)



Neutrinos

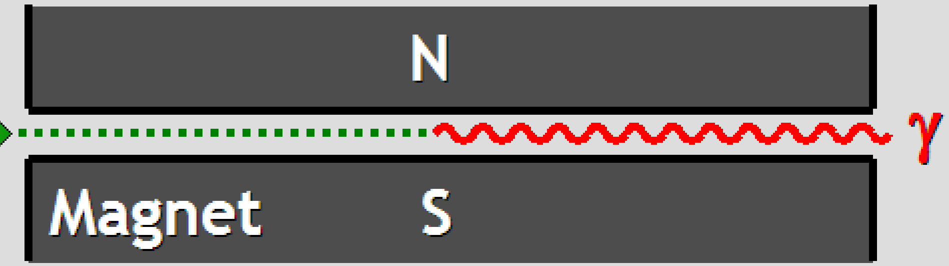
$\Sigma m_\nu < 0.65$ eV (95% CL)

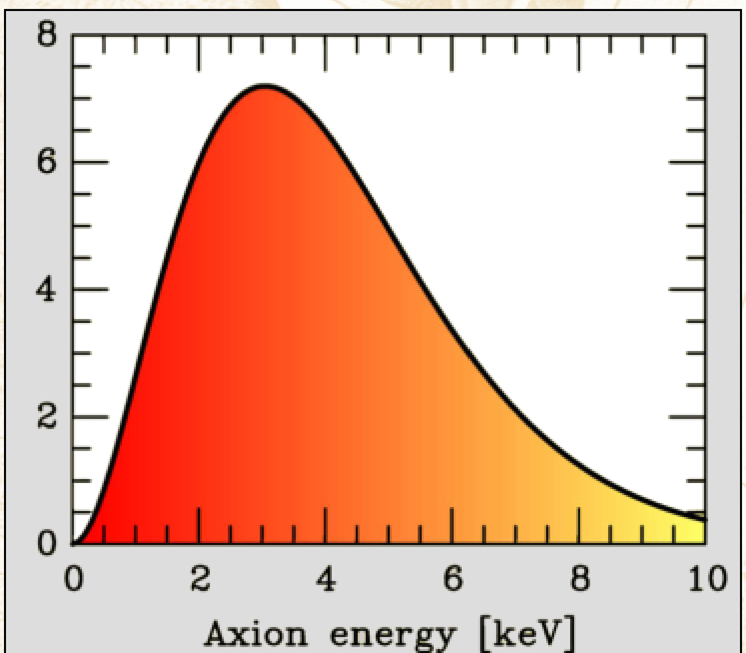
Search for Solar Axions



Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation



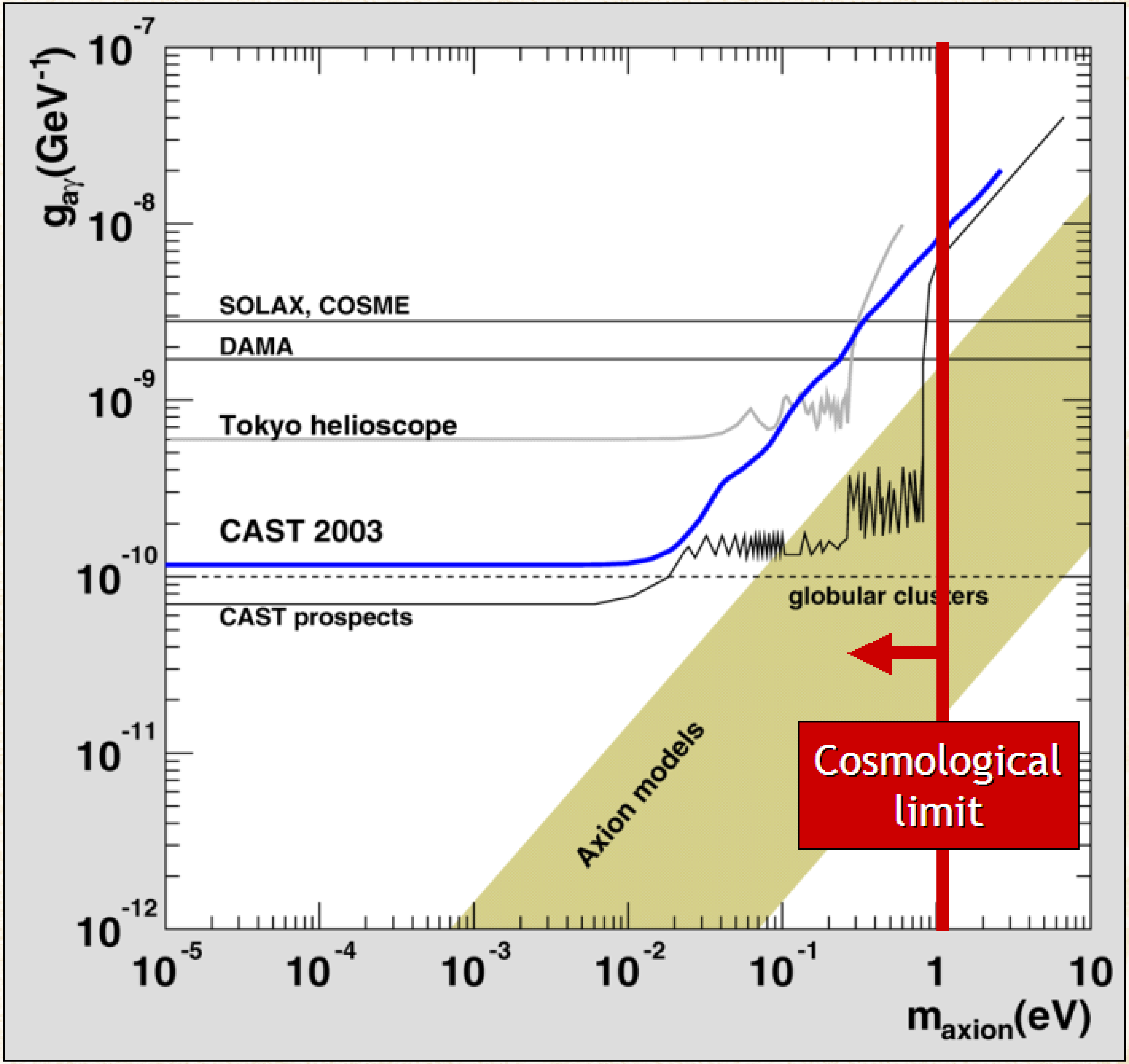


- ➔ Tokyo Axion Helioscope (Results since 1998)
- ➔ CERN Axion Solar Telescope (CAST) (Result since 2003)

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

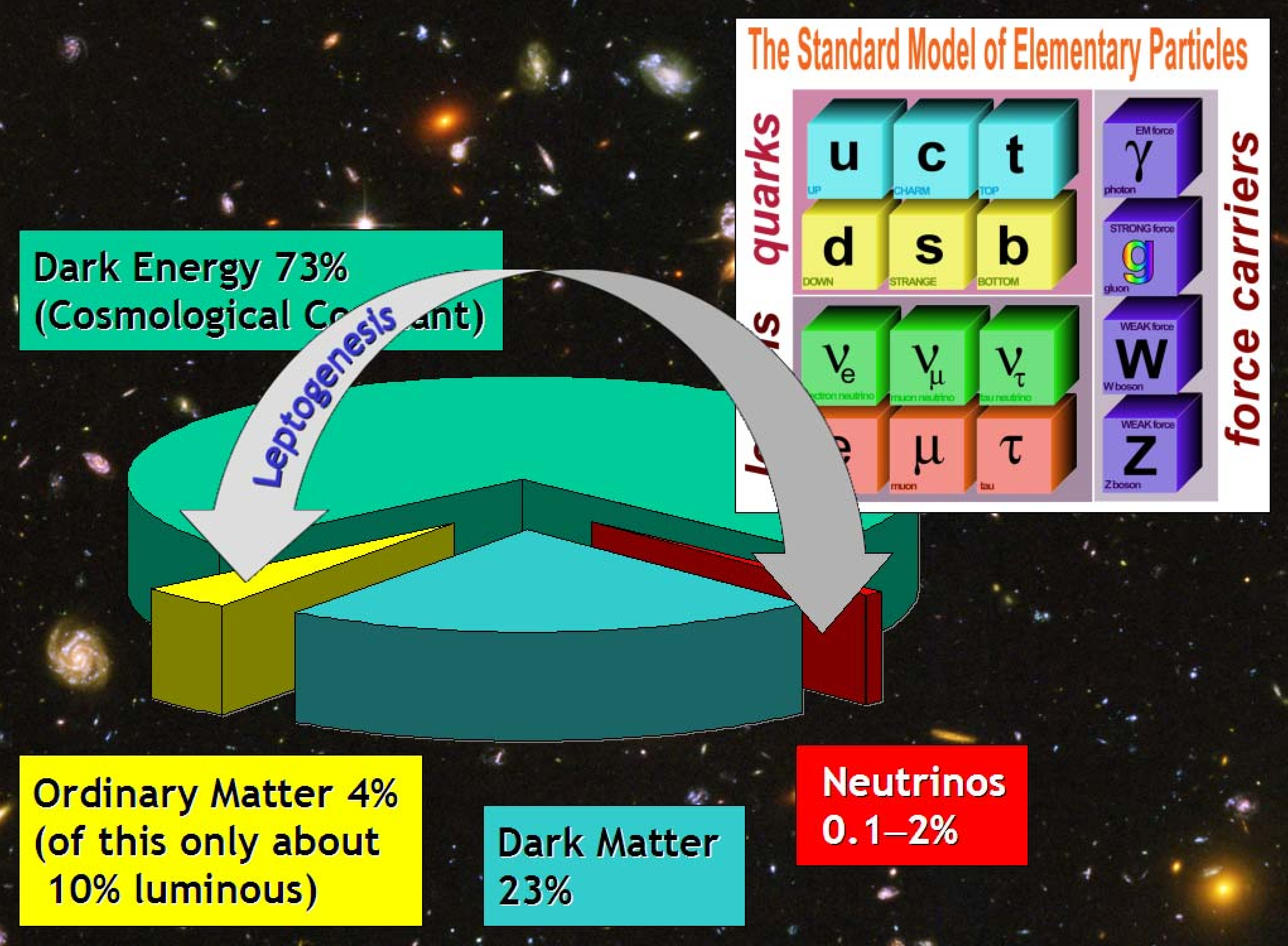


CAST Collaboration:

First results from the CERN Axion Solar Telescope (CAST)

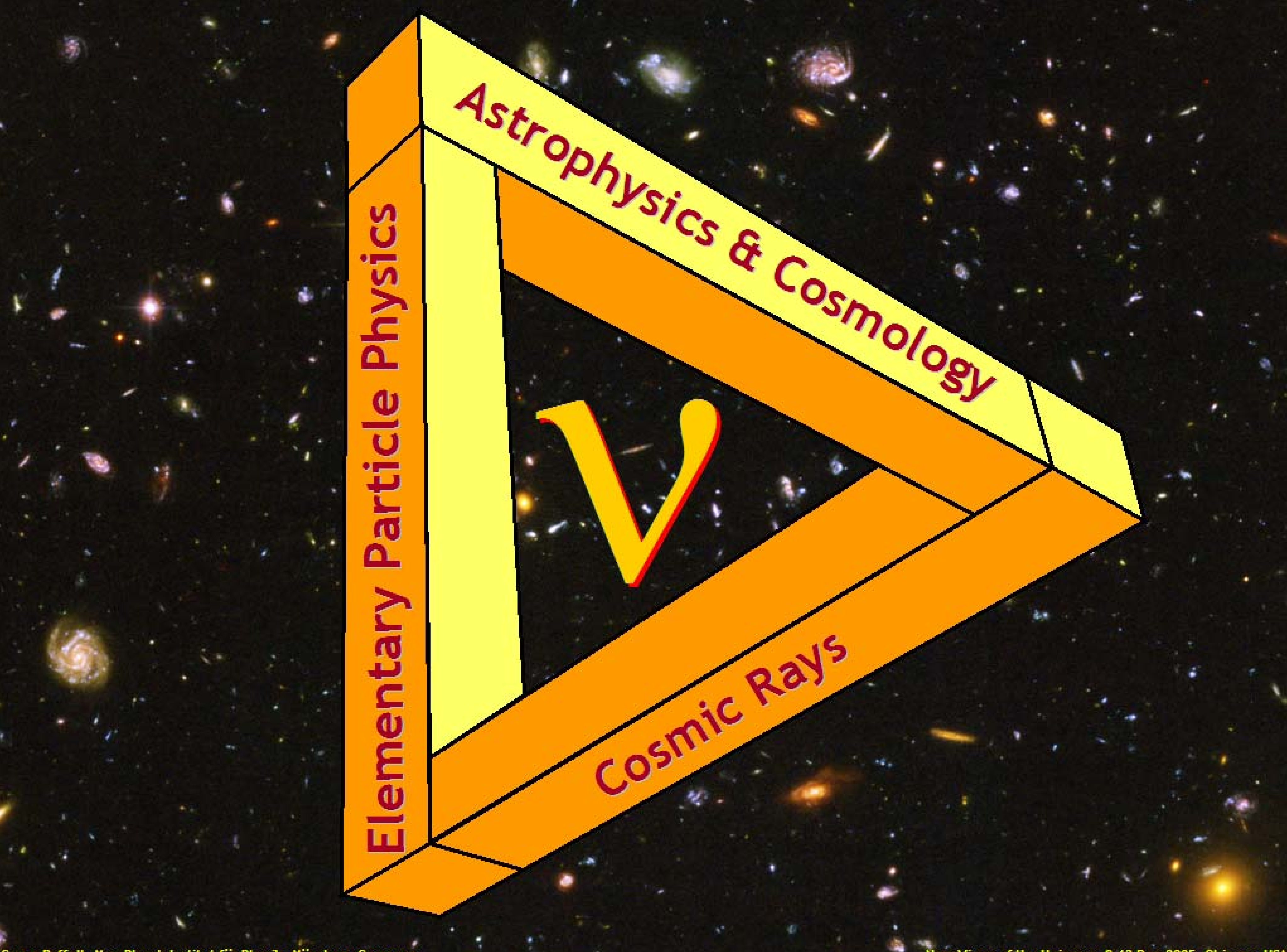
PRL, in press (2005) (hep-ex/0411033)

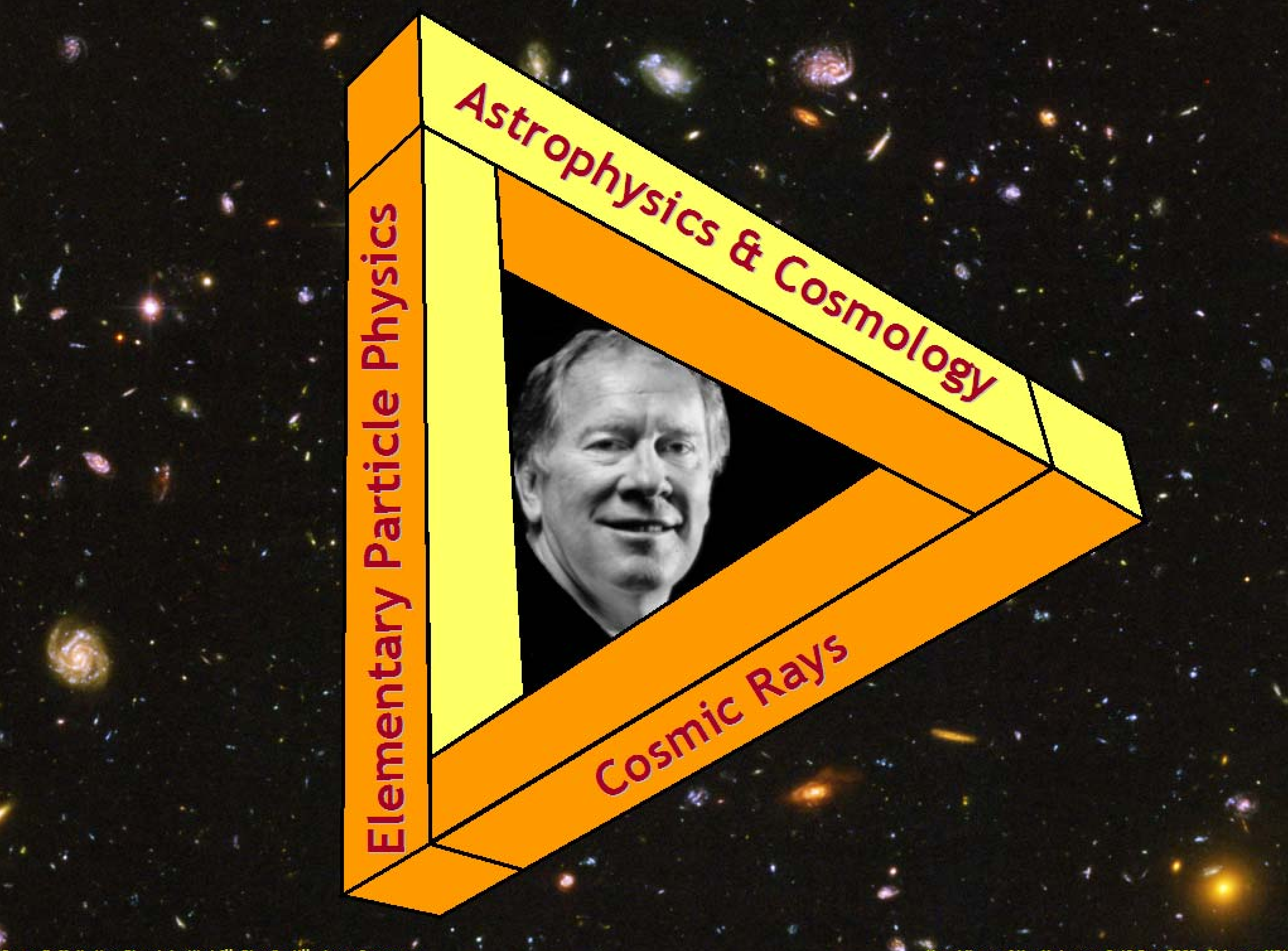
CAST Phase II and future cosmological sensitivity probably connect



Dark Energy 73%
(Cosmological Constant)
Leptogenesis
The Standard Model of Elementary Particles
quarks
force carriers
u
UP
c
CHARM
t
TOP
d
DOWN
s
STRANGE
b
BOTTOM
ν_e
ν_μ
muon neutrino
ν_τ
tau neutrino
μ
muon
τ
tau
EM force
γ
photon
STRONG force
g
gluon
WEAK force
W
W boson
WEAK force
Z
Z boson
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1–2%


ν


Astrophysics & Cosmology
Elementary Particle Physics
Cosmic Rays
ν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