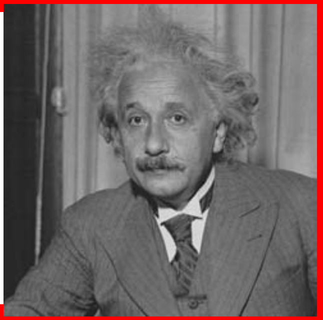
OPERA Versus

and



Do neutrinos really travel faster than light?

Do photons travel at the speed of light?

History in the Making?

- 1862: Maxwell found that there should be electromagnetic waves travelling at approximately the (known) speed of light
- 1905: Einstein used universal speed of light as foundation of geometric description of physics
- 2011: OPERA finds 6-σ discrepancy between neutrino speed and that of light

“Life in the fast lane”

NEWS

28 October 2011 Last updated at 14:31 GMT

LATEST: The US has launched NPP, its $1.5bn (£0.9bn) next-generation weather and climate satellite

Prosecutors contact Gaddafi son

International prosecutors are in "informal contact" with slain Libya leader Muammar Gaddafi's son, Saif al-Islam, who is wanted for war crimes.

Profile: Saif al-Islam

Gaddafi family tree

How Gaddafi died

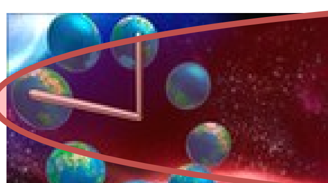
Bloody birth of new nation

Commonwealth ends male heir rule

Sons and daughters of future British monarchs will have equal rights to the throne, after the Commonwealth agrees to change centuries-old laws. 173

Overturning royal rules

Gillard praises succession change



Faster-than-light test runs again

Scientists who announced that sub-atomic particles might be able to travel faster than light are to repeat their experiment in a different way.

Light speed: Flying into fantasy

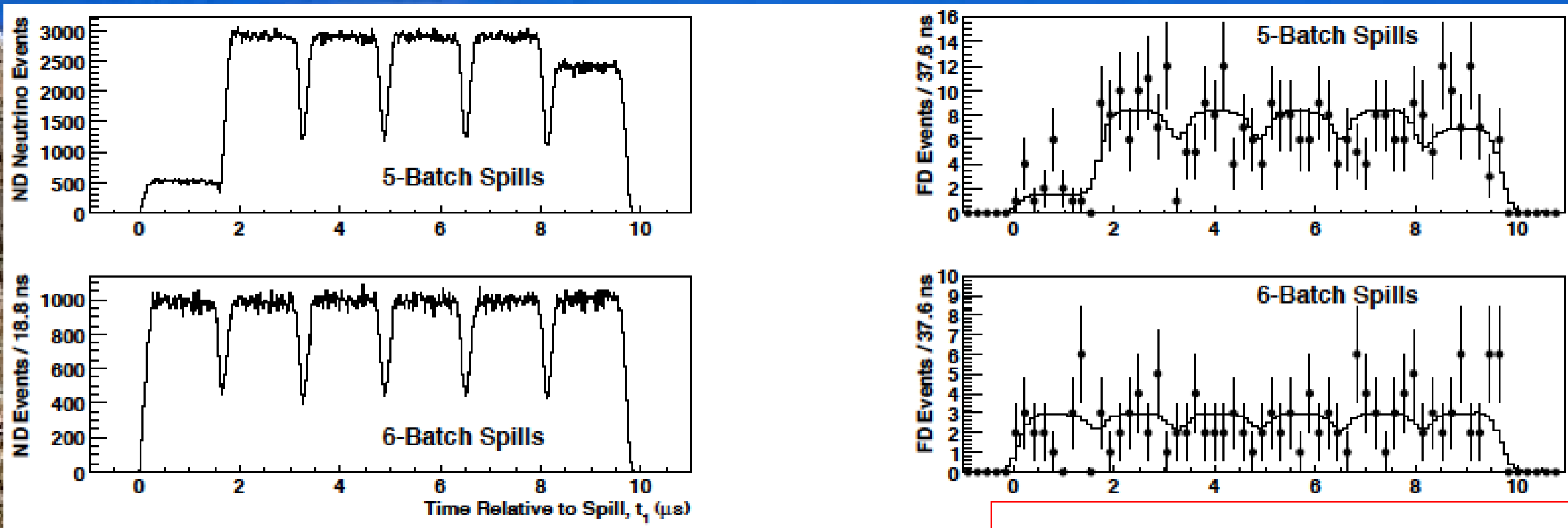
Cern mulls 'crazy' physics find

Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam

P. Adamson,[9,18] C. Andreopoulos,[23] K. E. Arms,[19] R. Armstrong,[12] D. J. Auty,[27] S. Avvakumov,[26] D. S. Ayres,[1] B. Baller,[9] B. Barish,[5] P. D. Barnes Jr.,[17] G. Barr,[21] W. L. Barrett,[31] E. Beall,[1,19] B. R. Becker,[19] A. Belias,[23] T. Bergfeld,[25] R. H. Bernstein,[9] D. Bhattacharya,[22] M. Bishai,[4] A. Blake,[6] B. Bock,[20] G. J. Bock,[9] J. Boehm,[10] D. J. Boehnlein,[9] D. Bogert,[9] P. M. Border,[19] C. Bower,[12] E. Buckley-Geer,[9] A. Cabrera,[21] J. D. Chapman,[6] D. Cherdack,[30] S. Childress,[9] B. C. Choudhary,[9] J. H. Cobb,[21] S. J. Coleman,[32] A. J. Culling,[6] J. K. de Jong,[11] A. De Santo,[21] M. Dierckxsens,[4] M. V. Diwan,[4] M. Dorman,[18,23] D. Drakoulakos,[2] T. Durkin,[23] A. R. Erwin,[33] C. O. Escobar,[7] J. J. Evans,[21] E. Falk Harris,[27] G. J. Feldman,[10] T. H. Fields,[1] T. Fitzpatrick,[9] R. Ford,[9] M. V. Frohne,[3] H. R. Gallagher,[30] G. A. Giurgiu,[1] A. Godley,[25] J. Gogos,[19] M. C. Goodman,[1] P. Gouffon,[24] R. Gran,[20] E. W. Grashorn,[19,20] N. Grossman,[9] K. Grzelak,[21] A. Habig,[20] D. Harris,[9] P. G. Harris,[27] J. Hartnell,[23] E. P. Hartouni,[17] R. Hatcher,[9] K. Heller,[19] A. Holin,[18] C. Howcroft,[5] J. Hylen,[9] D. Indurthy,[29] G. M. Irwin,[26] M. Ishitsuka,[12] D. E. Jaffe,[4] C. James,[9] L. Jenner,[18] D. Jensen,[9] T. Joffe-Minor,[1] T. Kafka,[30] H. J. Kang,[26] S. M. S. Kasahara,[19] M. S. Kim,[22] G. Koizumi,[9] S. Kopp,[29] M. Kordosky,[18] D. J. Koskinen,[18] S. K. Kotelnikov,[16] A. Kreymer,[9] S. Kumaratunga,[19] K. Lang,[29] A. Lebedev,[10] R. Lee,[10] J. Ling,[25] J. Liu,[29] P. J. Litchfield,[19] R. P. Litchfield,[21] P. Lucas,[9] W. Luebke,[11] W. A. Mann,[30] A. Marchionni,[9] A. D. Marino,[9] M. L. Marshak,[19] J. S. Marshall,[6] N. Mayer,[20] A. M. McGowan,[1,19] J. R. Meier,[19] G. I. Merzon,[16] M. D. Messier,[12] D. G. Michael,[5,*] R. H. Milburn,[30] J. L. Miller,[15,*] W. H. Miller,[19] S. R. Mishra,[25] A. Mislivec,[20] P. S. Miyagawa,[21] C. D. Moore,[9] J. Morfín,[9] L. Mualem,[5,19] S. Mufson,[12] S. Murgia,[26] J. Musser,[12] D. Naples,[22] J. K. Nelson,[32] H. B. Newman,[5] R. J. Nichol,[18] T. C. Nicholls,[23] J. P. Ochoa-Ricoux,[5] W. P. Oliver,[30] T. Osiecki,[29] R. Ospanov,[29] J. Paley,[12] V. Paolone,[22] A. Para,[9] T. Patzak,[8] Ž. Pavlović,[29] G. F. Pearce,[23] C. W. Peck,[5] C. Perry,[21] E. A. Peterson,[19] D. A. Petyt,[19] H. Ping,[33] R. Piteira,[8] R. Pittam,[21] R. K. Plunkett,[9] D. Rahman,[19] R. A. Rameika,[9] T. M. Raufer,[21] B. Rebel,[9] J. Reichenbacher,[1] D. E. Reyna,[1] C. Rosenfeld,[25] H. A. Rubin,[11] K. Ruddick,[19] V. A. Ryabov,[16] R. Saakyan,[18] M. C. Sanchez,[10] N. Saoulidou,[9] D. Saranen,[19] J. Schneps,[30] P. Schreiner,[3] V. K. Semenov,[13] S.-M. Seun,[10] P. Shanahan,[9] W. Smart,[9] V. Smirnitsky,[14] C. Smith,[18,27] A. Sousa,[21,30] B. Speakman,[19] P. Stamoulis,[2] P.A. Symes,[27] N. Tagg,[34,30,21] R. L. Talaga,[1] E. Tetteh-Lartey,[28] J. Thomas,[18] J. Thompson,[22,*] M. A. Thomson,[6] J. L. Thron,[1] G. Tinti,[21] I. Trostin,[14] V. A. Tsarev,[16] G. Tzanakos,[2] J. Urheim,[12] P. Vahle,[18] V. Verebryusov,[14] B. Viren,[4] C. P. Ward,[6] D. R. Ward,[6] M. Watabe,[28] A. Weber,[21,23] R. C. Webb,[28] A. Wehmann,[9] N. West,[21] C. White,[11] S. G. Wojcicki,[26] D. M. Wright,[17] Q. K. Wu,[25] T. Yang,[26] F. X. Yumiceva,[32] H. Zheng,[5] M. Zois,[2] and R. Zwaska[9]

(The MINOS Collaboration)

MINOS Measurement of ν Speed



Near & far

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

Uncertaintie

Published result

$$(v-c)/c = 5.1 \pm 2.9 \times 10^{-5}$$

almost 2 σ > 0

CERN-PH-TH/2008-088

Probes of Lorentz Violation in Neutrino Propagation

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Abstract

It has been suggested that the interactions of energetic particles with the foamy structure of space-time thought to be generated by quantum-gravitational (QG) effects might violate Lorentz invariance, so that they do not propagate at a universal speed of light. We consider the limits that may be set on a linear or quadratic violation of Lorentz invariance in the propagation of energetic neutrinos, $v/c = [1 \pm (E/M_{\nu QG1})]$ or $[1 \pm (E/M_{\nu QG2})^2]$, using data from supernova explosions and the OPERA long-baseline neutrino experiment. Using the SN1987a neutrino data from the Kamioka II, IMB and Baksan experiments, we set the limits $M_{\nu QG1} > 2.7(2.5) \times 10^{10}$ GeV for subluminal (superluminal) propagation, respectively, and $M_{\nu QG2} > 4.6(4.1) \times 10^4$ GeV at the 95 % confidence level. A future galactic supernova at a distance of 10 kpc would have sensitivity to $M_{\nu QG1} > 2(4) \times 10^{11}$ GeV for subluminal (superluminal) propagation, respectively, and $M_{\nu QG2} > 2(4) \times 10^5$ GeV. With the current CNGS extraction spill length of 10.5 μs and with standard clock synchronization techniques, the sensitivity of the OPERA experiment would reach $M_{\nu QG1} \sim 7 \times 10^5$ GeV ($M_{\nu QG2} \sim 8 \times 10^3$ GeV) after 5 years of nominal running. If the time structure of the SPS RF bunches within the extracted CNGS spills could be exploited, these figures would be significantly improved to $M_{\nu QG1} \sim 5 \times 10^7$ GeV ($M_{\nu QG2} \sim 4 \times 10^4$ GeV). These results can be improved further if similar time resolution can be achieved with neutrino events occurring in the rock upstream of the OPERA detector: we find potential sensitivities to $M_{\nu QG1} \sim 4 \times 10^8$ GeV and $M_{\nu QG2} \sim 7 \times 10^5$ GeV.

CERN-PH-TH/2008-088

April 2008

Constraints from Supernova 1987a

- Data from 3 experiments

IMB		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	38	7
0.412	37	7
0.650	28	6
1.141	39	7
1.562	36	9
2.684	36	6
5.010	19	5
5.582	22	5

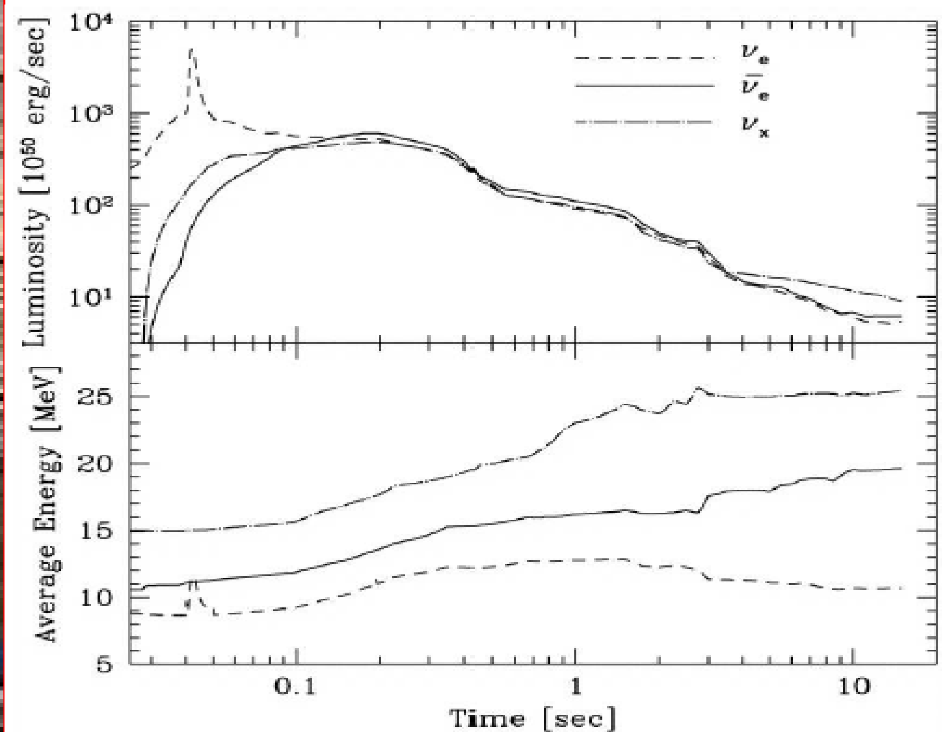
Baksan		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	10.3	4.1

Kamiokande II		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	20.0	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9

- Arrived hours before γ's

→ $\delta v < 10^{-9}$

- Supernova simulation

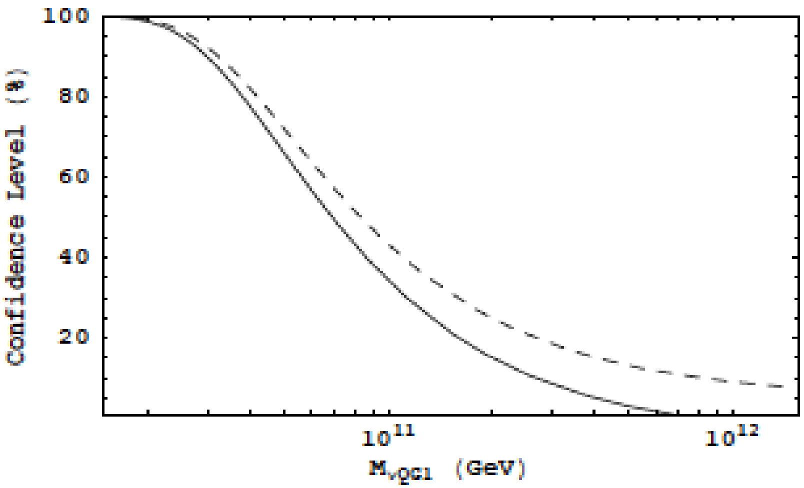


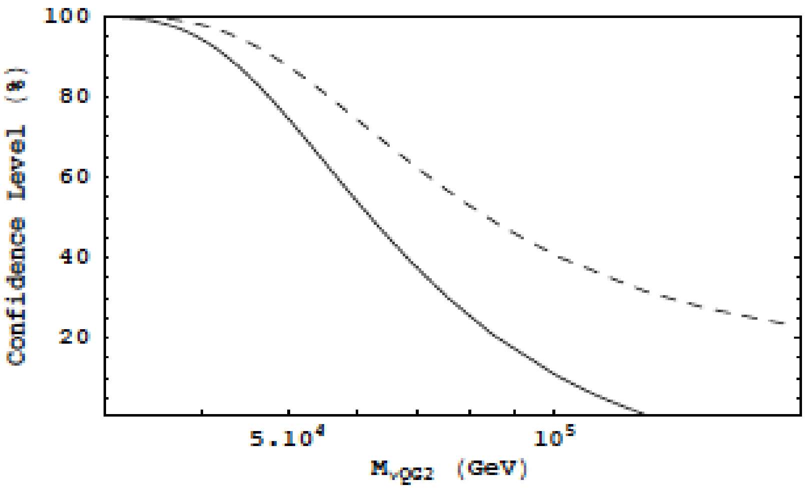
- Possible E dependence of δv constrained by bunching

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Constraints from SN1987a

- Fit to possible E-dependent time-lag



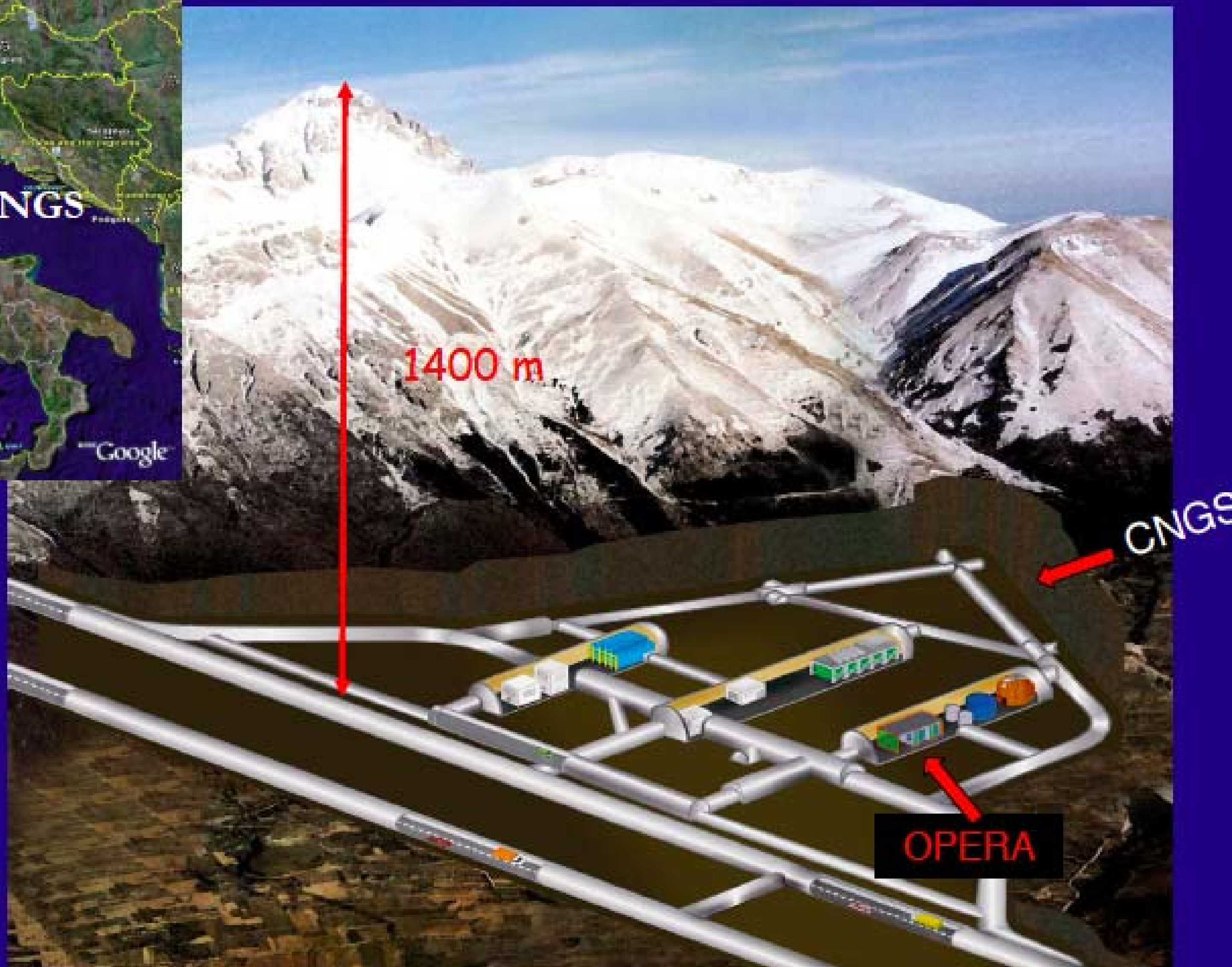


Subluminal and superluminal cases

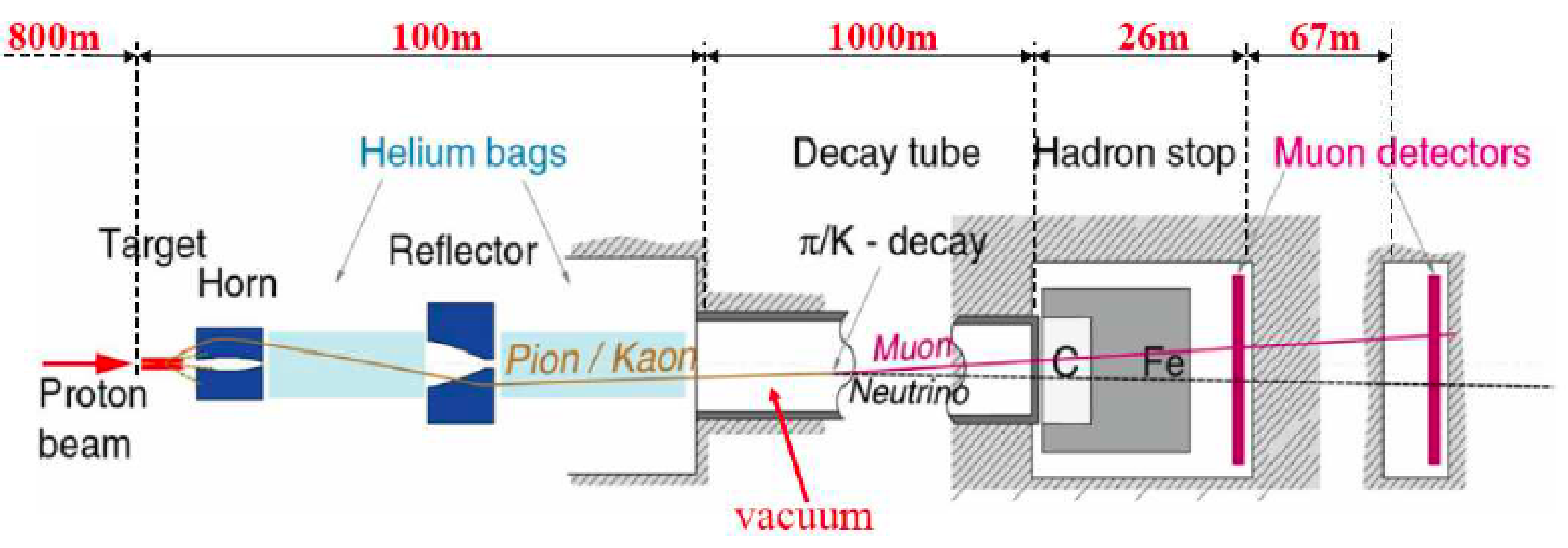
  - Linear: $M_{\nu QG1} > 2.7 \times 10^{10}$ GeV or $M_{\nu QG1} > 2.5 \times 10^{10}$ GeV
  - Quadratic: $M_{\nu QG2} > 4.6 \times 10^{4}$ GeV or $M_{\nu QG2} > 4.1 \times 10^{4}$ GeV

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

From CERN to the Gran Sasso



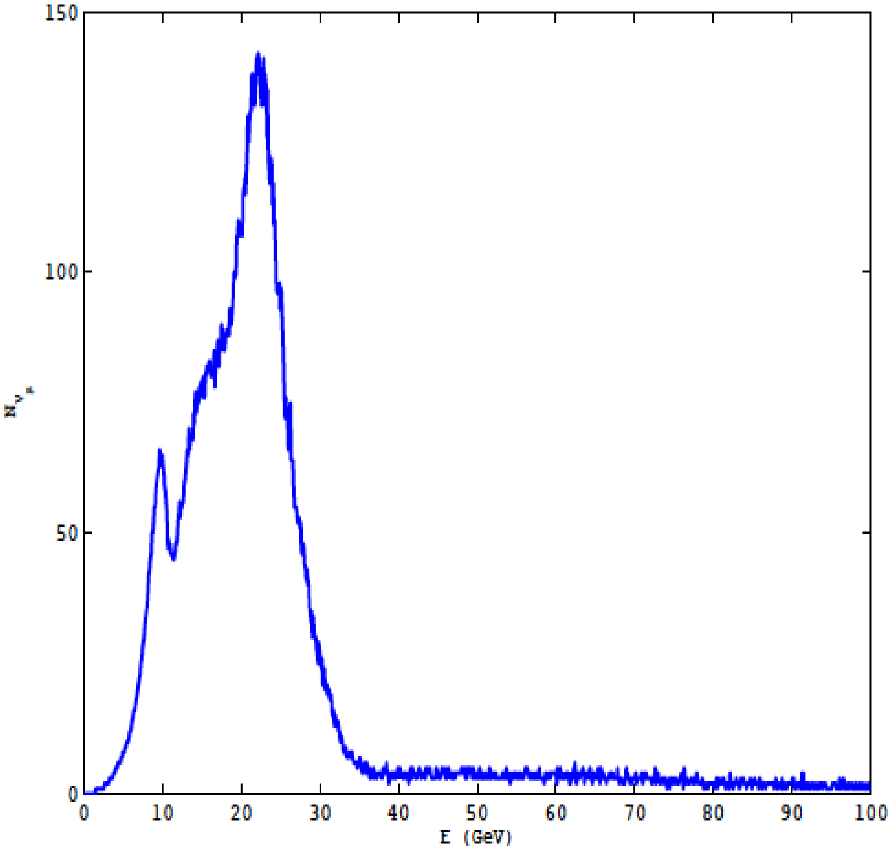
The Neutrino Target at CERN



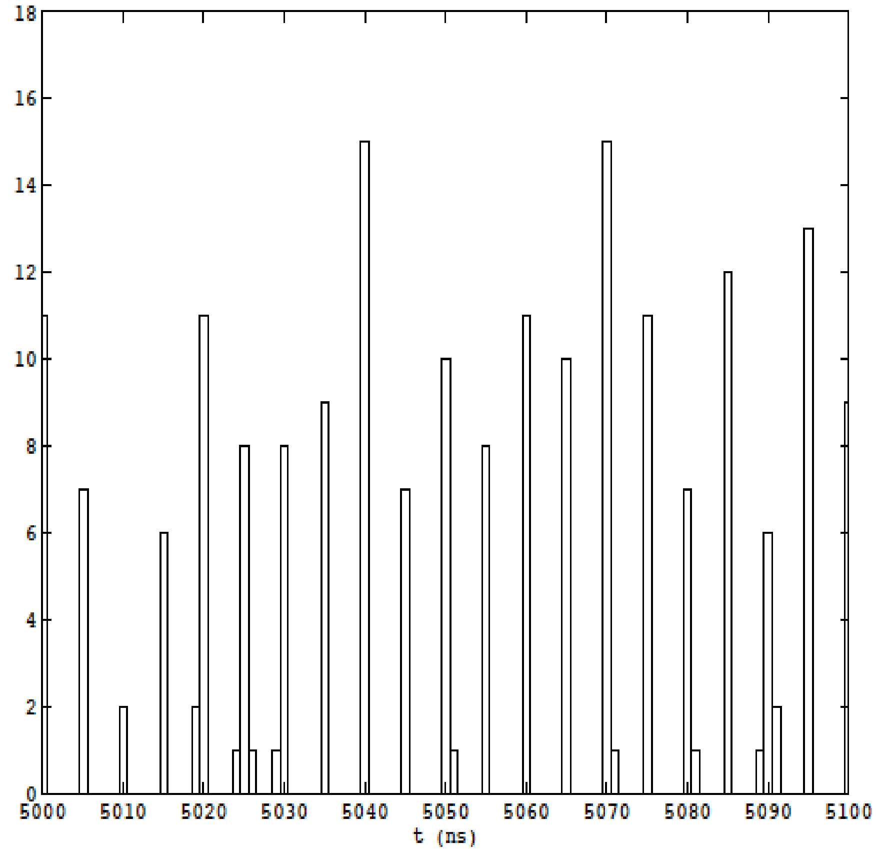
- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms
- Beam intensity: 2.4 10^{13} proton/extraction
- ~ pure muon neutrino beam (<E> = 17 GeV) travelling through the Earth's crust

Structure of CNGS Beam

- Energy Spectrum

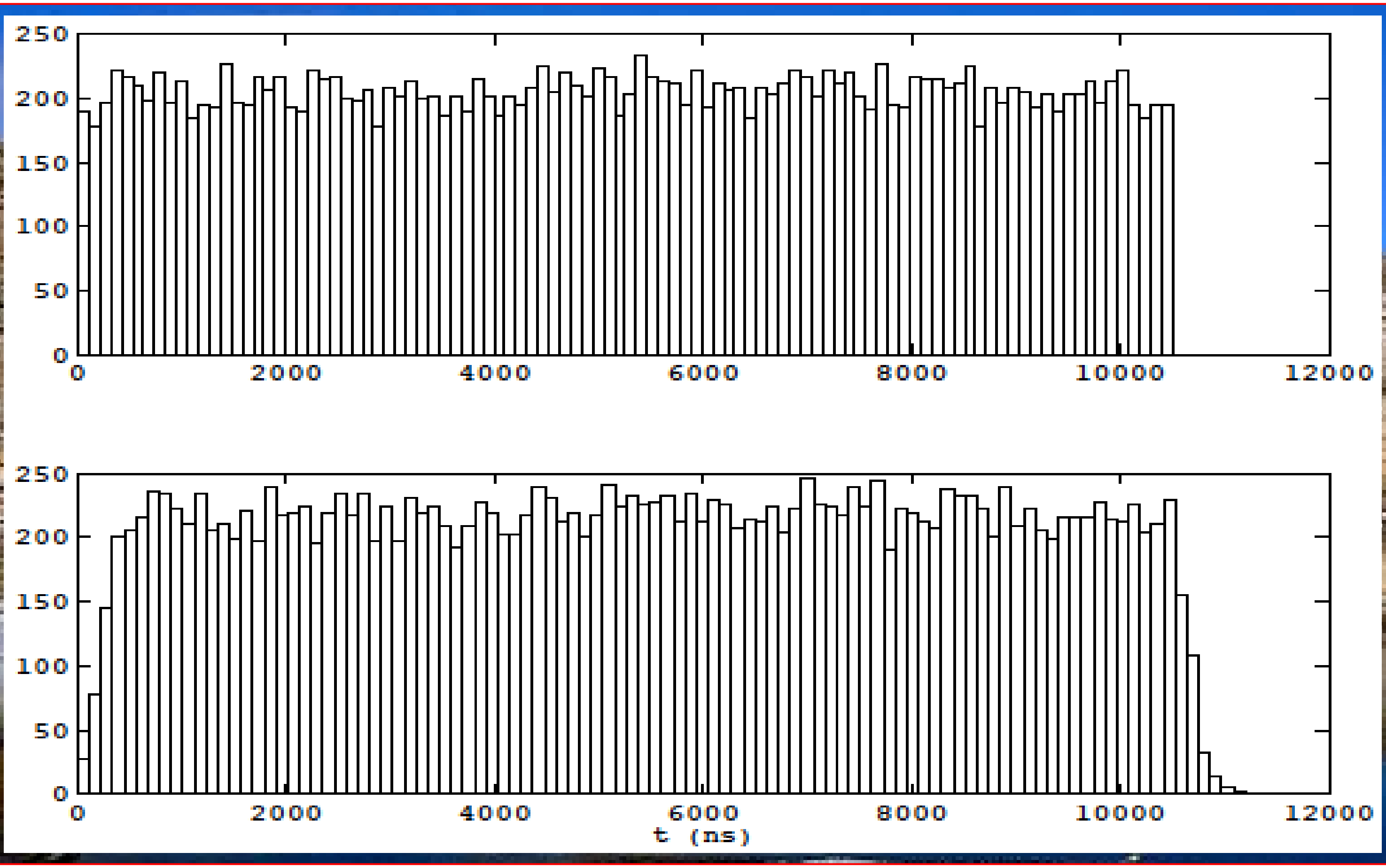


- Time structure



JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Possible Distortion of Spill

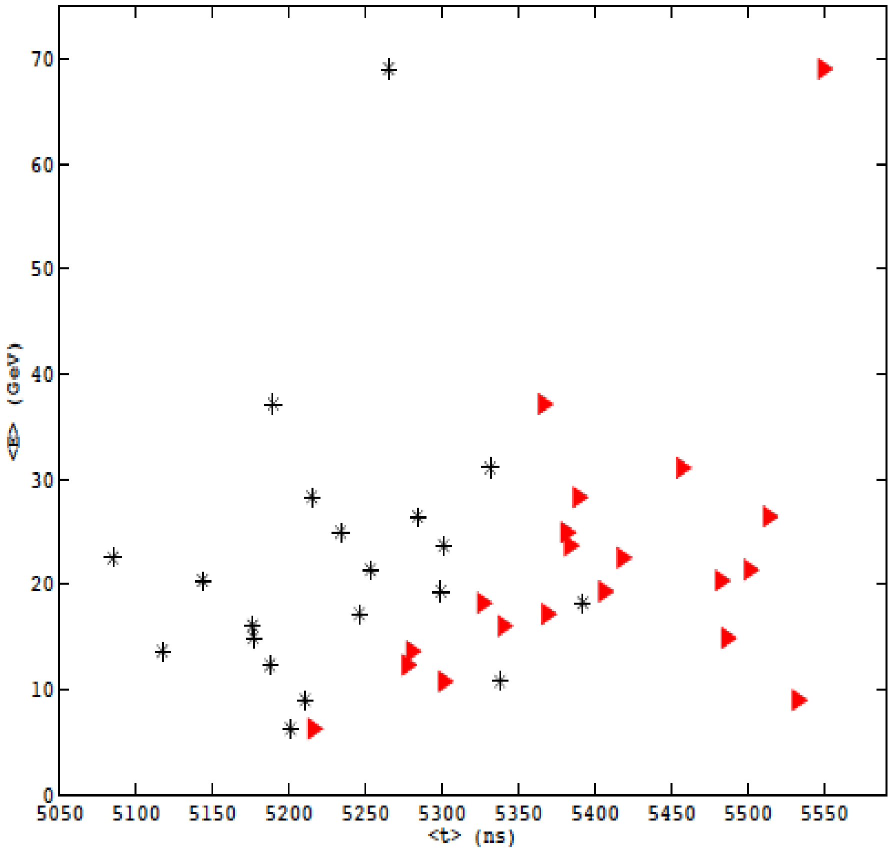


- 100 ns resolution, linear delay by 5 ns/GeV, corresponding to $M_{\nu\, QG1} = 4.85 \times 10^5$ GeV

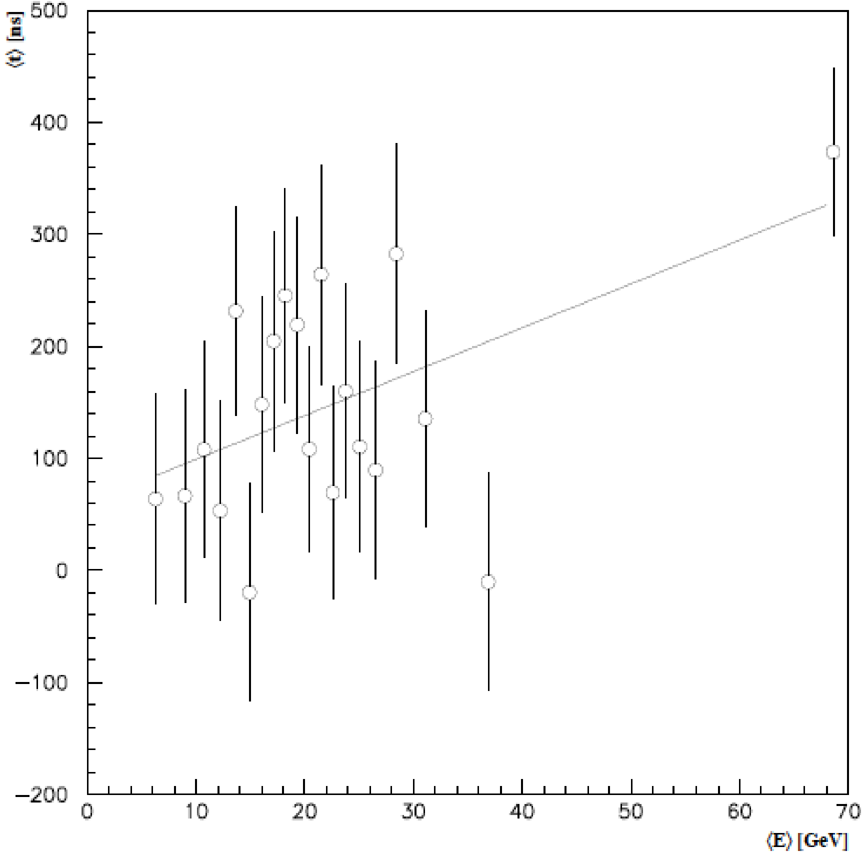
JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Arrival Times for Different Energies

- 1000-event slices



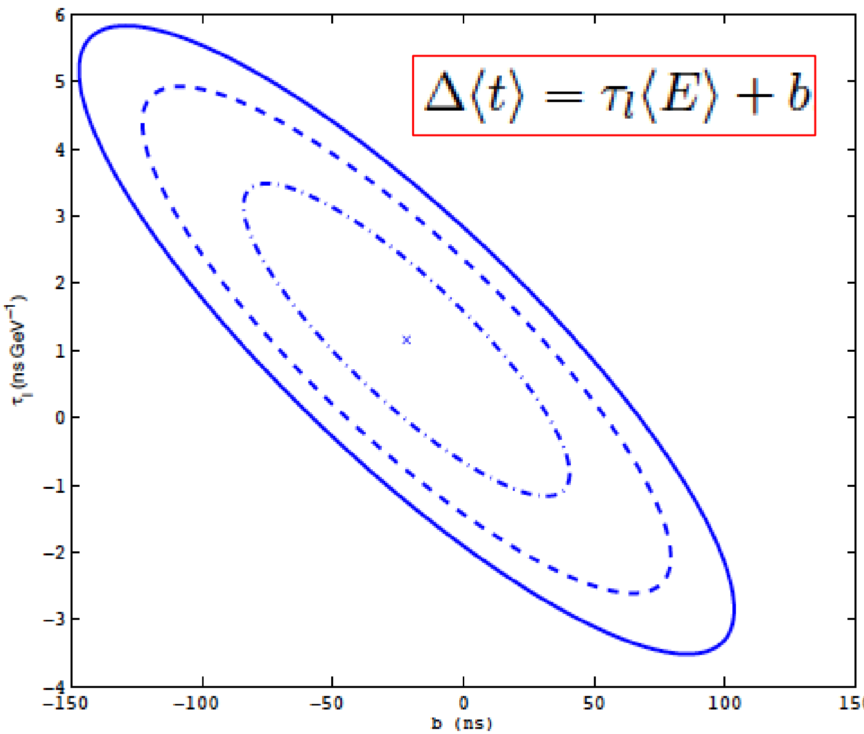
- Higher energies later



JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

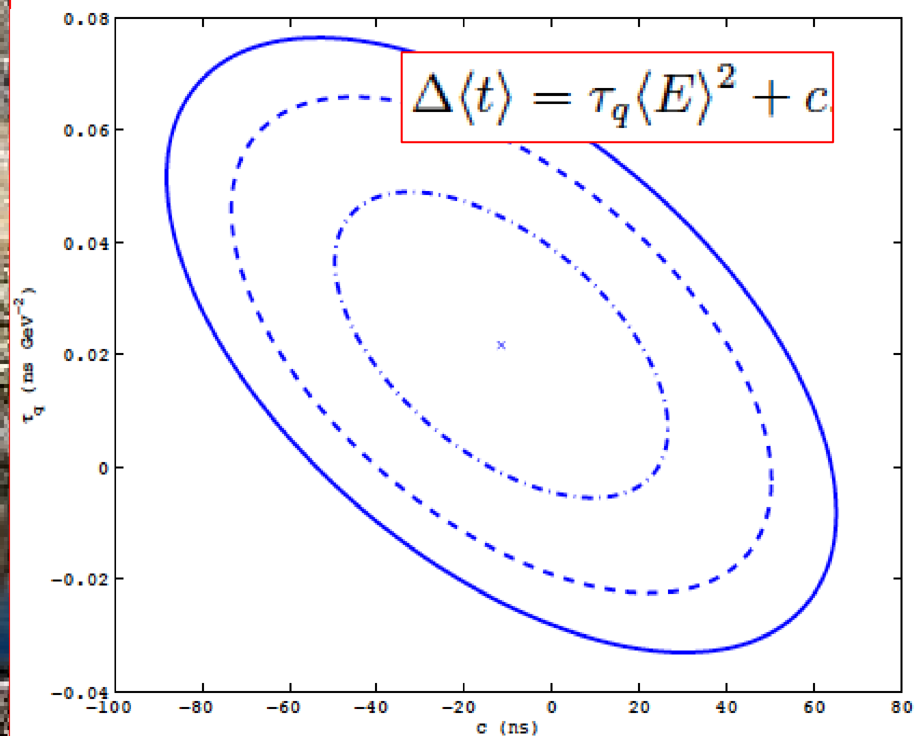
Fits to Simulated OPERA Data

- Linear case



- Sensitivity $M_{\nu QG1} \simeq 7 \times 10^5$ GeV

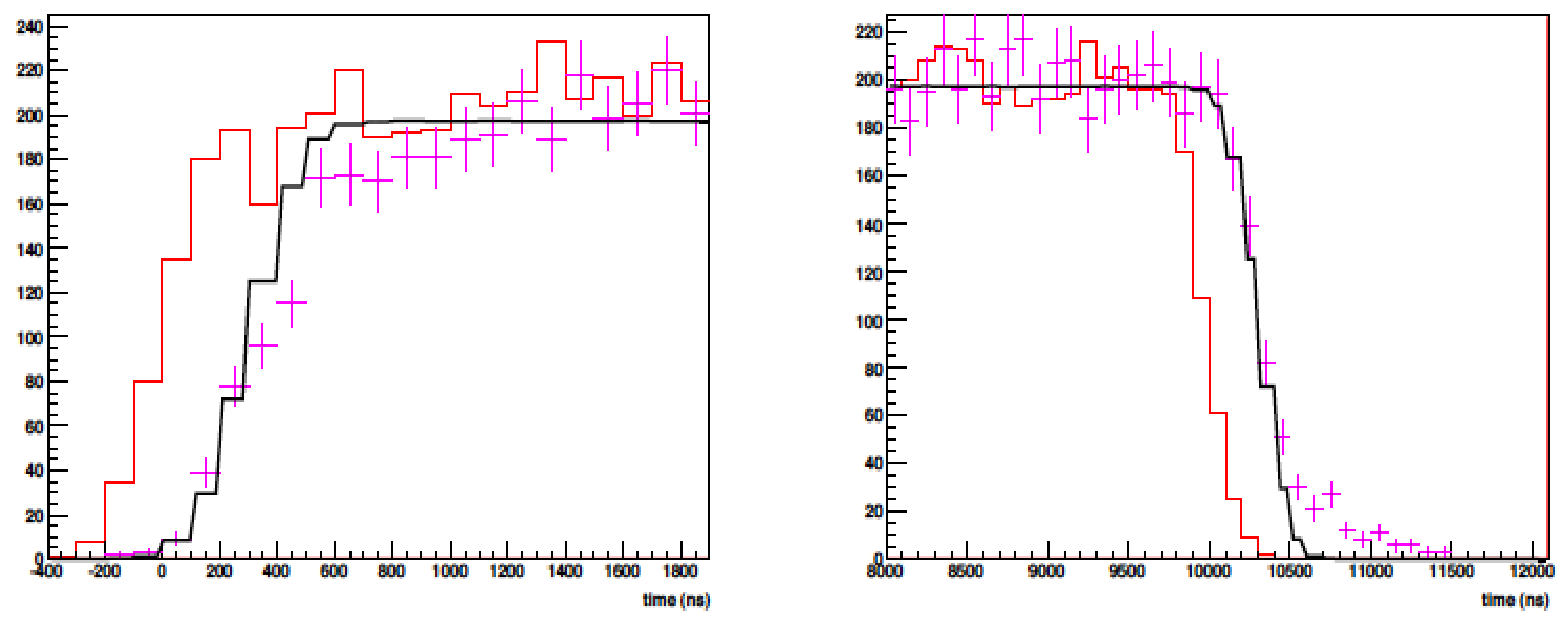
- Quadratic case



- Sensitivity $M_{\nu QG2} \simeq 8\times10^3$ GeV

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Fitting Edges of Spill

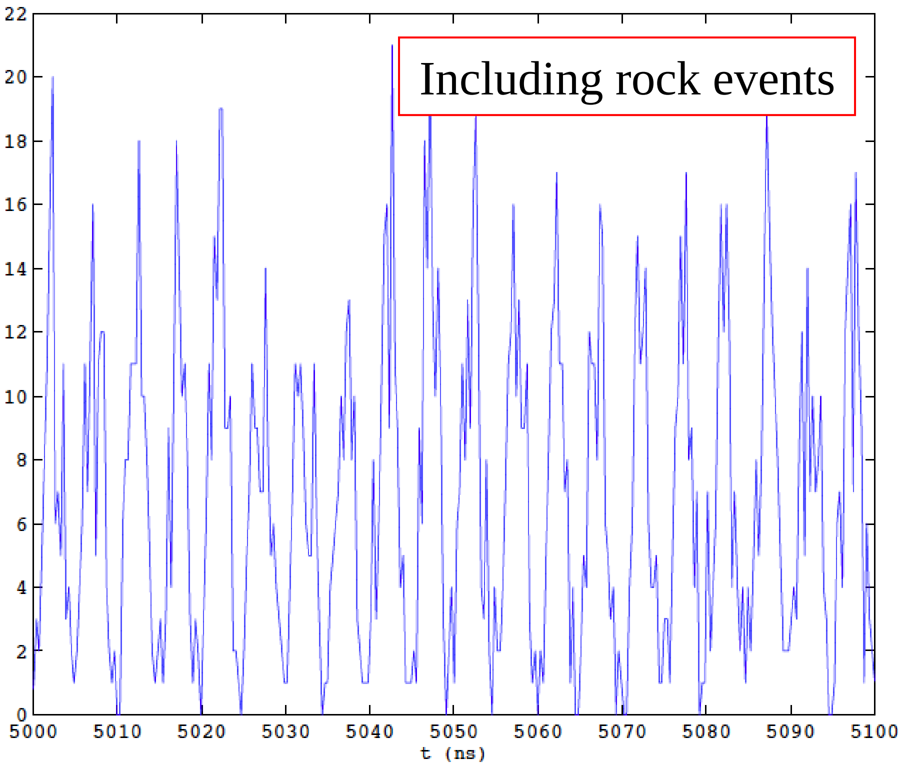


- Factor ~ 5 less sensitivity to energy dependence

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

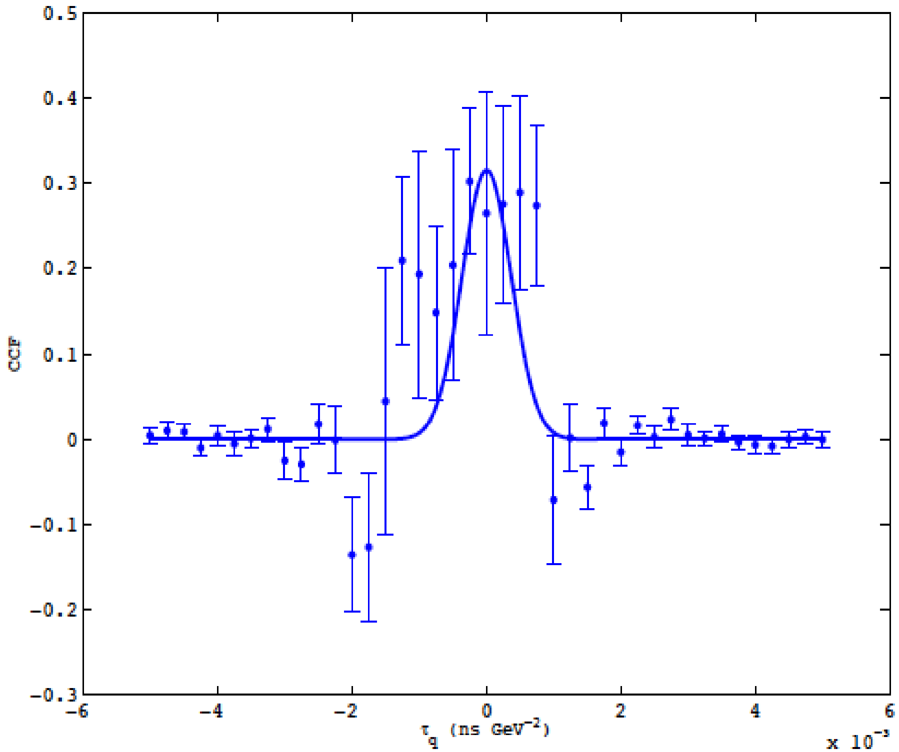
Using 5ns Bunch Structure

- 5 ns spacing, 1 ns bunches



- Sensitivity $M_{\nu QG1} \simeq 4 \times 10^8$ GeV

- Fit to quadratic case



- Sensitivity $M_{\nu QG2}$ 7×10^5 GeV

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

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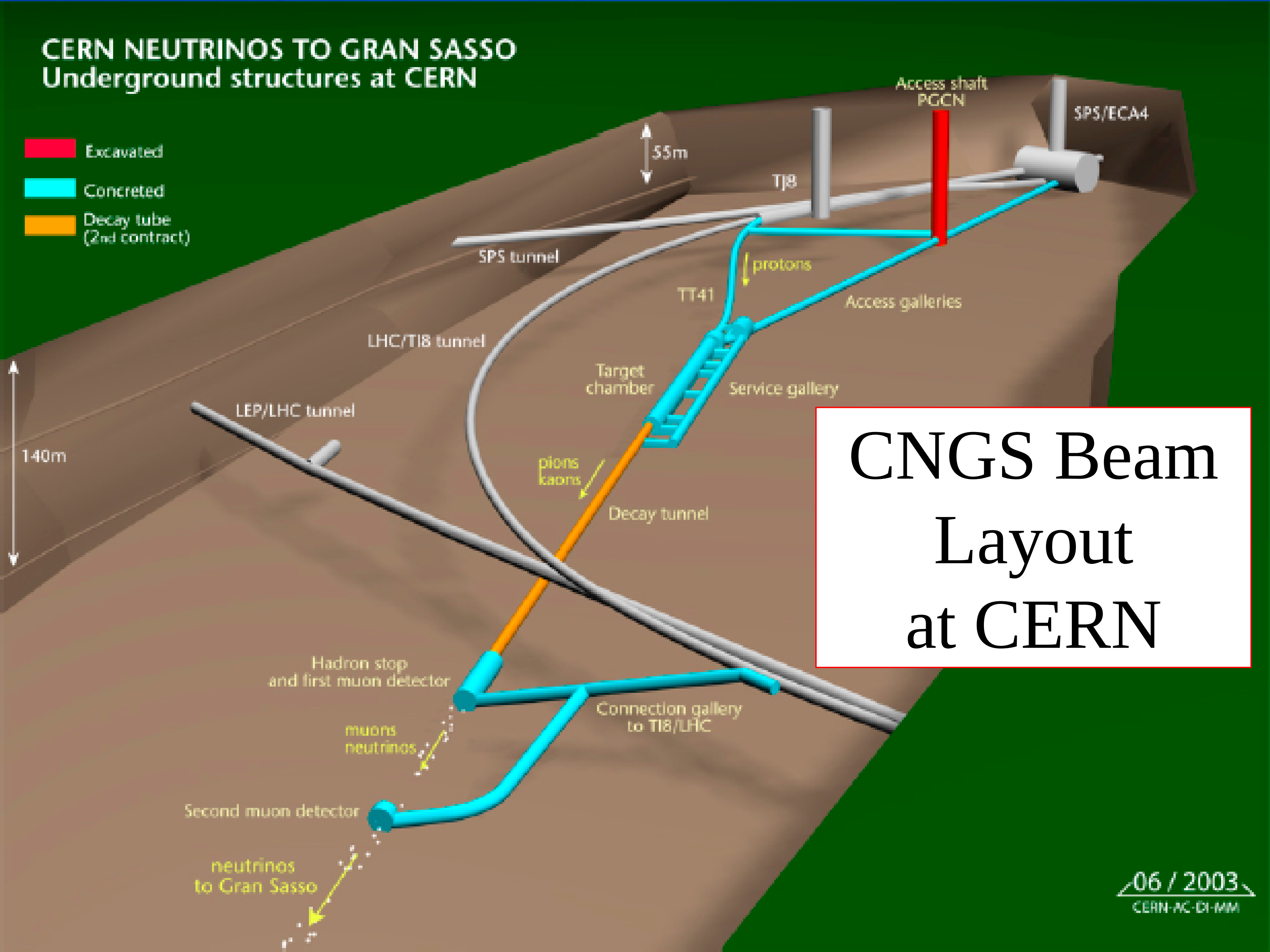
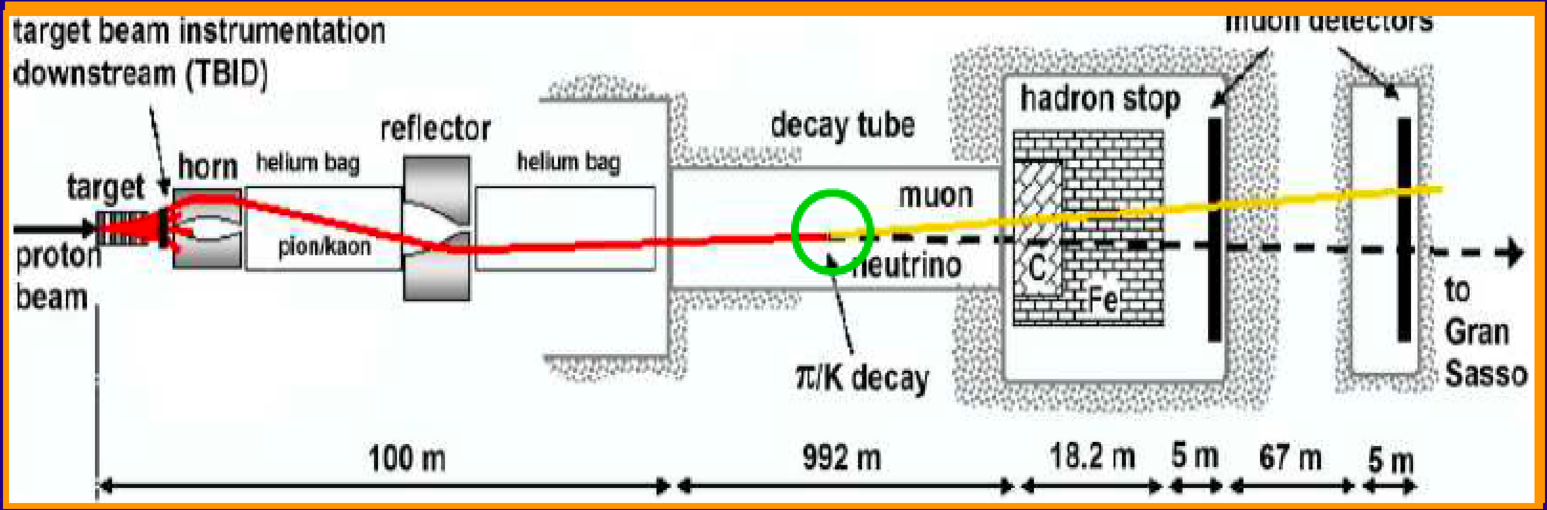
CNGS Beam Layout at CERN



Neutrino Beam Production



Unknown neutrino production point:

$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

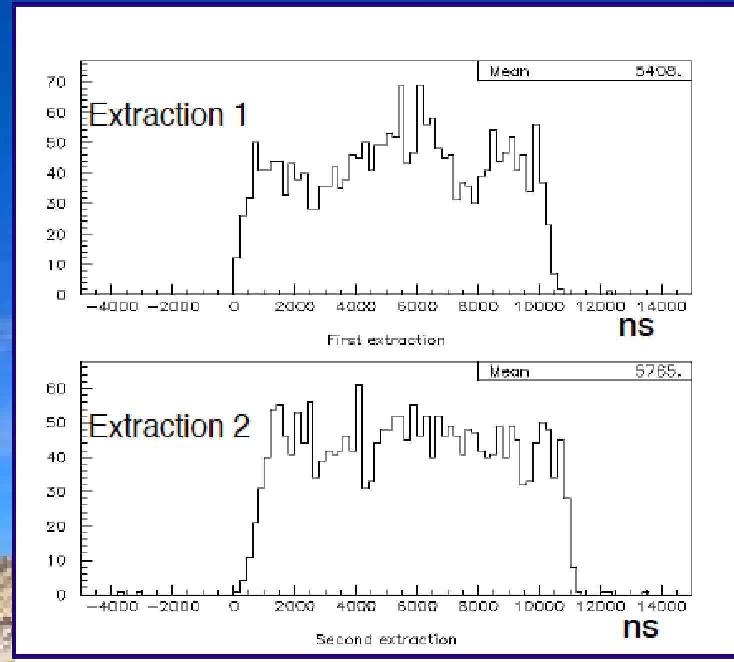
1)accurate UTC time-stamp of protons
2)relativistic parent mesons (full FLUKA simulation)

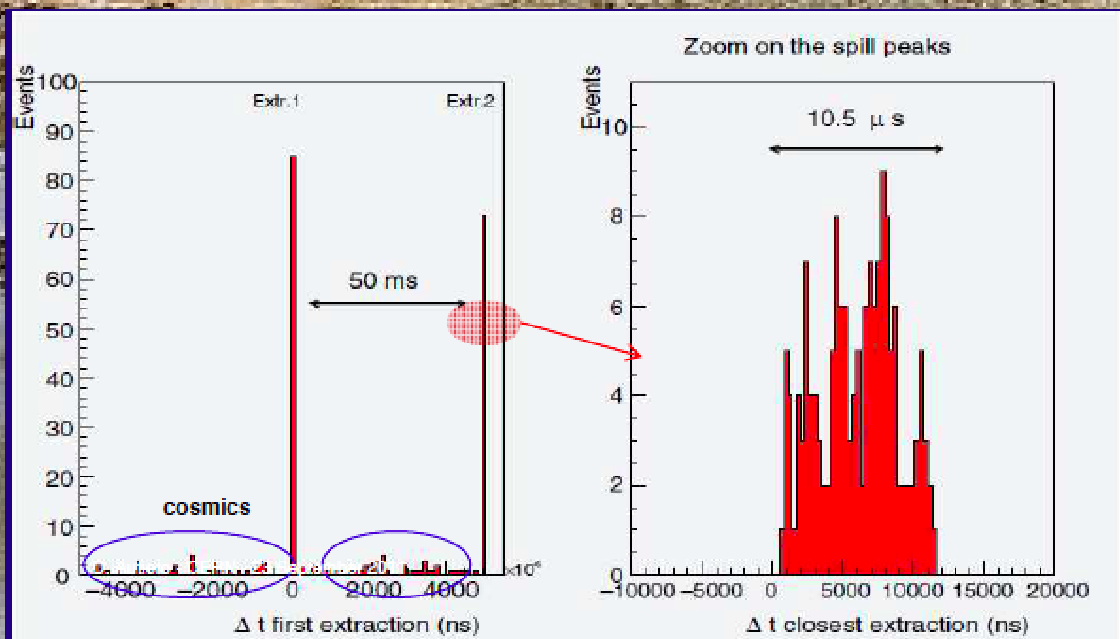
TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)
TOF_{true} = accounting for speed of mesons down to decay point
$\Delta t = TOF_{true} - TOF_c$

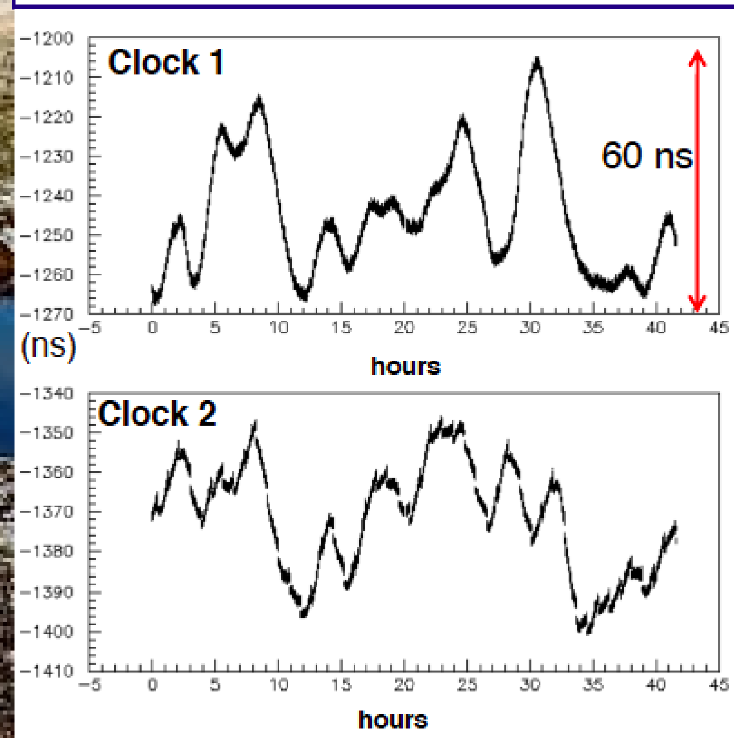
$\langle \Delta t \rangle = 1.4 \times 10^{-2}$ ns

OPERA Beam Structure

Pairs of extractions
Negligible cosmic-ray background
Fine structure within extractions
Clocks drift over time

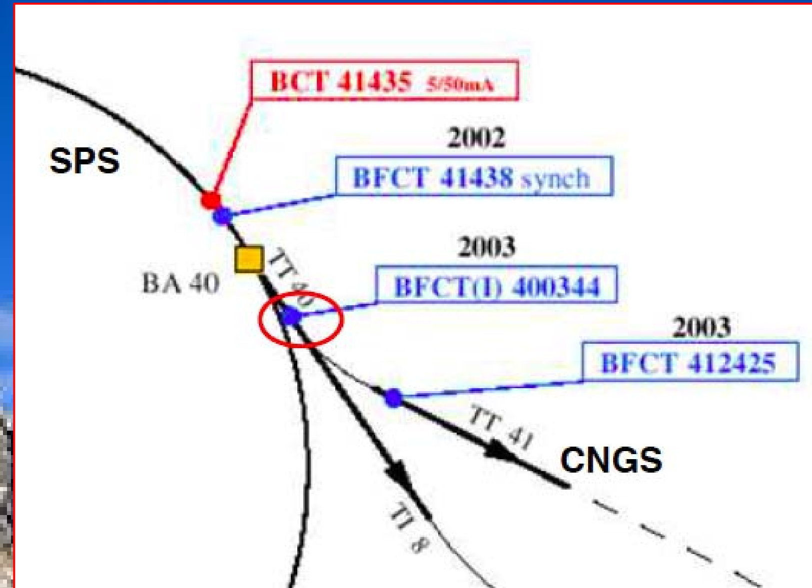


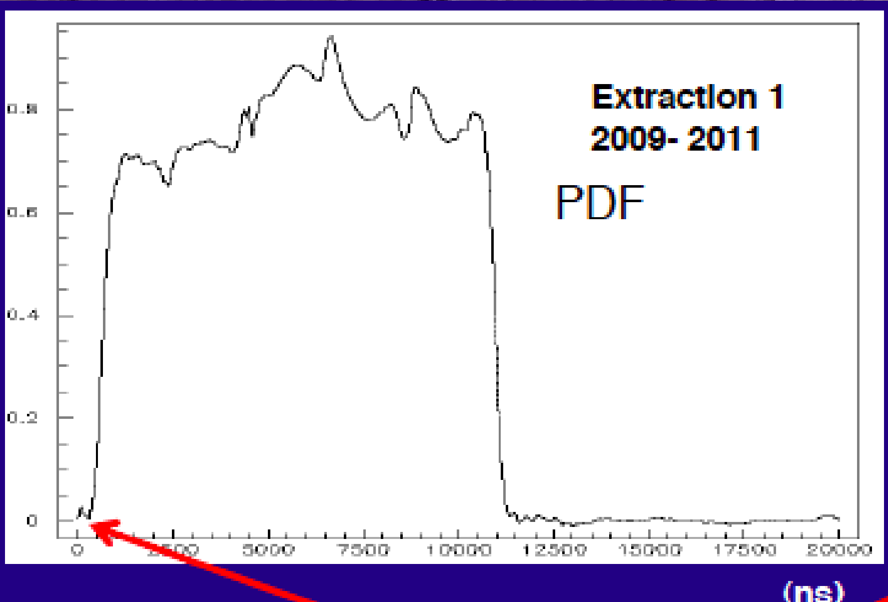


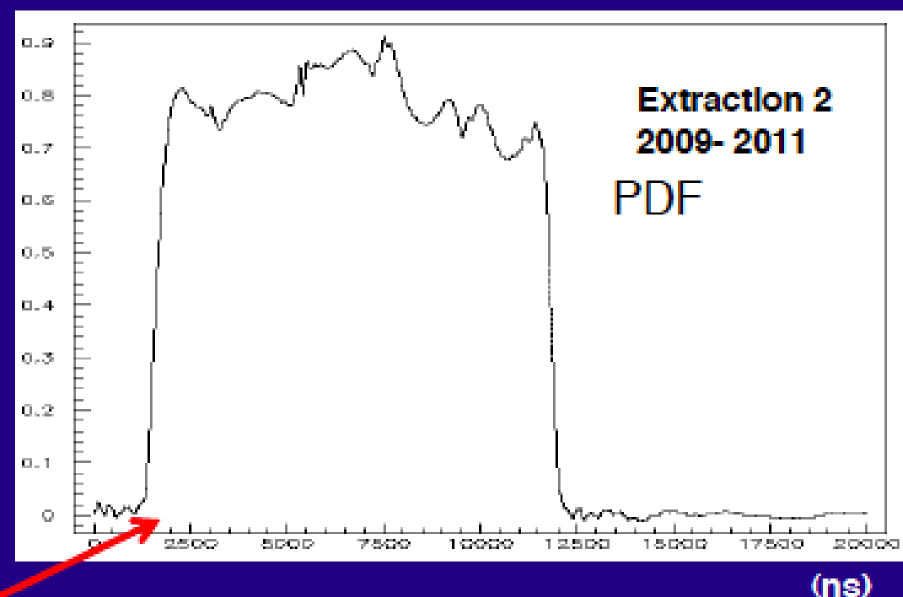


Time Structure of Proton Beam

As measured by
Beam Current Transformers
(BCTs)

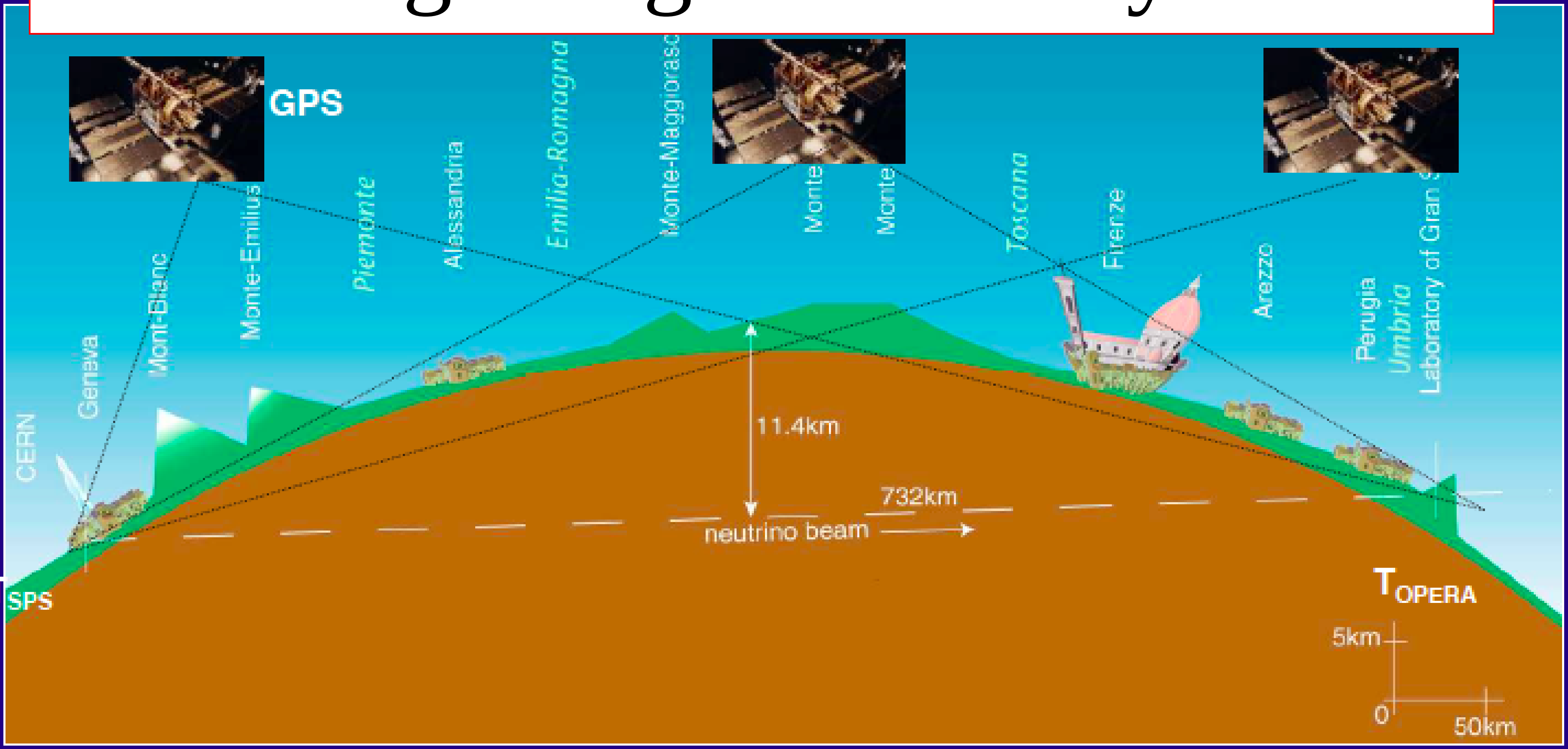






different timing w.r.t. kicker magnet signal

Timing using the GPS System

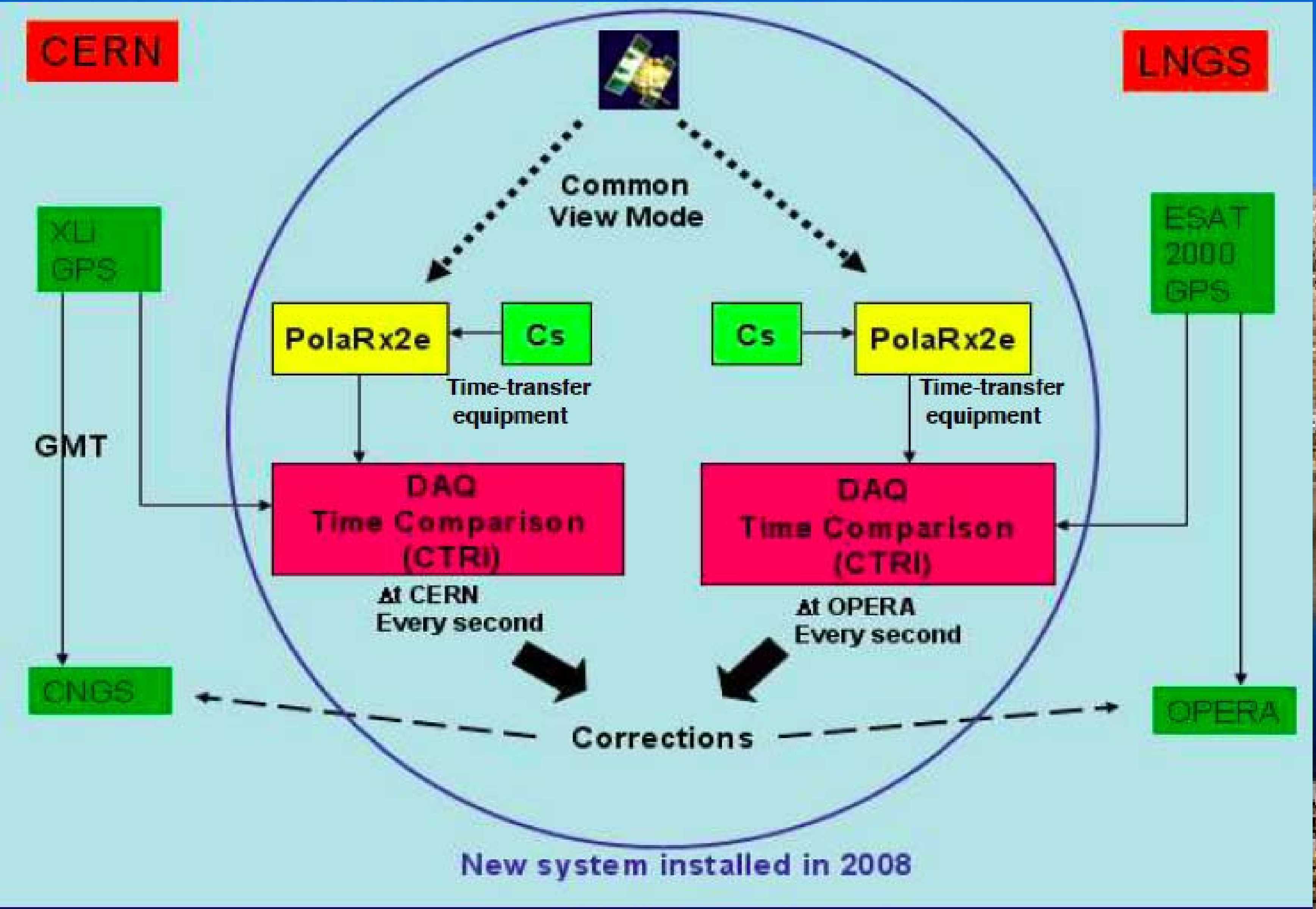


Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

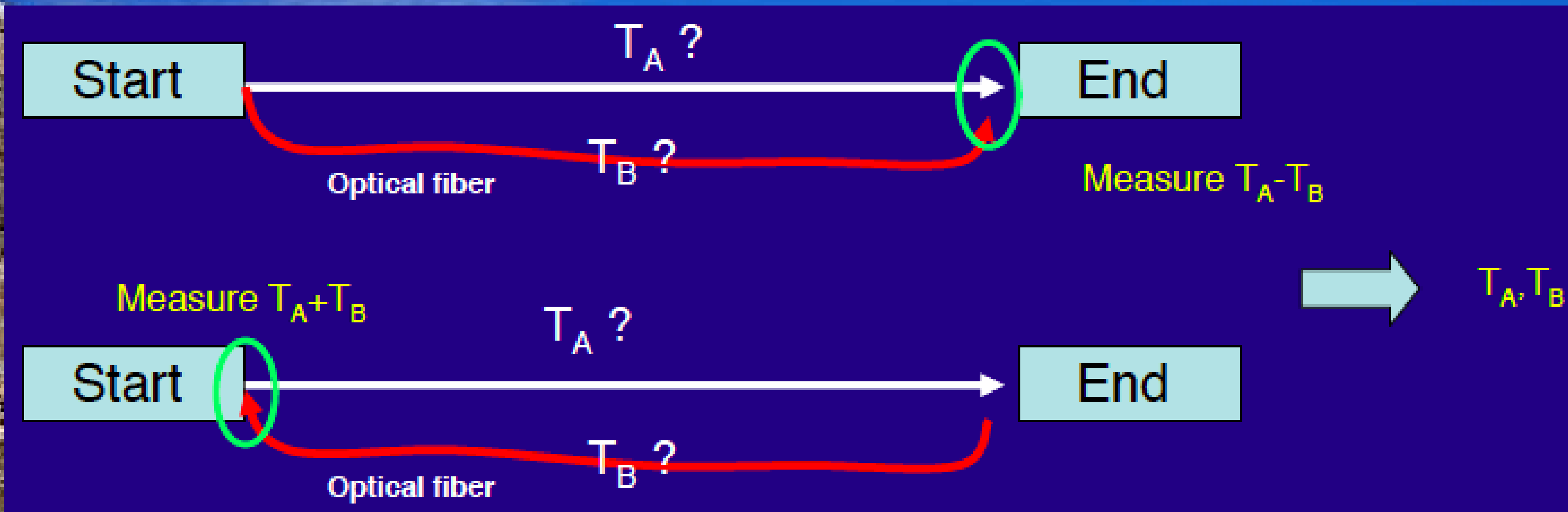
$$|T_{OPERA} - (T_{Kicker} + TOFc)| < 20\ \mu s$$

Synchronisation with standard GPS systems ~100 ns (inadequate for our purposes)

Summary of Synchronization Procedure



Principle of OPERA Detector Timing



Use two parallel paths for signal:

1) Measure difference in time delays T_A - T_B

2) Send signal out along one path, back along the other,

Measure sum of time delays T_A - T_B

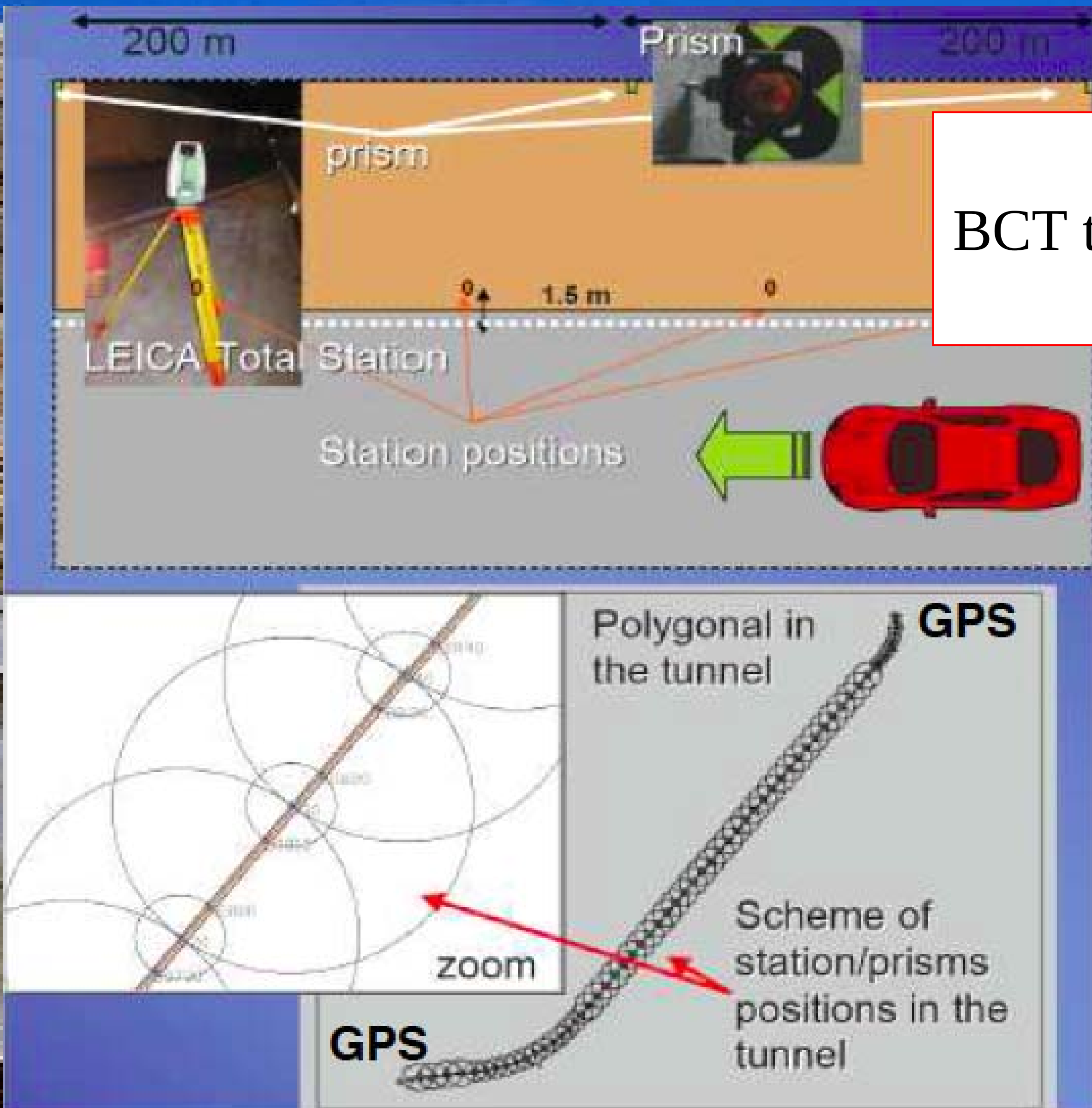
Combination provides both T_A and T_B

(Also used for accelerator timing)

Summary of Timing Uncertainties

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

LNGS Geodesy

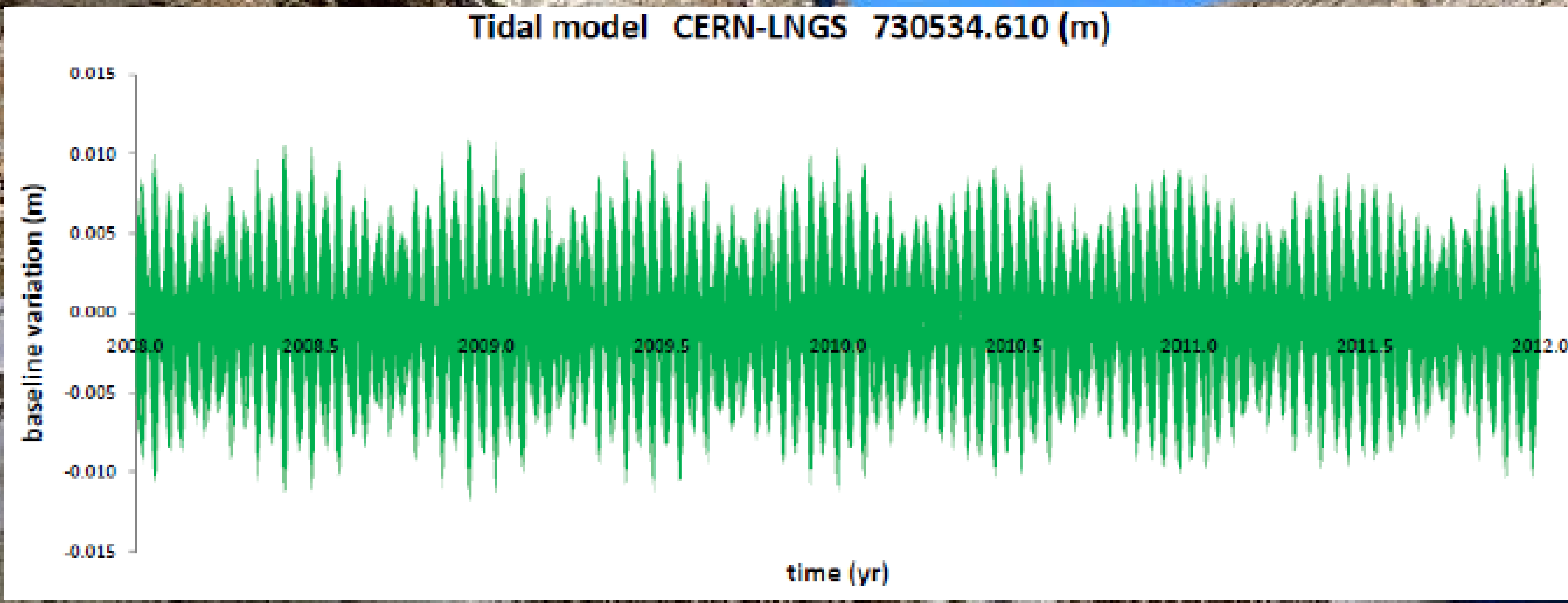


Resulting distance:
BCT to OPERA reference frame
731278.0 ± 0.2 m

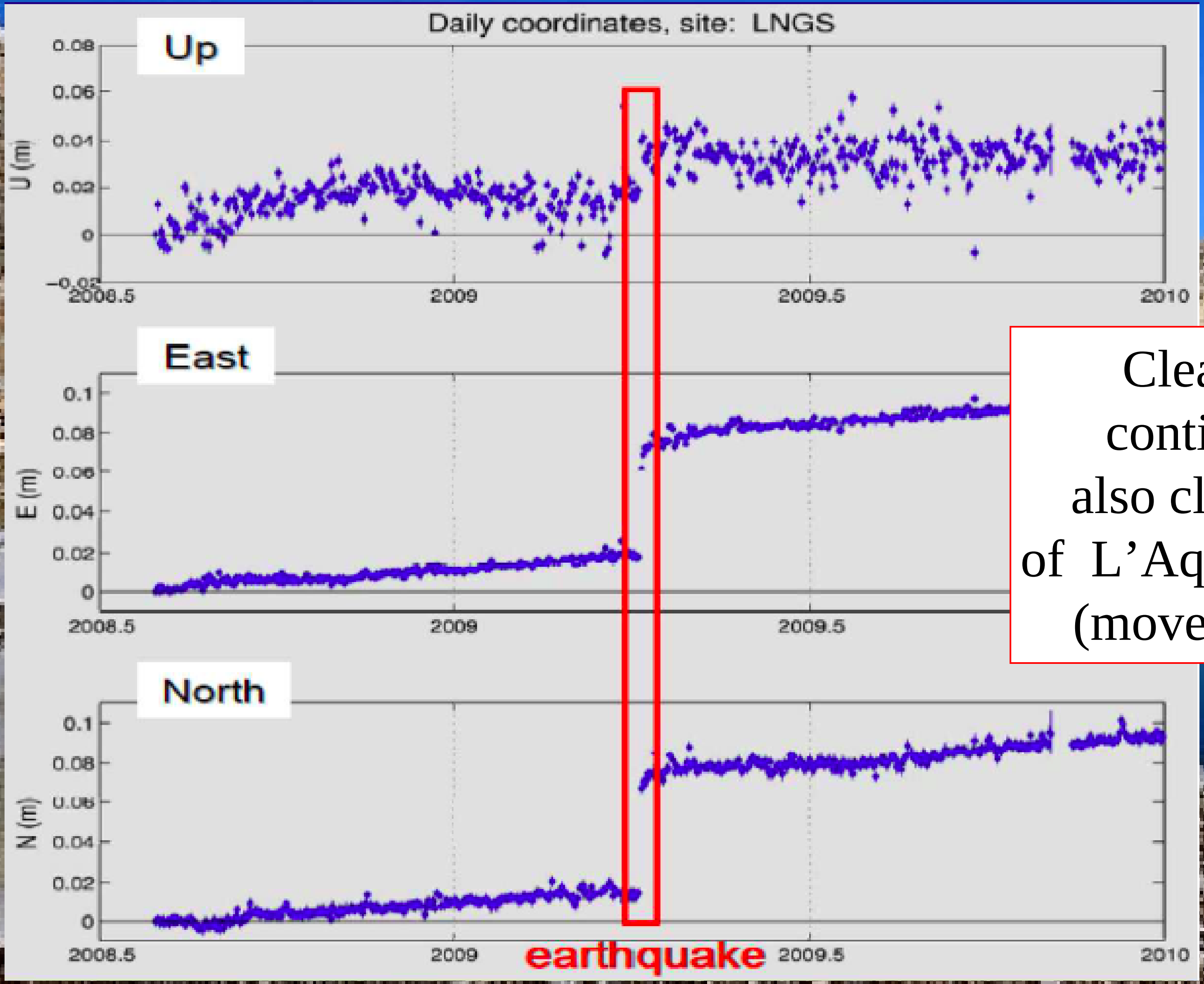
Analysis in Collaboration with Swiss and German National Institutes of Metrology, Checked by International Bureau of Standards in Paris, Belgian Royal Institute

Tides change CNGS Distance

- Earth’s tides

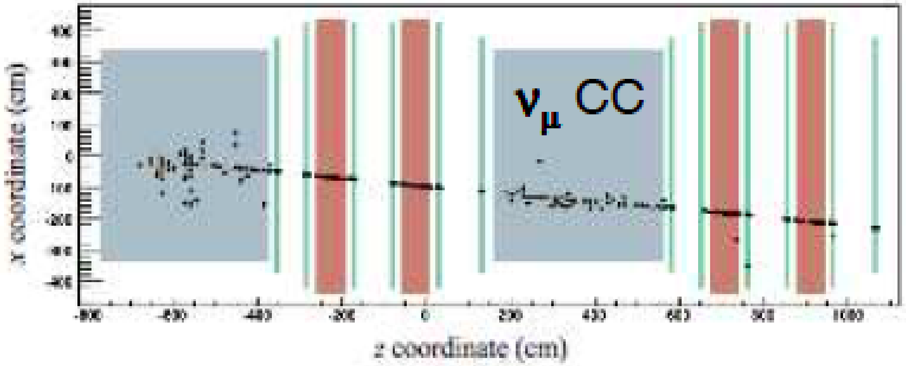


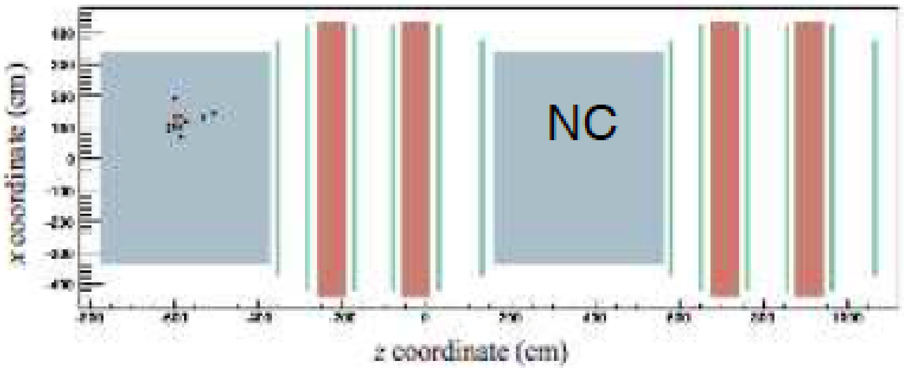
Continuous Distance Monitoring

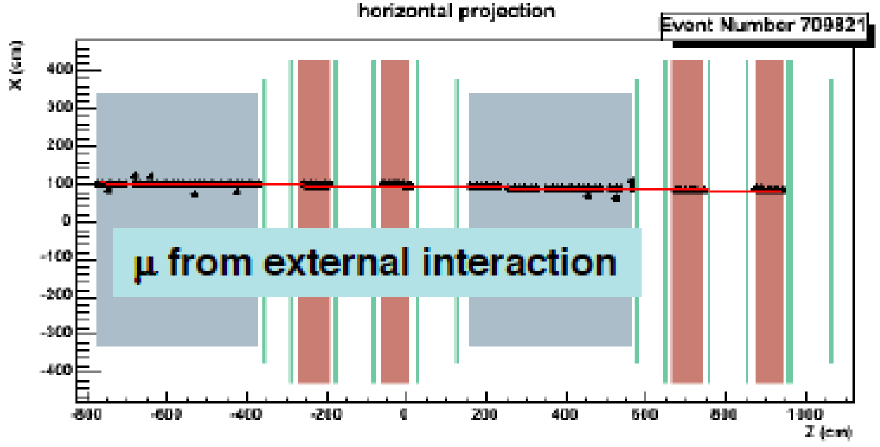


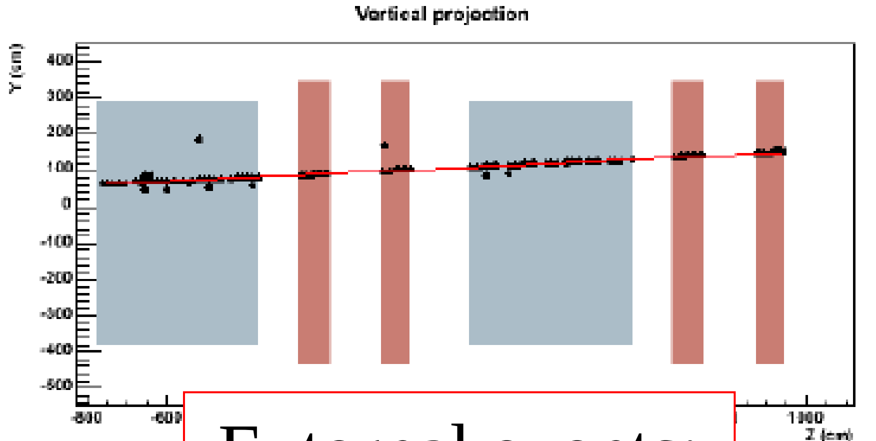
Clear effect of continental drift, also clear signature of L'Aquila earthquake (movement ~ 7 cm)

Classes of OPERA Events





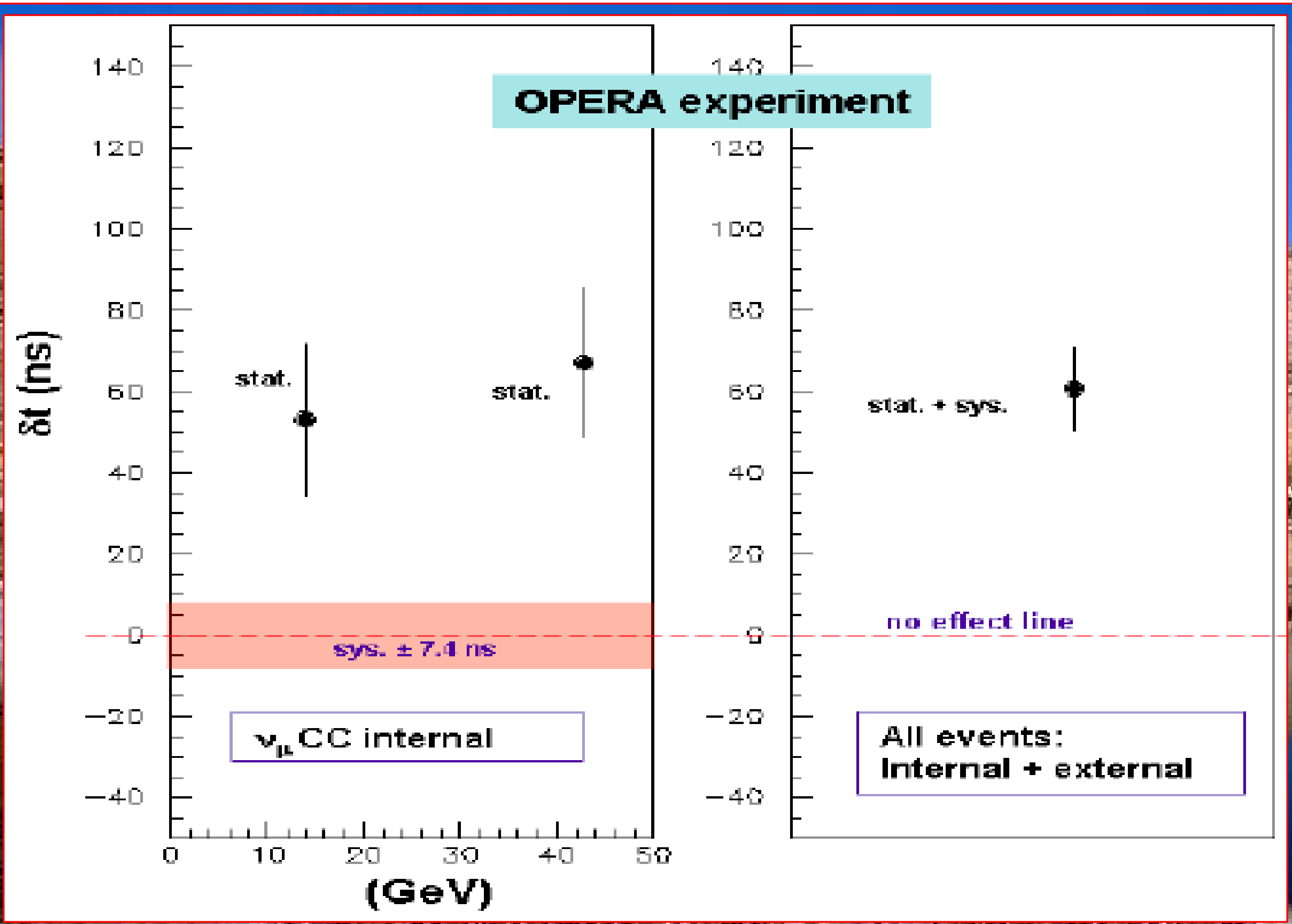




Internal events: inside detector

External events: In upstream rock

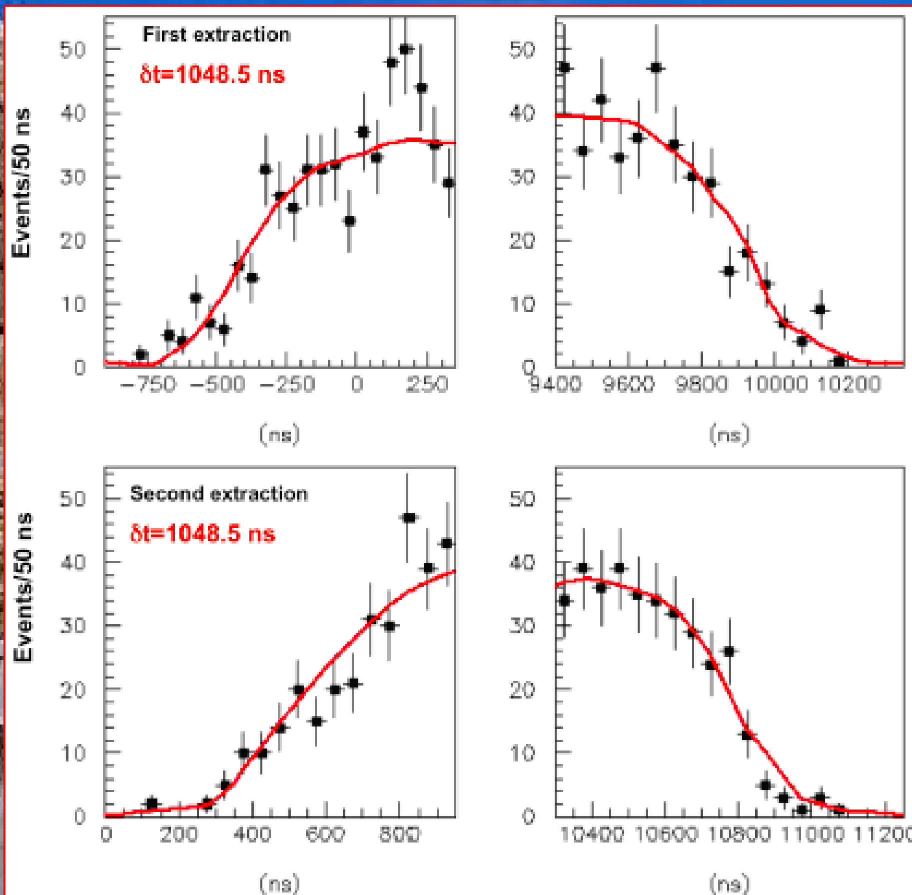
The Main Result

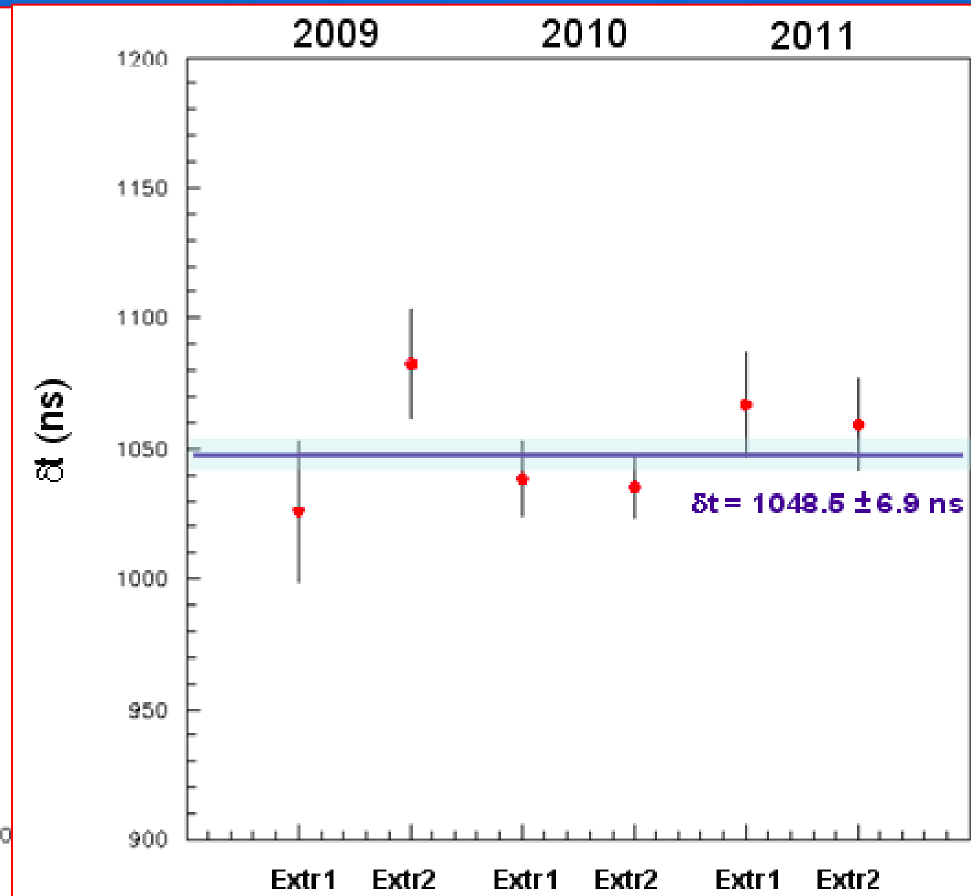


$\delta t = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns

$(v-c)/c = \delta t\ /(\text{TOF}'_c - \delta t) = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$

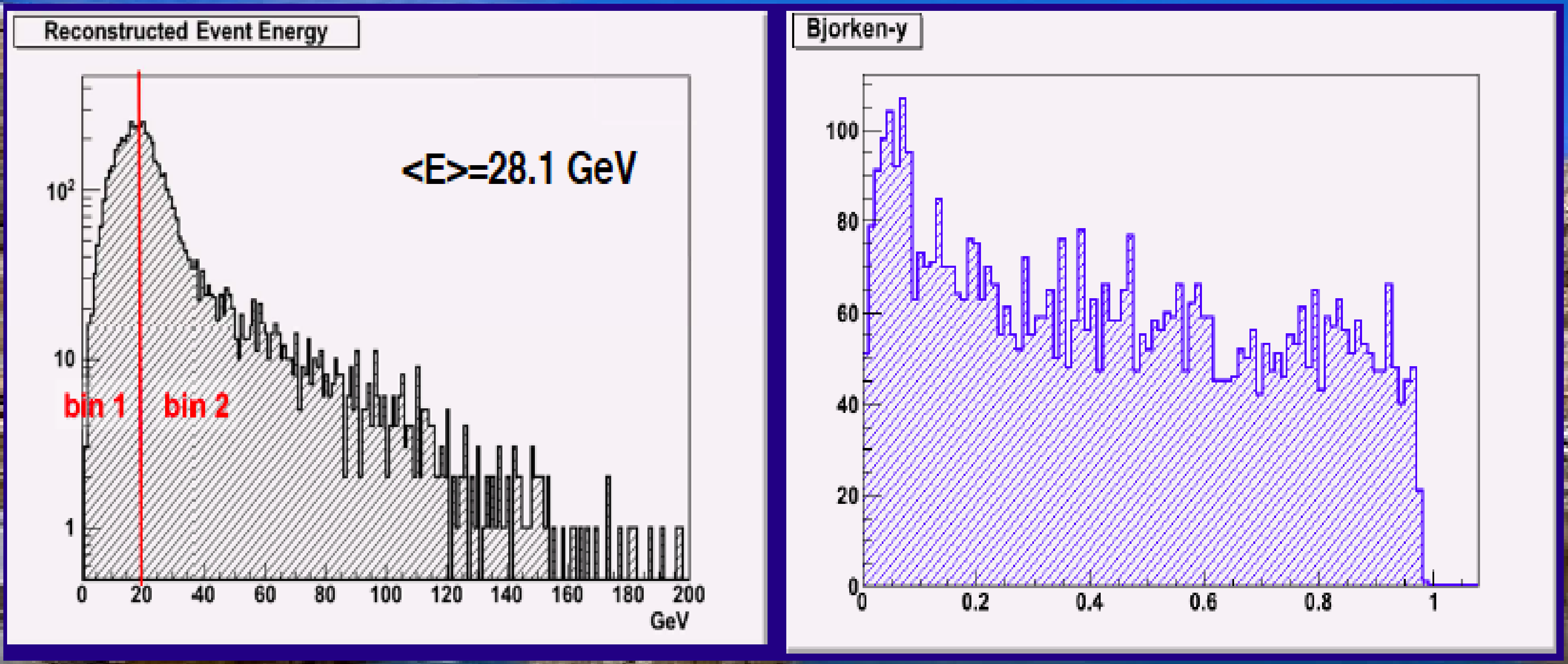
Fits to Different Extractions





Consistent results with leading and trailing edges of both extractions
Also consistent over 3 years 2009, 2010, 2011

Distortion of Energy Spectrum?



Events seen up to very high energies >> $\langle E_\nu \rangle$ = 28.1 GeV
No apparent distortion of kinematic observables
(relevant to possibility of Čerenkov radiation)

Special and General Relativity

- Sagnac effect (rotation of Earth during travel):

$$\delta t \simeq \frac{\vec{\omega}\cdot(\vec{r}_1 \times \vec{\Delta r})}{c^2}$$ **$\delta t = +\ 2.16$ ns**

- Tends to increase travel time
- Smaller than total error taken into account
- Schwartzschild effects ~ $\epsilon = \frac{r_s}{L} = \frac{2GM_e}{Lc^2} \simeq 1.2 \times 10^{-8}$

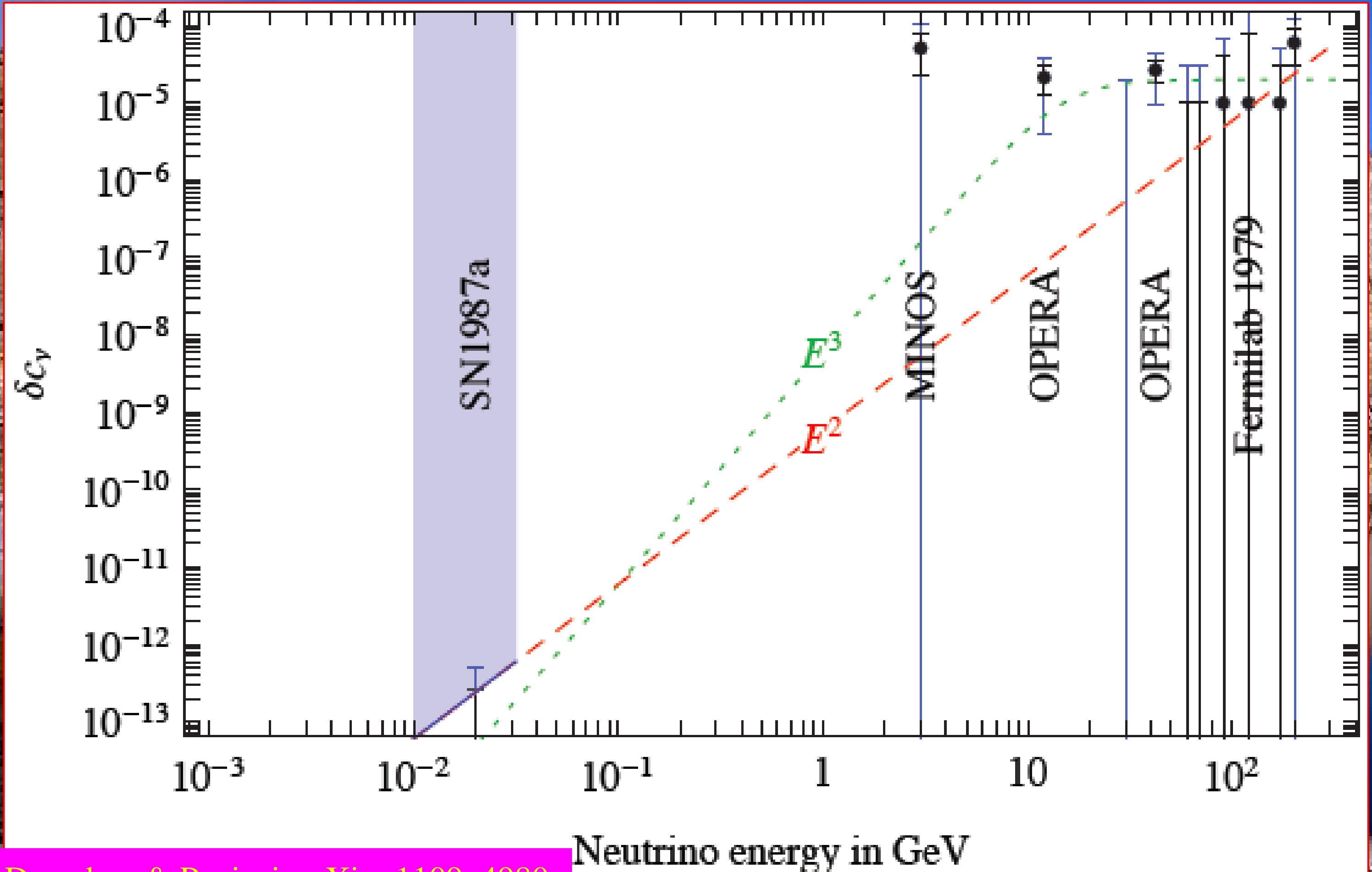
  Neutrinos follow geodesic, re-evaluate Euclidean distance

$$\delta_e^{(1)} \simeq \delta_e^{(2)} = -1.22 \times 10^{-9} \quad , \quad \delta_e^{(2)} - \delta_e^{(1)} \approx \times 10^{-12}$$

- Non-inertial effects, redshifts of clocks, dipole field, frame-dragging all negligible

Kiritsis & Nitti: OPERA public note 136

Comparison of Neutrino Constraints



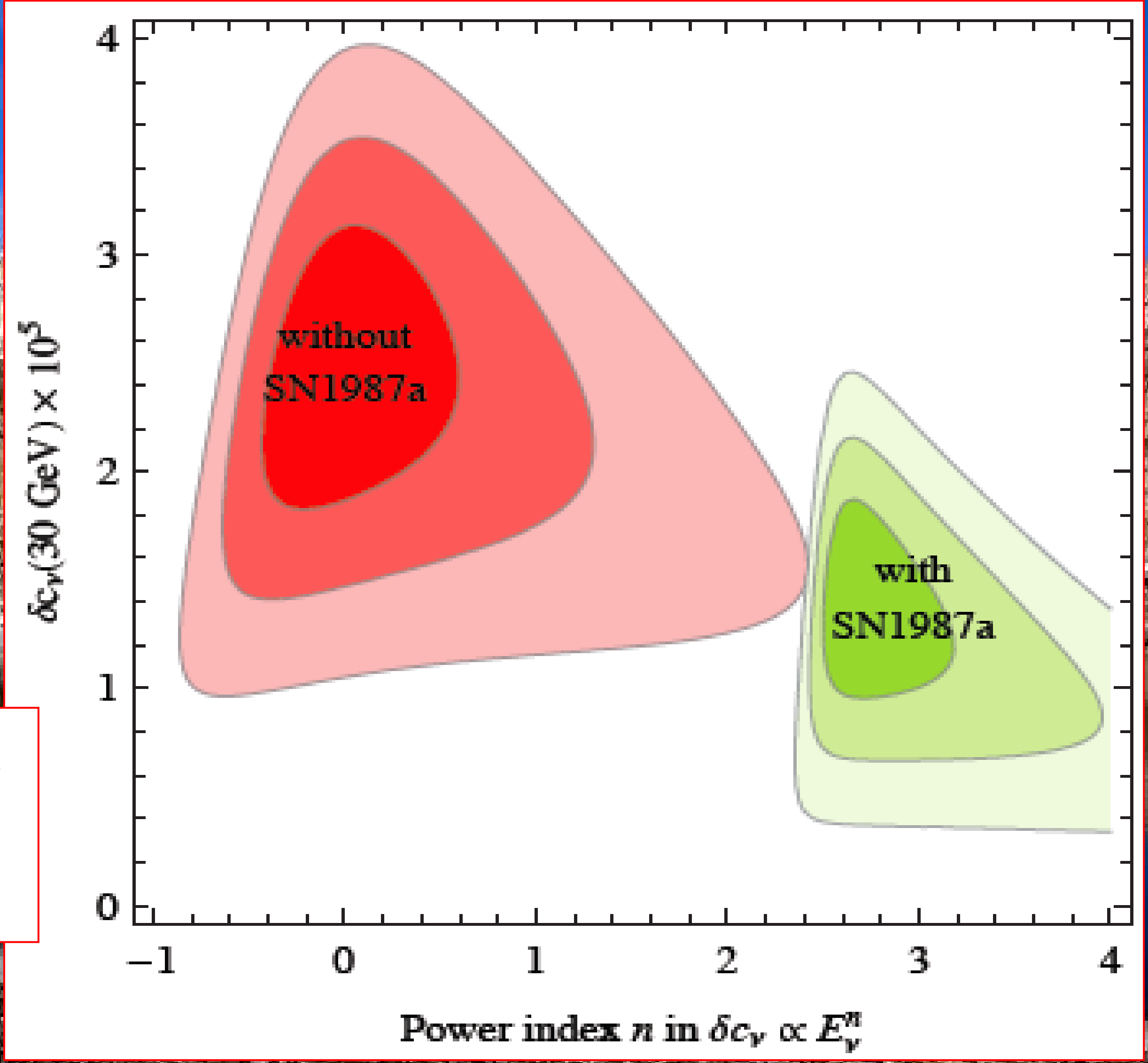
Cacciapaglia, Deandrea & Panizzi: arXiv: 1109. 4980

Giudice, Sibiryakov & Strumia: arXiv: 1109. 5682

Alexandre, JE & Mavromatos: arXiv: 1109.6296

SN1987a excludes $\delta v \sim E$ or E^2

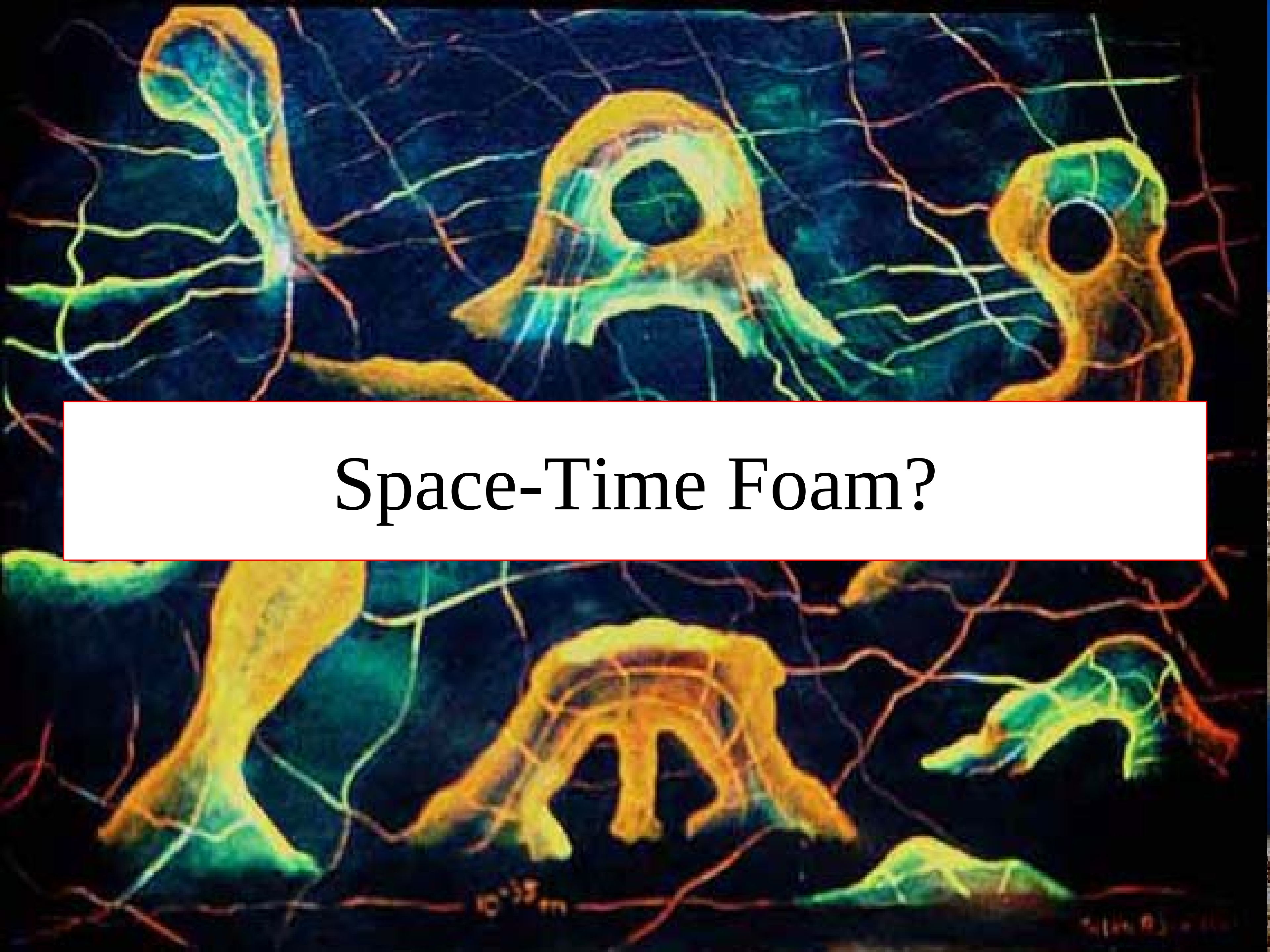
Power-Law Fit to Neutrino Data



Need $\delta v \sim E^n$ with n > 2.5

Giudice, Sibiryakov & Strumia: arXiv: 1109. 5682

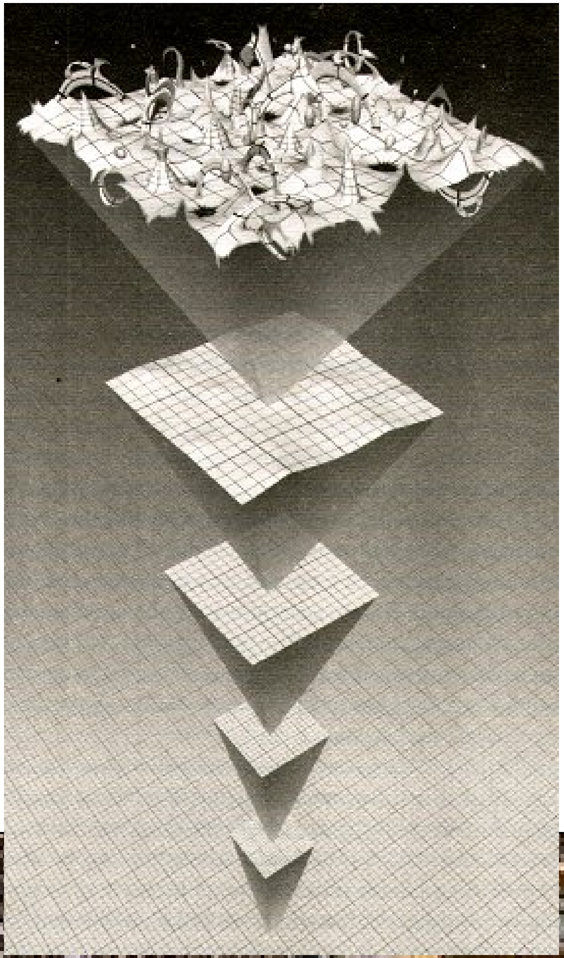
Space-Time Foam?



Nature of Quantum Gravity Vacuum

- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta \chi \sim 1$
- Fluctuations in energy, space, time, topology of order unity
- **"Space-time foam"** J.A.Wheeler
- **Induce Lorentz violation?**



Probes of Lorentz Violation for Photons

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{\rm QG}} \frac{L}{c}$$

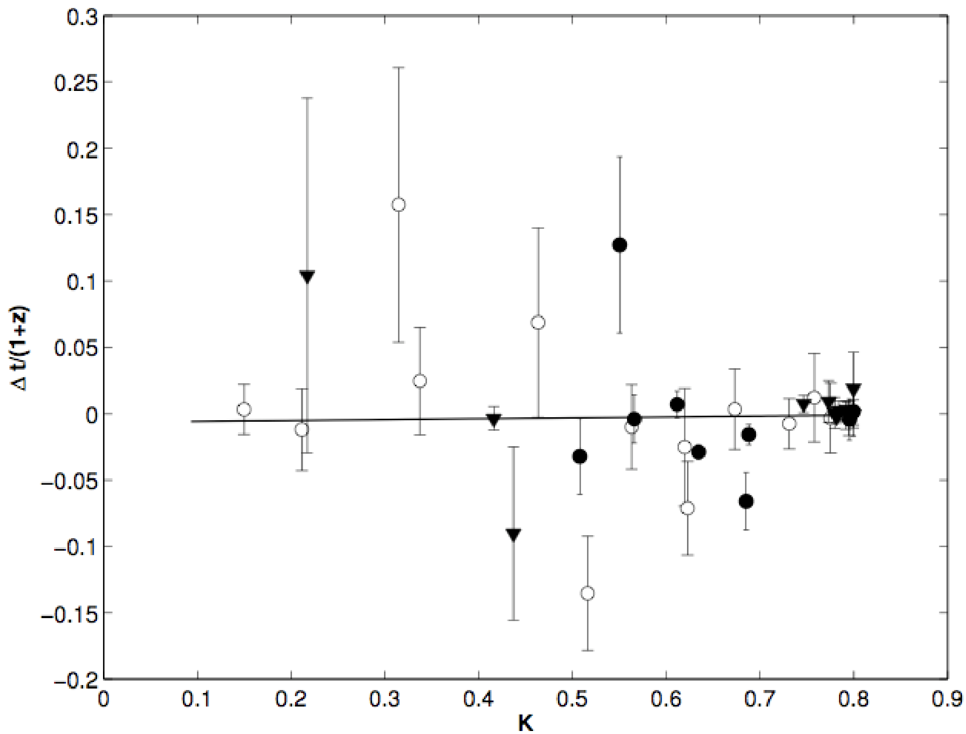
Amelino-Camelia, JE, Mavromatos, Nanopoulos + Sarkar: 1997

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δ t
- Gamma-Ray Bursters, pulsars, active galaxies, …
- Typical sensitivities:

Source	Distance	E	Δt	Sensitivity to M
GRB 920229 [a]	3000 Mpc (?)	200 keV	10^{-2} s	0.6×10^{16} GeV (?)
GRB 980425 [a]	40 Mpc	1.8 MeV	10^{-3} s (?)	0.7×10^{16} GeV (?)
GRB 920925c [a]	40 Mpc (?)	200 TeV (?)	200 s	0.4×10^{19} GeV (?)
Mrk 421 [b]	100 Mpc	2 TeV	280 s	$> 7 \times 10^{16}$ GeV
Crab pulsar [c]	2.2 kpc	2 GeV	0.35 ms	$> 1.3 \times 10^{15}$ GeV
GRB 990123	5000 Mpc	4 MeV	1 s (?)	2×10^{15} GeV (?)

Robust Analysis of GRB Data

- Corrected treatment of redshift



- Improved lower limit:

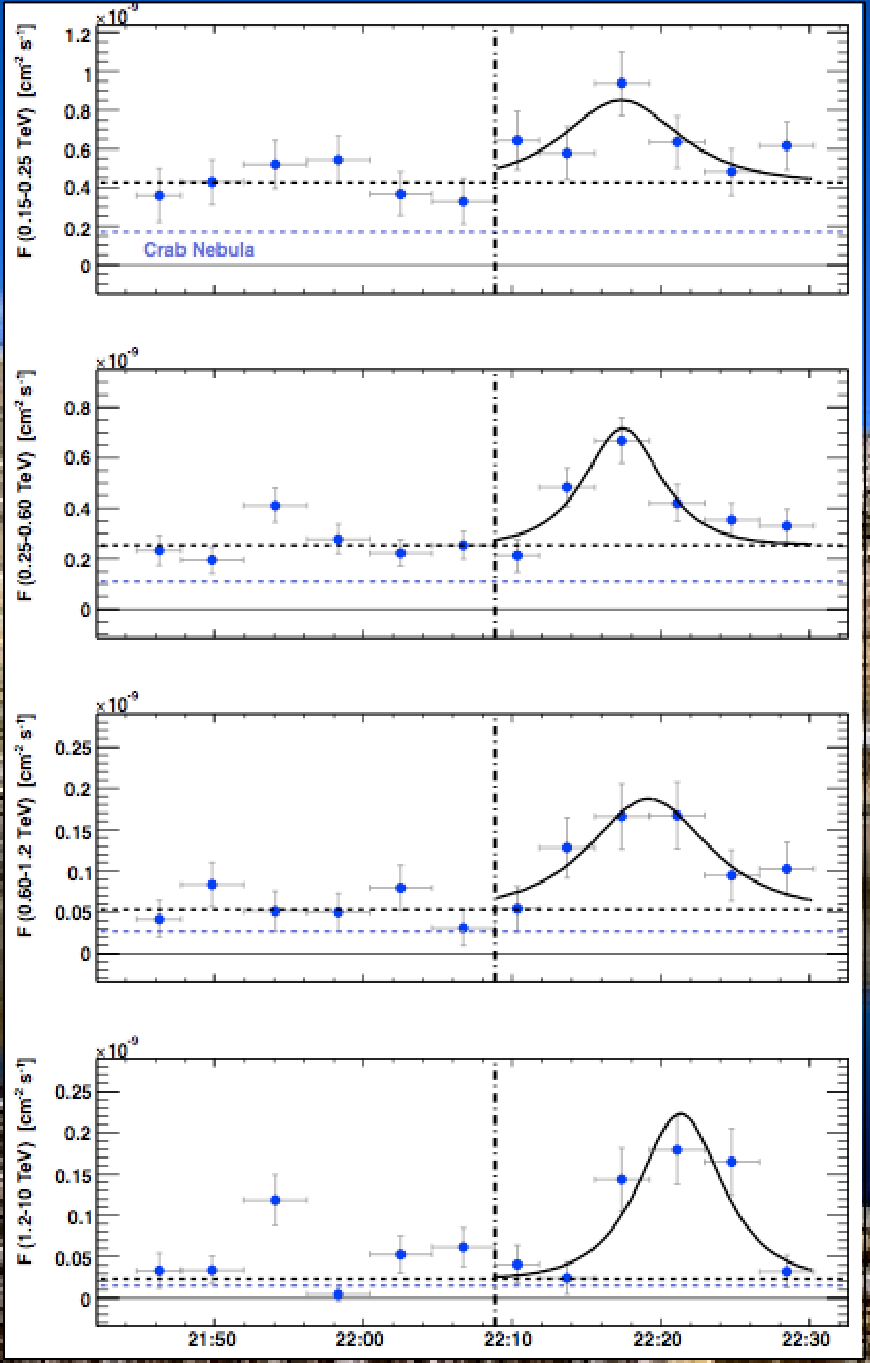
$$M \geq 1.4 \times 10^{16} \text{ GeV}$$

GRB	z	z Refs.	$\Delta t_{total}^{(E_{high}-E_{low})}$ (s)
BATSE (64 ms)			
970508	0.835	[24]	-0.059±0.044
971214	3.418	[25]	-0.098±0.045
980329	3.9	[23]	-0.084±0.036
980703	0.966	[26]	0.138±0.053
990123	1.600	[27]	-0.155±0.041
990308	1.2	[28]	0.0188±0.0138
990510	1.619	[29]	-0.0017±0.0143
991216	1.020	[30]	-0.0091±0.0012
990506	1.3060	[31]	-0.0503±0.0075
HETE (164 ms)			
010921	0.45	[32]	0.0357±0.0585
020124	3.198	[33]	-0.0046±0.0455
020903	0.25	[34]	-0.0150±0.0386
020813	1.25	[35]	-0.1602±0.0794
020819	0.41	[36]	0.222±0.145
021004	2.33	[37]	-0.0402±0.1109
021211	1.01	[23]	-0.0202±0.0639
030226	1.99	[23]	-0.0227±0.0568
030323	3.372	[38]	-0.0148±0.0570
030328	1.52	[23]	0.00825±0.07661
030329	0.168	[39, 23]	0.0037±0.0219
030429	2.66	[40]	-0.0123±0.0965
040924	0.859	[23]	-0.2516±0.0801
041006	0.716	[23]	0.1179±0.1228
050408	1.2357	[23]	-0.0562±0.0989
SWIFT (64 ms)			
050319	3.24	[41]	0.0054±0.0109
050401	2.9	[23]	-0.0135±0.0285
050416	0.653	[23]	-0.1491±0.1075
050505	4.3	[23]	-0.0012±0.0561
050525	0.606	[23, 42]	0.1261±0.0159
050603	2.821	[23]	-0.0032±0.0047
050724	0.258	[43]	0.131±0.1681
050730	3.968	[44]	0.094±0.1361
050820	2.612	[23]	0.033±0.0569
050904	6.29	[45]	0.004±0.0852
050922	2.17	[23]	0.0231±0.0208

JE, Mavromatos, Nanopoulos, Sakharov + Sarkisyan: astro-ph/0510172

Time Delay from Markarian 501?

- Arrival time delay of ~ 4 minutes reported for photons in highest-energy bin
- Sensitive to $M_{QG1} \sim 10^{16}$ GeV



MAGIC Collaboration: astro-ph/0702008

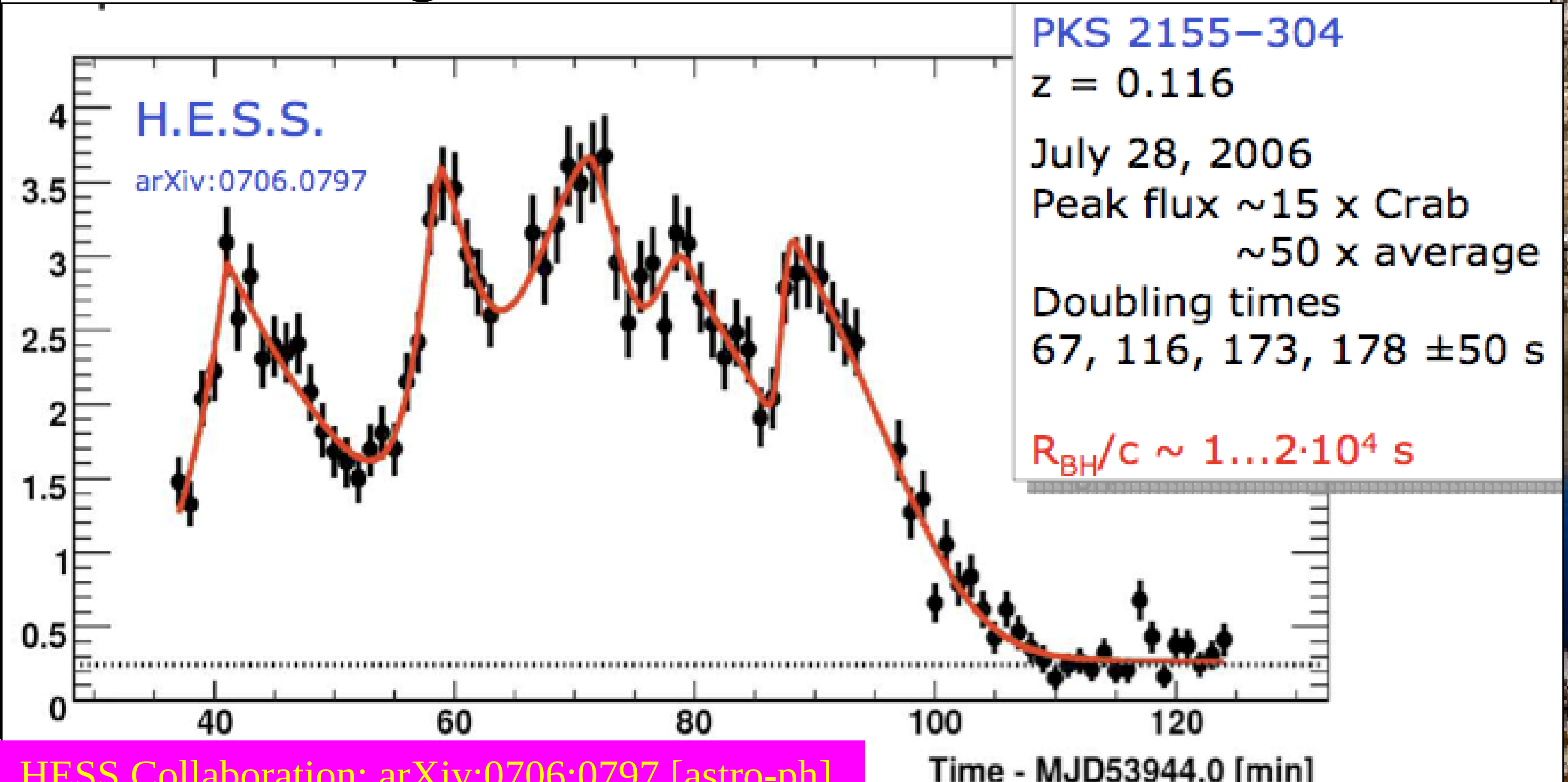
Results for AGN Markarian 501

- Significance of time delay < 95%
- Linear dispersion: (E/M_{QG1})
  - One-σ range: $M_{QG1} = (0.34 \text{ to } 0.78) \times 10^{18}$ GeV
  - 95% CL lower limit: $M_{QG1} > 0.26 \times 10^{18}$ GeV
- Quadratic dispersion: $(E/M_{QG2})^2$
  - One-σ range: $M_{QG2} = (0.47 \text{ to } 1.1) \times 10^{11}$ GeV
  - 95% CL lower limit: $M_{QG2} > 0.27 \times 10^{11}$ GeV
- Cannot exclude initial time delay at source

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Analysis of AGN PKS 2155-304

- Observation by HESS of multiple flaring of AGN at larger redshift with more statistics



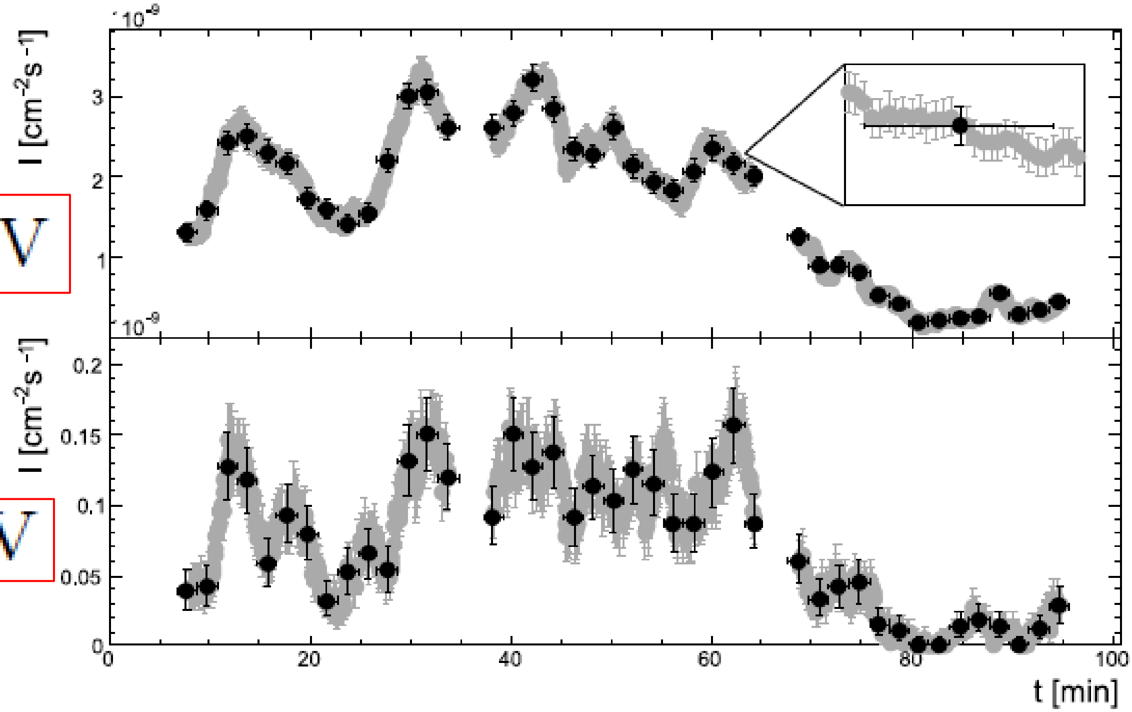
HESS Collaboration: arXiv:0706:0797 [astro-ph]

Analysis of AGN PKS 2155-304

- Comparison between HESS data in different energy bins

200-800 GeV

>800 GeV

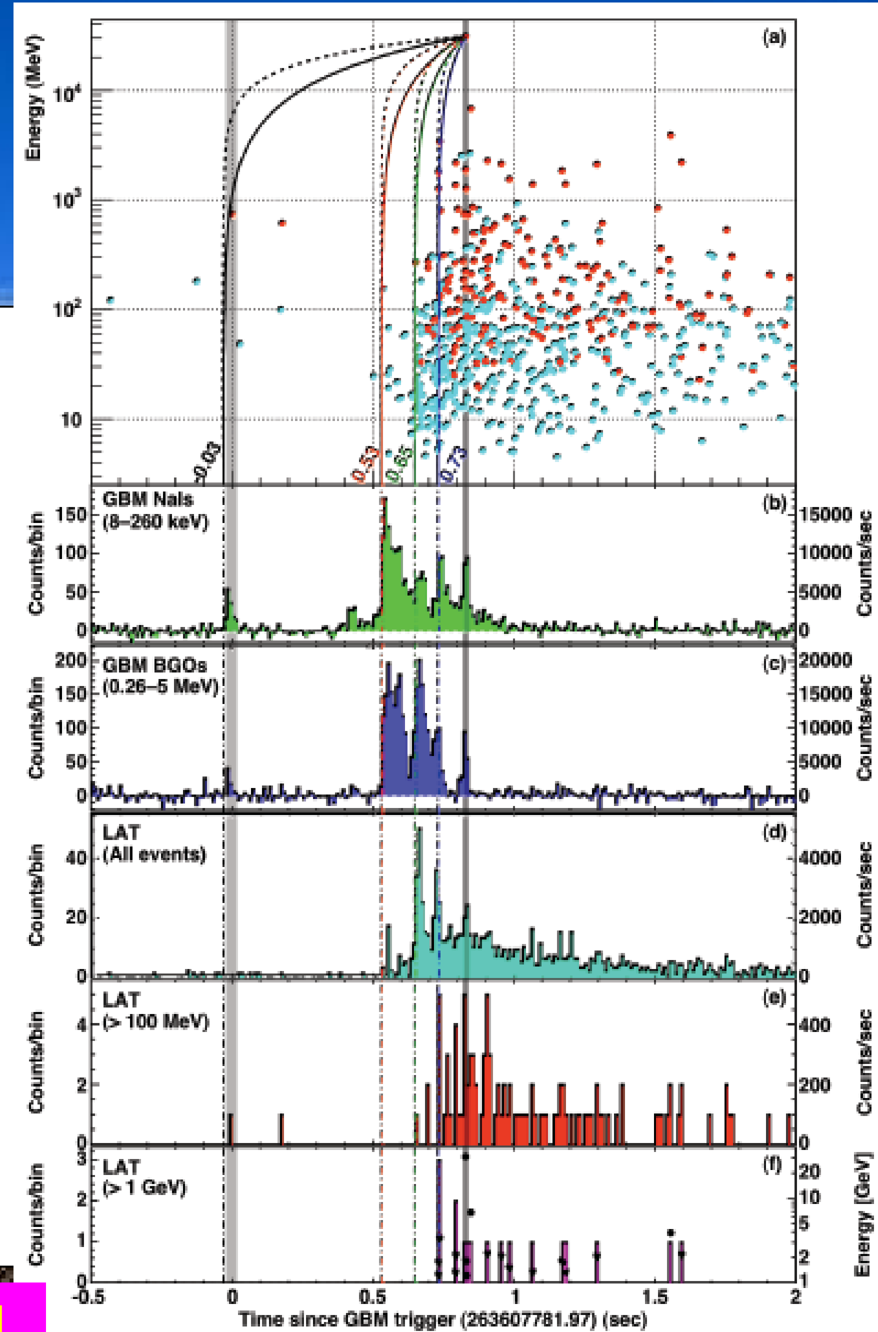


- No significant differences in arrival times
- Lower limit on $m_{QG} > 2.1 \times 10^{18}$ GeV

HESS Collaboration: arXiv:1101:33650 [astro-ph]

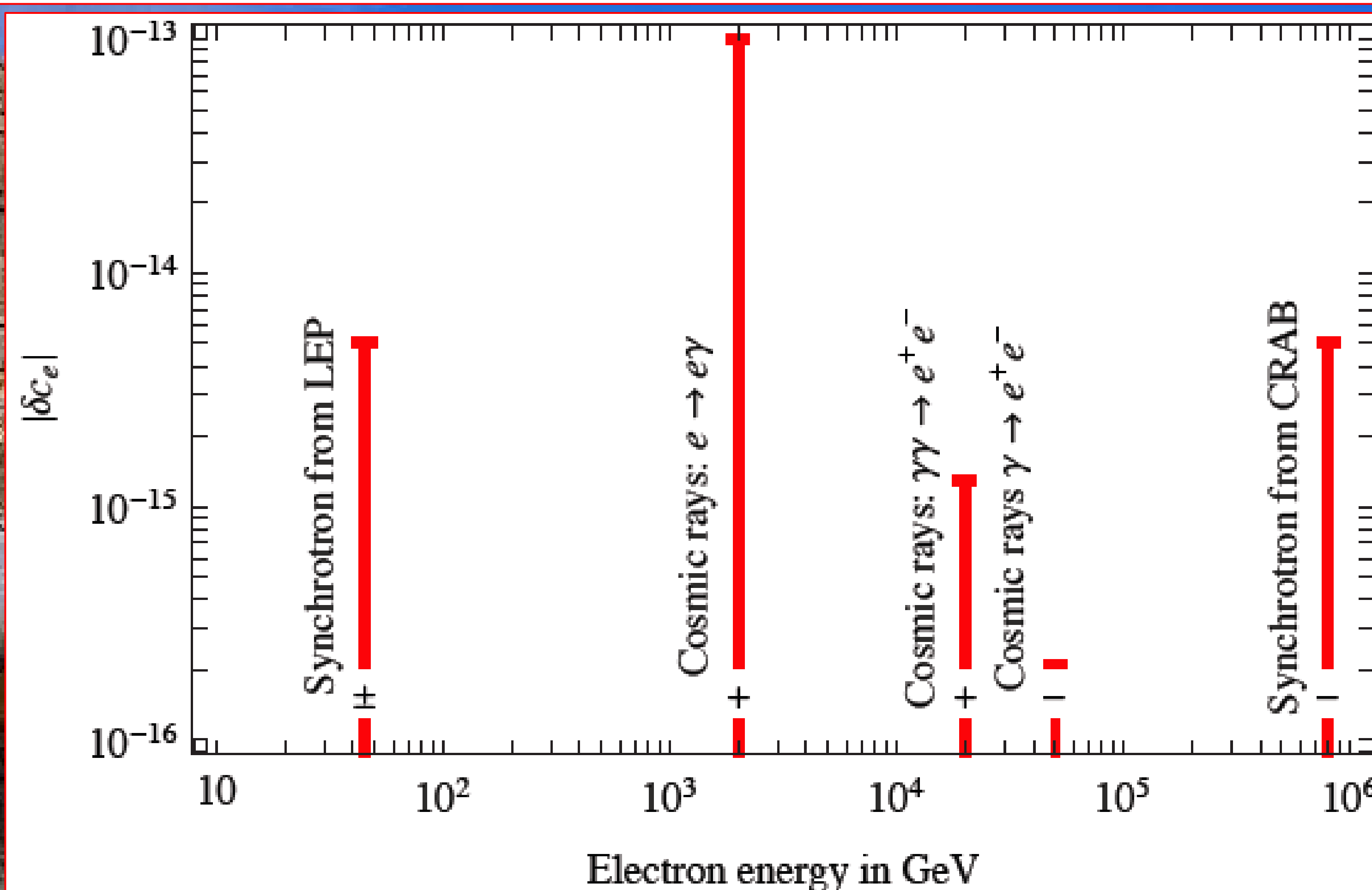
Fermi Analysis of GRB 090510

- Redshift z = 0.903 ± 0.003
- γ energies up to 31 GeV
- No hint of energy-dependent time delay
- Lower limit on m_{QG} depends sensitively on assumptions
- m > 1.2 to 102 m



Fermi Collaboration: arXiv:0908.1832 [astro-ph]

Comparison of Electron Constraints



Much stronger than ν constraints

Lifshitz-Type Field Theory

- Time and space dimensions scale differently
  (Interesting for quantum gravity, mass generation)
- Anisotropy parameter z
- Model for neutrino velocity: $[t] = -z = -3, \; [x] = -1$
- Action: $S_{4ferm} = \int dt d\vec{x} \left(\overline{\psi} i \gamma_0 \dot{\psi} - \overline{\psi}(M^2 - \Delta)(i\vec{\partial} \cdot \vec{\gamma})\psi + g(\overline{\psi}\psi)^2 \right)$ $\Delta \equiv -\partial_i \partial^i = \vec{\partial} \cdot \vec{\partial}$
- Dispersion relation: $\tilde{\omega}^2 = \mu^2_{dyn} + p^2 + \frac{2}{M^2} p^4 + \frac{p^6}{M^4}$
- Group velocity: $v_g = \frac{\partial \tilde{\omega}}{\partial p} > c$
- Superluminal propagation: $\delta v \sim E^2$

Alexandre, JE & Mavromatos: arXiv: 1109.6296

Lorentz-Violating Gauge Theory

- Background vector or axial U(1) gauge field:

$$\mathcal{L}_{V,A} = -\frac{1}{4}G_{\mu\nu}\left(1-\frac{\Delta}{M^2}\right)G^{\mu\nu} + \overline{\psi}\,(i\not\partial - g_{V,A}\not B\,\Gamma\,\underline{\tau})\,\psi - m\overline{\psi}\psi$$

- Dispersion relation:

$$\left(1-\frac{\alpha_{V,A}}{\pi}[2\ln 2-1]\right)^2\omega^2 = \left(1-\frac{\alpha_{V,A}}{\pi}[25/9-(10/3)\ln 2]\right)^2 p^2 + m^2$$

- Group velocity:

$$v_g = 1-\frac{\alpha_{V,A}}{\pi}\left(\frac{34}{9}-\frac{16}{3}\ln 2\right)+\mathcal{O}(\alpha_{V,A}^2) < 1$$

- Subluminal propagation

(so far …)

Alexandre, JE & Mavromatos: arXiv: 1109.6296

Background Gauge Field

- Add background gauge field:

$$\mathcal{L}_{\rm bckgrd} = \overline{\psi}\left(i\,\not{\partial} - g_{V,A}\,\not{B}^{(0)}\Gamma_{\underline{T}}\right)\psi - m\overline{\psi}\psi$$

- Disersion relations: $\omega_\nu = \sqrt{(\vec{p} - g_{V,A}\vec{B})^2 + m^2} + g_{V,A}B_0$

  ($\nu \neq$ anti- ν) $\omega_{\overline{\nu}} = \sqrt{(\vec{p} \mp g_{V,A}\vec{B})^2 + m^2} \pm g_{V,A}B_0$

- Subluminal group v: $v_g = \frac{\partial \omega_\nu}{\partial p} = 1 - \frac{1}{2p^2}(g^2_{V,A}B^2\sin^2\vartheta + m^2) + \cdots$
- Include anisotropic background: $g_{0i} = \vec{V}_i\,, \quad i = 1,2,3$
- Group velocity may be super- or subluminal:

$$v_g = 1 - V\cos\varphi - \frac{g^2_{V,A}B^2\sin^2\vartheta + m^2}{2p^2} + O(V^2)$$

- Dependent on direction!

Alexandre, JE & Mavromatos: arXiv: 1109.6296

Exotic Possibilities

- Neutrino speed ≠ antineutrino speed?
- Speed depends on direction?
- Possibility of diurnal variation as Earth rotates
- If no diurnal variation, *V* aligned with Earth's rotation axis
- In this case:
  – Neutrino going North (MINOS) subluminal
  – Null effect for neutrinos travelling East-West (T2K)

Alexandre, JE & Mavromatos: arXiv: 1109.6296

Čerenkov Radiation by Neutrinos

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma \\ \nu_\mu + \nu_e + \overline{\nu}_e \\ \nu_\mu + e^+ + e^- \end{cases}$$

Possible if speed > light

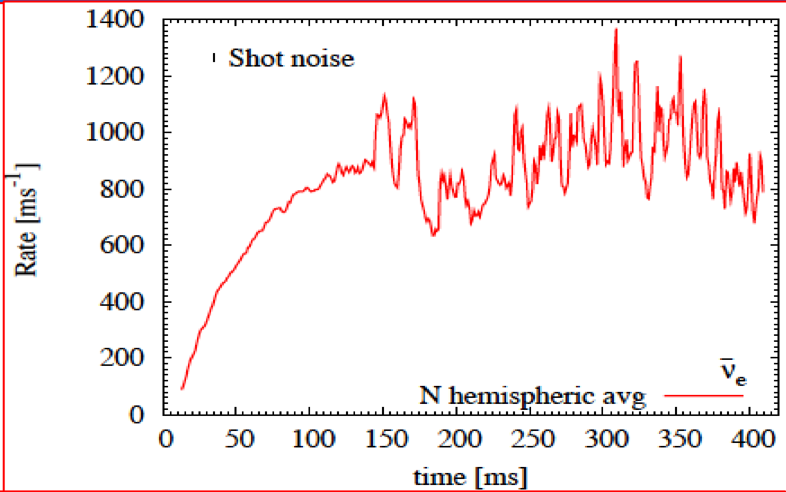
ninant process Bremsstrahlung of e^+e^-

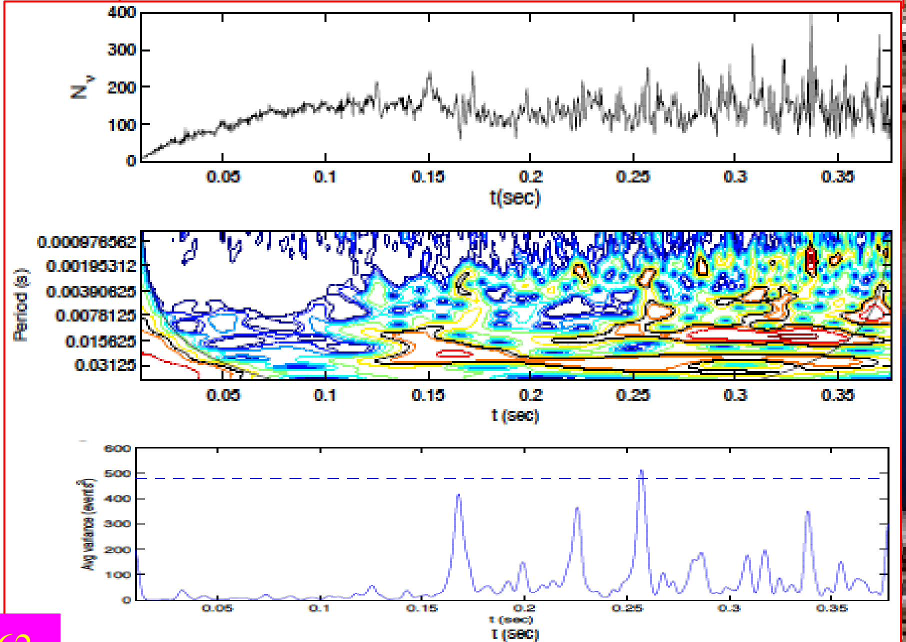
- Energy loss rate: $\frac{dE}{dx} = -k\frac{G_F^2}{192\pi^3}E^6\delta^3 \; : \; k = 25/448$
- Difference between initial/final energies, terminal energy E_T: $E^{-5} - E_0^{-5} = 5k\delta^3\frac{G_F^2}{192\pi^3}L \equiv E_T^{-5}$
- Sensitive to $\delta = 2\ \delta v$ and its E dependence
- Does not apply to models with distorted metrics
- Applied to IceCube data suggests $\delta < 1.7 \times 10^{-11}$

Cohen & Glashow: arXiv: 1109.6562

Revisiting Lorentz Violation with SN ν 's

- 2D SN simulations suggest ‘ringing’ on millisec scale
- If seen can be used to bound Lorentz violation
- Analyze emissions using Wavelets
- Smear with $\delta v(E)$
- Potential for strong bound on $\delta v(E)$





JE, Janka, Mavromatos, Sakharov & Sarkisyan: arXiv: 1109.6562

Revisiting Lorentz Violation with SN ν's

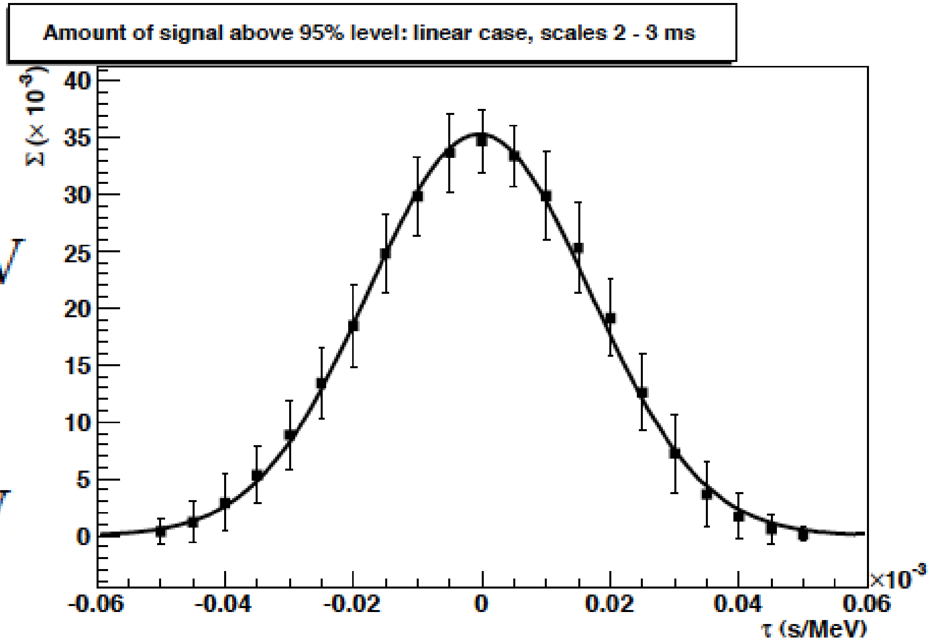
- Short time-scale power disappears for time delay τ > 0.04 (s/MeV)
- Possible constraints

$$M_{\nu LV1} \quad > \quad 2.68\,[2.61] \times 10^{13}\ \text{GeV}$$

in linear case

$$M_{\nu LV2} \quad > \quad 0.97\,[0.96] \times 10^{6}\ \text{GeV}$$

in quadratic case

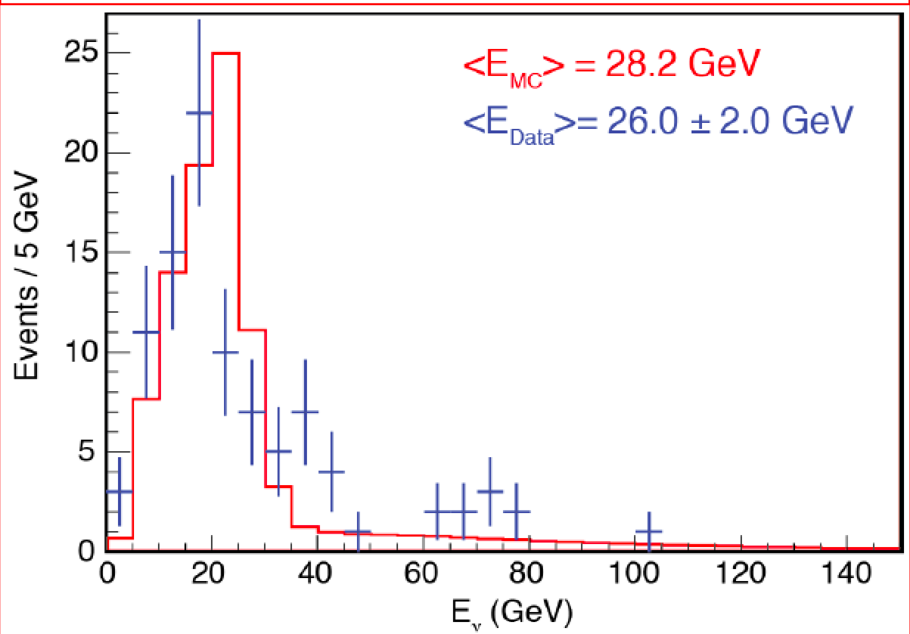


- For subluminal (superluminal) propagation
- Detectable in IceCube?

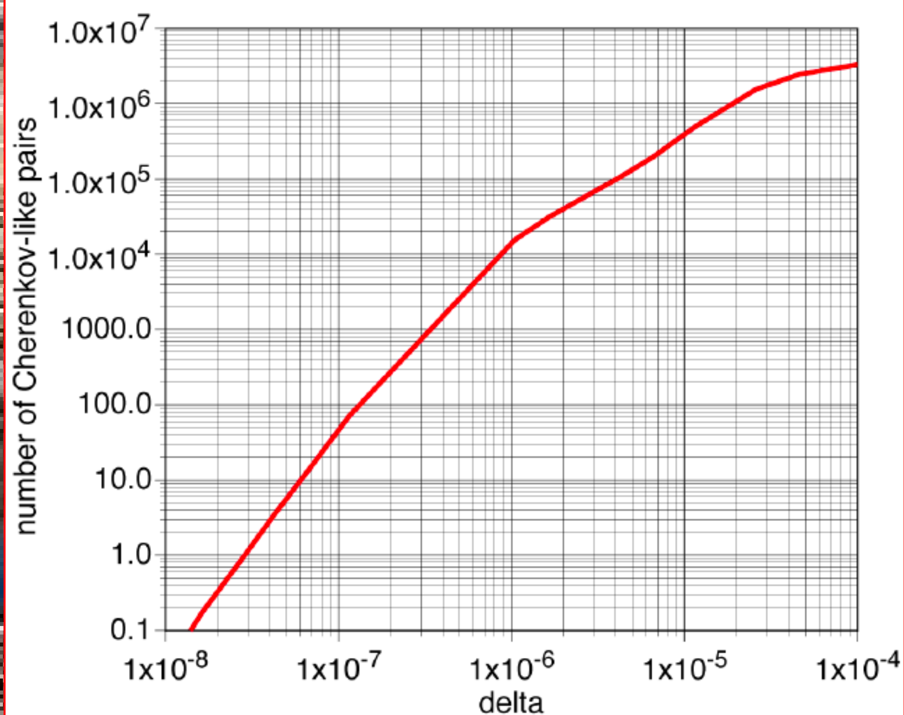
JE, Janka, Mavromatos, Sakharov & Sarkisyan: arXiv: 1109.6562

Constraints from ICARUS

- No visible distortion of neutrino energy spectrum



- No excess of e^+e^- pairs



Cohen & Glashow: arXiv: 1109.6562

ICARUS Collaboration: arXiv: 1110.3763

Gravitational Čerenkov Radiation

- Possible if speed > gravity waves, assumed = *c*
- Gravitational Čerenkov radiation: with OPERA $\delta v \sim 2.5 \times 10^{-5}$, maximum propagation time:

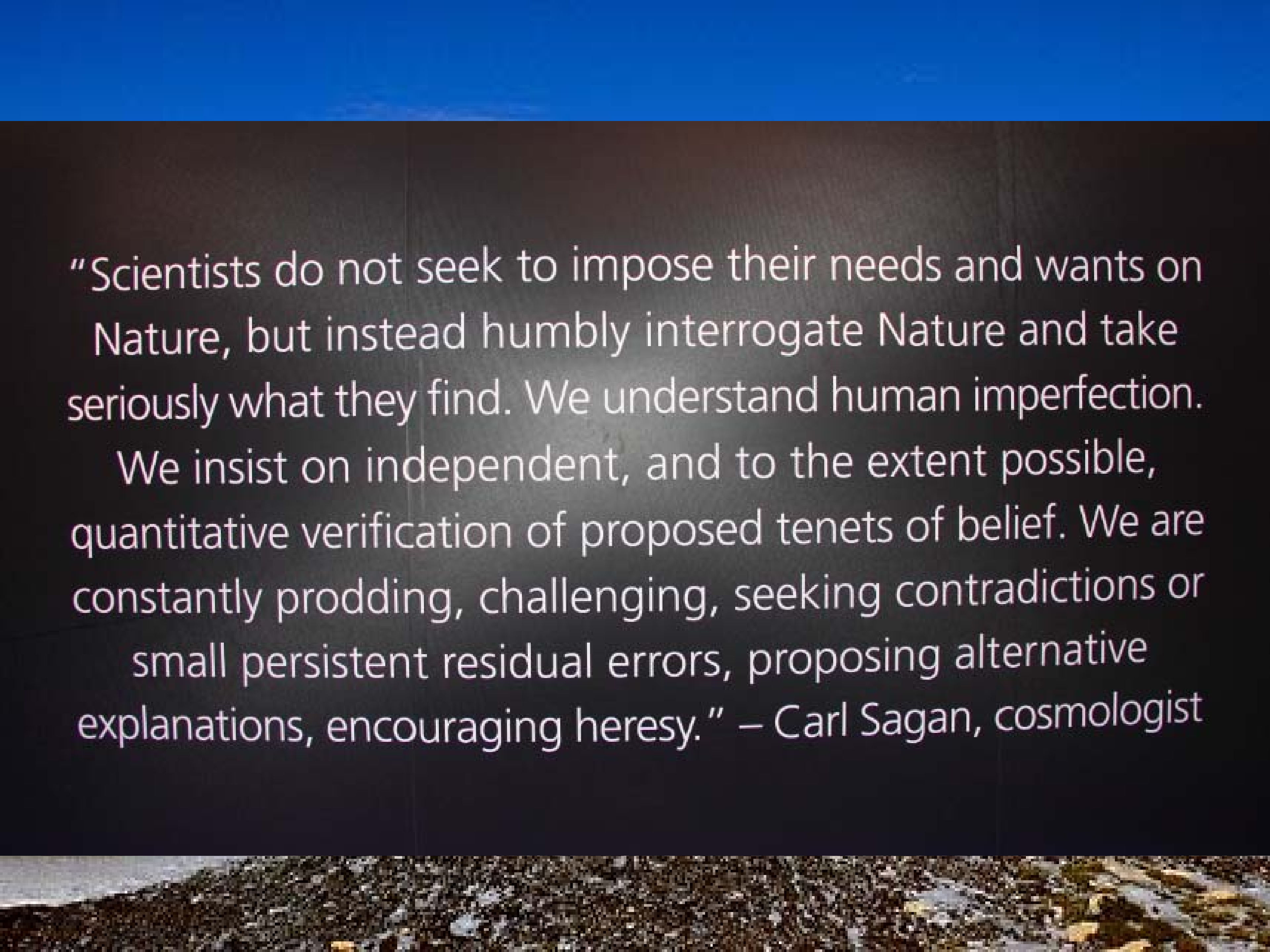
$$t_{max} \sim \frac{2 \times 10^8}{[E_\nu(\mathrm{GeV})]^3} \text{ years}$$

- Excludes GZK neutrinos ($E_\nu \sim 10^{10}$ GeV, $t \sim 10^8$ y) by many orders of magnitude
- IceCube sees no neutrinos with $E_\nu > 2 \times 10^6$ GeV: would have $t_{max} < 10^{-4}$ s

Alexandre, JE & Mavromatos: arXiv: 1109.6296

The Story so far

- No technical error found
- No theoretical error found
- Difficult to reconcile with other constraints
  (SN1987a, Cohen-Glashow radiation, …)
- No direct contradiction with other experiments
- OPERA carrying out test with separated bunches
- Other experiments are preparing to check
- This is how science should be done
  (technical scrutiny, verification, tests, theory)


“Scientists do not seek to impose their needs and wants on Nature, but instead humbly interrogate Nature and take seriously what they find. We understand human imperfection. We insist on independent, and to the extent possible, quantitative verification of proposed tenets of belief. We are constantly prodding, challenging, seeking contradictions or small persistent residual errors, proposing alternative explanations, encouraging heresy.” – Carl Sagan, cosmologist