Summary of
ITEP Winter School 2010
13.-20. February

Matthias Stein
DESY-CMS Hamburg

PHYSICS AT THE TERA SCALE
Helmholtz-Alliance

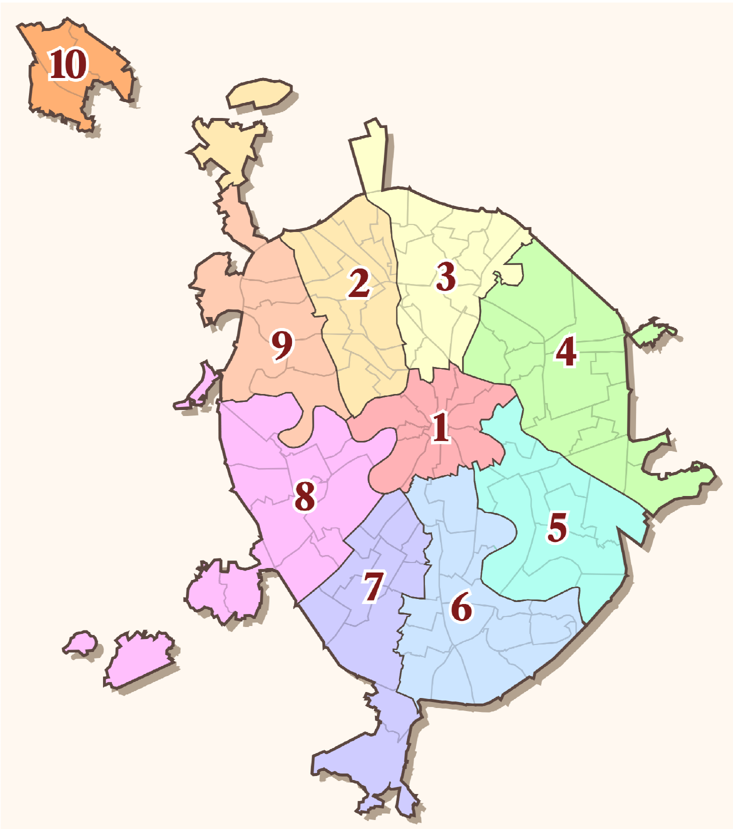
YIG Meeting
22th March 2010

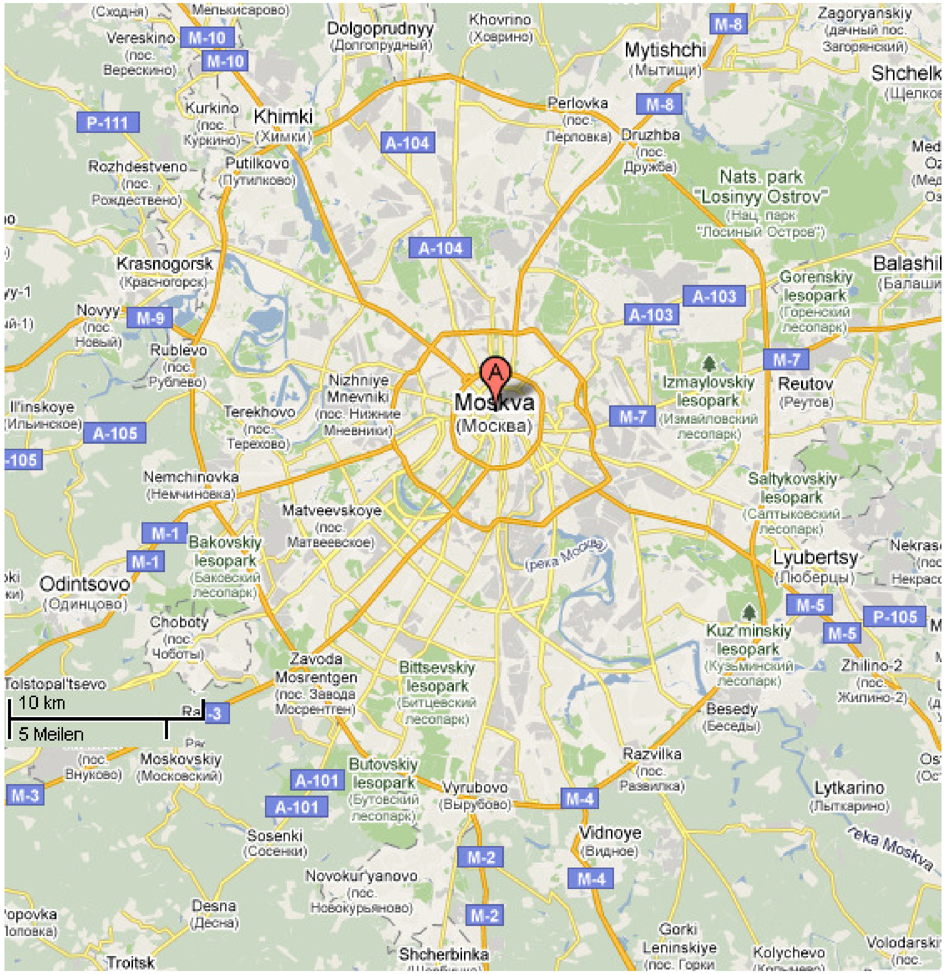
Overview
- Introduction
- Lectures
- Student sessions
- Program
- Impressions

Vladimir Andreev, Kerstin Borras, Dirk Krücker, Isabell Melzer-Pellmann, Peter Schleper

Moscow

- Fouded: 1147
- Inhabitants: 10.5 Mpersons
- Area: 1,081 km^2
- Population-density: 9,722 prs/ m^2
- Moscow-Wolga-Channel: 128 km
- Highway-ring: 109 km





Definition

ITEP := **I**nstitute for **T**heoretical and **E**xperimental **P**hysics

„A multiprofile center for research and education“ (Homepage):

- theoretical physics
- mathematical physics
- astrophysics (cosmology)
- neutrino physics
- high energy physics
- nuclear physics
- plasma physics
- solid-state physics
- nanotechnologies
- reactor and accelerator technologies
- medical physics
- computer science

Definition

- 1973: first school (for Russians)
- 1994: first international school
- 1998: Moscow Government became a General Sponsor of the School
- Since 2006: Proceedings are published by "Yadernaya Fizika" ("Physics of Atomic Nuclei").

→ ITEP School 2010 = 13th International Moscow School of Physics
= 38th ITEP Winter School of Physics

Main topics of the School are:

- Flavor physics
- Perturbative and non-perturbative QCD
- Beyond the SM
- Physics at LHC and ILC
- Neutrino physics
- Cosmology and Astrophysics

→ School language: English
→ ca. 80 Russians and 20 internationals

Program

	9.00 – 10.00	10.30 – 11.30	15.30 – 16.30	17.00 –18.00	18.15 –19.15	21.00 – 22.00
Sat., 13			Froidevaux	Golutvin	Golutvin	
Sun., 14	Froidevaux	Golutvin	Titov	Titov	Costantini	Tipunin
Mon., 15	Titov	Pakhlov	Pakhlov	Lindner	Costantini	Tipunin
Tue., 16	Pakhlov	Rubakov	Lindner	Lindner	Zakharov	students
Wed., 17	Lindner	Zakharov	Zakharov	Hewett	Rubakov	concert
Thu., 18	Hewett	Kistenev	Mizyuk	Rubakov	students	bonfire
Fri., 19	Hewett	Ski-event	Mizyuk	Blinnikov	Rubakov	students
Sat., 20	Hewett	Blinnikov				

Theorists say, there had been too many experimental lectures…

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Sat., 20	Hewett	Blinnikov				

Theory

Exp/ The

Students

Exp

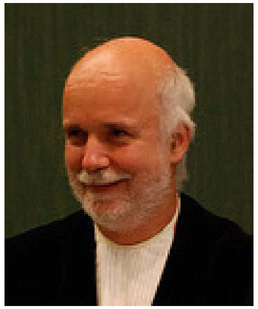
Else

Lecturers

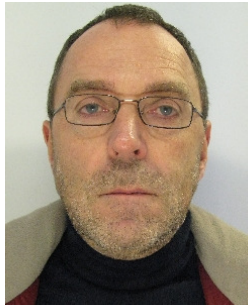
Heide Costantini (INFN Geneve)

Sergei Bilinnikov (ITEP, IPMU)

Joanne Hewett (SLAC)



Daniel Froidevaux (CERN, ATLAS)



Andrei Golutvin (ITEP,LHCb spokesman)

Kistenev

Manfred Lindner (MPI)

Roman Mizyuk

P. Pakhlov (ITEP)

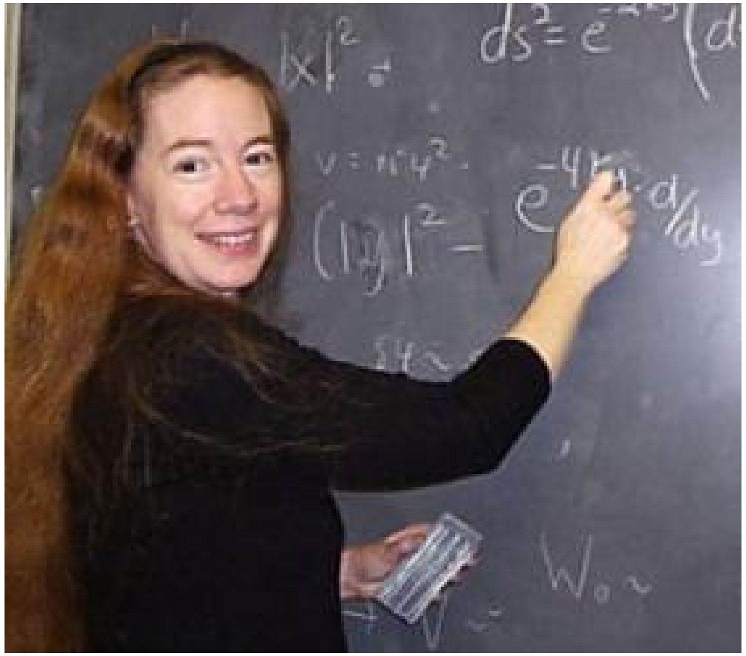
Valerii A. Rubakov

Tipunin

Maxim Titov (Tevatron)

Zakharov

J. Hewett – SLAC



Global Flavor Symmetries

SM matter secretly has a large symmetry:

U(45)

$$\begin{pmatrix} Q_1 \\ u_1 \\ d_1 \\ L_1 \\ e_1 \\ \cdot \\ \cdot_{\,2} \\ \cdot \\ \cdot_{\,3} \end{pmatrix}$$

Rotate 45 fermions into each other

Explicitly broken by gauging 3x2x1

$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$

Rotate among generations

Explicitly broken by quark Yukawas + CKM

$U(1)_B$

Baryon Number

Explicitly broken by charged lepton Yukawas

$U(1)_e \times U(1)_\mu \times U(1)_\tau$

Explicitly broken by neutrino masses

Lepton Number

$U(1)_L$

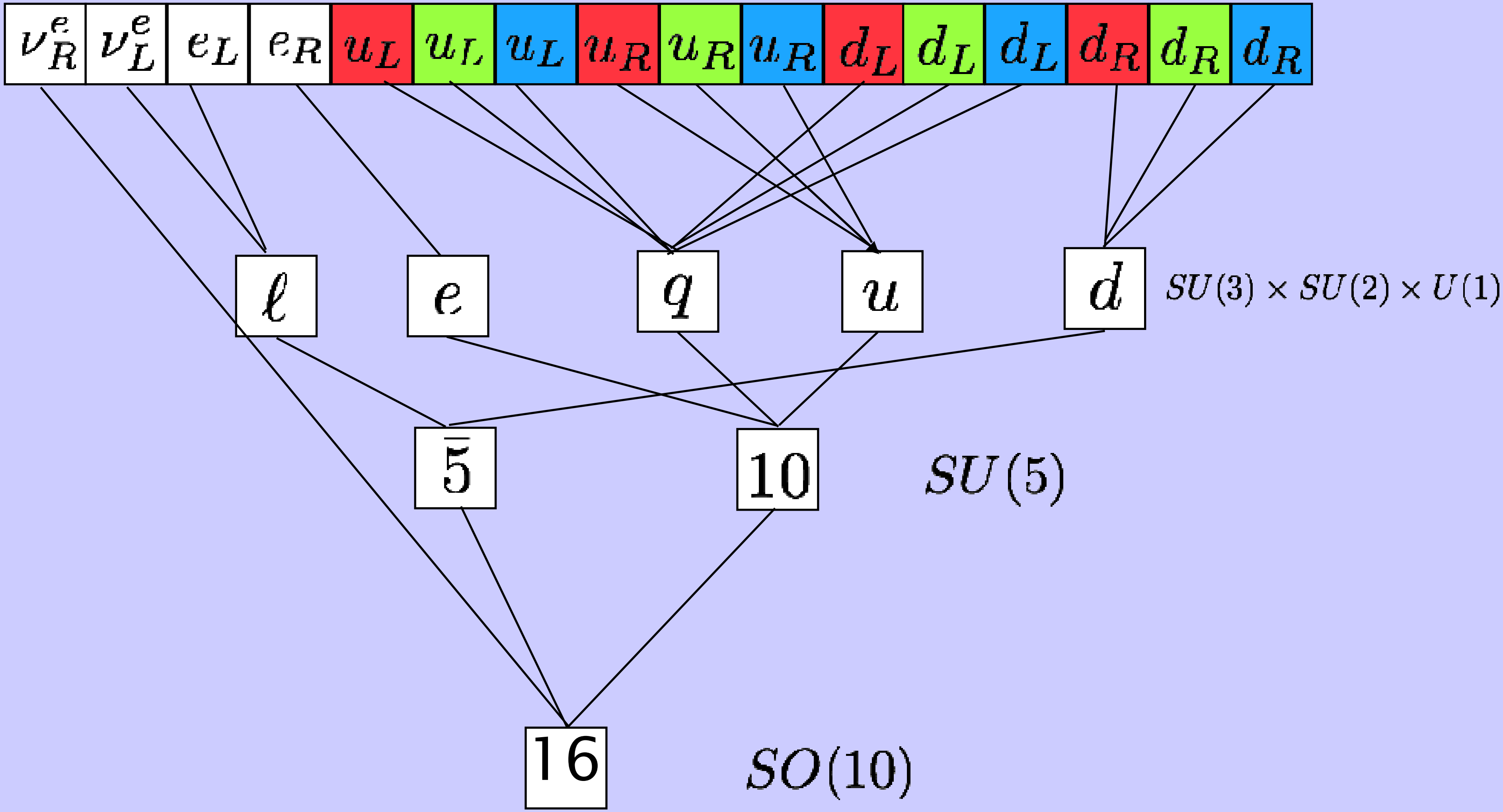
(Dirac)

(or nothing)

(Majorana)

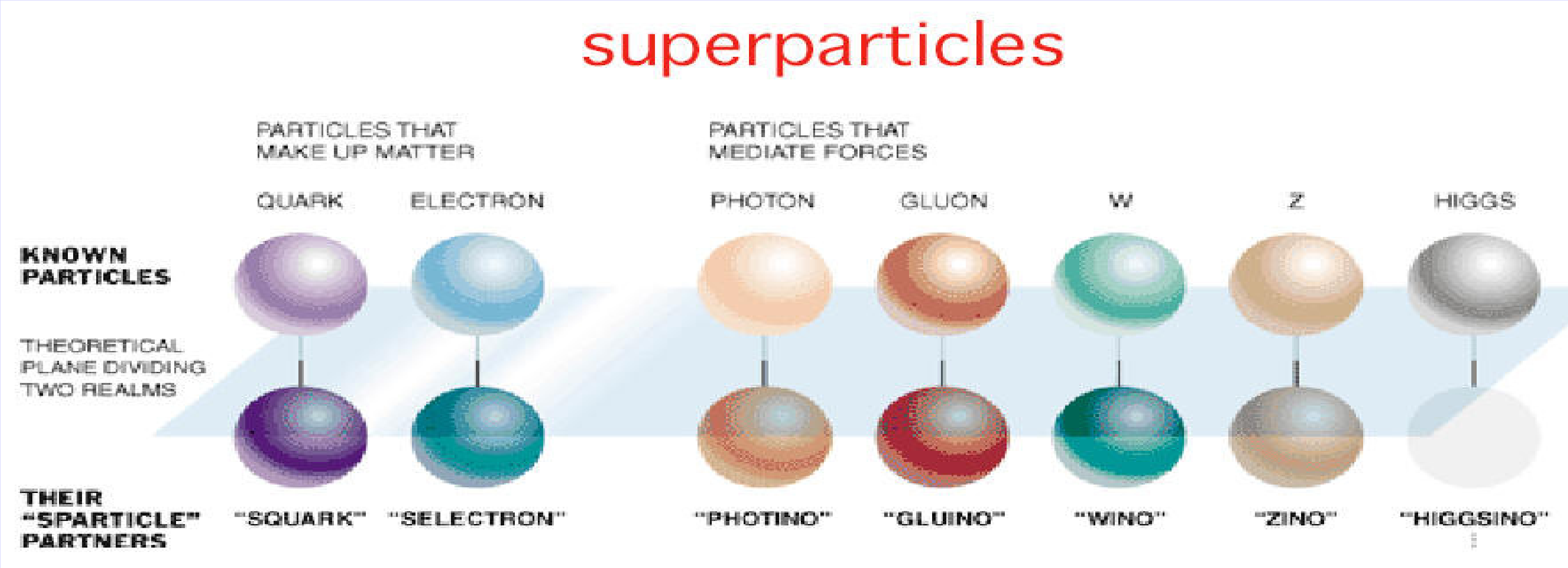
Grand Unification

Gauge coupling unification indicates forces arise from single entity



Supersymmetry: Recap

- Symmetry between fermions and bosons
- Predicts that every particle has a superpartner of equal mass ($\Rightarrow$ SUSY is broken: many competing models!)
- Suppresses quantum effects
- Can make quantum mechanics consistent with gravity (with other ingredients)

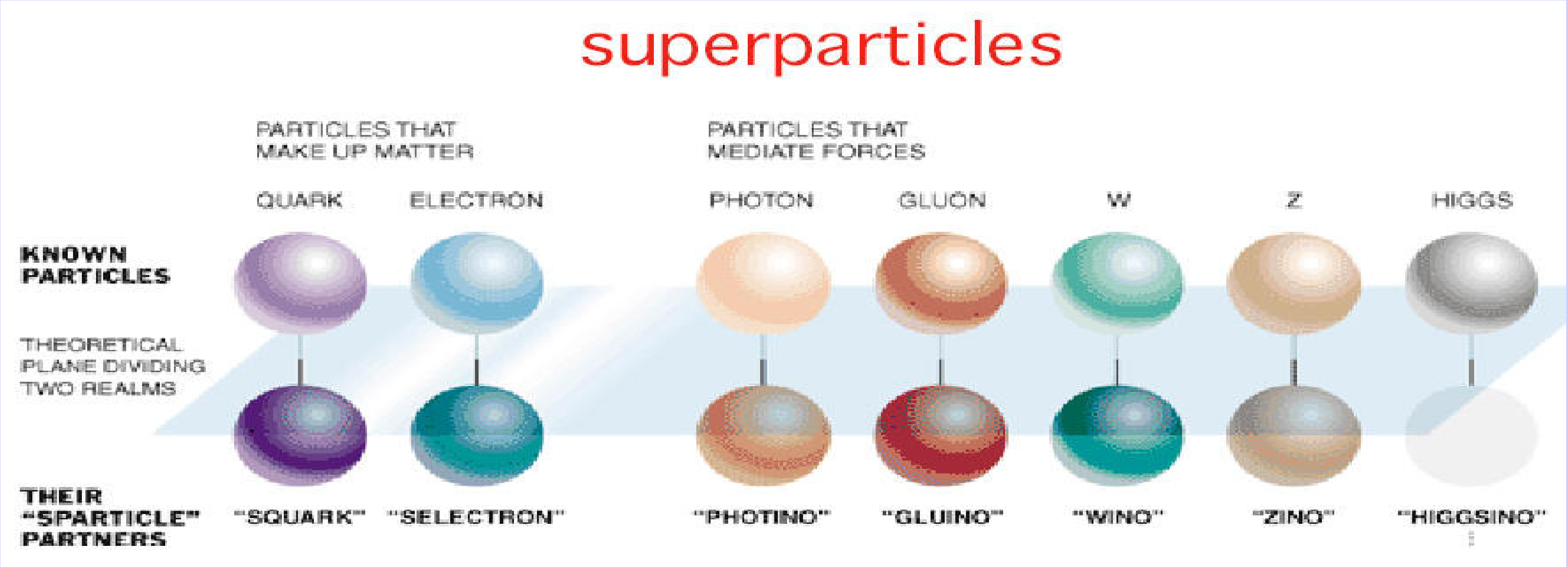


Minimal Supersymmetric Standard Model

Conserved multiplicative quantum number (R-parity)

- Superpartners are produced in pairs
- Heavier Superpartners decay to the Lightest
- Lightest Superpartner is stable

Collider signatures dependent on this assumption and on model of SUSY breaking



SUSY Breaking

SUSY is not an exact symmetry

We don't know how SUSY is broken, but SUSY breaking effects can be parameterized in the Lagrangian

$$\mathcal{L}_{\rm soft} = \mathcal{L}_{m_0^2} + \mathcal{L}_{m_{\frac{1}{2}}} + \mathcal{L}_A + \mathcal{L}_B$$

$$\begin{aligned}\mathcal{L}_{m_0^2} &= m_{\psi}^{2\,i}{}_j \, \tilde{\psi}_i^{\dagger} \tilde{\psi}^j \\ &\quad + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2\end{aligned}$$

$\psi \in Q, U^c, D^c, L, E^c$

$$\mathcal{L}_{m_{\frac{1}{2}}} = m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$

$$\mathcal{L}_A = a_u^{ij} \tilde{Q}_i \tilde{U}_j^c H_u + a_d^{ij} \tilde{Q}_i \tilde{D}_j^c H_d + a_e^{ij} \tilde{L}_i \tilde{E}_j^c H_d$$

$$\mathcal{L}_B = B_\mu H_u H_d$$

Gravity Mediated SUSY Breaking (mSUGRA)

- There are M_{Pl}-suppressed interactions. Minimal assumption: use these as the mediating interactions:

$$c_{ij}\frac{Z^\dagger Z}{M_{Pl}^2}\phi_i^*\phi_j \rightarrow \text{scalar masses}$$

$$c_a\frac{Z}{M_{Pl}}\lambda_a\lambda_a \rightarrow \text{gaugino masses}$$

$$c_{ijk}\frac{Z}{M_{Pl}}\phi_i\phi_j\phi_k \rightarrow A \text{ terms}$$

$$c\frac{Z^\dagger Z}{M_{Pl}^2}\phi_i\phi_j \rightarrow B \text{ term}$$

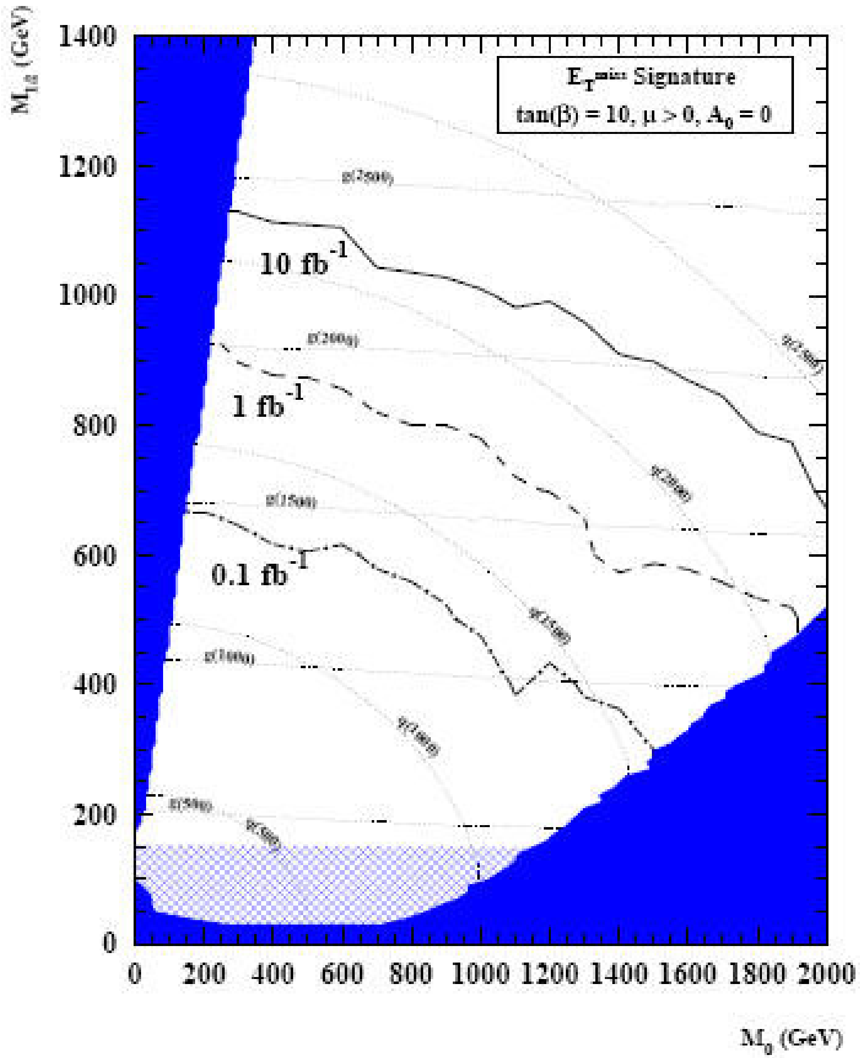
- The gravitino mass is

$$m_{\tilde{G}} \sim F/M_{Pl}$$

- For $F \sim (10^{10}\ \text{GeV})^2$, when $Z \rightarrow F$, the gravitino and all superpartner masses are ~ 100 GeV

LHC mSUGRA Discovery Reach (14 TeV)

Discovery reach as a function of luminosity



- $\sim$1300 GeV in 100 pb^{-1}
- $\sim$1800 GeV in 1 fb^{-1}
- $\sim$2200 GeV in 10 fb^{-1}

Fast discovery from signal statistics

Time for discovery determined by:

- Time to understand detector performance ($\not{E}_T$ tails, lepton id, jet scale)
- Time to collect sufficient statistics of SM control samples: W, Z+jets, $\bar{t}t$

Two main background classes:

- Instrumental $\not{E}_T$
- Real $\not{E}_T$ from neutrinos

The ATLAS SUSY analyses:

- 2,3,4-jet +MET
- 1l, ≥4-jet +MET
- Same Sign Di-Lepton
- Opposite Sign Di-Lepton
- Trileptons + (0,1)-j +MET

- τ +≥ 4j +MET
- ≥4j w/ ≥ 2btags + MET
- Stable particle search

Some Results From 70k pMSSM Models

Analysis	# with Z_n >5, no pystop	# with Z_n >5, incl. pystops
4j0l	58717 (88.251 %)	59146 (87.002 %)
2j0l	58000 (87.173 %)	58465 (86.001 %)
1l4j	27954 (42.015 %)	28014 (41.208 %)
1l3j	44678 (67.151 %)	44848 (65.97 %)
1l2j	46401 (69.74 %)	46606 (68.556 %)
OSDL	7083 (10.646 %)	7087 (10.425 %)
SSDL	13967 (20.992 %)	13976 (20.558 %)
3lj	8825 (13.264 %)	8834 (12.995 %)
3lm	1767 (2.6558 %)	1771 (2.6051 %)
tau	56025 (84.205 %)	56406 (82.972 %) *
b	48840 (73.406 %)	49179 (72.341 %)

*τ ID & reconstruction in PGS is a bit too optimistic & needs to be reaccessed

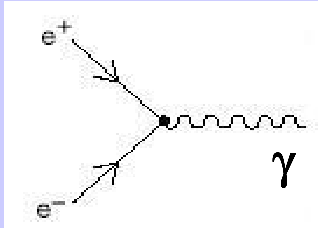
Conley, Gainer, JLH, Le, Rizzo In progress

Supersymmetry at the ILC

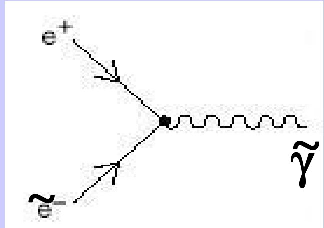
ILC Studies superpartners individually via $e^+e^- \to S\bar{S}$

Determines

- Quantum numbers (spin!)
- Supersymmetric relation of couplings



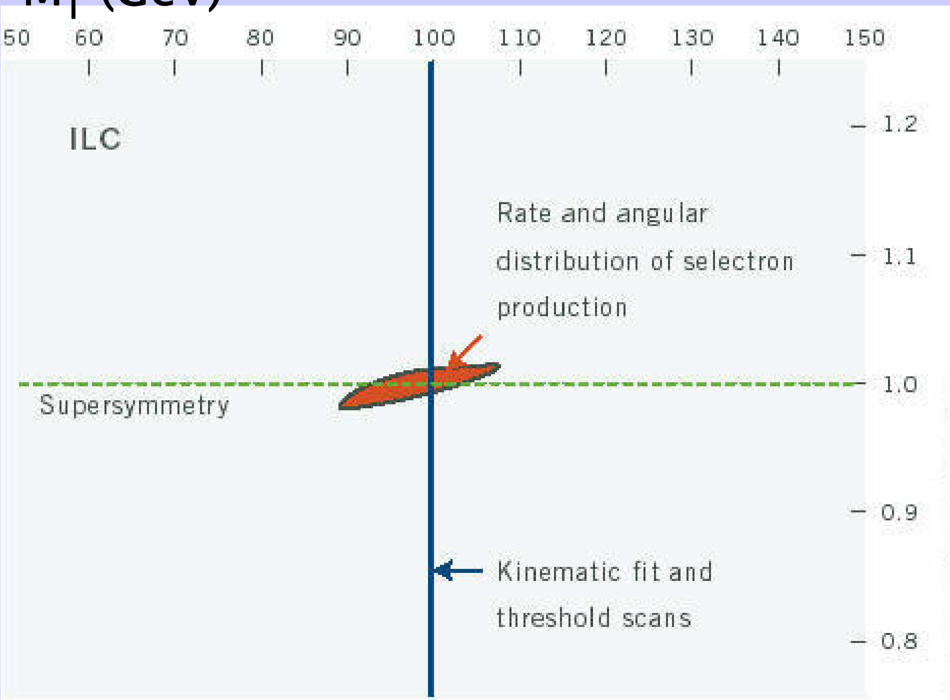
= e



= 2e

Selectron pair production

M_1 (GeV)



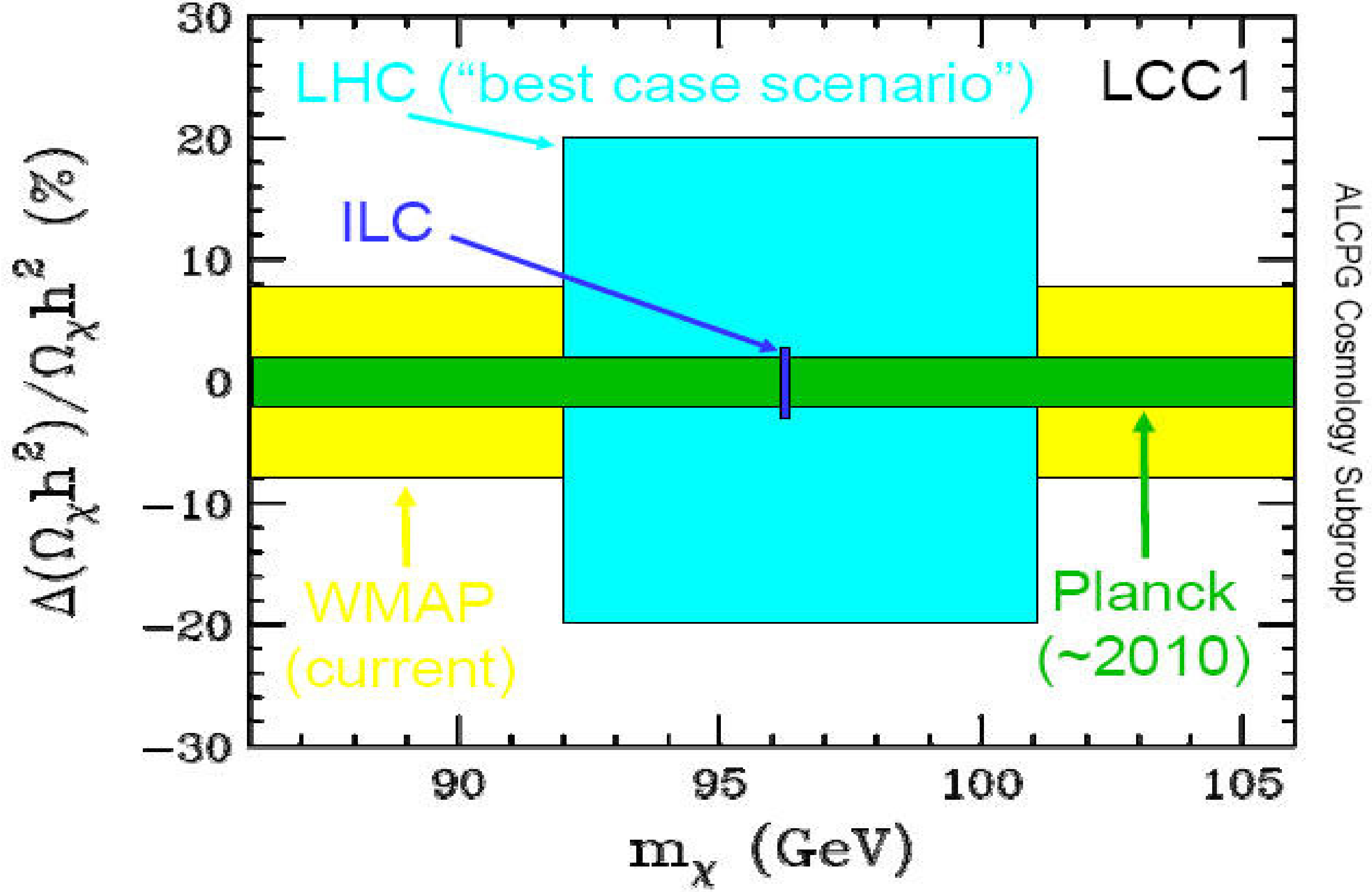
Ratio of Coupling Strengths

2% accuracy in determination of Supersymmetric coupling strength

Proof that it IS Supersymmetry!

- Parameter determination
- DM candidates (WIMPs)
- ILC + LHC

Relic Density Determinations



% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

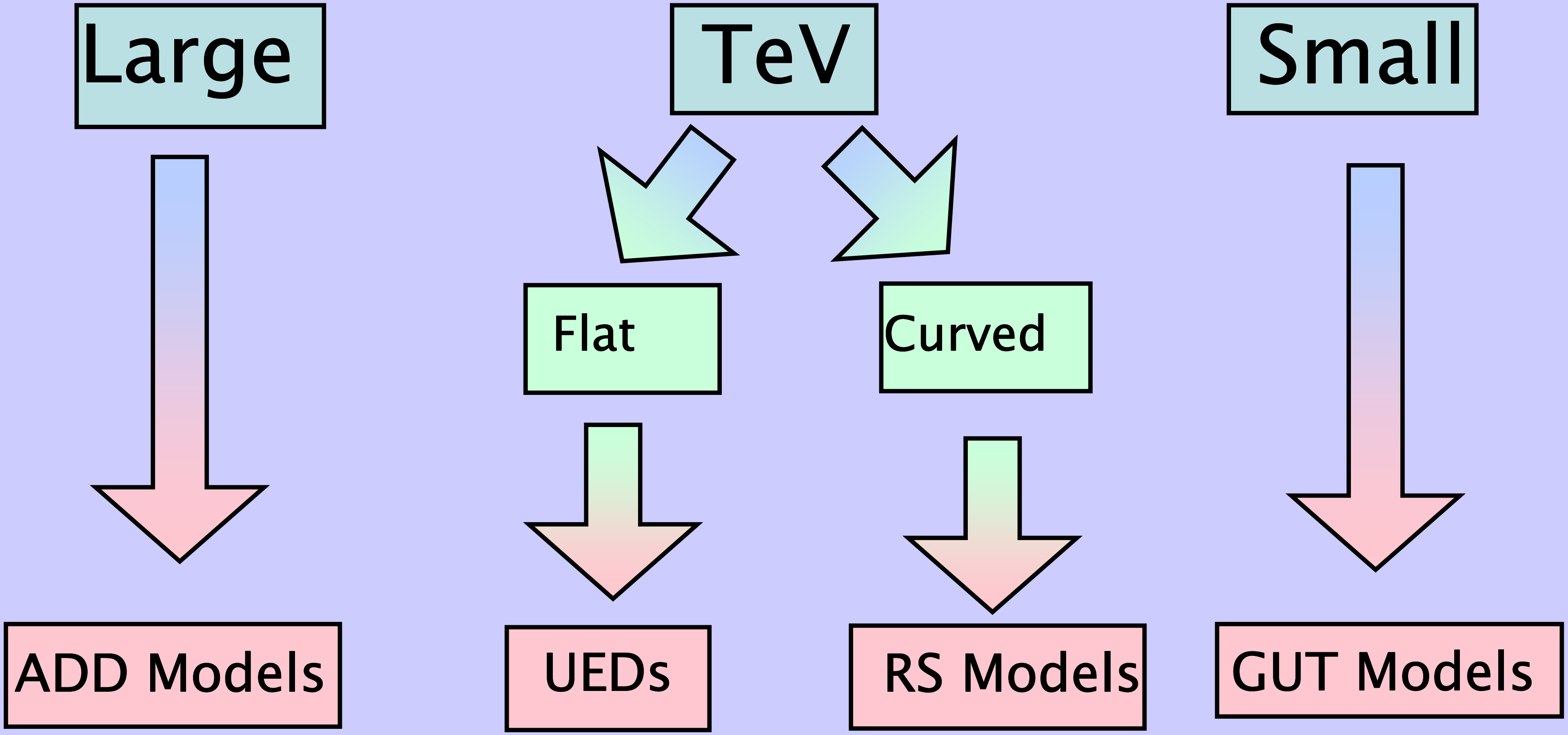
Supersymmetry Summary

- SUSY solves many questions:
  - Gauge hierarchy
  - EWSB
  - Gauge coupling unification
  - Dark Matter candidate

- SUSY has some issues:
  - 120 free parameters
  - In most natural case, we would have discovered it already
  - Has problems fitting indirect DM search data (PAMELA, Fermi)

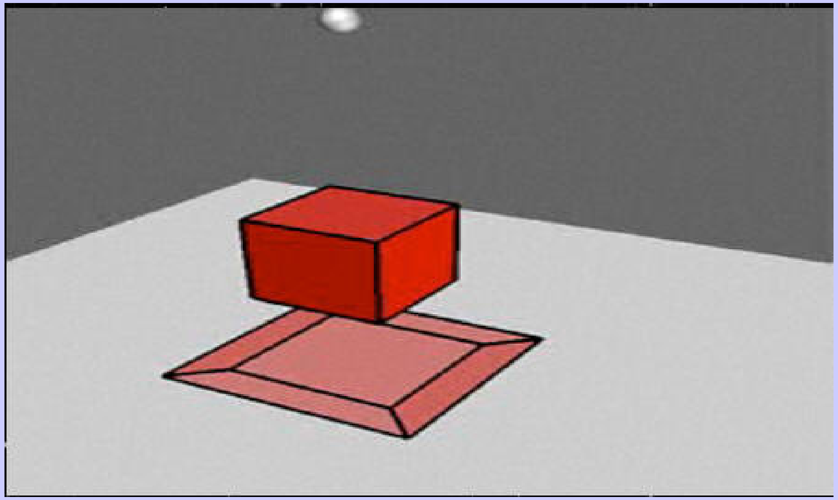
- LHC will tell us if SUSY is relevant to the weak scale or not! (If the signal isn't missed….)

Extra Dimensions Taxonomy



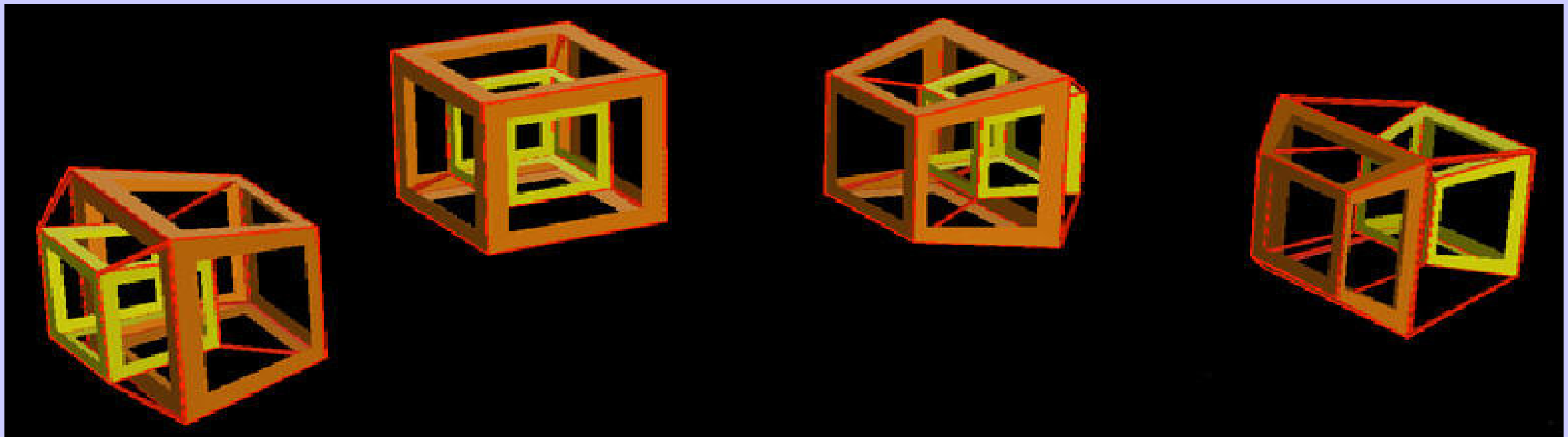
Extra dimensions can be difficult to visu

- One picture: shadows of higher dimensional objects



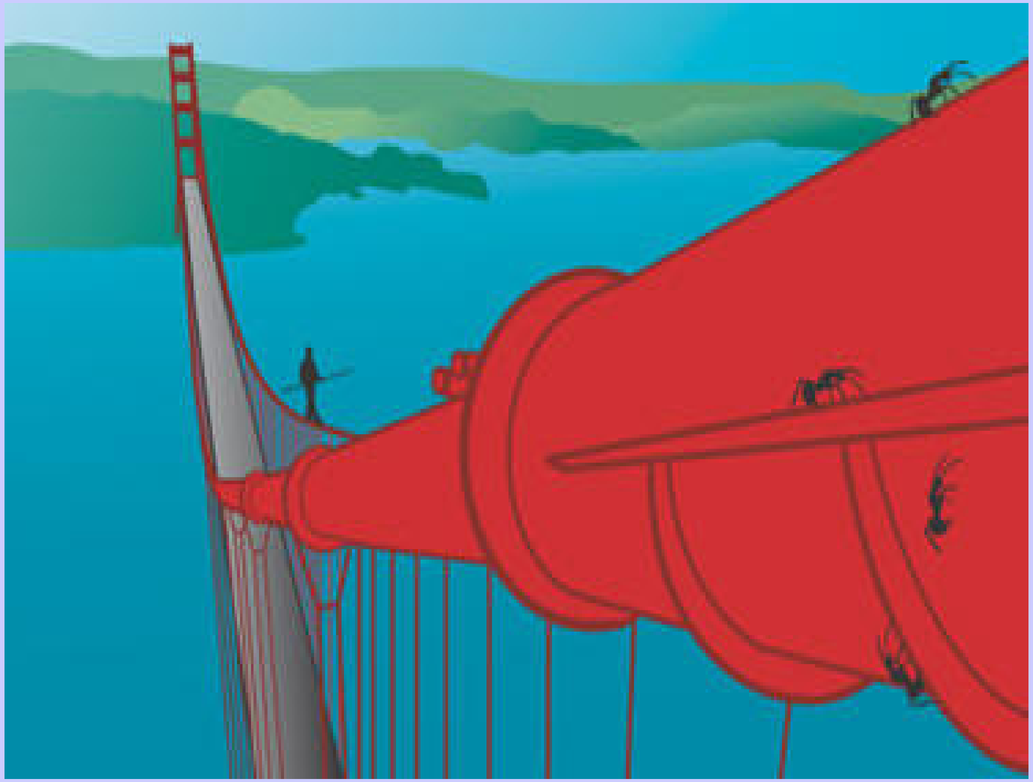
2-dimensional shadow of a rotating cube

3-dimensional shadow of a rotating hypercube



Extra dimensions can be difficult to visu

- Another picture: extra dimensions are too small for us to observe $\Rightarrow$ they are 'curled up' and compact

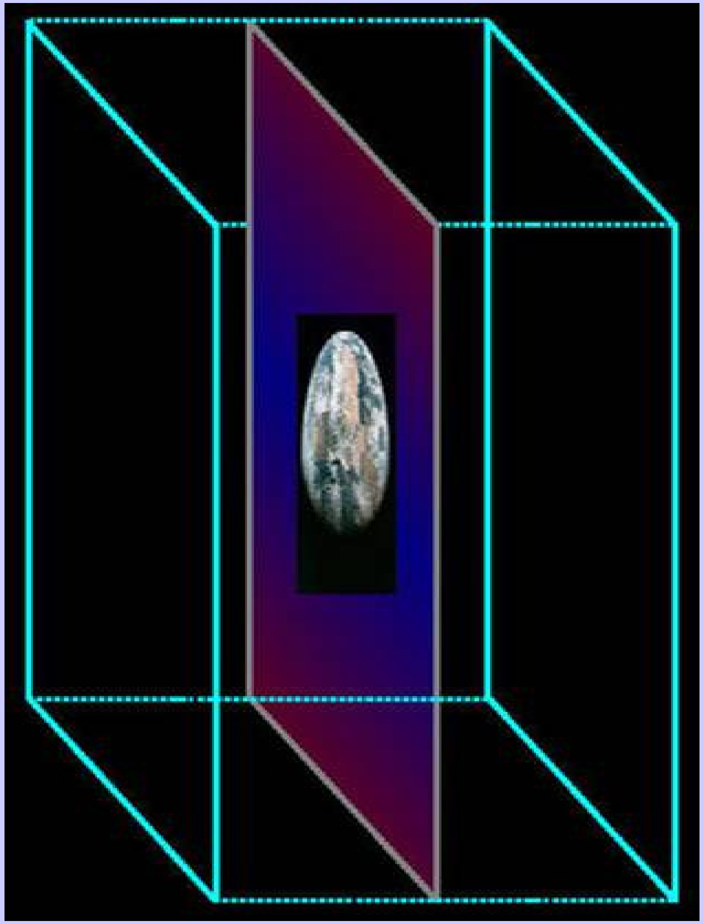


The tightrope walker only sees one dimension: back & forth.

The ants see two dimensions: back & forth and around the circle

The Braneworld Scenario

- Yet another picture



- We are trapped on a 3-dimensional spatial membrane and cannot move in the extra dimensions
- Gravity spreads out and moves in the extra space
- The extra dimensions can be either very small or very large

What are extra dimensions good for

- Can unify the forces
- Can explain why gravity is weak (solve hierarchy problem)
- Can break the electroweak force
- Contain Dark Matter Candidates
- Can generate neutrino masses

……

Extra dimensions can do everything SUSY can do!

- Kaluza-Klein model
- Large extra dimensions
- Searches for extra dimensions
- Linearized quantum gravity
- Graviton emission at LHC
- Black hole formation factor at LHC
- Several higgs scenarios
- …..

Most likely scenario @ LHC →

Supernova bangs as a tool to study Big Bang

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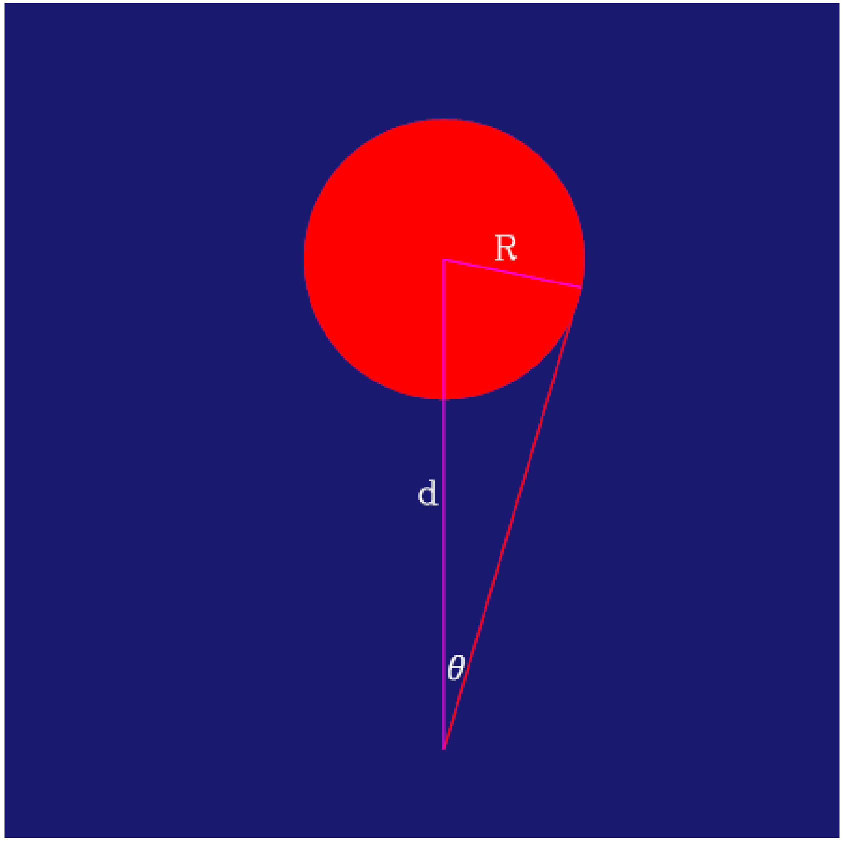
ITEP, IPMU

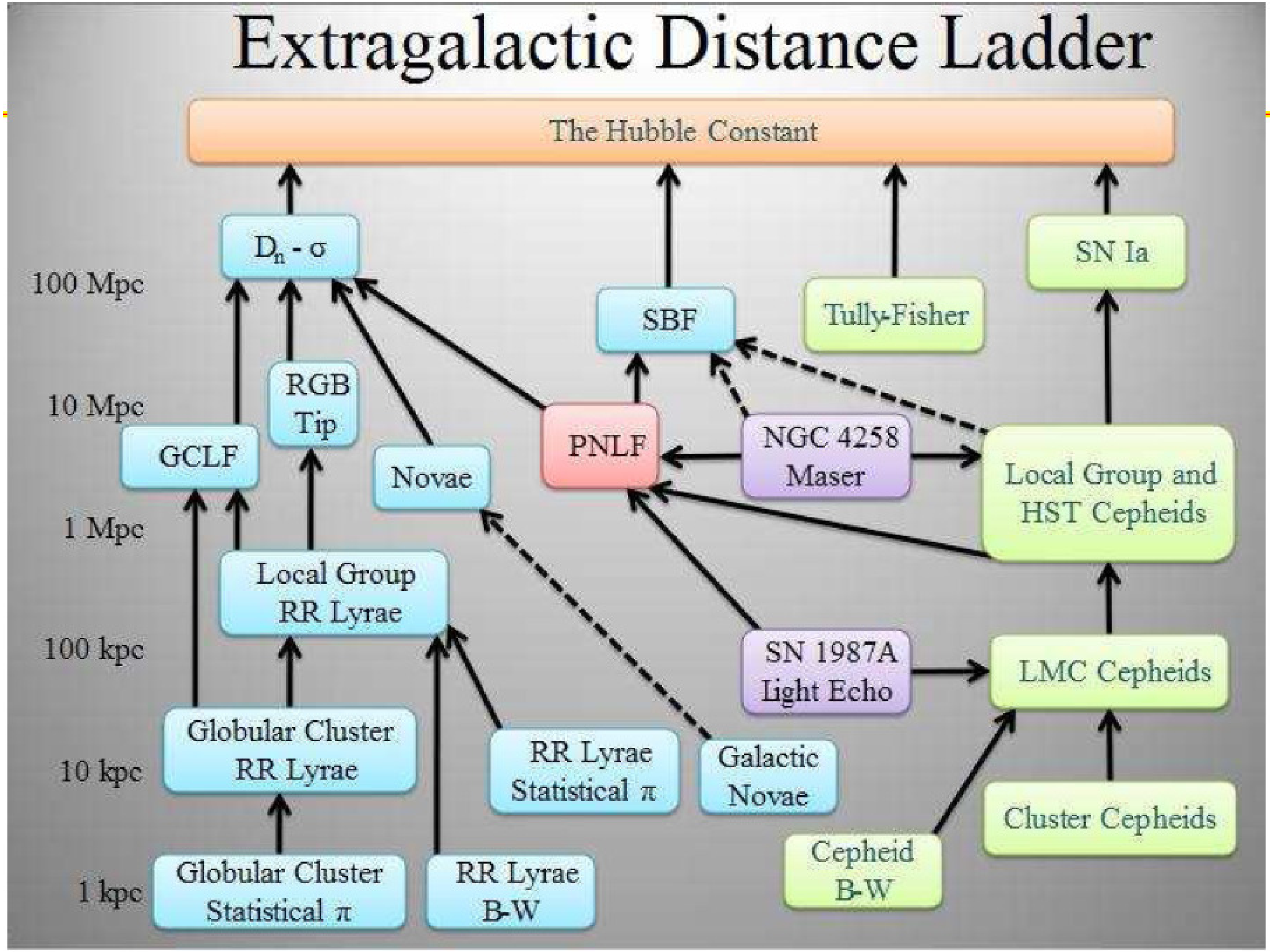
Cosmological distance ladder

Distances: photometric

Standard candle power L: $F = \frac{L}{4\pi d^2} \rightarrow d_{\rm ph}^2 = \frac{L}{4\pi F}$.

The same flux if the brightness is I: $F = \pi\theta^2 I = \pi I R^2/d_A^2$.




Extragalactic Distance Ladder
The Hubble Constant
D_n - σ
SBF
Tully-Fisher
SN Ia
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc

Friedmann-Robertson-Walker

The universe is not static, but changing with time.
The first GR cosmological models for the Universe with matter homogeneous and isotropic in space, but not static in time, were constructed by Alexander Friedmann (1922, 1924).
Metric FRW (i.e. Friedmann-Robertson-Walker):

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right],$$

with $a(t)$ – scale factor, and $k = \pm 1$ for curved Friedmann world, and $k = 0$ for the flat 3-space. It is easy to check that $k = -1$ gives another world, the negative curvature space with Lobachevsky geometry.

Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} \ .$$

This is known as the Friedmann equation.
On small scales the spacetime is flat and GR must reduce to nonrelativistic mechanics.

Wikipedioa:
“Die **Friedmann-Gleichungen** beschreiben theoretisch die Entwicklung des Universums. Konkreter machen sie je nach Energiegehalt des Universums Voraussagen über dessen Expansion oder Kontraktion.“

Hubble's Law, 1929

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{H_0 d}{c}$$

— true only for nearby objects $z \ll 1$, but already in the "Hubble flow".

Hubble parameter,

$$H = \dot{a}/a \; .$$

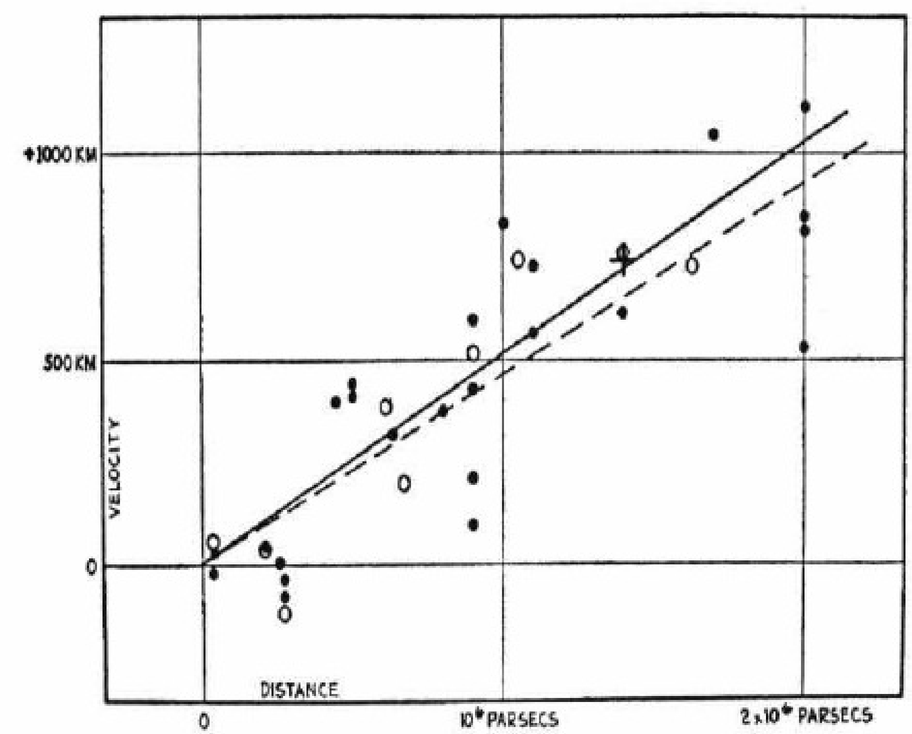
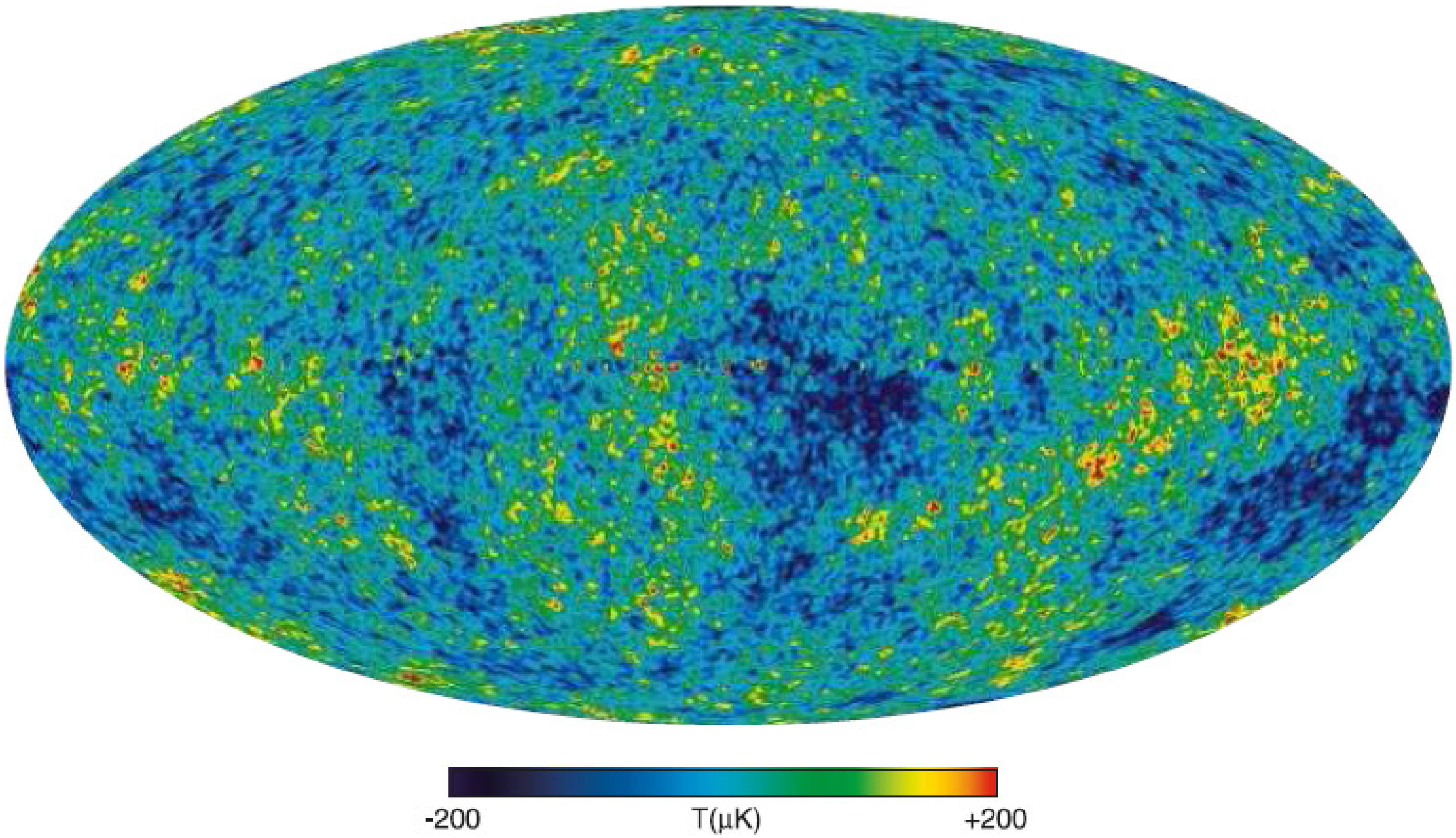


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

CMB temperature anisotropy

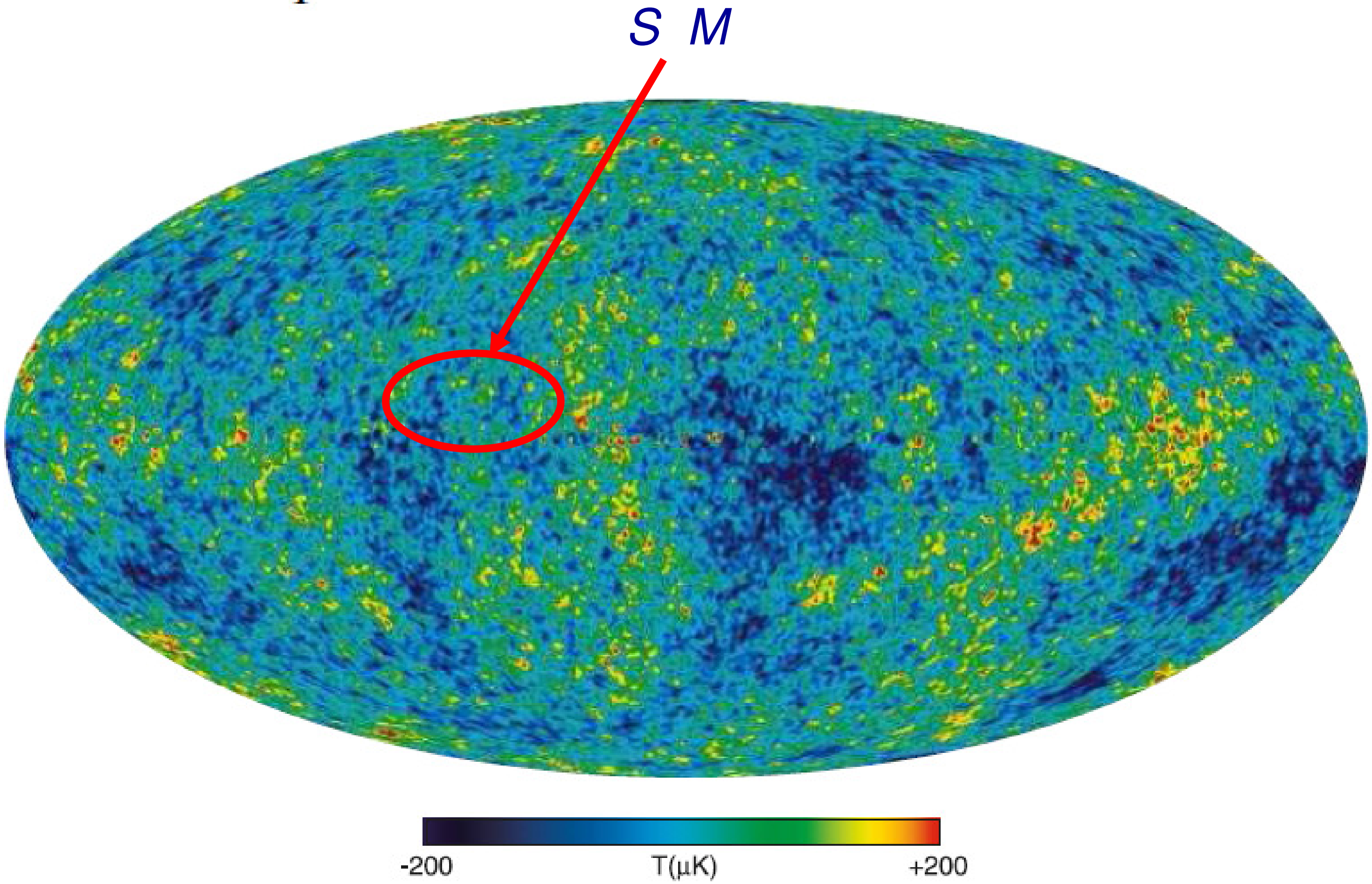
$$T = 2.725^\circ K, \quad \frac{\delta T}{T} \sim 10^{-5}$$



WMAP

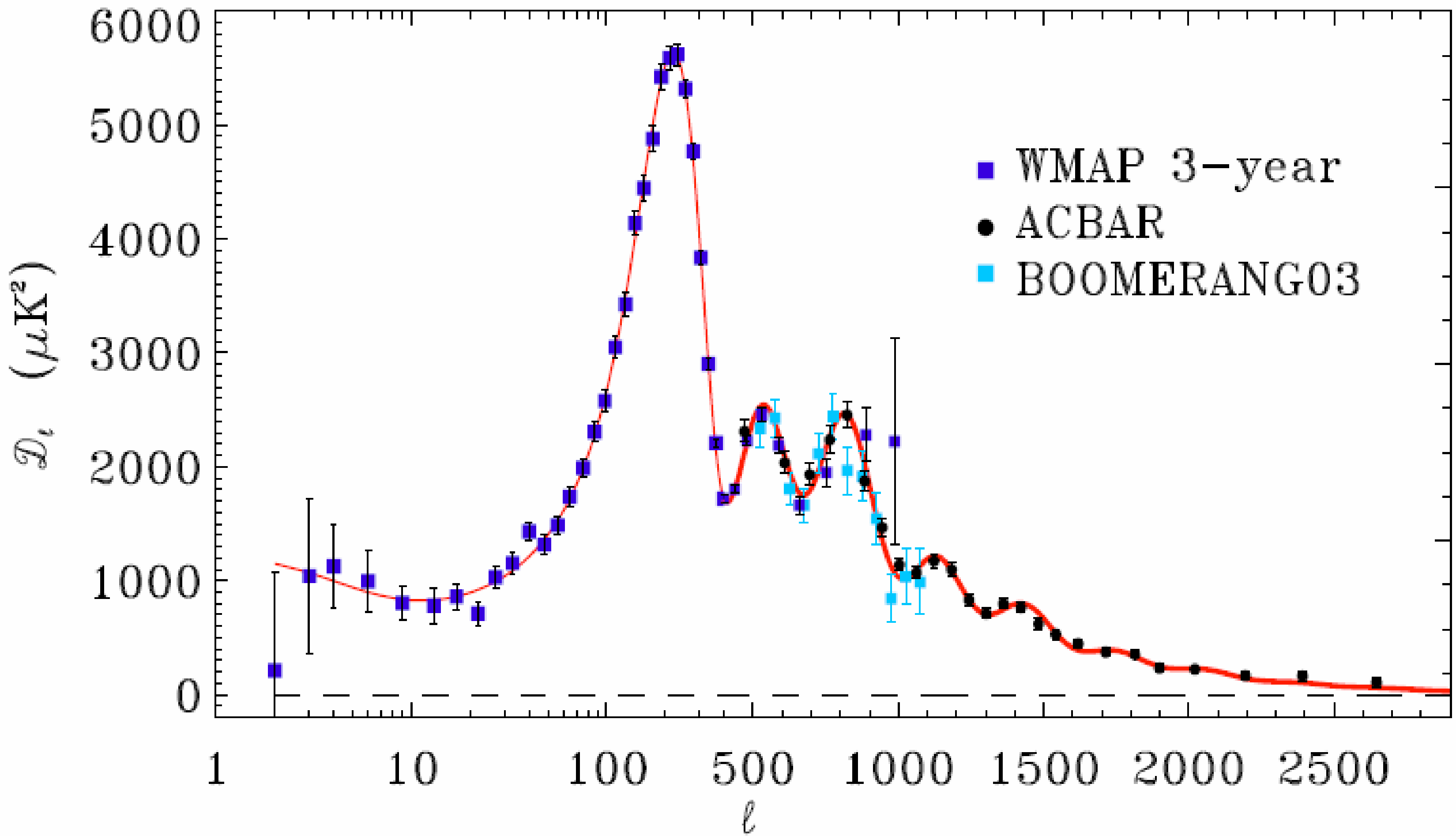
CMB temperature anisotropy

$$T = 2.725^\circ K, \quad \frac{\delta T}{T} \sim 10^{-5}$$



WMAP

CMB anisotropy spectrum

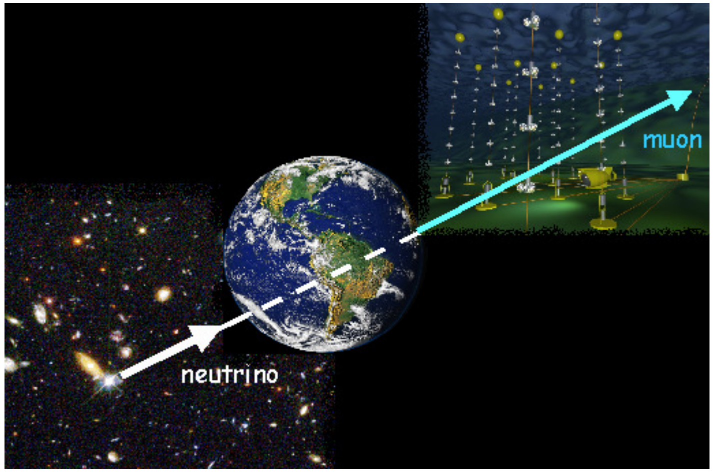


Other issues

- Lots of models about universe development
- Cosmological parameters
- Thermodynamic considerations
- Spectral classification
- Evolution of stars (HRD → knee…)

Neutrino Telescopes

Heide Costantini
INFN-Genova (Italy)



Lecture 1

Scientific motivation

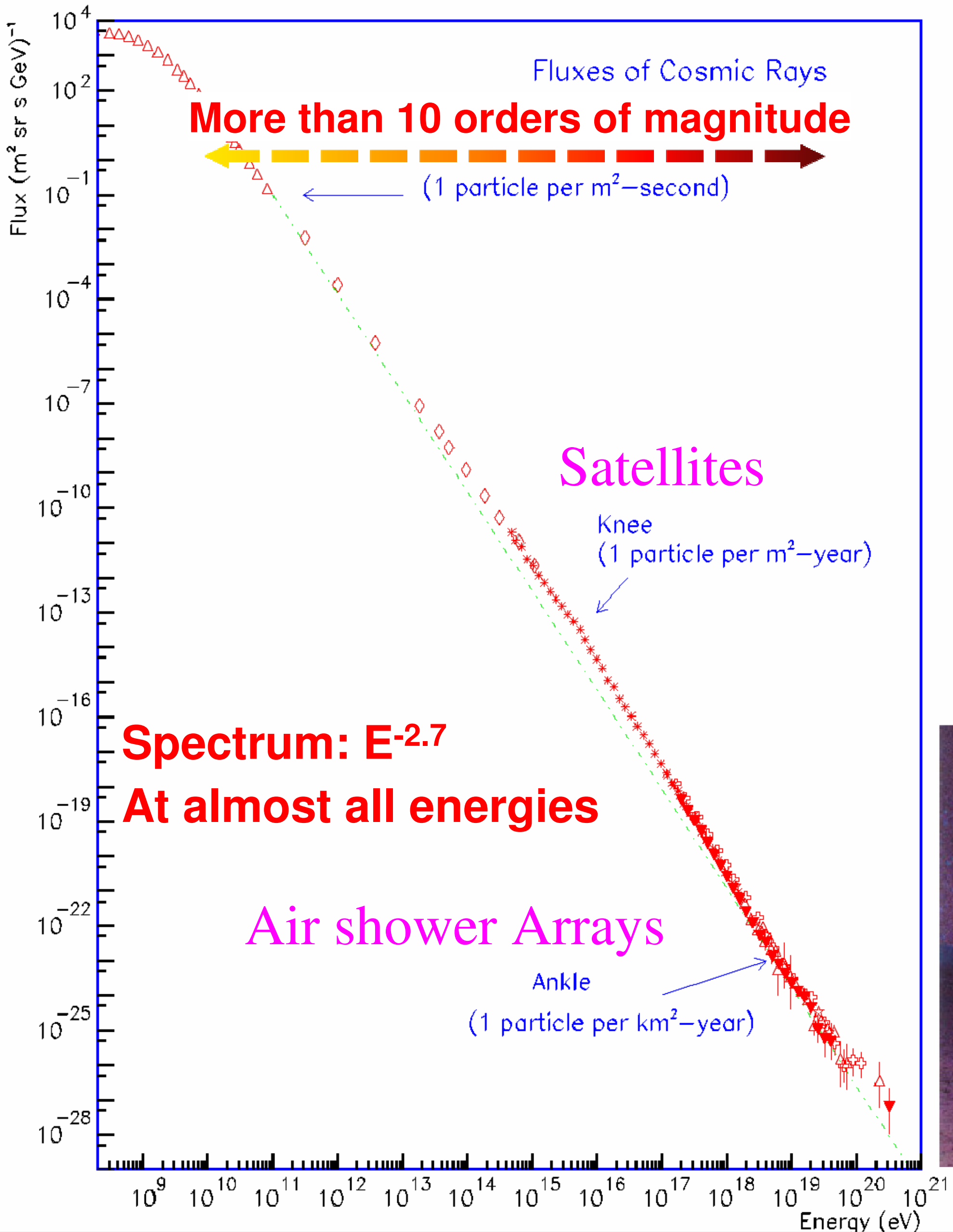
Detection principles of neutrino telescopes

The ANTARES detector as an example project

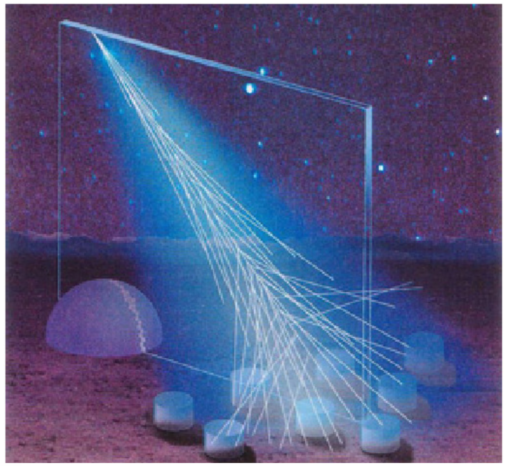
Lecture 2

The ANTARES detector operation
Existing results
Other neutrino telescope projects (Baikal, IceCube)

The Cosmic Ray (CR) Spectrum



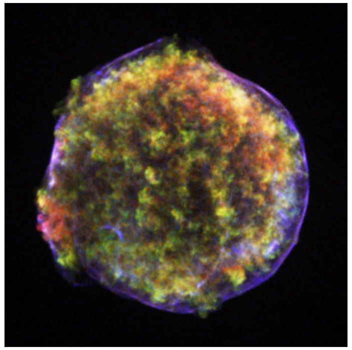
The CR sources are still unkown



Potential neutrino sources

GALACTIC

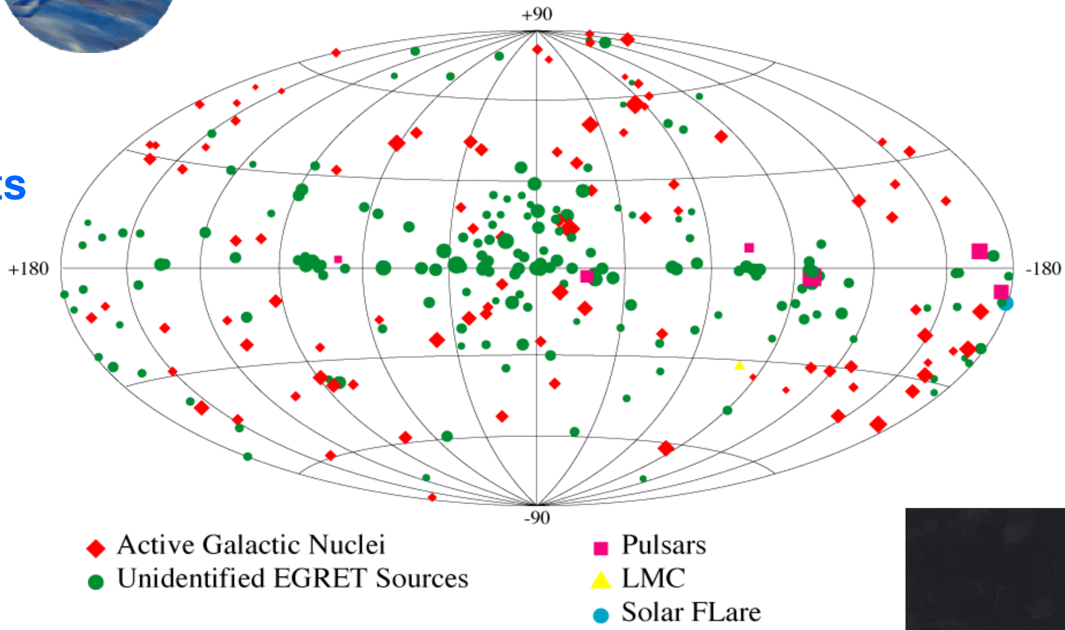
EXTRAGALACTIC

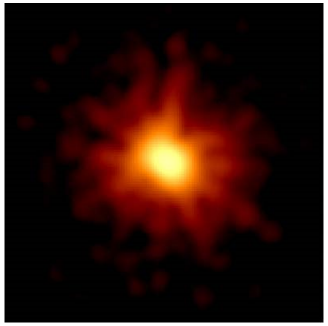


Supernova remnants

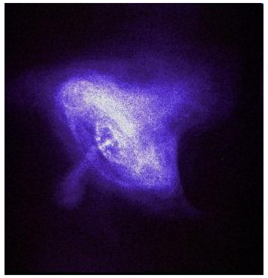
Third EGRET Catalog

E > 100 MeV

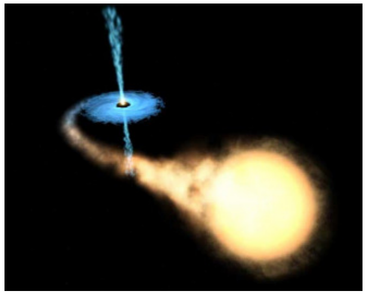




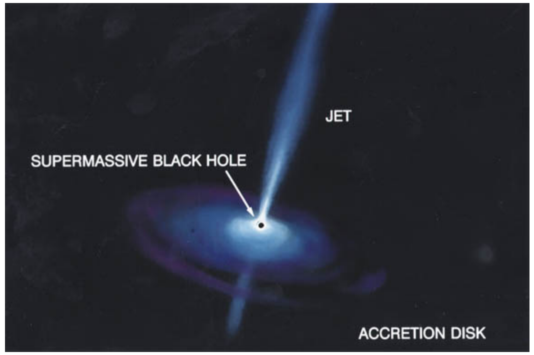
GRBs



Pulsars



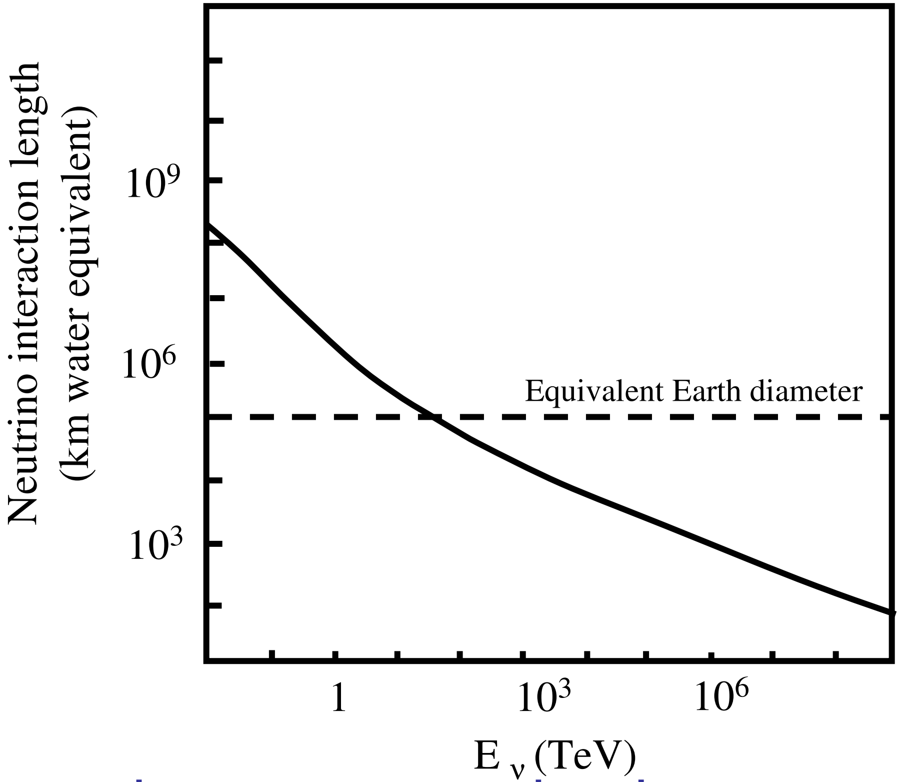
Microquasars



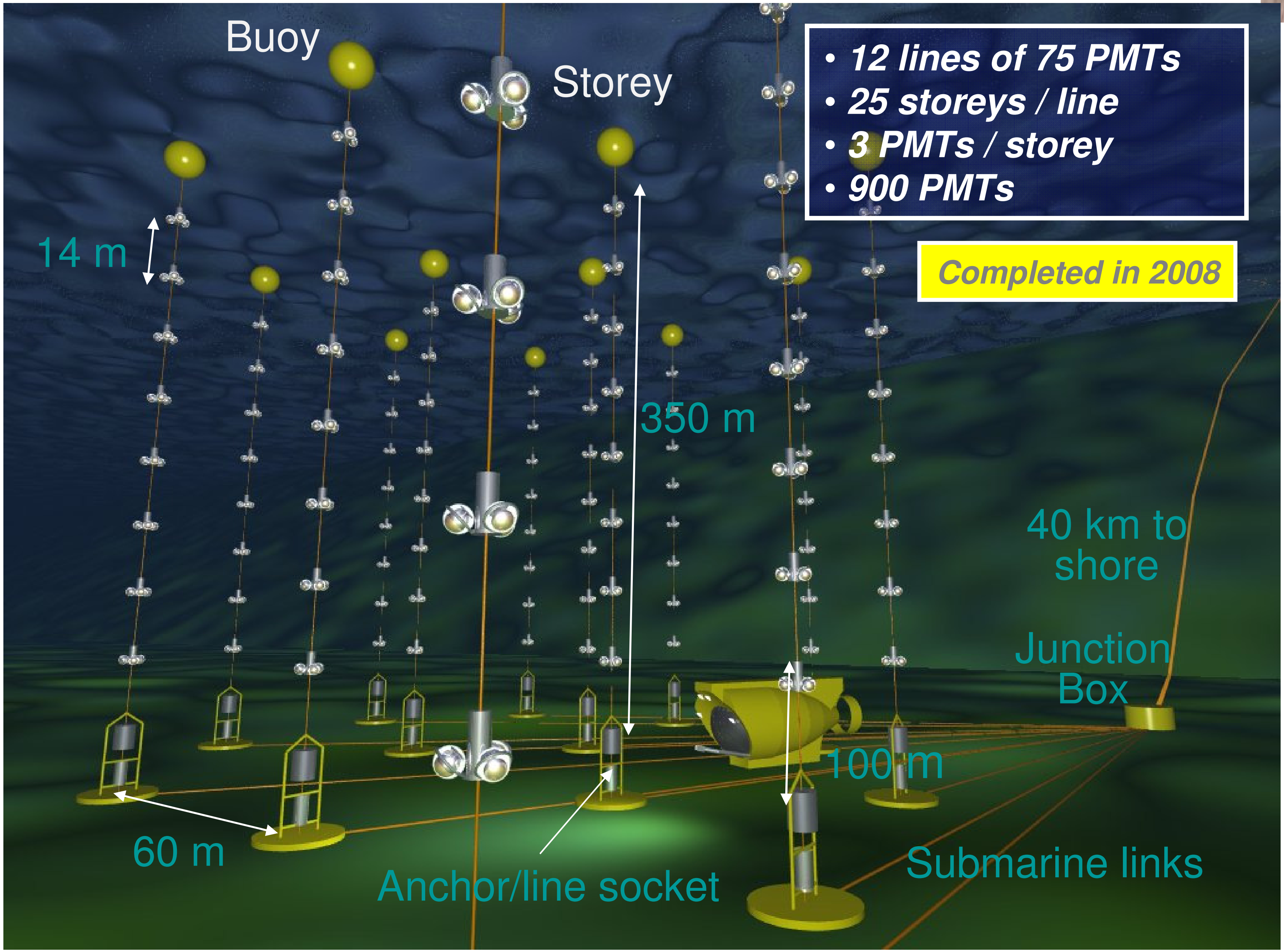
AGNs

Neutrino Interactions in Matter

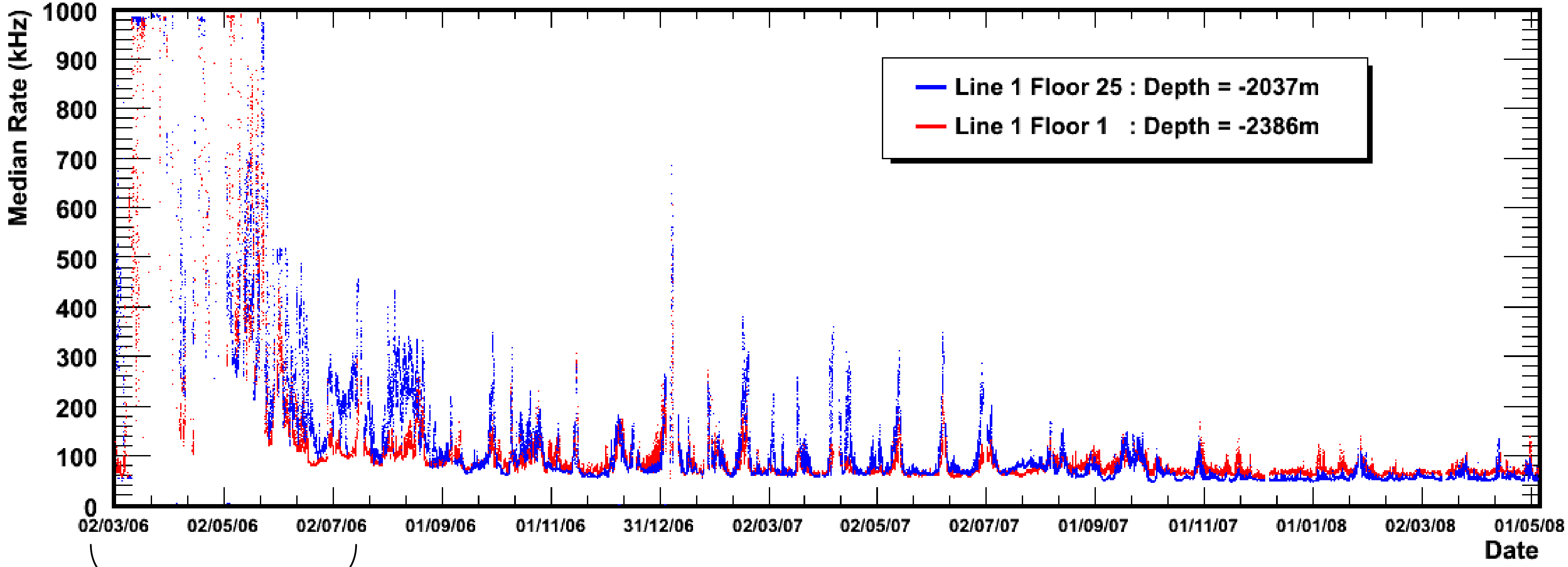
Interaction length of neutrinos vs energy



- → Astronomic sources and universe transparent to neutrinos
- → Earth transparent up to 100 TeV
- → Need massive detector
- → Probability of interaction ~ 10^{-5} / km water at 100 TeV


Buoy
Storey
• 12 lines of 75 PMTs
• 25 storeys / line
• 3 PMTs / storey
• 900 PMTs
Completed in 2008
14 m
350 m
40 km to shore
Junction Box
100 m
60 m
Anchor/line socket
Submarine links

Bioluminescence + ^{40}K



Cold winter…

IceCube deployment

Currently (IC59):

59 strings, each with:

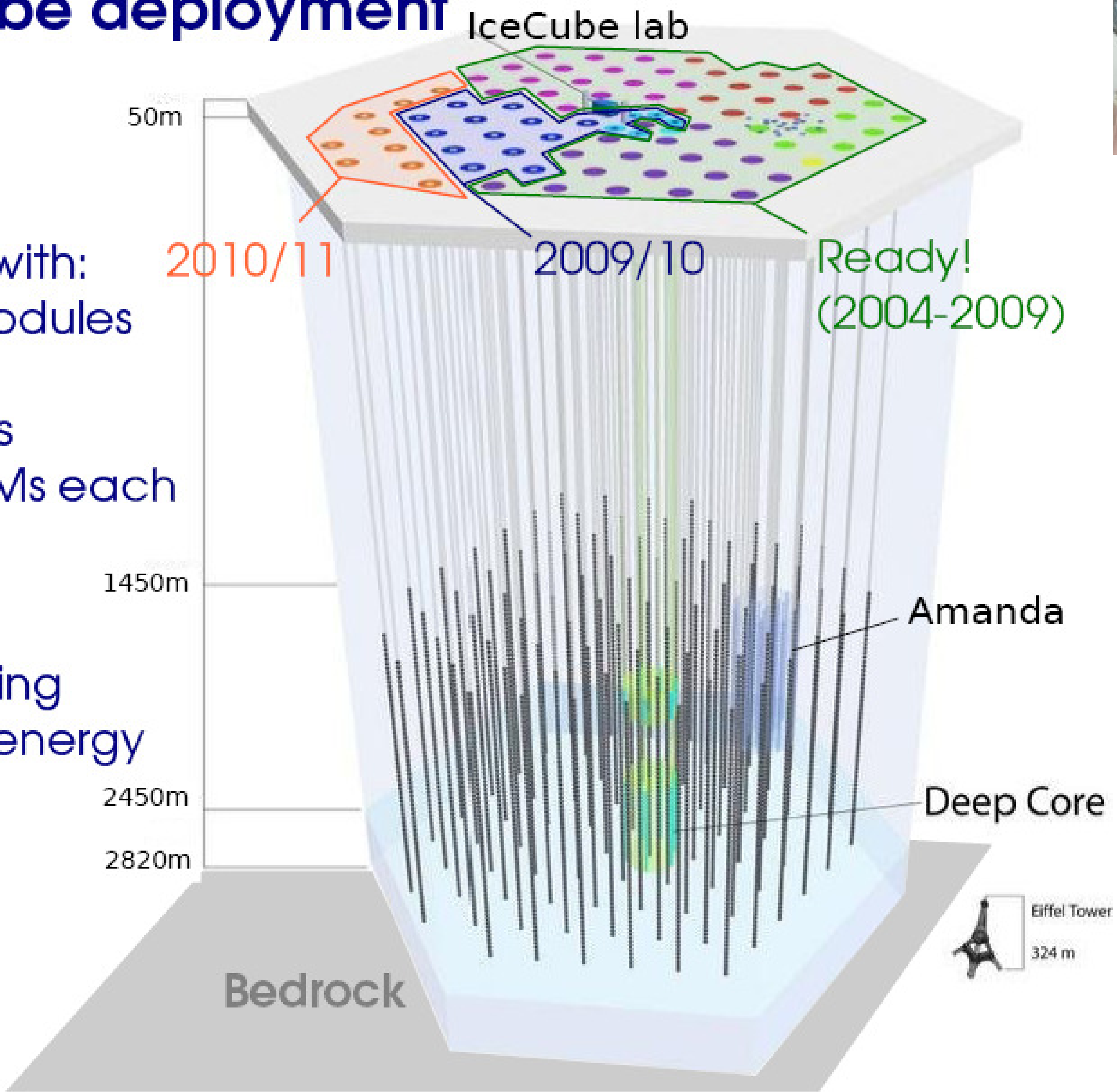
60 Optical modules in the ice

2 IceTop tanks with 2 DOMs each

In 2011 (IC86):

86 strings, including Deep Core low energy addition

59/86=68%



K.Hultqvist: IceCube

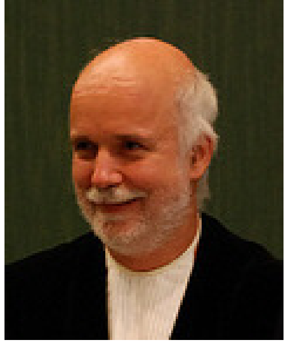
Conclusions

• Neutrinos are extremely interesting probes to detect cosmic sources in the faraway Universe

•Recent developments in constructing neutrino telescopes in Ice and Water have demonstrated the feasibility of those instruments

•A lot of exciting physics analysis is ahead: point source searches, multi-messenger astronomy….

Confession that one cannot win a flower pot with Antares…

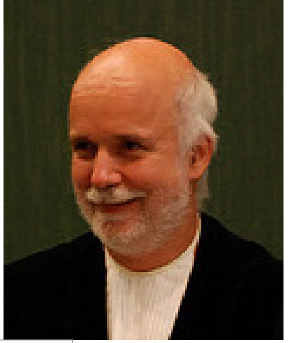


Lecture 1
- Introduction to ATLAS/CMS experiments at the LHC: historical perspective and physics goals
- Experimental environment and main design choices

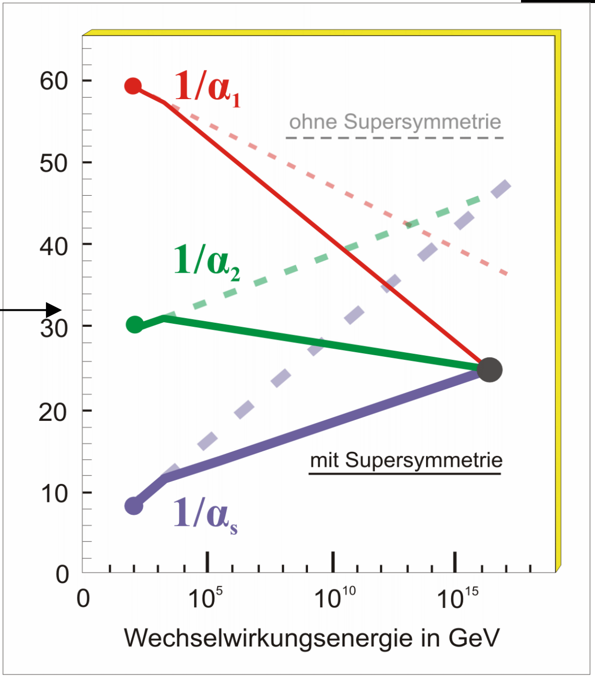
- Lecture 2
- Expected performances of ATLAS and CMS detectors

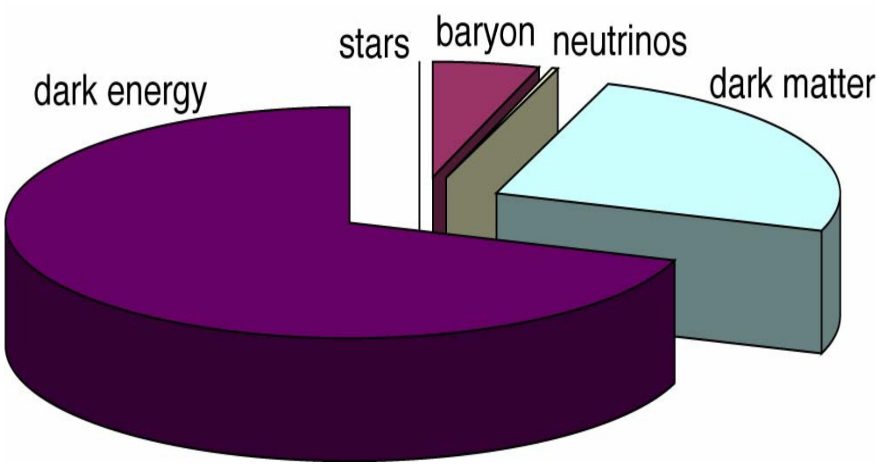
- Lecture 3
- Experience collected with cosmics (2008-2009), first data with collisions (end 2009) and expectations for early physics

Key Questions of Particle Physics



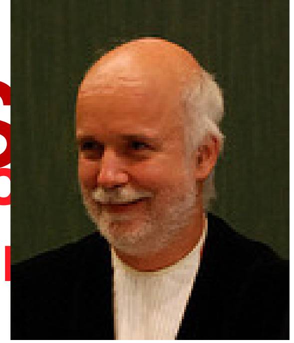
- origin of mass/matter or
  origin of electroweak symmetry breaking
- unification of forces
- fundamental symmetry of forces and matter
- unification of quantum physics
  and general relativity
- number of space/time dimensions
  - what is dark matter
  - what is dark energy

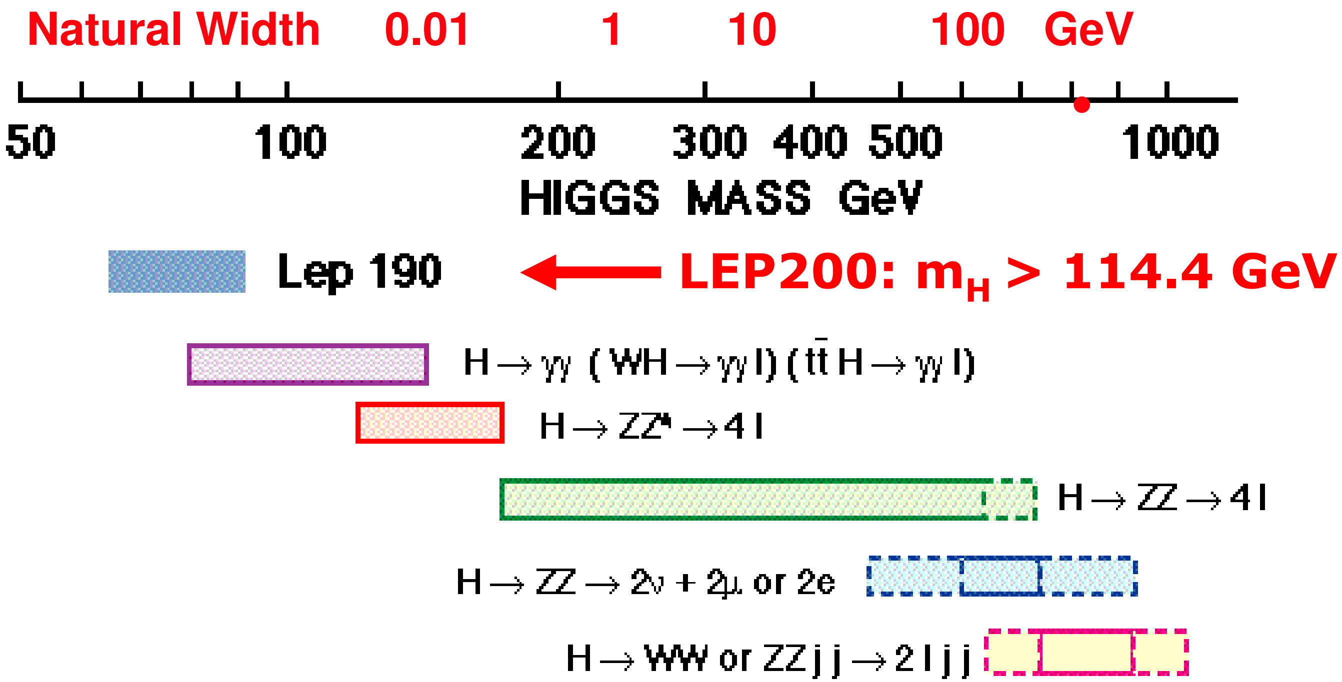


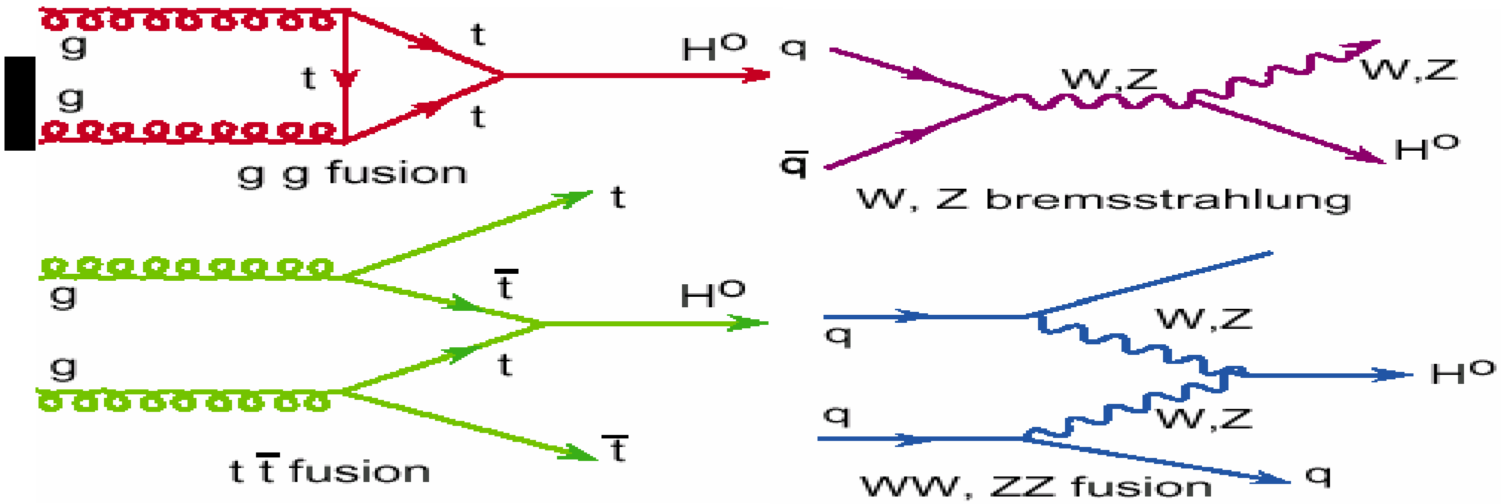


Physics Requirements

At the LHC the search for the SM Higgs boson pro
an excellent benchmark for detector performa

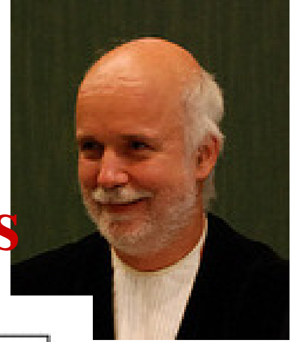




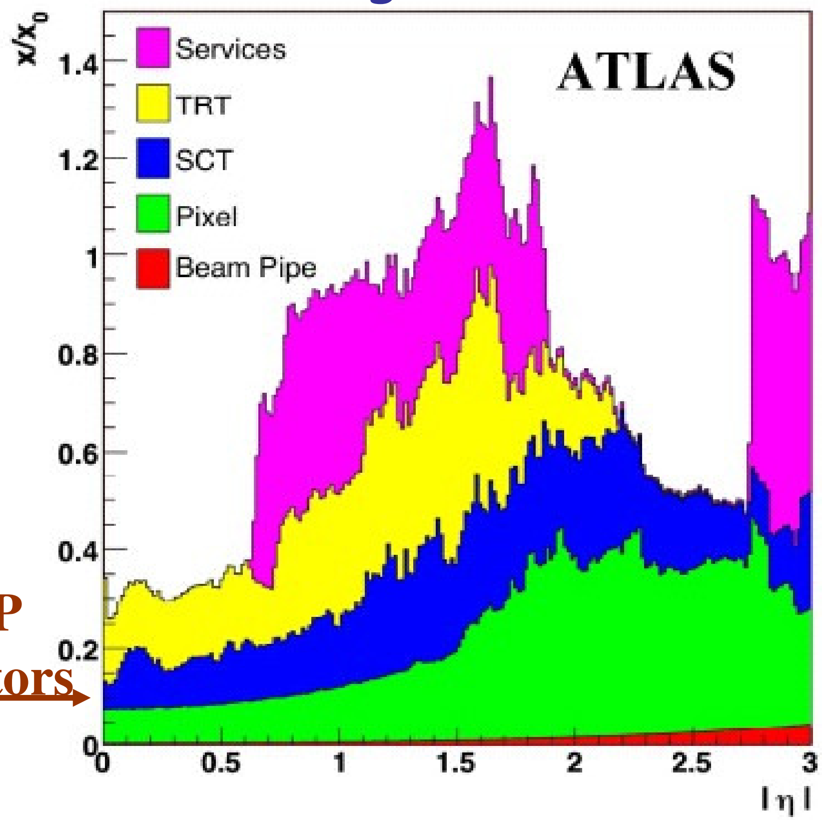


ATLAS/CMS: from design to reality

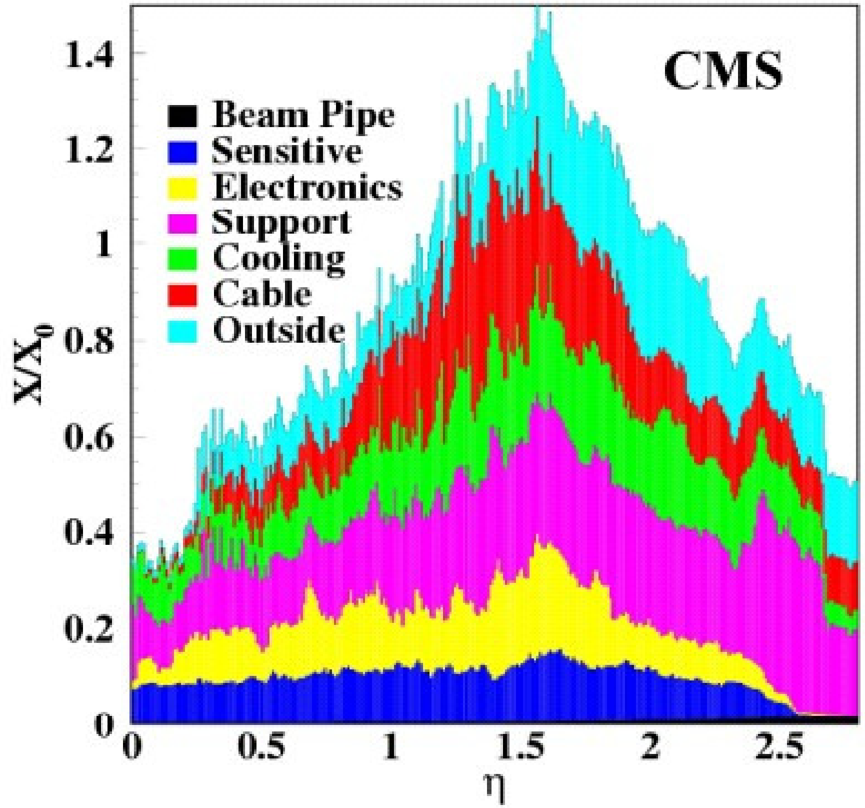
Amount of material in ATLAS and CMS inner trackers



Weight: 4.5 tons | **Weight: 3.7 tons**



LEP detectors



- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

ATLAS/CMS: from design to reality

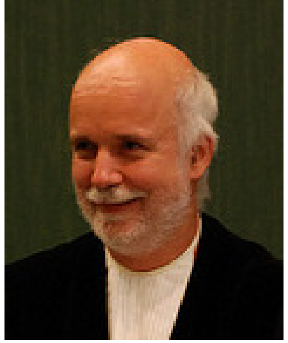


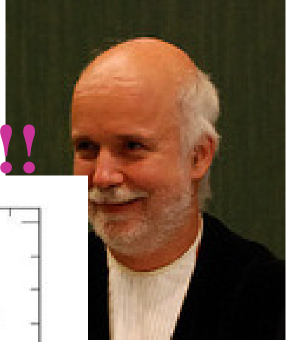
TABLE 7 Main performance characteristics of the ATLAS and CMS trackers

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	90	22–42
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	190	70

Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution. Vertexing and b-tagging performances are similar. However, impact of material and B-field already visible on efficiencies.

ATLAS/CMS: from design to reality

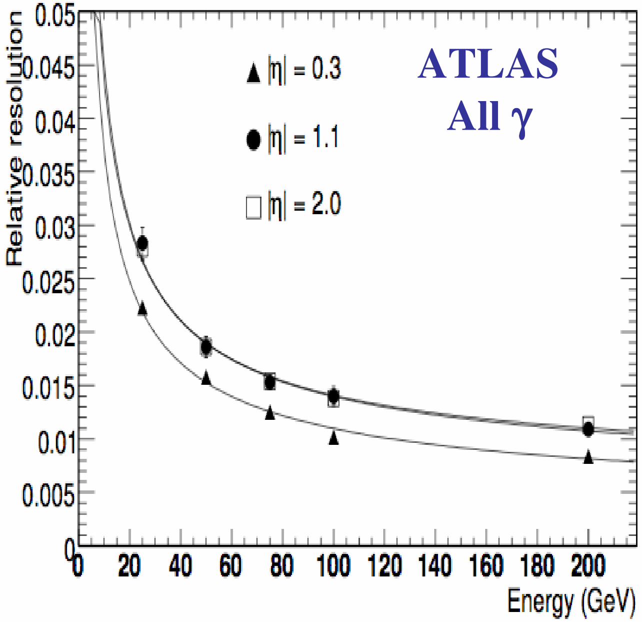
Actual performance expected in real detector quite different!!

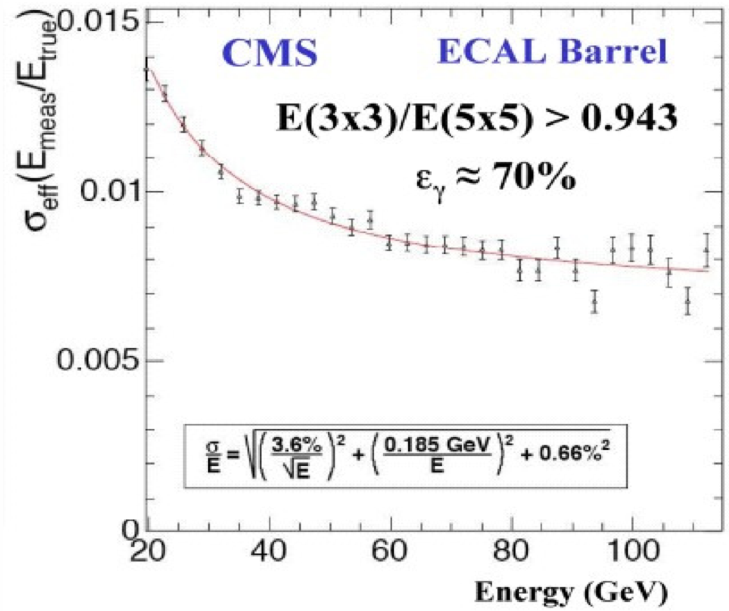


Photons at 100 GeV

ATLAS: 1-1.5%
energy resol. (all γ)

CMS: 0.8%
energy resol.
(ε_γ ~ 70%)

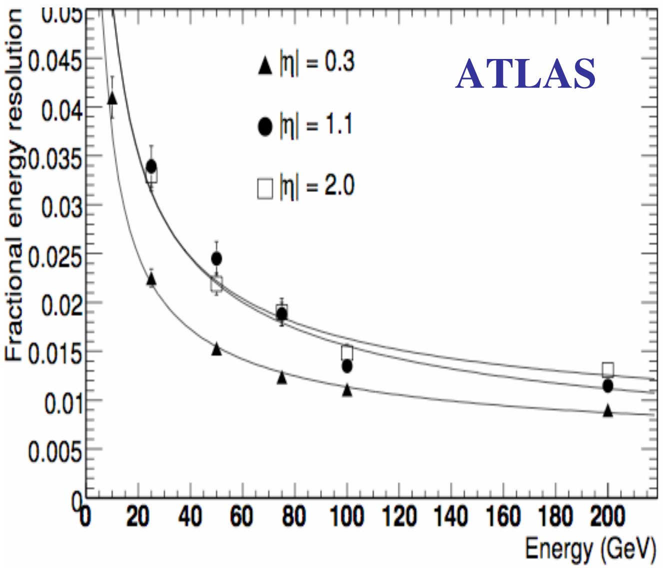


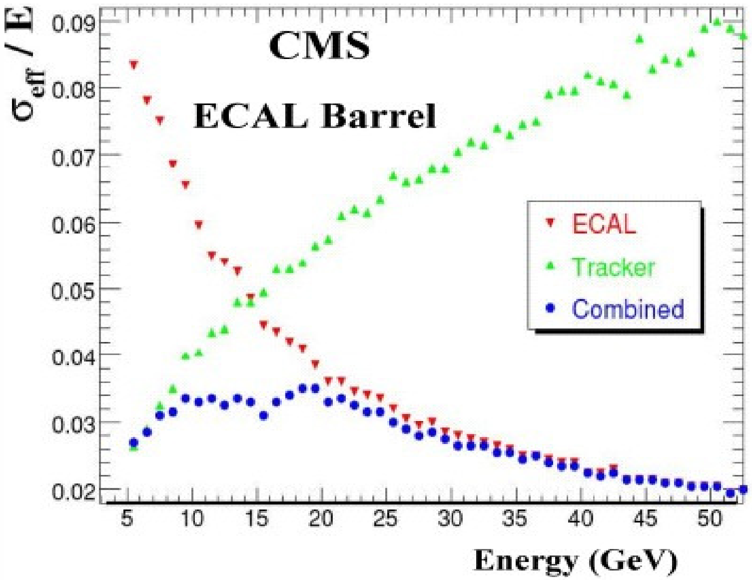


Electrons at 50 GeV

ATLAS: 1.5-2.5%
energy resol.
(use EM calo only)

CMS: ~ 2.0%
energy resol.
(combine EM calo and tracker)





ATLAS/CMS: from design to reality

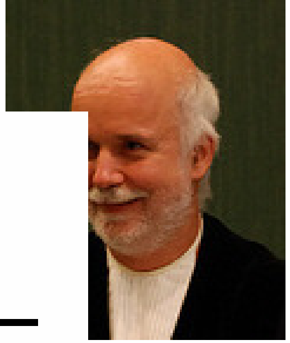


TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

Huge effort in test-beams to measure performance of overall calorimetry with single particles and tune MC tools: not completed!

ATLAS/CMS: from design to reality

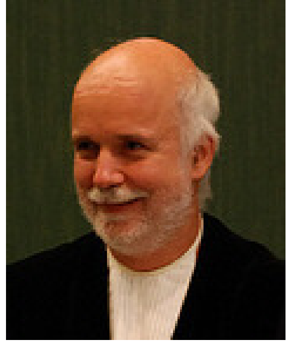
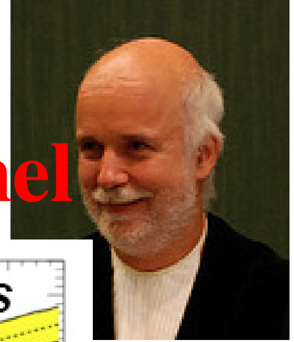


TABLE 12 Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

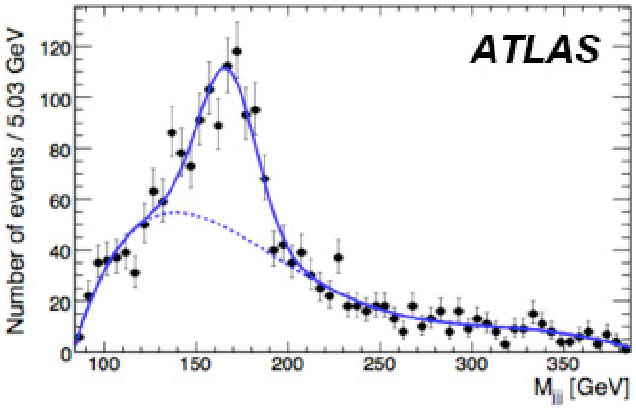
Parameter	ATLAS	CMS
Pseudorapidity coverage		
-Muon measurement	$\lvert\eta\rvert < 2.7$	$\lvert\eta\rvert < 2.4$
-Triggering	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (z-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	**2(+4)**
-Bending power (BL, in T· m) at $\lvert\eta\rvert \approx 0$	3	16
-Bending power (BL, in T· m) at $\lvert\eta\rvert \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

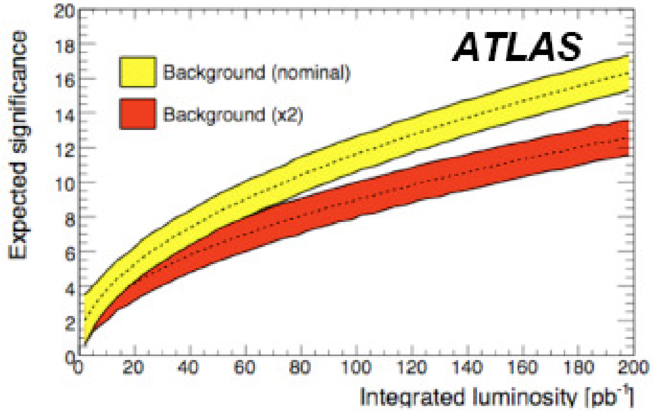
CMS muon performance driven by tracker: better than ATLAS at η ~ 0
ATLAS muon stand-alone performance excellent over whole η range

First top quarks seen outside Fermilab: top-pair cross-section through semileptonic channel

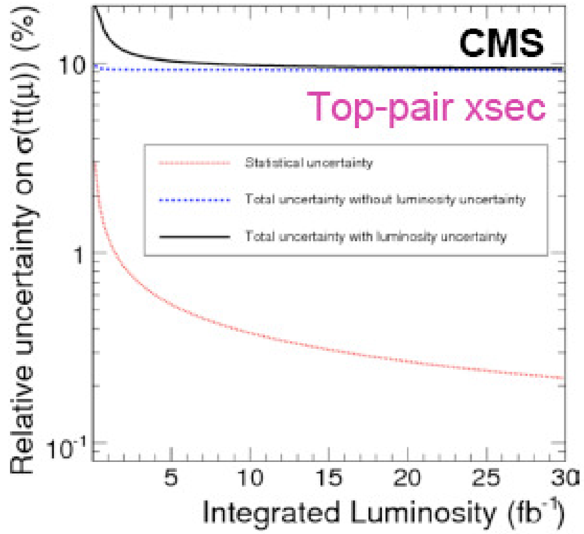


- Extract signal using event counting or fit to M_{jjj} distribution
  - Can establish signal for 100 pb^{-1} even with pessimistic background

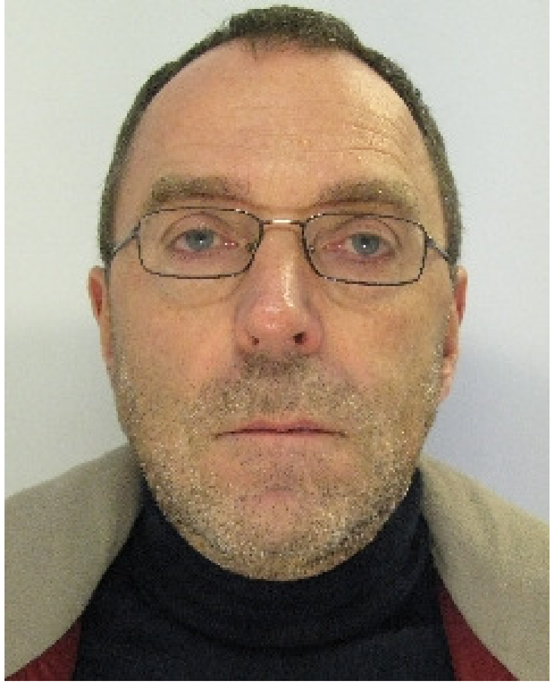




- With 100 pb^{-1} expect to commission b-tagging and understand efficiency to ~5% - use in selection
  - Require 1 or 2 b-tagged jets, reduces non-tt b/g and helps select correct combination
- For O(fb^{-1}), b-tagging, PDFs & luminosity become important

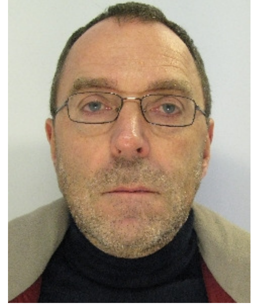


Expt	Int.L	Method	Stat (%)	Syst (%)	Lumi (%)
ATLAS	100 pb^{-1}	count ($W \to e$)	2.5	14	5
ATLAS	100 pb^{-1}	likelihood	7.4	15	5
CMS	1 fb^{-1}	count	1.2	9.2	10
CMS	10 fb^{-1}	count	0.4	9.2	3



Andrei Golutvin
Imperial College / ITEP / CERN

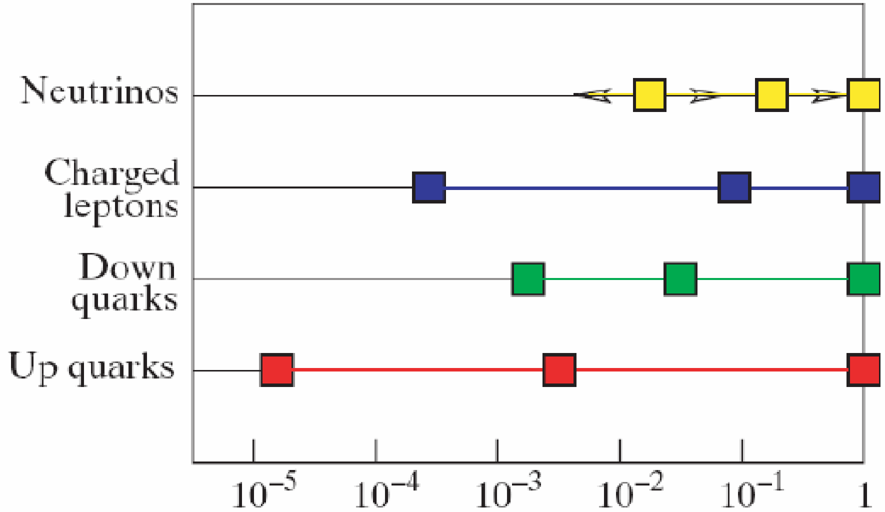
Flavour physics and CP violation informal introduction



The Standard Model Zoo

$SU(3) \times SU(2) \times U(1)$ $[\, g;\, W, Z;\, \gamma]$

Pattern of the fermion masses is not currently not understood !!!



Mass hierarchies (from *hep-ph/0603118*). The heaviest fermion of a given type has unit mass.

Masses come out of interactions in the Standard Model and these interactions conserve (or do not conserve…) particular symmetries.

SM is a gauge theory, based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$

8 massless gluons	}	12 spin-1 gauge fields
1 massless photon		
3 massive bosons: $W^{\pm}, Z^0$		

The fermionic matter content is given by 3-fold family structure

$$\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix}, \quad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix}, \quad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$$

where (each quark appears in 3 different colours)

$$\begin{bmatrix} \nu_\ell & q_u \\ \ell^- & q_d \end{bmatrix} \equiv \begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L, \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L, \ell^-_R, q_{uR}, q_{dR}$$

+ corresponding antiparticles

left-handed fields are $SU(2)_L$ doublets, while their right-handed partners transform as $SU(2)_L$ singlets. The 3 fermionic families appear to have identical properties (gauge interactions); they only differ by their mass and their flavour quantum number!

The gauge symmetry is broken by the vacuum → triggers the Spontaneous Symmetry Breaking

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{SSB} SU(3)_C \times U(1)_{QED}$$

- ✓ Appearance of a phys. scalar Higgs
- ✓ Quark masses & mixings also generated through SSB

QED

For a free Dirac fermion

$$\mathcal{L}_0 = i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) - m\bar{\psi}(x)\psi(x)$$

is invariant under global $U(1)$ transformation

$$\psi(x) \xrightarrow{U(1)} \psi'(x) \equiv \exp\{iQ\theta\}\psi(x)$$

"gauge principle": $U(1)$ phase invariance should hold locally $(\theta = \theta(x))$

$$\partial_\mu\psi(x) \xrightarrow{U(1)} \exp\{iQ\theta\}(\partial_\mu + iQ\partial_\mu\theta)\psi(x)$$

In order to cancel $\partial_\mu\theta$ term one introduces a new spin-1 field

$$A_\mu(x) \xrightarrow{U(1)} A'_\mu(x) \equiv A_\mu(x) + \frac{1}{e}\partial_\mu\theta$$

and defines the covariant derivative

$$D_\mu\psi(x) \equiv [\partial_\mu - ieQA_\mu(x)]\psi(x)$$

$$\hookrightarrow D_\mu\psi(x) \xrightarrow{U(1)} (D_\mu\psi)'(x) \equiv \exp\{iQ\theta\}D_\mu\psi(x)$$

Then

$$\mathcal{L} \equiv i\bar{\psi}(x)\gamma^\mu D_\mu\psi(x) - m\bar{\psi}(x)\psi(x) =$$

$$= \mathcal{L}_0 + eQA_\mu(x)\bar{\psi}(x)\gamma^\mu\psi(x)$$ is invariant under local $U(1)$ transformation

The gauge principle generated the int. between fermion and A (familiar QED vertex)

(corresponding eQ is completely arbitrary)

A possible mass term for the gauge field

$\mathcal{L}_m = \frac{1}{2}m^2A^\mu A_\mu$ is forbidden because it would violate gauge invariance $\Rightarrow m_\gamma = 0$!

N_G generations of fermions

$\nu_j', \ell_j', u_j', d_j'$ - members of the weak family with definite transf. properties under the gauge group

↪ most general Yukawa Lagrangian:

$$\mathcal{L}_Y = \sum_{jk} \left\{ (\bar{u}_j' \, \bar{d}_j')_L \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d_{kR}' + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} u_{kR}' \right] \right.$$

$$\left. + (\bar{\nu}_j', \bar{\ell}_j') \, c_{jk}^{(\ell)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \ell_{kR}' \right\} + h.c.$$

$c_{jk}^{(d)}, c_{jk}^{(u)}, c_{jk}^{(\ell)}$ - arbitrary coupling constants

After SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}_L' M_d' d_R' + \bar{u}_L' M_u' u_R' + \bar{\ell}_L' M_\ell' \ell_R' + h.c. \right\}$$

where d', u', ℓ' - vectors in N_G-dimensional flavour space

The corresponding mass matrices are given by

$$(M_d')_{ij} \equiv - c_{ij}^{(d)} \frac{v}{\sqrt{2}}, \quad (M_u')_{ij} \equiv - c_{ij}^{(u)} \frac{v}{\sqrt{2}}$$

$$(M_\ell')_{ij} \equiv - c_{ij}^{(\ell)} \frac{v}{\sqrt{2}}$$

The diagonalization of these mass matrices determines the mass eigenstates d_j, u_j and ℓ_j, which are linear combinations of the corresponding weak eigenstates d_j', u_j' and ℓ_j'

M_d' can be decomposed as $M_d' = H_d U_d = S_d^\dagger \mathcal{M}_d S_d U_d$

$M_u' = H_u U_u = S_u^\dagger \mathcal{M}_u S_u U_u$

$\mathcal{M}_d = \text{diag}(m_d, m_s, m_b, \ldots)$, $\mathcal{M}_u = \text{diag}(m_u, m_c, m_t, \ldots)$

$\mathcal{M}_\ell = \text{diag}(m_e, m_\mu, m_\tau, \ldots)$

↪ In terms of diagonal mass matrices

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}_L \mathcal{M}_d d_R + \bar{u}_L \mathcal{M}_u u_R + \bar{\ell}_L \mathcal{M}_\ell \ell_R \right\}$$

CKM matrix can be parameterized by four parameters in many different ways. The so called «Wolfenstein parameterization» is based on expansion in powers of $\lambda = |V_{us}| + O(\lambda^7) = 0.2272 \pm 0.0010$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

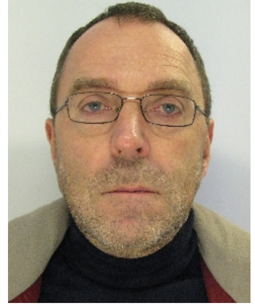
$V_{\mathrm{ud}}, V_{\mathrm{us}}, V_{\mathrm{cs}}, V_{\mathrm{cb}}, V_{\mathrm{tb}}$ are (practically) real

$V_{\mathrm{cd}}, V_{\mathrm{ts}}$ could be slightly complex

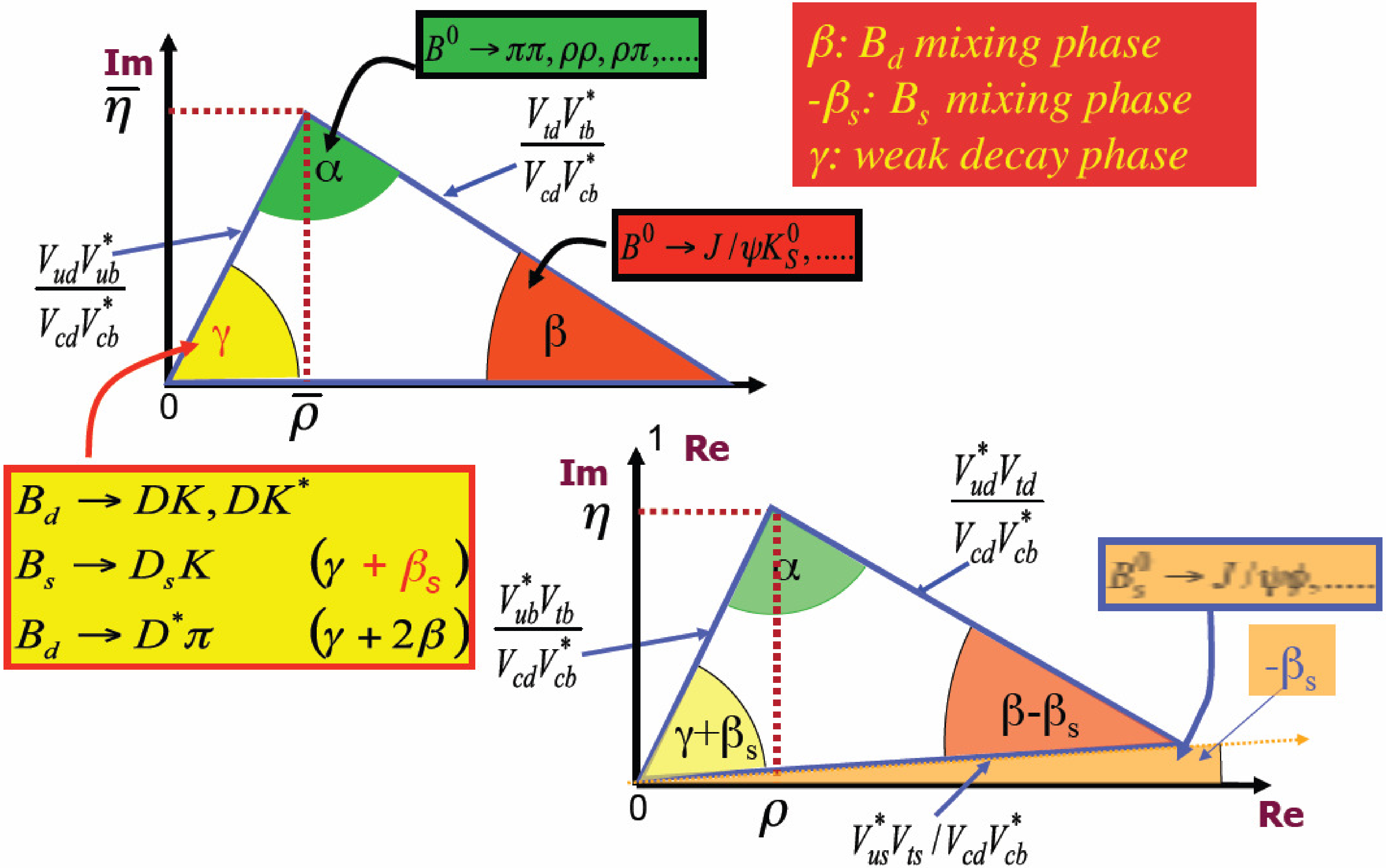
$V_{\mathrm{td}}, V_{\mathrm{ub}}$ could be complex

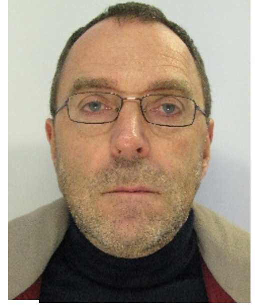
$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda\left[1 + A^2\lambda^4(\rho + i\eta)\right] & \left(1-\frac{\lambda^2}{2}\right) & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)\left(1-\frac{\lambda^2}{2}\right)\right] & -A\lambda^2\left[\left(1-\frac{\lambda^2}{2}\right)+\lambda^2(\rho+i\eta)\right] & 1 \end{pmatrix}$$

The Unitarity Triangle



β: B_d mixing phase
$-\beta_s$: B_s mixing phase
γ: weak decay phase





LHC Physics Goals

Main Goals:

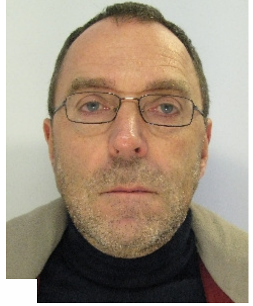
- *Search for the SM Higgs boson in mass range ~ 115 < m_H < 1000 GeV*
- *Search for New Physics beyond the SM*

- Explore TeV-scale directly (ATLAS & CMS) and indirectly (LHCb)

No space left for the 4th possibility

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Even if 4th possibility → Measurements of virtual effects will set the scale of New Physics

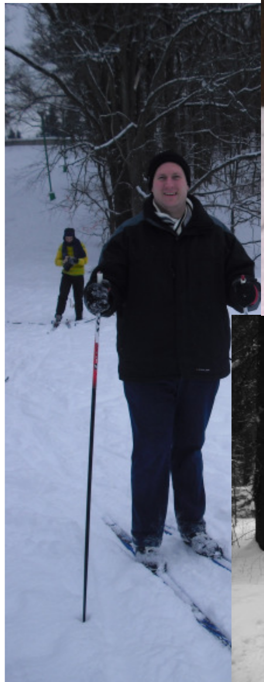


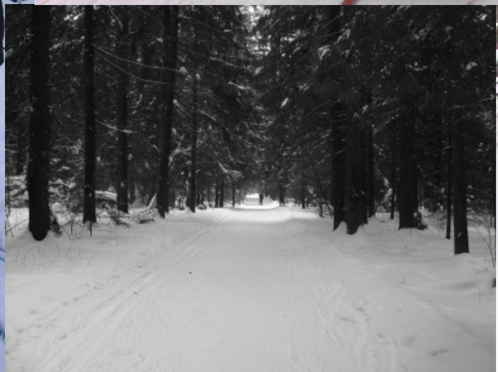
Conclusion

- *LHCb is ready for data taking*
- *First data are being used for calibration of the detector and trigger in particular. First exploration of low Pt physics at LHC energies. High class measurements in the charm sector may be possible*
- *With 150 – 200 pb^{-1} data sample LHCb will reach Tevatron sensitivity in a few golden channels in the beauty sector*
- *With 10 fb^{-1} LHCb has an excellent opportunity to both discover New Physics and to elucidate its nature. LHCb have an important role to complement physics programme of ATLAS and CMS*

Student Sessions

Skiing





Bonfire

- The way they spread the food…
  → "Take what you get!"
  → "Survival of the fittest!"

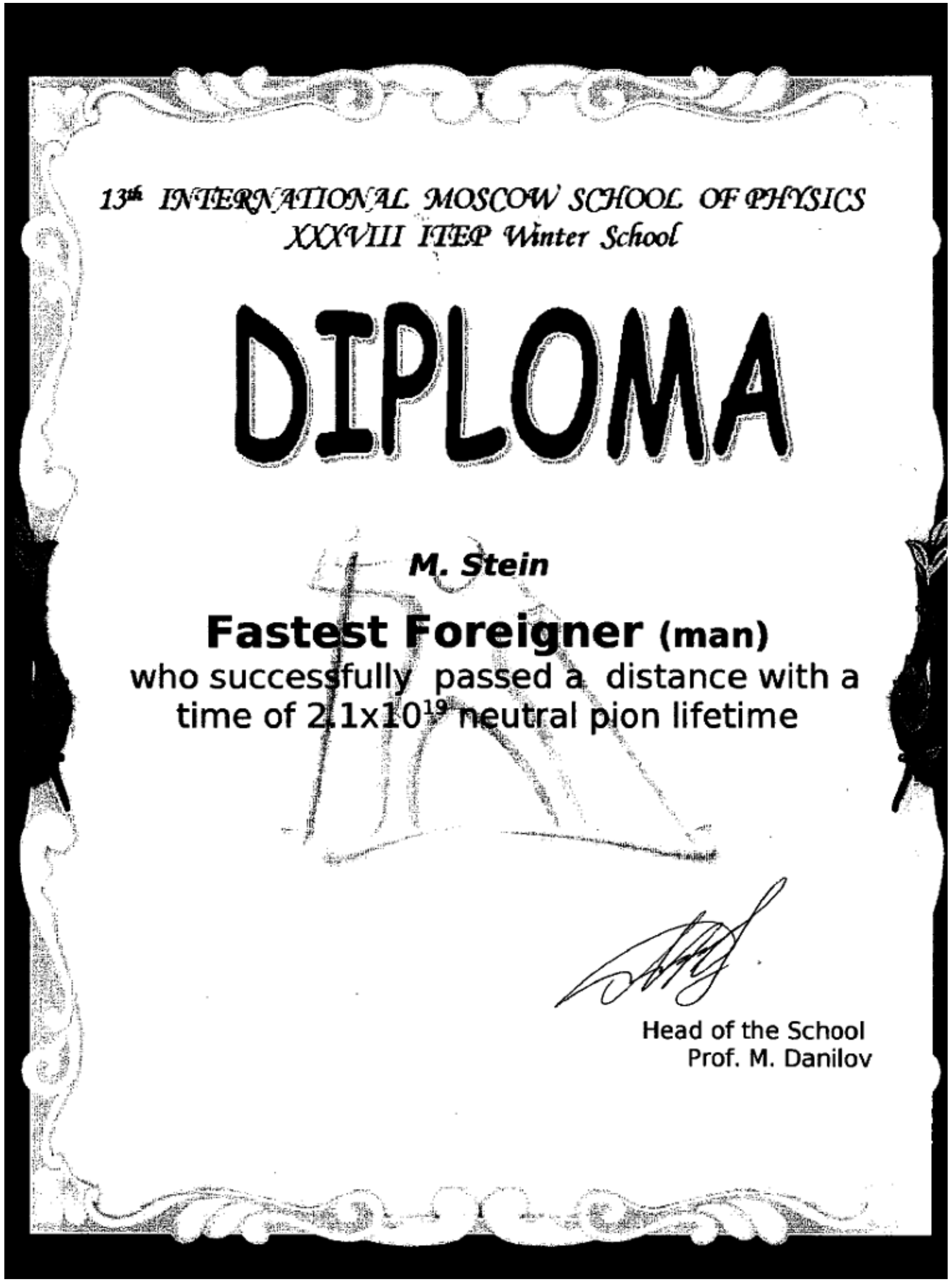
- The modern technique…

- Strange opening hours of the swimming pool

Sights

Two Major accomplishments

My Diploma…



13th INTERNATIONAL MOSCOW SCHOOL OF PHYSICS
XXXVIII ITEP Winter School

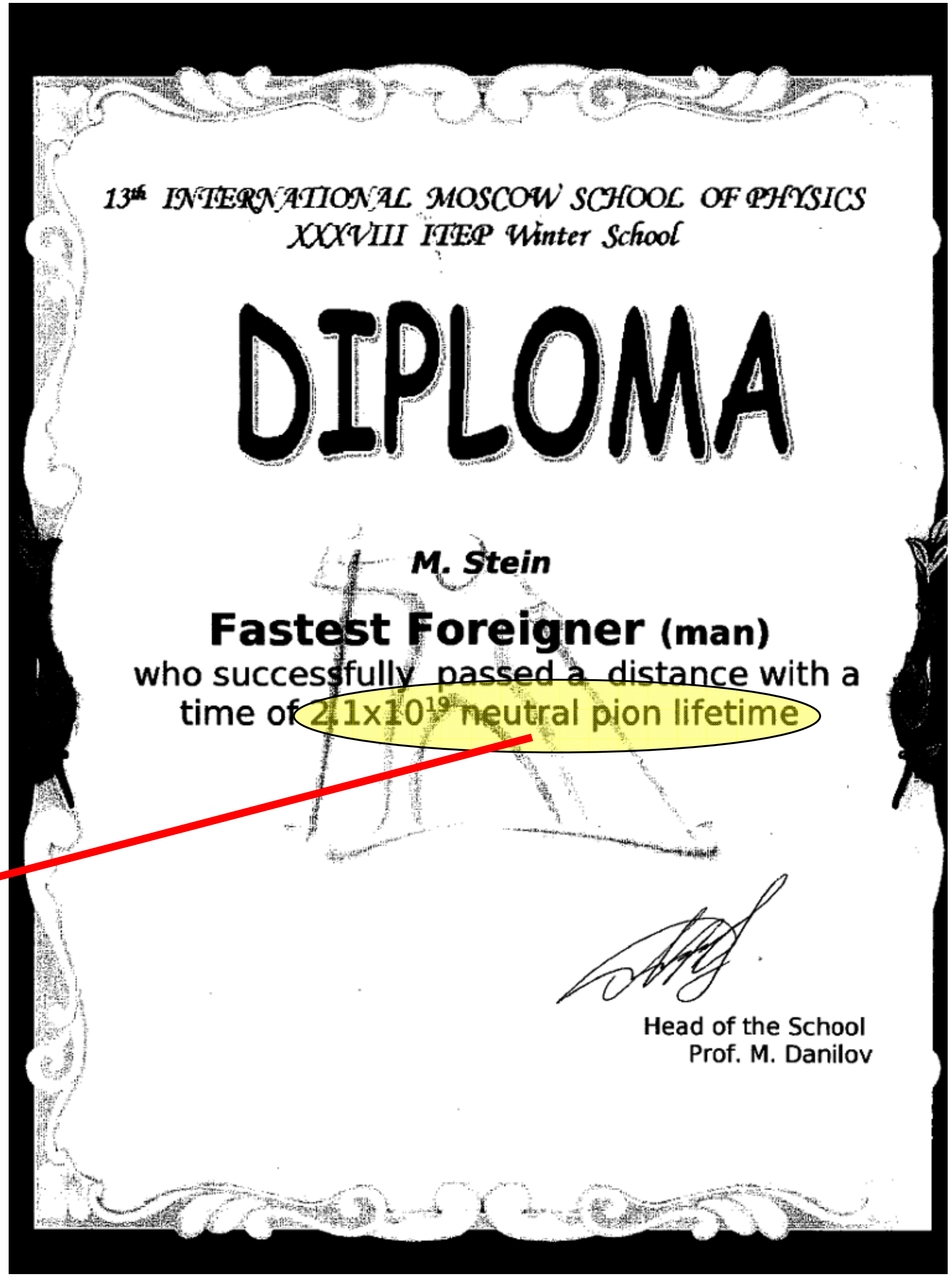
DIPLOMA

M. Stein

Fastest Foreigner (man)
who successfully passed a distance with a time of 2.1x10^{19} neutral pion lifetime

Head of the School
Prof. M. Danilov

My Diploma…



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$$2.1\times10^{19}\cdot(8.4\pm0.6)\times10^{-17}\,s$$
$$=1{,}764\,s=29.4\,\text{min}$$

My Doctor's Degree…

Russian Federation State Scientific Center

INSTITUTE FOR THEORETICAL AND EXPERIMENTAL PHYSICS

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This is to certify that **Dr. Matthias Stein** has paid the conference fee of 495 euro as a participant of XXXVIII ITEP Winter School of Physics held in Moscow on February 13-20, 2010.

School Director:

Yu.T. Kiselev

We had a good time…