Dark Matter Searches

Dark Matter and Particle Physics

A. Lindner, DESY

DESY Summer Student Lecture, 22 July 2011

HELMHOLTZ ASSOCIATION

Dark Matter Searches

- The Necessity of Dark Matter
  - Historical annotations
  - Dark Stuff in the Universe
  - What theory expects
- Dark Matter Scenarios
  - WIMPs: Weakly Interacting Massive Particles
  - GeV Dark Forces
  - WISPs: Weakly Interacting Sub-eV Particles
- Towards a low Energy Extension of the Standard Model
- Dark Matter Searches
  - Direct Dark Matter Searches
  - The Any-Light-Particle Experiment at DESY
- Outlook and Summary

The Standard Model of Constituents and Forces

Constituents:

> Quarks

> Leptons

Forces:

> electromagnetic

> strong

> weak

> gravitation

http://www.gridpp.ac.uk/cubes/

Only the Higgs boson is missing!

LHC is on the way to probe its existence.

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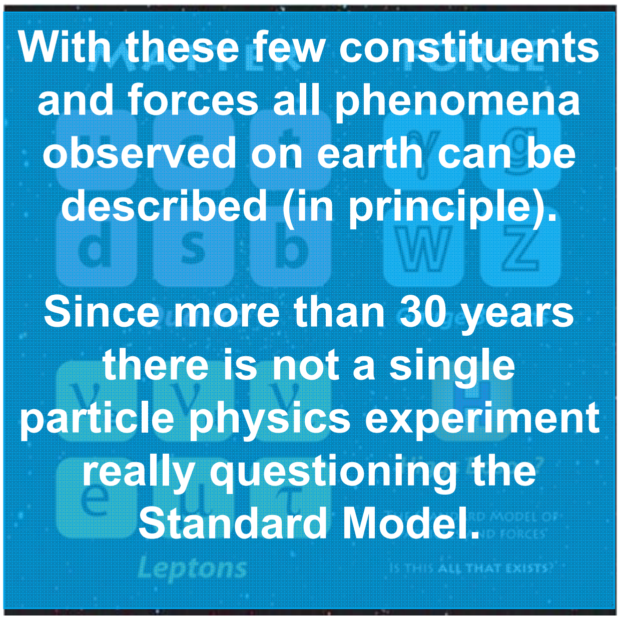


With these few constituents and forces all phenomena observed on earth can be described (in principle).

Since more than 30 years there is not a single particle physics experiment really questioning the Standard Model.

http://www.gridpp.ac.uk/cubes/

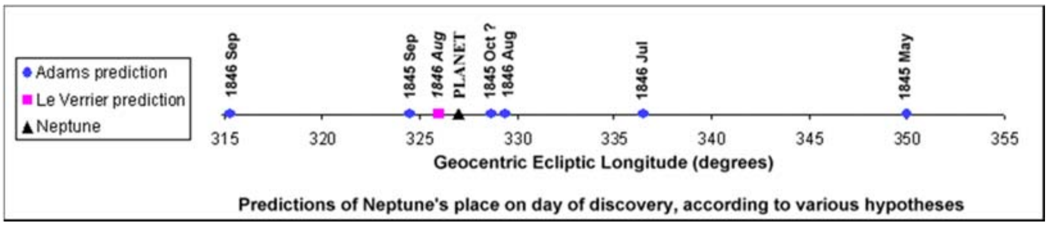
Only the Higgs boson is missing!

LHC is on the way to probe its existence.

Is there additional Dark Stuff around?

Some reminders from history:

> Discovery of Neptune by irregularities of the Uranus orbit:
Sept. 24th 1846 by Johann Gottfried Galle at the Berlin Observatory.



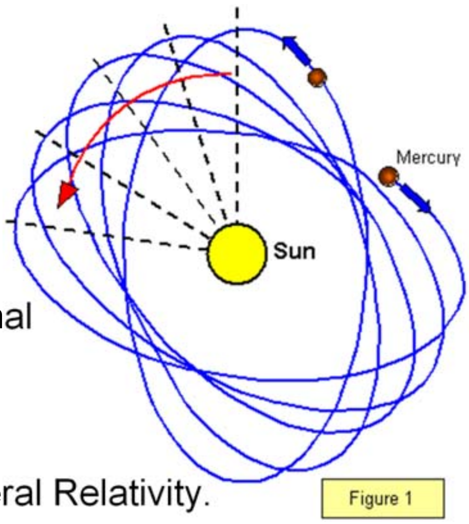
http://en.wikipedia.org/wiki/Discovery_of_Neptune

> An application of the known laws of nature (gravitation) led to the discovery of previously "invisible" mass.

Is there additional Dark Stuff around?

Some reminders from history:

> Motion of the perihelion of Mercury:
http://www.schoolphysics.co.uk/age16-19/Relativity/text/Perihelion_of_mercury/index.html



Attempts to describe this by the gravitational pull of a new planet "Vulcan" failed
(in spite of numerous "observations").

Finally the explanation was given by General Relativity.

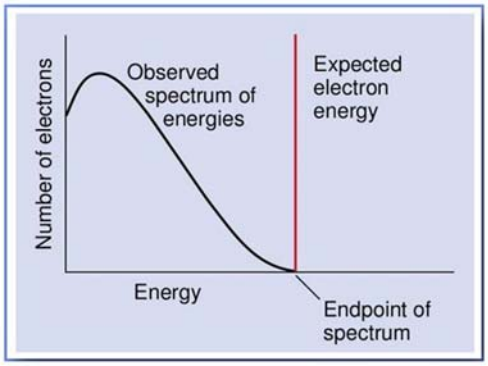
> A failed search for an "invisible" mass strongly supported an improved theory of gravitation.

Is there additional Dark Stuff around?

<u>Some reminders from history:</u>

> Beta decay:
http://www.lngs.infn.it/

W. Pauli postulated the neutrino in 1930 to preserve the conservation of energy, momentum and angular momentum.



Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

1956 the previously “invisible” neutrino was detected by Cowan and Reines.

> Observed deviations from fundamental physics were used to predict a new kind of matter.

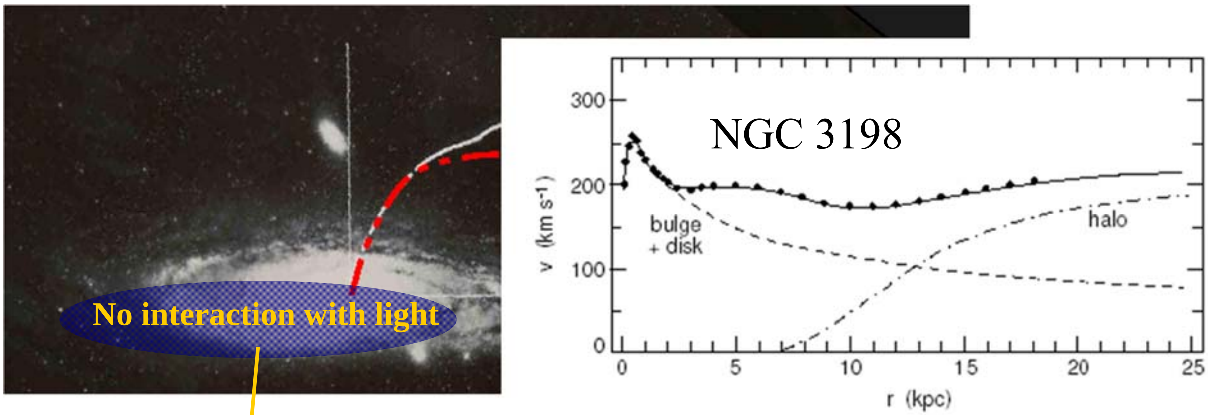
Discussion Time

> Which evidences do we have today for dark unknowns in the universe?

Observational Evidence for Dark Matter (1)

Rotation of galactic disks:

Dark Matter and experiments:
http://cdms.berkeley.edu/experiment.html



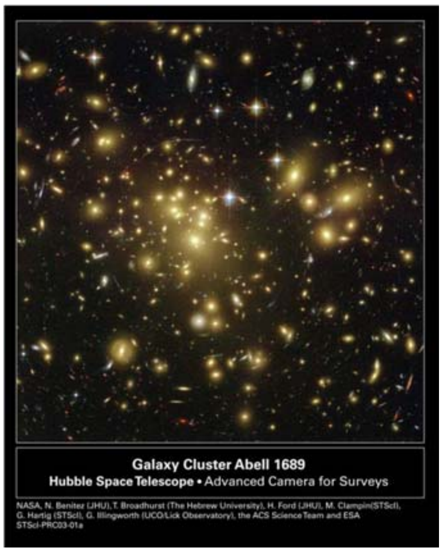
Dark Matter $\approx$ 10 · Luminous Matter

Observational Evidence for Dark Matter (2)

Motions of galaxies in clusters:

Clusters do not diffuse in spite of high speed of galaxies.

(Dark component first proposed 1933 by F. Zwicky after analysis of the Coma cluster)



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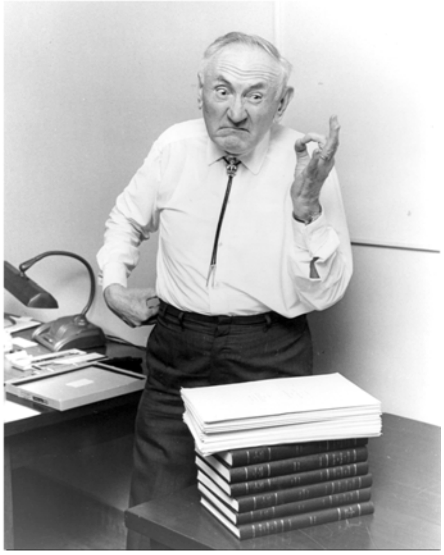

Dark Matter $\approx$ 30 · Luminous Matter

Observational Evidence for Dark Matter (3)

Hot gas in galaxy clusters:

Hot gas (measured by X-ray emission due to e^-- bremsstrahlung) contains too much kinectic energy to be bound by luminous matter in the cluster.

Mass (hot gas) $\approx$
5 · Luminous Matter

Dark Matter $\approx$ 30 · Luminous Matter

How to find Dark Matter in the Universe?

Search for Dark Matter via gravitational effects
(kind of definition of “dark”):

- bound systems
  (galaxies, clusters of galaxies, hot gas as shown before)

- distortion of images due to gravitational force on light

  “gravitational lensing”

Gravitation distorts Images

http://astronomyonline.org/Cosmology/GravitationalLensing.asp

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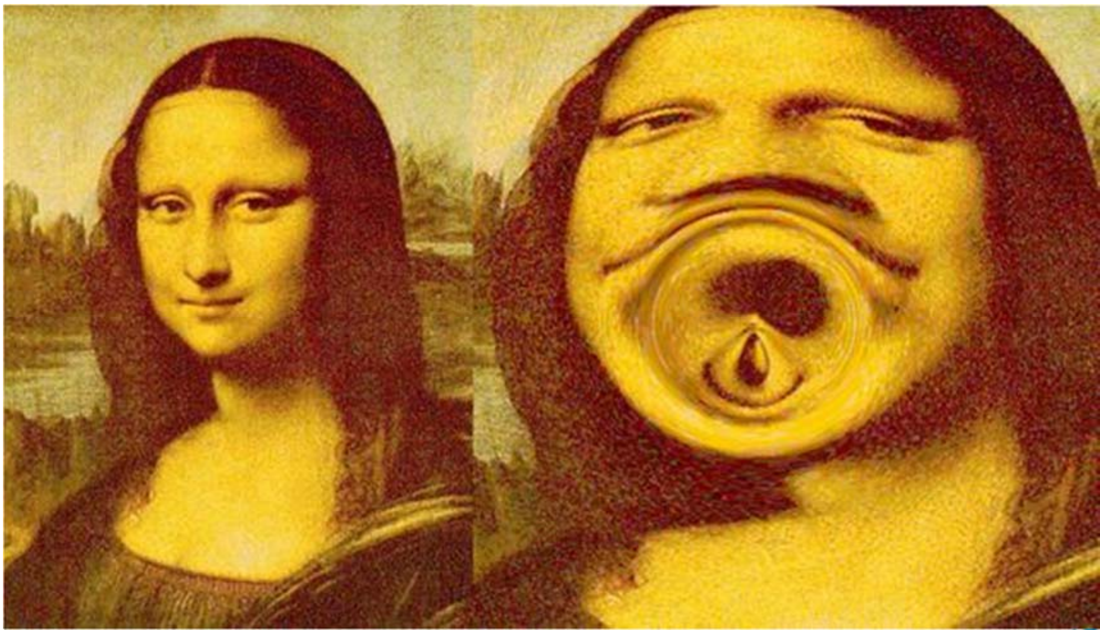
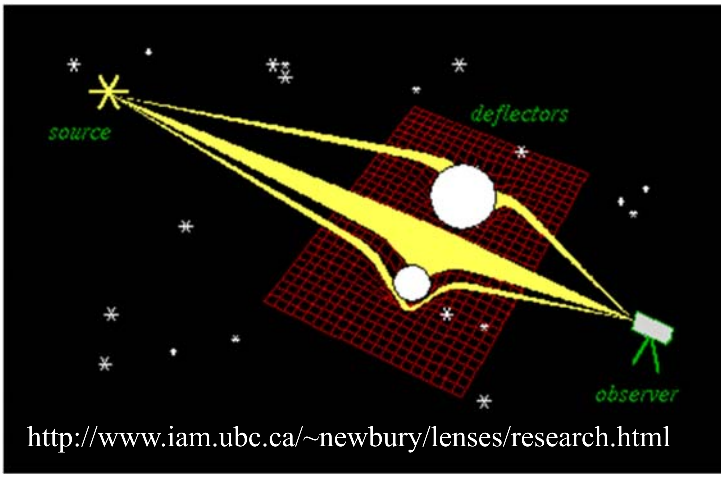
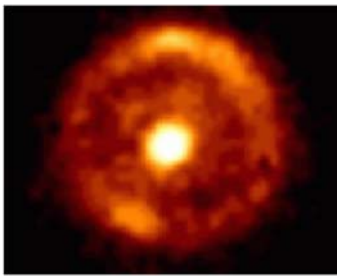


Gravitation distorts Images

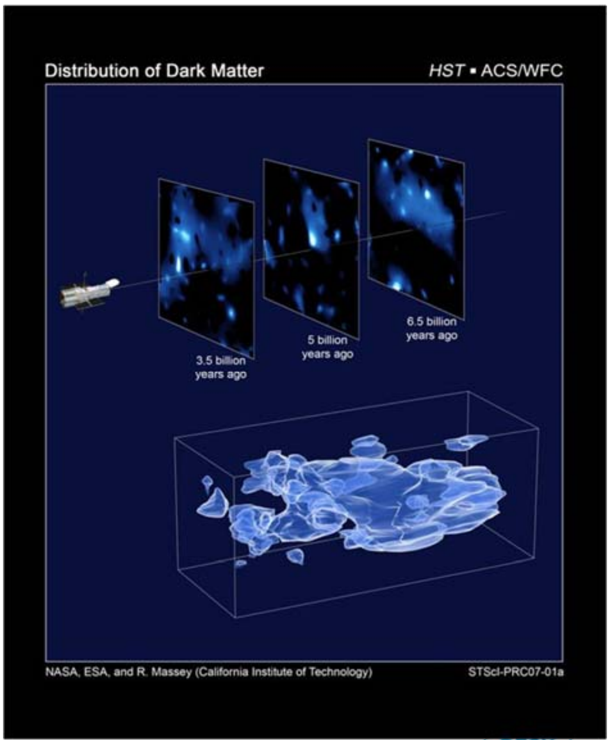




Gravitational lensing:

Derive mass of “lens” from properties of image .

Observational Evidence for Dark Matter (4)

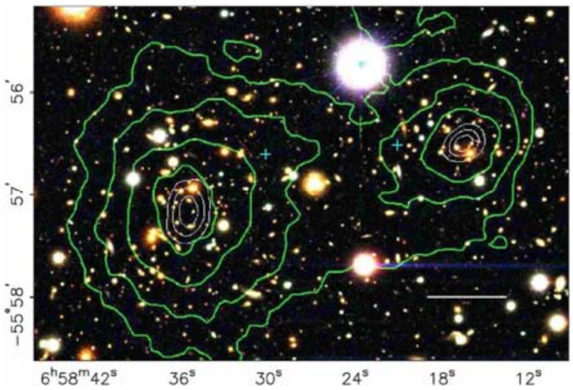


Dark Matter $\approx$ 30 · Luminous Matter

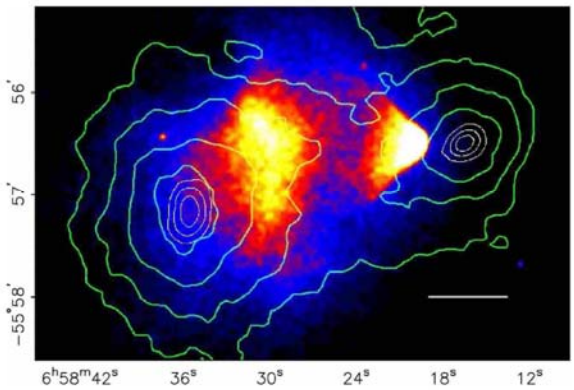
The Smoking Gun Observation (?)

Bullet cluster 1E 0657-56: merging of two galaxy clusters

(Clowe et al., astro-ph/0608407v1)

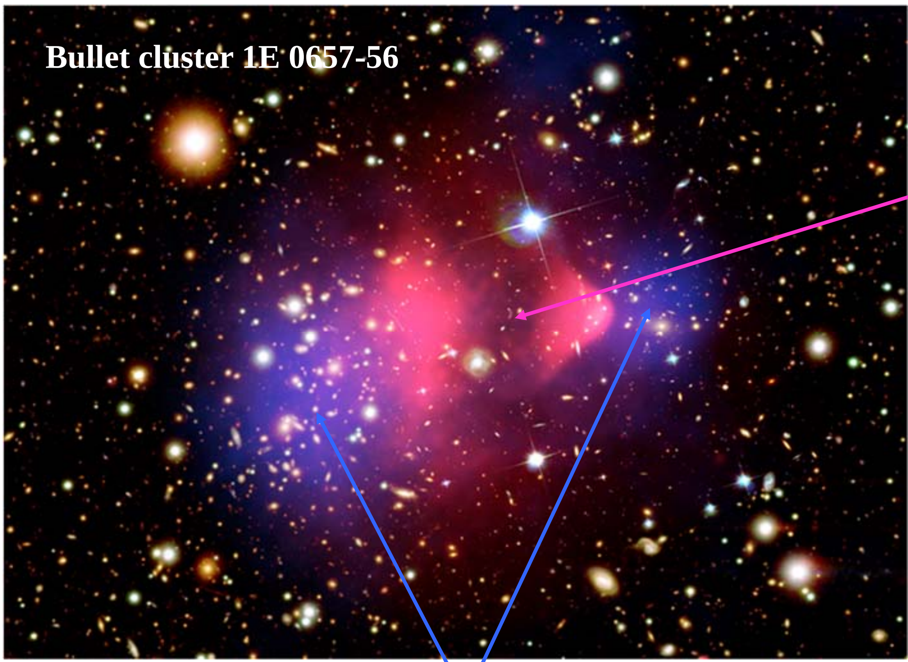


Contours from gravitational lensing

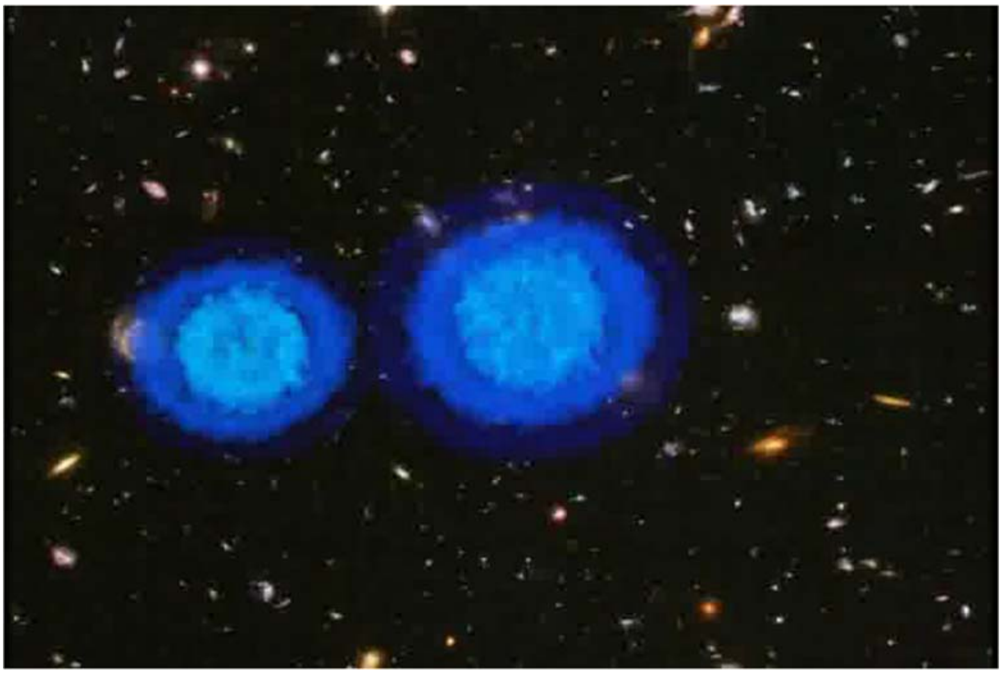


hot gas from X-rays

The Smoking Gun Observation (?)

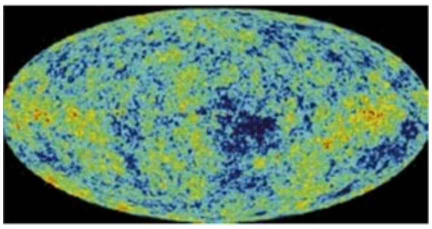


The Smoking Gun Observation (?)

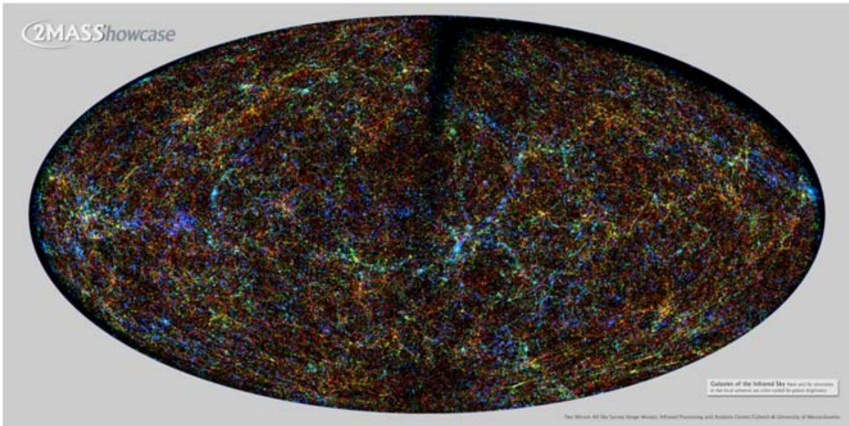


Further Evidences for Dark Matter

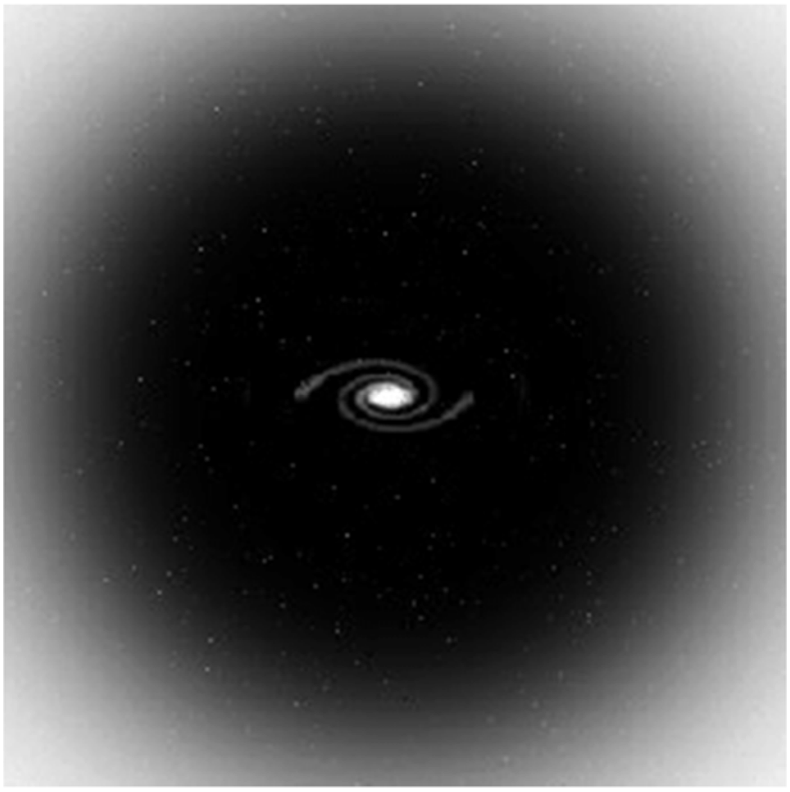
- Cosmic Microwave Background Radiation (CMBR) analyses



- Structure formation in the universe
  ➢ non relativistic “cold” dark matter is required as seeds for galaxies!



Model: Galaxies “swim“ in a Halo of Dark Matter



However, the detailed structure of such a halo is a matter of intense discussion!

Properties of the Dark Matter

> Dark Matter ≈ 30 · luminous matter (stars)

- Dark baryons (p, n) ≈ 5 · luminous matter
  (indirect observations (gas), big bang nucleosynthesis, CMBR)
- Unknown "dark" particles ≈ 6 · baryonic matter

  Only gravitational (and weak) interaction
  Should be non-relativistic ("cold")

These “dark” particles are not members of the Standard Model!

More dark Stuff: Dark Energy drives the Universe apart

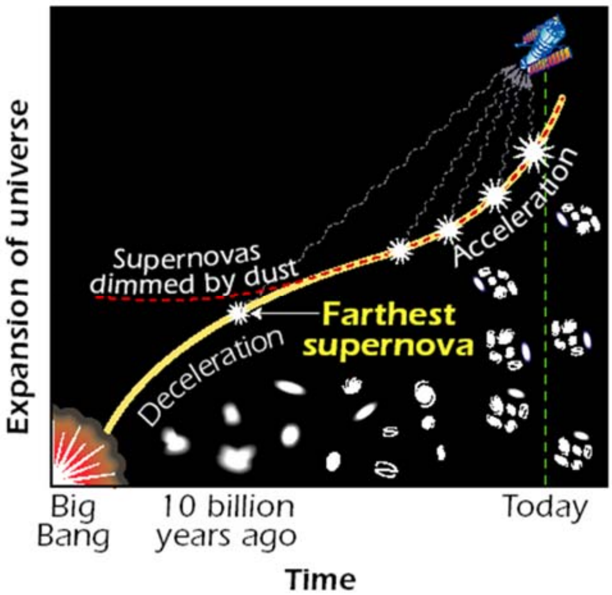
Measurements of Supernovae Ia by the Hubble Space Telescope (and others):

> There is a repulsive force ("anti-gravitation") best explained by “dark energy” (Einstein’s Λ)

> Dark energy is an attribute of space. Dark energy per volume is constant. The larger the universe, the larger the fraction of dark energy!

> The universe expands currently with increasing speed!

> This scenario is strongly confirmed by analyses of the Cosmic Microwave Background Radiation and many other data!



Precision Cosmology!

http://lambda.gsfc.nasa.gov/

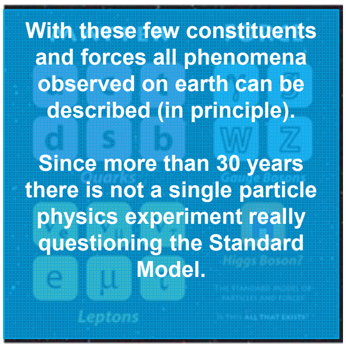
- Geometry of the Universe: flat
- Age of the Universe: 13.75   0.13 Gyr
- Hubble Constant: 71   3 km s^{-1} Mpc^{-1}
- Fluctuations compatible with inflation

- Ω_b (baryons): 0.045   0.003
- Ω_c (dark matter): 0.222   0.026
- Ω_Λ (dark energy): 0.734   0.029
- Early star light (re-ionisation): $\Omega_v << \Omega_{dm}$

Very good agreement among very different data (CMBR, supernova search with HST, galaxy counting, Big Bang Nucleon-synthesis, ...)

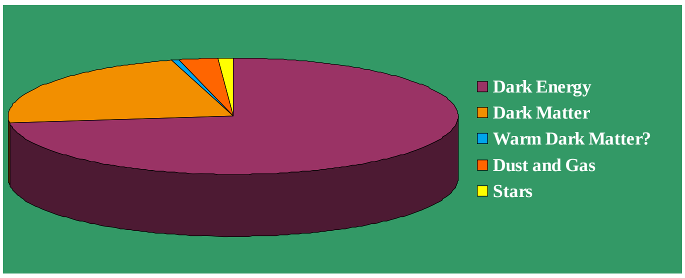
The Standard Model beyond Earth

The great success on earth:



is questioned by astrophysics and cosmology:

The Standard Model describes only 5% of the matter-energy content of the universe!



However: the dark stuff only shows up in gravitation!?

Discussion Time

> Why don't we notice dark matter and dark energy at earth?

> Are they real?

Dark Matter and Dark Energy in this Room

Why did physics overlook
Dark Matter and Dark Energy so long?

Densities in this room:

- Matter (earth's crust): 3 g/cm^3
- Dark Matter (DM): 0.0000000000000000000000005 g/cm^3
- Dark Energy (DE): 0.00000000000000000000000000001 g/cm^3

Why dominates matter here and DM und DE in the Universe?

- Matter is "clumpy", interacts strongly: planets are formed.
- Dark Matter interacts only very weakly: halos around galaxies.
- Dark Energy is distributed uniformly all over the universe.

Hitchhiker's Guide to the Galaxy

There is a theory which states that if ever anybody discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another theory which states that this has already happened.

Douglas Adams
English humorist & science fiction novelist (1952 – 2001)

Some Caveats on our Picture of a strange Universe

- The Copernican principle is used to interpret the data.
  - The Universe in our neighborhood is not special.

    Homogeneity (similarity in all regions of space)
    Isotropy (similarity in all directions).

  This principle is
  - compatible with observations (if you accept "Dark Energy"!),
  - **but fundamentally untested!**

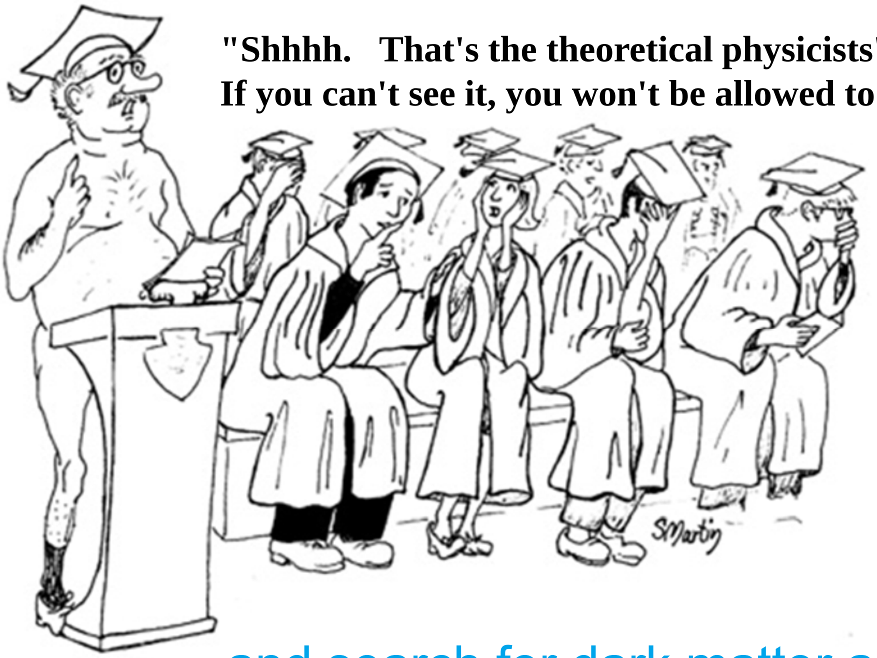
- Which is the relevant scale for homogeneity of the Universe?
  Does one have to take into account in-homogeneities when calculating cosmological parameters?

- Do we really understand gravity in the weak acceleration regime?
  - Globular clusters
  - Swing-by anomaly: J.D. Anderson et al., PRL 100, 091102 (2008)

For the time being …

… let's stick to the general accepted paradigm …

"Shhhh. That's the theoretical physicists' new particle uniform. If you can't see it, you won't be allowed to graduate."



http://www.softcom.net/users/greebo/laugh.htm

… and search for dark matter and dark energy.

Dark Matter Searches

> The Necessity of Dark Matter
  - Historical annotations
  - Dark Stuff in the Universe
  - What theory expects
> Dark Matter Scenarios
  - WIMPs
  - GeV Dark Forces
  - WISPs
> Towards a low Energy Extension of the Standard Model
> Dark Matter Searches
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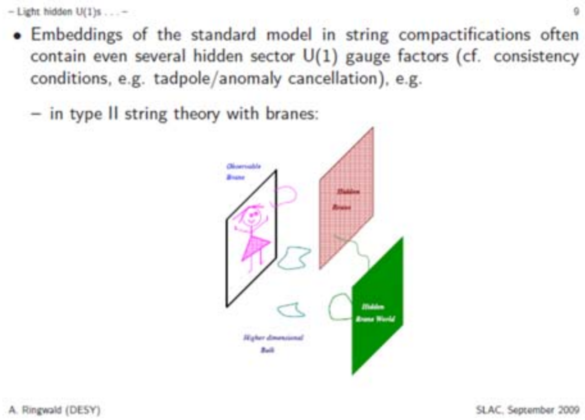
What Theory tells …

A *hidden sector* of particle physics could exist very well:

These particles would be uncharged with respect to electroweak and strong interactions and hence appear to be “dark”.

> The unification of forces requires extended gauge structures which led to singlets charged under some new gauge group. Thus GUTs or string theories can‘t avoid a hidden sector.



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> The unification of forces requires extended gauge structures which led to singlets charged under some new gauge group. Thus GUTs or string theories can‘t avoid a hidden sector.

> Gauge hierarchy problem:
how could one understand the huge difference between the electroweak scale of 10^2 GeV and the Planck scale of 10^{19} GeV?
A hidden sector introducing a dynamical SUSY breaking could take care for this.

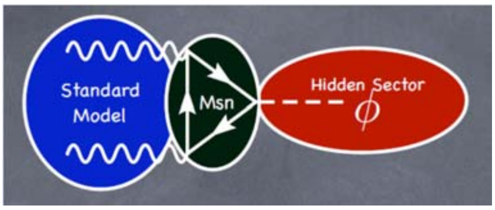
> There could be complex physics within the hidden sector with new forces and charges.

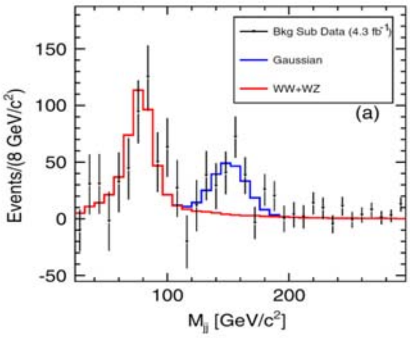
What Theory tells …

Particles from a *hidden sector* could interact in different manners with Standard Model particles:

> By gravitation (dark matter in the universe).

> By heavy messengers charged under the Standard Model and the hidden sector.



> 

CDF, Phys. Rev. Lett. 106, 171801 (2011)

Standard Model particles could be charged also under the hidden sector.
This would result in fifth forces.

In-Between-Summary

> Dark Stuff has paved the way to fundamental discoveries in the past.

> Dark Stuff is "seen" copiously in the universe.

> Dark Stuff is expected by numerous theories.

> Where to look for dark matter and dark energy?

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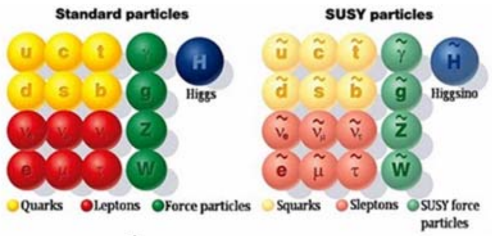
Dark Candidates

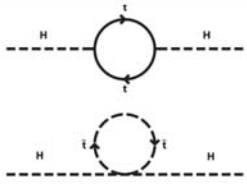
THE WIMP SCENARIO

SUSY and the Standard Model (Reminder)

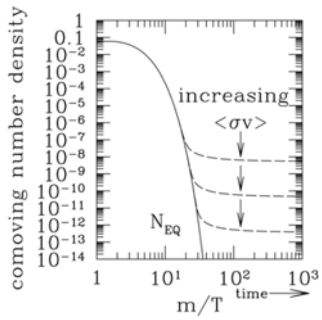
> Symmetry between bosons and fermions.



> Divergences cancel without fine tuning (if masses are sufficiently close).



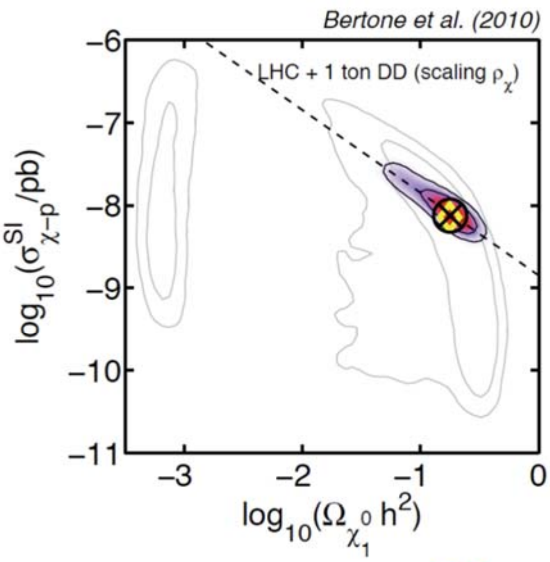
> The lightest SUSY particle is a **good dark matter candidate**.



SUSY and the Standard Model (Reminder)

> If the lightest SUSY particle makes up the dark matter in the universe

- the cross section is on the scale of weak interaction
- its mass is on the scale of weak interaction



> Weakly Interacting Massive Particle (WIMP)!

> Could be identified by combined data:

- LHC (measuring the mass)
- Direct dark matter detection (measuring the cross section and abundance)

> The WIMP scenario starts to get difficult, if LHC does not see evidence by 2012.

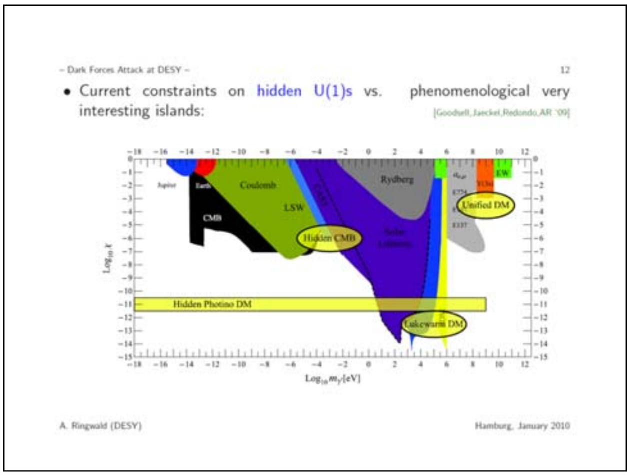
> **No clue on dark energy!**

Dark Candidates

THE GEV SCENARIO

GeV Dark Forces

> Hidden photons could explain dark matter.



GeV Dark Forces

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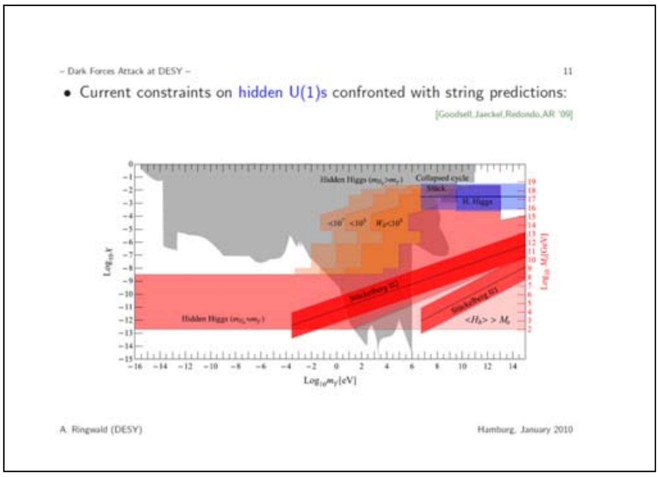

> Large parameter space to be probed by future experiments.

> **No clue on dark energy?**

Dark Candidates

THE LOW MASS SCENARIO
WISPS

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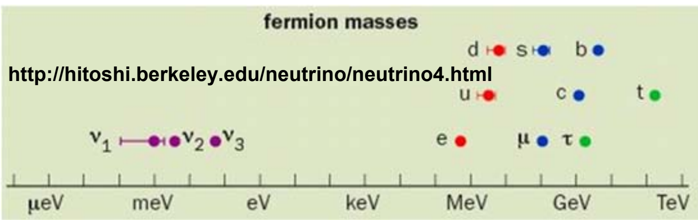
A Window beyond the Standard Model?

> In the Standard Model neutrinos are massless.

> Experiments have shown that they have masses in the meV scale.

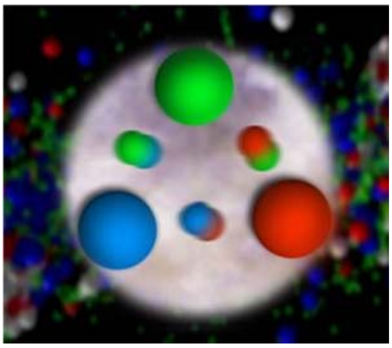


> At least one of the following SM extensions is realized in nature:
(see http://fejer.ucol.mx/dual/flavour_models_1.pdf):
  - There are right-handed neutrinos.
  - There is a different Higgs mechanism coupling also to right handed singlets.
  - There are non-renormalizable terms added to the Standard Model.
  - ….?

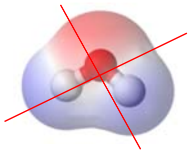
A Flaw in the Standard Model?

The neutron has a strange property:

It consists of three charged quarks, but does not show any static electric dipole moment.



http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html



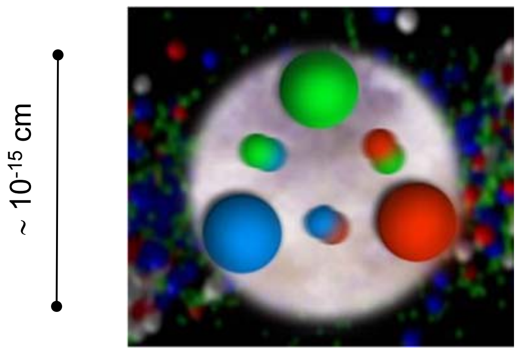
http://en.wikipedia.org

Why do the wave functions of the three quarks *exactly* cancel out any observable static charge distribution in the neutron?

A Flaw in the Standard Model?

Naively one expects for the neutron electric dipole moment:

$d_{n\text{-}QCD} \sim 10^{-15}$ e·cm.



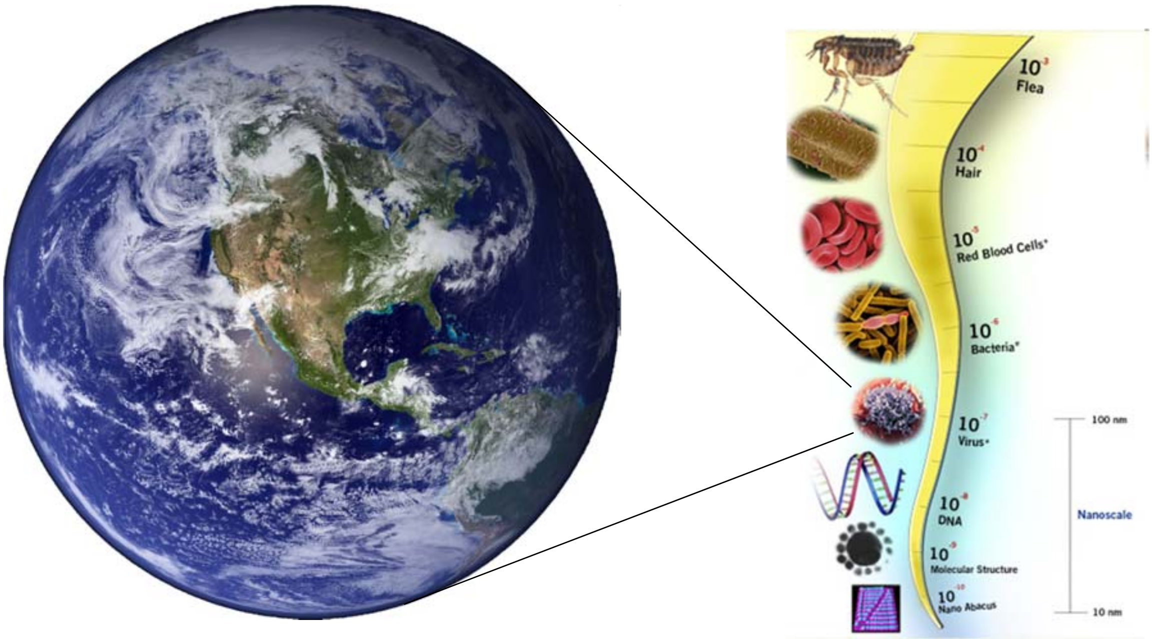
http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html

The data show: $d_{n\text{-}data} < 10^{-26}$ e·cm!

How to explain the difference of at least 11 orders of magnitude?

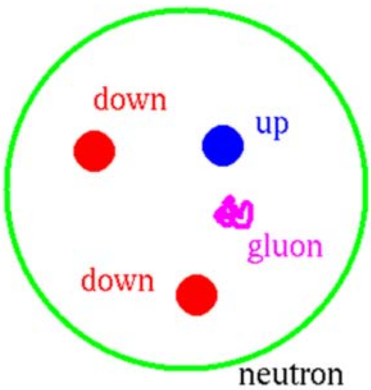
Eleven Orders of Magnitude

… expecting a planet and finding the nanoscale …



Discussion Time

> The neutron electric dipole moment and C, P, and T



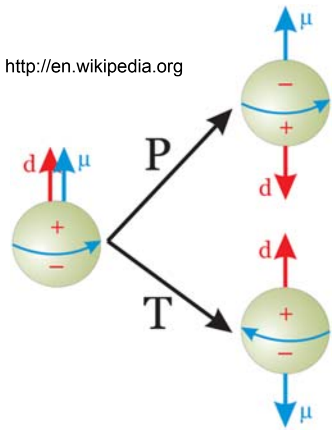
> C·P violation and matter – antimatter differences.

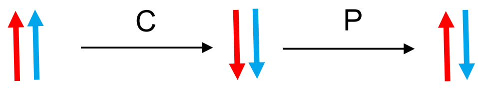
A Flaw and fundamental Properties of Nature

Electric and magnetic dipole moments of the neutron are related to fundamental symmetries:

> P (parity), T (time reversal)
  and C (charge conjugation) .

http://en.wikipedia.org





Neutron Antineutron Antineutron

If the neutron has an electric dipole moment
in addition to the measured magnetic dipole moment, C·P is not conserved.
Both moments would change from parallelism to anti-parallelism.

The strong interaction conserves CP $\leftrightarrow$ no neutron electric dipole moment

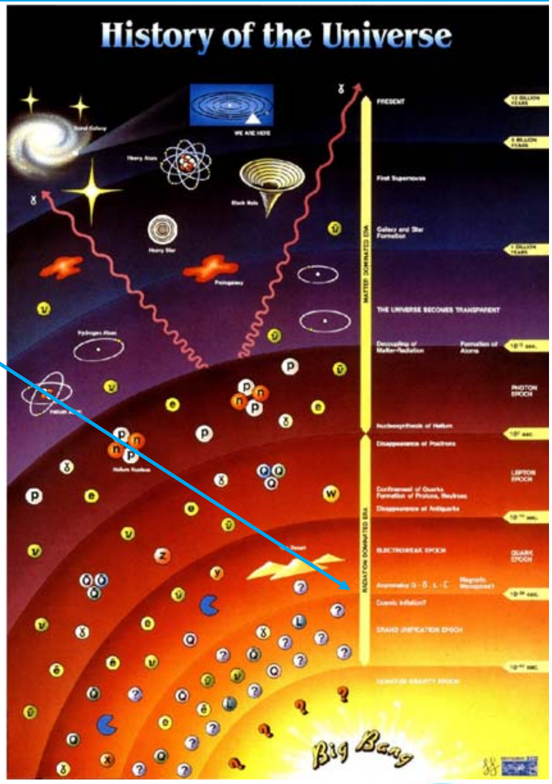
Detour: C·P is not only an academic Question!

C·P violation is essential to explain

why matter and antimatter did not annihilate completely about 10^{-34}s after the Big Bang

and hence essential to explain

our existence!



Unfortunately:

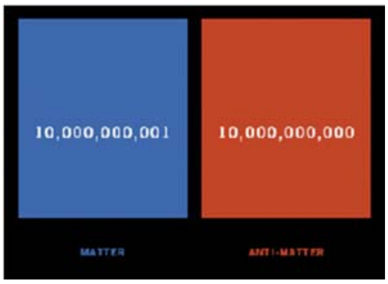
> C·P violation in weak interaction is much too weak for an explanation.

> QCD could do the job, but experiments show that QCD conserves C·P!

We still don't know, why we are here.

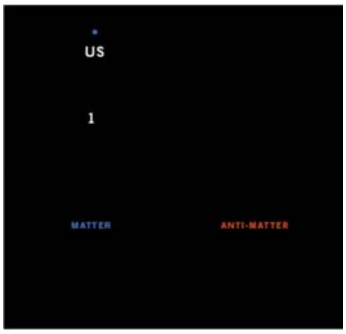
C·P, the Big Bang and us

> In the early universe matter and antimatter were produced in slightly different amounts. This requires <u>C·P violation!</u>



http://kellyoakes.wordpress.com/2010/07/29/why-do-we-need-the-lhcb/

> Most of matter and antimatter annihilated, only the tiny matter excess remained (0,00000001%):



This is the origin of everything we know of.

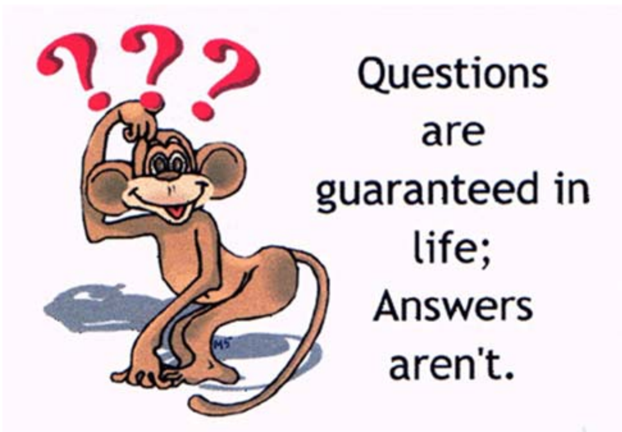
Questions

> What is the origin of C·P violation?

Not here, not now ….

> Why does QCD conserve C·P?

Let's try this first …



Two Possibilities

- The vanishing electric dipole moment of the neutron is just accidental. The parameters of QCD are “fine-tuned”, nothing remains to be explained.
  A physicist’s nightmare:

“I had the dream about meaningful employment again last night.”

- Can one think of any explanation? If yes, how to confirm this?

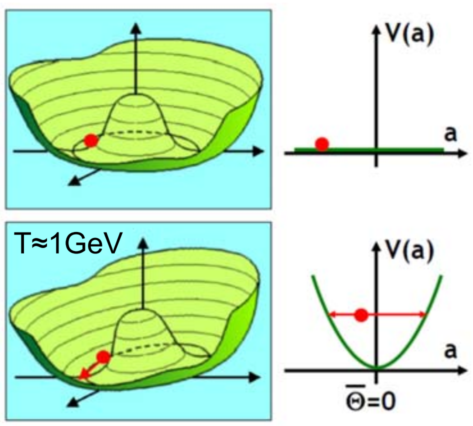
From a Flaw to a new Particle

The size of the neutron electric dipole moment is described by a angle Θ in QCD. There are no theoretical bounds on Θ, but from the missing neutron dipole moment $\Theta < 10^{-9}$ is concluded.

Is this a “just-so”, a “fine-tuning” of QCD? This would be very unsatisfying.

The theoreticians approach:
try to find a dynamic explanation!

<u>Peccei-Quinn 1977:</u>
Θ takes an arbitrary value by spontaneous symmetry breaking at a certain high energy scale f_a and roles down by non-perturbative QCD effects to its very small value observed in QCD at low energies.



S. Hannestaad, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

From a Flaw to a new Particle: the Axion

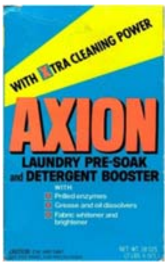
Wilczek and Weinberg independently noticed 1978:

The oscillations of Θ constitute an axion-field (christened by Wilczek).

Summary:

One can explain the vanishing electric dipole moment of the neutron in QCD if a new particle, the axion, exists.

The axion “cleans” QCD.



άξιον = worthy, deserving

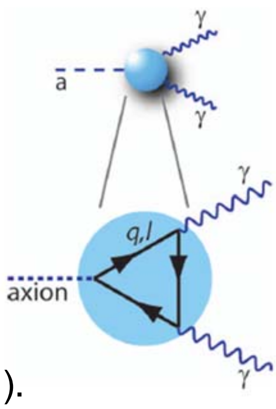
Properties of the QCD Axion

> The axion behaves like a light cousin of the π^0. It couples to two photons.

> Mass and the symmetry breaking scale f_a are related:
$m_a = 0.6\text{eV} \cdot (10^7\text{GeV} / f_a)$

> The coupling strength to photons is
$g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (\pi \cdot f_a)$, where g_γ is model dependent and O(1).

> The axion abundance in the universe is
$\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6}$.



The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

The QCD Axion and Dark Matter

> The axion abundance in the universe is $\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6}$.

> Take $\Omega_a / \Omega_c \sim 0.1$:

- $f_a = 10^{11}$ GeV
- $m_a = 10^{-5}$ eV
- $g_{a\gamma\gamma} = 10^{-13}$ GeV^{-1}

> Searching for ultra-light particles probes physics at extremely large energies!

From Axions to ALPs and WISPs

There might be much more than a QCD axion:

> ALPs: "axion-like particles"

String Axiverse
A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell,
arXiv:0905.4720 [hep-th]
String theory suggests the simultaneous presence of many ultralight axions, possibly populating each decade of mass down to the Hubble scale 10^{-33}eV. Conversely the presence of such a plenitude of axions (an "axiverse") would be evidence for string theory, ...

> WISPs, Weakly Interacting Slim Particles,
(axions and ALPs, hidden sector photons, mini-charged particles) occur naturally in string-theory motivated extensions of the Standard Model

Naturally Light Hidden Photons in LARGE Volume String Compactifications
M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald,
arXiv:0909.0515 [hep-ph], JHEP 0911:027,2009
Extra "hidden" U(1) gauge factors are a generic feature of string theory that is of particular phenomenological interest. They can kinetically mix with the Standard Model photon and are thereby accessible to a wide variety of astrophysical and cosmological observations and laboratory experiments.

In-Between-Summary

> Dark Stuff has paved the way to fundamental discoveries in the past.

> Dark Stuff is "seen" copiously in the universe.

> Dark Stuff is expected by numerous theories.

> Where to look for dark matter and dark energy?

- Essentially everywhere at all scales.
- Also due to LHC and other large scale facilities the SUSY / WIMP scenario has been studied best.
- My personal judgment: the low mass scenario is particular attractive.

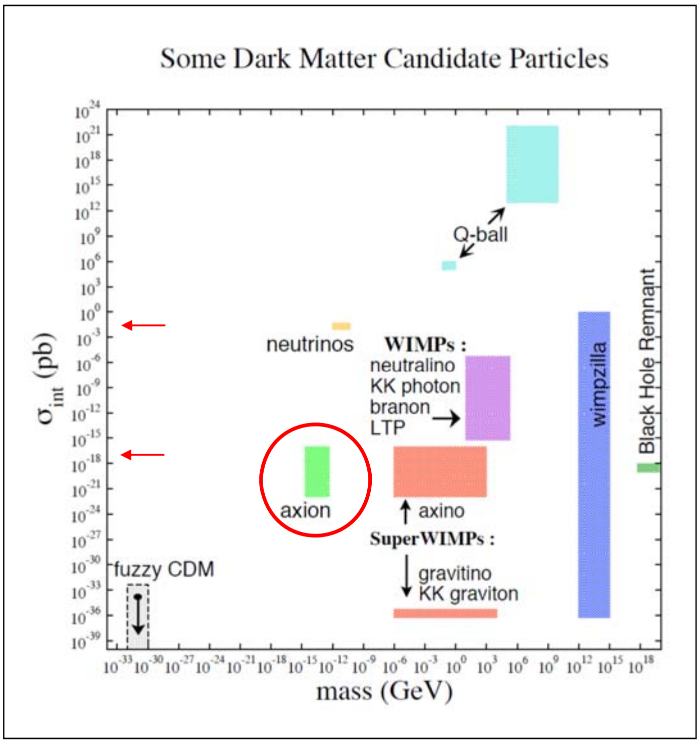
  - Neutrino masses point at new phenomena at the meV mass scale.
  - A light weight axion might explain properties of QCD and could be a dark matter.
  - Dark energy could be explained by meV scale scalar fields.

The prime DM Candidates

1. Weakly Interacting Massive Particles: WIMPs
   Most promising candidate: lightest supersymmetric particle (neutralino, a linear combination of photino, zino and higgsinos, to be found at LHC?),
   very heavy (around 10^{11}eV).

2. Axion or Axion Like Particles: ALPs
   Invented to explain CP conservation in QCD ("why is the electric dipole moment of the neutron zero or extremely small?").
   Non-thermal production in the early universe,
   very light (around 10^{-5}eV).

Dark Matter could be Axions!



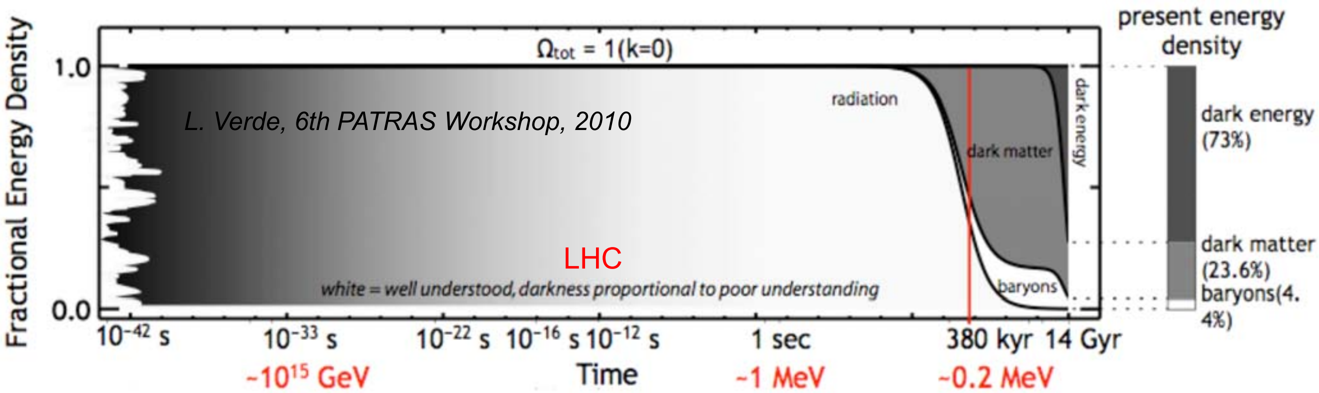
Due to their non-thermal production in the universe light axions would constitute *cold* dark matter.

Such axions couple extremely weakly to matter: the “invisible” axion.

The axion was *not* invented to solve the Dark Matter problem!

H. Baer, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

LHC and the present Universe

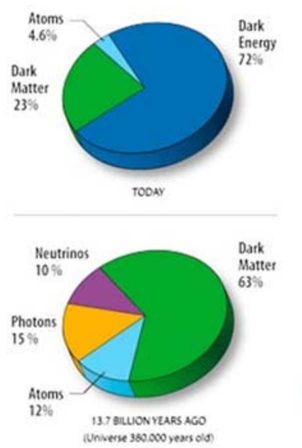


> LHC probes the very early universe when it was very small, hot and dense.

> Dark energy was totally negligible at those times.

> Surprisingly, we understand the early universe from fractions of a second to minute scales better than today’s universe.

> Dedicated “low energy” experiments are required to get a clue on Dark Energy.



Dark Matter Searches

> The Necessity of Dark Matter
  - Historical annotations
  - Dark Stuff in the Universe
  - What theory expects

> Dark Matter Scenarios
  - WIMPs: Weakly Interacting Massive Particles
  - GeV Dark Forces
  - WISPs: Weakly Interacting Sub-eV Particles

> Towards a low Energy Extension of the Standard Model

> Dark Matter Searches
  - Direct Dark Matter Searches
  - The Any-Light-Particle Experiment at DESY

> Outlook and Summary

Dark Matter Searches

> Astrophysics
  - Indirect:
    via gravitational effects
    searches for decay products (GeV photons, neutrinos)
  - Direct:
    Detection of dark matter particles in dedicated detectors

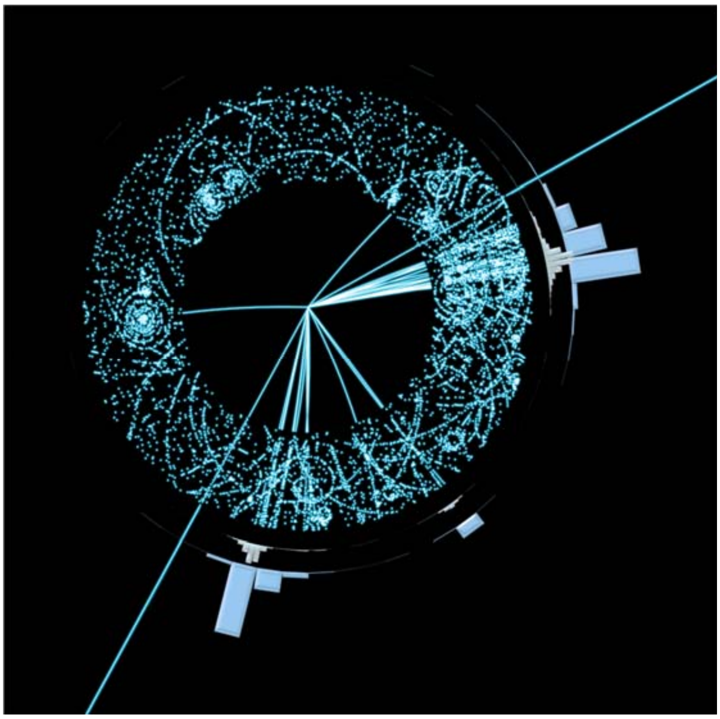
> Laboratory
  - WIMP candidate searches at colliders
  - WISP candidate searches:
    the ALPS experiment at DESY and future prospects.

WIMP Searches at Colliders (Reminder)

> A supersymmetric event at ATLAS:

Something is missing: a WIMP candidate?

> Difficult to determine:
  - Cross section
  - Life time



http://www.atlas.ch/photos/events-simulated-supersymmetry.html

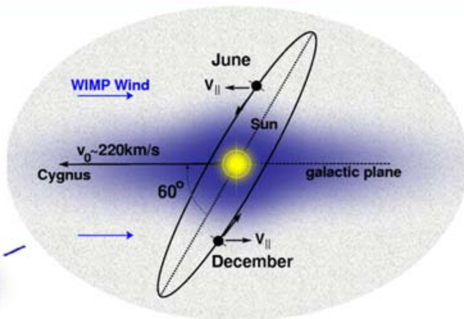
Direct Detection of Dark Matter WIMPs

Basic Idea:

> The earth moves through the WIMP halo.

> WIMPSs scatter elastically on nuclei.

> Measure nuclear recoils



Experimental challenge:

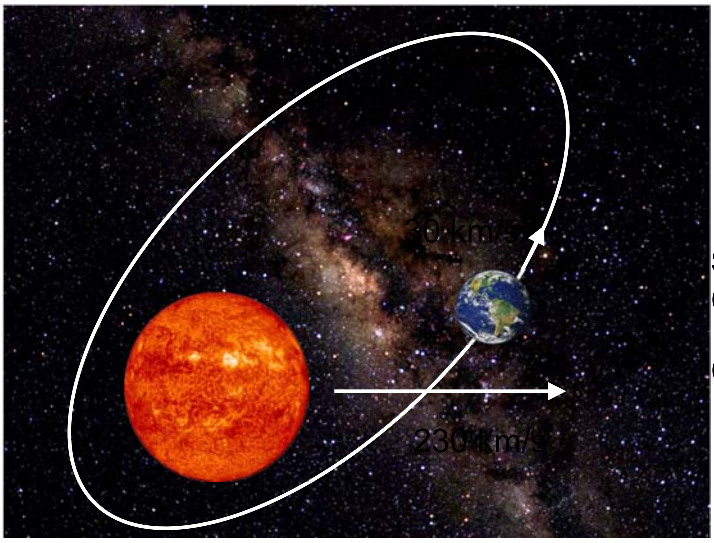
> WIMPS mass: 45 GeV to TeV (≈ mass of nuclei)

> Relative speed (earth - WIMP in galactic halo): 250 km/s
  ↳ kinetic energy ≈ keV

> Very low cross sections: $\sigma_\chi < 10^{-40}$ cm^2 = 10^{-4} pb ≈ $10^{-14}\,\sigma_{pp}$

> Local density ≈ 0.3 GeV / cm^3
  ↳ Event rate < 0.1 / day / kg (10^{-6} Hz / kg)

The "smoking Gun" of WIMP Detection

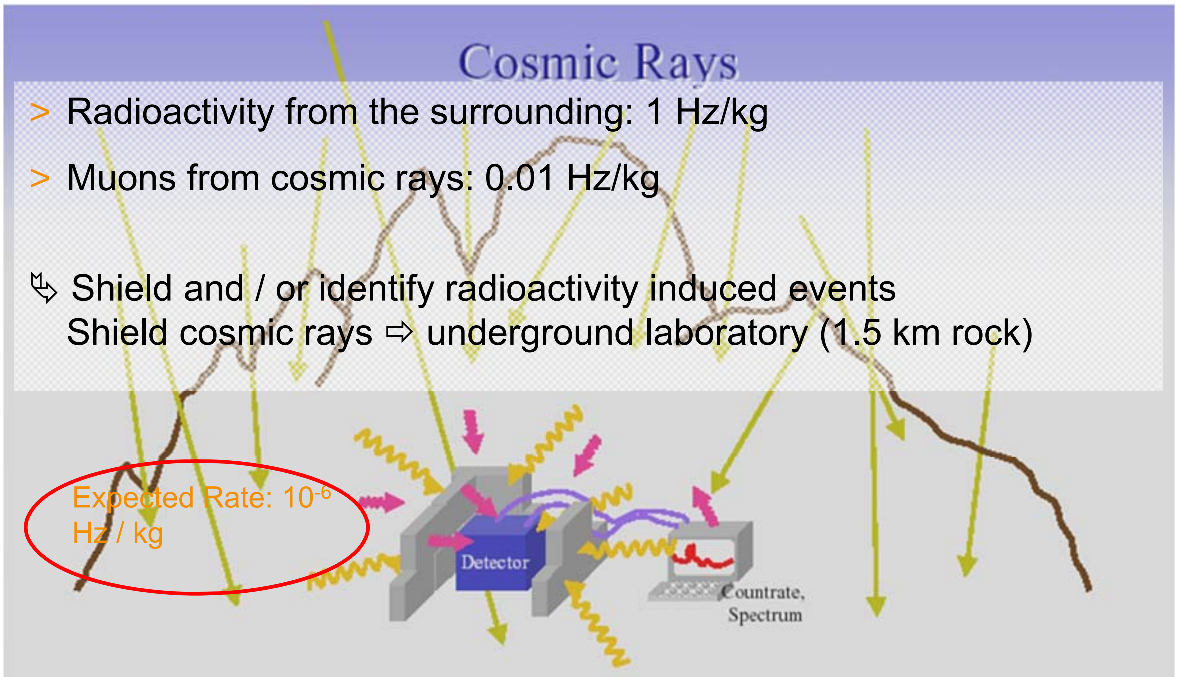


Speed relative to WIMP halo:
(230   15) km/s

(10^4 to 10^6 WIMPs/cm^2/s)

Due to varying speed of earth relative to galactic halo:
7% annual modulation of WIMP detection rate

Basic Detector Considerations



- Radioactivity from the surrounding: 1 Hz/kg
- Muons from cosmic rays: 0.01 Hz/kg

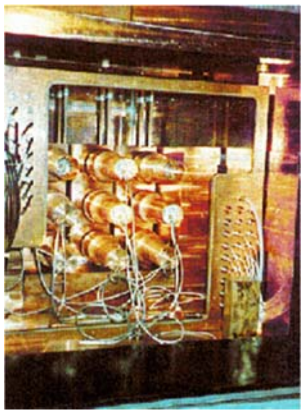
↳ Shield and / or identify radioactivity induced events
Shield cosmic rays ⇨ underground laboratory (1.5 km rock)

Expected Rate: 10^{-6} Hz / kg

DAMA/LIBRA: a "classical" Experiment

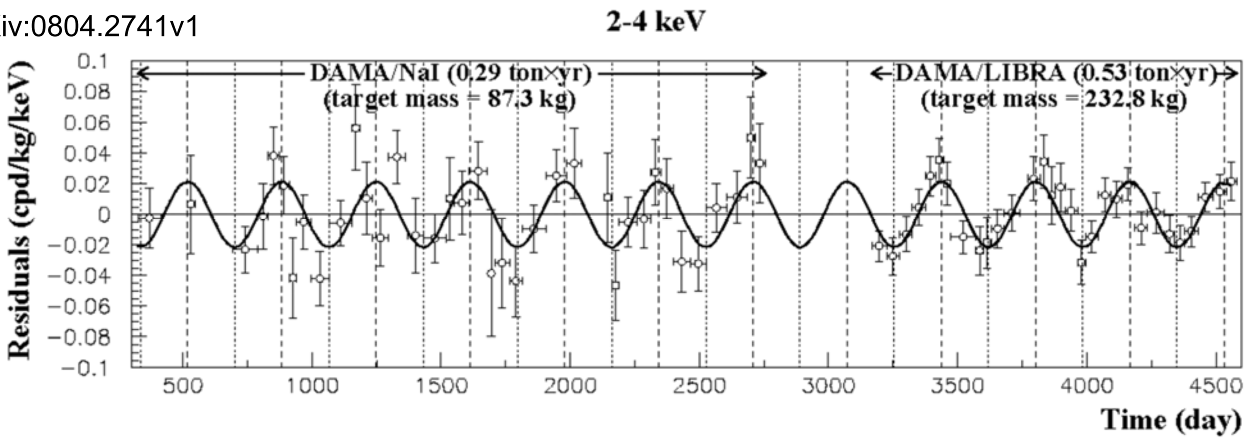
Detection of scintillating light from recoiled nuclei

- Large mass (240 kg NaI(Tl) detectors), careful shielding of radioactivity and cosmic muons
- No event-by-event background / signal identification



DAMA/LIBRA: Evidence for WIMPs?

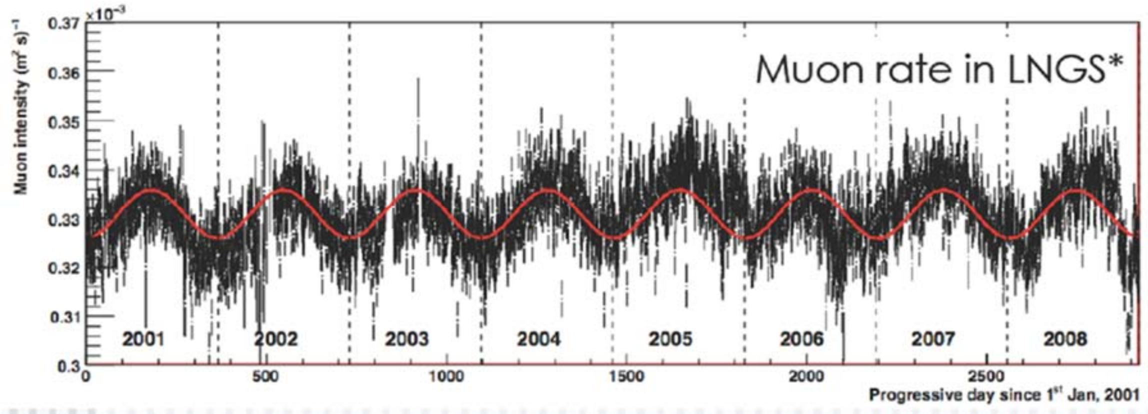
arXiv:0804.2741v1



Annual modulation!

Results (model dependent): $M_\chi \approx$ 15-100 GeV, $\sigma_\chi \approx 10^{-5}$ pb

DAMA/LIBRA: WIMPs or Background?

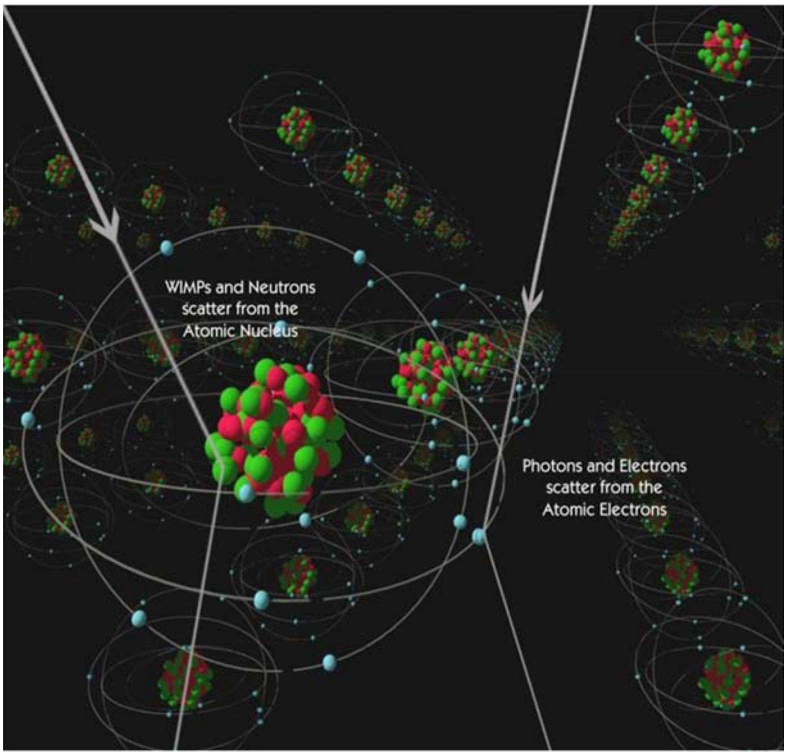


The muon rate at LNGS shows a similar annual modulation!

Is the background rellay under control?

Need new experimental approaches to reduce backgrounds.

New Experiments with Background Rejection



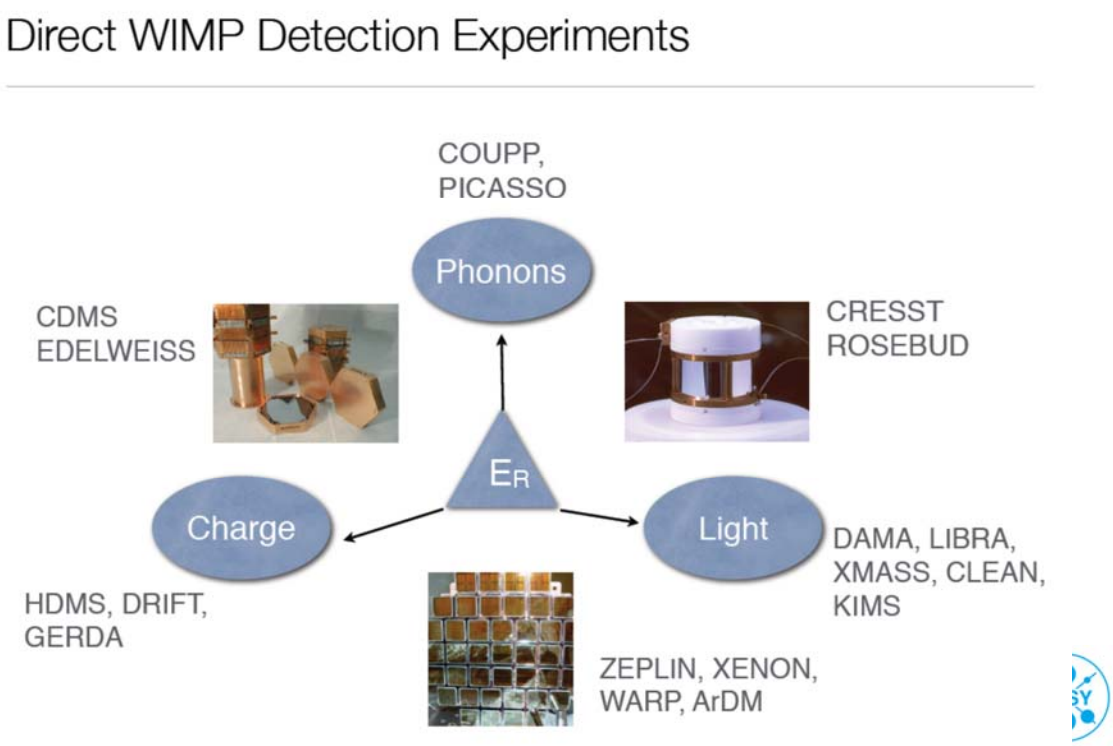
If ionisation could be measured (charge, scintillating light):

Distinguish em. radiation and nuclear recoils by the ratio

E(phonon)/E(ion.)

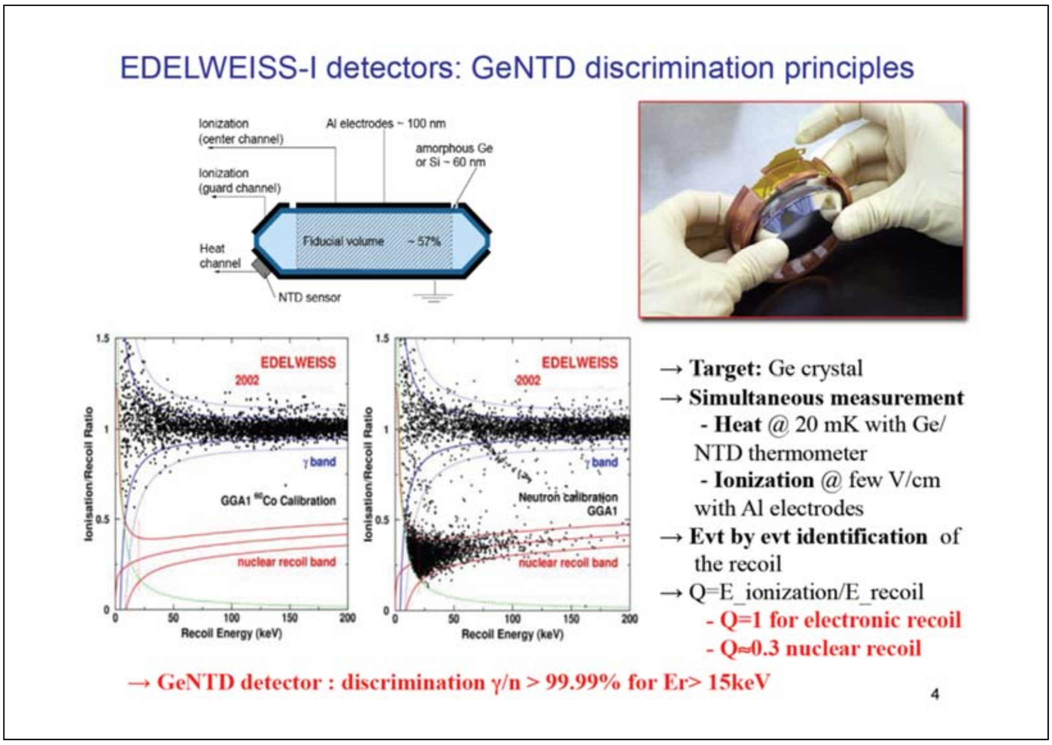
New Experiments with Background Rejection

Presentation by L. Baudis, Patras 2007, http://axion-wimp.desy.de



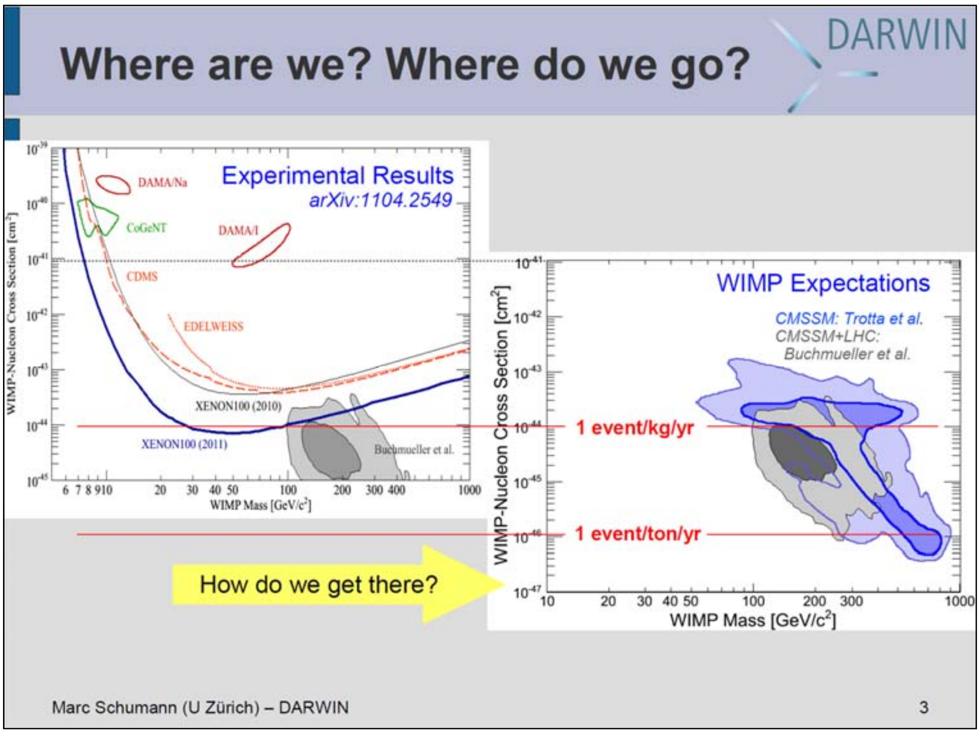
The EDELWEISS Experiment

Presentation by J. Gironet, Patras 2011, http://axion-wimp.desy.de



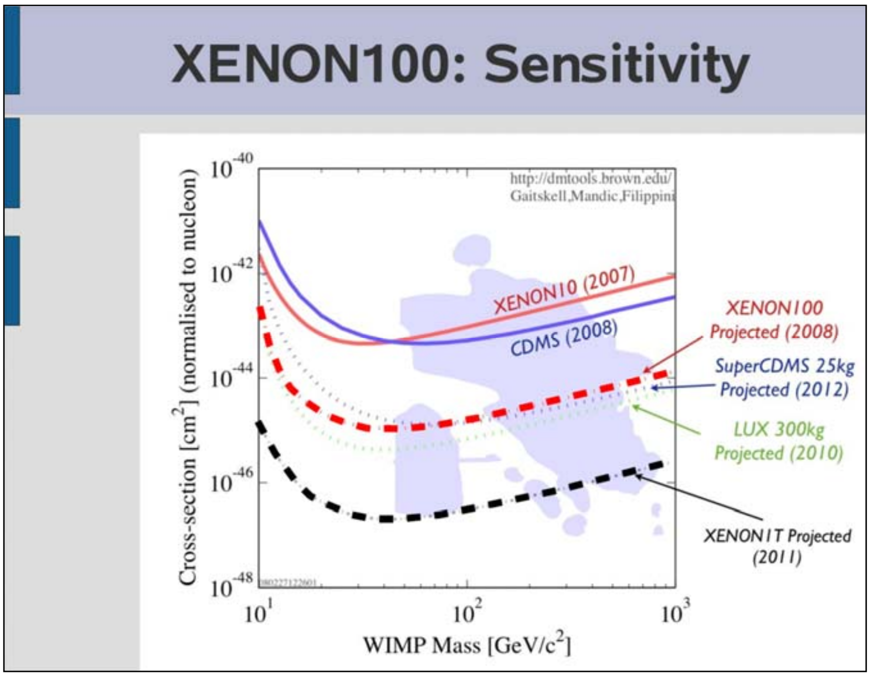
Summary of direct Dark Matter WIMP Searches

Presentation by M. Schumann, Patras 2011, http://axion-wimp.desy.de



Some Years ago …

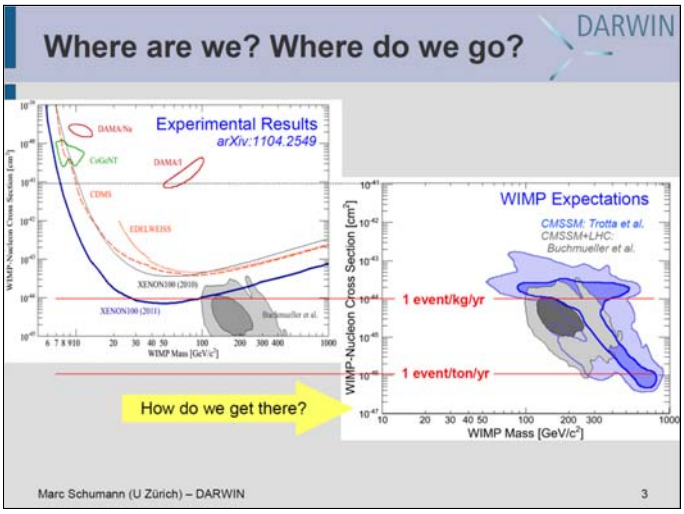
Presentation by M. Schumann, Patras 2008, http://axion-wimp.desy.de



- Dramatic improvements of detectors in the recent years.
- However, no stringent hint for WIMPs yet.
- Challenge: Get backgrounds under controll on a very detailed level!

WIMP Summary

Presentation by M. Schumann, Patras 2011, http://axion-wimp.desy.de



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- However, no stringent hint for WIMPs yet.
- Challenge:
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Are WIMPs fading away with new data from LHC and direct DM searches?

Dark Matter Searches

- The Necessity of Dark Matter
  - Historical annotations
  - Dark Stuff in the Universe
  - What theory expects
- Dark Matter Scenarios
  - WIMPs: Weakly Interacting Massive Particles
  - GeV Dark Forces
  - WISPs: Weakly Interacting Sub-eV Particles
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- Dark Matter Searches
  - Direct Dark Matter Searches
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- Outlook and Summary

Axions and WISPs

> The axion remains interesting as a
  - solution to the CP conservation of QCD,
  - candidate for Dark Matter.

> The might be a plenitude of Weakly Interacting Slim Particles
  - occurring naturally in string-theory inspired extensions of the Standard Model,
  - opening a window to physics beyond the TeV scale.

> Theory starts to develop detailed scenarios and predictions for WISPs to be probed by experiments.
  - Not only detections, but also upper-limits on WISP productions might become important ingredients for theory.

An Experimentalist's Motivation: Just Coincidences?

> Neutrinos have masses at the meV scale.

> The density of Dark Energy in our Universe is 10^{-29}g/cm^3, being equivalent to $\rho_{DE} \cong (2\ \text{meV})^4$.

The cosmological constant problem, *S. Weinberg*, Rev. Mod. Phys. 61, 1–23 (1989)	ute to the effective cosmological constant. In order to keep $\rho_V < 10^{-48}$ GeV^4, we need the scalar field adjustment to cancel the effect of gravitational and electromagnetic field fluctuations down to frequencies 10^{-12} GeV; for this purpose we must have $m_\phi < 10^{-12}$ GeV. A field this light will have a macroscopic range: $\hbar/m_\phi c \gtrsim 0.01$ cm.

> Today's energy density of the universe is about $(\text{meV})^4$.

Does this hint at new physics at the meV scale?

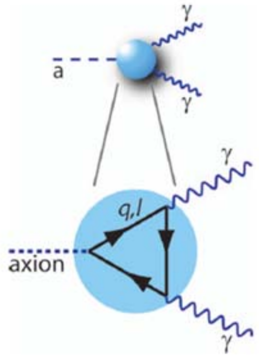
Presumably, LHC & Co. results will not explain these phenomena.

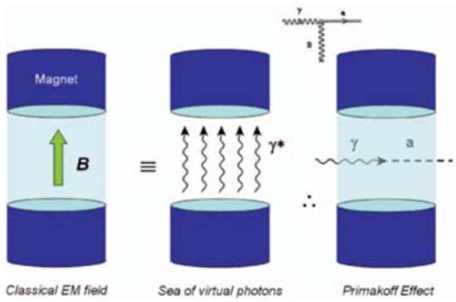
Let's strive for dedicated experiments!

How to search for “invisible” Axions: Primakoff Effect

- Axion and axion-like particles: exploit the coupling to photons.
- photon + photon ↔ ALP
  photon + ALP → photon
- photon + (virtual photon) → ALP
  ALP + (virtual photon) → photon

  A virtual photon can be provided by an electromagnetic field.

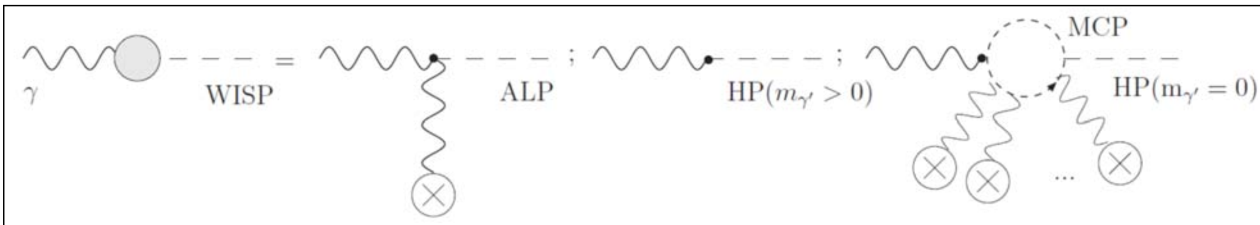




The Search for Axions,
Carosi, van Bibber, Pivovaroff,
Contemp. Phys. 49, No. 4, 2008

How to search for “invisible” WISPs: exemplary Basics

- Neutral scalar or pseudoscalar WISPs: exploit the Primakoff effect
- Neutral vectorbosons (“hidden sector photons” HP): exploit mixing with “ordinary” photons.
- Minicharged particles (MCP, about 10^{-6} e): “loop effects”.



Axion-Like Particles, *Hidden Photons,* *MiniCharged Particles*

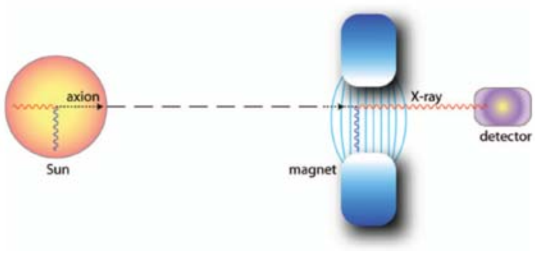
How to search for “invisible” WISPs: Astrophysics

> Indirect:
WISPs would open up new energy loss channels for hot dense plasmas

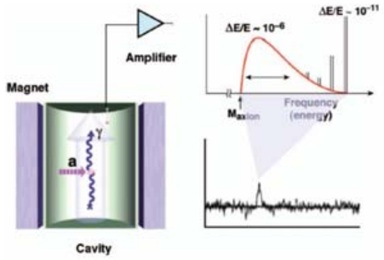
- stringent limits on WISP characteristics from the lifetime of stars, length of neutrino pulse from SN and cosmic microwave background radiation for example.

> Direct:

- Search for axions from the sun (CAST at CERN)



- Search for halo dark matter axions (ADMX at Livermore)



The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

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lhttp://cast.web.cern.ch

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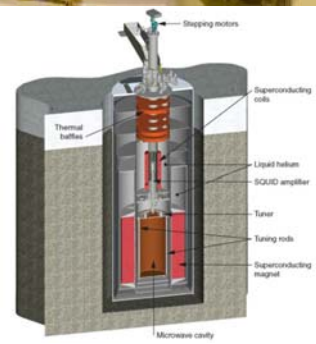
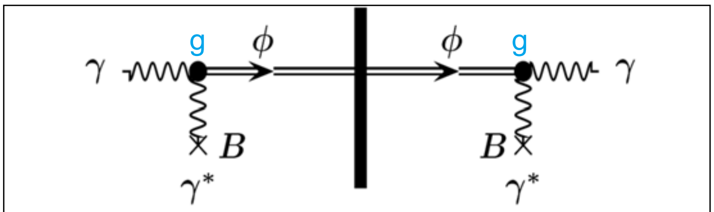


http://www.phys.washington.edu/groups/admx/home.htm

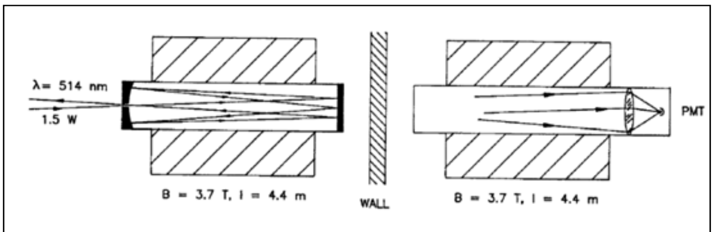
How to search for “invisible” WISPs: Lab Experiments

“Light-shining-through-a-wall” (LSW)



Okun 1982, Skivie 1983, Ansel‘m 1985, Van Bibber et al. 1987

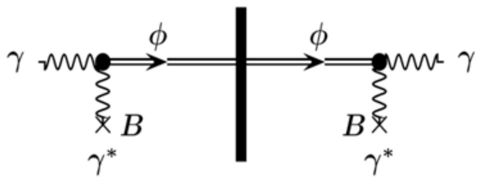
Note:
$P_{\gamma\to\Phi\to\gamma} \sim g^4$



G. Ruoso et al.
(BFRT Experiment),
Z. Phys. C 56 (1992) 505

Axion Production in a magnetic Field

> The production (and re-conversion) of WISPs takes place in a coherent fashion.

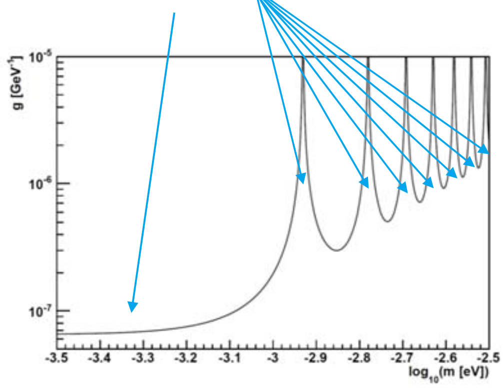


For ALPs (Φ):

$$P_{\gamma\to\phi}(B,\ell,q) = \frac{1}{4}\,(g\,B\,\ell)^2\;F(q\ell) \qquad F(q\ell) = \left[\frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}\right]^2$$

$q = p_\gamma - p_\Phi$
l: length of B field

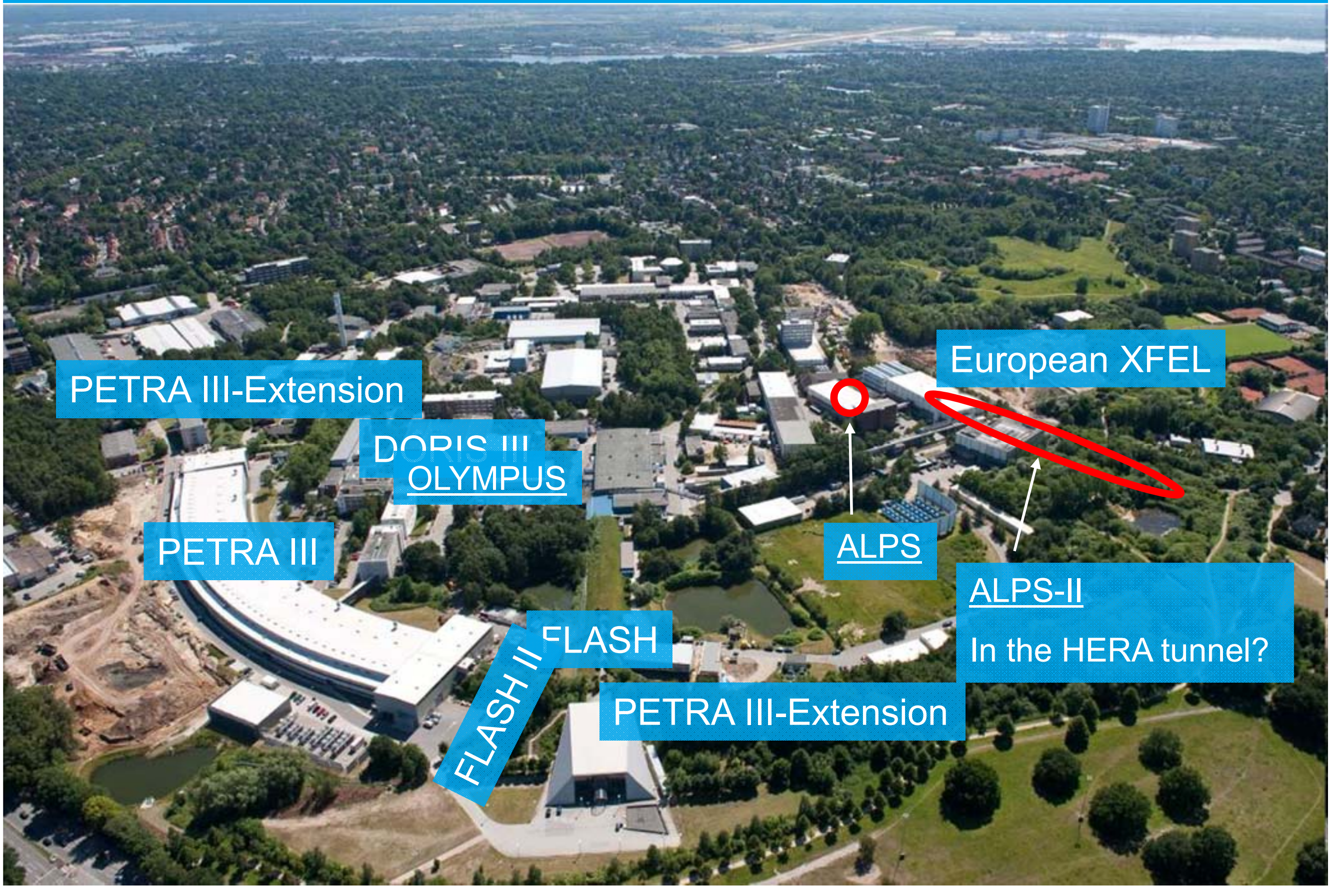
With $P_{\gamma\to\Phi} = P_{\Phi\to\gamma} = P$: $g = (P)^{1/4} \cdot 2 \cdot / (l\cdot B) / F^{1/2}$



Please take note:
P(B field) / P(beam dump) =
$10^6\cdot(\mathrm{mm}/\lambda_{abs})\cdot(B/T)^2\cdot(L/m)^2$

(A. Ringwald, J. Redondo, arXiv:1011.3741v1 [hep-ph])

ALPS @ DESY in Hamburg

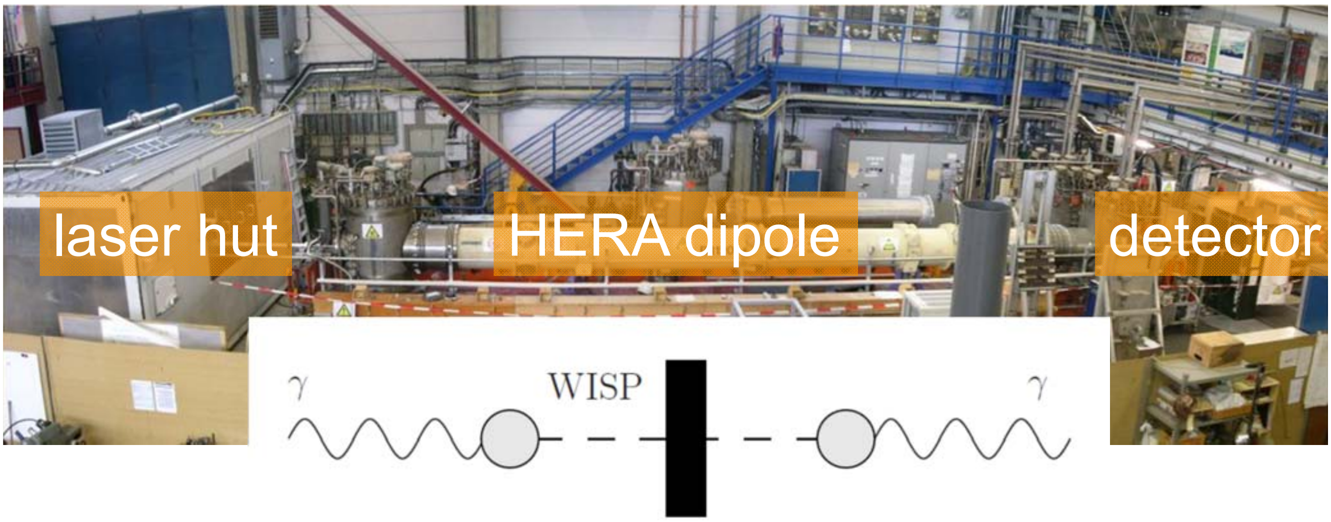


The ALPS Project

Axion-Like Particle Search @ DESY

The ALPS Project

Any Light Particle Search @ DESY



A "light-shining-through-a-wall" experiment

The ALPS Project

Any Light Particle Search @ DESY

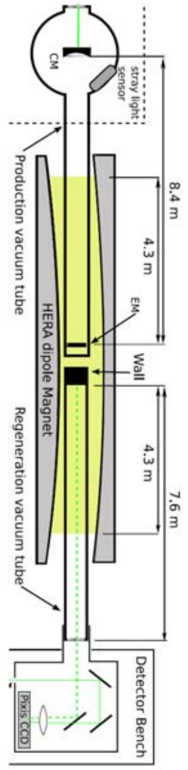
- DESY
- Max Planck Institute for Gravitational Physics (Albert Einstein Institute), and Institute for Gravitational Physics, Leibniz University Hannover
- Laserzentrum Hannover
- Hamburger Sternwarte

Three main ALPS Components

> Powerful laser:
optical cavity to recycle laser power
(high quality laser beam)

> Strong magnet:
HERA dipole: 5 T, superconducting

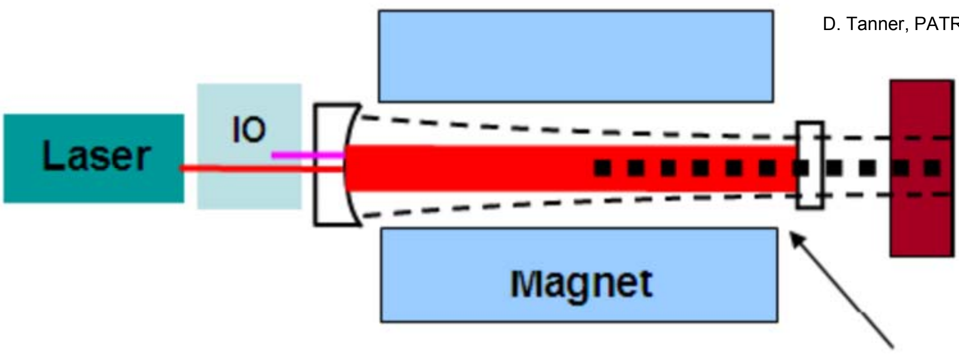
> Sensitive detector:
CCD
(determines wavelength of laser light!)



Tubes:
- diameter: 34 mm
- clear aperture: 14 mm

A powerful Laser System for ALPS

> Trick:
the light of a relatively low power laser with excellent beam characteristics is reflected back and forth inside the magnet,
the light is stored inside an optical resonator (cavity).

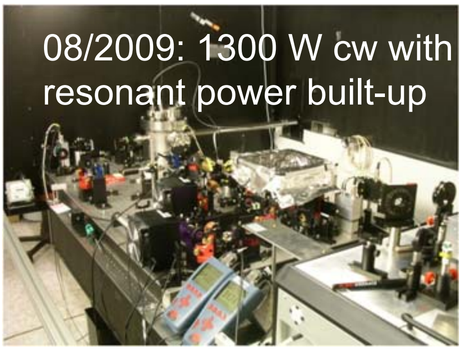


D. Tanner, PATRAS 2009

> ALPS succeeded to realize such a set-up for LSW for the first time
(doi:10.1016/j.nima.2009.10.102)

The ALPS Lasers

> Laser developments at ALPS from 2007 to 2009:



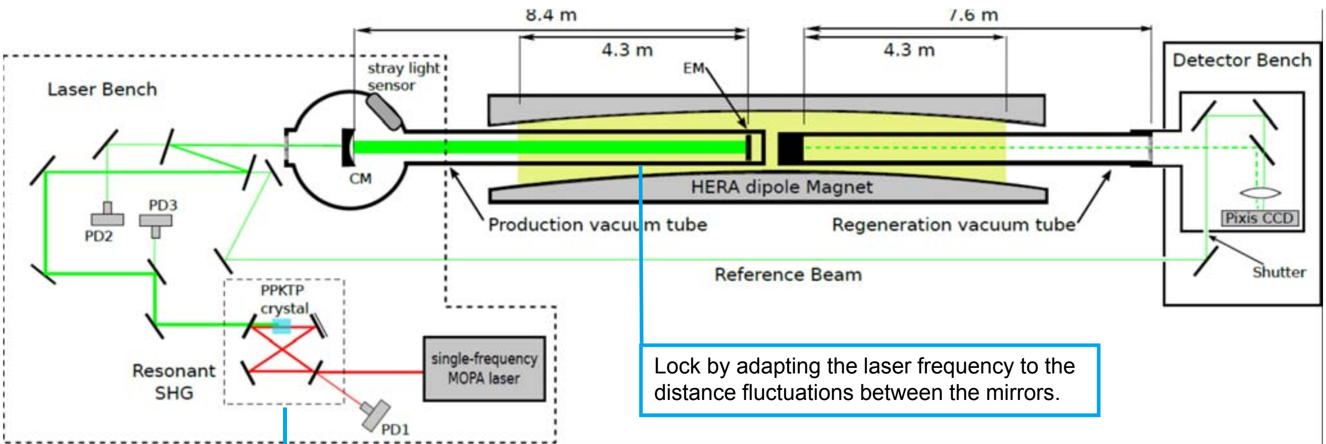
The 1300 W laser power is achieved from 4.4 W built-up in the resonator by a factor of 300.

The power is limited by the lifetime of the mirrors in vacuum (10-30 h) due to heating. However, a significant further improvement would also require investments into beam stabilization and new locking electronics.

1300 W is much more than we ever dreamt of!

The ALPS Laser System

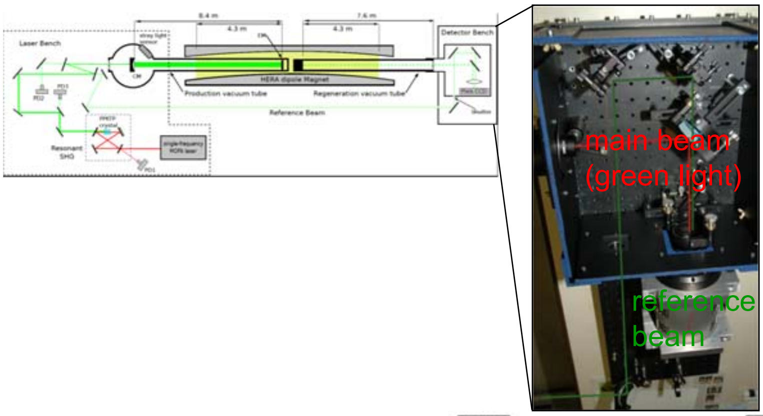
> We are running a quite complex and delicate apparatus!

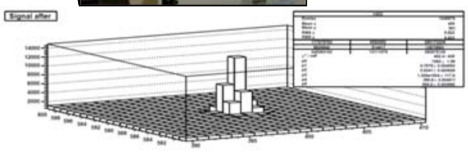


Lock by adapting the distance between the mirrors to the variations of the laser frequency.

The ALPS Detector

> Conventional low noise CCD, where the light is focused onto very few pixels to minimize dark current and read-out noise.



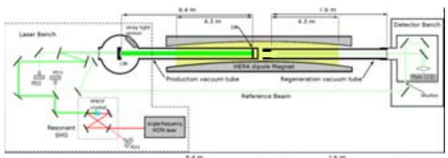


Beam spot on the CCD (pixel size 13 µm).

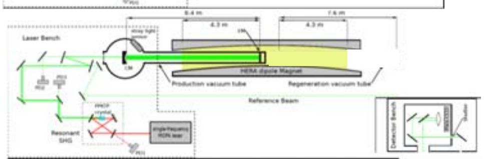
ALPS at Work

Steps of data taking:

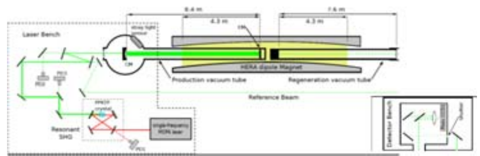
1. Test alignment with open detector tube and fraction of laser light passing the mirror (10^{-4}).



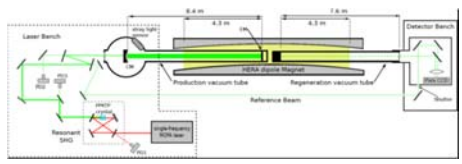
2. Demount detector and detector tube.



3. Close tube and reinstall everything.



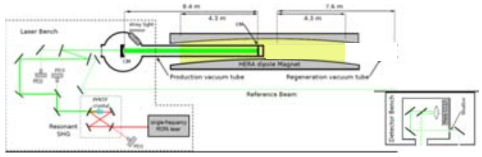
4. Take data (1h CCD exposures).



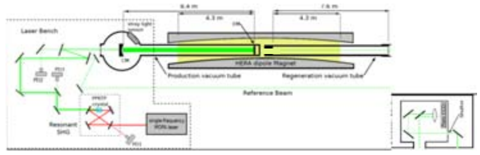
ALPS at Work

Steps of data taking:

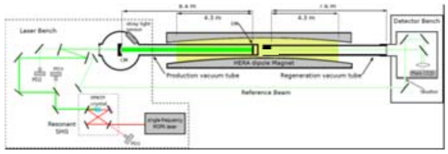
5. Demount detector and detector tube.



6. Open the tube and reinstall everything.



7. Test alignment with open detector tube and fraction of laser light passing the mirror (10^{-4}) to confirm that the alignment has not changed.



ALPS at Work

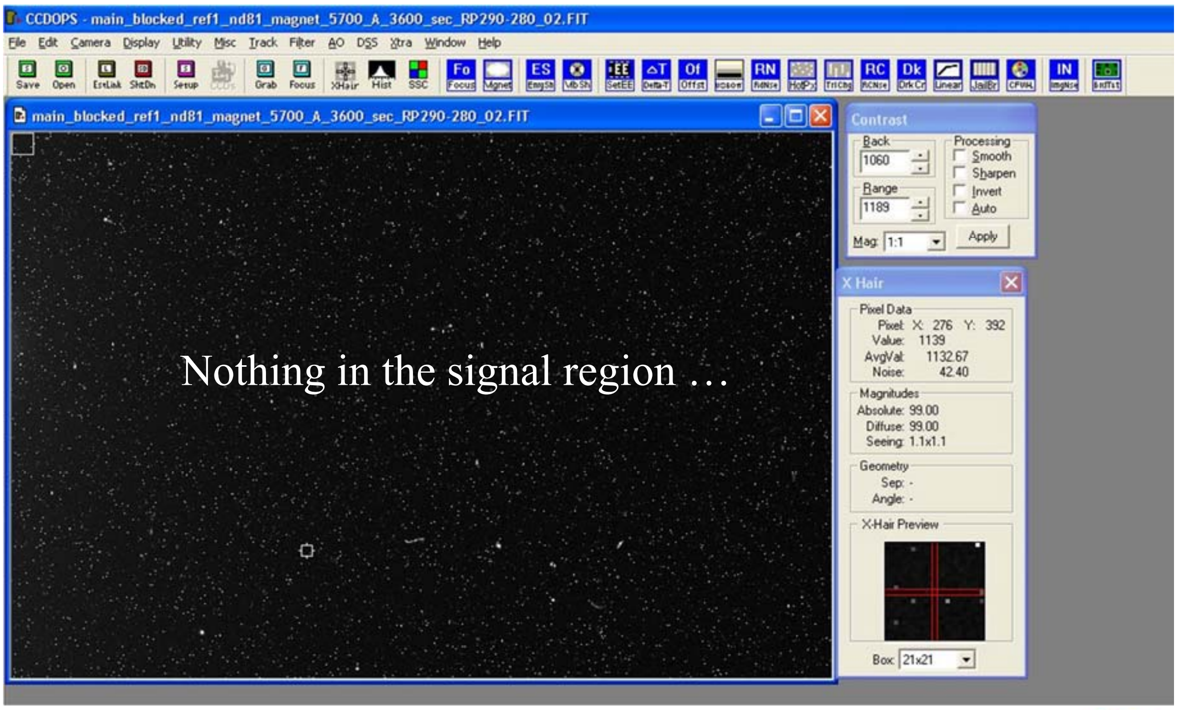
Steps of data taking:

5. Demount detector and detector tube.

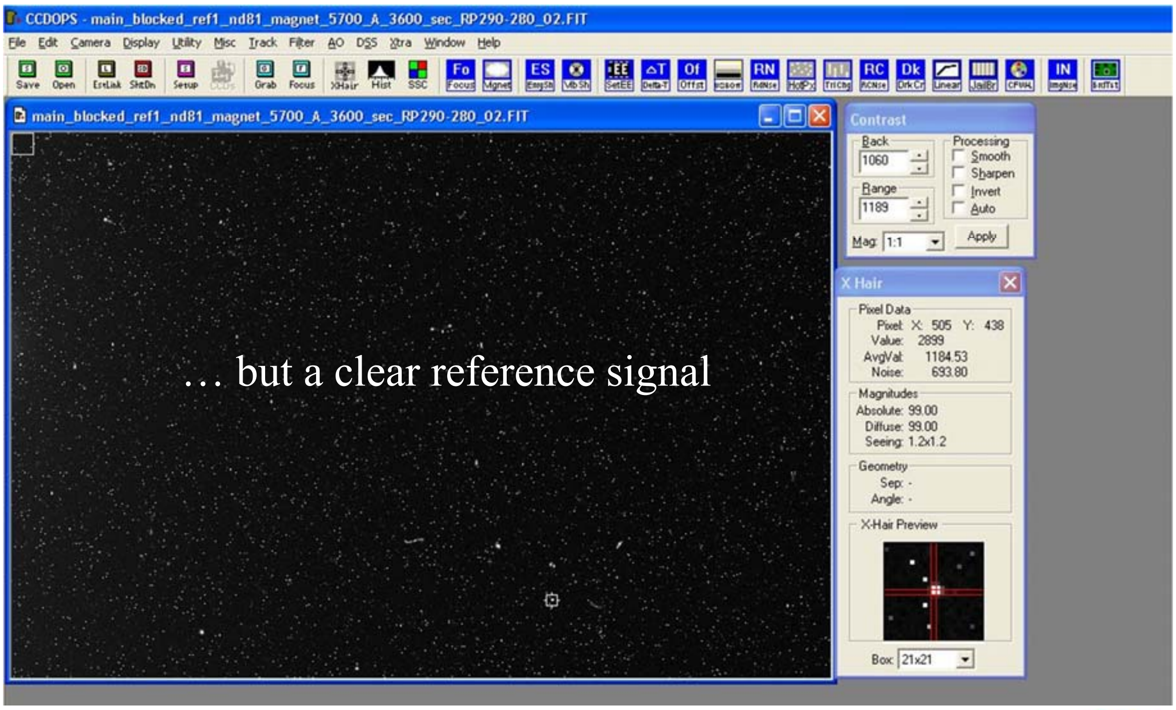
6. Open the tube and reinstall everything.

7. Test alignment with open detector tube and fraction of laser light passing the mirror (10^{-4}) to confirm that the alignment has not changed.

One Data Frame (SBIG ST-402)

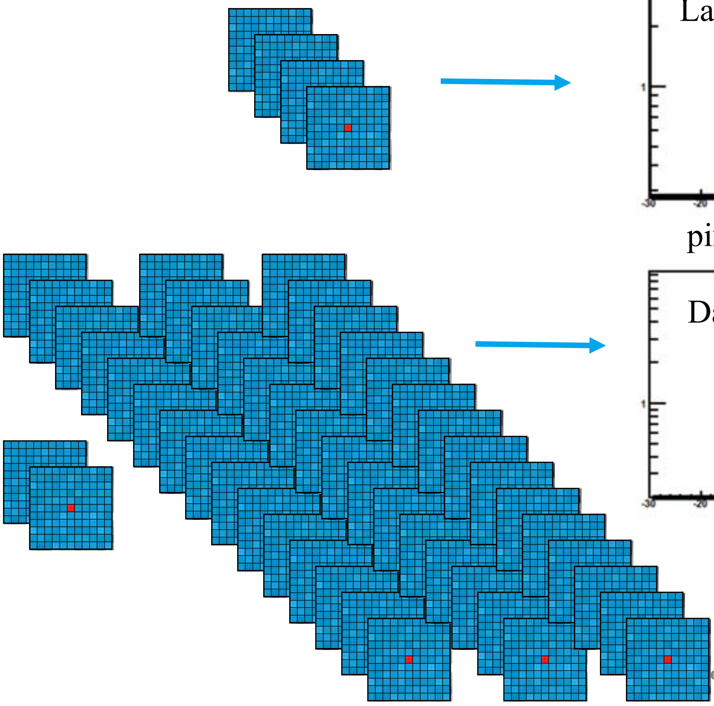


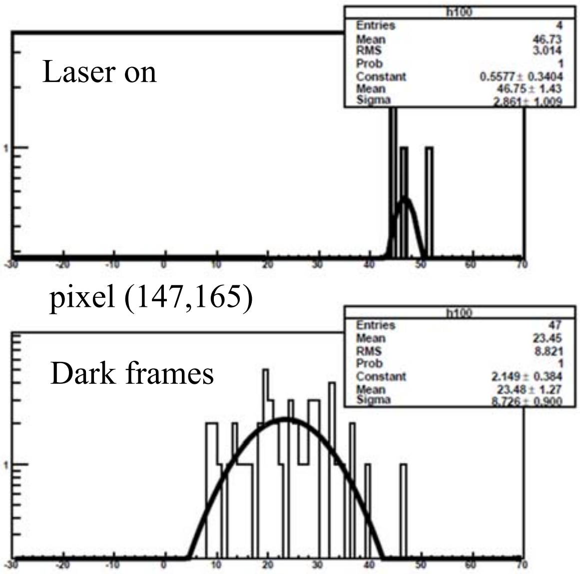
One Data Frame (SBIG ST-402)



A Glimpse into the Data Analysis

> Each 1 h exposure results in one entry (ADU value of the signal pixel) into the histogram:

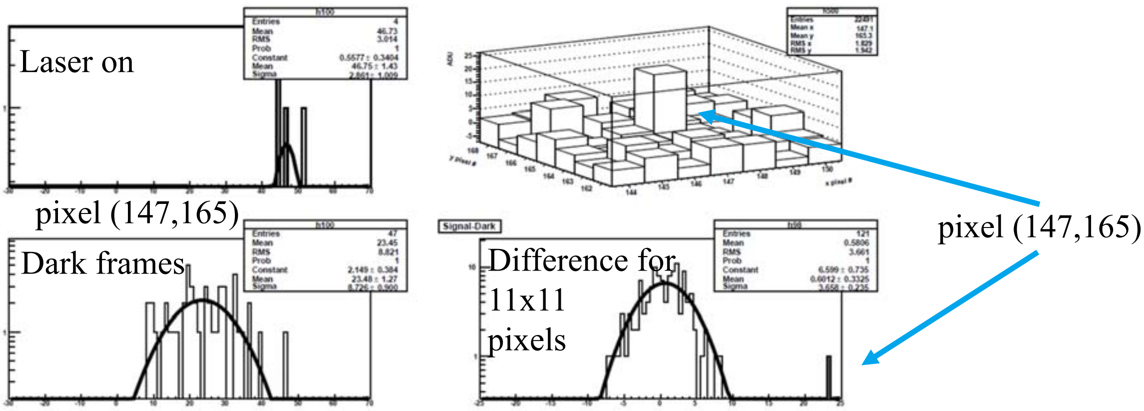




Compare mean ADU for "Laser on" and "Dark frames".

A Glimpse into the Data Analysis

> Test the CCD and the data analysis with a photon beam of extremely low intensity: between 5 mHz and 50 mHz.



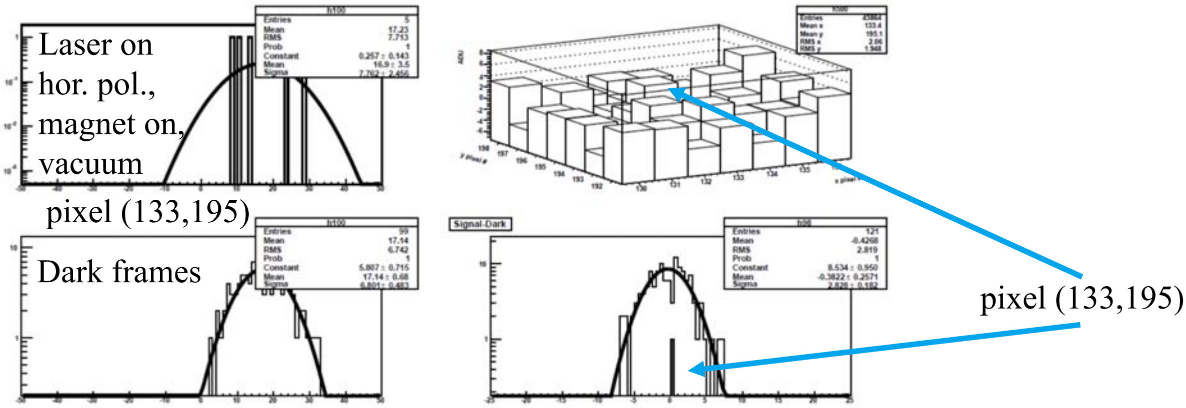
From Gaussians fitted to the data:

Δmean	Δwidth
23.27 3.20	-5.86±3.20

A photon flux of (7.9±1.2) mHz ($3 \cdot 10^{-21}$ W) is detected which agrees nicely to the expectation.

A Glimpse into the Data Analysis

> Example for a data run:



From Gaussians fitted to the data:

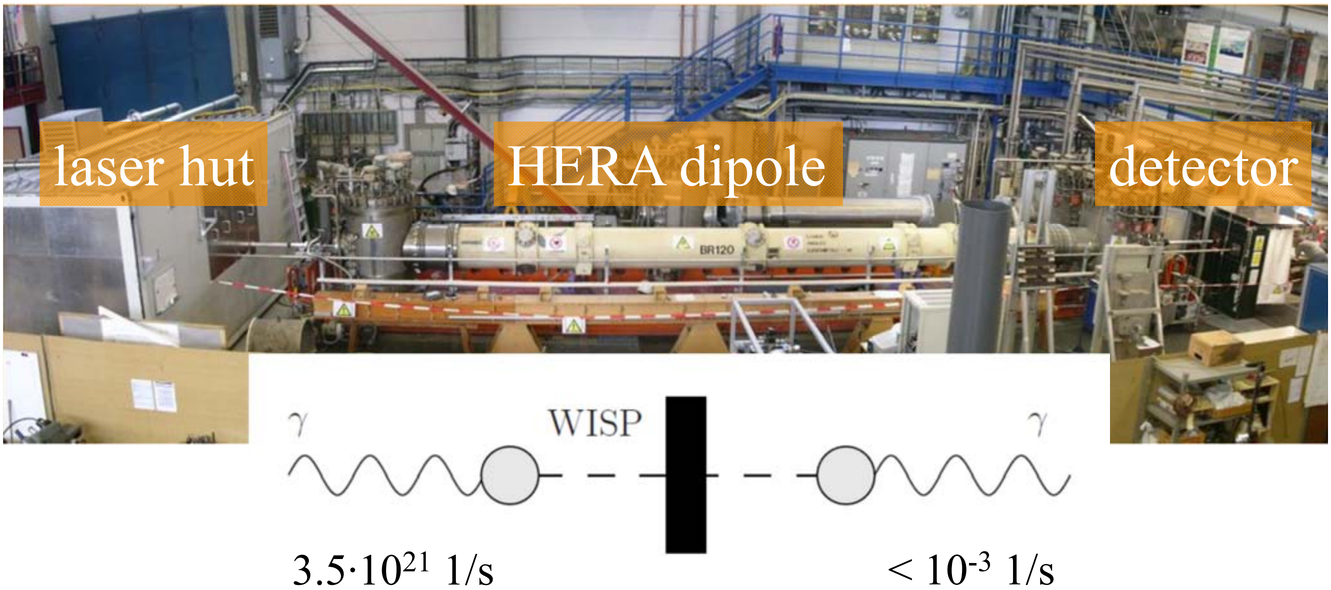
Δmean	Δwidth
-0.24±3.54	0.96±2.50

In none of the preliminary data analyses any evidence for WISP production shows up.

ALPS Results:

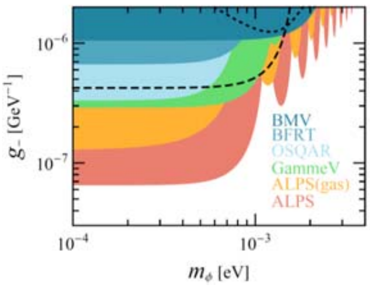
(PLB Vol. 689 (2010), 149, or http://arxiv.org/abs/1004.1313)

> Unfortunately, no light is shining through the wall!

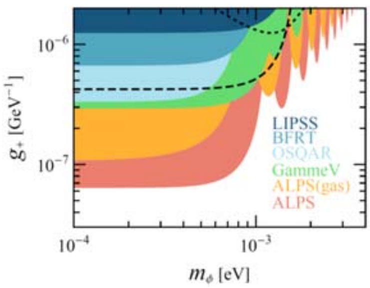


ALPS Results: http://arxiv.org/abs/1004.1313

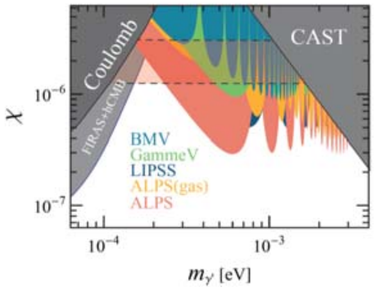
> ALPS is the most sensitive experiment for WISP searches in the laboratory.



pseudoscalar
and
scalar
axion-like particles

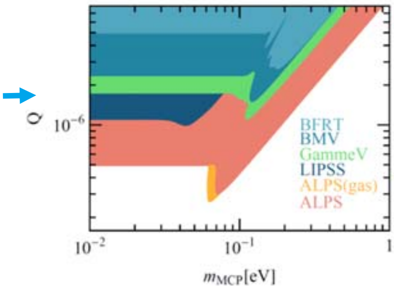


PLB 689 (2010), 149



hidden sector photons
and
minicharged particles

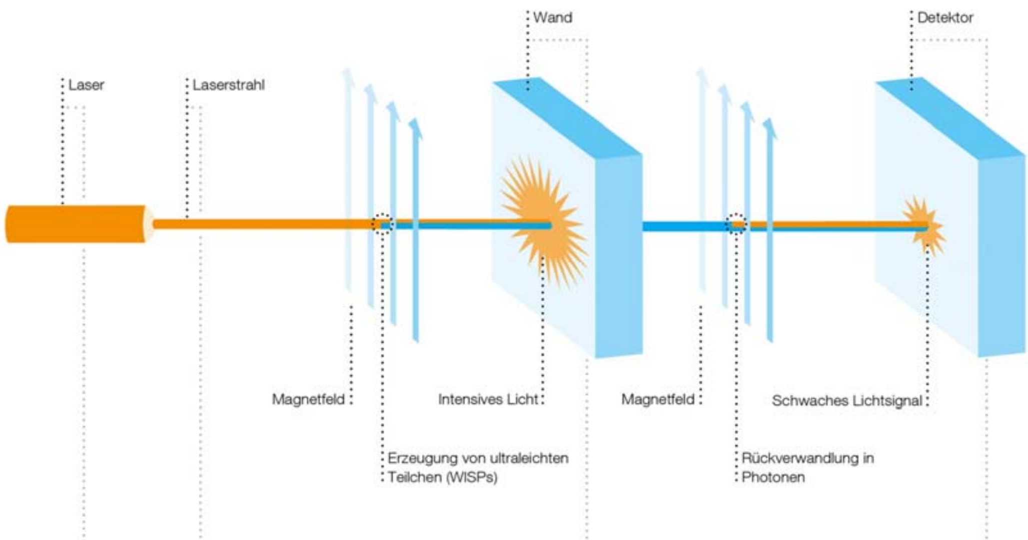
Filling a gap remaining from astrophysics and other experiments!



ALPS Results

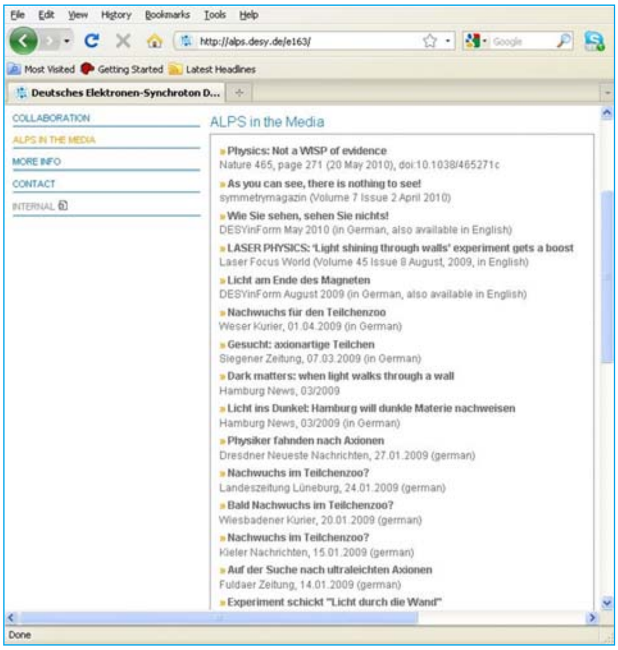
If one photon out of 1,000,000,000,000 photons converts into a WISP …

…and one out of 1,000,000,000,000 such WISPs converts back into a photon …



… you would have read this in the newspapers!.

In spite of Limits only: many ALPS Articles in the Press



New Hints for WISP Physics?

Theory:

> A QCD axion in the mass region of 10^{-5} to 10^{-4} eV would be a "perfect" cold Dark Matter candidate.

> A zoo of WISPs is expected from string theory inspired extensions of the Standard Model
A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, arXiv:0905.4720 [hep-th]
M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, arXiv:0909.0515 [hep-ph], JHEP 0911:027,2009

Astrophysics:

> *Axions and the cooling of white dwarf stars.*
J. Isern et al., arXiv:0806.2807v2 [astro-ph], Astrophys.J.L. 682 (2008) L109

> *Evidence for a New Light Boson from Cosmological Gamma-Ray Propagation?*
M. Roncadelli et al., arXiv:0902.0895v1 [astro-ph.CO]

> Does the X-ray spectrum of the sun points at a 10 meV axion?
K. Zioutas et al., arXiv:0903.1807v4 [astro-ph.SR]

> Large-Scale Alignments of Quasar Polarization Vectors: Evidence at Cosmological Scales for Very Light Pseudoscalar Particles Mixing with Photons?
D. Hutsemekers et al., arXiv:0809.3088v1 [astro-ph]

> Signatures of a hidden cosmic microwave background
J.Jaeckel, J. Redondo, A. Ringwald, Phys.Rev.Lett.101:131801,2008

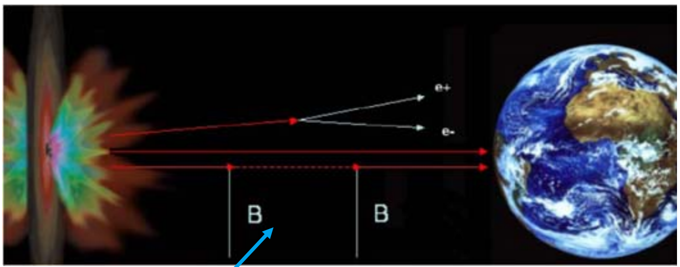
Hints for ALP Physics: Cosmological TeV γ Propagation

TeV photons should be absorbed by e^+e^- pair production due to interaction with the extragalactic background light (EBL):

$\gamma_{TeV} + \gamma_{eV} \rightarrow e^+ + e^-$

However, the TeV spectra of distant galaxies do hardly show any absorption.

M. Roncadelli, presentation at the 4th Patras Workshop on Axions, WIMPs and WISPs, 2008



TeV photons may "hide" as ALPs!

Prospects for ALPS-II Components

> Laser with optical cavity to recycle laser power, switch from 532 nm to 1064 nm, 150 kW instead of 1 kW

> Magnet: upgrade to 12+12 *straightened* HERA dipoles instead of ½+½.

> Regeneration Cavity and single photon counter (transition edge sensor?).

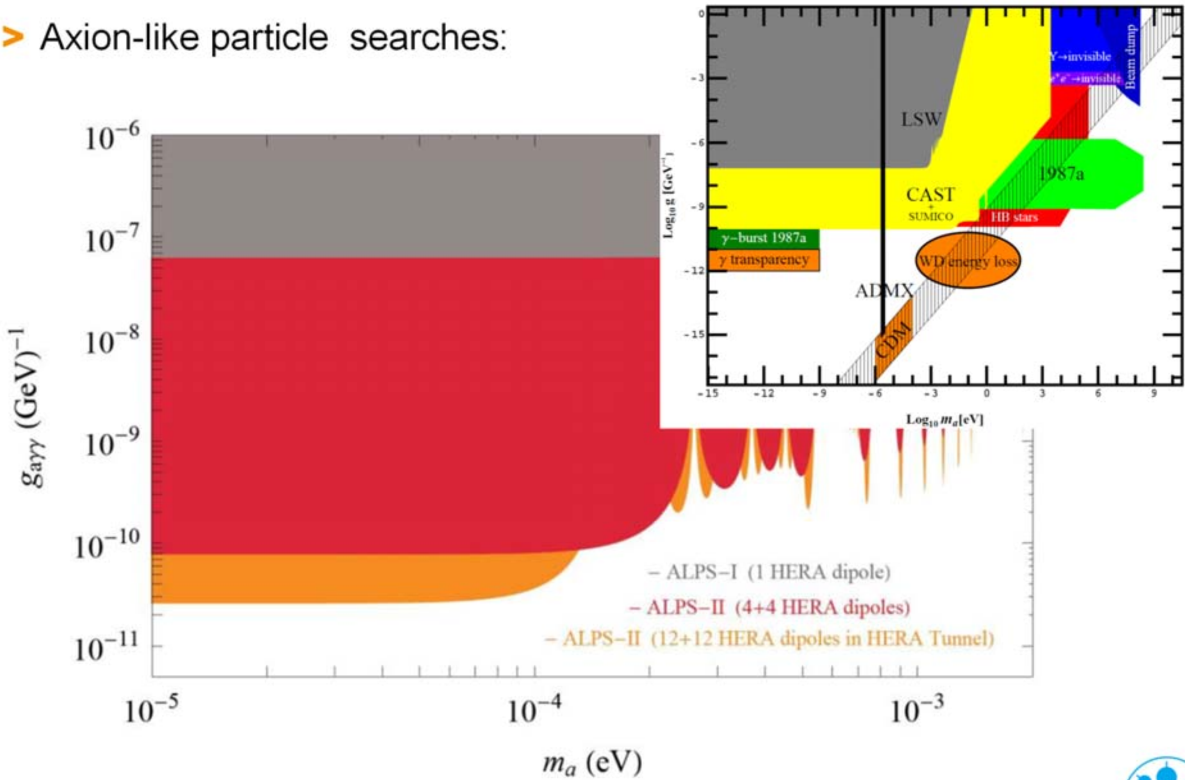
All set up in a clean environment!

ALPS-II: Schedule

- Step 0 (spring 2012):
  Technical Design Reports.
- Step 1 (end of 2012):
  2 x 10 m long experiments to search for “hidden photons”.
  This works without magnets.
- Step 2 (end of 2014):
  Search for “hidden Photons” in the HERA-tunnel with 2 x 100 m vacuum tubes.
- Step 3 (in 2017):
  Search for axion-like particles and other WISPs in the HERA-tunnel with HERA dipoles.

The ALPS-II Potential

- Axion-like particle searches:



The ALPS-Community

> ALPS-I:

- DESY
- Sternwarte Bergedorf
- AEI Hannover
- Laser Zentrum Hannover

> ALPS-II

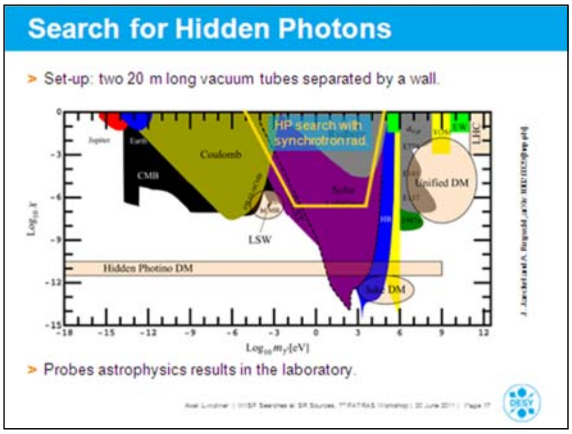
- New: Hamburg University
- New: neoLASE Hannover

> New support for detector development:

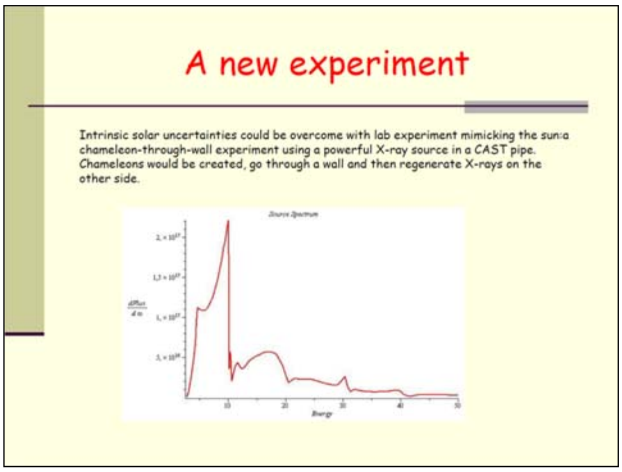
- PTB Berlin
- Italy:
  INRIM
  INFN
  Uni. Camerino, Genua, Triest
- NIST (USA)

Further Options at DESY

> Particle physics with synchrotron radiation:



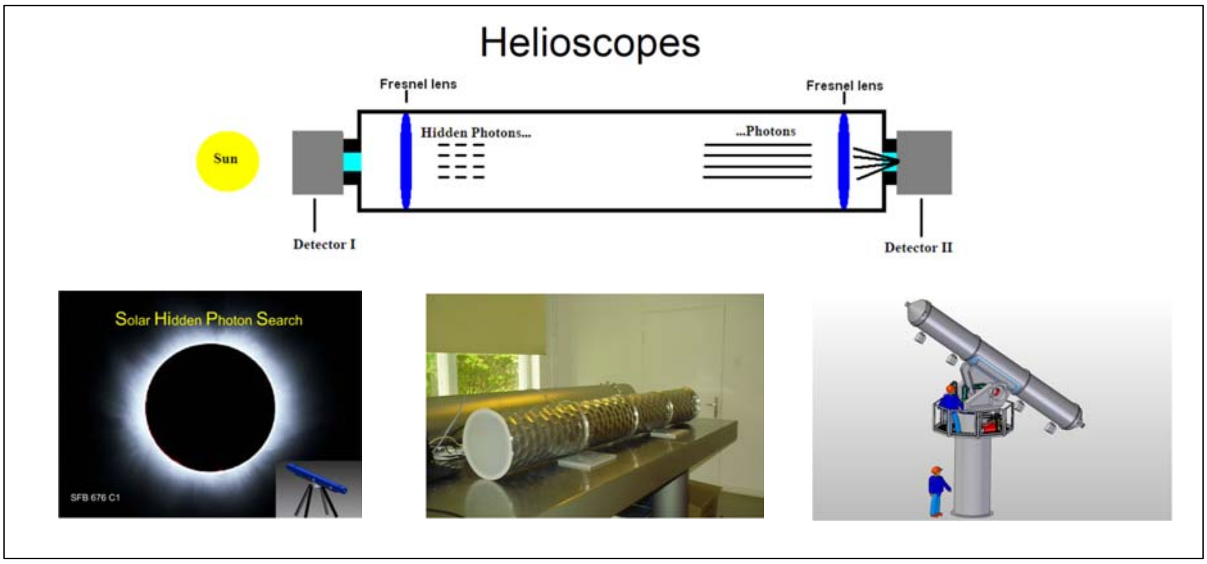
P. Brax, Patras 2011, http://axion-wimp.desy.de



Possibility to probe
Dark Energy
in the laboratory?

And even more Options

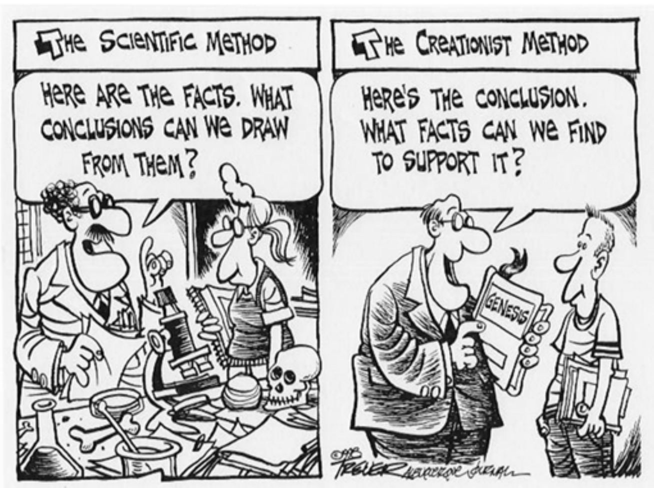
> Solar Hidden Photon Search (SHIPS) at Hamburg.



> WISP searches using microwave cavities from accelerators.

Discussion Time

> What is your favorite Dark Matter candidate?



> Why?

To take home

> It is almost certain that Dark Matter of unknown constituents exist.

> It is well possible that in addition Dark Energy exists.

- We might know just 5% of the universe.

> Constituents making up the Dark Matter in the universe could be essentially anything from ultra-light to extremely heavy.

- A lot of experiments search for WIMPs at the high energy frontier, also at LHC.
- The low energy frontier (WISPs) is tackled by relatively modest approaches.

> Dark Energy might be related to WISP physics.

> There might be complex hidden sectors with dark particles

- Dark matter might be composed of more than one constituent.

WISP Searches is fun: Thanks to my ALPS Colleagues

> DESY:
Paola Arias, Jan Dreyling-Eschweiler, Klaus Ehret, Samvel Ghazaryan, Reza Hodajerdi, Ernst-Axel Knabbe, Axel Lindner, Dieter Notz, Javier Redondo (now MPI), Andreas Ringwald, Jan Eike von Seggern, Dieter Trines

> Universität Hamburg / Sternwarte Bergedorf:
Dieter Horns, Günter Wiedemann

> AEI Hannover:
Robin Bähre, Tobias Meier, Benno Willke

> LZH Hannover / neoLASE:
Maik Frede

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- LZH Hannover / neoLASE:
  Maik Frede

Theory	**Particle Physics**	**Accelerator Physics**
Astronomy	**Astroparticle Physics**	**Laser Physics**
	Surfaces Physics	

ALPS