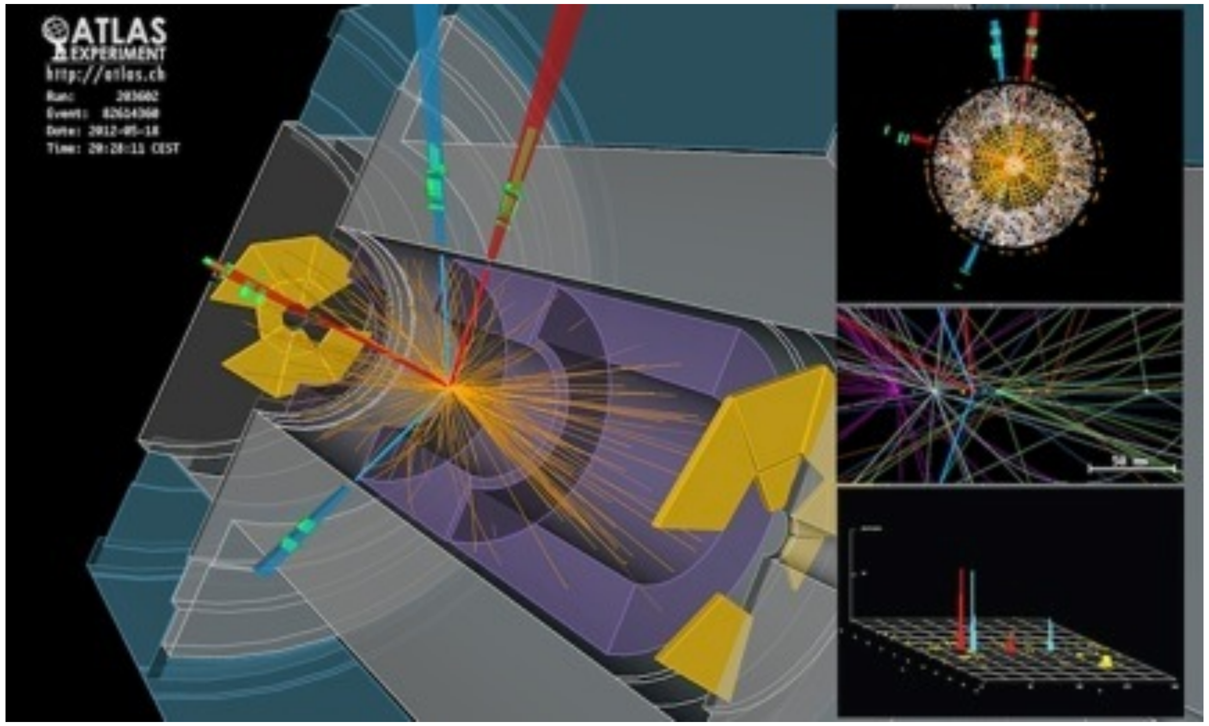
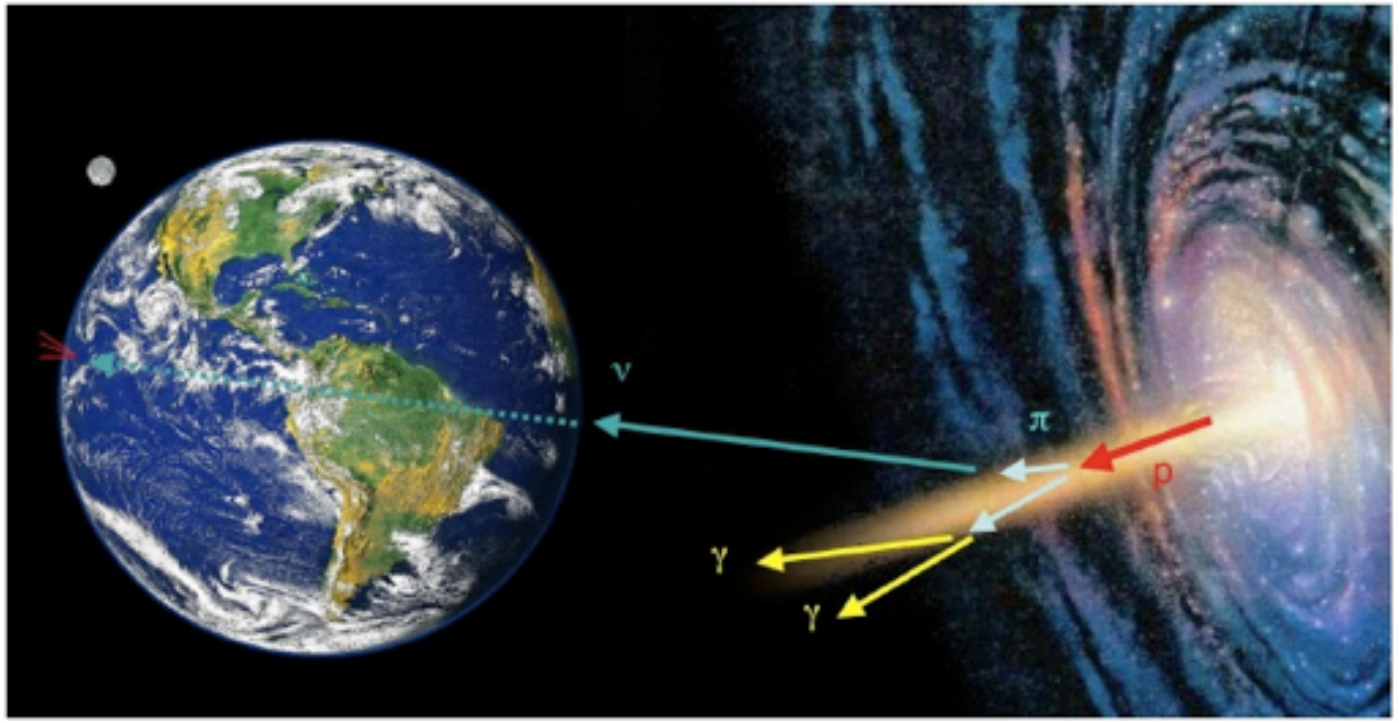
Particle Physics with
Accelerators and Natural Sources





01. Introduction & Recap: Particle Physics & Experiments

29.04.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Goal / Content of the Lecture

- The connections of particle and astro-particle physics
- Precision tests of the Standard Model of particle physics
- Dark Matter - WIMPs and Axions
- Neutrinos in the cosmos, from accelerators and natural sources
- Precision experiments at accelerators and the physics of heavy quarks
- Gravitational waves

- We are open to other topics as well - just let me know!

Organisation

- Time and place:
  - Mondays, 14:00 - 16:00
  - Physik II, Seminarraum PH 127

If not done yet: please sign up in TUM Online!

- Prerequisites:
  - Introductory lecture to Particle, Nuclear & Astrophysics

- Exercise Classes: None
- Exams: On request - contact me via email

- Slides (FS) / Lecture Notes (BM): Available on-line in MPP indico system https://indico.mpp.mpg.de/category/135/

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.06.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Accelerator Neutrinos	*F. Simon*
01.07.	Precision Experiments with low-energy accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*

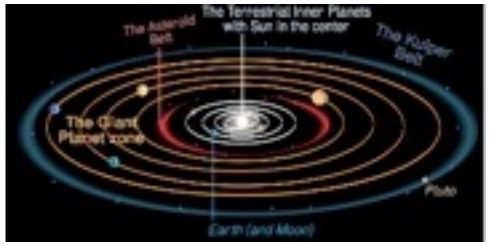
Topics Today

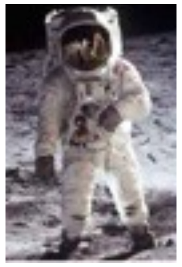
- Introduction & Reminder:
  - The Standard Models of Particle Physics and Cosmology
  - Open Questions
  - Experimental Strategies
- Experimental Tools
  - Interaction of particles with matter
  - Detection techniques
  - Selected detector examples

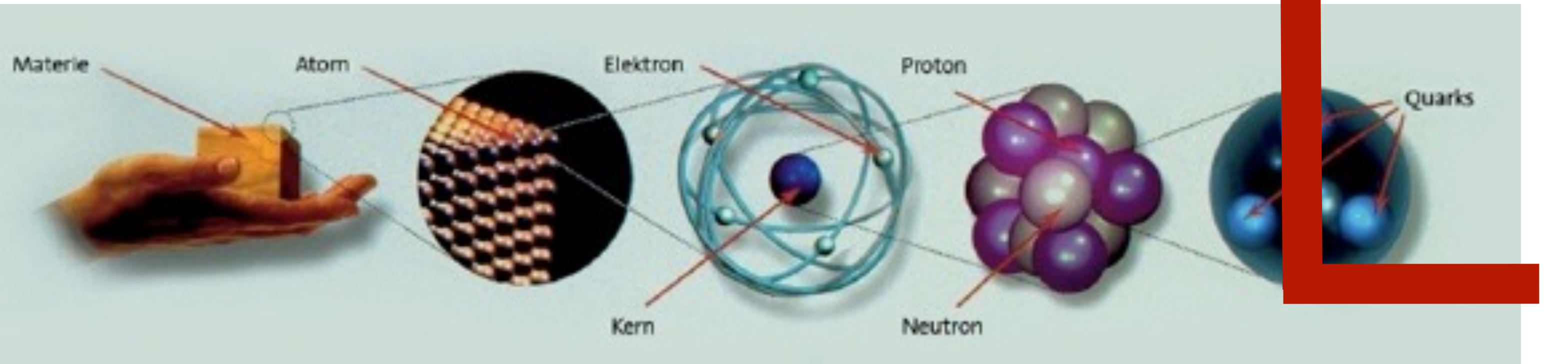
Introduction:

Our Understanding of Particle Physics and the Universe

From the very big to the very small







	Size	Mass
Universe	10^{26} m	10^{52} kg
Galaxy	10^{21} m	10^{41} kg
Solar system	10^{13} m	10^{30} kg
Earth	10^{7} m	10^{24} kg
Man	10^{0} m	10^{2} kg
Atom	10^{-10} m	10^{-26} kg
Nucleus	10^{-14} m	10^{-26} kg
Nucleon	10^{-15} m	10^{-27} kg
Quarks, Leptons	$<10^{-18}$ m	10^{-30} kg

“Astroteilchenphysik in Deutschland”, http://www.astroteilchenphysik.de/, und darin angegebene Referenzen

Fundamental Forces

- Four known Forces
  - Gravitation governs our every-day life, evolution of the Universe
  - ‣ It is irrelevant on the scales of particle physics

couples to mass	couples to charge	couples to weak isospin	couples to color

Relative strength at low energies

~10^{-40}	1/137	10^{-13}	~1

due to the high mass of W, Z:
W: ~ 80 GeV , Z: ~ 91 GeV

The Standard Model of Particle Physics

- The SM describes our visible Universe by a (reasonably small) set of particles:
  - The particles that make up matter: Spin 1/2 Fermions
  - … and the force carriers: Spin 1 Vector bosons

Elementary Particles

	Generation 1	2	3
Quarks	**u** **d**	**c** **s**	**t** **b**
Leptons	ν_e **e**	ν_μ μ	ν_τ τ

Elementary Forces

	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	$W^\pm$, Z^0	10^{-14}
Gravitation	*G*	10^{-40}

… plus the Higgs particle as a consequence of the mechanism to generate mass

Underlying theories: QCD

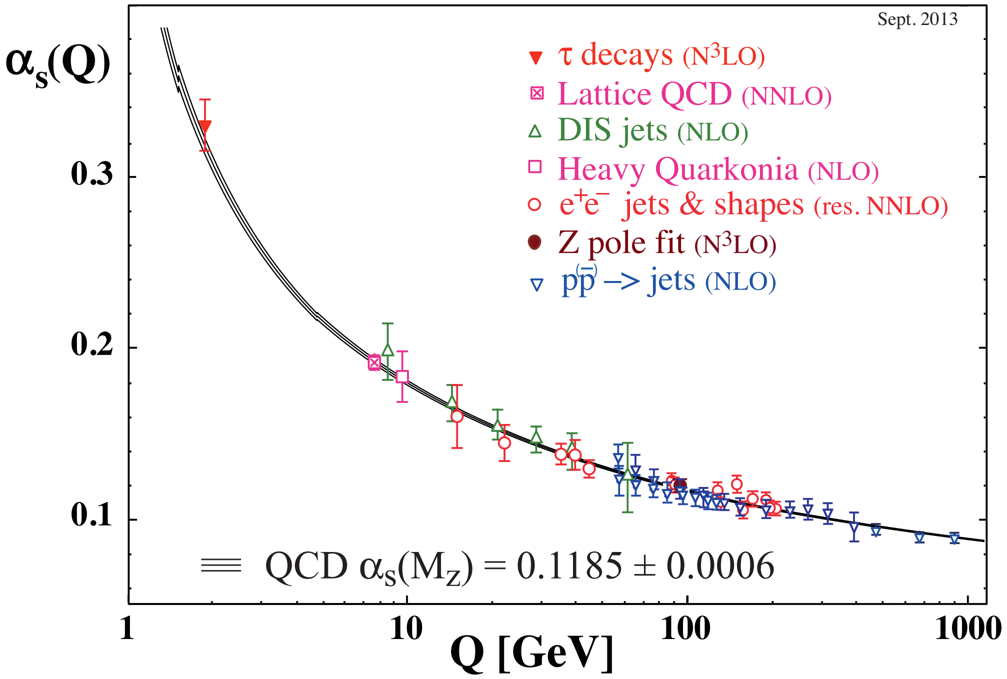
QED / weak interaction
➫ electroweak unification (GSW)

Key Elements of the Standard Model: Electroweak

- The electroweak part of the SM is based on the gauge group SU(2) x U(1)
- This gives rise to the gauge bosons W^+, W^-, Z for SU(2) and γ for U(1)
- Left-handed fermion fields transform as doublets under SU(2) - right handed fermions as singlets (no coupling of right-handed fermions to W; **V-A structure of the weak interaction** (maximum parity violation))
- There are three fermion families
- A complex scalar Higgs field is added for mass generation through spontaneous symmetry breaking to give mass to the gauge bosons and fermions -> Gives rise to one physical neutral scalar particle, the Higgs boson
- The electroweak SM describes in lowest order ("Born approximation") processes such as f_1f_2 -> f_3f_4 with only 3 free parameters: α, G_f, $\sin^2\theta_W$

Key Elements of the Standard Model: Strong

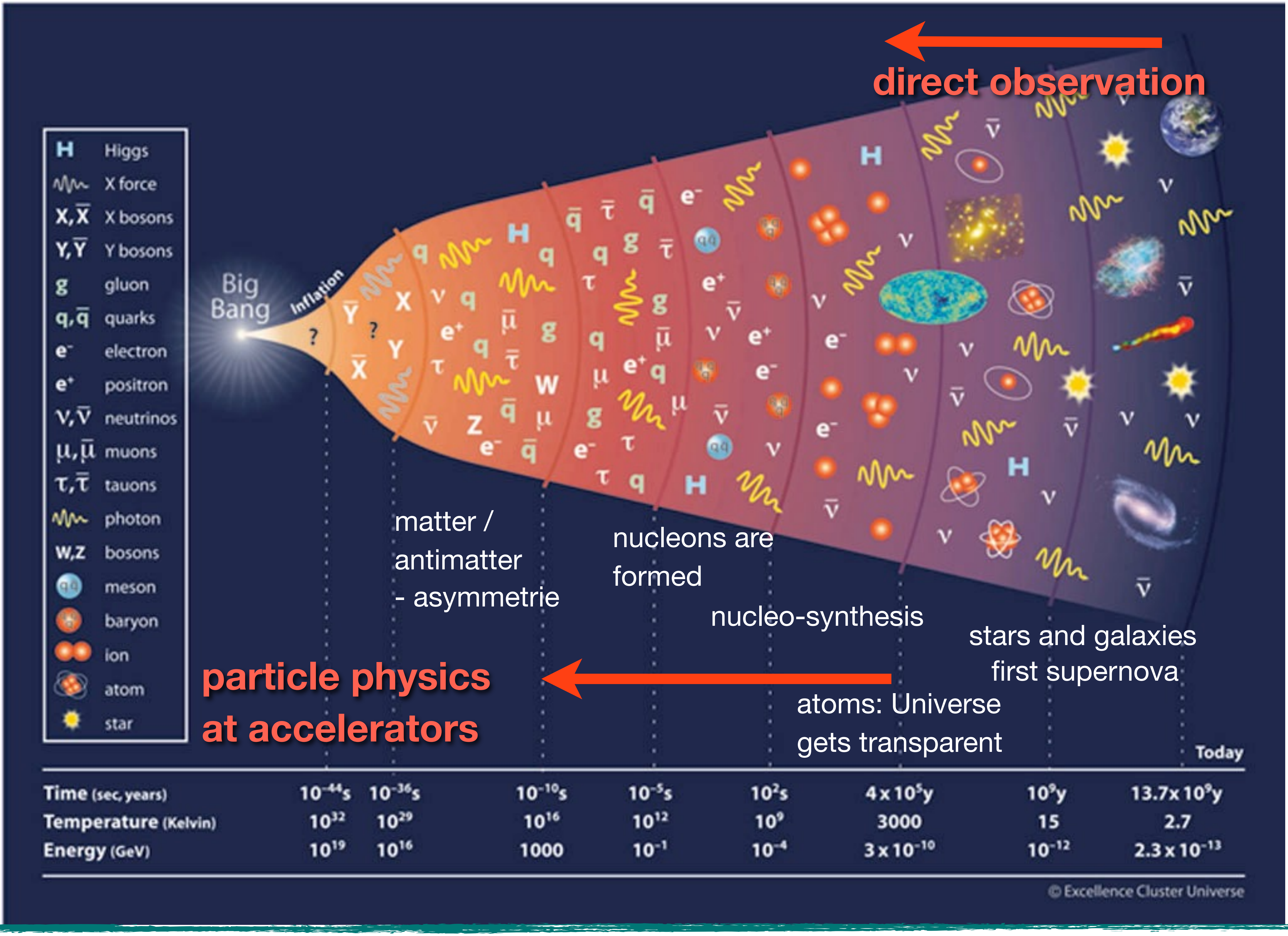
- Described by **Quantum Chromodynamics (QCD),** gauge group SU(3)
- Gluons as exchange bosons, couple to “color”, a “charge” carried by quarks
- Gluons themselves carry color charge: can self-interact
  - The coupling constant of the strong interaction (α_s) decreases with increasing momentum transfer: In the limit of very short distances, the coupling vanishes: **asymptotic freedom**



- On the other hand: coupling tends to infinity for large distances: It is impossible to separate color charges, at large distance new particle / anti-particle pairs are created from the increasing field energy. Only color-neutral objects can exist as free particles: **Confinement**

- Gives rise to the rich structure of hadrons, the complexity of the proton and of final states in particle collisions

The Evolution of the Universe



direct observation

matter / antimatter - asymmetrie

nucleons are formed

nucleo-synthesis

stars and galaxies
first supernova

atoms: Universe gets transparent

particle physics at accelerators

								Today
Time (sec, years)	10^{-44}s	10^{-36}s	10^{-10}s	10^{-5}s	10^{2}s	4×10^{5}y	10^{9}y	13.7×10^{9}y
Temperature (Kelvin)	10^{32}	10^{29}	10^{16}	10^{12}	10^{9}	3000	15	2.7
Energy (GeV)	10^{19}	10^{16}	1000	10^{-1}	10^{-4}	3×10^{-10}	10^{-12}	2.3×10^{-13}

The Evolution and Composition of the Universe

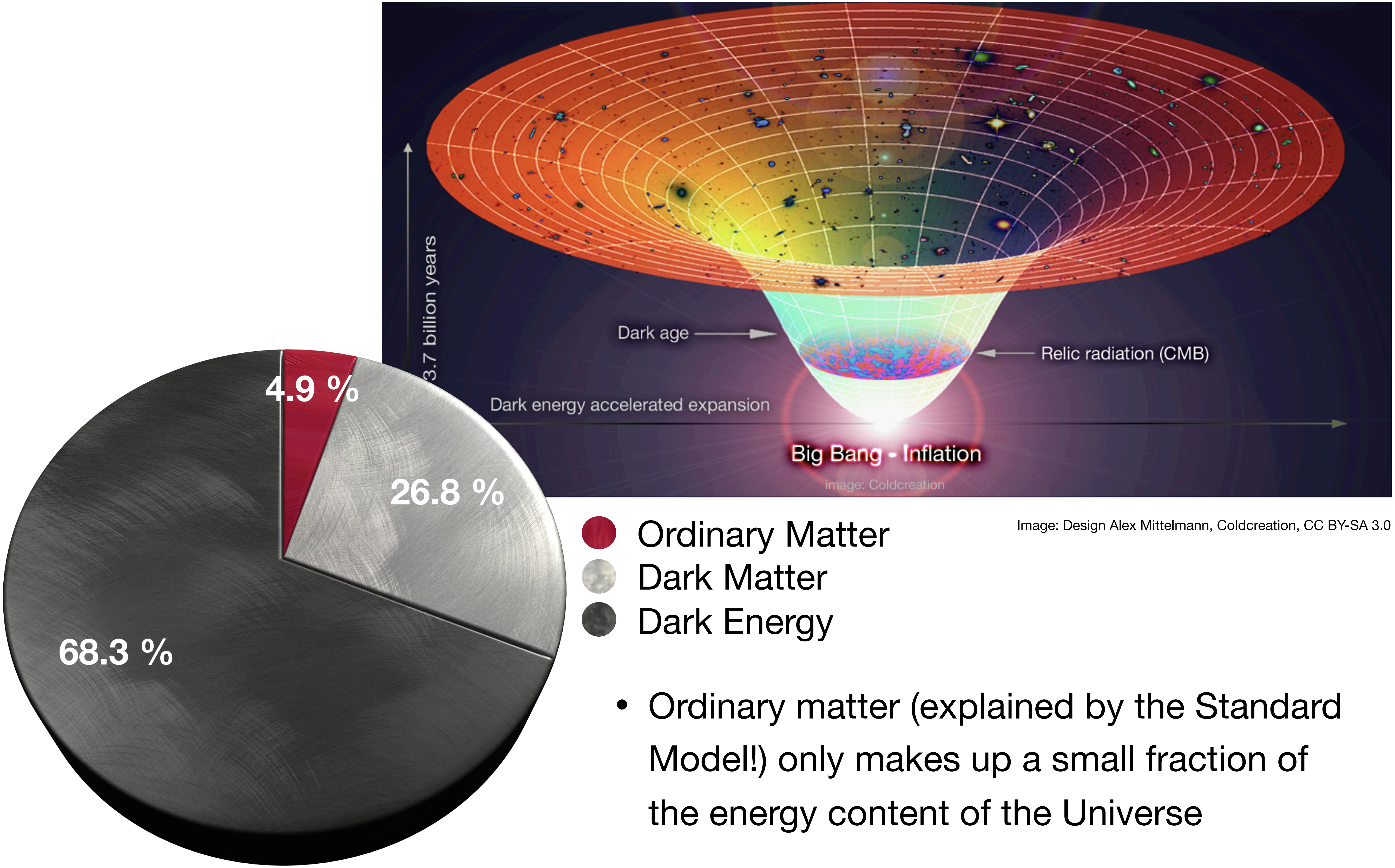


Image: Design Alex Mittelmann, Coldcreation, CC BY-SA 3.0

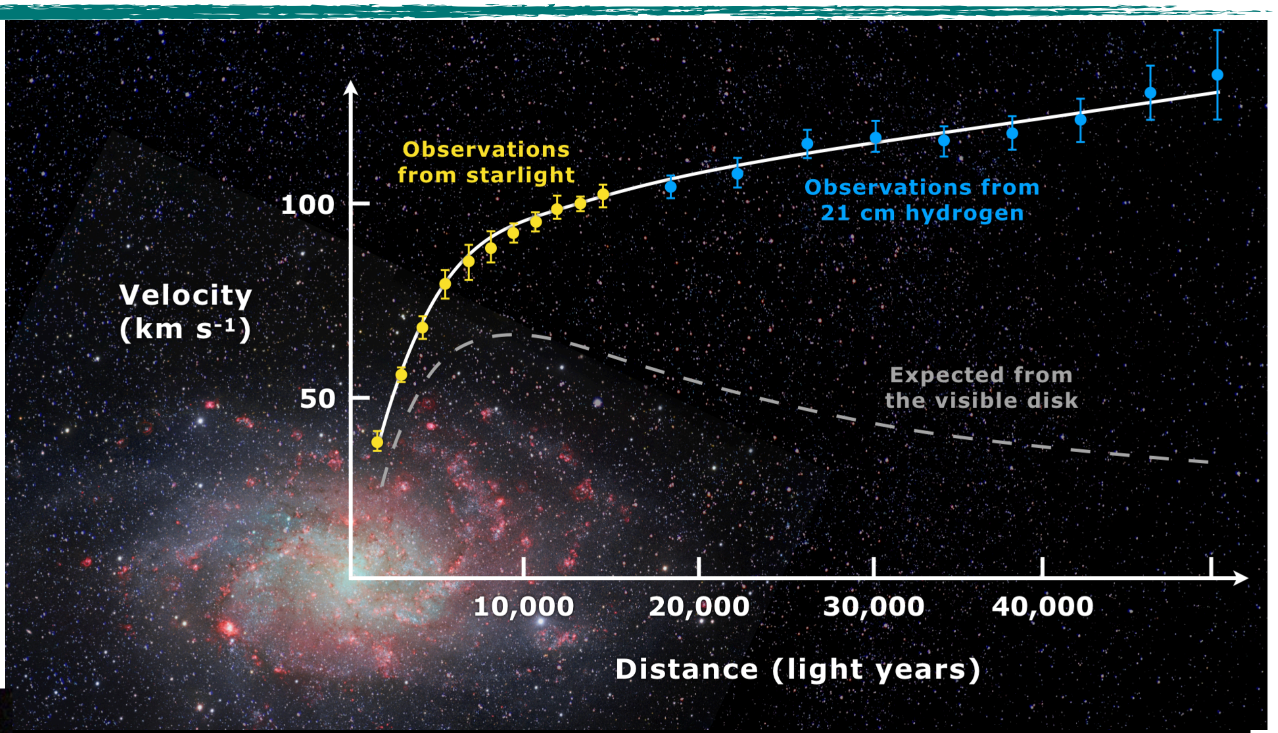
● Ordinary Matter
● Dark Matter
● Dark Energy

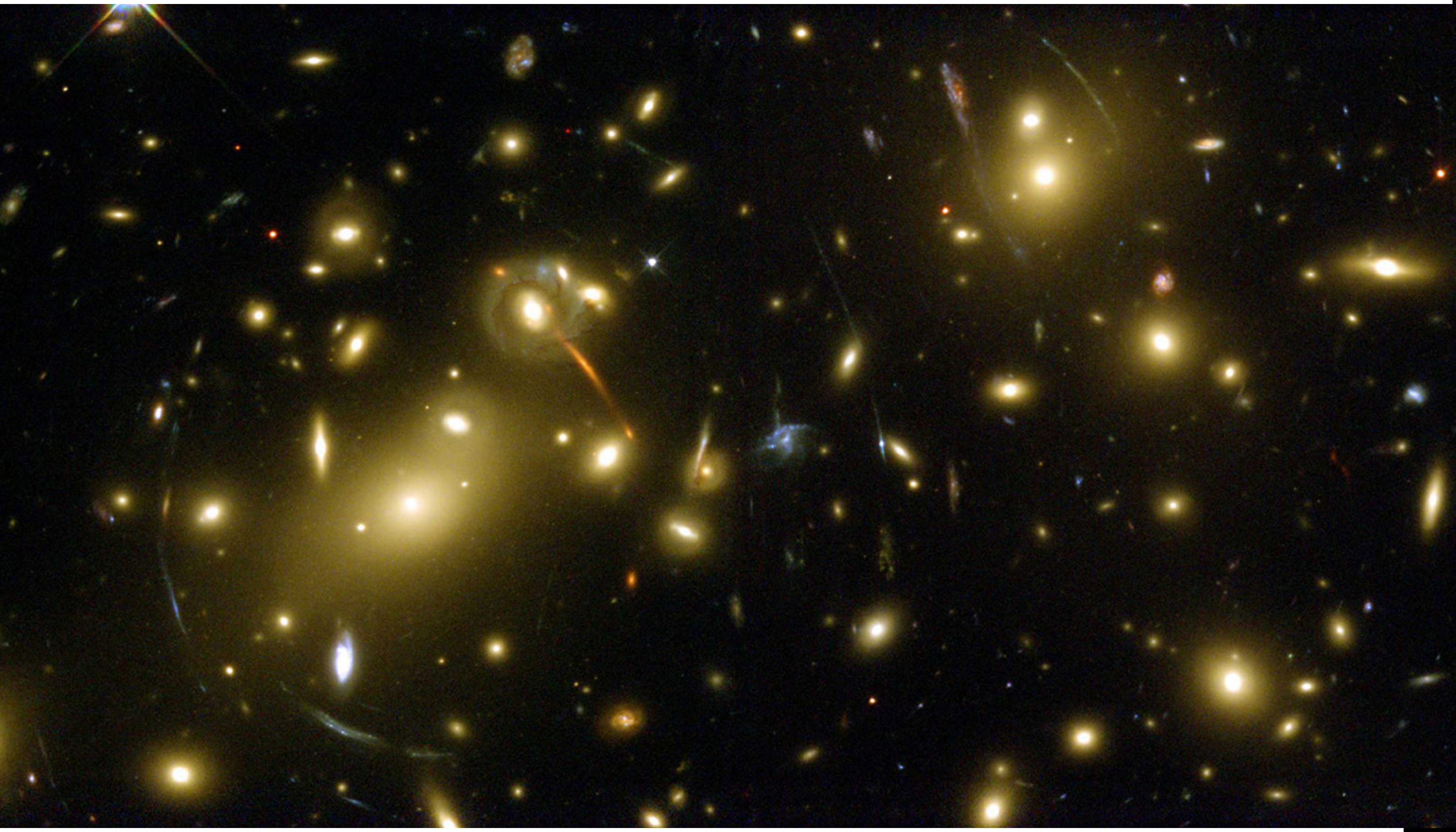
- Ordinary matter (explained by the Standard Model!) only makes up a small fraction of the energy content of the Universe

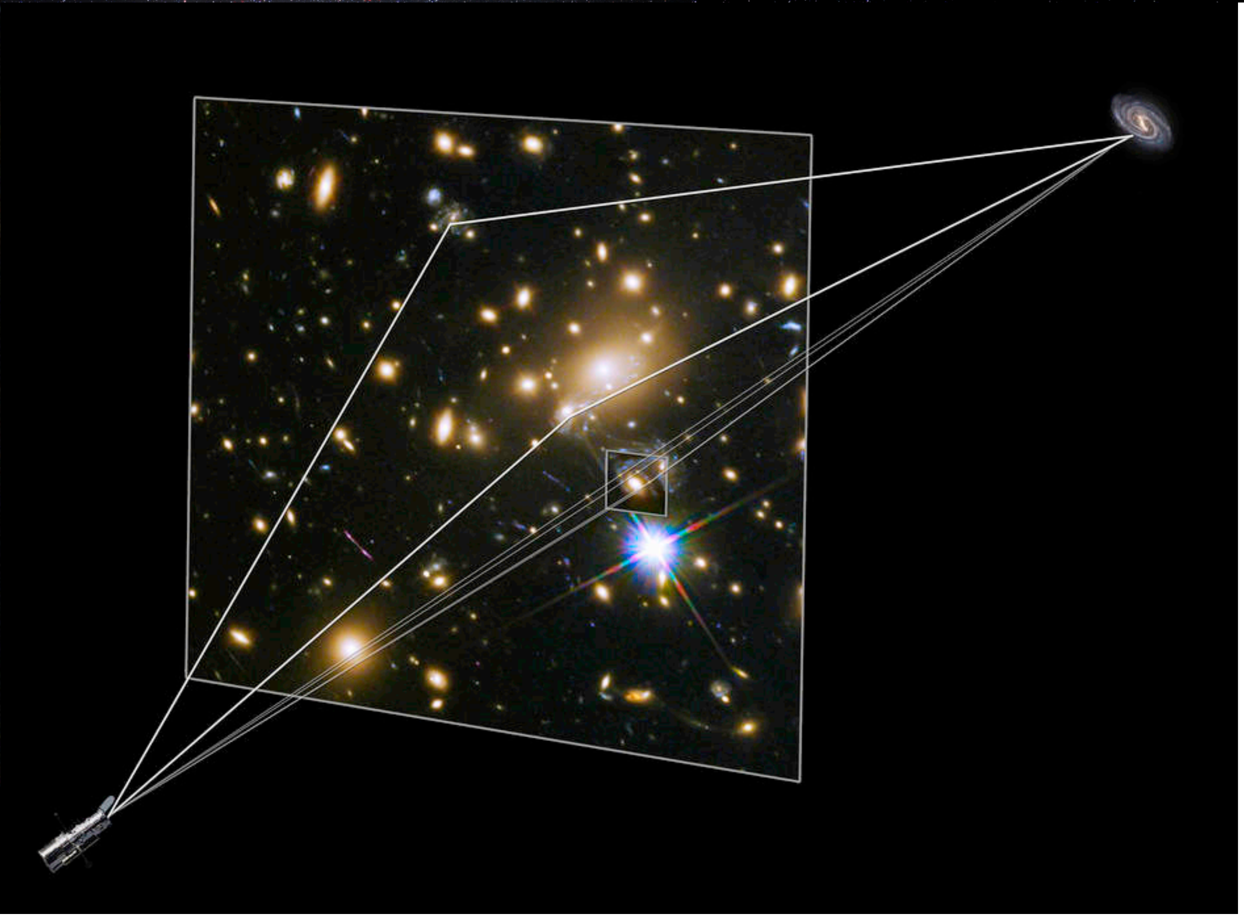
How do we know the composition?

- The movement of galaxy clusters shows the matter density

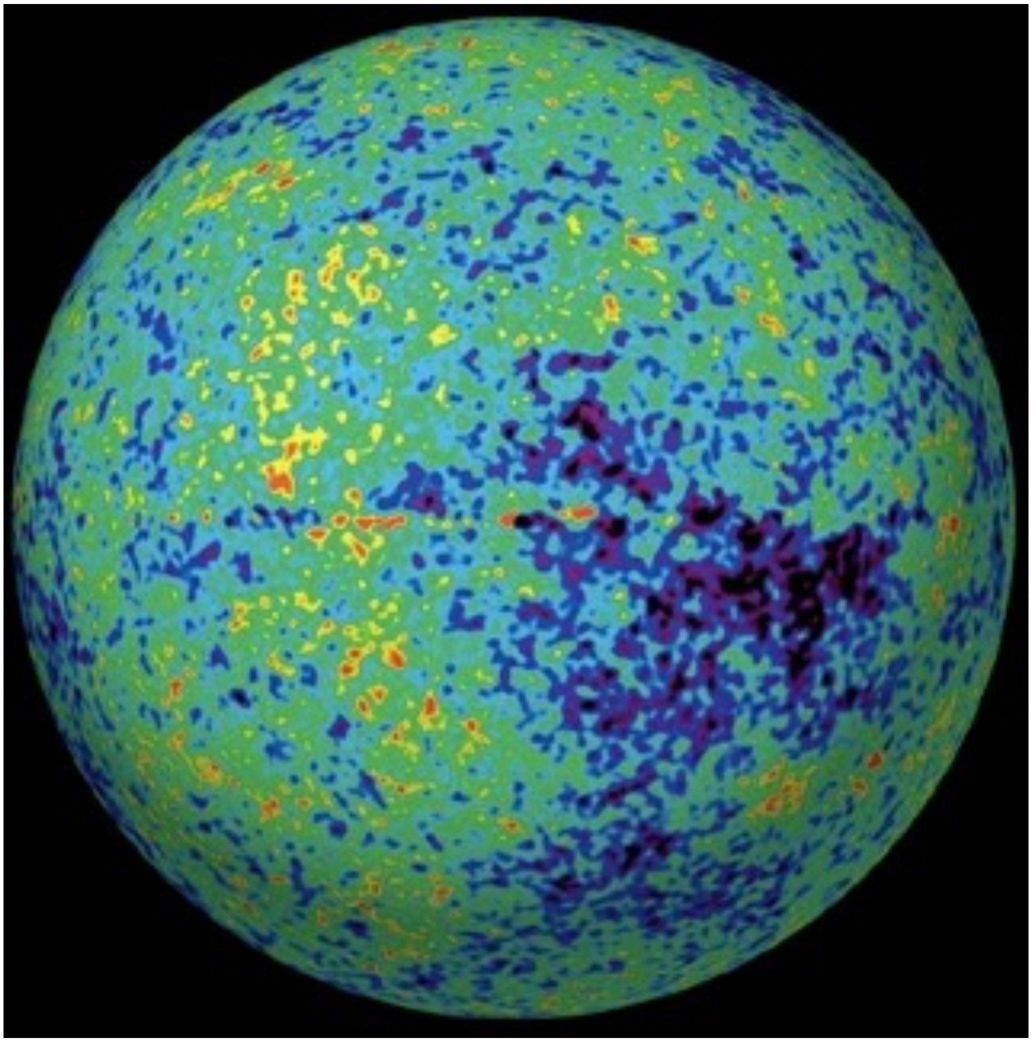
Also: Galaxy rotation, gravitational lensing, …



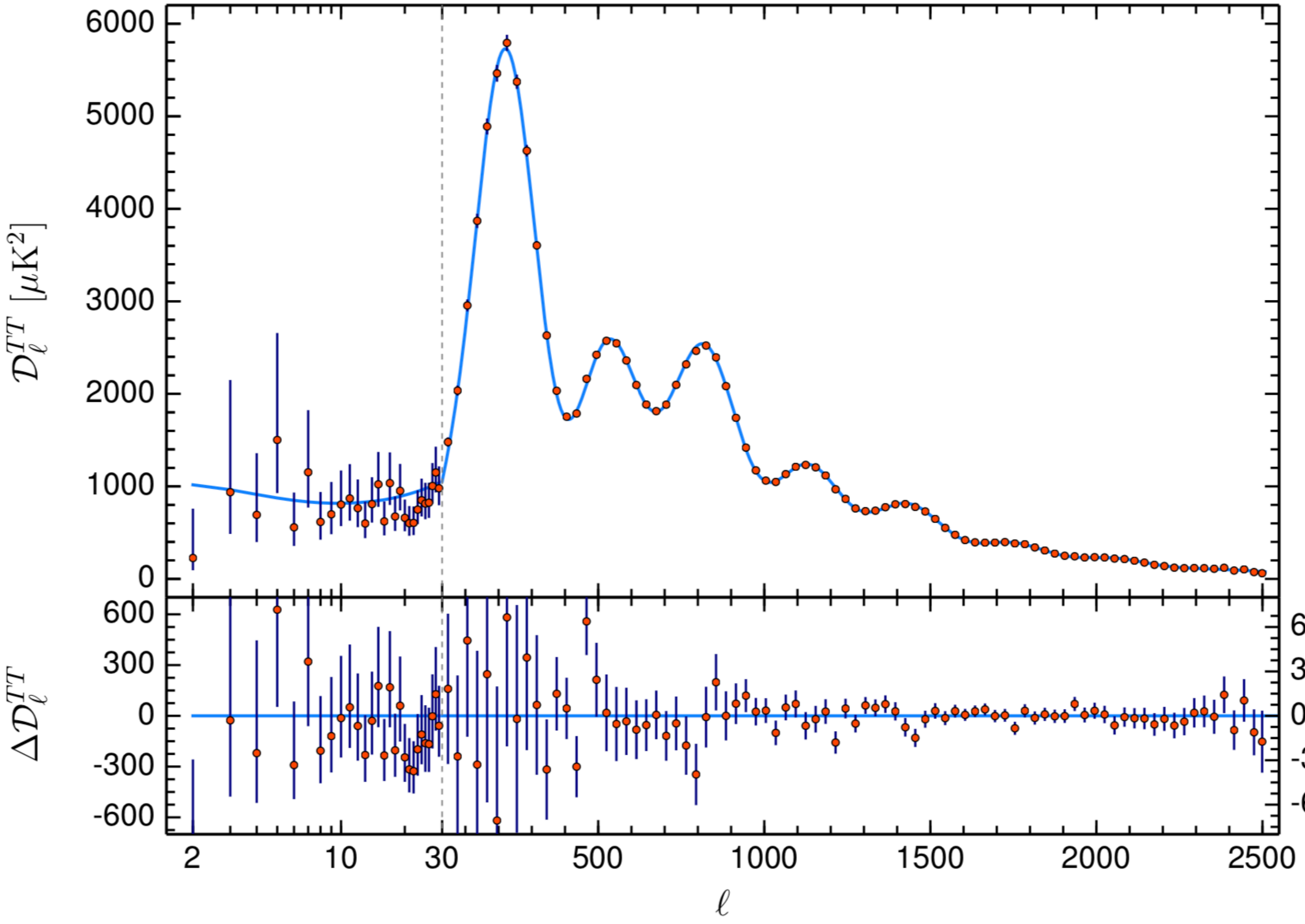




How do we know the composition?



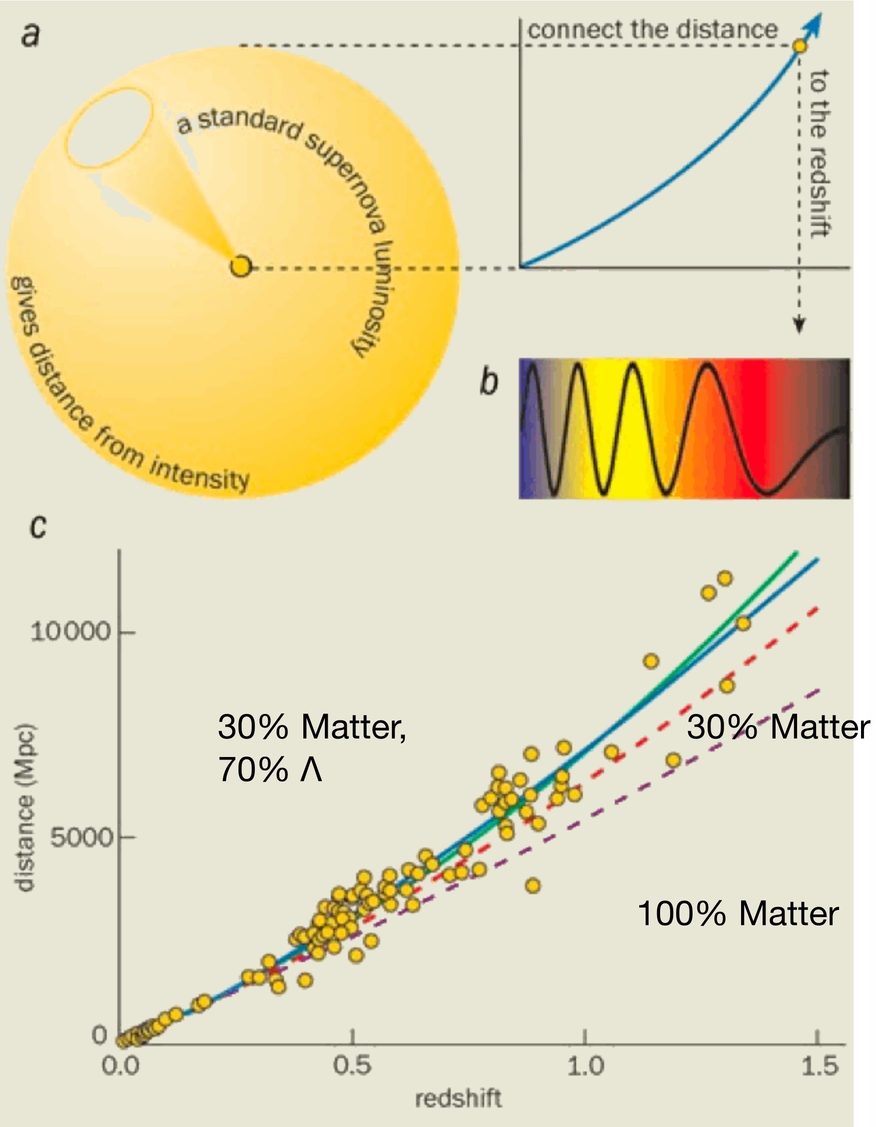
- CMB - fluctuations show that the universe is “flat”: $\Omega_\Lambda + \Omega_M = 1$



- Power spectrum contains information on baryonic and dark matter densities - extracted from “acoustic peaks”

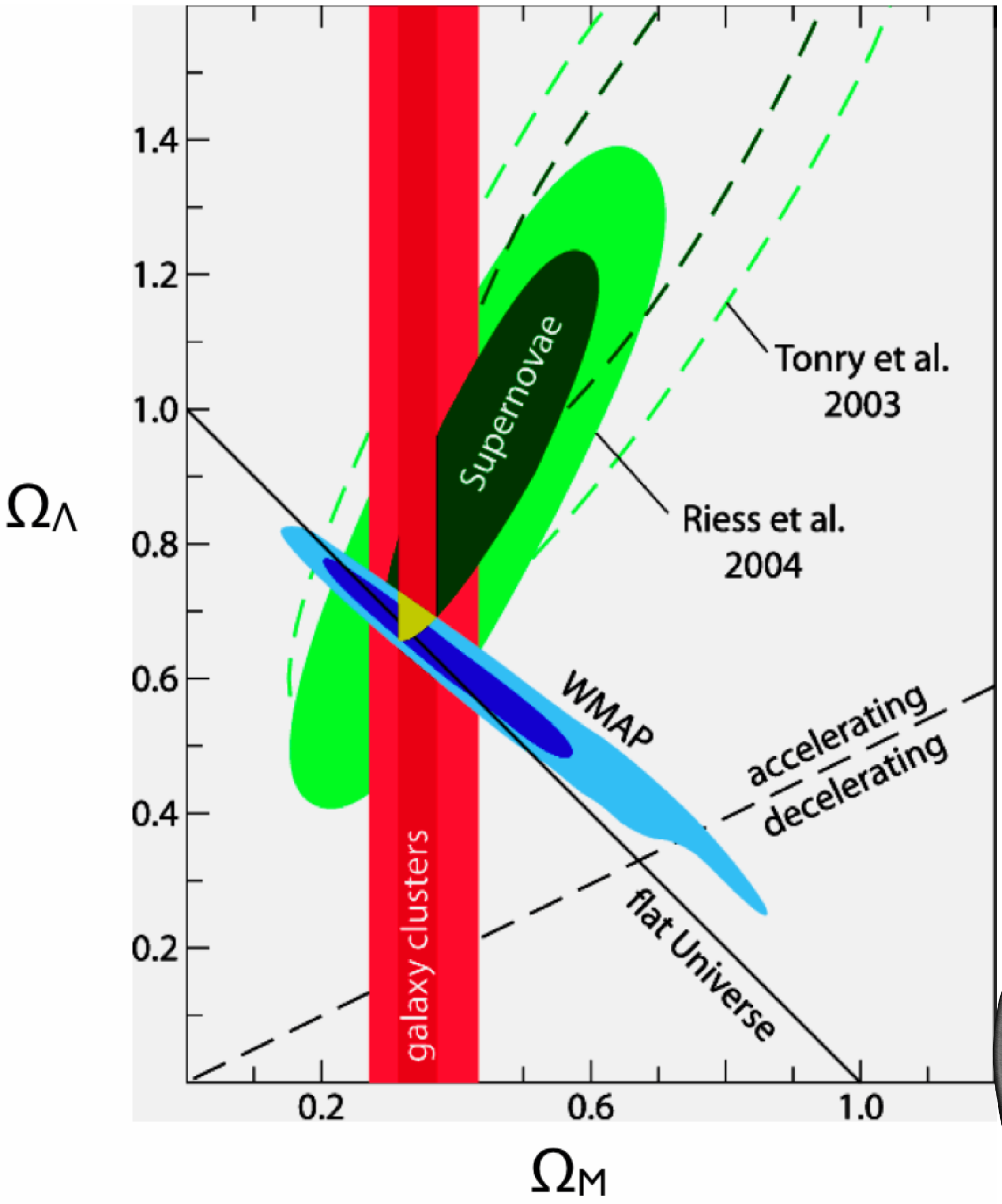
How do we know the composition?

- Supernova data show that the expansion is accelerating

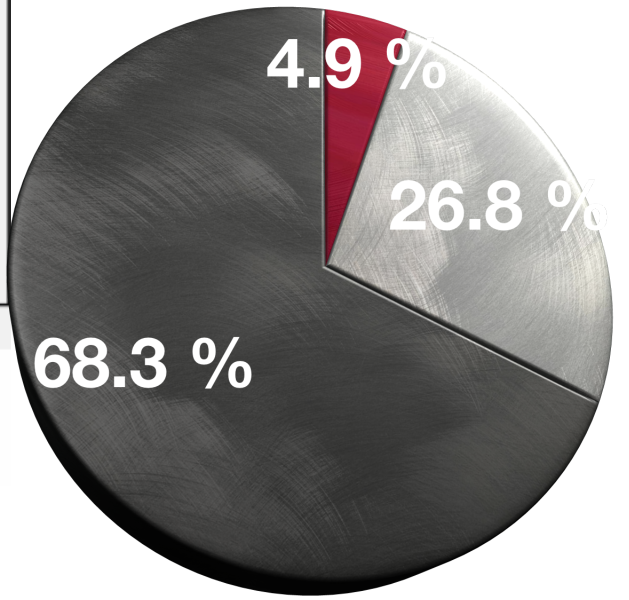


http://physicsworld.com/cws/article/print/19419

- All together:



The cosmic pie chart



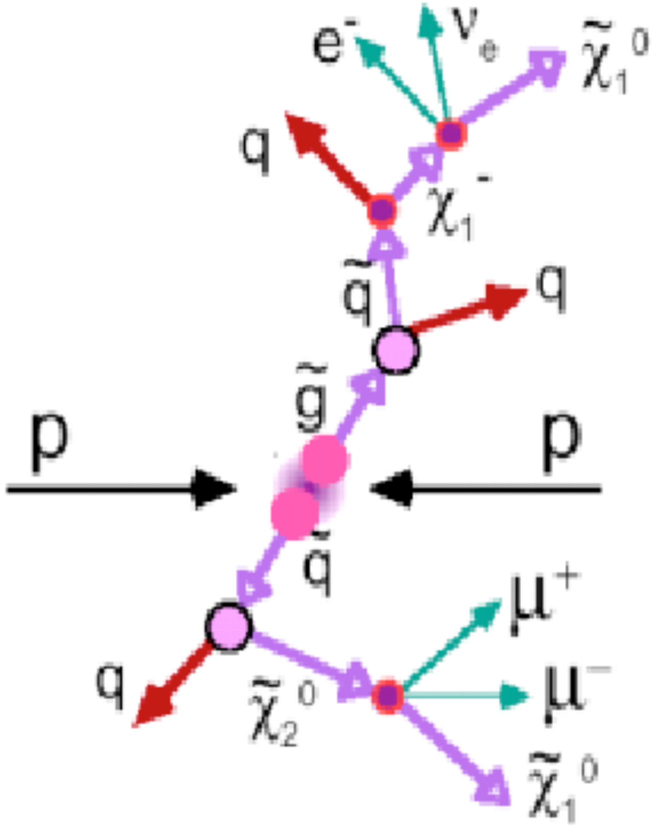
Fundamental Open Questions

- Particle Physics Experiments and Astronomical / Astrophysical Observations reveal unexplained phenomena currently not answered by the Standard Model
  - **“obvious” problems:**
    - What is Dark Matter? What is Dark Energy?
    - What caused the Matter / Antimatter asymmetry in the Universe?
      - Requires: Baryon Number violation, C and CP violation, Reactions out of thermal equilibrium (Sakharov Conditions)
    - How are Neutrino Masses generated?
    - …
  - ***“theoretically justified” problems:***
    - Origin of electroweak symmetry breaking
    - Hierarchy problem
    - …

Resolution *requires* new experimental evidence!

Strategies for Discovery in Particle Physics

- Two complementary approaches:



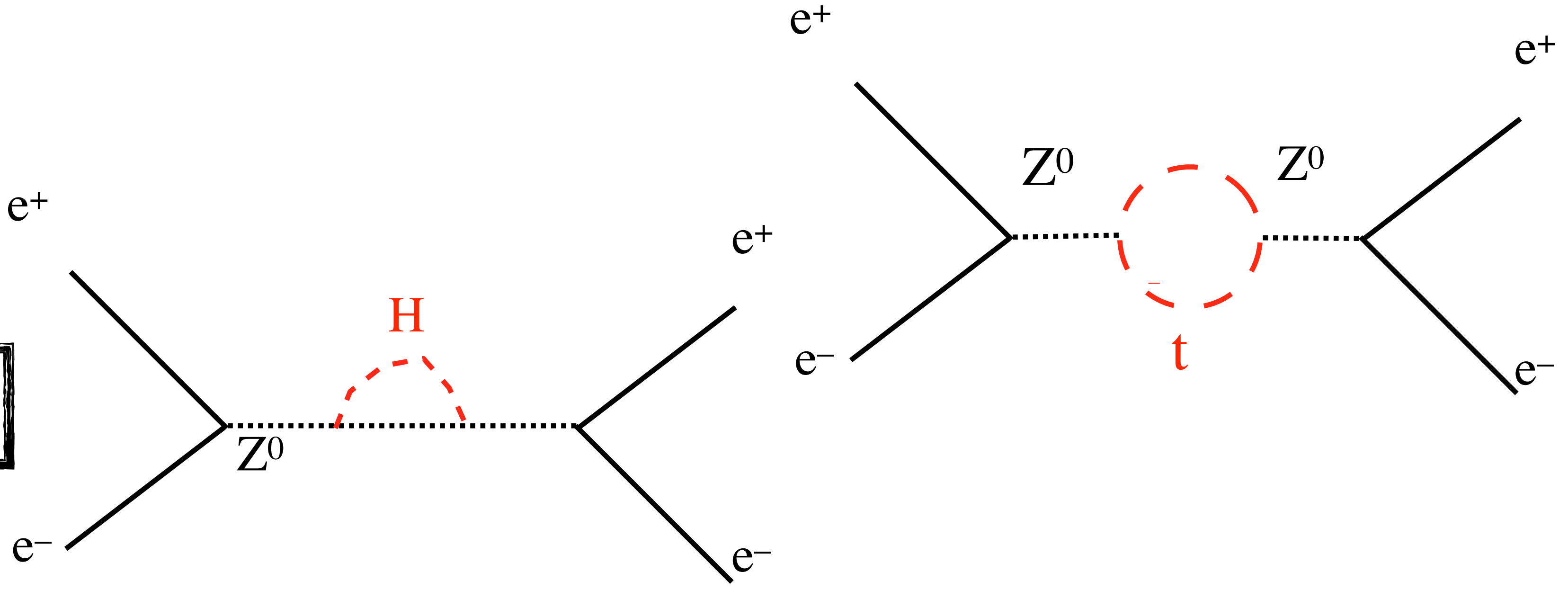
Direct searches at highest energies:

Production and detection of new particles

Precision measurements:

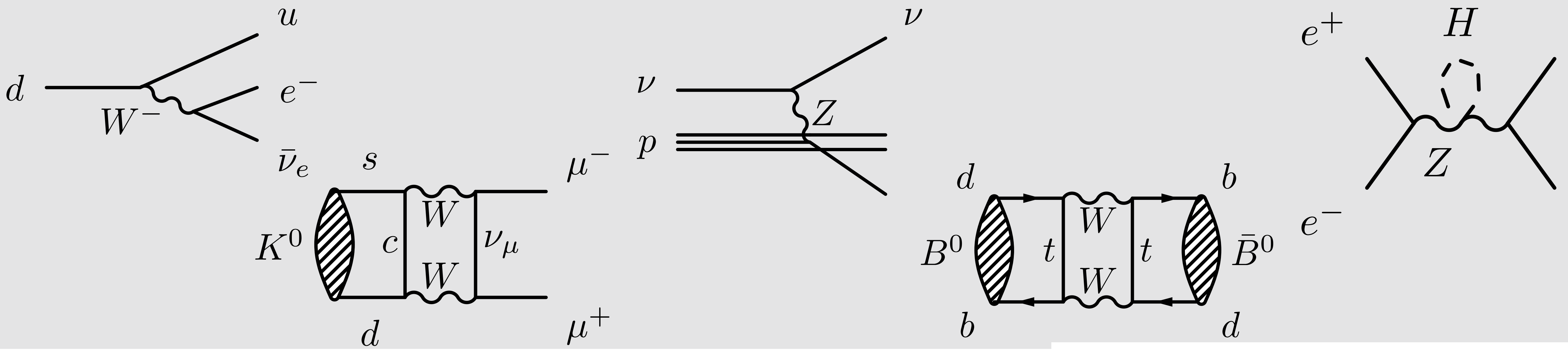
Indirect evidence for new particles in virtual quantum loops

The Emphasis in this semester



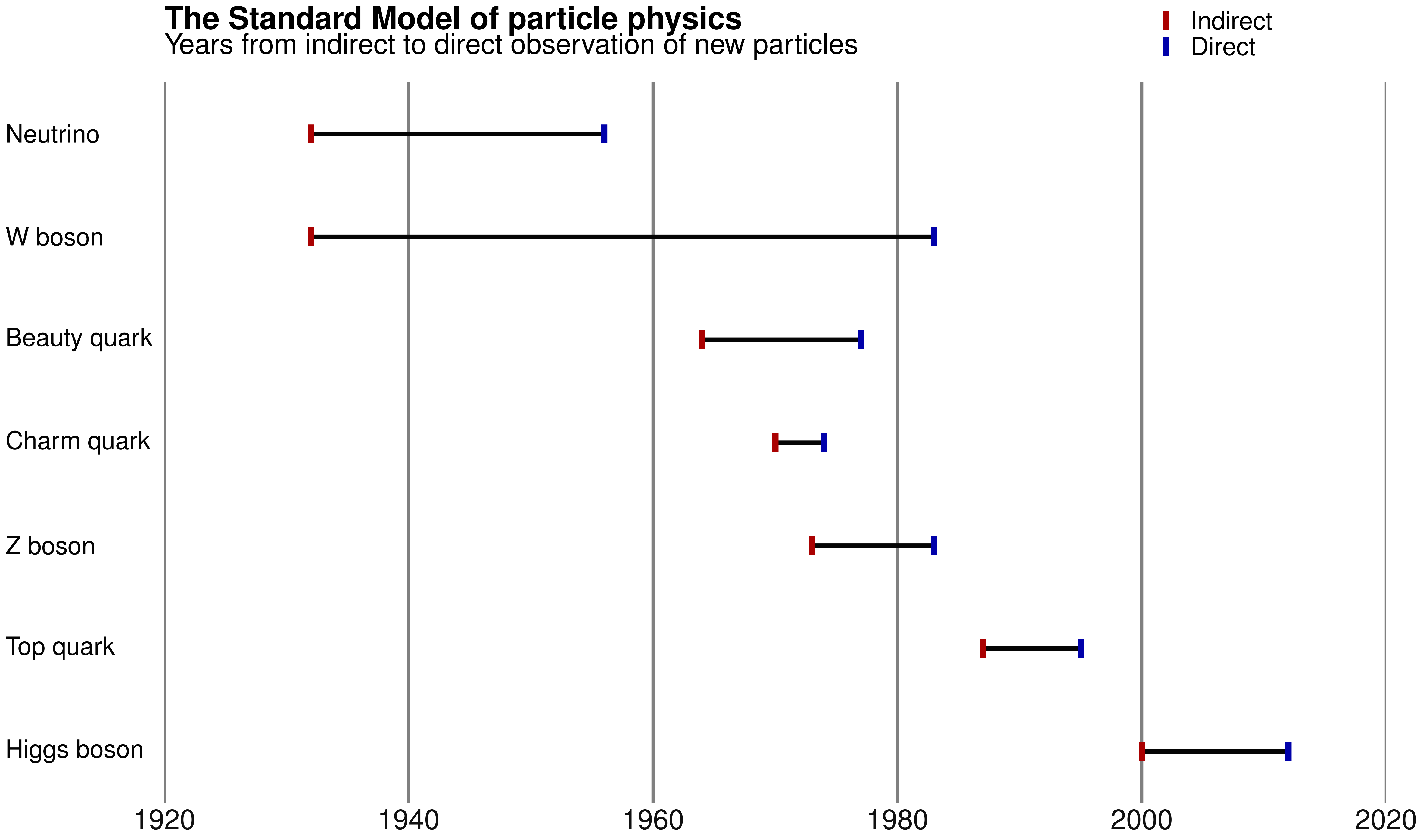
Indirect Discoveries: Brief History

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?



taken from Niels Turing, ICHEP 2018

Indirect Discoveries: Brief History



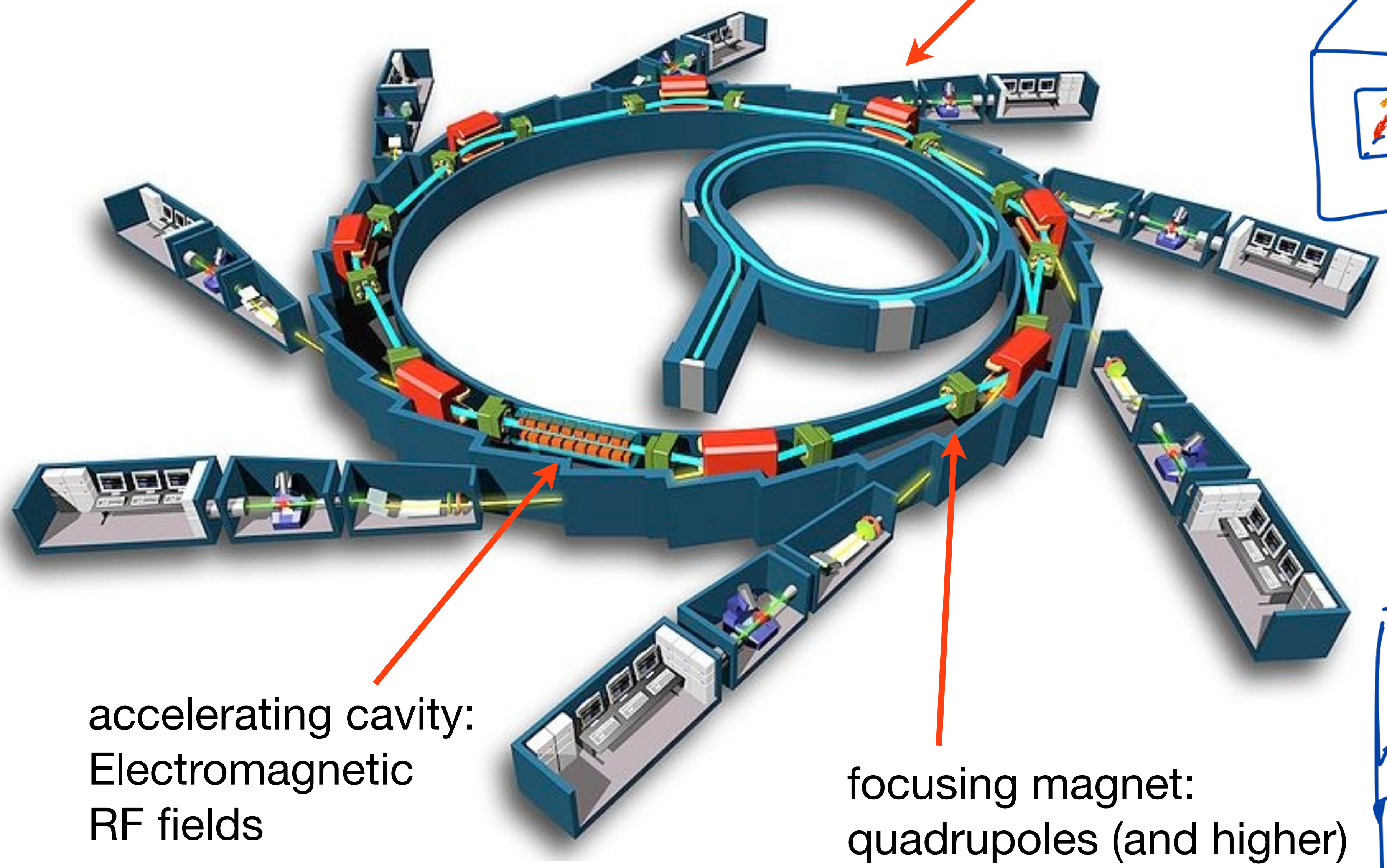
taken from Niels Turing, ICHEP 2018

Experimental Techniques in Particle Physics

Experimental Tools: Accelerators

- Acceleration of charged particles to (ultra)relativistic energies: GeV to TeV range

Mostly: Synchrotrons

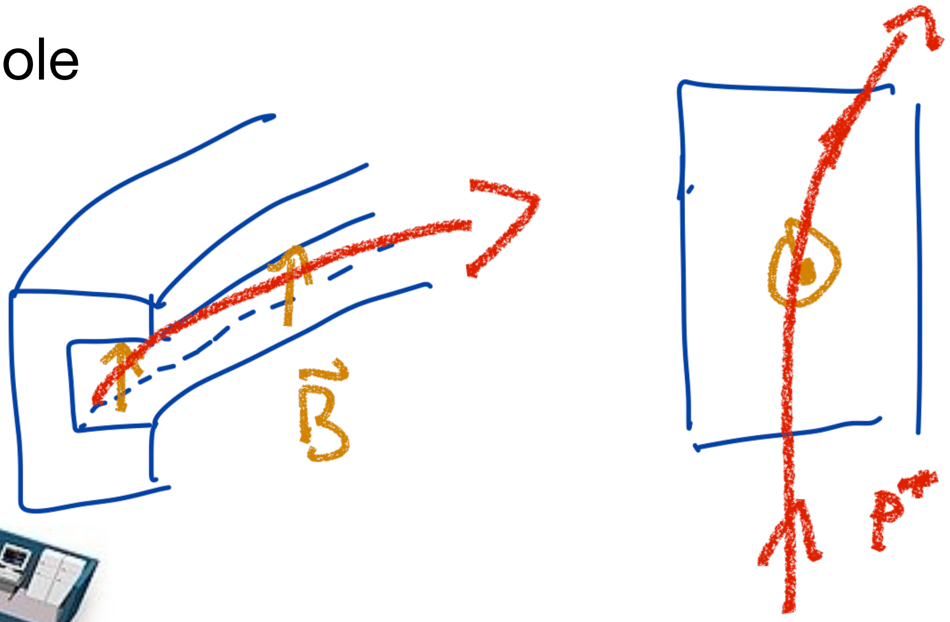


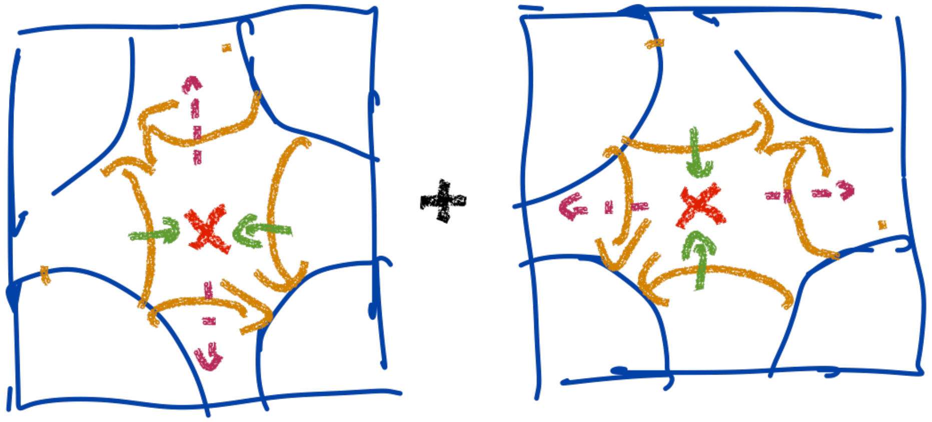
bending magnet: dipole

accelerating cavity:
Electromagnetic
RF fields

focusing magnet:
quadrupoles (and higher)

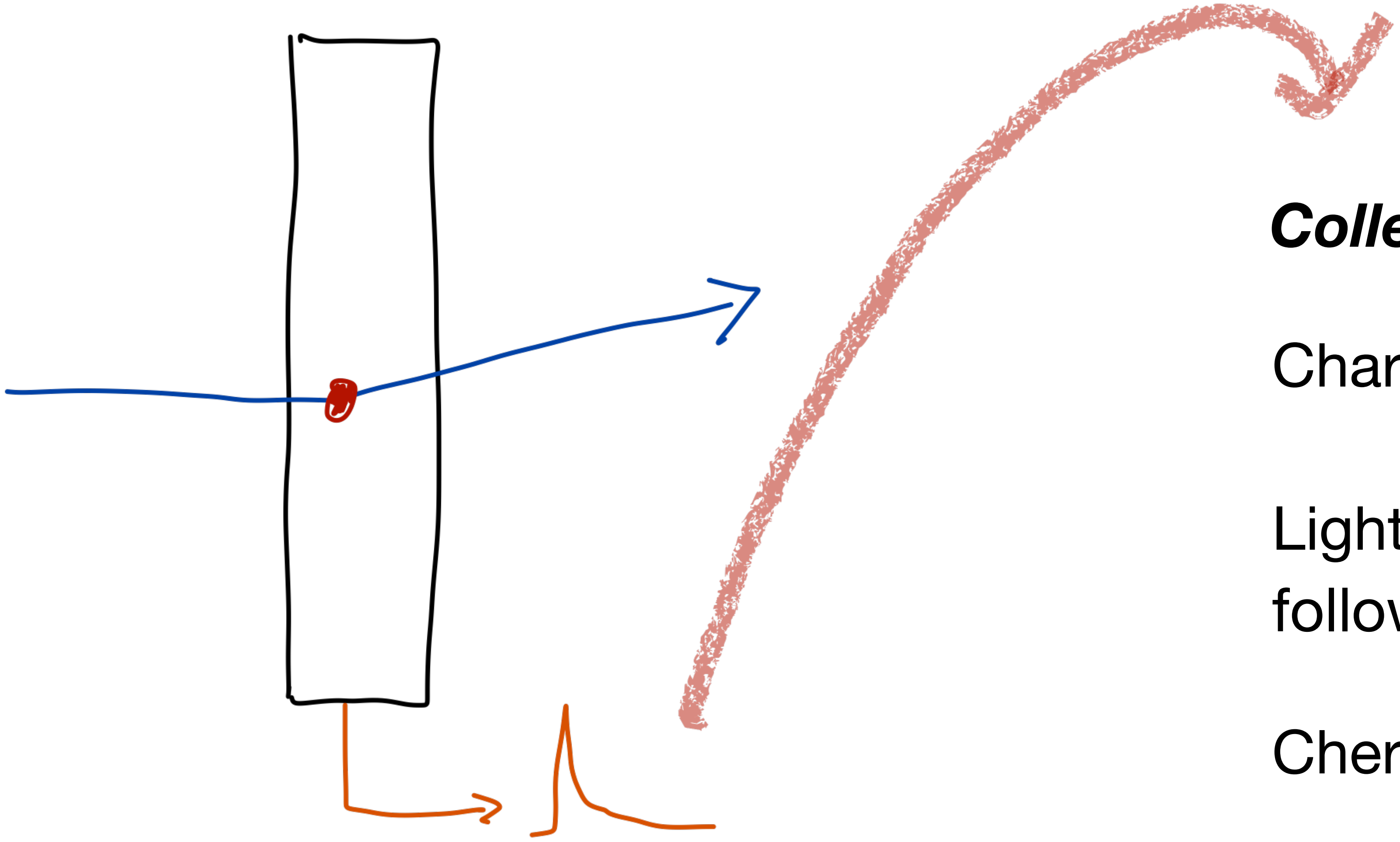
credit:EPSIM 3D/JF Santarelli, Synchrotron Soleil





Experimental Tools: Particle Detectors

- The goal of a particle detector: Provide sensitivity to particles by generating a signal from interactions with detector material



Collect:

Charge from ionisation

Light produced by scintillation following ionisation

Cherenkov light

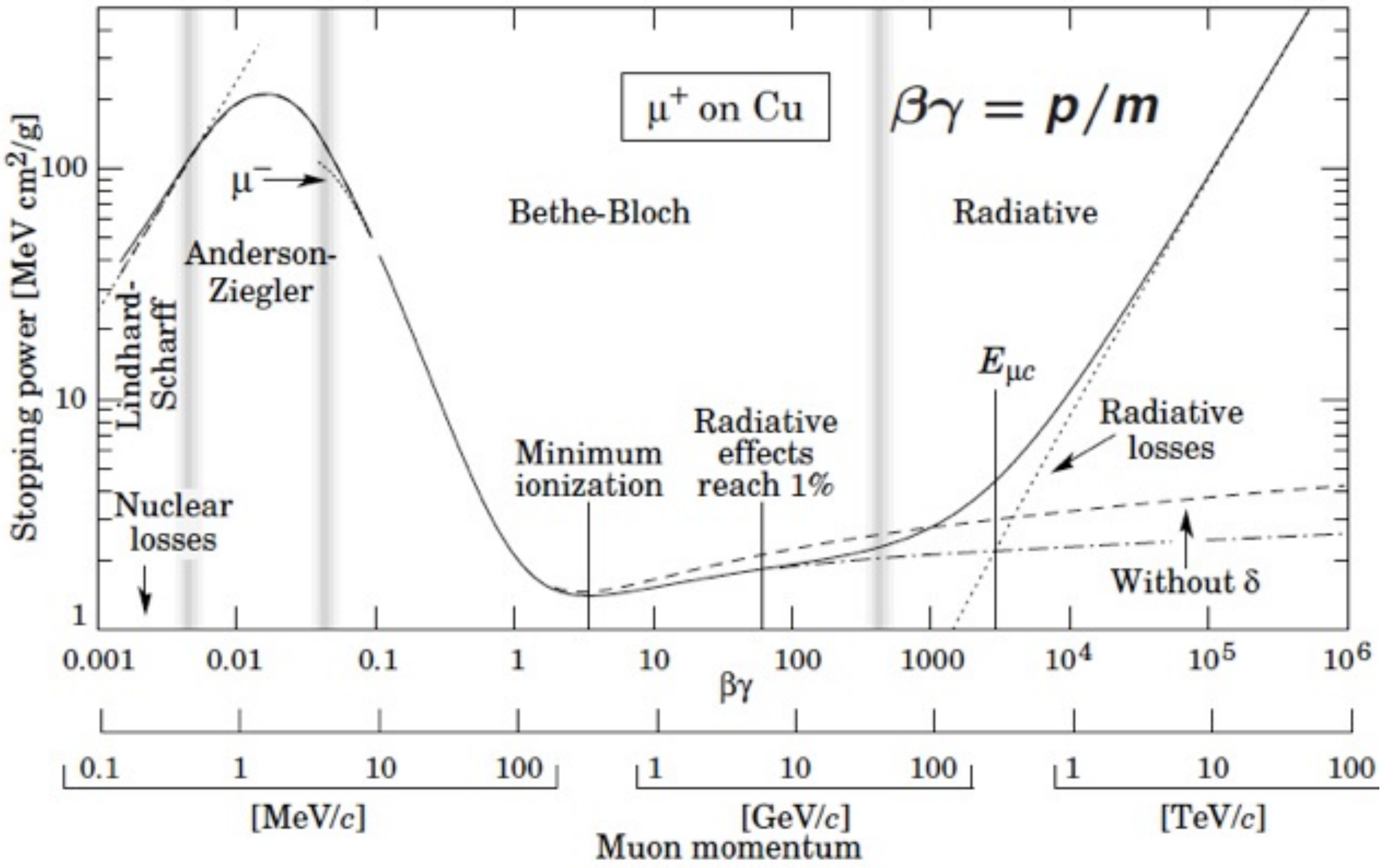
…

Particle Detectors: Energy Loss in Matter

- Ionisation energy loss: Most prominent interaction - and signal generation mechanism

Described by **Bethe-Bloch equation**

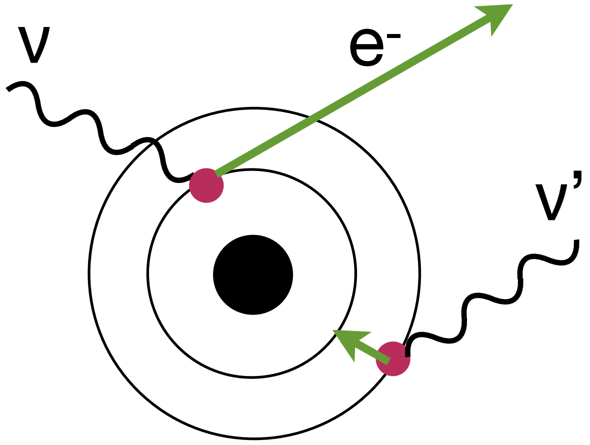
$$\underbrace{-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]}_{\longleftrightarrow}$$



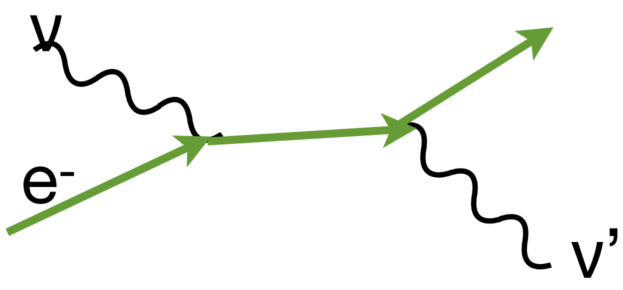
- Valid in intermediate energy range: ~0.1 < βγ < ~ 1000
  - at low energies: atomic effects at high energies: radiative energy loss in addition
- Z/A Dependence: high energy loss in H
- $1/\beta^2$ for low momenta: Heavy particles loose more energy
- Minimum at p/m ~ 3-4: minimum ionizing particle MIP
- Logarithmic rise for high energy
- Additional density effect due to polarization of absorber

Interaction of Photons

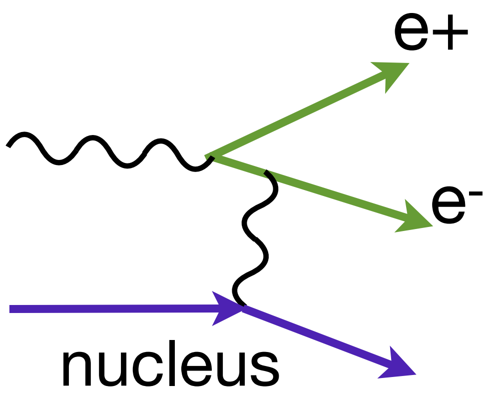
Photo effect



Compton scattering



Pair creation



energy threshold:
2 m_e = ~1.022 MeV

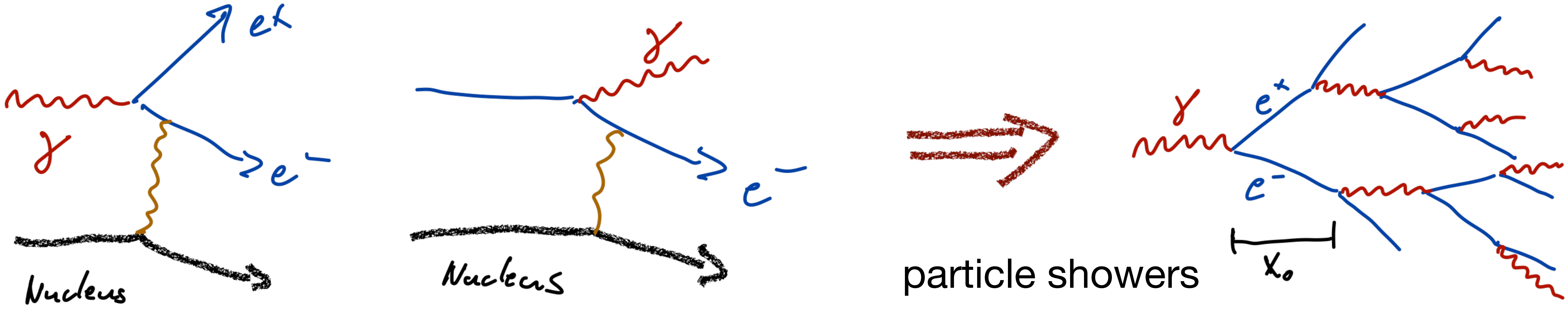
- In contrast to dE/dx of charged particles:
  "all-or-nothing" reactions with a certain probability

➪ Decrease of photon intensity with material thickness

$$I(x) = I_0 e^{-\mu x}$$

High-Energy Electrons and Photons

- Two related processes: Pair Production and Bremsstrahlung

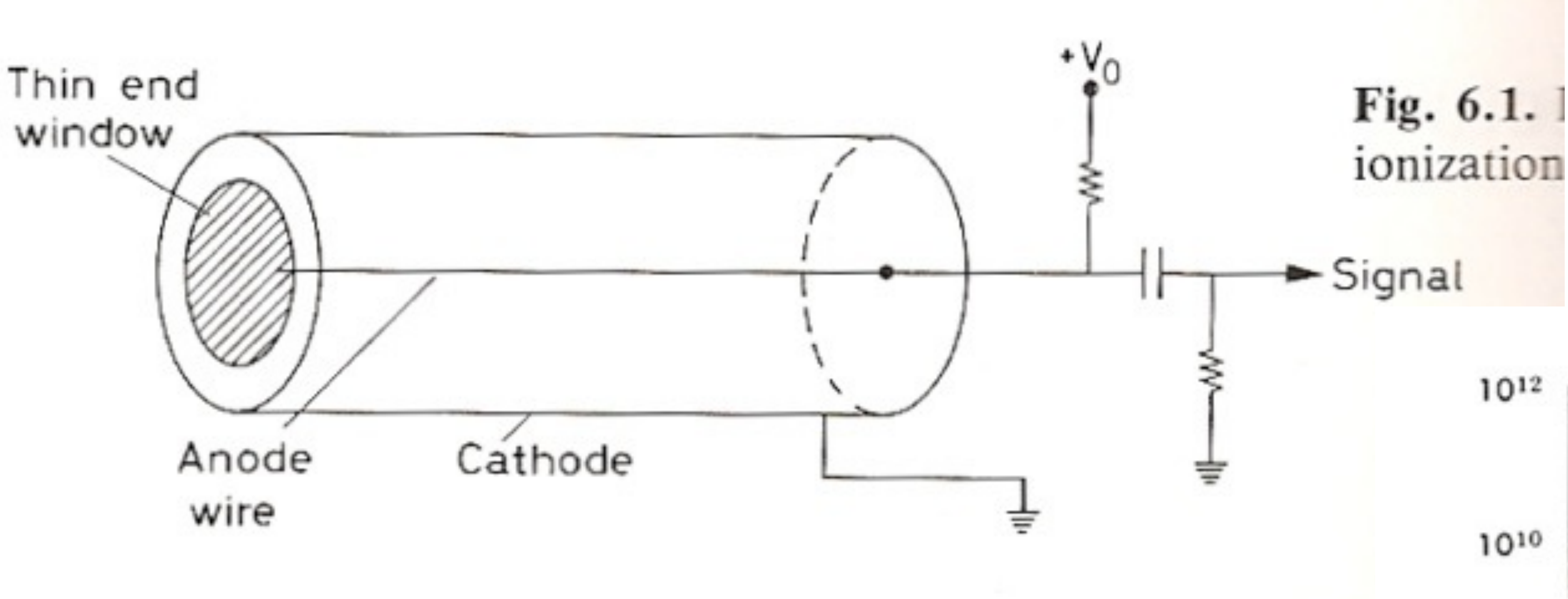


particle showers

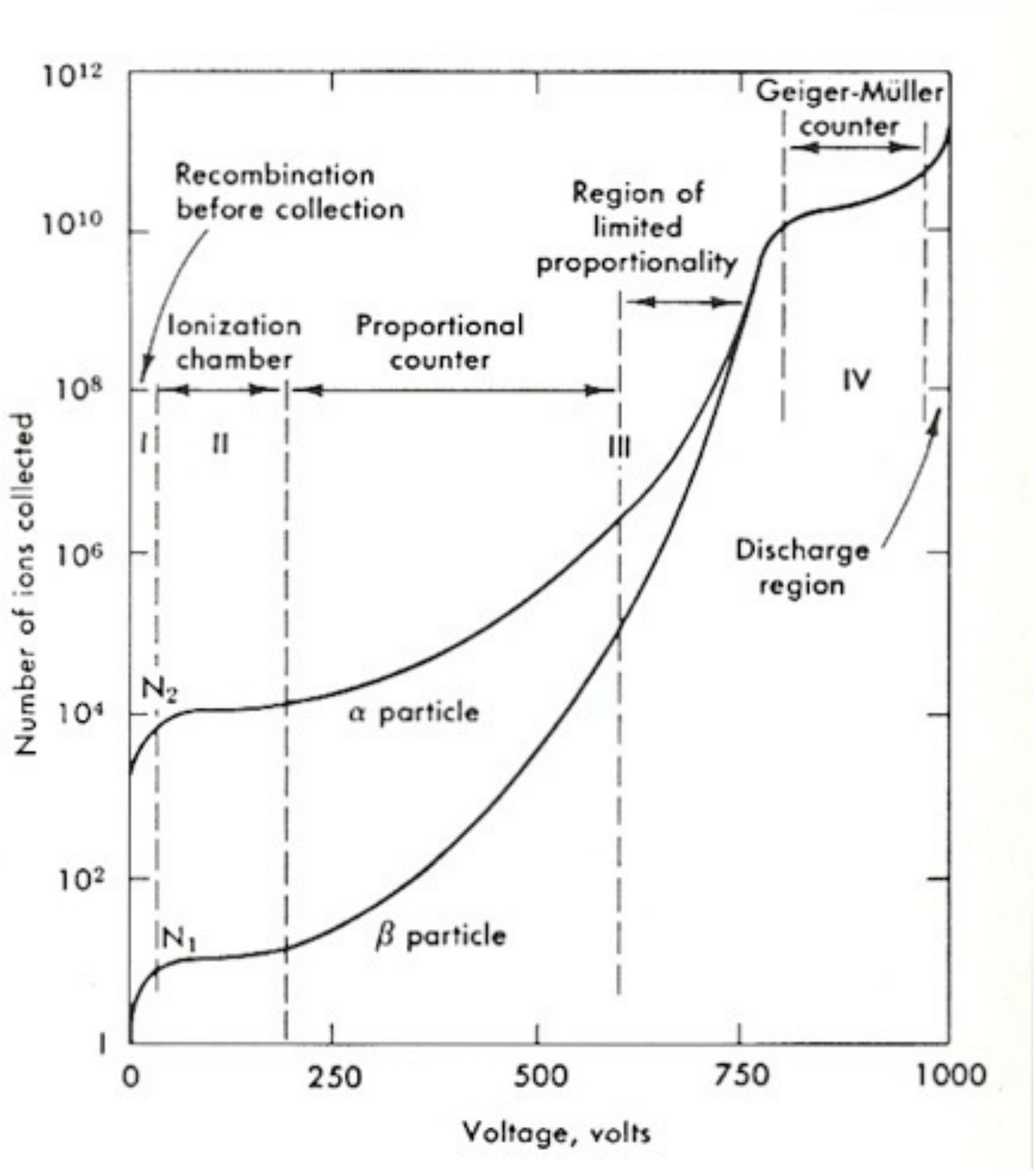
- The relevant length scale: one radiation length
  - Describes high-energy electrons and photons (Energy loss via Bremsstrahlung and e^+e^- - pair creation, respectively)
  - Defined as the amount of matter that has to be traversed such that
    - an electron loses all but 1/e of its energy via Bremsstrahlung
    - 7/9 of the mean free path for pair creation for high-energy photons

empirical: $$X_0 = \frac{716.4\,A}{Z(1+Z)\,ln(287/\sqrt{Z})}\,\frac{g}{cm^2} \propto \frac{A}{Z^2}$$

Detection Techniques: Ionization

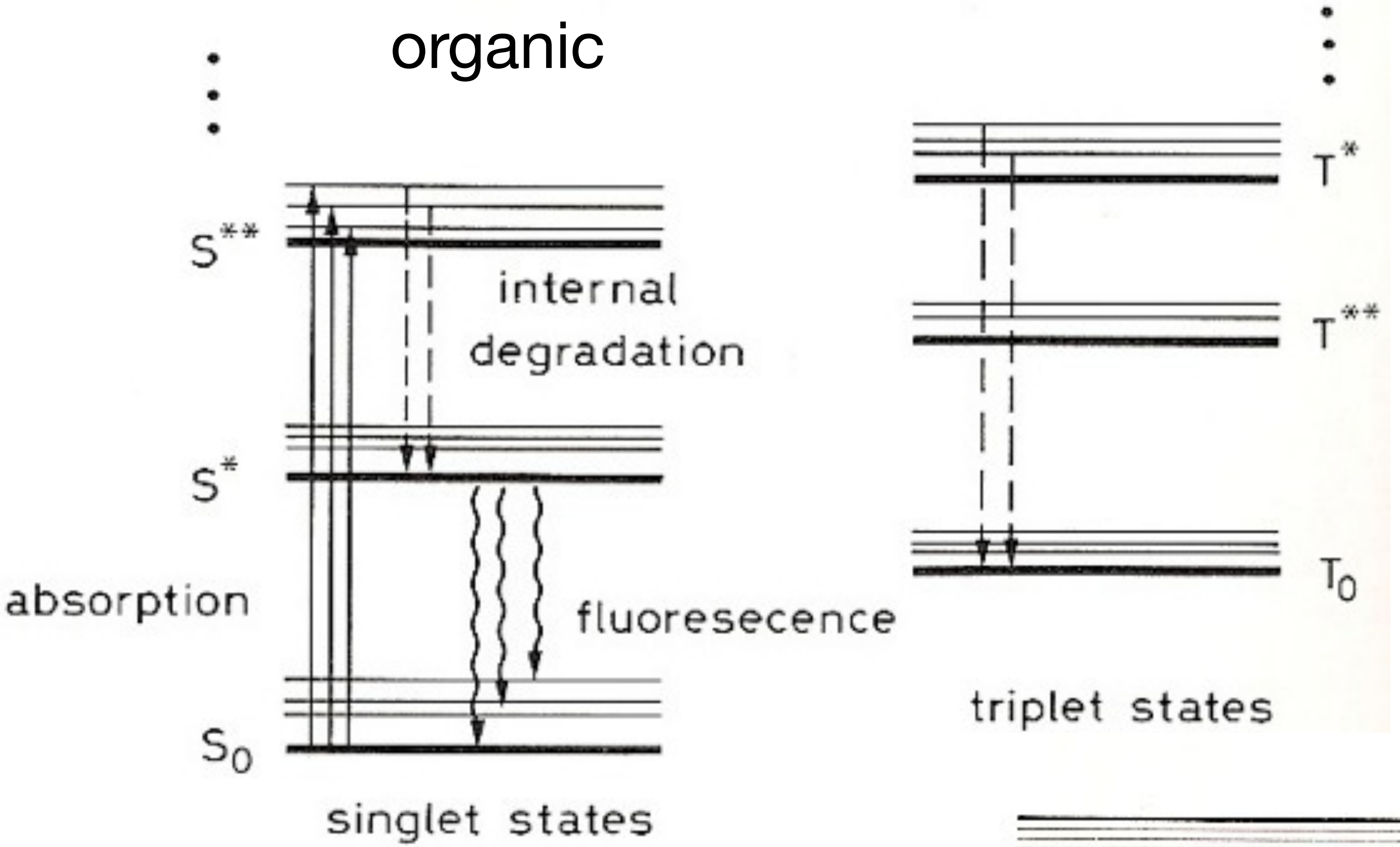


- Passage of particles creates electron-ion pairs in the gas volume
- Electrons are accelerated by strong electric field - avalanche multiplication takes place
- Depending on the voltage the signal is either proportional to the originally deposited charge, or goes into saturation



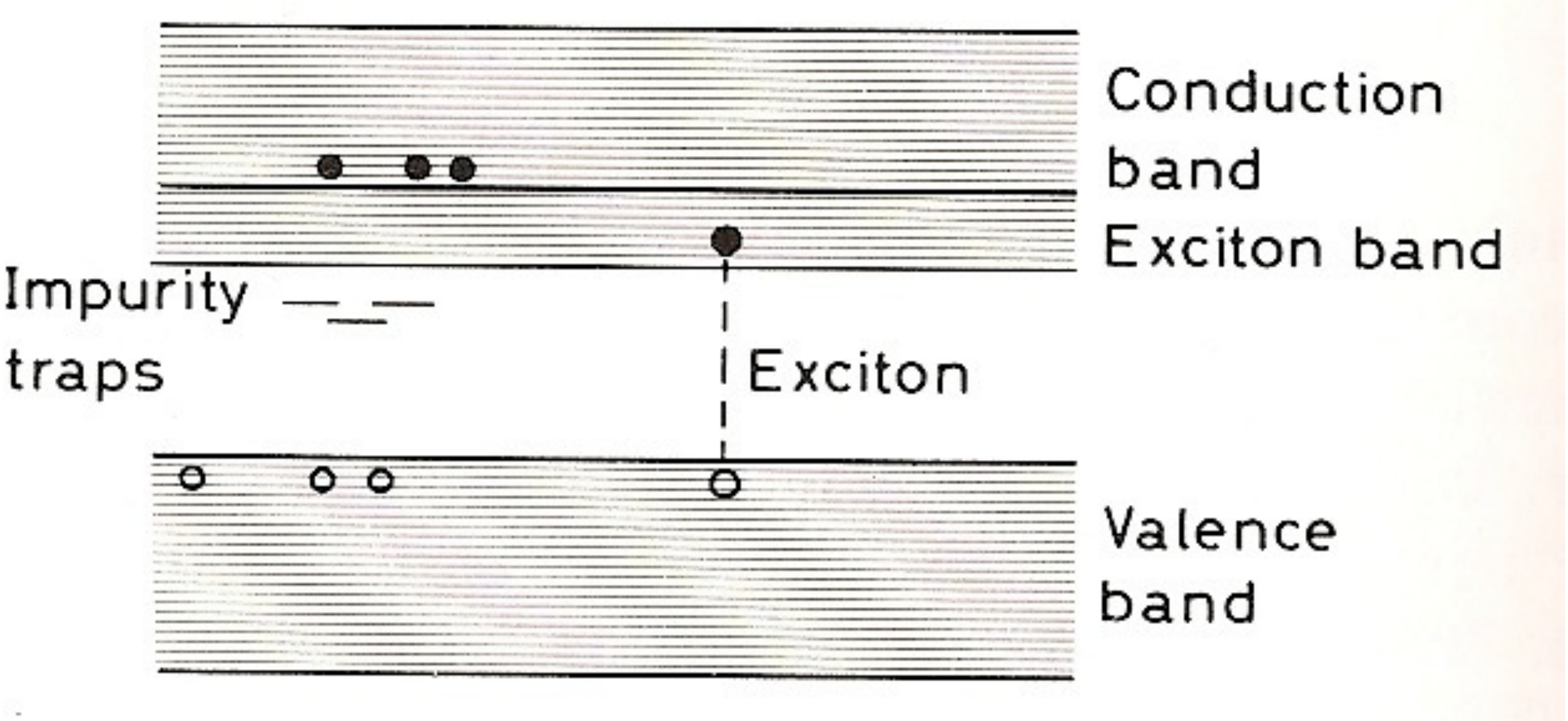
Detection Techniques: Szintillation

organic



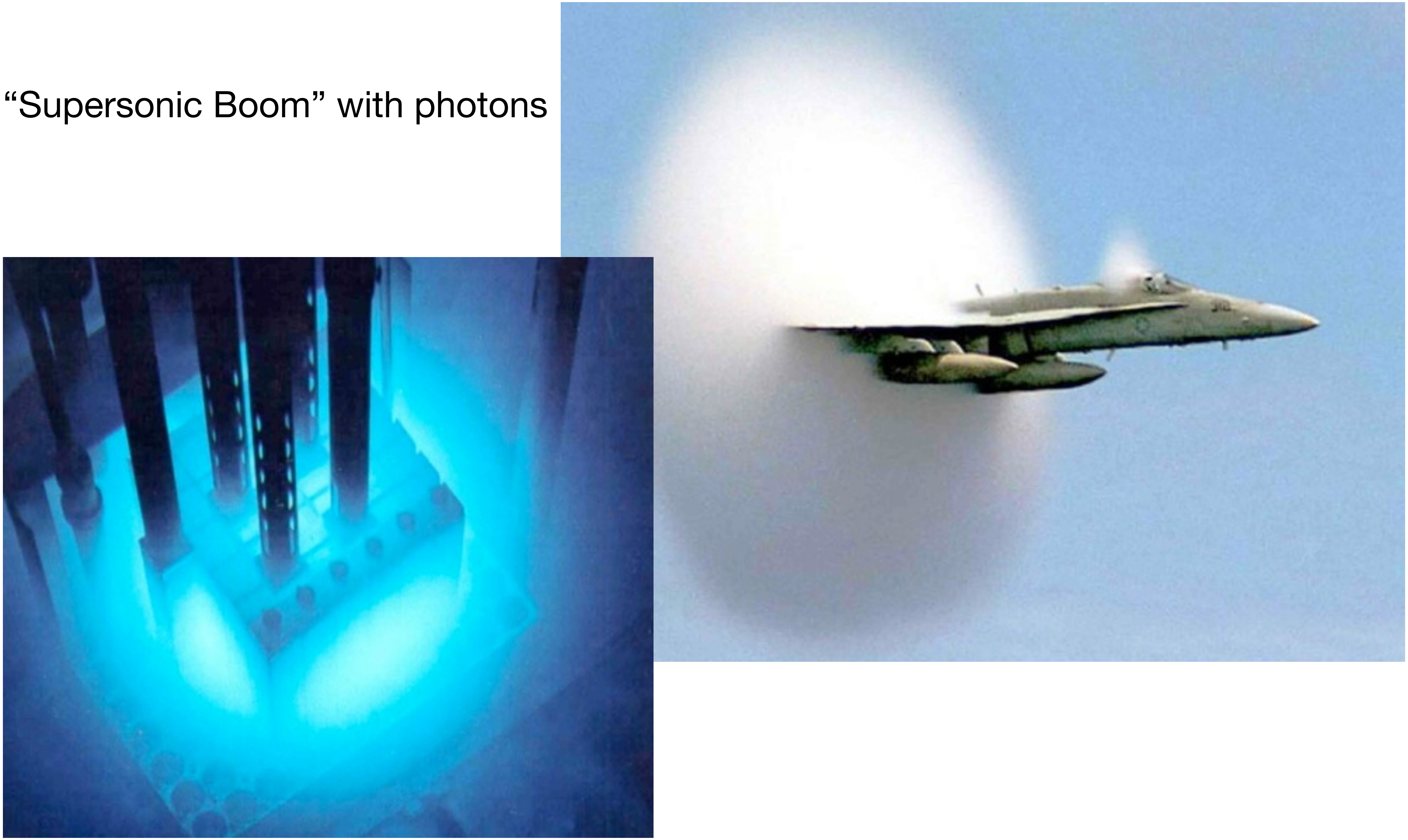
- Scintillators emit light when traversed by ionizing particles
  - Excitation of atomic and molecular states, metastable states (organic scintillators) or Defects in Crystals (inorganic scintillators)

inorganic:

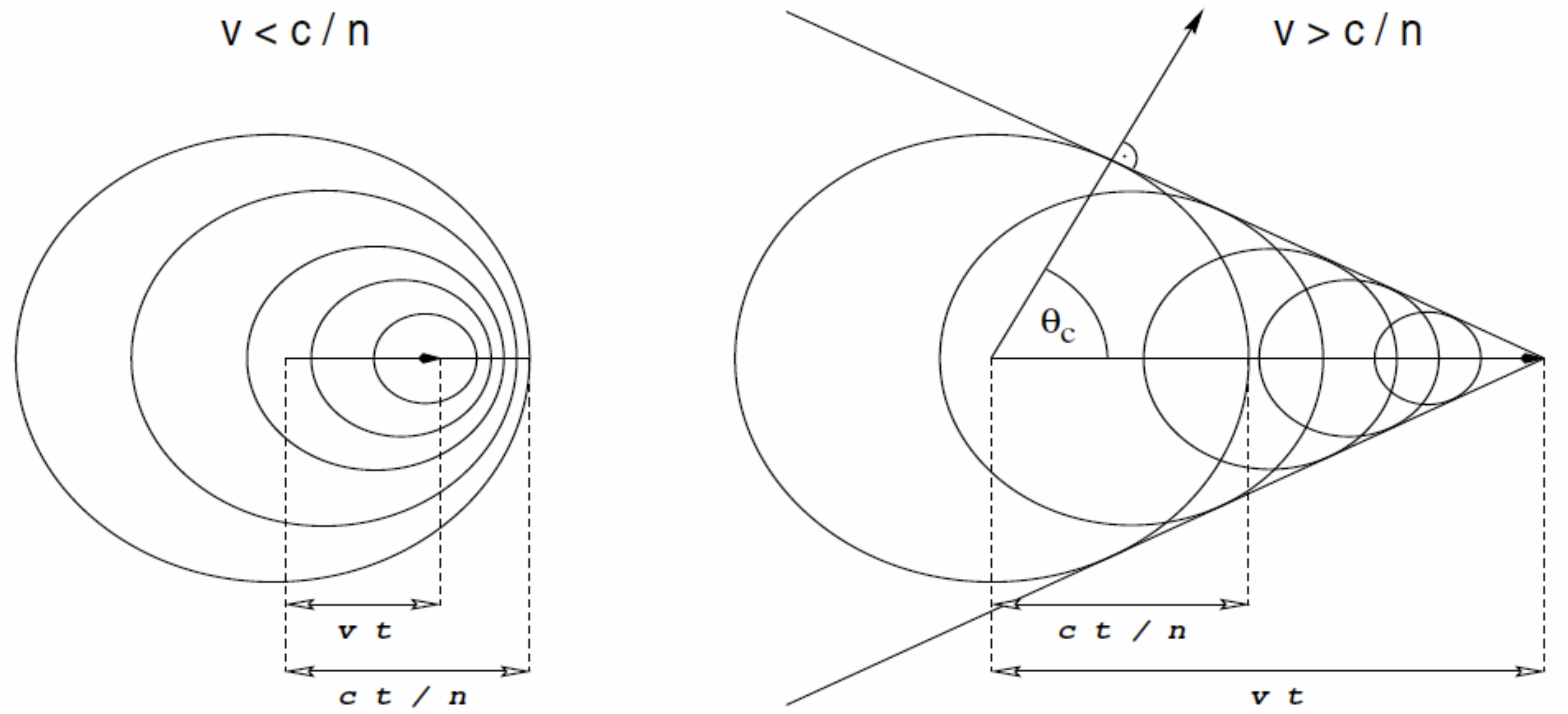


Detection Techniques: Cherenkov Light

“Supersonic Boom” with photons



Detection Techniques: Cherenkov Light



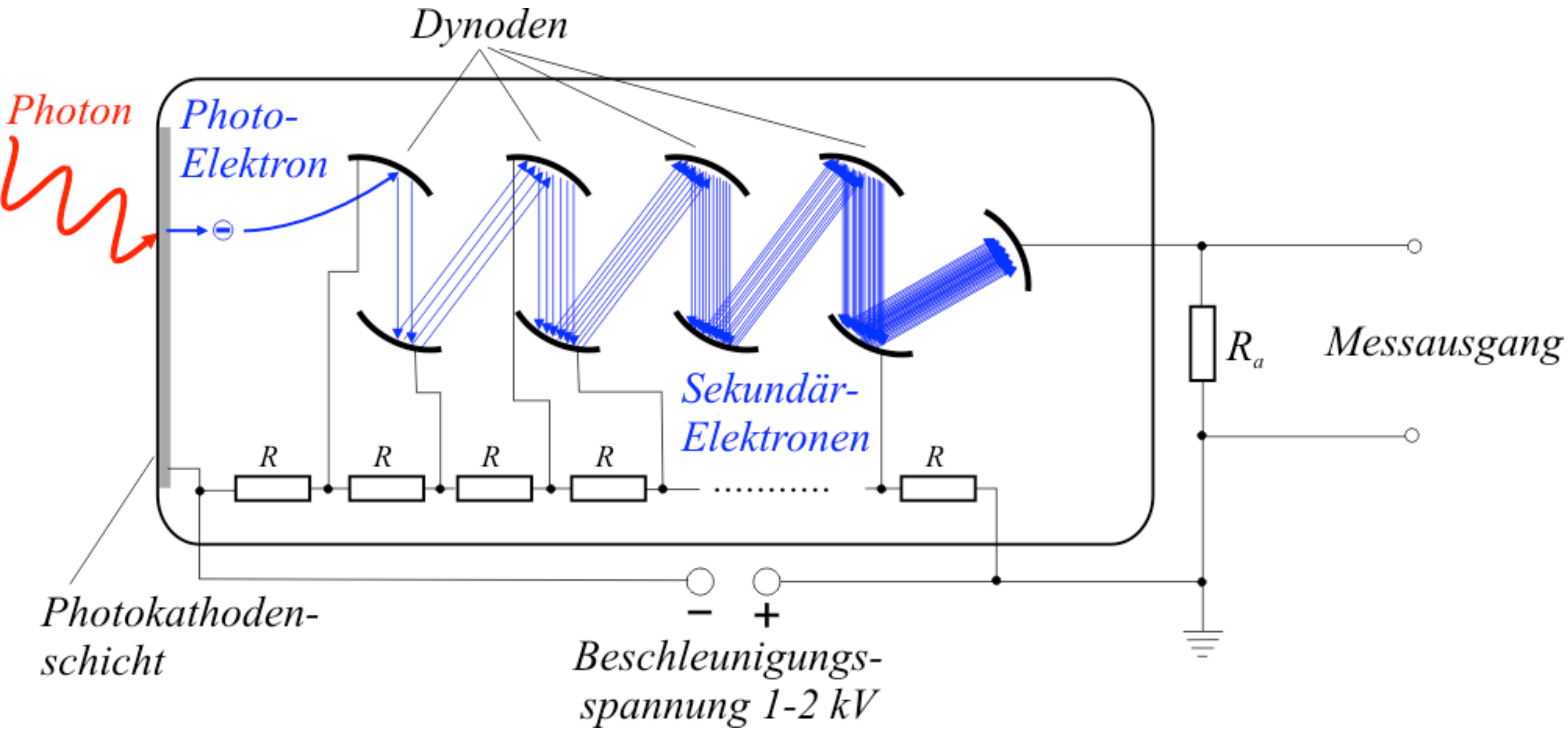
- Emission of photons by charged particles which are faster than the speed of light in the medium: constructive interference

Emission with a characteristic angle:

$$\cos\theta_c = \frac{c\,t\,/\,n}{v\,t} = \frac{1}{n\beta}$$

Detection Techniques: Light Detection

- The classic way to detect visible (or near-visible) photons:



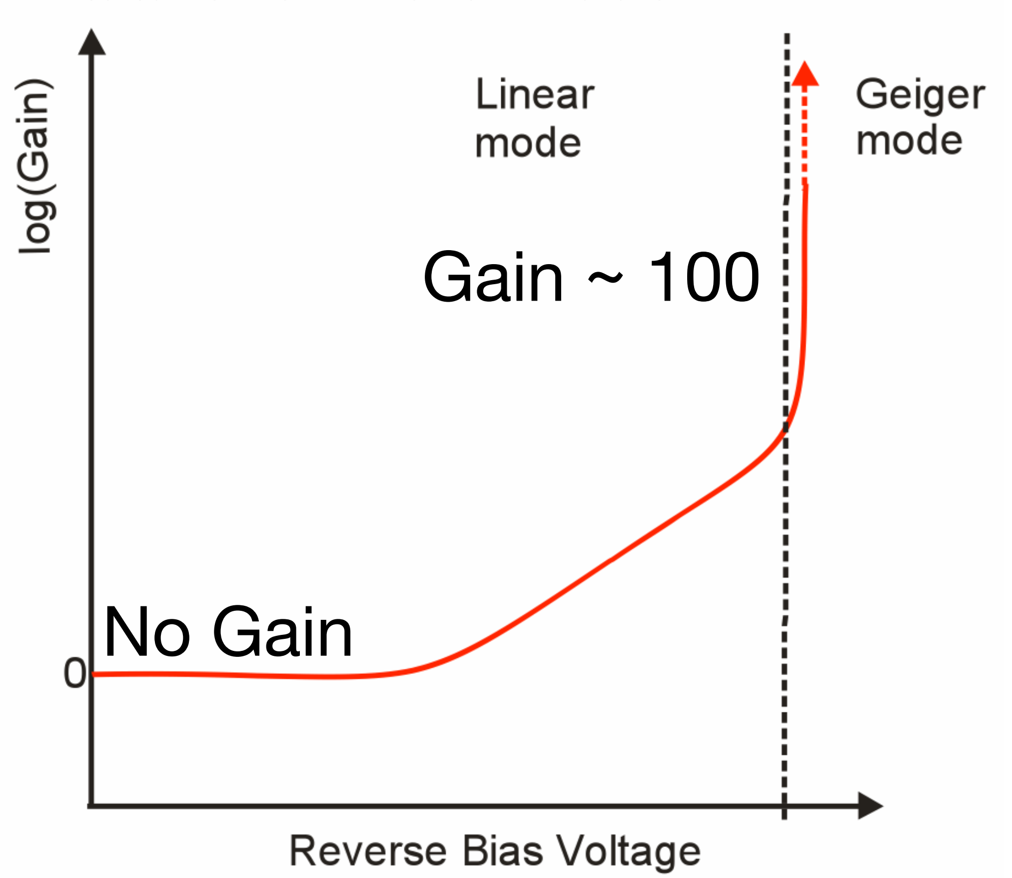
- Conversion of the photon to a photo-electron on a photo-cathode
- Amplification of single-electron signal to a detectable signal with several dynodes

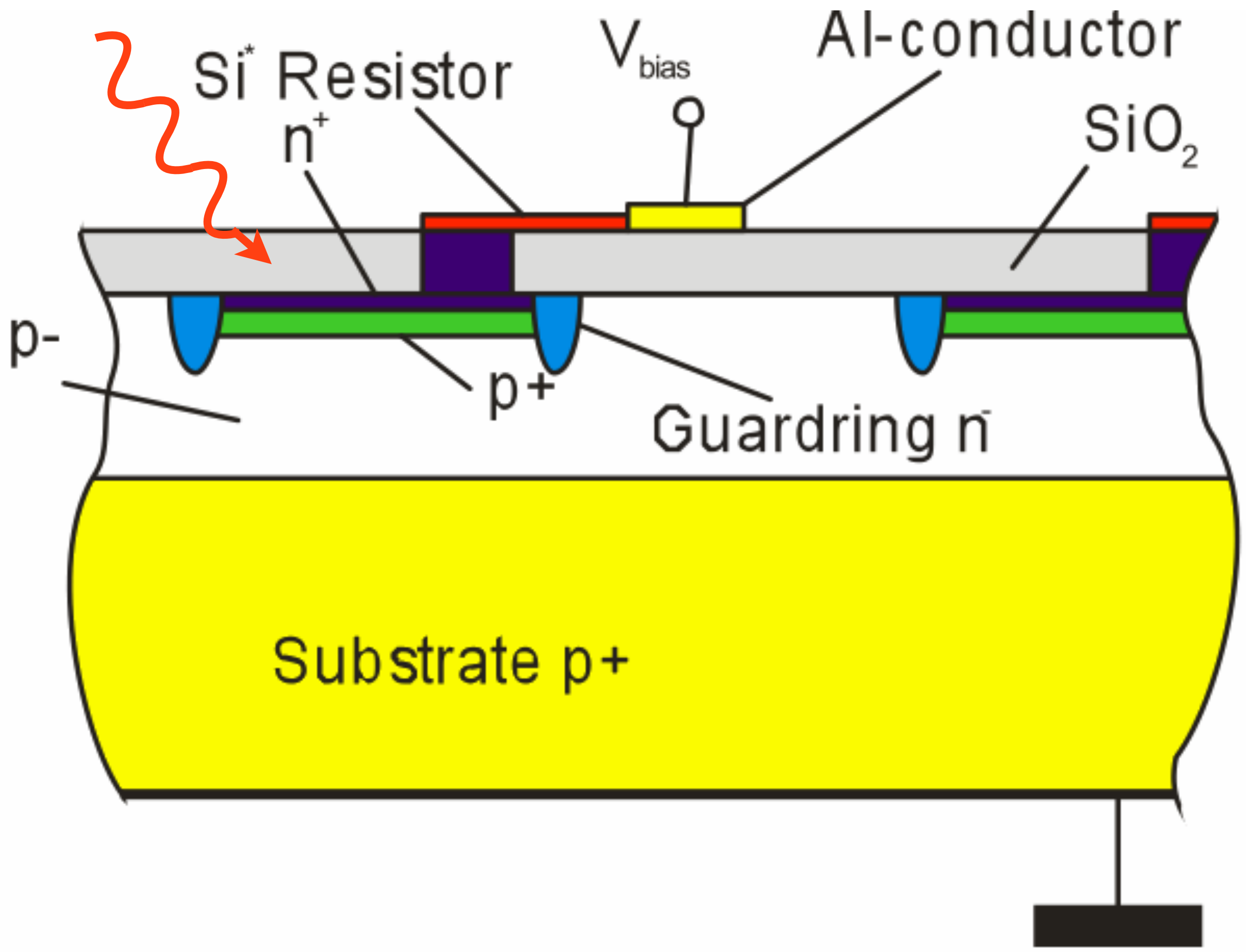
- Suited for a wide range of wavelengths ranging from UV to IR, good efficiency, up to ~ 25% (with special techniques up to ~ 40%), single photons can be detected
- Large active areas are possible: SuperKamiokande uses PMTs with an active area 460 mm in diameter

Detection Techniques: Light Detection with Silicon

- Silicon detectors can also be used to detect visible photons, but:
    - Photo effect only creates a single electron-hole pair (very different from the situation with charged particles): Amplification is crucial!
    - ▸ The usual charge amplification of up to ~100 reachable in silicon is insufficient to detect single photons with high efficiency n

Avalanche Photo Diode APD

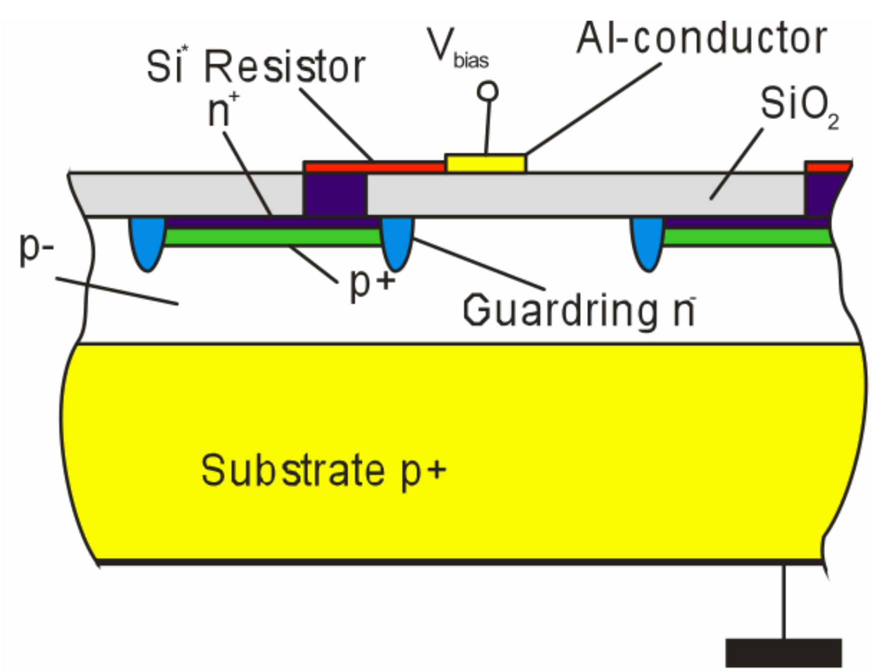


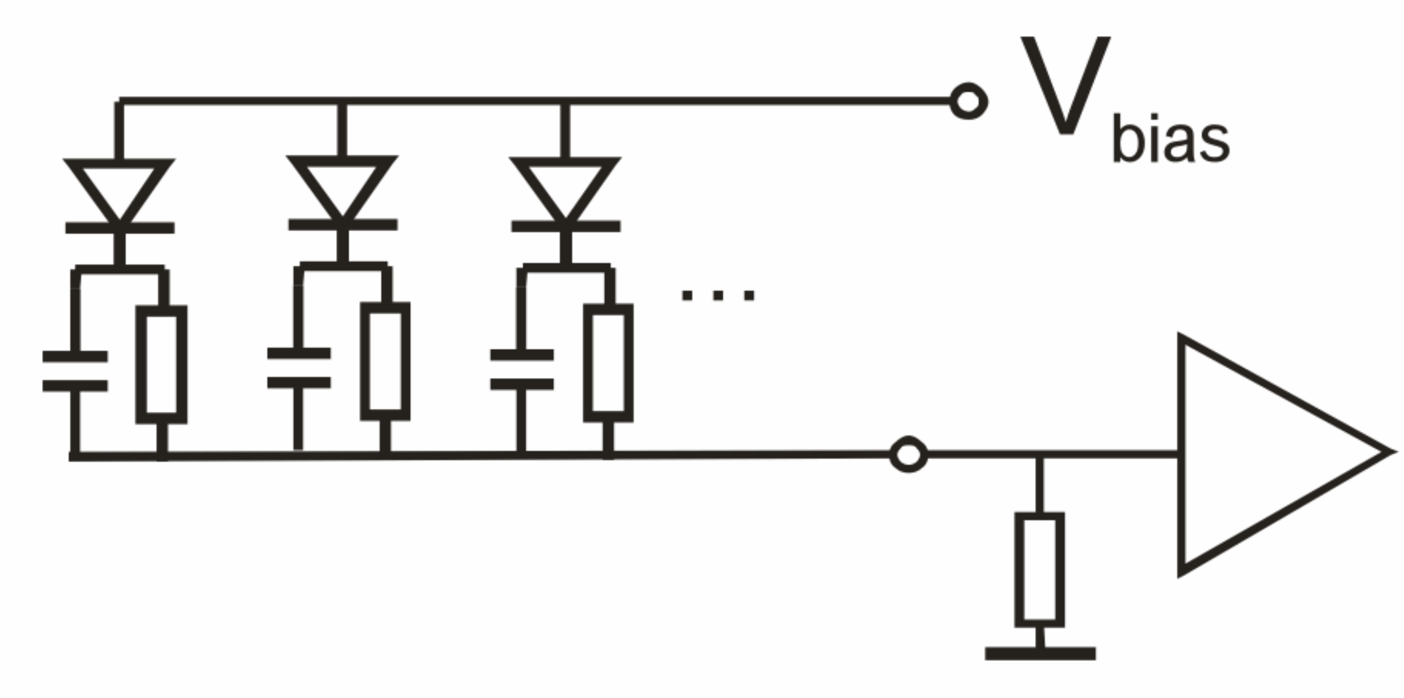


Detection Techniques: Light Detection with Silicon

- Highest amplification (~ 10^6) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons
- The trick: Put many small APDs on a chip, read out the summed-up signal
  - Easy handling: Only one channel (as a PMT, hence the name)
  - Extreme amplification: Detection of single photons not a problem!

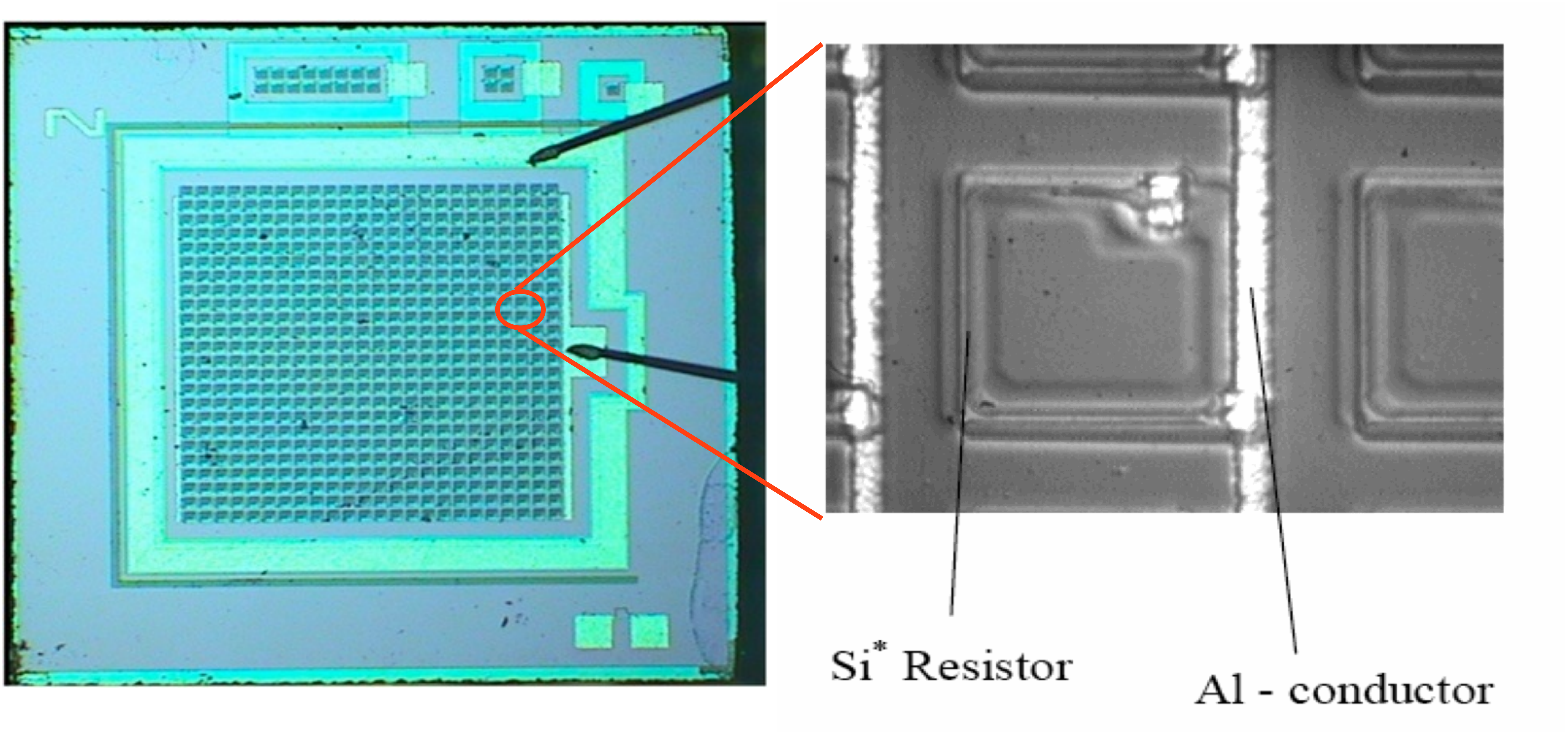
N x



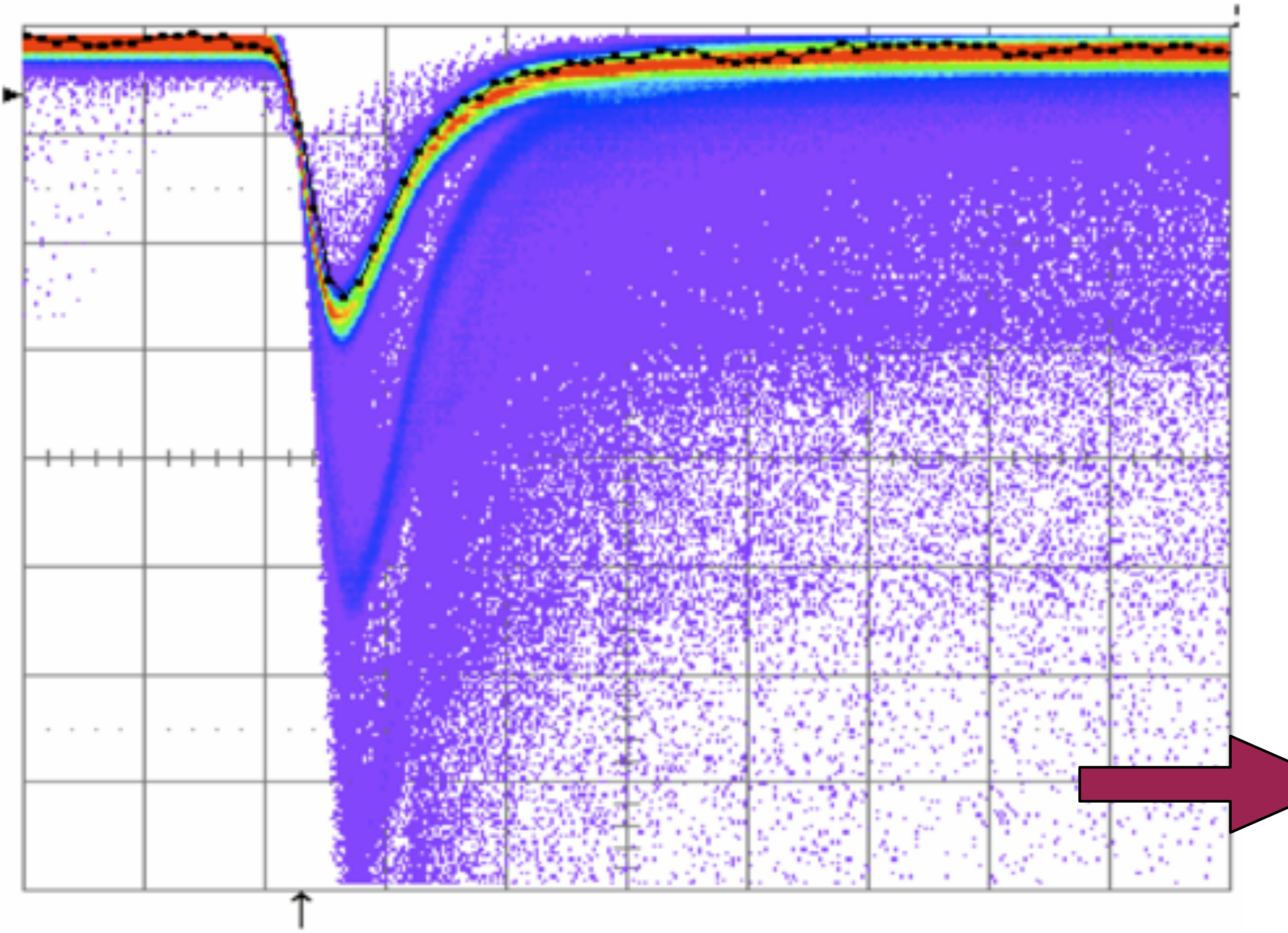


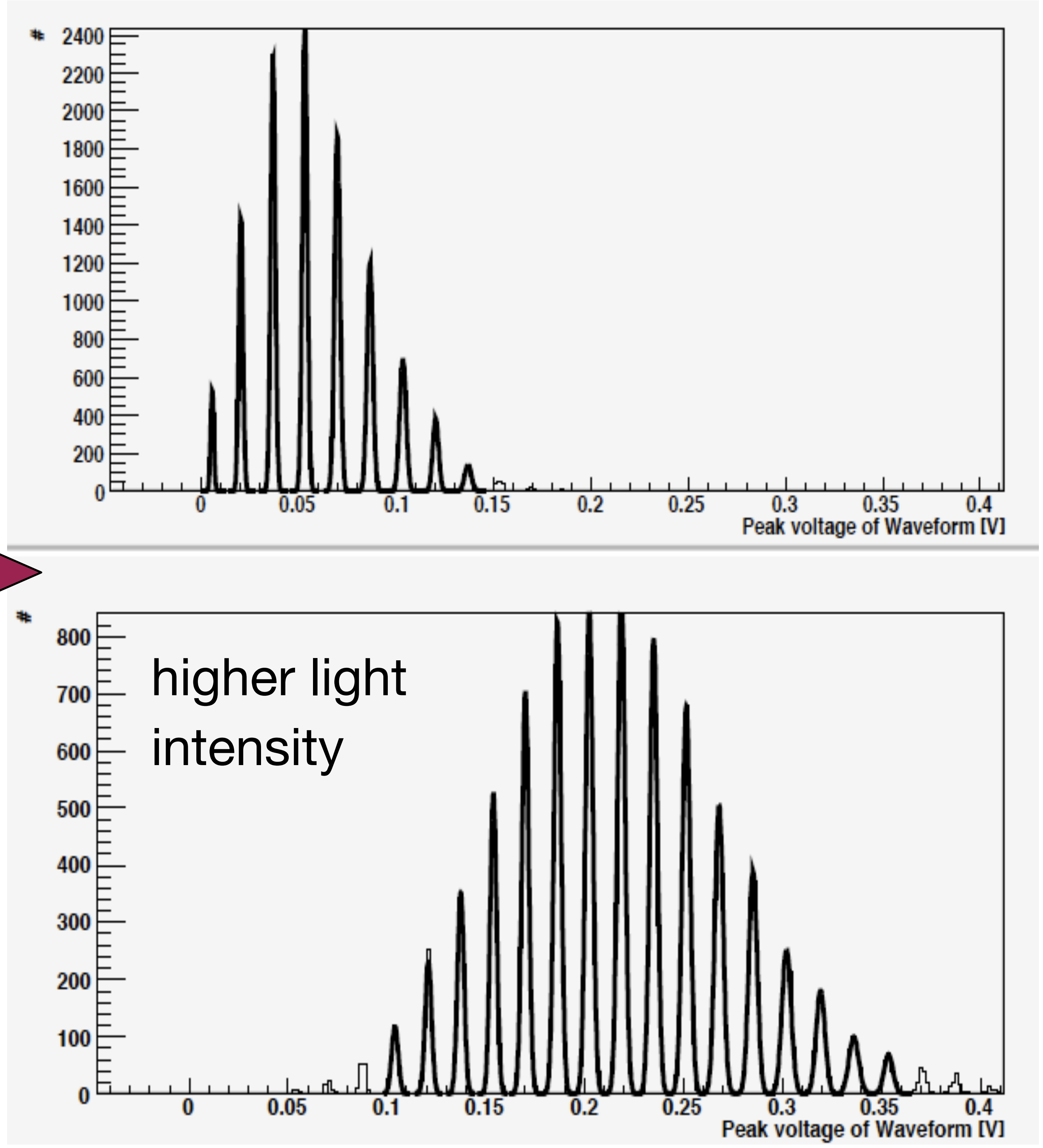
Detection Techniques: Light Detection with Silicon

- The Silicon Photomultiplier



Detection Techniques: Light Detection with Silicon





higher light intensity

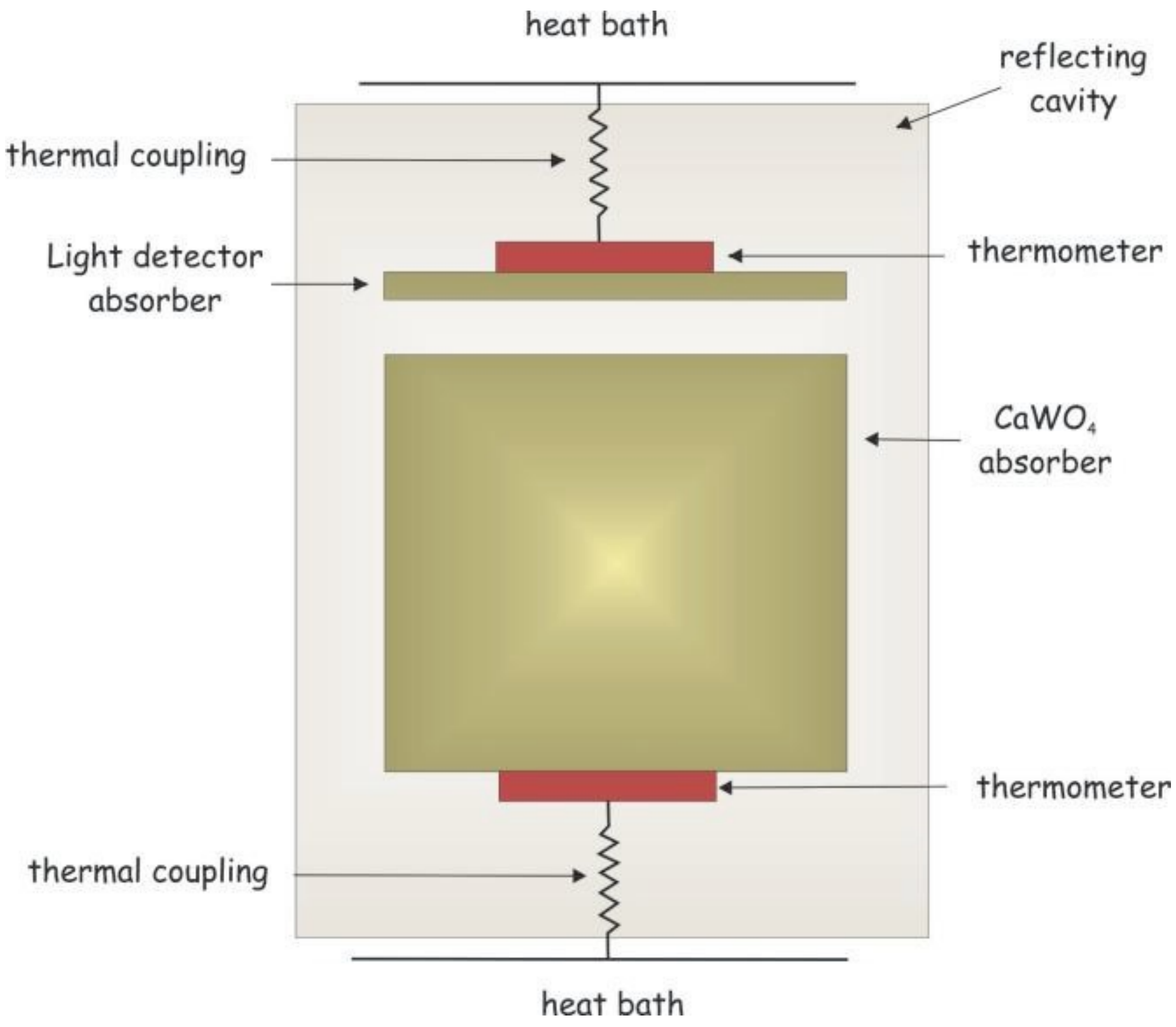
Single photons can be resolved

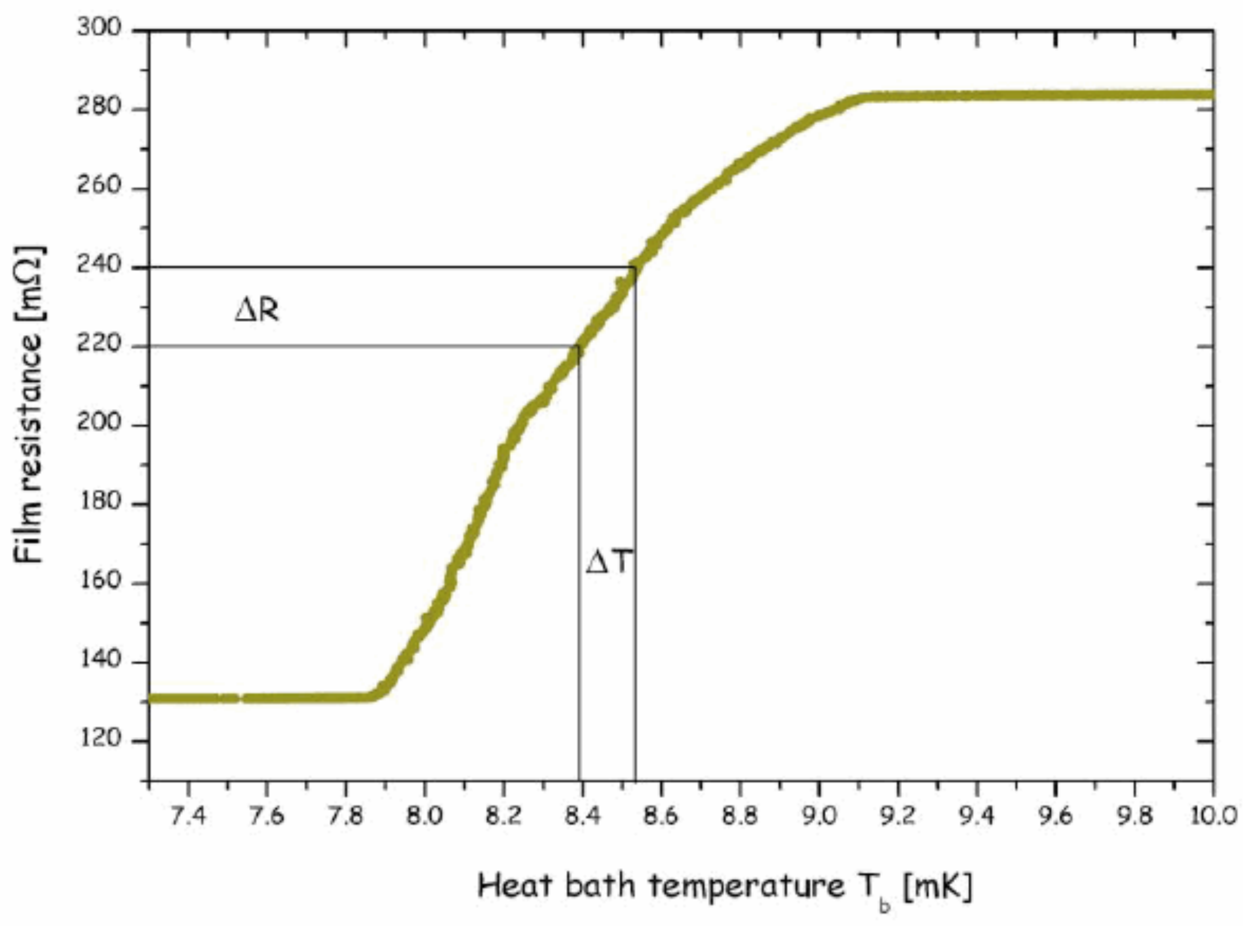
Low Background / Precision Experiments:

A few Examples

Cryogenic Detectors for Dark Matter: CRESST

- Cryogenic Rare Event Search with Superconducting Thermometers
- Search for weakly interacting massive particles (WIMPs)
- Detection via nuclear recoil in crystals, measured with superconducting thermometers
  - Recoil energy is transformed to phonons, increases temperature of thermometer, change of resistance is detected with SQUIDs



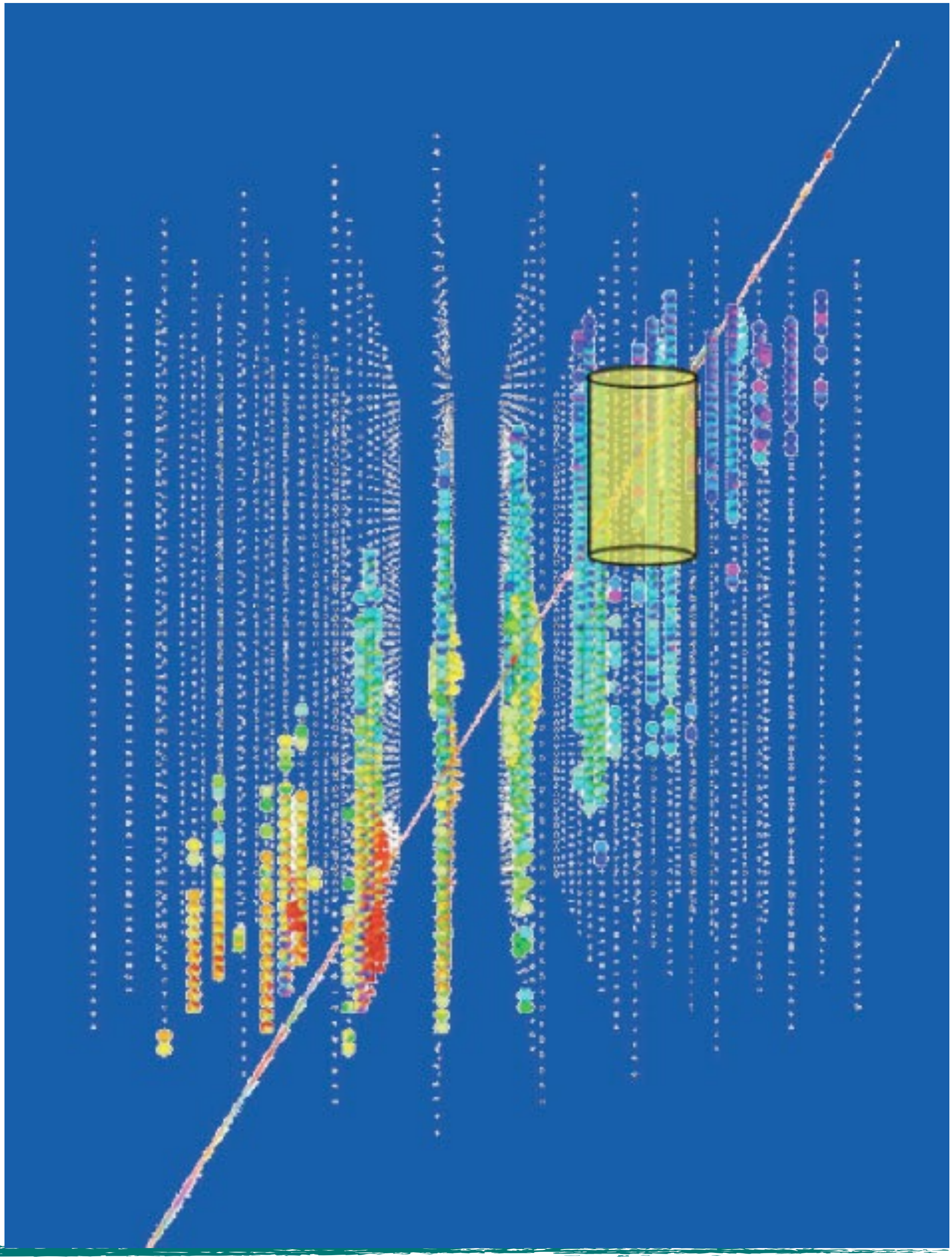


Cherenkov Detectors for Neutrinos

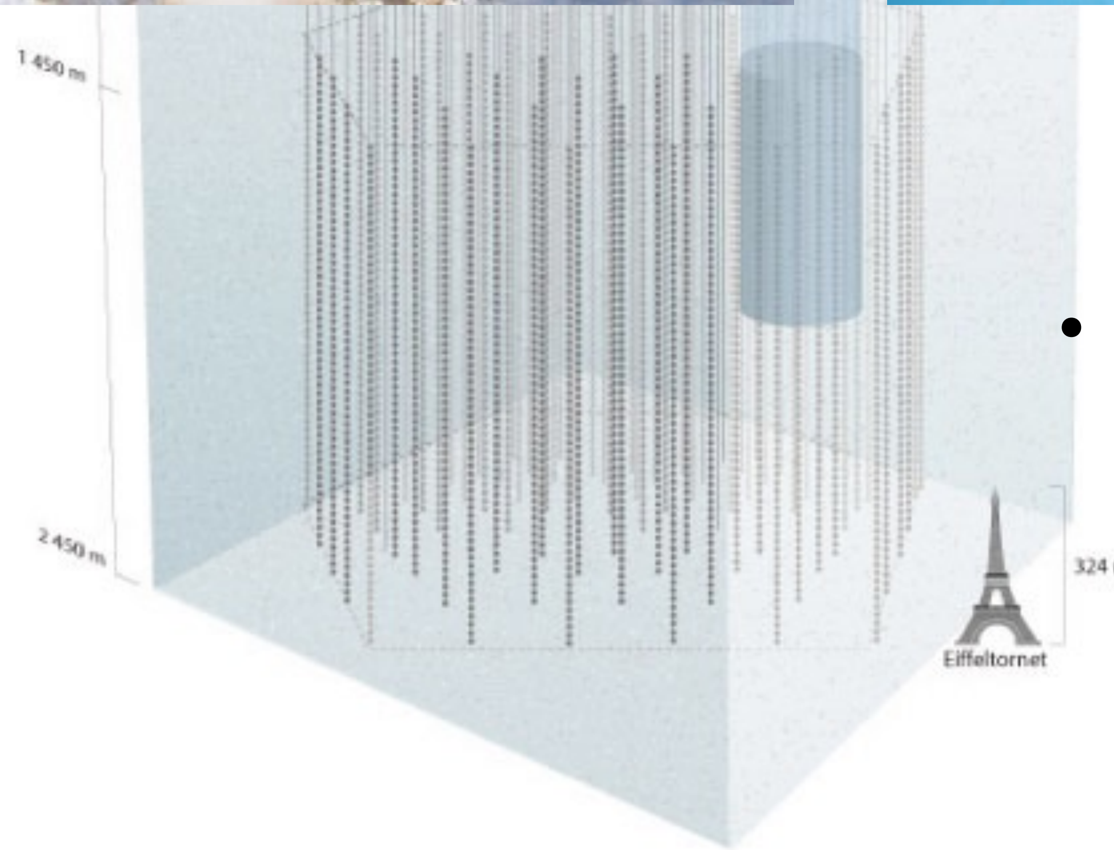
- Detection in deep underground detectors via Cherenkov light of muons or electrons produced in charged current reactions
  Example: Muon in IceCube (Ice as Cherenkov medium)

- Atmospheric neutrinos:
  - Are produced in air showers via pion and muon decay
  - Observation of neutrino oscillations

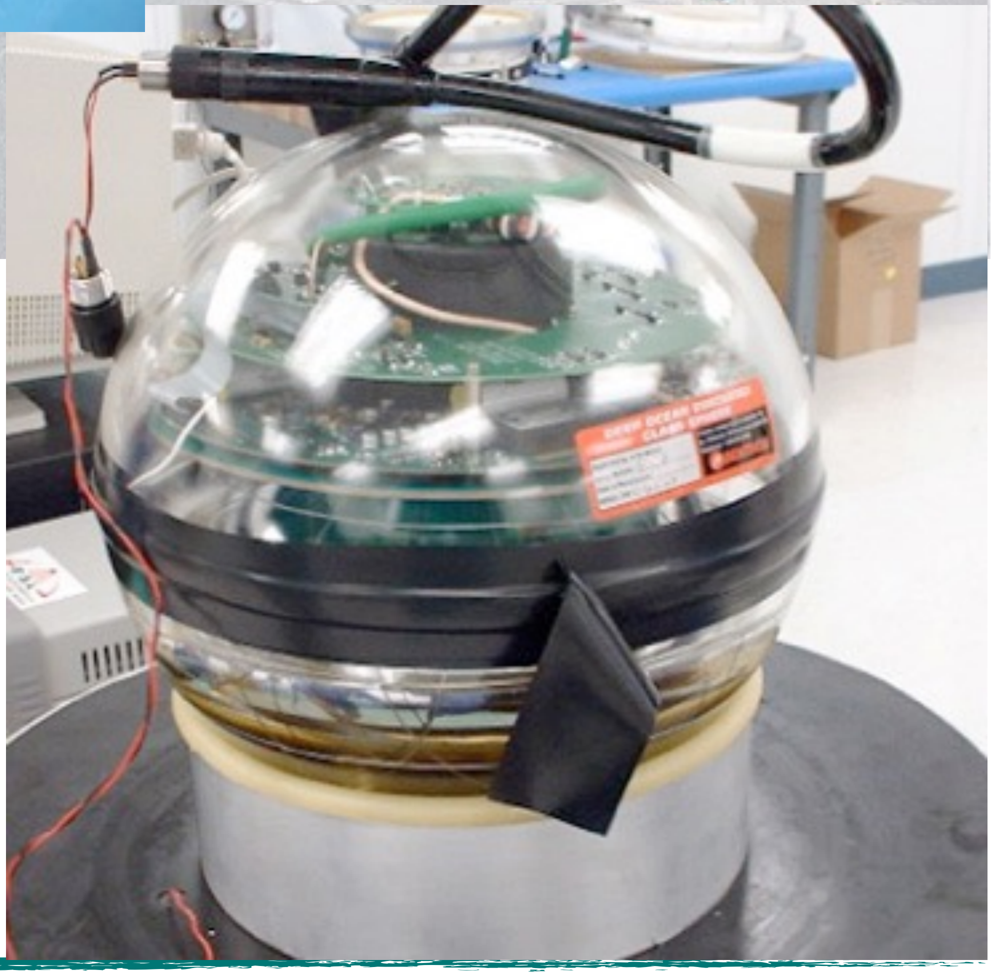
- Cosmic neutrinos
  - Supernovae
  - Other cosmic sources?



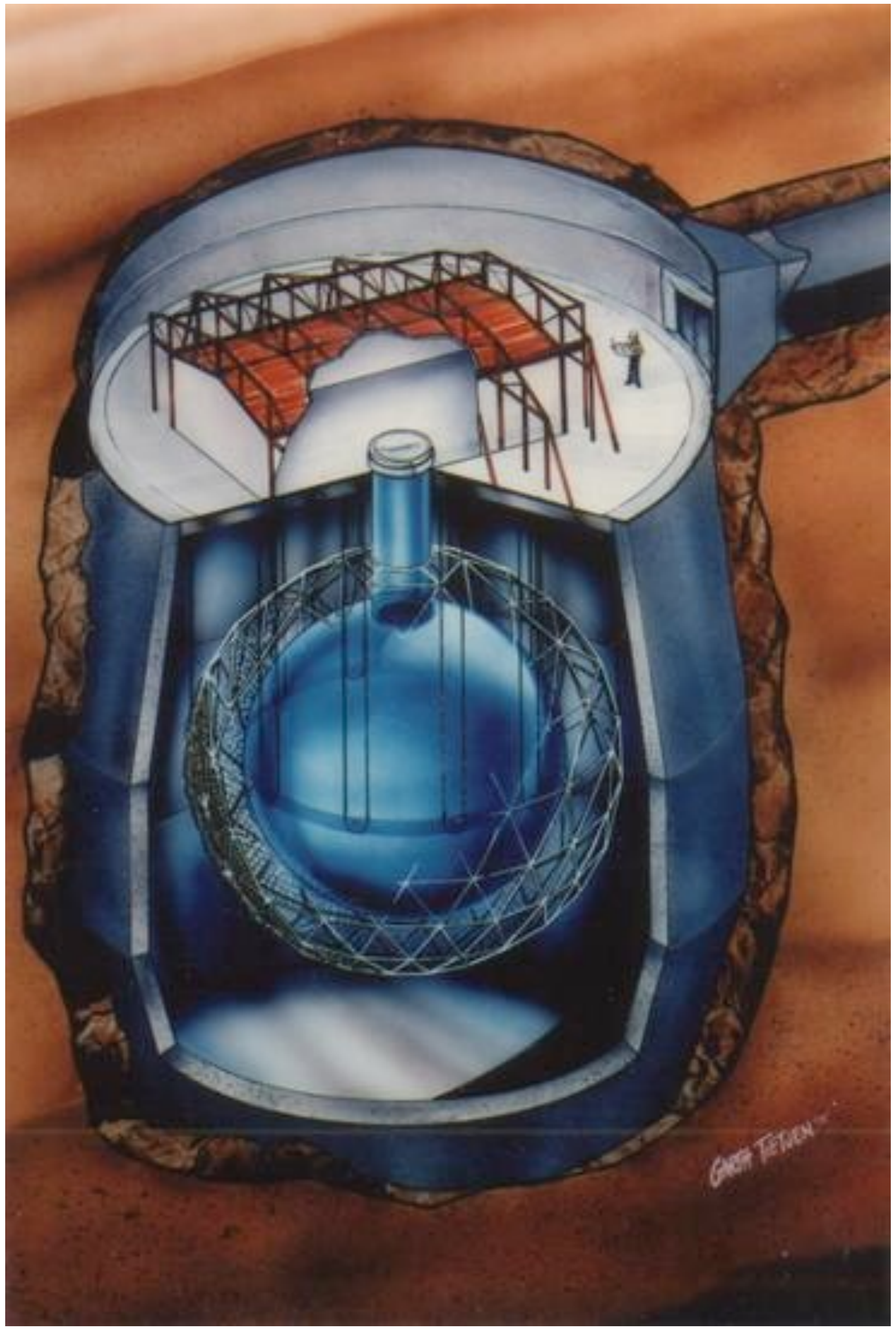
Cherenkov Detectors for Neutrinos



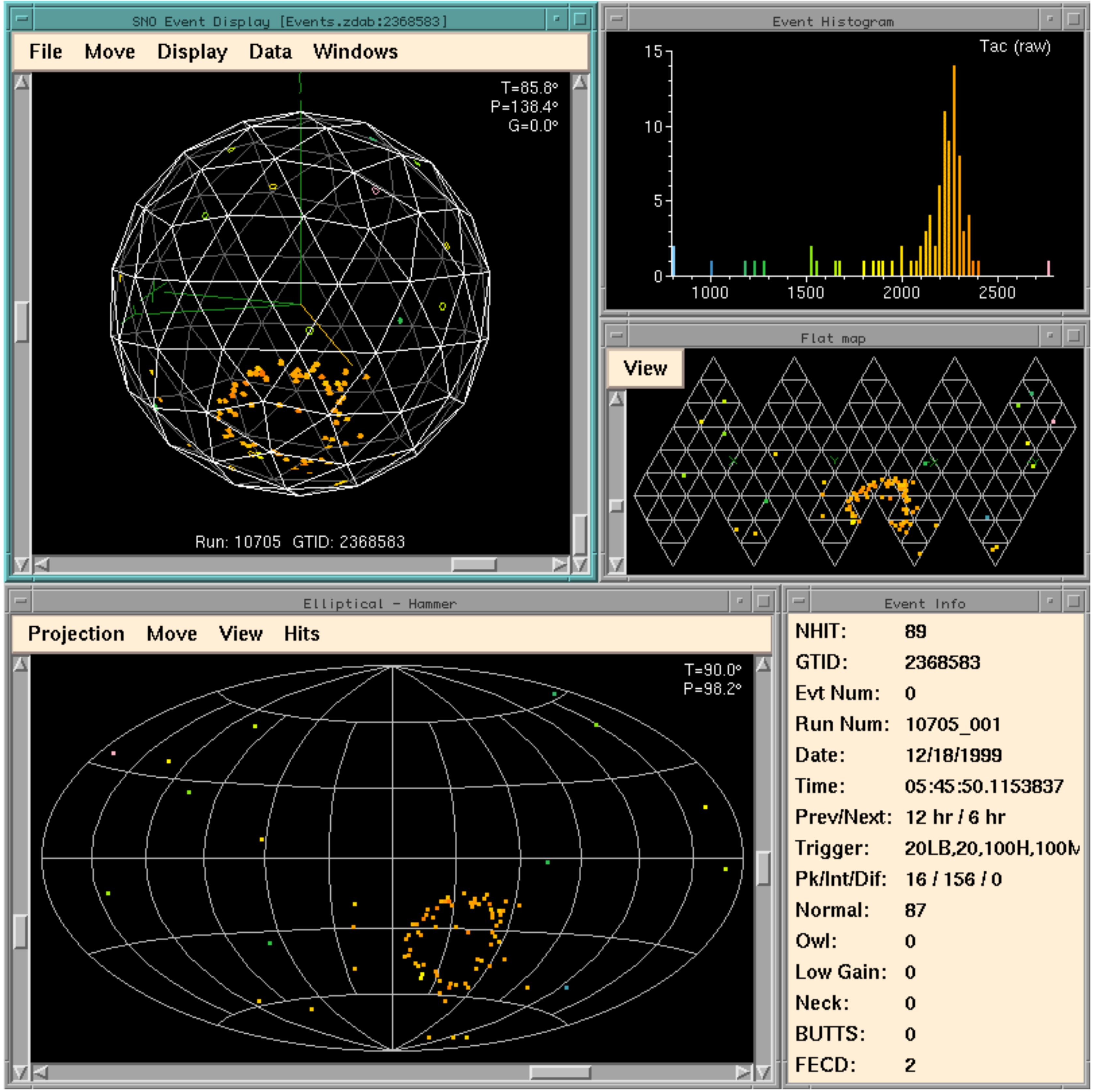
- 1 km^3 instrumented volume in the ice sheet at the south pole



Cherenkov Detectors for Neutrinos

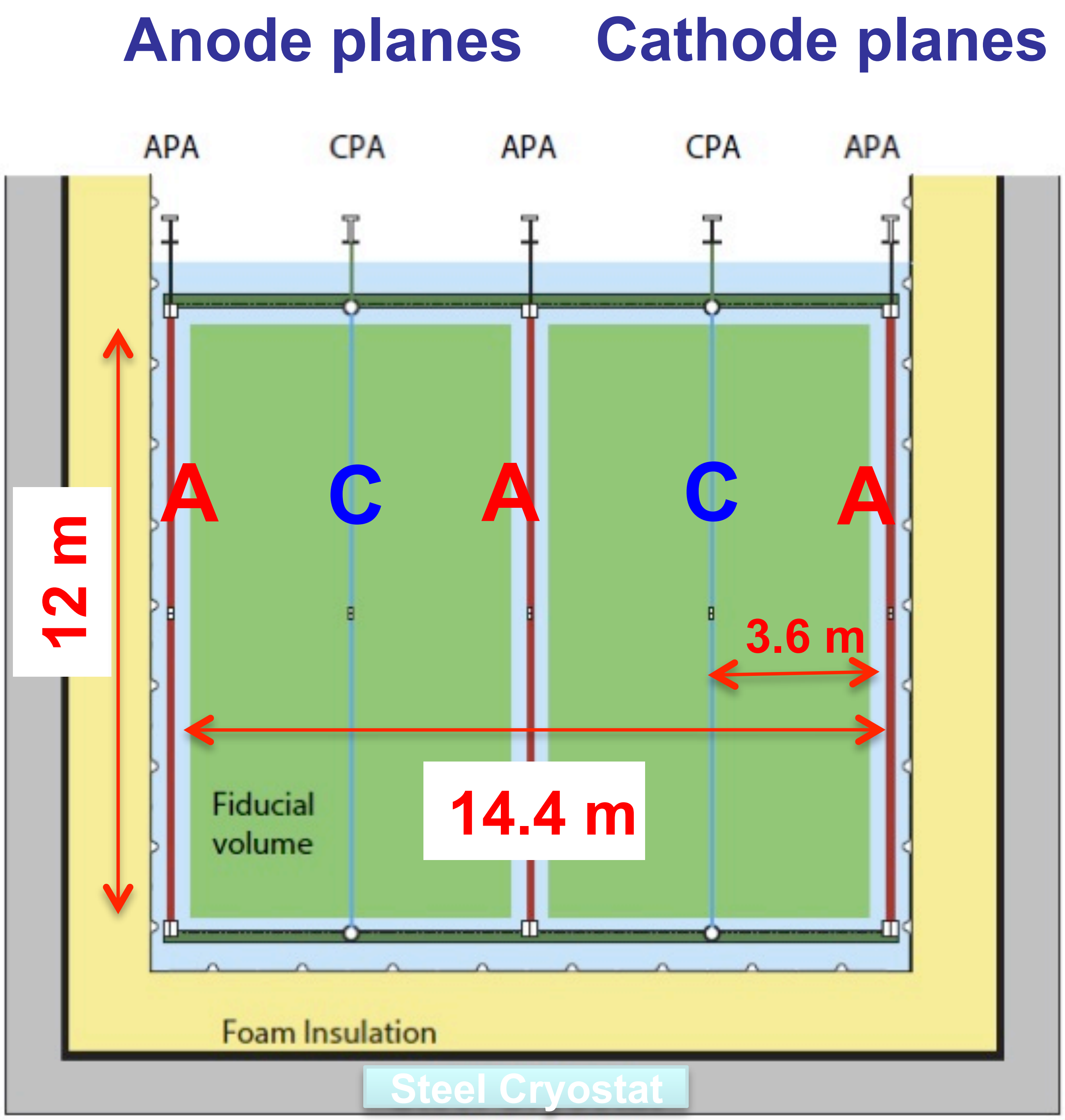


The SNO detector: Heavy water; targeting solar neutrinos

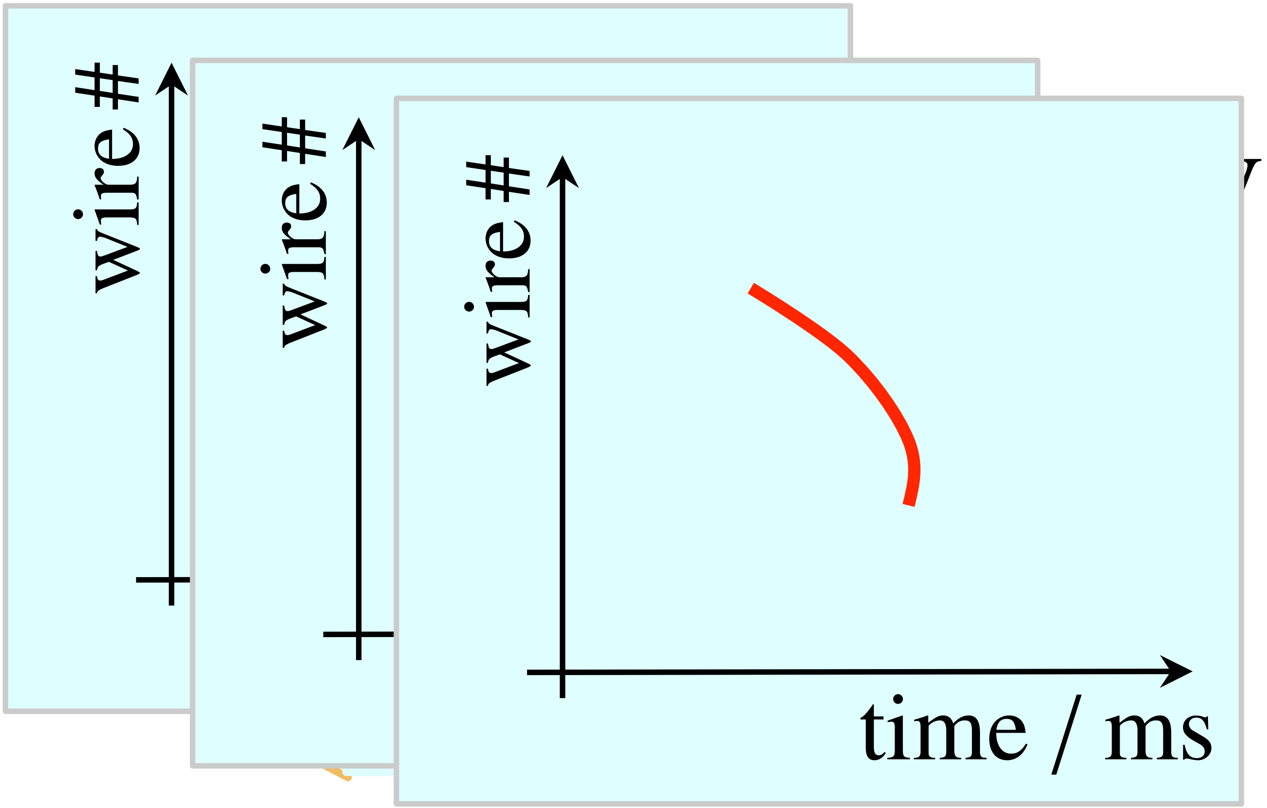


NHIT: 89
GTID: 2368583
Evt Num: 0
Run Num: 10705_001
Date: 12/18/1999
Time: 05:45:50.1153837
Prev/Next: 12 hr / 6 hr
Trigger: 20LB,20,100H,100M
Pk/Int/Dif: 16 / 156 / 0
Normal: 87
Owl: 0
Low Gain: 0
Neck: 0
BUTTS: 0
FECD: 2

Large Cryogenic Time Projection Chambers



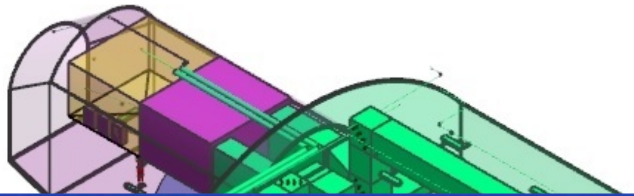
- TPCs: A technique to get 3D Images with 2D readout + time, with large volume detectors
  - Commonly used in large gas-filled volumes
  - For neutrino experiments: liquid nobel gasses: liquid argon



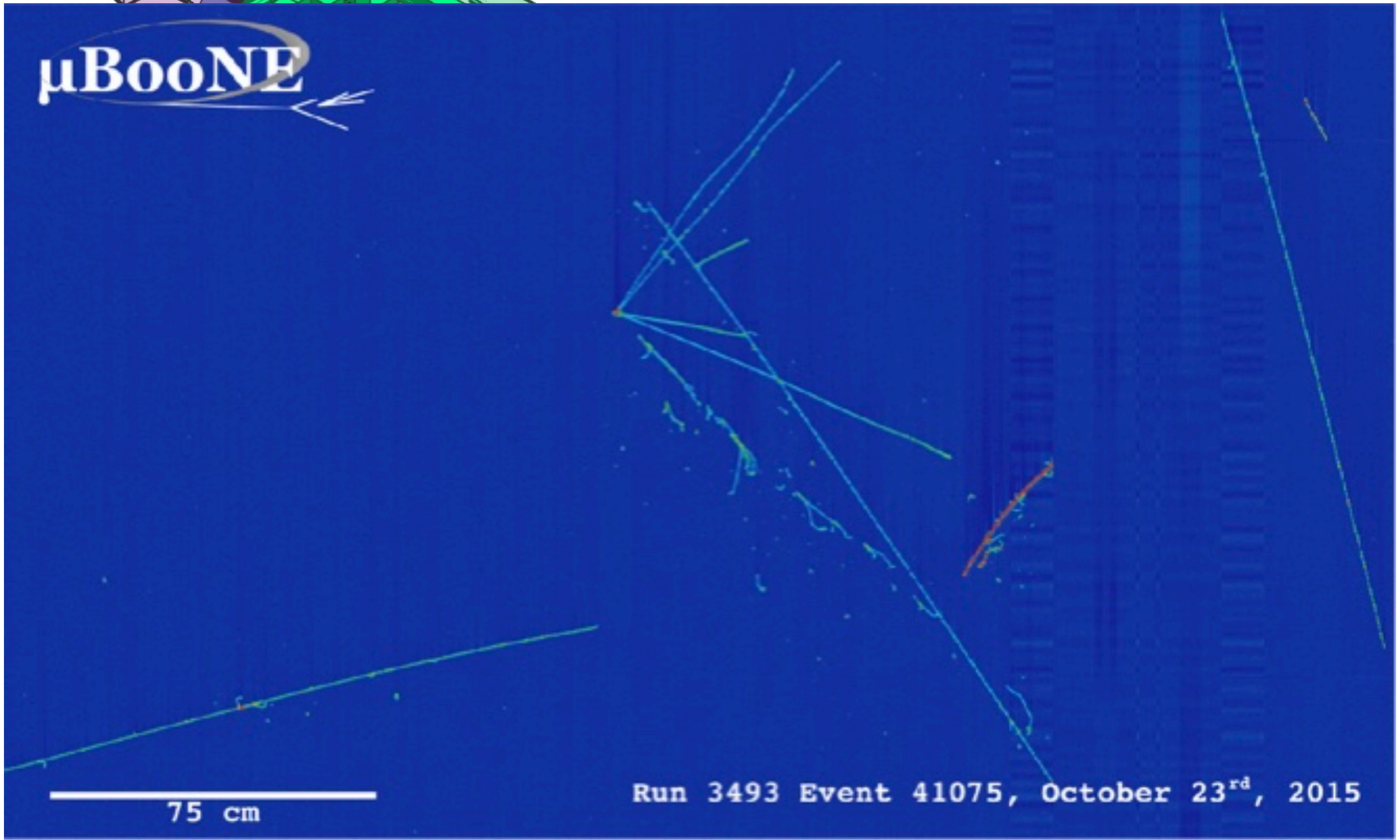
Large Cryogenic Time Projection Chambers

- For DUNE (Deep Underground Experiment), under construction at Fermilab, USA: 4 LAr TPCs, each with 10 kT fiducial volume (17 kT total volume)

Each detector:
60 m long, 14 m wide,
12 m high

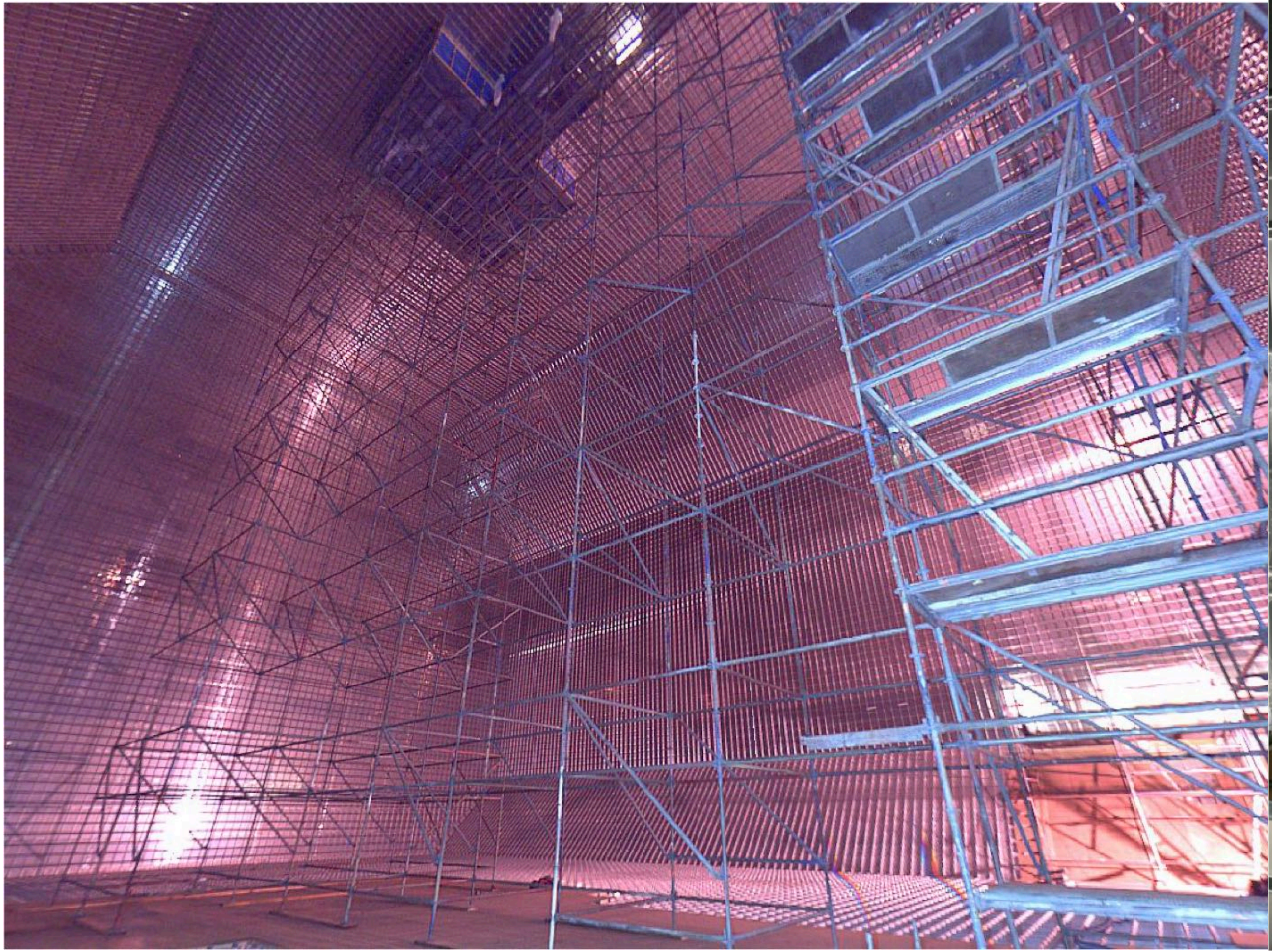


Events from a smaller (170 t) LAr TPC: Demonstrates spatial resolution, pattern recognition capabilities



Large Cryogenic Time Projection Chambers

- Interesting challenge: contain 10 000 m^3 of liquid Argon (87 K, -186 C)
  - Technologies from LNG ships



Summary

- Particle physics with accelerators, astroparticle physics and cosmology have provided a consistent and detailed picture of elementary particles, their interactions, and the structure and evolution of the Universe
  - Despite this success, fundamental questions remain unanswered, requiring physics beyond the Standard Model
- Detector technology is crucial for experiments exploring these questions

We'll explore these questions, and discuss relevant experiments in the course of the lecture.

Next Lecture: 06.05., "Dark Matter axions and ALPs: Where do they come from?", B. Majorovits

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.05.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Accelerator Neutrinos	*F. Simon*
01.07.	Precision Experiments with low-energy accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*