SATURDAY MORNING
PHYSICS
AT TEXAS A&M

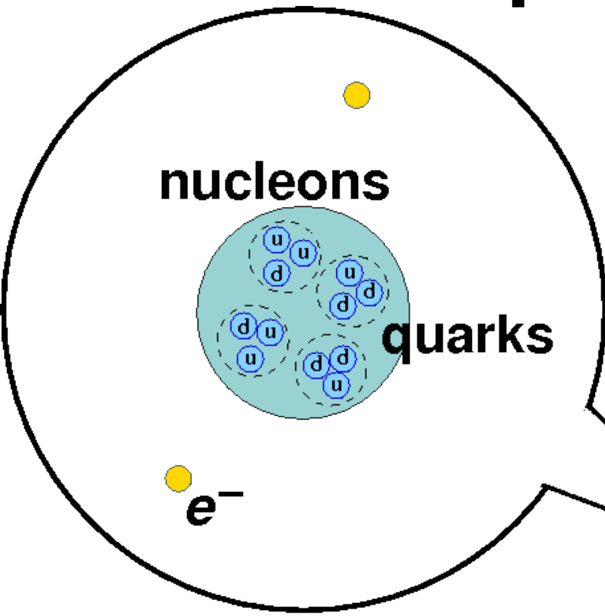
Symmetries in Nature

A glimpse into the beauty and art of science

Dan Melconian
Texas A&M University
Cyclotron Institute
Feb 28, 2009

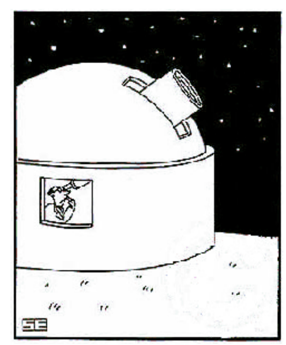
Scope of modern physics

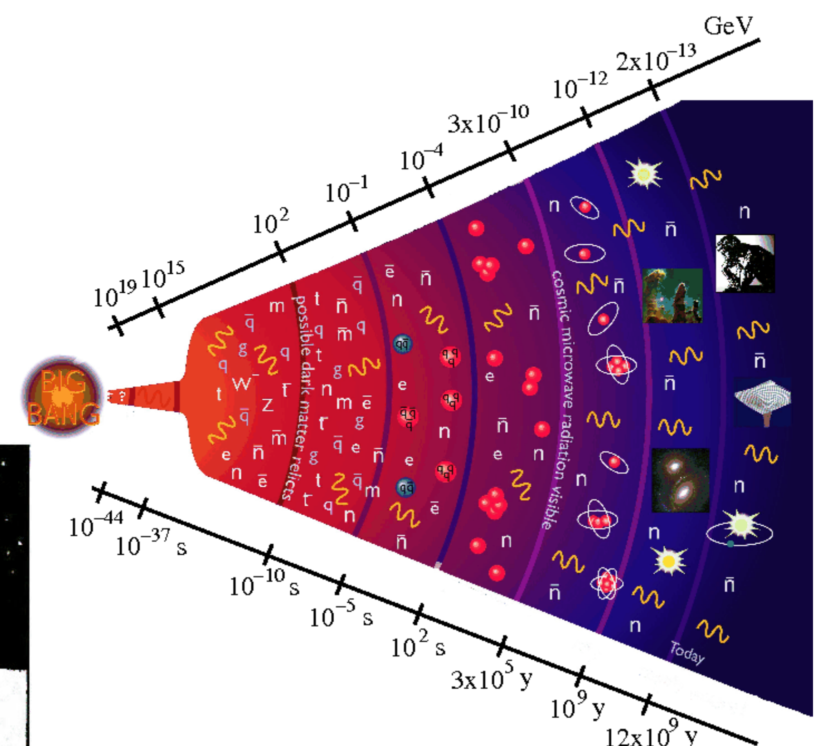
From the very smallest scales ...



the atom

... to the very largest





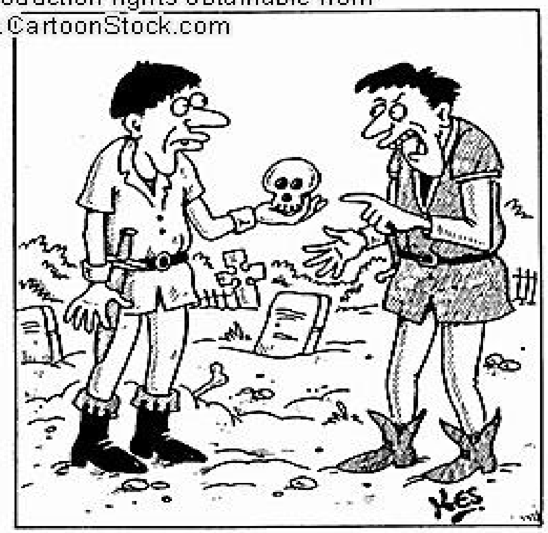
Physics lets us understand the world around us

Art vs Science?

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

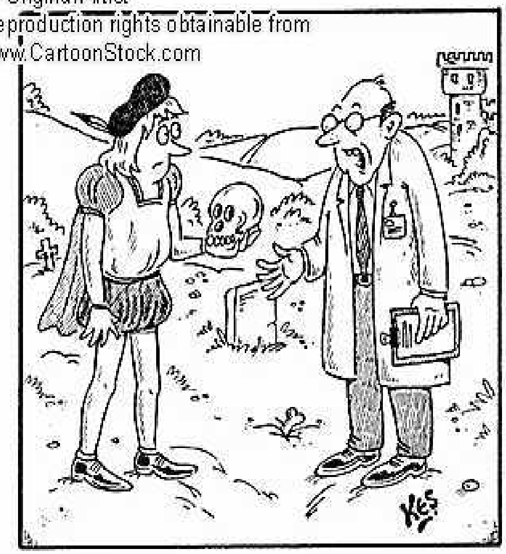
Hamlet, Act I, Scene V

Science vs Art?



'Oh come on!How can you possibly know that it's Yorick without a proper forensic reconstruction?"

"Alas irrefutable confirmation."



"Yorick? No, I don't think so, unless of course he was a Neanderthal!"

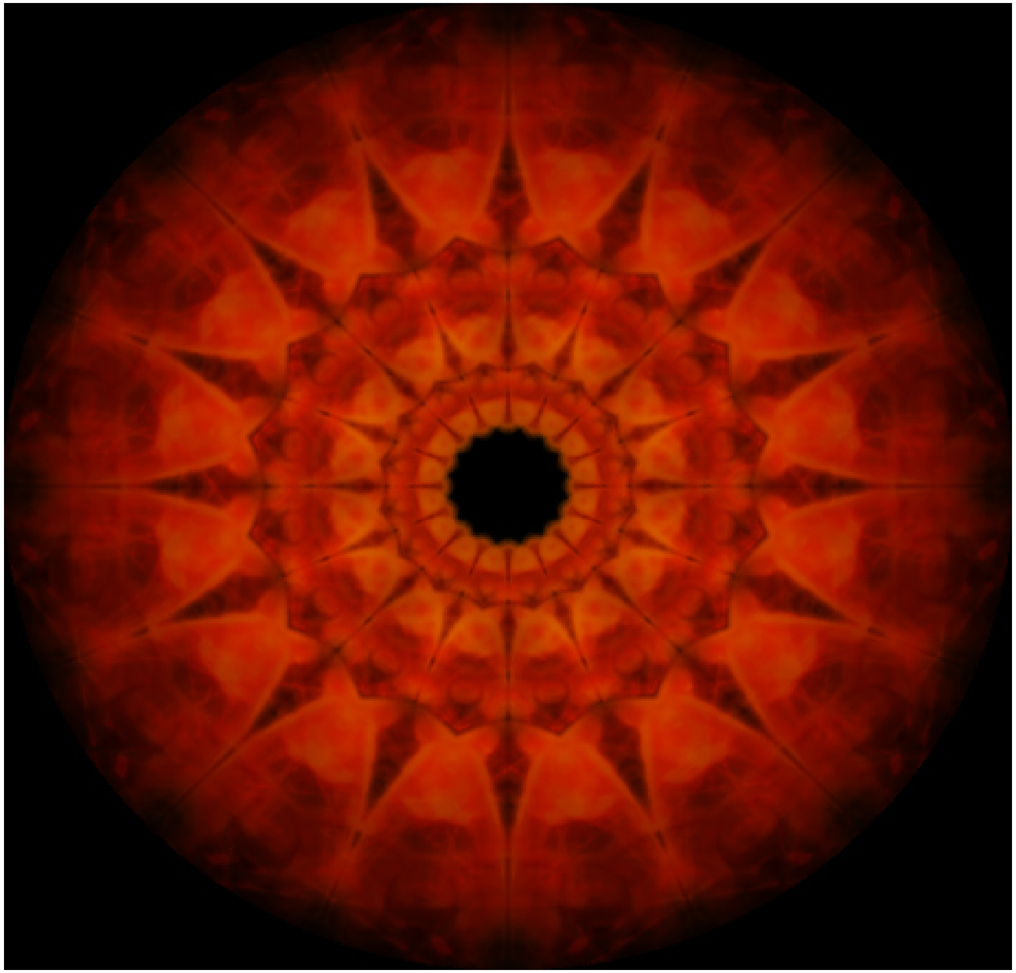
Symmetry

<u>Oxford English Dictionary:</u>

Due or just proportion; harmony of parts with each other and the whole; fitting, regular, or balanced arrangement and relation of parts or elements; the condition or quality of being well-proportioned or well-balanced.

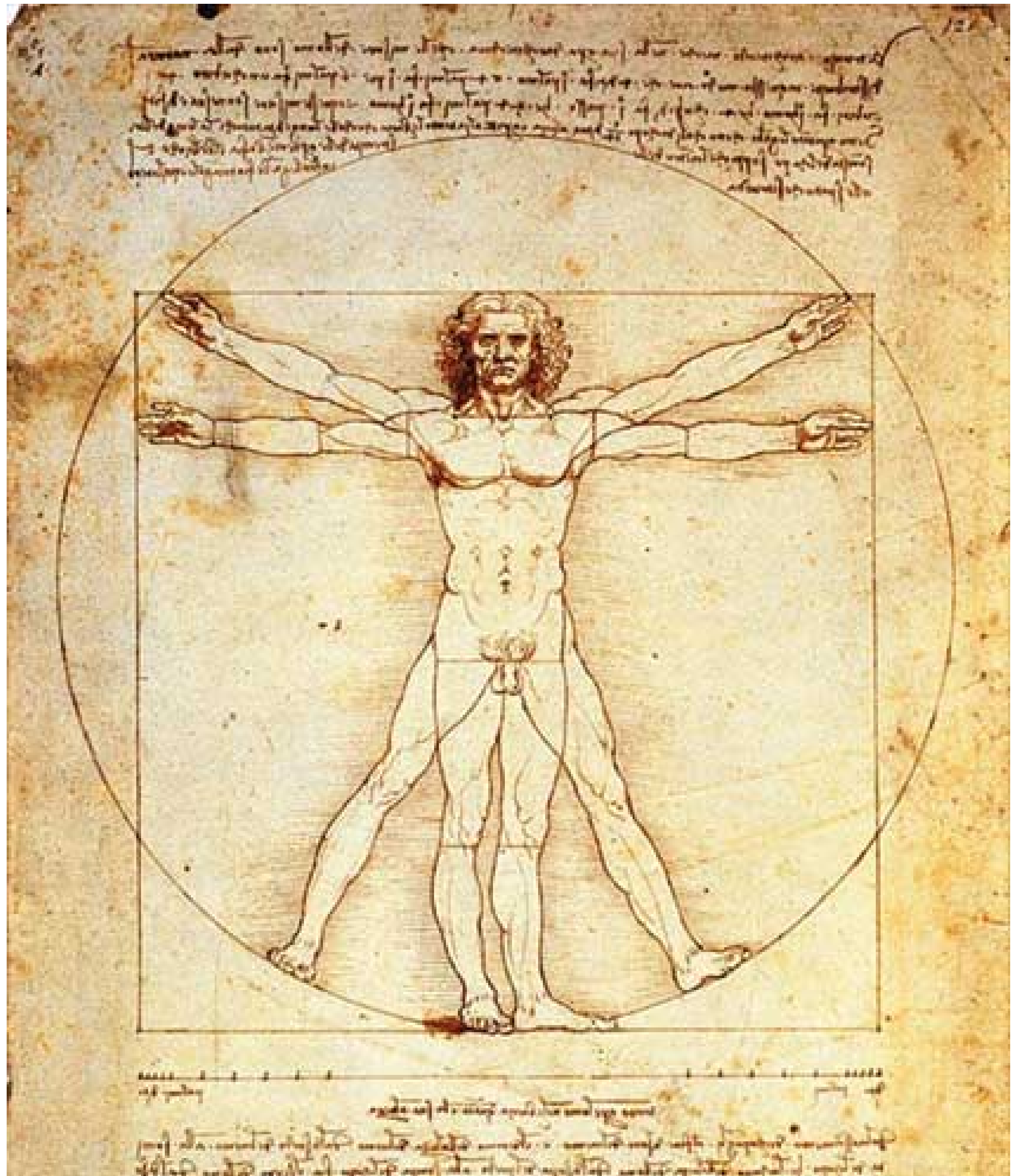
Regularity and beauty of form, fair or fine appearance, comeliness.

Symmetries in Art



Symmetries in Architecture

Symmetries in Art & Science



Types of Symmetries

- Translational
  - Art: M.C. Escher

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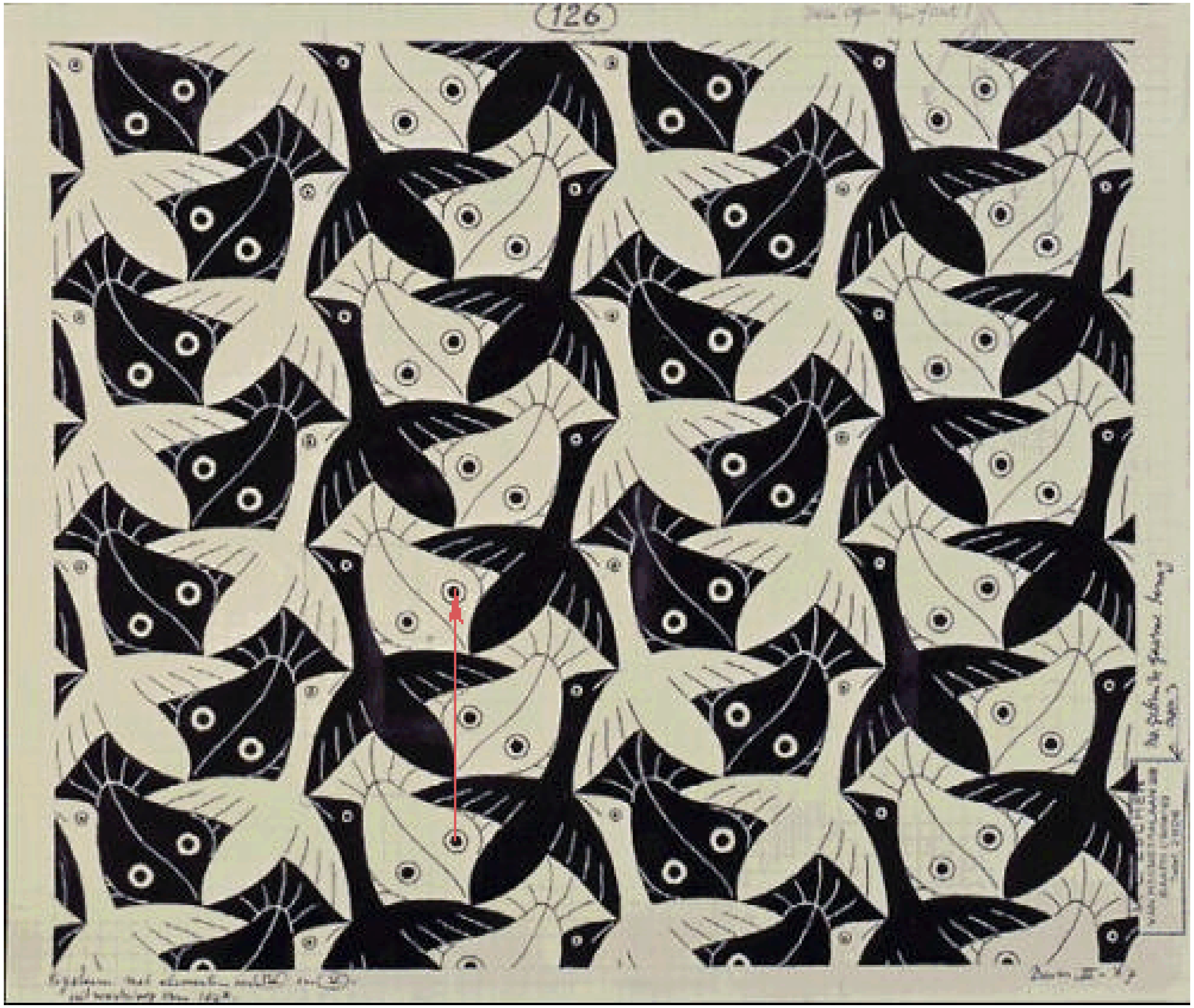

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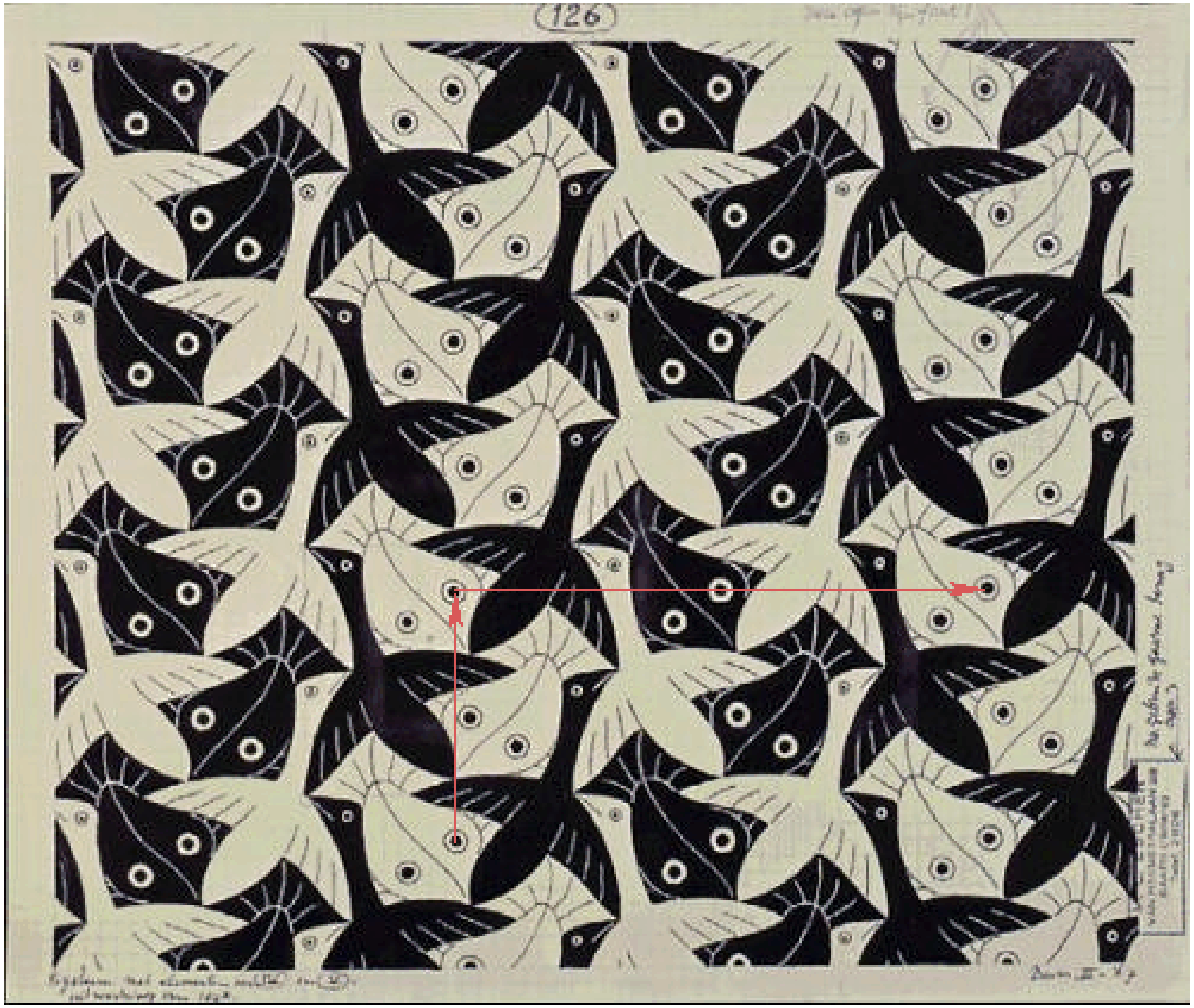

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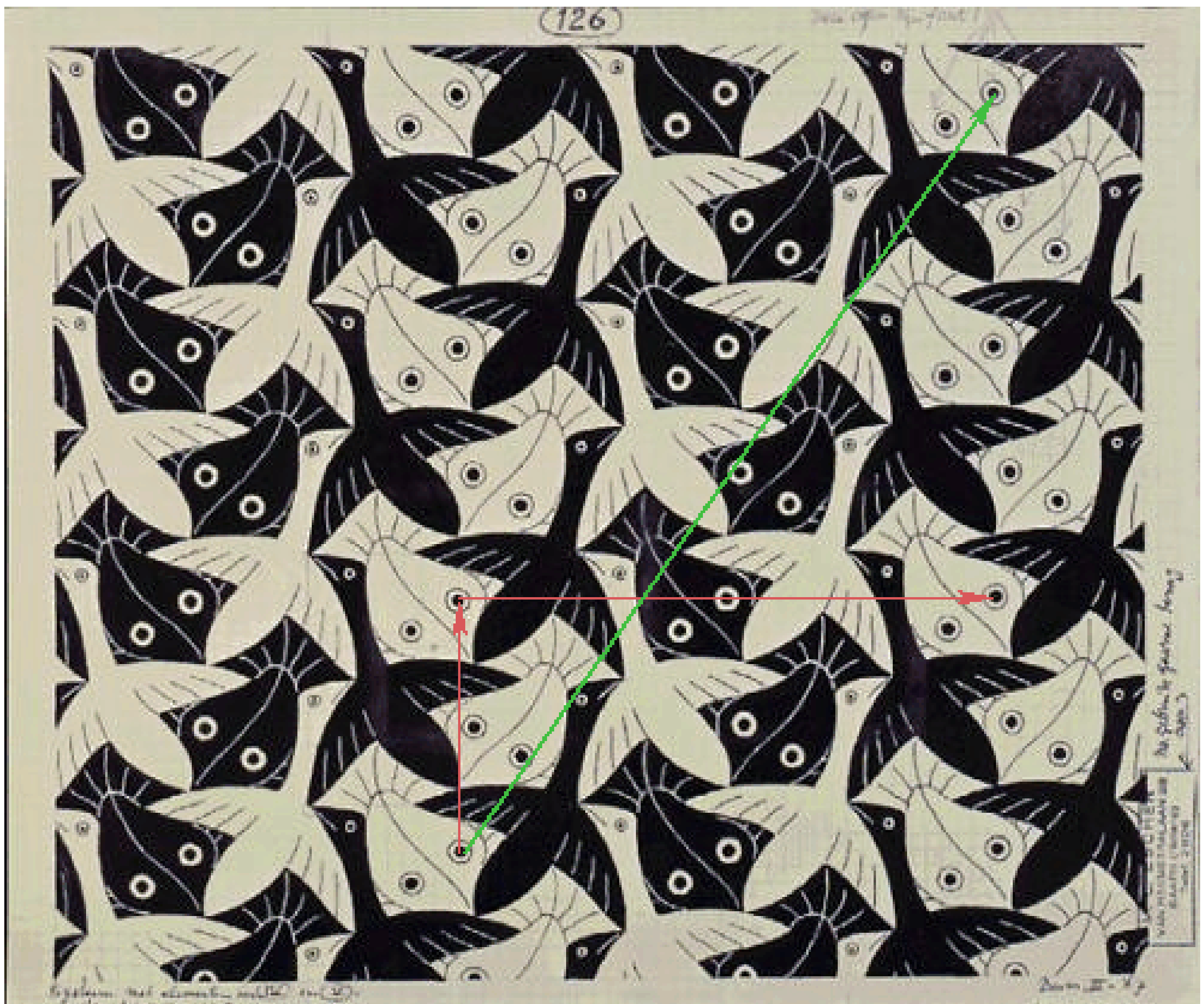


Types of Symmetries

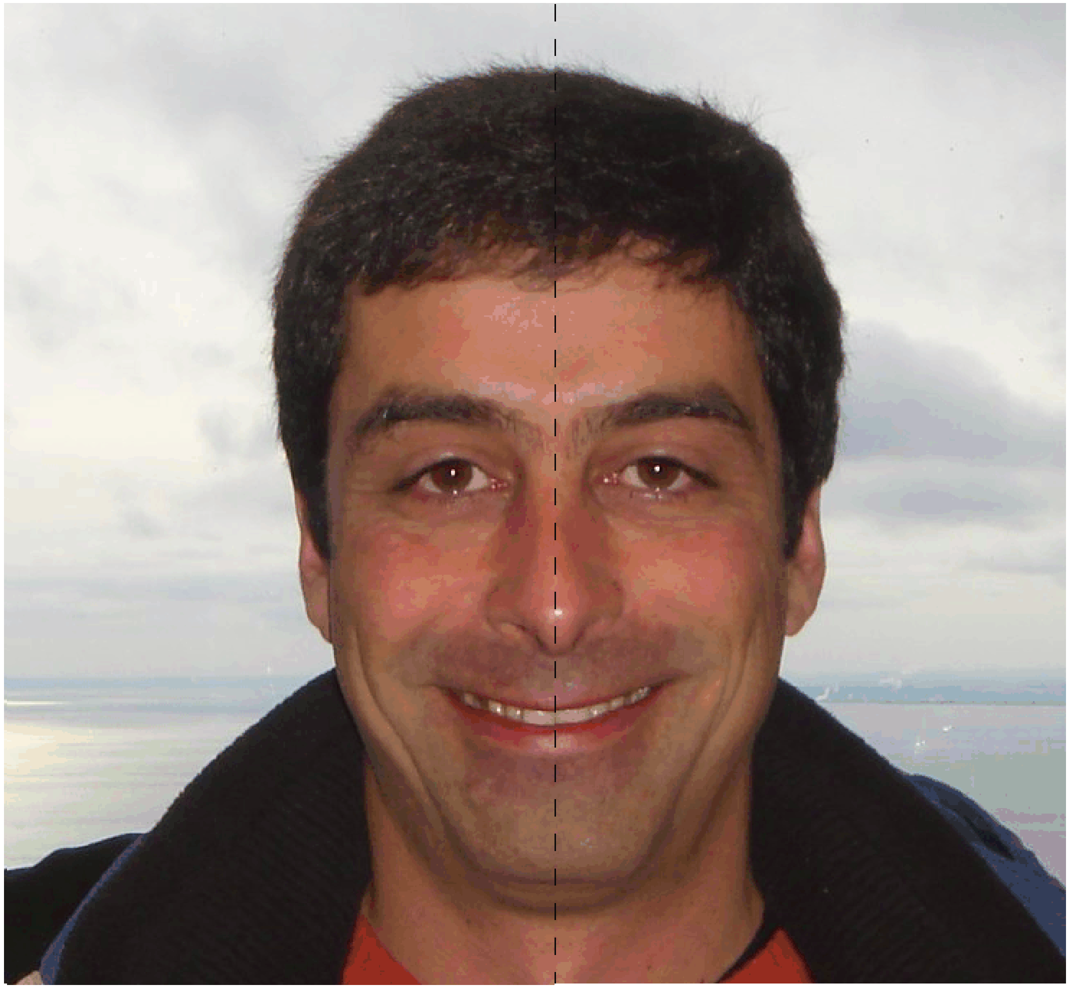
- Reflections
  - the Taj Mahal

Types of Symmetries

- Reflections
  - People

Types of Symmetries

- Reflections
  - People



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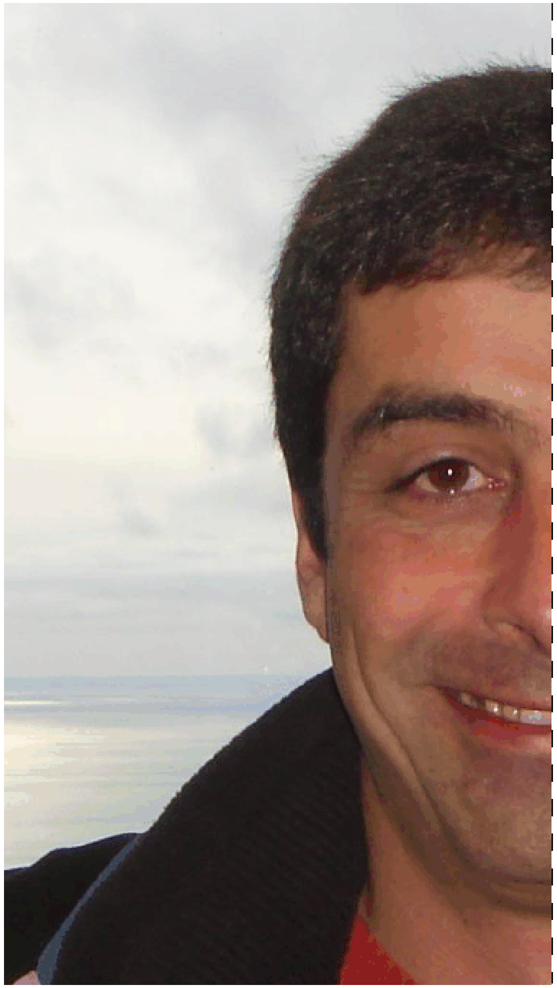

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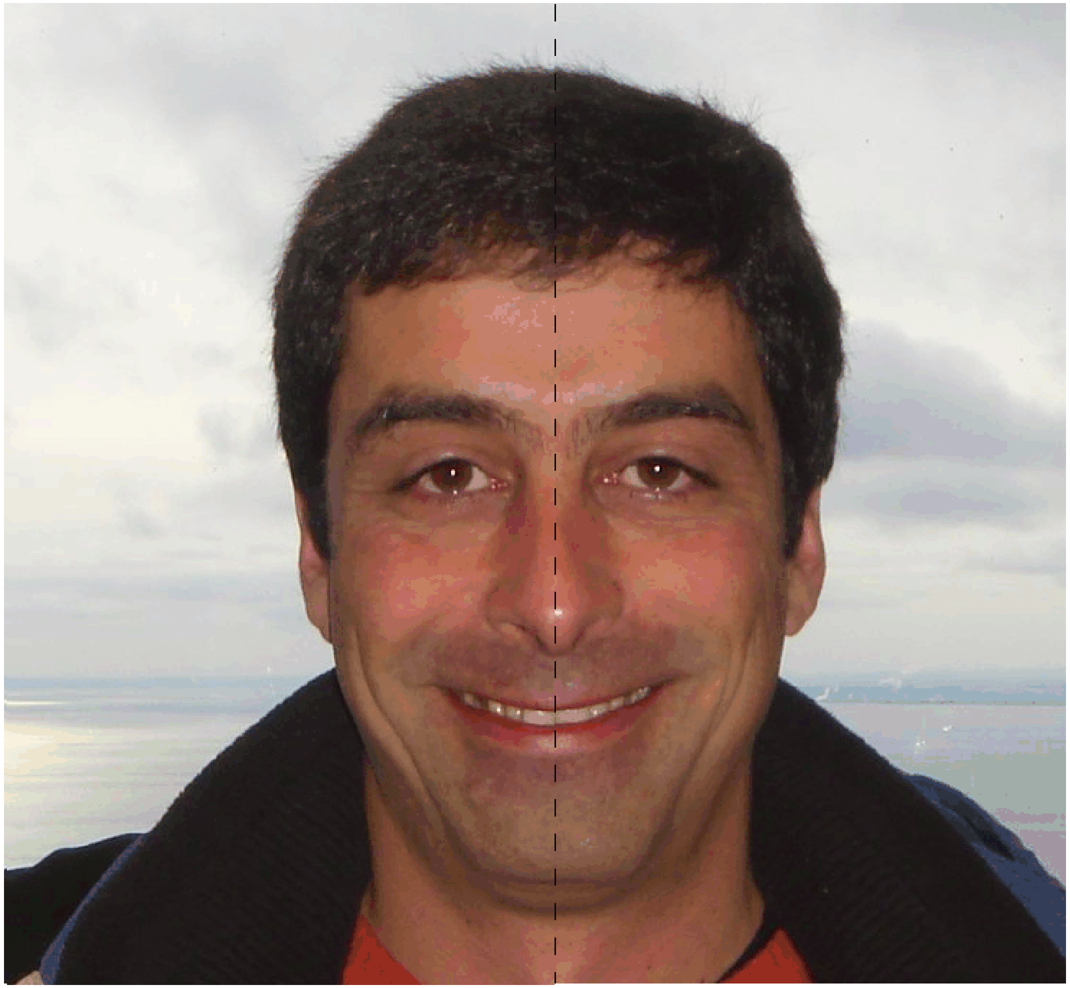

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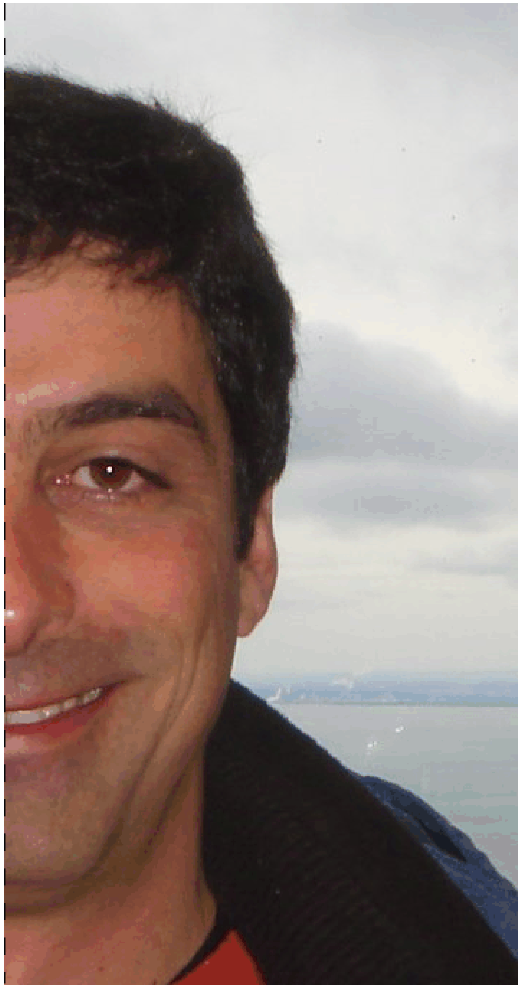

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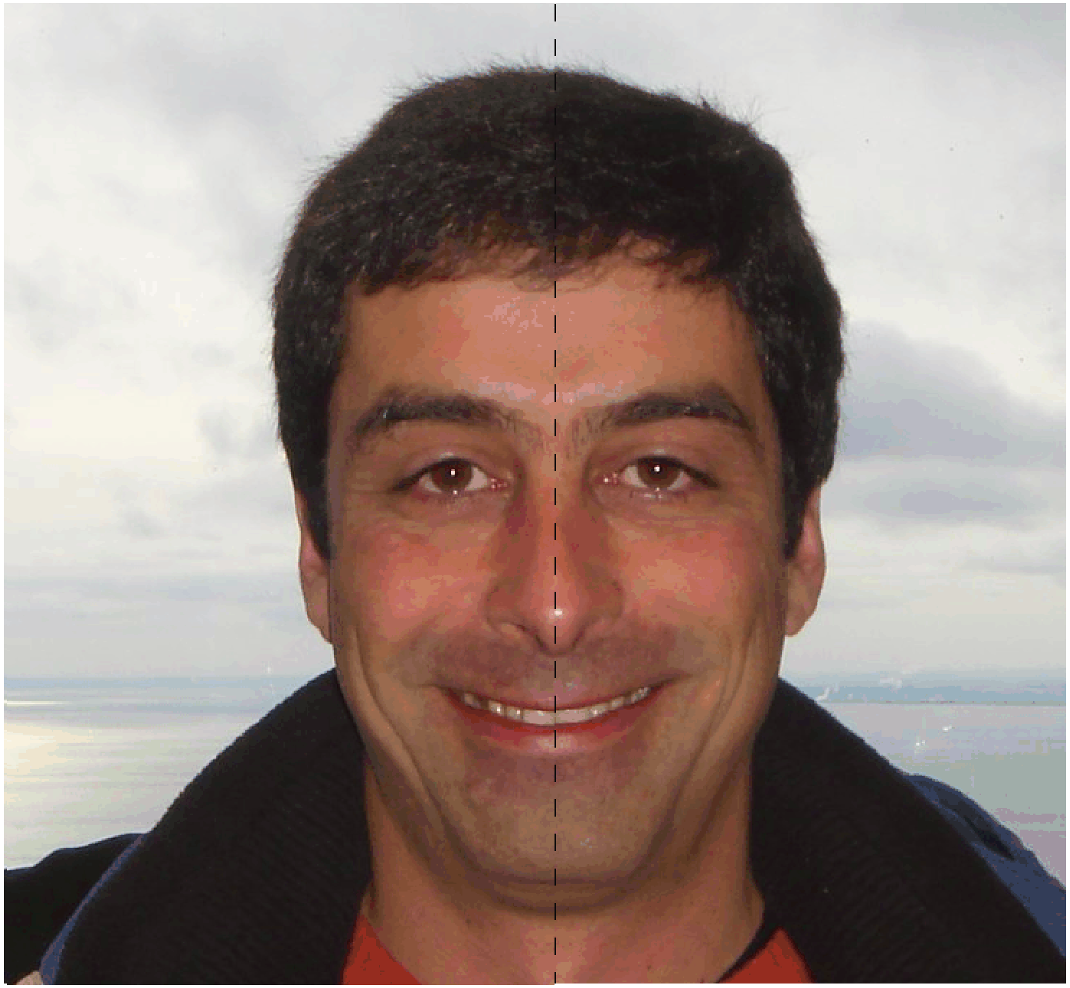

Types of Symmetries

- Rotations
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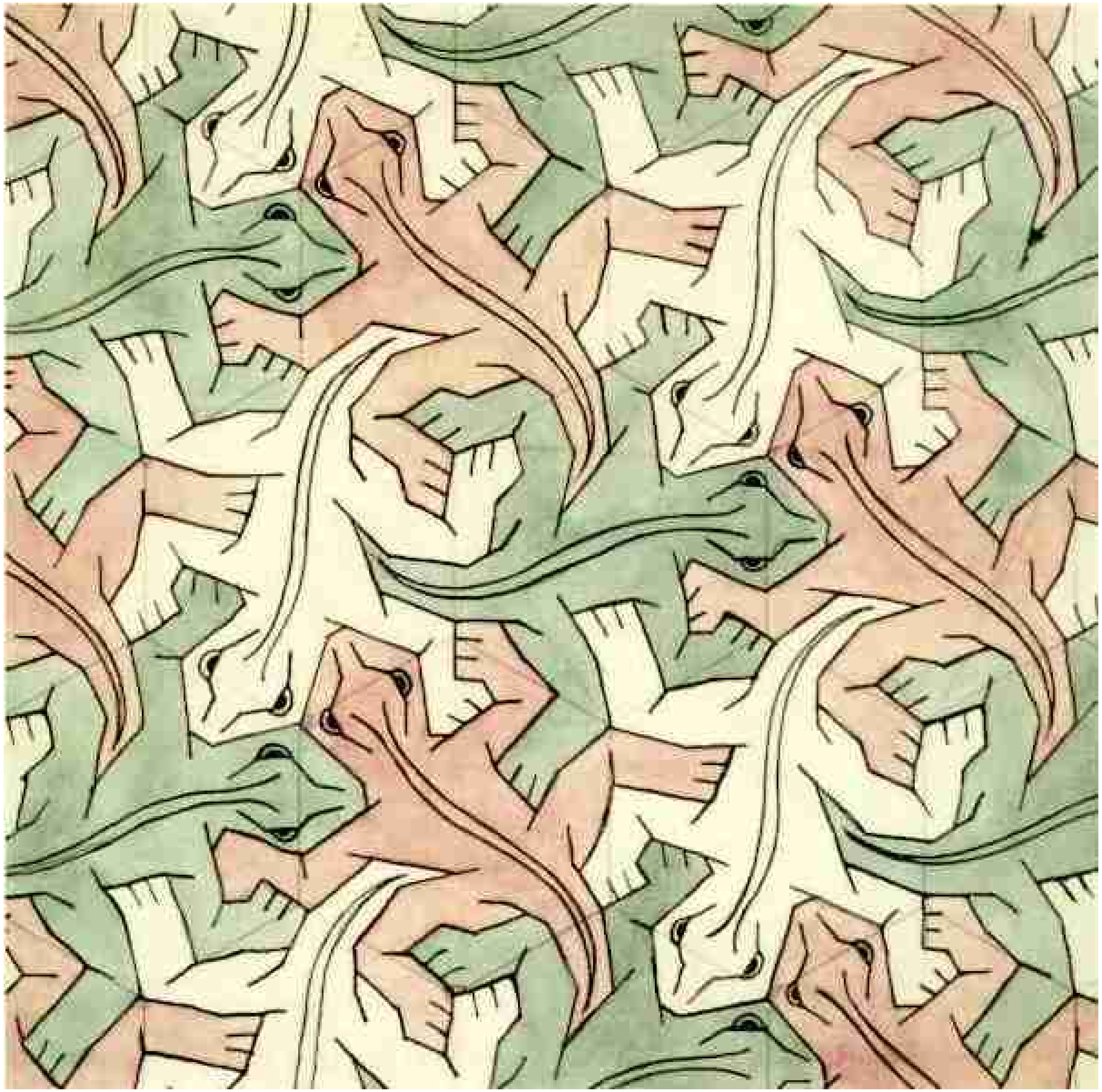
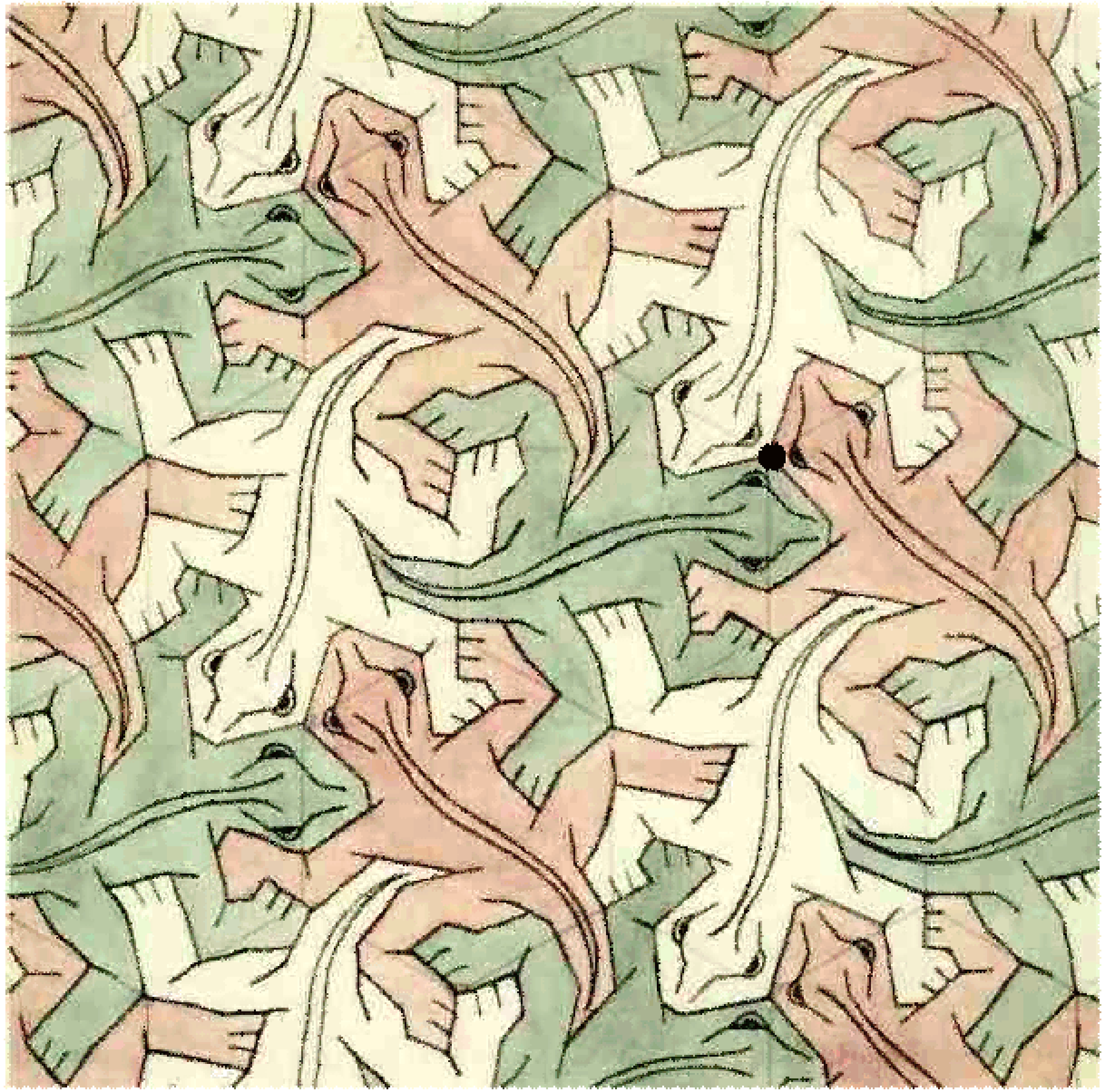


Types of Symmetries

- Rotations



Types of Symmetries

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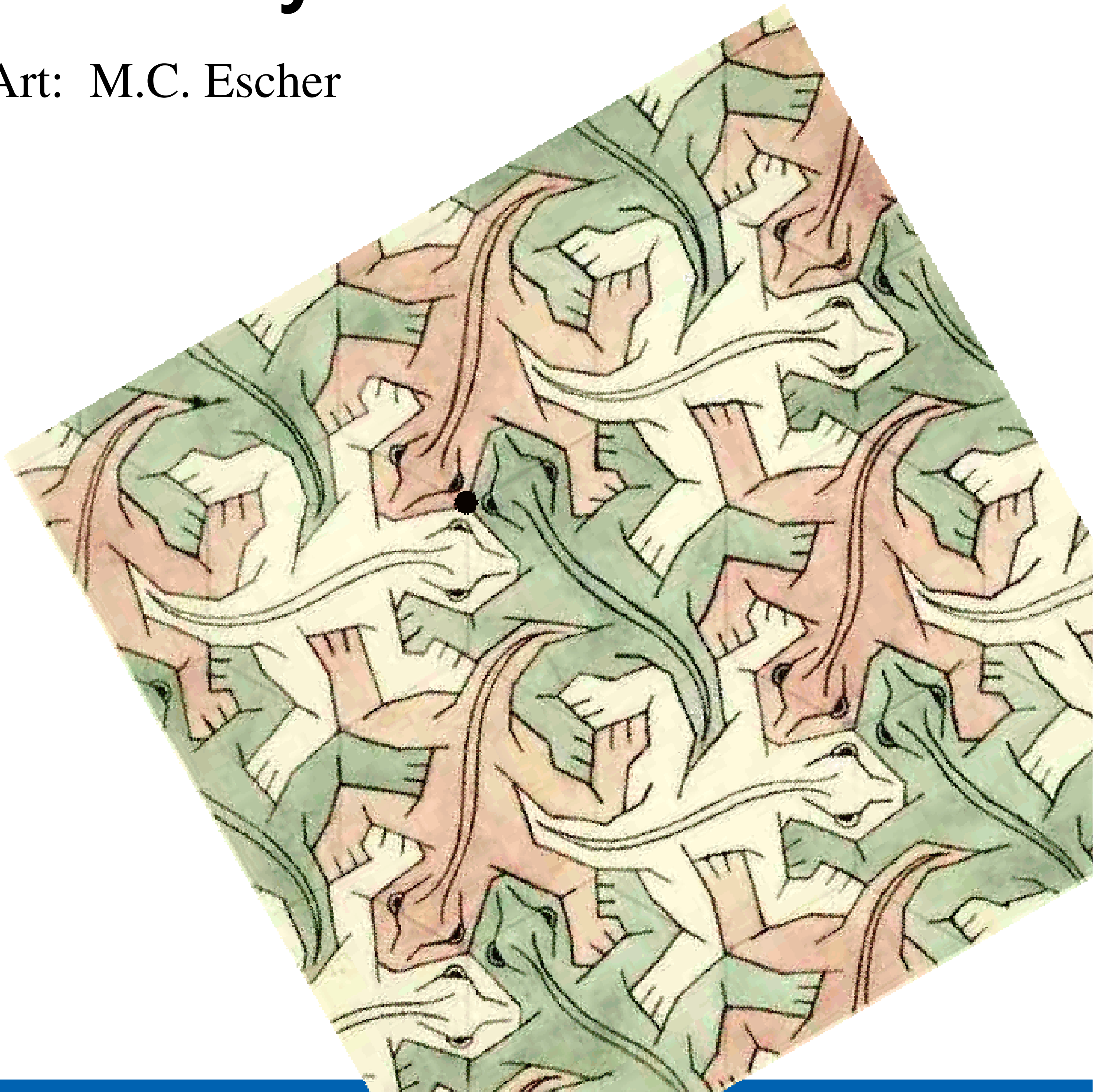
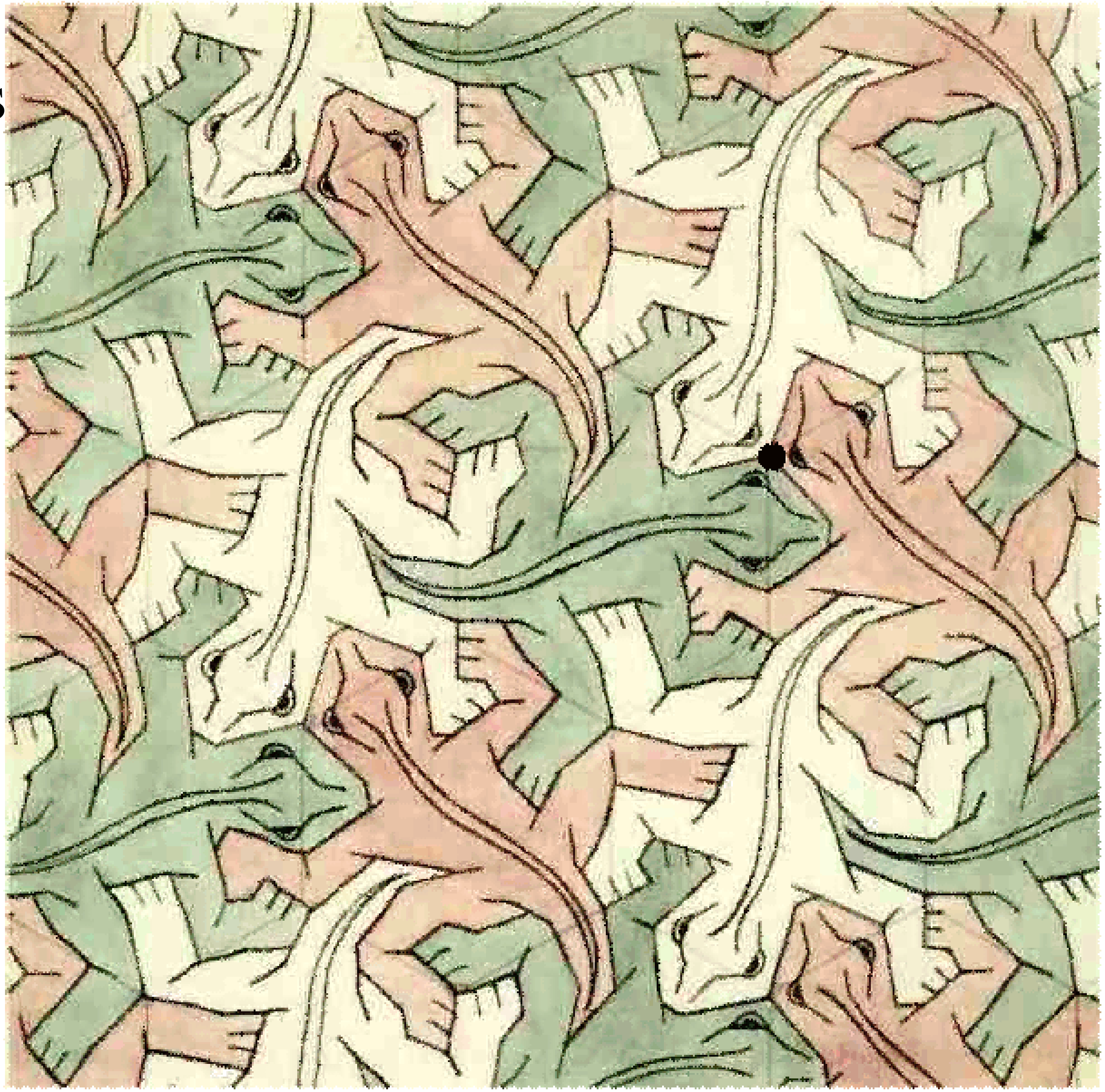


Types of

- Rotations
  - Art:

Types of Symmetries

- Rotations



Symmetries in Physics

Murray Gell-Mann's
"Eightfold Way"

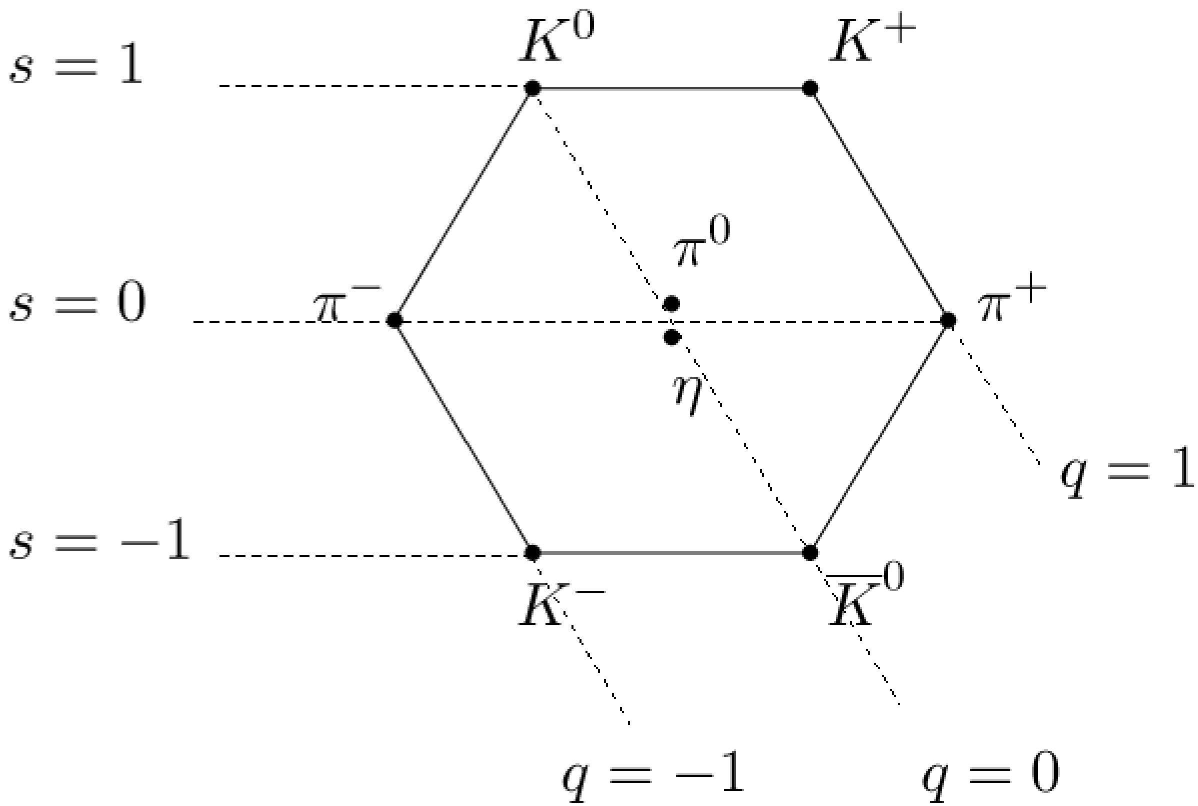
Organized the zoo of particles
that emerged by 1961

c.f. the Periodic Table

"Young man, if I could remember the names of these particles, I would have been a botanist"
Wolfgang Pauli to Leon Lederman

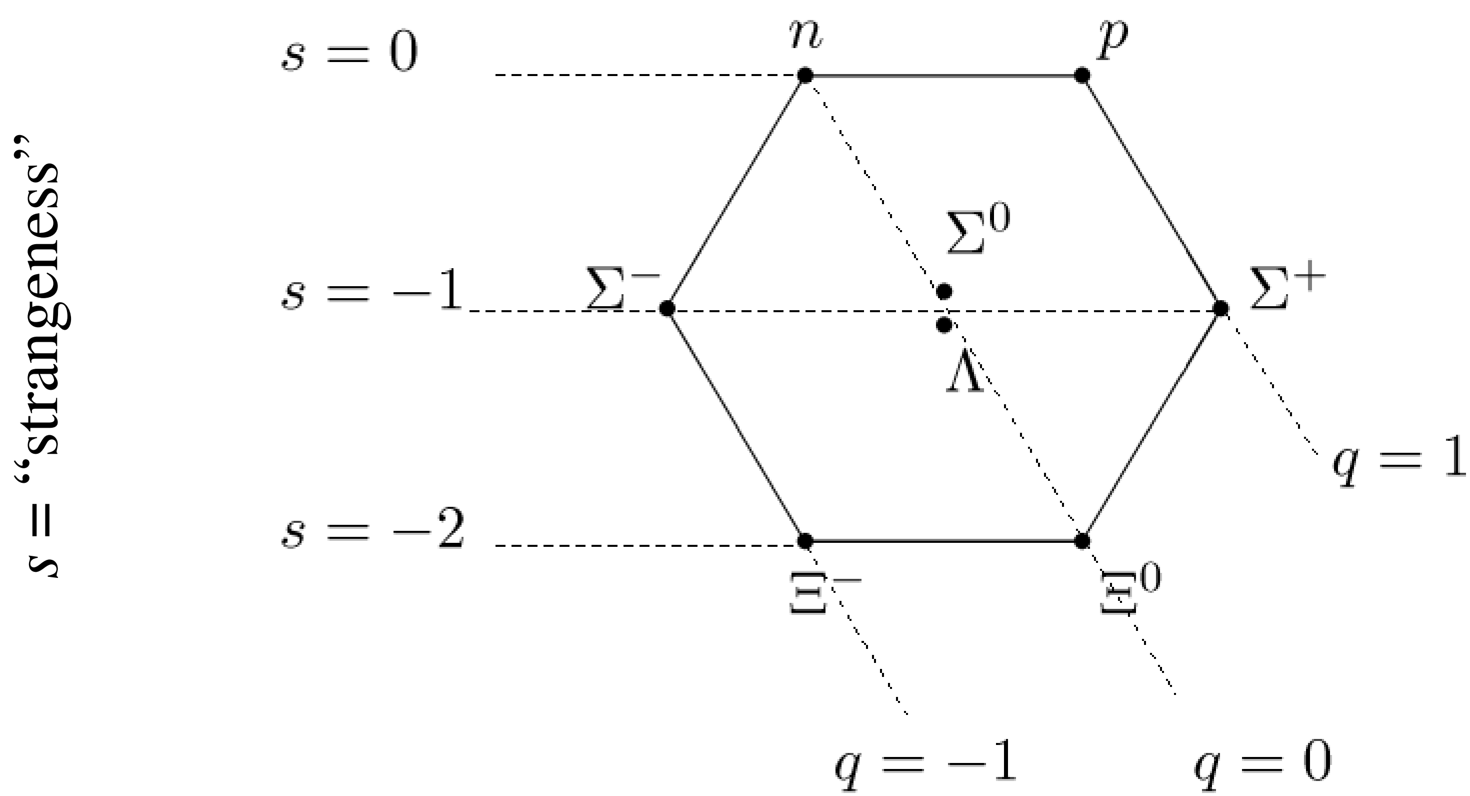
The meson octet

s = “strangeness”



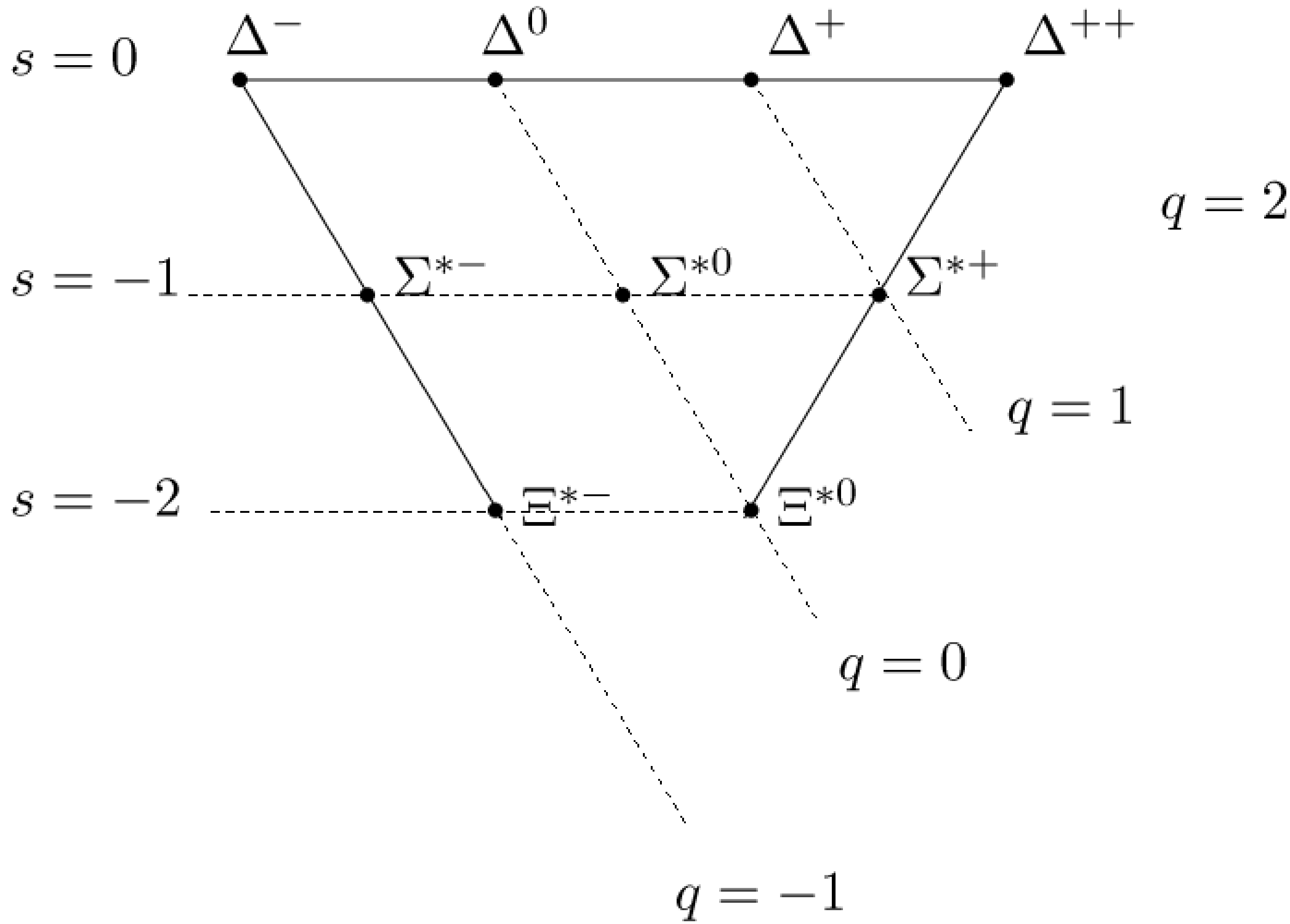
q = electric charge

The baryon octet



q = electric charge

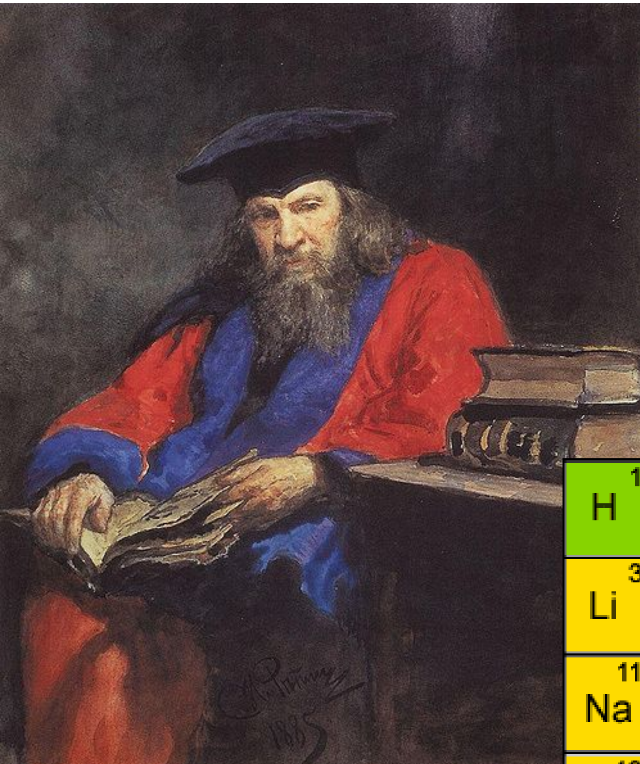
The other baryons



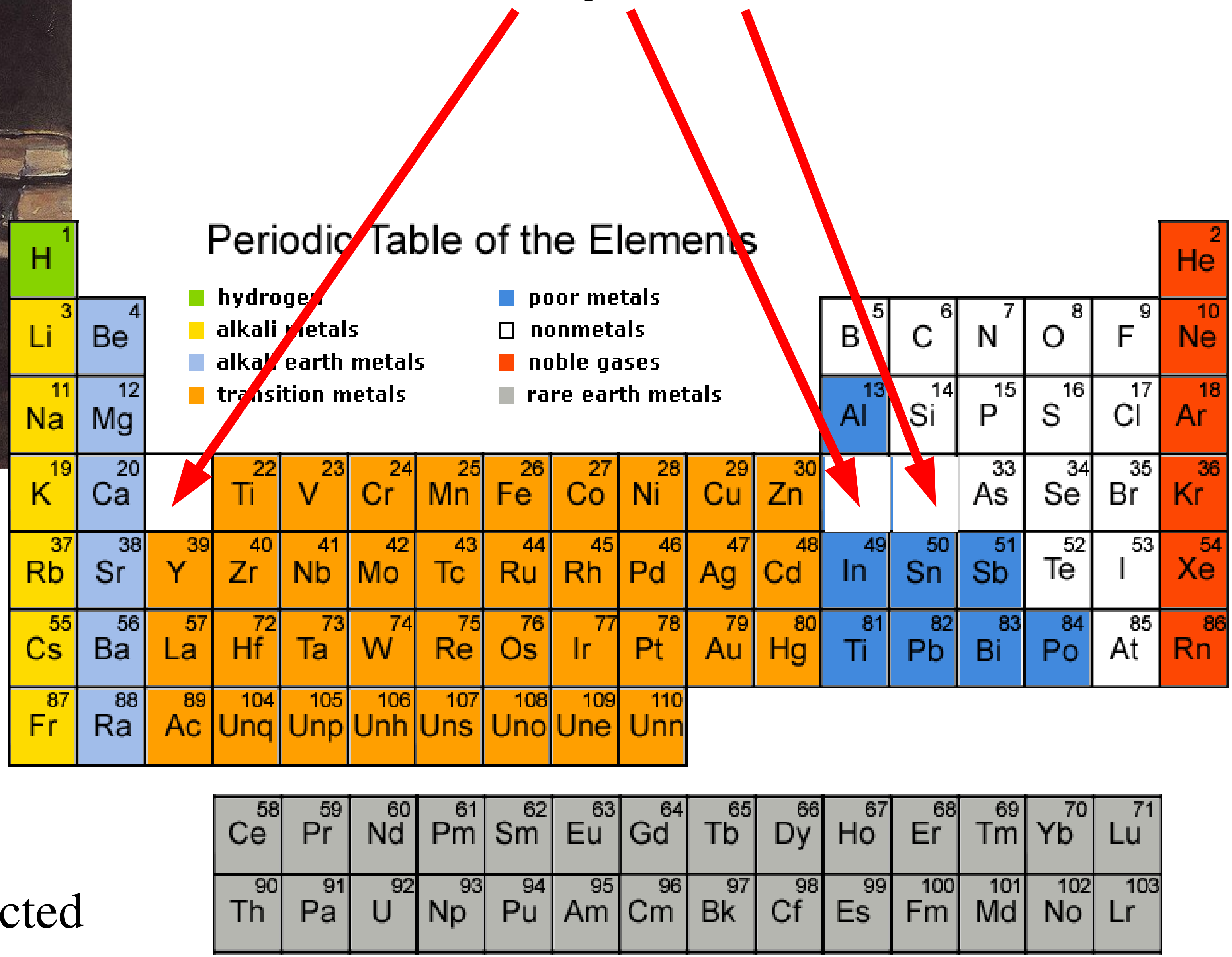
s = "strangeness"

q = electric charge

Mendeleev's bold prediction

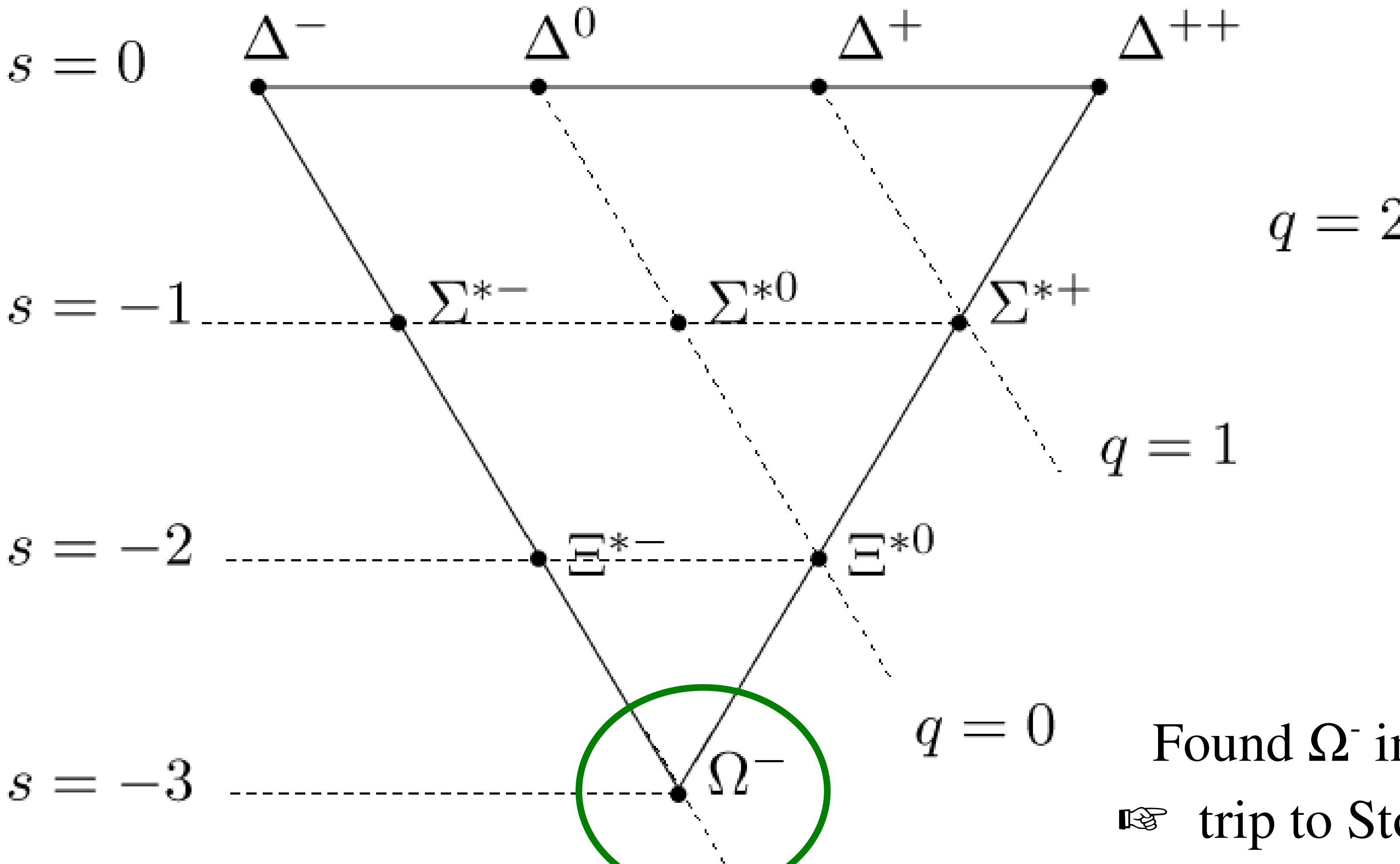


Missing elements!



Sc, Ga & Ge
all discovered
20 yrs after their
existence was predicted

Gell-Mann: the Mendeleev of particle physics

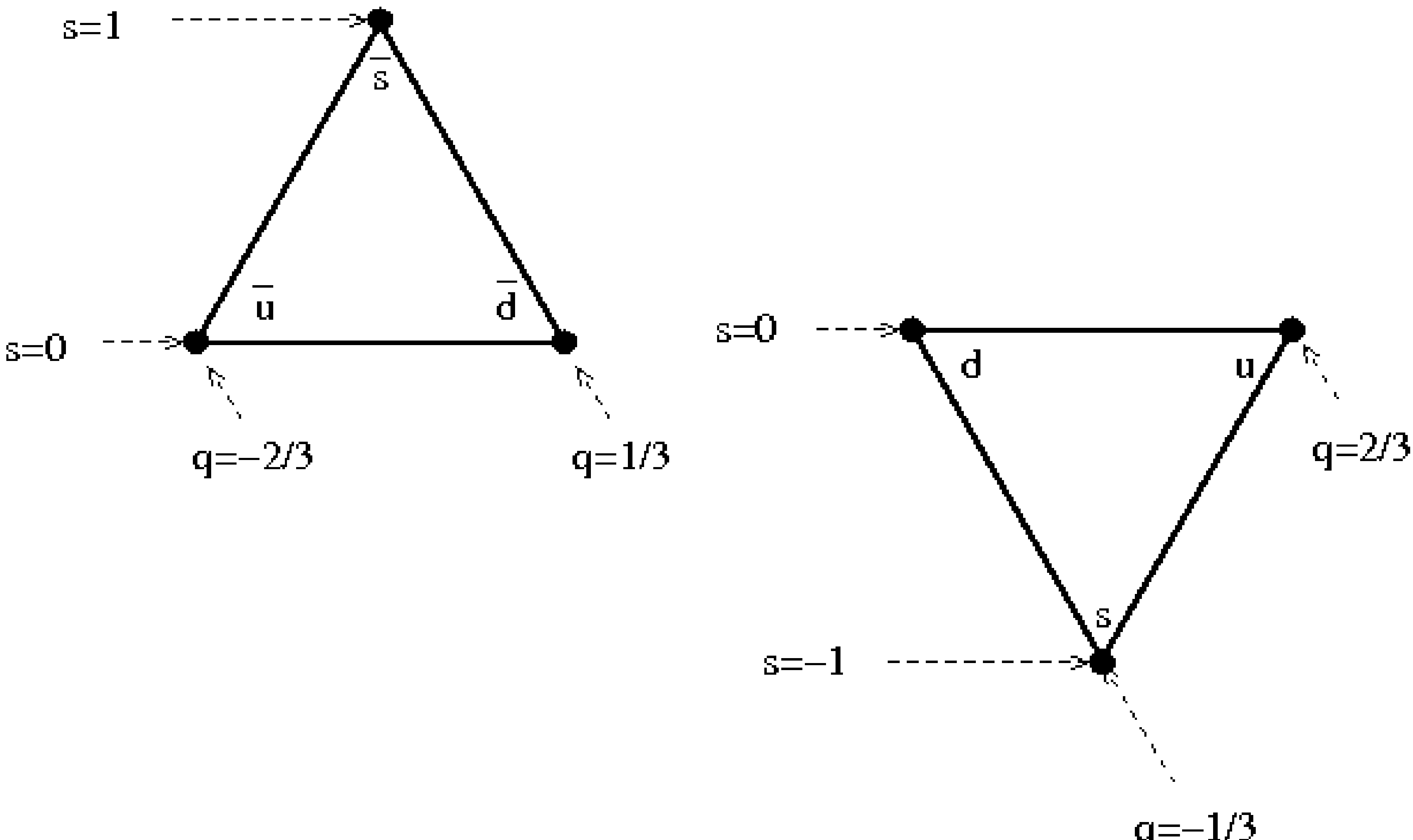


Found Ω^- in 1964

☞ trip to Stockholm!

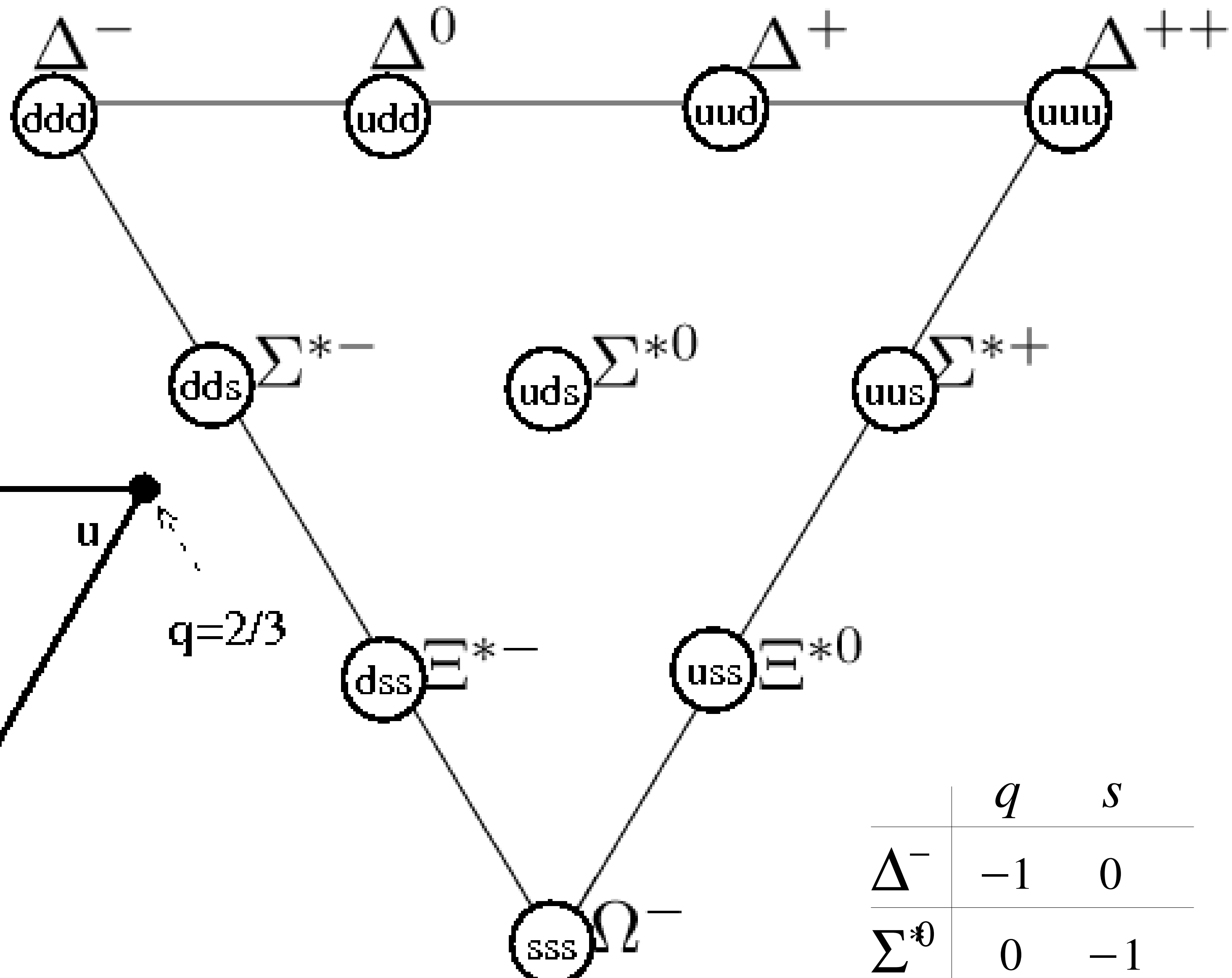
Multiplet of quarks/anti-quarks

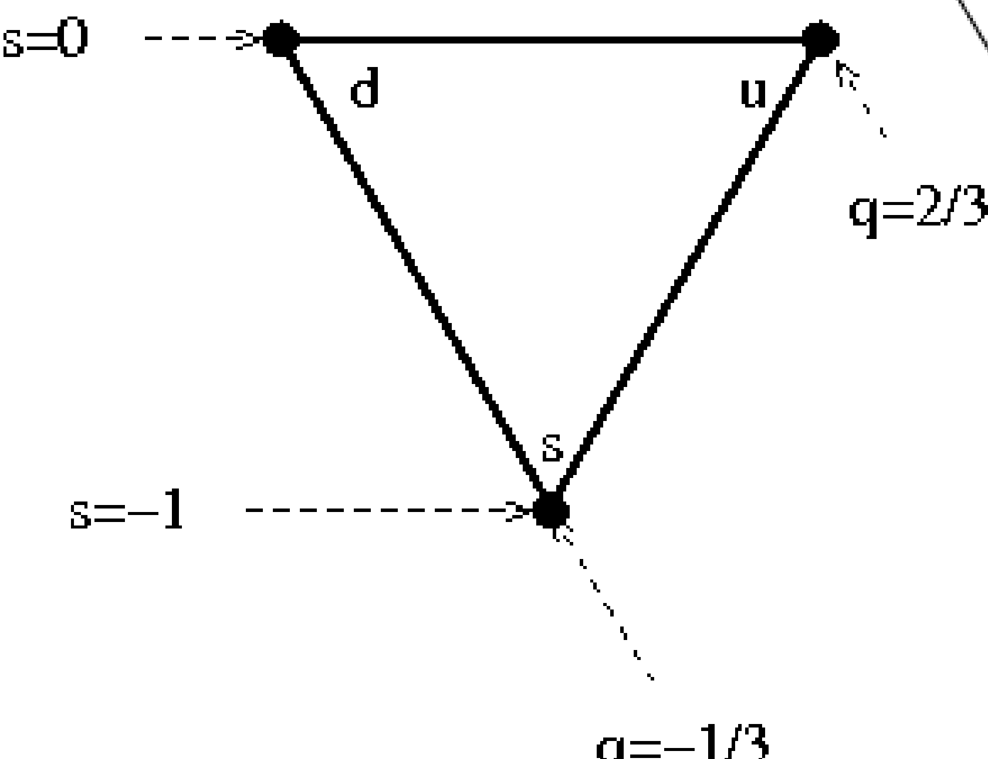
Gell-Mann & Zweig



Baryon decuplet in terms of quarks

	q	s
u	$+2/3$	0
d	$-1/3$	0
s	$-1/3$	-1

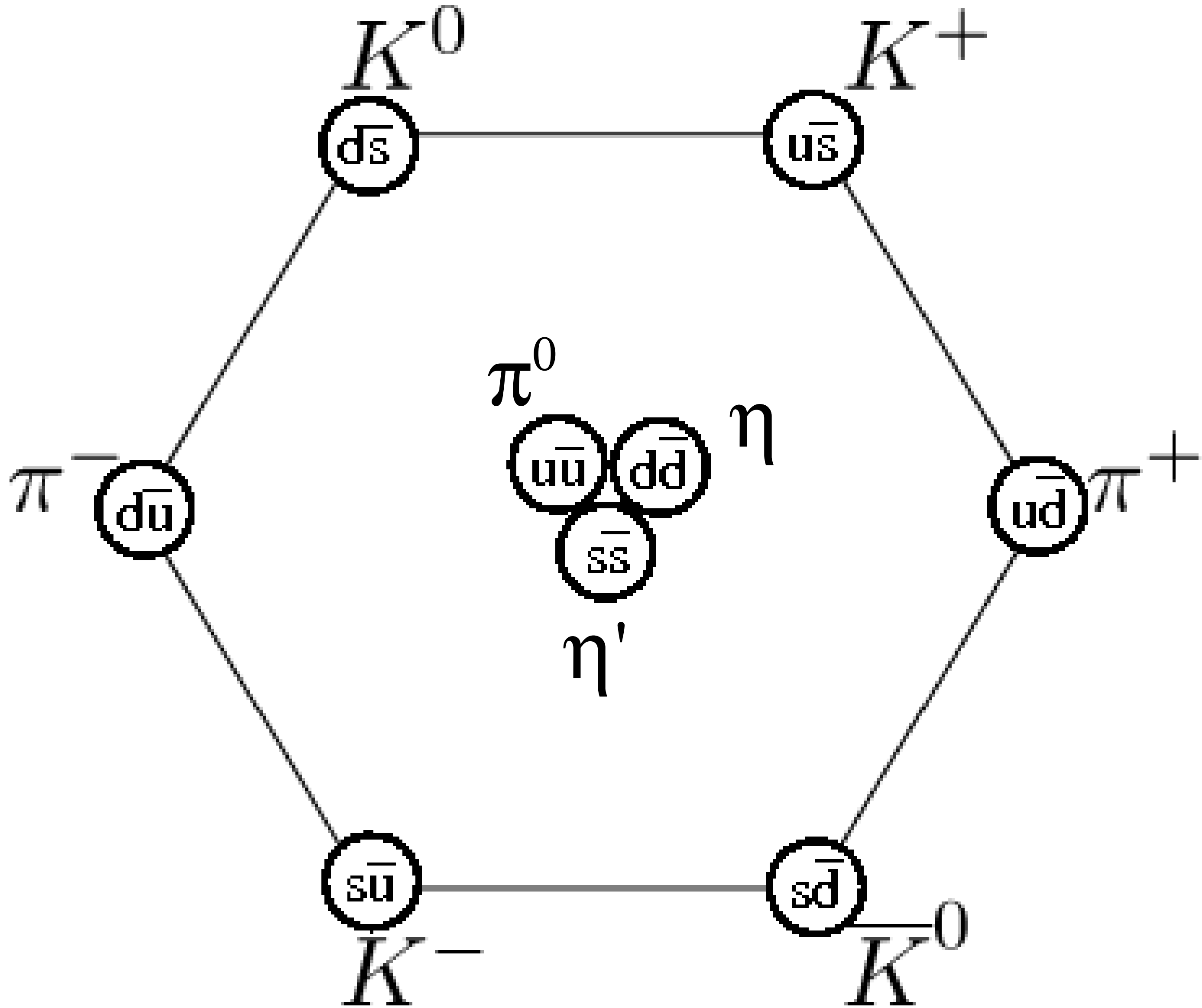




	q	s
Δ^-	-1	0
Σ^{*0}	0	-1
Ξ^{*0}	0	-2

(etc)

The meson *nonet*



Basic consituents of matter

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

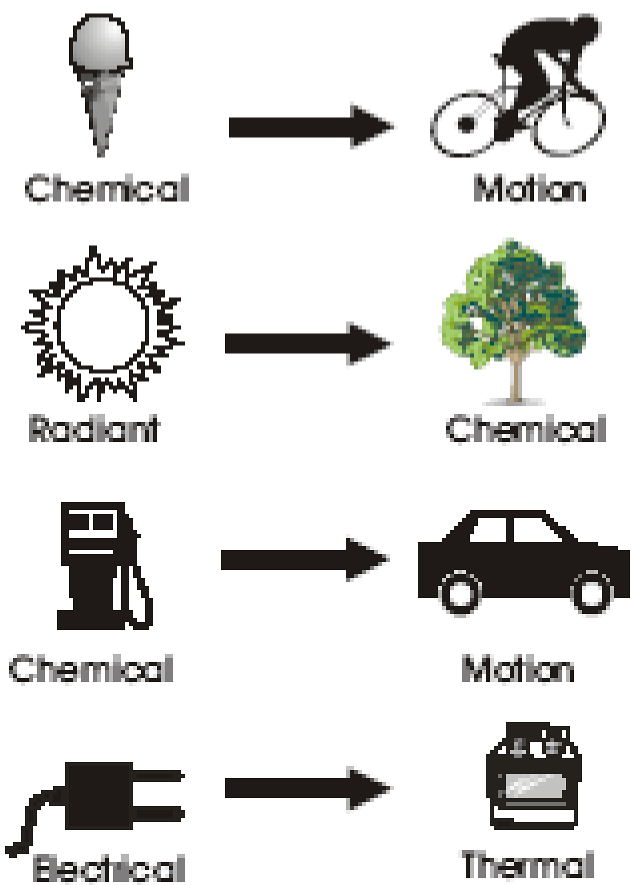
Fundamental symmetries

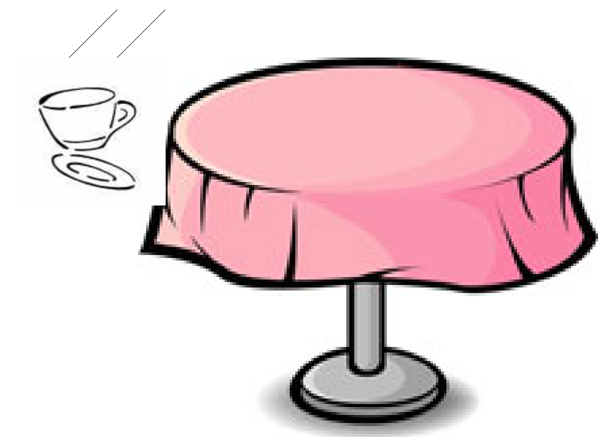
Noether's Theorem: Symmetries ↔ Conservation Law

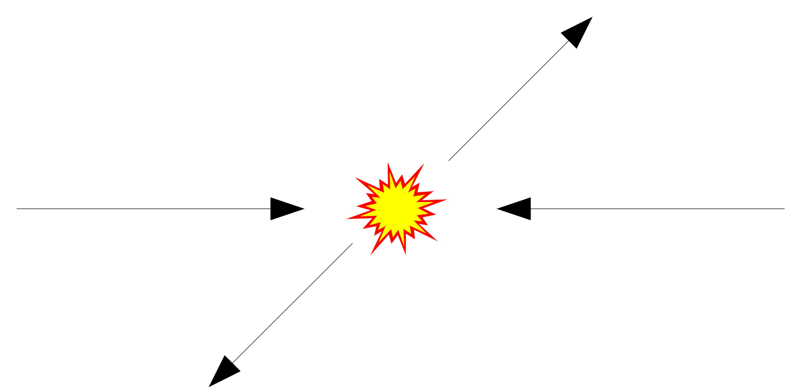
Fundamental symmetries

Noether's Theorem: Symmetries ↔ Conservation Law

Energy is conserved ↔ time-reversal symmetry







Fundamental symmetries

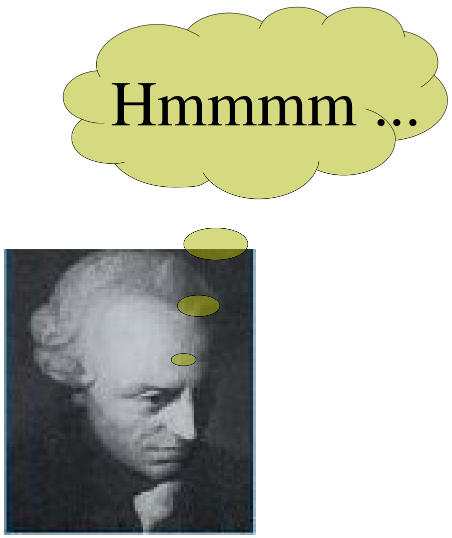
Noether's Theorem: Symmetries $\leftrightarrow$ Conservation Law

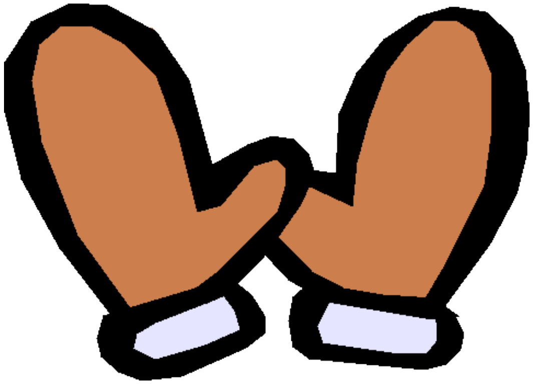
Energy is conserved	$\leftrightarrow$	time-reversal symmetry
Momentum is conserved	$\leftrightarrow$	translational symmetry
Angular momentum is conserved	$\leftrightarrow$	rotational symmetry
Charge is conserved	$\leftrightarrow$	"gauge" symmetry
$\vdots$		$\vdots$

History of parity

History of parity

- 1786: Kant debates the nature of incongruent counterparts





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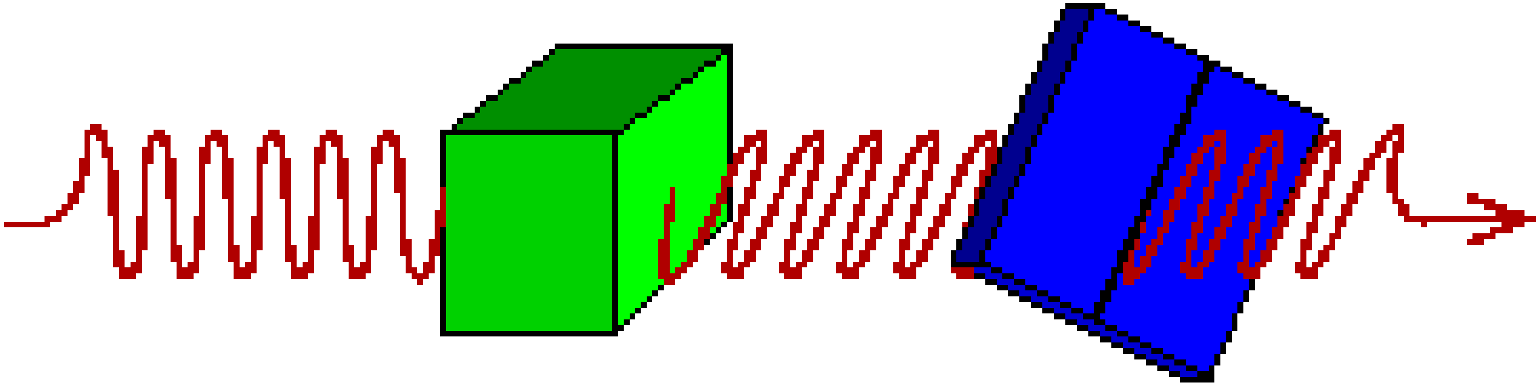

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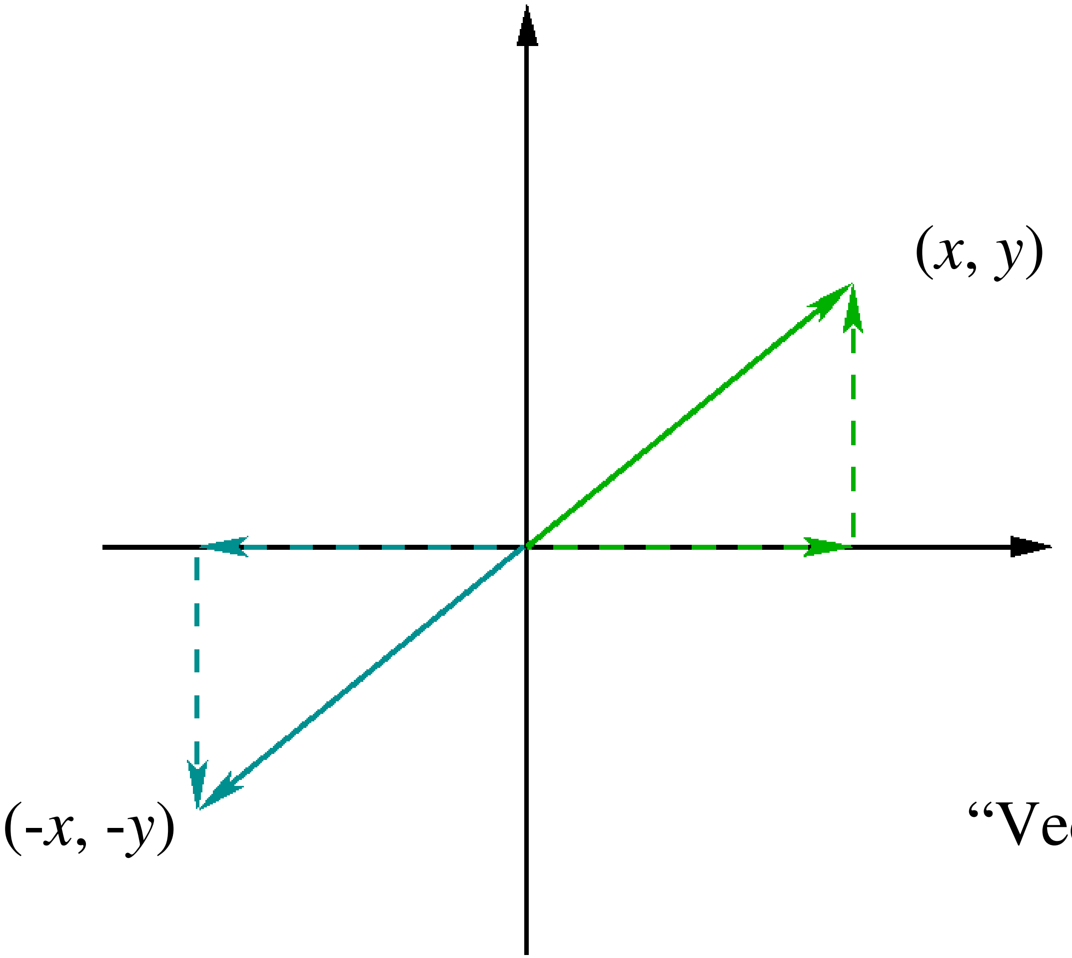

"Vector" interaction

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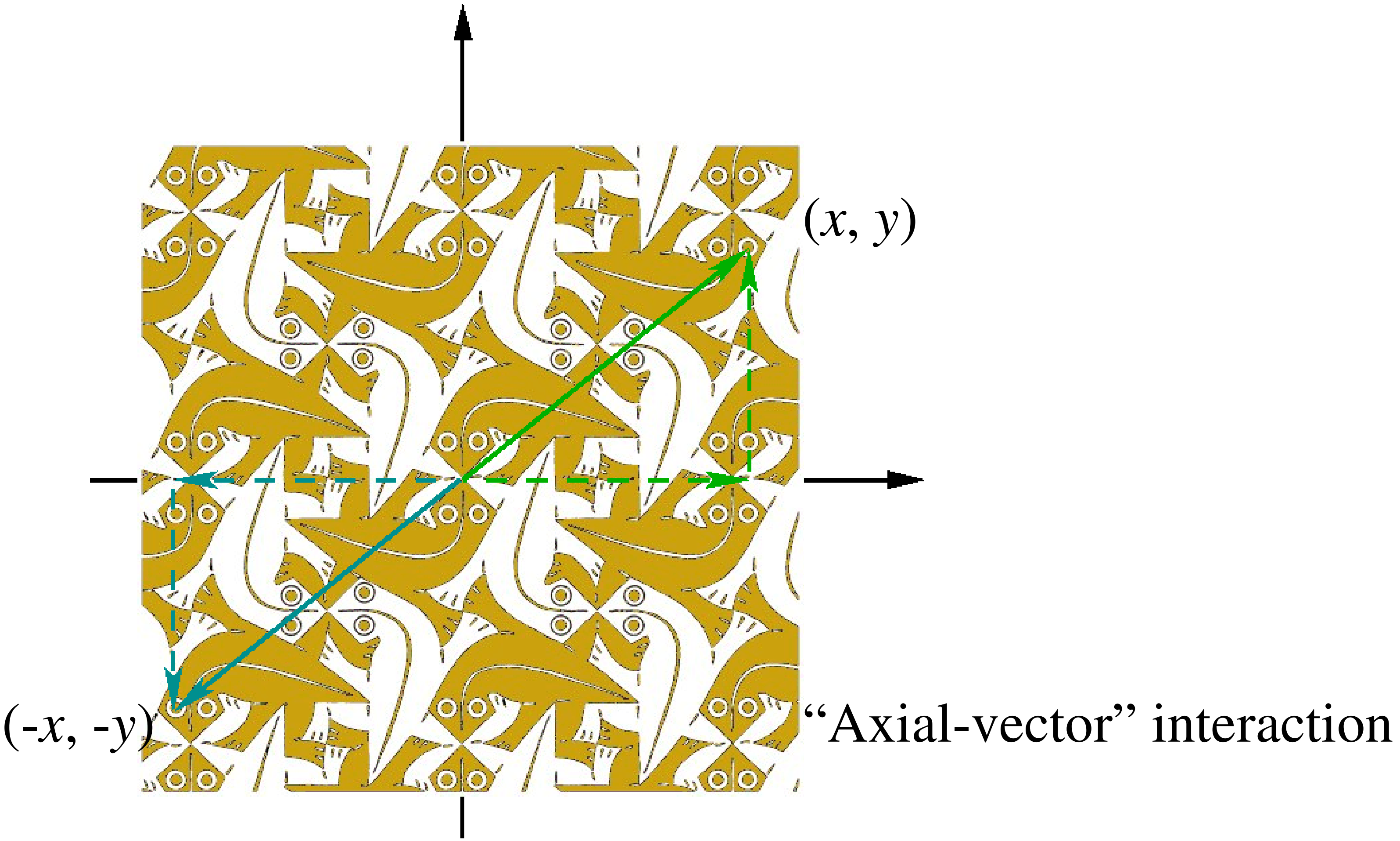

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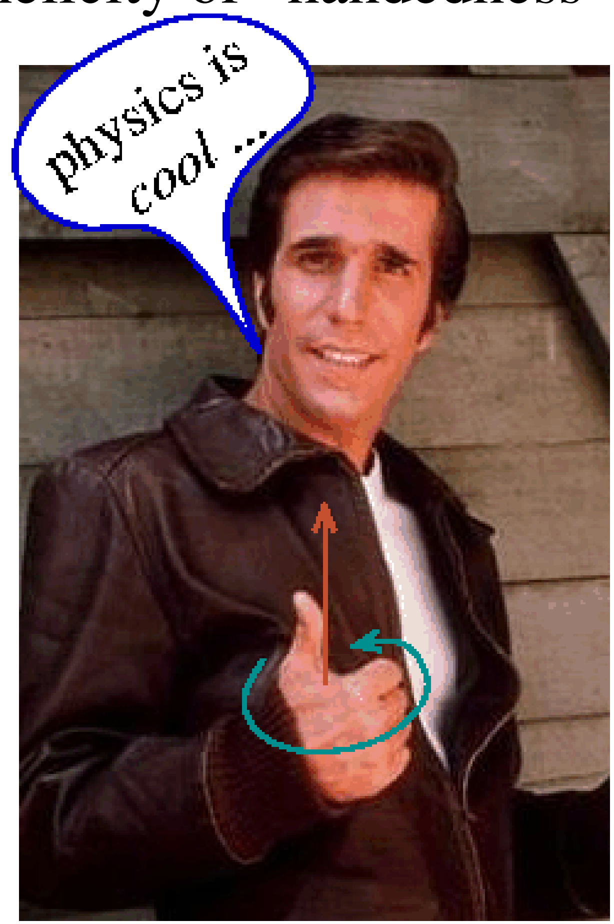
Intrinsic parity ⟺ helicity or “handedness”



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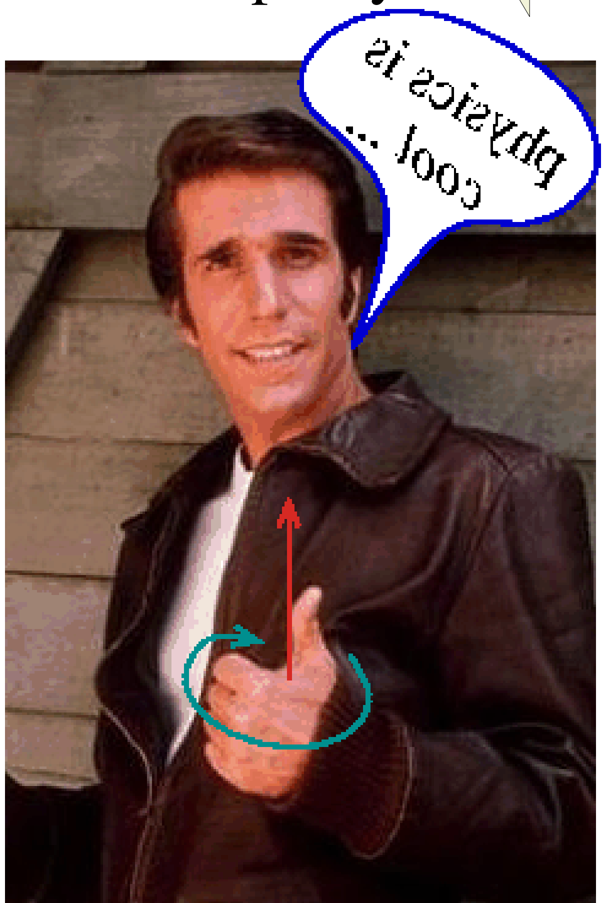

History of parity

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- 1848: Pasteur observes optical rotation in chemical isomers
- 1924: Laporte introduces idea of parity conservation in quantum mechanics
- 1927: Wigner proves Maxwell's equations of electromagnetism conserve parity

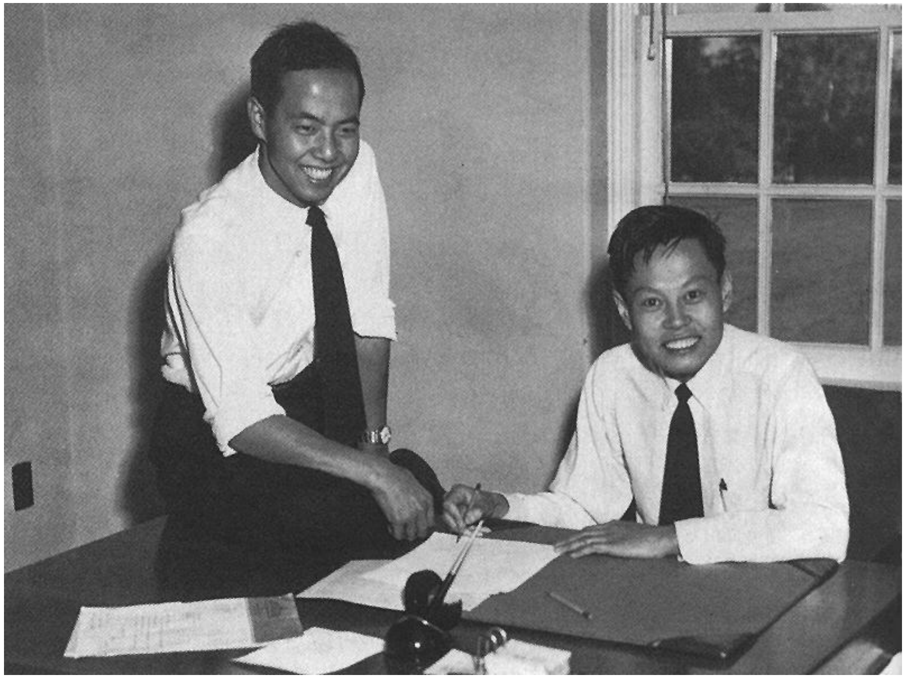
⋮

- 1953: Experiments indicate weak interaction is (S,T)
- 1953: Dalitz points out "θ-τ puzzle":

$$\theta \to \pi^0\pi^+ \qquad \text{vs} \qquad \tau \to \pi^+\pi^+\pi^-$$

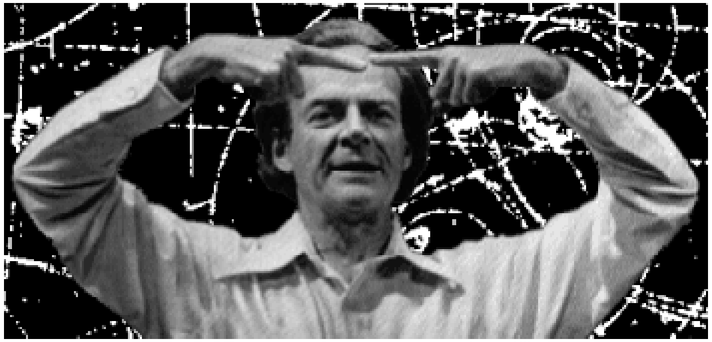
same half-life, same mass, same charge, ...

Is parity always conserved?



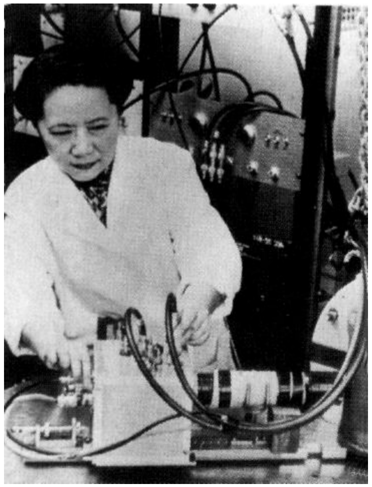
Prompted Lee and Yang to note:

"... existing experiments do indicate parity conservation in strong and electromagnetic interactions, but that for weak interactions ... parity conservation is so far only an extrapolated hypothesis, unsupported by experimental evidence."



Feynman bets parity stays conserved

C.S. Wu's experiment



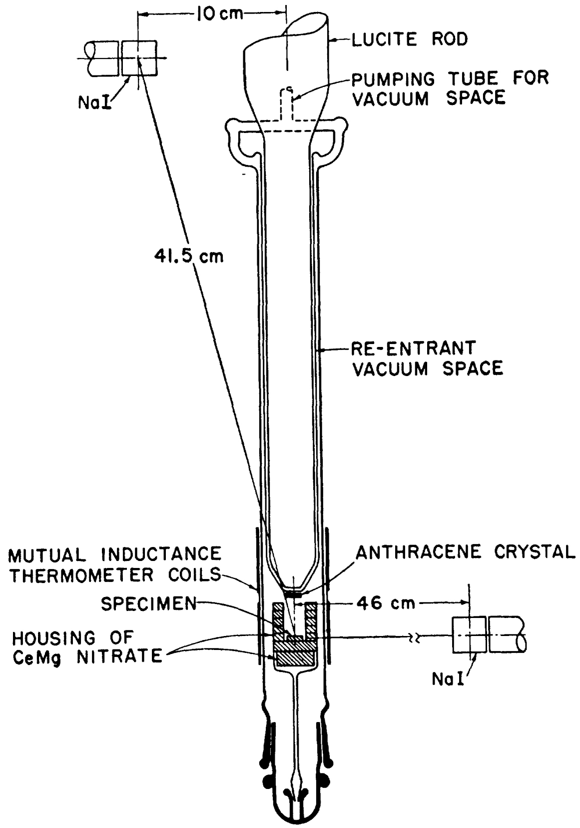
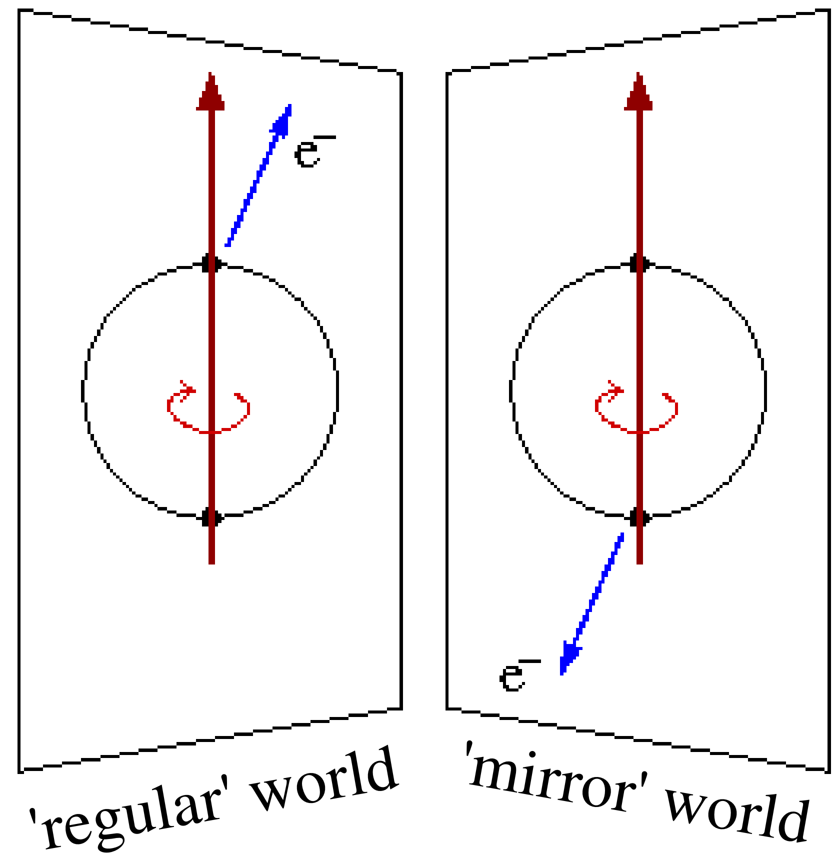


FIG. 1. Schematic drawing of the lower part of the cryostat.

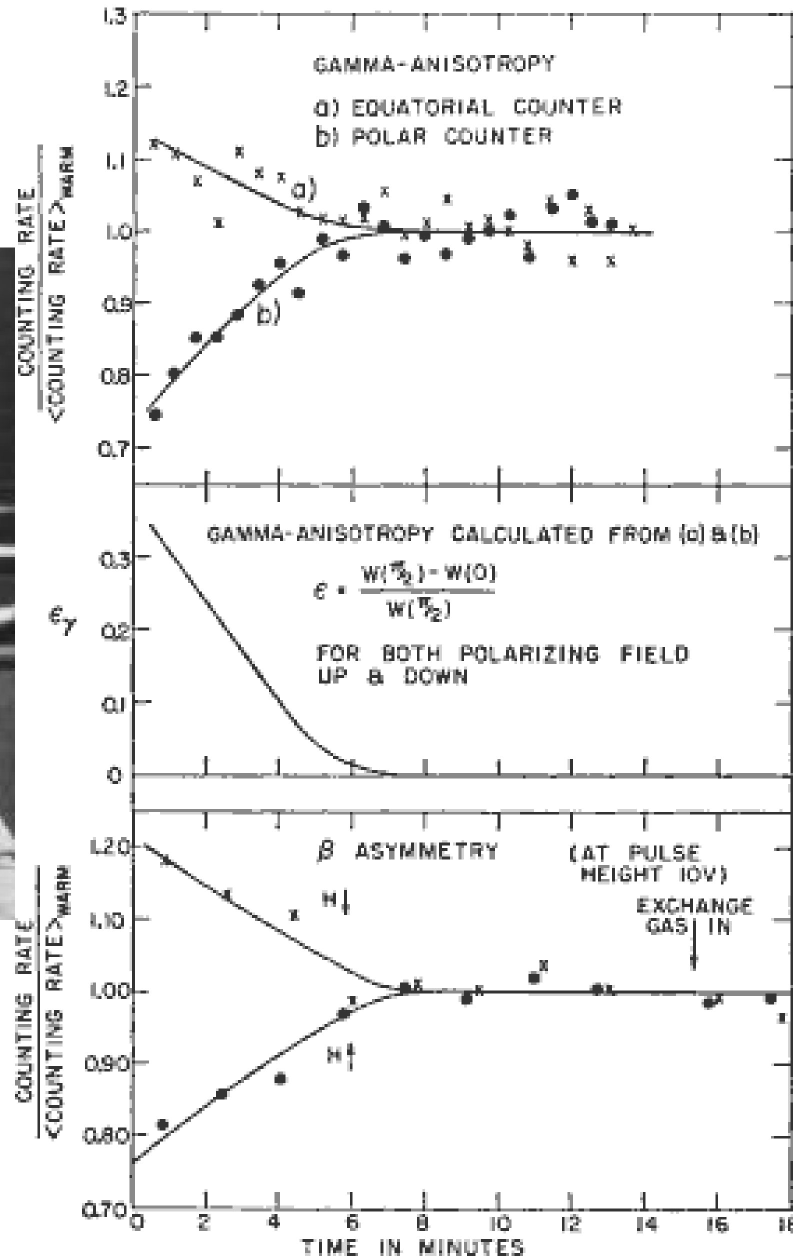


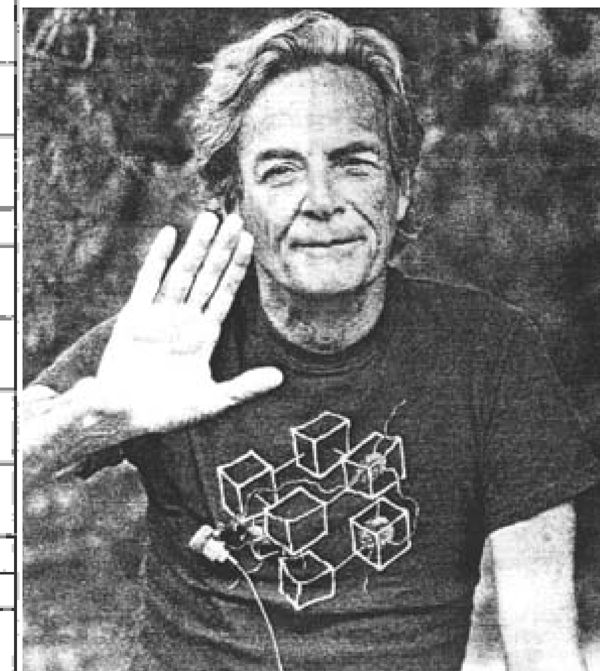
e^- direction is a vector: $\boldsymbol{p} = \Delta x/\Delta t \rightarrow -\boldsymbol{p}$

spin is an axial-vector: $\boldsymbol{J} = r \times p \rightarrow \boldsymbol{J}$

If there is a correlation between ***p*** and ***J***, parity is not conserved!

Feynman loses $50





Parity is NOT conserved in weak interactions!

Now the question is ...

The standard model of particle physics assumes the weak interaction is

$$V - A$$

which *maximally* violates parity (not $V - 0.1A$, for example)

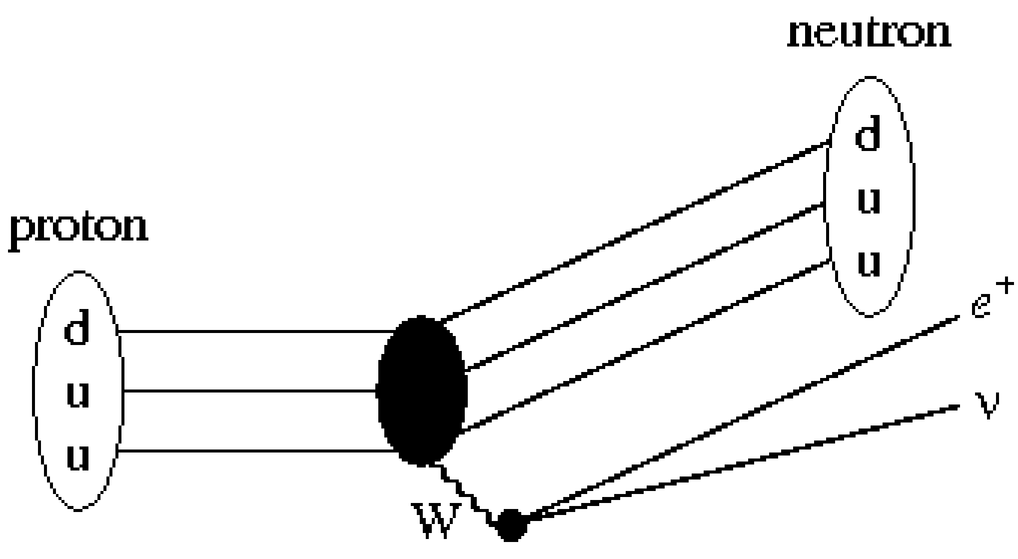
Are there any $V + A$ components we just haven't seen yet?

Is Nature truly left-handed, or is it ambidextrous?

Why would it care whether a process occured in the mirror world or not?

Nuclear physics continues the search

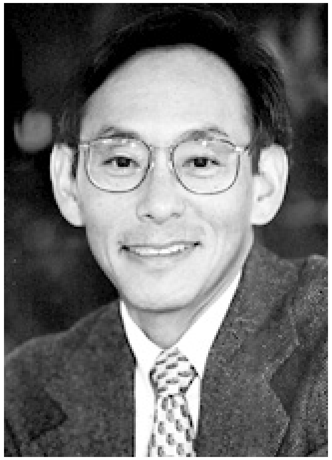
Nuclear β decay:



Textbook assumptions:

- decay occurs from rest
- decay occurs from a point-source
- the particles escape without distortions
- the polarization is perfect

Magneto-optical traps



Steven Chu

Claude Cohen-Tannoudji

William Philips

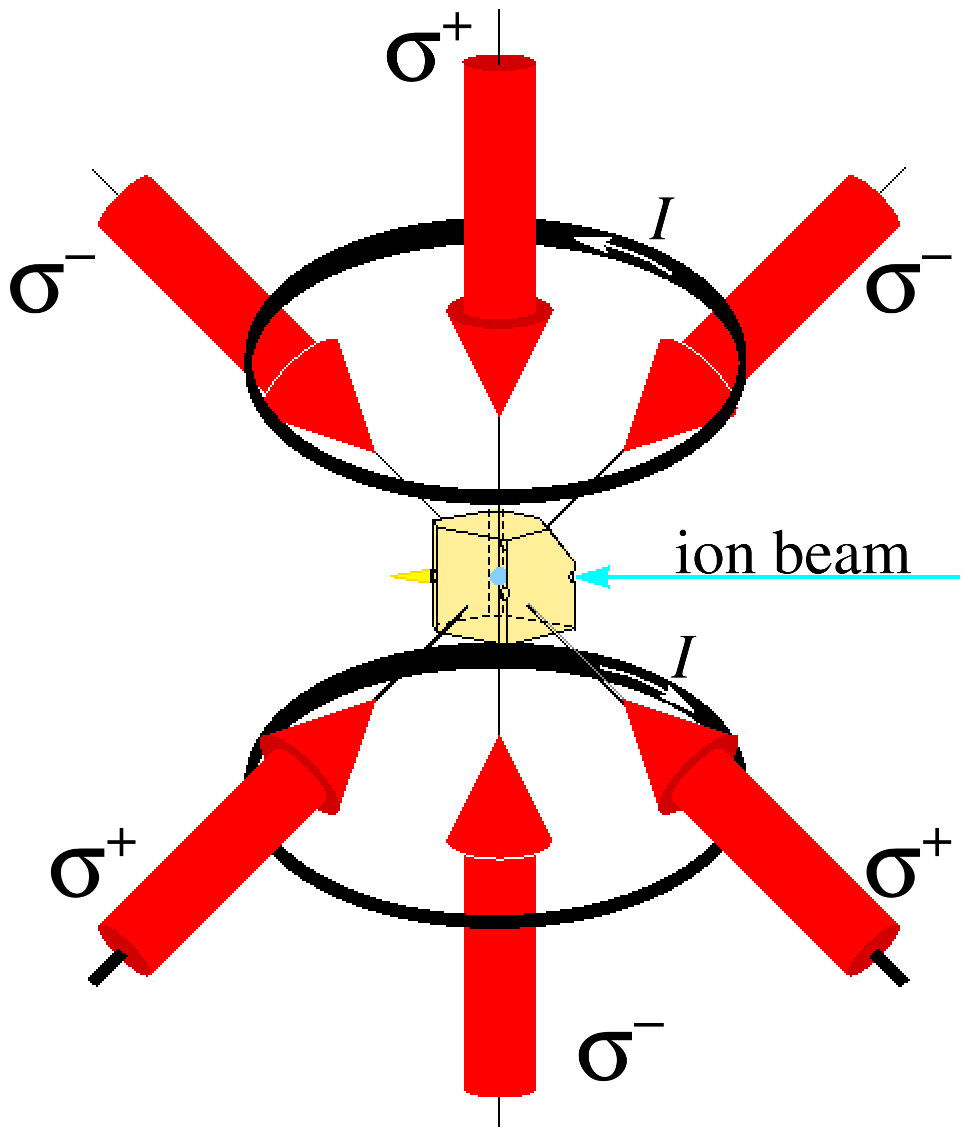
1997

“For development of methods to cool and trap atoms with laser light”

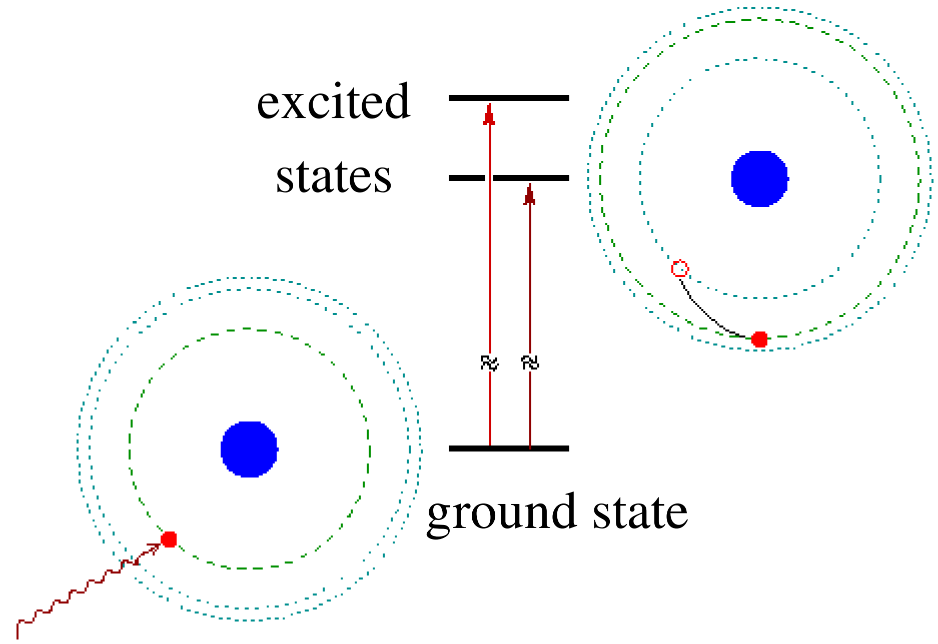
Textbook assumptions:

- decay occurs from rest ✔
- decay occurs from a point-source ✔
- the particles escape without distortions ✔
- the polarization is perfect ?

A vapour-cell MOT



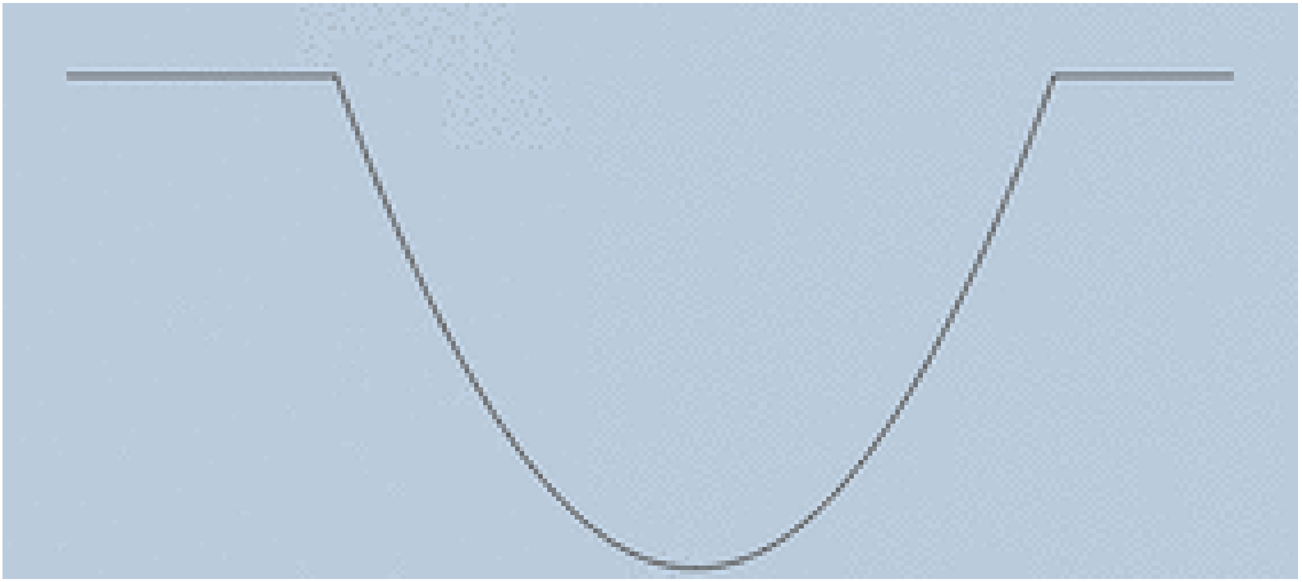
Laser excites atomic transitions:



Basic idea behind *any* trap

Speed-dependent force: dampens the motion and slows particles down

Position-dependent force: defines where particles get trapped

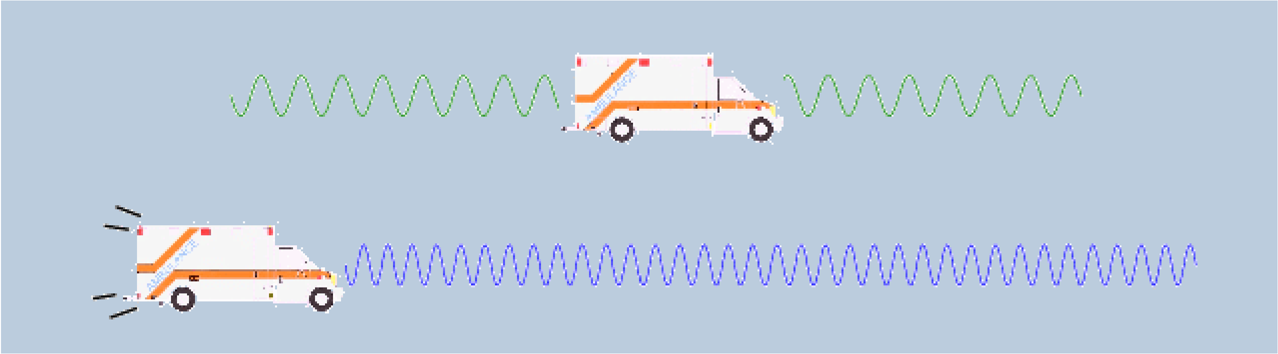


E.g.: Ball in a valley ... *with* friction

How does a MOT work?

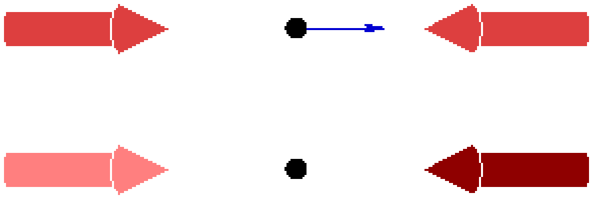
Speed-dependent force: the Doppler effect

Position-dependent force: magnetic fields make absorption rate depend on distance from centre



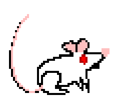
Lab frame:

Atom's frame:

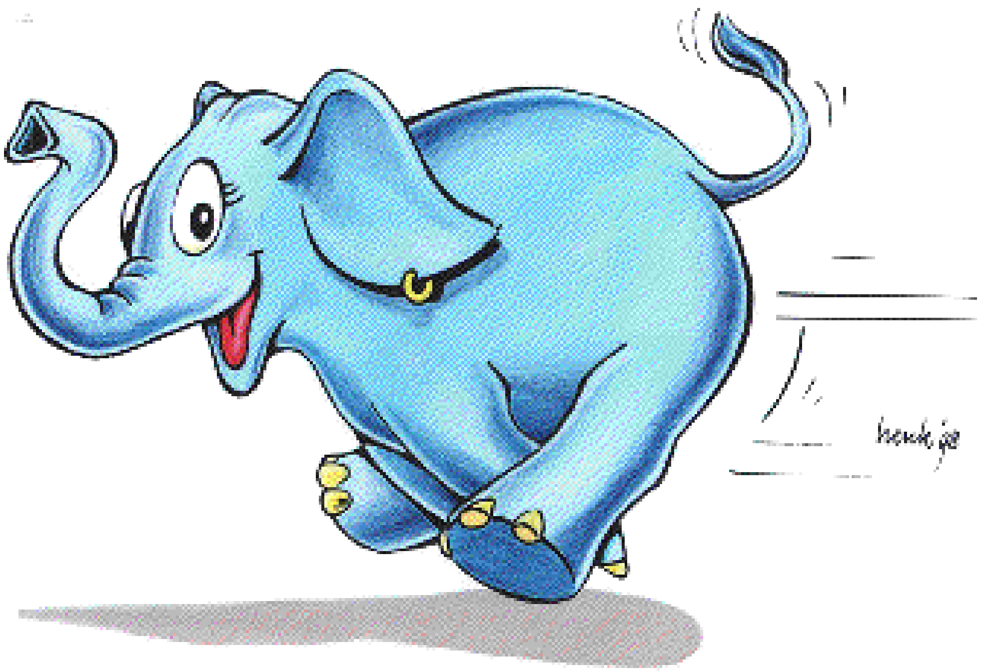


The Doppler effect changes rate of absorbing laser beam

Atom—photon interactions



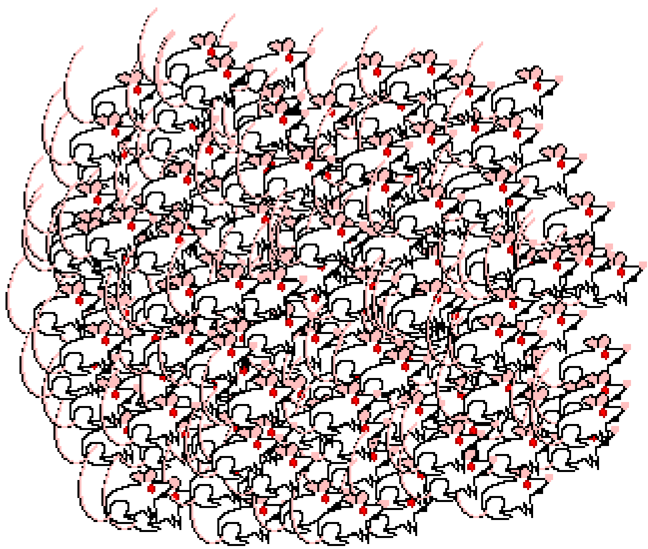
vs.



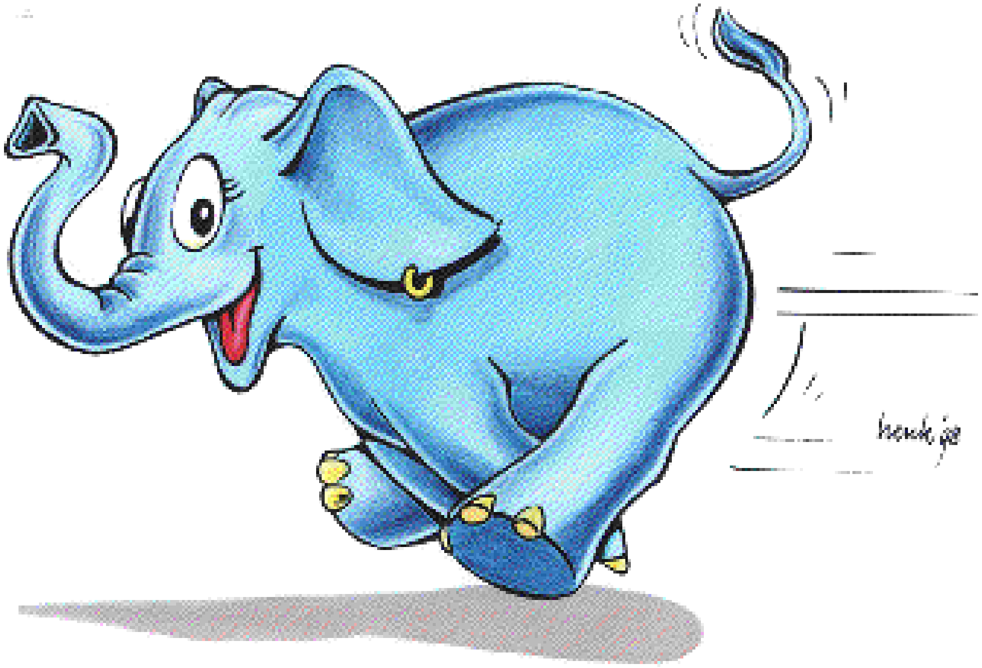
$\hbar\vec{k} \sim 1.5$ eV/c

$M\vec{v} \sim 45$ keV/c

Atom—photon interactions

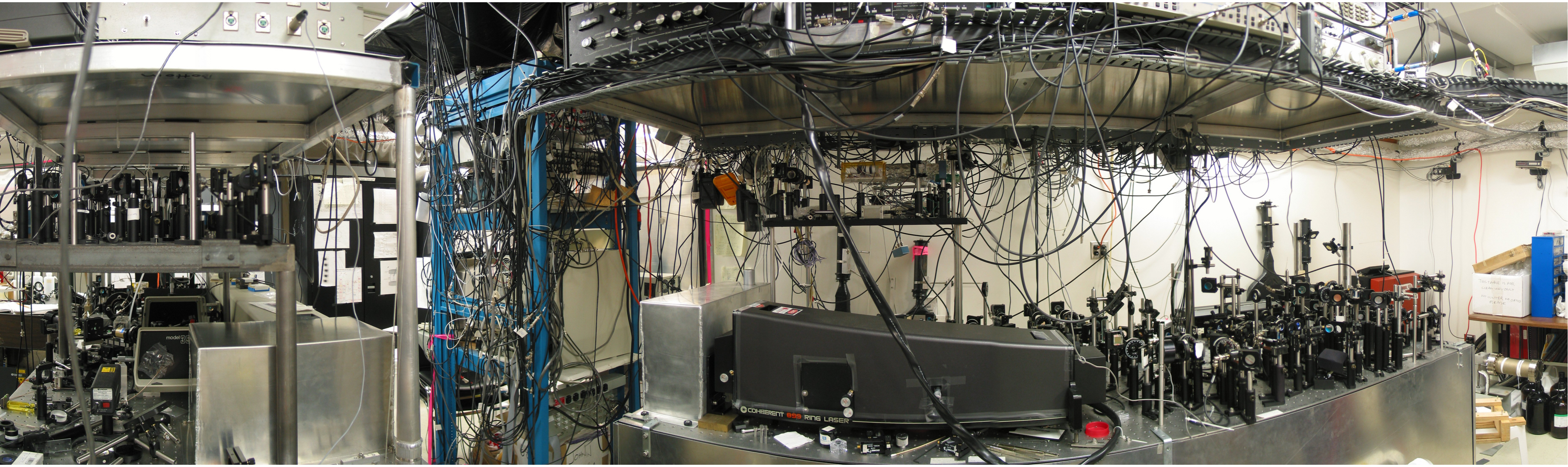


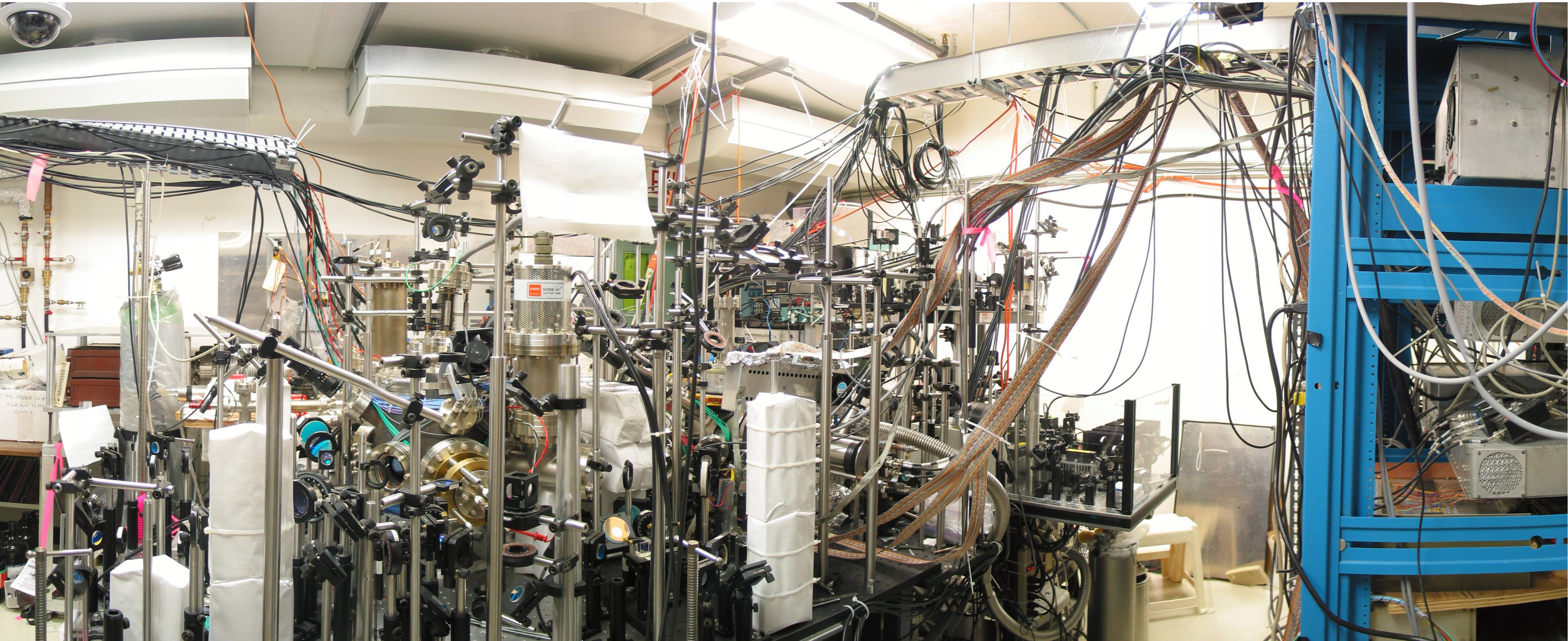
vs.



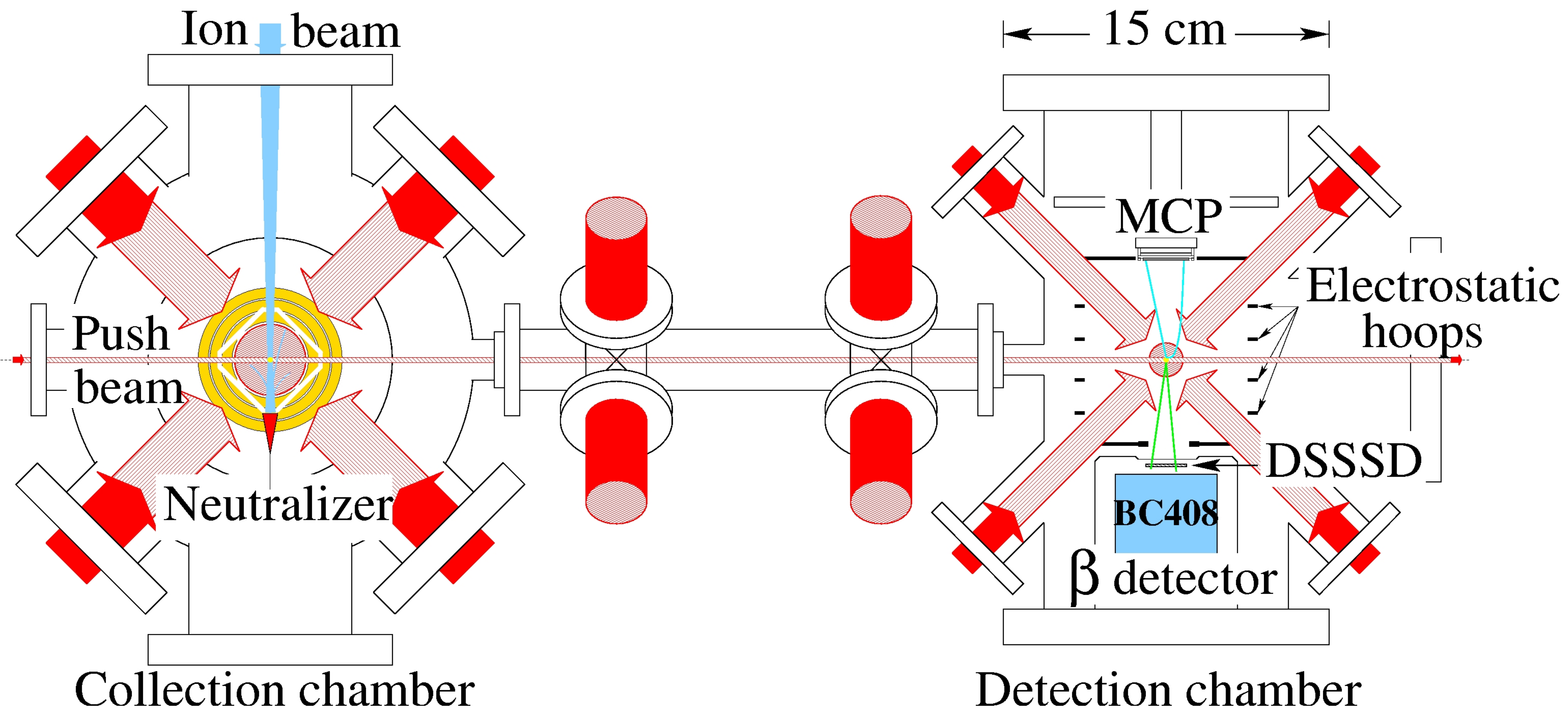
Cycling transitions!!

Just in case you thought it was *easy* ...!!





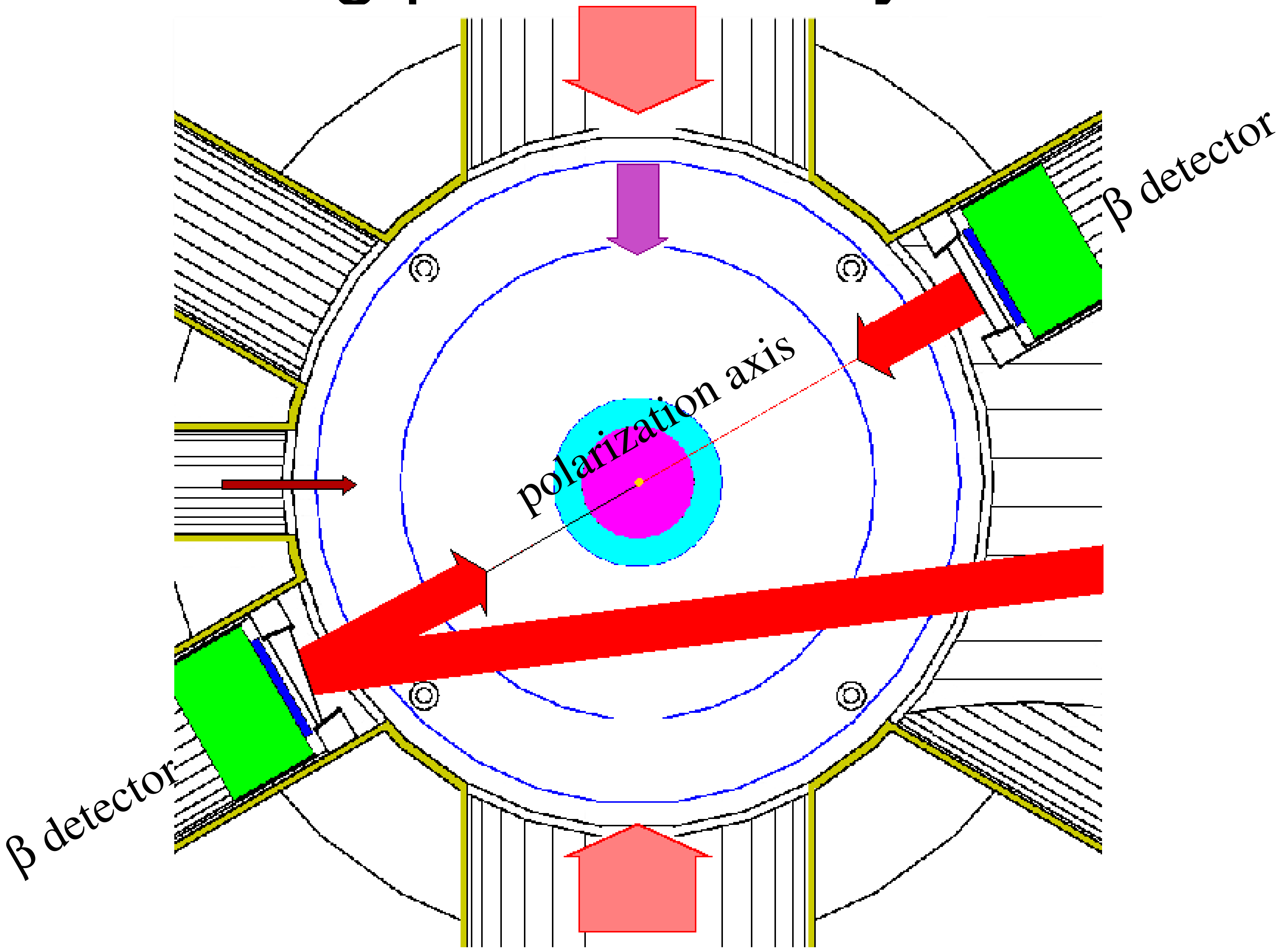
A double-MOT system



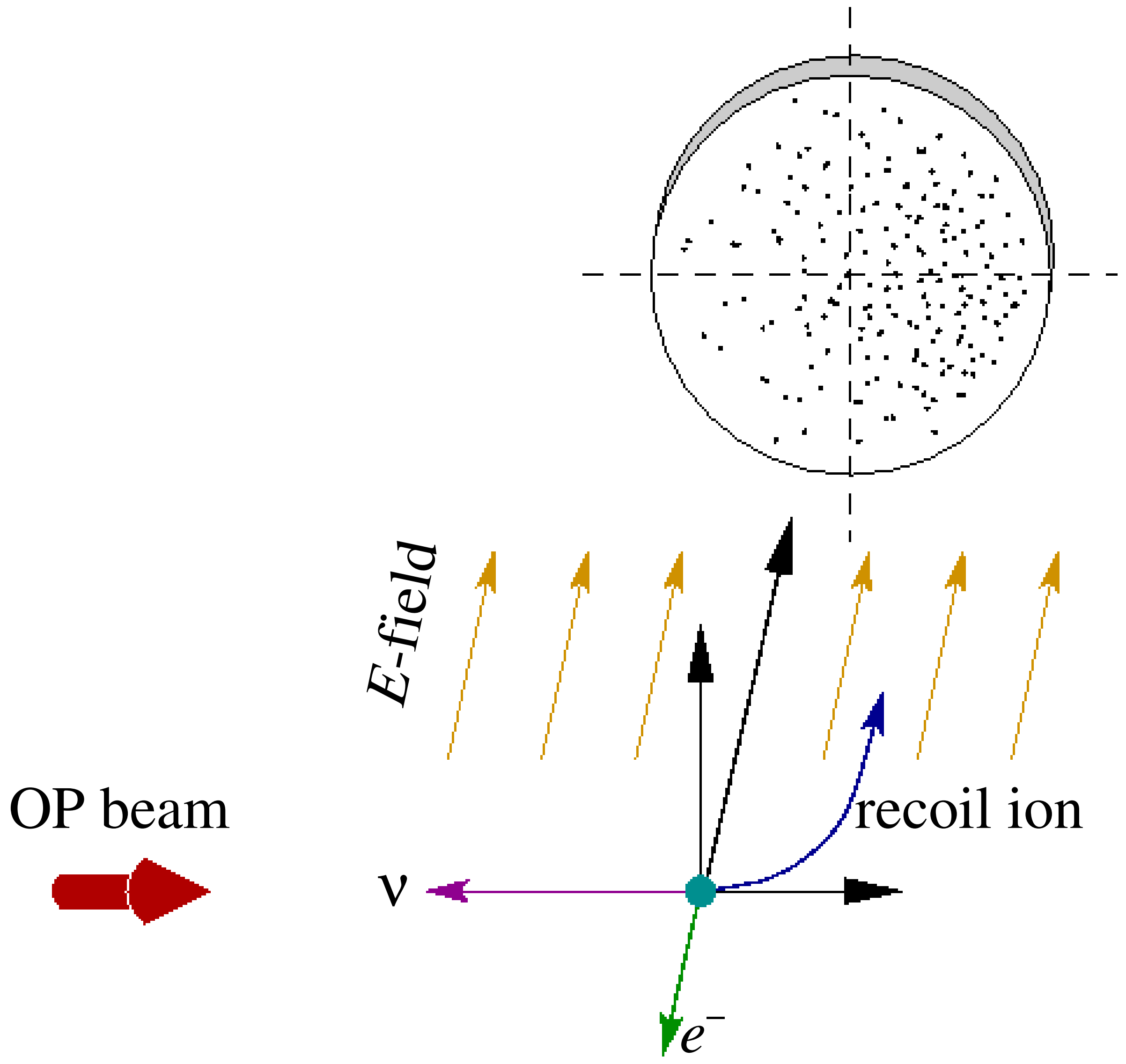
Traps provide a **backing-free**, **cold** (~1mK), **localized** (~1mm^3) source of **short-lived** radioactive atoms

Detect $\vec{p}_e$ and $\vec{p}_{recoil} \Rightarrow$ deduce $\vec{p}_\nu$!

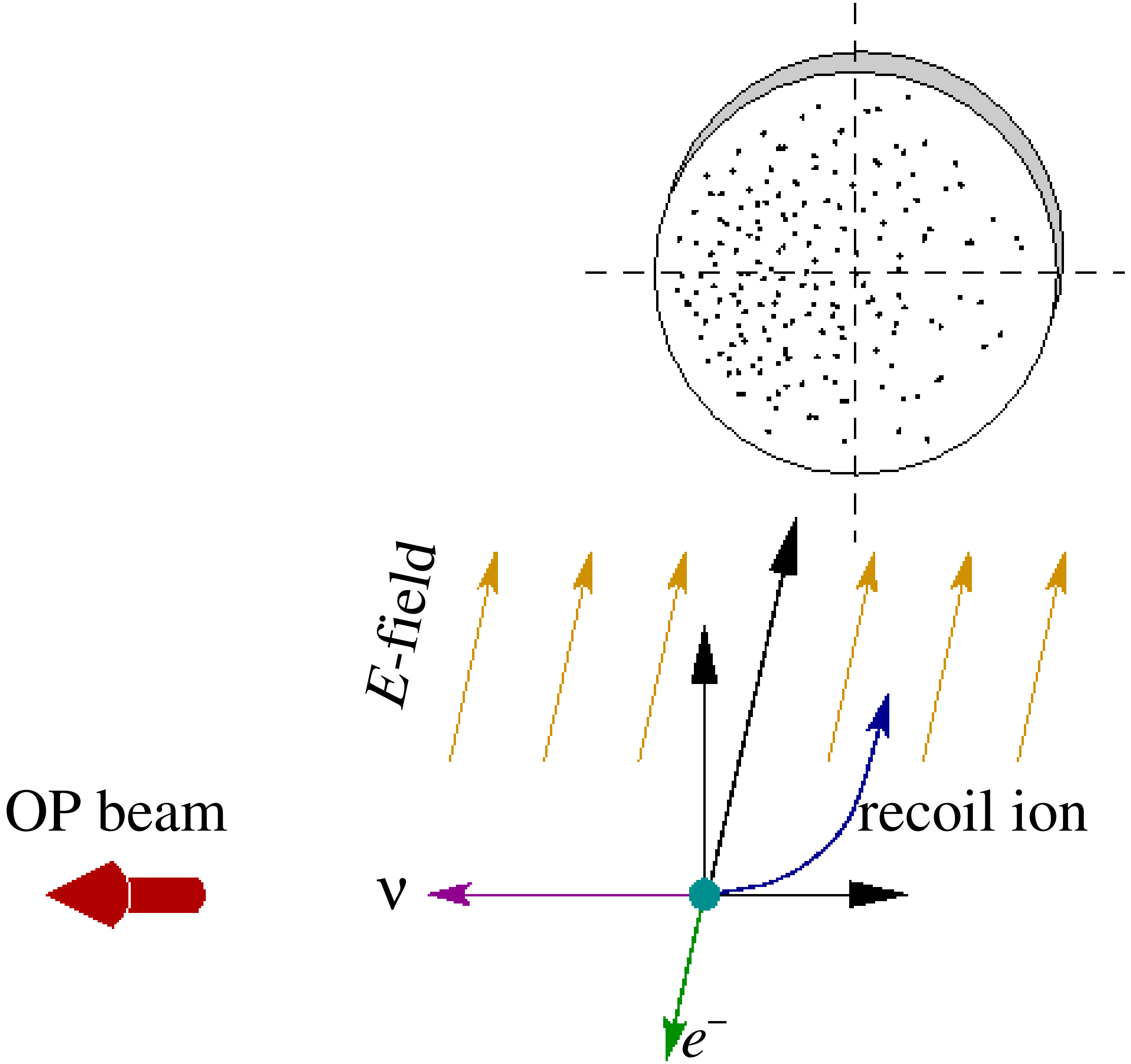
Measuring polarized asymmetries



The neutrino asymmetry

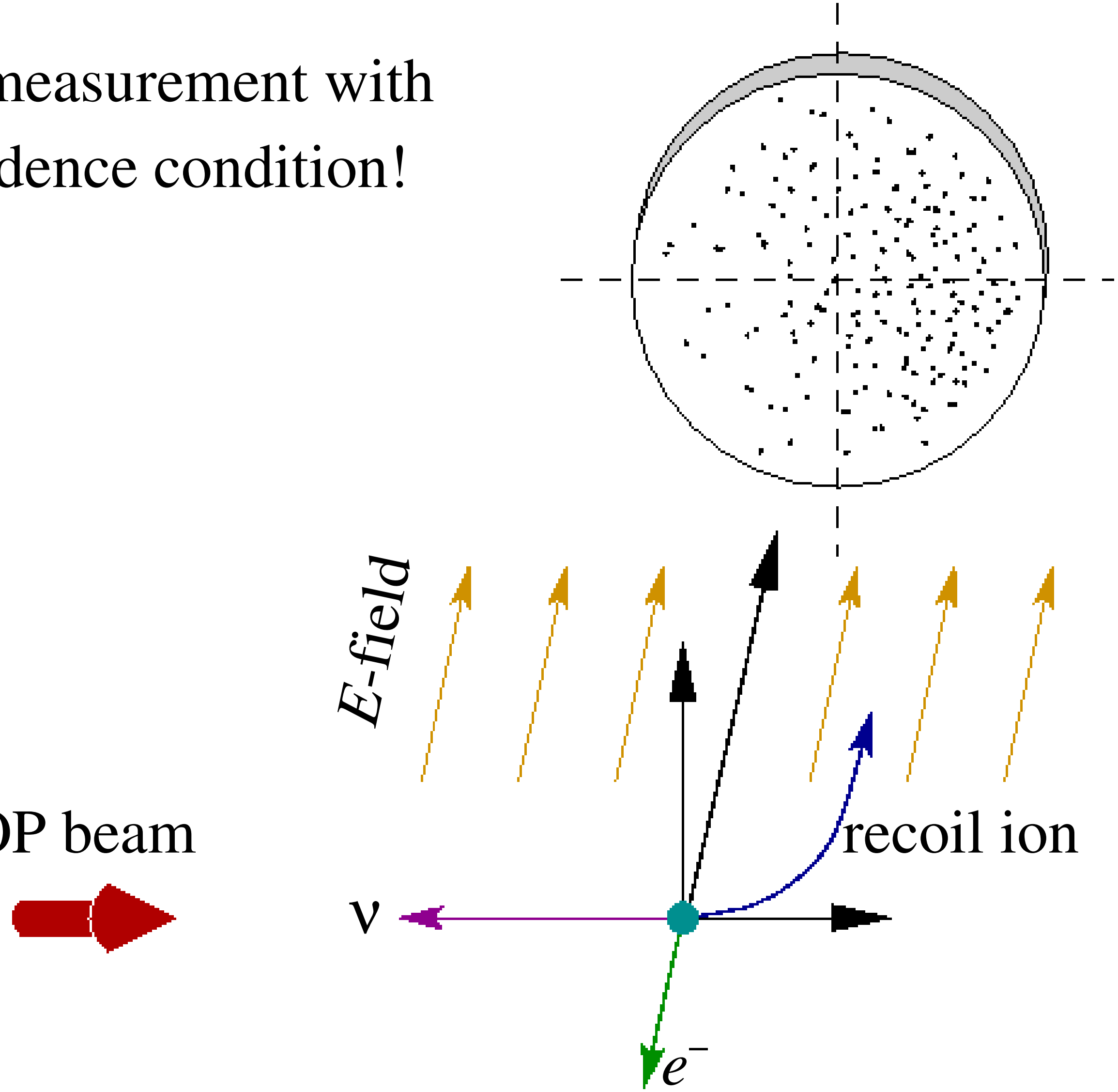


The neutrino asymmetry

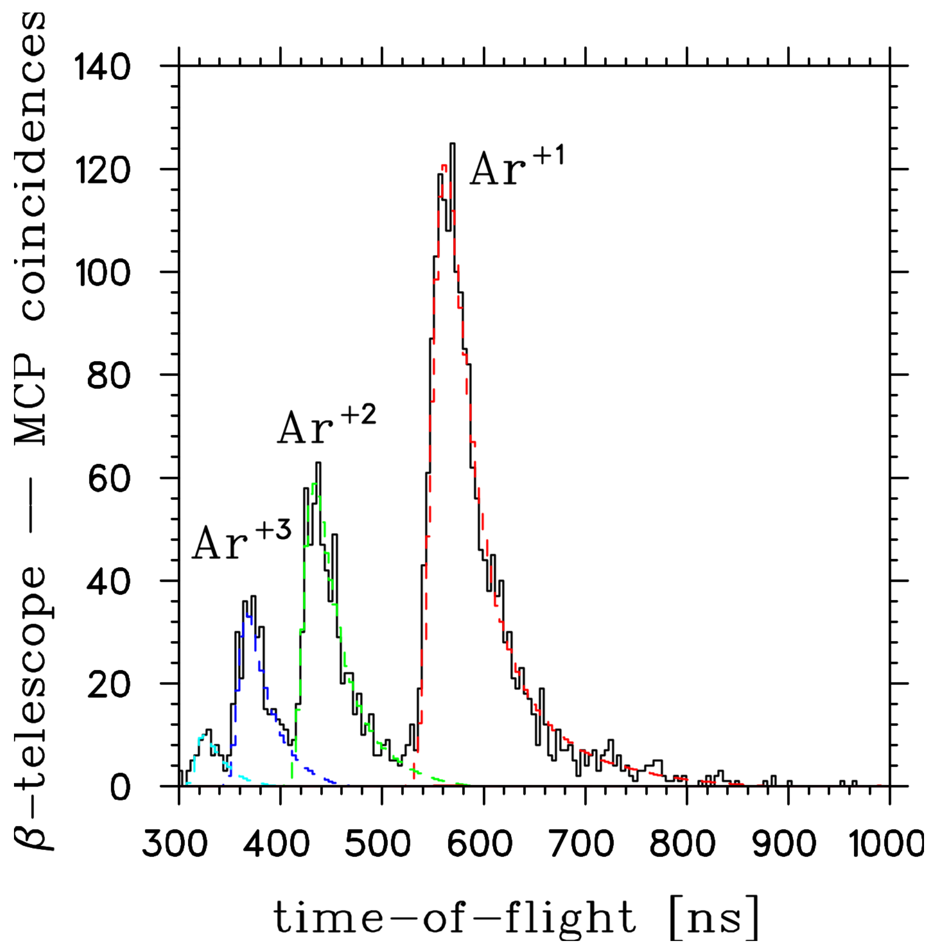


The neutrino asymmetry

Clean measurement with coincidence condition!

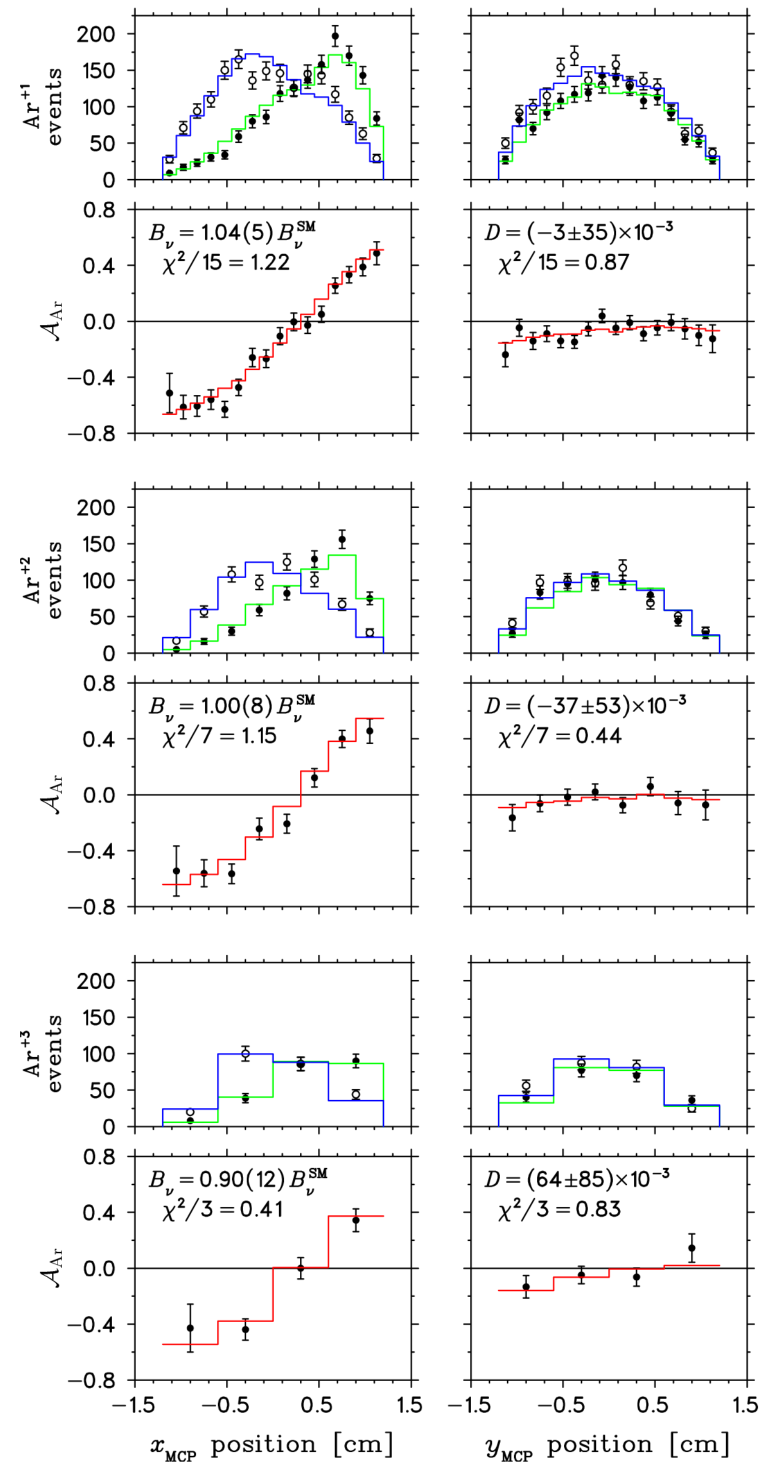


Results



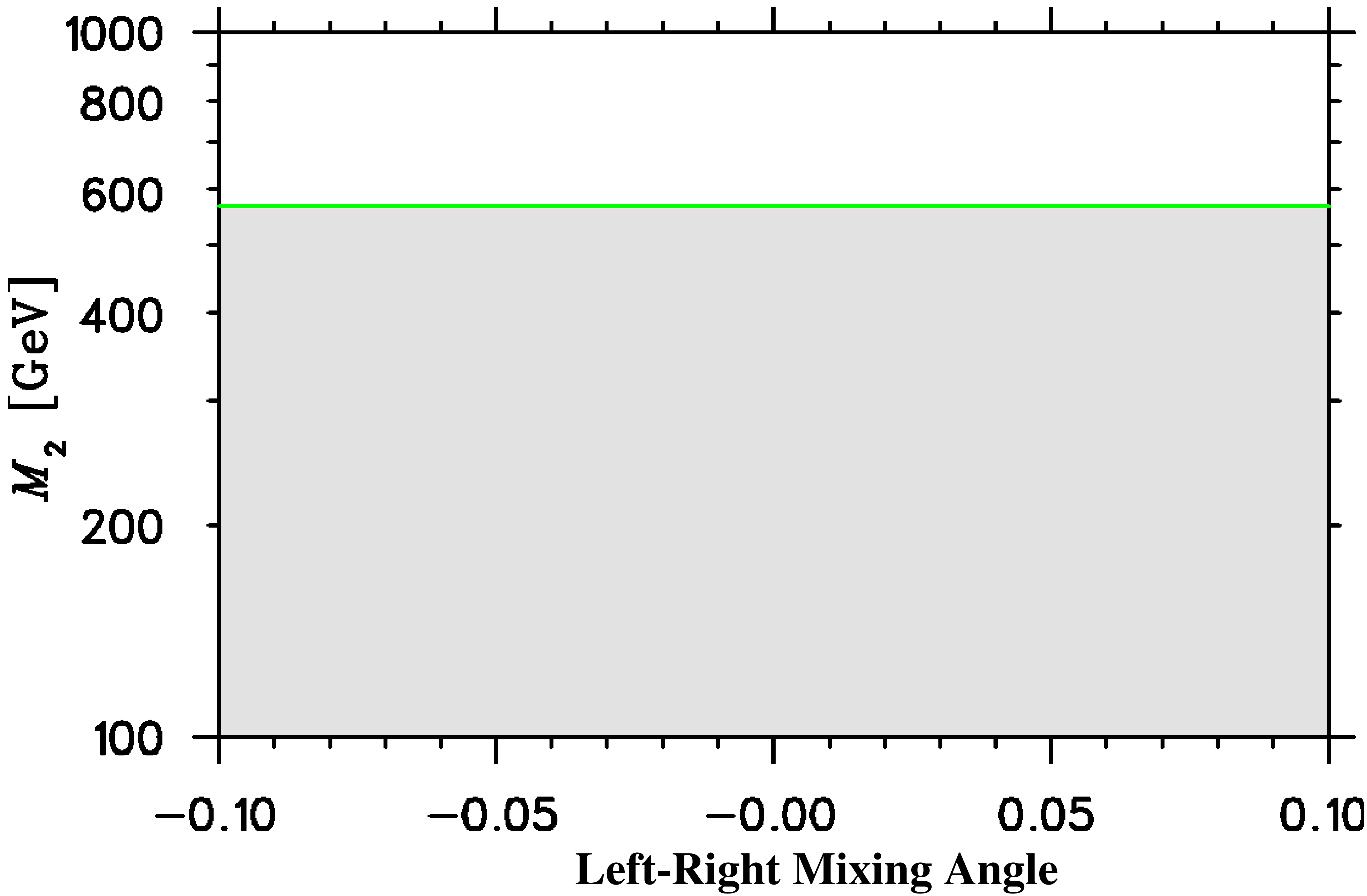
$$B_\nu = -0.755 \pm 0.020 \pm 0.013$$

This is about 20x better than Wu's experiment, but that was a long time ago ...



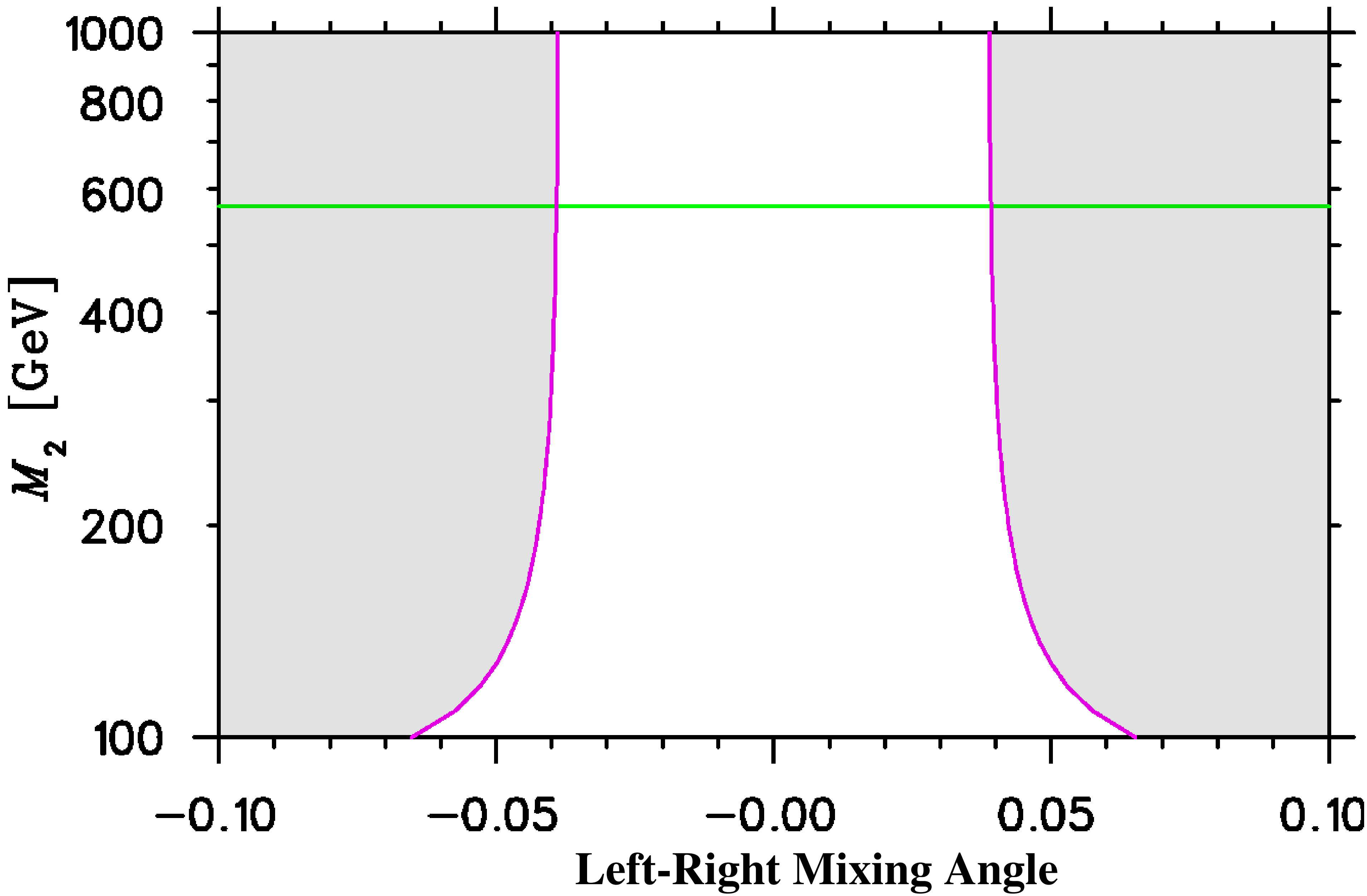
Current limits

proton-proton colliders

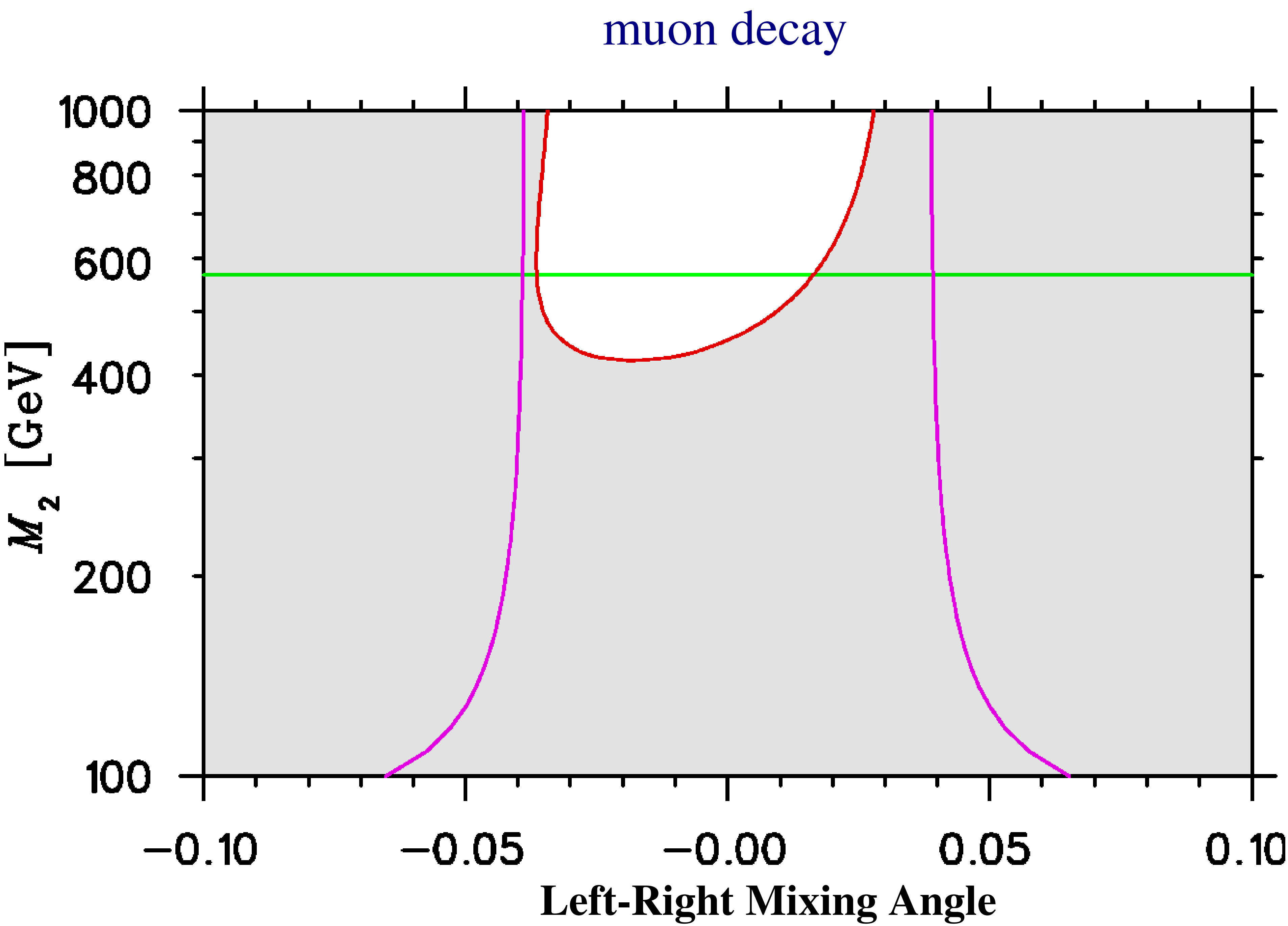


Current limits

neutrino-nucleon scattering

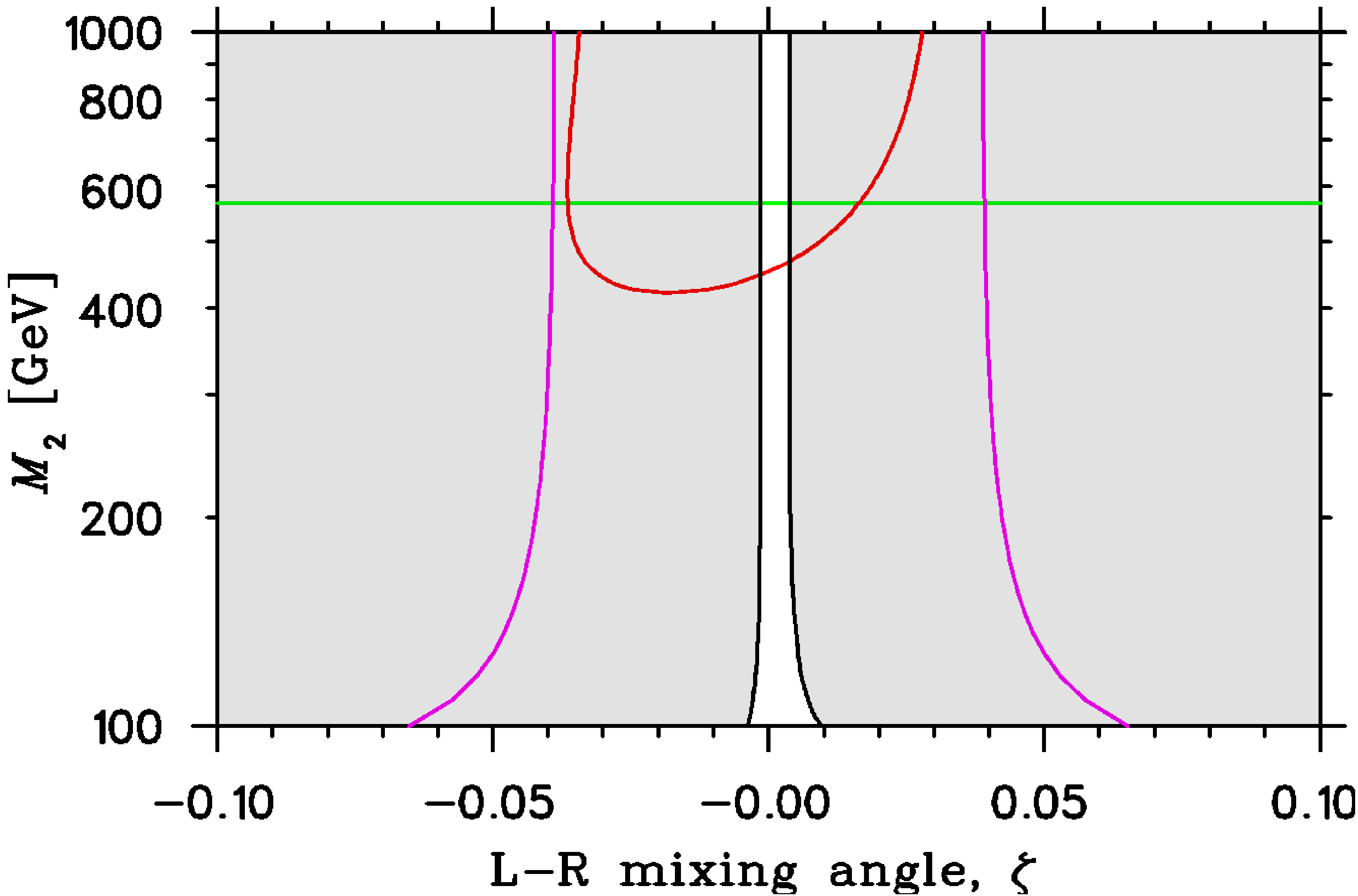


Current limits



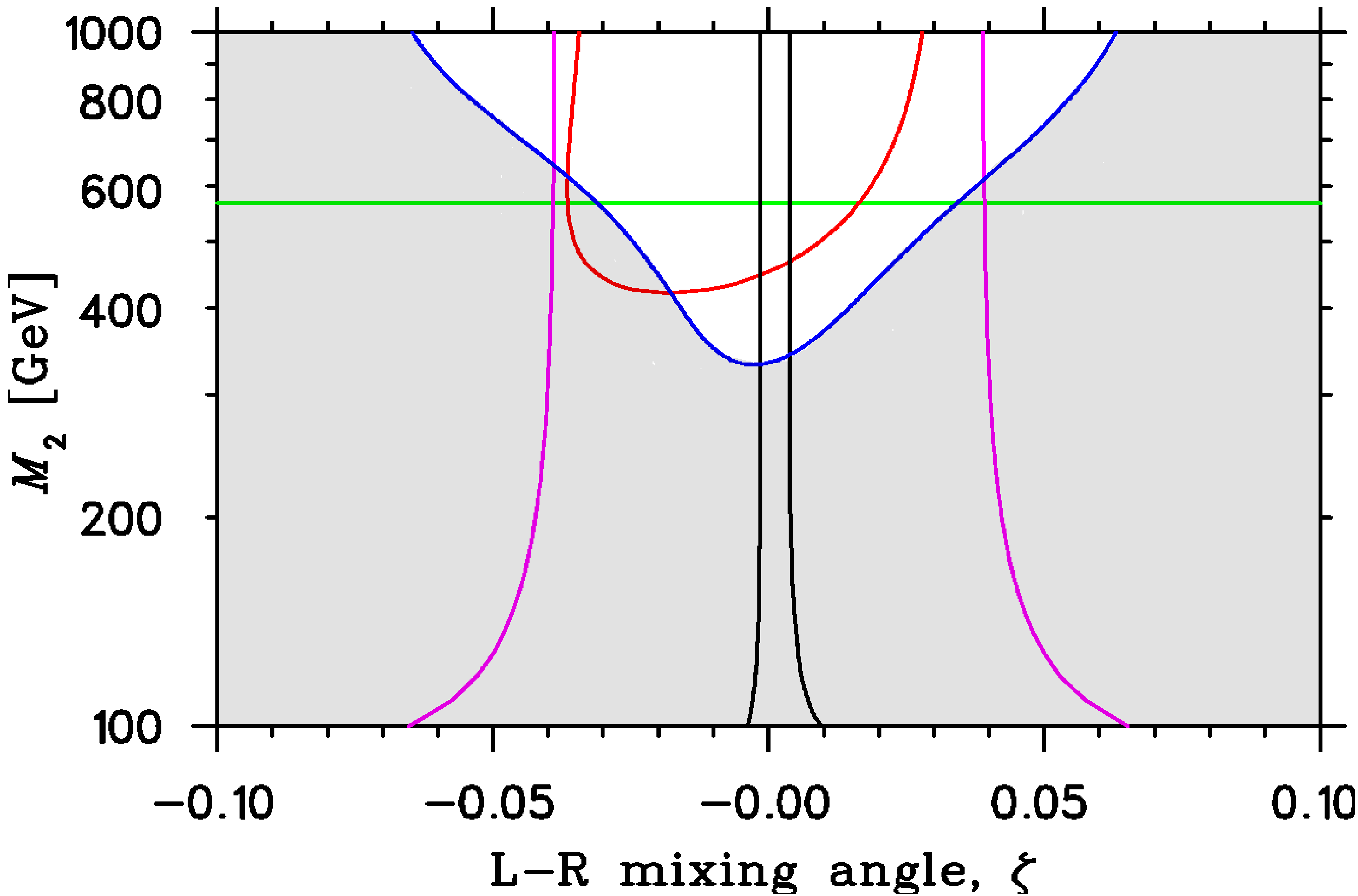
Current limits

superallowed β decay



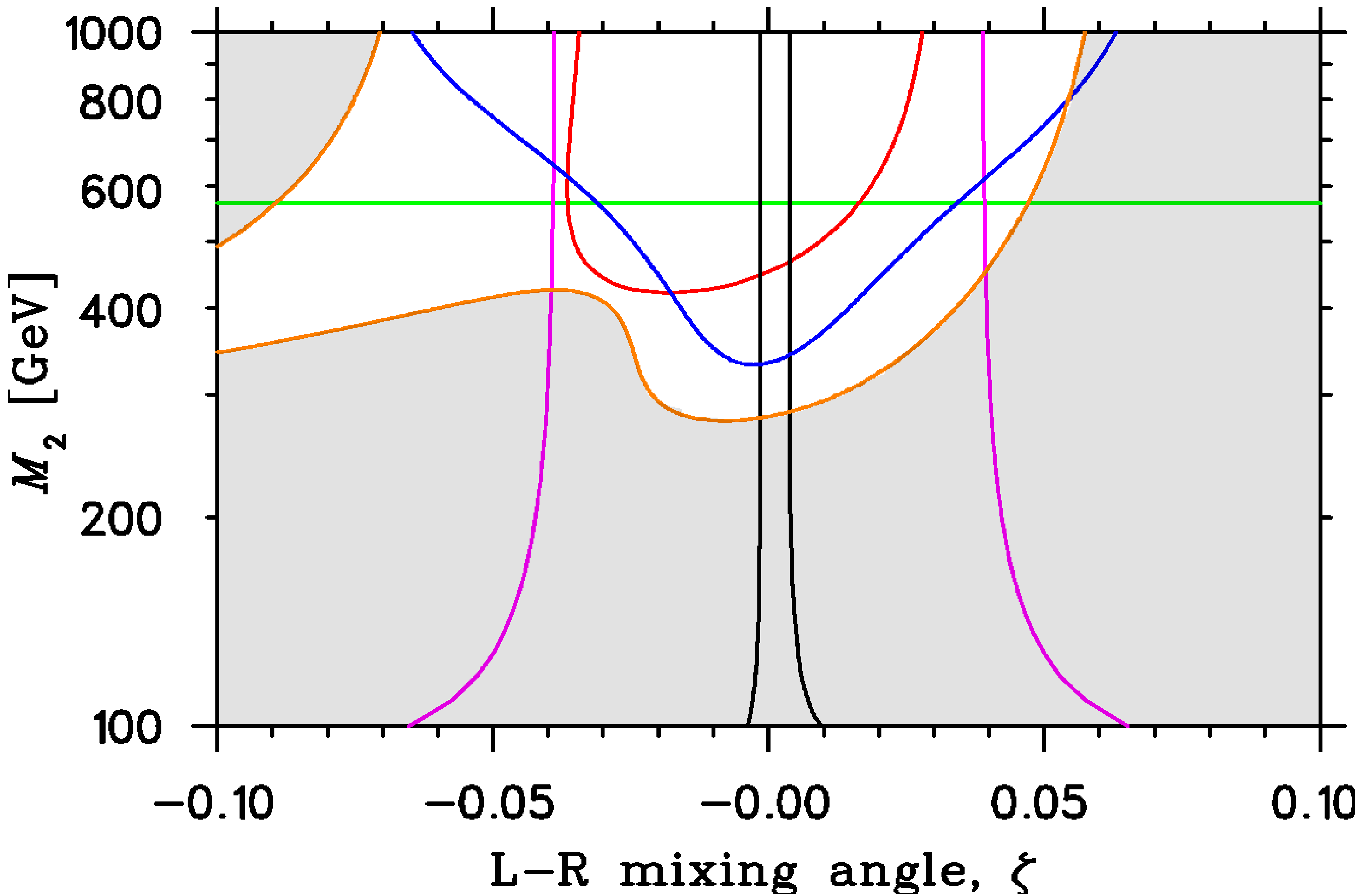
Current limits

world average of β decay



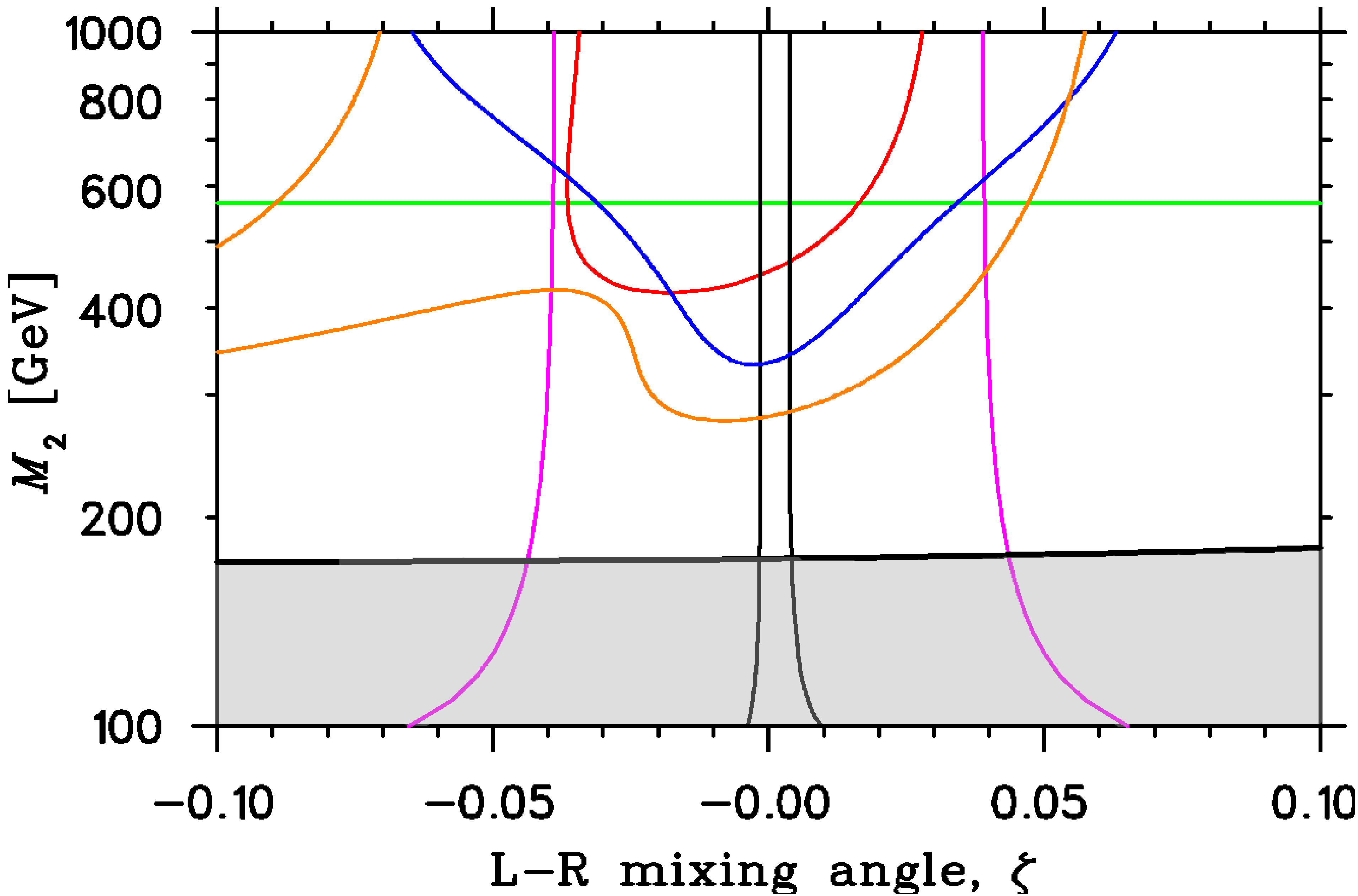
Current limits

world average of neutron decay



Current limits

result using trapped ^{37}K



Current limits

expected results with improved ^{37}K experiment