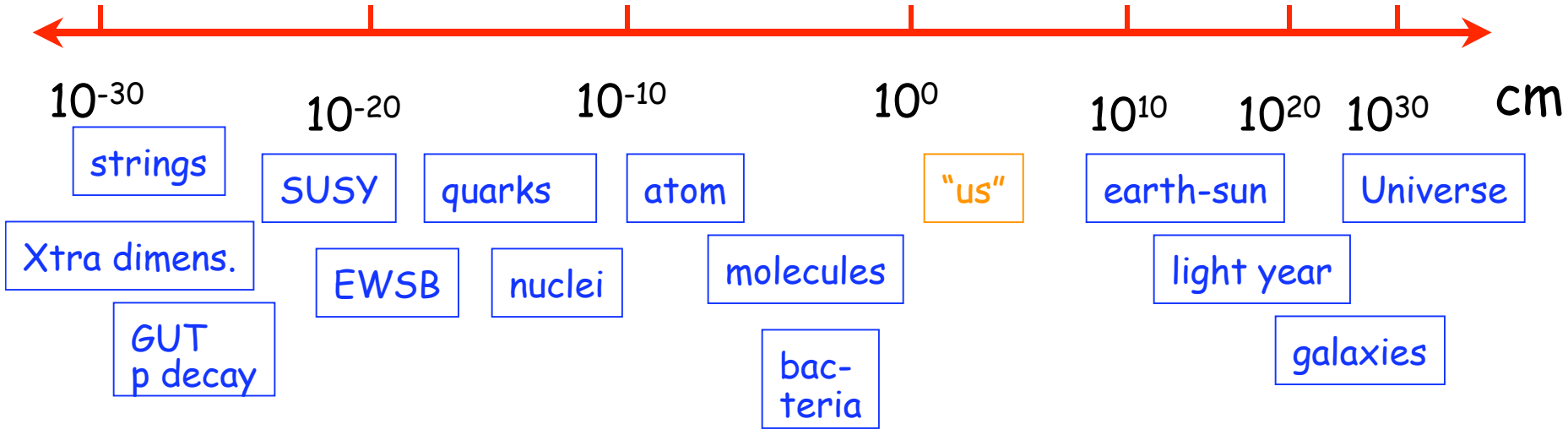
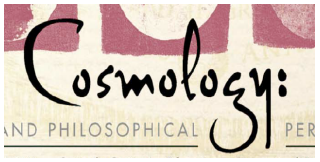
The Snake biting its Tail -- Fundamental Physics and the Universe

Ikaros Bigi, Notre Dame du Lac

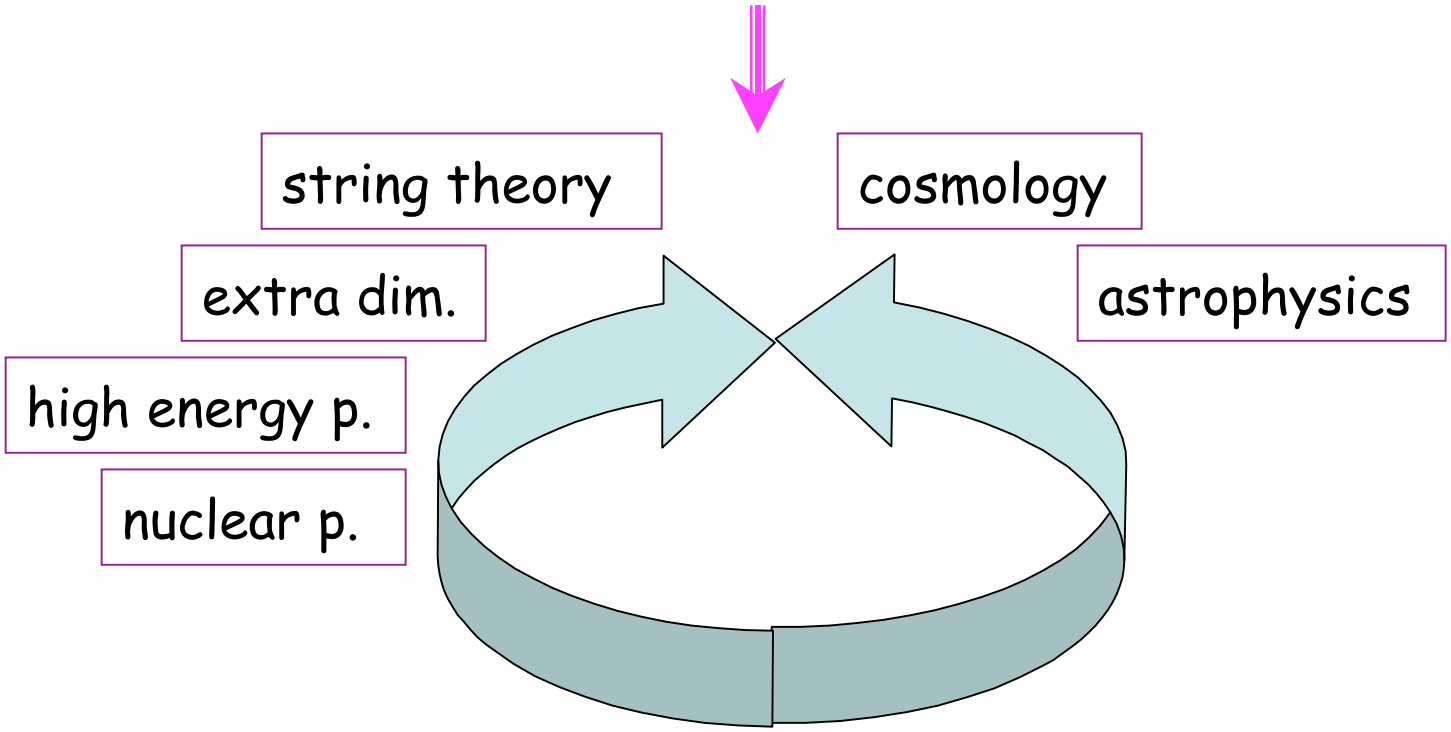
Tip O'Neill

"All P. is local!"



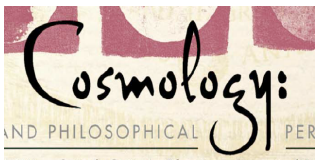


Big bang cosmology !



➥ particle accelerators with higher & higher energies

recreate the Universe at earlier & earlier times



alternate title

From the Earth to the Heavens -- & back again

Galileo … Newton … Olaf Roemer …

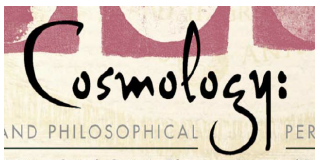
will sketch recent and on-going examples for this strategy

physics ⟷ philosophy

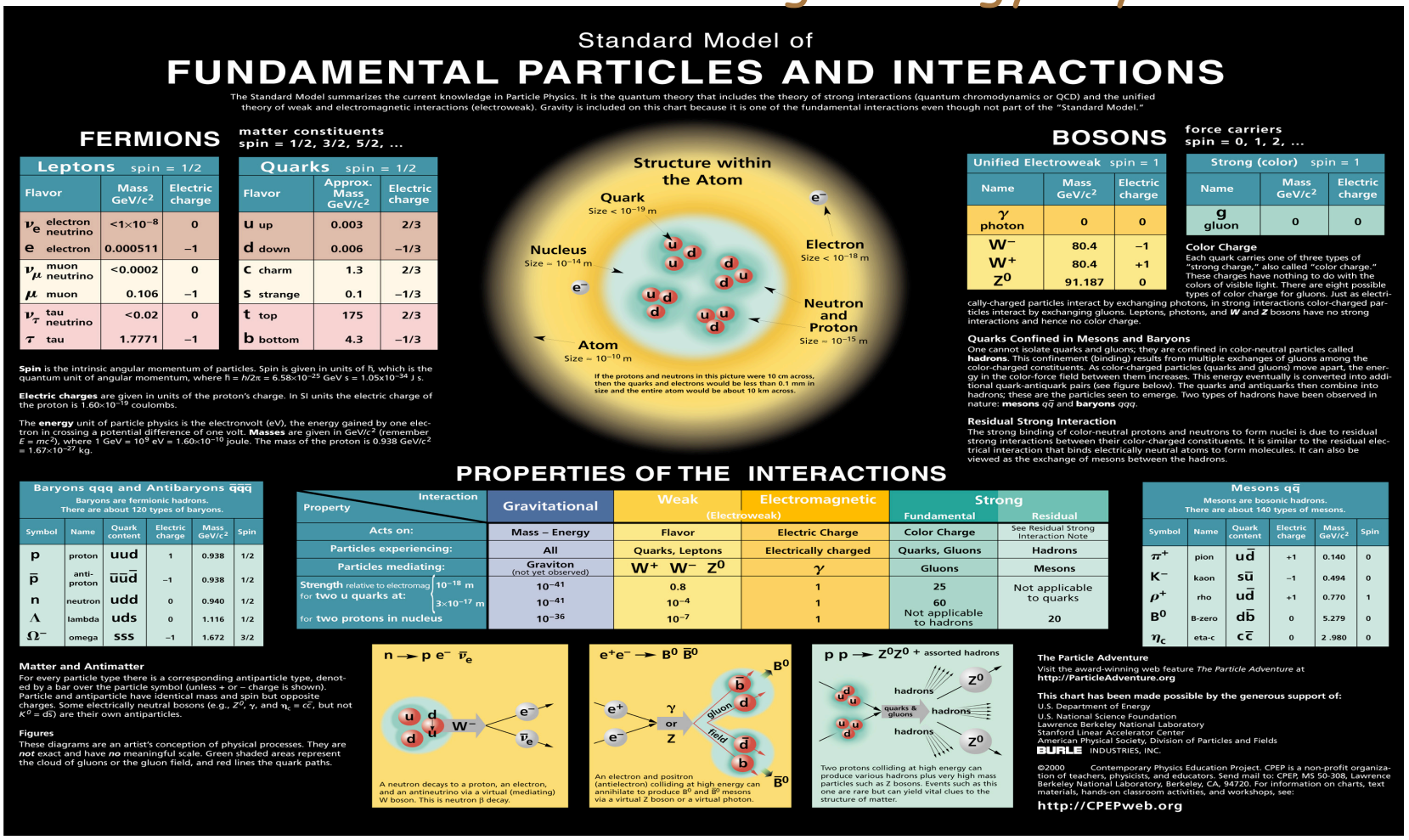
(Monty Python and the Holy Grail)

3 insights from Yogi-ism

- on experimental science
- on quantum mechanics
- on cosmology



The Standard Model of High Energy Physics



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom

Quark Size < 10^{-19} m
Nucleus Size = 10^{-14} m
Electron Size < 10^{-18} m
Neutron and Proton Size = 10^{-15} m
Atom Size = 10^{-10} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and *W* and *Z* bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\,\bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

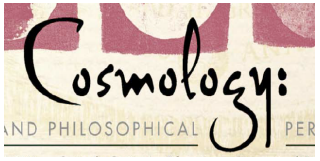
$p\,p \rightarrow Z^0Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

very successful in describing (though not necessarily explaining) earthly data



yet compelling evidence from astrophysics & cosmology

that Standard Model is incomplete!

The Menu

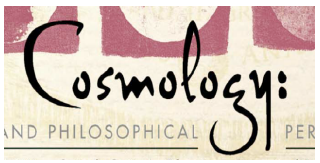
I Dark Matter
Neutrino Oscillations
`Dark Energy' → Peter Garnavich

II Microscopic Time Reversal
brief comment on Black Holes

III Baryogenesis in the Universe

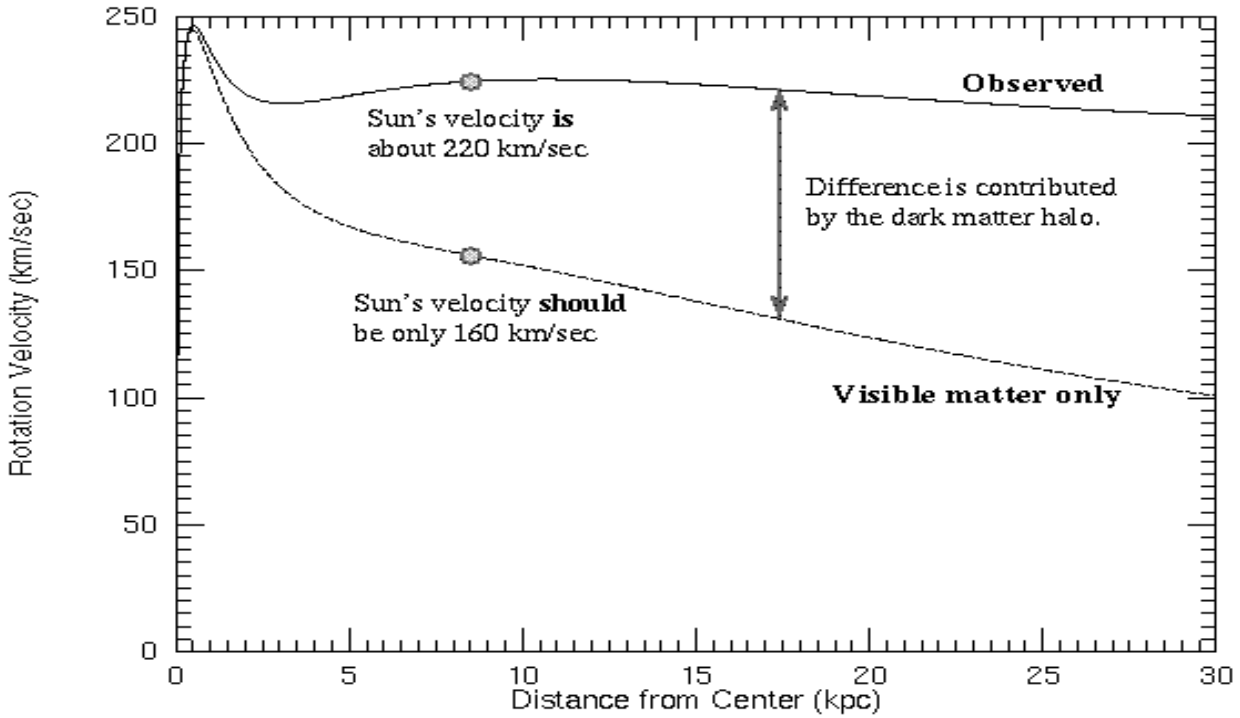
IV My Bet for the emerging New Physics

V Outlook



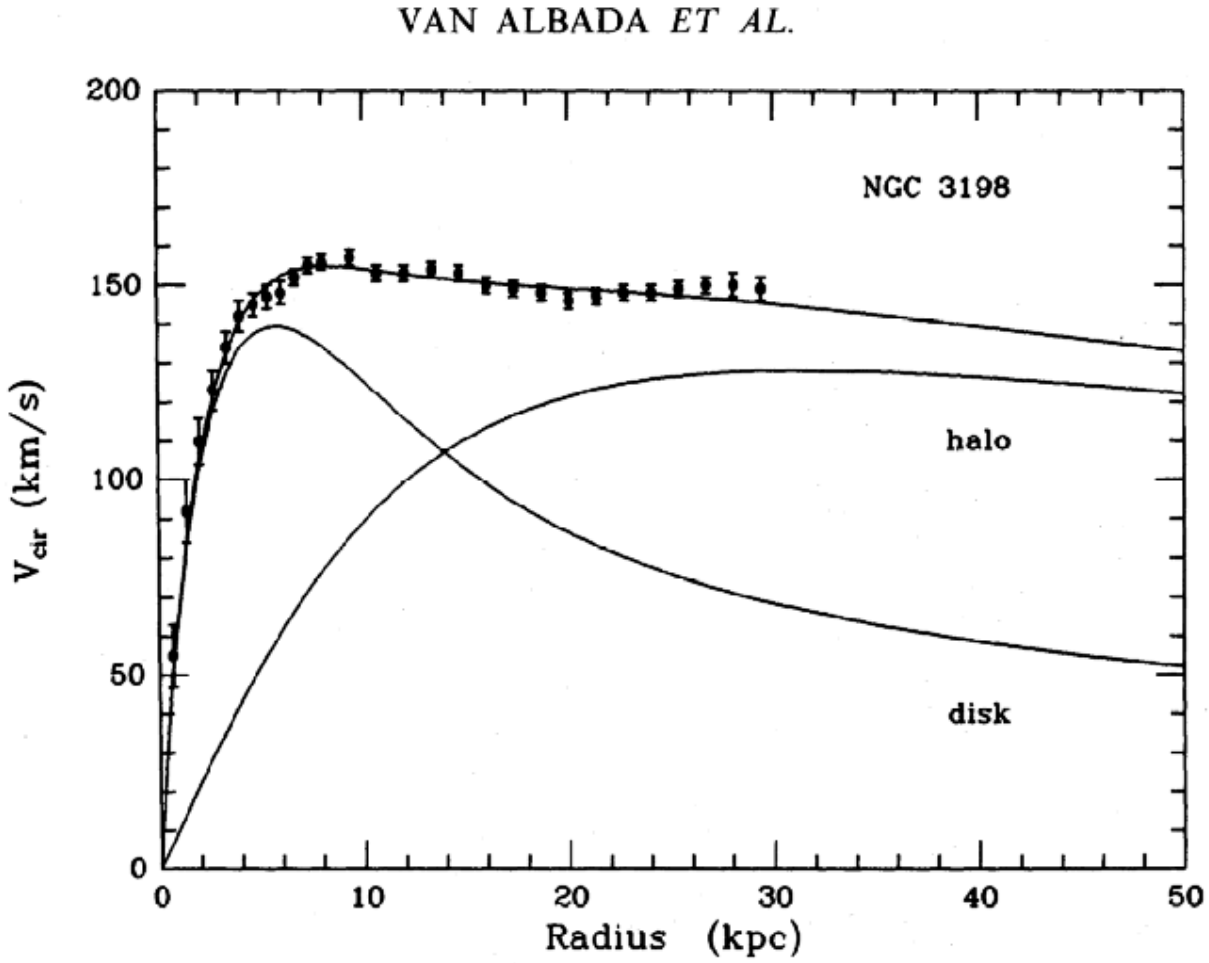
I Yogi-ism Insight # 1: "You can observe a lot by watching!"

I.1 Rotation Curves and Dark Matter



The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

From D. Bennet



From D. Bennet

A lot more `stuff' -- i.e. gravitating agents -- out there than meets the eye!

this large excess of gravitating `stuff' over visible matter repeats itself over all scales

➥ about 1/4 of gravitating agents in the Universe are `dark matter', mostly non-baryonic

☞ Standard Model has no candidates for it!

I.2 Neutrino Astronomy

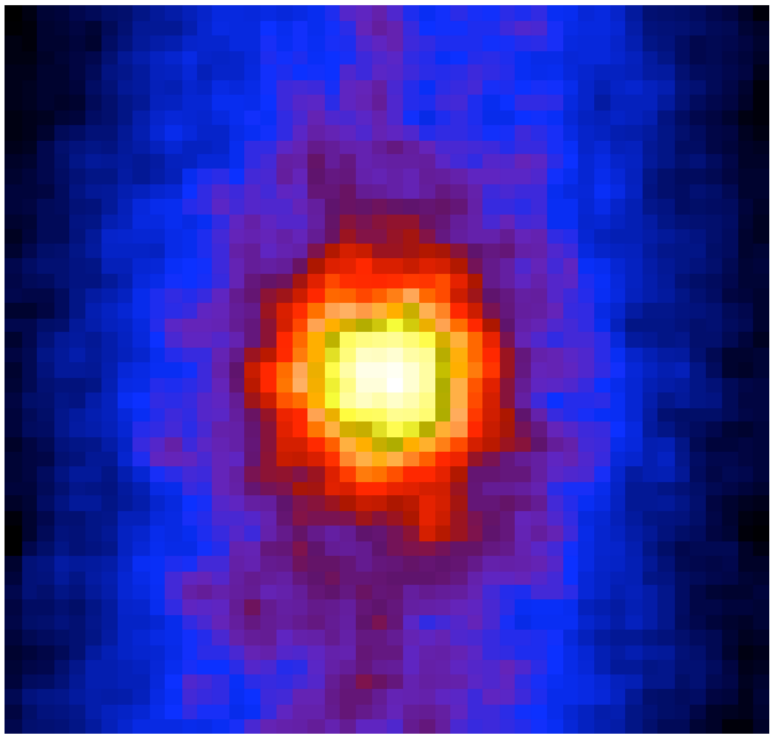
- □ introduced by Pauli for accounting purposes (energy, momentum, quantum statistics) in $n \to p\ e\ \square$
- essential step in evolution of Standard Model was discovery of weak neutral currents

  neutrinos couple to those

  SU(5) predicted { the coupling strength correctly (it seemed)

  SU(5) predicted { proton decay $p \to e^+ \square$

2 huge water C detector were built to discover proton decay
IMB in the US & Kamiokande in Japan
completed in time -- to register neutrinos from SN87!
Kamiokande upgraded to Super-Kamiokande



From R. Svoboda

Our sun seen by Super-K in the `light' of neutrinos

Davis experiment and other solar neutrino observatories `saw' `only' ~1/3 - 1/2 of the predicted □ flux

➥ something `happened' to the solar neutrinos on their way

☞ □'s of one kind oscillate into □'s of another kind!

➧ 3 known kinds of □'s have non-degenerate masses -- contrary to SM □'s !

✍ yet cannot be major component of dark matter

Conclusion #1:

About 1/4 of the Universe's matter exerts gravitational pull like ordinary matter, yet is distinct from it.

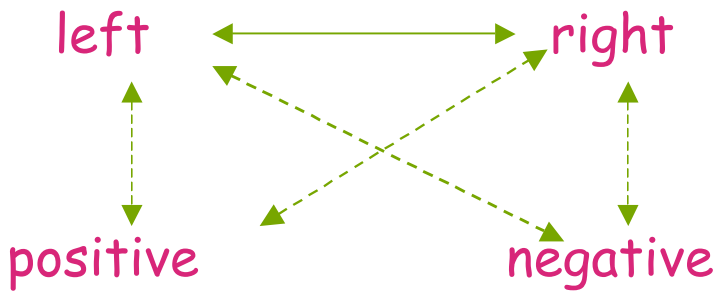
- Nothing is known empirically about its microscopic features
- Even a slightly extended SM has no candidates for it

II Microscopic Time Reversal

discovery of ~~P~~ in '57 a great shock --

yet theorists quickly recovered

"politics and ~~P~~"



3 discrete symmetries

- parity **P**: **x**→**-x** (mirror reflect.)
- charge conjugation **C**:
  particle → antiparticle
- time reversal **T** = reversal of motion

  $t \to -t$ $\quad$ $\mathbf{p} \to -\mathbf{p}$

$\pi^- \to e_L^- \nu$ or $\pi^+ \to e_R^+ \nu$

"L" = f ("-")

CP: $(\pi^- \to e_L^- \nu) \Rightarrow (\pi^+ \to e_R^+ \nu)$

If CP √ ⇒ "L" pure convention!

"the thumb is left on the right hand!"

~~CP~~ discovered in 1964 in K_L decays!

➥ L ≠ R

CPT √

➥ ~~CP~~ ⇒ ~~T~~

☞ time reversal invariance broken on

microscopic level!

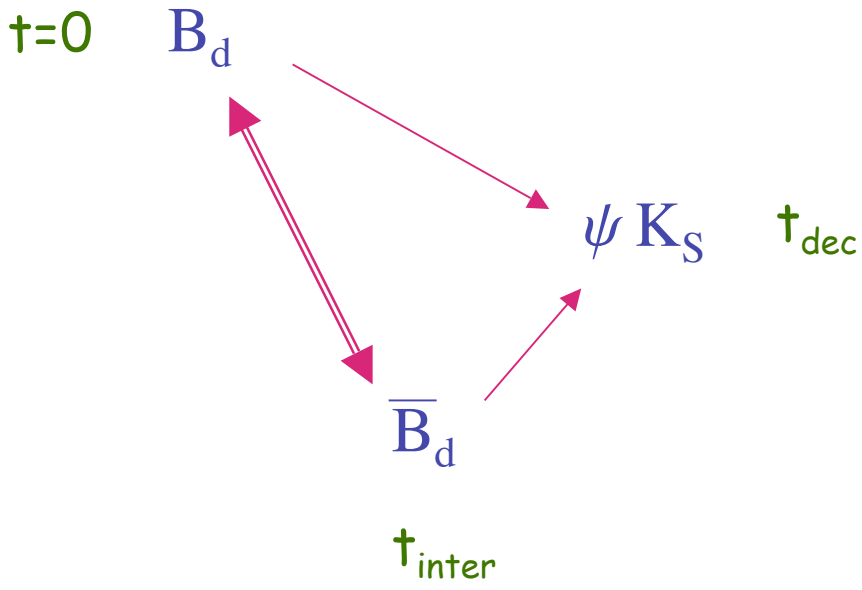
➥ baryogenesis in the Universe -- see later

We had to wait till 2001 before ~~CP~~ was observed in decays of particles other than neutral K mesons

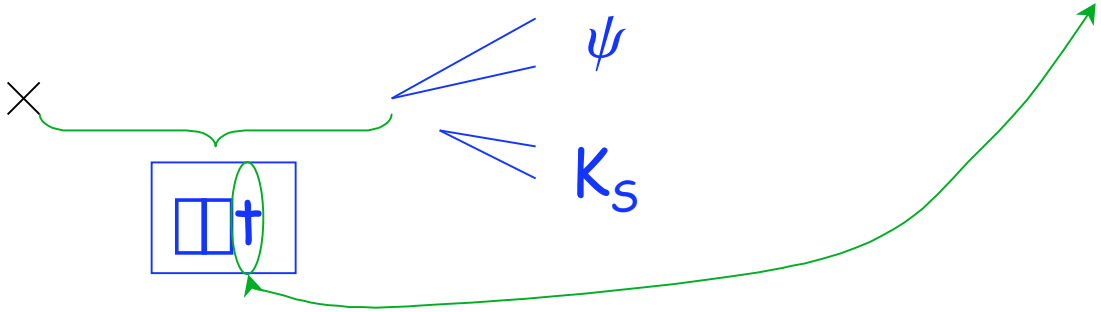
II.1 Yogi-ism Insight # 2:

"When you come to a fork in the road -- take it!"

$B_d \to \psi K_S$



☺ $\text{rate}(B_d\ [\overline{B}_d](t_{dec}) \to \psi K_S) \propto e^{-\Gamma t}(1 - [+][A \sin \Delta m_d t])$

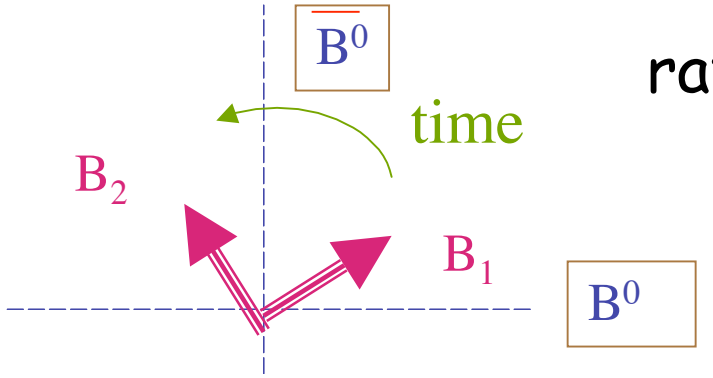


Cosmology: AND PHILOSOPHICAL PER

☹ $e^+e^- \to B_d \bar{B}_d$: $c\tau \sim 0.45$ mm vs. product. region ~ 1 mm

☺ EPR to the rescue!

$e^+e^- \to B_1 B_2$ in $C=-$: Bose-Einstein $B_1 \perp B_2$ -- till decay!



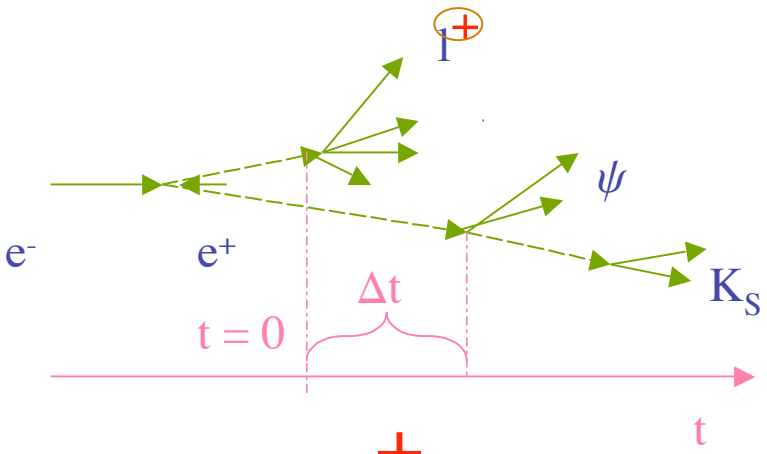
$$\text{rate}(e^+e^- \to B_d\bar{B}_d \to [l^\pm X]_t [\psi K_S]_{t+\Delta t}) \sim$$

$$\sim \ldots (1 \pm A\sin\Delta m_d \Delta t)$$

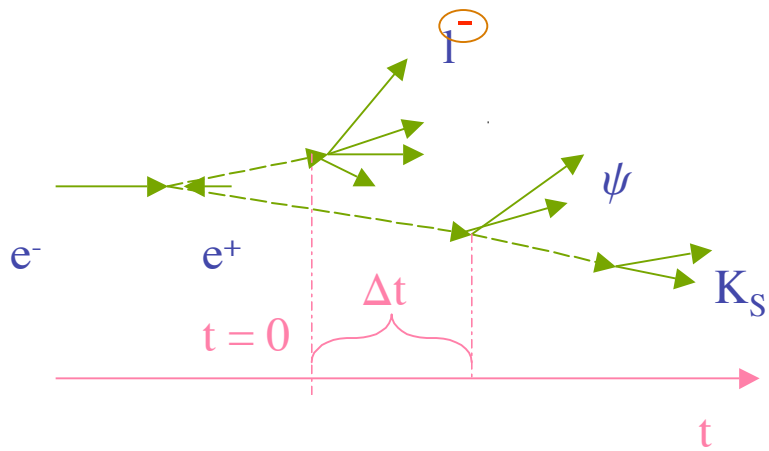
➙ only relative times Δt matter

➥ only distance between vertices needs to be measured

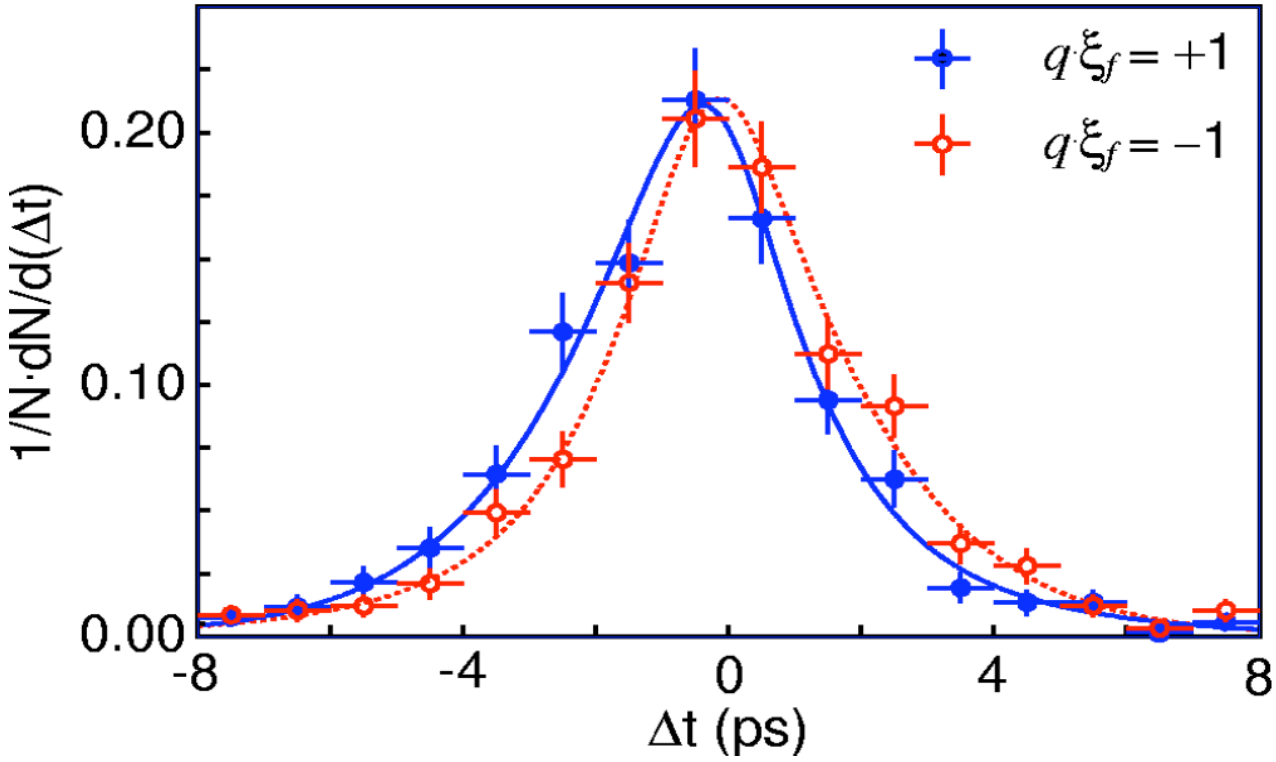
Cosmology: AND PHILOSOPHICAL PER

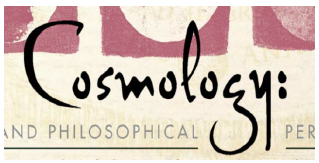


vs.

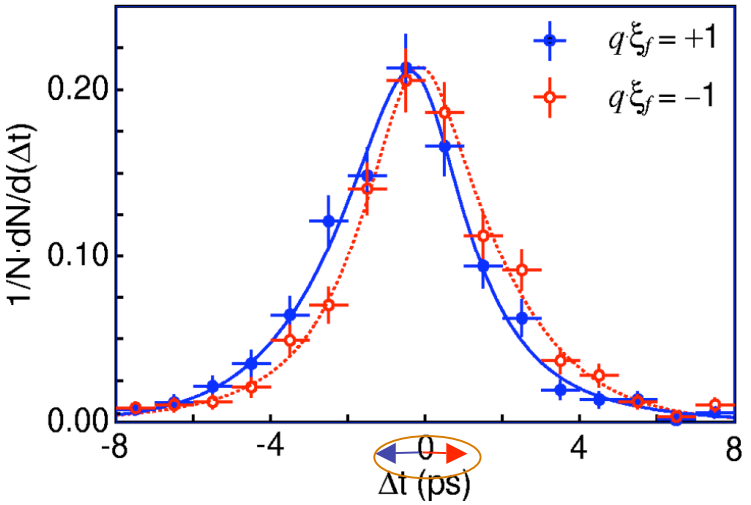


- if $e^+e^- \to l^+ X + \psi K_S \neq e^+e^- \to l^- X + \psi K_S$
  - ➥ ~~CP~~ !





There is even more to it: ~~CP~~ $\Leftrightarrow$ ~~T~~ in B decays



$B \to l^- X$ $\qquad$ $B_d \to \psi K_S$

EPR $\qquad$ EPR

CPT in SL decays

$B_d \to \psi K_S$ $\qquad$ $B \to l^+ X$

➥ ~~CP~~ $\Leftrightarrow$ ~~T~~ in $B \to \psi K_S$

assuming CPT merely in SL B decays

Cosmology: AND PHILOSOPHICAL PER

Status of CP studies

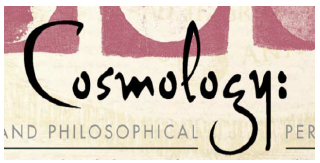
- CP asymmetry established in $B \to \psi K_S$
  - it is `huge': 73.6 ± 4.9 % --
  - as predicted in the SM
    - ➥ it validates KM description of theory of ~~CP~~ in particle decays
  - core element of experimental analysis: use of EPR correlations routinely on a massive and numerically precise scale

    EPR essential for definition of asymmetry as a matter of principle and for its measurement in practice

    EPR -- a reliable work horse, not a paradox

- `demystification of ~~CP~~':

  if dynamics can support ~~CP~~, it can be large!



II.2 Brief Comment on Black Holes

`elementary particle' = irreducible representation of the Poincare group

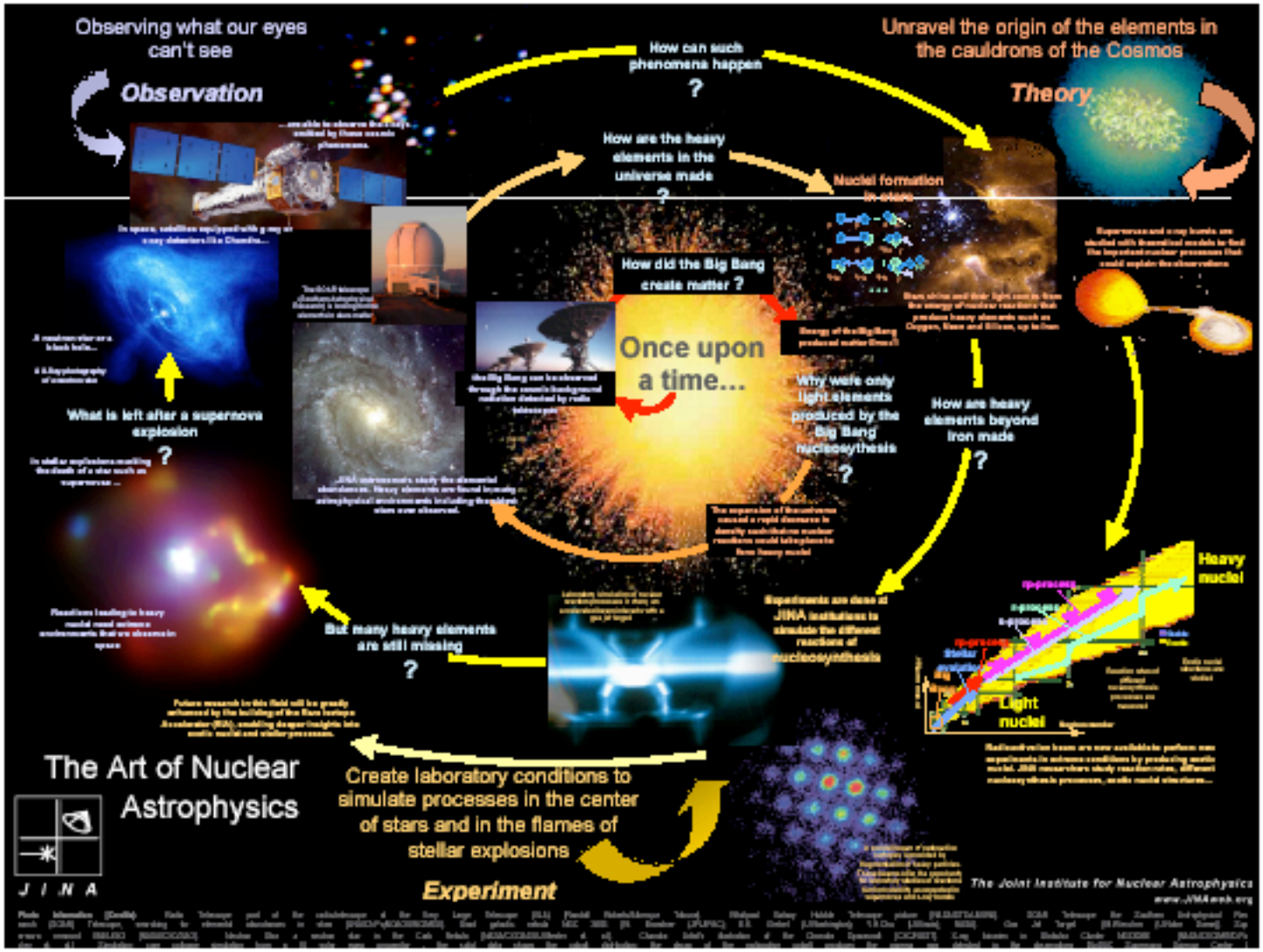
➥ labelled by its mass and spin --

as is a black hole!
(i.e. black holes vs. elementary particles -- exactly the same, only different)

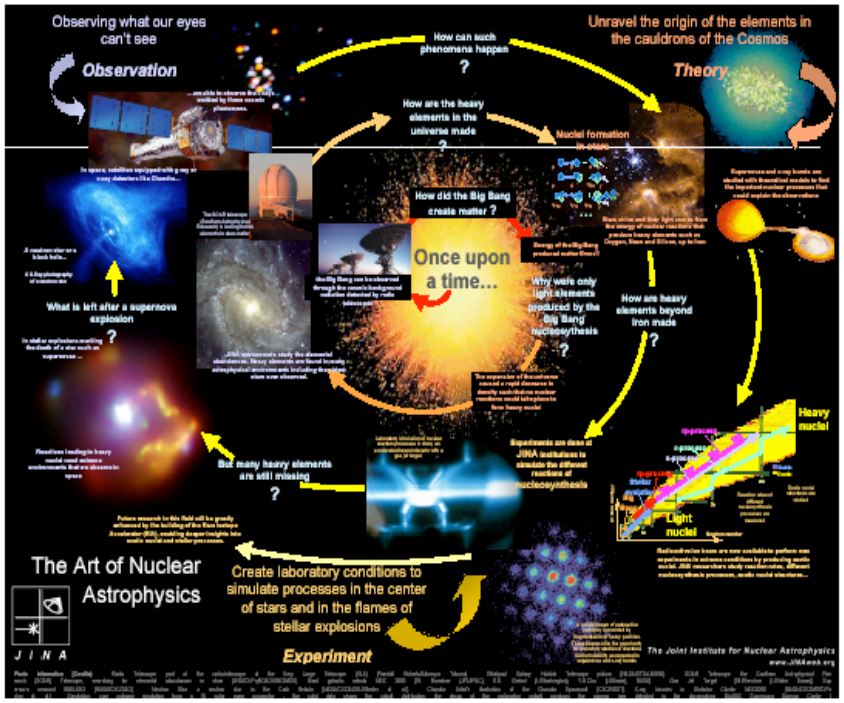
"The true laws of physics are about certainties, not probabilities."

G. 't Hooft (2000/2), based on studies of the QM of black holes

III Baryogenesis in the Universe



A cathedral of the Knowledge Age



⇔

intellectually equivalent --

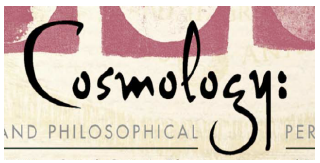
complex, multilayered, with a coherent theme

not complicated

Crucial element: Big Bang Cosmology

Nuclear astrophysics has scored impressive successes in explaining observed abundances of light elements in big bang cosmology
(it also predicted the existence of at most three light neutrinos from light nuclei abundances well before high energy physics confirmed it)

Greatest form of flattery is imitation!



III.1 Yogi-ism Insight # 3:

"If the world were perfect, it wouldn't be!"

In lay man's terms:

In a matter-antisymmetric world all the `stuff' would annihilate into pure energy.

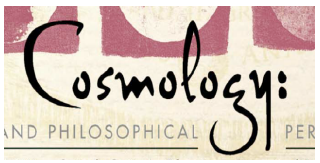
Yet our Universe is not empty, only almost empty:

$$\#(\text{baryons})/\#(\text{photons}) \sim O(10^{-9})$$

Challenge: explain observed baryon number not as an initial value, but as a dynamically generated and thus calculable quantity

$$N_{bar}\,(t_{init}) = 0 \quad \Rightarrow \quad N_{bar}\,(t_{today}) \sim O(10^{-9})\, N_{\gamma}(t_{today})$$

dynamics



Sakharov ('65)

need three ingredients

❶ baryon number changing processes √

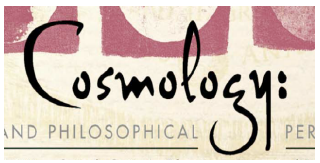
❷ ~~CP~~ !

❸ Universe out of thermal equilibrium
at least 2 phase transitions happened
EWSB & GUTSB √

😐 *standard* CKM irrelevant for baryon number of universe

☺ New Physics exists!

☺ New CP Paradigm: ~~CP~~ phases can be large



IV My Bet for the emerging New Physics

It is Supersymmetry!

mundane arguments in its favour:

- it provides natural candidates for Dark Matter;
- it provides extra sources of ~~CP~~ that could generate the baryon number of the Universe
- it might provide an explanatory framework for Dark Energy

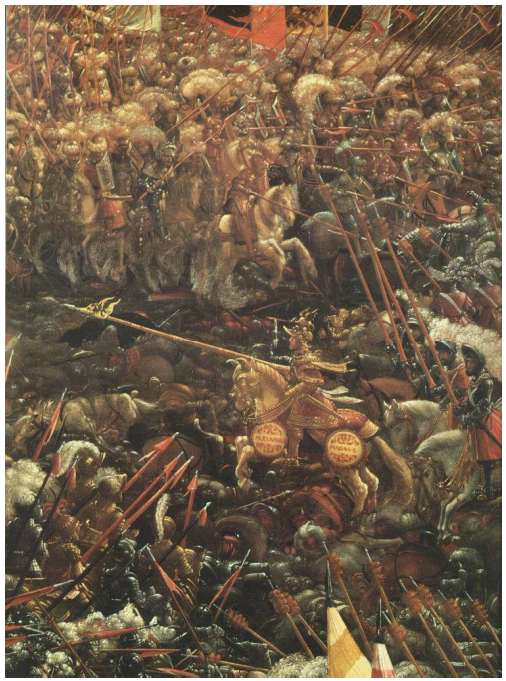
often heard argument: it solves the `gauge hierarchy problem',

i.e. why the scales for EWSB and GUTSB differ by ~O(10^{13})

All true -- yet for me not the main reason!

remember Altdorfer's `Alexander Battle'

indeed it shows the climactic moment of the battle at Issos in 333 BC



yet it is largely marginal to the significance of the painting, which is its unusual beauty and the novel vistas it opens --

as is the case with Supersymmetry

Cosmology:
AND PHILOSOPHICAL PER

V Concluding Remarks

Times have been exciting recently (and not so recently) with the emergence of

- the Standard Model of High Energy Physics
- the Standard Model of Cosmology
- empirical evidence for New Physics

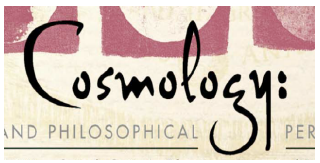
fascinating questions:

Are there extra dimensions -- extra time dimensions?

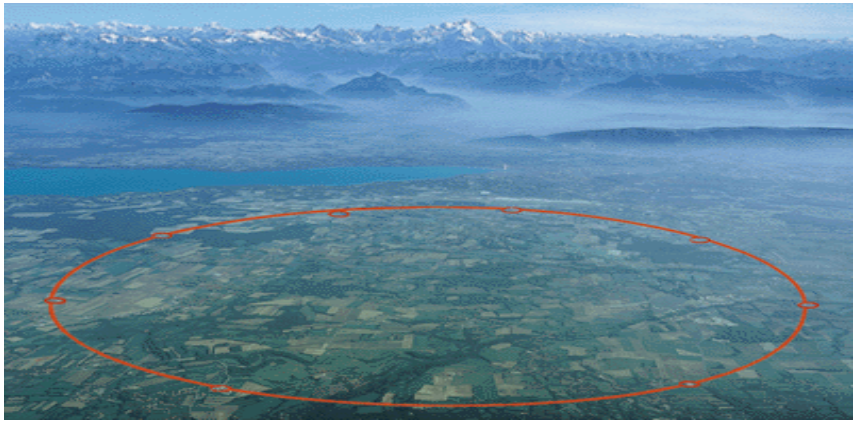
Are the `elementary particles' just different modes of intrinsically non-local objects like strings?

Do Nature's constants change in time?

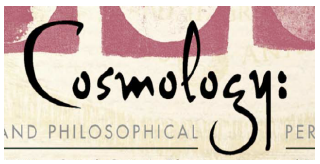
~~Universe~~ ⇒ ~~Cosmos~~



The L(arge)H(adron)C(ollider) recreating the early phase of `our' corner of the Universe will operate 2007ff



- McMullin Fest II in 2015
  - Supersymmetry has been discovered empirically
  - microscopic features of Dark Matter have been identified
  - The Really Big Discovery ?
- McMullin Fest III in 2025
  - Extra Dimensions ?
  - The Really Big Discovery !



From "Monty Python and the Holy Grail", 1975:

A peasant named Dennis demands an explanation from King Arthur, how he became king.

King Arthur: "The Lady of the Lake, her arm clad in purest shimmering samite, held Excalibur aloft from the bosom of the waters to signify that by divine providence, I, Arthur, was to carry Excalibur. That is why I am your king!"

Dennis: "Strange women lying on their backs in ponds handing over swords -- that's no basis for a system of government. Supreme executive power derives from a mandate from the masses, not from some farcical aquatic ceremony."