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**UC Santa Cruz**

**Santa Cruz Institute for Particle Physics**

# **Dark Matter: Exploring the Hidden Universe**

**QUARKNET**

**UC Santa Cruz, July 11, 2013**



# Cosmology

*Camille Flammarion, L'Atmosphère: Météorologie Populaire 1888, artist unknown*

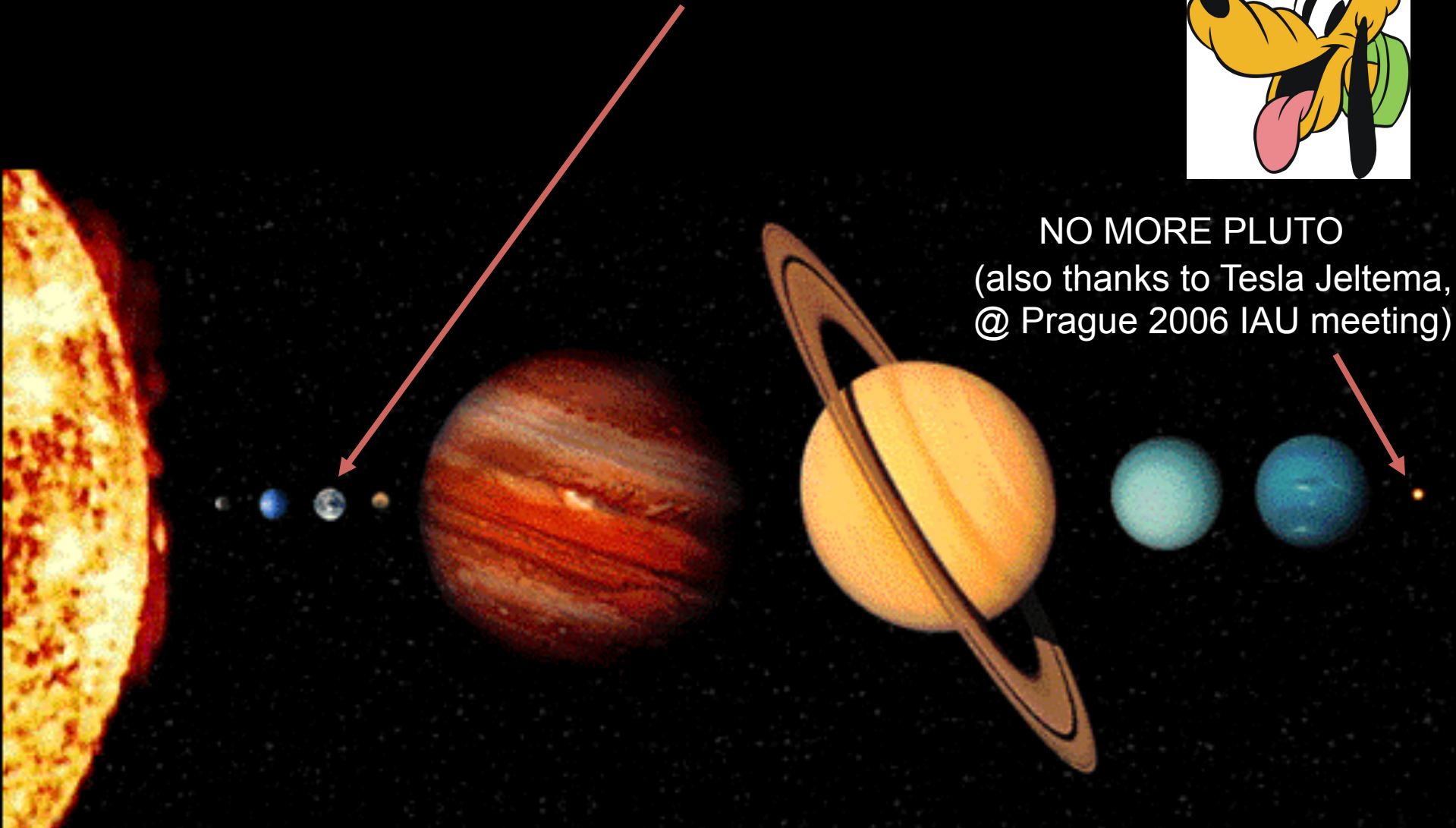
# Our Cosmic Address



# Our Cosmic Address



NO MORE PLUTO  
(also thanks to Tesla Jeltema,  
@ Prague 2006 IAU meeting)

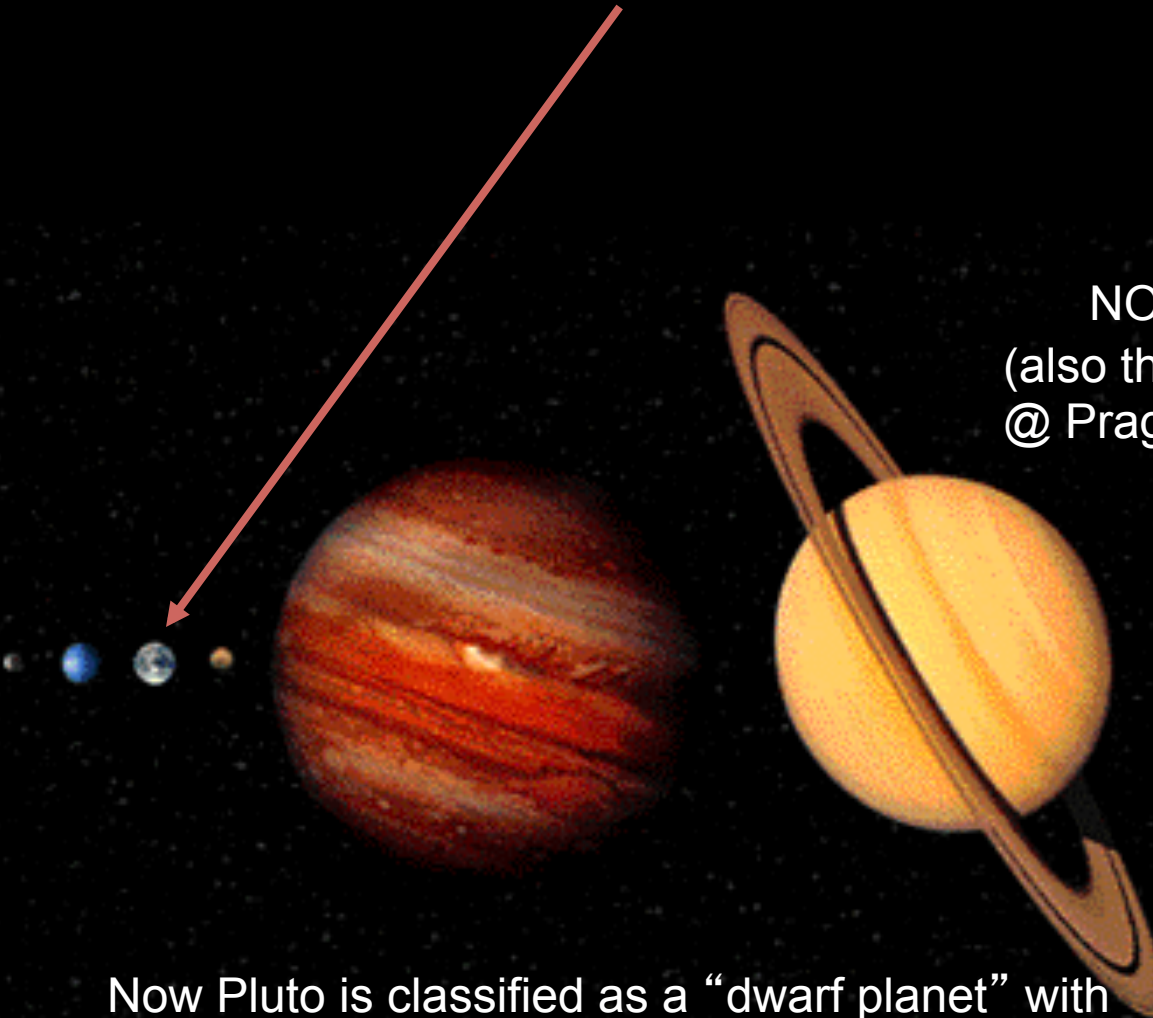
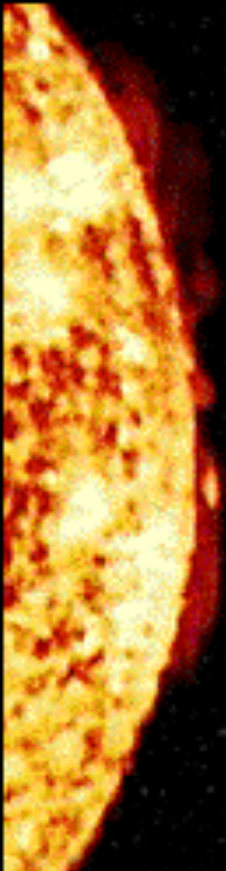




# Our Cosmic Address



NO MORE PLUTO  
(also thanks to Tesla Jeltema,  
@ Prague 2006 IAU meeting)



Now Pluto is classified as a “dwarf planet” with  
(bigger) Eris and Ceres – all Kuiper belt objects

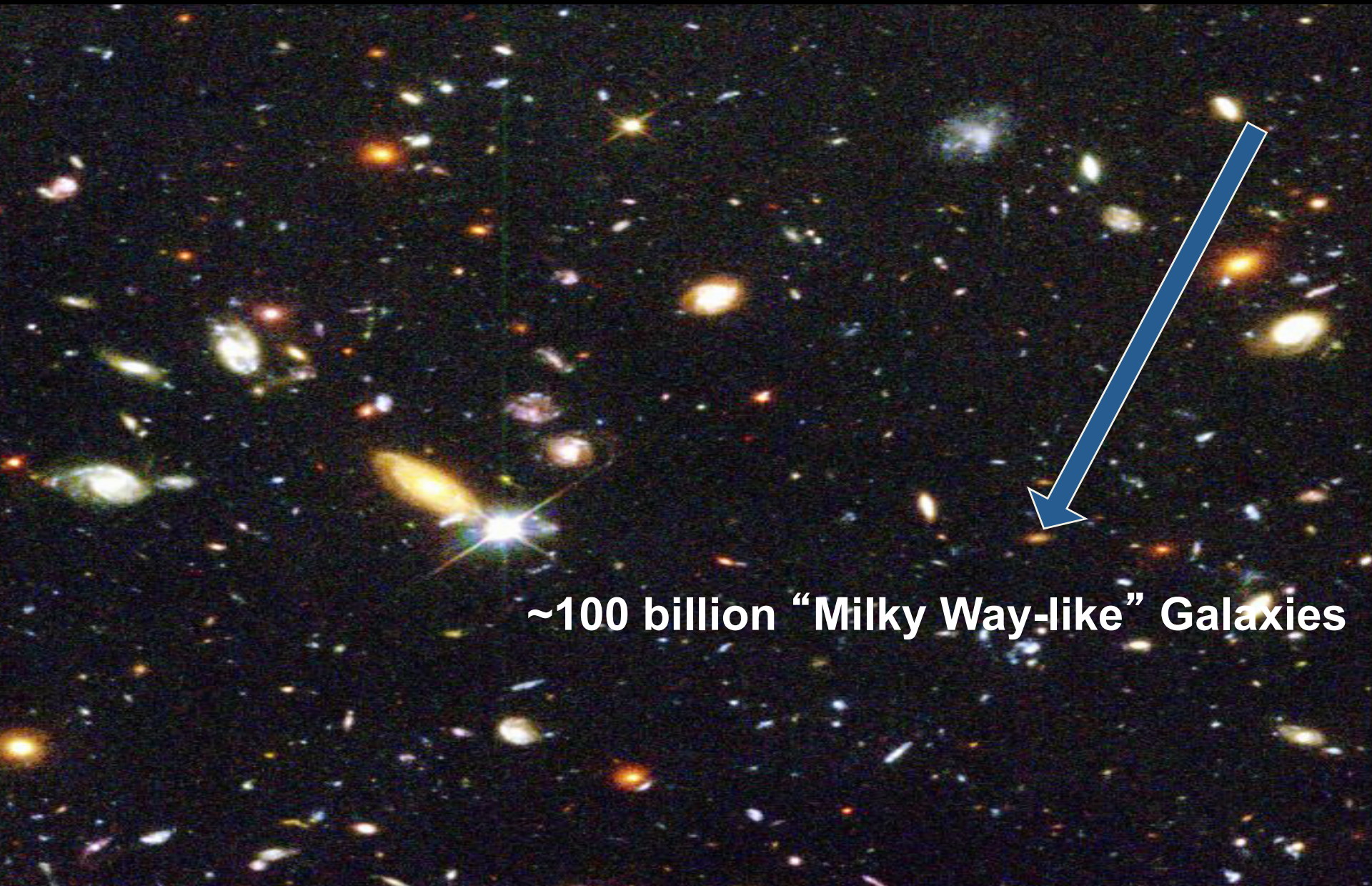


# Our Cosmic Address





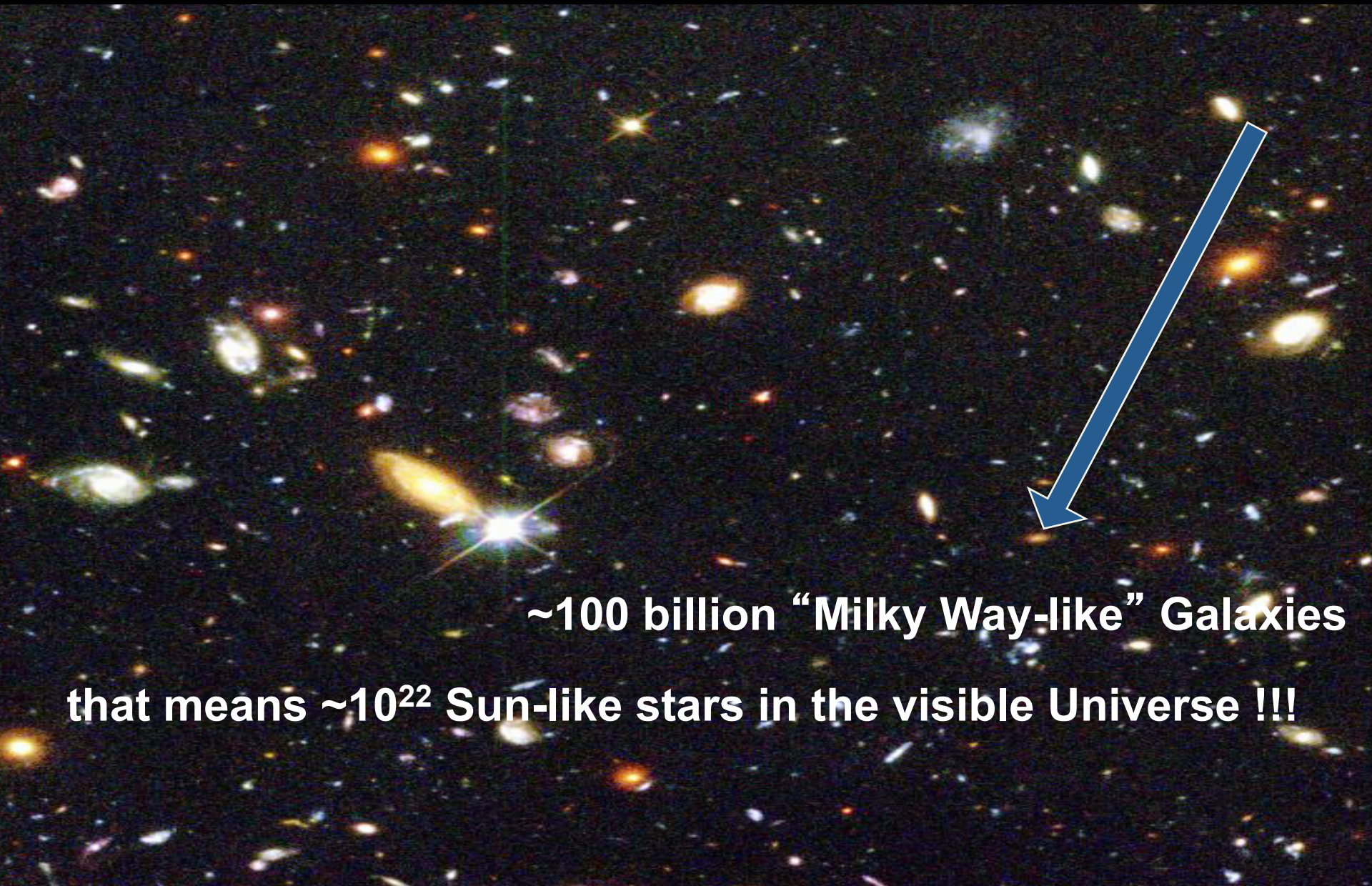
# Our Cosmic Address



**~100 billion “Milky Way-like” Galaxies**



# Our Cosmic Address

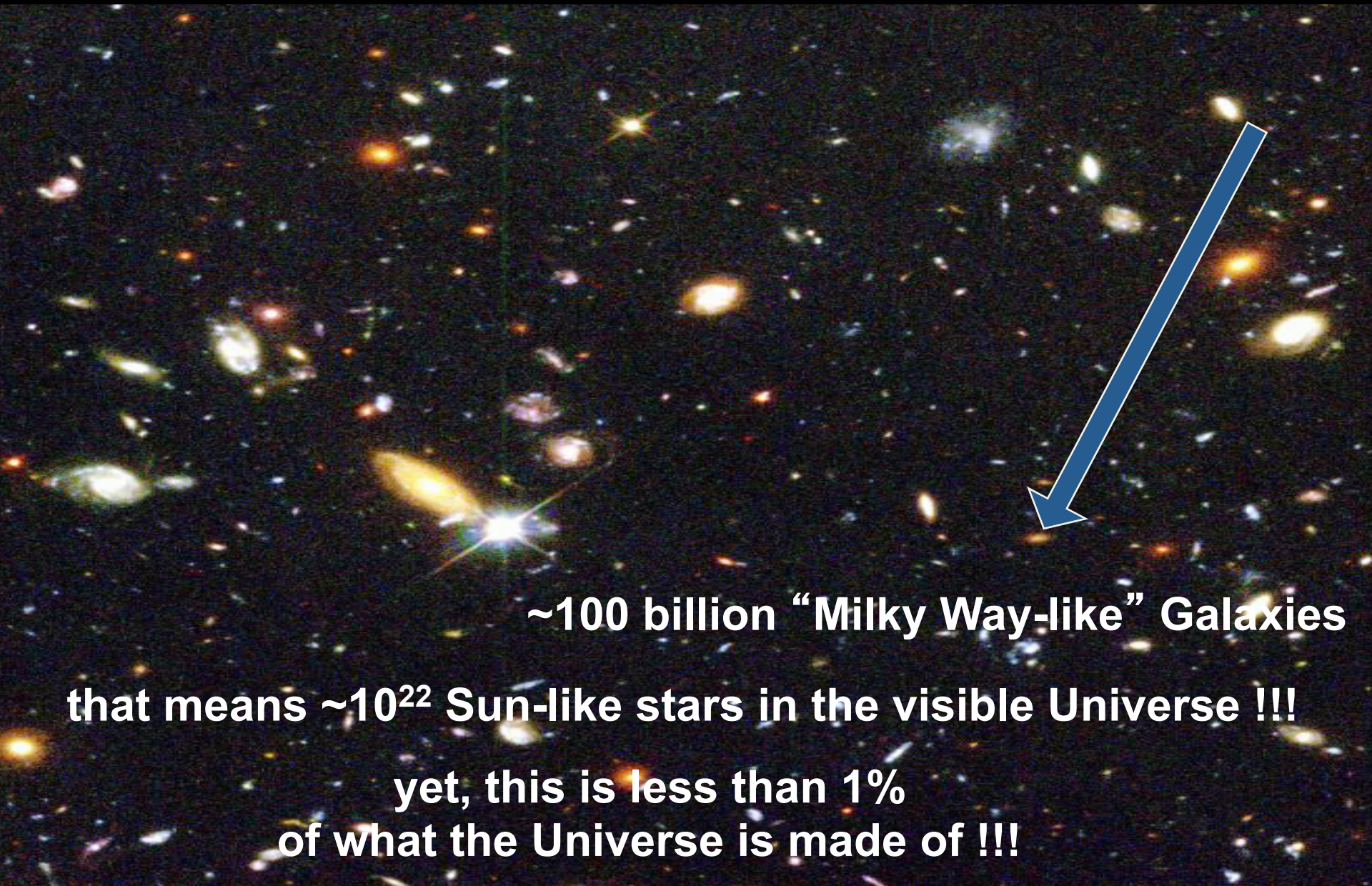


**~100 billion “Milky Way-like” Galaxies**

**that means  $\sim 10^{22}$  Sun-like stars in the visible Universe !!!**



# Our Cosmic Address



**~100 billion “Milky Way-like” Galaxies**

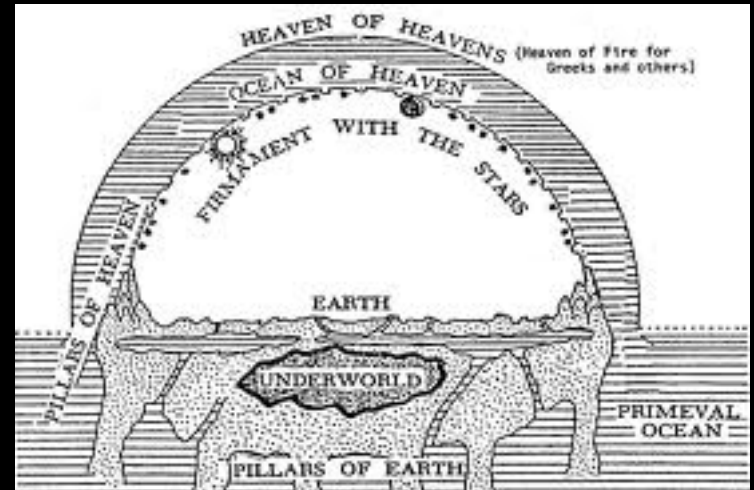
**that means  $\sim 10^{22}$  Sun-like stars in the visible Universe !!!**

**yet, this is less than 1%  
of what the Universe is made of !!!**





Cosmology = Cosmos+Logos  
*“knowledge of the order”*



Ancient Cosmologies...

“Extrapolations”      “Observations”

A horizontal timeline with a dashed line pointing left and a solid line pointing right, meeting at a central point. The left side is labeled "Extrapolations" and the right side is labeled "Observations".

# “Observations”

# Big Bang

## Time

$10^{-44} \text{ s}$	$10^{-35} \text{ s}$	$10^{-32} \text{ s}$	$10^{-10} \text{ s}$	300 s	$3 \times 10^5 \text{ yr}$	$1 \times 10^9 \text{ yr}$	$15 \times 10^9 \text{ yr}$
Superstring (?) Era	GUT Era	Inflation Era	Electro-weak Era	Particle Era	Recombination Era	Galaxy and Star Formation	Present Era

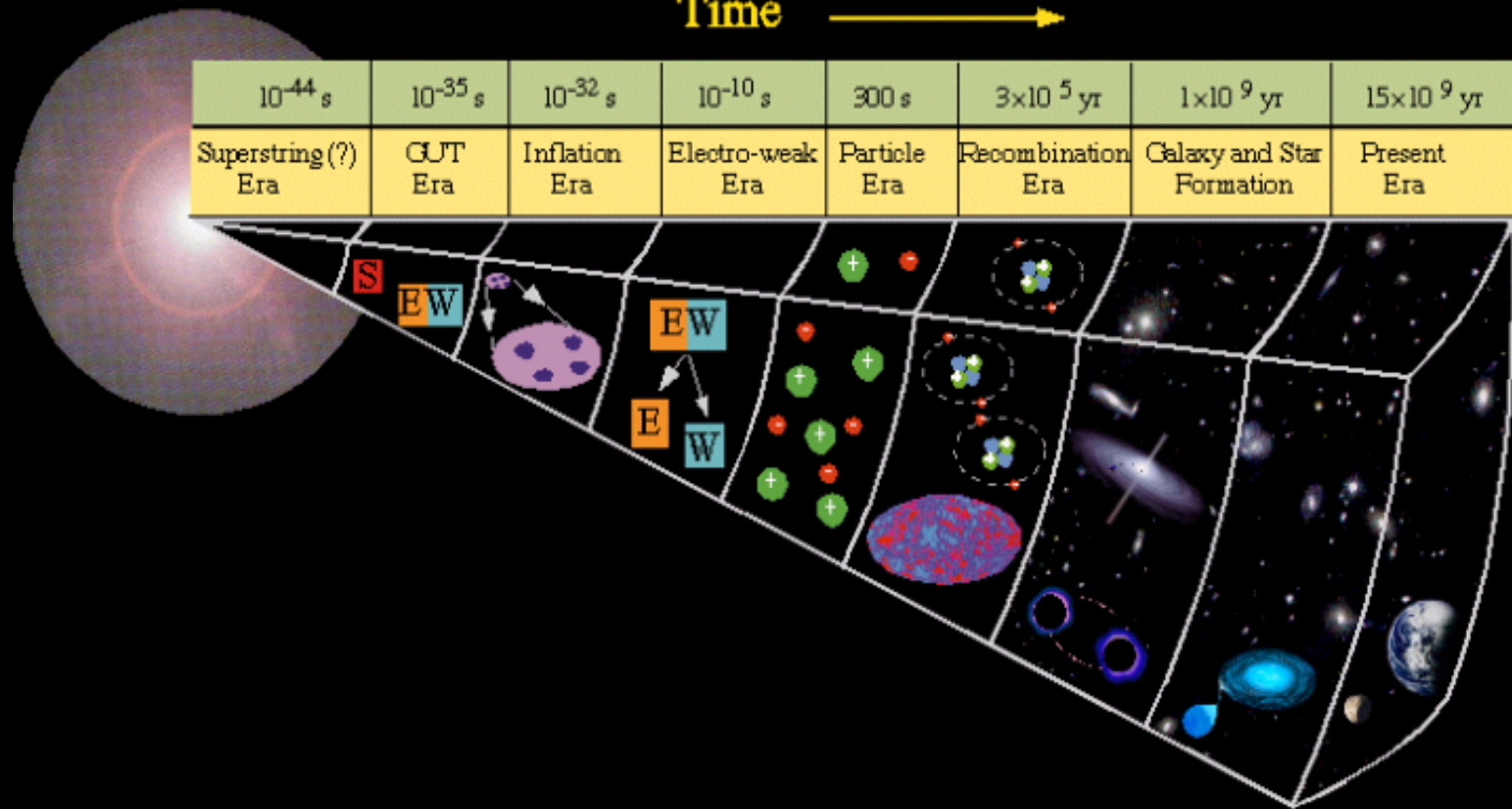
# Particle Physics

# Modern Cosmology!

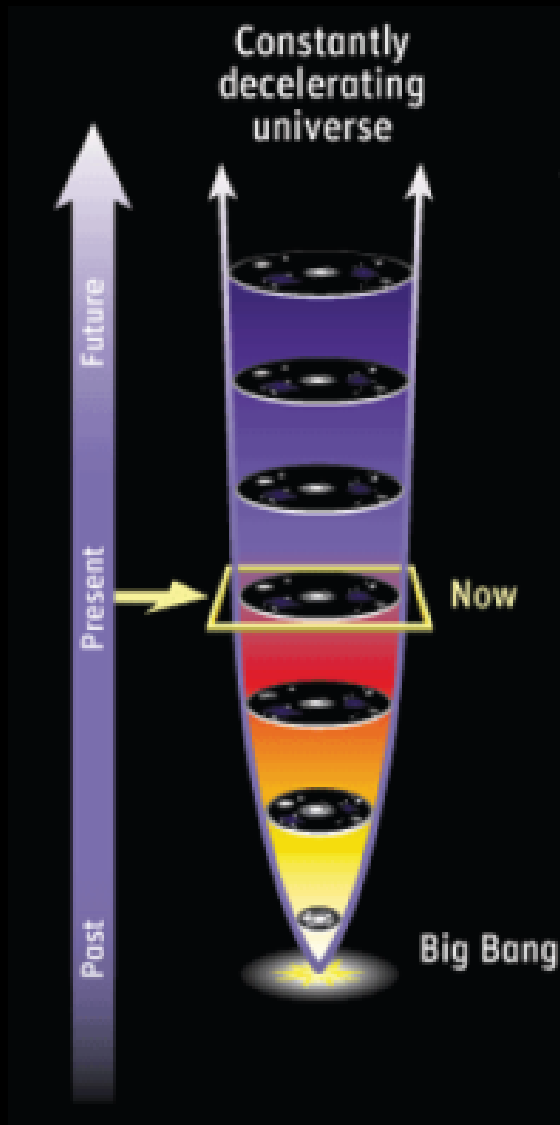


Big  
Bang

Time →



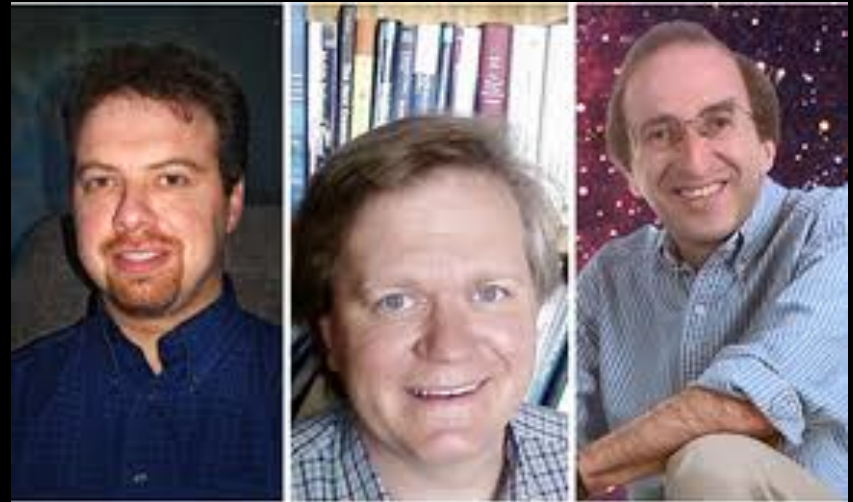
# Standard Cosmological Model



**Matter Only**



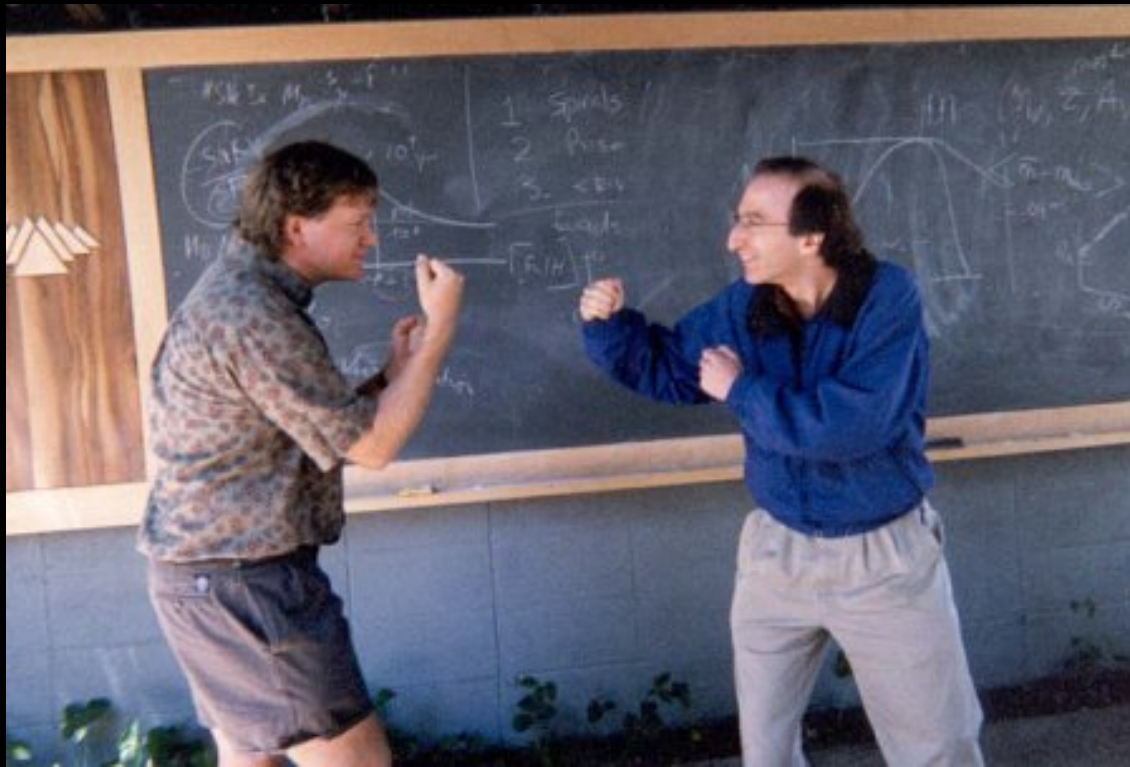
Brian Schmidt  
(Australian Nat. U.)



Adam Riess  
(Johns Hopkins)

Saul Perlmutter  
(LBNL, UC Berkeley)

*“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”*



A **scientific discussion** between Brian **Schmidt** (left, Australian National University) leader of the High-Z Supernova Search Team and Saul **Perlmutter** (right, Lawrence Berkeley Nat.Lab and UC), leader of the Supernova Cosmology Project





*“Preposterous Universe” was the name of a blog by Sean Carroll. Since 2005 Carroll has been blogging on “Cosmic Variance”*



DON'T LET THE BRIGHT  
LIGHTS FOOL YOU

THE DARK SIDE  
CONTROLS THE UNIVERSE

OUR UNIVERSE

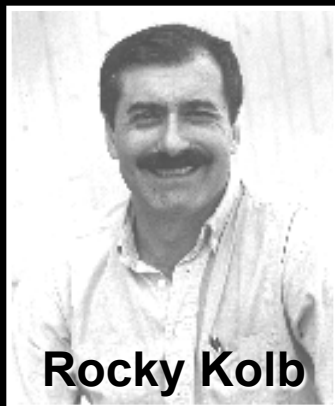
STARS: 0.0%

DARK MATTER: 33%

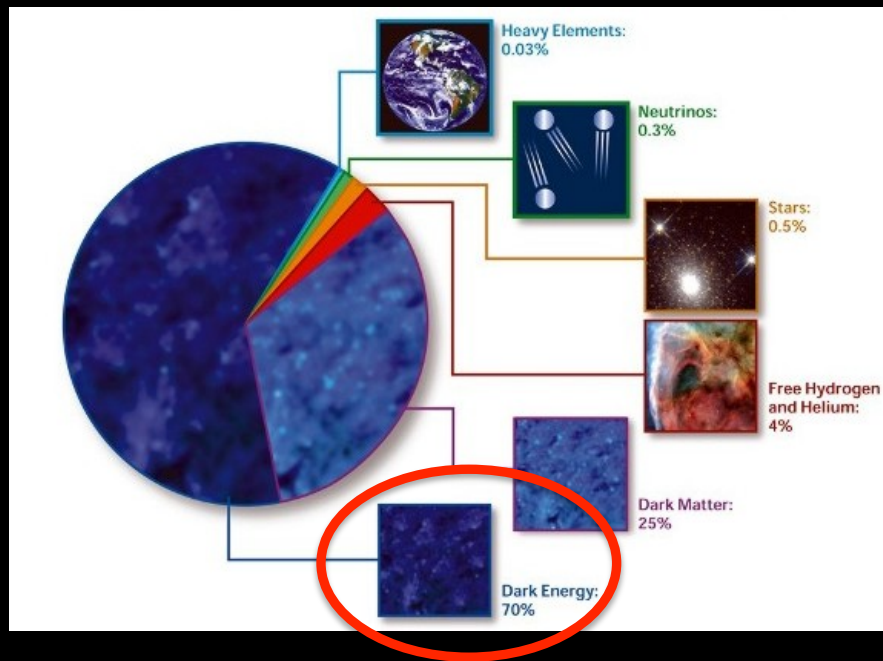
DARK ENERGY: 66%

DARK MATTER HOLDS IT TOGETHER

DARK ENERGY DETERMINES HIS DESTINY



Rocky Kolb



# Dark Energy

an (big) open problem  
...with a trivial solution!

## Einstein's Equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$

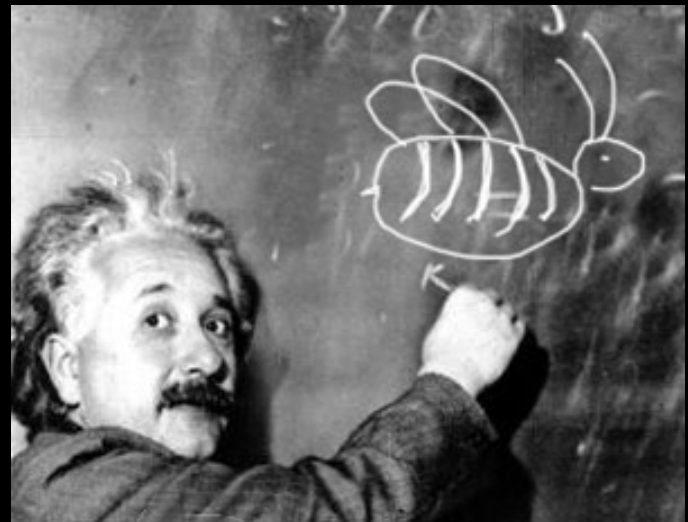
$$T_{\mu\nu} = T_{\mu\nu}^{(M)} - \rho_{vac}g_{\mu\nu}$$

$$\rho_{vac} = \frac{\Lambda}{8\pi G} = -P_{vac}$$

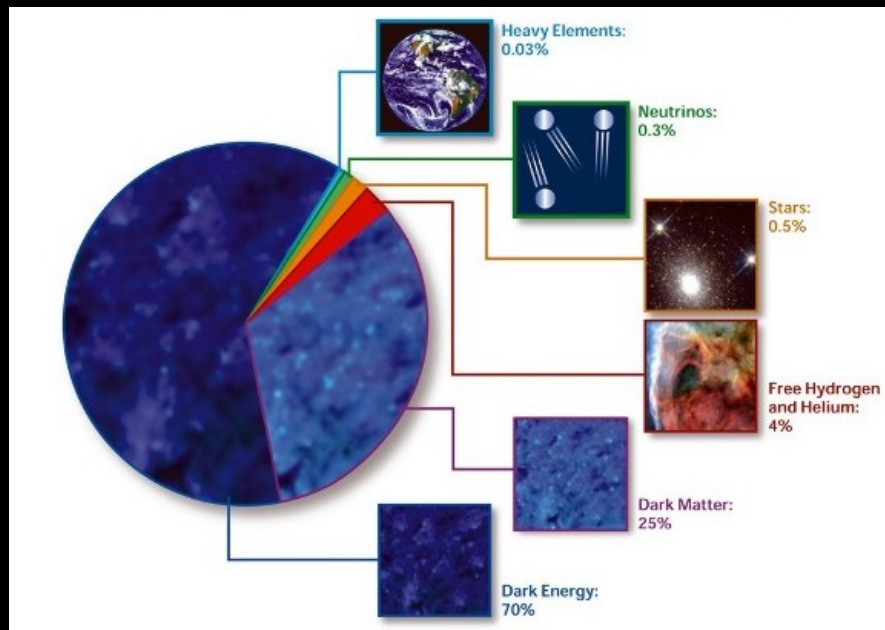
“negative  
pressure”  
fluid

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}$$

the resulting “**dark energy**”  
effect on **cosmology** is  
**compatible** with all  
observational data!







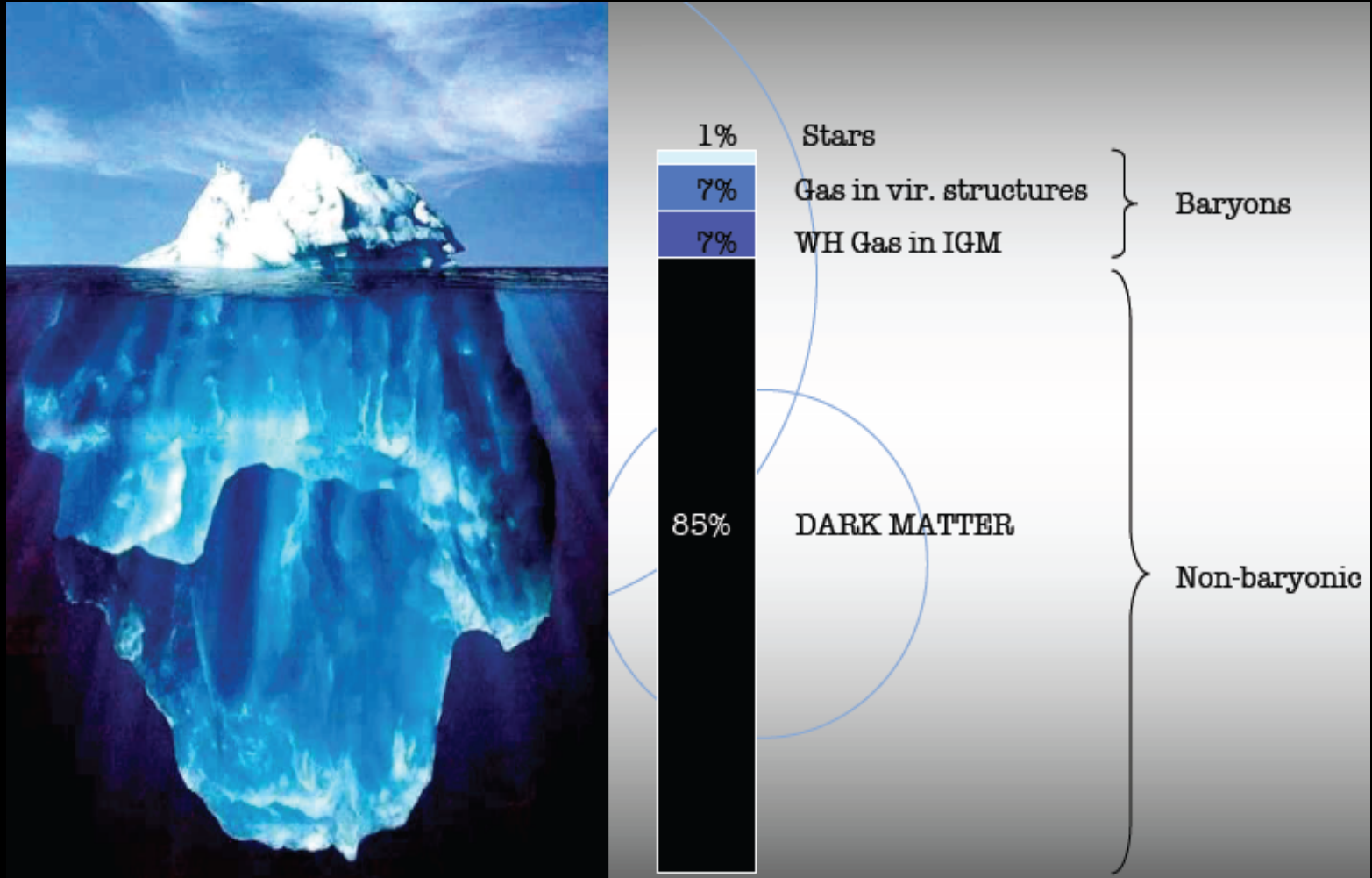
# Dark Energy

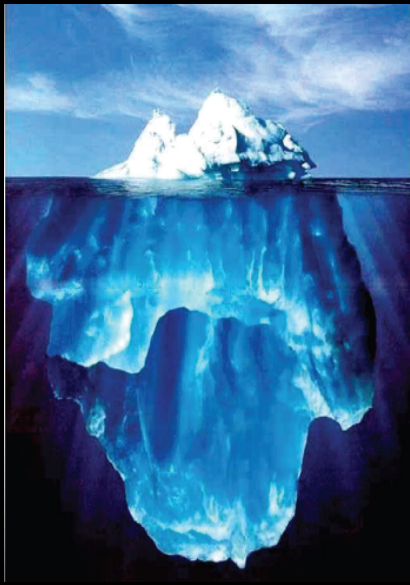
...worth think about model building

...but there exists a compelling, and simple,  
candidate: **cosmological constant**

# Dark Matter

no standard candidates:  
indicates **New Physics**  
(beyond the Standard Model)





# Dark Matter

(i) why is this the **qualitative** picture?

(ii) why is this the **quantitative** picture?

(i) why is this the **qualitative** picture?

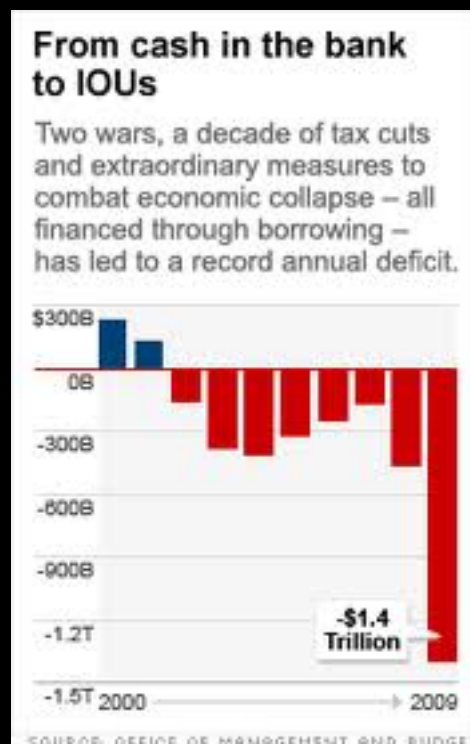
1. Clusters of Galaxies and the Virial Th.

2. Galactic Rotation Curves

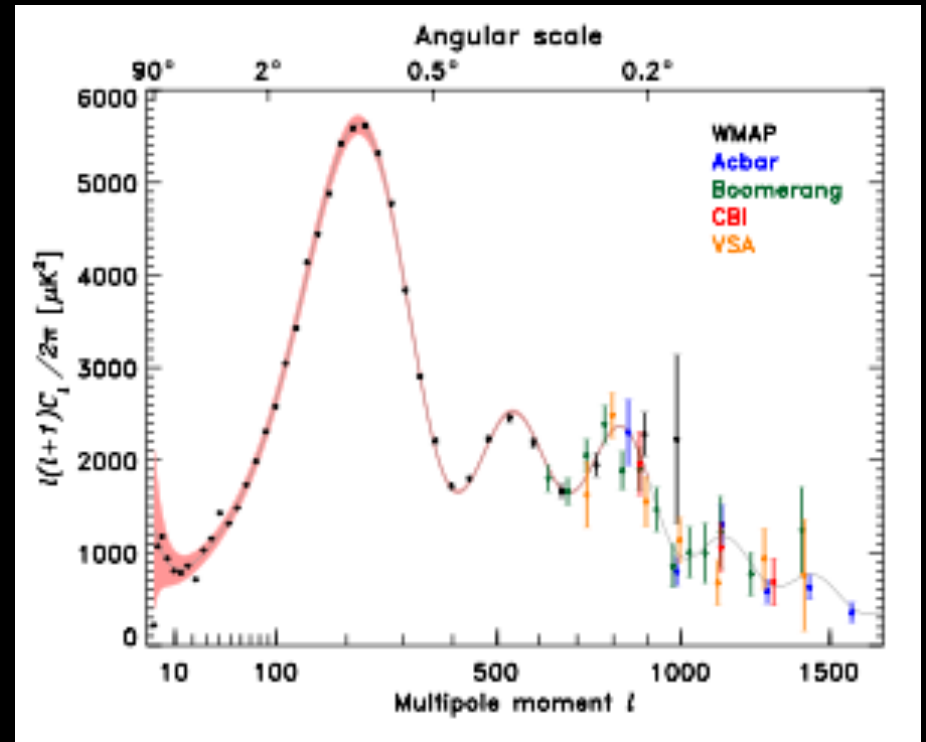
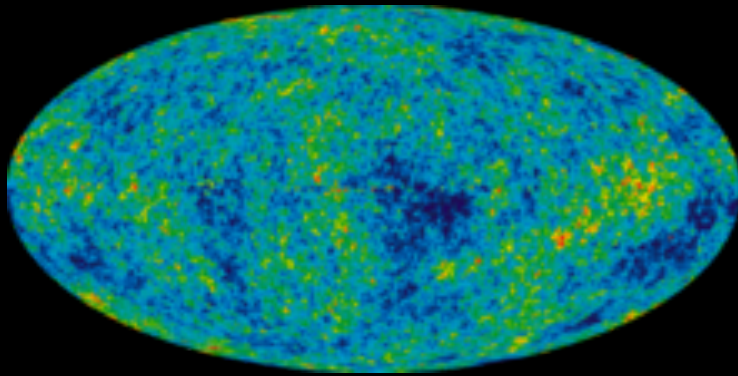
3. Structure Formation

(ii) why is this the **quantitative** picture?

a **Budget**  
Problem



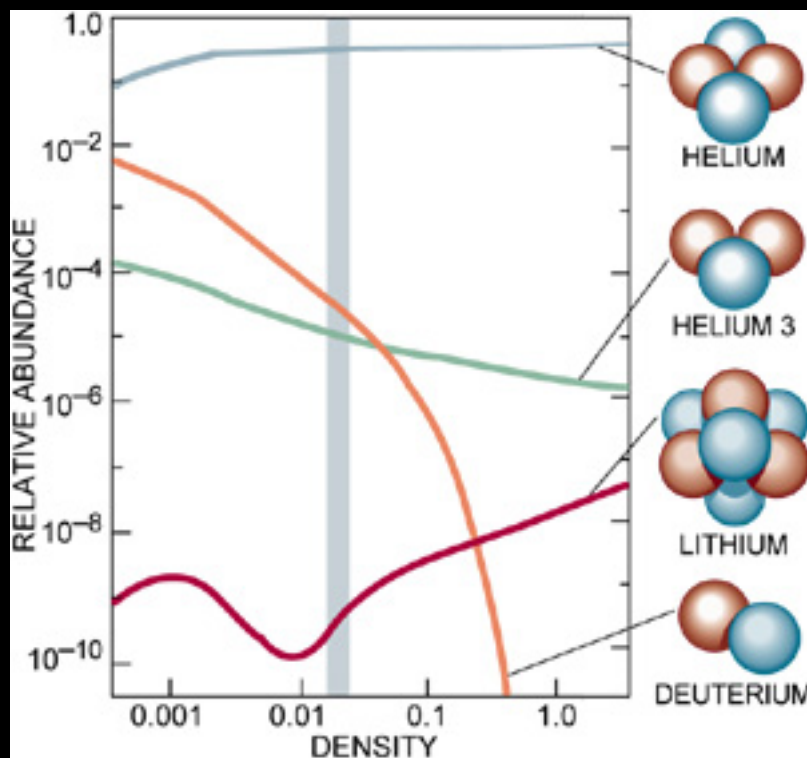




The universe is “**flat**” (density = critical density)

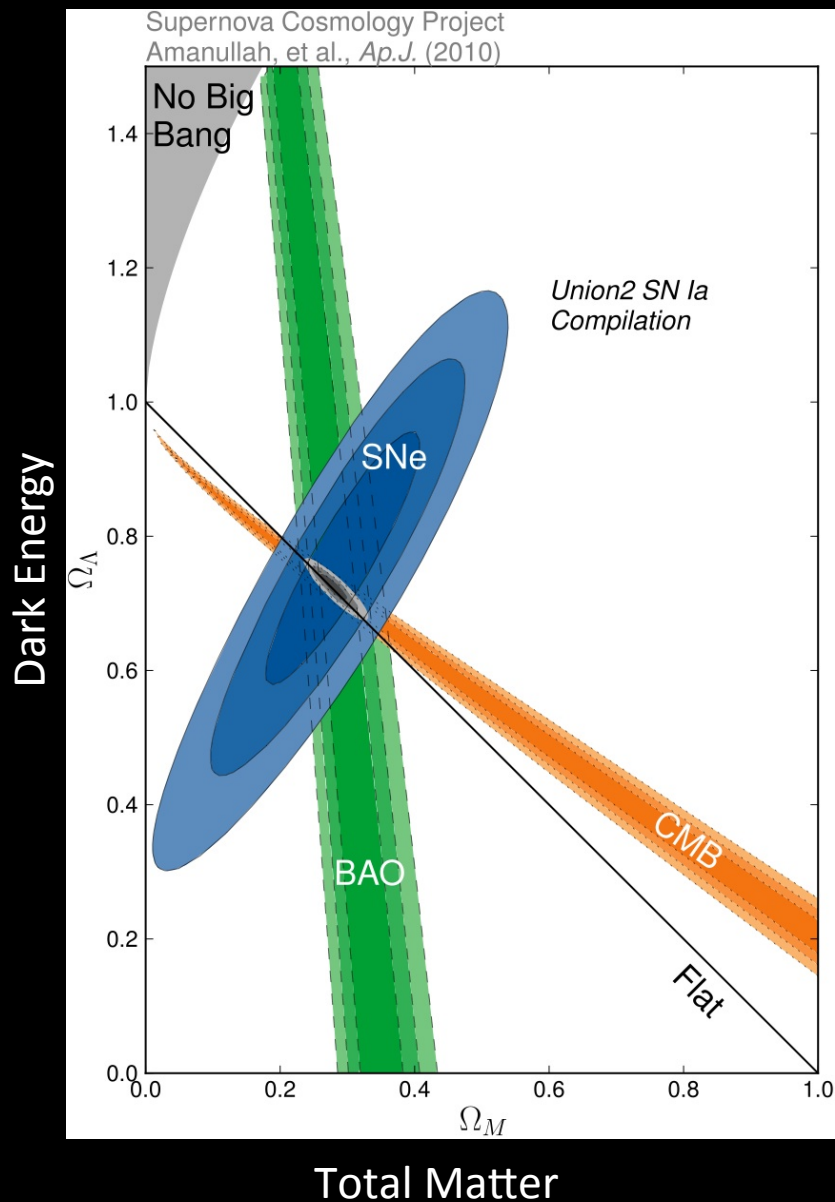
Relative height of second and first acoustic peak:  
**baryon abundance** is  $\sim 4\%$  of critical density

# Primordial (“Big Bang”) Synthesis of **Light elements**



Abundances can be **predicted** as functions of the density of baryons

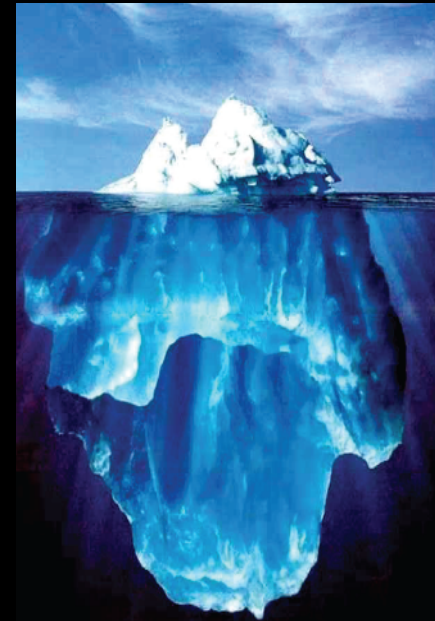
Conclusion: **baryons** are **~4%** of critical density



Total **matter** density:  $\sim 30\%$

Total **baryonic** matter density:  $\sim 4\%$

**Dark Matter:**  $30\% - 4\% = 26\%$



Dark Matter:  $\sim 80\%$  of matter budget!

# Dark Matter

(best) evidence  
for **New Physics**  
Beyond the  
Standard Model





# MATTER



*Quarks*



*Leptons*

# FORCE



*Gauge Bosons*

*Higgs Boson?*

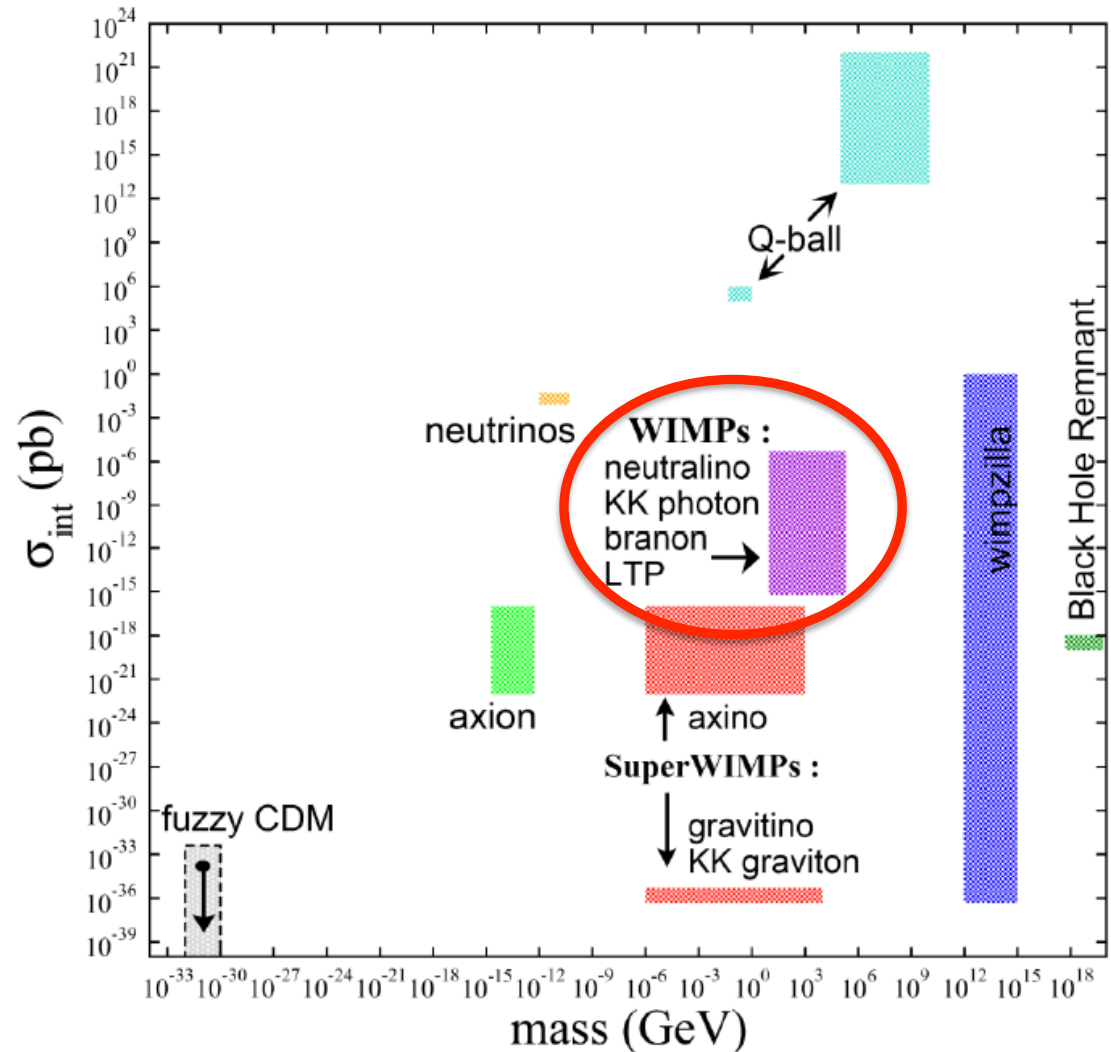
THE STANDARD MODEL OF  
PARTICLES AND FORCES

IS THIS ALL THAT EXISTS?

# Dark Matter Candidates

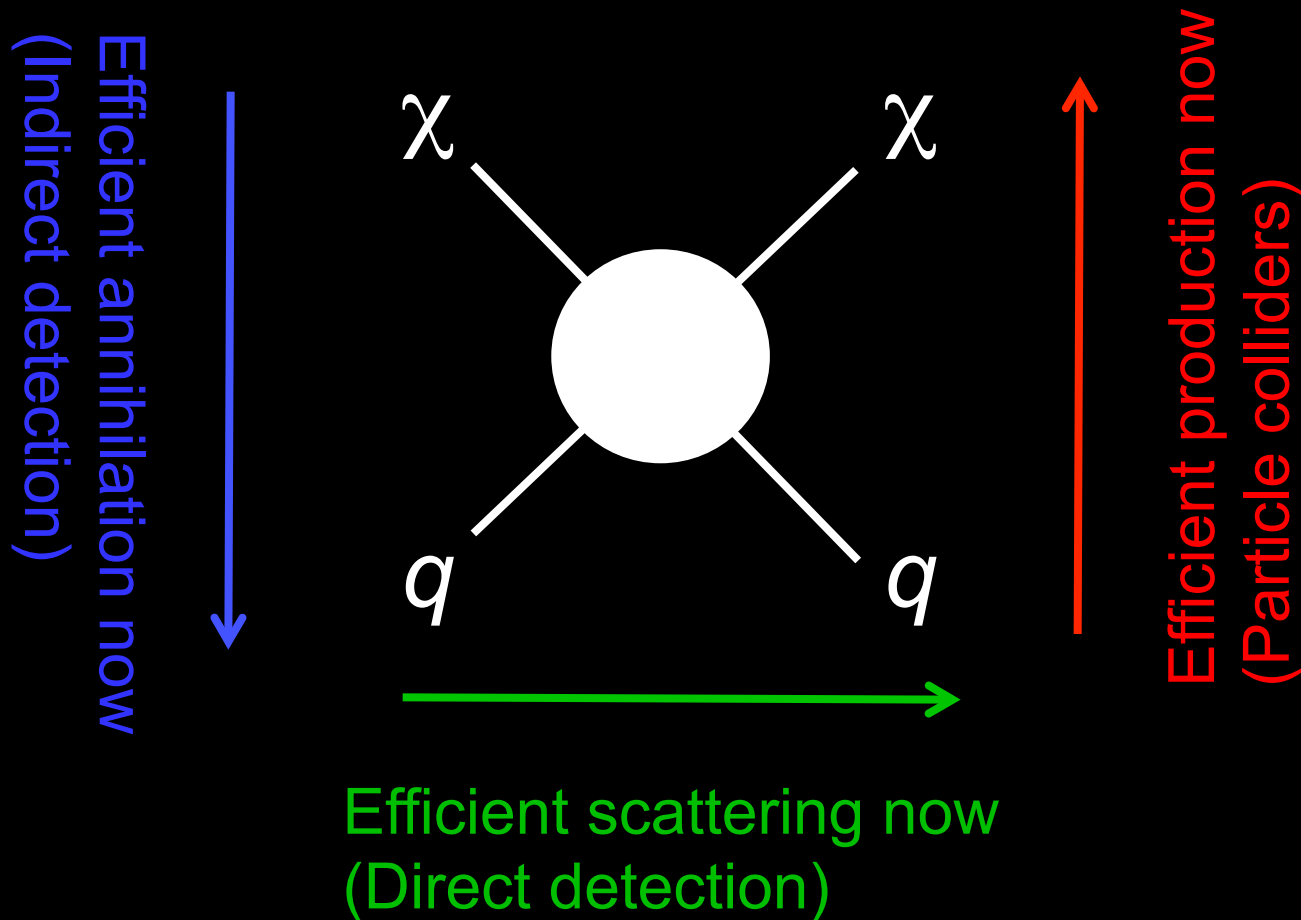
Observational  
**constraints**  
are no match for  
the **creativity**  
of theorists...

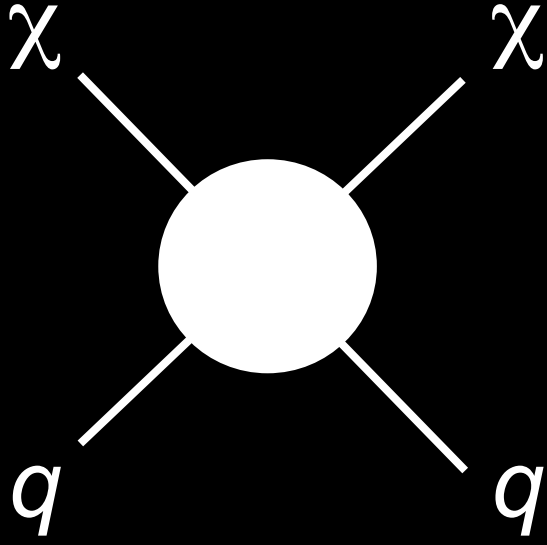
...but some  
candidates are  
**better motivated**  
than others



HEPAP/AAAC DMSAG Subpanel (2007)

# The search for (Weakly Interacting) Dark Matter

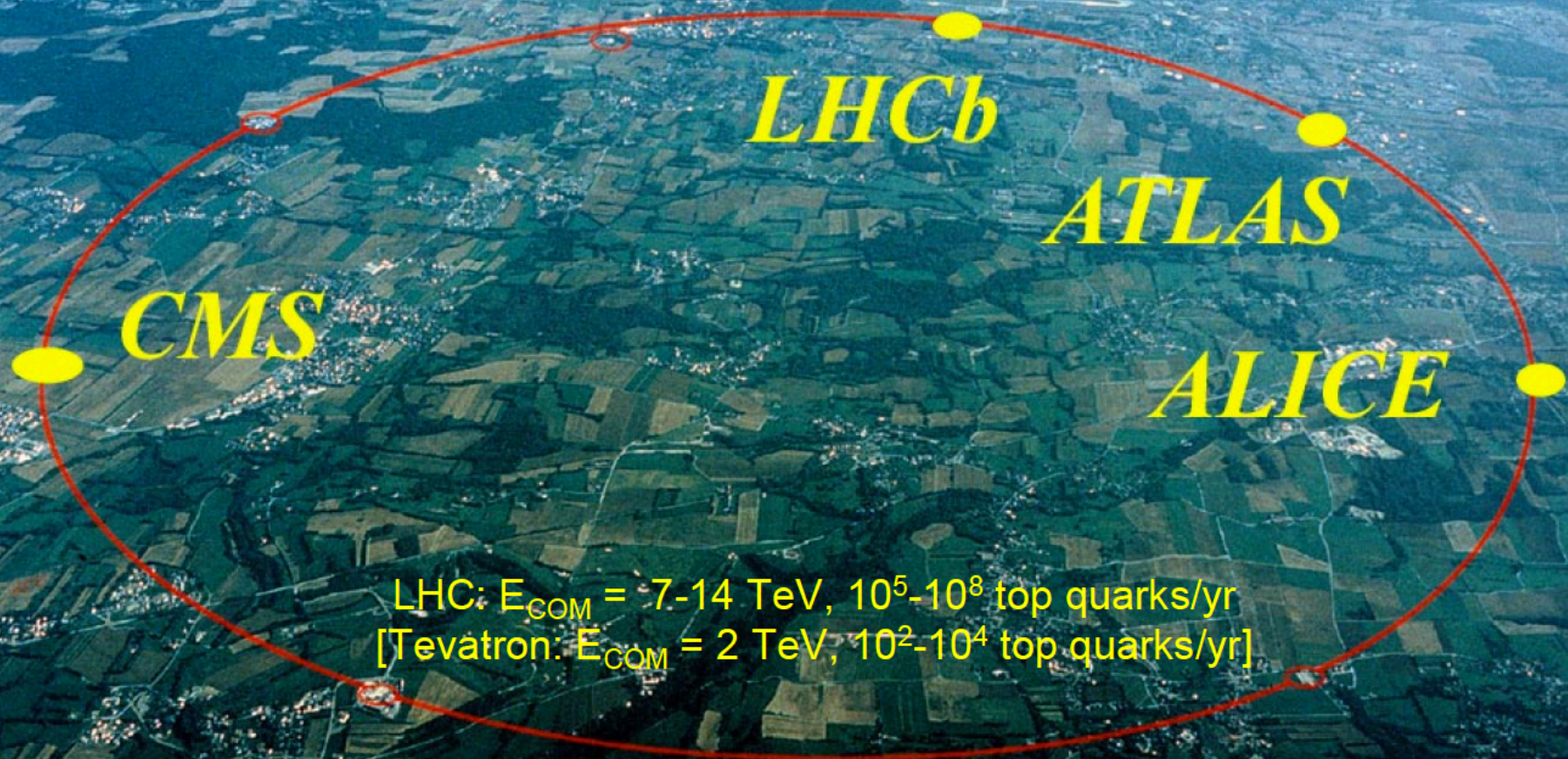




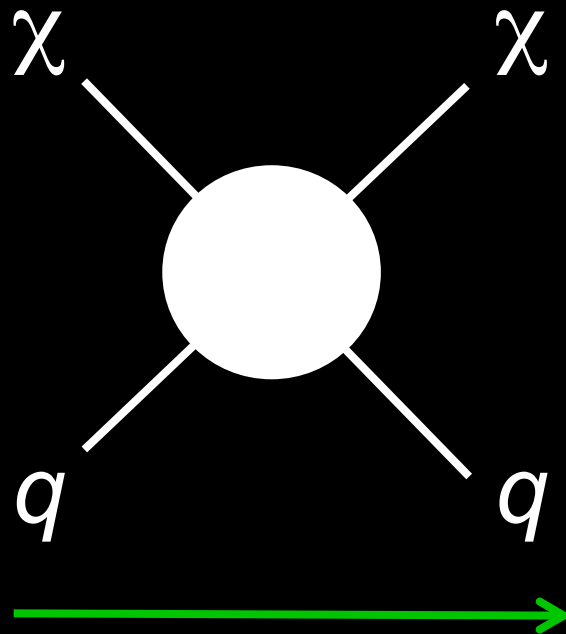
Efficient production now  
(Particle colliders)



# PARTICLE COLLIDERS

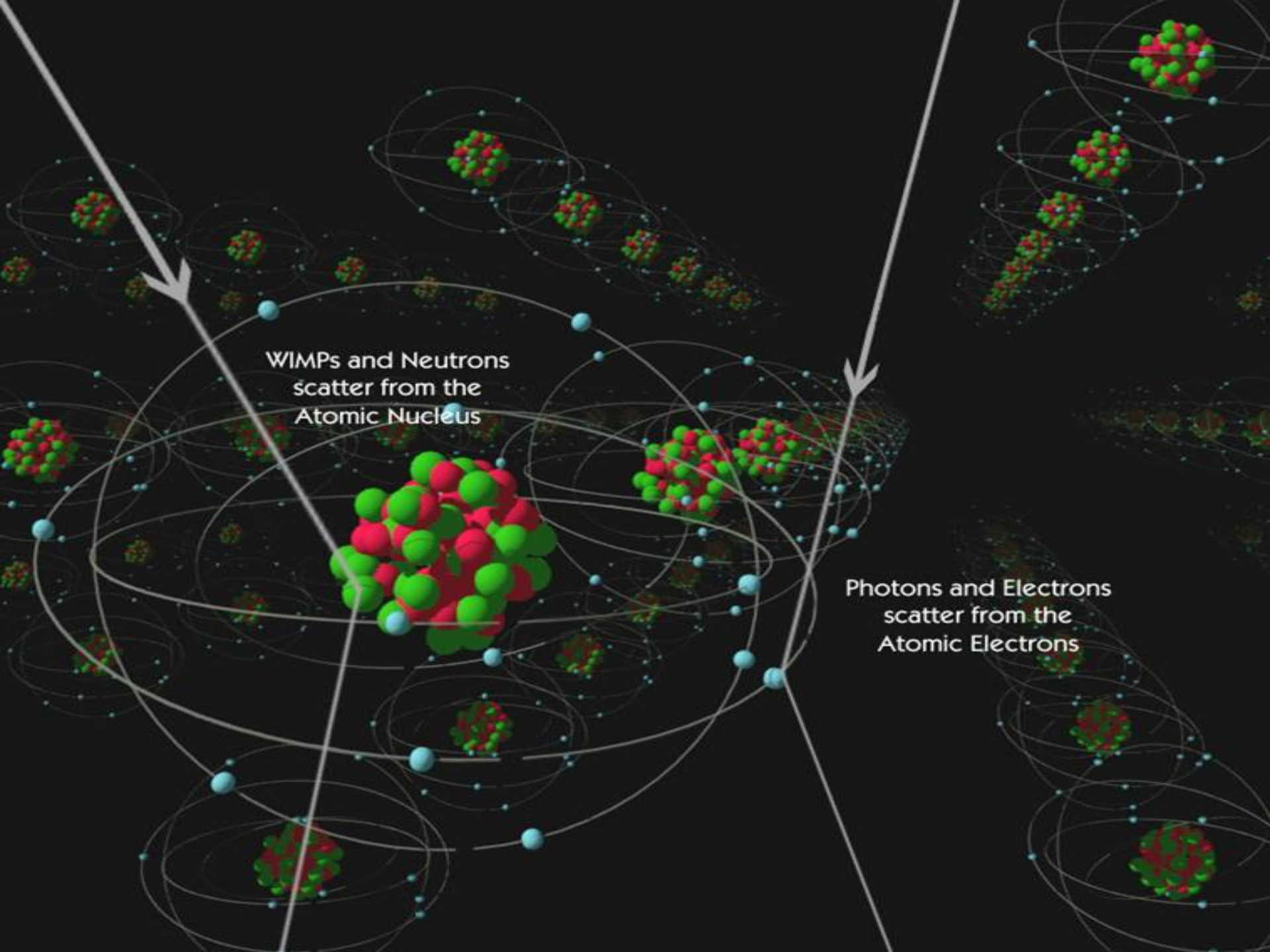


LHC:  $E_{\text{COM}} = 7\text{-}14 \text{ TeV}$ ,  $10^5\text{-}10^8$  top quarks/yr  
[Tevatron:  $E_{\text{COM}} = 2 \text{ TeV}$ ,  $10^2\text{-}10^4$  top quarks/yr]



Efficient scattering now  
(Direct detection)





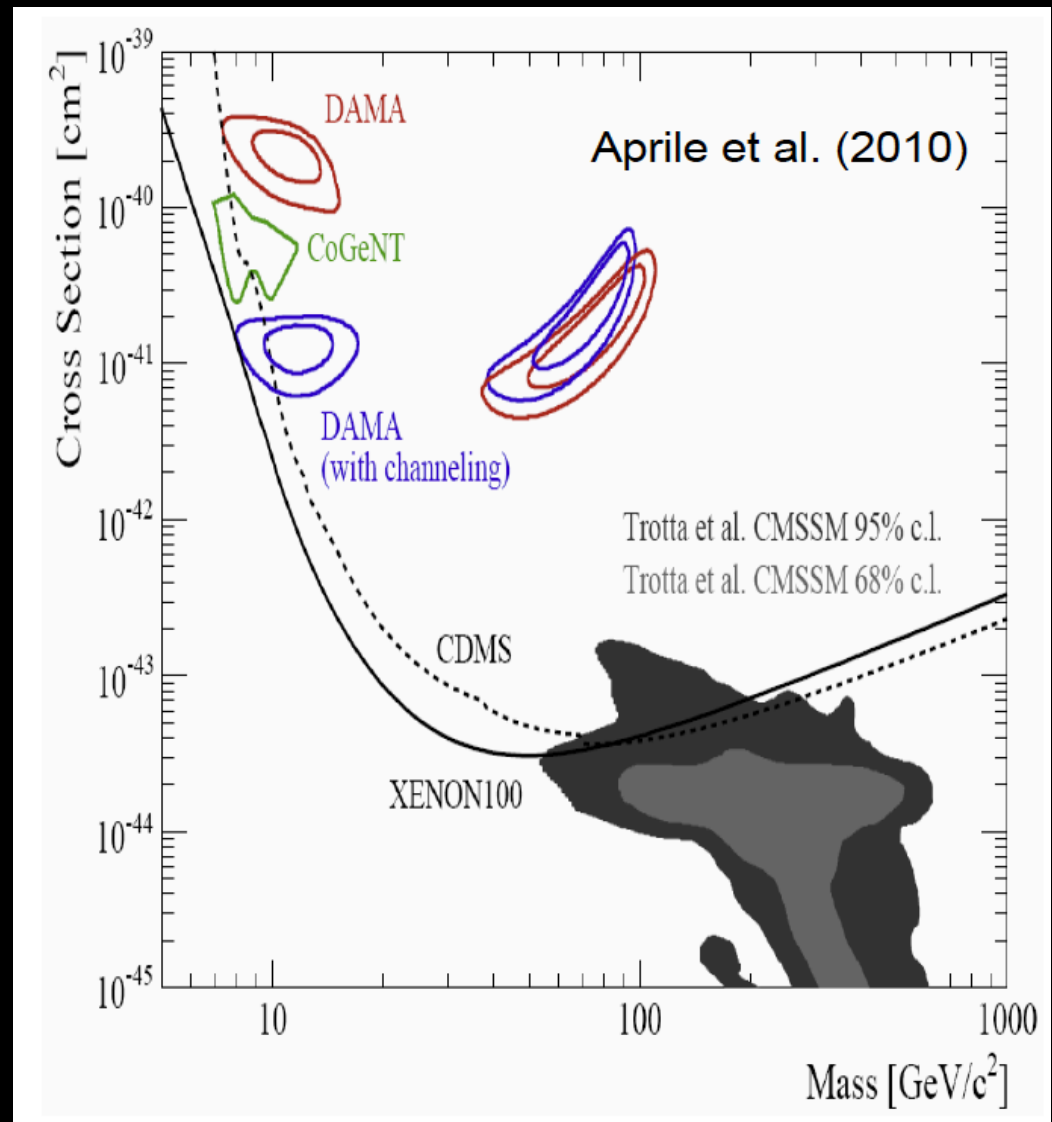
WIMPs and Neutrons  
scatter from the  
Atomic Nucleus

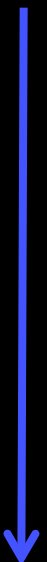
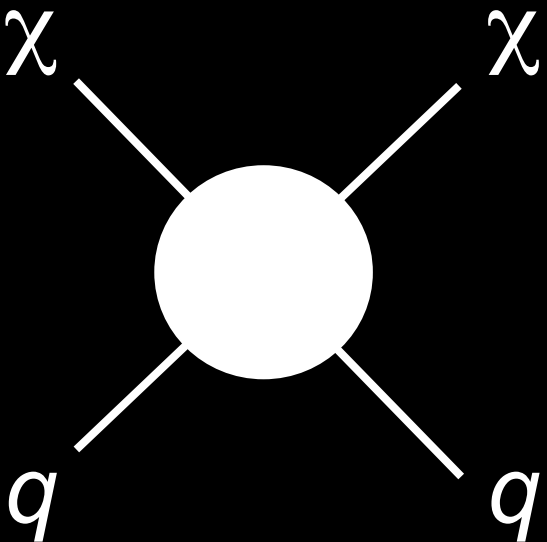
Photons and Electrons  
scatter from the  
Atomic Electrons



**anomalous** signals  
reported by several  
experimental  
collaborations

**contradictory** results,  
perhaps indicating  
we are getting close  
to **needed sensitivity**?





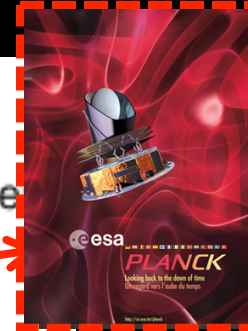
Efficient annihilation now  
(Indirect detection)

# “Indirect” Dark Matter Detection

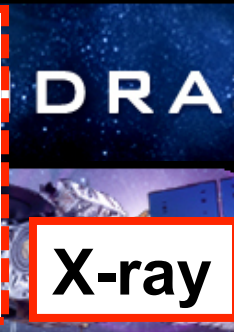
Can we do fundamental physics with indirect DM detection?

- ✓ Multi-messenger endeavor
- ✓ Fight -- understand -- astrophysical backgrounds!

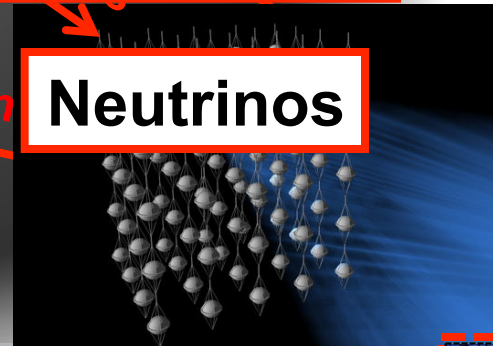
Radio



X-ray



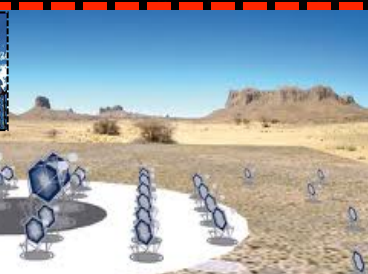
Neutrinos



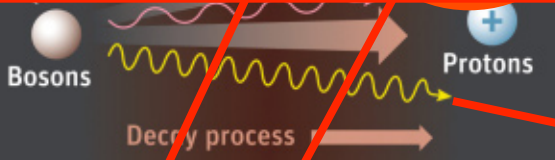
Gamma Ray



Antimatter



Supersymmetric neutralinos



Gamma

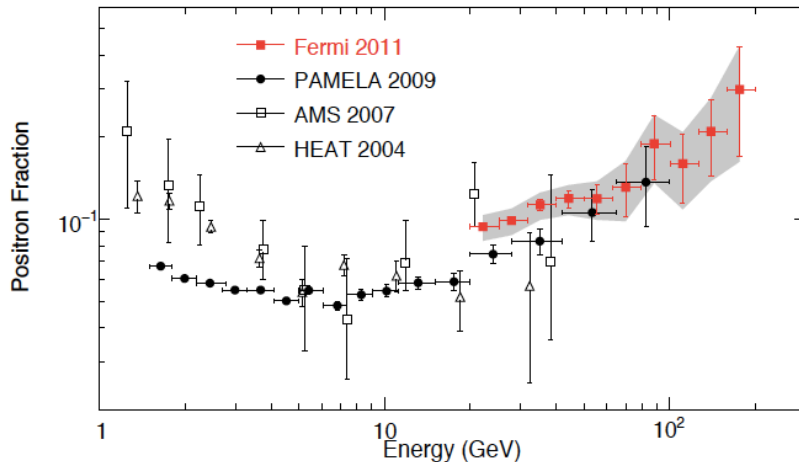


Matter Experiments

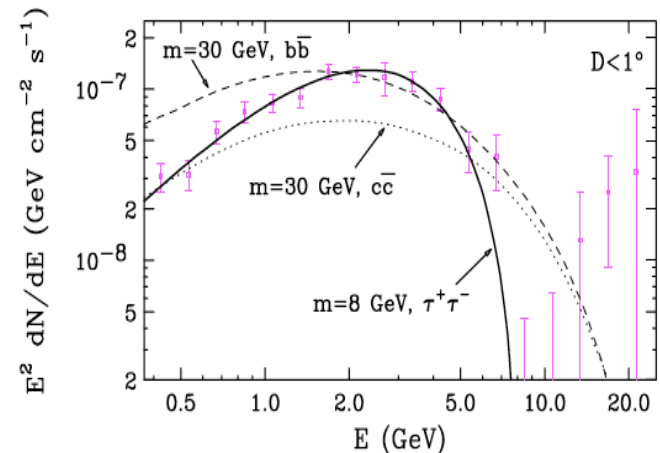


# Worse Astrophysical **Backgrounds** = Most **Exciting** Places to Look at!

## Cosmic Ray Electrons and Positrons: the Pamela Anomaly

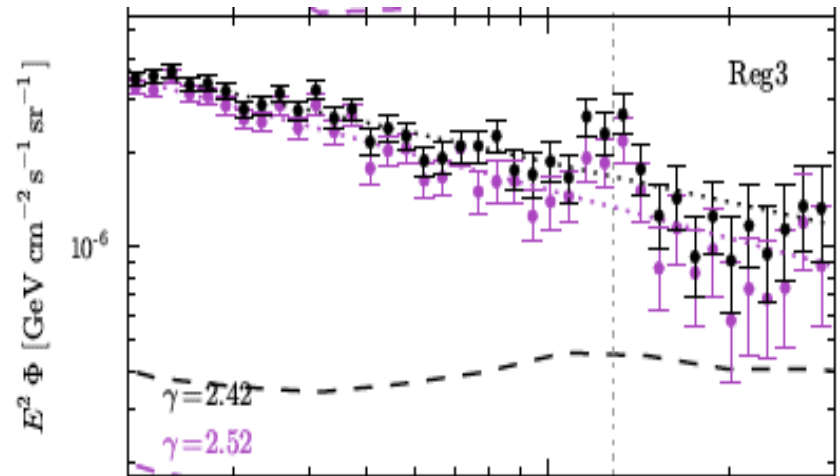
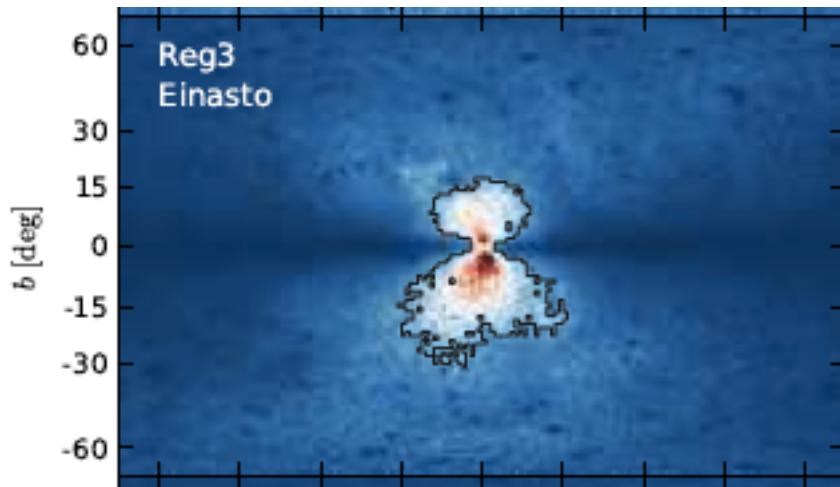


## Dark Matter annihilation in the Galactic Center?



# Worse Astrophysical **Backgrounds** = Most **Exciting** Places to Look at!

## A 130 GeV Gamma-Ray Line?



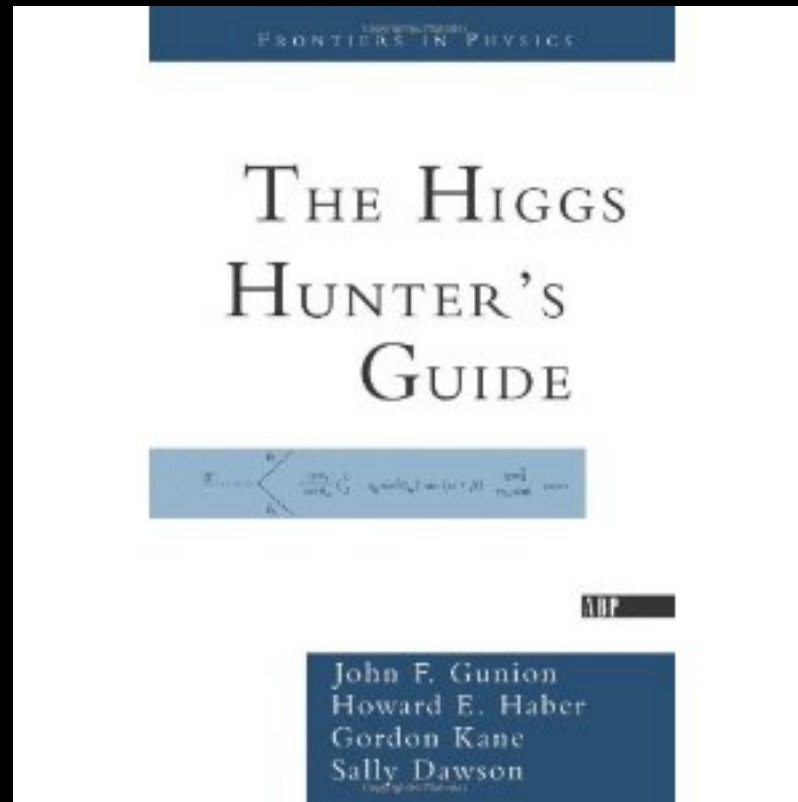
# Theoretical Particle Physics at UCSC







# Howie Haber: the Higgs Hunter





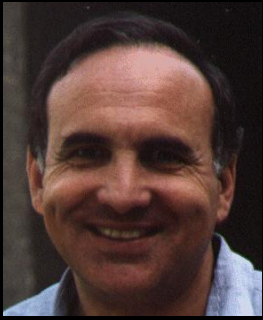
# Howie Haber: the Higgs Hunter



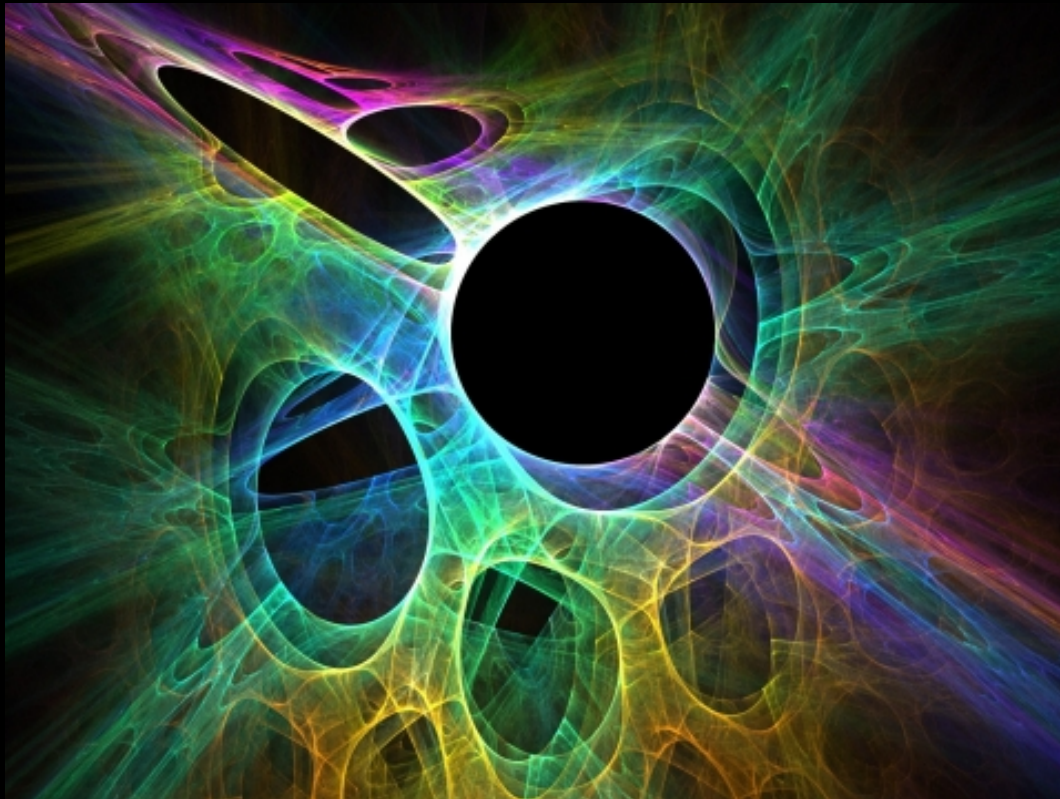


# Michael Dine: axions as dark matter and baryogenesis

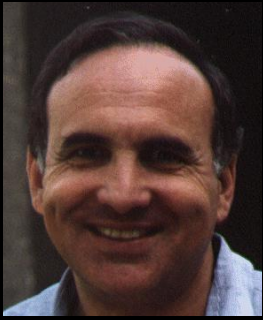




# Tom Banks: string theory and QCD







# Tom Banks: string theory and QCD

## STRING THEORY SUMMARIZED:

I JUST HAD AN AWESOME IDEA.  
SUPPOSE ALL MATTER AND ENERGY  
IS MADE OF TINY, VIBRATING "STRINGS."

