IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Studying the Universe Underground

Hitoshi Murayama (IPMU Tokyo & Berkeley)

Physics Colloquium, BNL, Oct 16, 2008

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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- New intl research institute in Japan
  - astrophysics
  - particle theory
  - particle expt
  - mathematics

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INSTITUTE FO
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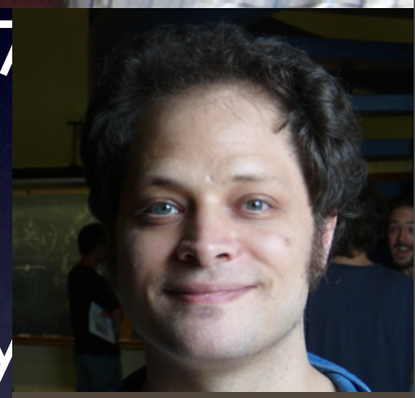
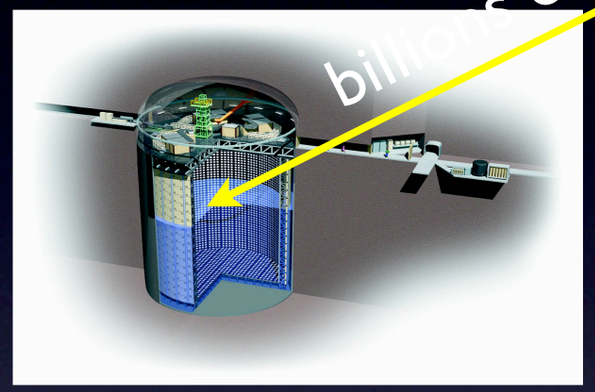


IPMU initiatives in experiments

- Vagins: let SuperK detect neutrinos from long past supernovae
- Kozlov: use KamLAND to see if $\nu=\bar{\nu}$?
- Suzuki/Nakahata/Martens: XMASS to detect dark matter
- Aihara/Takada/Yoshida/ Spergel/Turner: leadership in designing new camera HSC at Subaru and data analysis to study dark energy
- Also new photodetector developments (e.g. HPD)

IPMU initiatives in experiments



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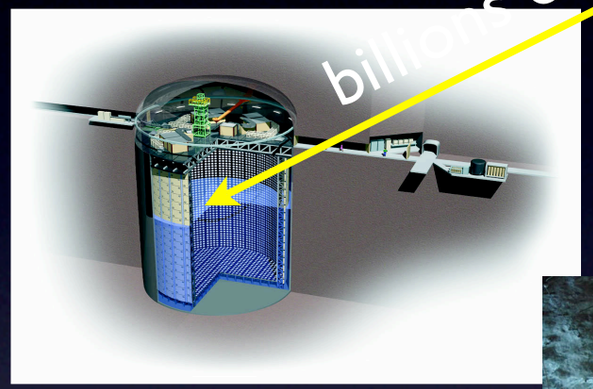

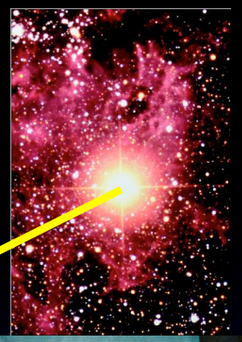

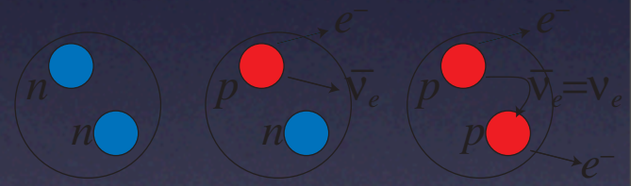

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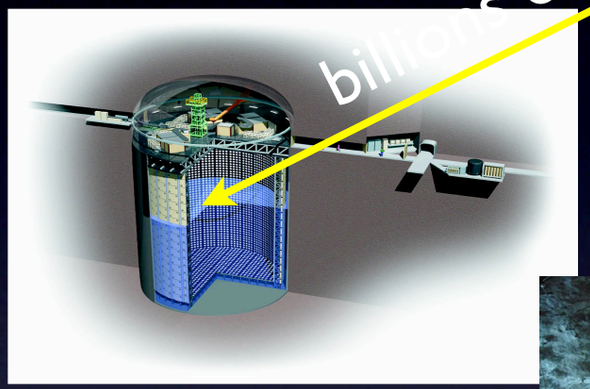

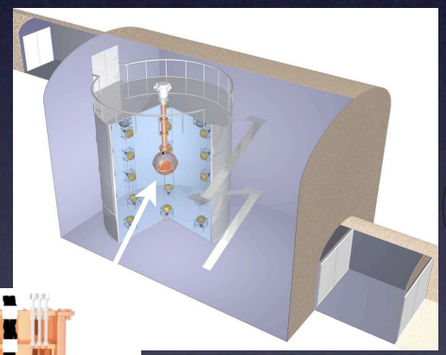

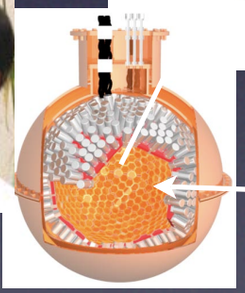

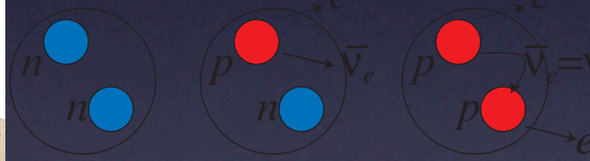

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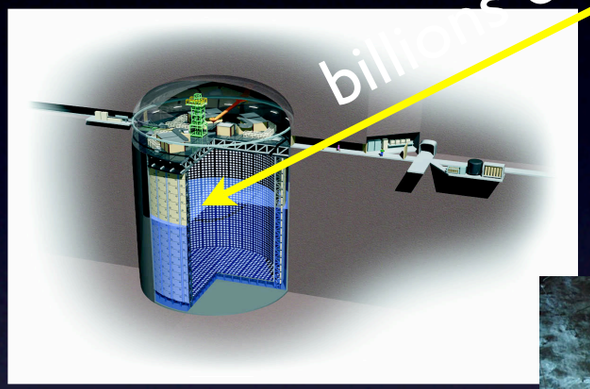
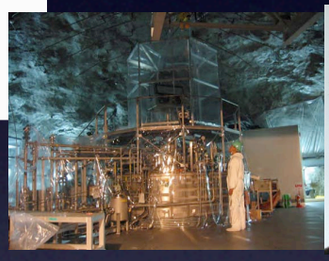
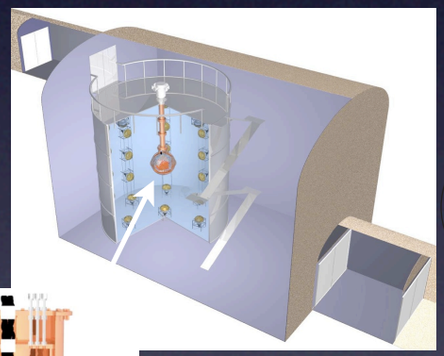
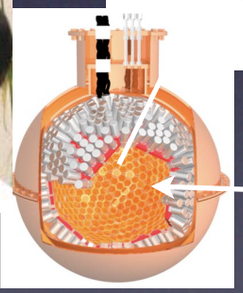
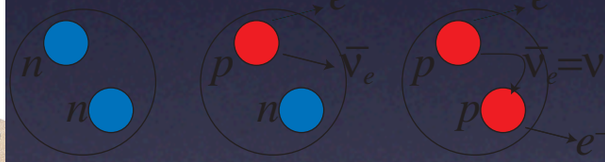
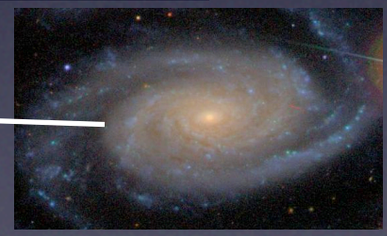


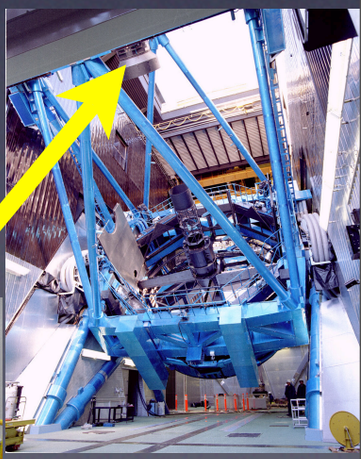


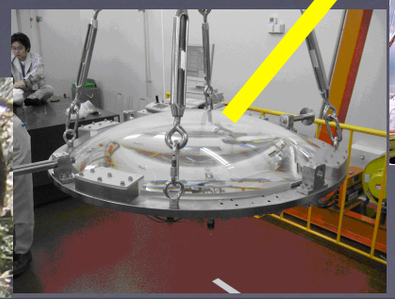




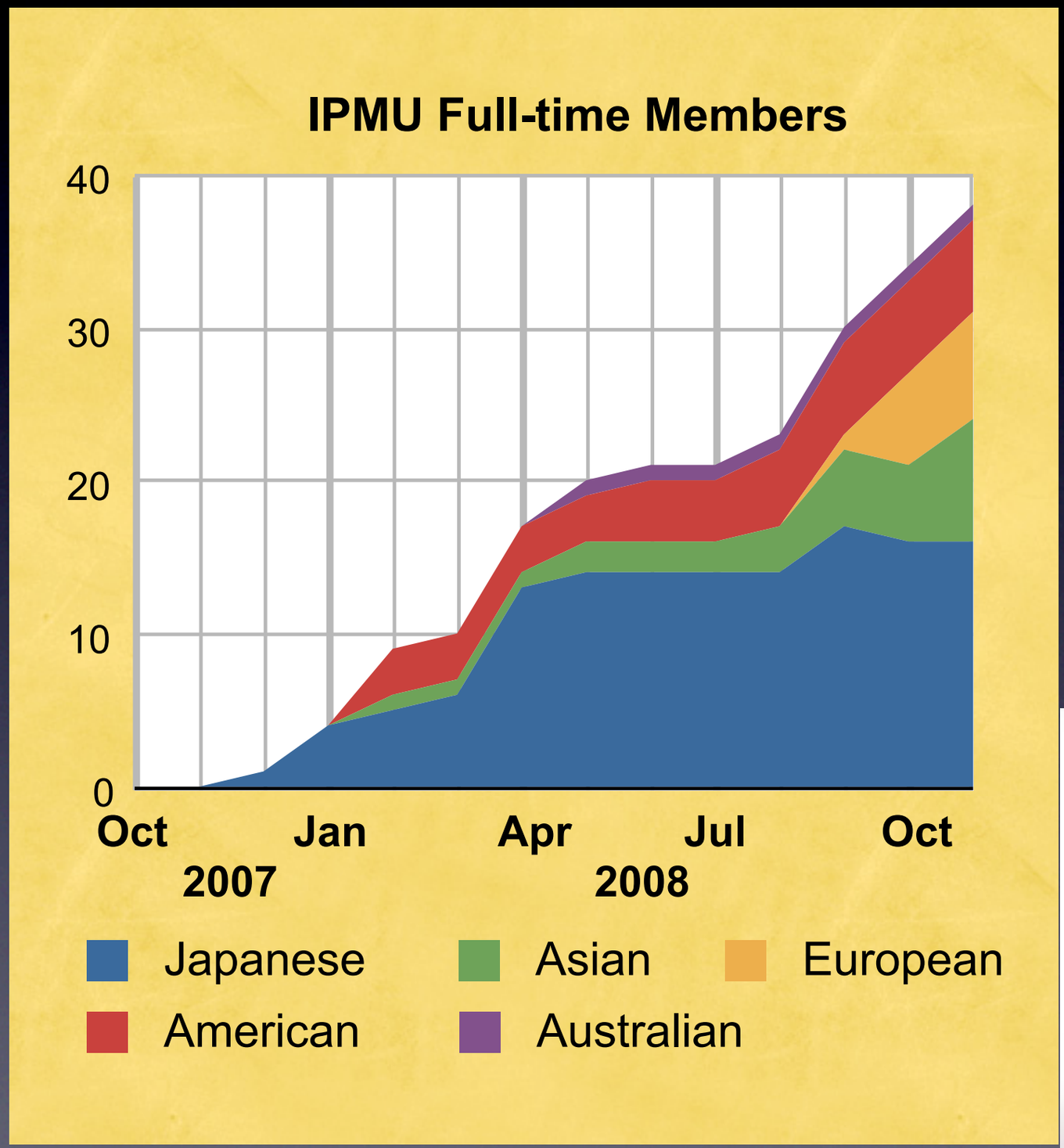


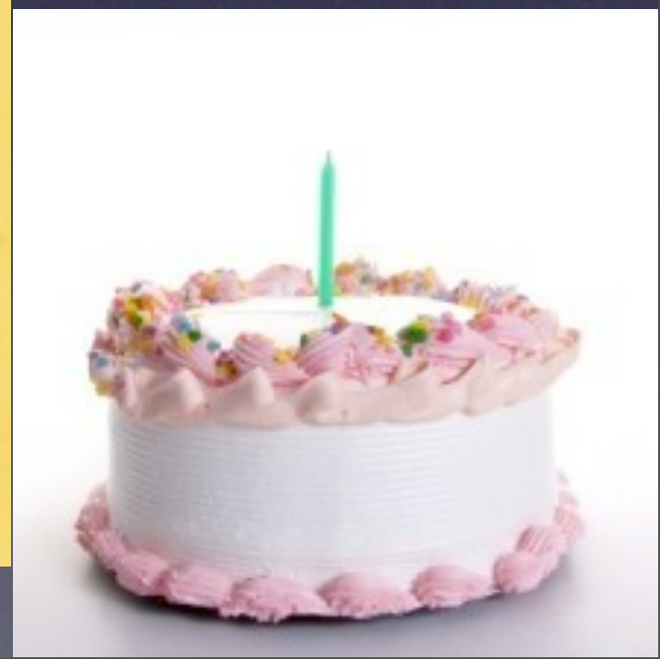






On Site Scientists





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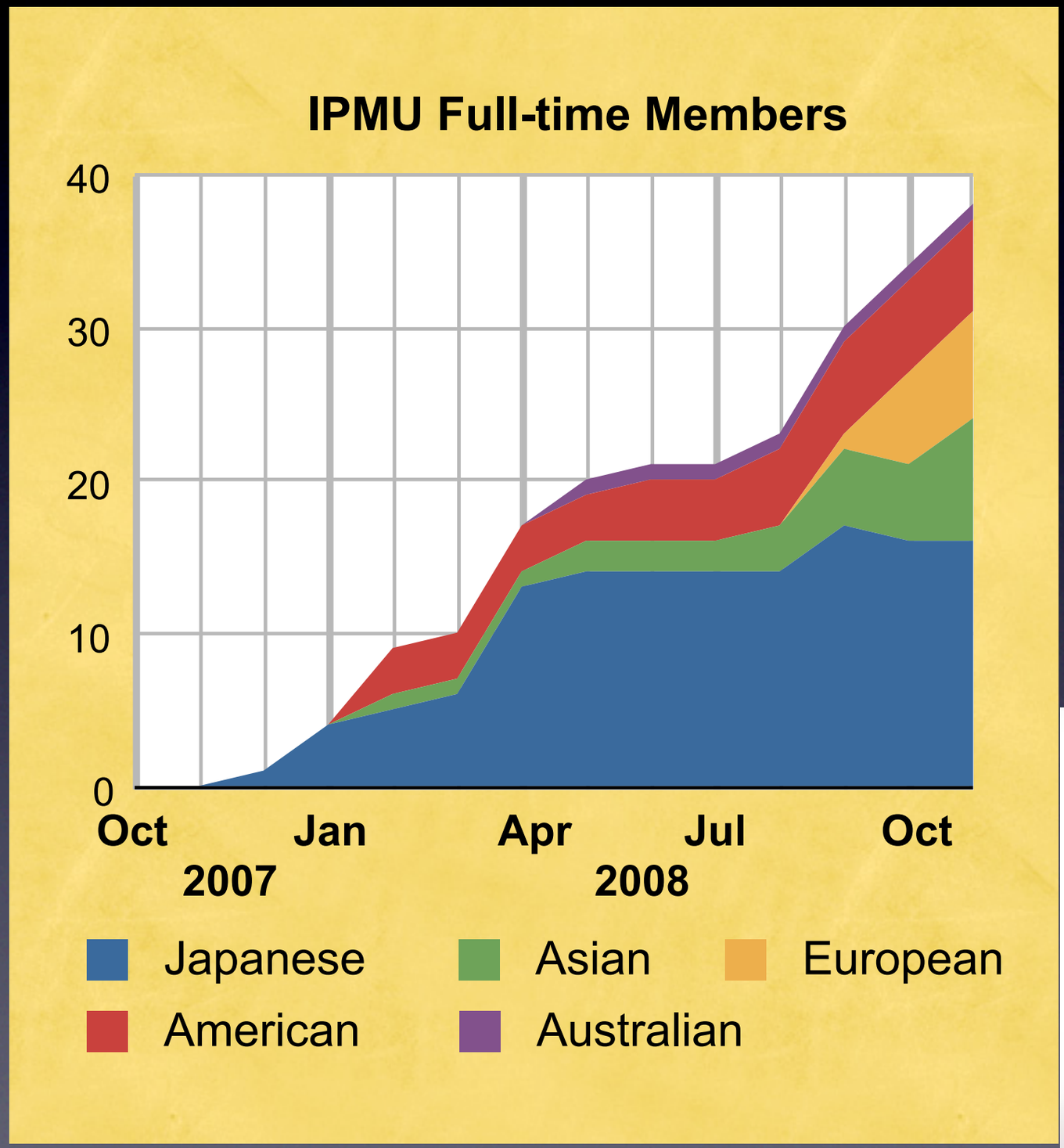
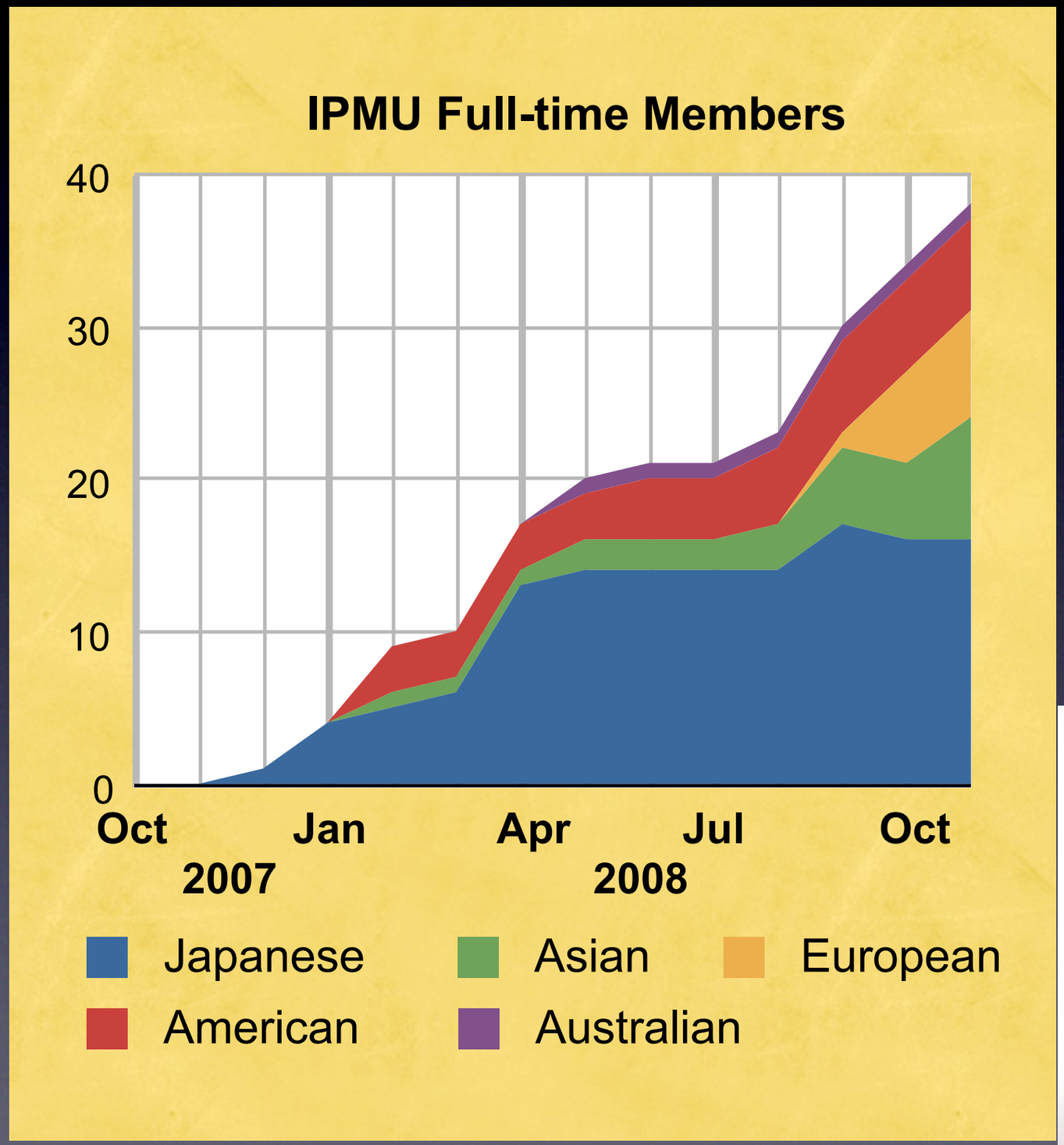


non-Japanese 50%

On Site Scientists

Expect ~15 positions this year



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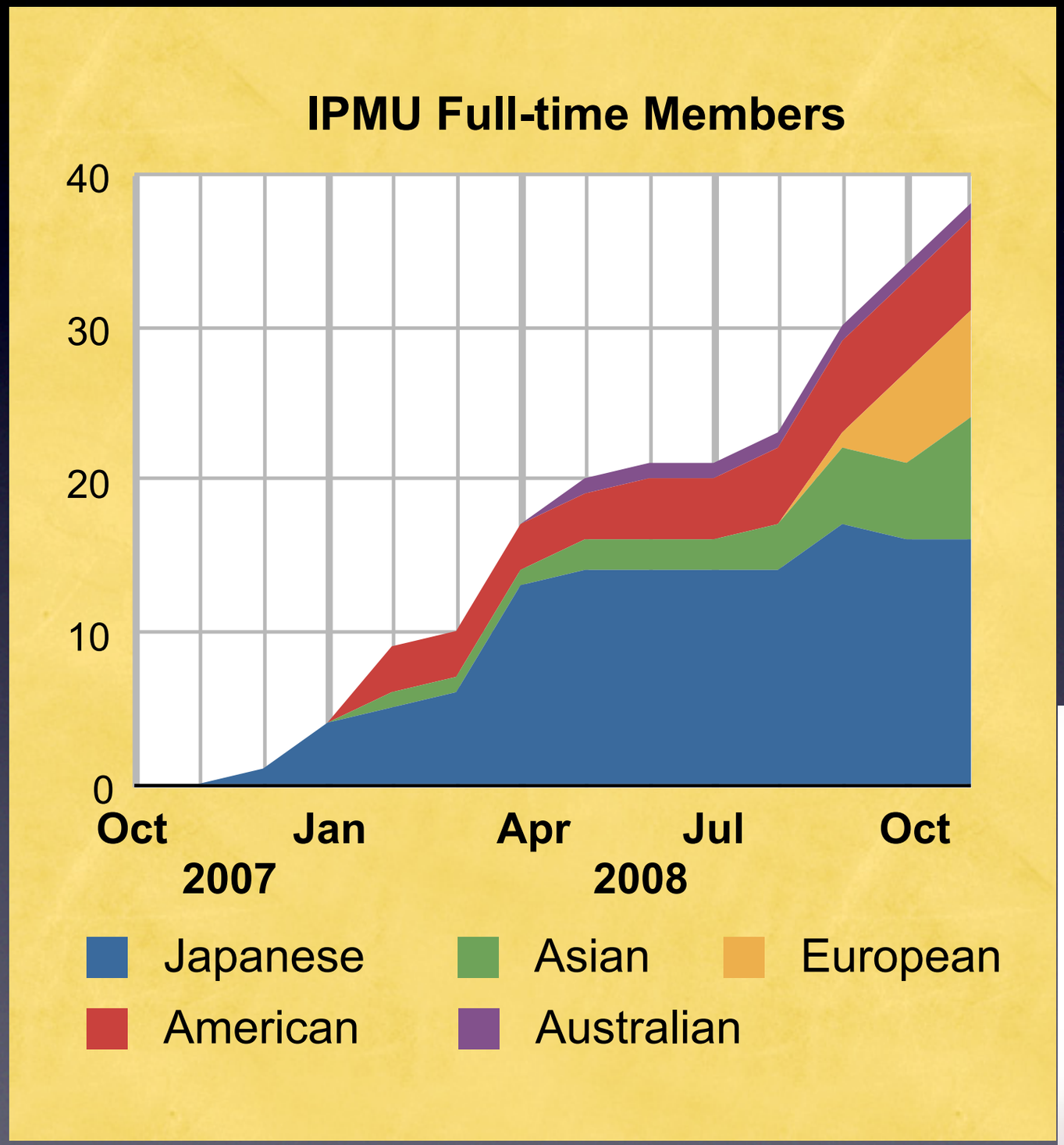
Check out www.ipmu.jp



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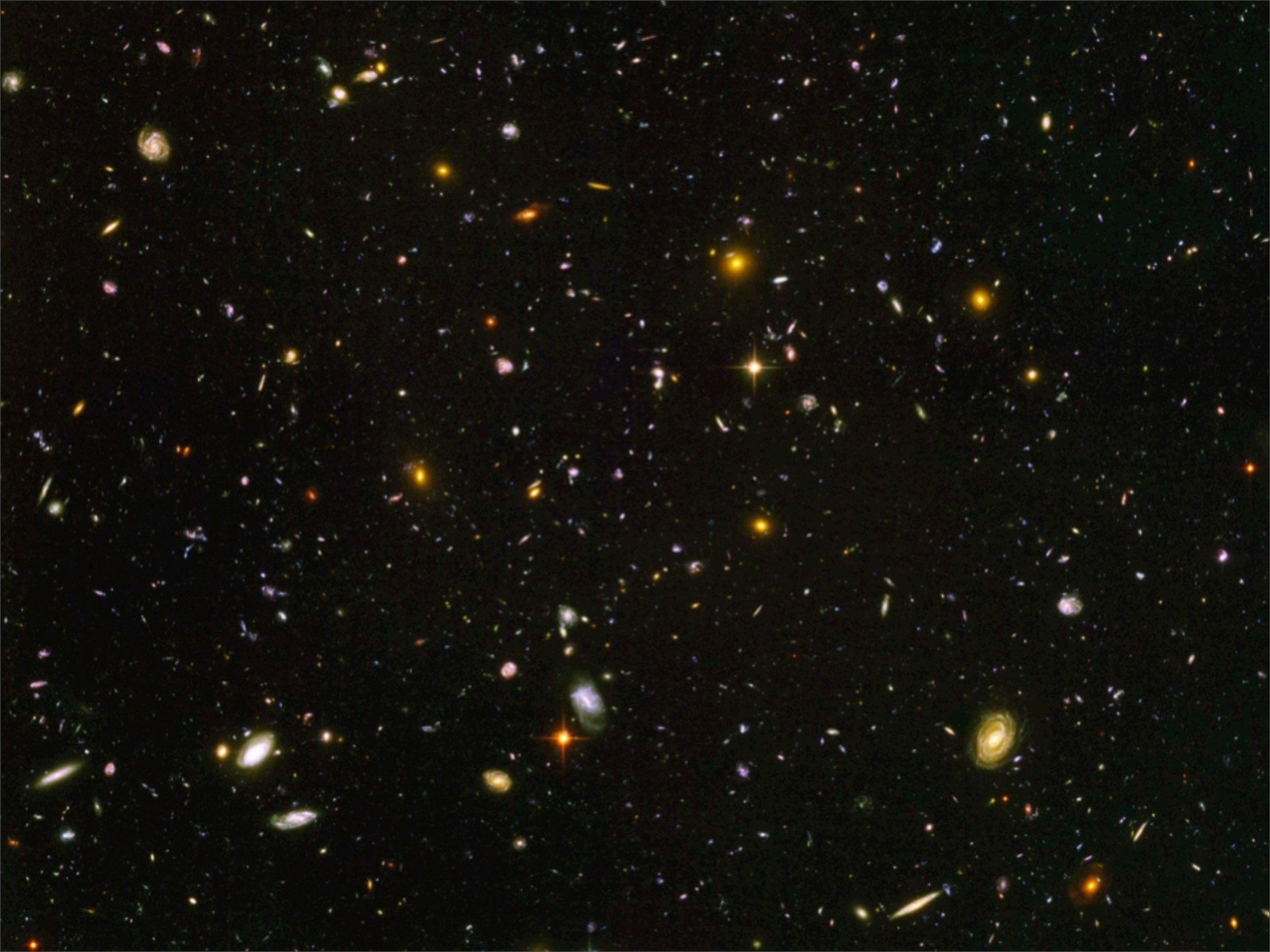

There are many
things we don't see

Energy Budget of the Universe

- Stars are only ~0.5%

stars
atoms
neutrinos
dark matter
dark energy

Energy Budget of the Universe

- Stars are only ~0.5%
- Neutrinos are ~0.1–1.5%

stars
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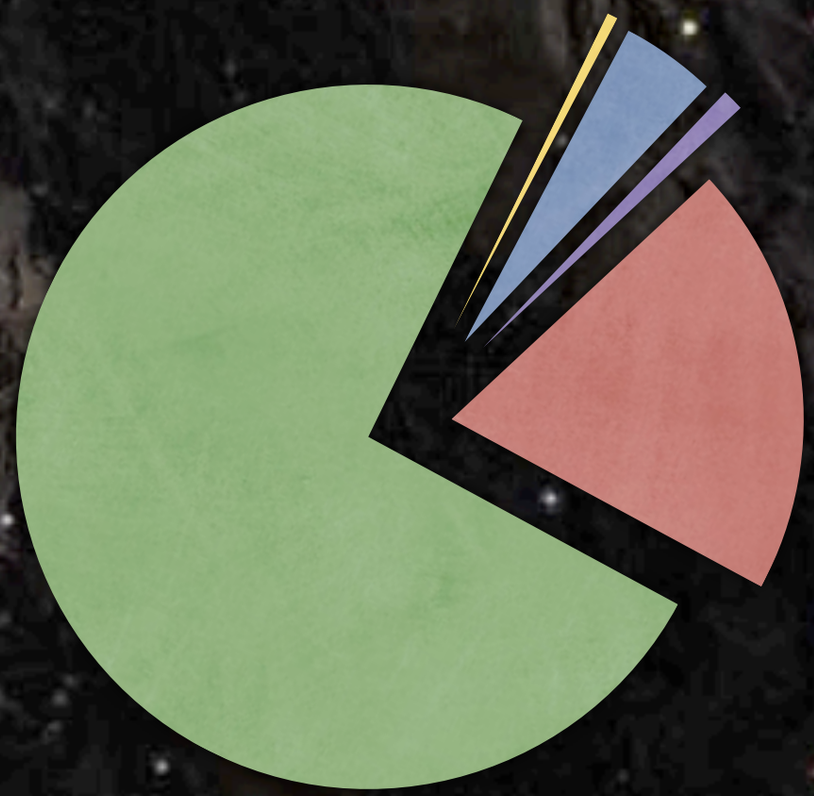

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- Stars are only ~0.5%
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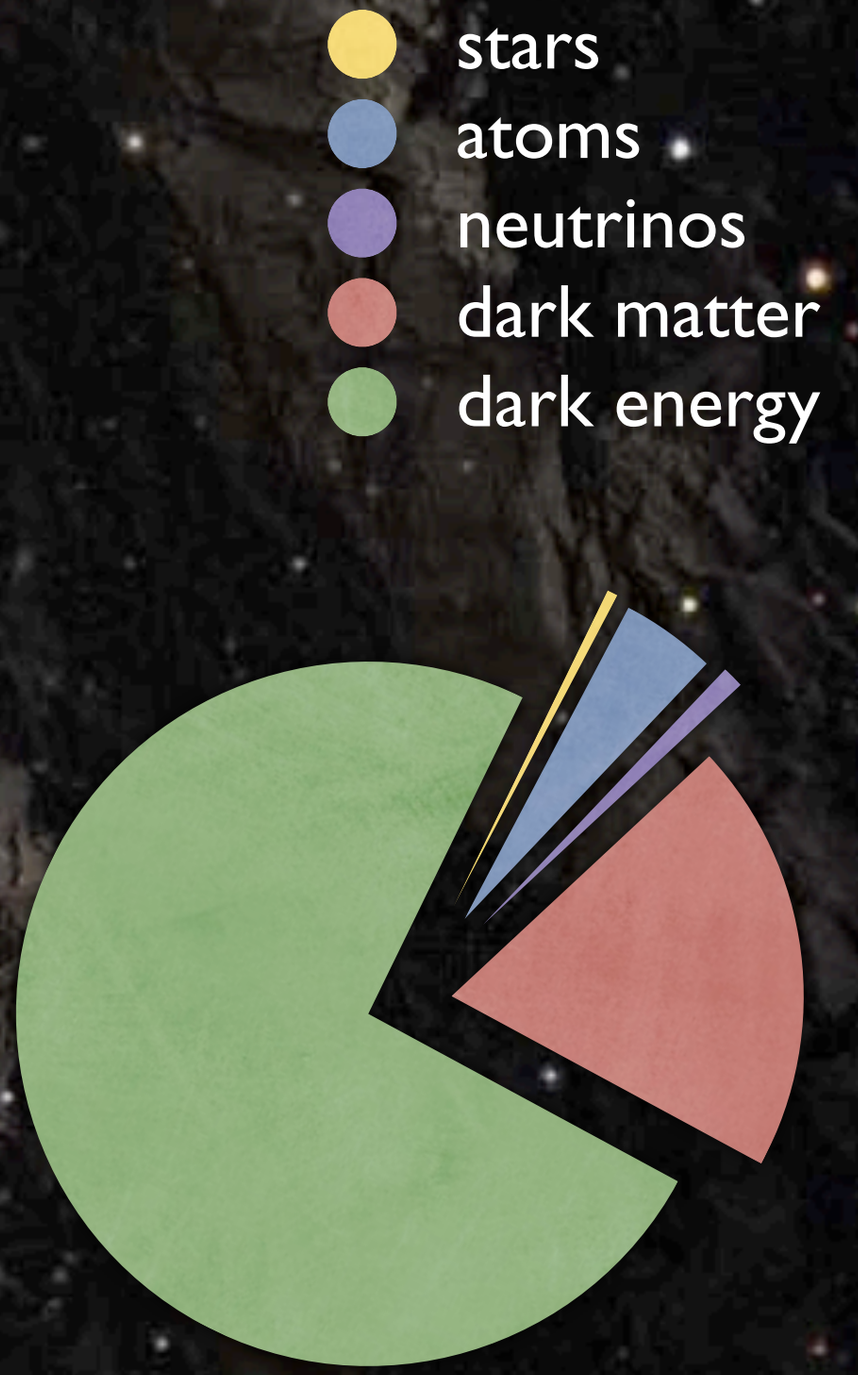
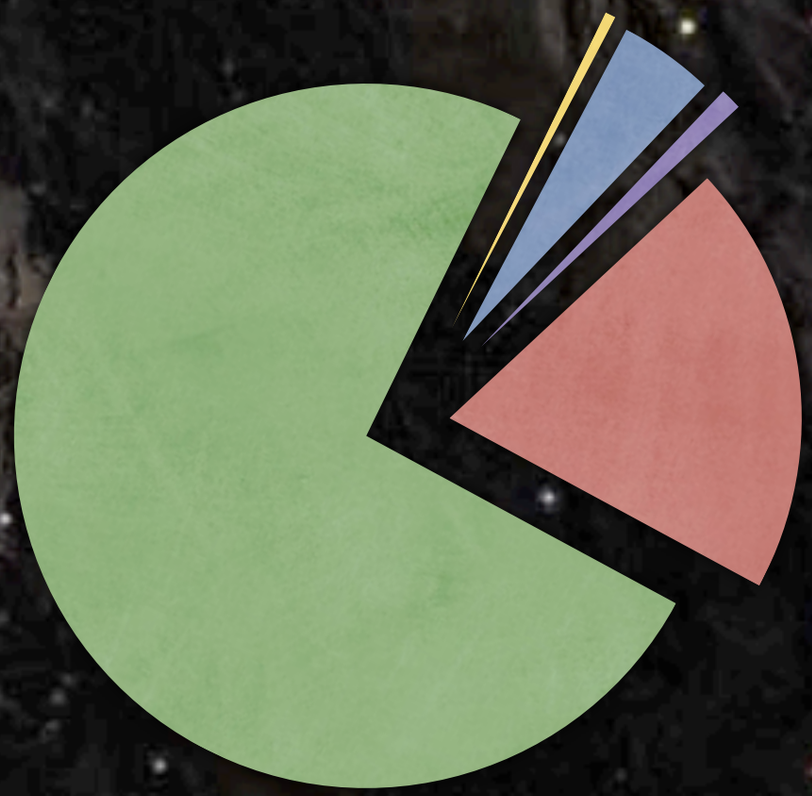
- Rest of ordinary matter (atoms) 4.4%



Energy Budget of the Universe

- Stars are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (atoms) 4.4%
- Dark Matter 20%

stars
atoms
neutrinos
dark matter
dark energy



Energy Budget of the Universe

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- Neutrinos are ~0.1–1.5%
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- Dark Matter 20%
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stars
atoms
neutrinos
dark matter
dark energy

Energy Budget of the Universe

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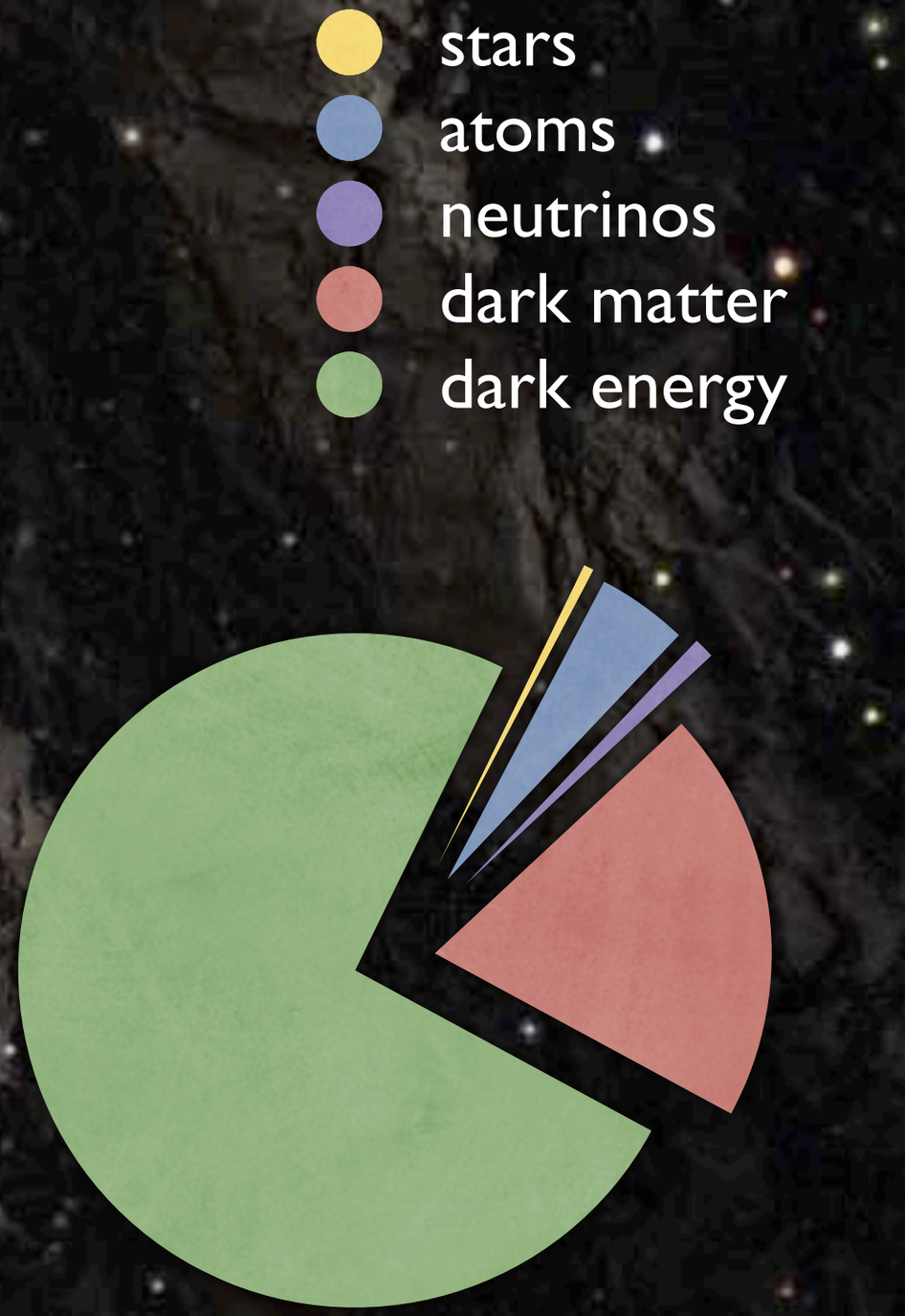

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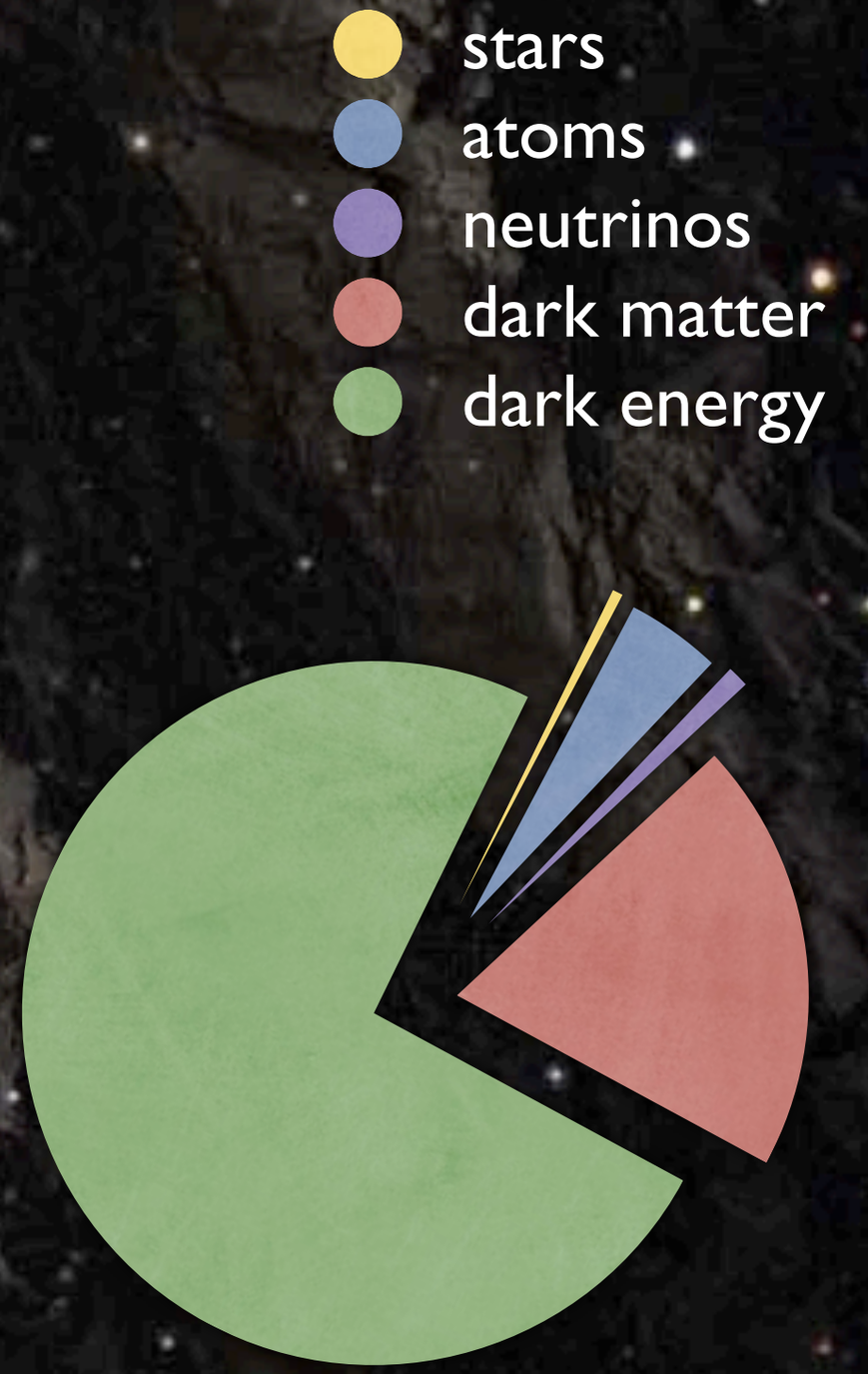
deficit not accounted for



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stars
atoms
neutrinos
dark matter

"The deficit poses a significant obstacle to long-term stability"

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The New York Times

Late Edition

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RECORDED PHONE CALLS

Tracing Troop Moves — Russia Rejects Claim It Was Aggressor

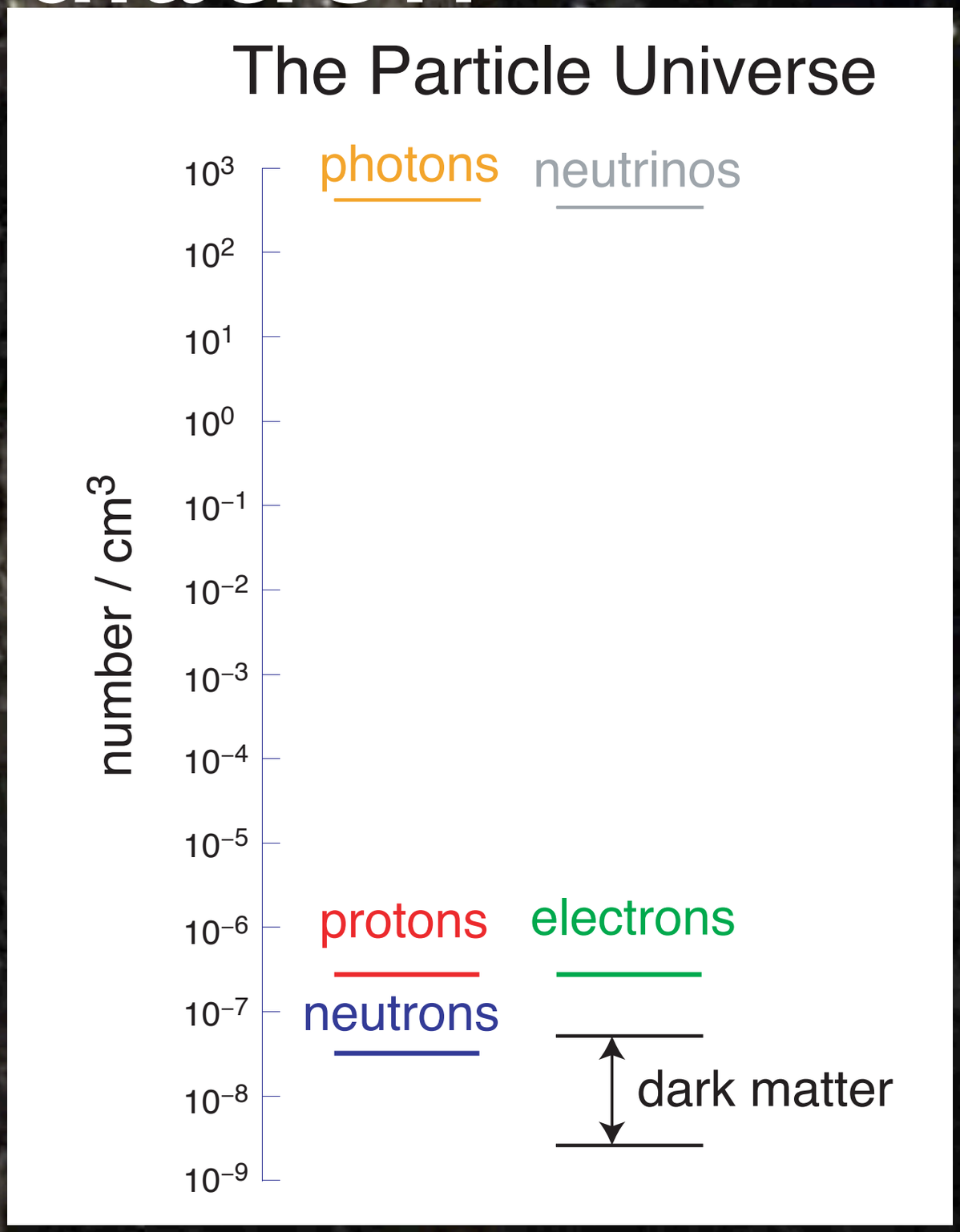
On Peninsula In the Storm: No Way Out

After 4 Days, 'Miracle' for a Texas Couple

WALL ST. IN WORST LOSS SINCE '01 DESPITE REASSURANCES BY BUSH

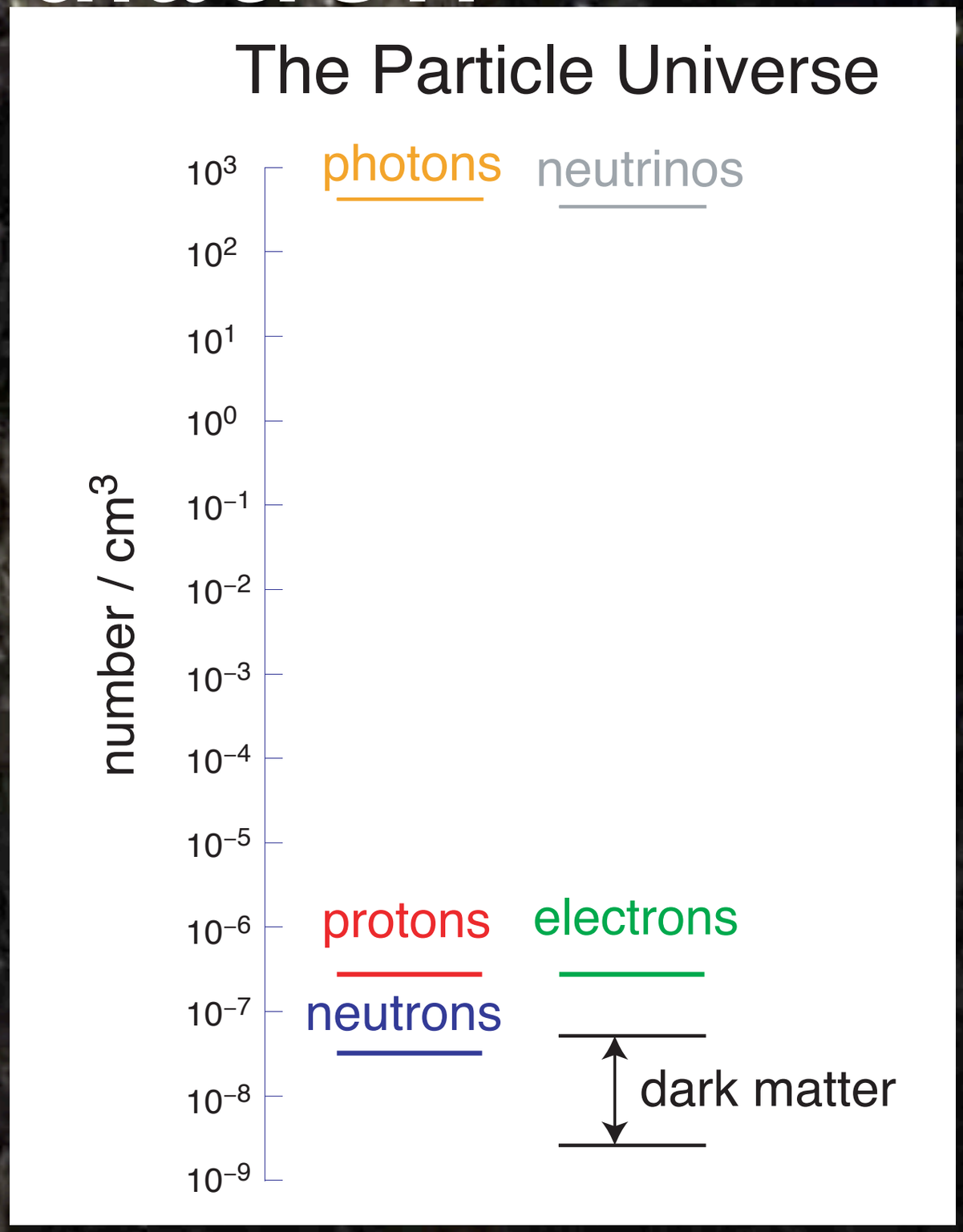
"The deficit poses a significant obstacle to long-term stability"

The Population



The Population

- Most ubiquitous particle is light (photons)



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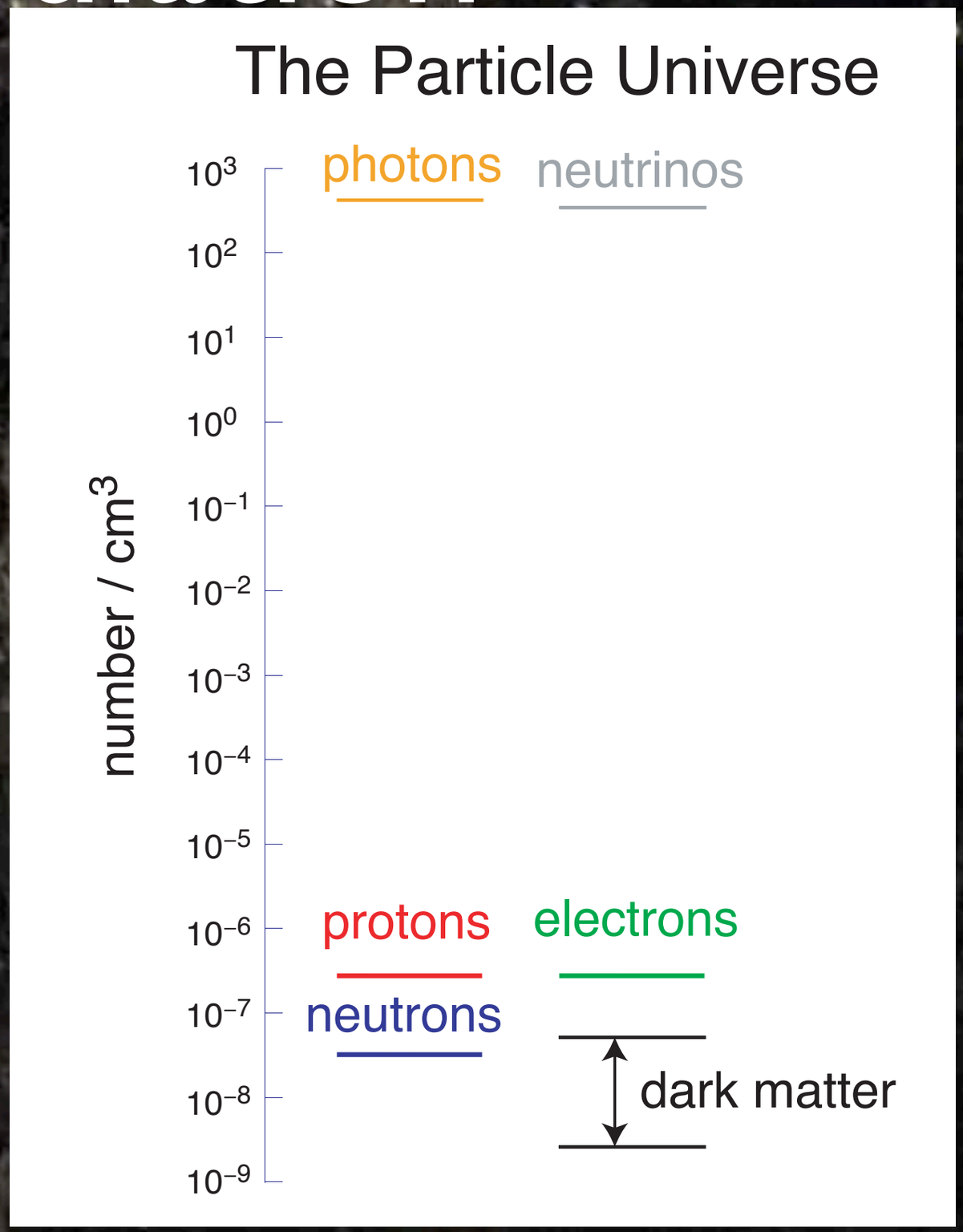

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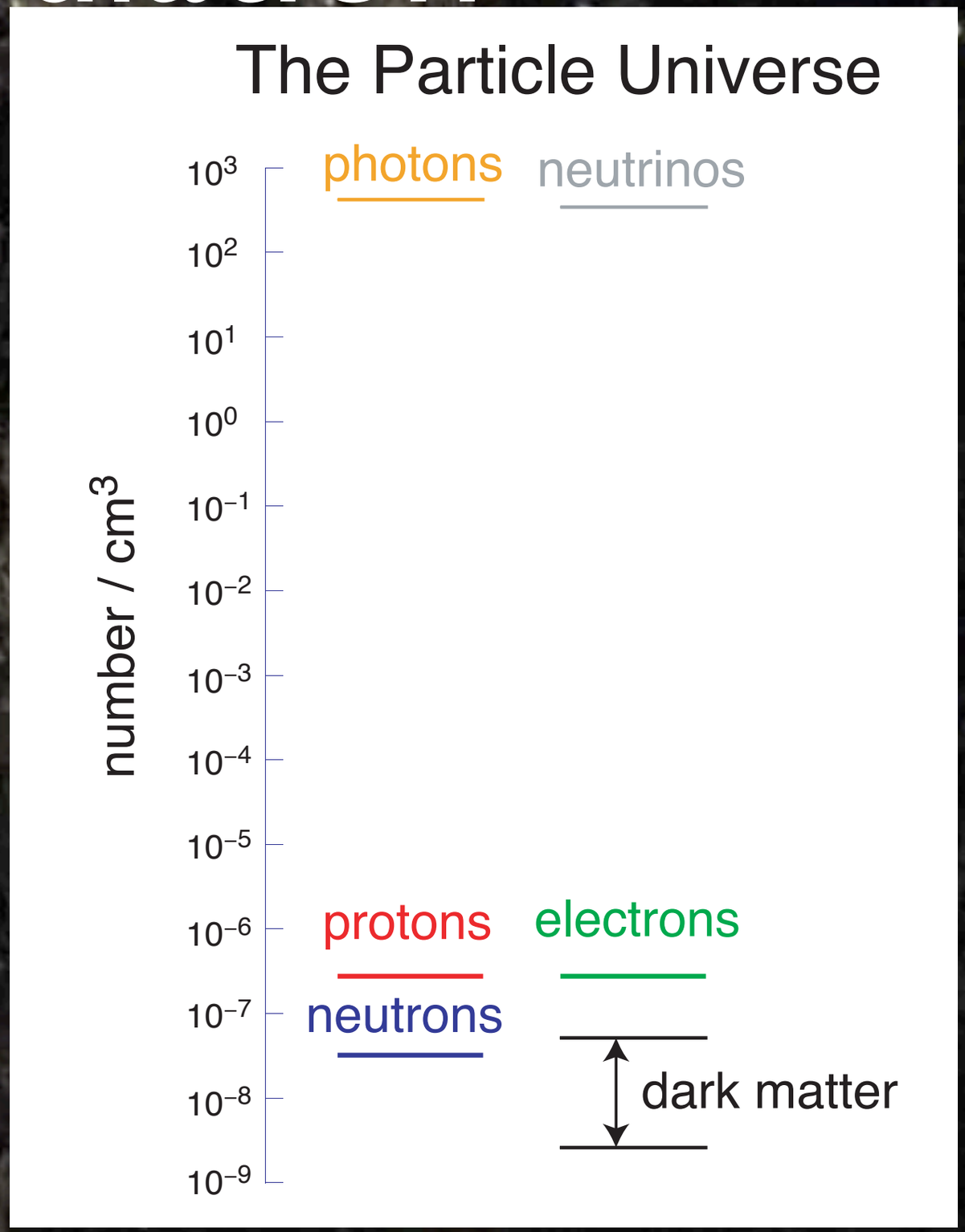
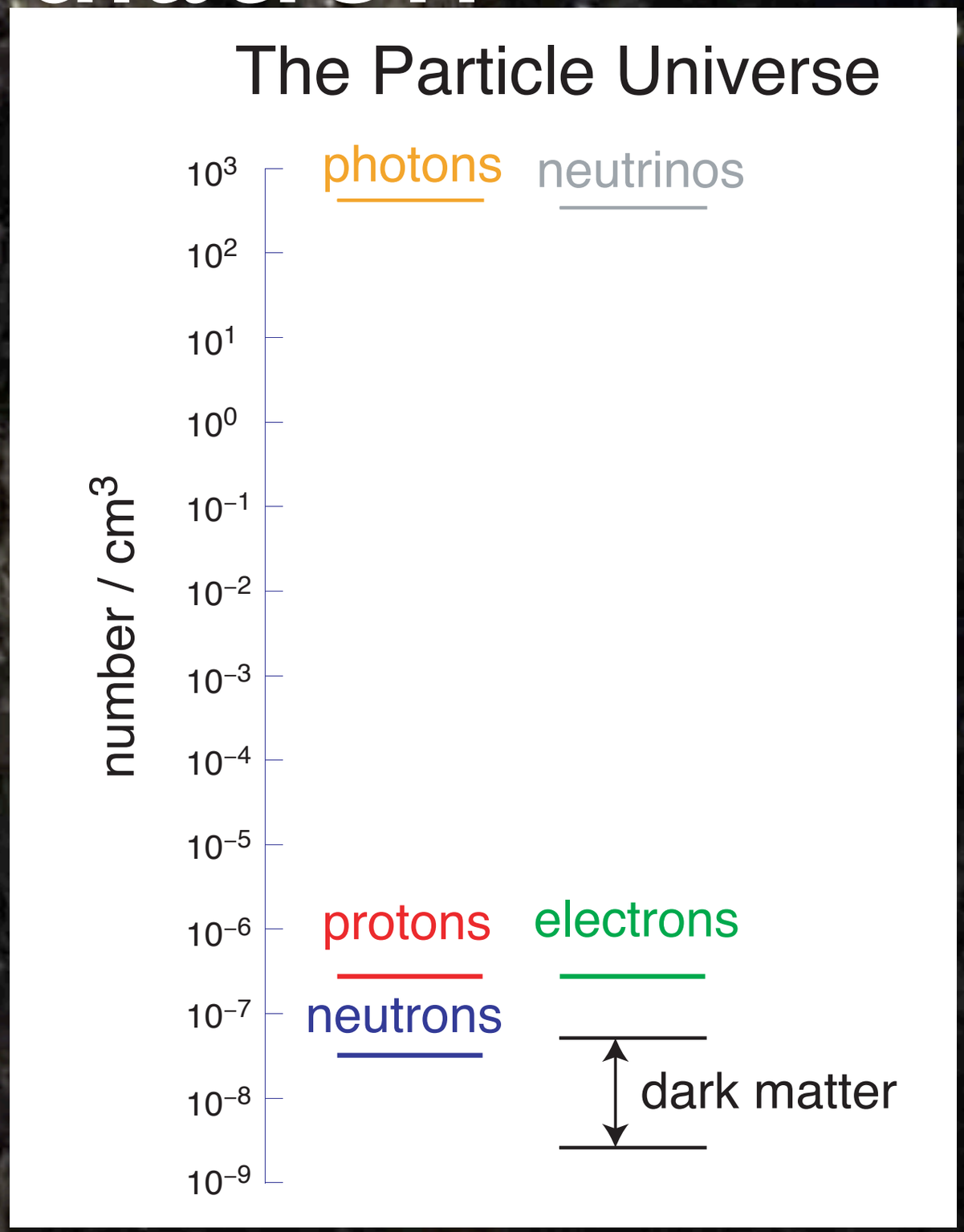


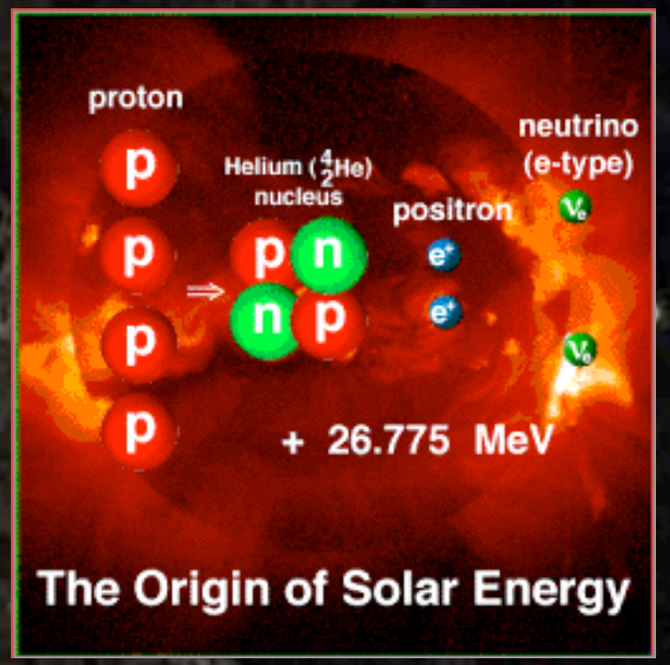
The Population

- Most ubiquitous particle is light (photons)
- Most ubiquitous matter particle is neutrinos
- Clearly we need to understand and use them to study the universe
- But neutrinos, dark matter all invisible!



Don’t be afraid of invisibles

Trillions of neutrinos go through our body every second coming from the Sun



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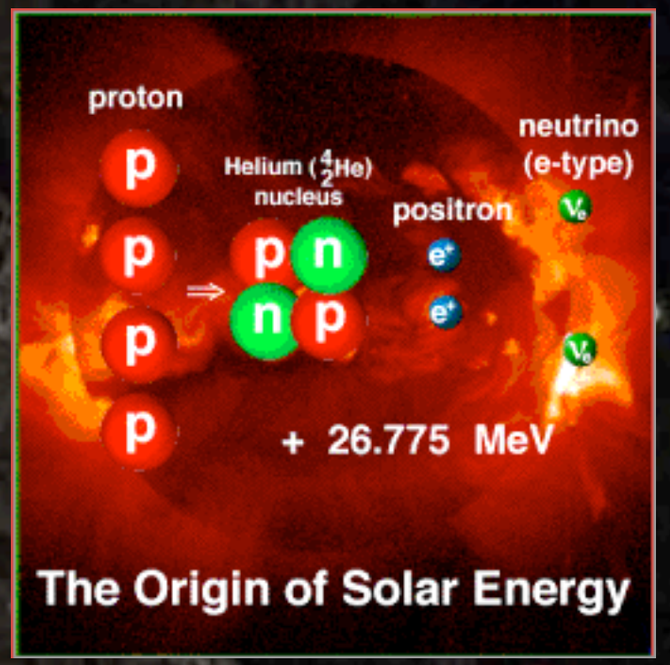

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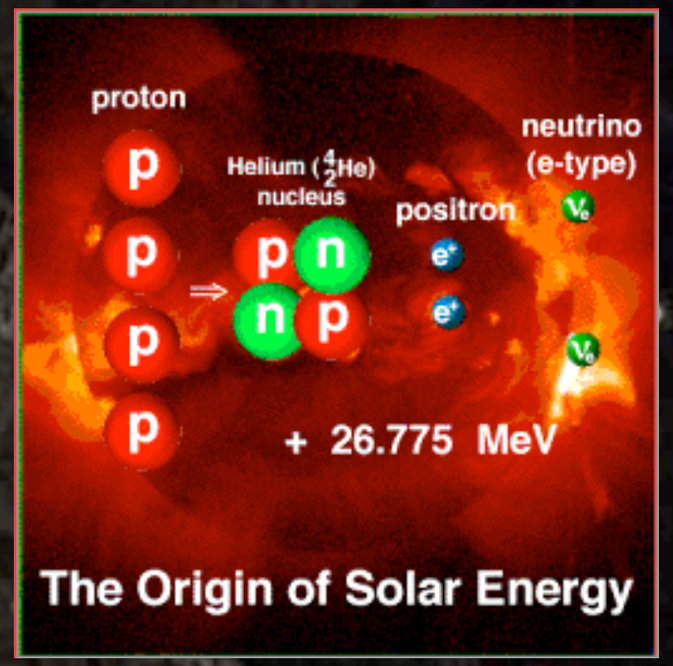

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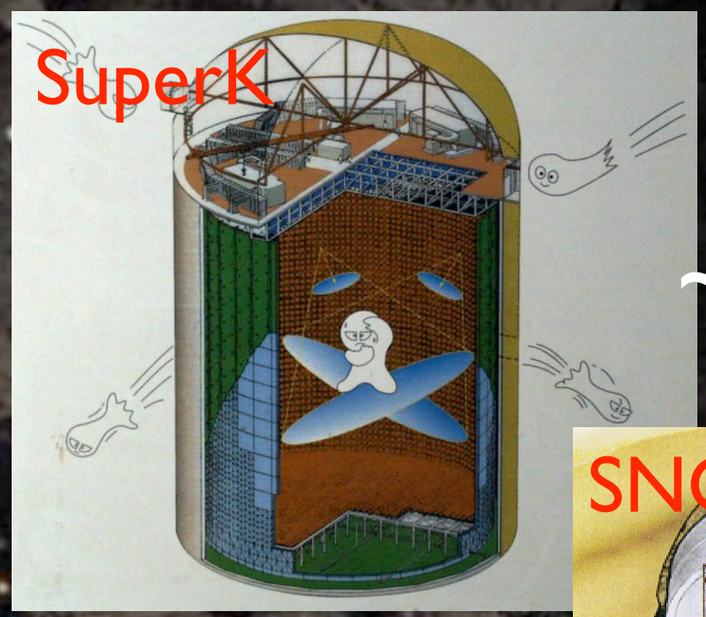

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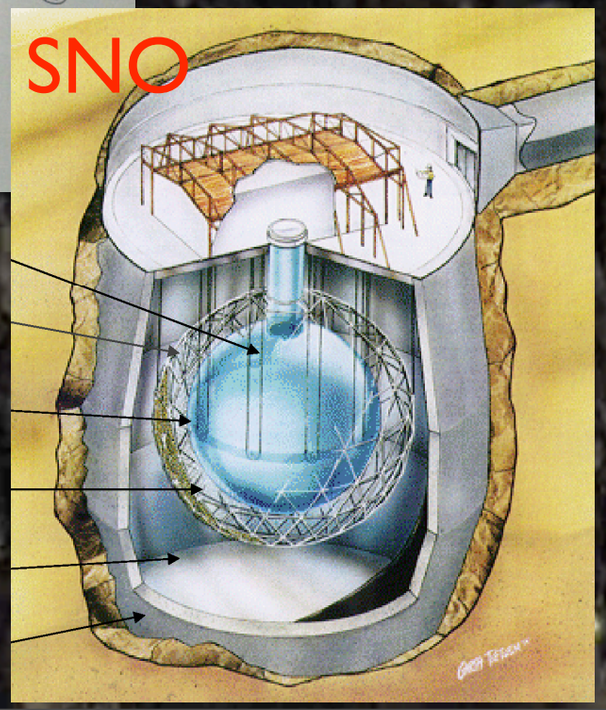

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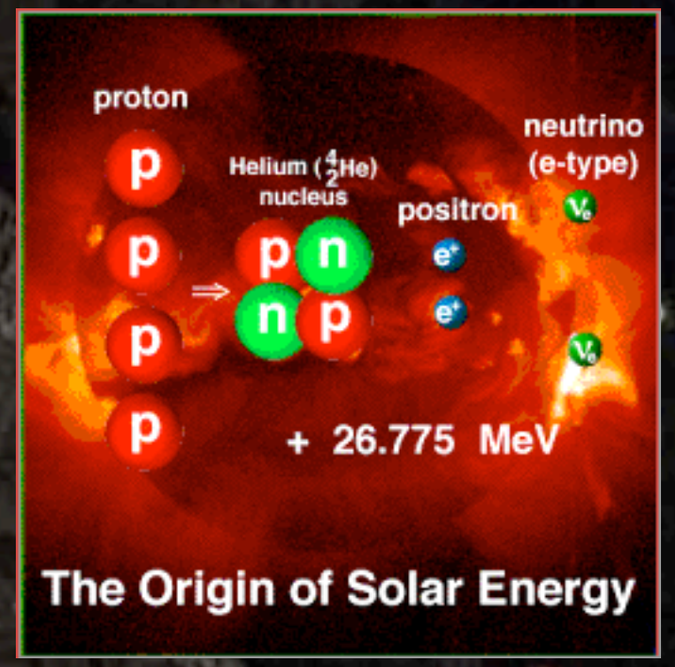

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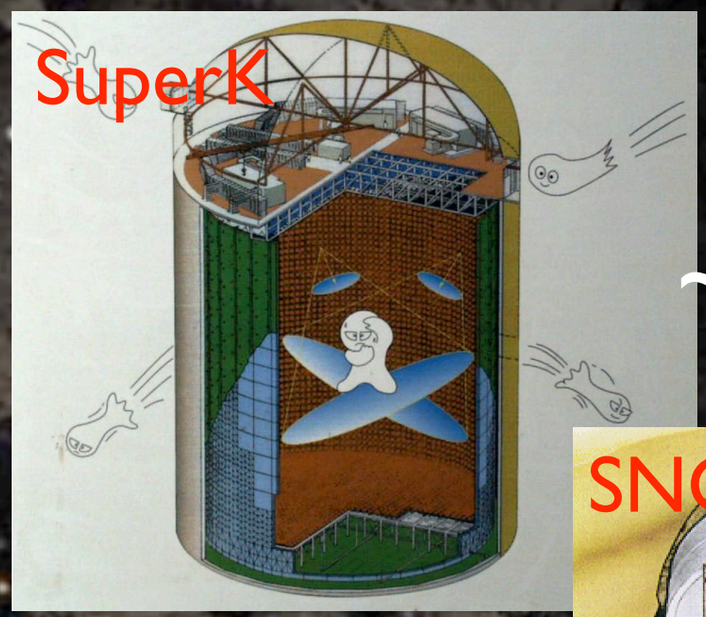

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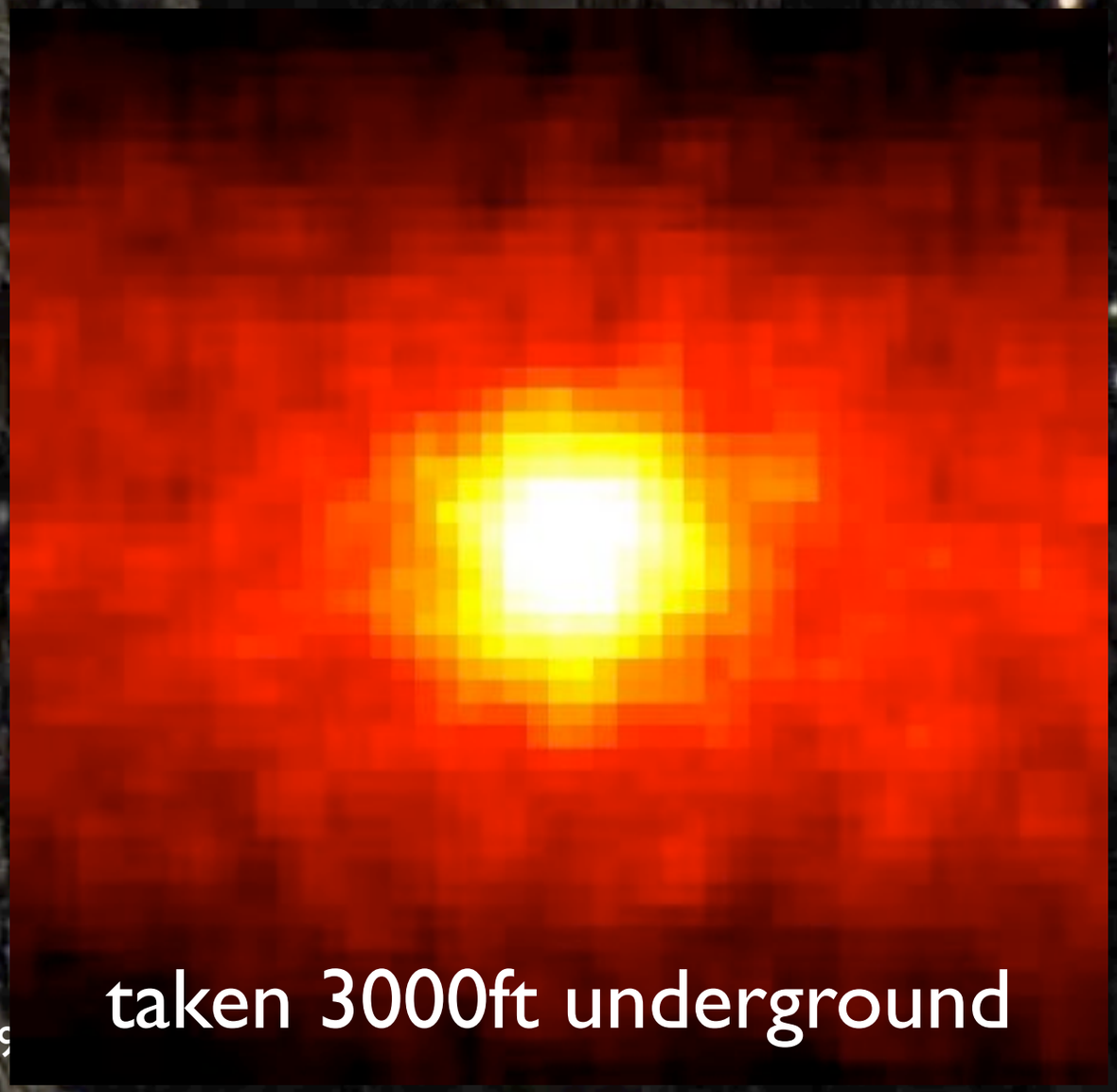
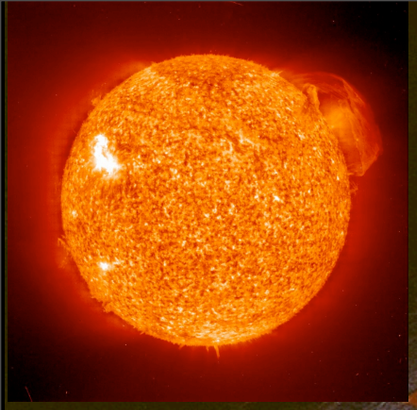
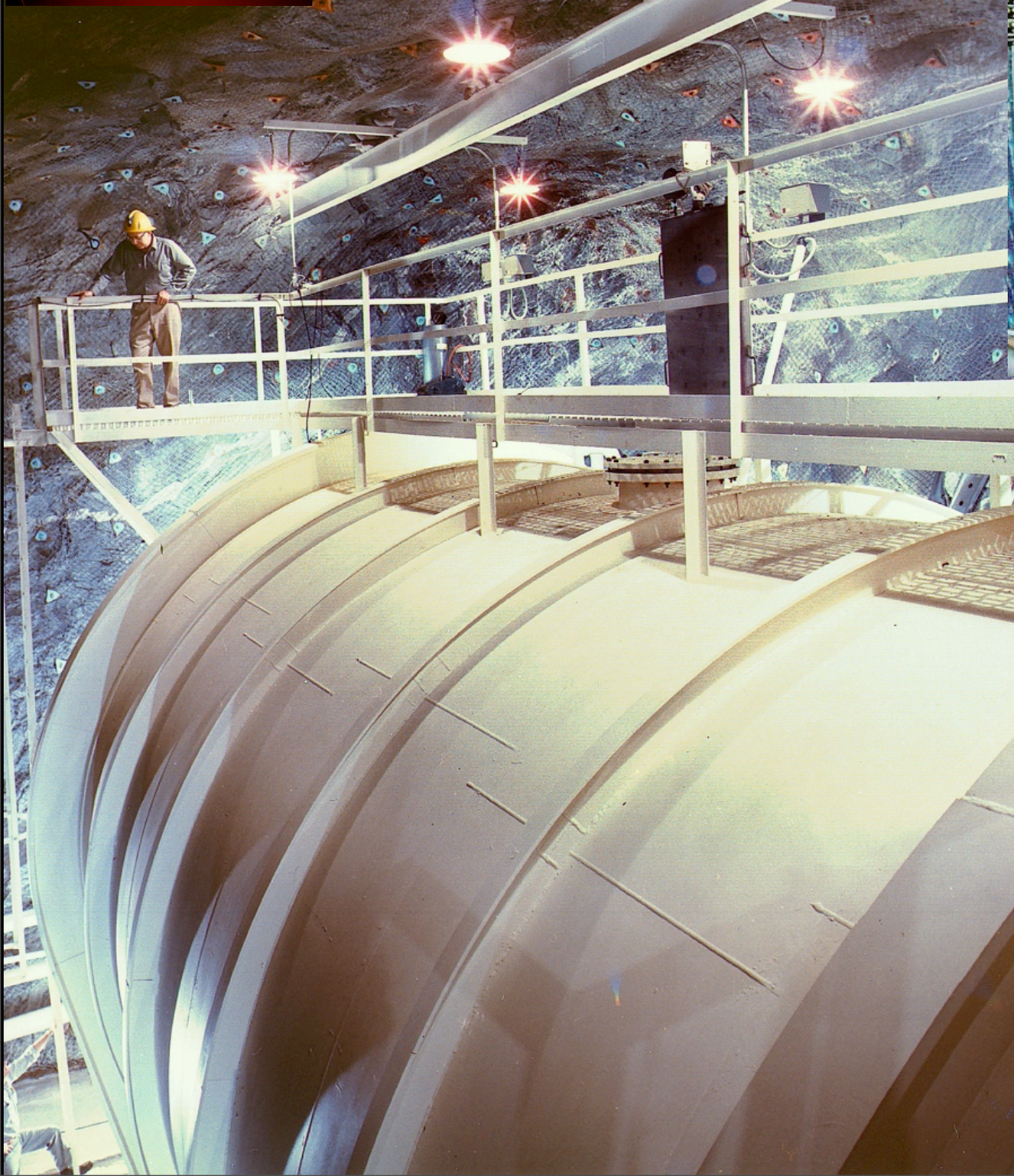
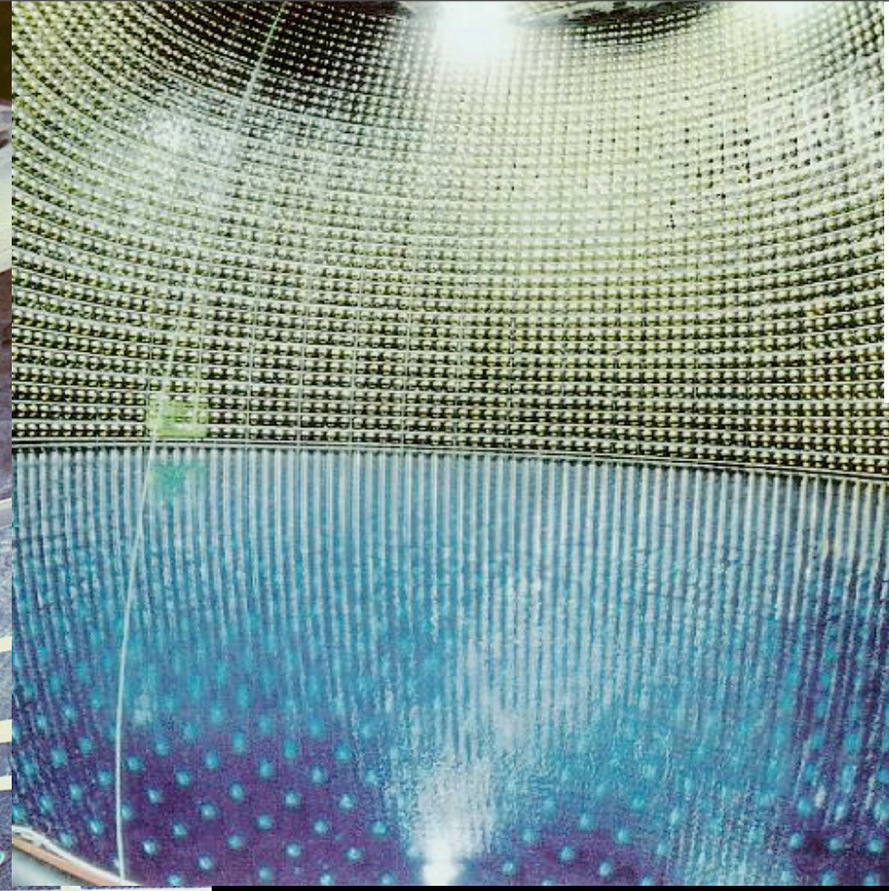


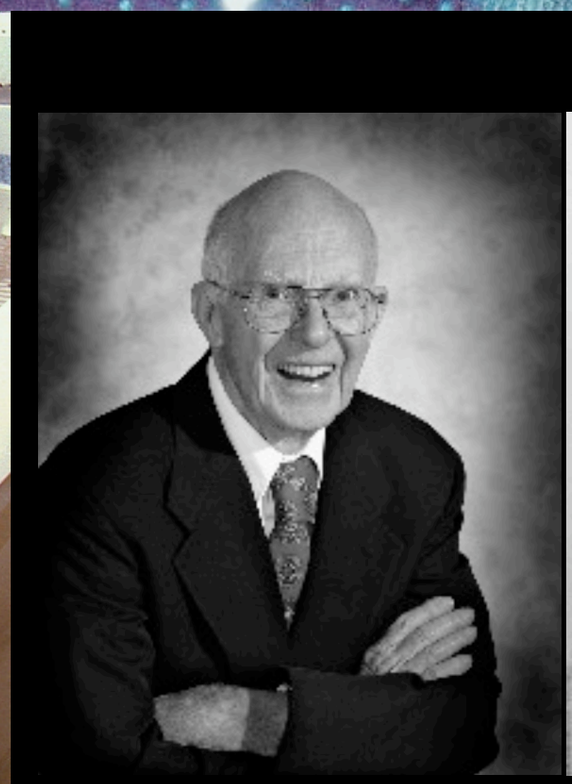
taken 3000ft underground



Homestake







Nobel Prize in Physics 2002

Disney PRESENTS A PIXAR FILM

THE INCREDIBLES

NOW PLAYING

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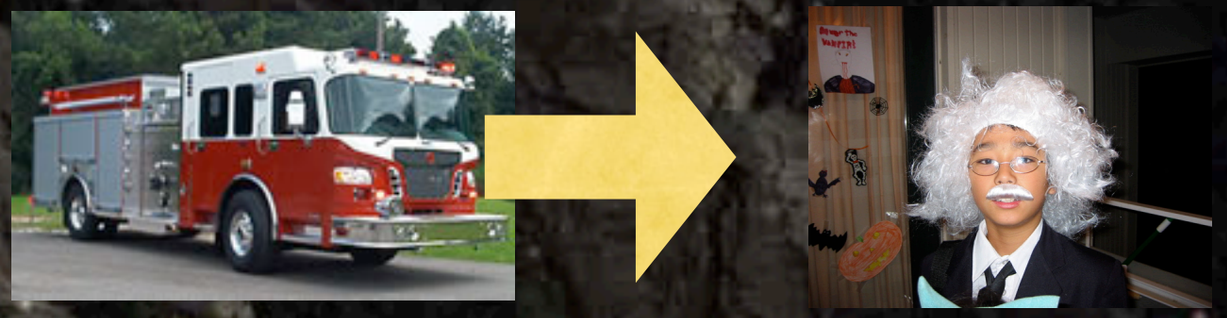
Big-Bang

Universe is expanding

- Approaching ambulance: higher key
- Moving-away ambulance: lower key
- Much the same way, moving-away stars: lower key (redder) in spectrum of light
- We see distant stars/ galaxies are redder

Universe is expanding



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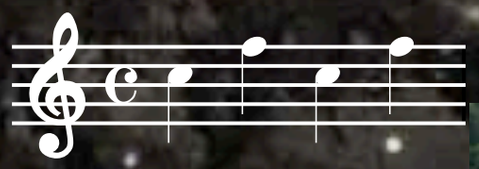

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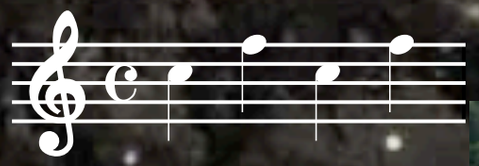

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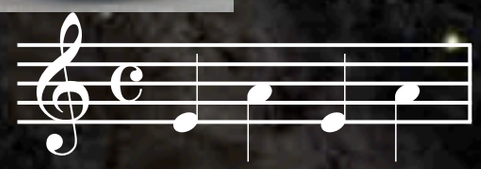

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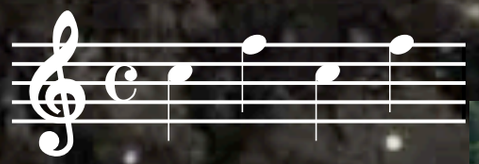

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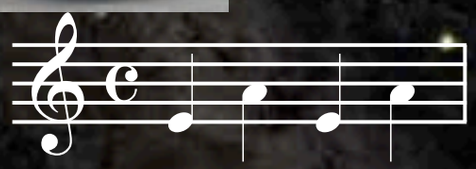

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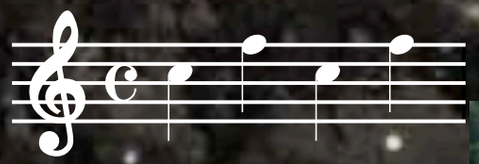

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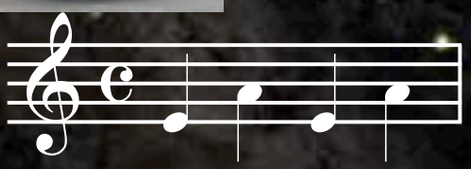
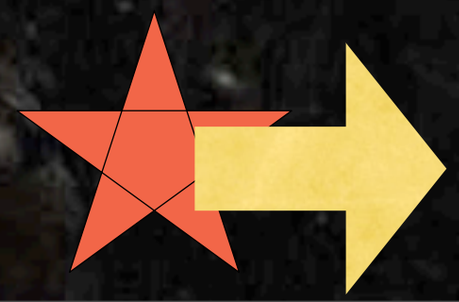
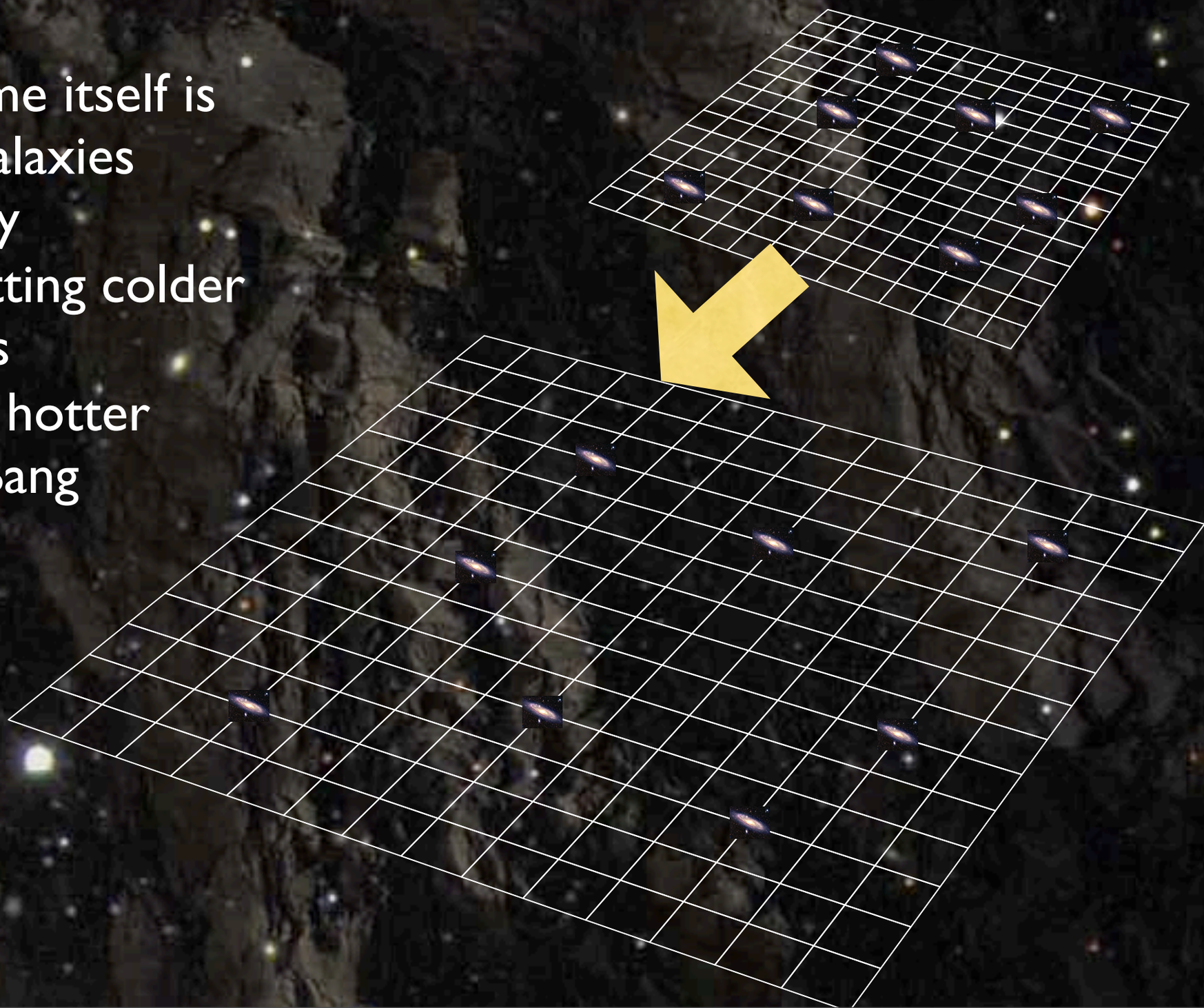


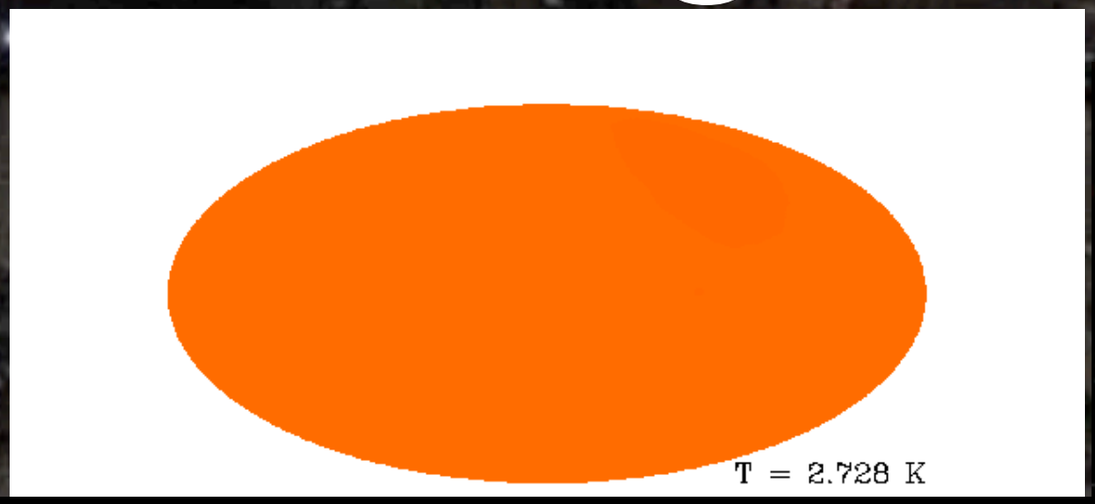


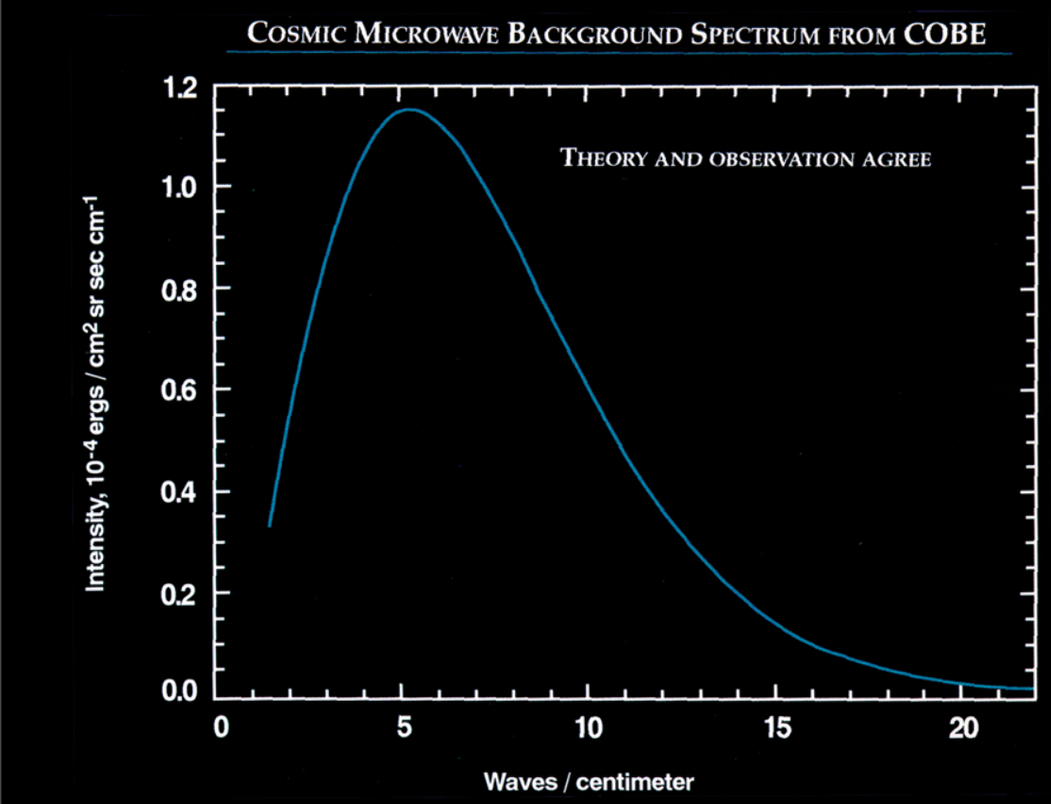
Expansion of Space

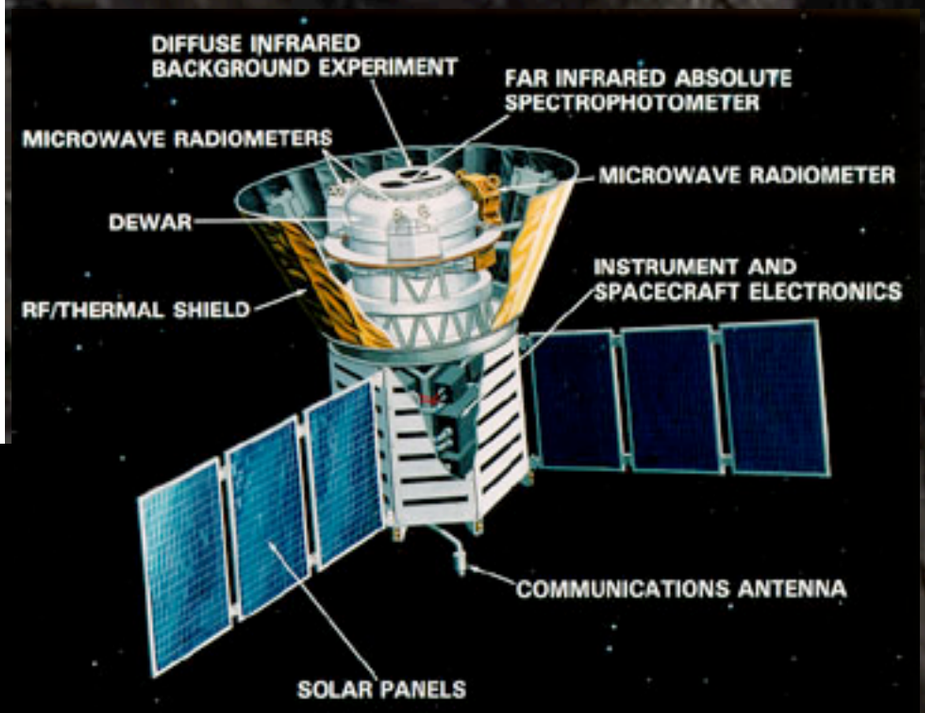
- The spacetime itself is stretching, galaxies dragged away
- Universe getting colder as it expands
- It was much hotter earlier: Big Bang



Afterglow of Big Bang







COBE satellite

Nobel Prize in Physics 2006

History of the Universe

BIG BANG

Inflation

?

high-energy cosmic rays

Accelerators
LHC
Tevatron
RHIC

10-10 sec

1min

400Kyr

13.7Byr

possible dark matter relicts

cosmic microwave radiation visible

t 10-44 10-37 s
T 1032 1028
E 1019 1015

10-10 s
1015
102

10-5 s
1012
10-1

102 s
109
10-4

3x105 y
3000
3x10-10

109 y
15
10-12

12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)

Today

Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq meson
- qqq baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

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History of the Universe

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BBN

CMB

t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15

10-10 s
10 15
10 2

10-5 s
10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
3x10 -10

10 9 y
15
10-12

12x10 9 y (sec,yrs)
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Cosmic Questions for DUSEL

- What is the Universe made of?
- What is Dark Matter?
- Did neutrinos form galaxies?
- Where did the Anti-Matter go?
- Where did we come from?

Dark Matter

Solar system moves
at 130 miles/sec

There are not enough stars to
hold us inside the galaxy!

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at 130 miles/sec

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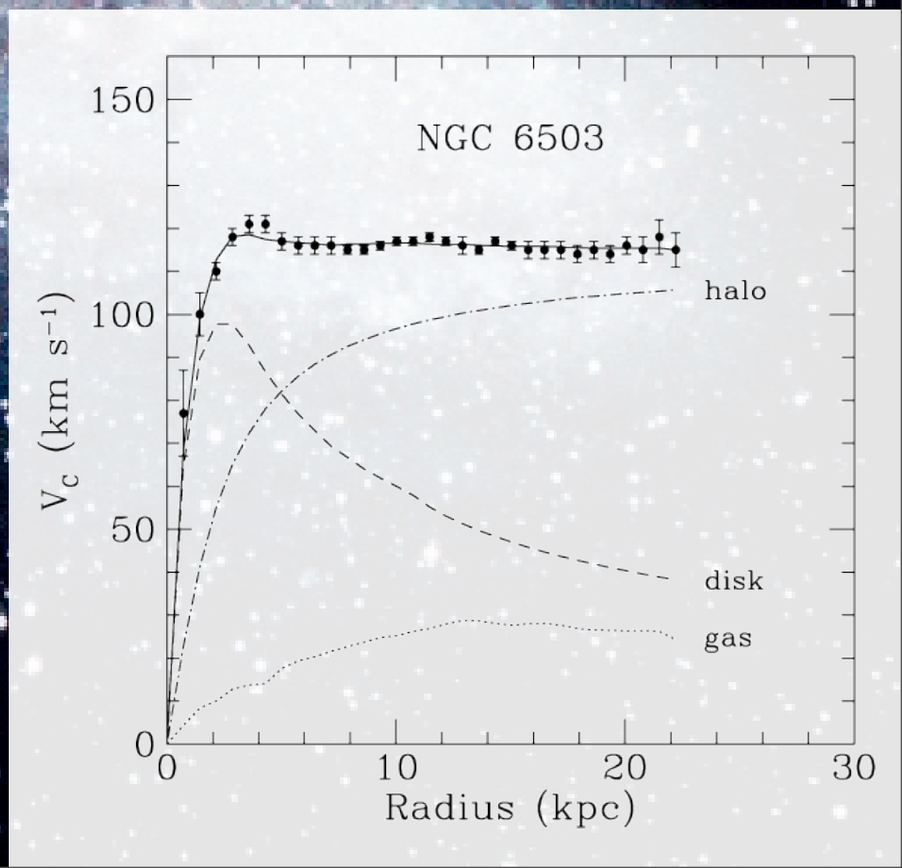
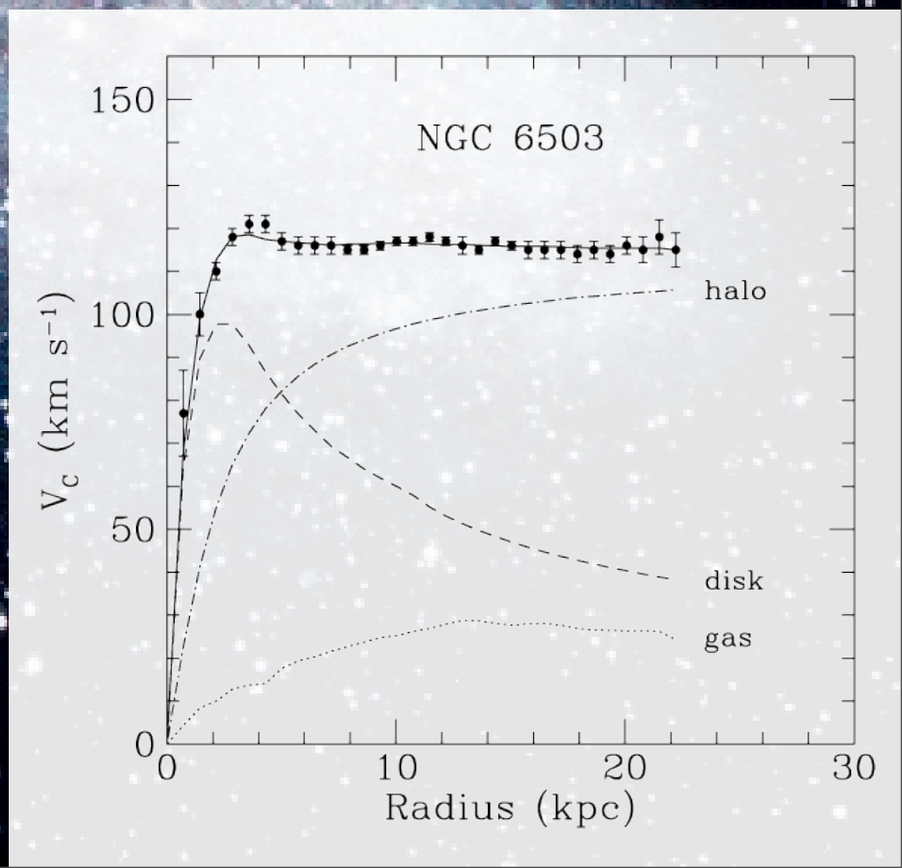


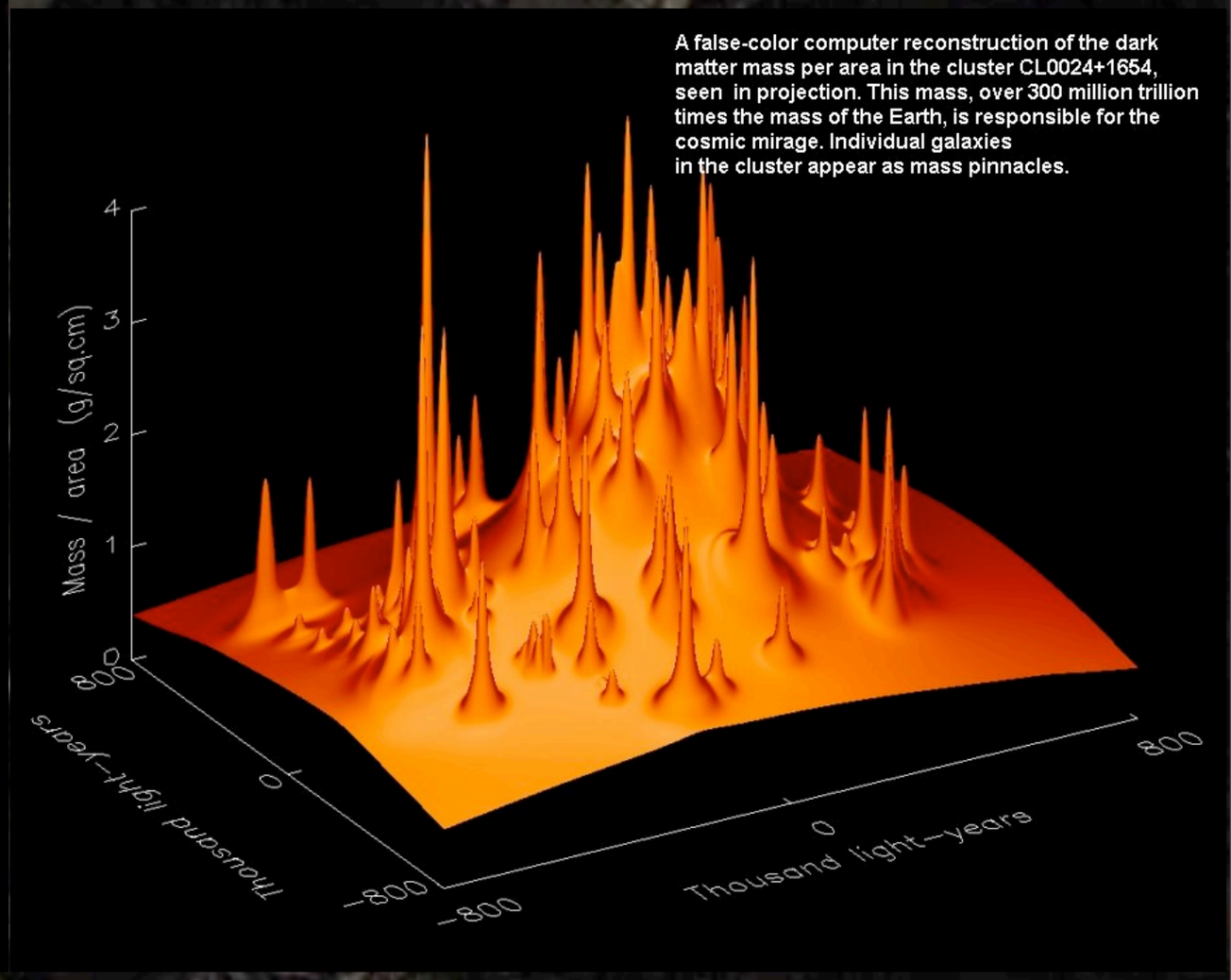
Solar system moves
at 130 miles/sec

There are not enough stars to
hold us inside the galaxy!

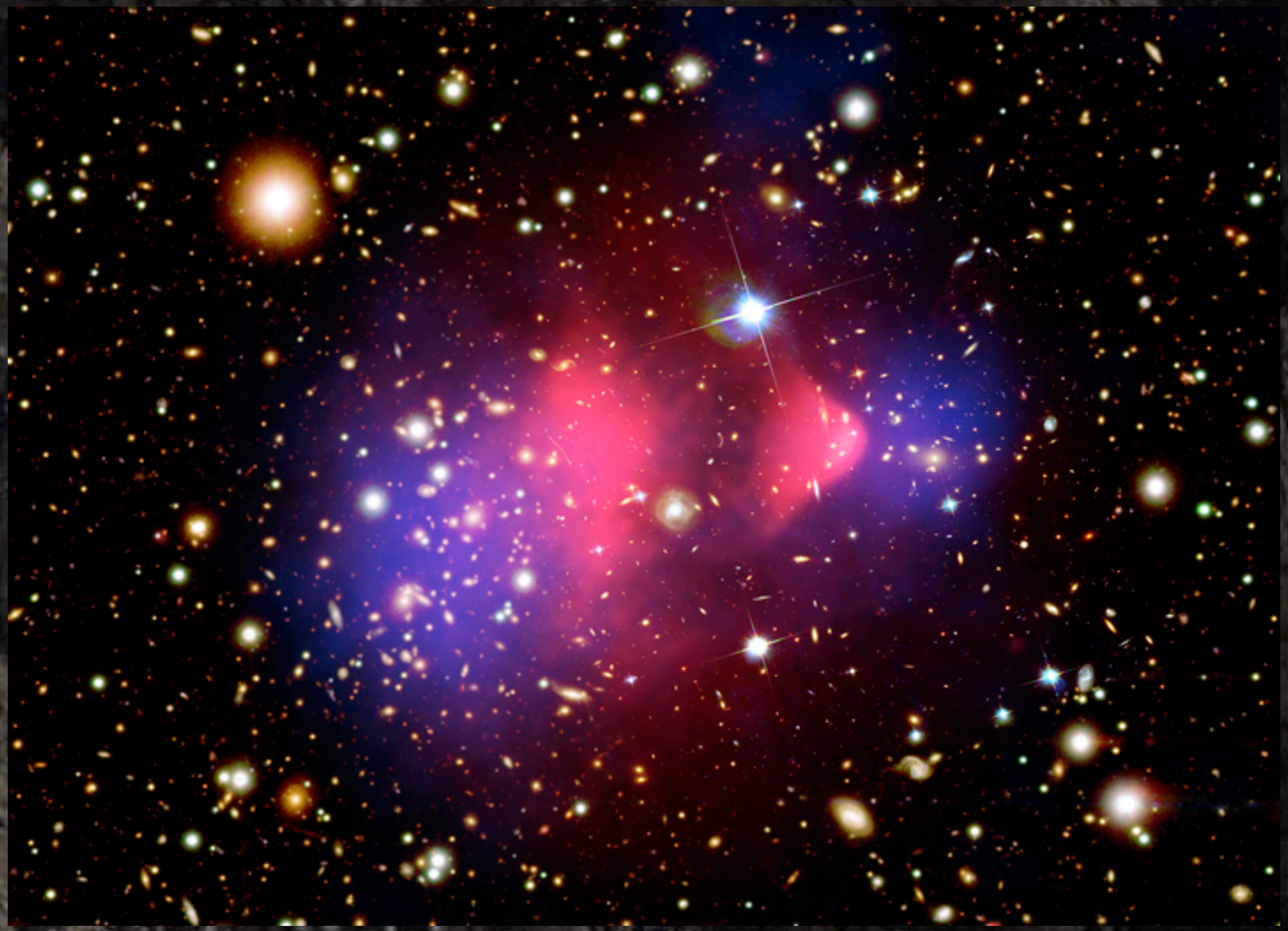
Something else we can't see is keeping us inside the galaxy



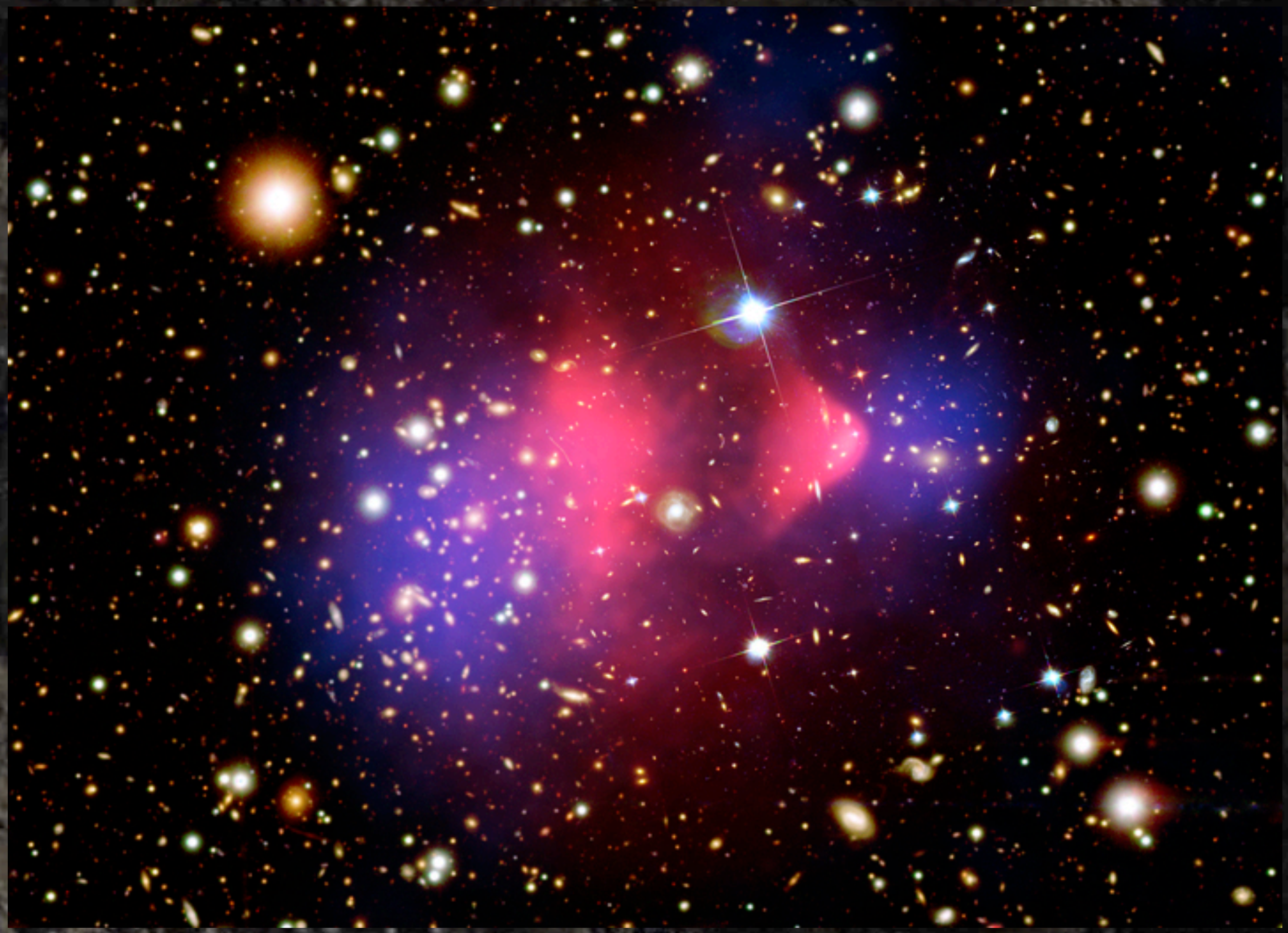
Cluster of galaxies



A false-color computer reconstruction of the dark matter mass per area in the cluster CL0024+1654, seen in projection. This mass, over 300 million trillion times the mass of the Earth, is responsible for the cosmic mirage. Individual galaxies in the cluster appear as mass pinnacles.



You don’t want to be there

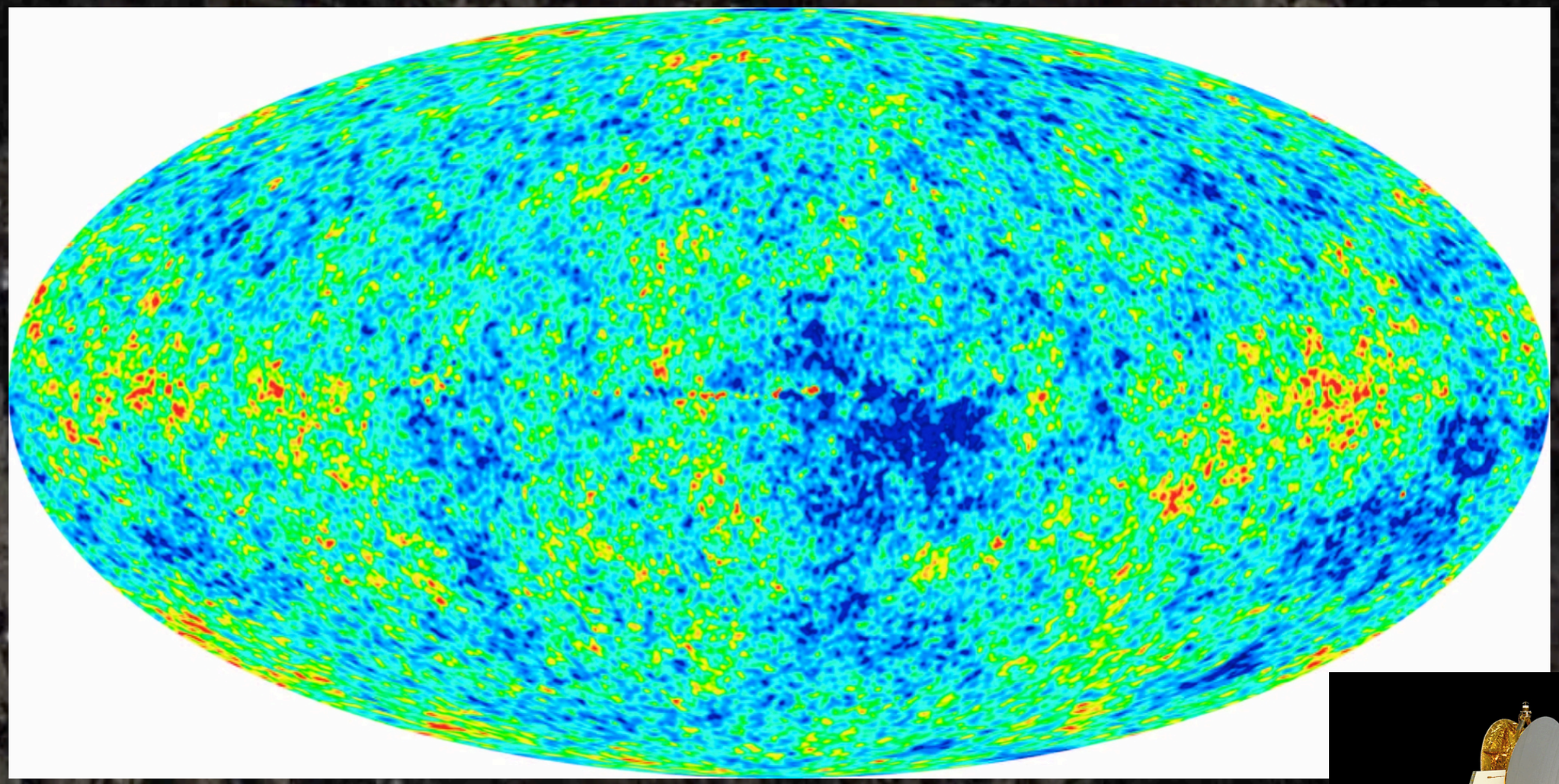


You don’t want to be there

You don’t want to be there

You don’t want to be there

Whole Universe



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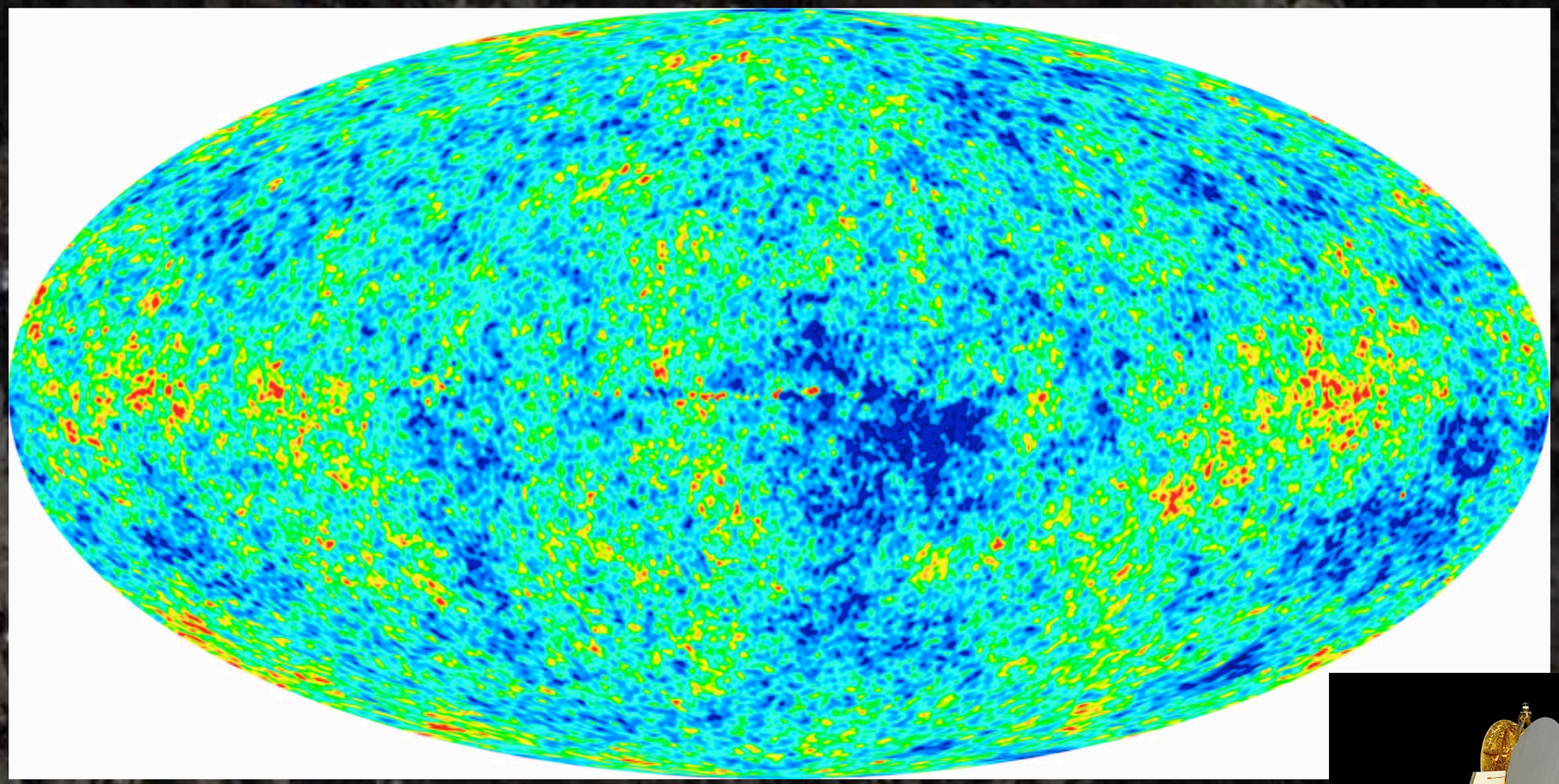
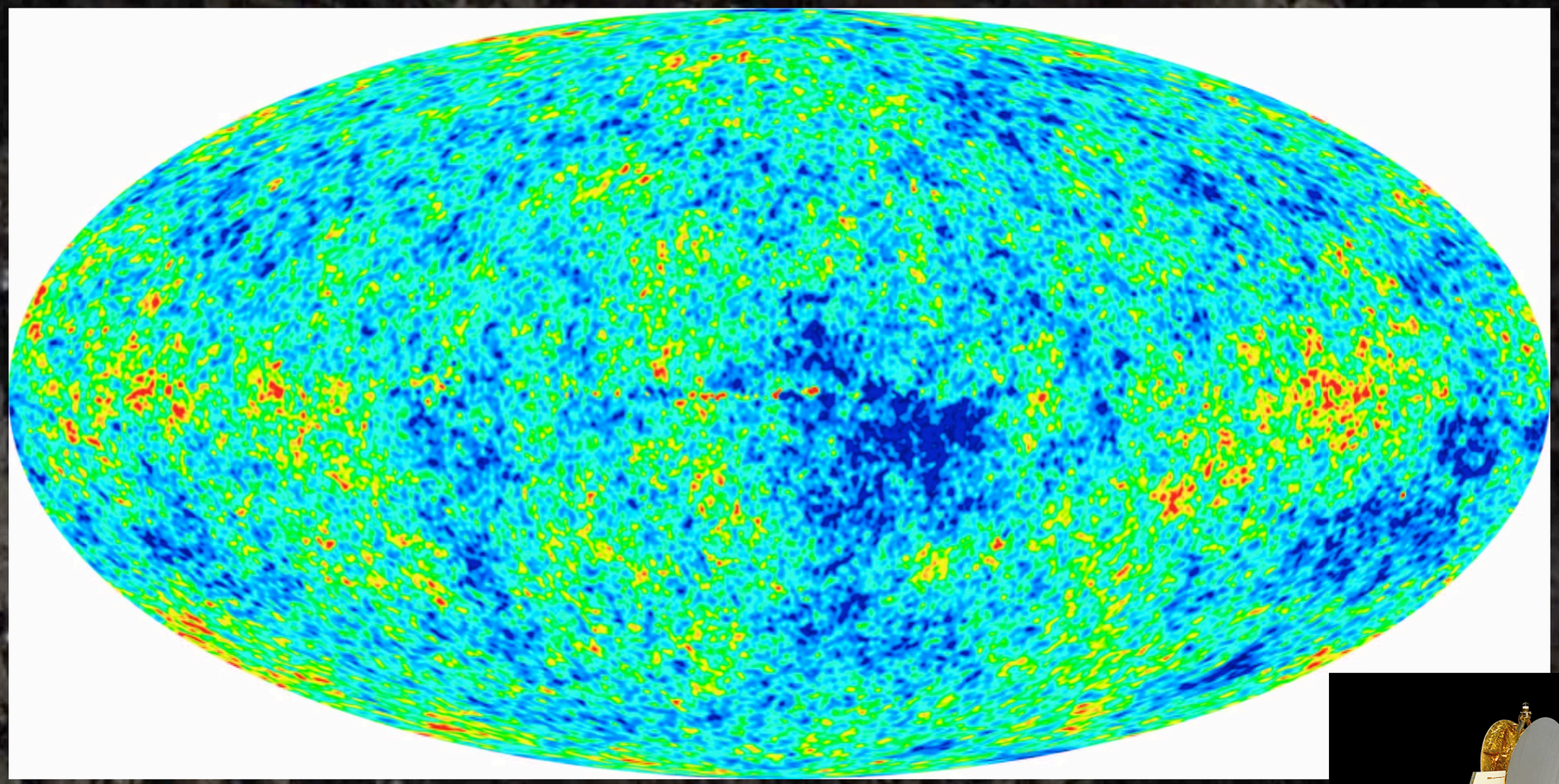


- matter=all atomsx6

Whole Universe



- matter=all atomsx6
- invisible & unknown matter dominates the universe!

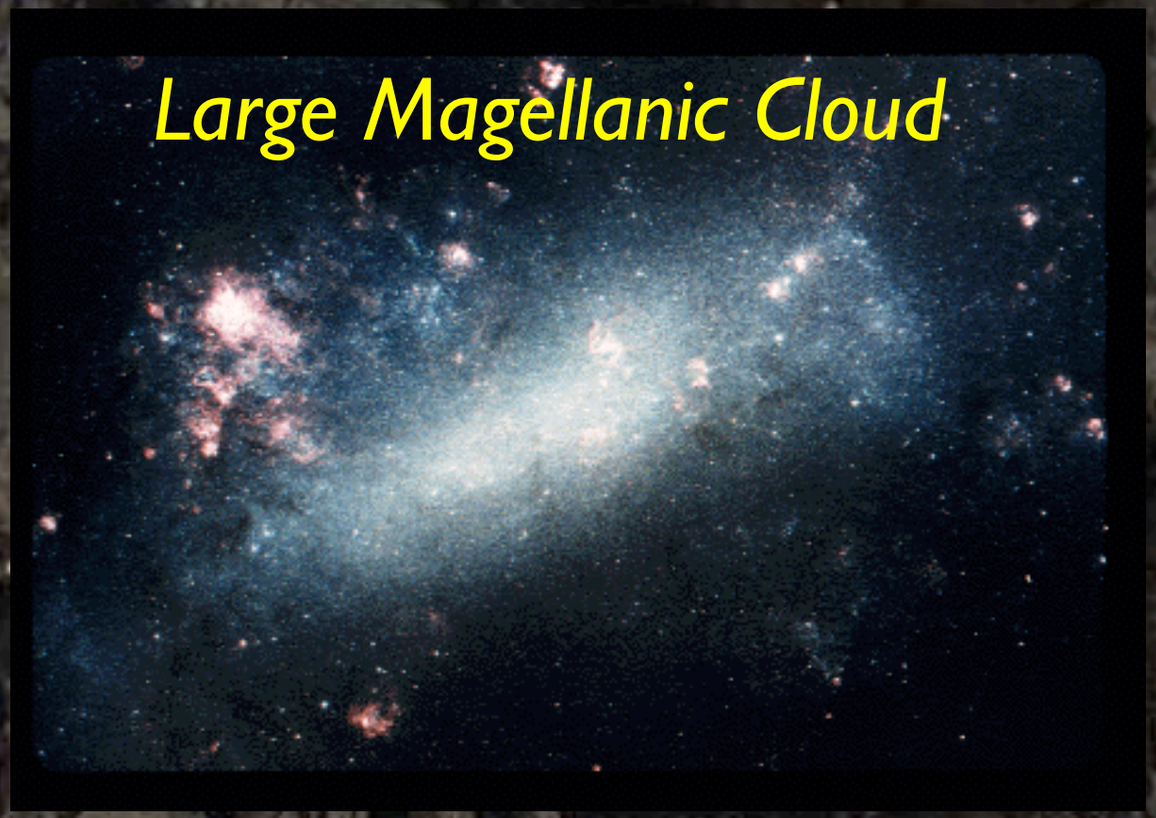
We don’t exist without dark matter

Without Dark Matter

With Dark Matter

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)



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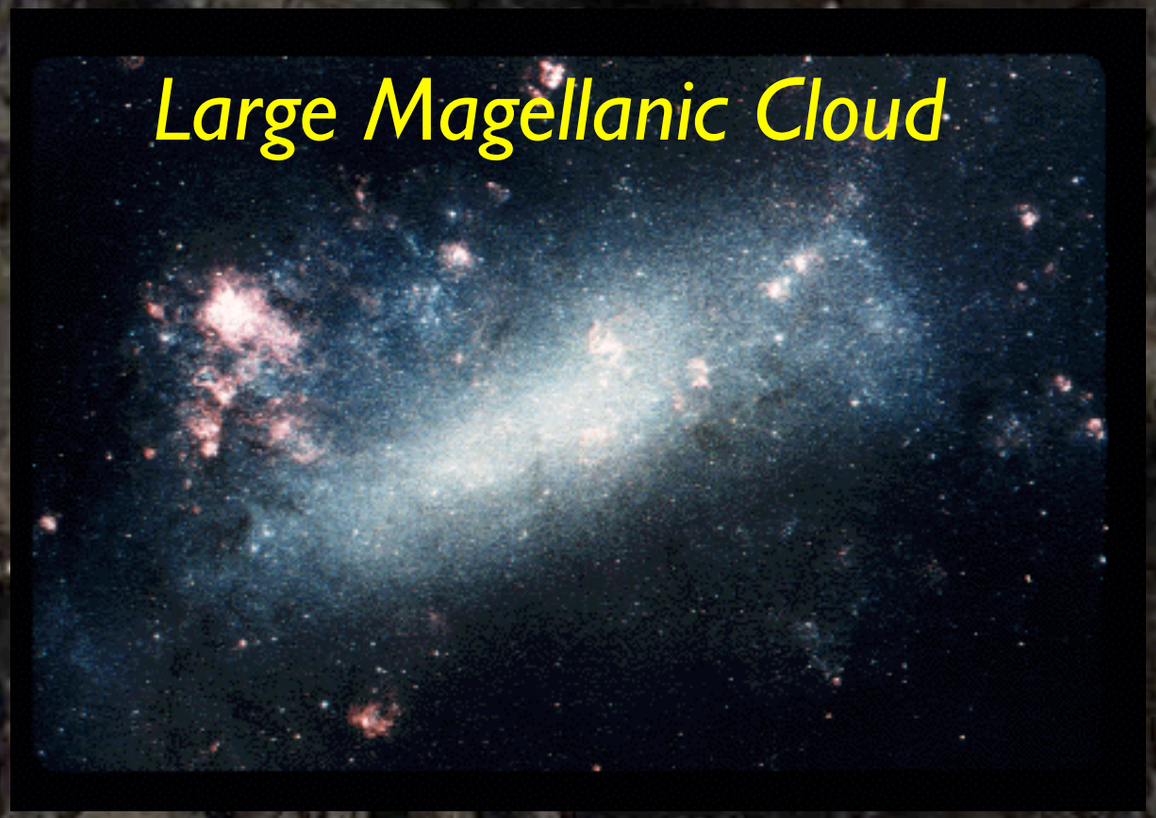

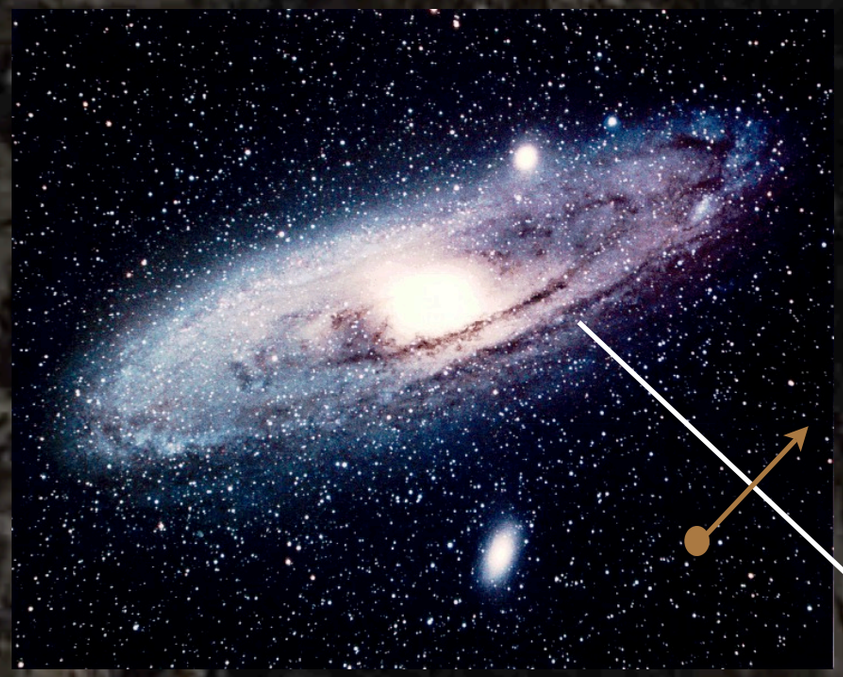

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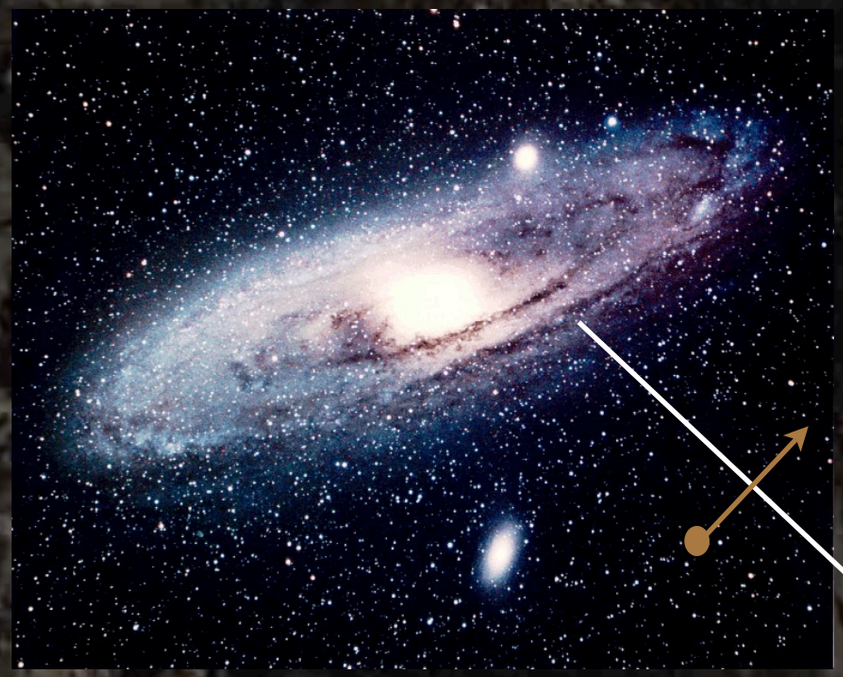

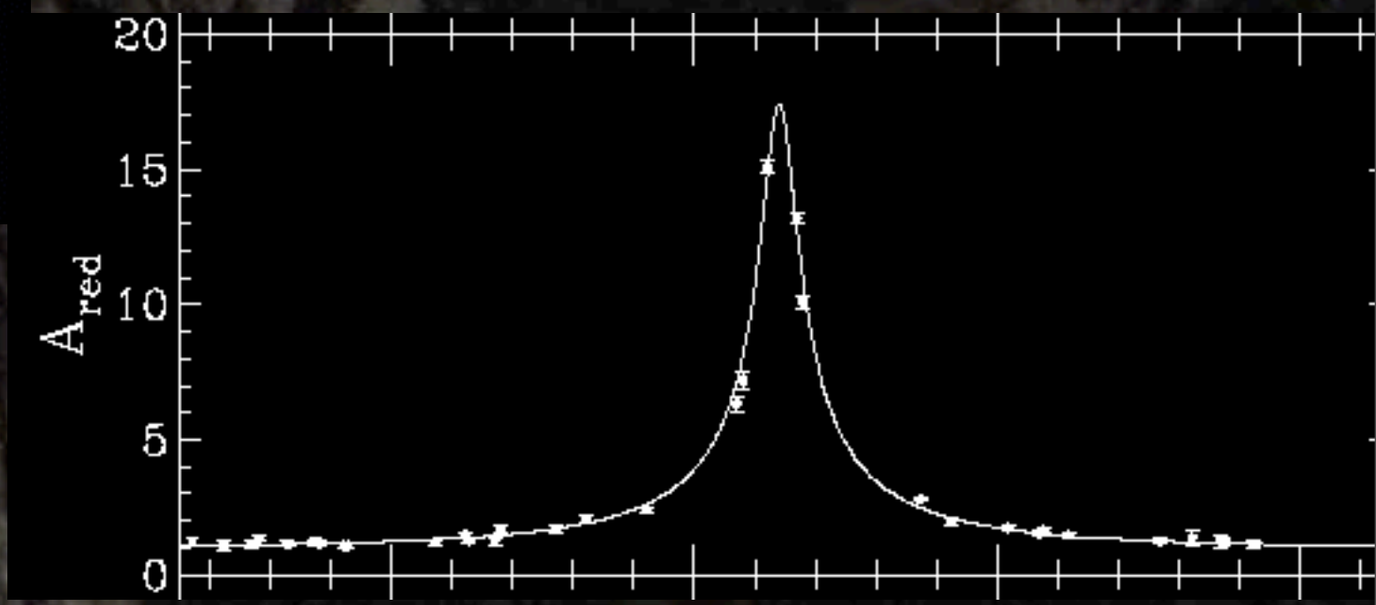

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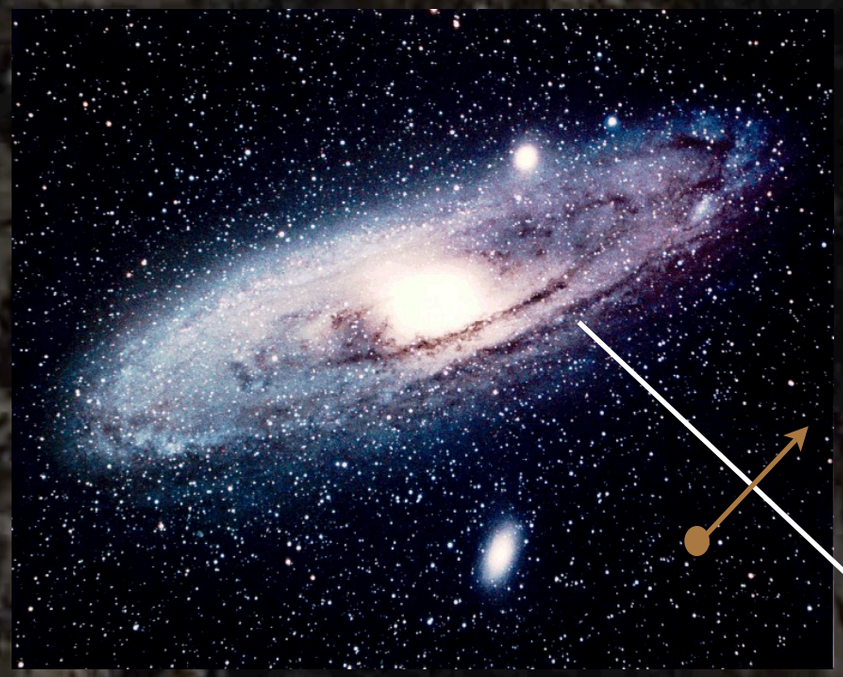

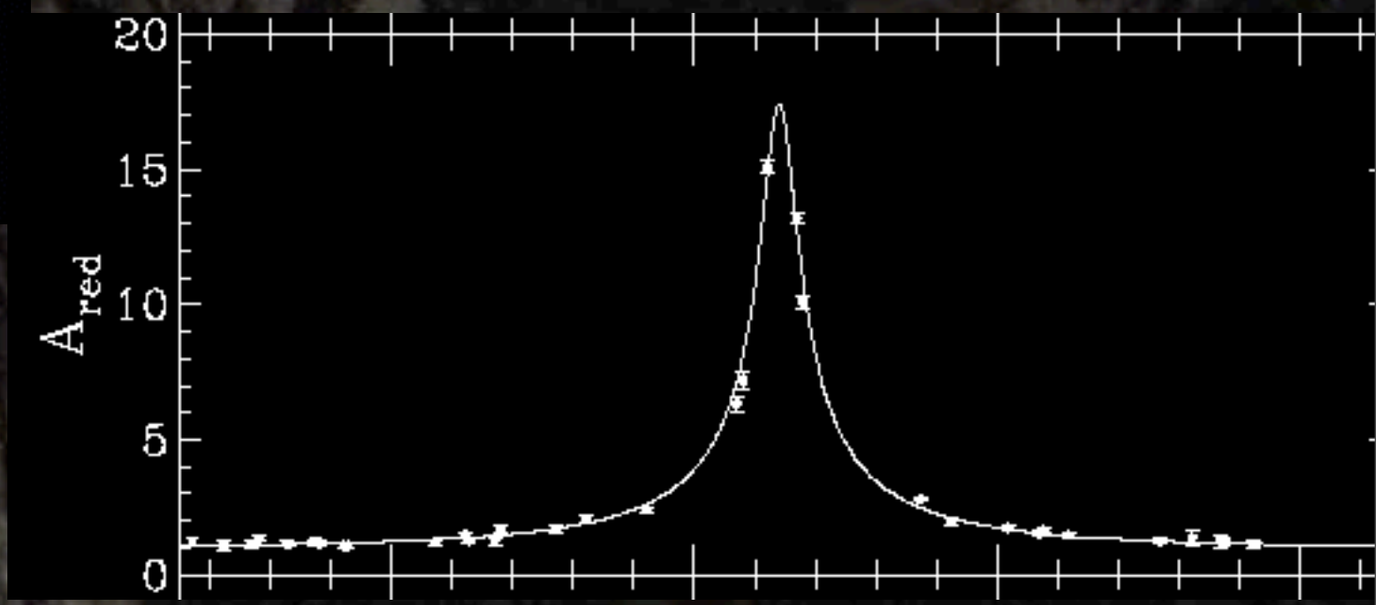

Not enough of them!

Dim Stars?

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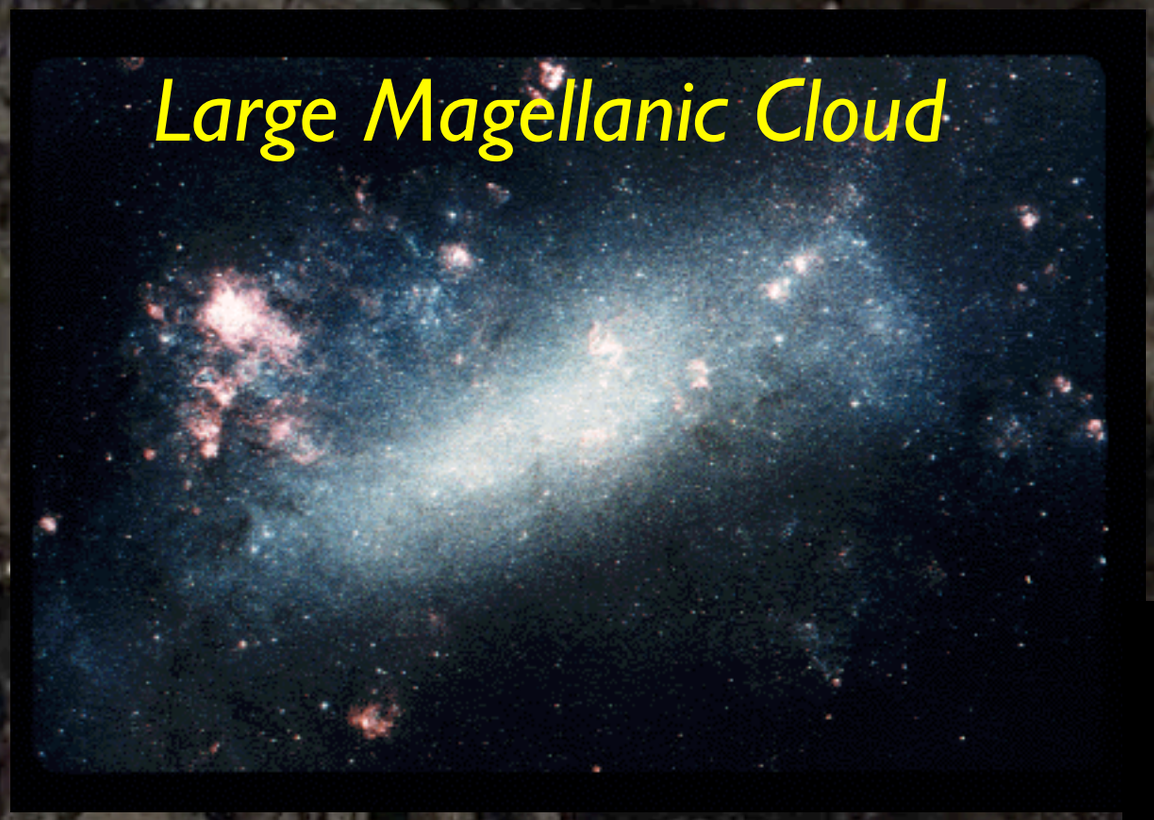

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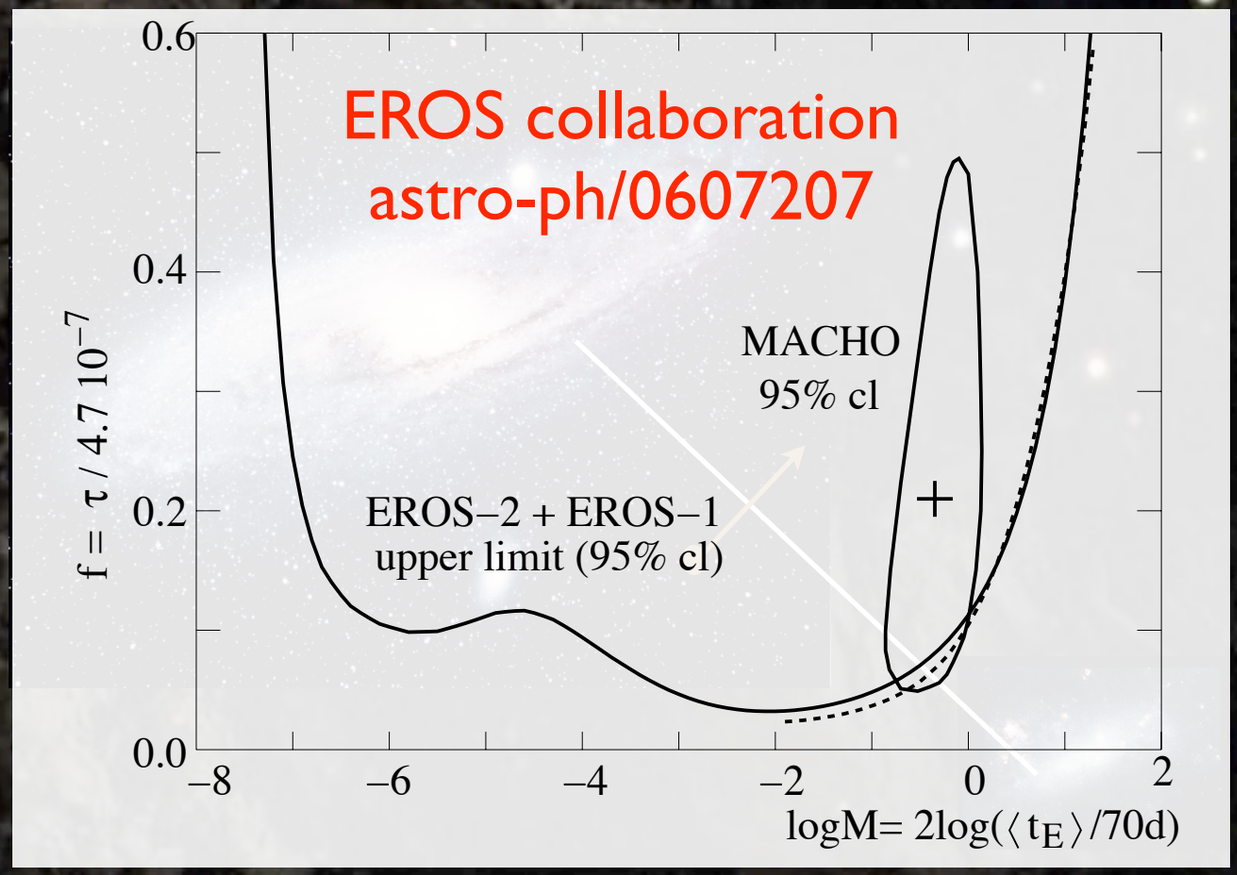
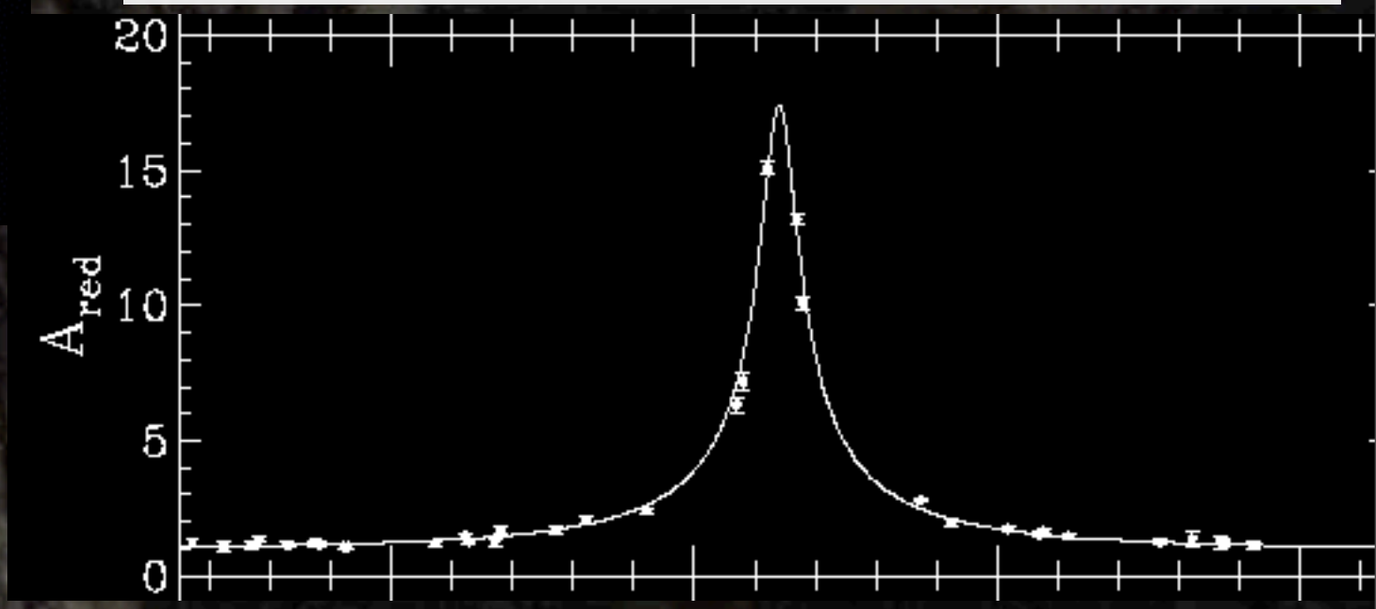
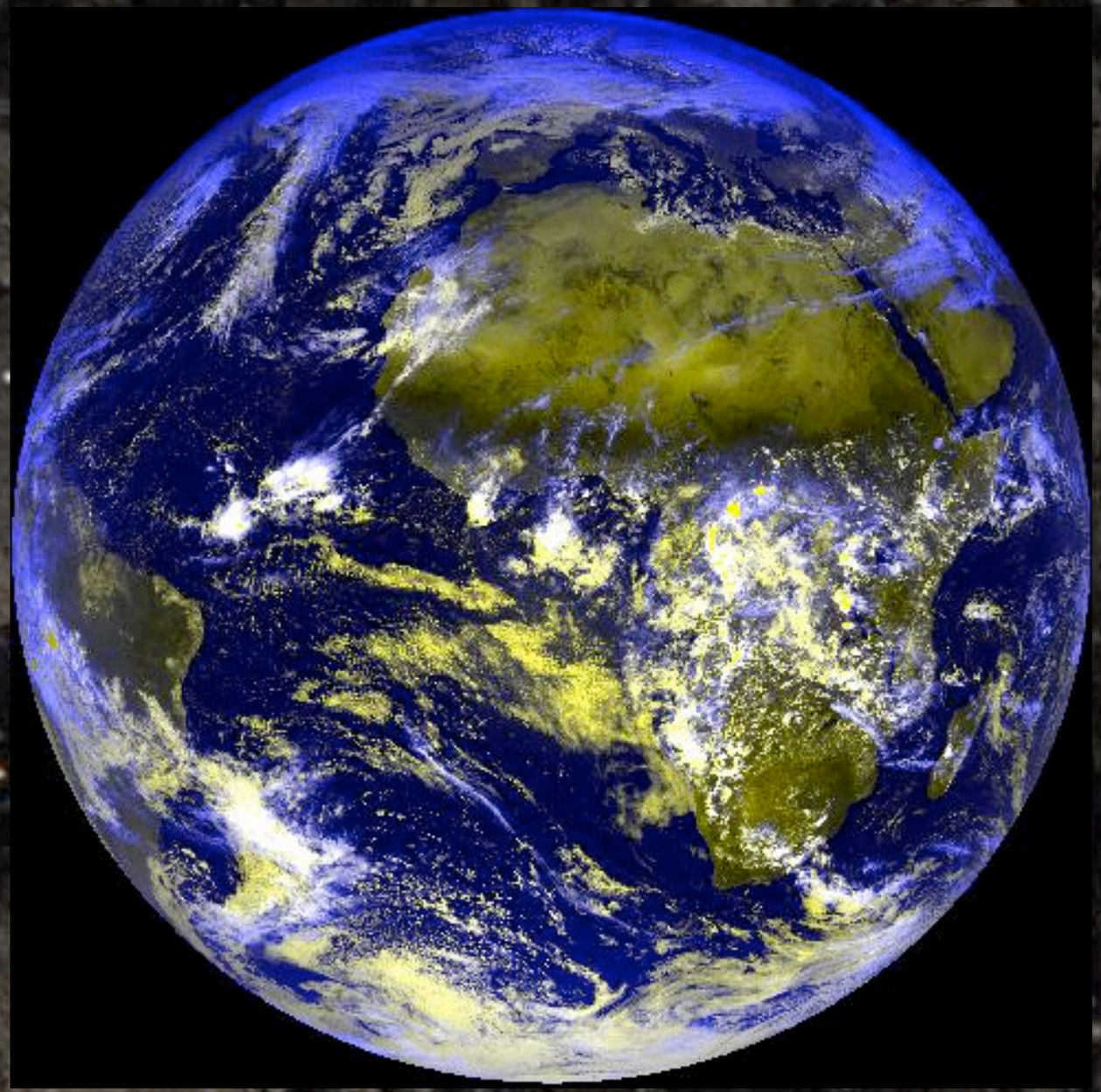




MACHO ⇒ WIMP



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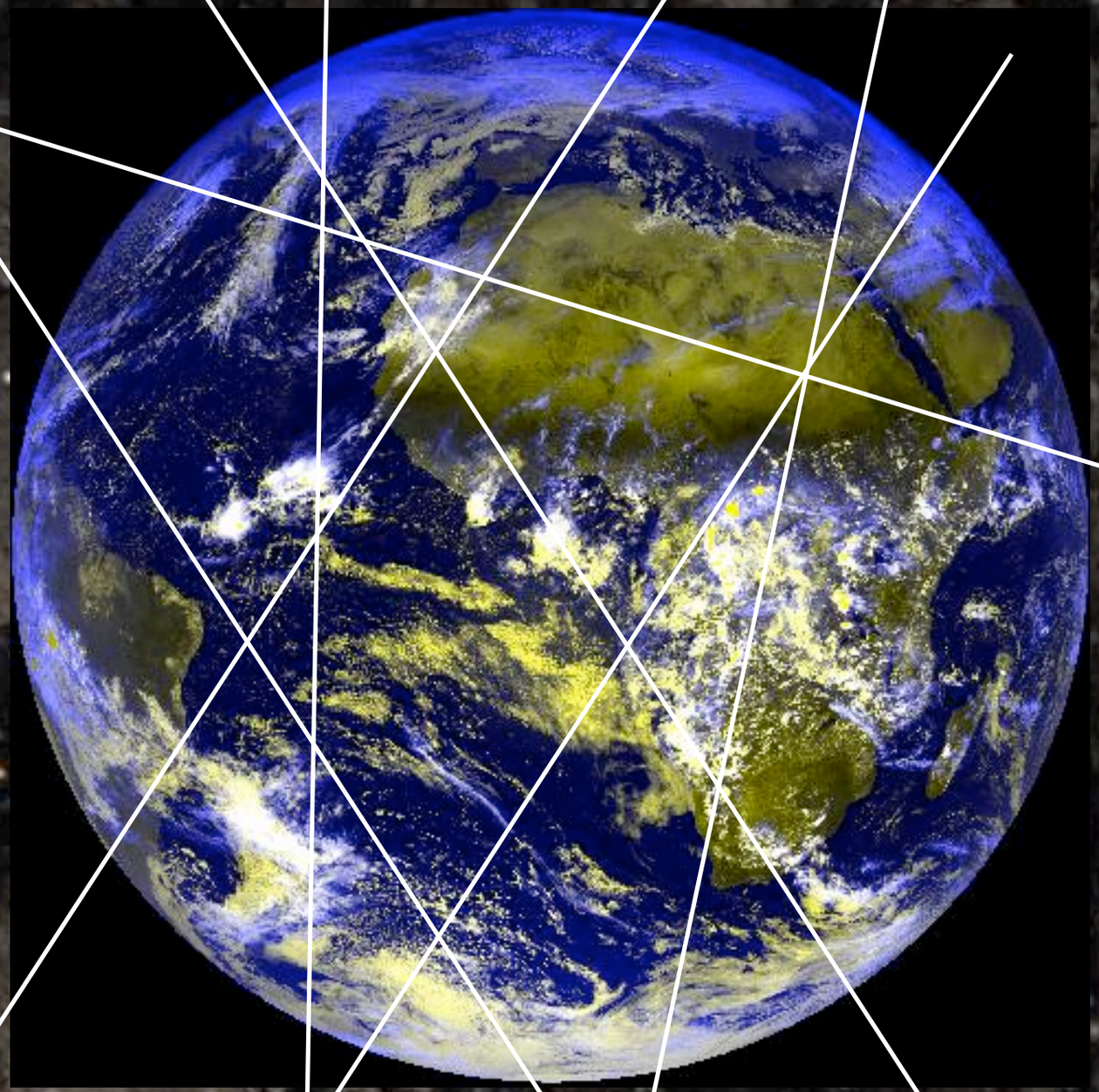

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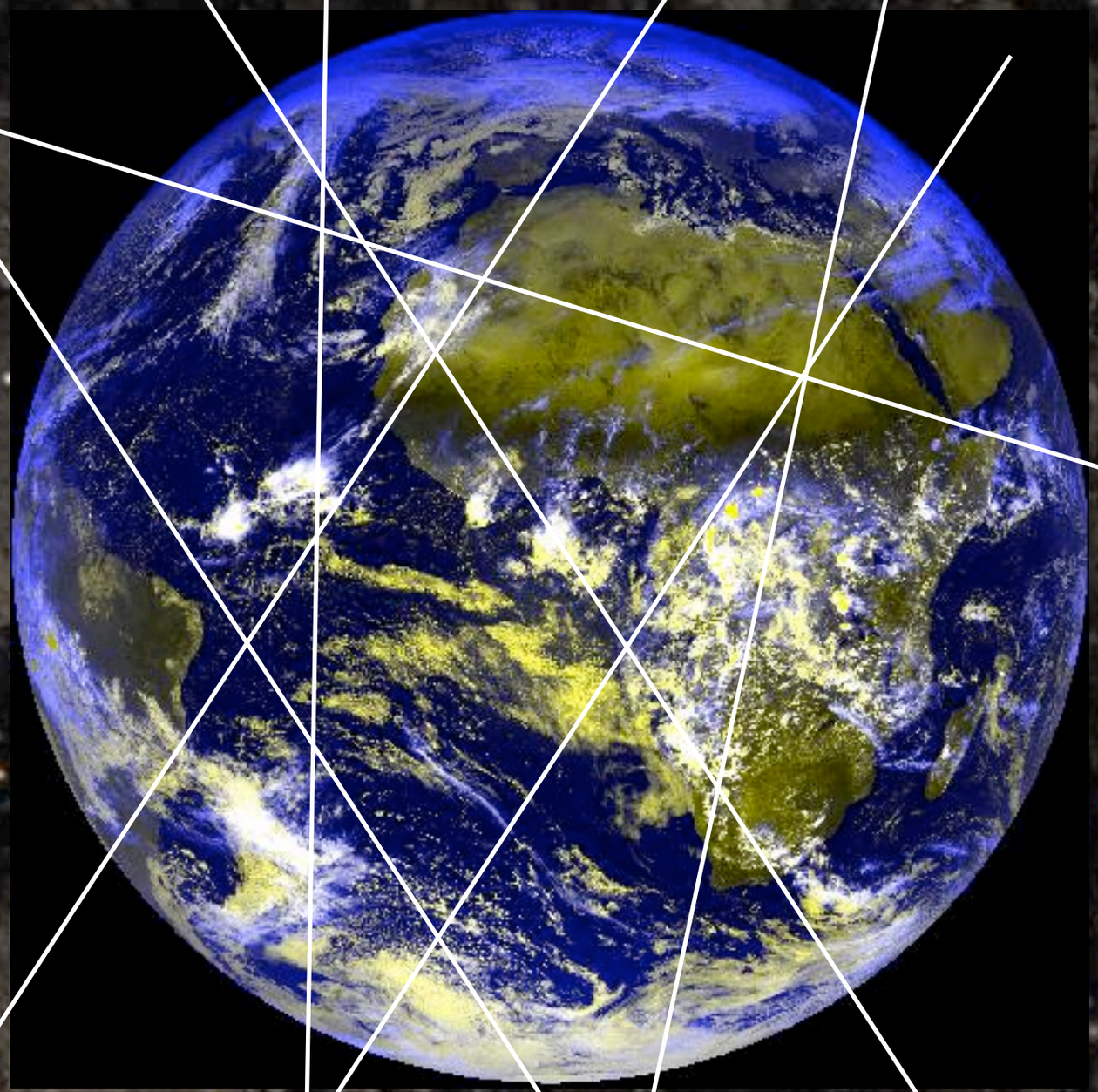
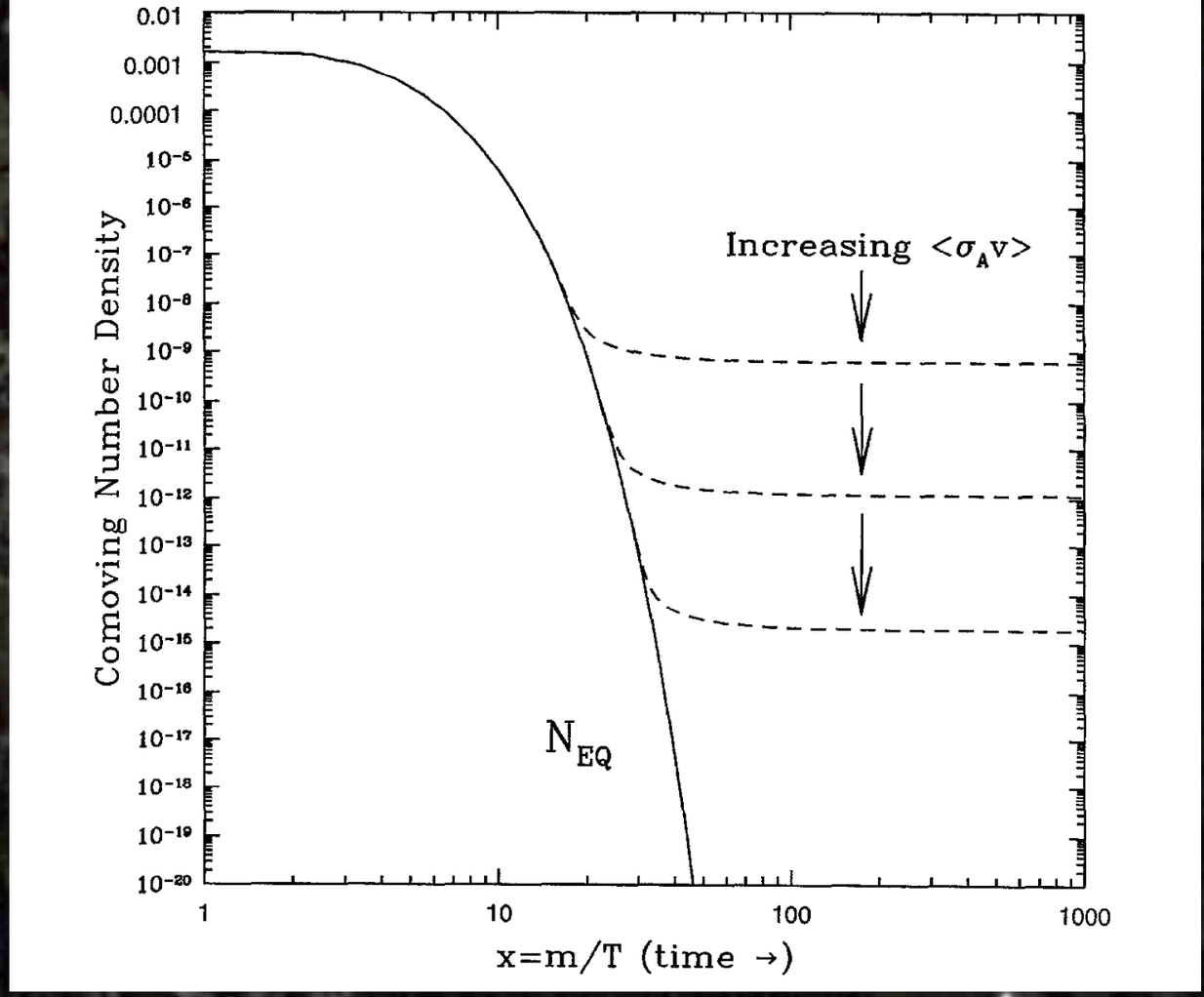


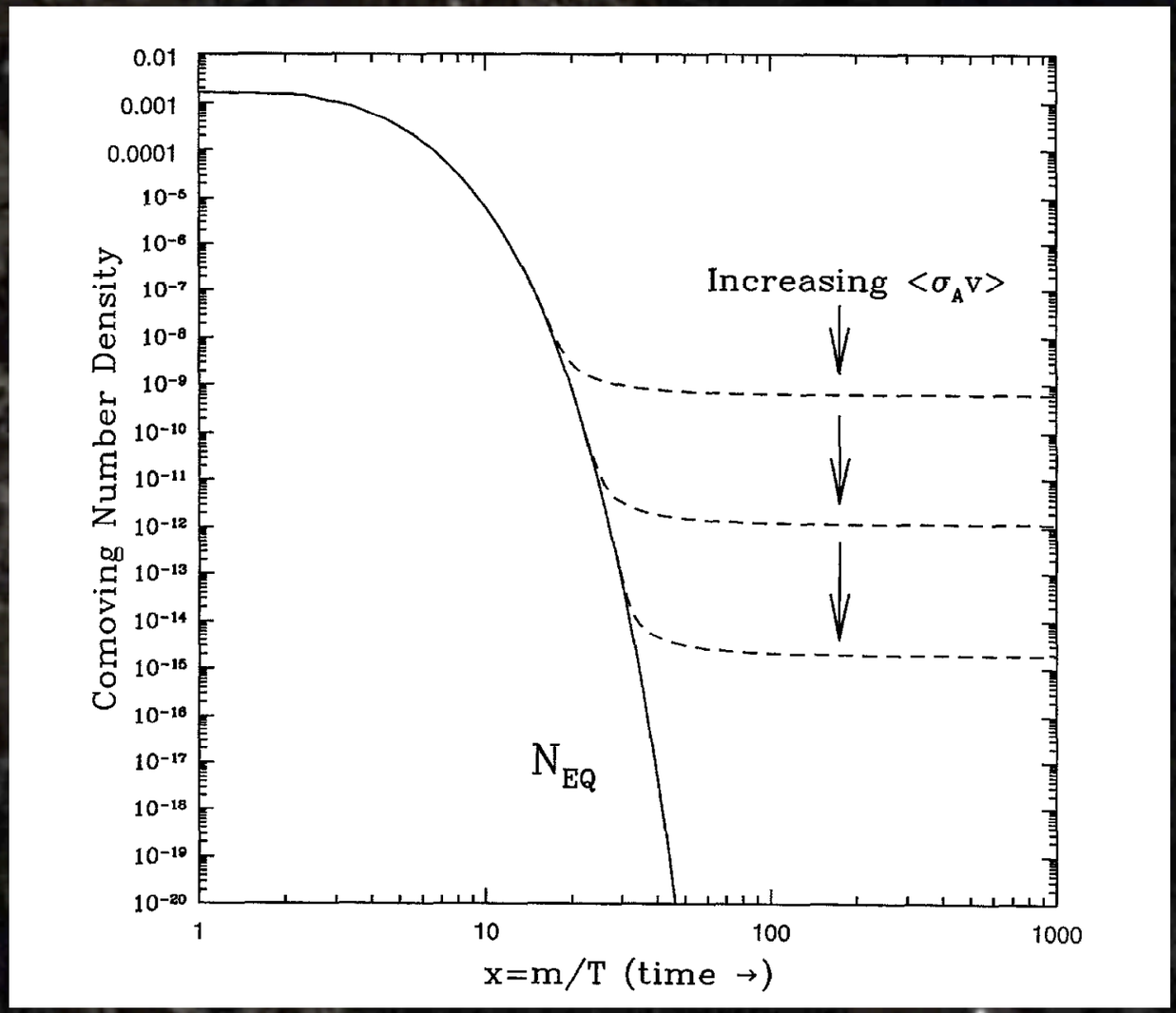
- *It must be WIMP (Weakly Interacting Massive Particle)*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

thermal relic



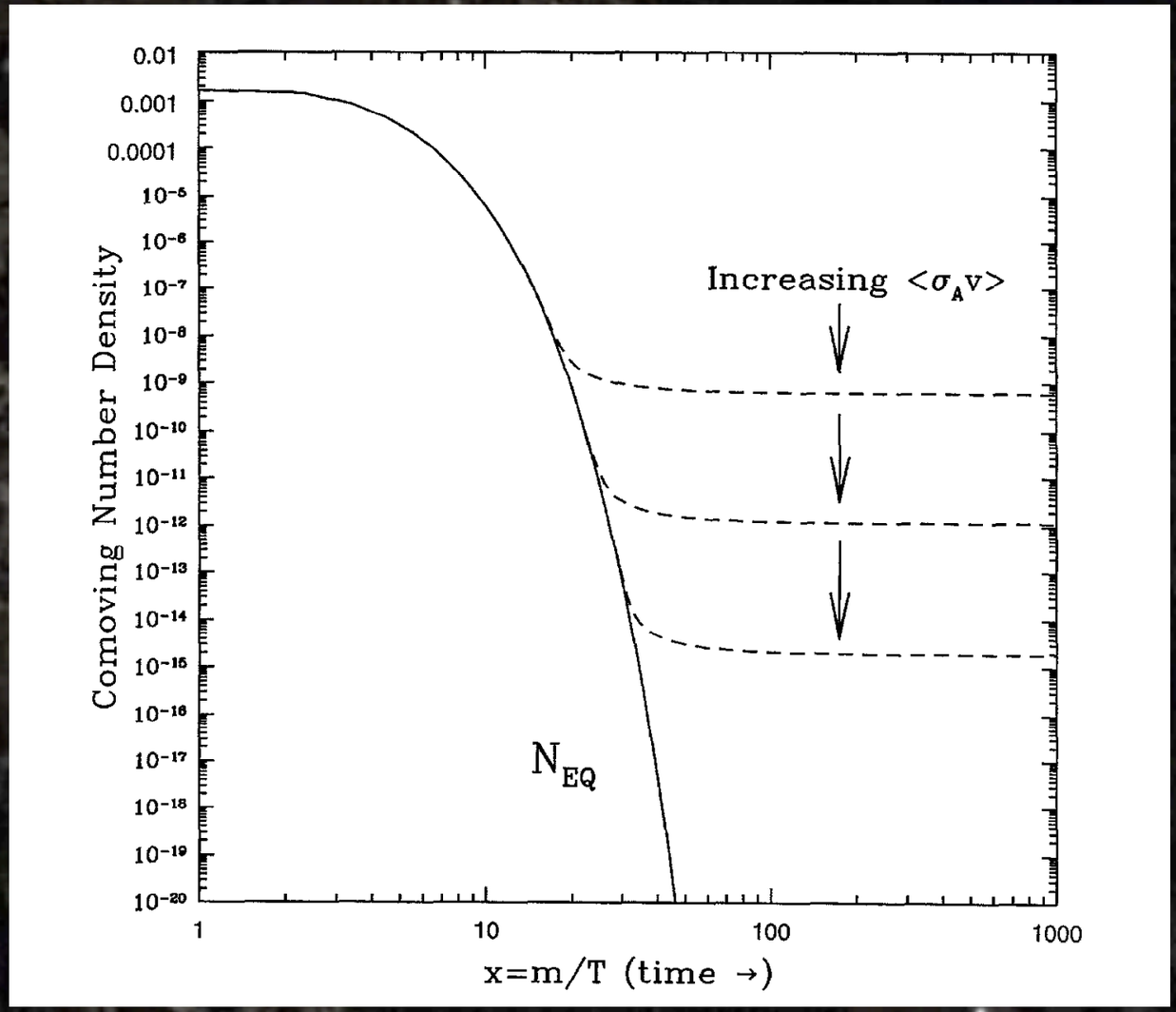
thermal relic

- thermal equilibrium when $T > m_\chi$



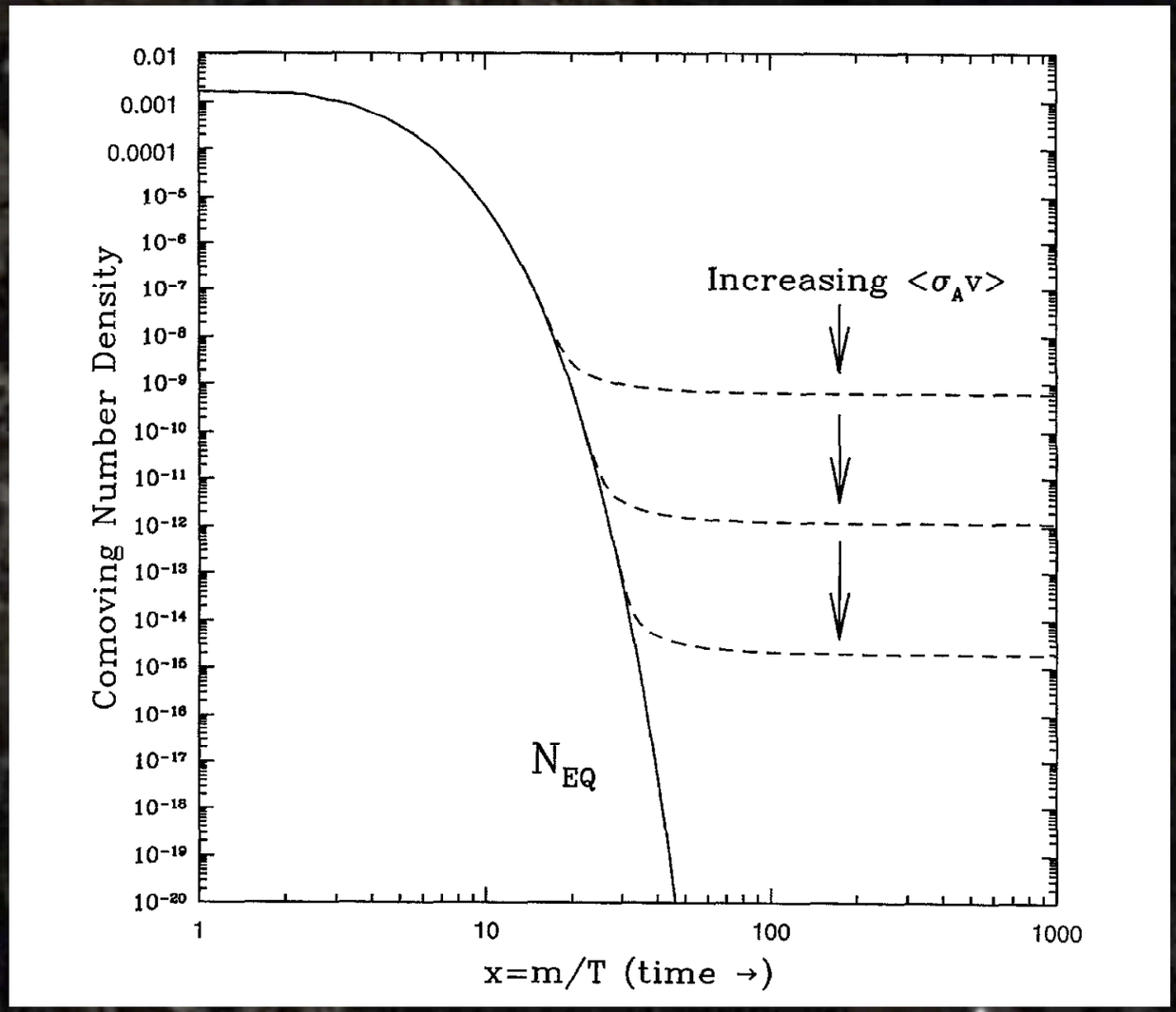
thermal relic

- thermal equilibrium when $T>m_\chi$
- Once $T<m_\chi$, no more χ created



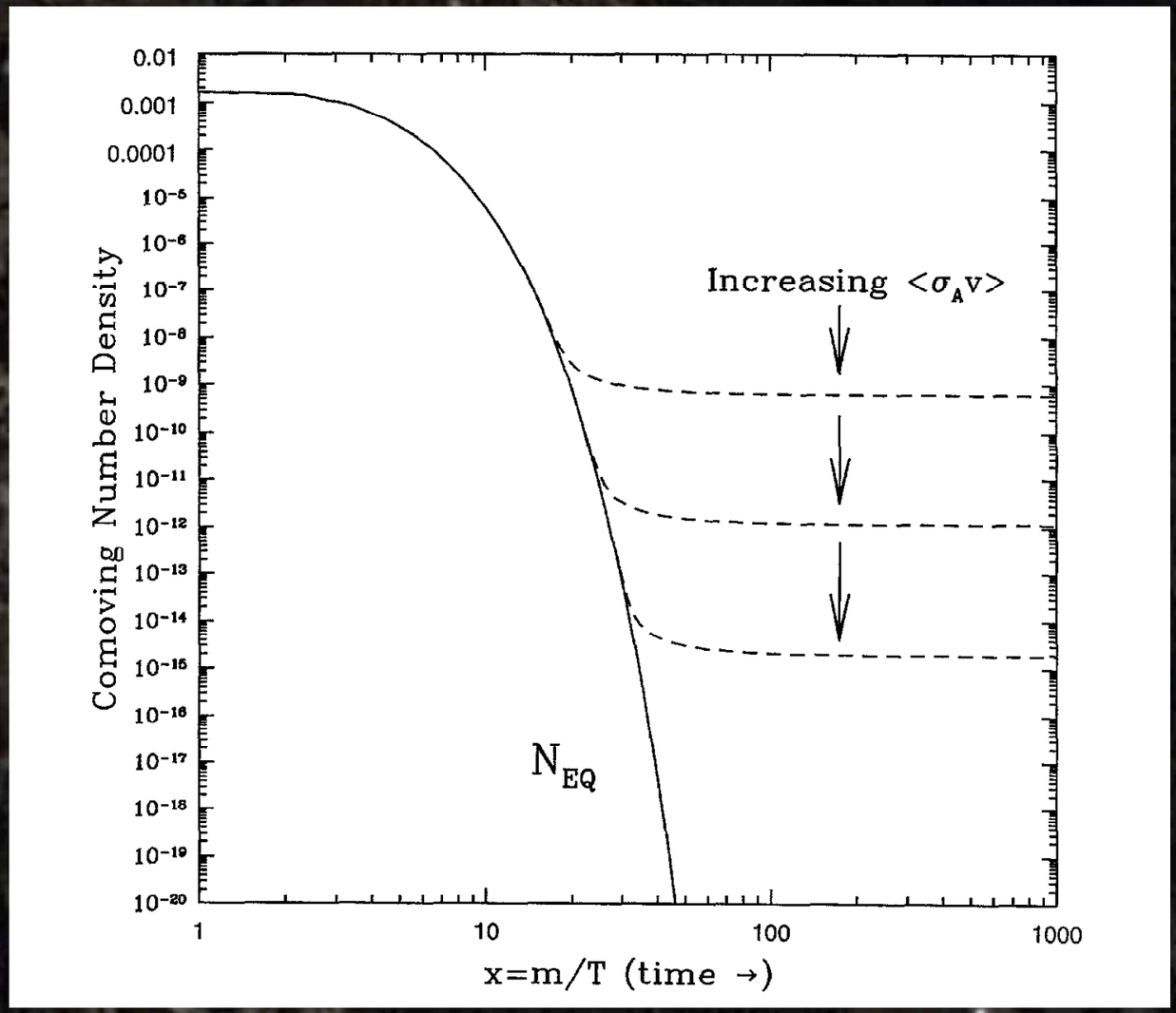
thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more χ created
- if stable, only way to lose them is *annihilation*



thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more χ created
- if stable, only way to lose them is *annihilation*
- but universe expands and χ becomes dilute



thermal relic

- thermal equilibrium when $T > m_\chi$
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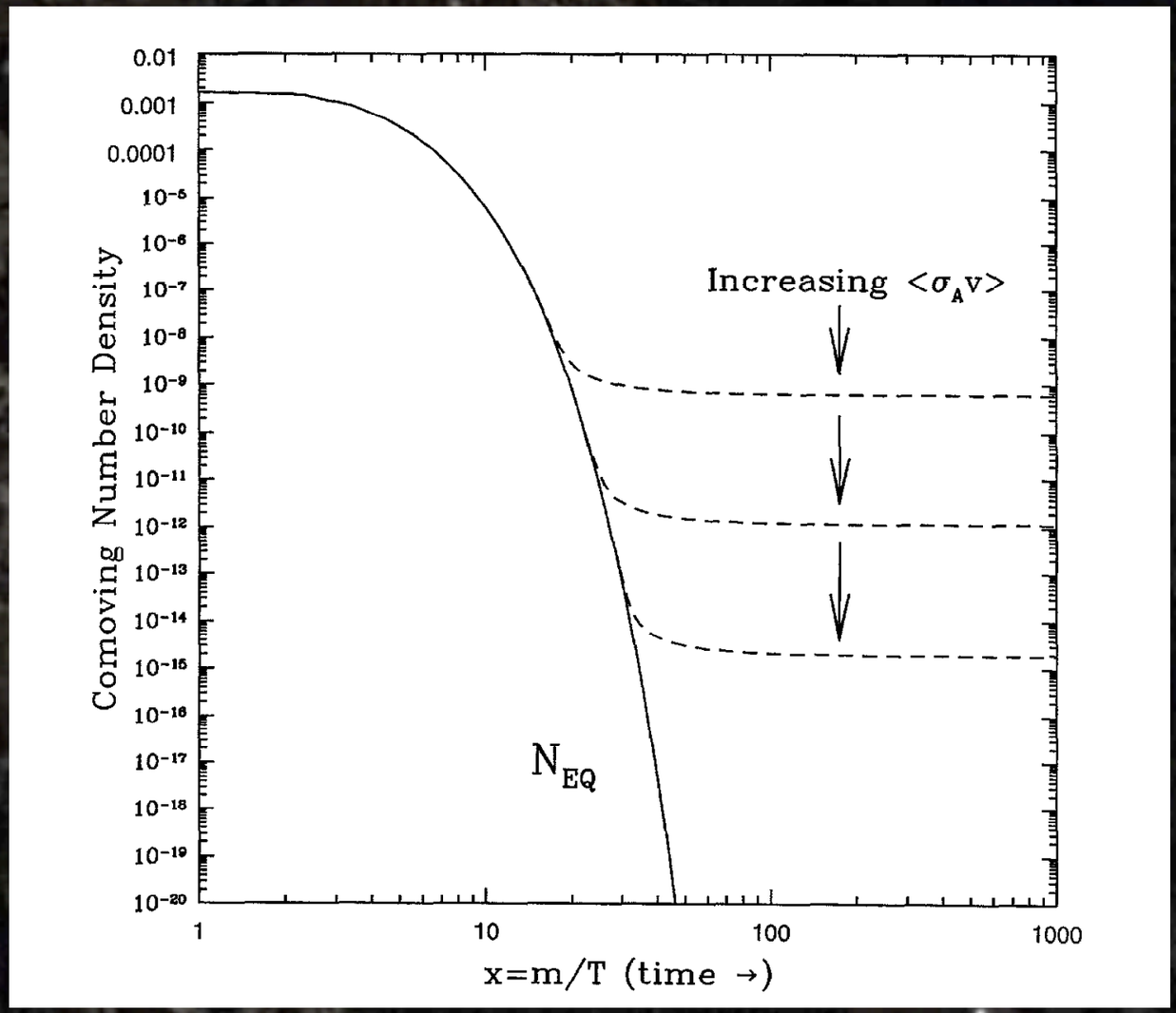
- at some point they can't find each other



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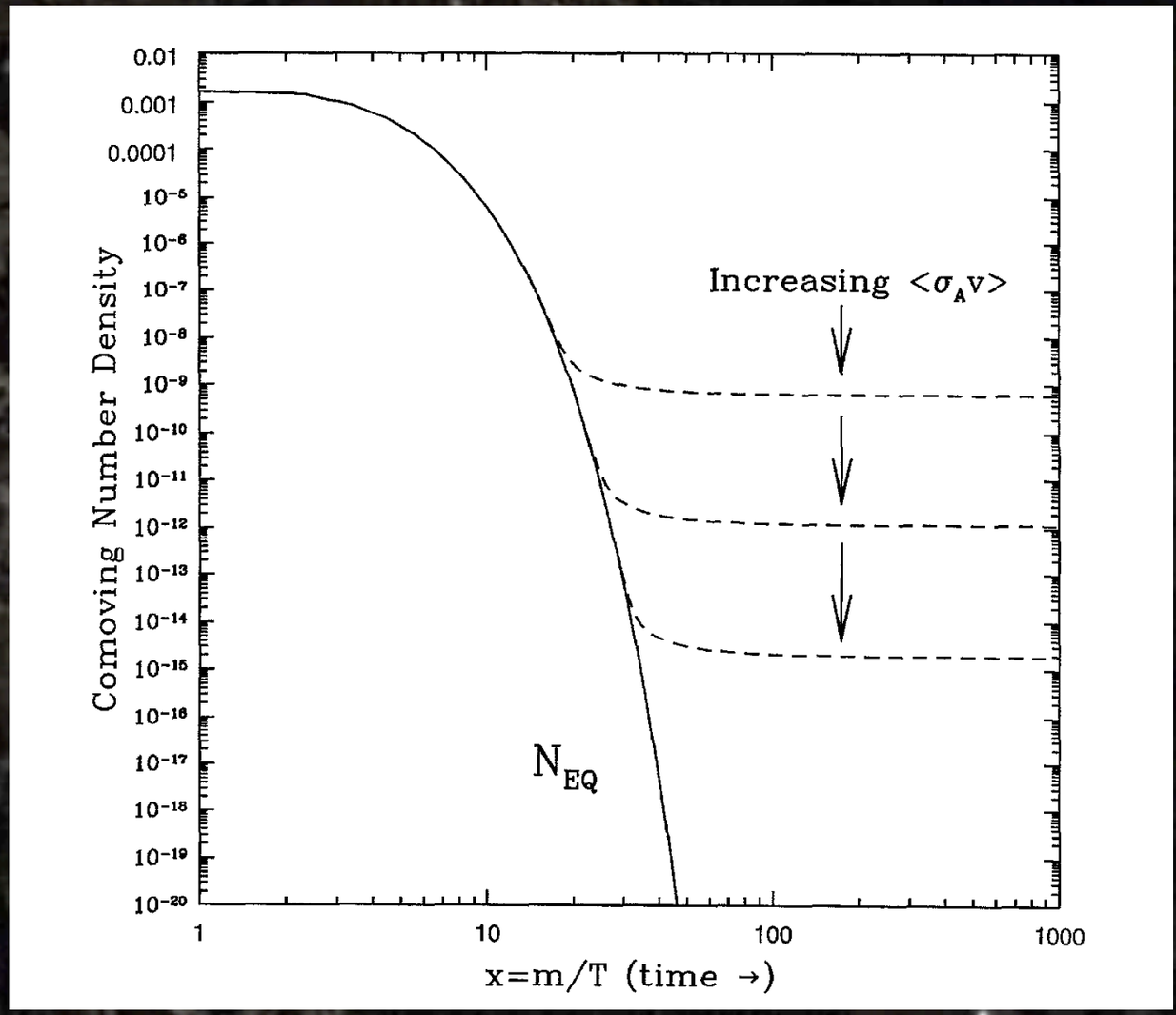
- their number in comoving volume "frozen"



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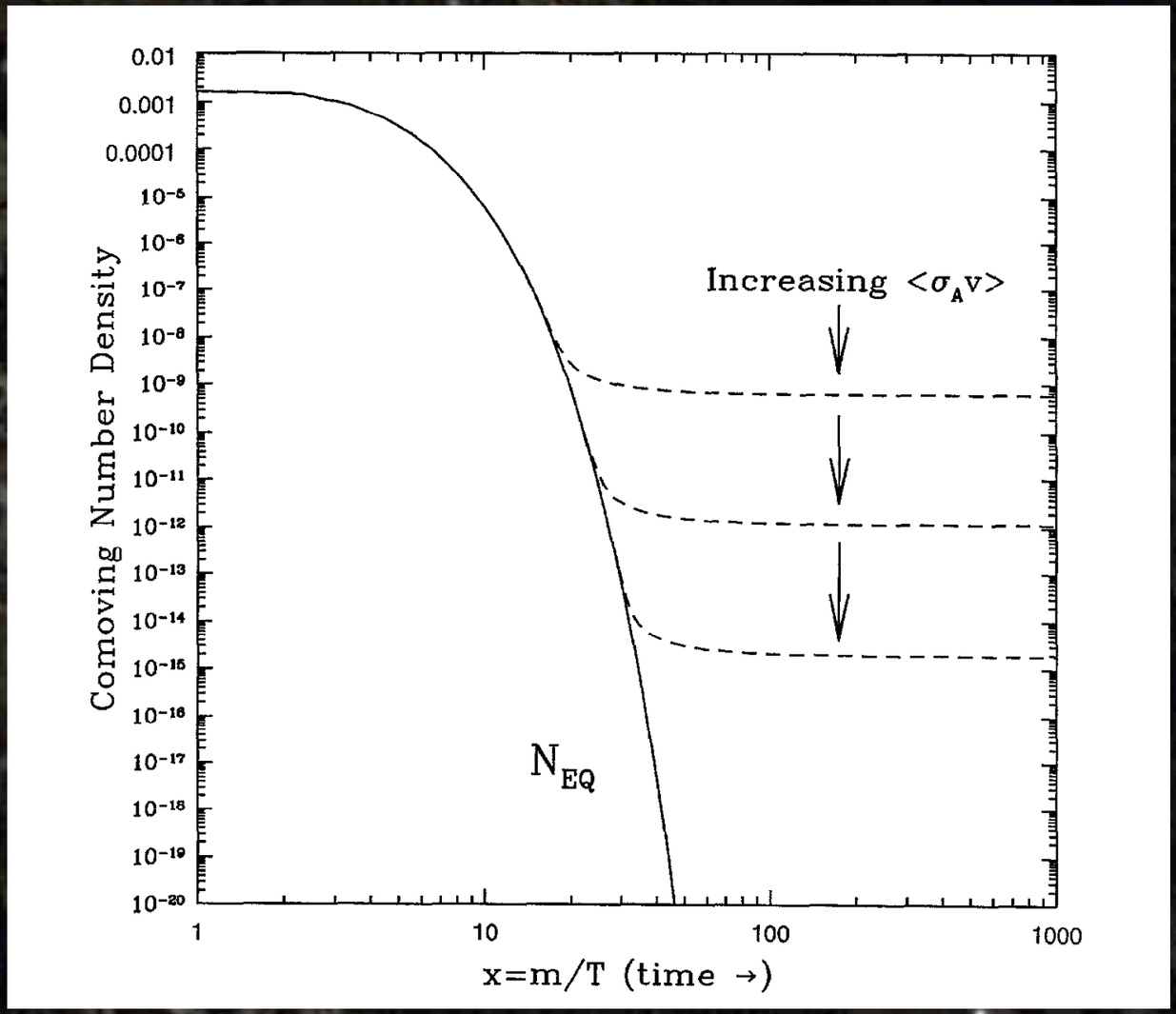
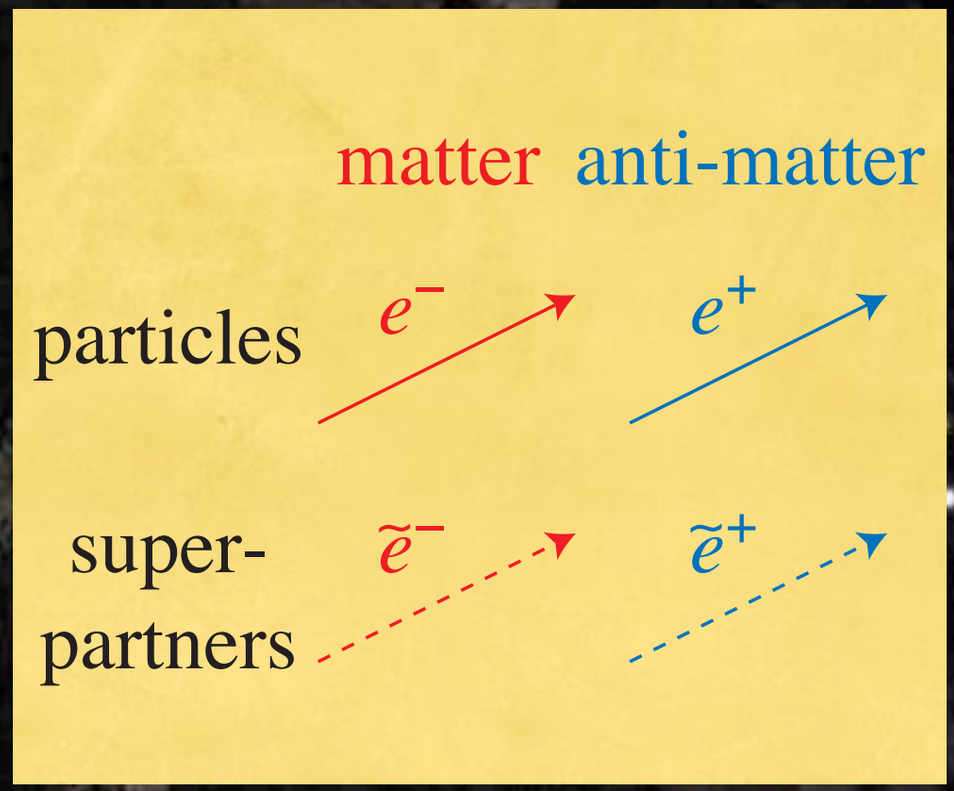


$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

Quantum Dimension

- The best candidate suggested by string theory: supersymmetry
- every particle has anti-matter counterpart: doubled the number
- Nature may do it again
- The lightest superparticle is stable, neutral, weakly interacting

⇒ Dark Matter candidate



Listening to Faint Sound

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Can’t hear subtle intonation

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Need to be shielded from noise!

Listening to Faint Sound

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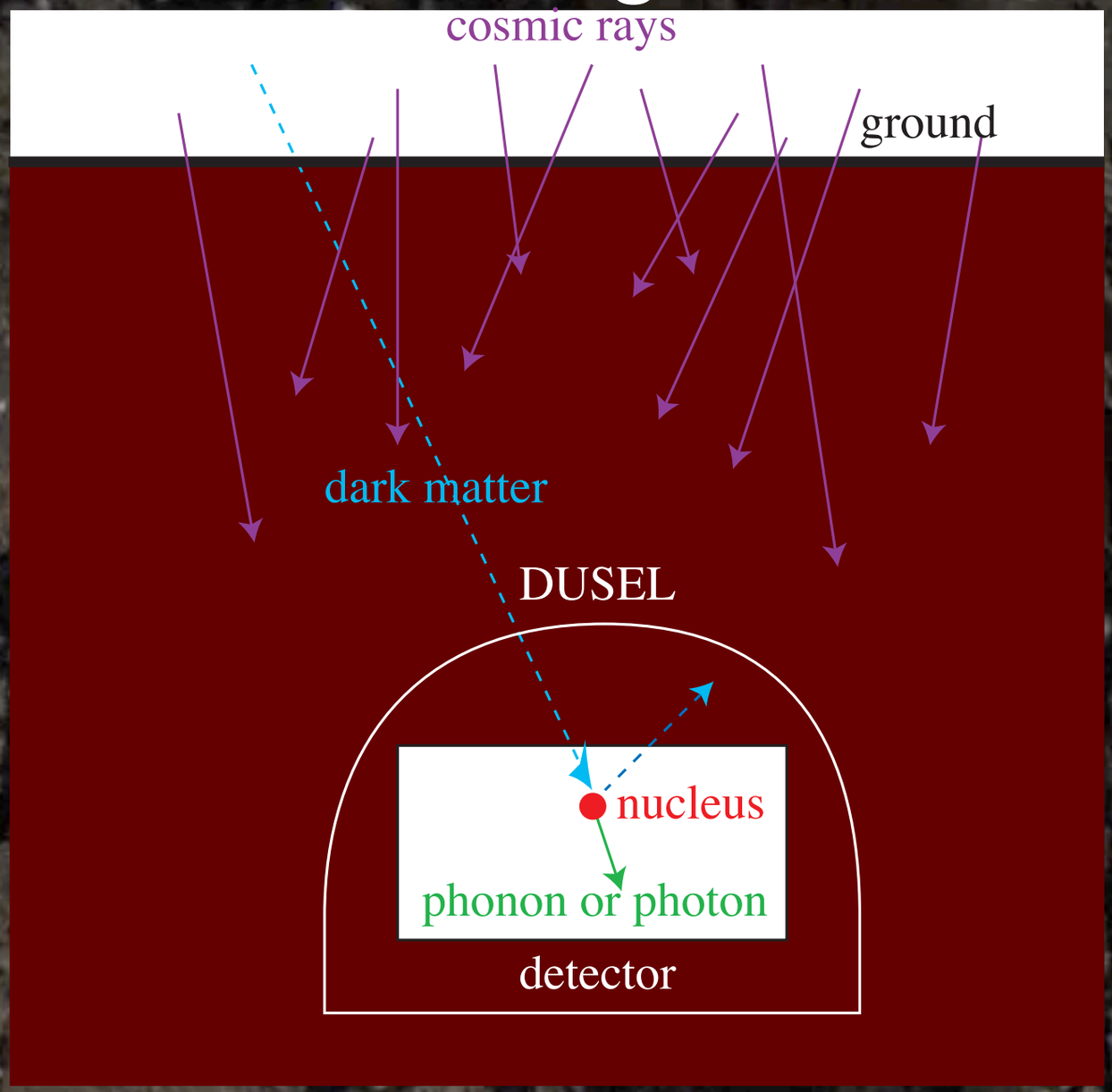
To listen to the faint sound of dark matter,
go where it's quiet

Finding Dark Matter

Go underground!



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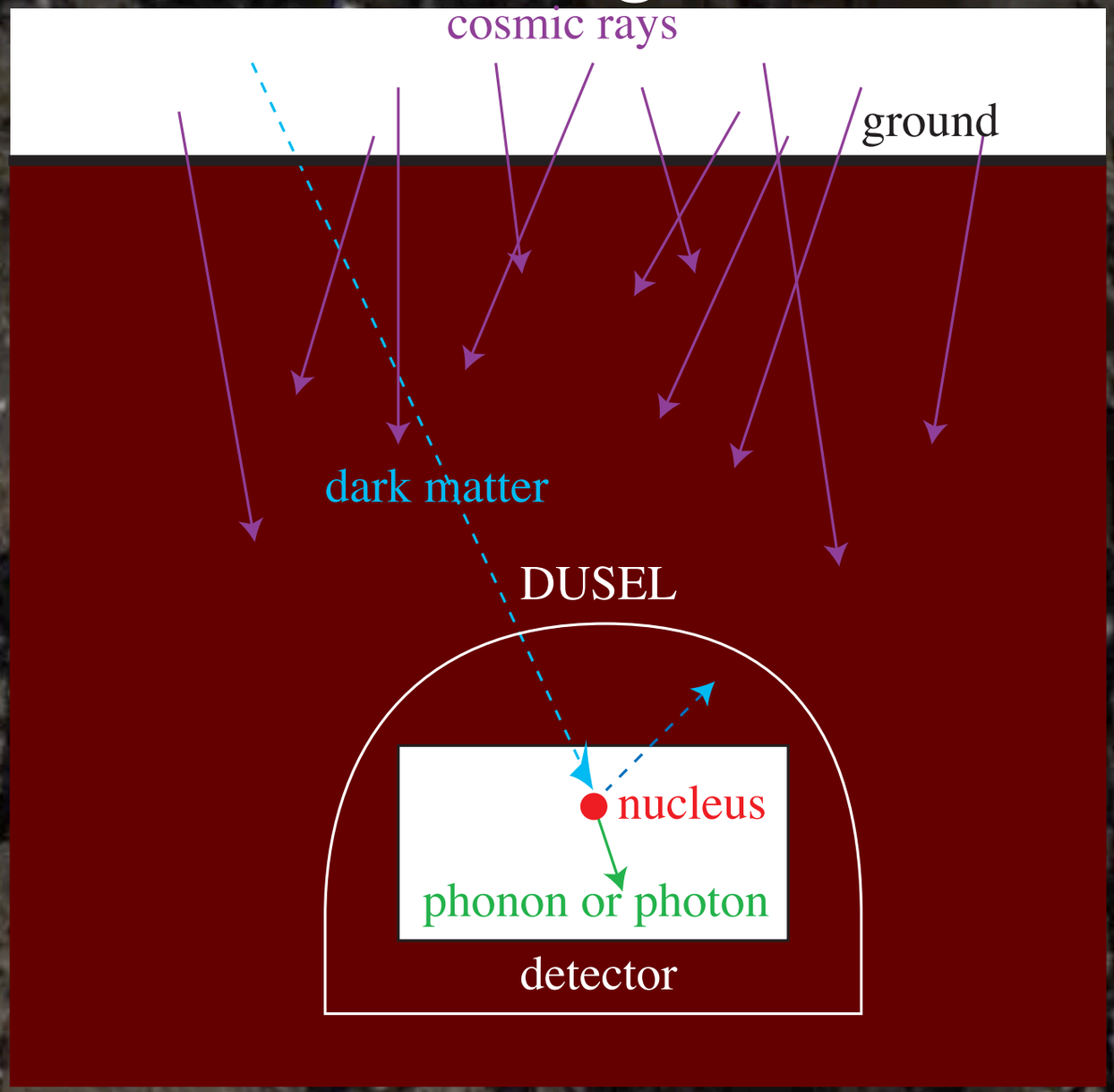

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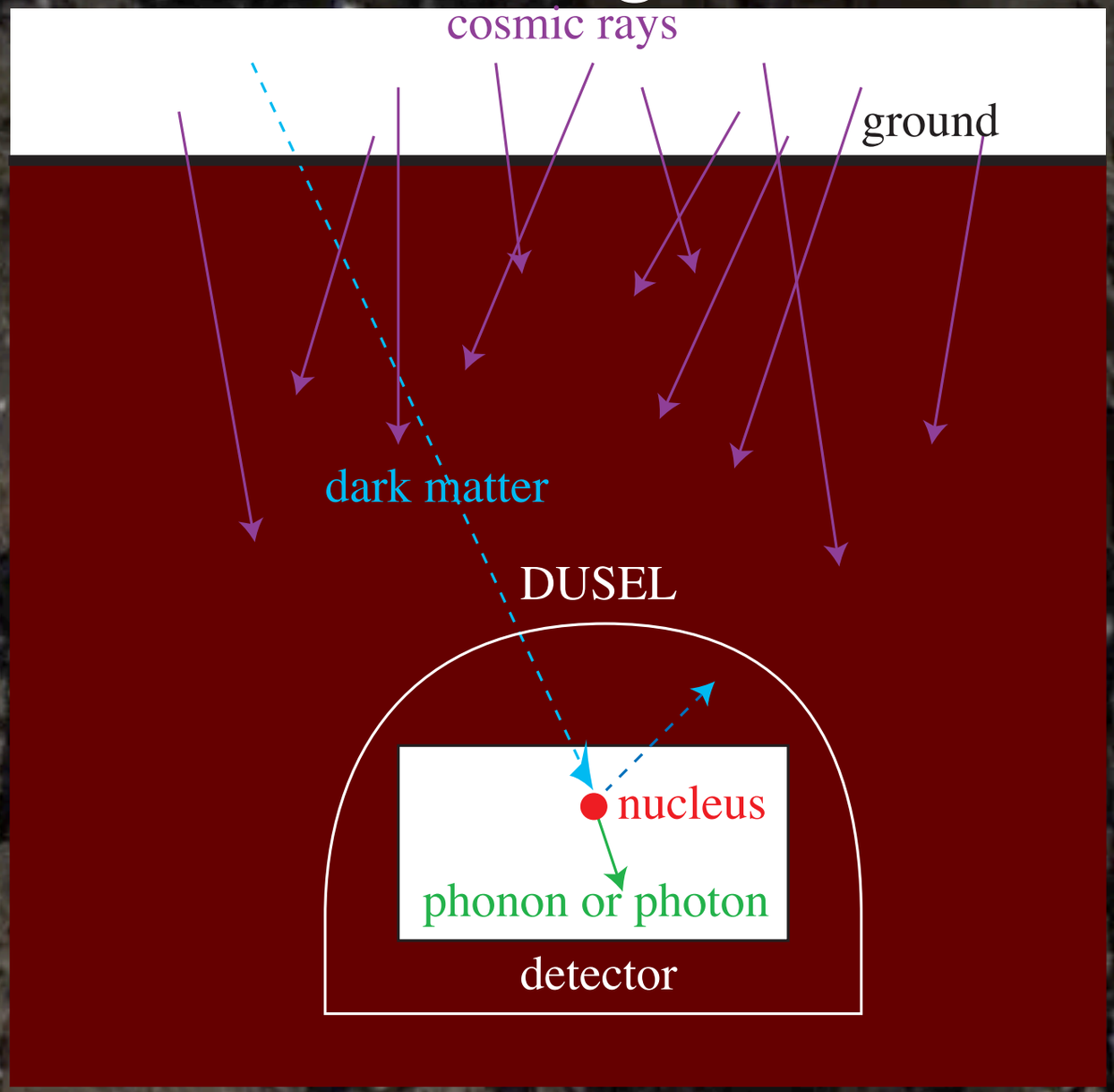
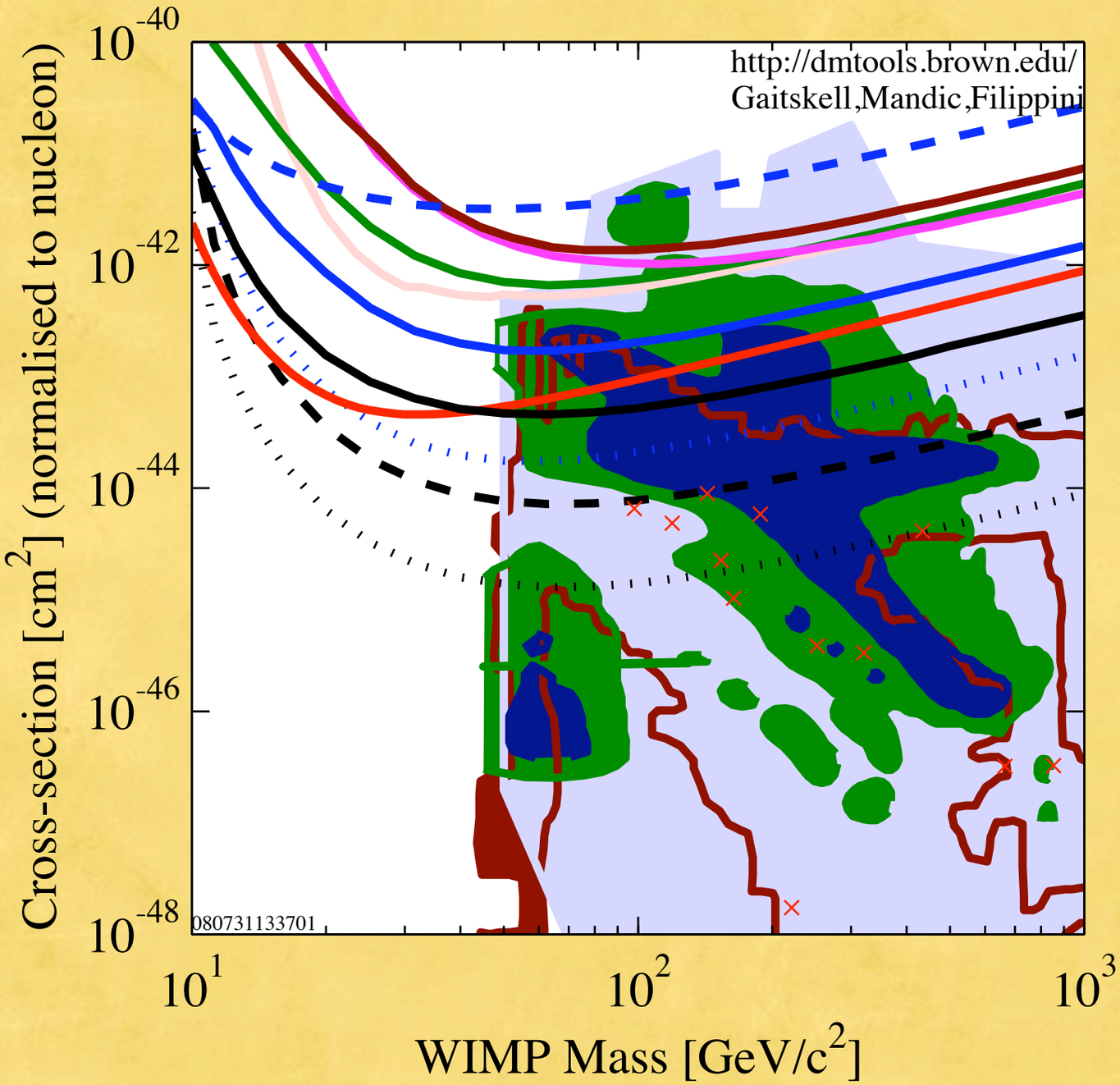


Soudan, MN: too shallow

Getting There



ZEPLIN-II, 2007

CDMS-II, 2005

XENON10, 2007

CDMS-II, 2008

History of the Universe

BIG BANG

Inflation

?

high-energy cosmic rays

Accelerators
LHC
Tevatron
RHIC

10-10 sec

1min

400Kyr

13.7Byr

possible dark matter relicts

cosmic microwave radiation visible

BBN

CMB

t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15

10-10 s
10 15
10 2

10-5 s
10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
3x10 -10

10 9 y
15
10-12

12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)

Today

Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq̄ meson
- baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

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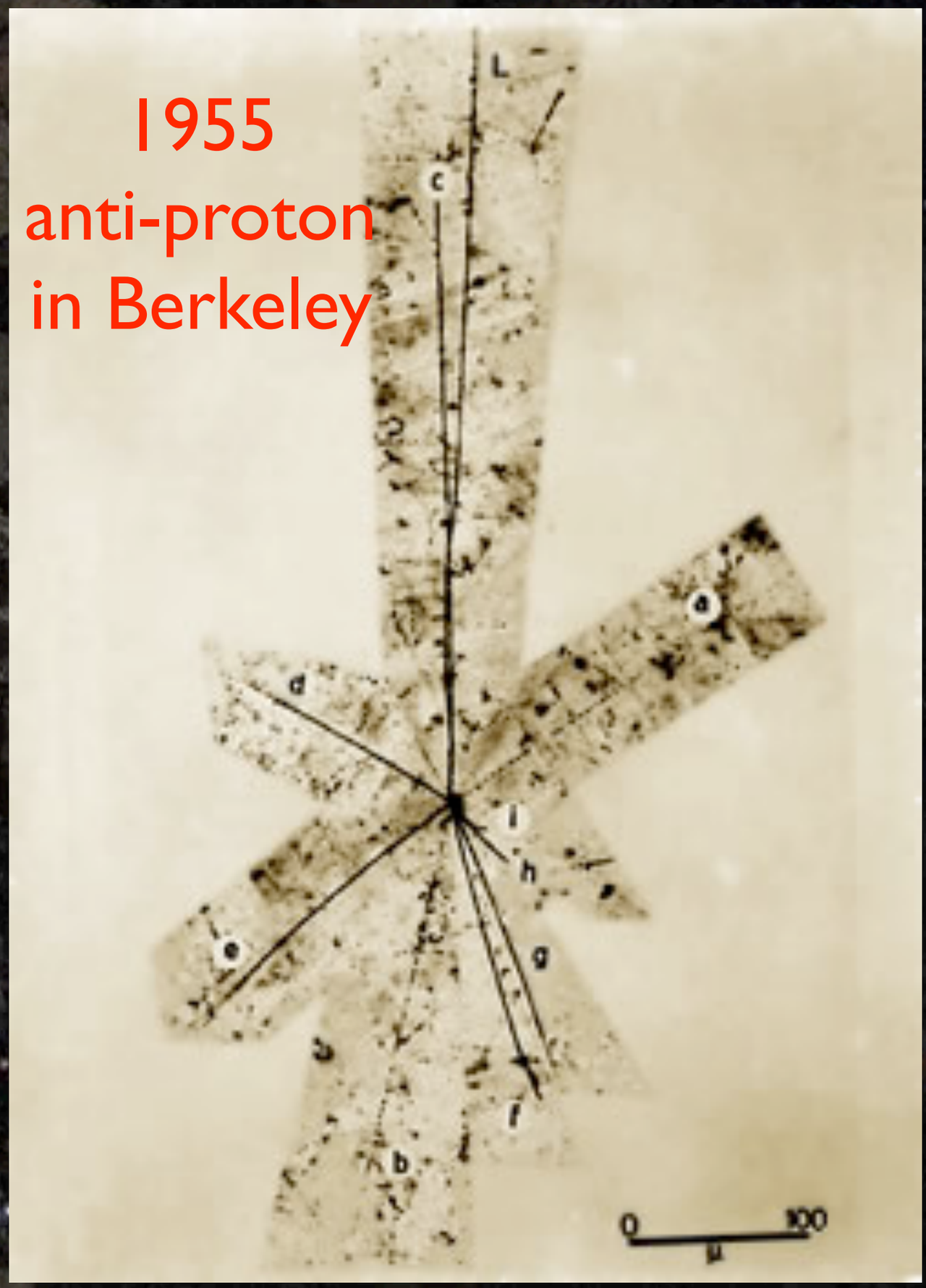
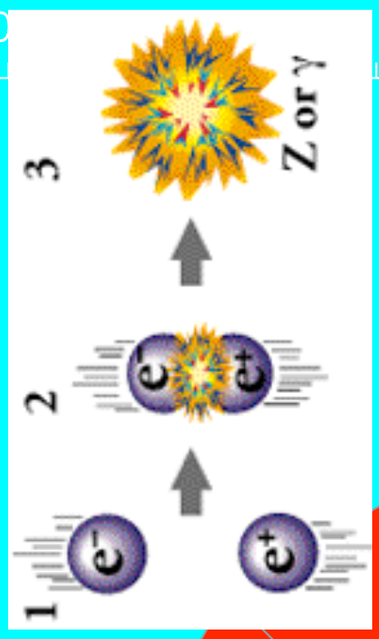
Anti-Matter

1955
anti-proton
in Berkeley



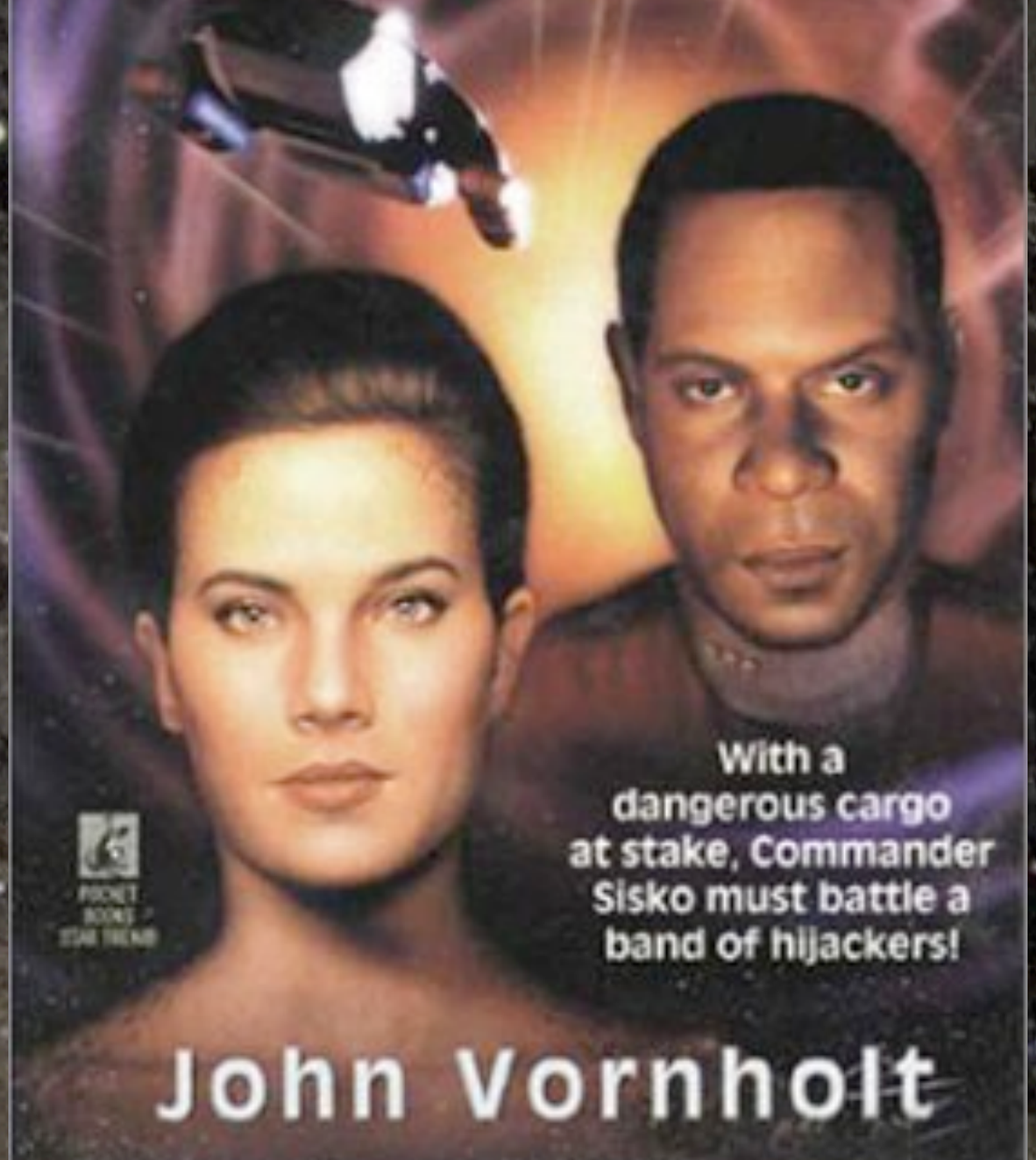

1
2
3
Z or γ

#8

STAR TREK

DEEP SPACE NINE

ANTIMATTER



With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!

POCKET BOOKS / STAR TREK

John Vornholt

BESTSELLING AUTHOR OF *DIGITAL FORTRESS*

DAN BROWN

A NOVEL

ANGELS & DEMONS

"A breathless, real-time adventure…Exciting, fast-paced, with an unusually high IQ." —*San Francisco Chronicle*

Matter and Anti-Matter Early Universe

1,000,000,001

1,000,000,000

matter

anti-matter

Matter and Anti-Matter Current Universe

matter *anti-matter*

The Great Annihilation

Baryo-Genesis

Baryo-Genesis

- How did we survive the Great Annihilation?

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⇒ the search is on!

Proton Decay

- If matter and anti-matter transform to each other, maybe $p \rightarrow e^{+}$+light

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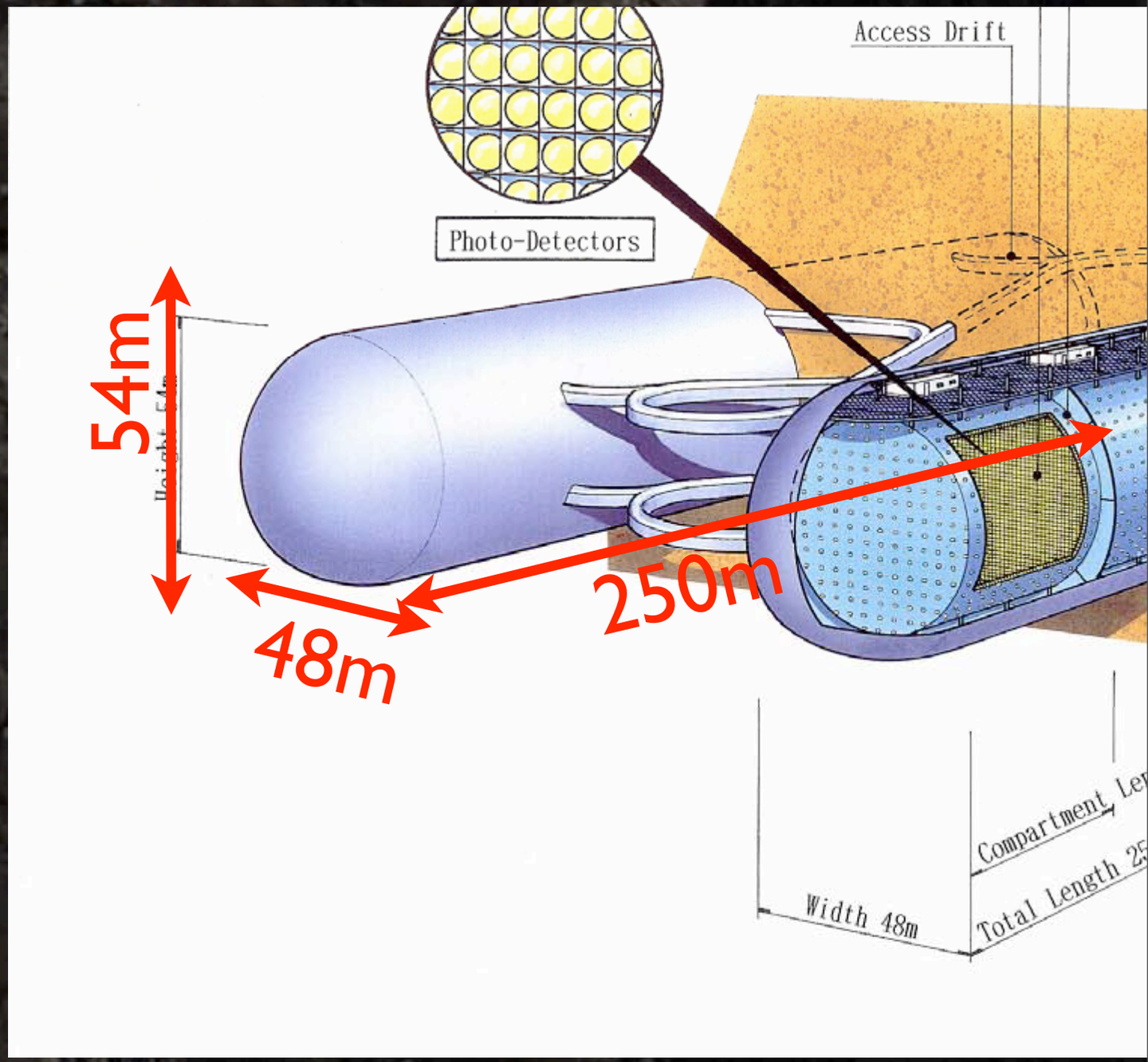

Neutrinoless Double-beta Decay

- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity!
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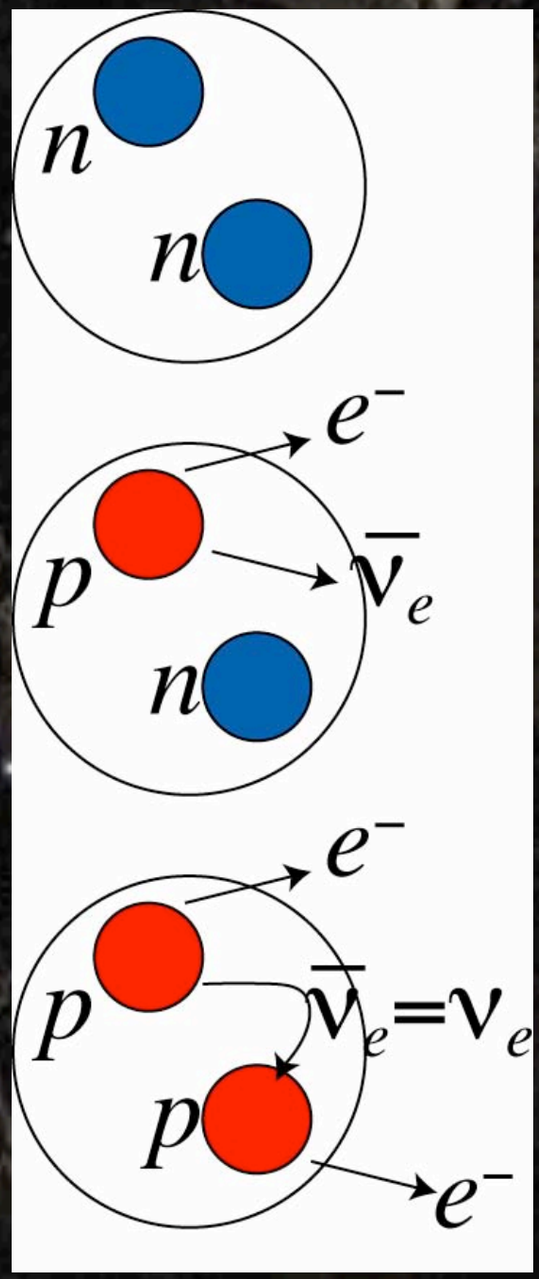

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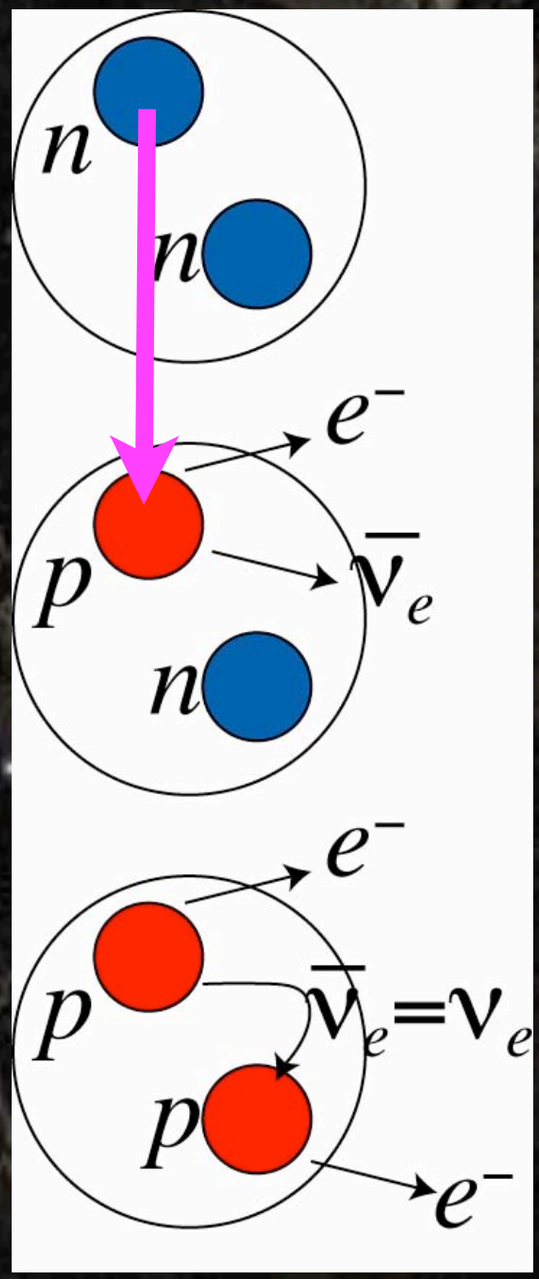

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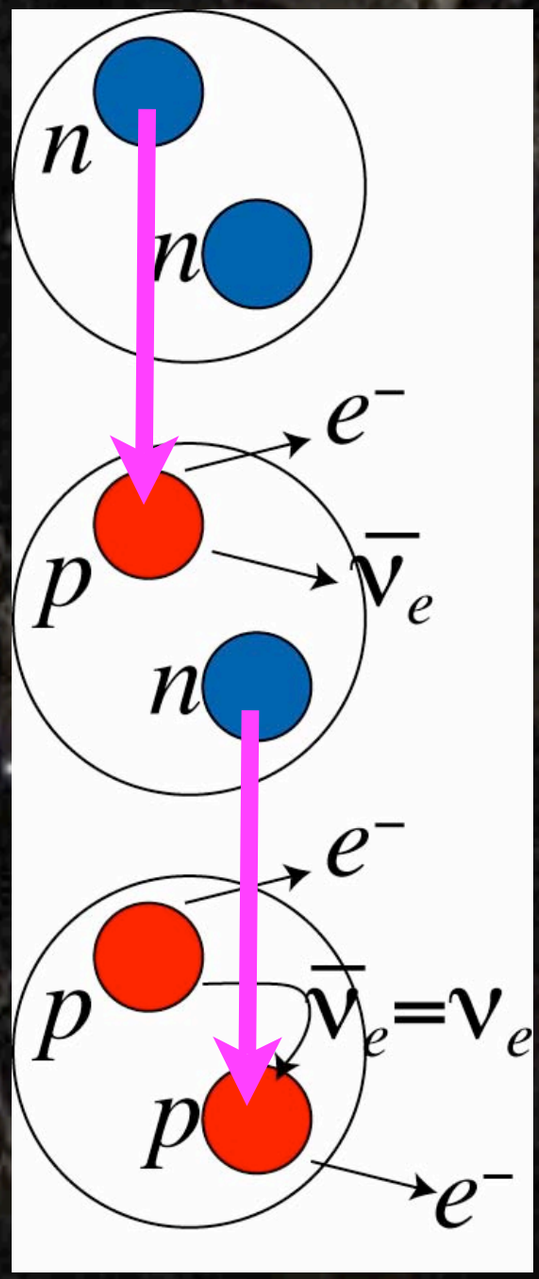

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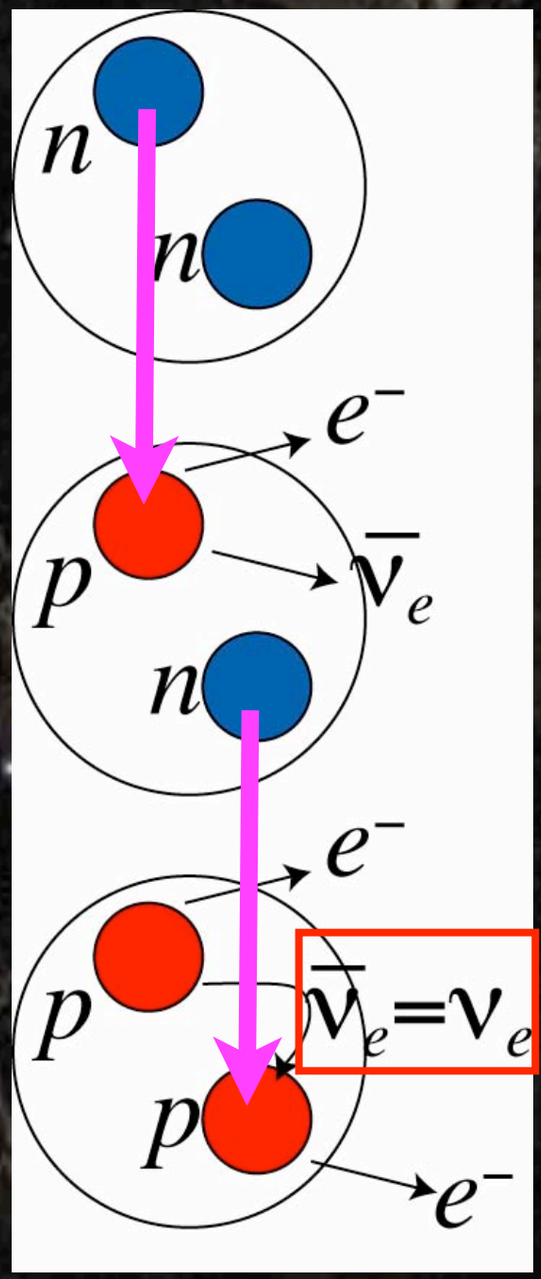

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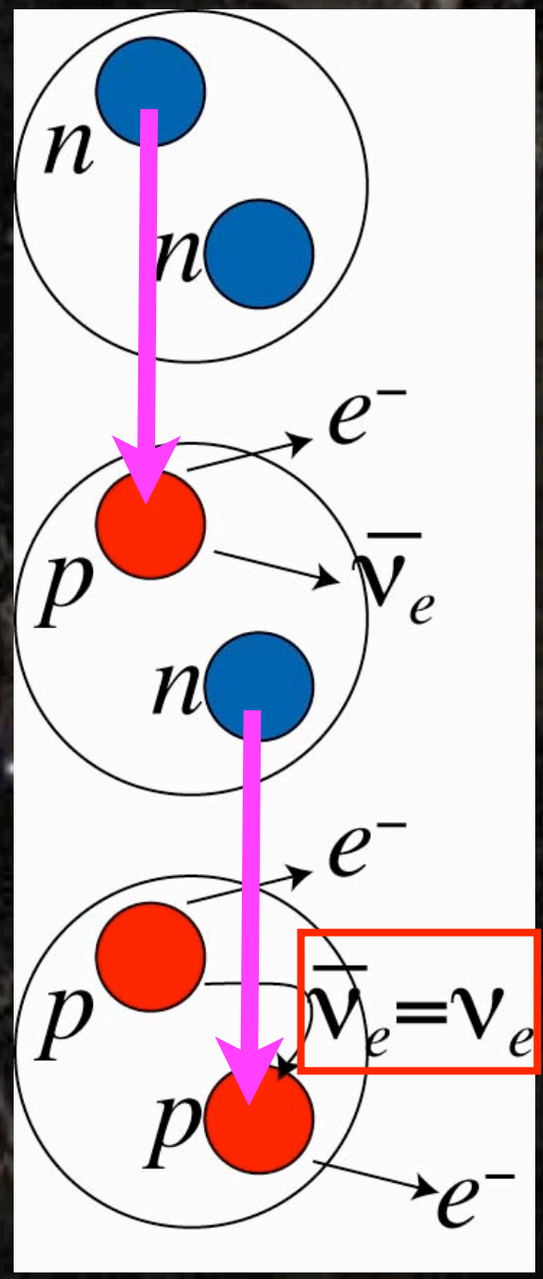
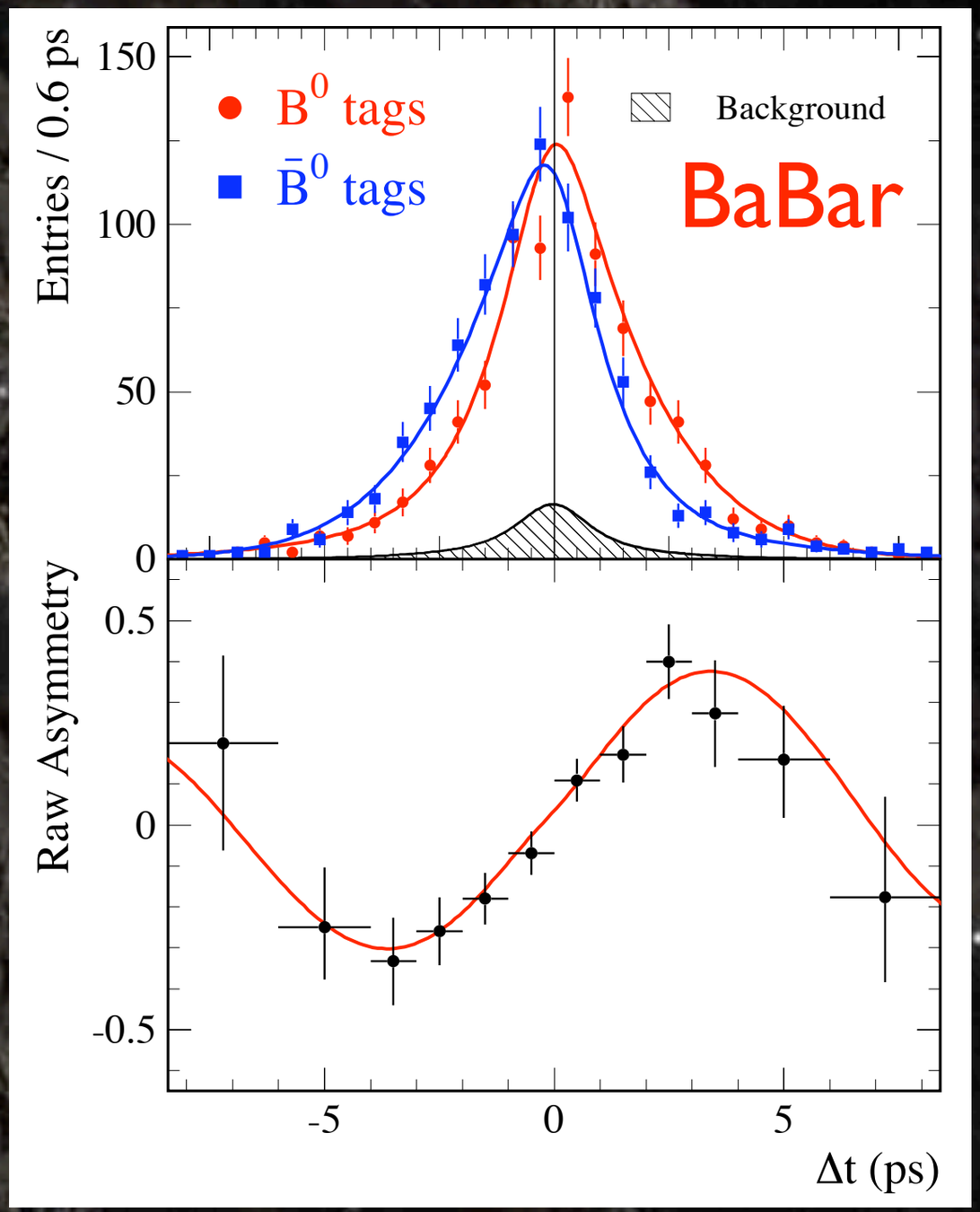
Also n-$\bar{n}$ oscillation



CP Violation



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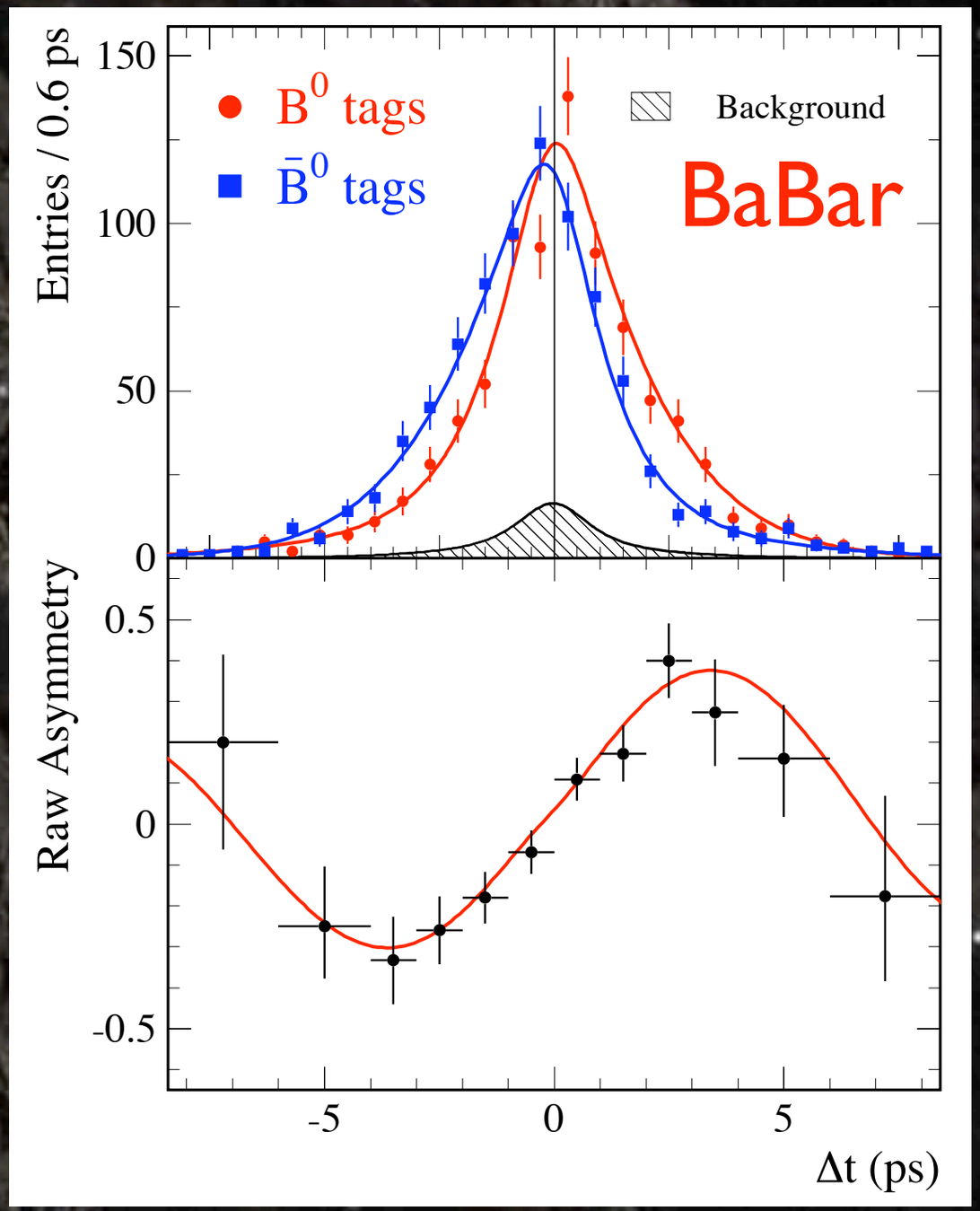

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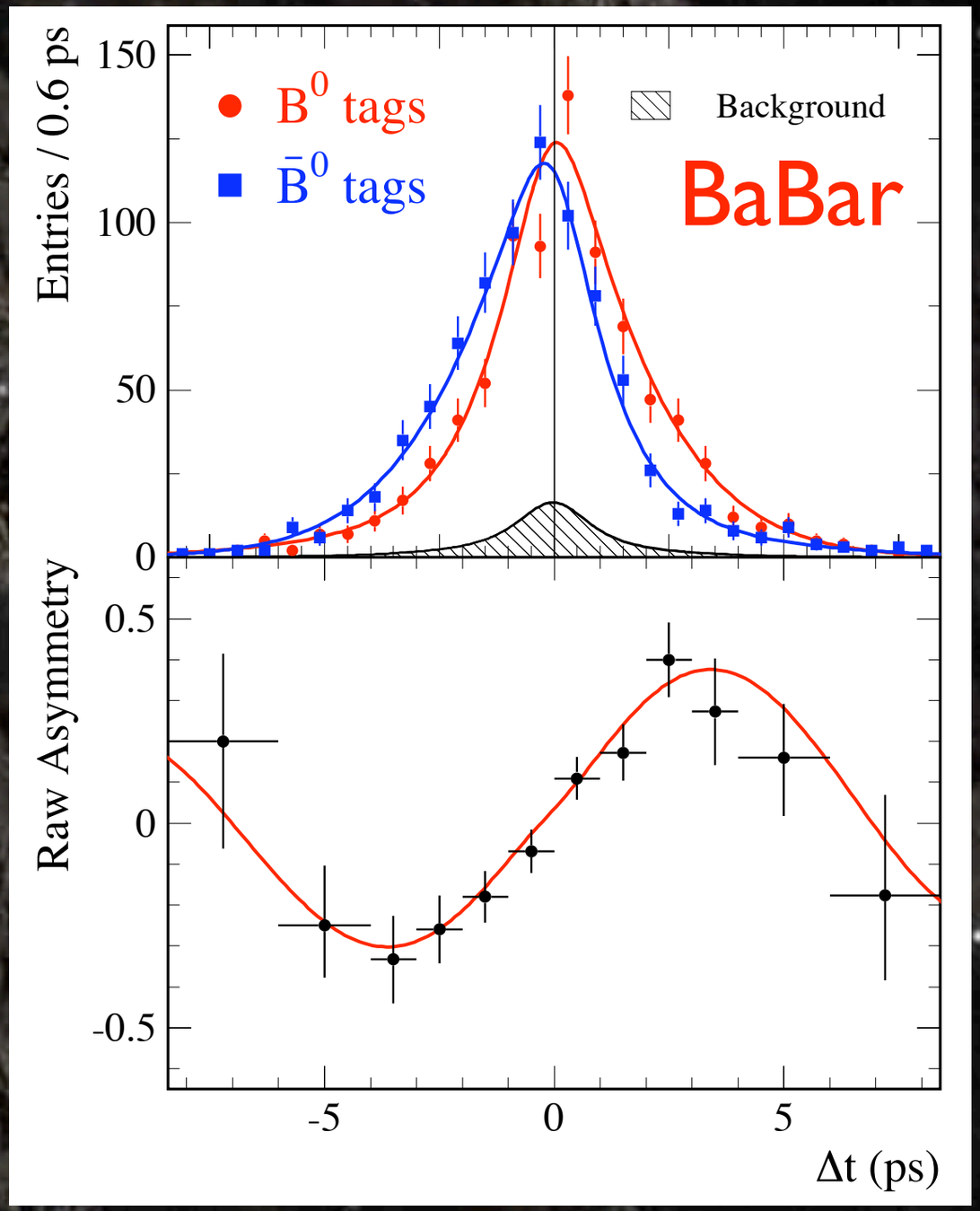

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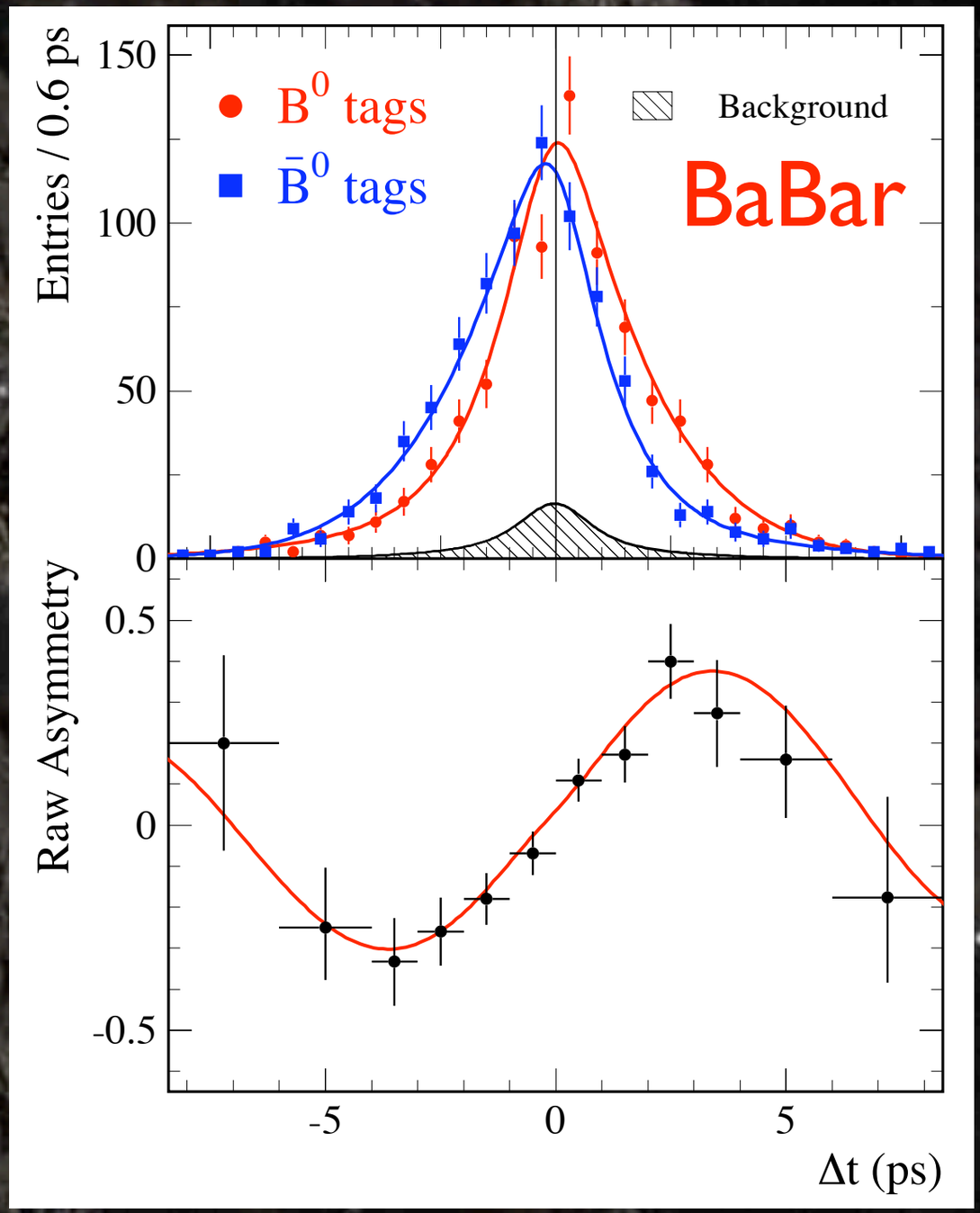

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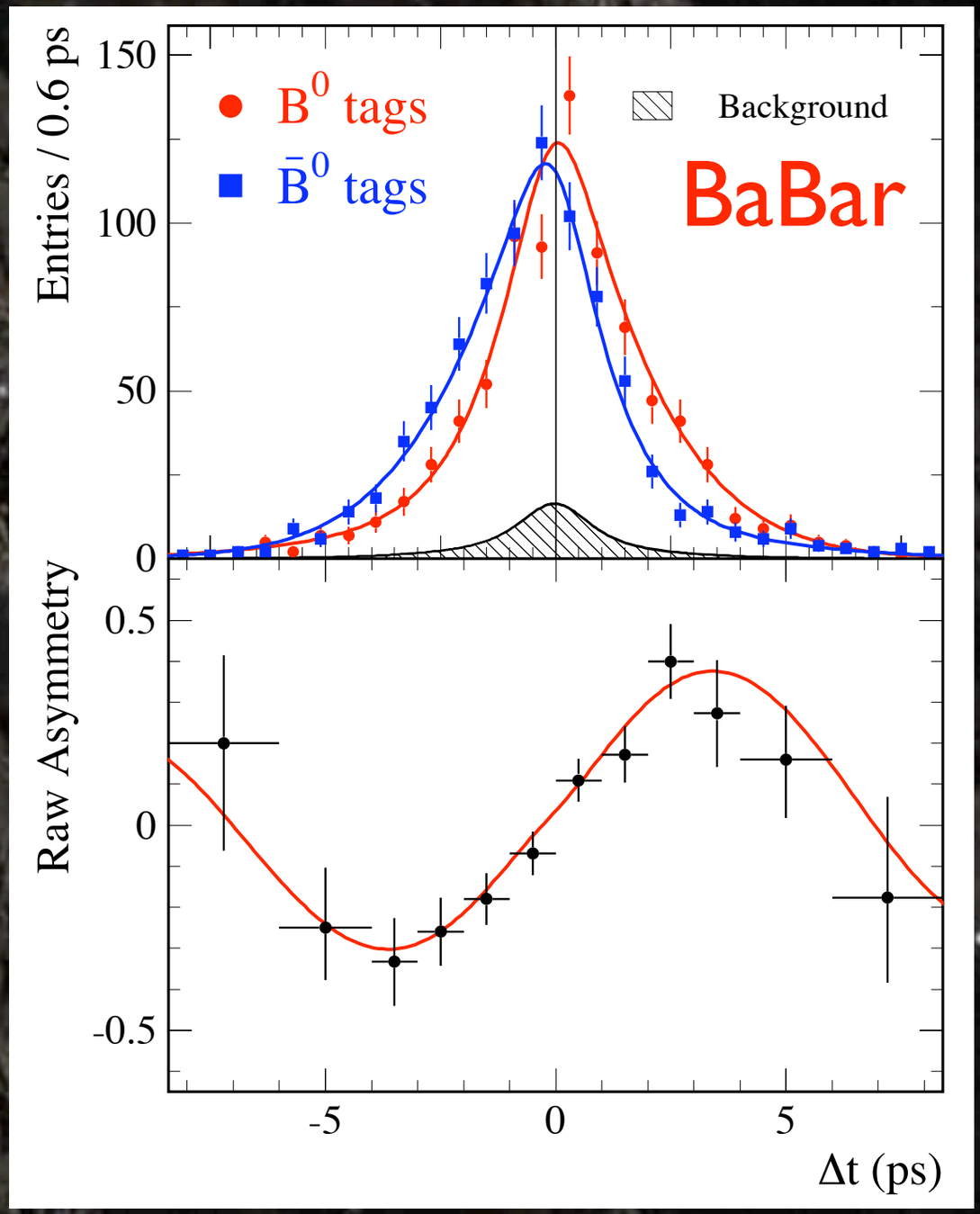

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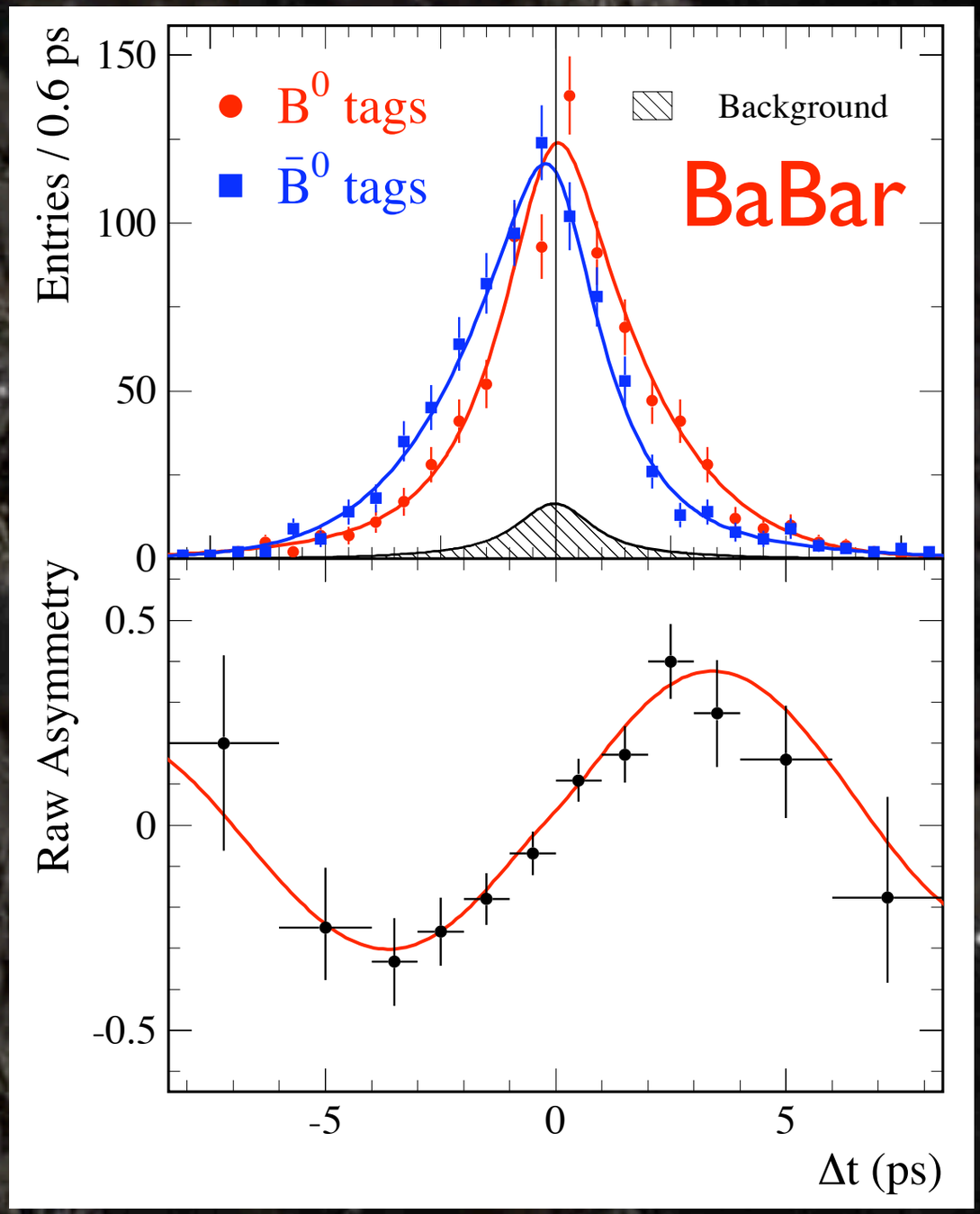

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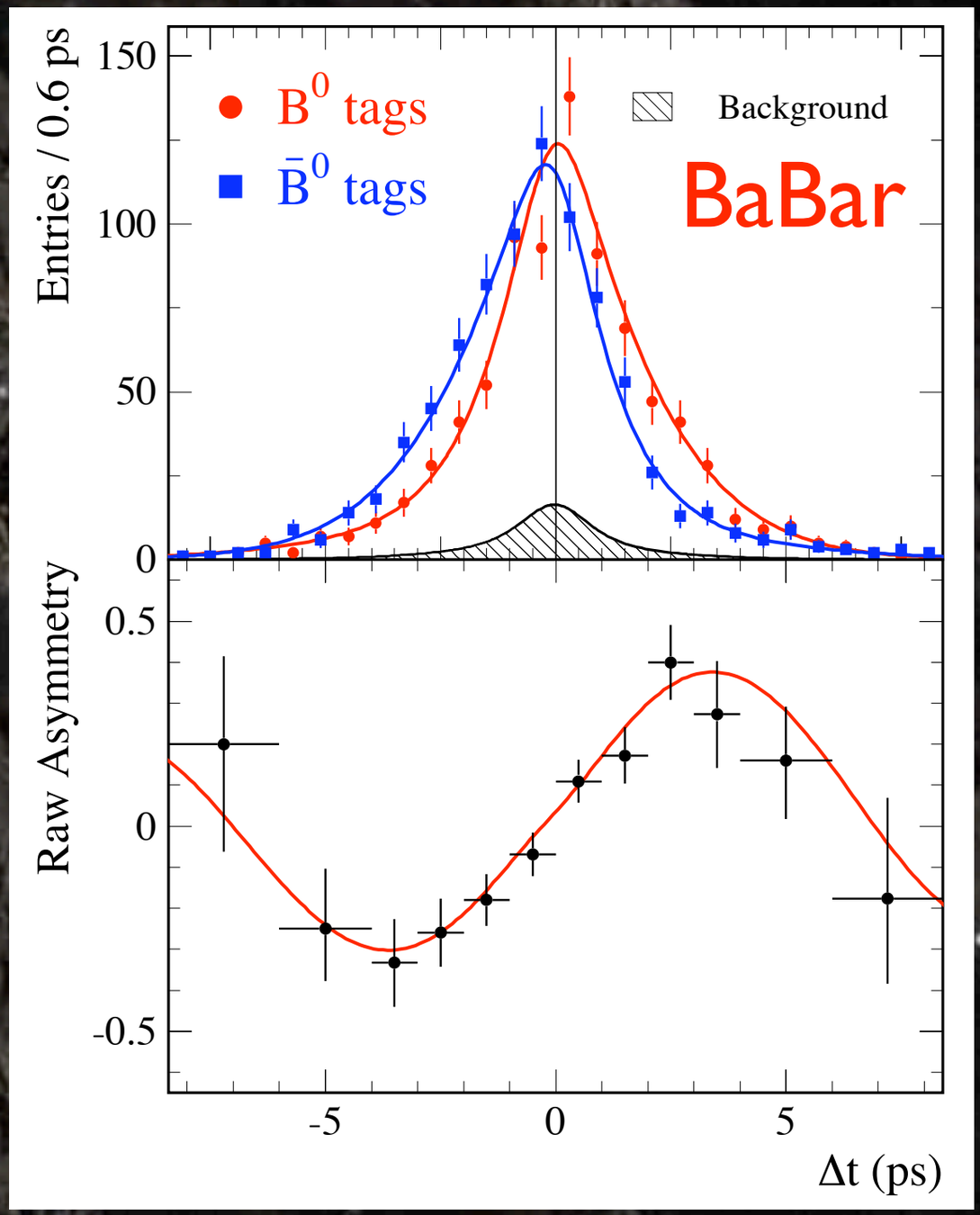

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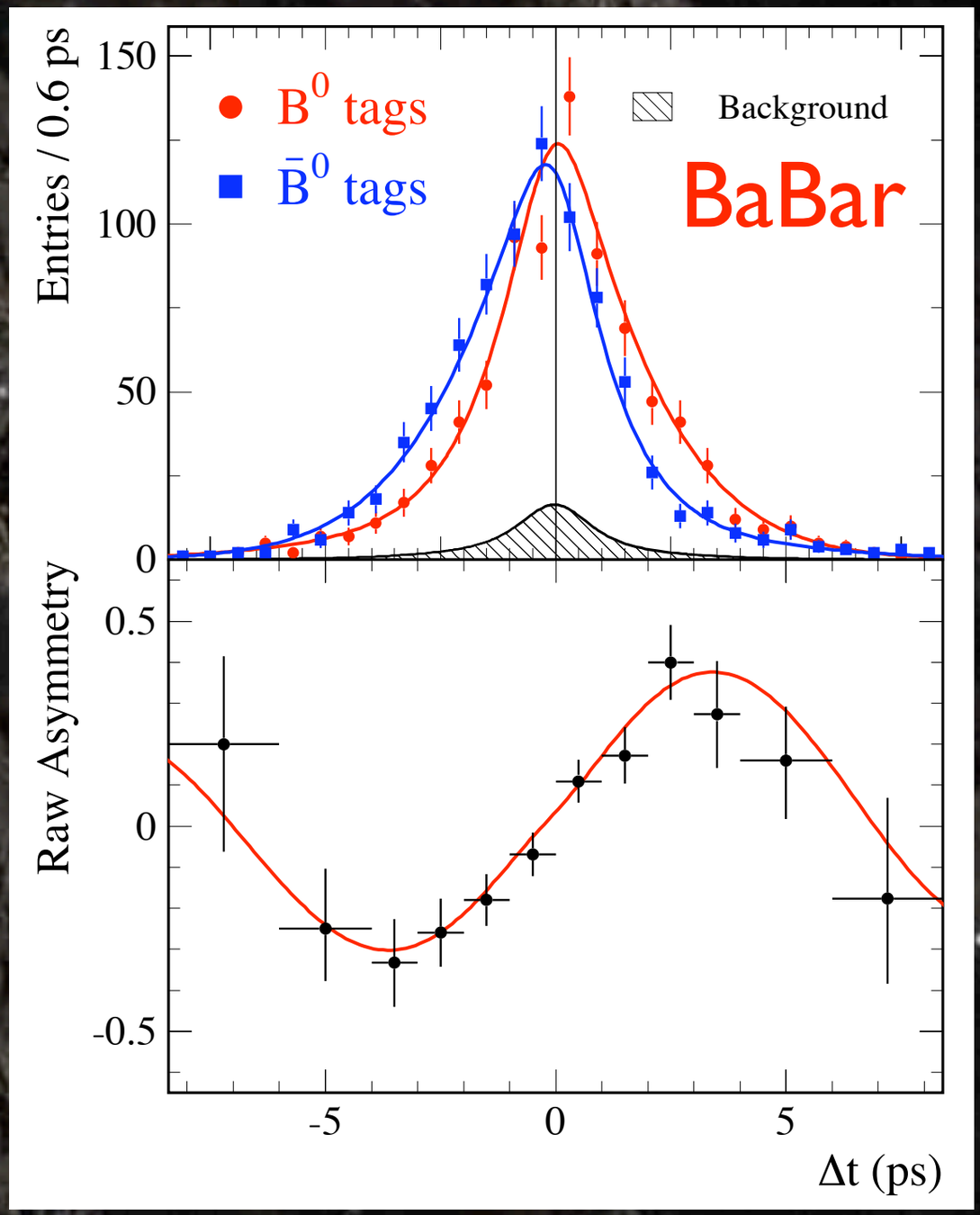
But observed CP violation is not large enough to explain the excess of matter by $\approx 10^{-10}$



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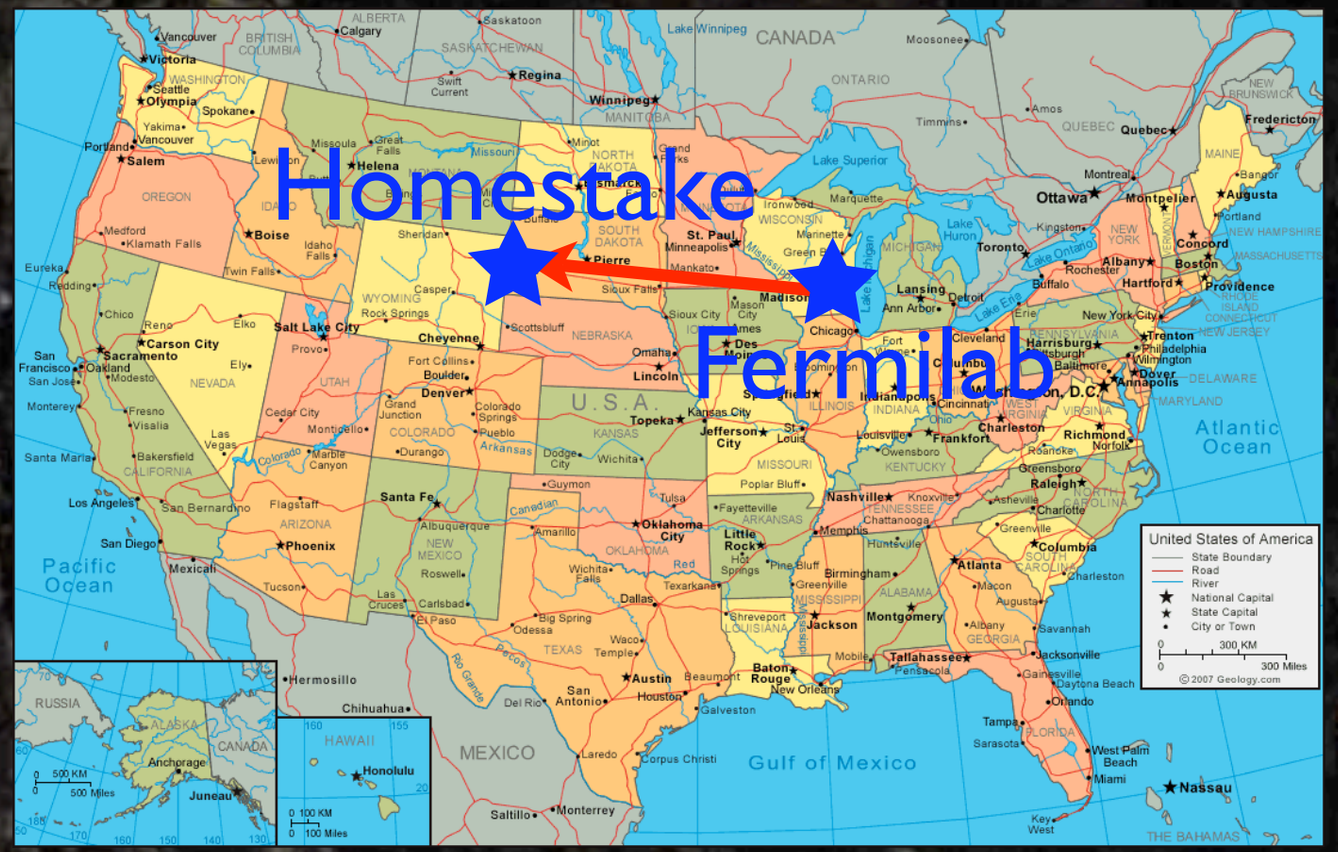
Shoot the neutrino beams over thousands of kilometers to see this subtle difference



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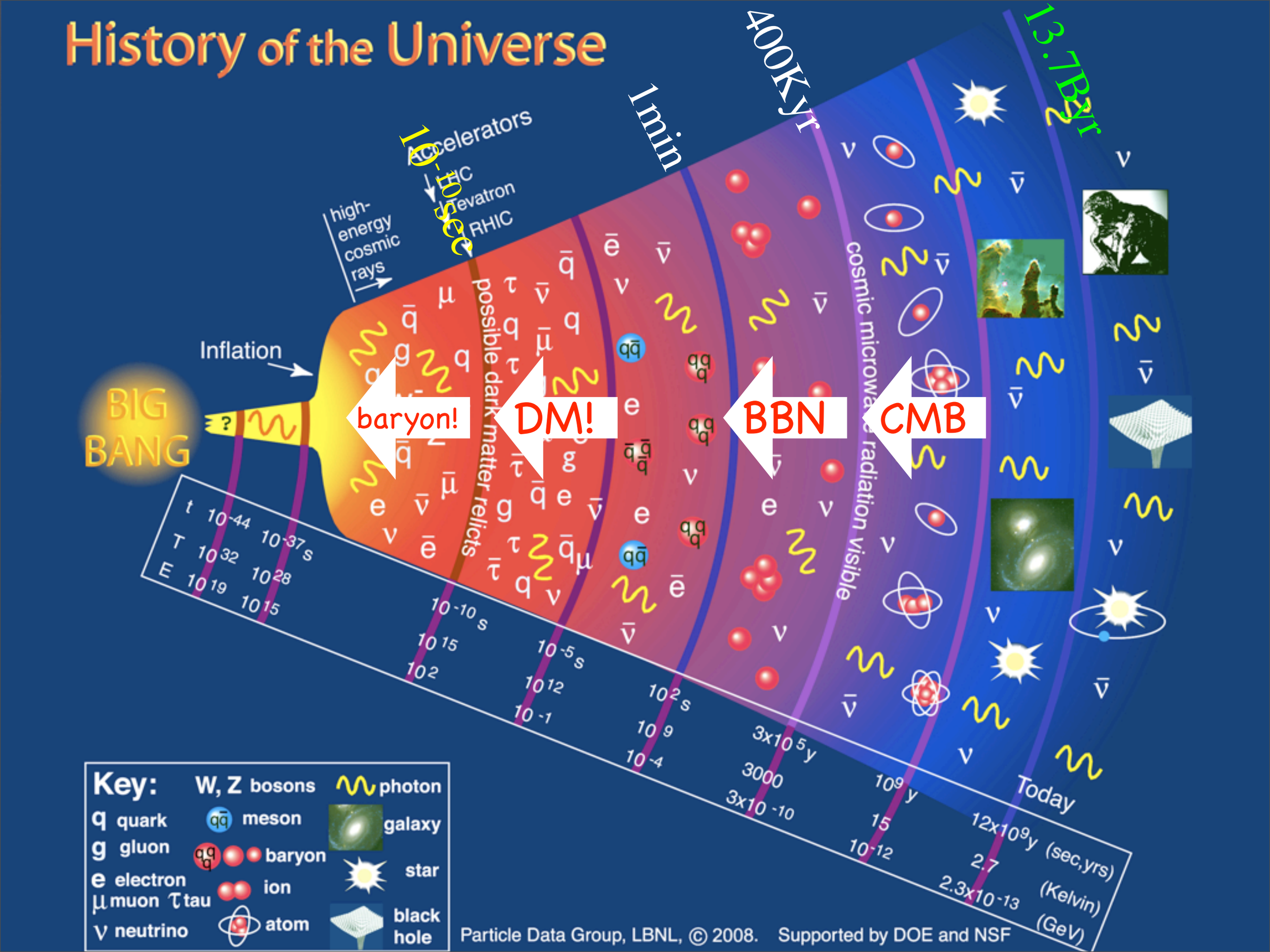
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF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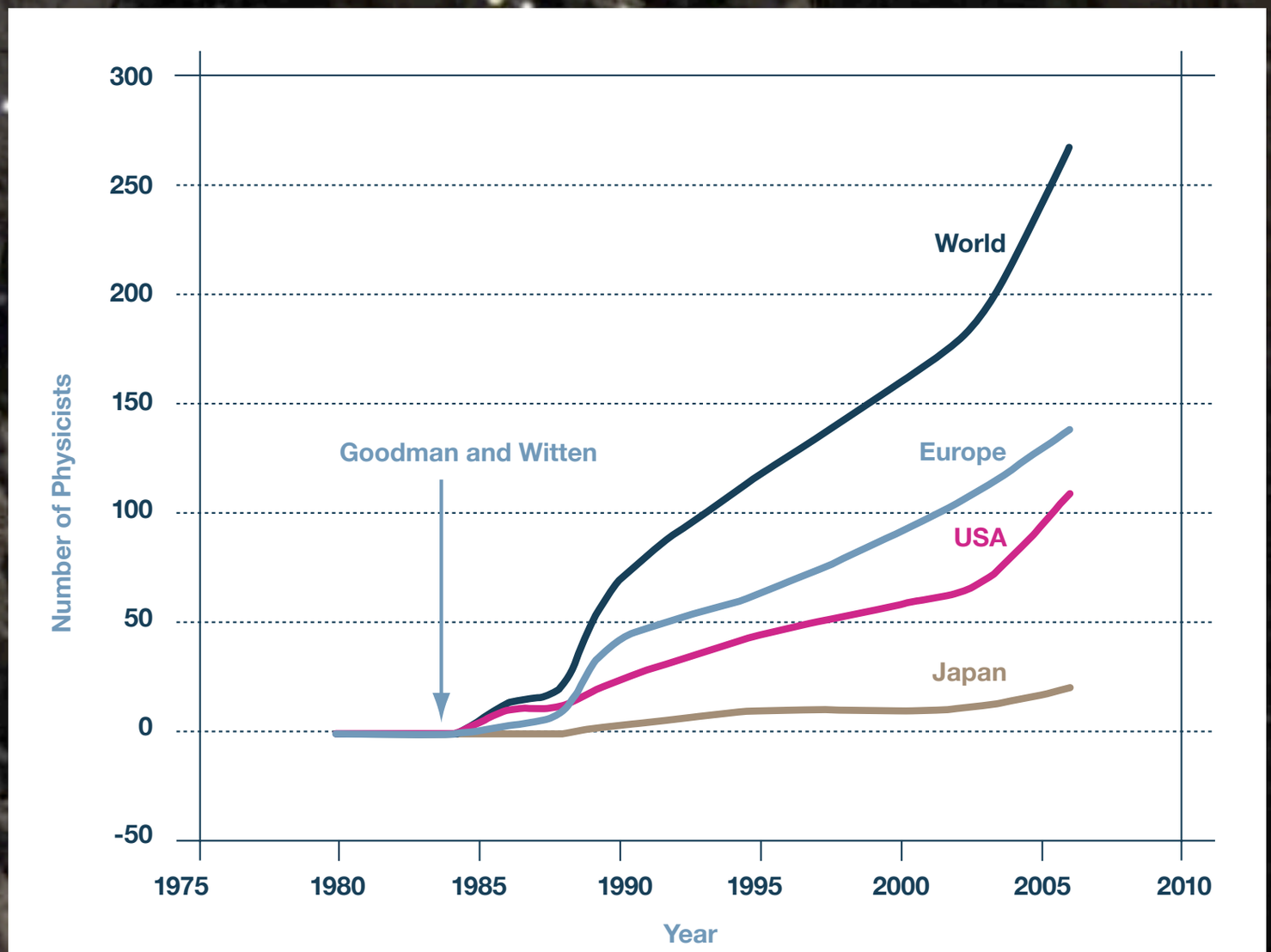
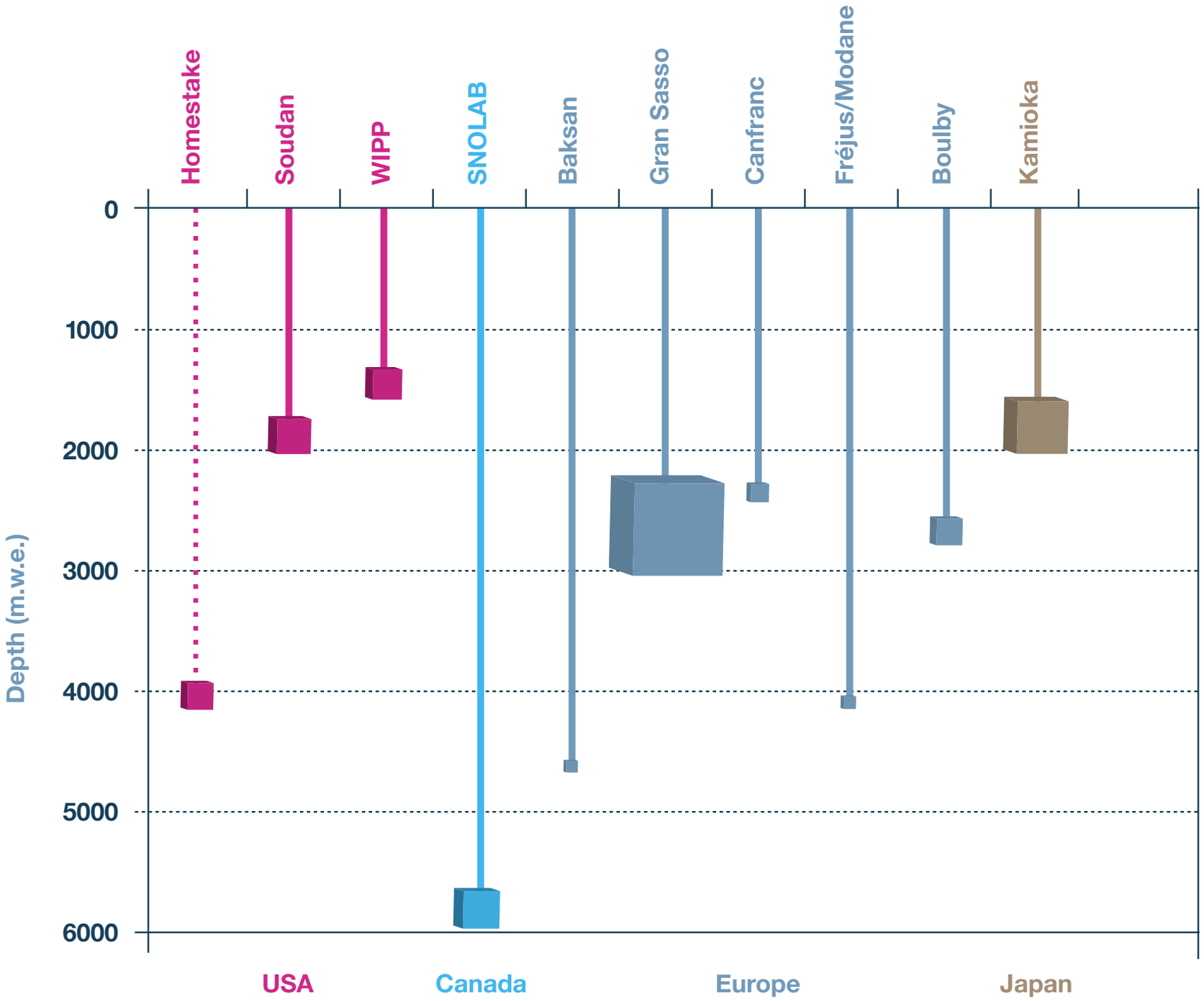
Making It Happen

Growing Community

- number of scientists involved in direct search for dark matter



World Facilities



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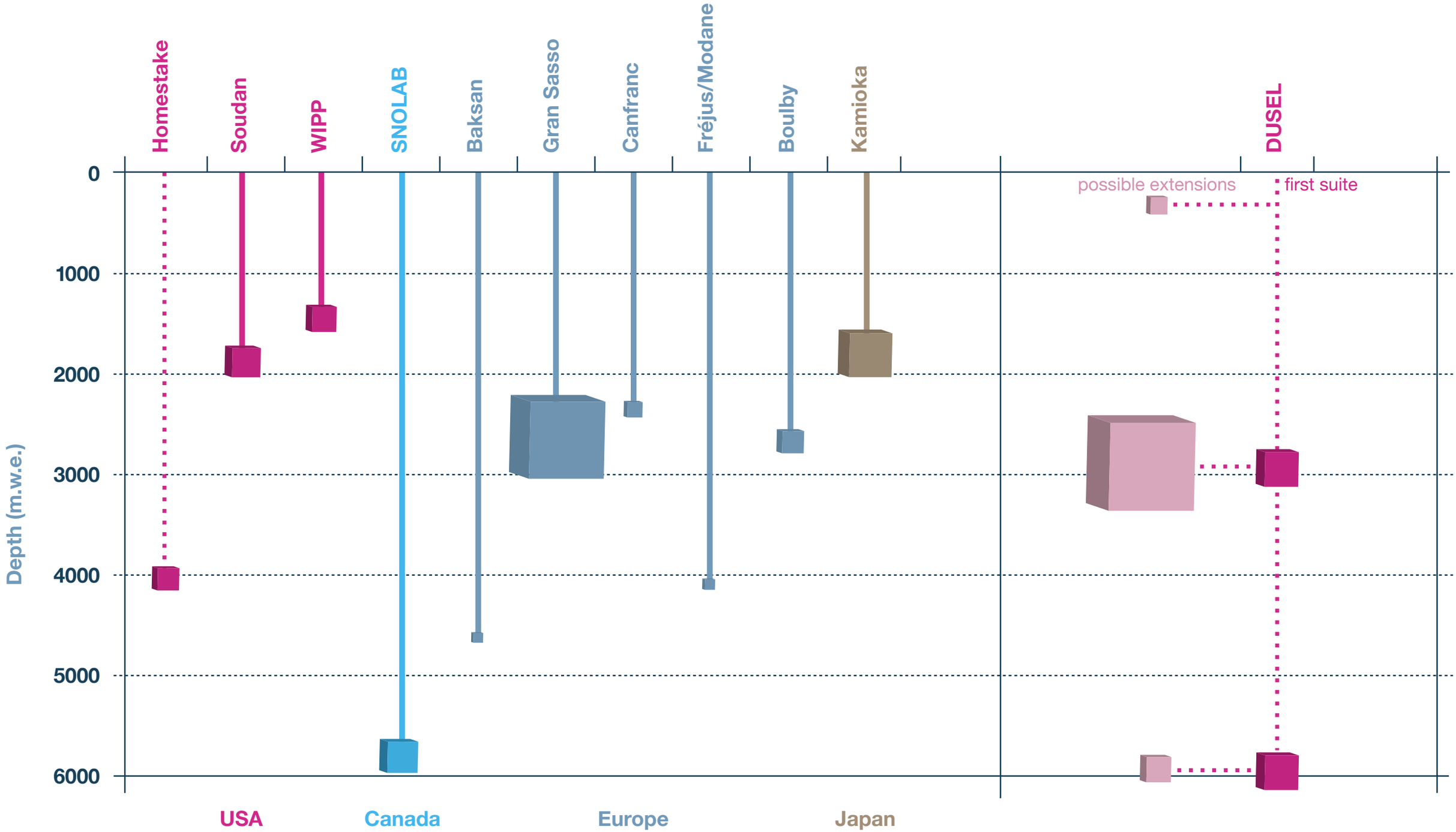


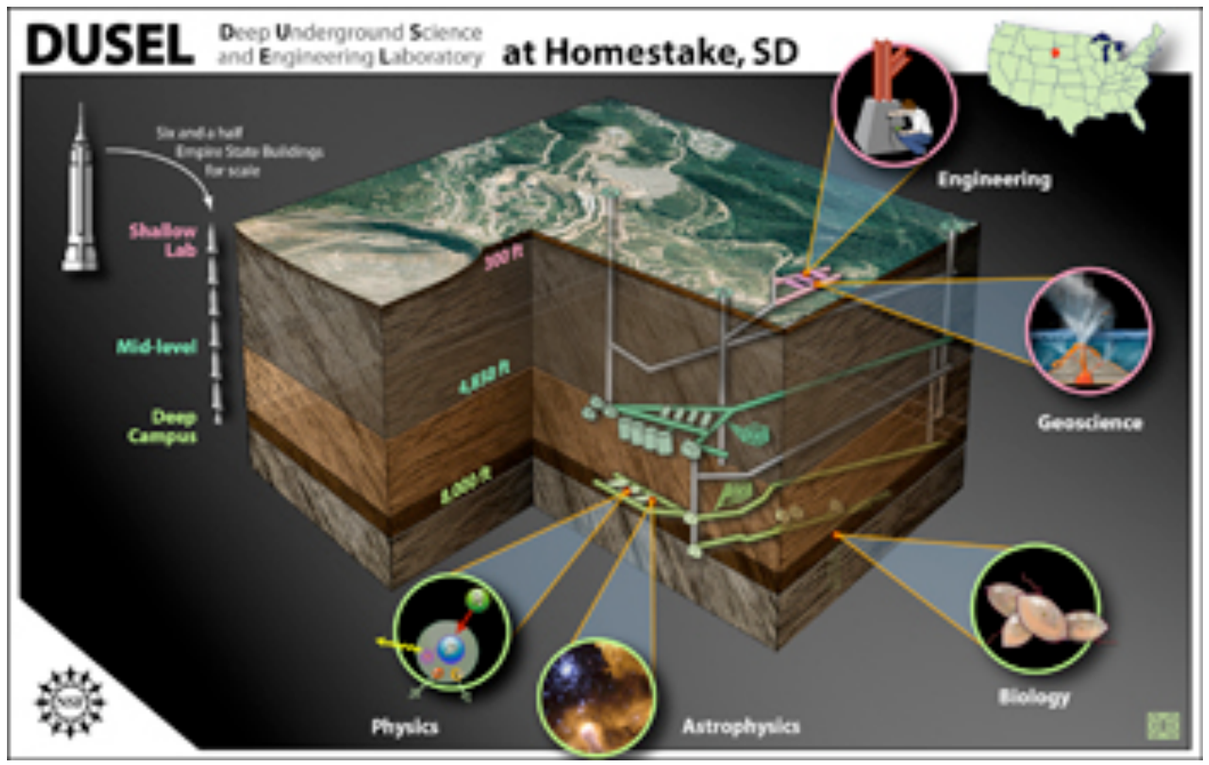
National Science Foundation
WHERE DISCOVERIES BEGIN

National Science Foundation

- *Where should this exciting science to study the universe underground done?*
- Initially many possible sites
- South Dakota state legislature committed $36 million
- down to one in 2007: Homestake

Press Release 07-075

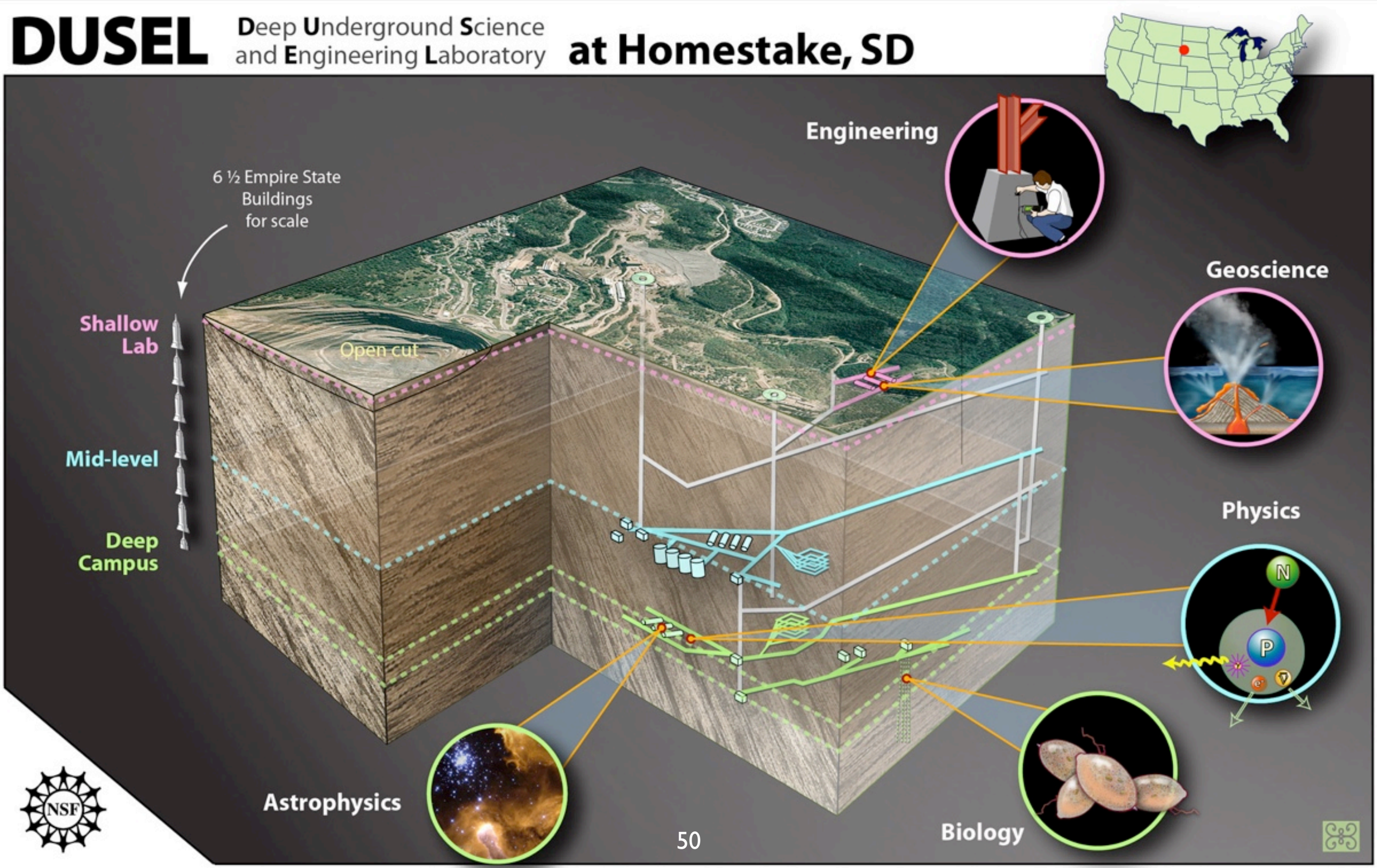
Team Selected for the Proposed Design of the Deep Underground Science and Engineering Laboratory



An artist's rendition of the proposed Deep Underground Science and Engineering Laboratory design.
Credit and Larger Version

July 10, 2007

A Lot of Science



Kick-start

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Sanford Laboratory at Homestake

Kick-start

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Cosmic Questions for DUSEL

What is the Universe made of?

What is Dark Matter?

Did neutrinos form galaxies?

Where did the Anti-Matter go?

Where did we come from?

We need to go underground to answer the cosmic questions!

Captivate the young minds, nurture the next generation

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