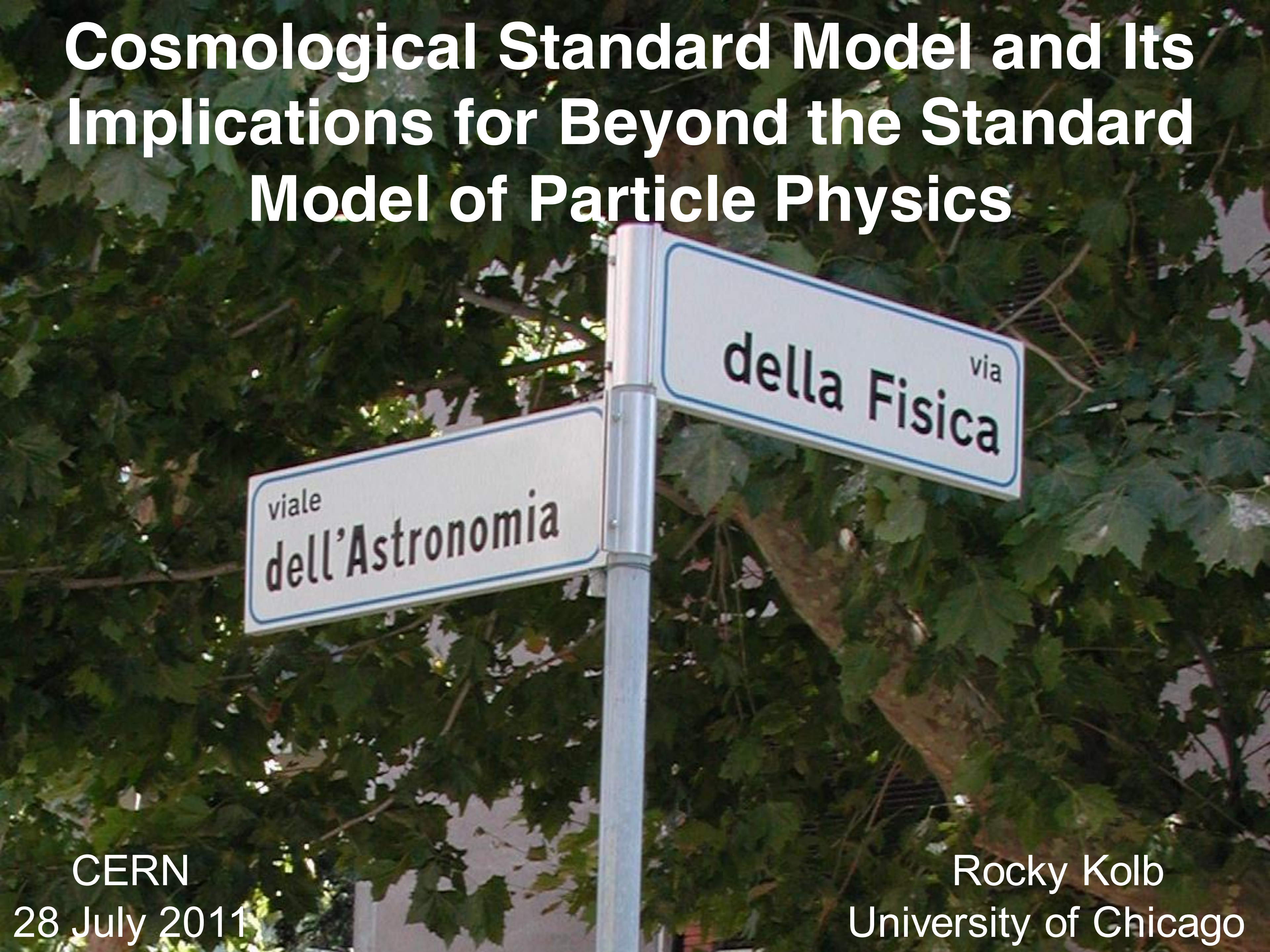
Cosmological Standard Model and Its Implications for Beyond the Standard Model of Particle Physics



CERN
28 July 2011

Rocky Kolb
University of Chicago

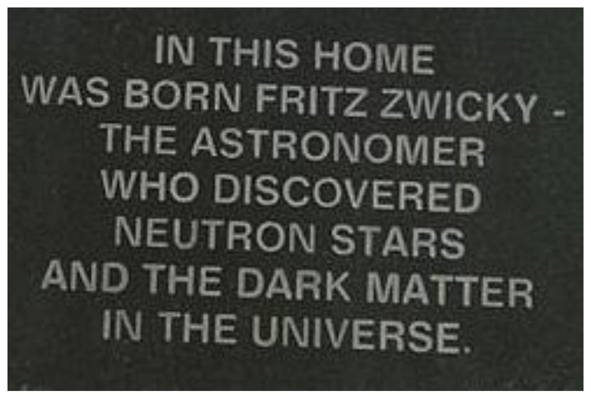
Standard Cosmological Model ΛCDM

"How helpful is astronomy's pedantic accuracy, which I used to secretly ridicule!"

Einstein's to Arnold Sommerfeld on December 9, 1915 (measurements of the perihelion advance of Mercury)

Beyond Standard Model Physics

Dark Matter



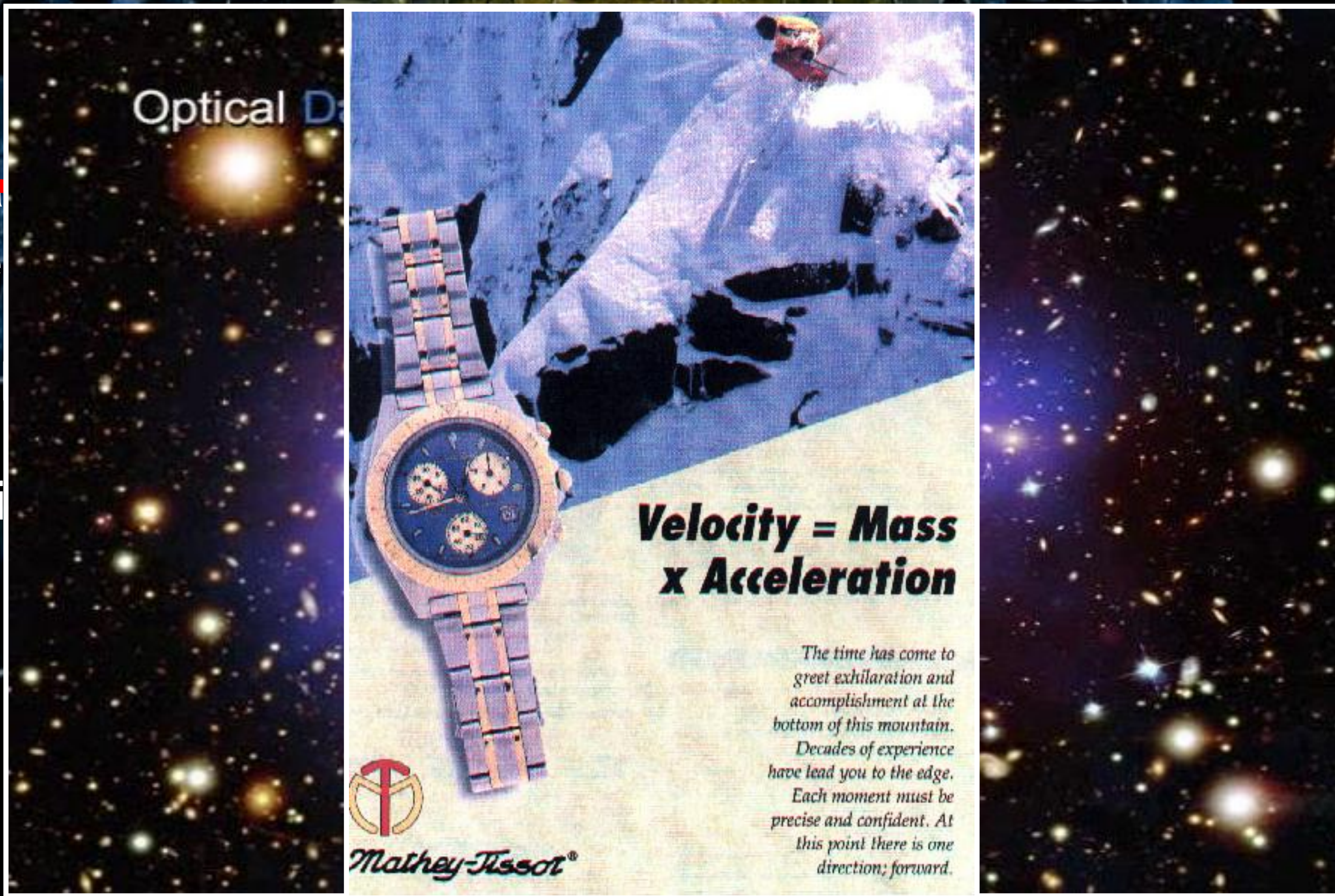
Varna, Bulgaria

Fritz Zwicky
Clusters 1930s
Swiss (Mollis, Glarus)
ETHZ: Weyl,
Scherrer, & Debye


Fritz Zwicky

Dark Matter

- Modified Newtonian Dynamics
- Plan
- ~~Dwa~~
  Size
- Blac
- Parti



Particle Relic from the Bang

- neutrinos
- sterile neutrinos, gravitinos
- LSP (neutralino)
- LKP (lightest Kaluza-Klein particle)

} thermal relics

- B.E.C.s, axions, axion clusters
- solitons (Q-balls, B-balls, odd-balls, …)
- supermassive wimpzillas

} nonthermal relics

<u>Mass range</u>

$10^{-22}\,\mathrm{eV}\ \ (10^{-56}\,\mathrm{g})$ B.E.C.

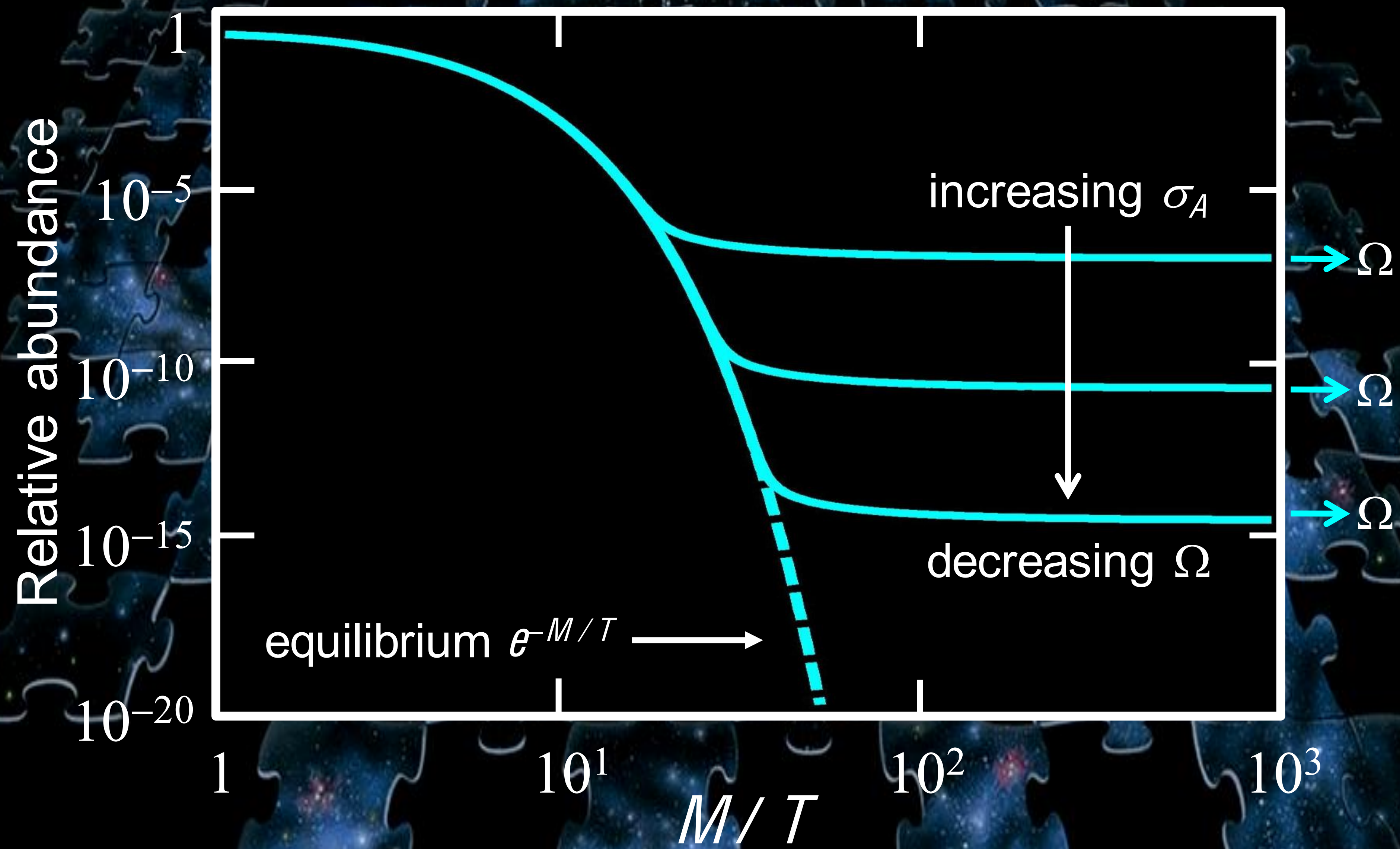
$10^{-8}\,M_{\odot}\ \ (10^{25}\,\mathrm{g})$ axion clusters

<u>Interaction strength range</u>

Only gravitational: wimpzillas

Strongly interacting: B balls

*Cold Thermal Relics**

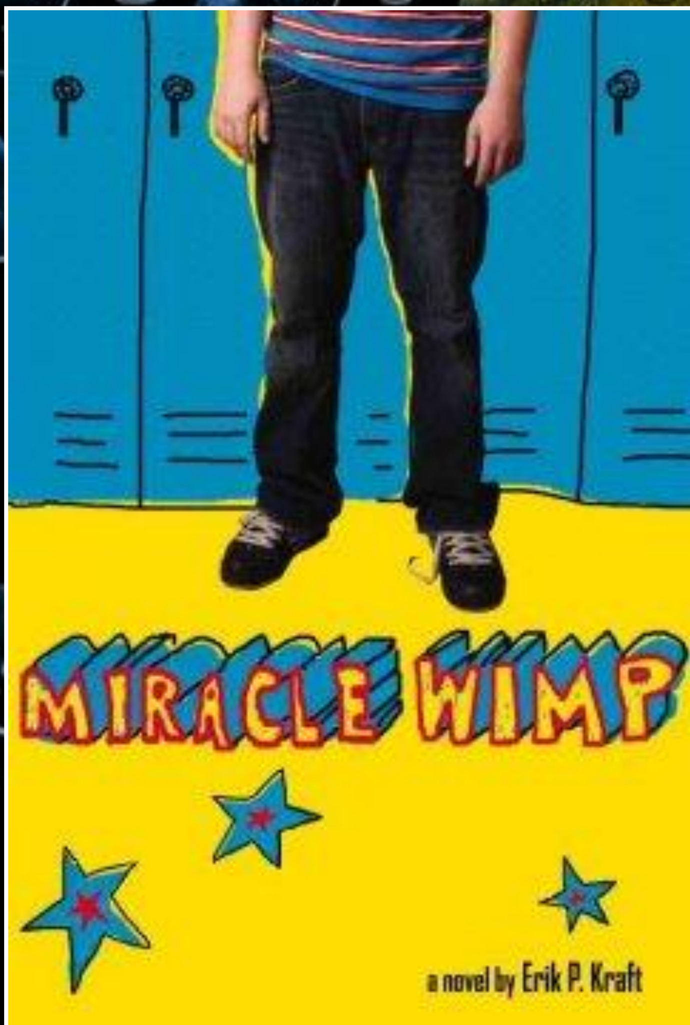


* An object of particular veneration.

The WIMP "*Miracle*"

$\Omega \Rightarrow$ Cross section (& mass ?) of order weak scale

WIMP (<u>W</u>eakly <u>I</u>nteracting <u>M</u>assive <u>P</u>article)



mir·a·cle
\ˈmir-i-kəl \
noun

1 : an extraordinary event manifesting divine intervention in human affairs

Coincidence or Causation?

WIMPs

Goal: Discover dark matter and its role in shaping the universe

<u>Particle Physics:</u>

Discover dark matter and learn how it is …

… grounded in physical law

… embedded in an overarching physics model/theory

<u>Astro Physics:</u>

Understand the role of dark matter in …

… formation of structure

… evolution of structure

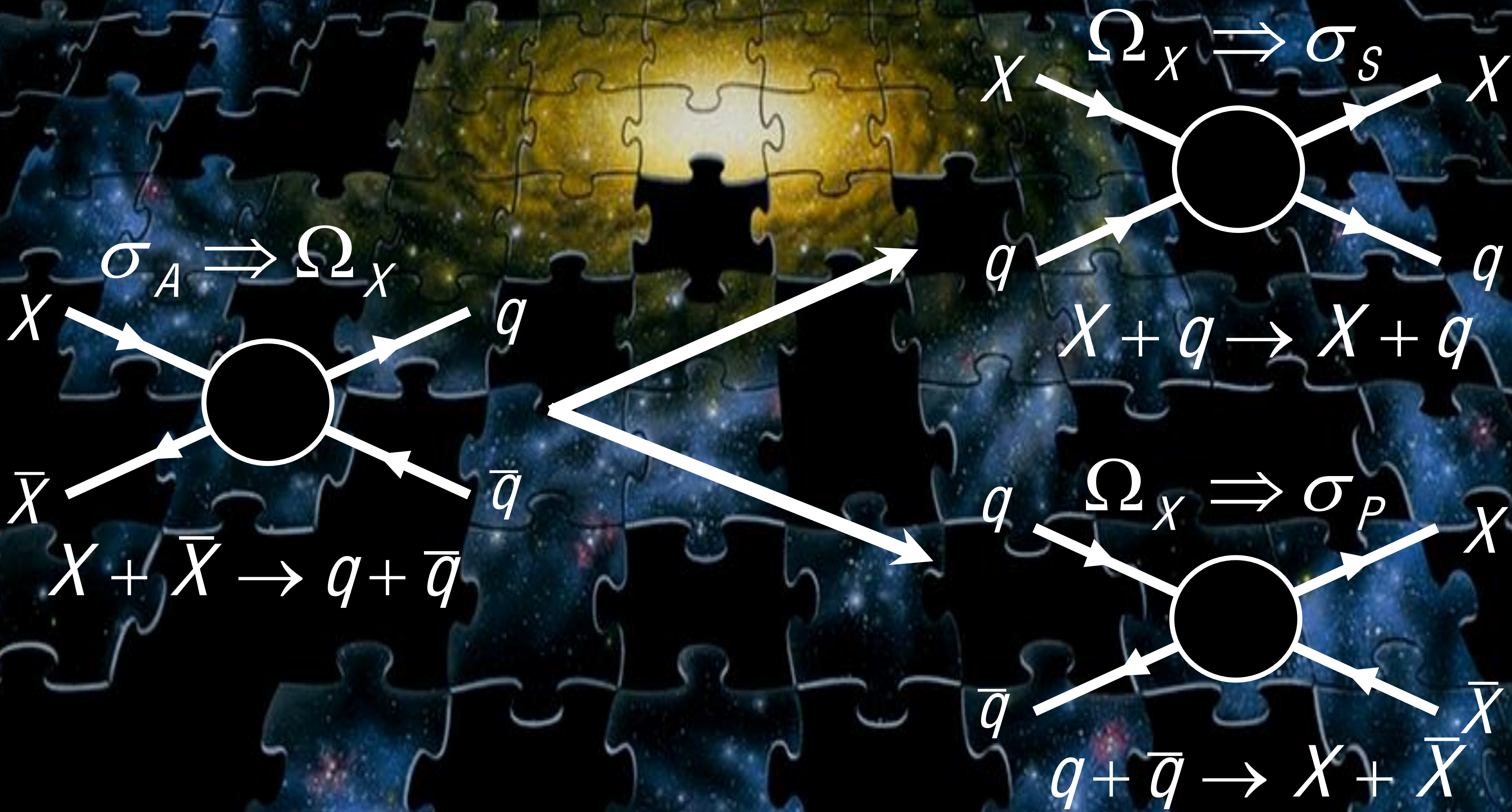
<u>WIMPs</u>:

massive, stable, “weakly” interacting, $SU(3)_C \times U(1)_{EM}$ singlet

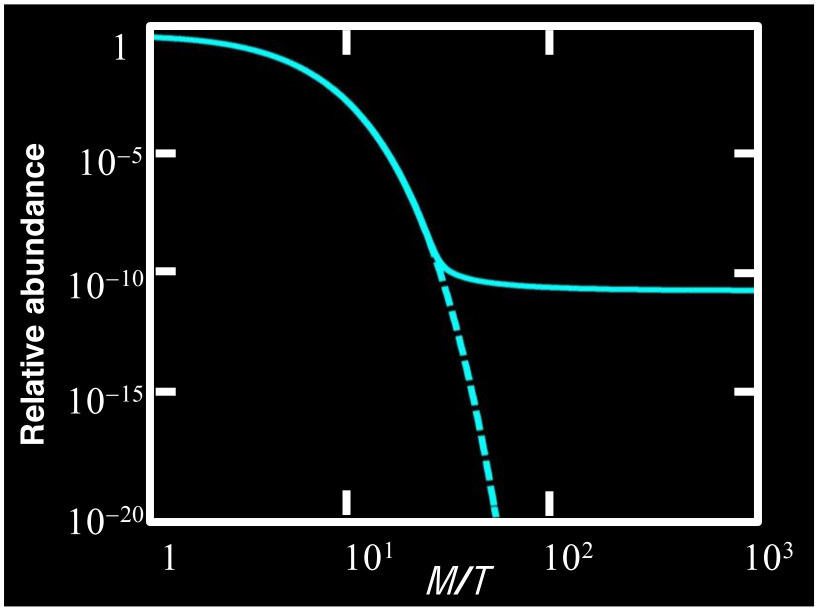
WIMP must be a *BSM* (but perhaps not far BSM) particle.

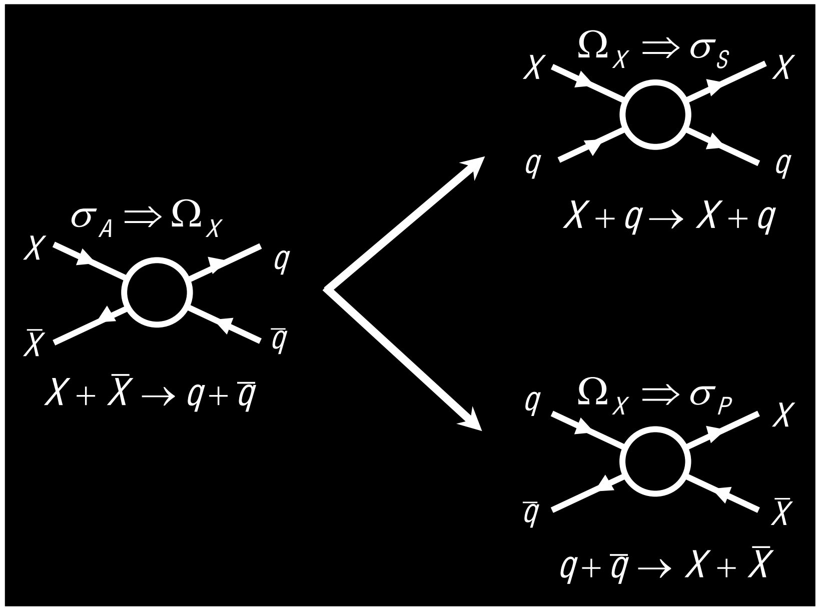
WIMPs

Too good to be true?



WIMPs





Not quite so simple:

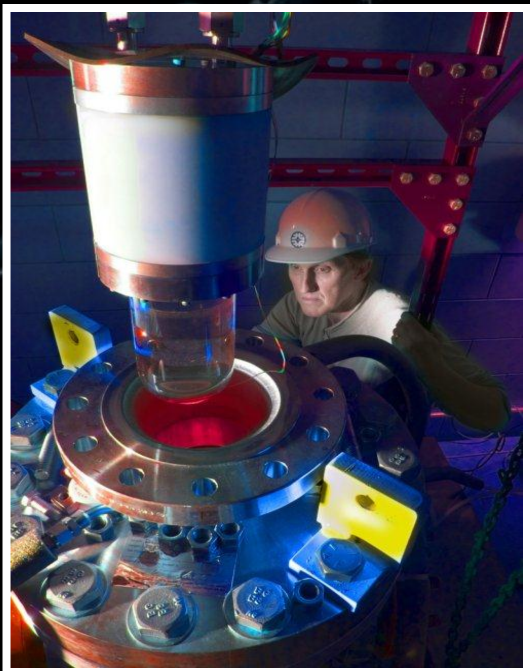
- velocity dependence
- co-annihilation
- resonances
- superwimps
- dependence on M, g_*,
- ...

Not quite so simple:

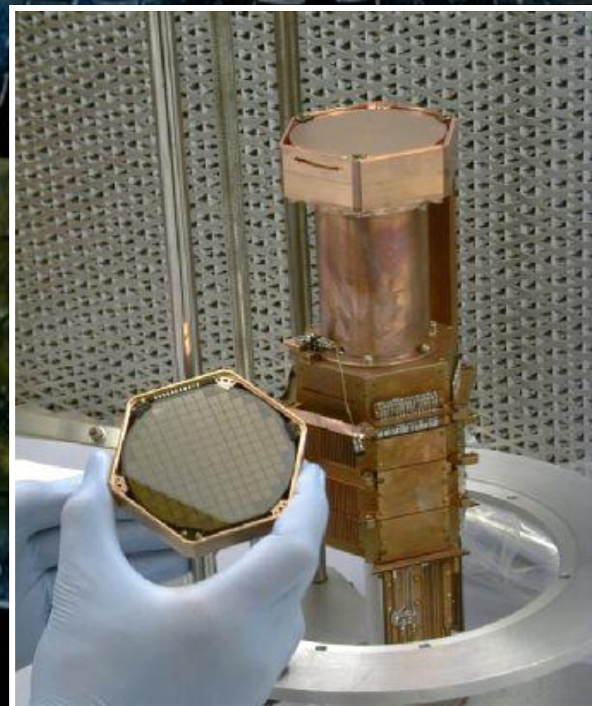
- velocity dependence
- local phase-space density
- flavor dependence
- co-production
- Sommerfield enhancement
- …

Direct Detection

COUPP



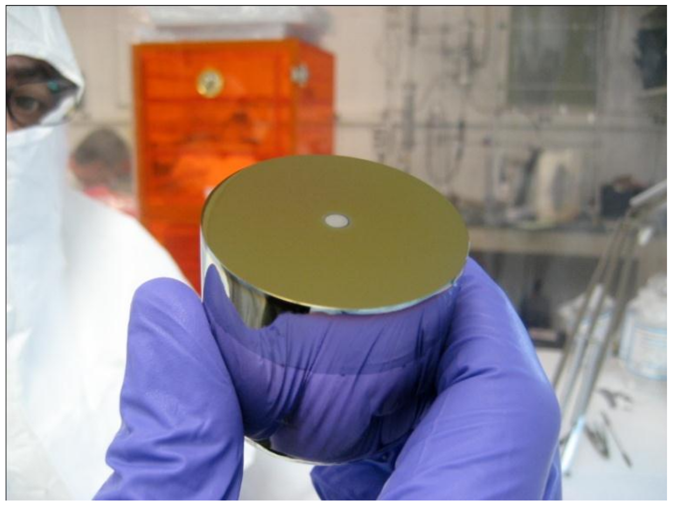
CDMS



XENON

DAMA

CoGeNT



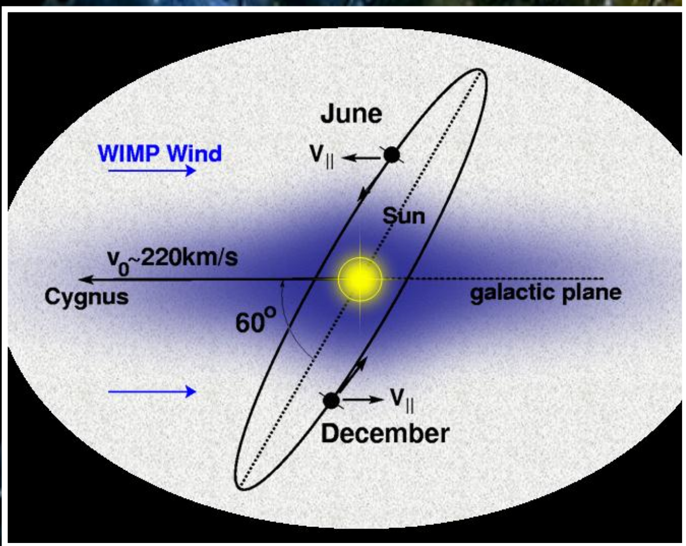
(+ EDELWEISS, CRESST, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

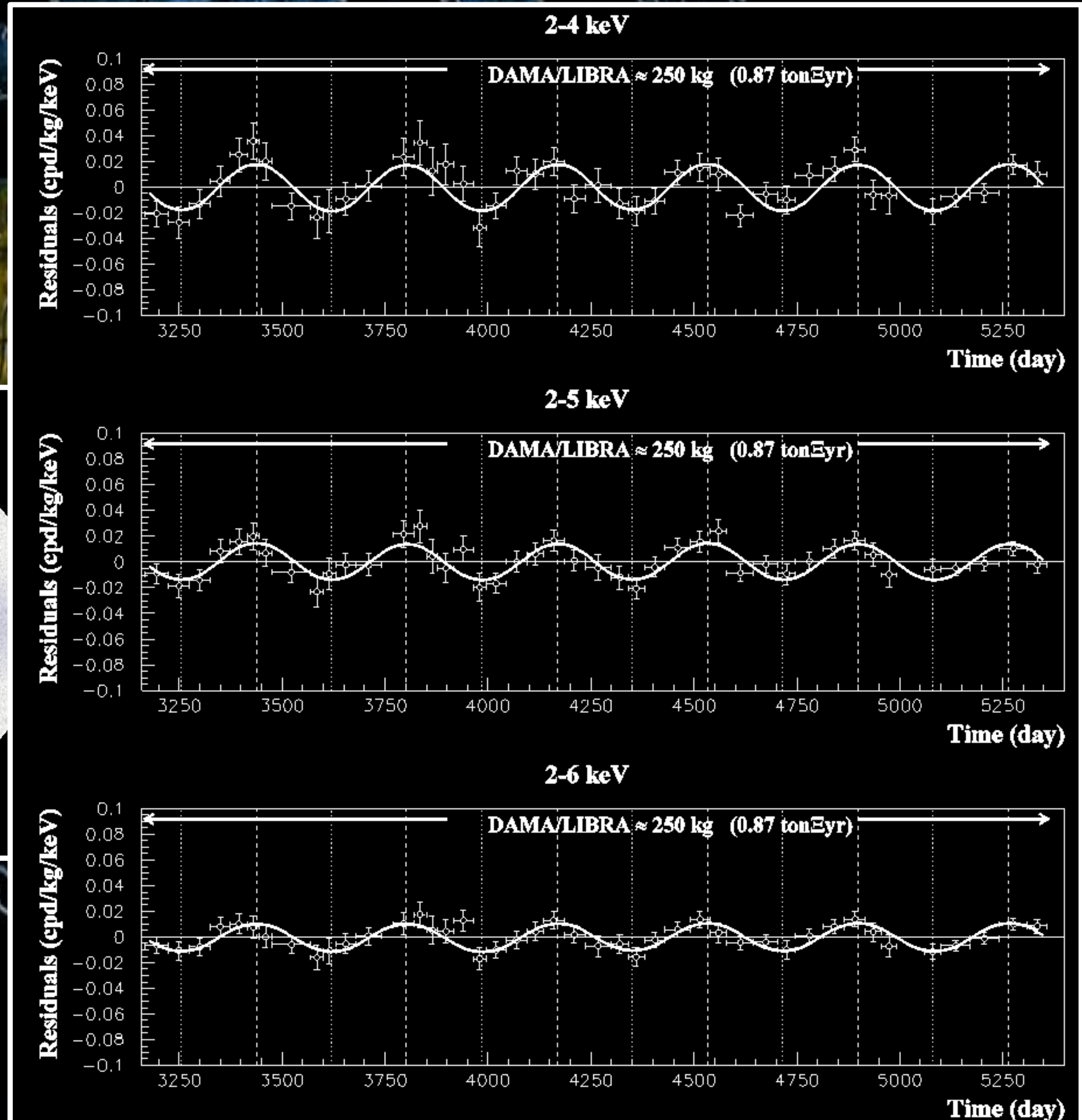
DAMA

$\cos\,\omega(t - t_0)$

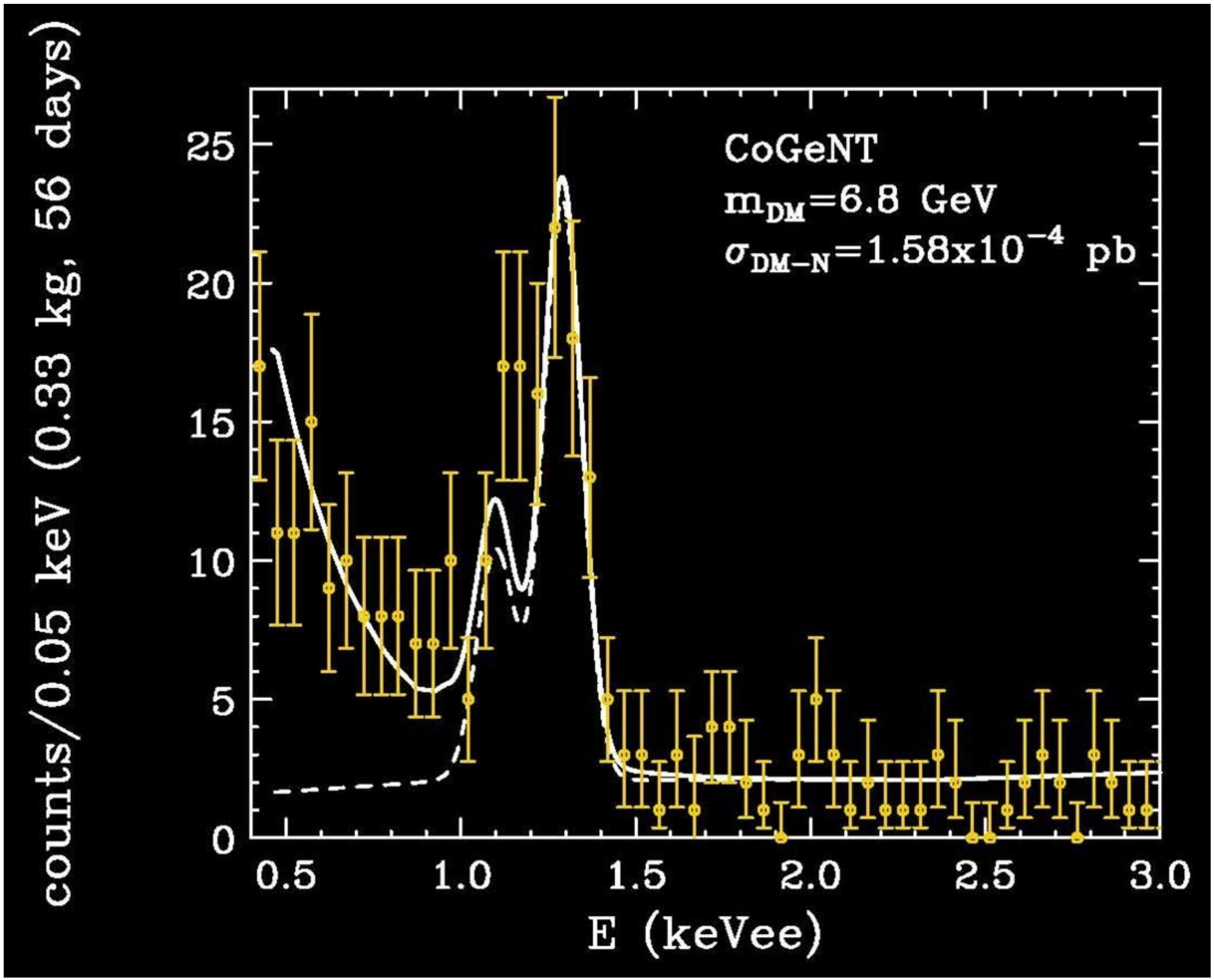
$T = 2\pi/\omega = 1$ year

$t_0 = 152.5^d$ (2 June)



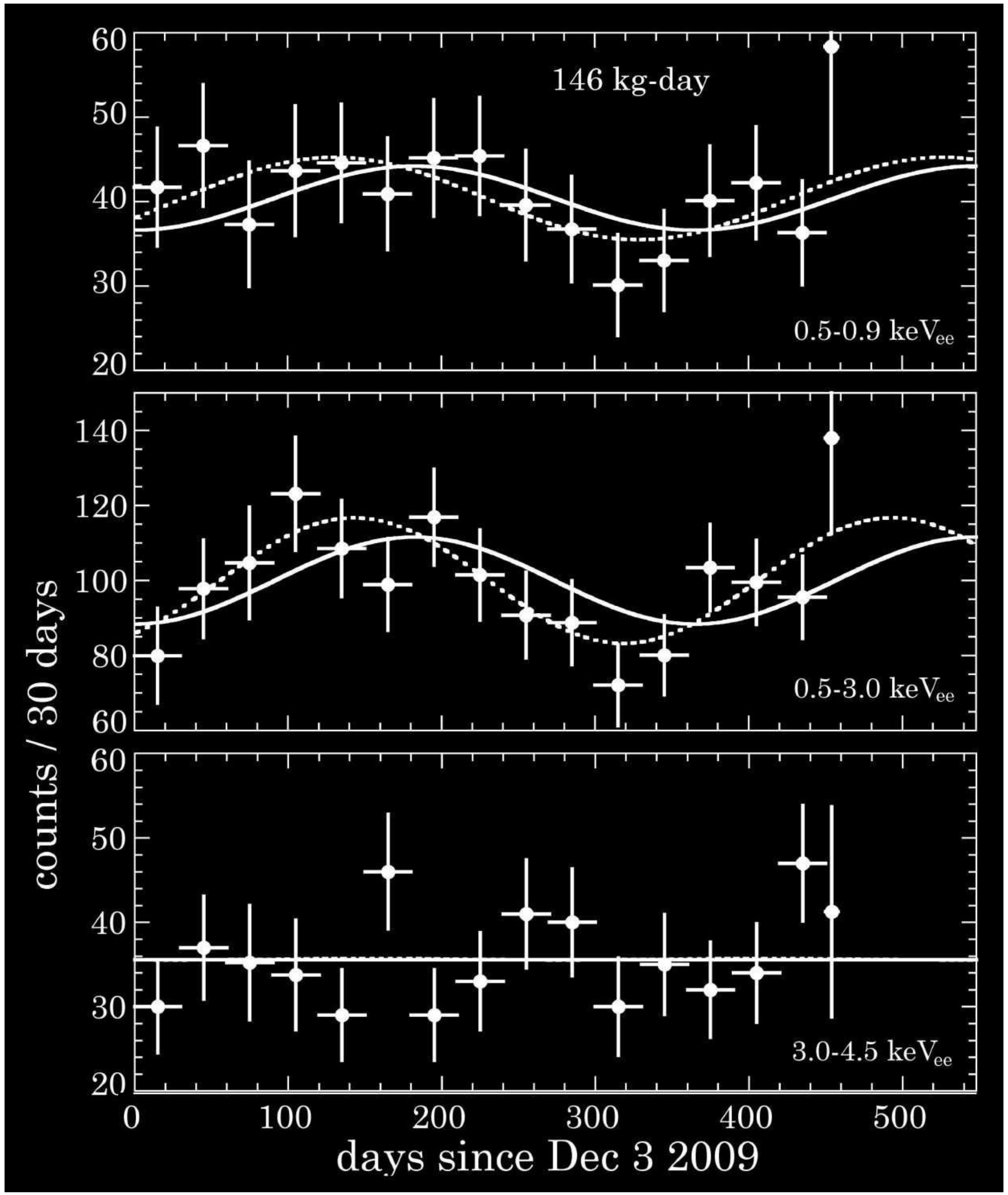


CoGeNT



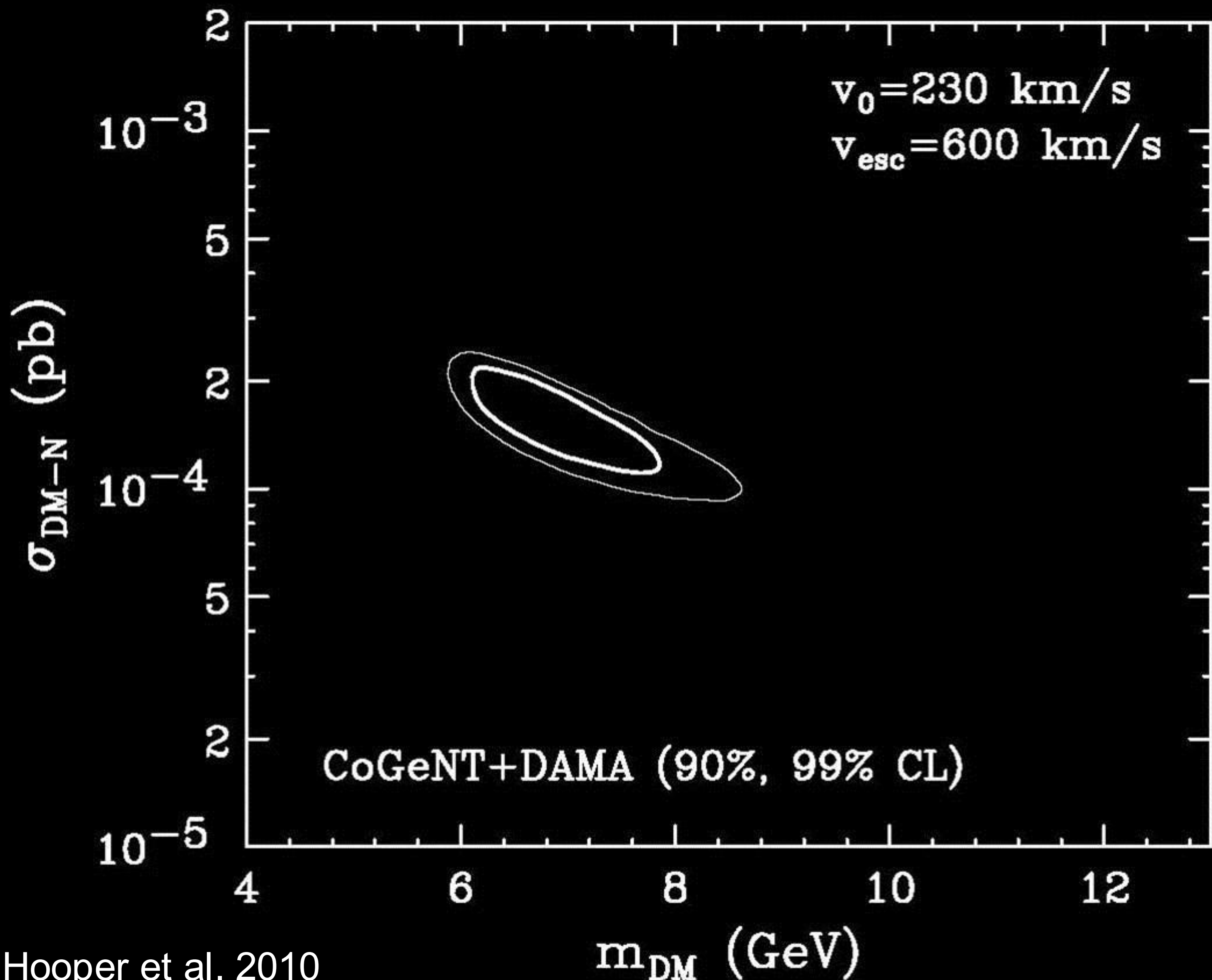
CoGeNT
m_{DM}=6.8 GeV
σ_{DM-N}=1.58x10^{-4} pb
counts/0.05 keV (0.33 kg, 56 days)
E (keVee)
0
5
10
15
20
25
0.5
1.0
1.5
2.0
2.5
3.0

CoGeNT



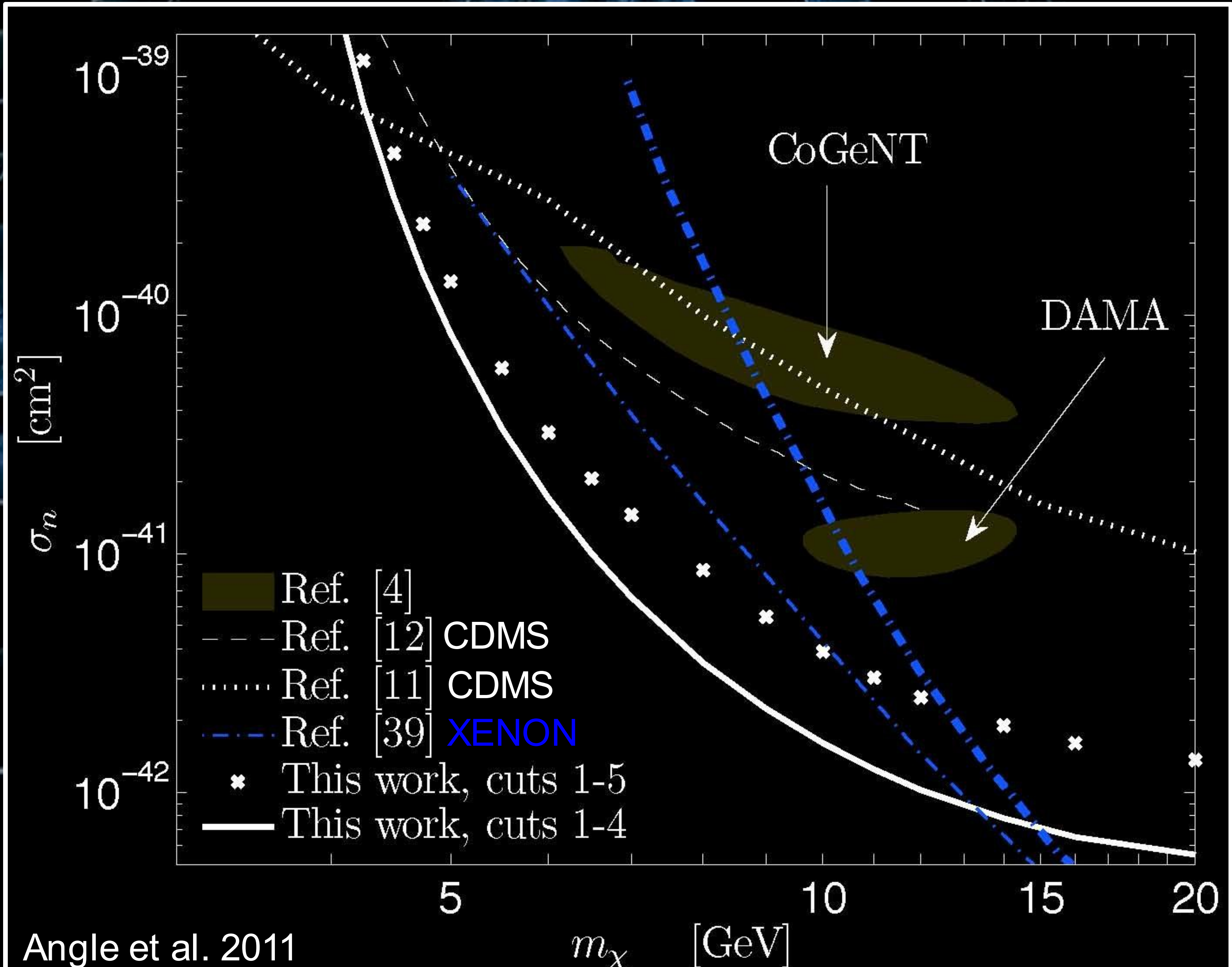
annual modulation
at 2.8σ
Aalseth et al. 2011

CoGeNT + DAMA



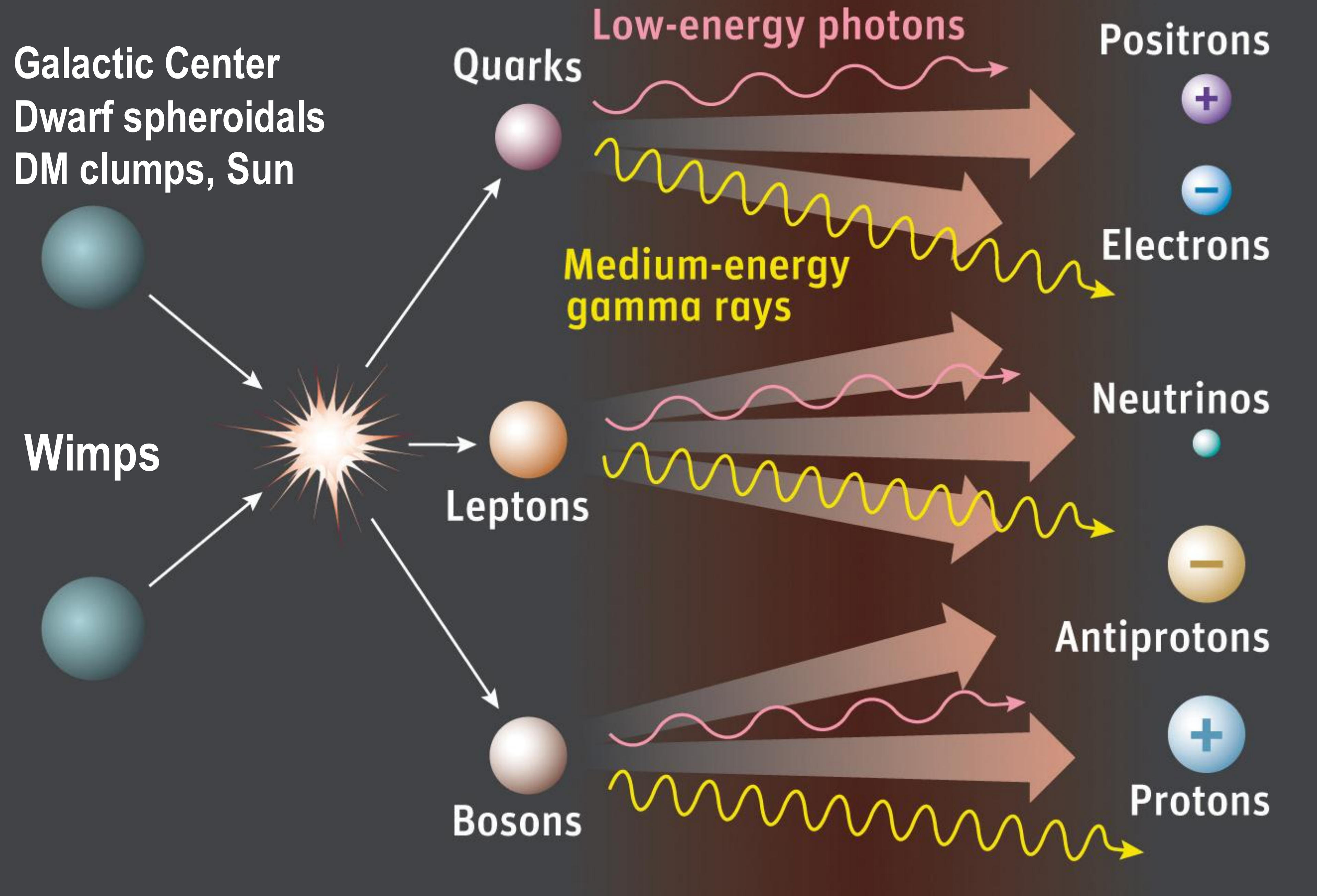
Hooper et al. 2010

XENON/CDMS

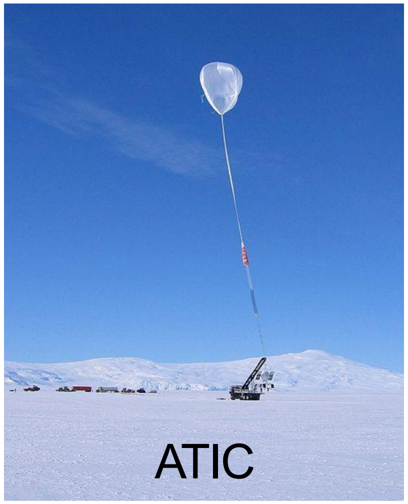


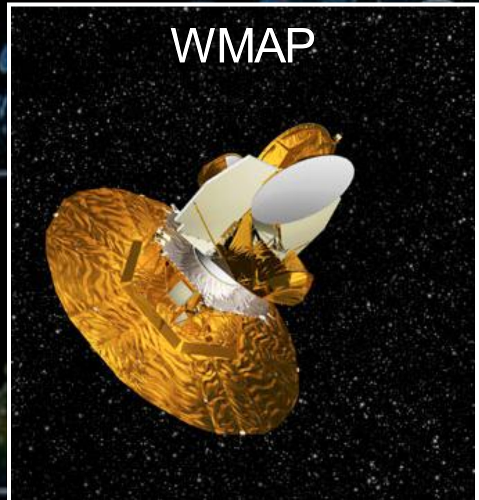
10^{-39}
10^{-40}
10^{-41}
10^{-42}
σ_n [cm^2]
CoGeNT
DAMA
Ref. [4]
Ref. [12] CDMS
Ref. [11] CDMS
Ref. [39] XENON
This work, cuts 1-5
This work, cuts 1-4
5
10
15
20
m_χ [GeV]
Angle et al. 2011

Indirect Detection

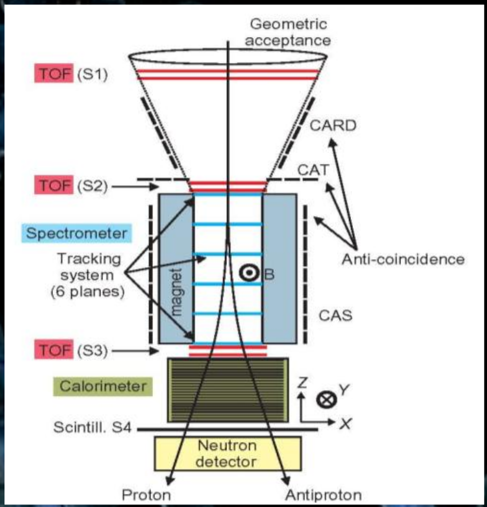


Indirect Detection

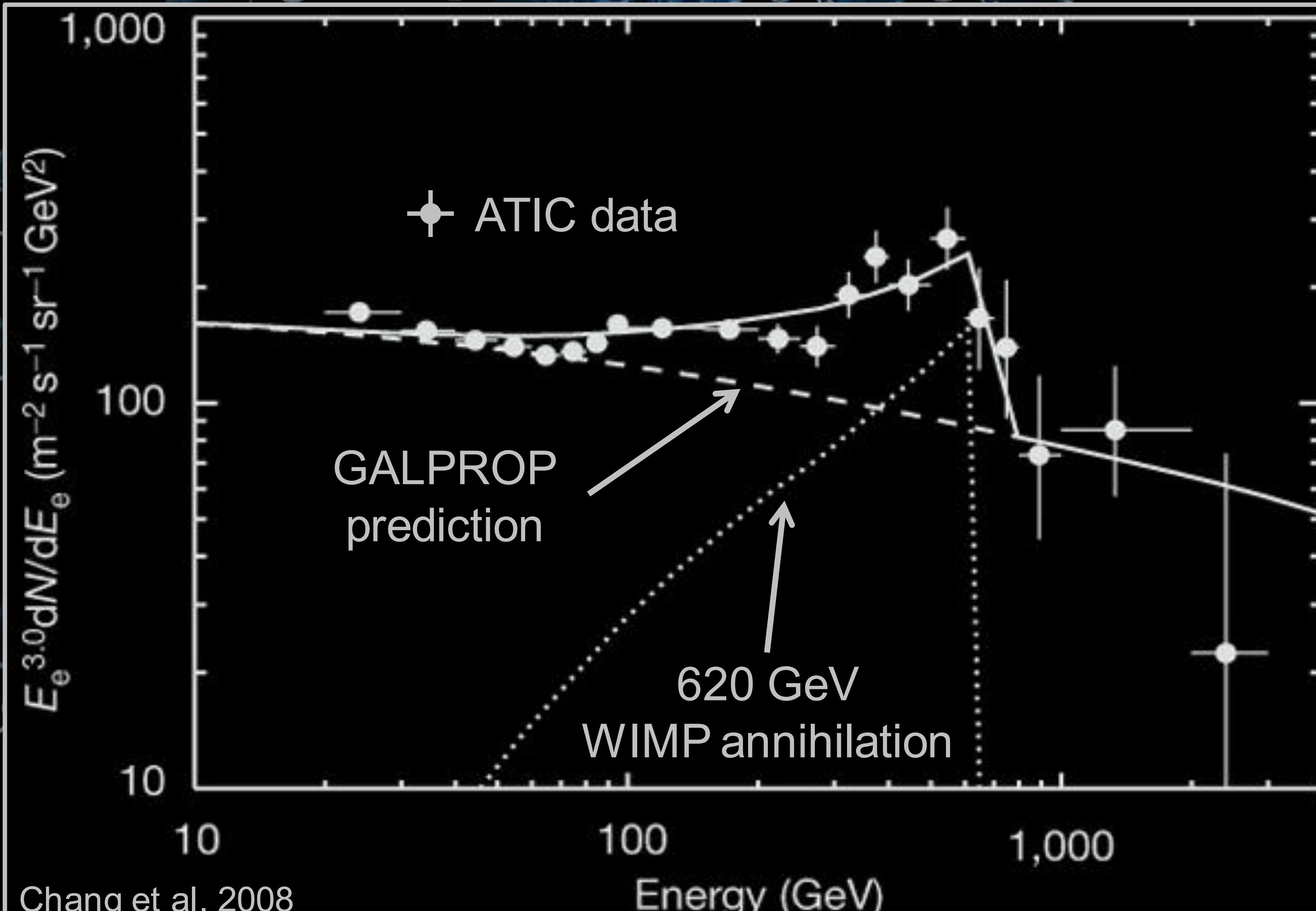




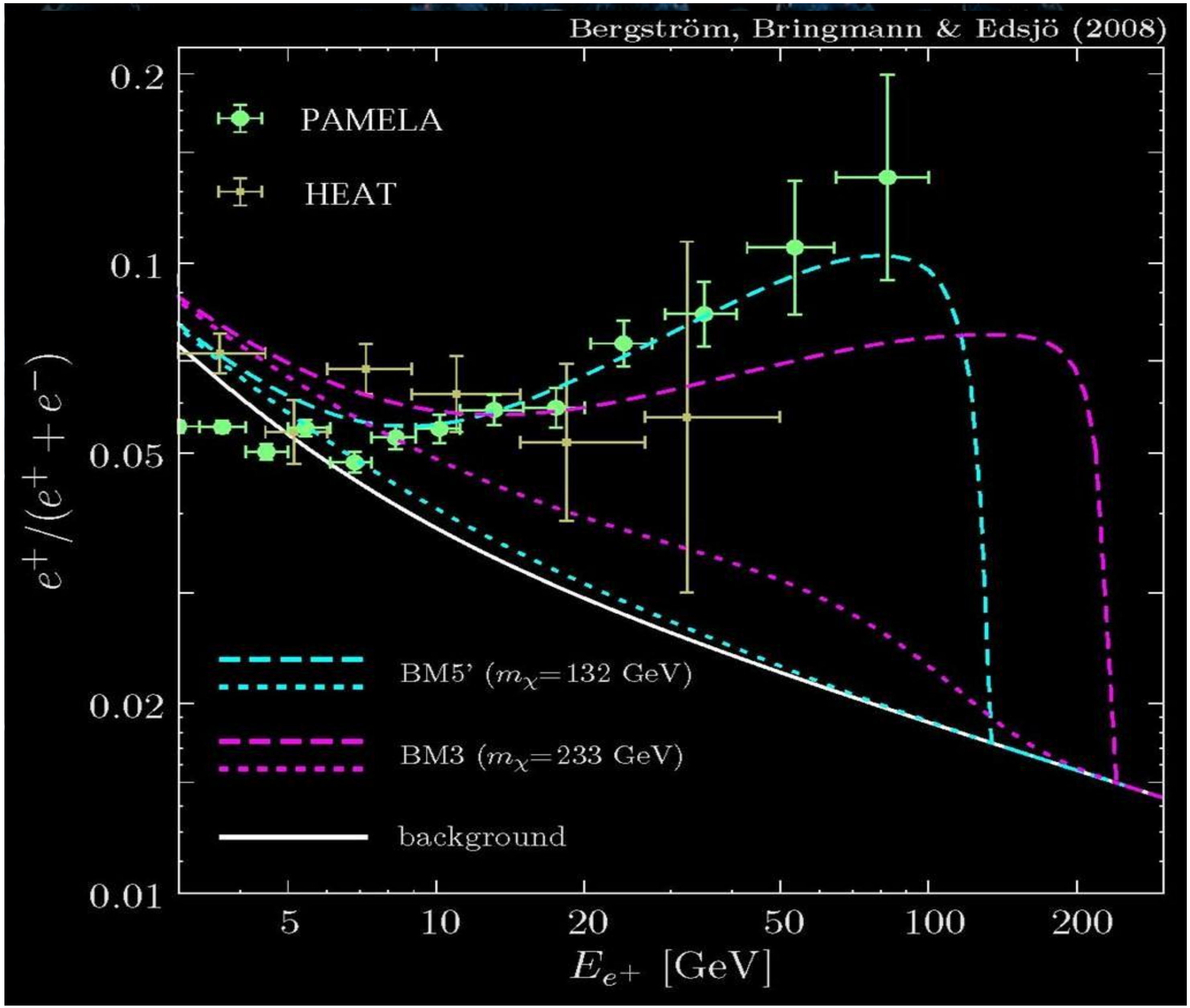
PAMELA



ATIC

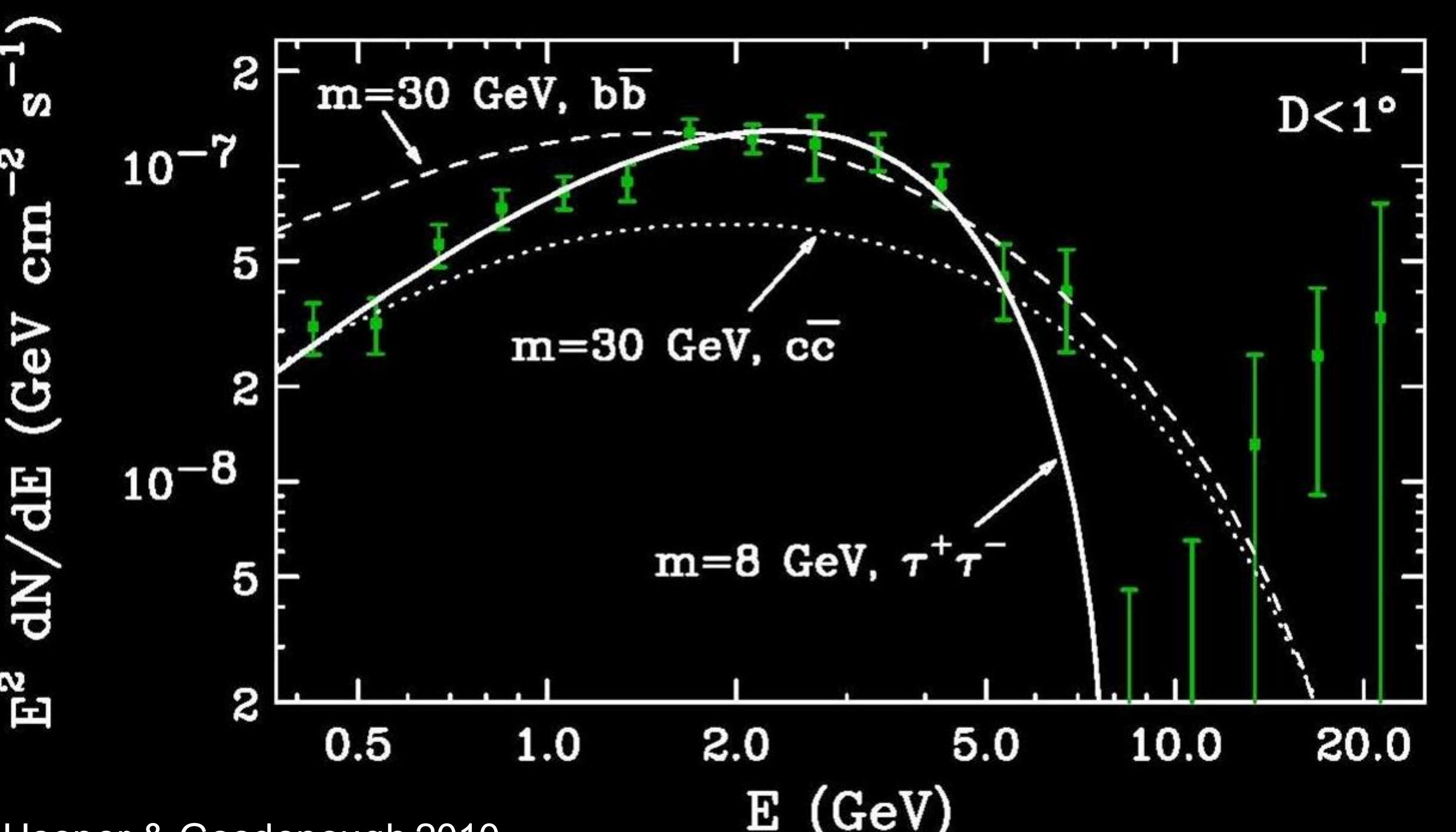

1,000
100
10
$E_e^{3.0} dN/dE_e$ (m^{-2} s^{-1} sr^{-1} GeV^2)
ATIC data
GALPROP prediction
620 GeV WIMP annihilation
10
100
1,000
Energy (GeV)
Chang et al. 2008

PAMELA



Bergström, Bringmann & Edsjö (2008)
PAMELA
HEAT
0.2
0.1
0.05
0.02
0.01
$e^+/(e^+ + e^-)$
BM5' (m_χ=132 GeV)
BM3 (m_χ=233 GeV)
background
5
10
20
50
100
200
E_{e^+} [GeV]

Fermi/GLAST



Hooper & Goodenough 2010

WIMPs

- WIMPs: causation or coincidence?
- Situation now is muddled
  - direct hints: DAMA/LIBRA, CoGeNT, CRESST II, …
  - indirect hints: PAMELA, ATIC, Fermi/GLAST, …
  - LHC will soon weigh in: …

WIMPs

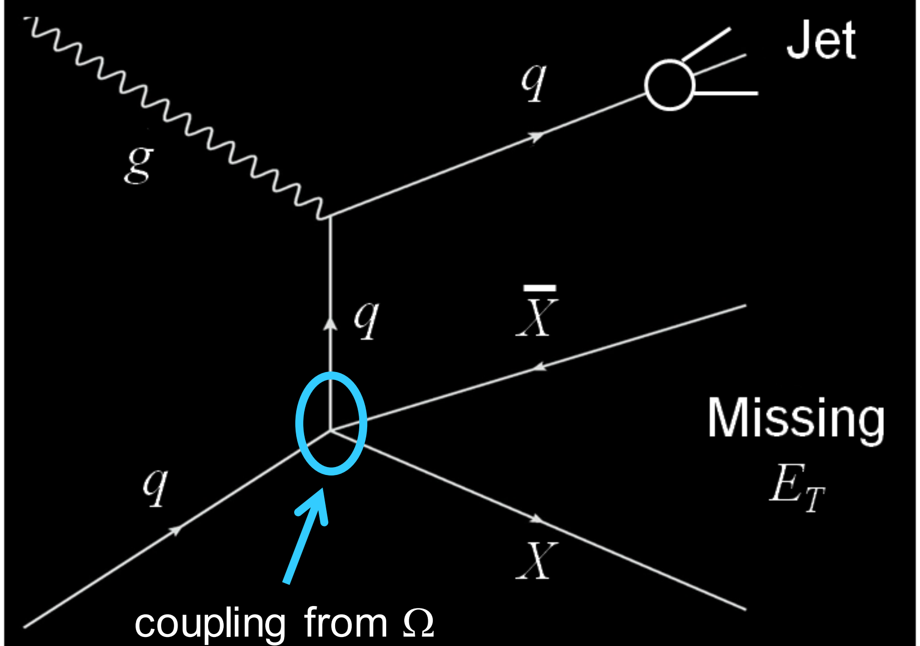
Collider Searches

<u>Maverick WIMP</u>	<u>Social WIMP</u>
• WIMP is a loner.	• WIMP part of a social network.
• Use effective field theory, e.g.: 4-Fermi interaction.	• Motivated model framework, e.g.: low-energy SUSY.
• WIMP only new species.	• Many new particles/parameters.
• Clear relationships between annihilation-scattering-production cross sections.	• Muddy relationships between annihilation-scattering-production cross sections.

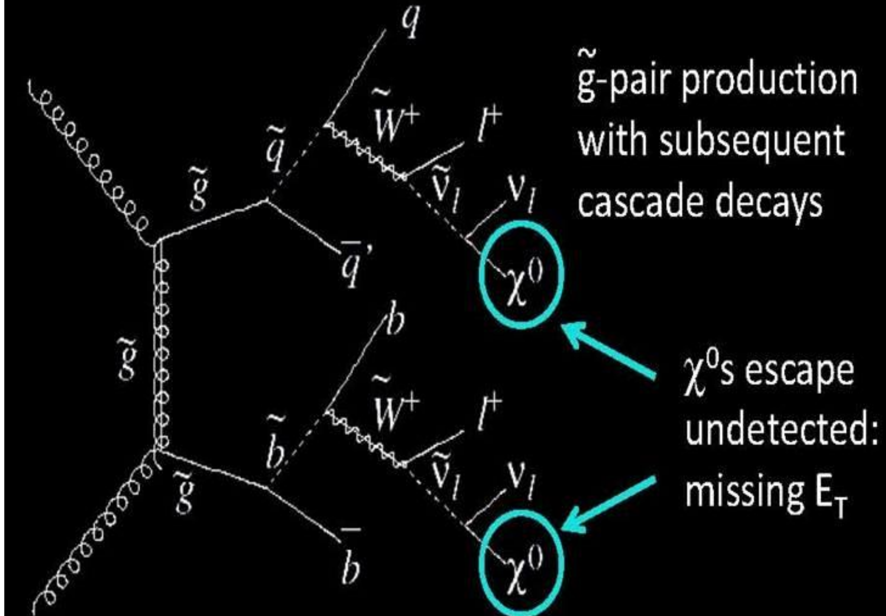
WIMPs

Collider Searches

Maverick WIMPs



Social WIMPs



Backgrounds (neutrino, QCD, …)

Complicated decay chain

WIMPs

- WIMPs: causation or coincidence?
- Situation now is muddled
  - direct hints: DAMA/LIBRA, CoGeNT, CRESST II, …
  - indirect hints: PAMELA, ATIC, Fermi/GLAST, …
  - LHC will soon weigh in: …
- In the next decade the WIMP hypothesis will have either convincing evidence, or a near-death experience.
- Direct, indirect, collider information: confusing decade.
- How will we all know they all see the same phenomenon?

<u>Let's hope for this problem!!!!</u>

Dark Questions

- Why only one WIMP?
- If social network of several WIMPs, stronger interacting ones:
  - — Easier to detect
  - — Smaller Ω
- Super-WIMPs
- Self-interacting WIMPs
- Inelastic WIMPs
- Leptophilic WIMPs
- Flavor-dependent WIMP couplings
- Haze, fog, mist

And this is just for WIMPs!

WIMPs

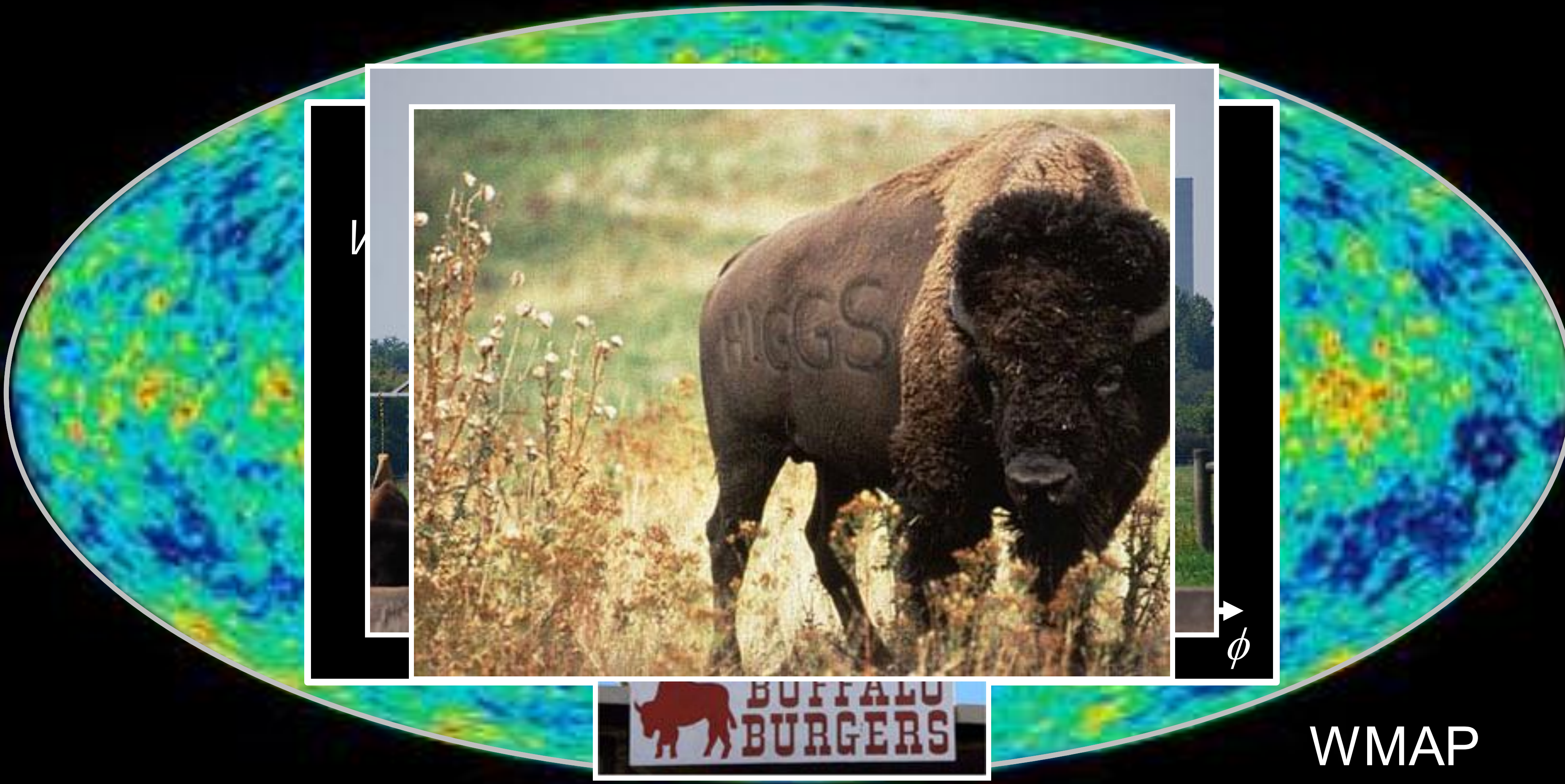
Dark matter is a complex physical phenomenon.

WIMPs are a simple, elegant, compelling explanation for a complex physical phenomenon.

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

— *Tommy Gold*

Inflation



WMAP

Classical Equations of Motion

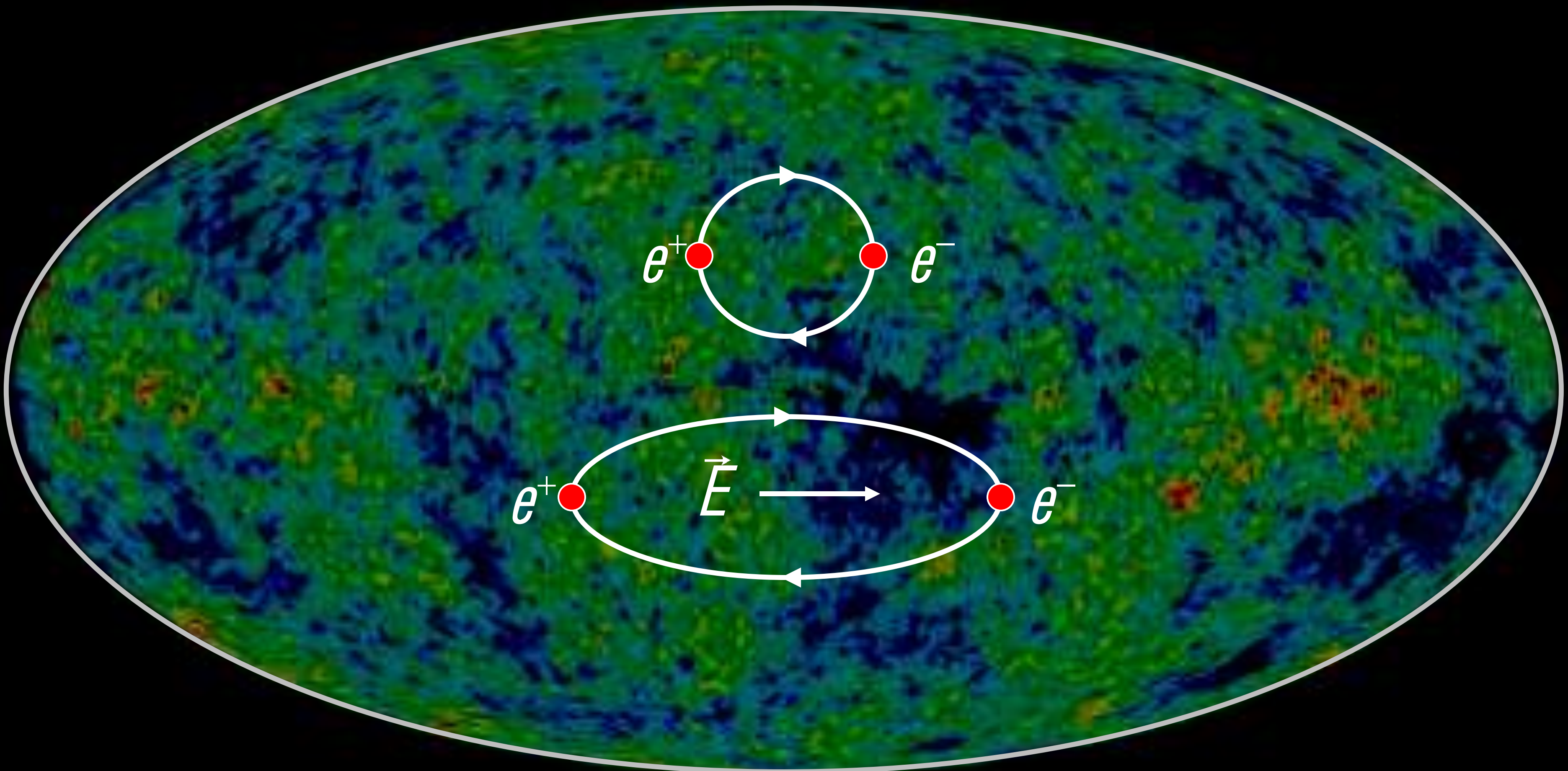
$V(\phi) \neq 0 \longrightarrow V(\phi) = 0$

Quantum Fluctuations

$\delta\phi \longrightarrow \delta\rho \longrightarrow \delta T$

Disturbing the Quantum Vacuum

Changing Electric field → Particle creation

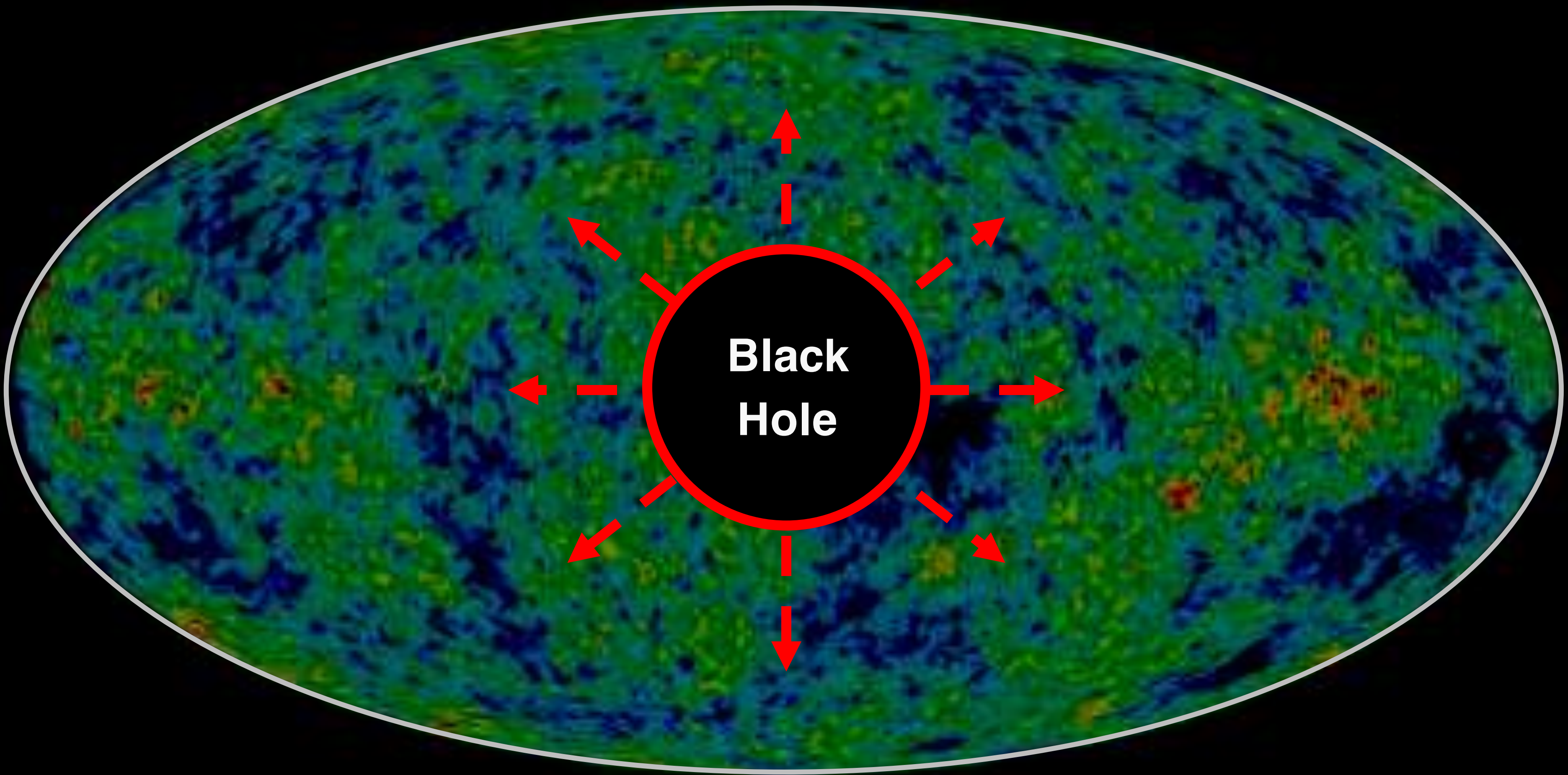


Particle creation if energy gained in acceleration from electric field over a Compton wavelength exceeds the particle's rest mass.

Schwinger (1951); Heisenberg & Euler (1935); Weisskopf (1936)

Disturbing the Quantum Vacuum

Tidal gravitational field → Particle creation

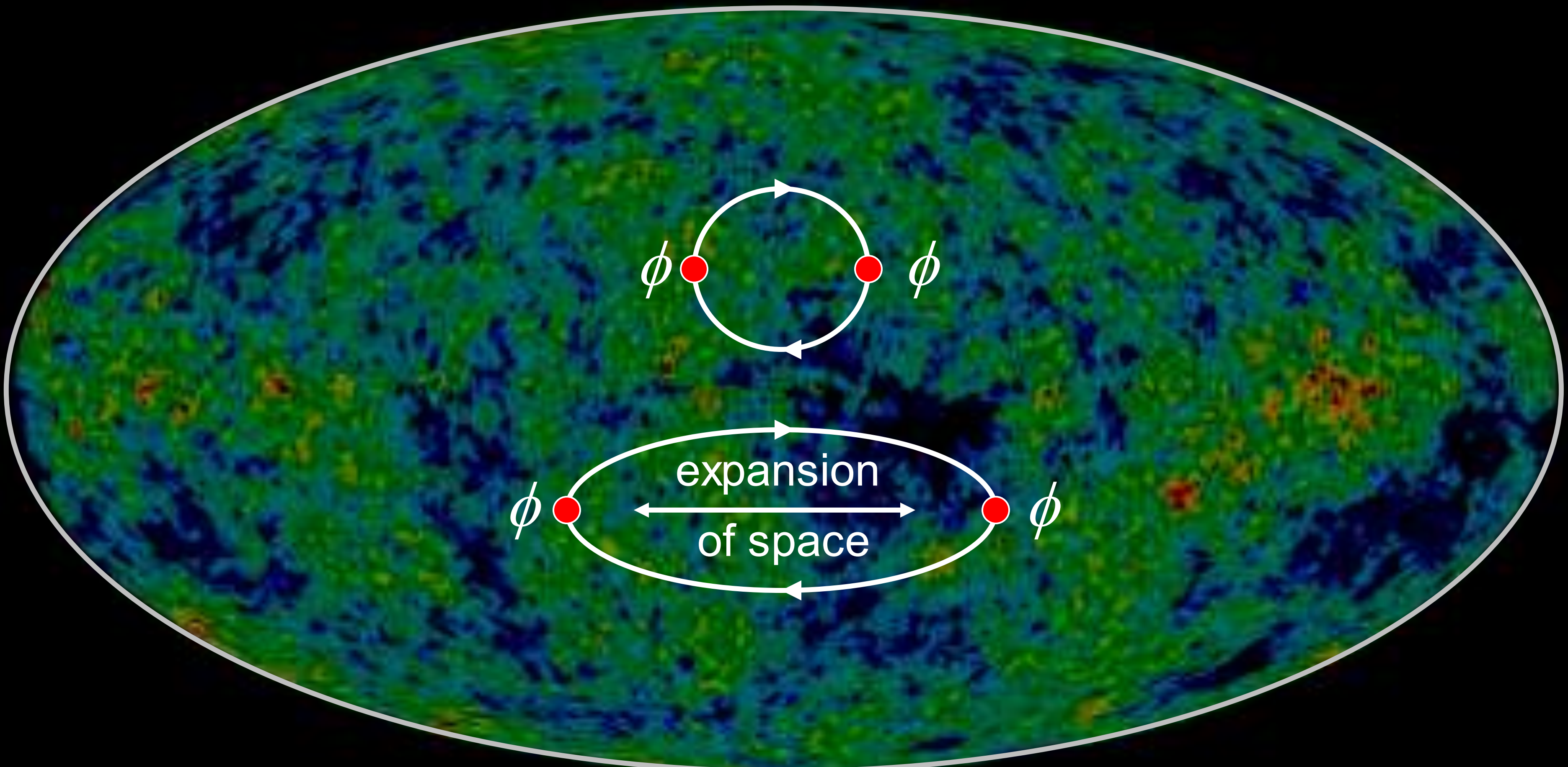


Particle creation if energy gained in acceleration from gravitational field over a Compton wavelength exceeds the particle's rest mass.

Hawking (1974); Bekenstein (1972)

Disturbing the Quantum Vacuum

Expanding Universe ⟶ Particle creation

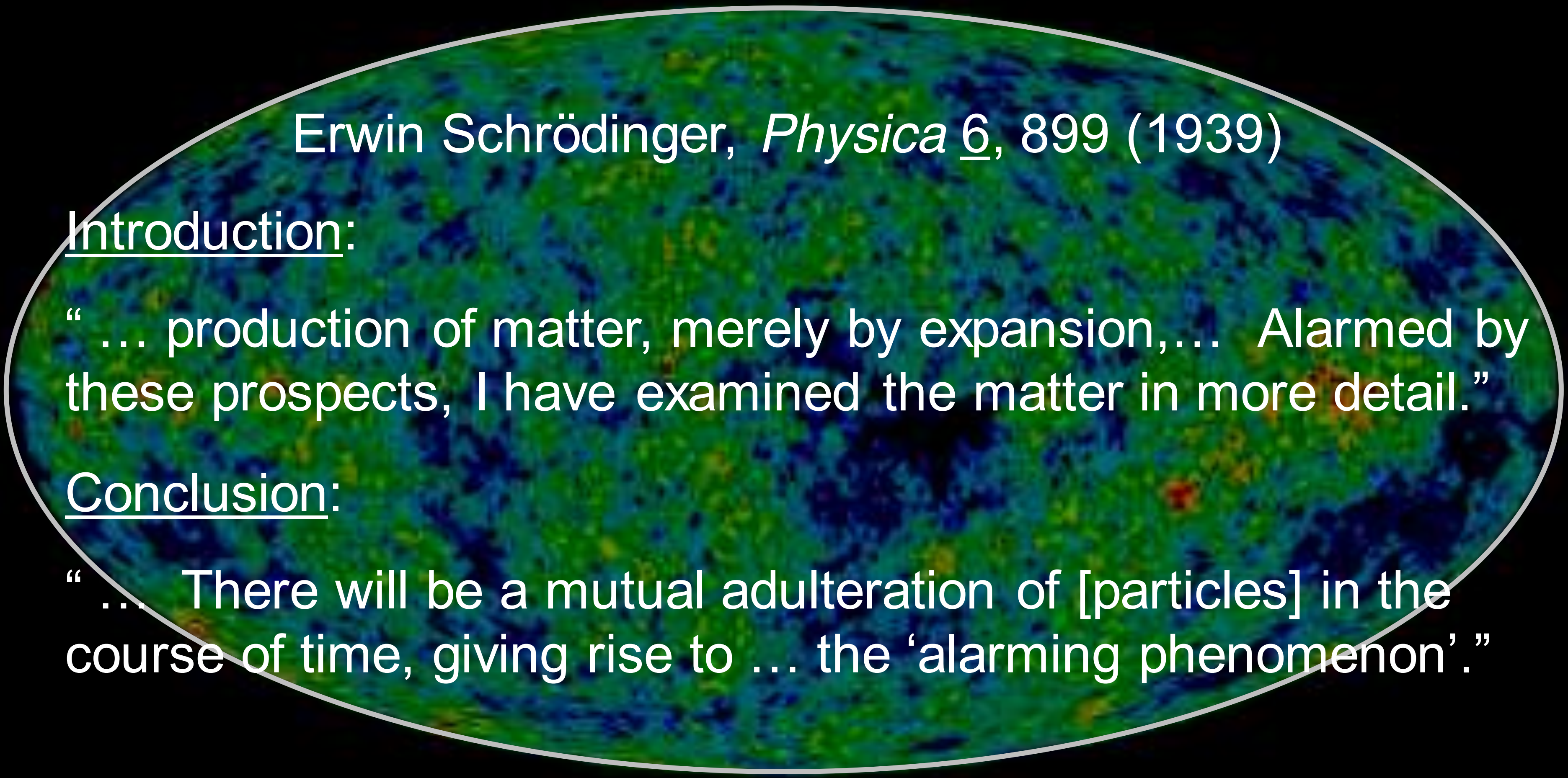


Particle creation if energy gained in expansion over a Compton wavelength exceeds the particle's rest-mass.

Schrödinger's alarming phenomenon (1939)

Disturbing the Quantum Vacuum

The Proper Vibrations of the Expanding Universe



Erwin Schrödinger, *Physica* 6, 899 (1939)

Introduction:

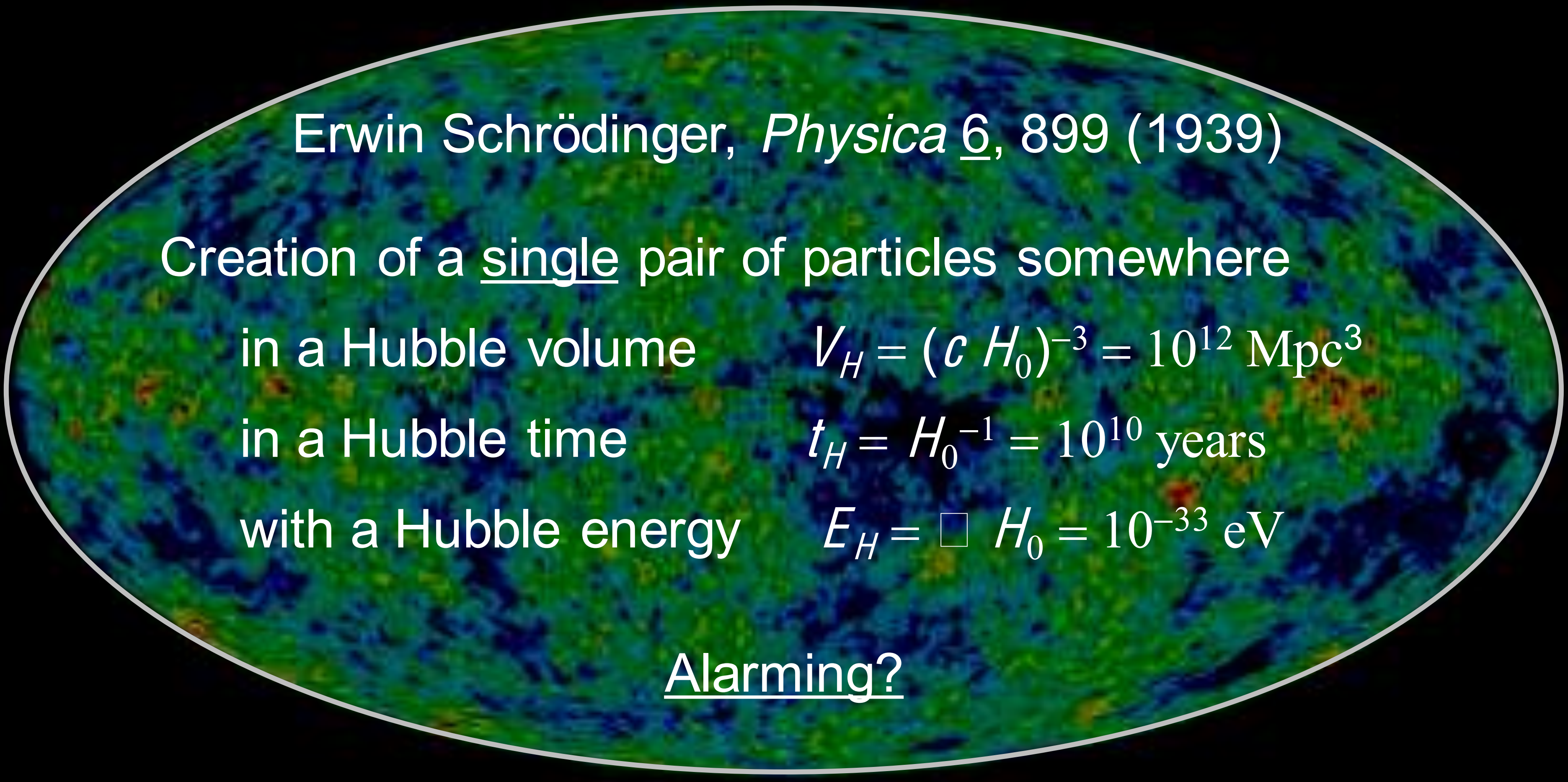
" … production of matter, merely by expansion,… Alarmed by these prospects, I have examined the matter in more detail."

Conclusion:

" … There will be a mutual adulteration of [particles] in the course of time, giving rise to … the 'alarming phenomenon'."

Disturbing the Quantum Vacuum

The Proper Vibrations of the Expanding Universe



Erwin Schrödinger, *Physica* 6, 899 (1939)

Creation of a single pair of particles somewhere

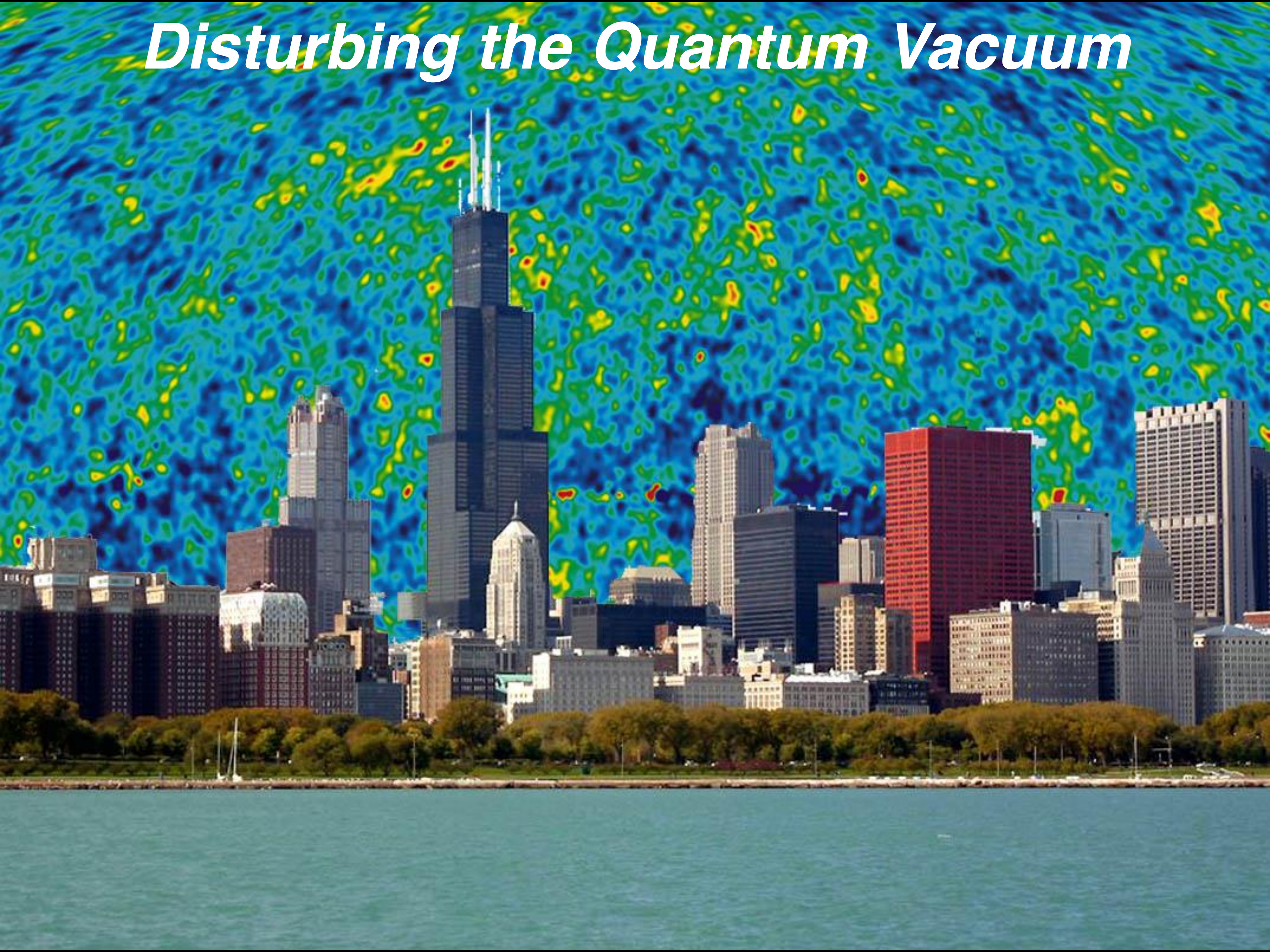
in a Hubble volume $V_H = (c\, H_0)^{-3} = 10^{12}\ \mathrm{Mpc}^3$

in a Hubble time $t_H = H_0^{-1} = 10^{10}$ years

with a Hubble energy $E_H = \hbar\, H_0 = 10^{-33}$ eV

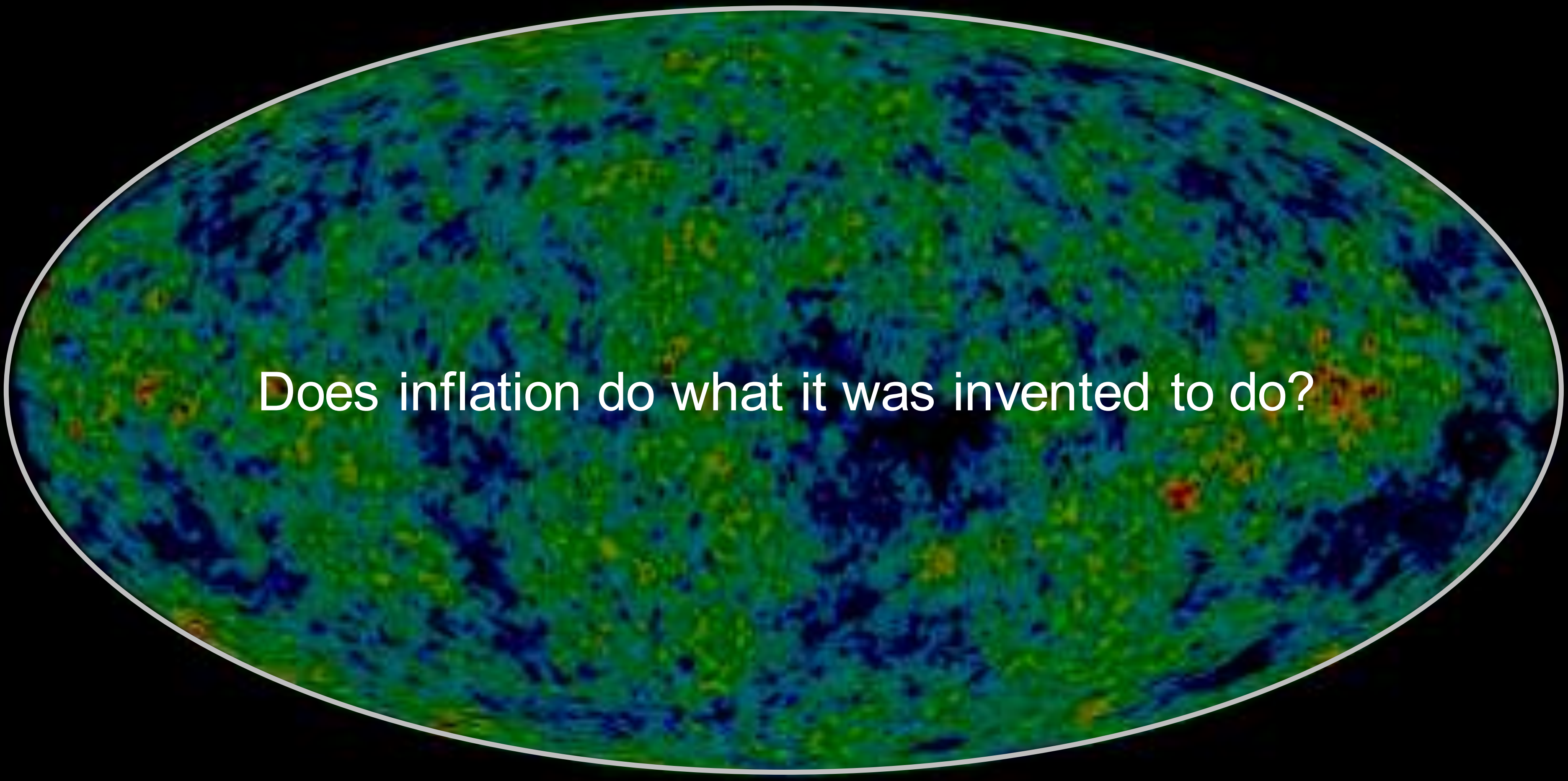
Alarming?

Disturbing the Quantum Vacuum



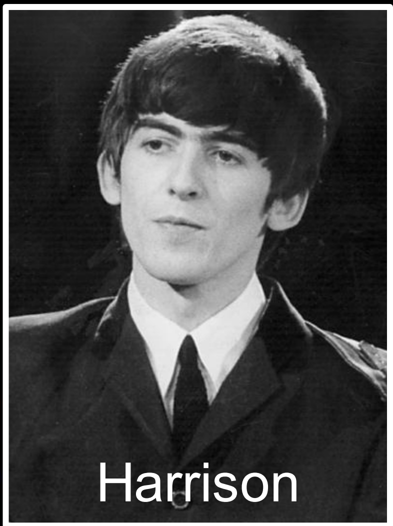
Most Fundamental Question

1. Is inflation eternal? Is there a multiverse?



Next Most Fundamental Question

2. What if exact Harrison-Zel'dovich perturbation spectrum?



spectral index exactly unity
no gravitational waves
exactly gaussian perturbations
only curvature perturbations

- What do observations tell us about spectral index (n)?
- Search for gravitational waves from B-mode polarization (r).
- Search for non-gaussianity ($f_{\rm NL}$).
- Theory developments: effective field theory approach.
- Who is the inflaton … superstrings $\Rightarrow$ inflaton ?

Inflation & Superstrings Are a Match

physicsmatch.com

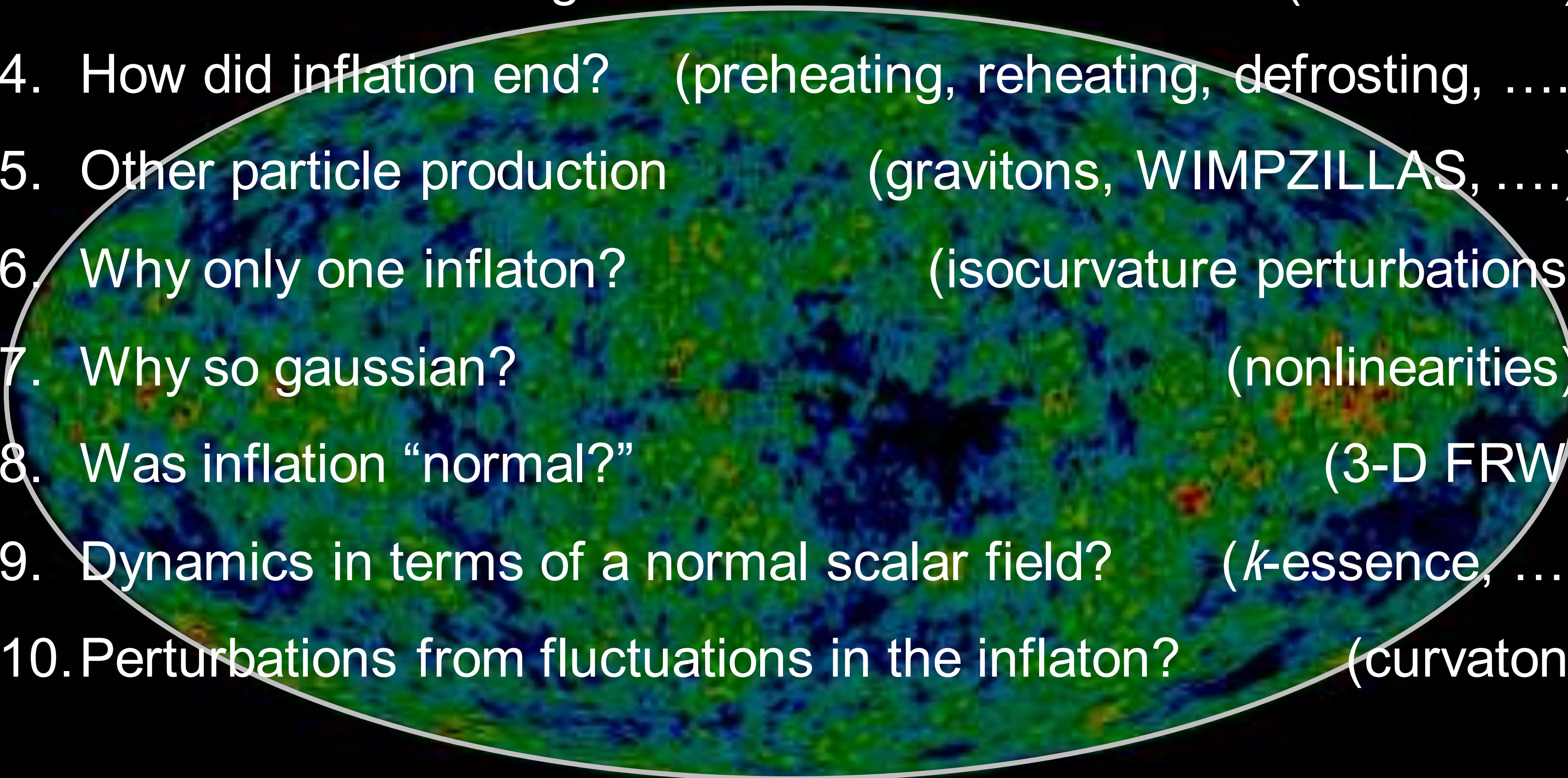
Strings attached?

Mature 37-year-old idea (superstrings) seeks a partner to develop some physical implications.

Make some perturbations?

Lonely 32-year-old scalar field (inflaton) seeks a fundamental theory in which to be embedded.

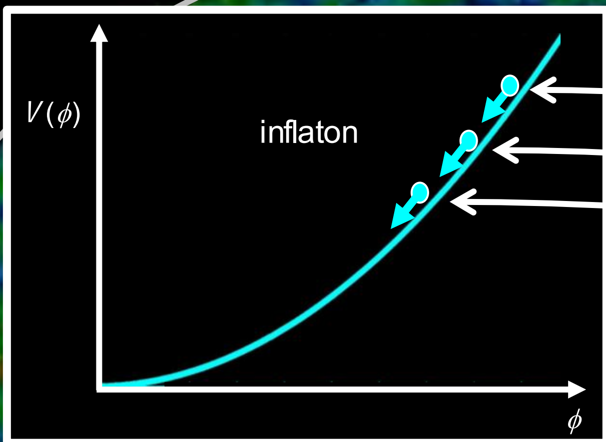
Additional Fundamental Questions

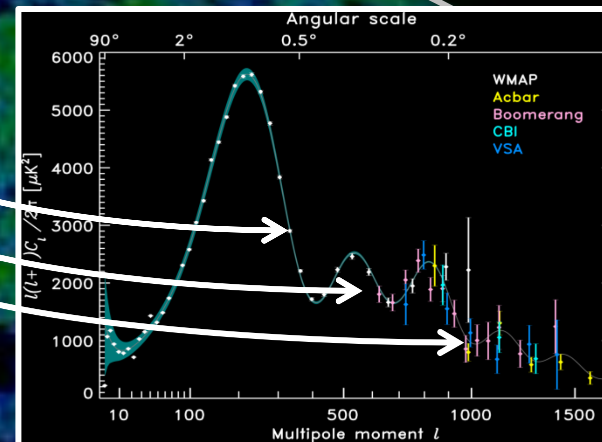


3. How did inflation begin? (is it eternal)
4. How did inflation end? (preheating, reheating, defrosting, ….)
5. Other particle production (gravitons, WIMPZILLAS, ….)
6. Why only one inflaton? (isocurvature perturbations)
7. Why so gaussian? (nonlinearities)
8. Was inflation "normal?" (3-D FRW)
9. Dynamics in terms of a normal scalar field? (*k*-essence, …)
10. Perturbations from fluctuations in the inflaton? (curvaton)

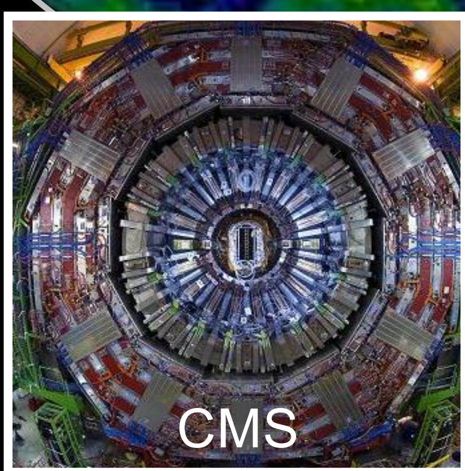
Additional Fundamental Questions

11. What was the expansion rate during inflation?
12. What was the general shape of the potential (reconstruction)?



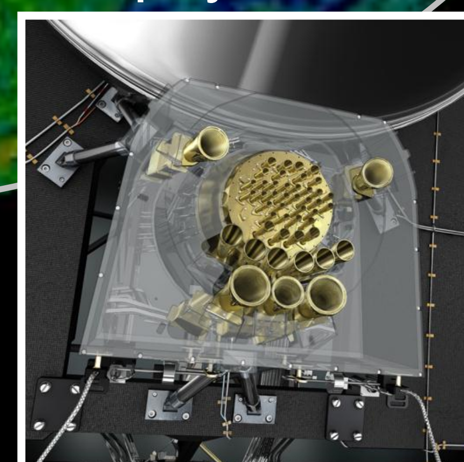


13. Can we learn about unification, strings, Planck physics?

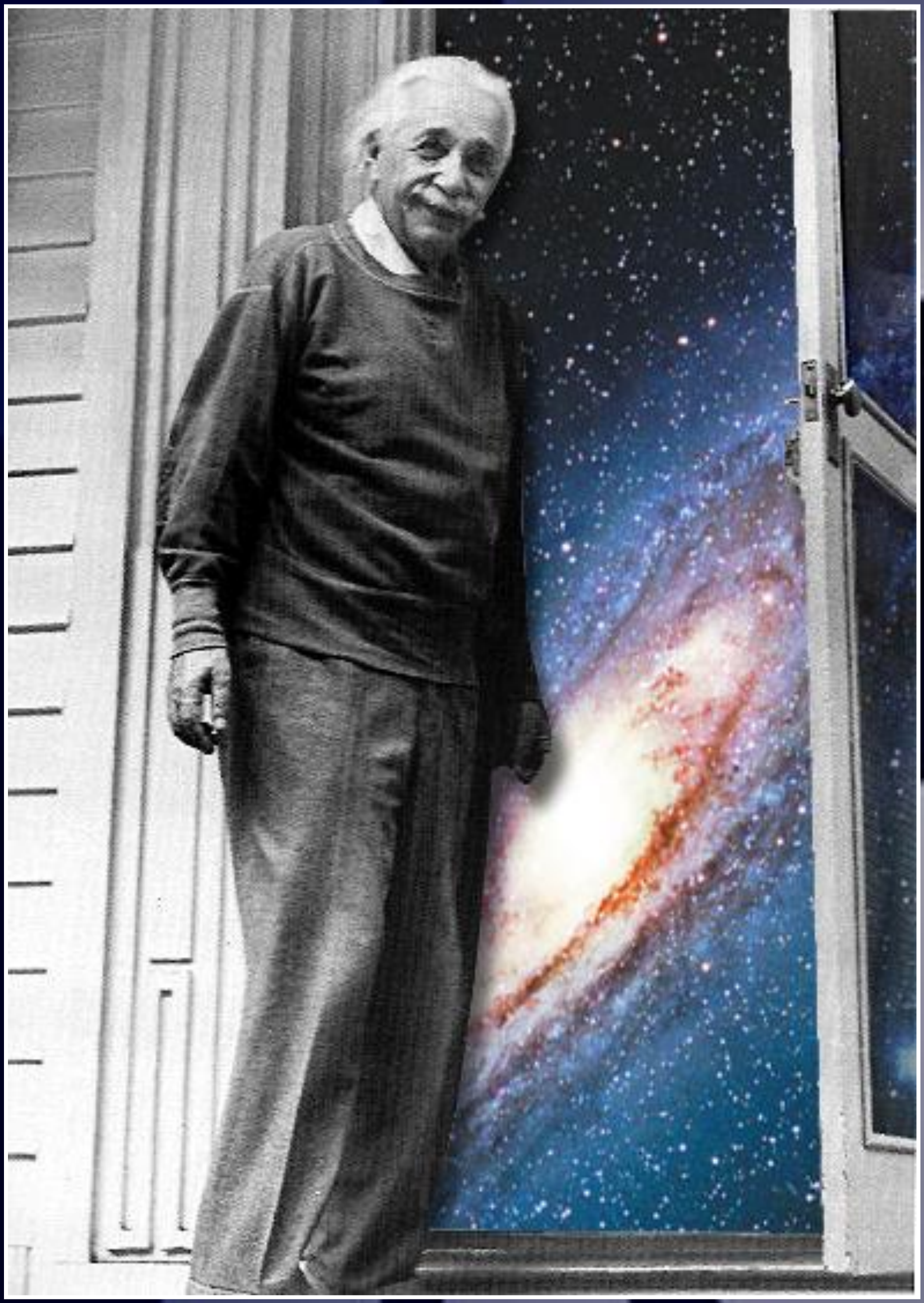


Weak-scale detectors

Planck-scale detectors



Cosmological Constant (Dark Energy)



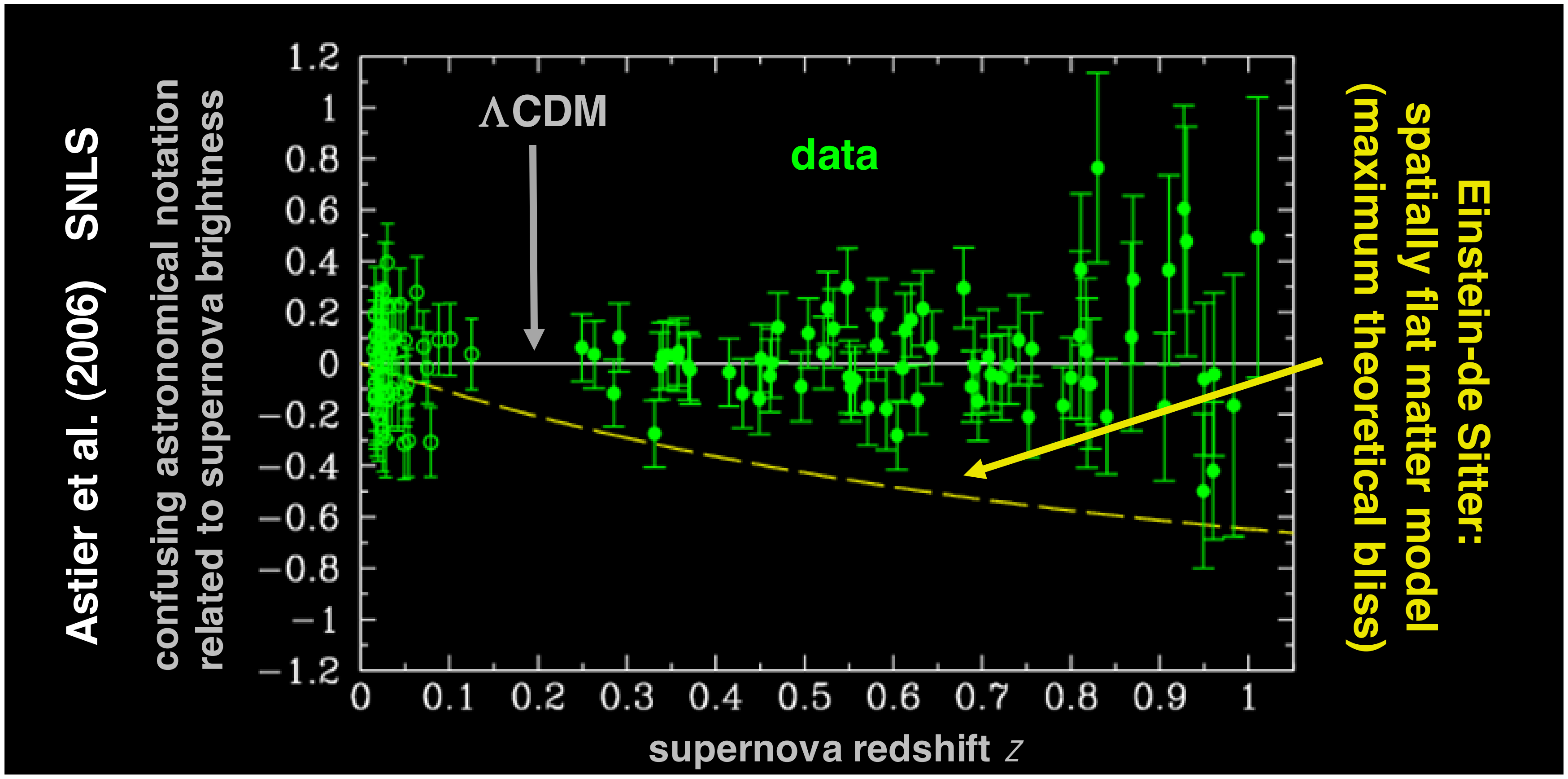
1917 Einstein proposed cosmological constant, Λ.

1929 Hubble discovered expansion of the Universe.

1934 Einstein called it "my biggest blunder."

1998 Astronomers found evidence for it, and renamed it "Dark Energy."

The Cosmological Constant



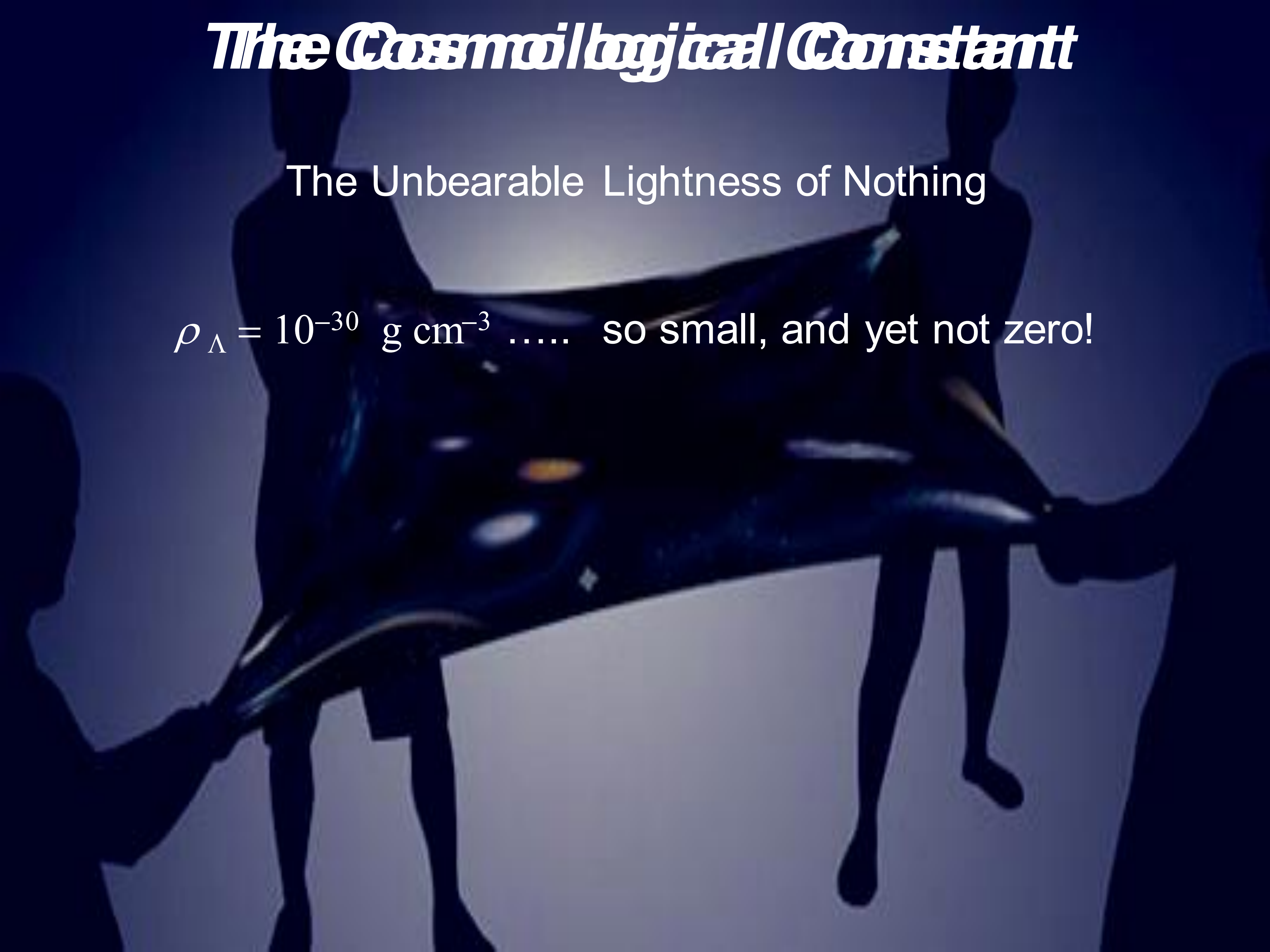
The case for Λ:

1) Hubble diagram (SNe)
2) Cosmic Subtraction $(1 - 0.3 = 0.7)$
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

The Cosmological Constant

The Unbearable Lightness of Nothing

$\rho_\Lambda = 10^{-30}$ g cm^{-3} ….. so small, and yet not zero!



Taking Sides!

Can't hide from the data – ΛCDM too good to ignore

- SNe
- Subtraction: $1.0 - 0.3 = 0.7$
- Baryon acoustic oscillations
- Galaxy clusters
- Weak lensing
- …

} $H(z)$ not given by Einstein–de Sitter

$$G_{00}\,(\text{FLRW}) \neq 8\pi\, G\, T_{00}(\text{matter})$$

Modify <u>right-hand side</u> of Einstein equations (ΔT_{00})

1. Constant ("just" a cosmoillogical constant)
2. Not constant (dynamics described by a scalar field)

Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})

3. Beyond Einstein (non-GR)
4. (Just) Einstein (back reaction of inhomogeneities)

Tools to Modify the <u>Right-Hand</u> Side

anthropic principle the landscape

scalar fields (quintessence)

Anthropic/Landscape/DUCTtape

- Many sources of vacuum energy.
- String theory has many ($>10^{500}$?) vacua … the landscape.
- The multiverse could populate many (all?) vacua.
- Very, very rarely vacua have cancellations that yield a small Λ.
- While exponentially uncommon, they are preferred because …
  … more common values of Λ results in an inhospitable universe.

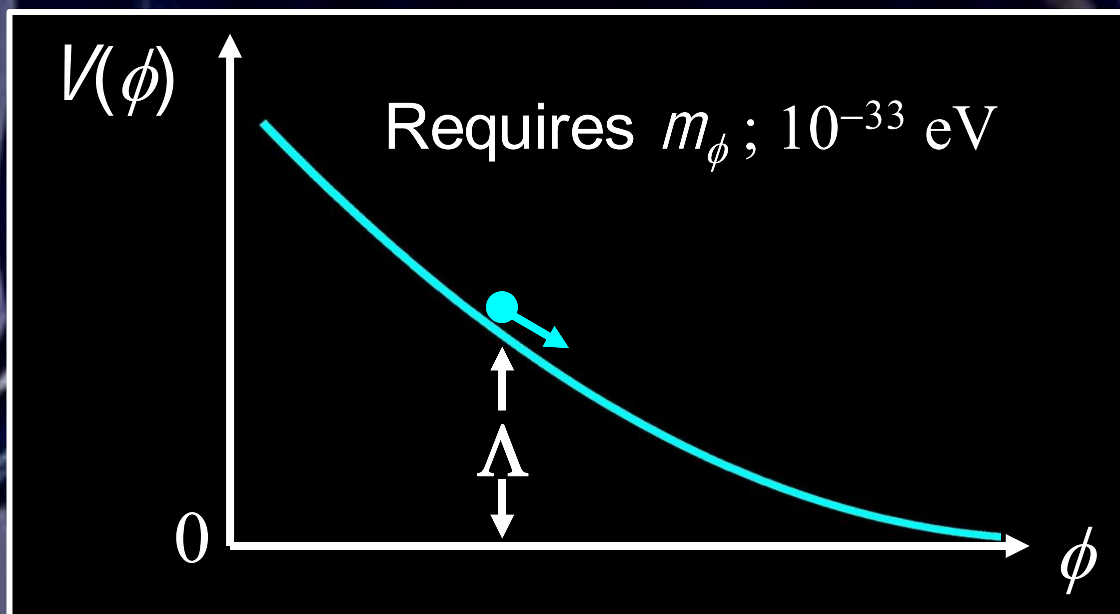
Anthropic principle requires $\Lambda \square \Lambda_{\mathrm{OBS}}$.
Explains a $(10^{120}-1)\sigma$ result.

Anthropic/Landscape/DUCTtape

- The anthropic "principle" can explain the cosmoillogical constant.
- Perhaps there is no better idea than the anthropic principle …
  … (people without ideas can still have principles).
- But principles must not be applied selectively.
- What does this mean for particle physics?
  - Does it explain the weak scale/Planck scale hierarchy?
  - Who needs low-energy SUSY?
  - Give up searching for many answers (masses, etc.).
  - No dreams of a final theory.
- Is particle physics an environmental science?

Quintessence/WD–40

- Many possible contributions.
- Why then is total so small?
- Perhaps some dynamics sets global vacuum energy to zero …
  … but we're not there yet!



- Can nature admit ultralight scalar fields?
- Long-range forces?

Tools to Modify the Left-Hand Side

- Braneworld modifies Friedmann equation

  Friedmann equation not from $G_{00} = 8\pi G\, T_{00}$ — Binetruy, Deffayet, Langois

- Gravitational force law modified at large distance

  Five-dimensional at cosmic distances — Deffayet, Dvali, Gabadadze

- Tired gravitons

  Gravitons unstable-leak into bulk — Gregory, Rubakov & Sibiryakov

- Gravity changes at distance $R \approx \mathrm{Gpc}$

  Becomes repulsive — Csaki, Erlich, Hollowood & Terning

- $n = 1$ KK graviton mode very light

  $m \approx (\mathrm{Gpc})^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago

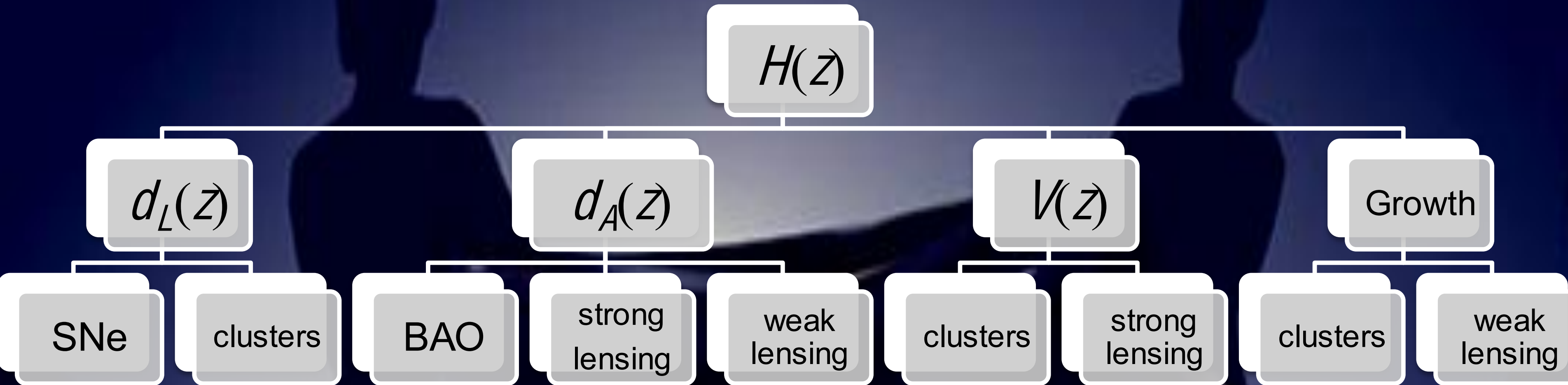
- Einstein & Hilbert got it wrong

  $f(R)$ $S = (16\pi G)^{-1} \int d^4x \sqrt{-g}\left(R - \mu^4/R\right)$ — Carroll, Duvvuri, Turner & Trodden

- "Backreaction" of inhomogeneities

  No dark energy — Räsänen, Kolb, Matarrese, Notari, Riotto, Buchert; Ellis; Celerier

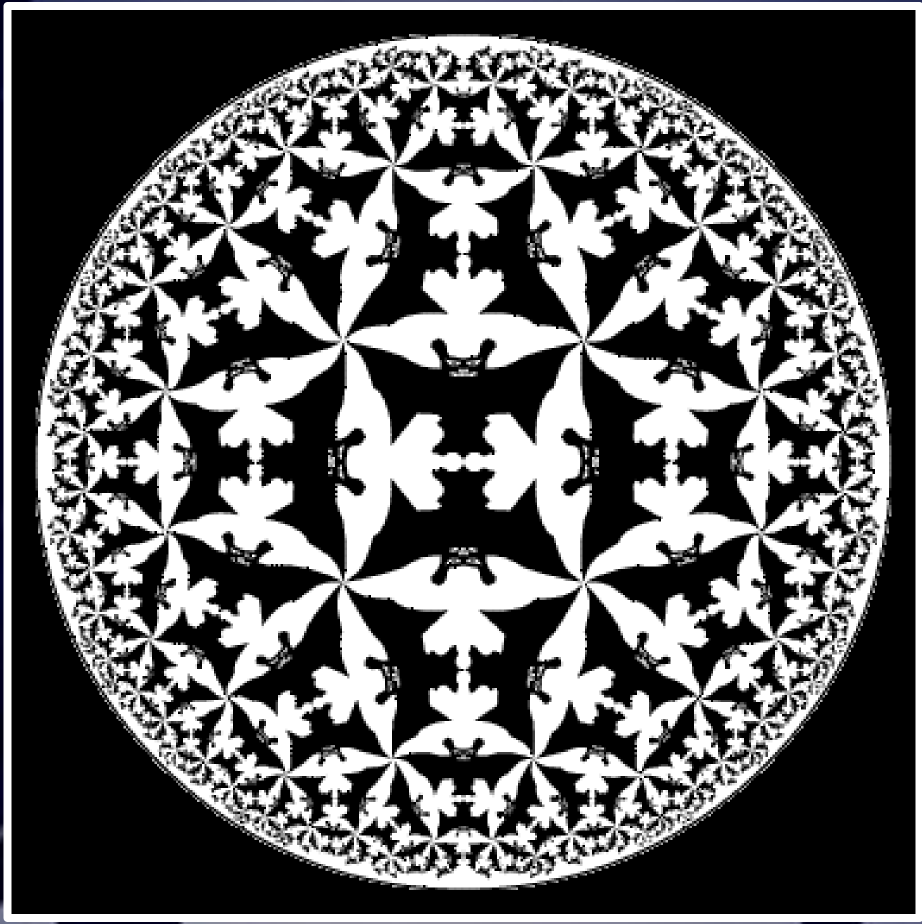
Dark Energy



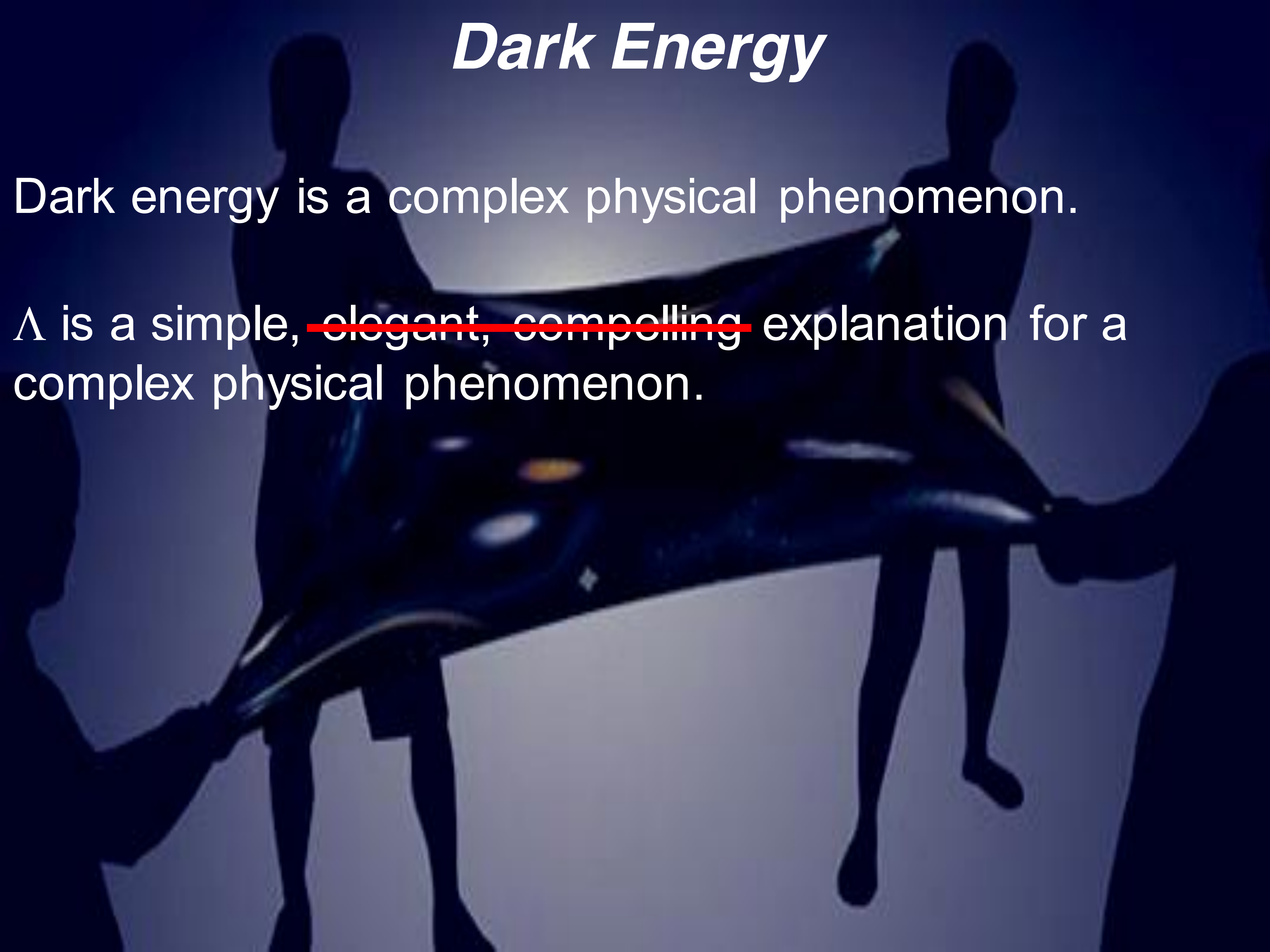
"Nothing more can be done by the theorists. In this matter it is only you, the astronomers, who can perform a simply invaluable service to theoretical physics."

Einstein in August 1913 to astronomer Erwin Freundlich encouraging him to measure the deflection of light by the sun.

Asymptotic de Sitter Space?



- Our cosmic horizon is limited — finite visible Universe
- Finite-dimensional Hilbert space
- Have to do astronomy now!

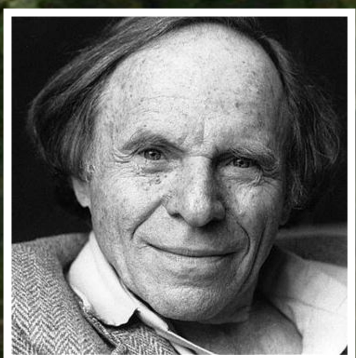


Dark Energy

Dark energy is a complex physical phenomenon.

Λ is a simple, ~~elegant, compelling~~ explanation for a complex physical phenomenon.

Cosmological Standard Model and Its Implications for Beyond the Standard Model of Particle Physics



"Until cosmology and particle physics can be brought together in the same context, there is not much hope for real progress in cosmology."
— N. Bohr, 1939

CERN
28 July 2011

Rocky Kolb
University of Chicago