
# Exotic Physics: Dark Matter and Dark Energy

| | | |
|---|---|---|
| Rocky I: | (Wednesday) | Dark Matter |
| Rocky I.5: | (Thursday) | Dark Matter II |
| Rocky II: | (Thursday) | Dark Energy |

Rocky Kolb

University of Chicago

# WIMPs: Socialists or Mavericks

# WIMPs: Socialists or Mavericks

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

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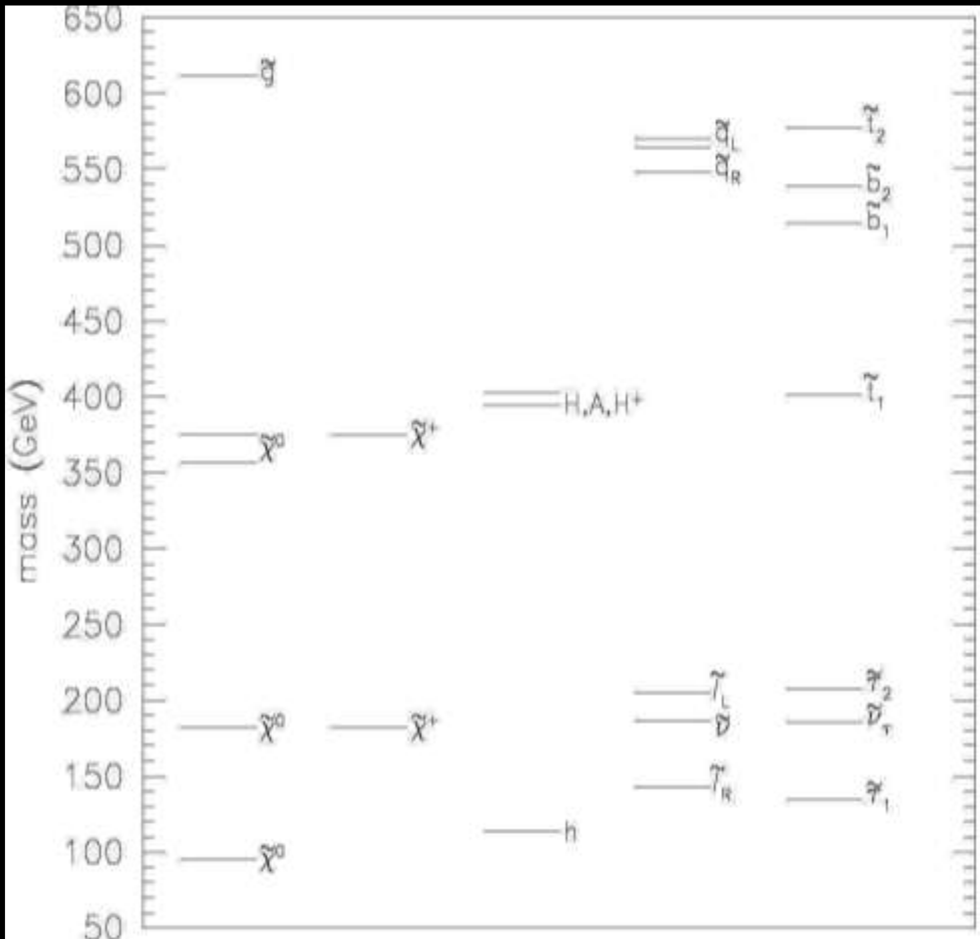
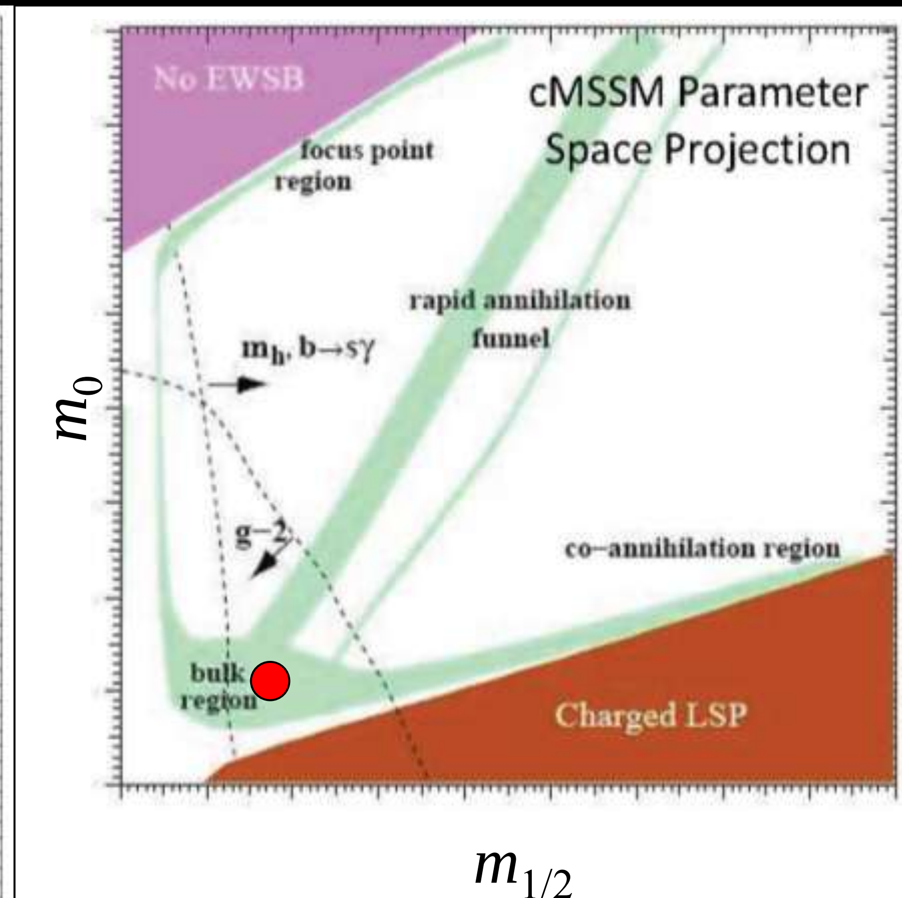
* Beltran, Hooper, Kolb, Krusberg, Tait 1002.5137
Rajaraman, Shepherd, Tait, Wijangco 1108.1196
Fox, Harnik, Kopp, Tsai 1109.4398

# SUSY WIMPs

Bulk Region: light superpartners




Ellis, Olive, Santoso, Spanos

LHC chewing away at allowed region

# Maverick WIMPs

Dirac fermion Maverick WIMP, $\chi$

$$\mathcal{L} = \sum_q \frac{G_{i,2}}{\sqrt{2}} \left[\bar{\chi}\, \Gamma_i\, \chi\right]\left[\bar{q}\, \Gamma_j\, q\right]$$

$$\Gamma_{i,j} = \left\{1, \gamma^5, \gamma^\mu, \gamma^\mu \gamma^5, \sigma^{\mu\nu}\right\}$$

Complex scalar Maverick WIMP, $\phi$

$$\mathcal{L} = \sum_q \frac{F_{i,2}}{\sqrt{2}} \left[\phi^\dagger\, \Gamma_i\, \phi\right]\left[\bar{q}\, \Gamma_j\, q\right]$$

$$\Gamma_i = \left\{1, \partial^\mu\right\}$$

Expect terms that break $\mathrm{SU}(2)_\mathrm{L}$ must do so through SM Yukawa couplings, so operators that flip quark chirality should be $\propto m_q$.

Some terms vanish for Majorana $\chi$.

Can write $G$ as $M_*^{-2}$
$F$ as $M_*^{-1}$

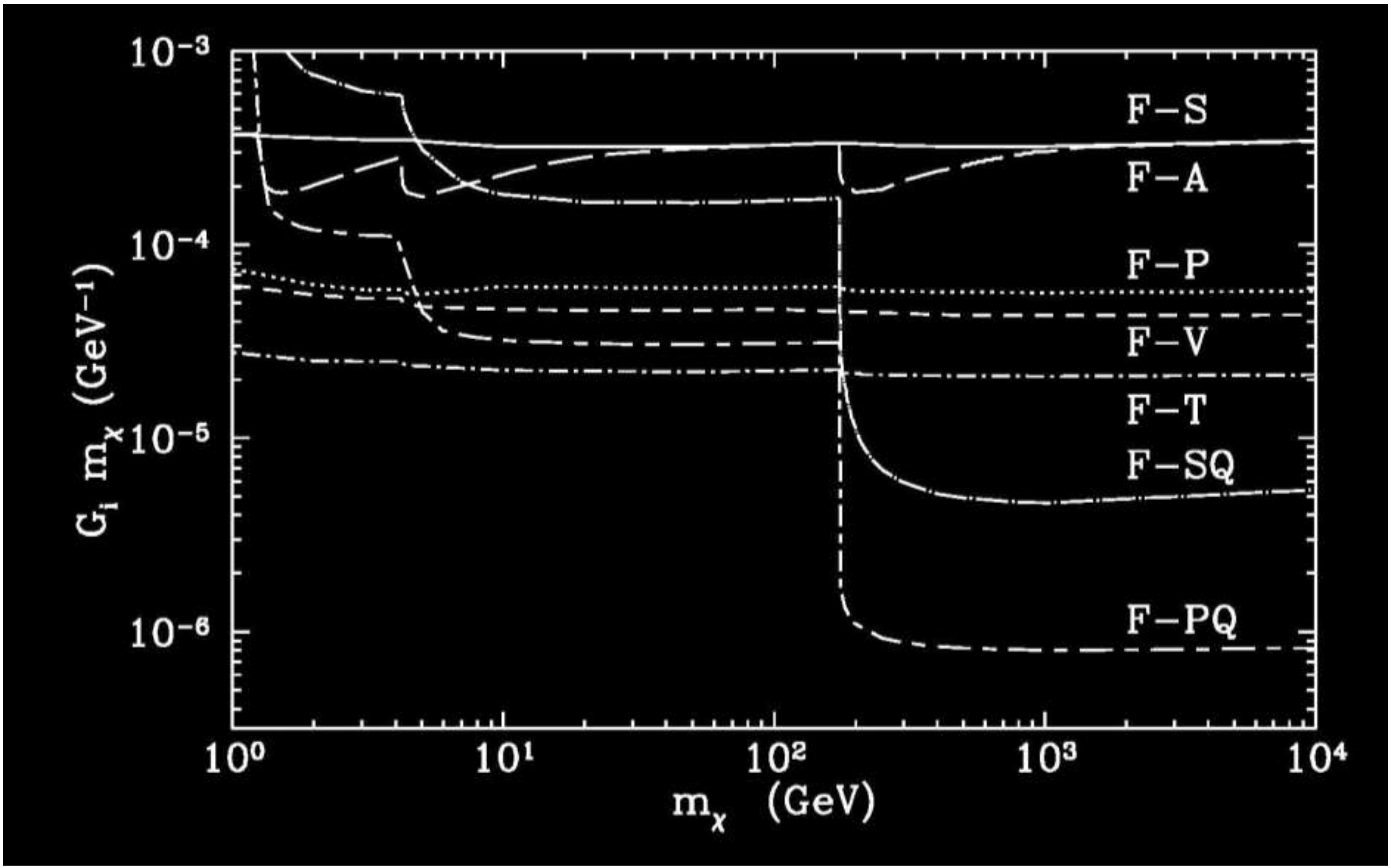
Fierz identities relate various combinations

# Maverick WIMPs

| Spin | Operator | Coupling | Label |
|---|---|---|---|
| 0 | $\phi^\dagger\phi\bar{q}q$ | $F_{S,q} = F_S$ | S-S |
| | $\phi^\dagger\phi\bar{q}q$ | $F_{S,q} \sim m_q$ | S-SQ |
| | $\phi^\dagger\phi\bar{q}\gamma^5 q$ | $F_{SP,q} = F_{SP}$ | S-SP |
| | $\phi^\dagger\phi\bar{q}\gamma^5 q$ | $F_{SP,q} \sim m_q$ | S-SPQ |
| | $\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu q$ | $F_{V,q} = F_V$ | S-V |
| | $\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$ | $F_{VA,q} = F_{VA}$ | S-VA |
| 1/2 | $\bar{\chi}\chi\bar{q}q$ | $G_{S,q} = G_S$ | F-S |
| | $\bar{\chi}\chi\bar{q}q$ | $G_{S,q} \sim m_q$ | F-SQ |
| | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $G_{SP,q} = G_{SP}$ | F-SP |
| | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $G_{SP,q} \sim m_q$ | F-SPQ |
| | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $G_{P,q} = G_P$ | F-P |
| | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $G_{P,q} \sim m_q$ | F-PQ |
| | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $G_{PS,q} = G_{PS}$ | F-PS |
| | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $G_{PS,q} \sim m_q$ | F-PSQ |
| | $\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$ | $G_{V,q} = G_V$ | F-V |
| | $\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$ | $G_{VA,q} = G_{VA}$ | F-VA |
| | $\bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5 q$ | $G_{A,q} = G_A$ | F-A |
| | $\bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu q$ | $G_{AV,q} = G_{AV}$ | F-AV |
| | $\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma^{\mu\nu} q$ | $G_{T,q} = G_T$ | F-T |

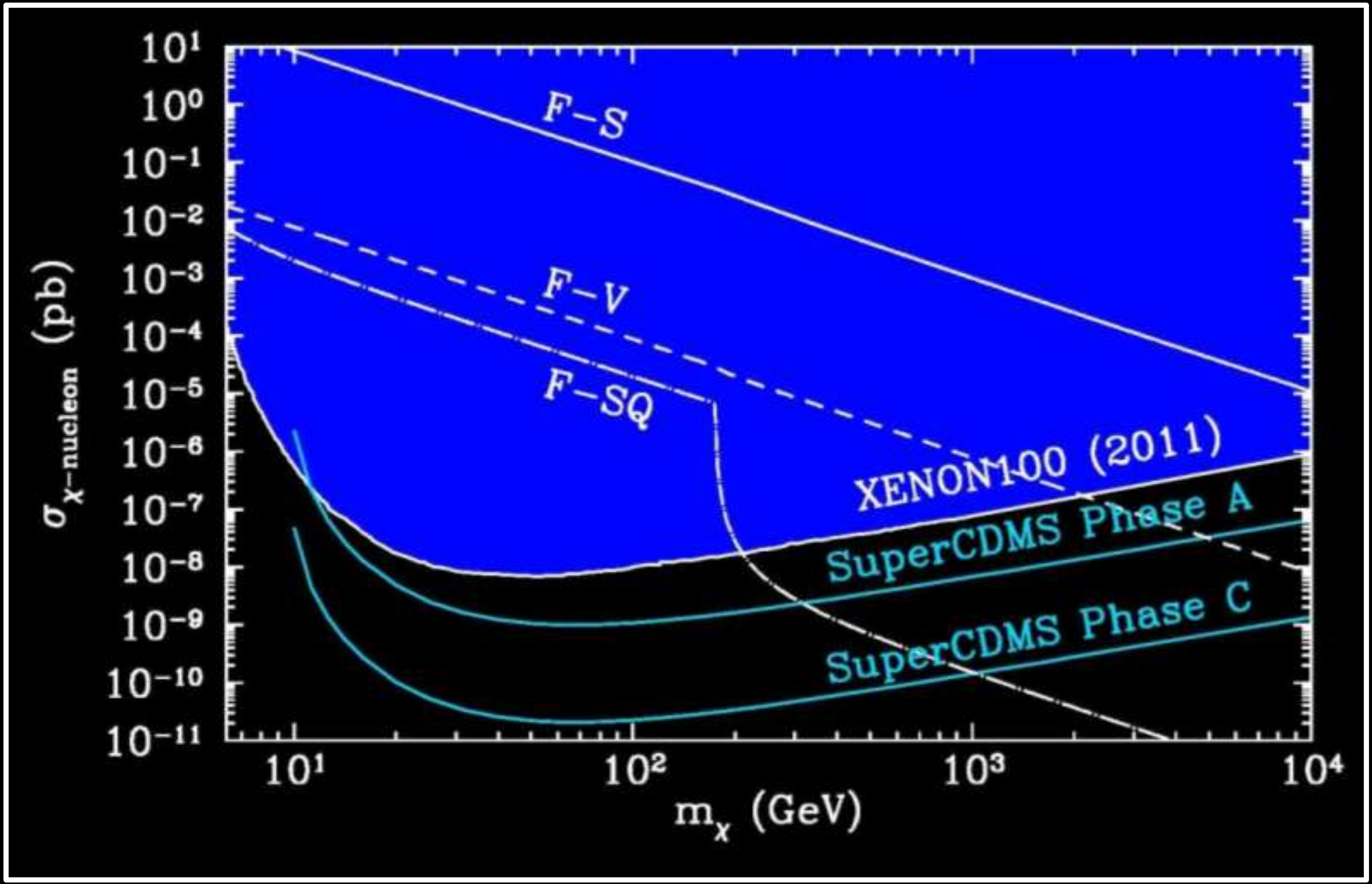
# Maverick WIMPs

Values of $G$ to give correct dark matter density



# Maverick WIMPs

spin-independent

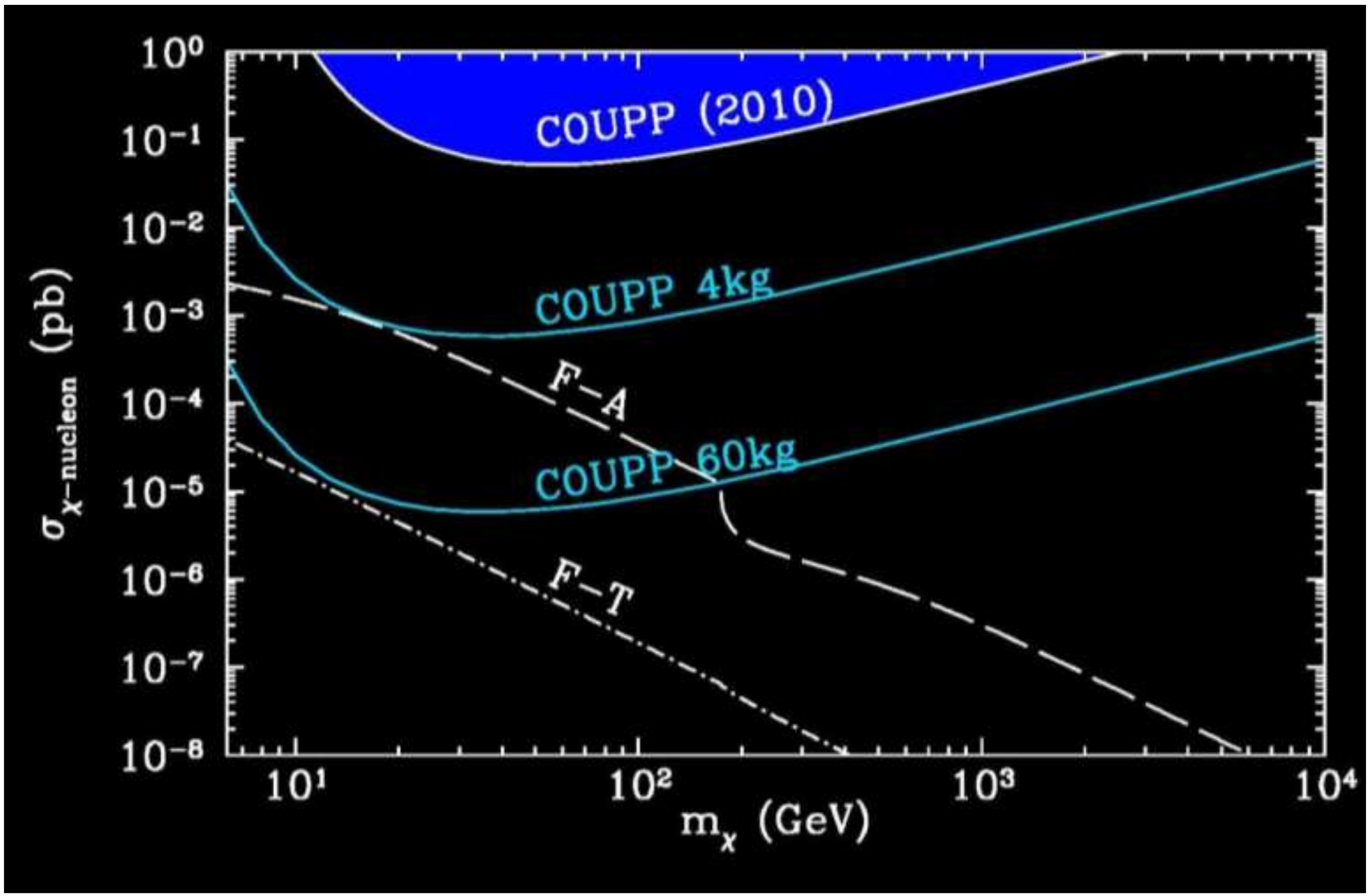



For $m \geq 10$ GeV or so $\sigma \leq 10^{-7}$ pb

Around a few GeV $\sigma \sim 10^{-6}$ pb

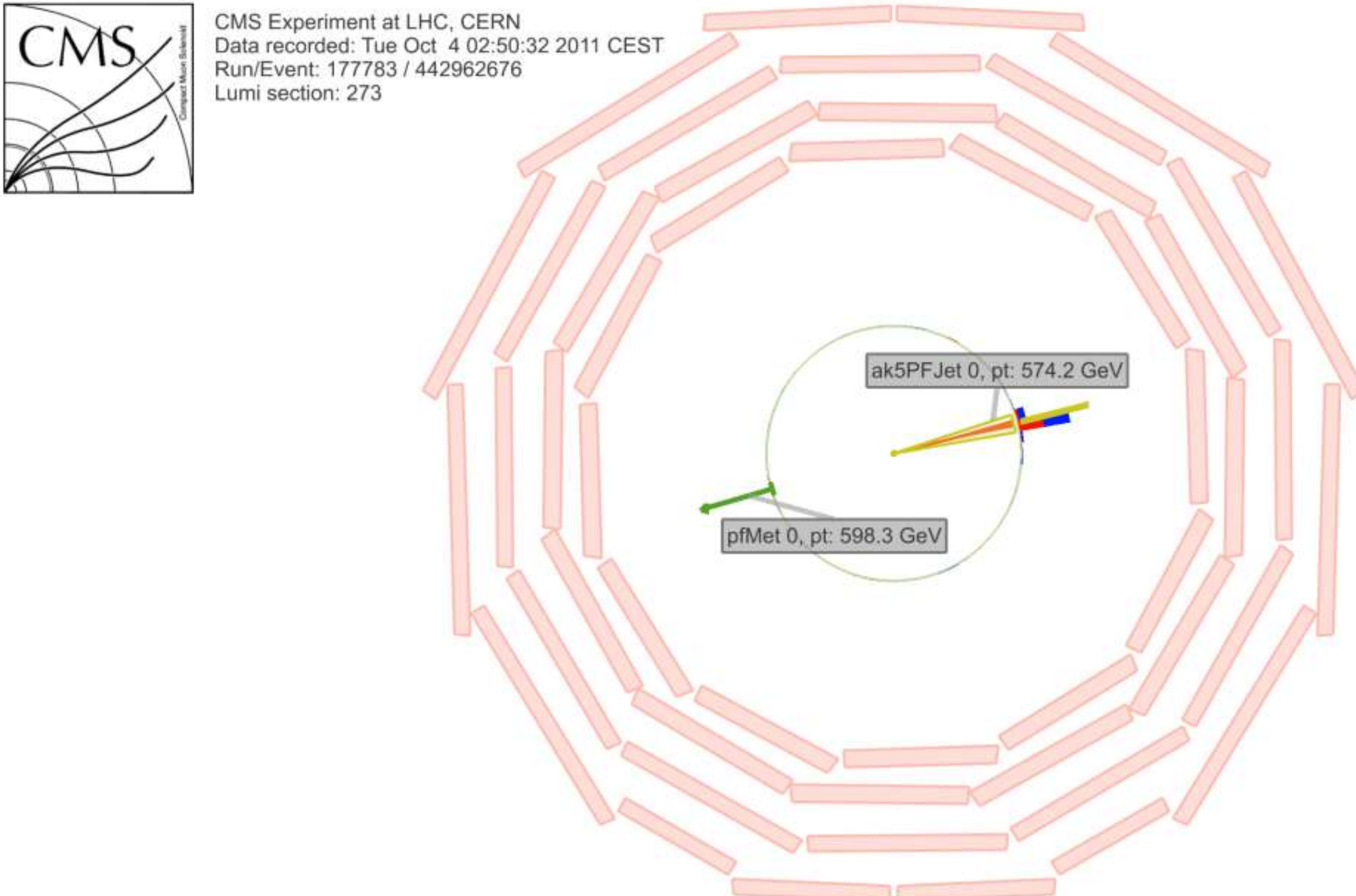
# Maverick WIMPs

spin-dependent




$\sigma$ can be as large as $10^{-3}$ pb to $10^{-6}$ pb

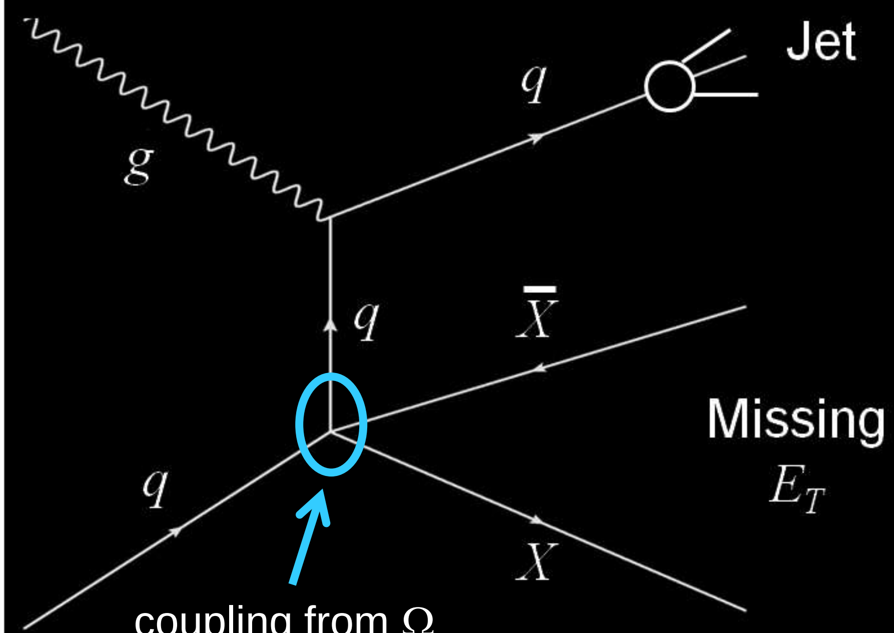
# Missing Momentum = Missing Mass?



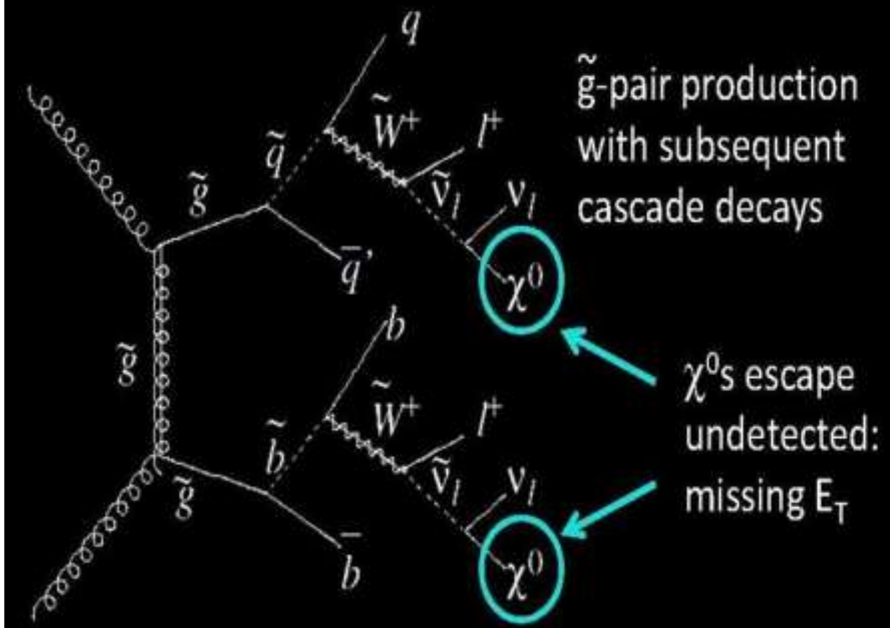

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

# WIMPs
## Collider Searches

### Maverick WIMPs




### Social WIMPs



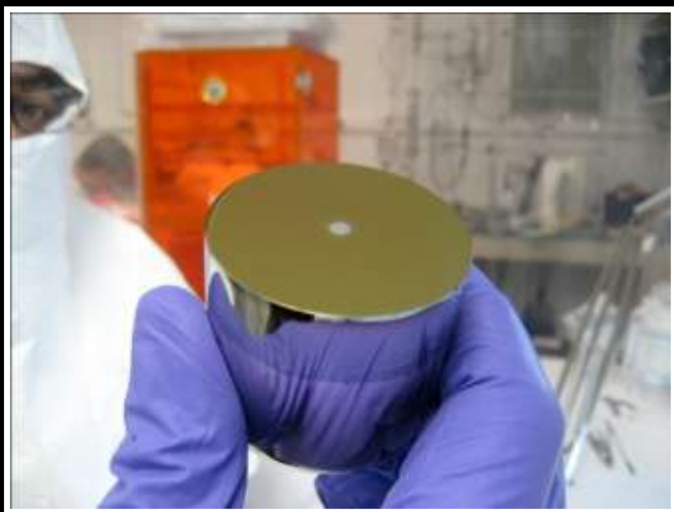

Backgrounds (neutrino, QCD, …)

Complicated decay chain

Beltran, Hooper, Kolb, Krusberg, Tait 1002.5137
Rajaraman, Shepherd, Tait, Wijangco 1108.1196
Fox, Harnik, Kopp, Tsai 1109.4398

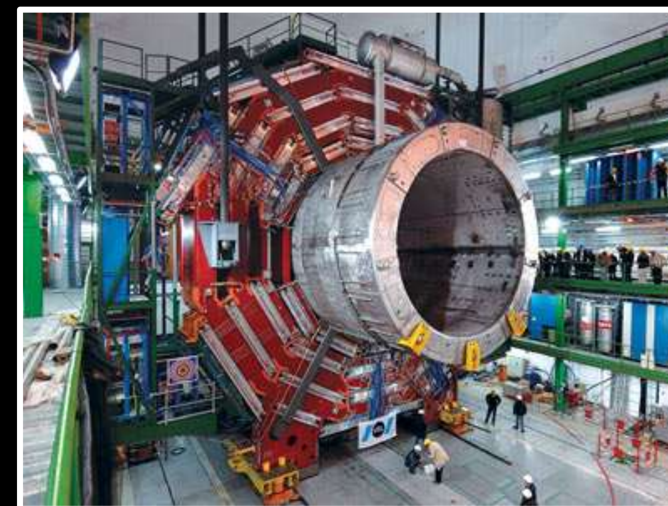
# WIMPs

CoGeNT



Model Dependent

LHC



**nonrelativistic**

$$\chi + N \rightarrow \chi + N$$

$10^{-4}$ **pb** – $10^{-6}$ **pb**

Described by
Effective field theory

**relativistic**

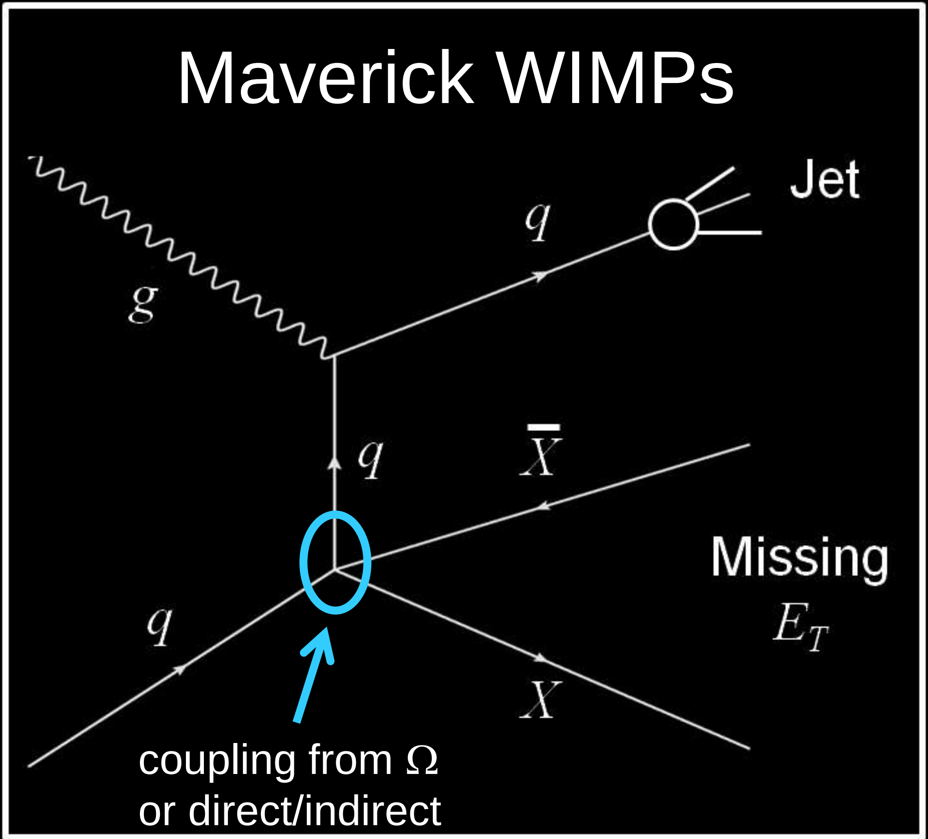
$$q + \bar{q} \rightarrow \chi + \chi$$

???

Assume described by
effective field theory

# Maverick WIMPs

## Collider Searches

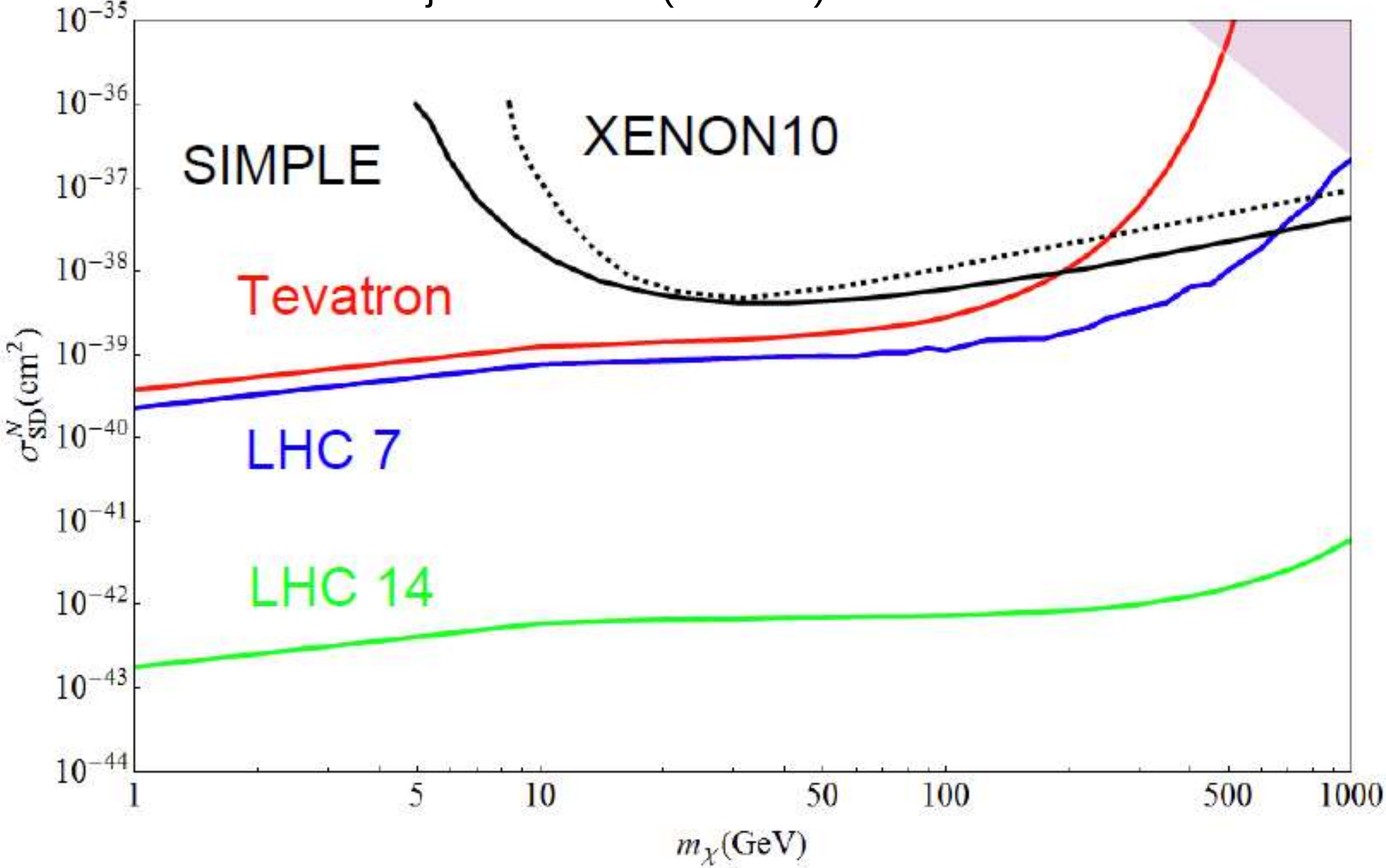



Backgrounds (neutrino, QCD, …)

- MadGraph/MadEvent:
  Feynman diagrams,
  cross sections,
  parton-level events
- Pythia:
  Hadron-level events
  via Monte Carlo showering
- PGS:
  Reconstructed events
  at collider

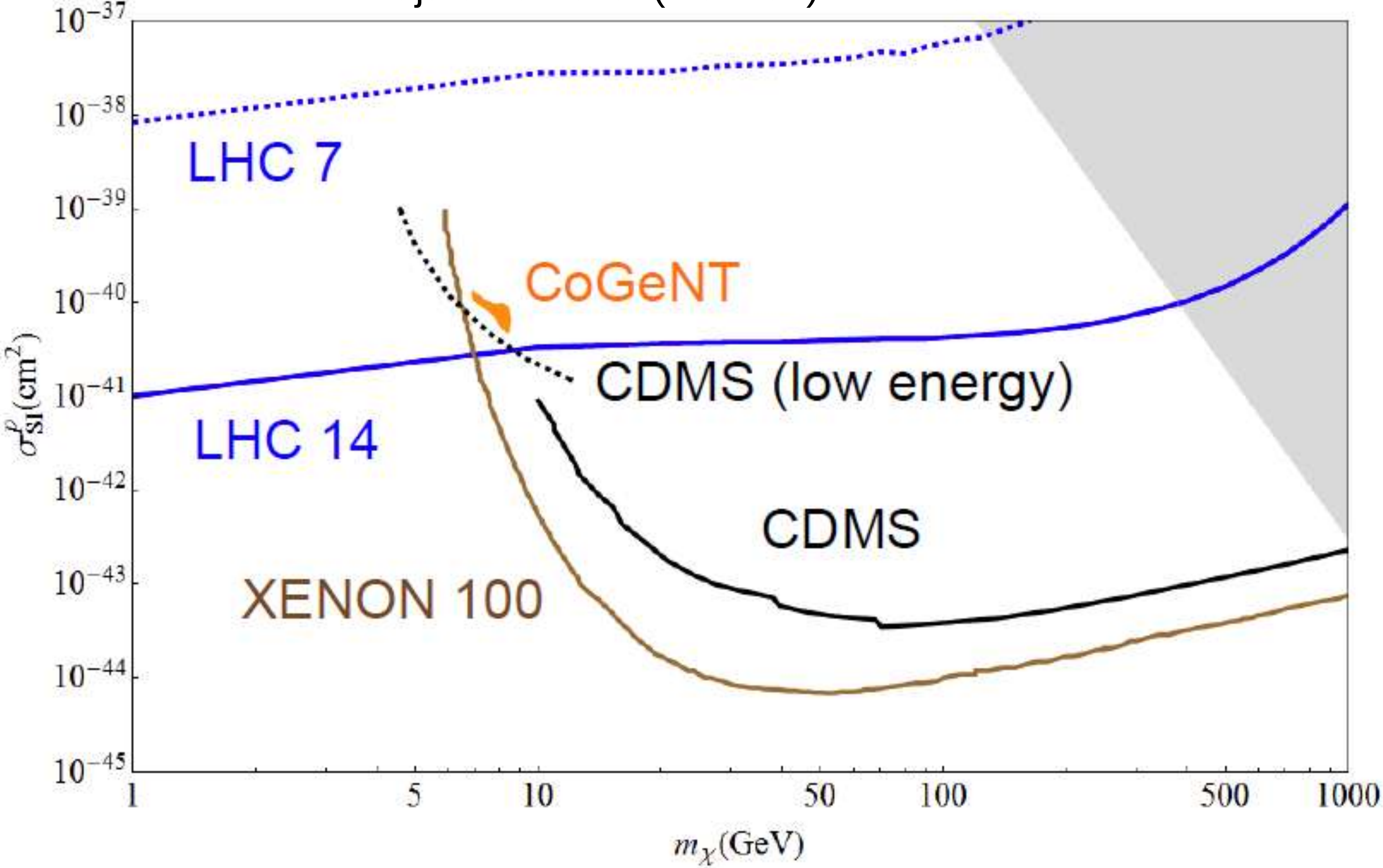
# Predicted LHC Sensitivity

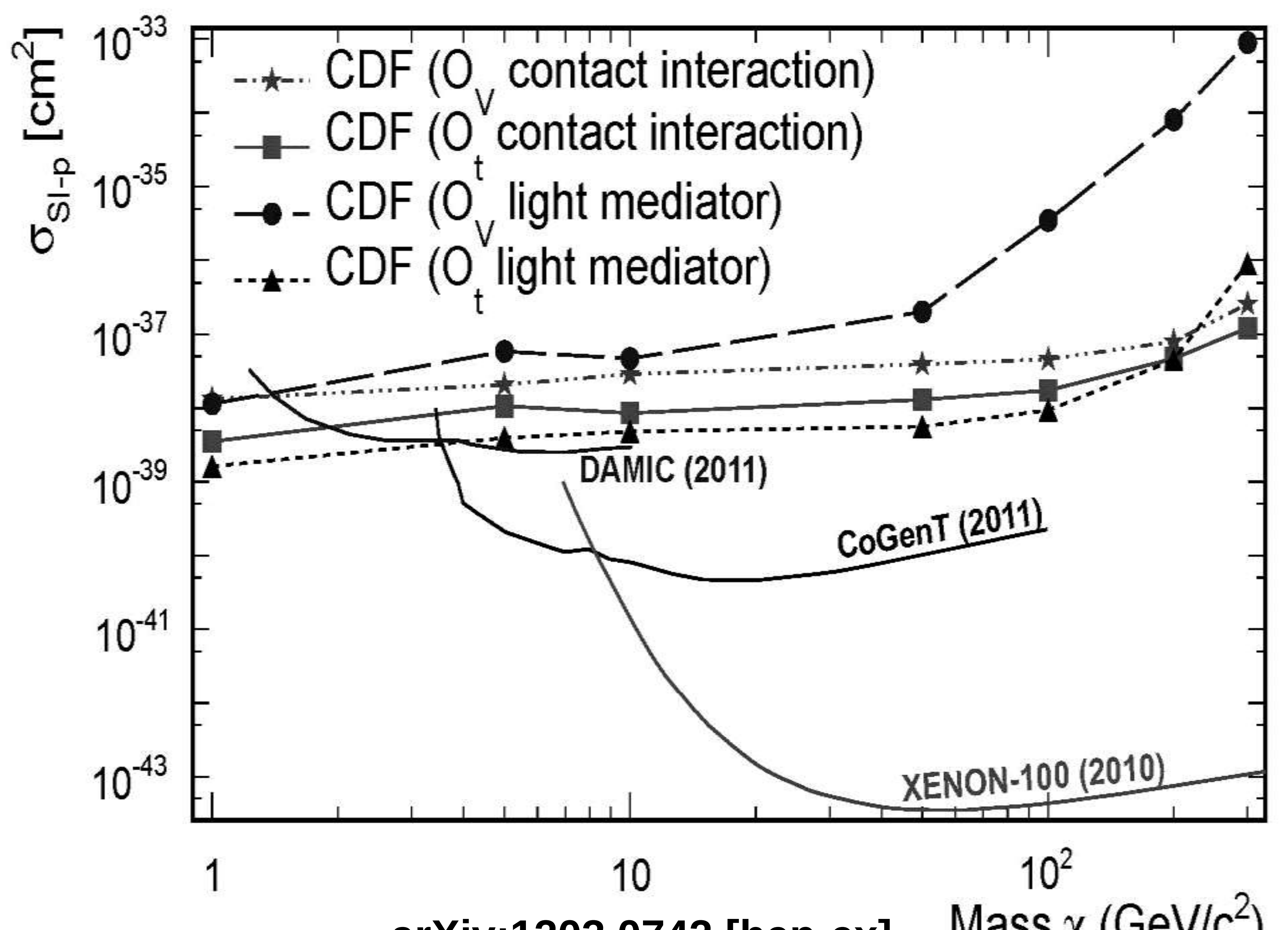
Rajaraman et al (incl. Tait) PRD 2011



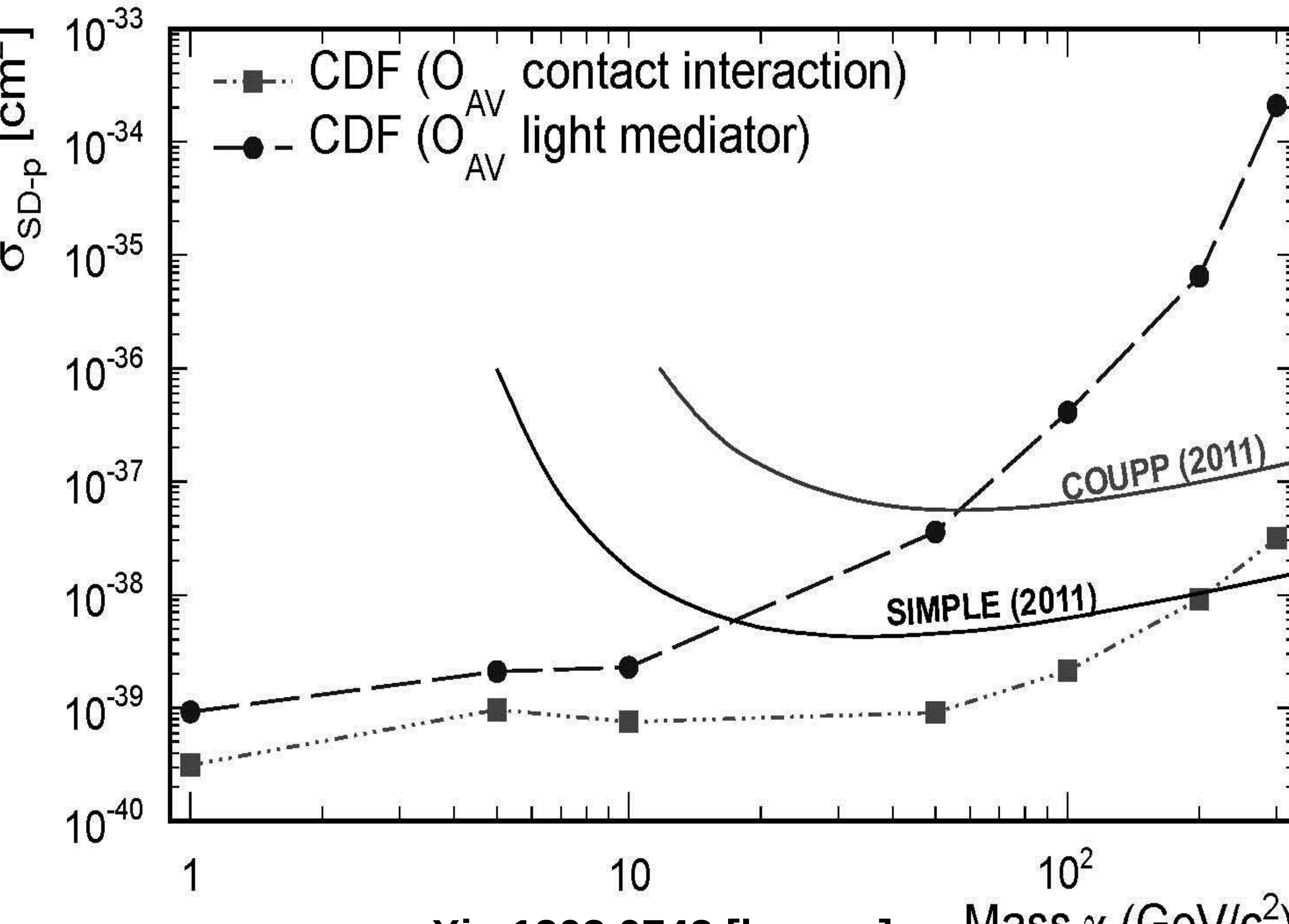
# Predicted LHC Sensitivity

Rajaraman et al (incl. Tait) PRD 2011






arXiv:1203.0742 [hep-ex]

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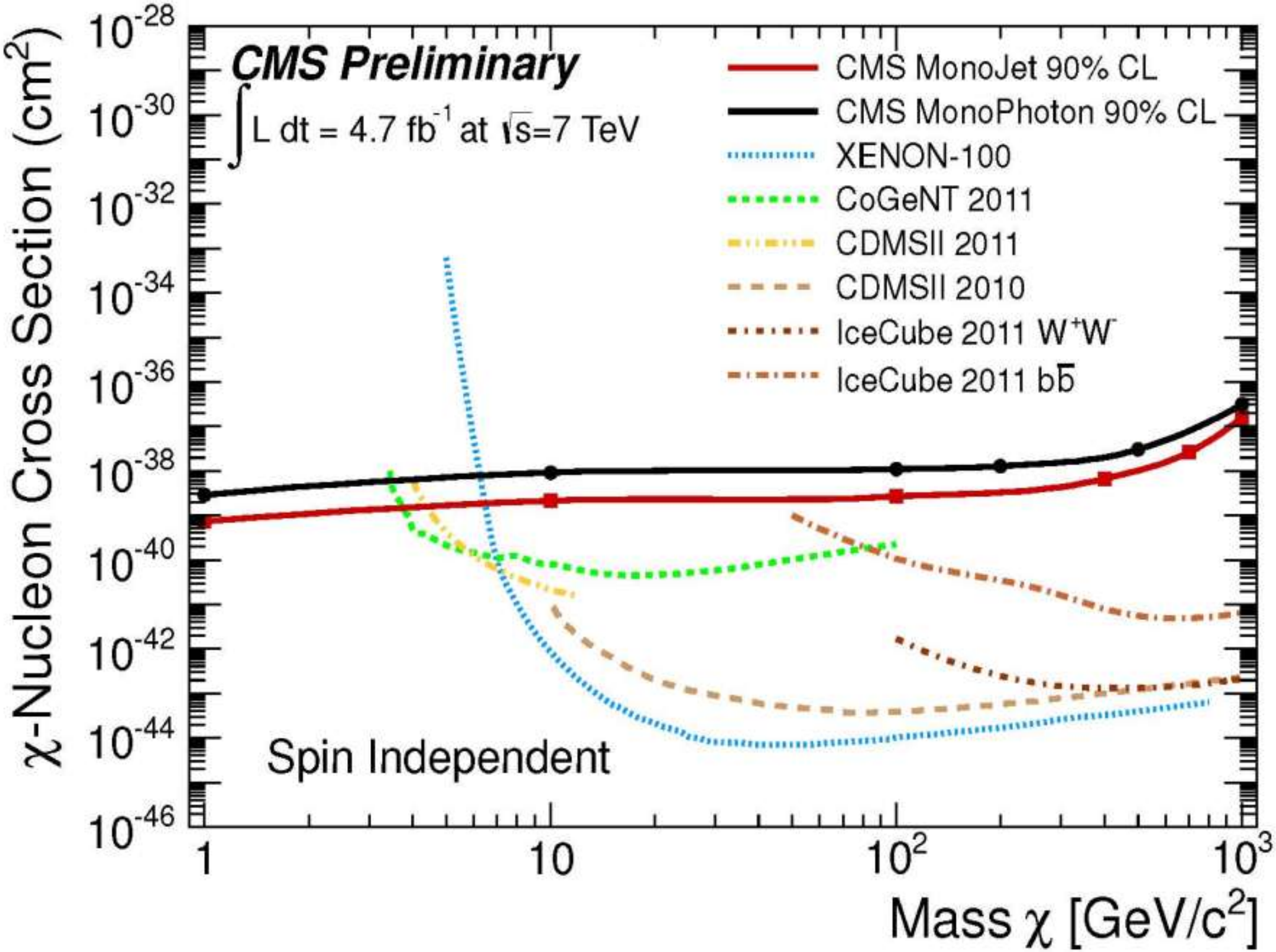

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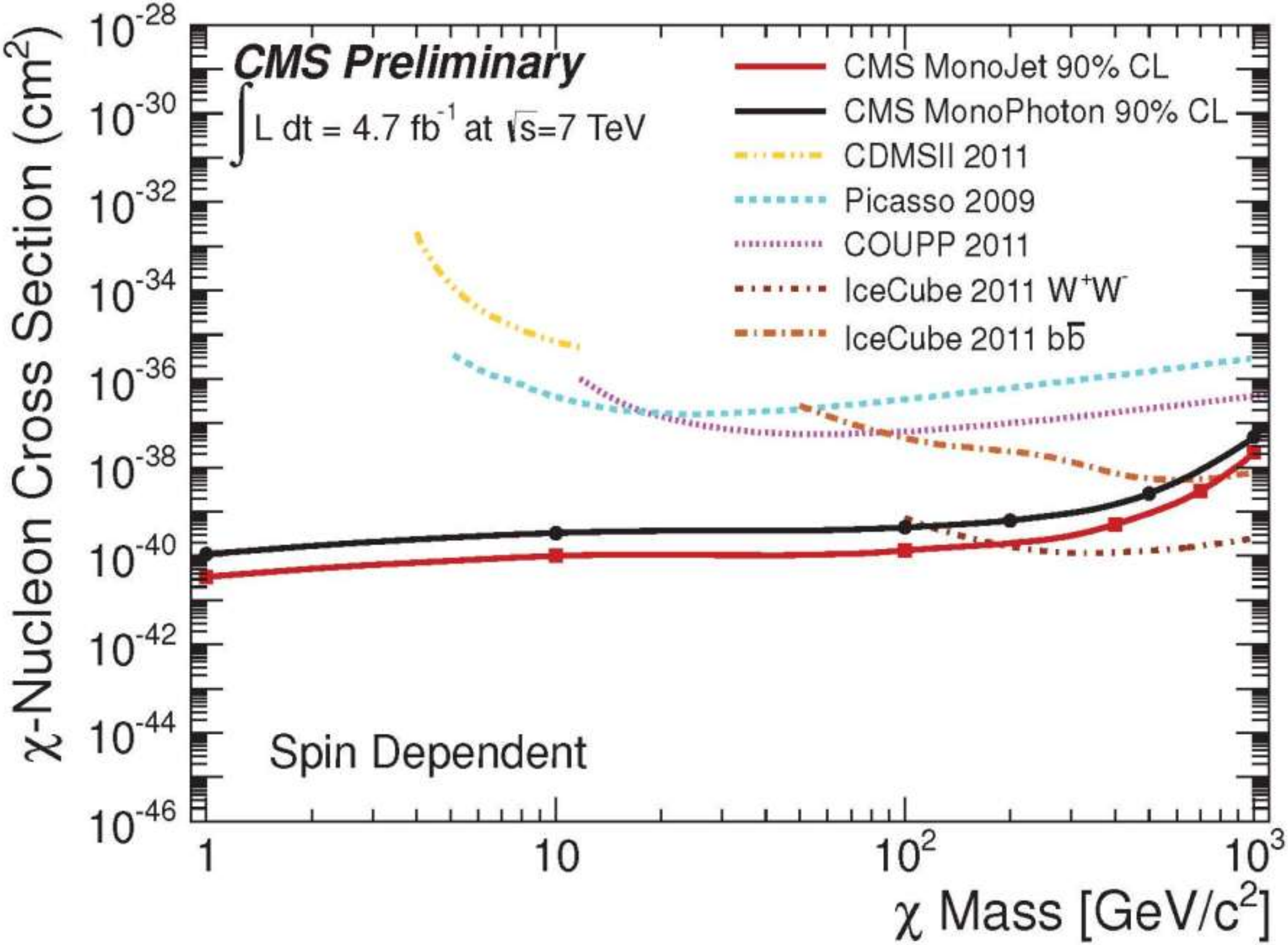
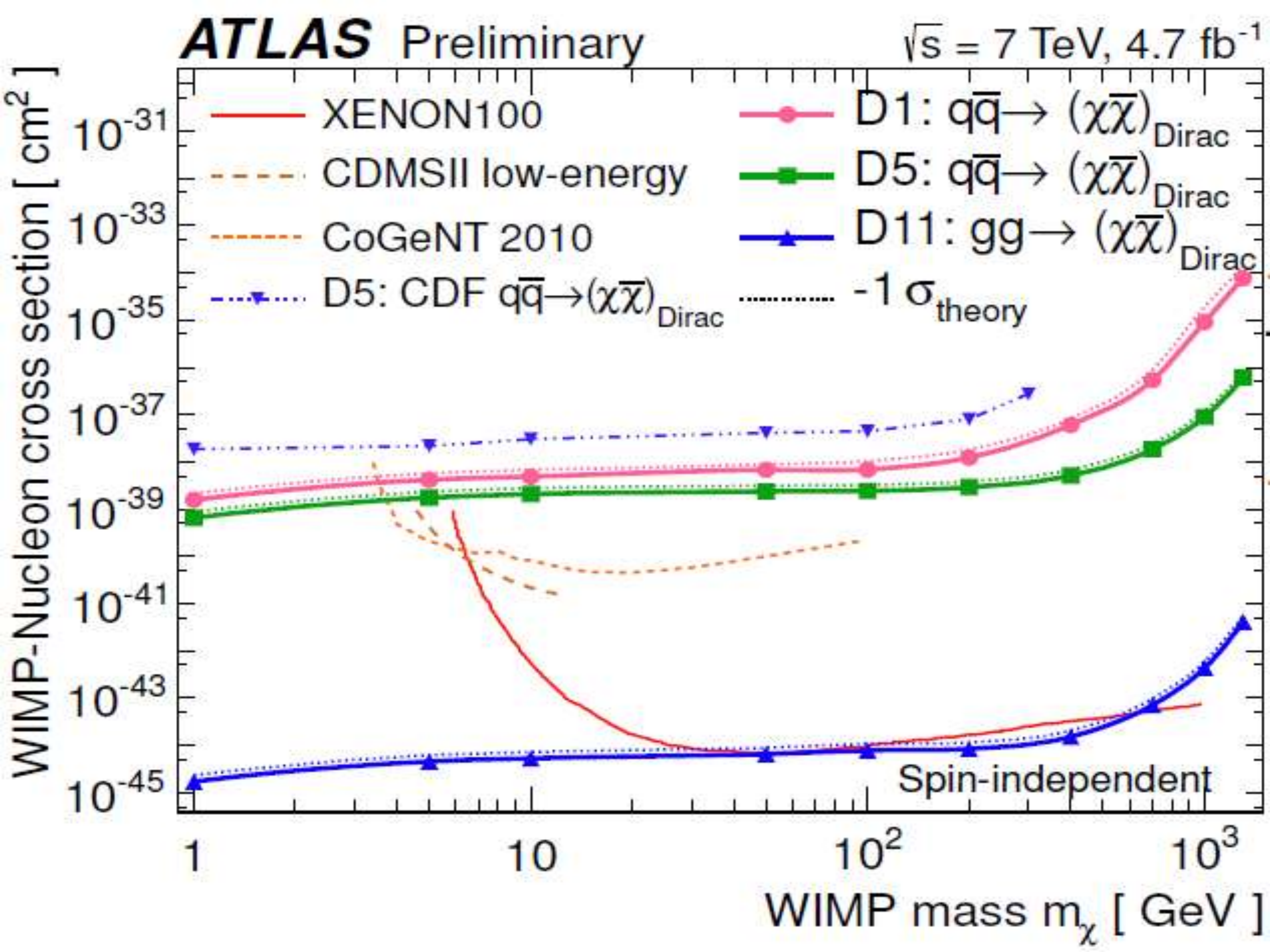
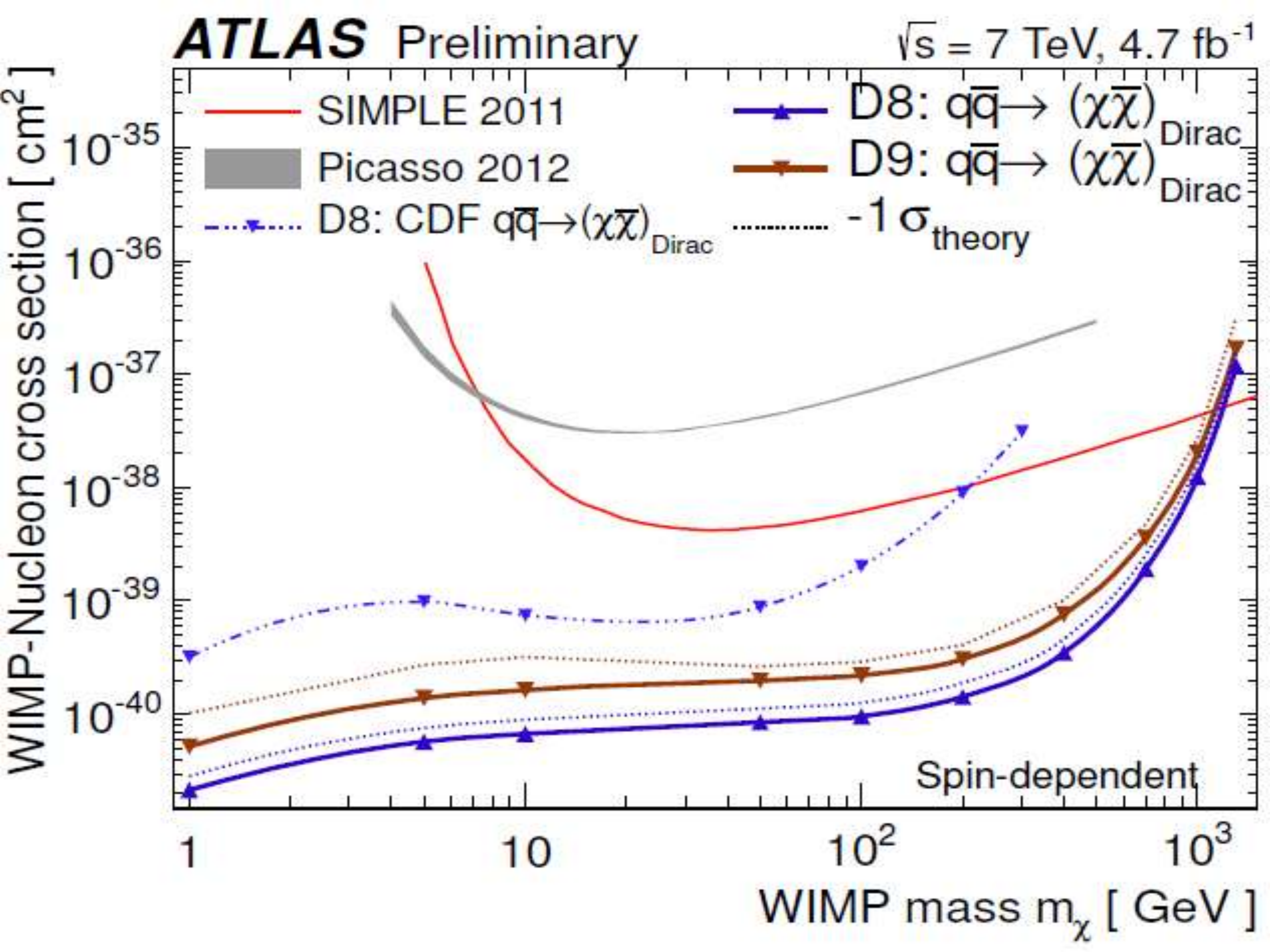




ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.7 fb$^{-1}$
XENON100
CDMSII low-energy
CoGeNT 2010
D5: CDF $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D1: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D5: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D11: $gg\rightarrow(\chi\bar{\chi})_{Dirac}$
-1 $\sigma_{theory}$
Spin-independent
WIMP-Nucleon cross section [ cm$^2$ ]
WIMP mass $m_\chi$ [ GeV ]
$10^{-31}$
$10^{-33}$
$10^{-35}$
$10^{-37}$
$10^{-39}$
$10^{-41}$
$10^{-43}$
$10^{-45}$
1
10
$10^2$
$10^3$



ATLAS Preliminary
√s = 7 TeV, 4.7 fb⁻¹
SIMPLE 2011
Picasso 2012
D8: CDF qq̄→(χχ̄)Dirac
D8: qq̄→ (χχ̄)Dirac
D9: qq̄→ (χχ̄)Dirac
-1 σtheory
Spin-dependent
WIMP-Nucleon cross section [ cm² ]
WIMP mass mχ [ GeV ]

# WIMP Questions

- Only <u>one</u> WIMP?

  The 4% of matter we see is pretty complex and varied.
  If social network of several WIMPs, stronger interacting ones:
    - Easier to detect
    - Smaller $\Omega$
- Thermal Production of WIMPS?
    - Super-WIMPs
    - Asymmetric Freeze out
- Maverick WIMPs?
    - Suppose LHC only sees SM Higgs?
    - Wither SNOOZY?
- Leptophilic, Leptophobic, Flavorful, Self-Interacting WIMPs?
- Annual modulation: do we really understand DM phase space?
- Indirect detection gives indirect information

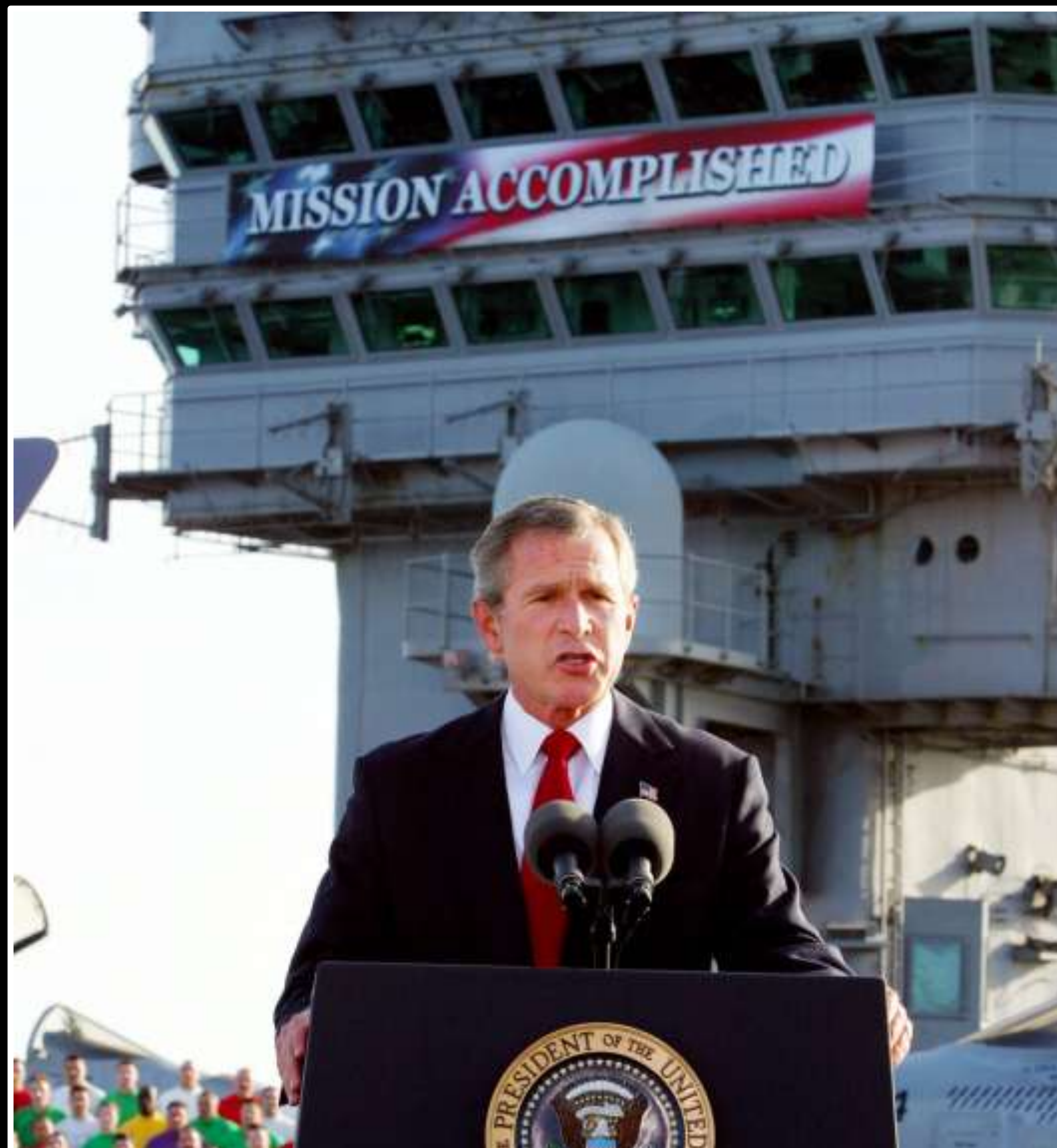
# The Decade of the WIMP

- WIMP coincidence or causation (it ain't a miracle)?
- Situation now is muddled
- Ten years from now the WIMP hypothesis will have either: convincing evidence or near-death experience
- Direct detectors, indirect detectors, & colliders race for discovery
- Suppose by 2020 have credible signals from all three???
- Do we need three (direct + indirect + accelerator) "miracles" for WIMP sainthood?

**How will we know they are all seeing the same phenomenon?**

- When do we stop?

# “Mission Accomplished”
## What Would It Take?



# IT TAKES THE VILLAGE PEOPLE

Big Chief Spokesperson

Cowboy Cosmologist

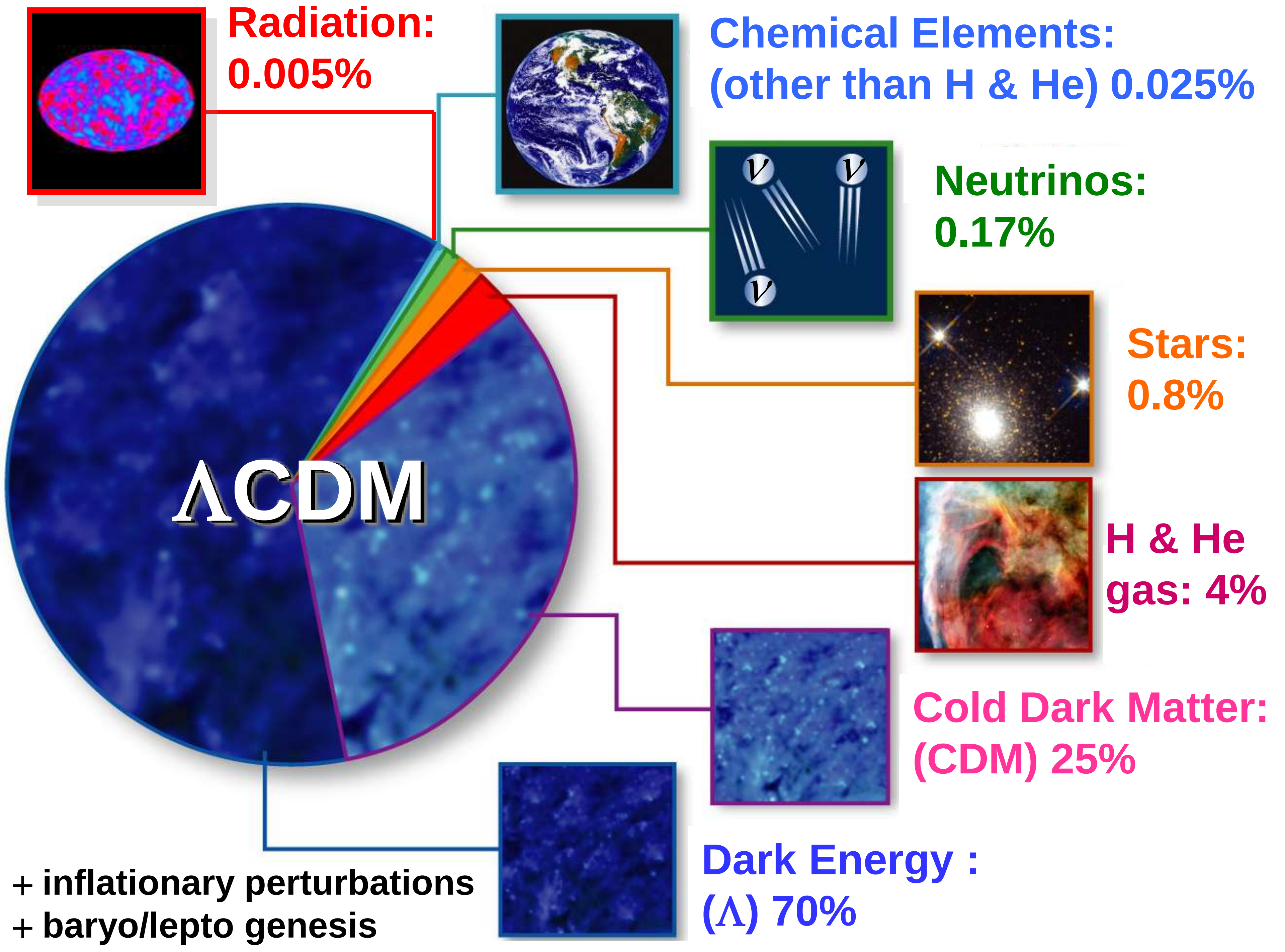
Hardhat Experimentalist

Swiss-Army at CERN

Beyond SM Guy

SUSY Cop

# Yet More To The Dark Side



Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He
gas: 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy :
(Λ) 70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

# Expansion History of the Universe $H(z)$

Einstein's Equations: $R_{\mu\nu} - \square\, g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

Robertson–Walker metric

$k = +1\ ({}^3S);\ -1\ ({}^3H);\ 0\ ({}^3R)$

Comoving coordinates $r$, $\Omega$

Scale factor $a(t)$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Stress-Energy Tensor: $T_{\mu\nu} = -g_{\mu\nu}\, p + (\rho + p)\, U_\mu U_\nu$

Expansion rate of the Universe: $H \equiv \frac{\dot a}{a}$

$$\left(\frac{\dot a}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi}{3} G\rho$$

Friedmann Equation

$$\frac{\ddot a}{a} = -8\pi G(\rho + 3p)$$

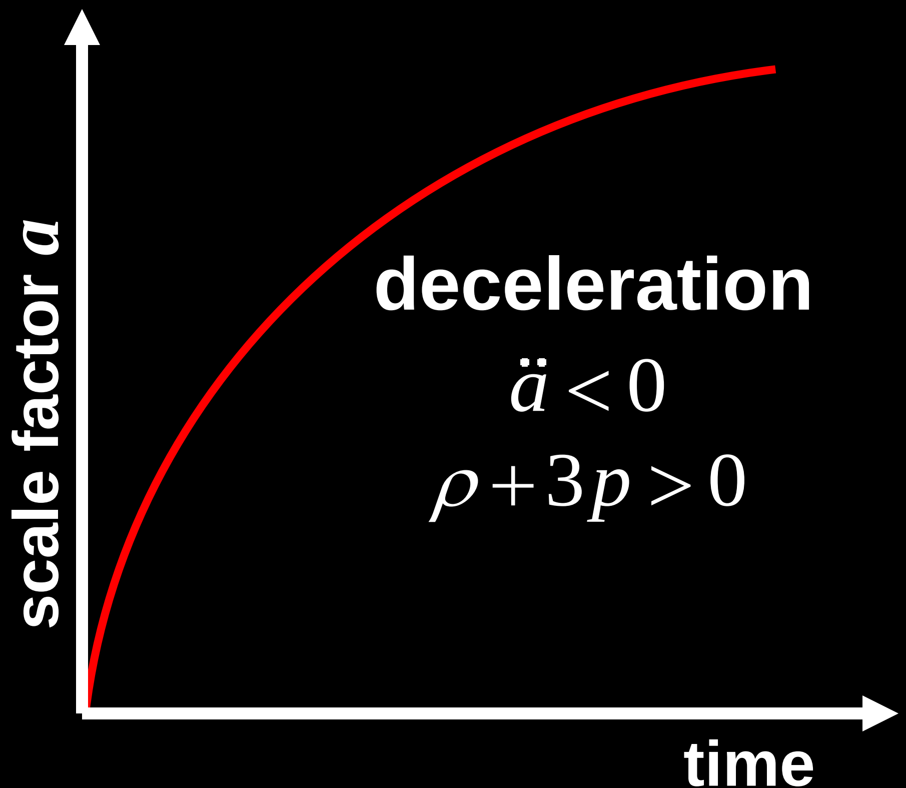
Deceleration Parameter

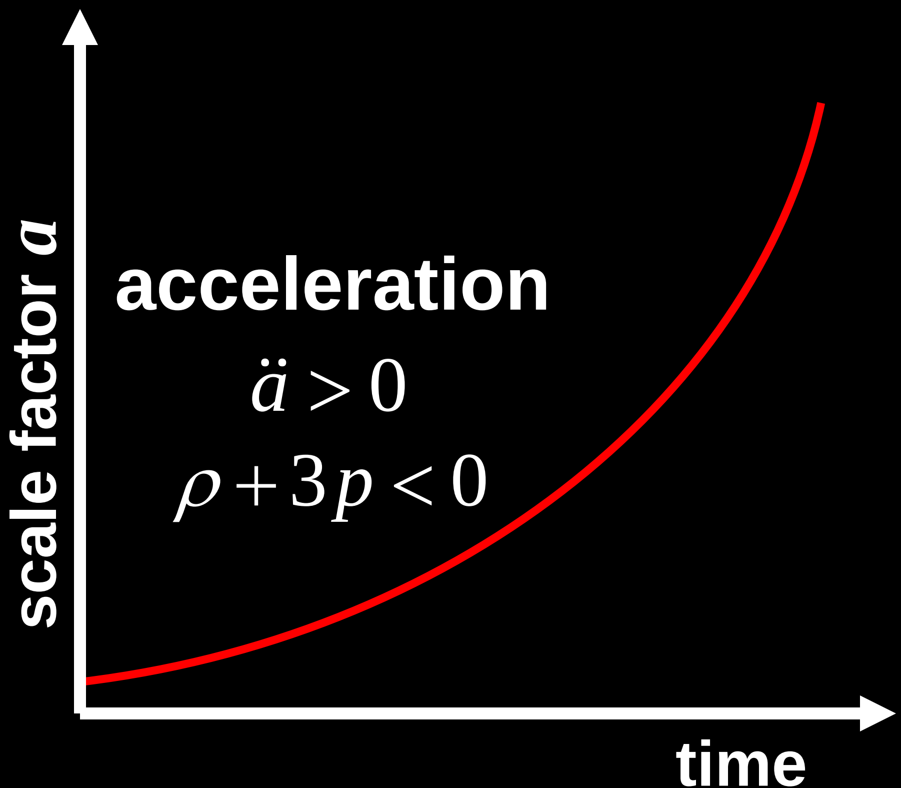
# Expansion History of the Universe $H(z)$

distance: $a \propto D$ (cosmic scale factor)

velocity: $\dot{a} \propto H$ (Hubble parameter)

acceleration: $\ddot{a} \propto -G(\rho + 3p)$



# Expansion History of the Universe $H(z)$

Einstein's Equations: $R_{\mu\nu} - \square\, g_{\mu\nu} R - \Lambda\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

Equation of State: $T_{\mu\nu} = -g_{\mu\nu}\, p + (\rho + p)\, U_\mu\, U_\nu$

Conservation of stress-energy: $T^{\mu\nu}{}_{;\nu} = 0 \rightarrow \rho \propto a^{-3(1+w)}$ if $p = w\,\rho$

1. If $p = -\rho \quad (w = -1)$ then $T_{\mu\nu} = g_{\mu\nu}\,\rho$ and $\Lambda \square\, 8\pi G\, \rho_\Lambda$

   Cosmological constant behaves like fluid with $w = -1$

2. Vacuum energy unchanged in expansion $\rho \propto a^0$

   Vacuum energy behaves like fluid with $w = -1$

**Vacuum energy indistinguishable from cosmological constant:**

$$\Lambda \square\, 8\pi G\, \rho_\Lambda$$

# Expansion History of the Universe $H(z)$

- Robertson–Walker metric
  $k=+1$ ($^3S$); $-1$ ($^3H$); $0$ ($^3R$)

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

- Photons travel on geodesics:
  $ds^2 = 0$

$$\frac{dr}{\sqrt{1-kr^2}} = \frac{dt}{a(t)} = \frac{da}{\dot{a}(t)a(t)}$$

- Define expansion rate $H \equiv \dot{a}/a$
  and redshift $1+z \equiv a_0/a$

$$\int \frac{dr}{\sqrt{1-kr^2}} = \int \frac{da}{Ha^2} = \int \frac{dz}{H(z)}$$

- Photon emitted from $r(z)$ detected
  by observer today

$$r(z) = \left.\begin{matrix}\sin \\ 1 \\ \sinh\end{matrix}\right\}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

# Expansion History of the Universe $H(z)$

Consider luminosity distance $d_L(z)$ :   Flux = (Luminosity / $4\pi\, d_L{}^2$)

Source at position $r(z)$ with luminosity □.  Flux detected is

$$\text{Flux} = \frac{\text{energy}}{\text{area} \times \text{time}} = \frac{\square}{(1+z)^2 \;\; 4\pi\, a_0{}^2\, r^2} = \frac{\square}{4\pi\, d_L{}^2}$$

Redshift of energy of photons $1+z$
Stretch of time: $1+z$

area of a two-sphere
observer at center, source at $r$

$$\boxed{d_L(z) \propto (1+z)\, r(z)}$$

# Expansion History of the Universe $H(z)$

Robertson–Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Many observables based on $H(z)$ through coordinate distance $r(z)$

$$r(z) = \left.\begin{matrix}\sin\\ 1\\ \sinh\end{matrix}\right\}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

- Luminosity distance

  Flux = (Luminosity / $4\pi d_L{}^2$)

$$d_L(z) \propto r(z)(1+z)$$

- Angular diameter distance

  $\alpha =$ Physical size / $d_A$

$$d_A(z) \propto \frac{r(z)}{(1+z)}$$

- Volume (number counts)

  $N$ / $V^{-1}(z)$

$$dV = \frac{r^2(z)}{\sqrt{1-kr^2(z)}}\, dr\, d\Omega$$

- Age of the universe

$$t(z) \propto \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

# Expansion History of the Universe $H(z)$

Friedmann equation ($G_{00} = 8\pi G T_{00}$)

$$\begin{bmatrix}\text{expansion}\\ \text{rate }(z)\end{bmatrix}^2 = \begin{bmatrix}\text{Hubble}\\ \text{const.}\end{bmatrix}^2 \times \Big[\text{curvature }(z) + \text{matter }(z) + \text{radiation }(z)\Big]$$

$$H^2(z) = H_0^2 \times \left[\Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4\right]$$

$$\Omega_M = \frac{\rho_M}{3H_0^2/8\pi G} \qquad \Omega_R = \frac{\rho_R}{3H_0^2/8\pi G} \qquad \Omega_k = \frac{-3k/8\pi G a_0^2}{3H_0^2/8\pi G}$$

- At $z = 0$, $H = H_0 \Rightarrow \Omega_k + \Omega_M + \Omega_R = 1$

$$H^2(z) = H_0^2 \times \left[(1-\Omega_M-\Omega_R)(1+z)^2 + \Omega_M(1+z)^3 + \Omega_R(1+z)^4\right]$$

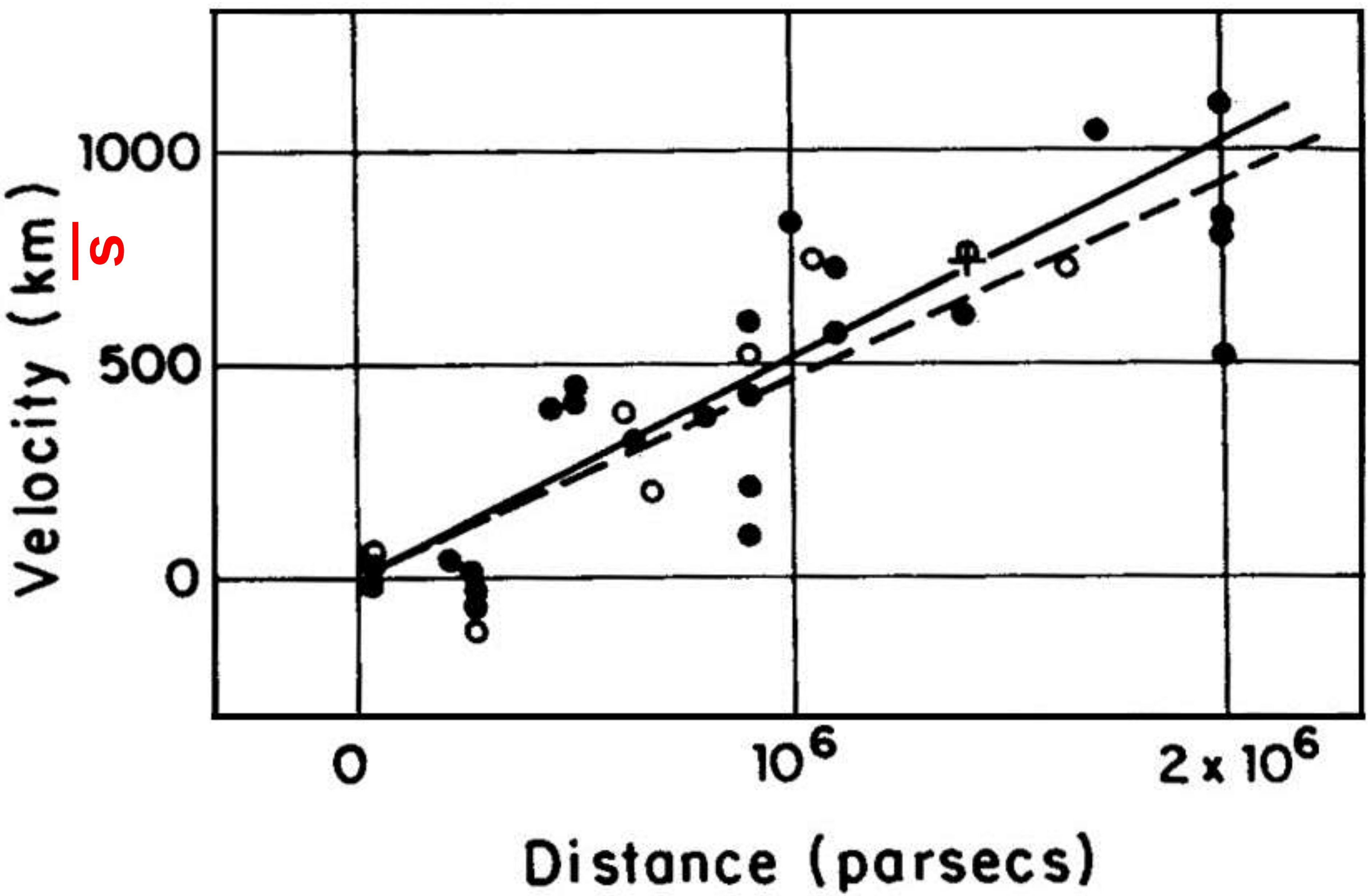
- radiation contribution ($\Omega_R$) small for $z \ll 10^3$

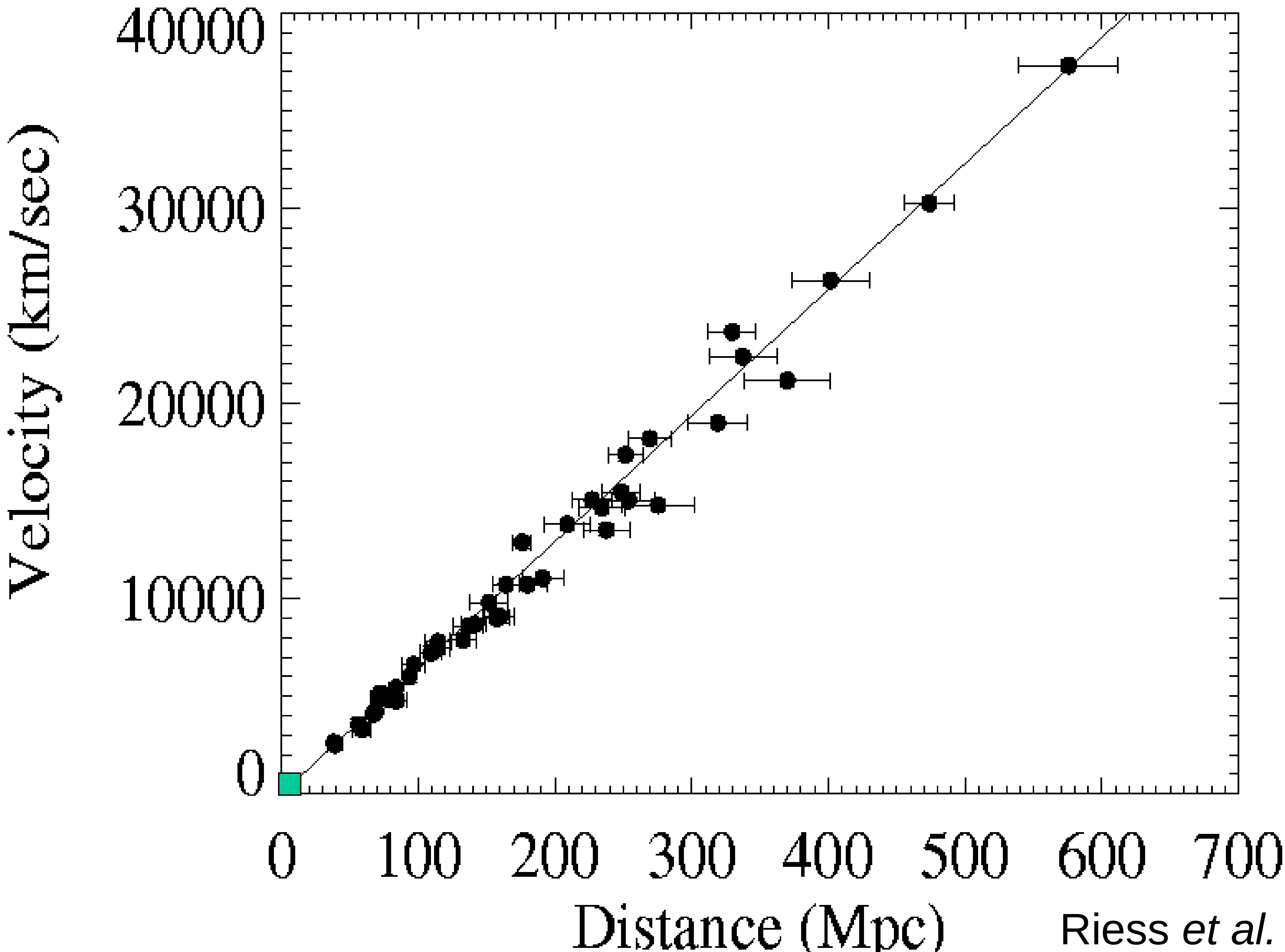
$$H^2(z) = H_0^2 \times \left[(1-\Omega_M)(1+z)^2 + \Omega_M(1+z)^3\right]$$

- “All of observational cosmology is a search for two numbers.” ($H_0$ and $q_0 = \Omega_M/2$) — Sandage, *Physics Today,* 1970


**University of Chicago 1909 National Champions**

# Hubble's Discovery Paper - 1929

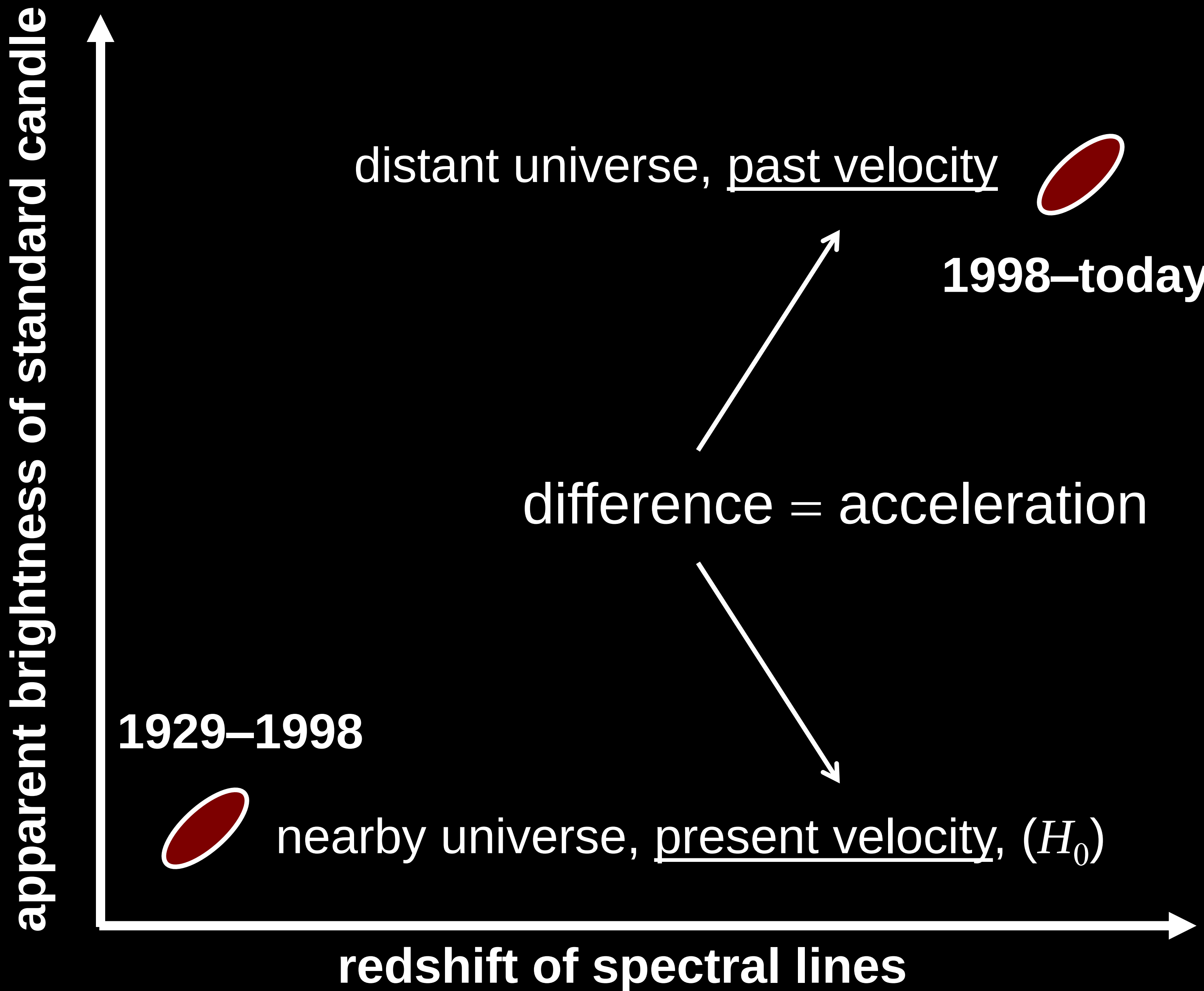




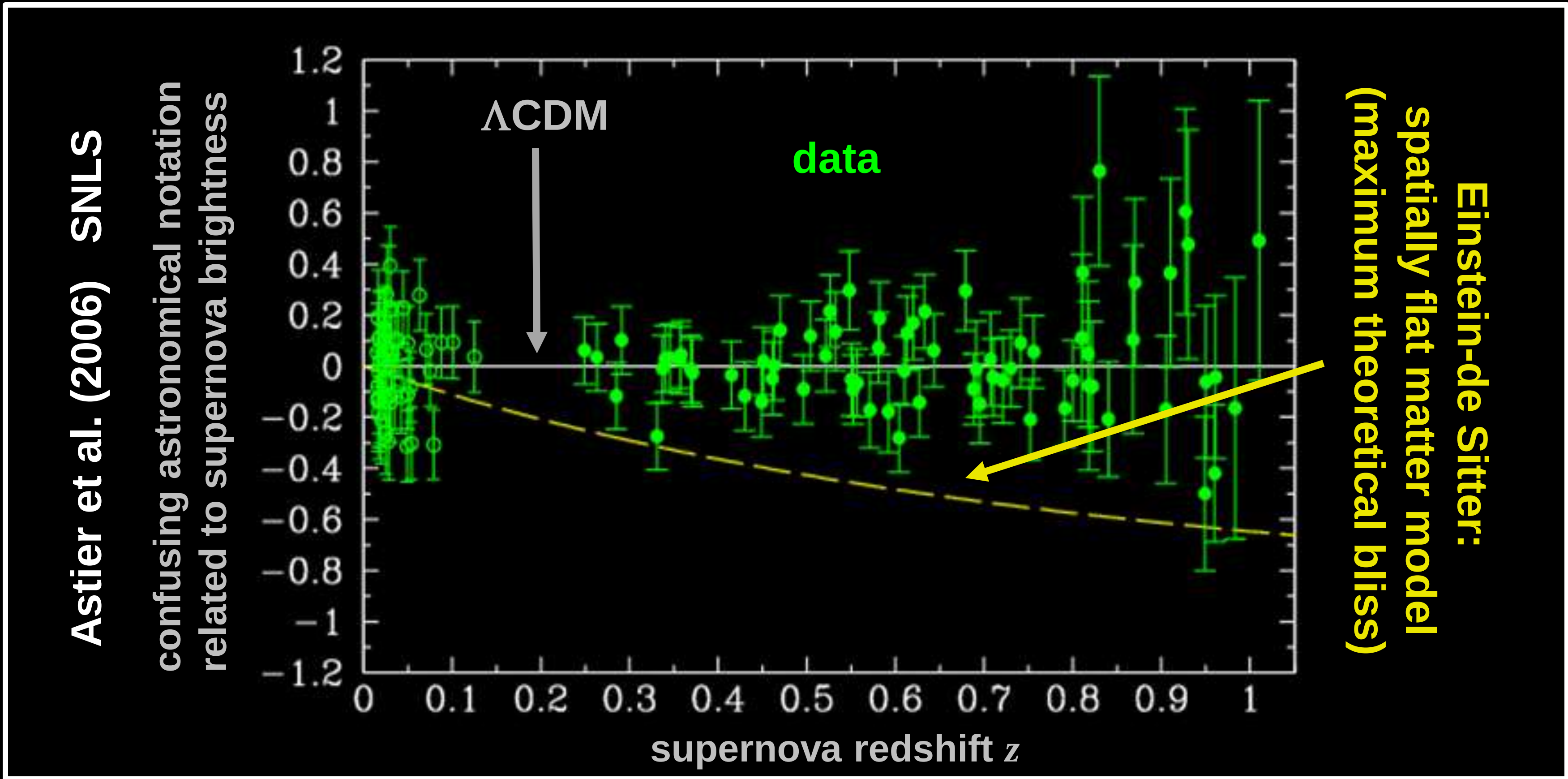
Velocity (km/sec)
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)


Riess *et al.*

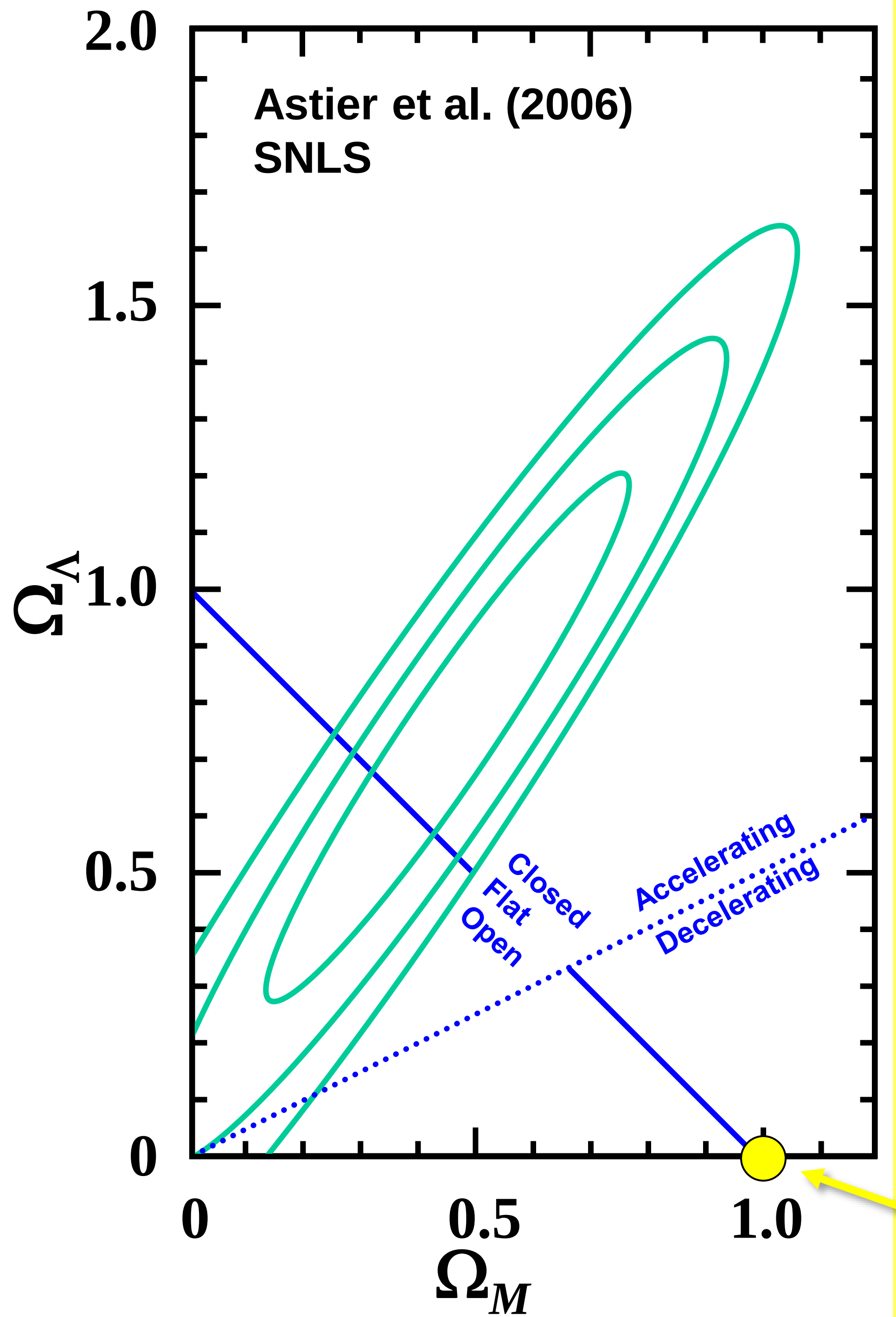
# Hubble Diagram



# Hubble Diagram



# Hubble Diagram




1. Find standard candle (SNe Ia)
2. Observe magnitude & redshift
3. Assume a cosmological model
4. Compare observations & model

Einstein–de Sitter model

# Expansion History of the Universe $H(z)$

# Cosmological Constant (Dark Energy)

1917 Einstein proposed cosmological constant, $\Lambda$.

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."

# Cosmological Constant (Dark Energy)

$$R_{\mu\nu} - \square\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ Einstein 1915

$$R_{\mu\nu} - \square\, g_{\mu\nu} R - \Lambda^{\mathrm{CC}} g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$ Einstein 1917

$\Lambda^{\mathrm{CC}} =$ **cosmological constant**

$$R_{\mu\nu} - \square\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ Einstein 1934

$$R_{\mu\nu} - \square\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu} + 8\pi G\, T_{\mu\nu}^{\mathrm{vacuum}}$$ QFT+

$T_{\mu\nu}^{\mathrm{vacuum}}$: $\rho^{\mathrm{vacuum}} = -p^{\mathrm{vacuum}}$ $\qquad \rho^{\mathrm{vacuum}} + 3\,p^{\mathrm{vacuum}} < 0$

$$R_{\mu\nu} - \square\, g_{\mu\nu} R - \Lambda^{\mathrm{CC}} g_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda^{\mathrm{vacuum}} g_{\mu\nu}$$

$$\Lambda^{\mathrm{vacuum}} = 8\pi G \rho^{\mathrm{vacuum}}$$

**CC (*à la* Einstein) & $\rho^{\mathrm{vacuum}}$ indistinguishable**

# Expansion History of the Universe $H(z)$

Friedmann equation ($G_{00} = 8\pi G T_{00}$)

Hubble constant | cosmological constant | curvature | matter | radiation

$$H^2(z) = H_0^2 \times \left[ \Omega_\Lambda (1+z)^0 + \Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 \right]$$

- [Could add $\Omega_{\text{walls}}\,(1+z)^1$]
- $1 = \Omega_\Lambda + \Omega_k + \Omega_M + \Omega_R$
- radiation contribution ($\Omega_R$) small for $z \ll 10^3$
- $\Omega_k$ well determined (close to zero) from CMB
- $\Omega_M$ reasonably well determined

# Expansion History of the Universe $H(z)$

Friedmann equation ($G_{00} = 8\pi G T_{00}$)

Hubble constant | dark energy | curvature | matter | radiation

$$H^2(z) = H_0^2 \times \left[ \Omega_w (1+z)^{3(1+w)} + \Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 \right]$$

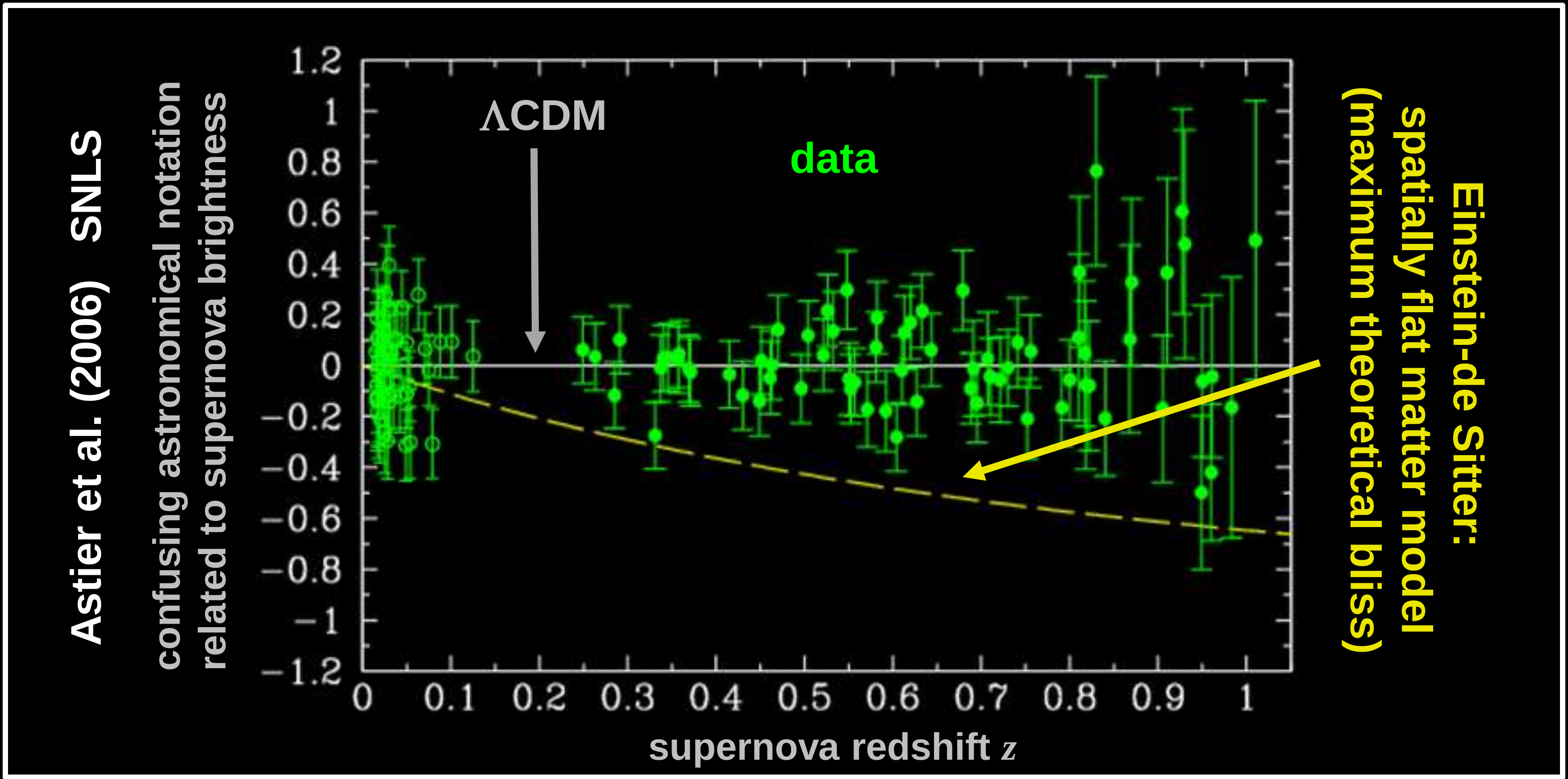
Equation of state parameter: $w = p/\rho$ ($w = -1$ for $\Lambda$)

if $w = w(z)$: $$(1+z)^{3(1+w)} \rightarrow \exp\left( -3 \int_0^z \frac{dz'}{z'} \left[ 1 + w(z') \right] \right)$$

parameterize: $w(z) = w_0 + w_a\, z / (1+z)$

Cosmology is a search for two numbers ($w_0$ and $w_a$).

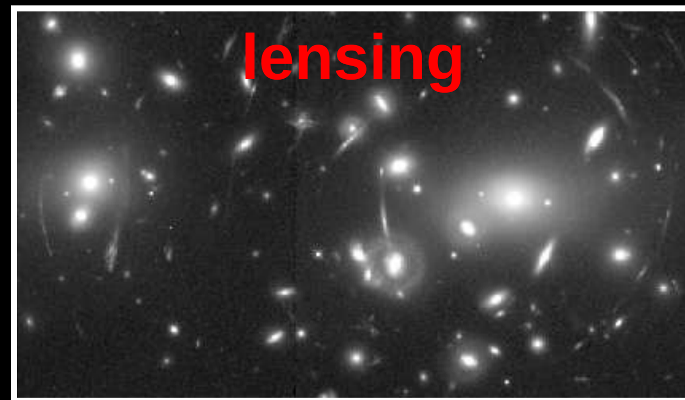
# The Cosmological Constant

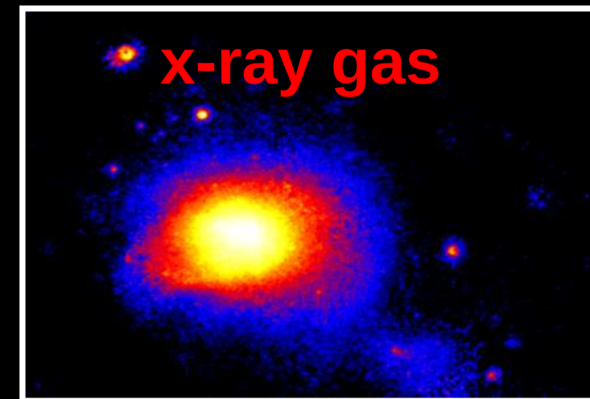


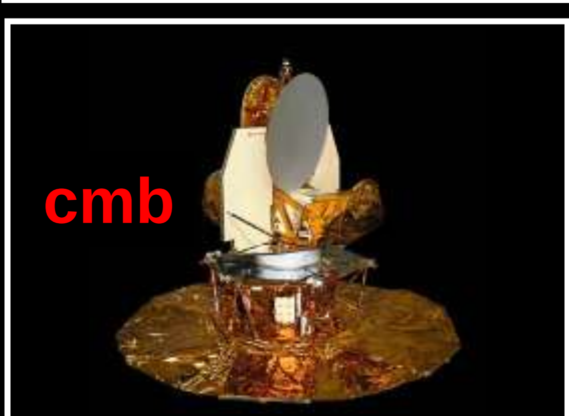

The case for $\Lambda$:

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

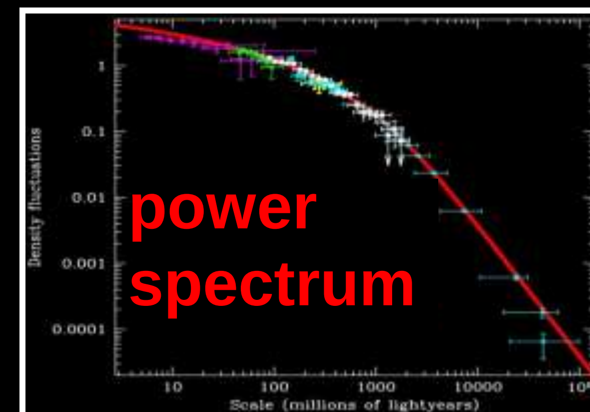
# The Cosmological Constant






$\Omega_{\text{TOTAL}} = 1$

**CMB**

$\Omega_M \sim 0.3$

**many methods**

$$1.0 - 0.3 = 0.7 \neq 0$$

# The Cosmological Constant

The Unbearable Lightness of Nothing

$$\rho_{\Lambda} = 10^{-30}\ \text{g cm}^{-3}$$

# The Cosmological Constant

Dark (and Useless) Energy

$$\rho_{\Lambda} = 1 \ \text{MeV liter}^{-1}$$

US006960975B1

(12) United States Patent
Volfson

(10) Patent No.: US 6,960,975 B1
(45) Date of Patent: Nov. 1, 2005

# (54) SPACE VEHICLE PROPELLED BY THE PRESSURE OF INFLATIONARY VACUUM STATE

(76) Inventor: **Boris Volfson**, 5707 W. Maple Grove Rd., Apt. 3046, Huntington, IN (US) 46750

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 8 days.

(21) Appl. No.: **11/079,670**

(22) Filed: **Mar. 14, 2005**

**Related U.S. Application Data**

(63) Continuation of application No. 10/633,778, filed on Aug. 4, 2003, now abandoned.

(51) **Int. Cl.**[7] .............................. **H01F 6/00**; F03H 5/00
(52) **U.S. Cl.** ........................................ **335/216**; 60/200.1
(58) **Field of Search** ......................... 335/216; 60/200.1

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*Primary Examiner*—Ramon M. Barrera

(57) **ABSTRACT**

A space vehicle propelled by the pressure of inflationary vacuum state is provided comprising a hollow superconductive shield, an inner shield, a power source, a support structure, upper and lower means for generating an electromagnetic field, and a flux modulation controller.

A cooled hollow superconductive shield is energized by an electromagnetic field resulting in the quantized vortices of lattice ions projecting a gravitomagnetic field that forms a spacetime curvature anomaly outside the space vehicle. The spacetime curvature imbalance, the spacetime curvature being the same as gravity, provides for the space vehicle's propulsion. The space vehicle, surrounded by the spacetime anomaly, may move at a speed approaching the light-speed characteristic for the modified locale.

**13 Claims, 6 Drawing Sheets**

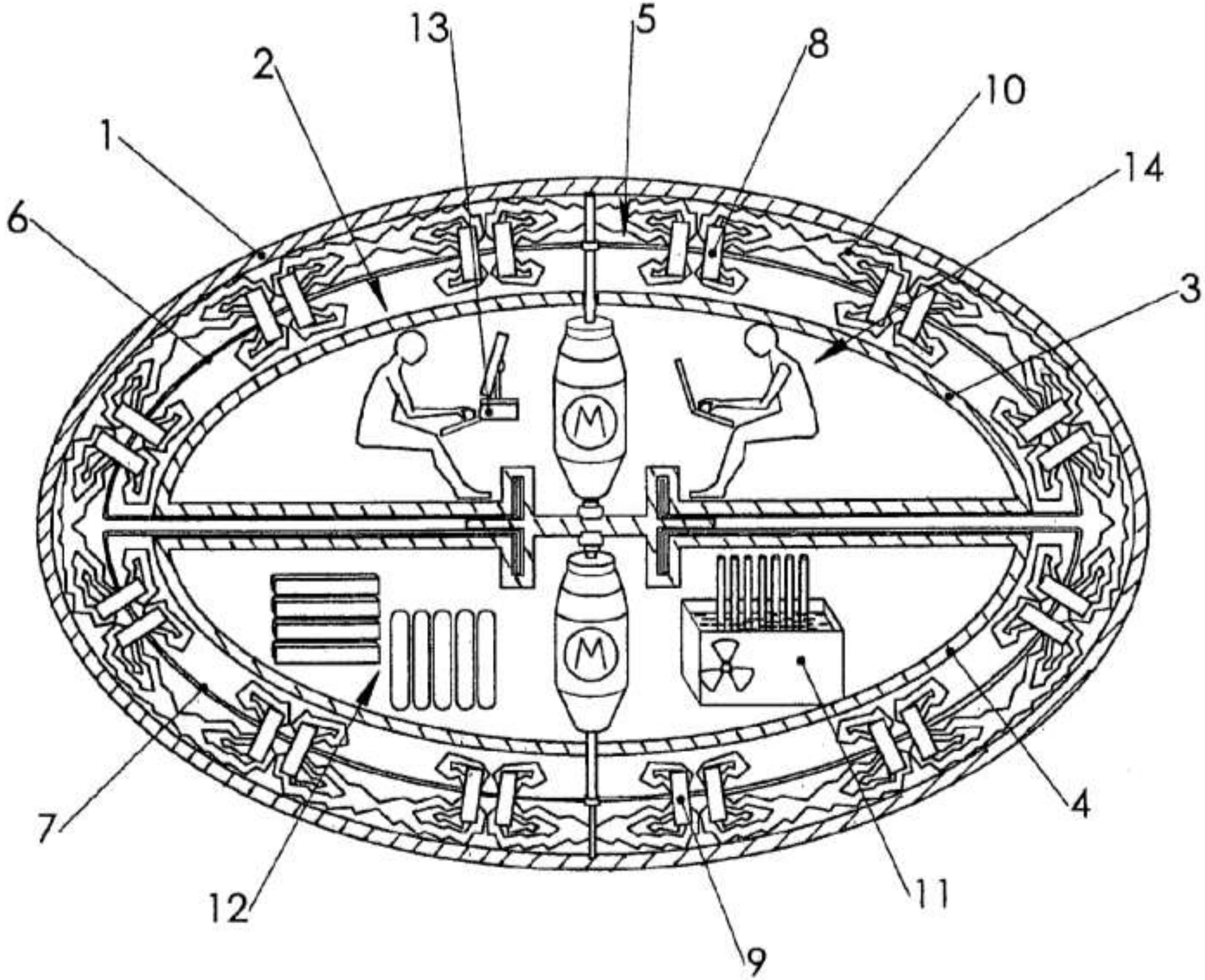



FIG. 1

# The Cosmological Constant

The Unbearable Lightness of Nothing

$$\rho_\Lambda = 10^{-30}\ \text{ g cm}^{-3}$$

so small, and yet not zero!

# The Cosmoillogical Constant

## $10^{-30}$ grams per cc

## 0.000000000000000000000000000001 grams per cubic centimeter

## The Unbearable Lightness of Nothing

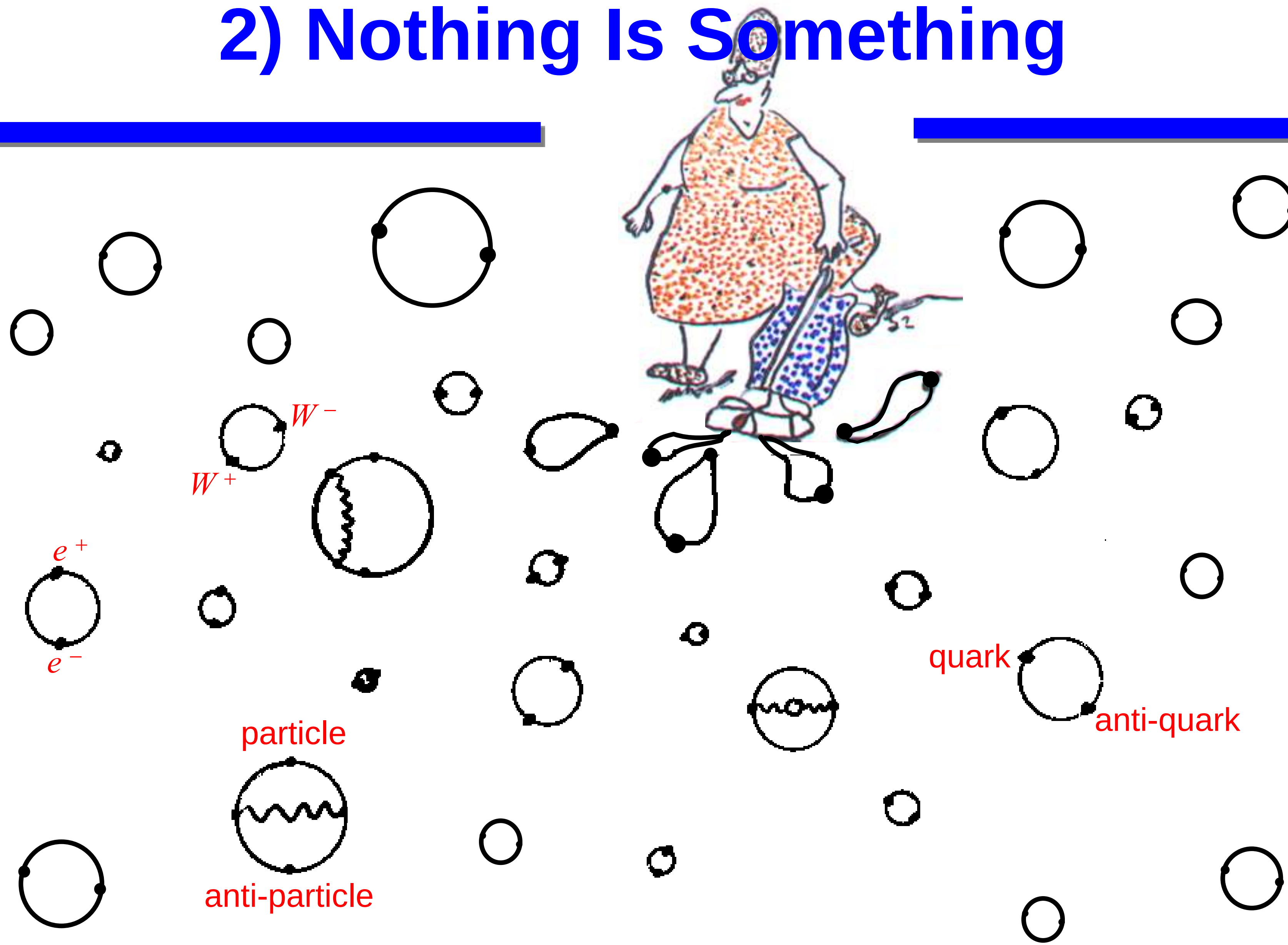
**Seven Secrets Of Nothingness**

1) Nothing is uncertain
2) Nothing is something
3) Nothing has energy
4) Nothing changes
5) Nothing is hidden
6) Nothing is mysterious
7) Nothing matters

# 1) Nothing Is Uncertain

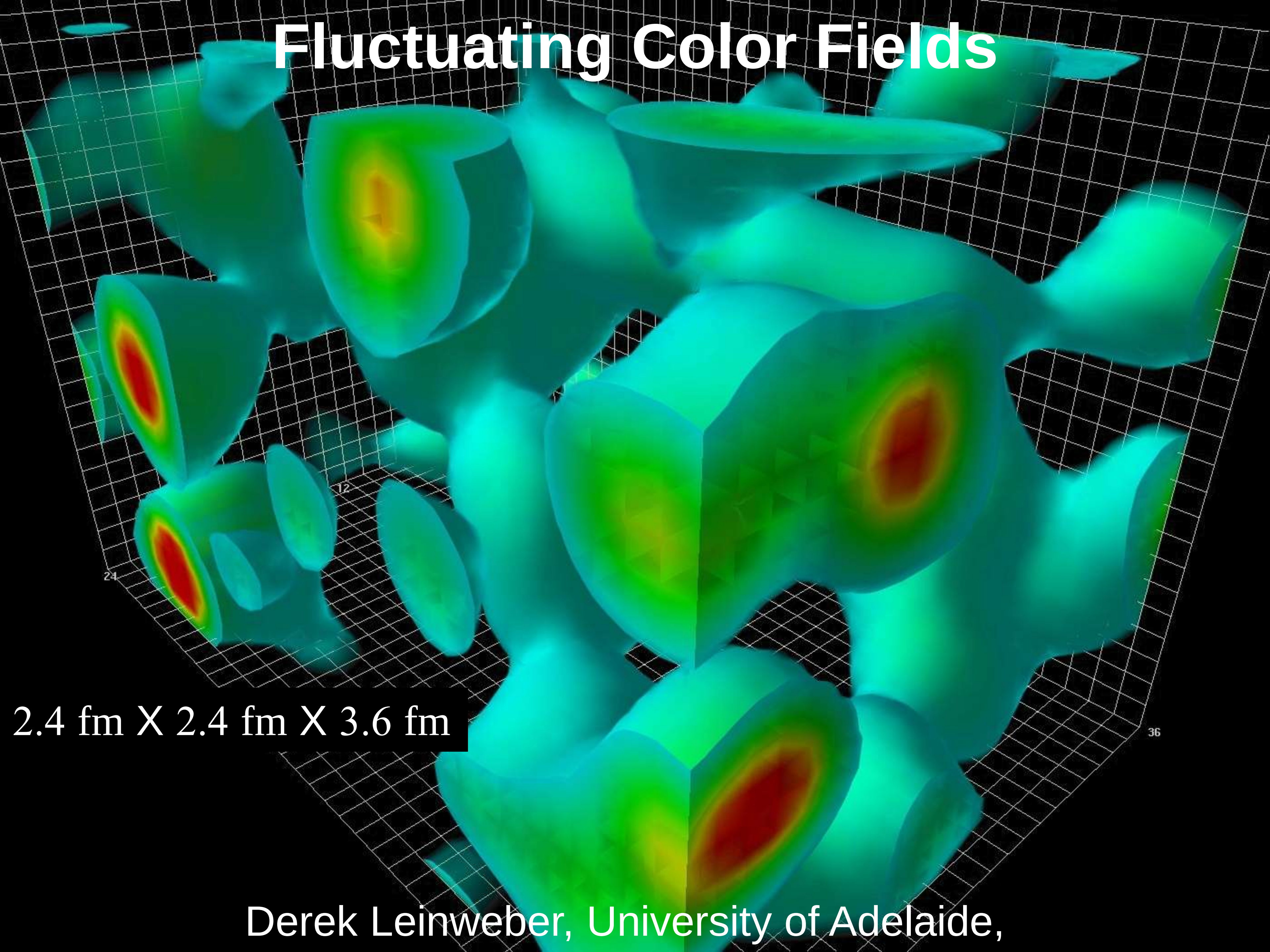

Werner Heisenberg  1901—1976

# 2) Nothing Is Something

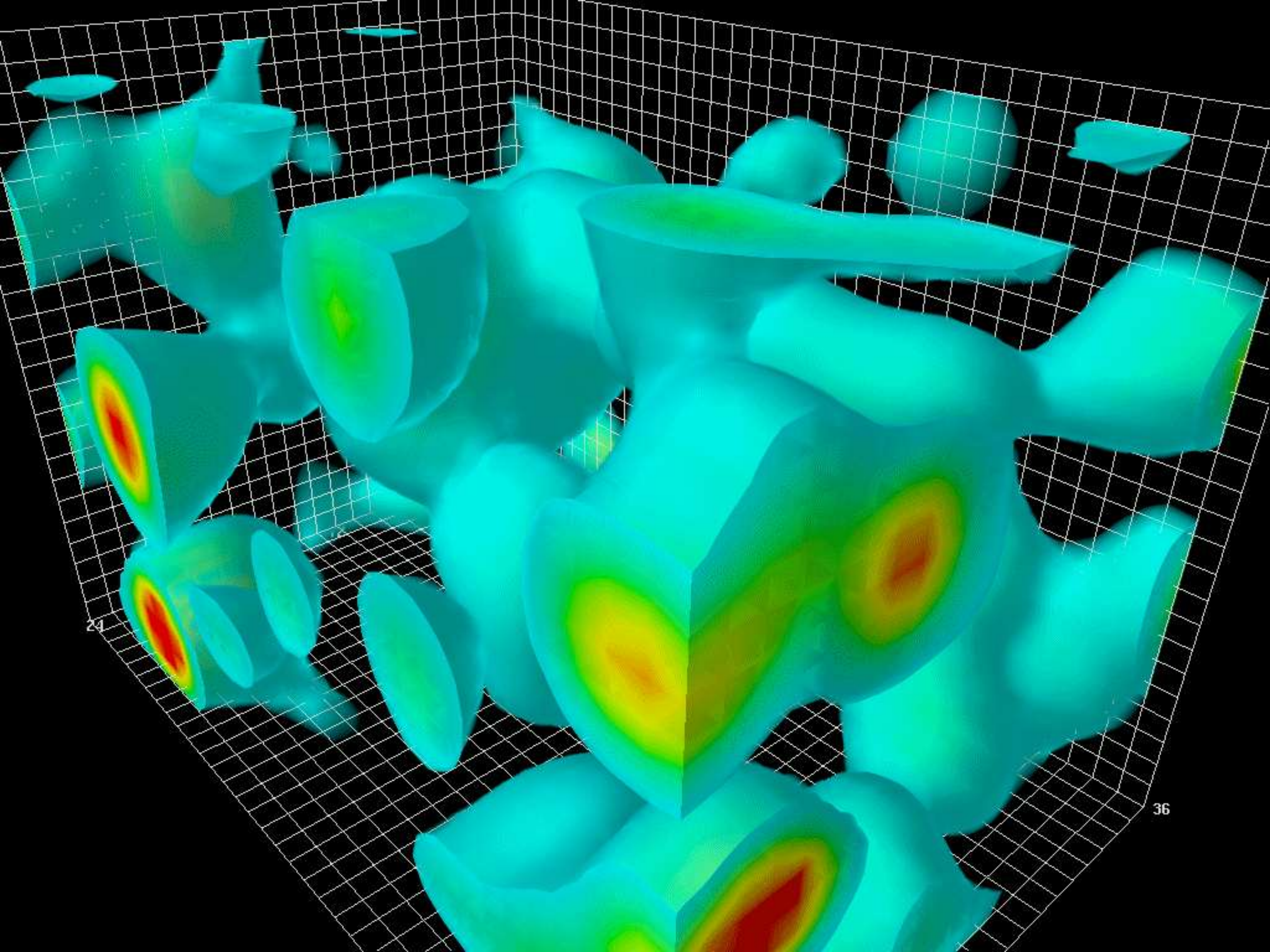



**There is Something in the Quantum Vacuum**

# Fluctuating Color Fields



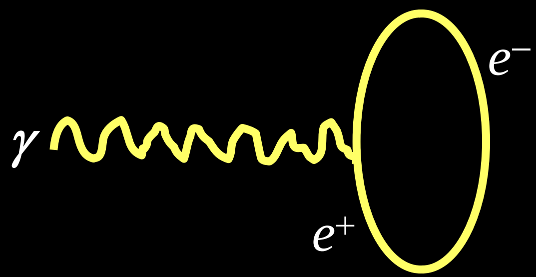

Derek Leinweber, University of Adelaide,


24
36

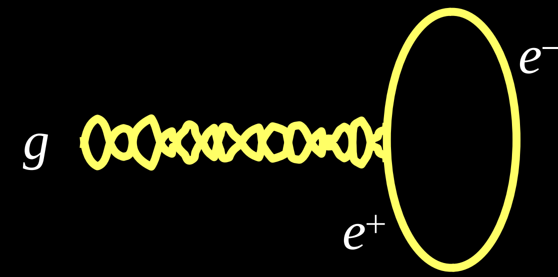
# 3) Nothing Has Energy

## All fields: harmonic oscillators with zero-point energy

Photons: Lamb shift




Gravitons: Vacuum energy




$$\rho = \sum_{\text{all particles}} \pm \int d^3k \sqrt{k^2 + m^2} \sim \sum_{\text{all particles}} \pm \int^{\Lambda_C} dk\ k^3$$

$$\Lambda_C = \infty: \qquad \rho_\Lambda = \infty^4 \qquad = \text{bad prediction}$$

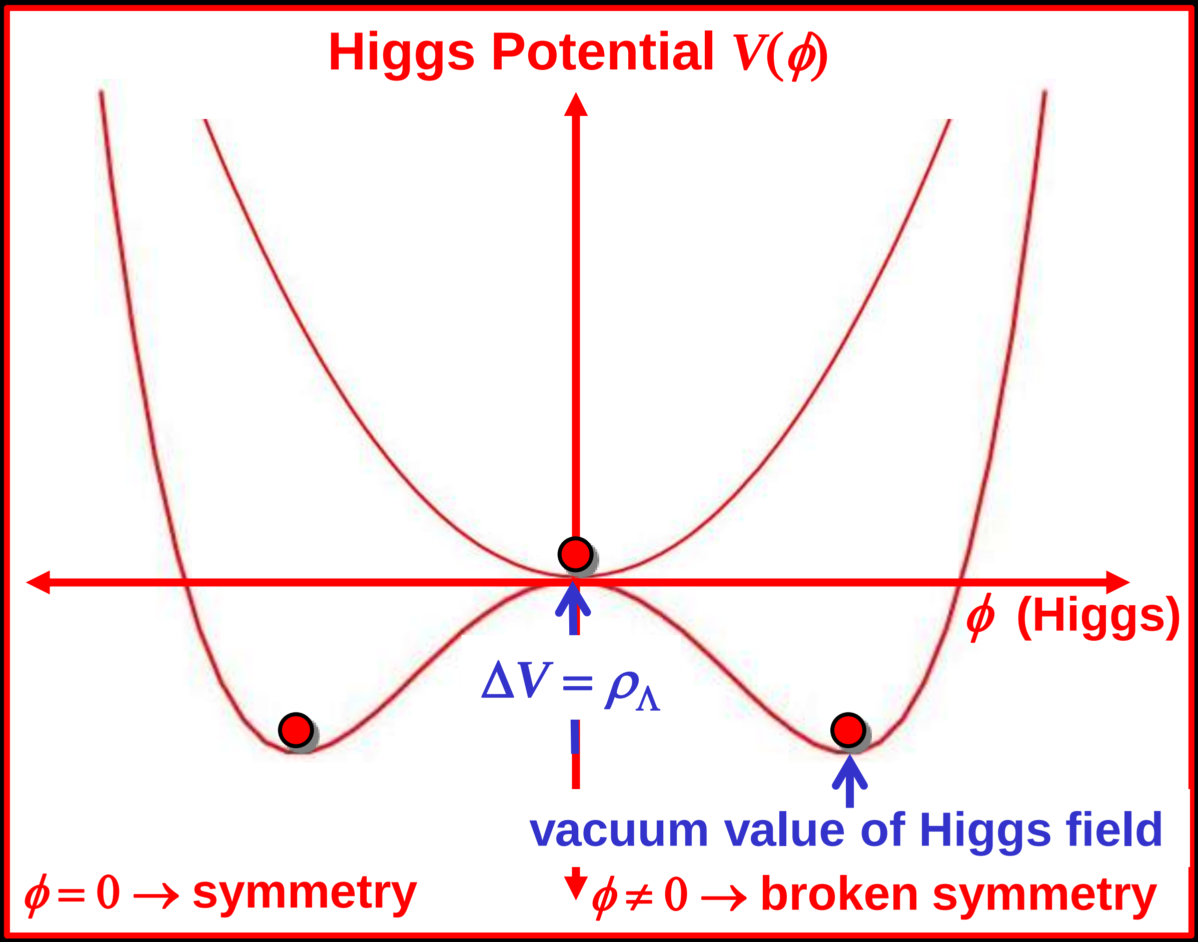
$$\Lambda_C = M_{Pl}: \qquad \rho_\Lambda = M_{Pl}^4 \qquad = 10^{+90}\ \text{g cm}^{-3}$$

$$\Lambda_C = M_{SUSY}: \qquad \rho_\Lambda = M_{SUSY}^4 \qquad = 10^{+30}\ \text{g cm}^{-3}$$

$$\Lambda_C = 10^{-4}\,\text{eV}: \qquad \rho_\Lambda = \text{Observed} \qquad = 10^{-30}\ \text{g cm}^{-3}$$

# 3) Nothing Has Energy

- “Nature weaves her tapestry from the longest threads.” — Richard Feynman
- Nature seems to like symmetry, then hide it



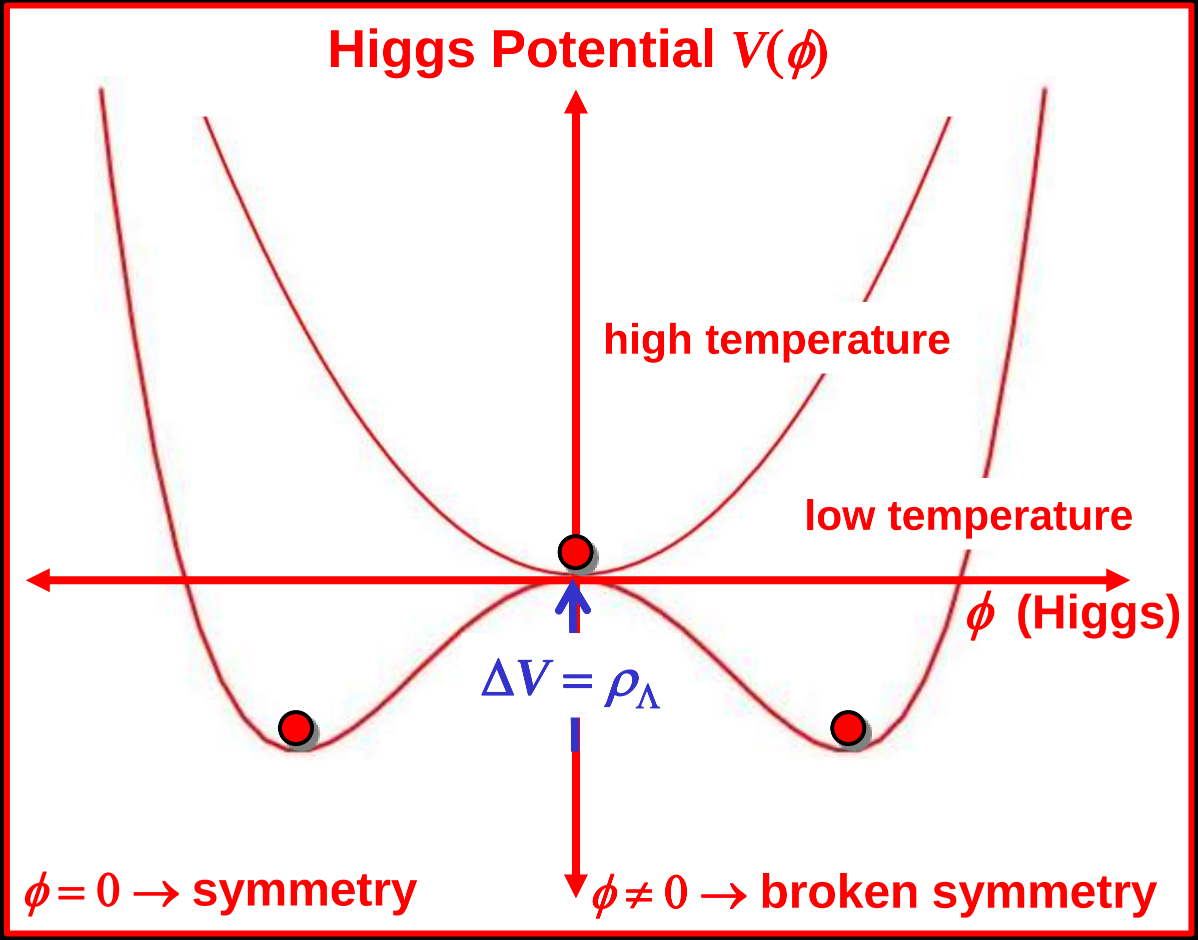

**GUT:** $10^{74}$ g cm$^{-3}$ **SUSY:** $10^{30}$ g cm$^{-3}$

**EWK:** $10^{24}$ g cm$^{-3}$ **CHIRAL:** $10^{13}$ g cm$^{-3}$

**OBSERVED:** $10^{-30}$ g cm$^{-3}$

# 4) Nothing Changes

- The Higgs potential changes with temperature



# 5) Nothing Is Hidden

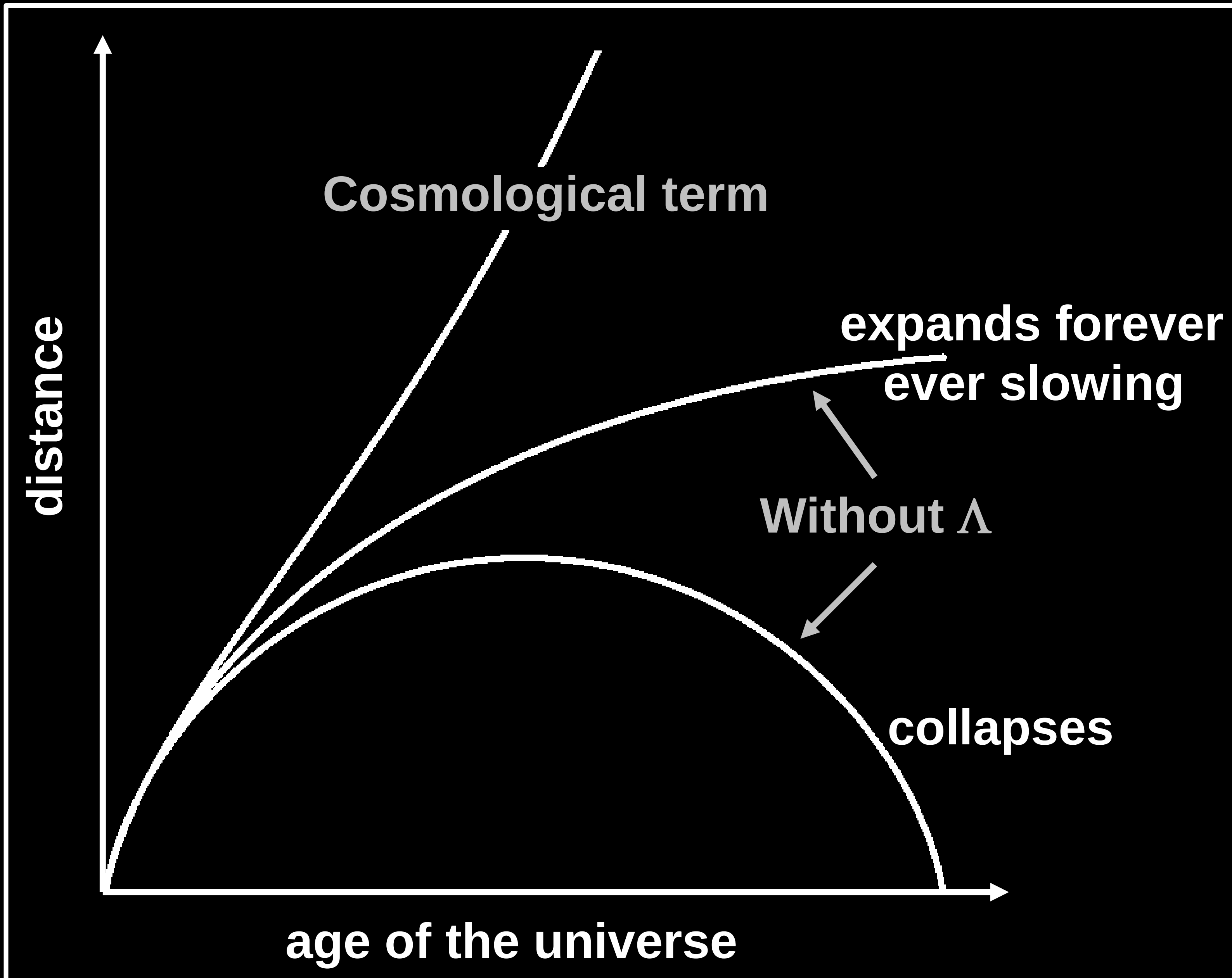
# 6) Nothing Is Mysterious

## Illogical magnitude (what's it related to?):

**Observed Dark Energy Density:** $10^{-30}$ g cm$^{-3}$

| | | | | |
|---|---|---|---|---|
| **Uncertainty Energy** | | $\infty^{4}$ g cm$^{-3}$ | | $10^{30}$ g cm$^{-3}$ |
| | | $10^{90}$ g cm$^{-3}$ | | |
| **Symmetry Breaking** | **GUT:** | $10^{74}$ g cm$^{-3}$ | **SUSY:** | $10^{30}$ g cm$^{-3}$ |
| | **EWK:** | $10^{24}$ g cm$^{-3}$ | **CHIRAL:** | $10^{13}$ g cm$^{-3}$ |
| **Extra Dimensions** | | $10^{90}$ g cm$^{-3}$ | | |

# 7) Nothing Matters



# The Cosmoillogical Constant

**Illogical magnitude (what's it related to?):**

$$\rho_\Lambda \sim 10^{-30}\,\mathrm{g\ cm^{-3}} \sim \left(10^{-4}\ \mathrm{eV}\right)^4 \sim \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

$$\Lambda = 8\pi G \rho_\Lambda \sim \left(10^{29}\,\mathrm{cm}\right)^{-2} \sim \left(10^{-33}\,\mathrm{eV}\right)^2$$

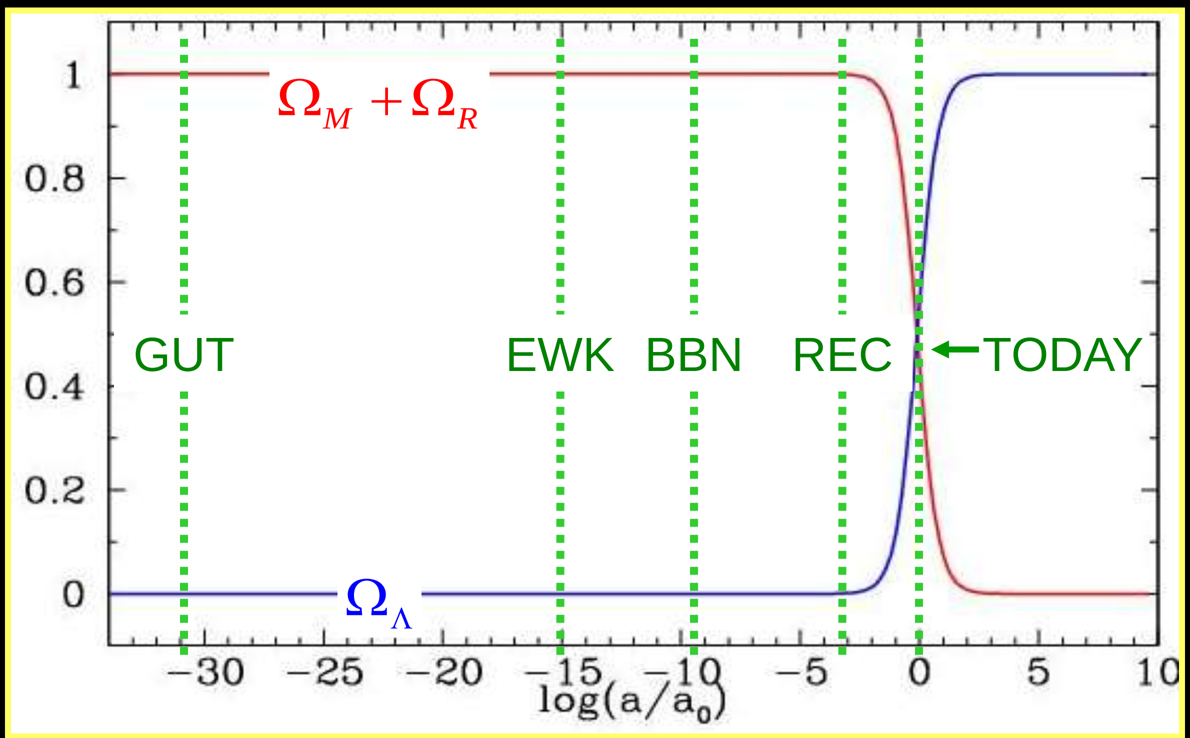
# Cosmoillogical Constant

**Illogical magnitude (what's it related to?):**

$$\rho_\Lambda \sim 10^{-30}\,\mathrm{g\ cm^{-3}} \sim \left(10^{-4}\ \mathrm{eV}\right)^4 \sim \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

$$\Lambda = 8\pi G \rho_\Lambda \sim \left(10^{29}\,\mathrm{cm}\right)^{-2} \sim \left(10^{-33}\,\mathrm{eV}\right)^2$$

**Illogical timing (cosmic coincidence?):**



# Cosmoillogical Constant

Do not directly *observe*

- acceleration of the universe
- cosmoillogical constant
- dark energy

We <u>*infer*</u> acceleration/dark energy by comparing
<u>*observations*</u>
with the predictions of a
<u>*model*</u>

All evidence for dark energy/acceleration comes
from measuring the expansion history of the Universe

# Taking Sides!

Can’t hide from the data – $\Lambda$CDM 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

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

Modify right-hand side of Einstein equations $(\Delta T_{00})$

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

Modify left-hand side of Einstein equations $(\Delta G_{00})$

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

# Tools to Modify the Right-Hand Side

1964 Austin-Healey Sprite

1974 Fiat 128

# Tools to Modify the Right-Hand 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 $\Lambda$.
- While exponentially uncommon, they are preferred because …
  … more common values of $\Lambda$ results in an inhospitable universe.

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

A change in the $47^{th}$ decimal place in the up-quark mass makes a $100\%$ change in $\Lambda$.

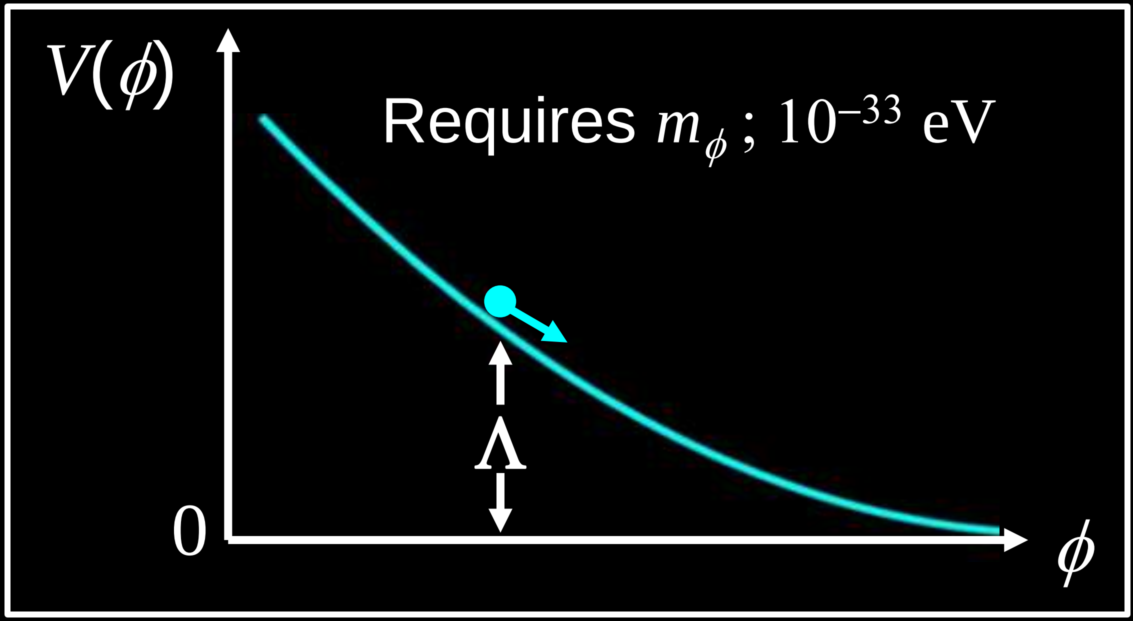
# Anthropic/Landscape/DUCTtape

- 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

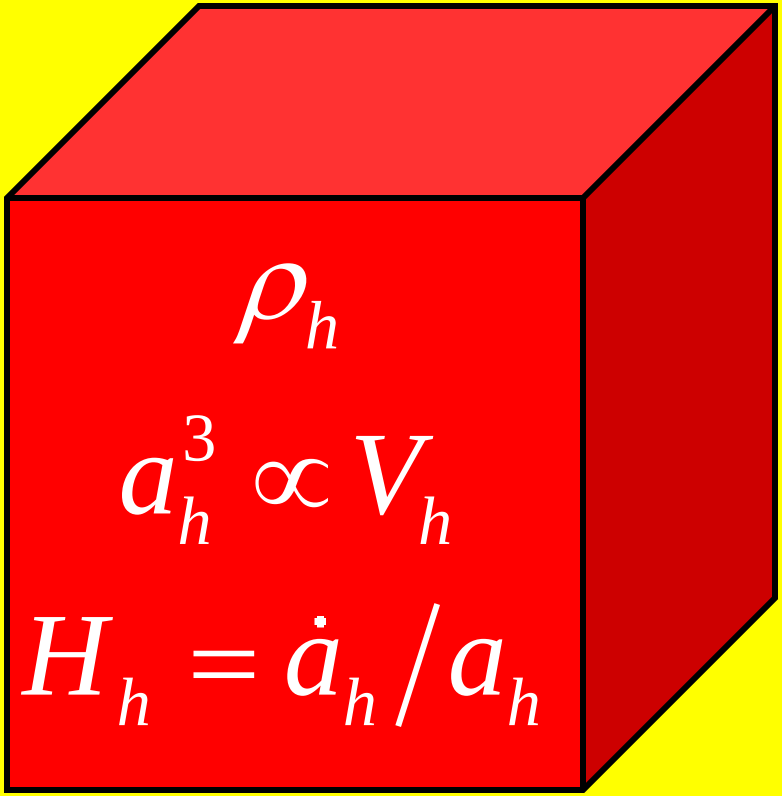
  $f(R)$ $S = (16\pi G)^{-1} \int d^4x \sqrt{-g} \left( R - \mu^4 / R \right)$ Carroll, Duvvuri, Turner & Trodden

- “Backreaction” of inhomogeneities

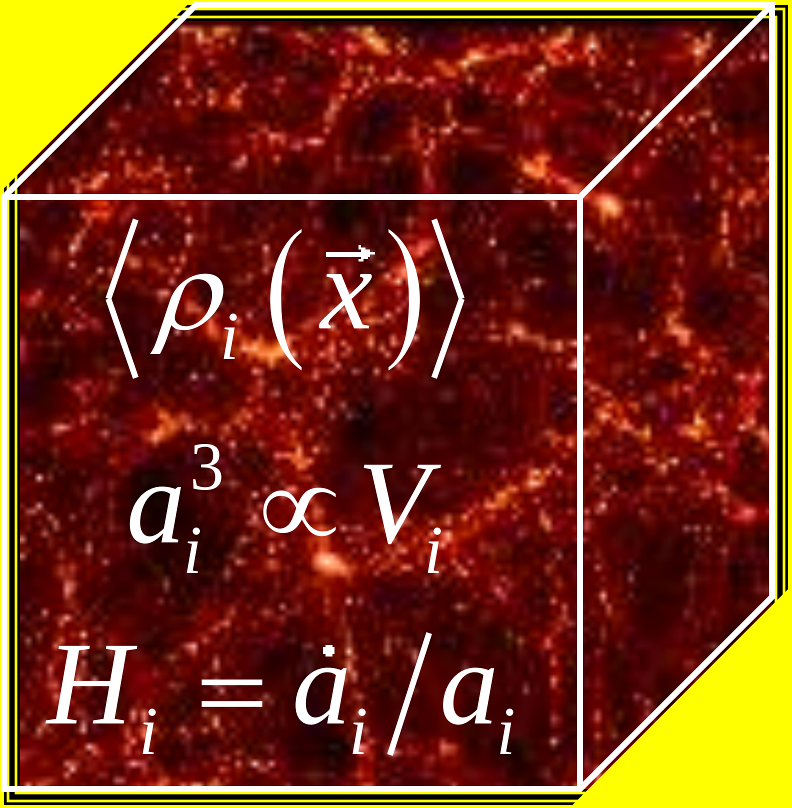
  No dark energy Räsänen, Kolb, Matarrese, Notari, Riotto, Buchert; Ellis; Celerier

# Backreaction of Inhomogeneities

Homogeneous model




Inhomogeneous model




$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i \ ?$$

We think not!

(Buchert & Ellis)

# Backreaction of Inhomogeneities

$$G_{\mu\nu}(g_{\mu\nu}) = T_{\mu\nu}$$

$$\langle G_{\mu\nu}(g_{\mu\nu})\rangle = \langle T_{\mu\nu}\rangle$$

$$G_{\mu\nu}(\langle g_{\mu\nu}\rangle) \neq \langle T_{\mu\nu}\rangle$$

$$\left\langle G_{\mu\nu}(g_{\mu\nu})\right\rangle \neq G_{\mu\nu}\left(\left\langle g_{\mu\nu}\right\rangle\right)$$

# Backreaction of Inhomogeneities

- The expansion rate of an *inhomogeneous* universe of average density $\langle\rho\rangle$ *need NOT be!* the same as the expansion rate of a *homogeneous* universe of average density $\langle\rho\rangle$!

Ellis, Barausse, Buchert

- Difference is a new term that enters an effective Friedmann equation — the new term need not satisfy energy conditions!
- We deduce dark energy because we are comparing to the wrong model universe.

Célérier; Räsänen; Kolb, Matarrese, Notari & Riotto; Schwarz, …

# 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."

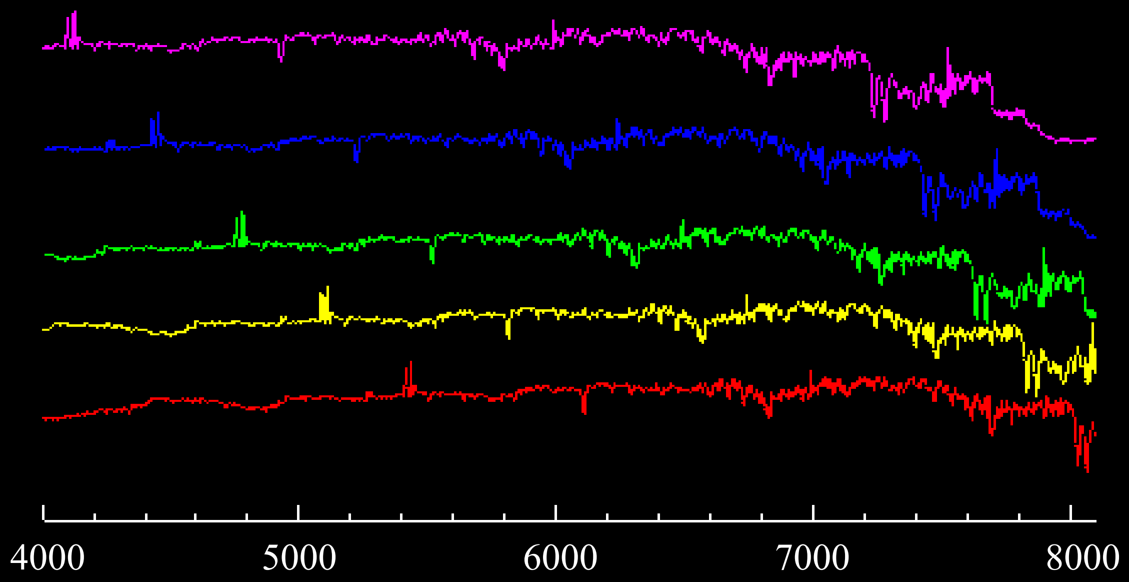
*Einstein in August 1913 to astronomer Erwin Freundlich encouraging him to measure the deflection of light by the sun.*

- $H(z)$
  - $d_L(z)$
    - SNe
    - clusters
  - $d_A(z)$
    - BAO
    - strong lensing
    - weak lensing
  - $V(z)$
    - clusters
    - strong lensing
  - Growth
    - clusters
    - weak lensing

# Supernova Type Ia

- Measure redshift and intensity as function of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, etc.)
- A lot of information per supernova
- Well developed and practiced
- Present procedure:
  - Discover SNe by wide-area survey (the “easy” part)
  - Follow up with spectroscopy (the “hard” part)
    (requires a lot of time on 8m-class telescopes)
  - Photometric redshifts?

# Photometric Redshifts




**Traditional redshift from spectroscopy**

**Photometric redshift from multicolor photometry**

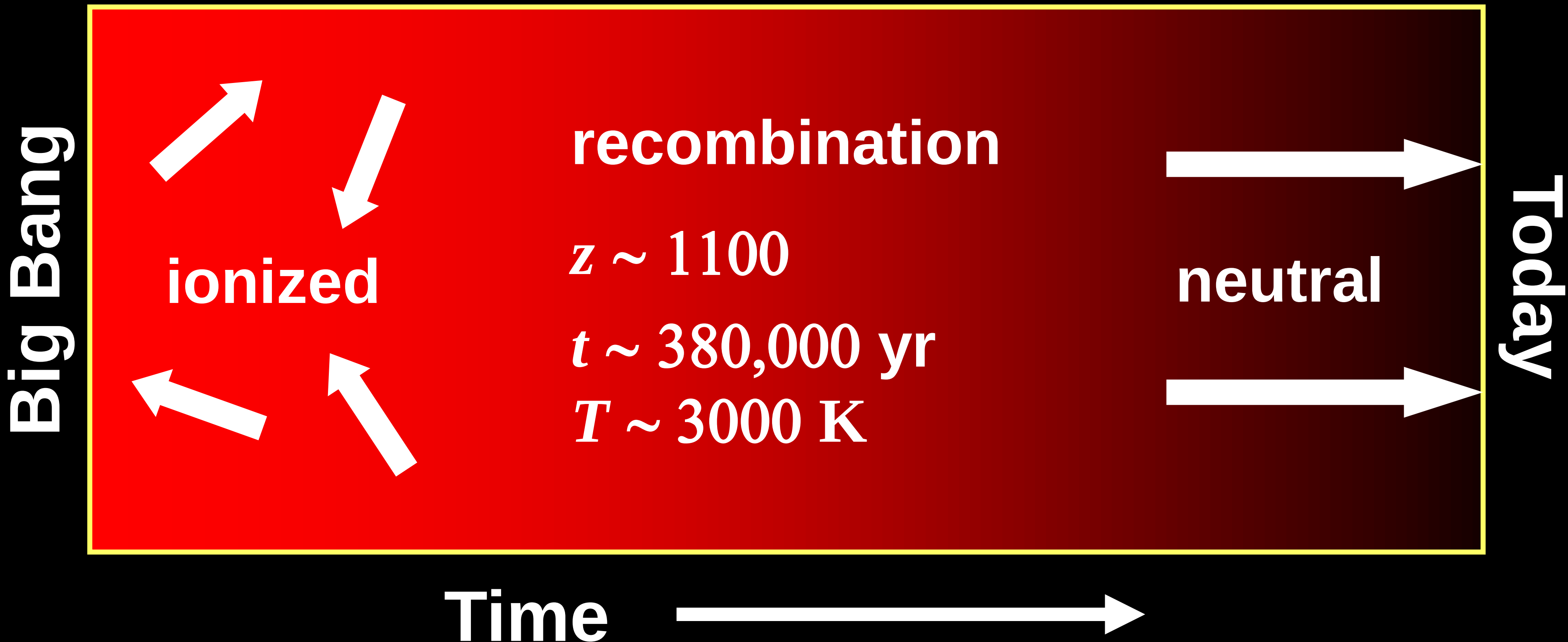
# Baryon Acoustic Oscillations

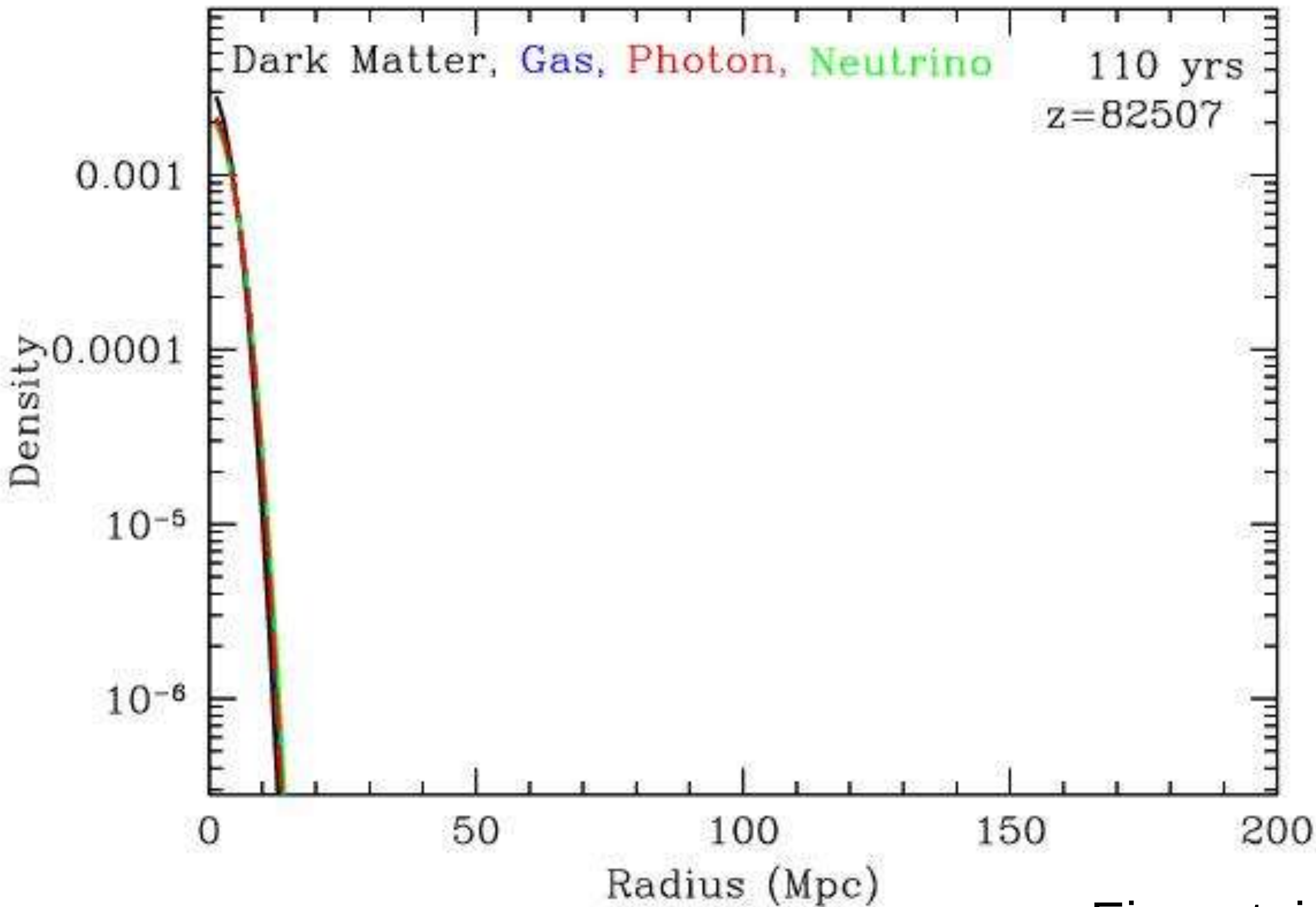
<u>Pre-recombination</u>

- universe ionized
- photons provide enormous pressure and restoring force
- perturbations oscillate (acoustic waves)

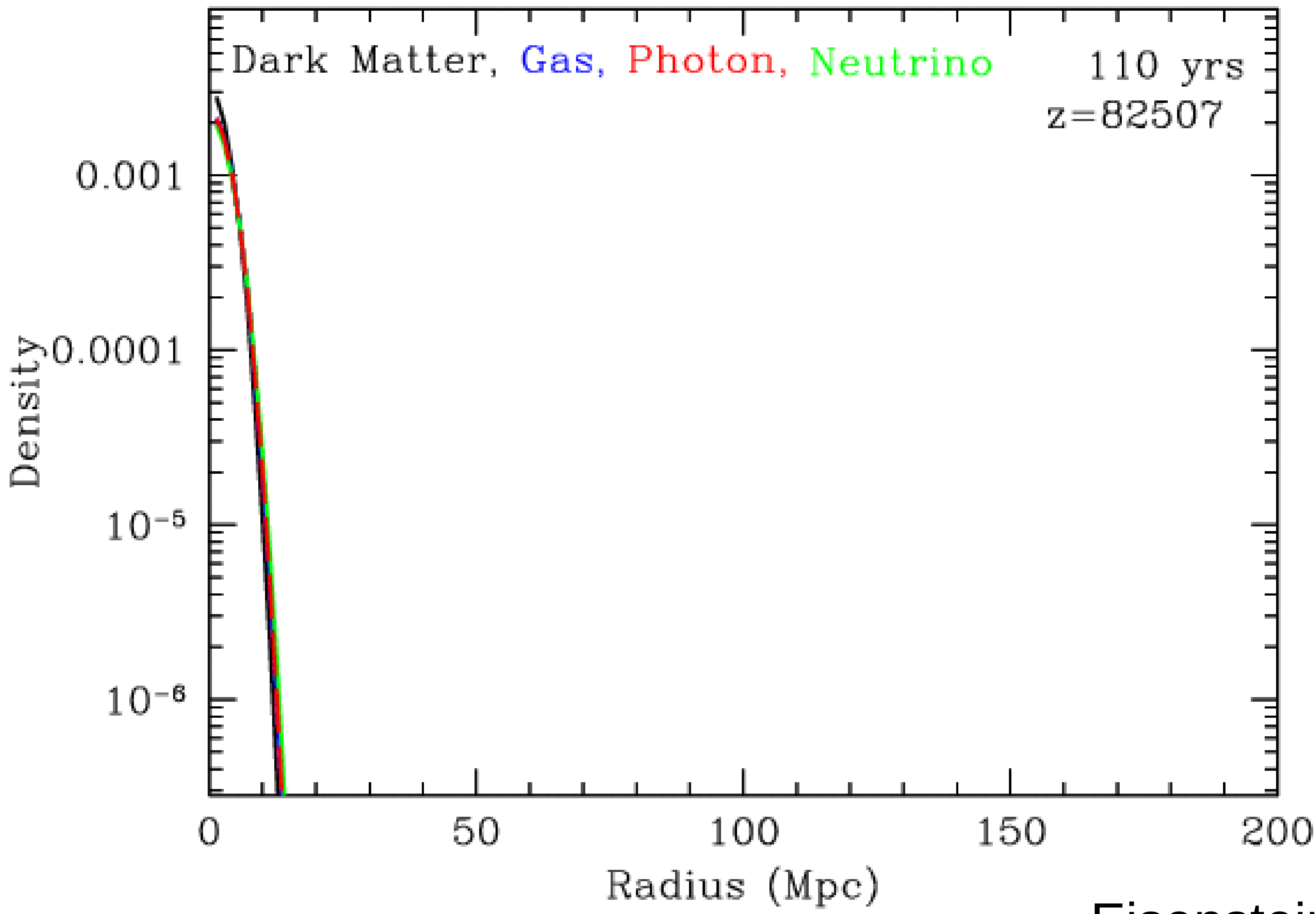
<u>Post-recombination</u>

- universe neutral
- photons travel freely (decoupled from baryons)
- perturbations grow (structure formation)




Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
0.001
0.0001
$10^{-5}$
$10^{-6}$
Density
0
50
100
150
200
Radius (Mpc)

Eisenstein

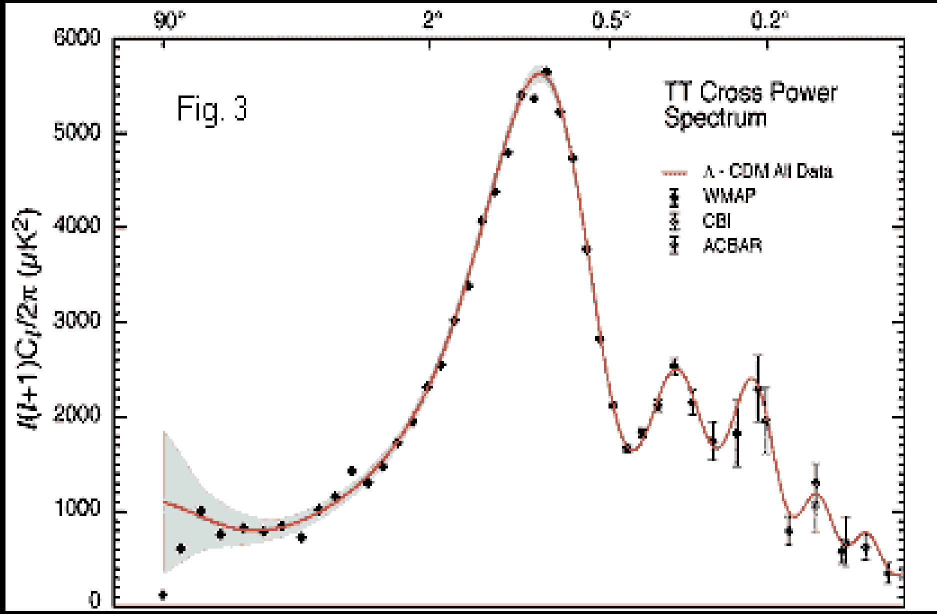


Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
Density
0.001
0.0001
$10^{-5}$
$10^{-6}$
0
50
100
150
200
Radius (Mpc)

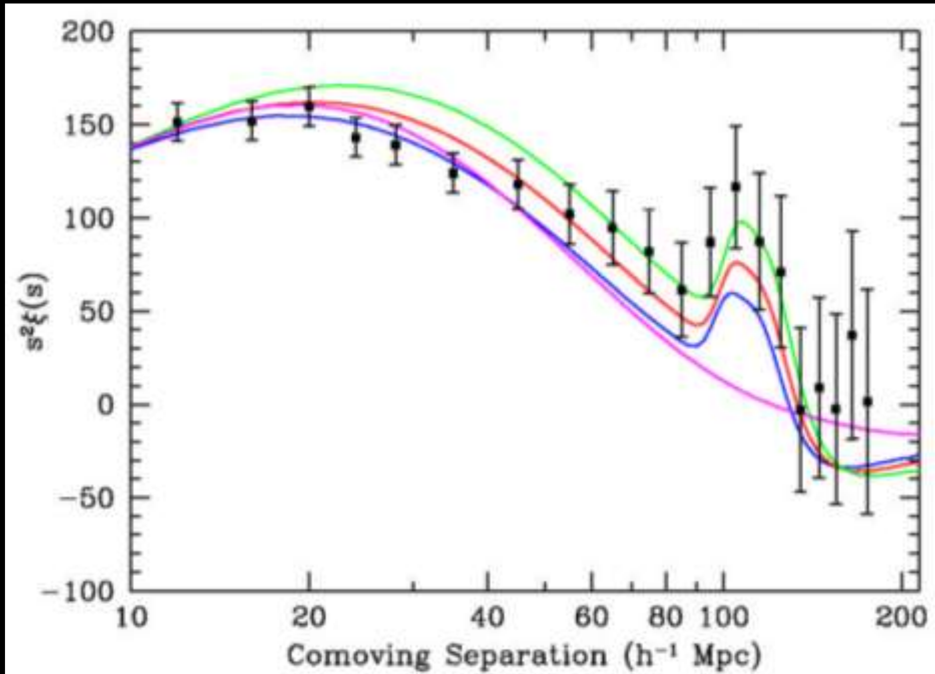

Eisenstein

# Baryon Acoustic Oscillations

- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $c/\sqrt{3}$
- Photons decouple, travel to us and observable as CMB acoustic peaks



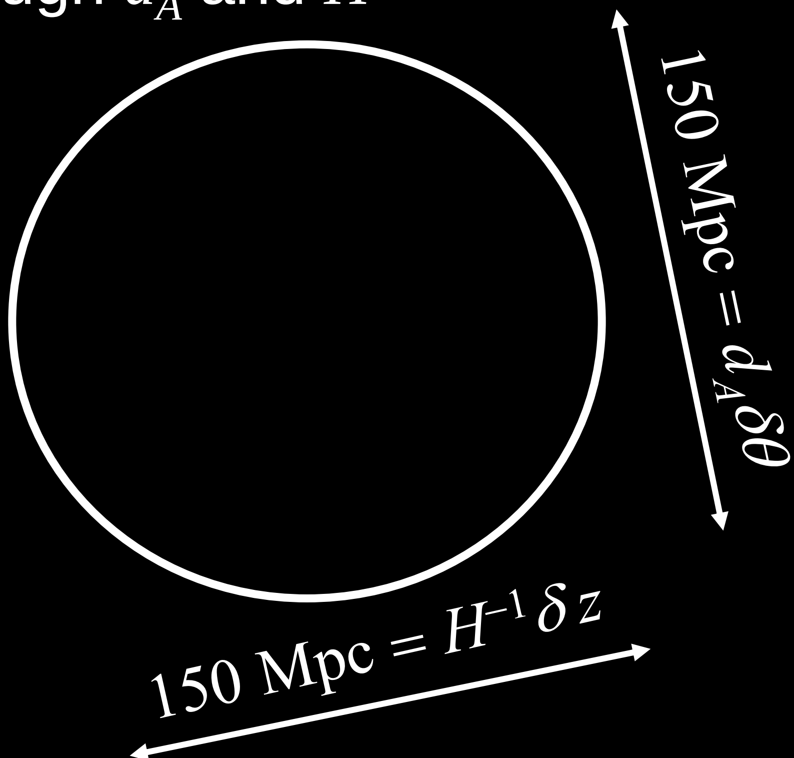

- Sound speed plummets, wave stalls
- Total distance traveled 150 Mpc imprinted on power spectrum



# Baryon Acoustic Oscillations

- Acoustic oscillation scale depends on $\Omega_M h^2$ and $\Omega_B h^2$ (set by CMB acoustic oscillations)

- It is a small effect ($\Omega_B h^2 \ll \Omega_M h^2$)
- Dark energy enters through $d_A$ and $H$




# Baryon Acoustic Oscillations

- Virtues
  - Pure geometry.
  - Systematic effects should be small.
- Problems:
  - Amplitude small, require large scales, huge volumes
  - Photometric redshifts?
  - Nonlinear effects at small $z$, cleaner at large $z \sim 2$–$3$, but … dark energy is not expected to be important at large $z$

# Weak Lensing


dark energy
affects growth
rate of $M$

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho\delta = 0$$

observe
deflection
angle

$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$

dark energy
affects geometric
distance factors

# Weak Lensing

The signal from any single galaxy is *very* small,
but there are a *lot* of galaxies! Require photo-$z$'s?

Space vs. Ground:

- Space: no atmosphere PSF
- Space: Near IR for photo-$z$'s
- Ground: larger aperture
- Ground: less expensive

- DES (2012)
  - 1000's of sq. degs. deep multicolor data
- LSST (2021)
  - full hemisphere, very deep 6 colors
- JDEM/Euclid (???)

# Galaxy Clusters

Cluster redshift surveys measure

- cluster mass, redshift, and spatial clustering

Sensitivity to dark energy

- volume-redshift relation
- angular-diameter distance–redshift relation
- growth rate of structure
- amplitude of clustering

Problems:

- cluster selection must be well understood
- proxy for mass?
- need photo-$z$'s

# DETF* Experimental Strategy:

- Determine as well as possible whether the accelerating expansion is consistent with being due to a cosmological constant. (Is $w = -1$?)

- If the acceleration is not due to a cosmological constant, probe the underlying dynamics by measuring as well as possible the time evolution of the dark energy. (Determine $w(z)$.)

- Search for a possible failure of general relativity through comparison of the effect of dark energy on cosmic expansion with the effect of dark energy on the growth of cosmological structures like galaxies or galaxy clusters. (Hard to quantify.)

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* Dark Energy Task Force

# DETF Cosmological Model

Parameterize dark-energy equation of state parameter $w$ as:

$$w(a) = w_0 + w_a(1 - a)$$

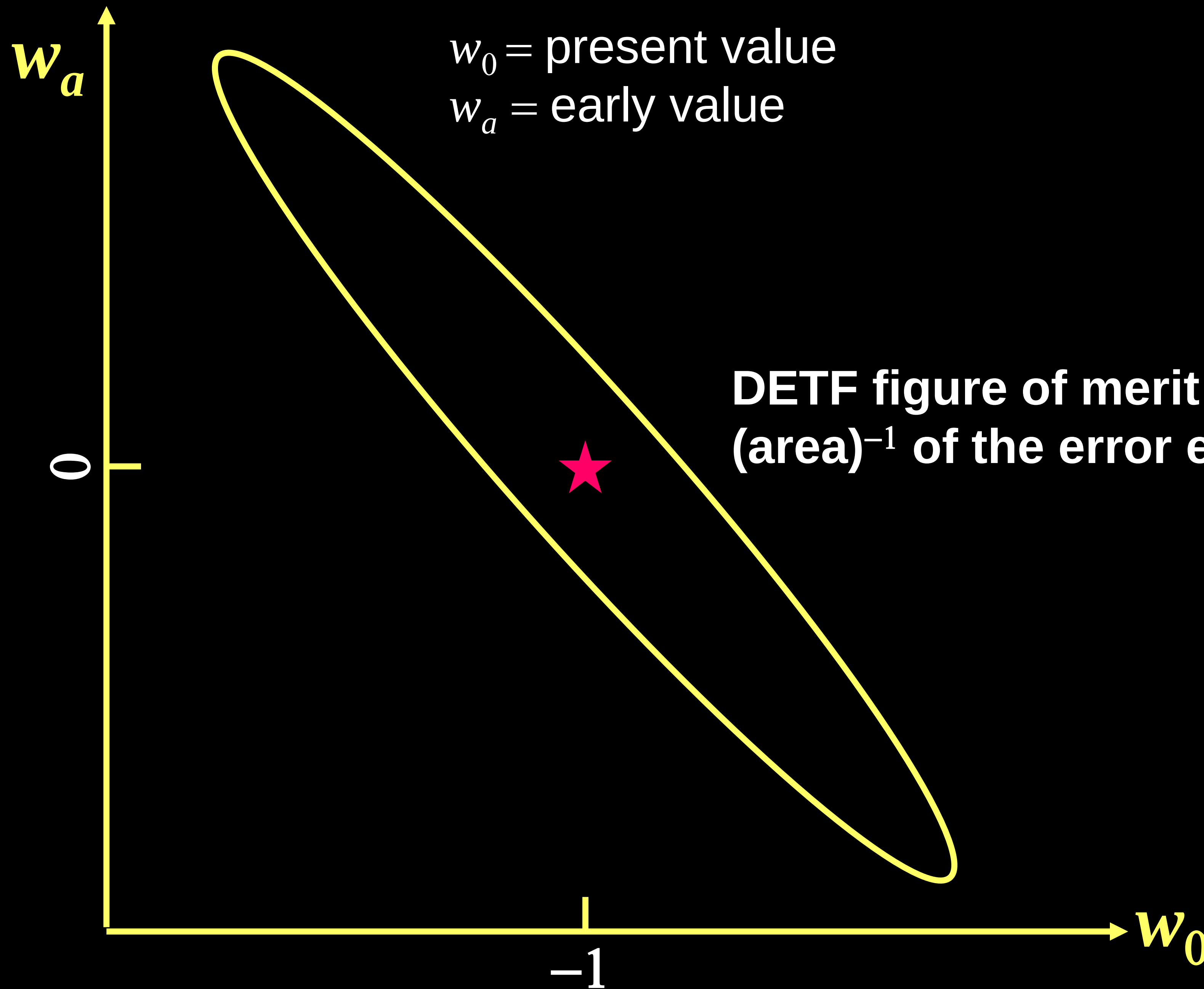
- Today ($a = 1$) $\quad w(1) = w_0$
- In the far past ($a \rightarrow 0$) $\quad w(0) = w_0 + w_a$

Standard eight-dimensional cosmological model:

$w_0$ : the present value of the dark-energy *eos* parameter
$w_a$ : the rate of change of the dark-energy *eos* parameter
$\Omega_{DE}$ : the present dark-energy density
$\Omega_M$ : the present matter density
$\Omega_B$ : the present baryon density
$H_0$ : the Hubble constant
$\delta_\zeta$ : amplitude of *rms* primordial curvature fluctuations
$n_S$ : the spectral index of primordial perturbations.

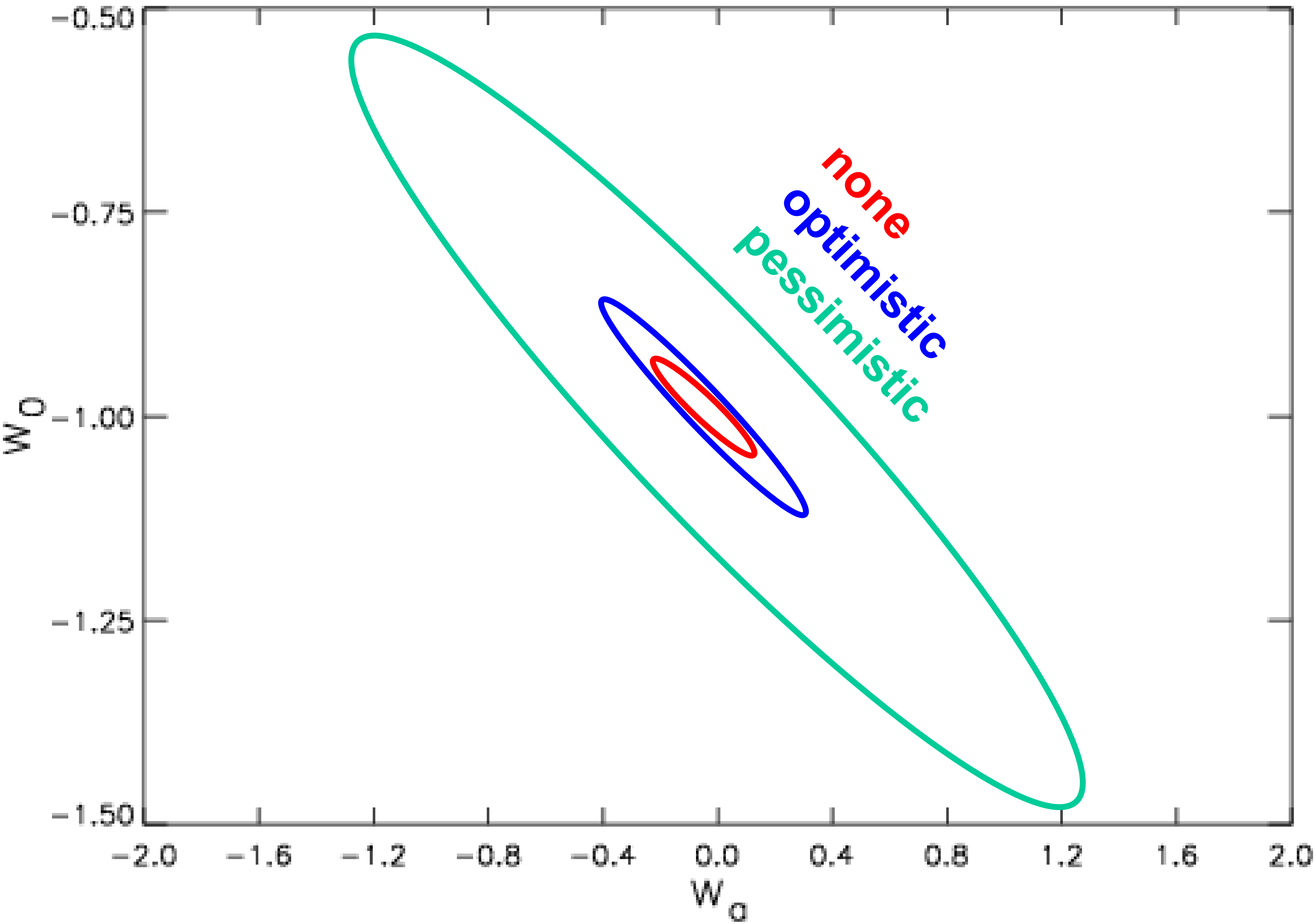
$$w(a) = w_0 + w_a(1-a)$$

$w_0$ = present value
$w_a$ = early value

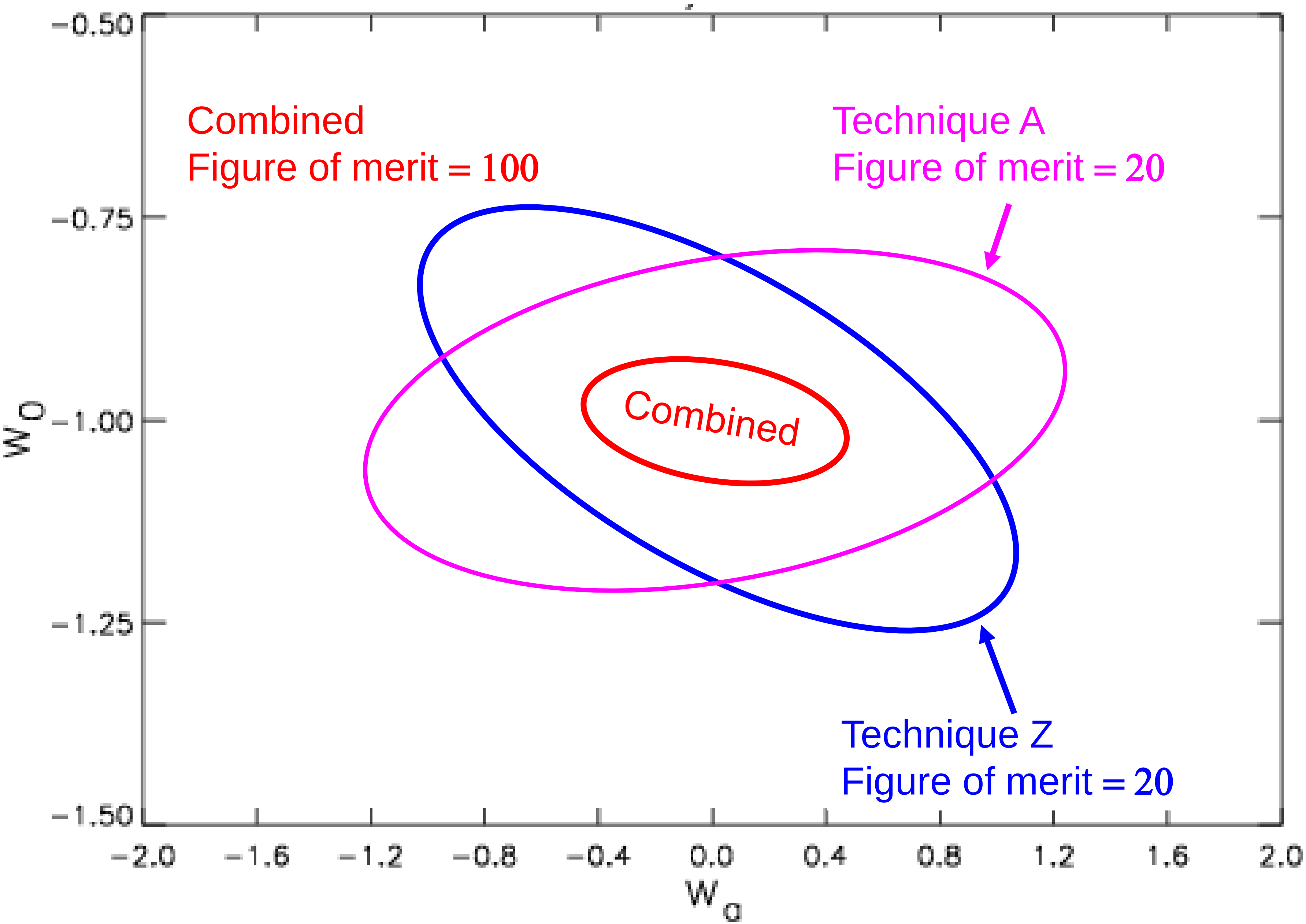


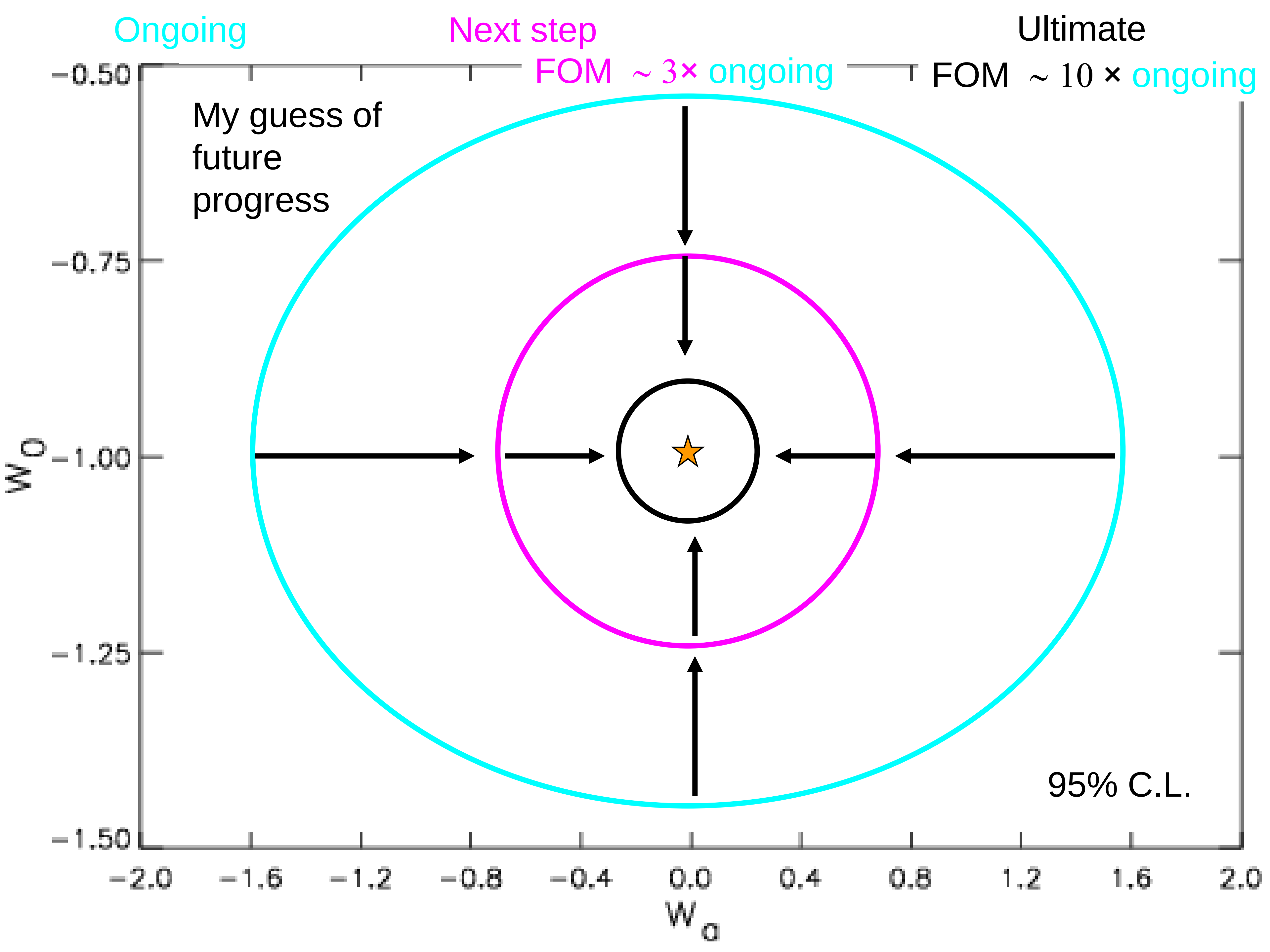

**DETF figure of merit:**
**(area)$^{-1}$ of the error ellipse**

# Systematics Are The Key

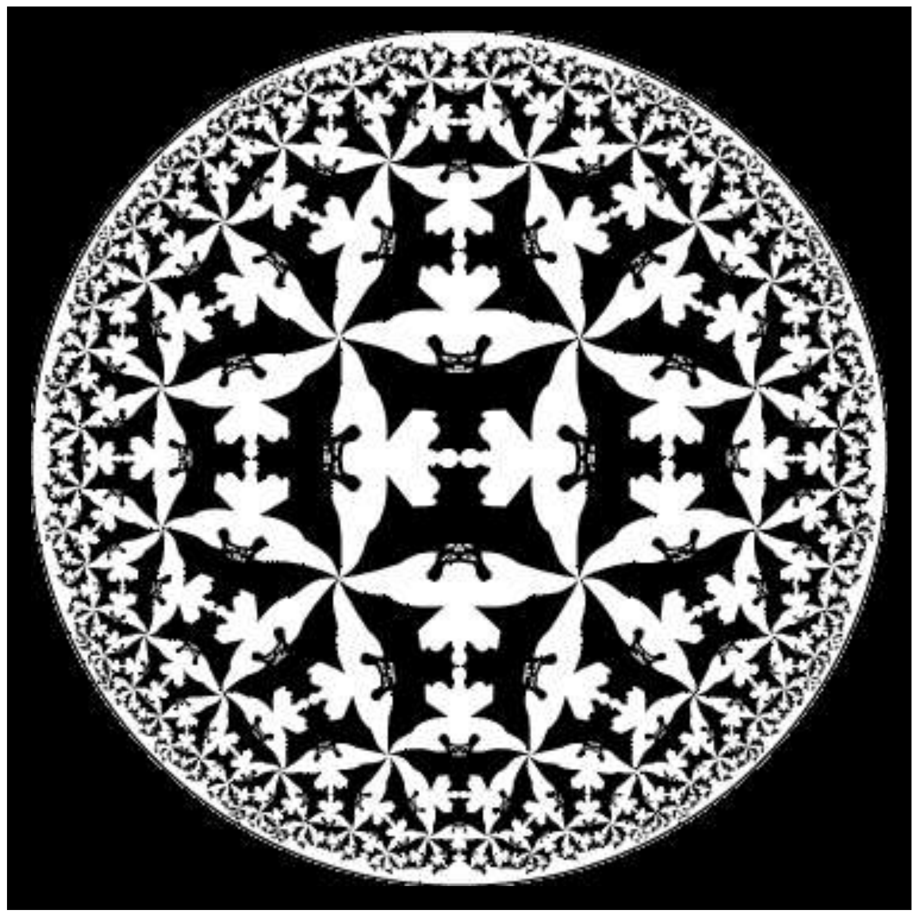


# The Power of Two (or 3, or 4)




Ongoing
Next step
FOM ~ 3× ongoing
Ultimate
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.50
−0.75
−1.00
−1.25
−1.50
−2.0
−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
2.0
$w_0$
$w_a$

# Asymptotic de Sitter Space?

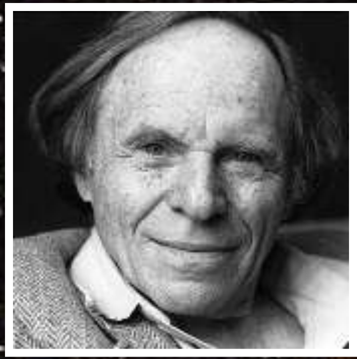


- Our cosmic horizon is limited — finite visible Universe
- Finite-dimensional Hilbert space
- Have to do astronomy now!

# Dark Energy

Dark energy is a complex physical phenomenon.

$\Lambda$ is a simple, ~~elegant, compelling~~ explanation for a complex physical phenomenon.



"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

ISAPP International School on AstroParticle Physics

2 - 13 July 2012
Paris (France)

European Doctorate School

International School of AstroParticle Physics

*Multi-Messenger Approach in High Energy Astrophysics*

# Exotic Physics: Dark Matter and Dark Energy

**Rocky I: (Wednesday) Dark Matter**
**Rocky I.5: (Thursday) Dark Matter II**
**Rocky II: (Thursday) Dark Energy**

Rocky Kolb University of Chicago