Neutrinos and the birth and growth of particle astrophysics and cosmology

Neutrinos in Physics and Astrophysics

Celebrating the contributions of Baha Balantekin and George Fuller

January 2025

Rocky Kolb

The University of Chicago

Neutrinos in Physics and Astrophysics

According to iNSPIRE HEP I’ve written 42 papers with “neutrino” in the title

- Averaging a little less than one per year.
- But none in the last 10 years (last with Beacom or perhaps Hooper).
- Most of the papers I remember, some I’d just as soon forget.
- Anyone who works in cosmology or particle astrophysics studies neutrinos.
- They were my entry into particle cosmology.
- Never collaborated with George or Baha, although I’ve known them for a long time (George for a really long time).

So, my plan is

- Talk about the role of neutrinos and wrong experiments in establishing particle cosmology.
- Few words about days with George.
- What I am working on now (not neutrinos).

Two wrong experiments and neutrino cosmology

First, background we all know:

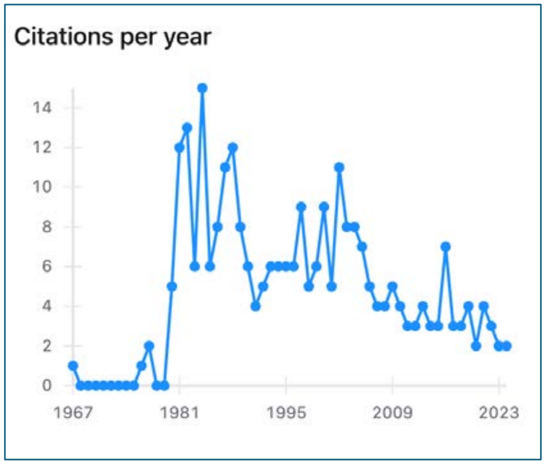
- Neutrinos are in LTE in the early universe
- They “freeze-out” of LTE at temperatures of about an MeV
- “Light” stable neutrinos contribute to the present mass density $\Omega_\nu h^2 \approx 0.3\ \frac{m_\nu}{30\,\mathrm{eV}}$

Two wrong experiments and neutrino cosmology

Theory Prehistory:

S. Gerstein and Ya. Zel'dovich
JETP Letters **4**, 120 (1966)
"Rest mass of muonic neutrino and cosmology"

$$m_\nu < 400\ \mathrm{eV}$$



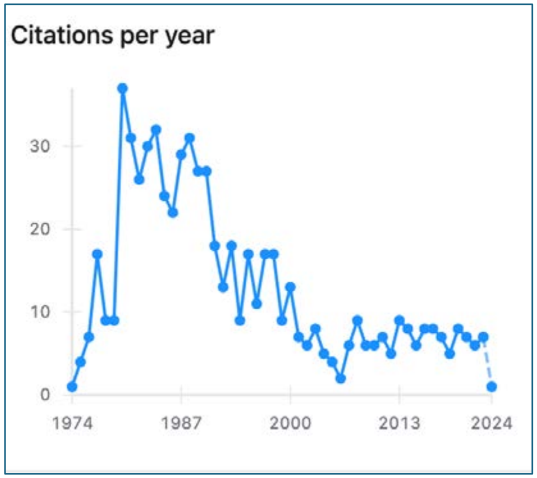
G. Marx and A. Szalay
Neutrino '72
"Cosmological limit on neutrino mass"
+ subsequent publications

$$m_\nu < 130\ \mathrm{eV}$$

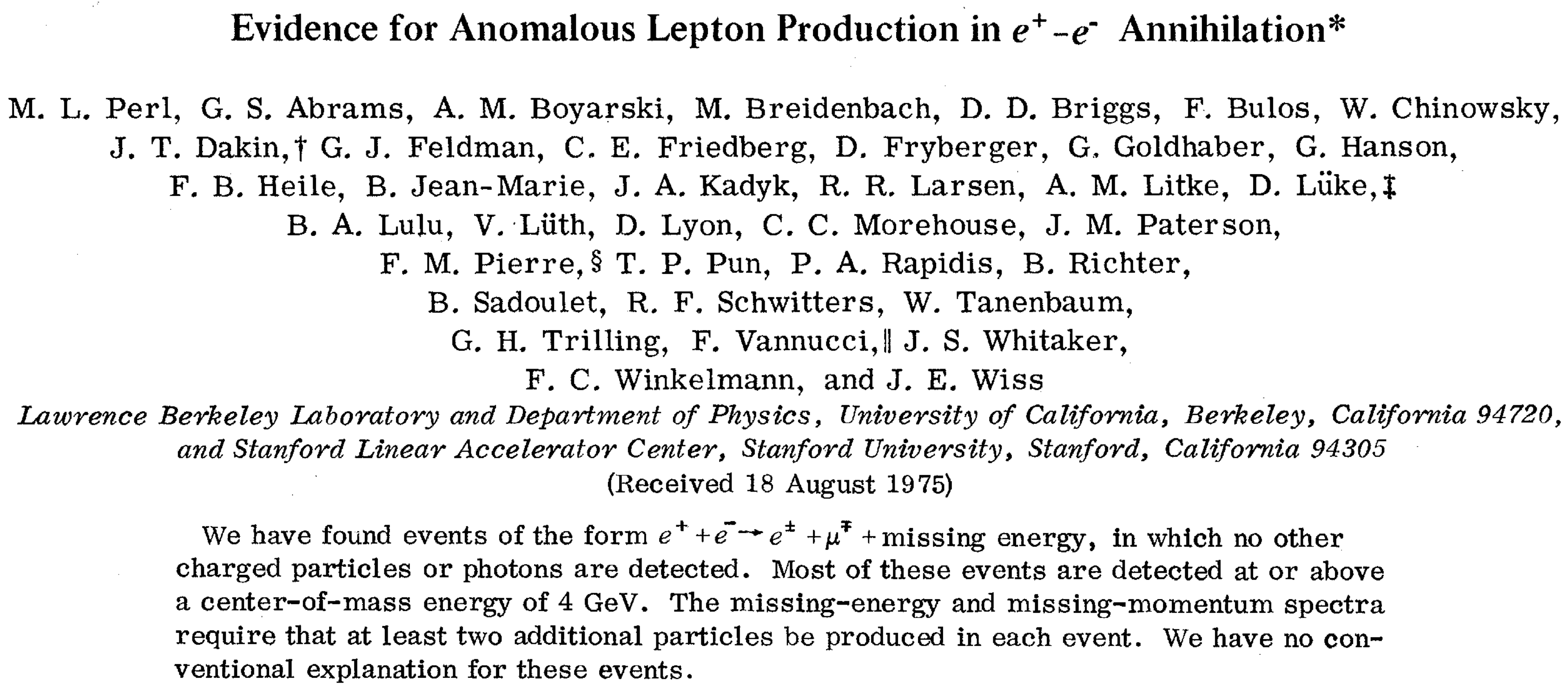
1976: $m_\nu < 13.5\ \mathrm{eV}$

R. Cowsik and J. McClelland
Phys. Rev. Lett. **29**, 669 (1972)
"An upper limit on the neutrino rest mass"
(UC Berkeley)

$$m_\nu < 8\ \mathrm{eV}$$



But first, a correct experiment: discovery of τ (and ν_τ)

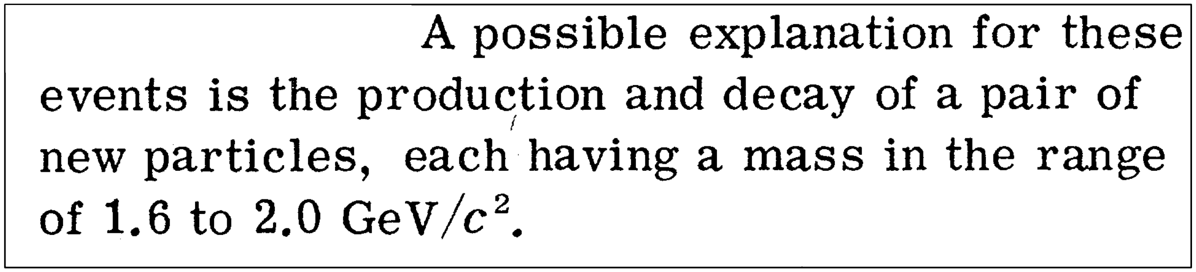


Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky,
J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson,
F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡
B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson,
F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter,
B. Sadoulet, R. F. Schwitters, W. Tanenbaum,
G. H. Trilling, F. Vannucci,‖ J. S. Whitaker,
F. C. Winkelmann, and J. E. Wiss
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720,
and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

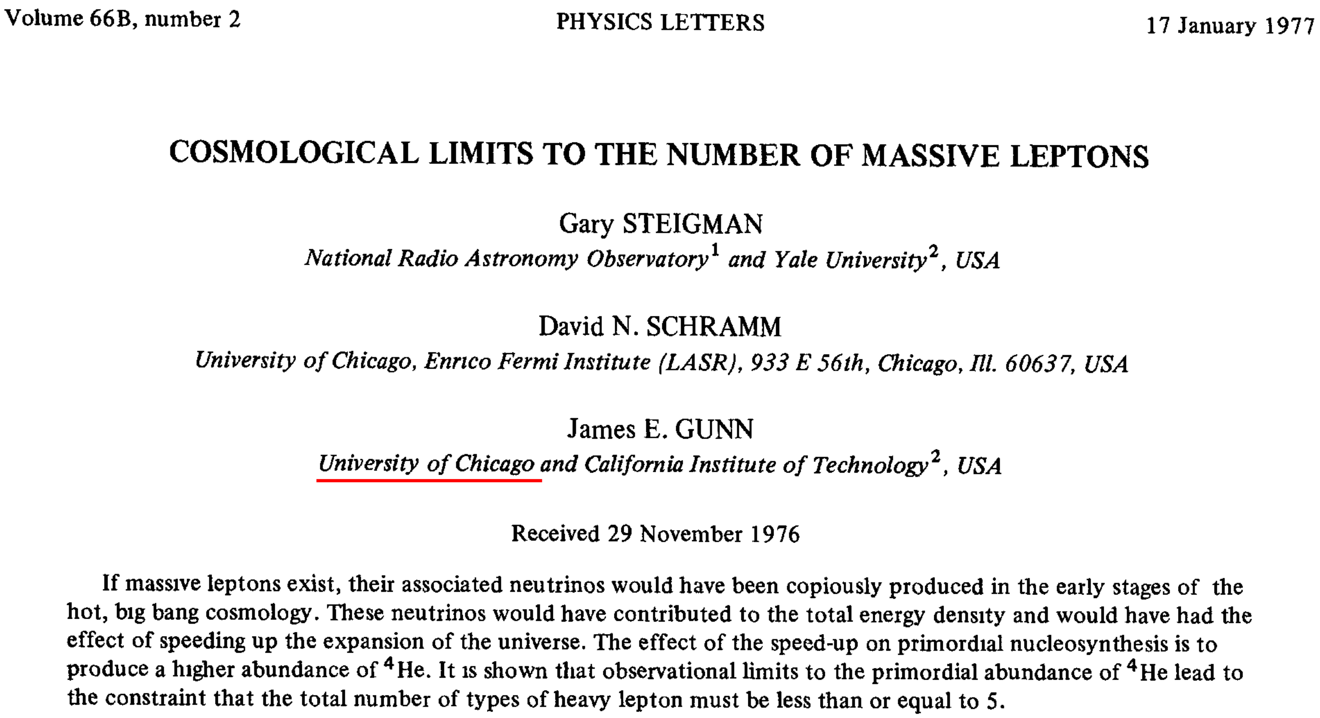
We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.



A possible explanation for these events is the production and decay of a pair of new particles, each having a mass in the range of 1.6 to 2.0 GeV/c^2.

A Third Family!

- How many families?



Volume 66B, number 2 PHYSICS LETTERS 17 January 1977

COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

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University of Chicago, Enrico Fermi Institute (LASR), 933 E 56th, Chicago, Ill. 60637, USA

James E. GUNN
University of Chicago and California Institute of Technology[2]*, USA*

Received 29 November 1976

If massive leptons exist, their associated neutrinos would have been copiously produced in the early stages of the hot, big bang cosmology. These neutrinos would have contributed to the total energy density and would have had the effect of speeding up the expansion of the universe. The effect of the speed-up on primordial nucleosynthesis is to produce a higher abundance of ^{4}He. It is shown that observational limits to the primordial abundance of ^{4}He lead to the constraint that the total number of types of heavy lepton must be less than or equal to 5.

Asymptotic freedom:
$N_{\text{families}} < 16$

Cosmology:
$N_{\text{families}} < 8$

- What is the mass of the ν_τ (and ν_e , ν_μ) ?
- Mass of neutrinos of subsequent generations ?

First wrong experiment

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov, V. Kosik
Physics Letters **B94**, 266 (1980)
“An estimate of the ν_e *mass from the* β *-spectrum of tritium in the valine molecule”*

$$14 \text{ eV} < m_\nu < 46 \text{ eV } (99\% \text{ C.L.})$$

Lots of papers on neutrino masses and cosmology:

Szalay and Marx (1976): $m_\nu \simeq 13.5 \text{ eV}$
Schramm and Steigman (1981) : $4 \text{ eV} < m_\nu < 40 \text{ eV}$
Flood of others

First wrong experiment

Several problems:

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov, V. Kosik
Physics Letters **B94**, 266 (1980)
"An estimate of the ν_e *mass from the* β*-spectrum of tritium in the valine molecule"*

$$14 \text{ eV} < m_\nu < 46 \text{ eV } (99\% \text{ C.L.})$$

Experiments:	$m_\nu < 18 \text{ eV } (95\% \text{ C.L.})$	Fritschi et al. (1986)
	$m_\nu < 9.3 \text{ eV } (95\% \text{ C.L.})$	Robertson et al. (1991)
	.	
	.	
	.	
	.	
	$m_\nu < 0.8 \text{ eV } (90\% \text{ C.L.})$	PDG (2022)

First wrong experiment

Several problems:

Cosmology:

- Neutrinos are fermions—can’t pack them too tightly (Tremaine–Gunn limit)
- Neutrinos are hot dark matter-–ruled out by observations of large-scale structure*
- But evidence that relic WIMPs exist!

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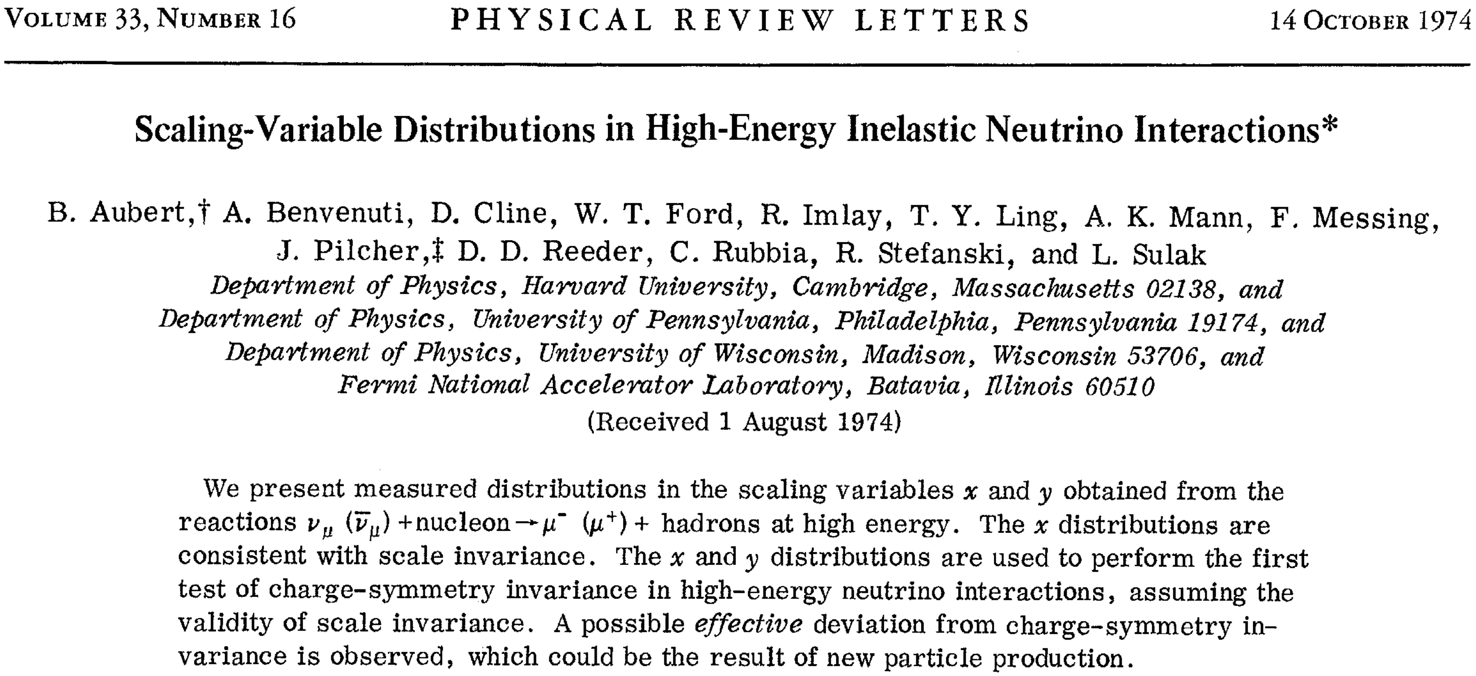
* Light sterile neutrinos can be cold (Shi-Fuller)

Second wrong experiment: the “high-y anomaly”



VOLUME 33, NUMBER 16 PHYSICAL REVIEW LETTERS 14 OCTOBER 1974

Scaling-Variable Distributions in High-Energy Inelastic Neutrino Interactions*

B. Aubert,† A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, F. Messing, J. Pilcher,‡ D. D. Reeder, C. Rubbia, R. Stefanski, and L. Sulak
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, and
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174, and
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, and
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 1 August 1974)

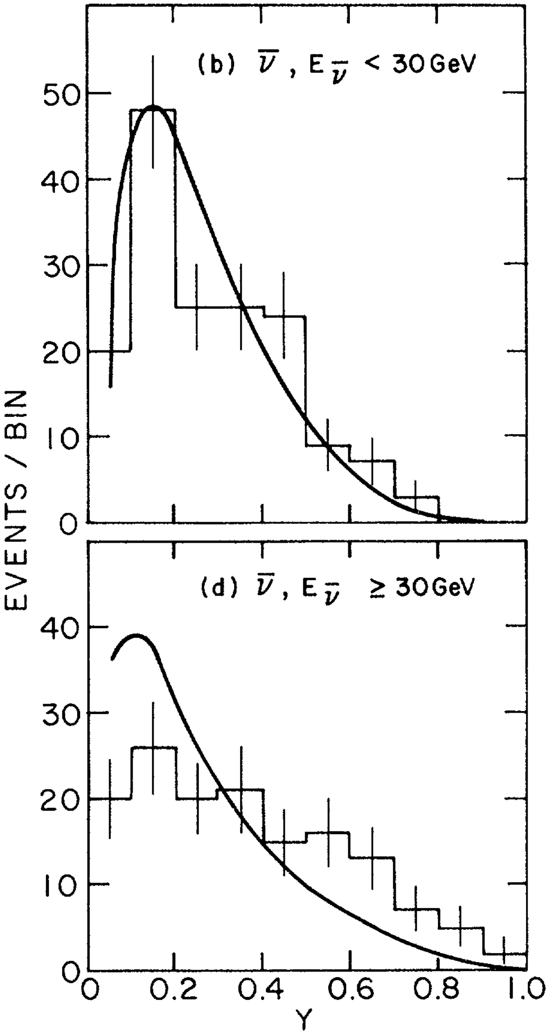
We present measured distributions in the scaling variables x and y obtained from the reactions ν_μ $(\bar{\nu}_\mu)$ + nucleon $\rightarrow \mu^-$ (μ^+) + hadrons at high energy. The x distributions are consistent with scale invariance. The x and y distributions are used to perform the first test of charge-symmetry invariance in high-energy neutrino interactions, assuming the validity of scale invariance. A possible *effective* deviation from charge-symmetry invariance is observed, which could be the result of new particle production.

Fermilab neutrino experiment $\bar{\nu}_\mu + \text{nucleon} \rightarrow \mu^+ + \text{hadrons}$

$$y = \frac{E_{\text{hadrons}}}{E_{\bar{\nu}_\mu}}$$

No anomaly in $\nu_\mu + \text{nucleon} \rightarrow \mu^- + \text{hadrons}$

Popular explanation: new, heavy neutral lepton of mass few GeV



Can there be GeV neutrinos? $\Omega_\nu h^2 \approx 0.3\ \frac{m_\nu}{30\,\mathrm{eV}}$

- Gerstein, Zel'dovich, Marx, Szalay, Cowsik, McClelland limit assumes neutrinos relativistic at decoupling.

- Neutrinos decouple at $T \sim \mathrm{MeV}$.

- If $m_\nu \gtrsim$ few MeV, then freeze-out abundance smaller.

- If $m_\nu \approx$ few GeV, neutrino could be dark matter.

Jim Peebles, *Cosmology’s Century*

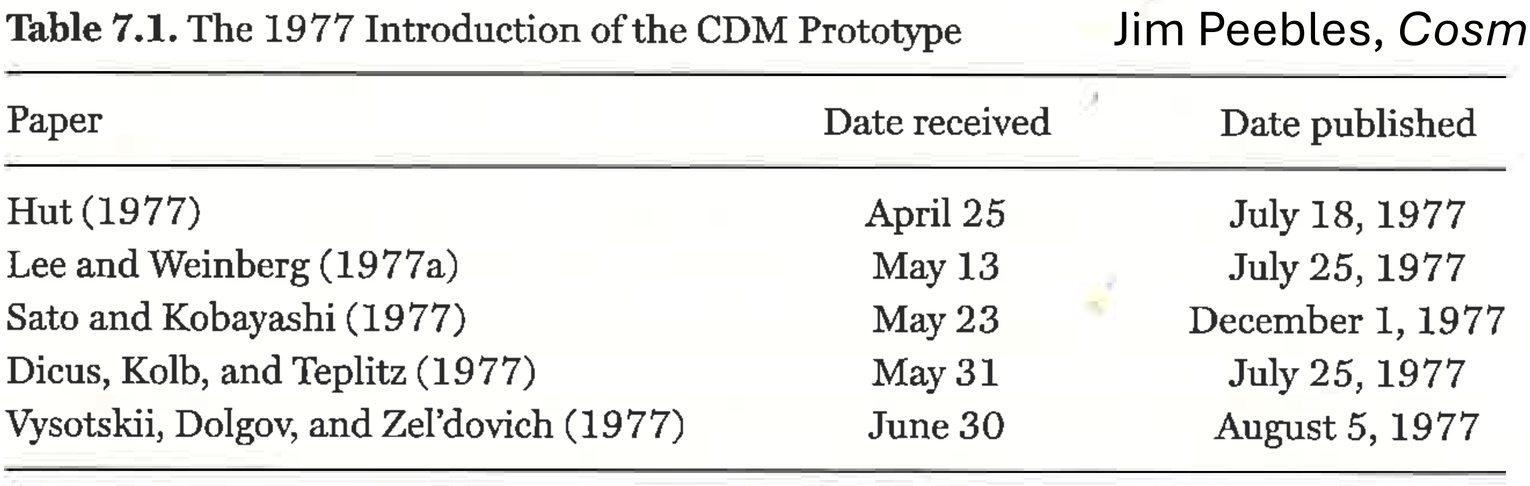


Table 7.1. The 1977 Introduction of the CDM Prototype

Paper	Date received	Date published
Hut (1977)	April 25	July 18, 1977
Lee and Weinberg (1977a)	May 13	July 25, 1977
Sato and Kobayashi (1977)	May 23	December 1, 1977
Dicus, Kolb, and Teplitz (1977)	May 31	July 25, 1977
Vysotskii, Dolgov, and Zel’dovich (1977)	June 30	August 5, 1977

- (Lee & Weinberg, at least) hugely influential.
- Dark Matter from freeze-out of a thermal relic.
- Boltzmann equation for freeze-out calculation.
- Interacts with SM through the “Z-portal.”
- Very shortly ruled out but set framework for particle dark matter (CDM prototype).
- Led to “WIMP Miracle” (mass and interaction strength comparable to weak scale)

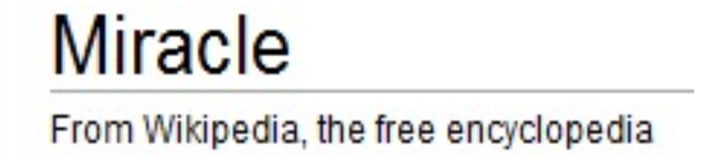
The WIMP "Miracle"

Merriam-Webster

Merriam-Webster OnLine

mir·a·cle
\ˈmir-i-kəl \
noun

1 : an extraordinary event manifesting divine intervention in human affairs



Miracle

From Wikipedia, the free encyclopedia

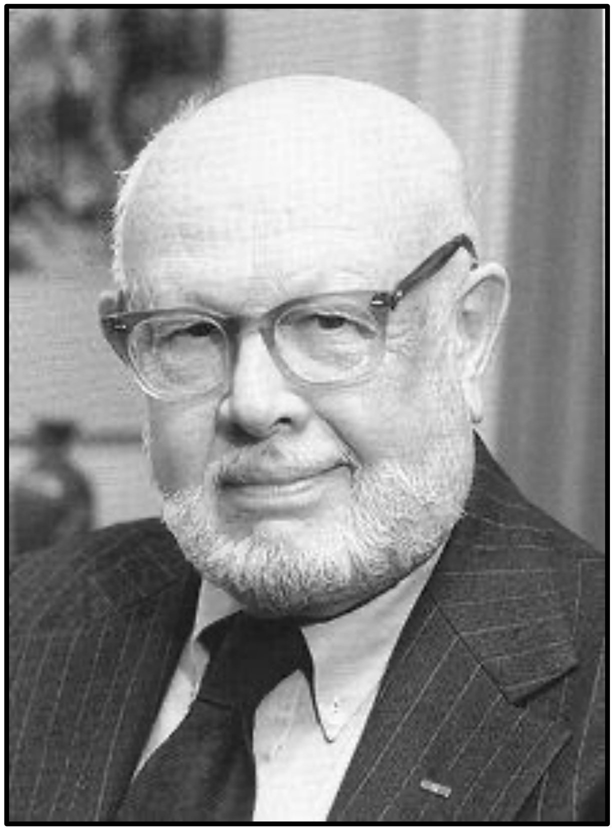
WIKIPEDIA
The Free Encyclopedia

… often used to give an impression of great and unusual value in a trivial context …

WIMP "miracle" not realized

Wrong Experiments Can Be Important & Lead to Interesting Results

George and I are (sort of) brothers: we are two of Willy's Boys



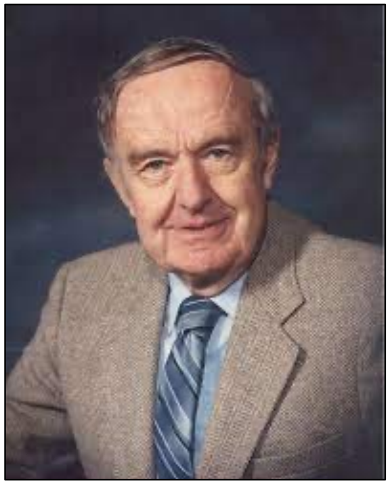
1978 ⇨1980. We were officemates in Kellogg Radiation Laboratory

George was Willy's (last?) student
I was (almost his last?) postdoc

First met George my first evening in Pasadena at Dick Bond's graduation party. Wild!

When I arrived at Caltech I was in an entangled state: a superposition of cosmologist and particle (neutrino) theorist.

Observations collapsed my wavefunction and I became a cosmologist



Caltech, Autumn 1978—Alan Rex Sandage lecture series on "Cosmology."

- All cosmology is a search for two numbers Ω_0 and q_0.
- Rude introduction to astronomy: metallicity corrections, Malmquist bias, crowding, aperture corrections, nonlinearities, K-corrections, …
- "Fifth brightest galaxy in a cluster is a standard candle."
- Plots w/scattered data points, no error bars, connected by straight lines.
- Worst lecture series ever! Forget cosmology!

Caltech, Autumn 1978—??? Lecture(s) on "(not yet Super) String Theory."

- Very mathematical, no connection to experiment.
- I was too naïve to grasp possibilities.
- Murry Gell-Mann stood up and announced, "This is the future of particle physics."
- Maybe cosmology wasn't so bad!

Now some non-ν comments

Neutrino (and most of all) particle cosmology assumes LTE in the radiation-dominated era in the early Universe.

But the Universe became radiation dominated only at reheating following inflation.

The reheat temperature could be as low as a few MeV (set by BBN and neutrinos).

What about fields with $m > T_{\mathrm{RH}}$ or interactions too feeble to establish LTE?

Is there another way to produce particles other than colliding SM particles?

Yes: Neutrino oscillations (Dodelson-Widrow; Shi-Fuller).

Yes: Gravitational Particle Production (GPP). The expanding universe creates particles!

Disturbing the Quantum Vacuum

Electric field ⟶ Particle creation

In vacuum

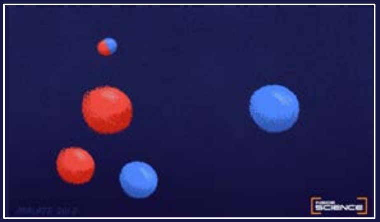


Image: Malate 2017 (AIP)

Turn on $\vec{E}$ field ● ⟵ $\vec{E}$ ⟶ ●

Particle creation if energy gained in acceleration from $\vec{E}$ field over a Compton wavelength exceeds the particle's rest mass.

$$\left|\vec{E}_{\rm crit}\right| = \frac{m_e^2 c^3}{e\hbar} \approx 10^{16}\ {\rm V\ cm}^{-1} \qquad \Gamma \propto e^{-\left|\vec{E}_{\rm crit}\right|/\left|\vec{E}\right|}$$

Sauter (1931); Heisenberg & Euler (1935); Weisskopf (1936); Schwinger (1951)

Disturbing the Quantum Vacuum

Expanding space ⟶ Particle creation

In vacuum

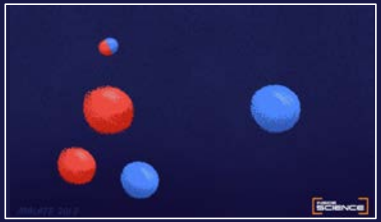
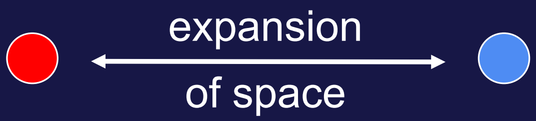


Image: Malate 2017 (AIP)

In presence of expanding space



$$H_{\text{crit}} = m \qquad \Gamma \propto e^{-m/H}$$

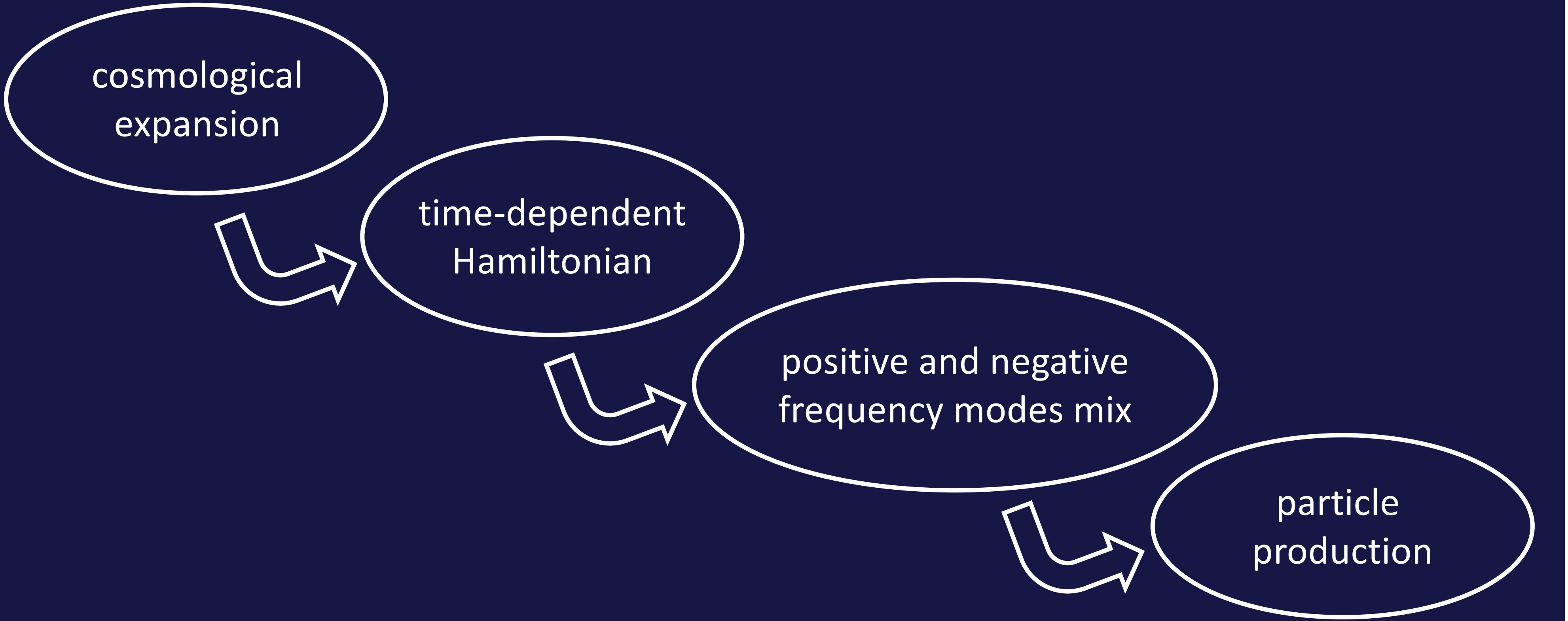
Particle creation if energy gained in acceleration from expansion of space over a Compton wavelength exceeds the particle's rest mass.

Schrödinger (1939)

Cosmological Gravitational Particle Production (CGPP)

- In Minkowskian QFT, a particle is an IR of the Poincaré group.
- But, expanding universe not Poincaré invariant.
- Notion of a “particle” is approximate.

Schrodinger (1939); Parker (1965, 68); Fulling, Ford, & Hu; Zel’dovich; Starobinski; Grib, Frolov, Mamaev, & Mostepanenko; Mukhanov & Sasaki, Birrell & Davies…

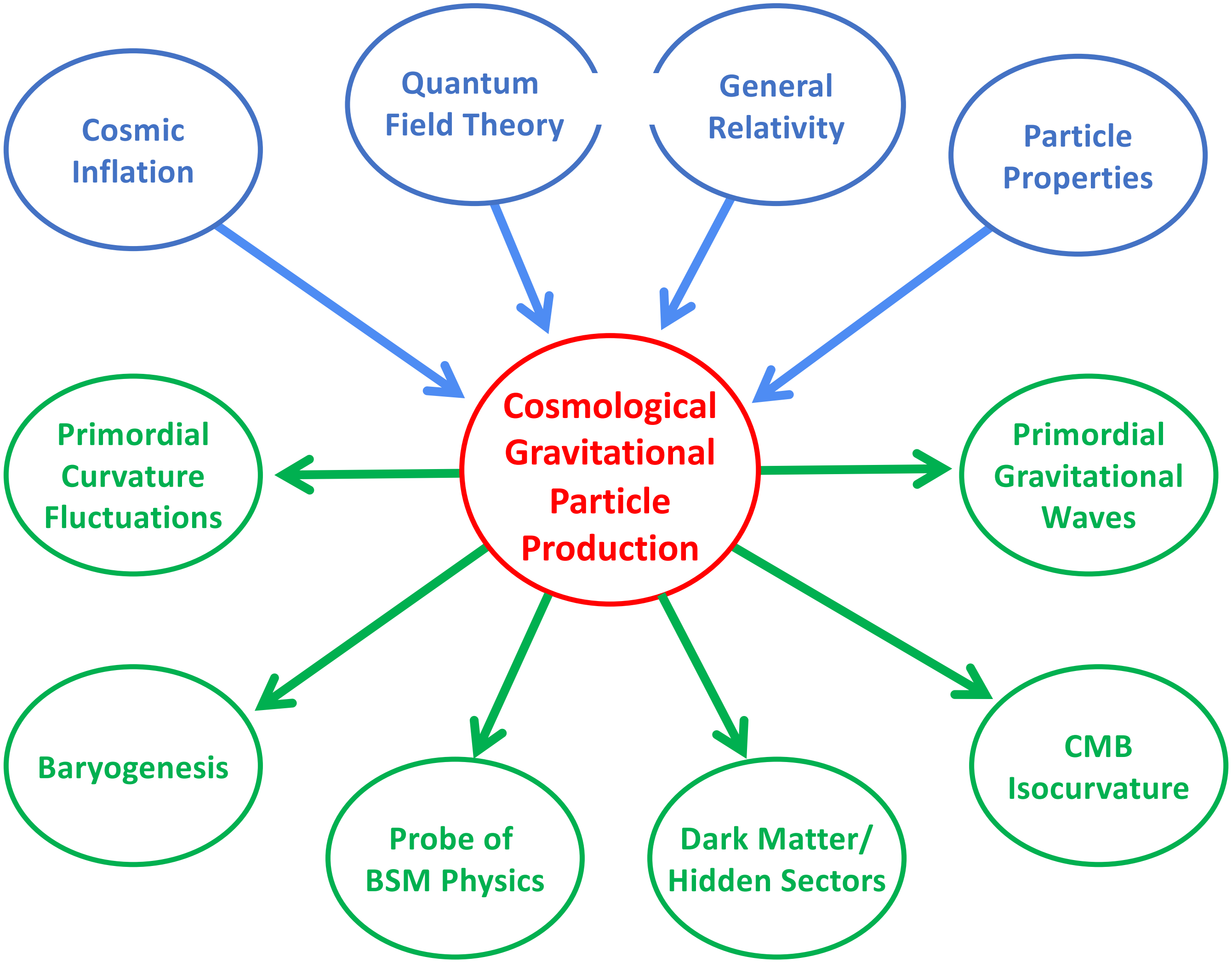


cosmological expansion

time-dependent Hamiltonian

positive and negative frequency modes mix

particle production



Cosmic Inflation

Quantum Field Theory

General Relativity

Particle Properties

Cosmological Gravitational Particle Production

Primordial Curvature Fluctuations

Primordial Gravitational Waves

Baryogenesis

Probe of BSM Physics

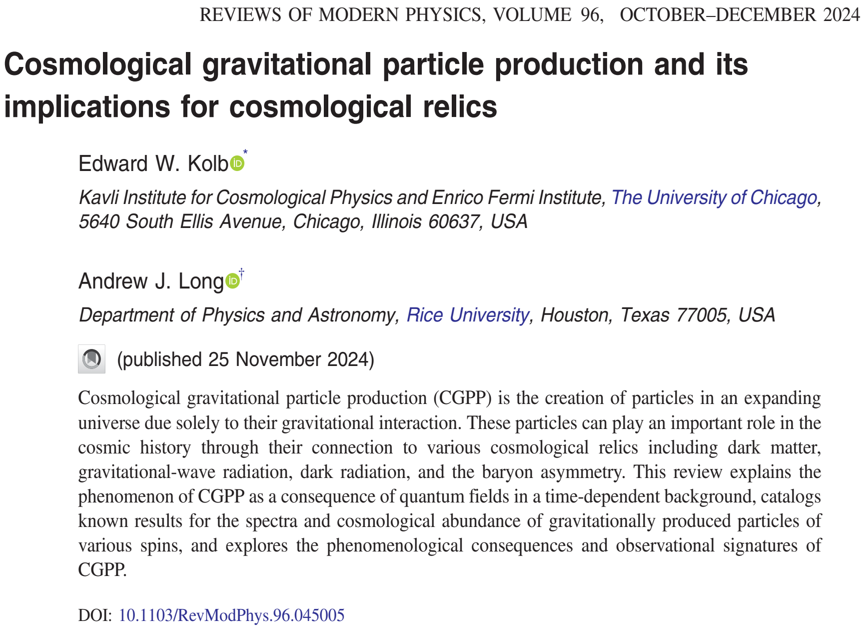
Dark Matter/ Hidden Sectors

CMB Isocurvature

Quantum Field Theories in the Early Universe

1. QFTs, well-behaved in Minkowski space, can develop pathologies when promoted to FRW.
2. This is especially acute for “higher-spin” QFTs (1, $3/2$, 2, …).
3. And some funny business for spin-0.
4. Is there a swampland of Minkowskian QFTs?
5. Or should we just accept restrictions on parameters of the QFTs (mass, couplings, etc.).

More complete treatment in



REVIEWS OF MODERN PHYSICS, VOLUME 96, OCTOBER–DECEMBER 2024

Cosmological gravitational particle production and its implications for cosmological relics

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Cosmological gravitational particle production (CGPP) is the creation of particles in an expanding universe due solely to their gravitational interaction. These particles can play an important role in the cosmic history through their connection to various cosmological relics including dark matter, gravitational-wave radiation, dark radiation, and the baryon asymmetry. This review explains the phenomenon of CGPP as a consequence of quantum fields in a time-dependent background, catalogs known results for the spectra and cosmological abundance of gravitationally produced particles of various spins, and explores the phenomenological consequences and observational signatures of CGPP.

DOI: 10.1103/RevModPhys.96.045005

Quantum Field Theories in the Early Universe

How should one regard QFTs, perfectly healthy in Minkowski spacetime, but have issues in a non-pathological, classical gravitational background?

1. (H_I–dependent, T_{RH} –dependent, and spin–dependent) limits on stable particles masses from Ω.
   Is that an issue with the QFT, or just a result like $m_\nu \lesssim \mathrm{eV}$?

2. Stable, *minimally-coupled* scalars have infrared issues unless $m \gtrsim H_I$ [Chung, EWK, Riotto, Senatore (05)].
   Is that an issue with the QFT, or just "not in our universe"?

3. Dark photons have issues with runaway production if non-minimally coupled [Campanelli, Jenks, EWK, McDonough (24)].
   Shared with massive Kalb-Ramond fields. [Campanelli, Jenks, EWK, McDonough (24)].

4. Massive Rarita-Schwinger fields can have catastrophic production unless $m \gtrsim H_I$ [EWK, Long, McDouough (21)].
   SUGRA people should pay attention.

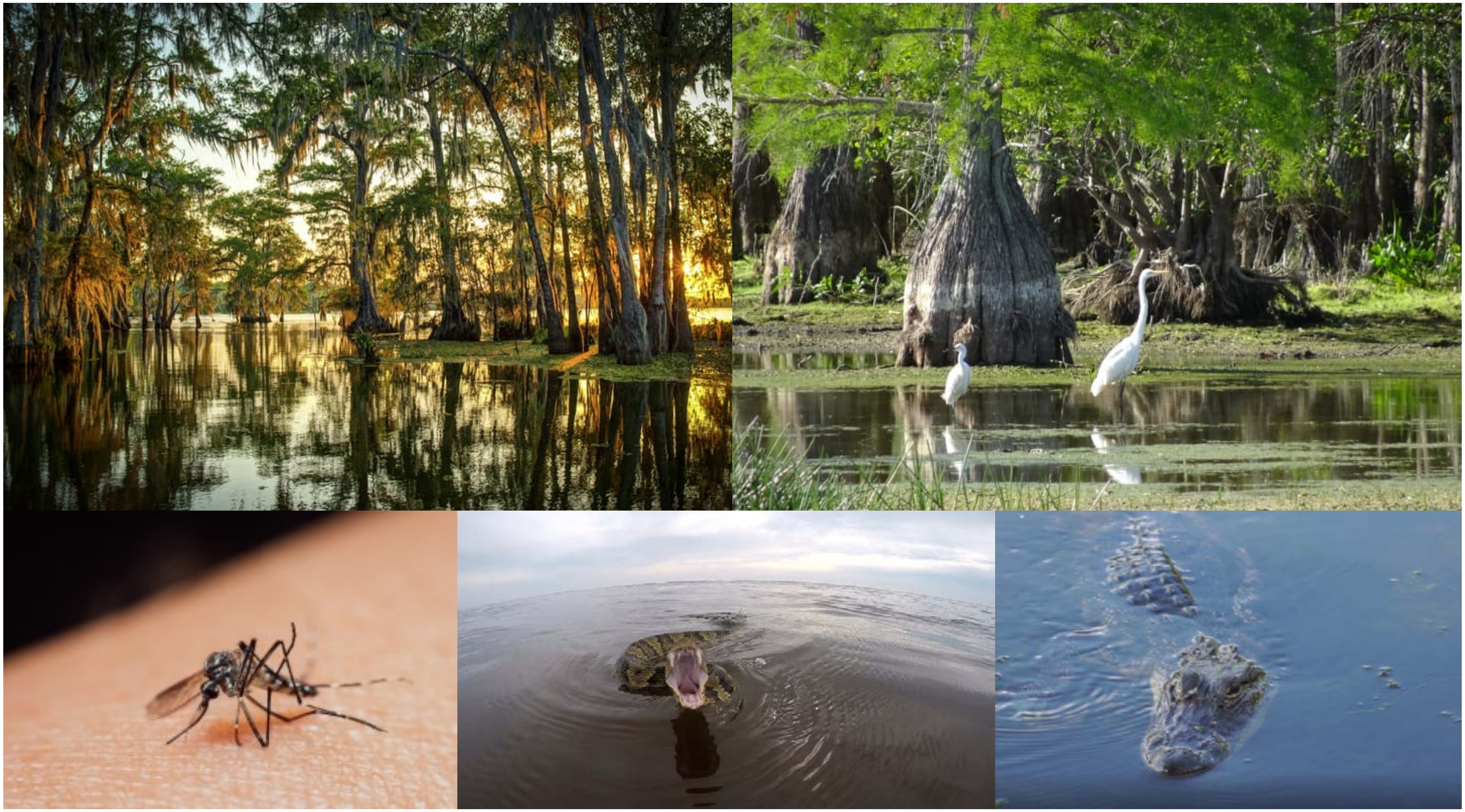
5. Massive Fierz-Pauli fields can develop ghosts and gradient instabilities unless $m \gtrsim H_I$ [EWK, Ling, Long, Rosen (21)].
   Is there a better formulation of massive gravity?

6. Do we have to look at different gravity theories at high-energy.
   Torsion, contorted geometry [Mavromatos & Sarkar); disformal gravity [Hell].

7. Is there a Flatland Swampland?

https://louisianaswamp.com/

A swamp can be beautiful and teeming with life (that will sting, bite, or eat you)



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January 2025 Rocky Kolb The University of Chicago