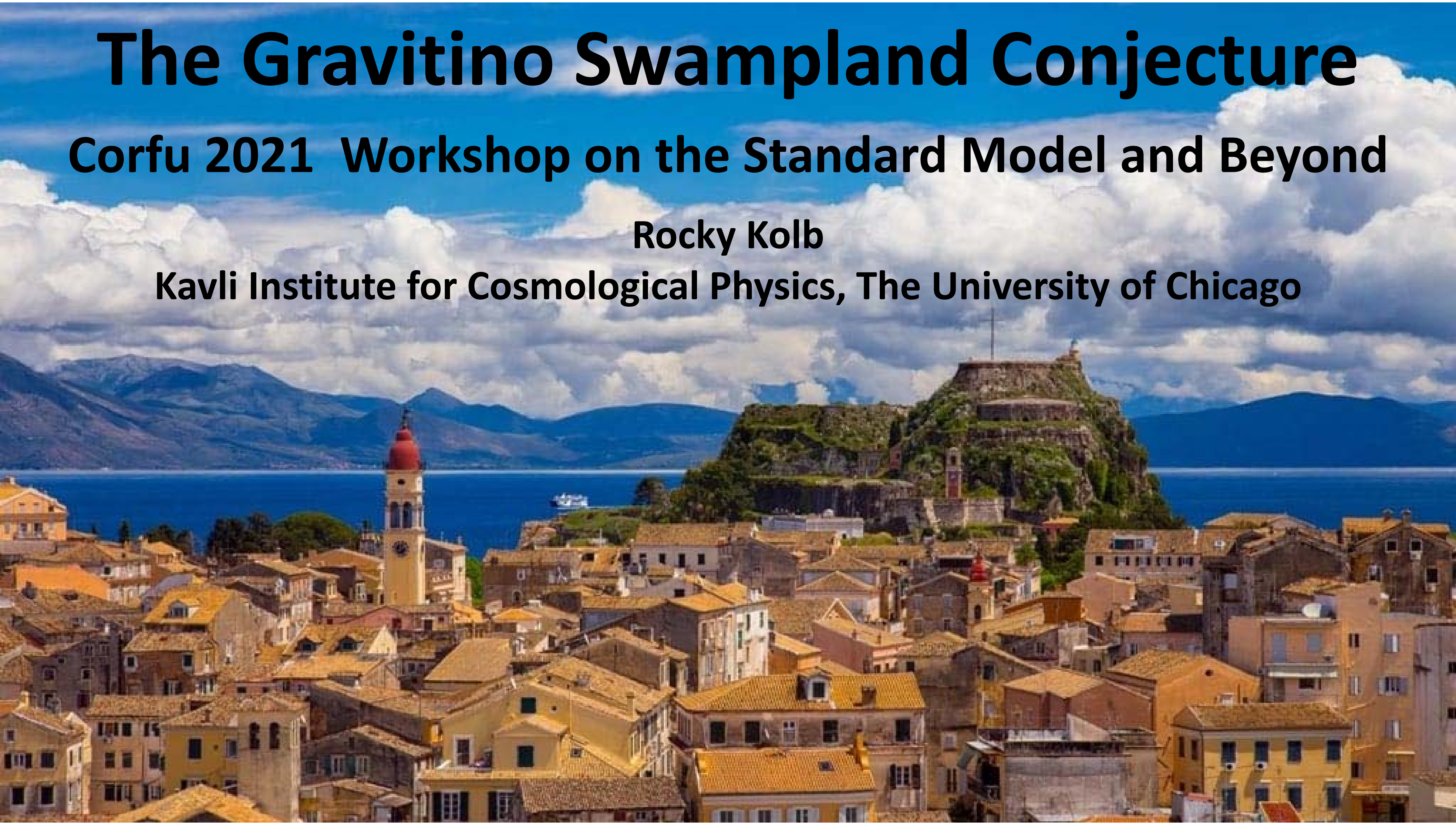
The Gravitino Swampland Conjecture

Corfu 2021 Workshop on the Standard Model and Beyond

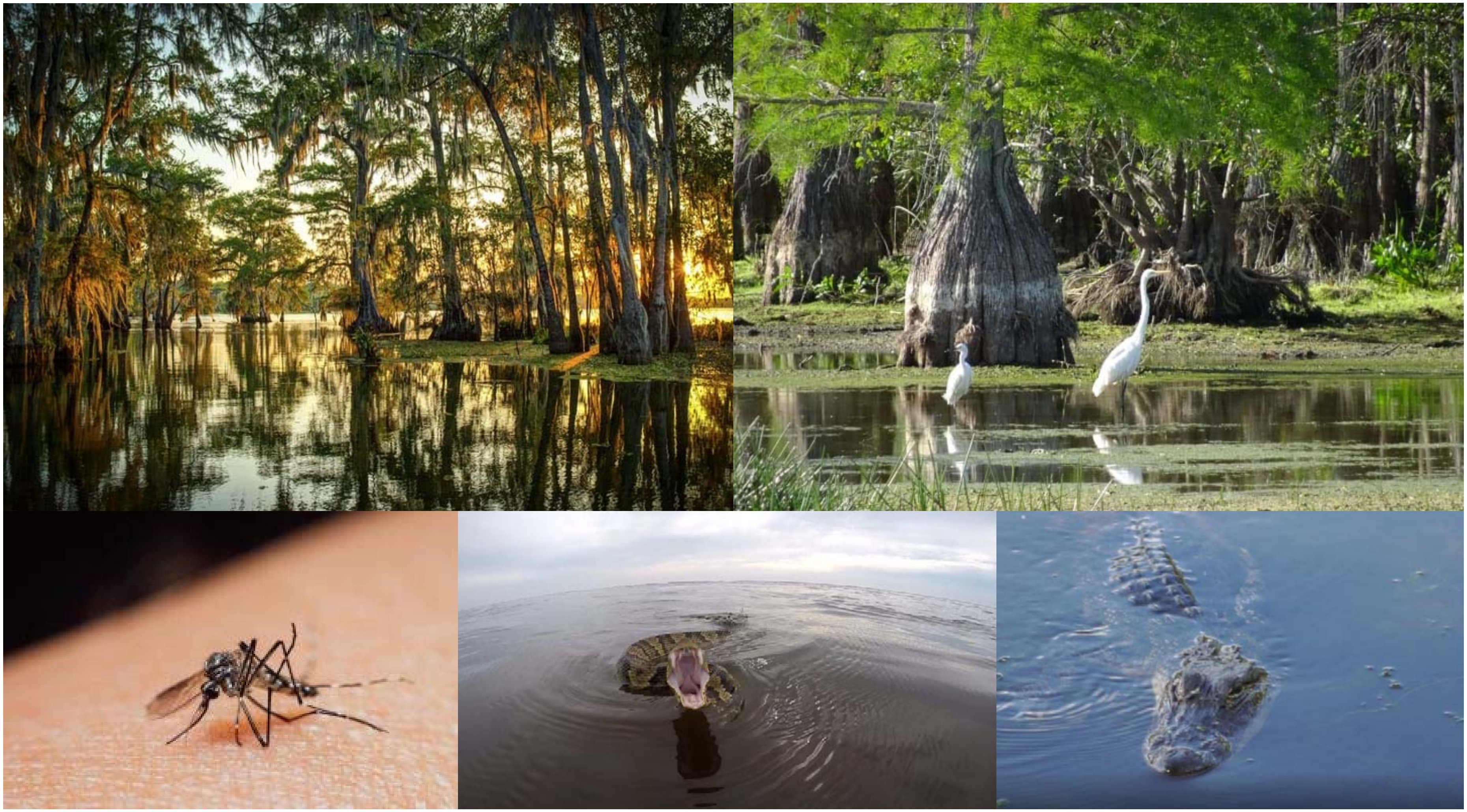
Rocky Kolb

Kavli Institute for Cosmological Physics, The University of Chicago



https://louisianaswamp.com/

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



Work presented here based on

Catastrophic Production of Slow Gravitinos
arXiv:2102.10113 Phys. Rev. D, to appear

With more on the way!

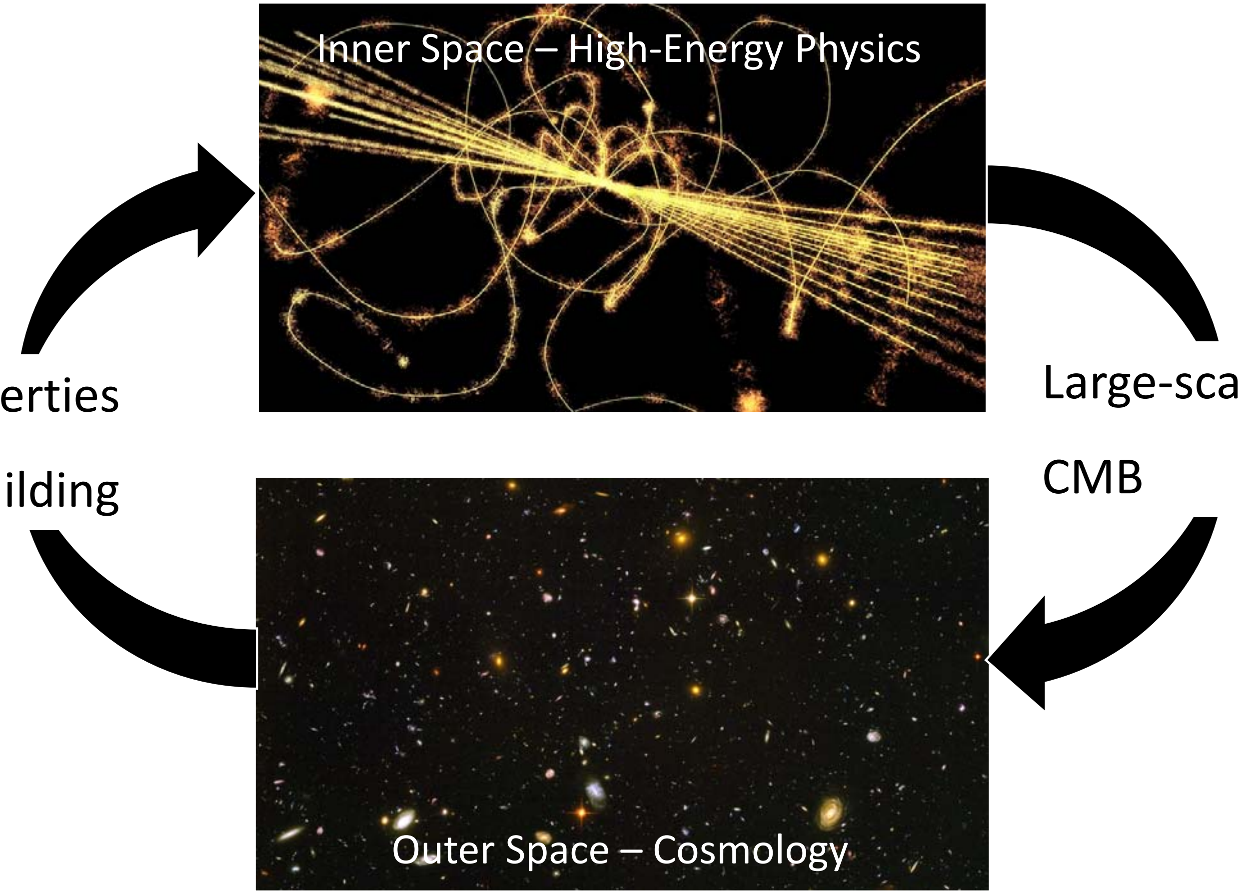
The Gravitino Swampland Conjecture
arxiv :2103.10437 Phys. Rev. Lett., to appear

In collaboration with:

Andrew J Long (Rice University)

Evan McDonough (University of Winnipeg)

Particle Cosmology



Inner Space – High-Energy Physics

Particle properties

Model building

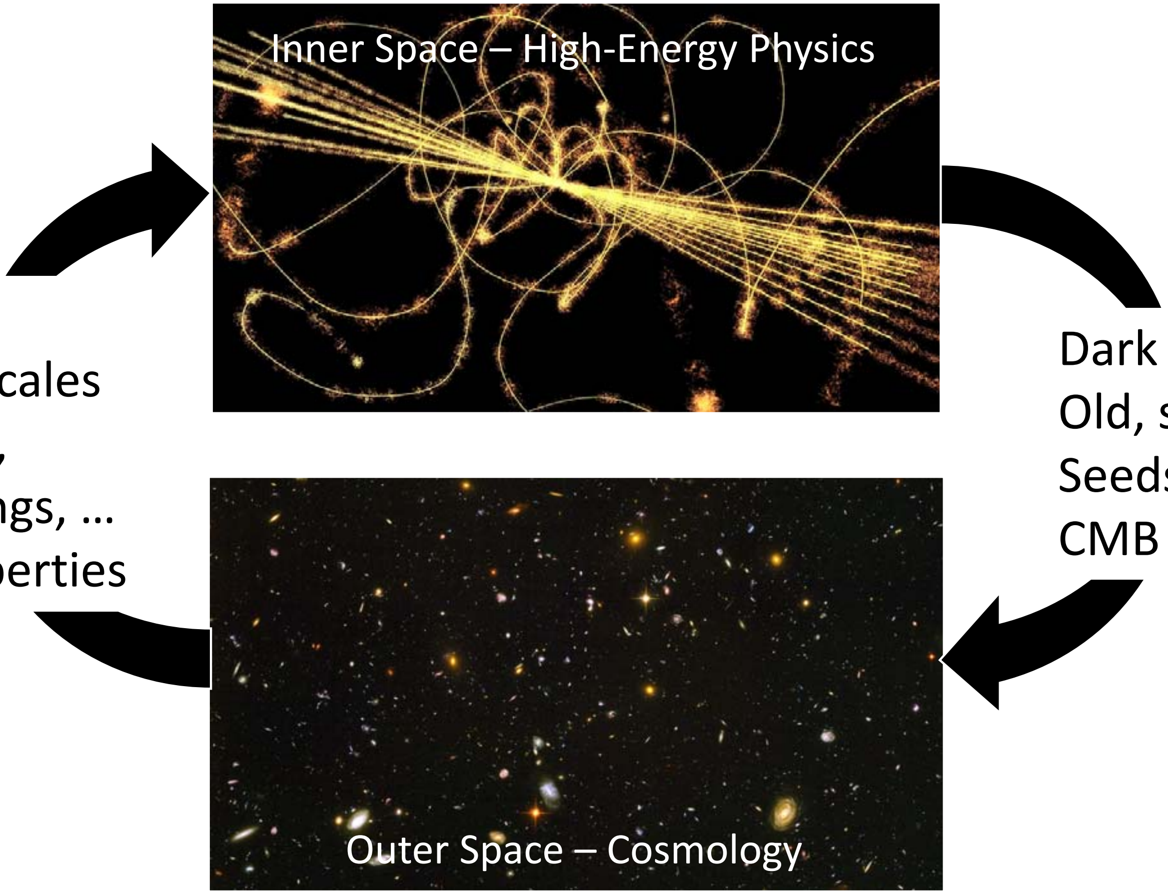
Large-scale structure

CMB

Outer Space – Cosmology

Particle Cosmology

Inflation

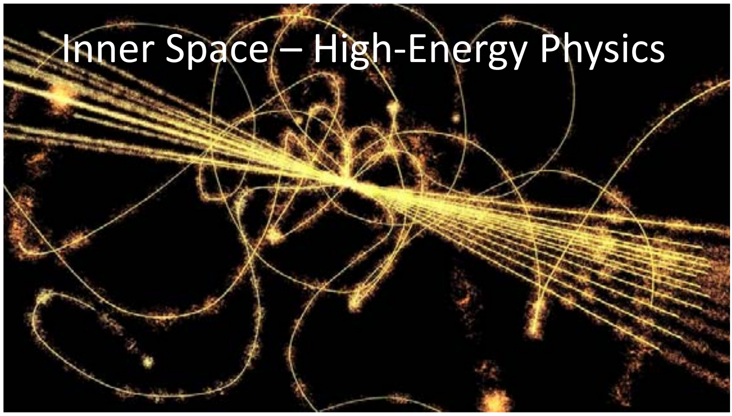


Potential insight to
    very high energy scales
Model building: GUTs,
    SUSY, SUGRA, Strings, …
Limits to particle properties

Dark Matter
Old, spatially flat universe
Seeds of structure
CMB fluctuations

Particle Cosmology

Inflation



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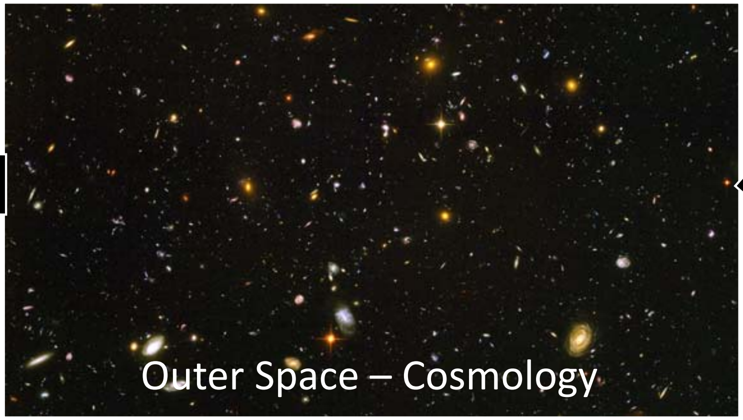
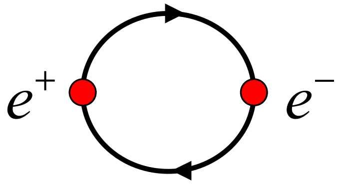


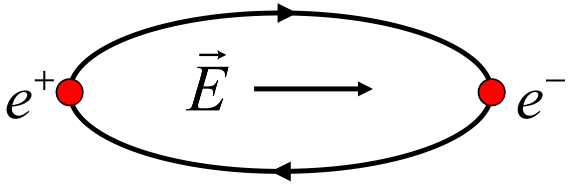
Expansion of the universe lifts particles from the vacuum! Gravitational Particle Production (GPP)

Disturbing the Quantum Vacuum

Electric Field → Particle creation

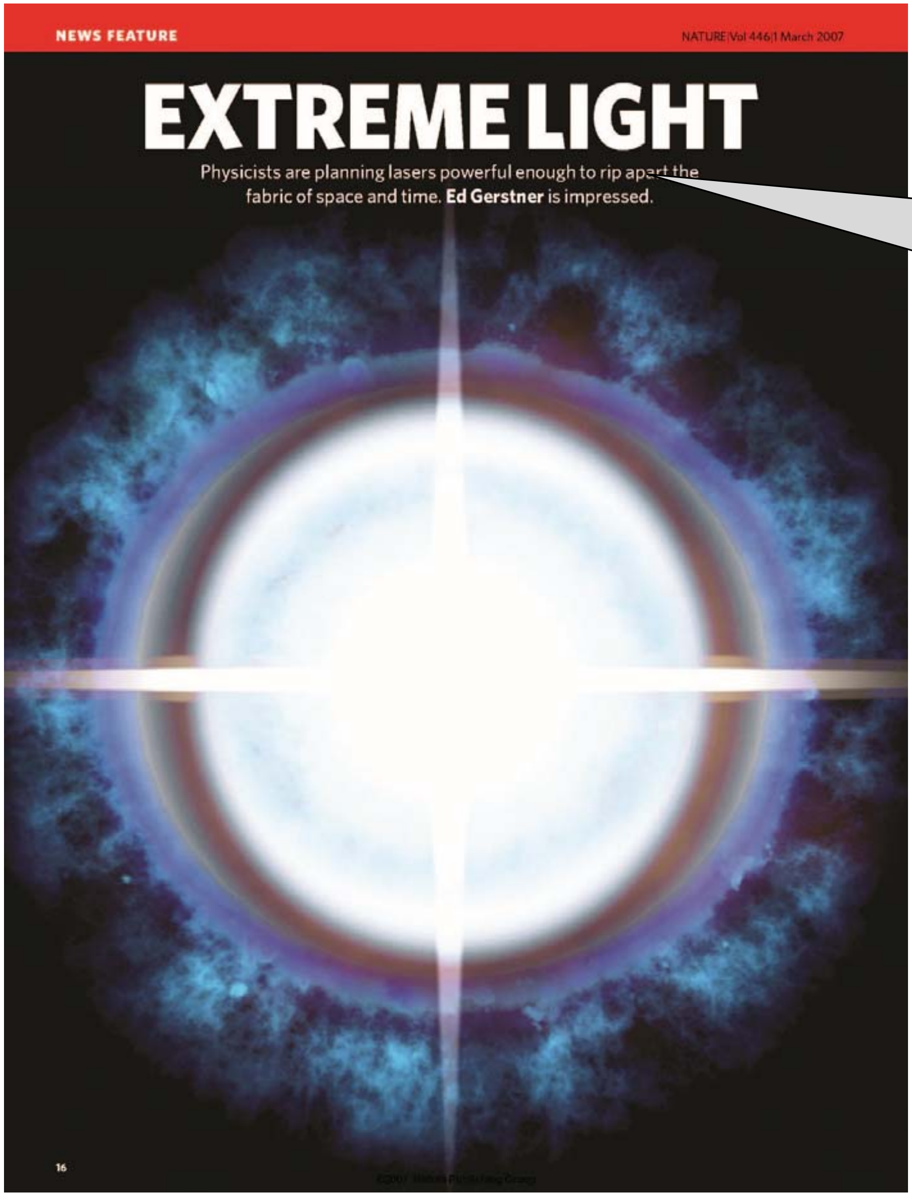


Particle creation if energy gained in acceleration from electric field over a Compton wavelength exceeds the particle's rest mass.



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

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



NEWS FEATURE

NATURE|Vol 446|1 March 2007

EXTREME LIGHT

Physicists are planning lasers powerful enough to rip apart the fabric of space and time. **Ed Gerstner** is impressed.

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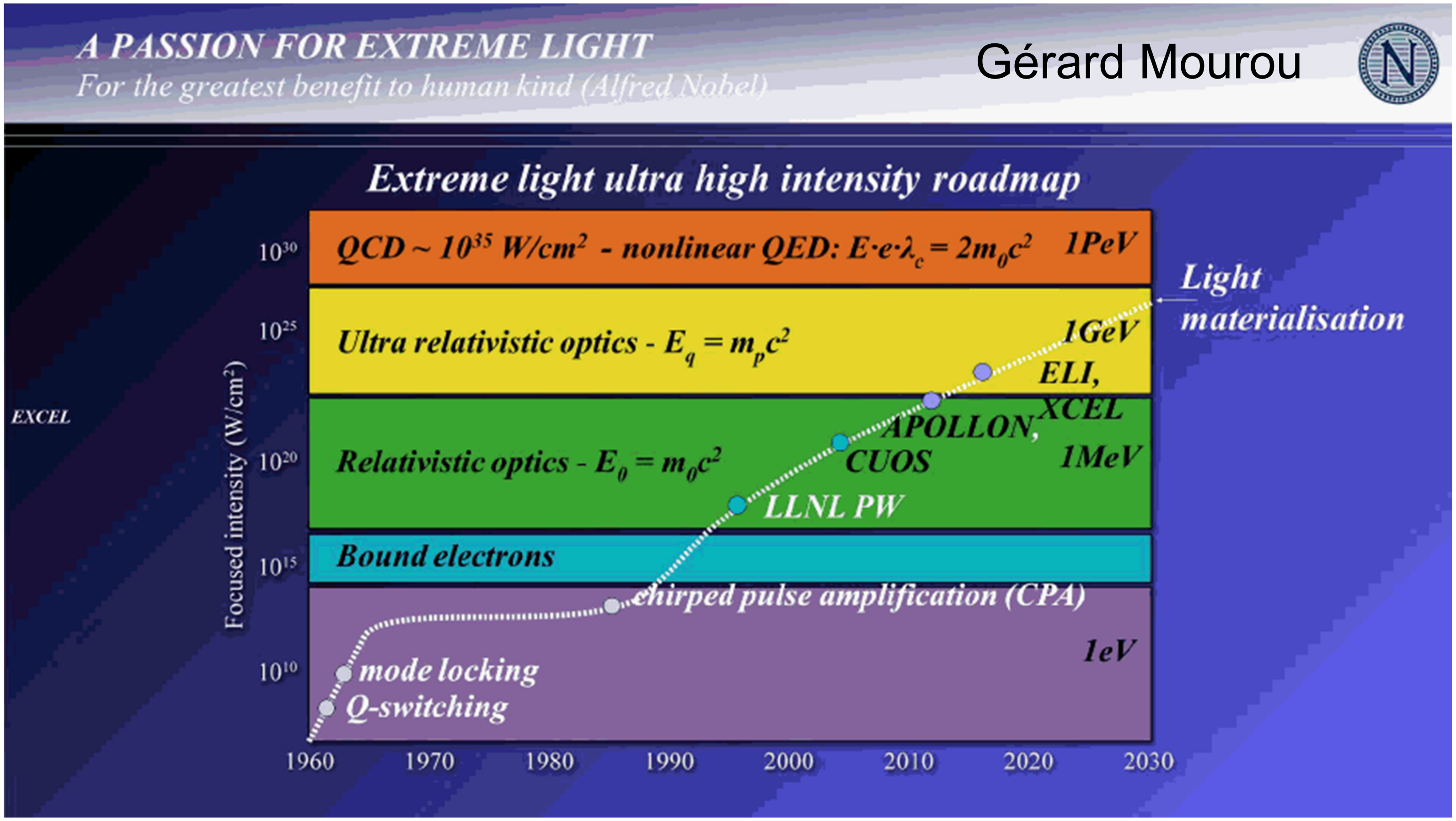
NATURE, Vol 446/1 March 2007

Physicists are planning lasers powerful enough to rip apart the fabric of space and time.

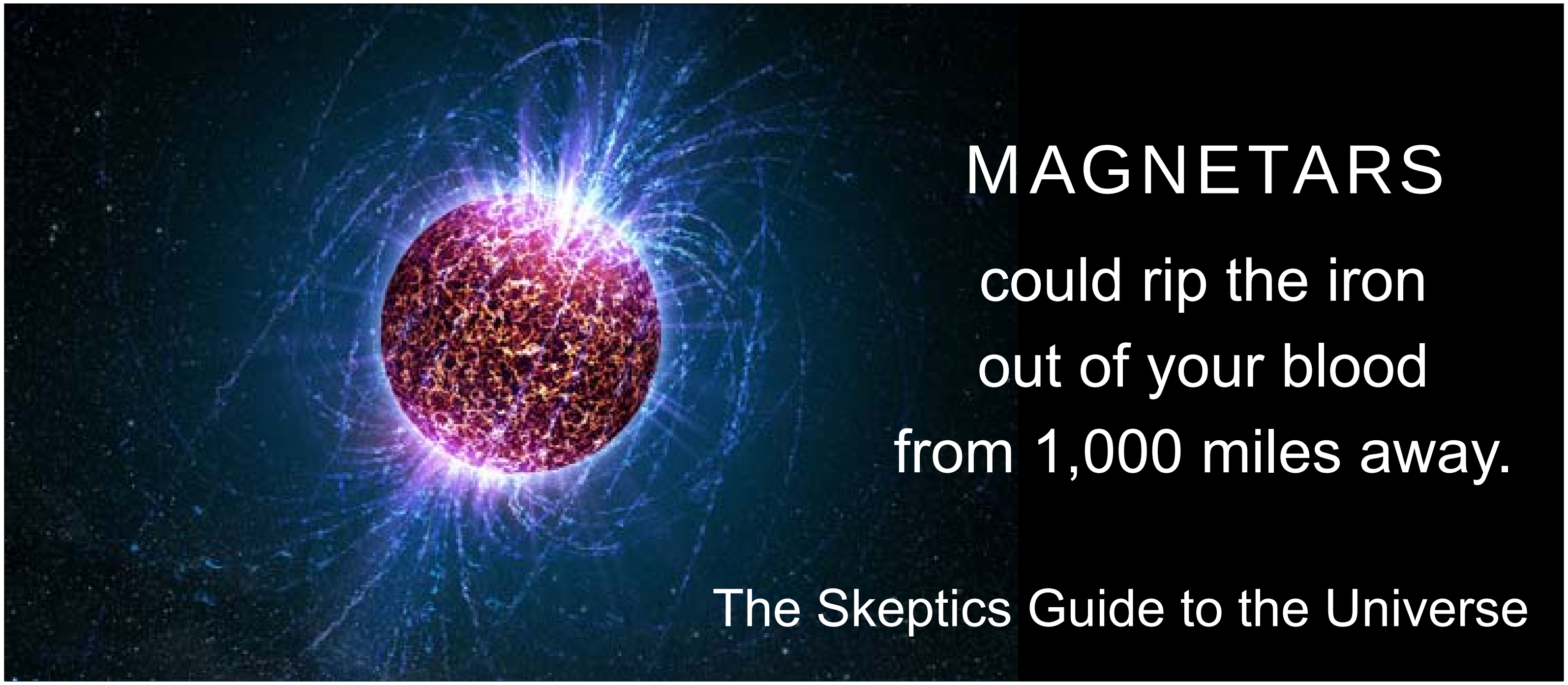
"We're going to change the index of refraction of the vacuum and produce new particles."

Gérard Mourou

Disturbing the Quantum Vacuum



$$I_C \approx \frac{c}{8\pi}\left|\vec{E}_{\text{crit}}\right|^2 \sim 10^{30}\ \text{W cm}^{-2}$$



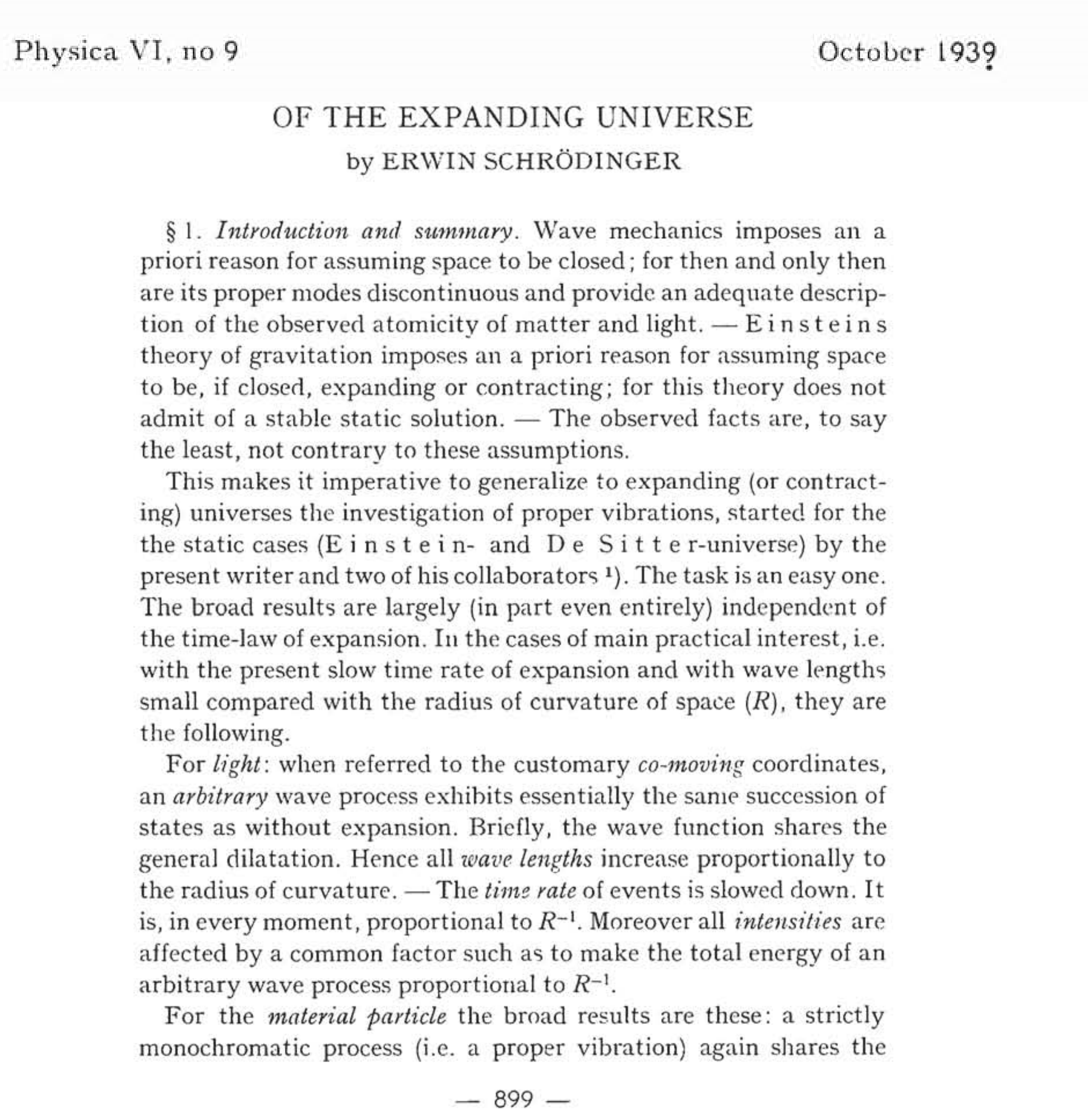
$$\left|\vec{B}_{\text{crit}}\right| = \frac{m_e^2}{e} \sim 5\times10^{13}\ \text{G}$$

Crab pulsar $3\times10^{13}\ \text{G}$

Magnetars 10^{14} -- $10^{15}\ \text{G}$

Strong magnetic fields imply existence of strong electric fields.

Many interesting phenomena associated with pulsars, magnetars, etc.



Physica VI, no 9 October 1939

OF THE EXPANDING UNIVERSE

by ERWIN SCHRÖDINGER

§ 1. *Introduction and summary*. Wave mechanics imposes an a priori reason for assuming space to be closed; for then and only then are its proper modes discontinuous and provide an adequate description of the observed atomicity of matter and light. — Einsteins theory of gravitation imposes an a priori reason for assuming space to be, if closed, expanding or contracting; for this theory does not admit of a stable static solution. — The observed facts are, to say the least, not contrary to these assumptions.

This makes it imperative to generalize to expanding (or contracting) universes the investigation of proper vibrations, started for the the static cases (Einstein- and De Sitter-universe) by the present writer and two of his collaborators [1]). The task is an easy one. The broad results are largely (in part even entirely) independent of the time-law of expansion. In the cases of main practical interest, i.e. with the present slow time rate of expansion and with wave lengths small compared with the radius of curvature of space (R), they are the following.

For *light*: when referred to the customary *co-moving* coordinates, an *arbitrary* wave process exhibits essentially the same succession of states as without expansion. Briefly, the wave function shares the general dilatation. Hence all *wave lengths* increase proportionally to the radius of curvature. — The *time rate* of events is slowed down. It is, in every moment, proportional to R^{-1}. Moreover all *intensities* are affected by a common factor such as to make the total energy of an arbitrary wave process proportional to R^{-1}.

For the *material particle* the broad results are these: a strictly monochromatic process (i.e. a proper vibration) again shares the

— 899 —

THE PROPER VIBRATIONS OF THE EXPANDING UNIVERSE

by ERWIN SCHRÖDINGER

Physica **VI**, 899 (1939)

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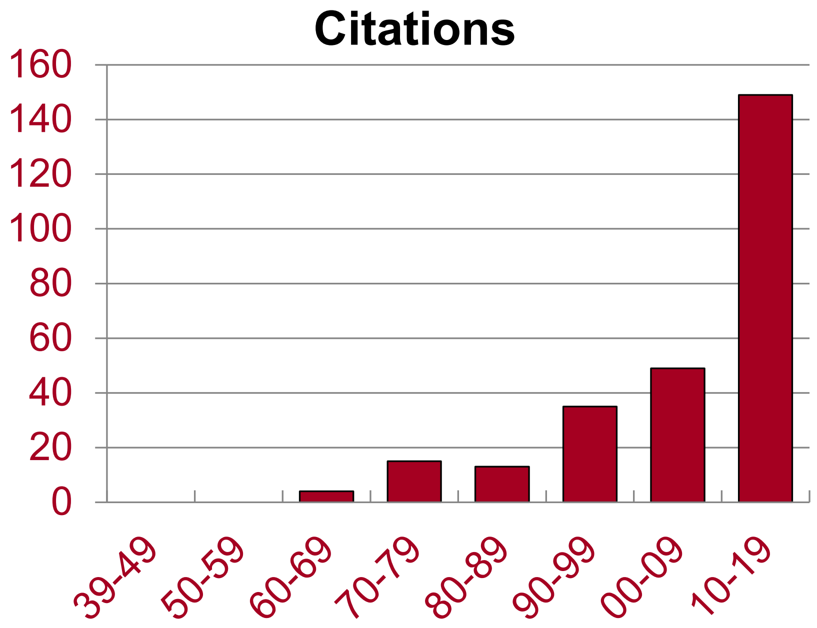
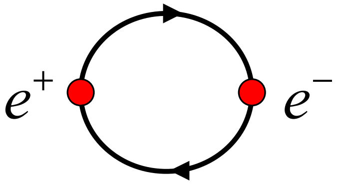
Cited 268 times (Google Scholar)

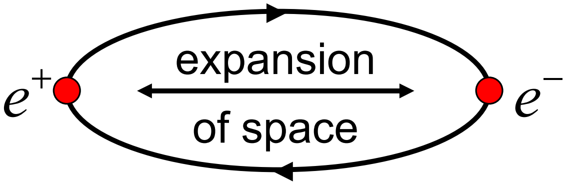


Disturbing the Quantum Vacuum

Expanding universe → Particle creation



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

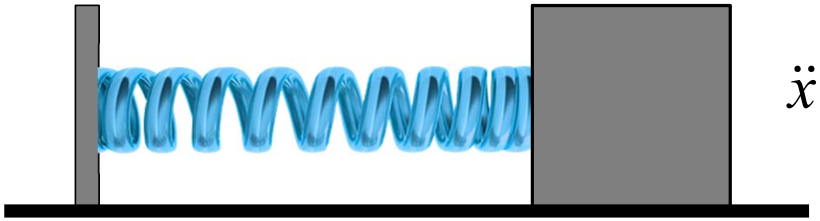


$\mathrm{v} = c$ at Hubble radius

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

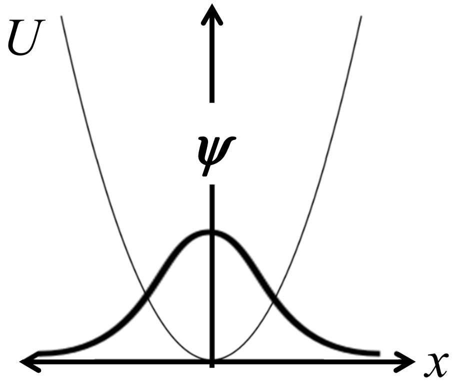
Schrödinger's Alarming Phenomenon

Expansion of the universe causes explicit time dependence in action for "spectator" fields. Initial ~ de Sitter (early-time) vacuum may not evolve to final ~ Minkowski (late-time) vacuum, but to an excited state populated by particles.

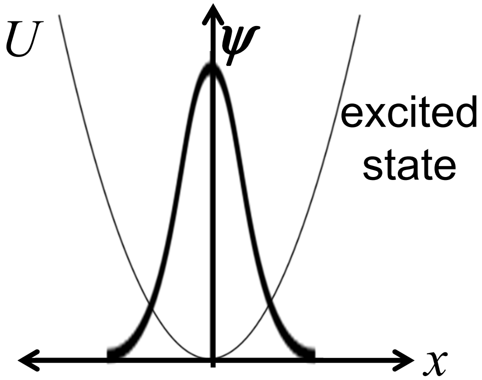


$$\ddot{x}(t)+\omega^2(t)\;x(t)=0$$

Spring constant varied slowly (adiabatically)



Spring constant varied abruptly (nonadiabatically)



Schrödinger's Alarming Phenomenon

Couple scalar field ϕ to gravity:

$\mathcal{R}$ is Ricci scalar, ξ is a constant. Conformally invariant in limit $\xi = 1/6, M = 0$ (& $\hbar = 0$)

$$S = \int d^4x \sqrt{-g} \left[\tfrac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - \tfrac{1}{2} m^2 \phi^2 - \xi \mathcal{R} \phi^2 \right]$$

In conformal time η, $d\eta \equiv a^{-1}(t)\, dt$ [$a(t)$ = FRW scale factor], mode functions χ_k satisfy a wave equation with <u>time-dependent</u> mass:

$$\chi_k''(\eta) + \omega_k^2(\eta)\chi_k(\eta) = 0$$

$$\omega_k^2(\eta) = \left|\vec{k}\right|^2 + a^2(\eta)\left[m^2 + \tfrac{1}{6}(1 - 6\xi)\mathcal{R}(\eta)\right]$$

(Rescaled field, $\chi \rightarrow \phi\, a$, for a canonical kinetic term)

Schrödinger’s Alarming Phenomenon

Solutions to wave equation include both + and – frequency terms

$$\chi_k(\eta) = \frac{\alpha_k(\eta)}{\sqrt{2\omega_k(\eta)}} e^{-i\int \omega_k(\eta) d\eta} + \frac{\beta_k(\eta)}{\sqrt{2\omega_k(\eta)}} e^{+i\int \omega_k(\eta) d\eta}$$

$$\partial_\eta \alpha_k = \frac{1}{2} \frac{\partial_\eta \omega_k}{\omega_k^2} \omega_k \, e^{2i\int_\eta d\eta_1 \, \omega_k} \beta_k$$

$$\partial_\eta \beta_k = \frac{1}{2} \frac{\partial_\eta \omega_k}{\omega_k^2} \omega_k \, e^{-2i\int_\eta d\eta_1 \, \omega_k} \alpha_k$$

Initial conditions: $|\alpha_k| = 1$ $|\beta_k| = 0$

Pure outgoing (+ frequency) good solution if $A_k \equiv \left| \frac{\partial_\eta \omega_k(\eta)}{\omega_k^2(\eta)} \right| \ll 1$ Adiabaticity parameter

Abrupt changes in $a(\eta)$ leads to nonadiabatic changes in $\omega_k(\eta)$, which *adulterates* positive and negative frequency modes, leading to *Schrödinger’s Alarming Phenomenon* of particle creation in the expanding universe.

Schrödinger's Alarming Phenomenon

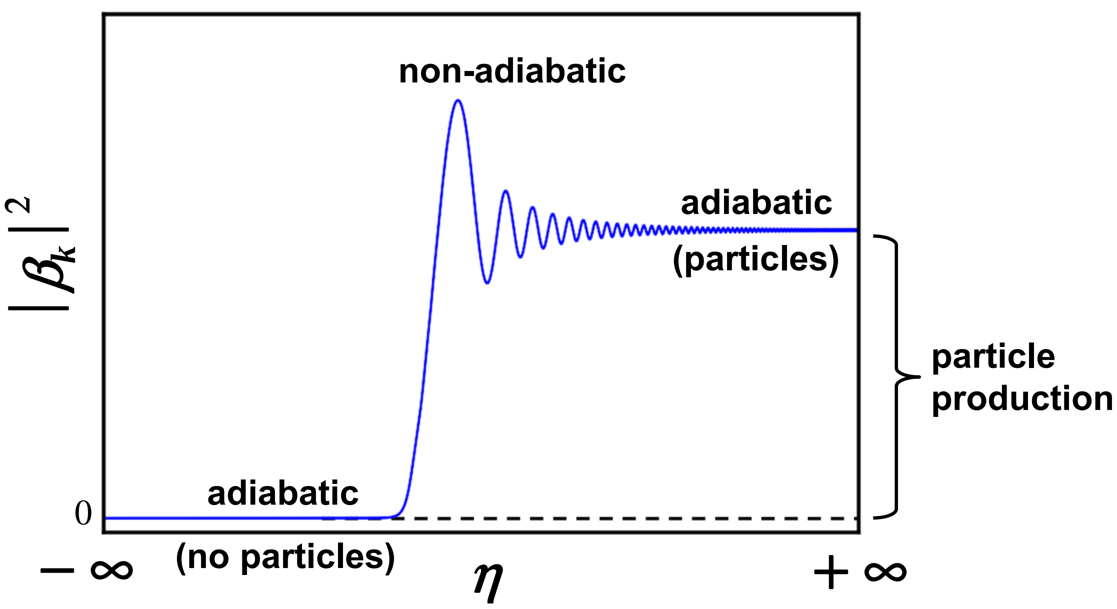
Comoving number density of particles at late times:

$$\lim_{a\to\infty} a^3 n = \frac{1}{(2\pi)^3}\int d^3\vec{k}\,\left|\beta_k(\eta)\right|^2$$

Program:

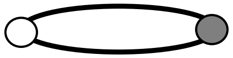
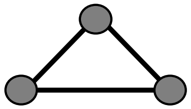
- Assume initial adiabatic conditions (true for inflation)
- Solve wave equation with initial conditions $\left|\alpha_k\right|^2 = 1, \quad \left|\beta_k\right|^2 = 0.$
- Assume late-time adiabatic conditions (true for FRW)
- Calculate late-time value of

$$\left|\beta_k\right|^2 = \frac{\omega_k}{2}\left|\chi_k\right|^2 + \frac{1}{2\omega_k}\left|\partial_\eta \chi_k\right|^2 - \frac{1}{2}$$


Conformally coupled scalar

One- Two- and Three-Point Functions

One-point function	→	number density (dark matter)
Two-point function	→	CMB isocurvature
Three-point function	→	CMB nongaussianities

	1-pt function 	**2-pt function** 	**3-pt function*** 
Observable	**Dark Matter**	**Isocurvature Fluctuations**	**CMB Non-Gaussianities**
Massive scalar field (conformal)	Kuzmin & Tkachev (99)	Expected to be very small	Chung & Yoo
Massive scalar field (minimal)	Kuzmin & Tkachev (99)	Chung, Kolb, Riotto & Senatore	
Massive Dirac field	Chung, Kolb & Riotto (98, 99) **WIMPZILLAS**	Similar to conformal scalar	Similar to conformal scalar?
Proca-de Broglie field	Massive: Kolb & Long Light: Graham, Mardon & Rajendran		
Massive Rarita-Schwinger field	Giudice, Riotto & Tkachev; Kallosh, Kofman, Linde & Van Proeyn; Kolb, Long, McDonough **(THIS TALK)**		
Massive Fierz-Pauli field	Kolb, Ling, Long, and Rosen (in progress)		

Complexity ↓

Complexity →

* related to but not cosmological collider program

1. Limits on particle masses
2. Restrictions on coupling to gravity
3. Potential ghosts
4. Potential catastrophic production signaling breakdown of EFT

Spin $3/2$: Ψ_μ

- First, straight-ahead Rarita-Schwinger (R-S) 1941 field in FRW, but allow varying mass
- Ψ_μ is a "vector-spinor" from direct product
  $(½,½) \otimes [(½,0) \oplus (0,½)] = (½,1) \oplus (½,0) \oplus (1,½) \oplus (0,½)$
  $(½,1) \oplus (1,½)$ is spin $3/2$ field with helicities $1/2$ and $3/2$
- QFT for spins ≥ 1 is often pathological (Weinberg, Coleman-Mandula, Boulware-Deser, Velo-Zwanziger, …) esp. if leave Minkowski space (superluminal propagation, wrong # degrees of freedom, ghosts, …)
- For spin-$3/2$ many issues resolved in context of Supergravity (SUGRA) (Das & Freedman)
- Spin $3/2 =$ gravitino (superpartner of graviton)
  Mass from super-Higgs mechanism,
  Goldstino extra dof from fermion in chiral multiplet
- SUGRA has torsion, $2-$ and $4-$ fermion interactions … assumed not important for EFT
- In some SUGRA models gravitino mass is time-dependent in FRW, while constant in some

Spin $3/2$: Ψ_μ

- Useful references:
  Giudice, Riotto & Tkachev, JHEP 08 (1999) 009 and JHEP 11 (199) 036
  Kallosh, Kofman, Linde, Van Proeyen, CQG 17 (2000) 4269
  Hasegawa et al., PLB 767 (2017) 392
  Freedman & Van Proeyen, *Supergravity*

- Start with Rarita-Schwinger action in FRW (very many very messy technical steps)

- Can project $\chi_\mu = a^{1/2}\psi_\mu$ into two propagating degrees of freedom with polarizations $3/2$ & $1/2$

- Field equations for Fourier modes in conformal time η:

$$\left[i\gamma^0\partial_\eta - \vec{k}\cdot\vec{\gamma} - am \right]\chi_{3/2} = 0$$ Like Dirac fermion

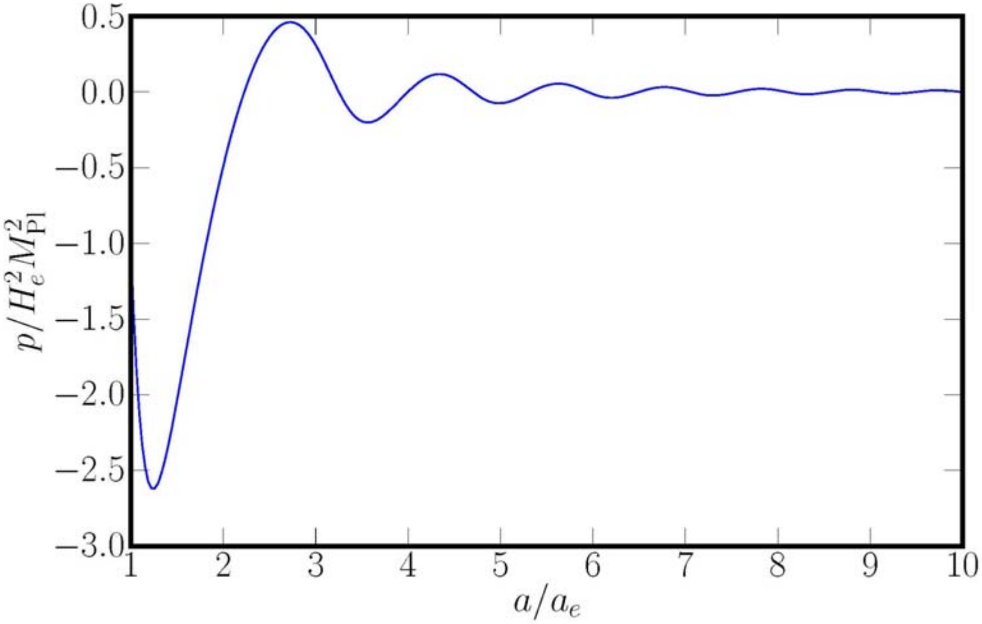
$$\left[i\gamma^0\partial_\eta - \left(C_A + i\,C_B\gamma^0\right)\vec{k}\cdot\vec{\gamma} - am \right]\chi_{1/2} = 0$$ Not like Dirac fermion

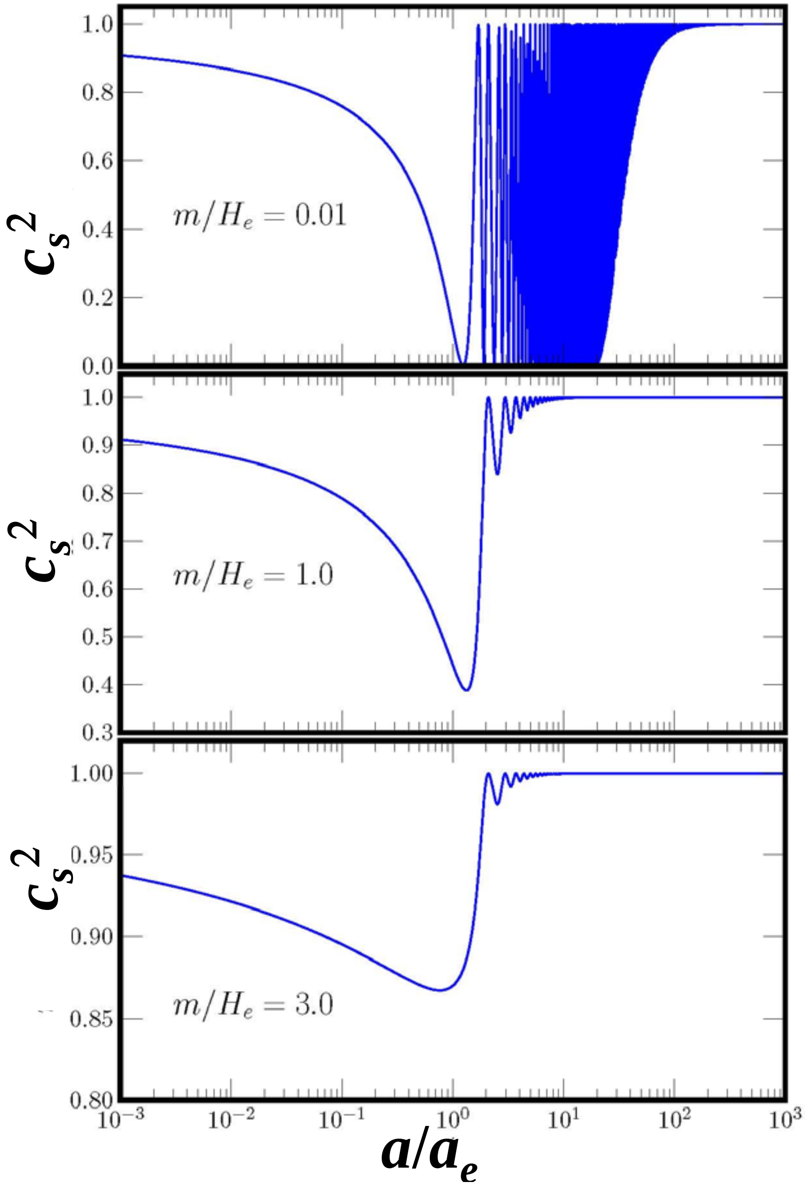
- Dispersion relation for helicity $1/2$ is $\omega_k^2 = (C_A^2 + C_B^2)\,k^2 + a^2m^2$

- C_A & C_B complicated functions of H, R, m, and $\partial_\eta m$ $\sqrt{C_A^2 + C_B^2}$ = sound speed

Spin 3/2: Ψ_μ

- $\omega_k^2 = c_s^2 k^2 + a^2 m^2$
- Sound speed (squared) is $$c_s^2 = \frac{1}{9}\left(H^2+m^2\right)^{-2}\left[\left(-\frac{1}{3}R - H^2 + 3m^2\right)^2 + 4\frac{\left(\partial_\eta m\right)^2}{a^2}\right]$$
- In terms of ρ & p: $$c_s^2 = \frac{\left(p-3m^2M_{\rm Pl}^2\right)^2}{\left(\rho+3m^2M_{\rm Pl}^2\right)^2} + \frac{4a^{-2}M_{\rm Pl}^4\left(\partial_\eta m\right)^2}{\left(\rho+3m^2M_{\rm Pl}^2\right)^2}$$
- First take $\partial_\eta m = 0$, pure R-S.
- Sound speed vanishes if $p = 3m^2 {M_{\rm Pl}}^2$
- After inflation, inflaton field (presumably) has damped oscillations about minimum of potential $\Longrightarrow$ damped oscillations of p & ρ
- If $\partial_\eta m = 0$, sound speed will vanish if $3m^2/{H_e}^2 \lesssim 0.5$, or $m/H_e \lesssim 0.41$





$$\omega_k^2 = (C_A^2 + C_B^2)\,k^2 + a^2 m^2$$

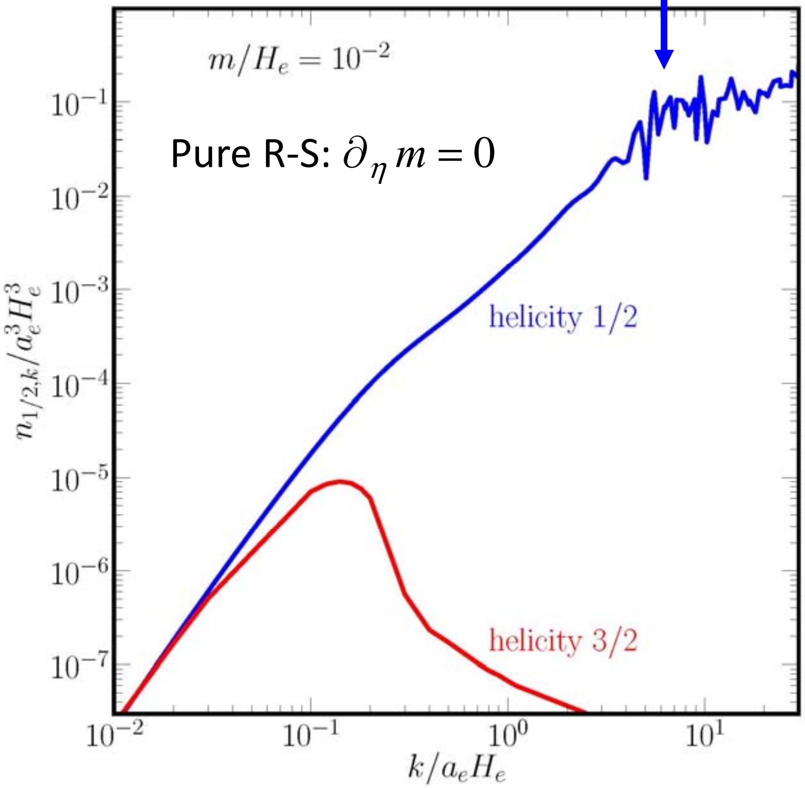
$$c_s^2 \equiv C_A^2 + C_A^2 = \frac{\left(p - 3m^2 M_{\rm Pl}^2\right)^2}{\left(\rho - 3m^2 M_{\rm Pl}^2\right)^2}$$

- ${c_s}^2 = 0 \rightarrow$ high-momentum modes are “free”
- H_e is expansion rate at end of inflation
  a_e is scale factor at end of inflation
- $m/H_e \lesssim 0.4$, sound speed vanishes
  (potentially many times)
- $m/H_e \gtrsim 0.4$, sound speed doesn’t vanish
  (but can still be less than unity)
- $m/H_e \gtrsim$ 10-ish, sound speed remains ≈ 1

${c_s}^2 \le 1$ in all cases

Number density $\propto \int d \ln k \; n_k$

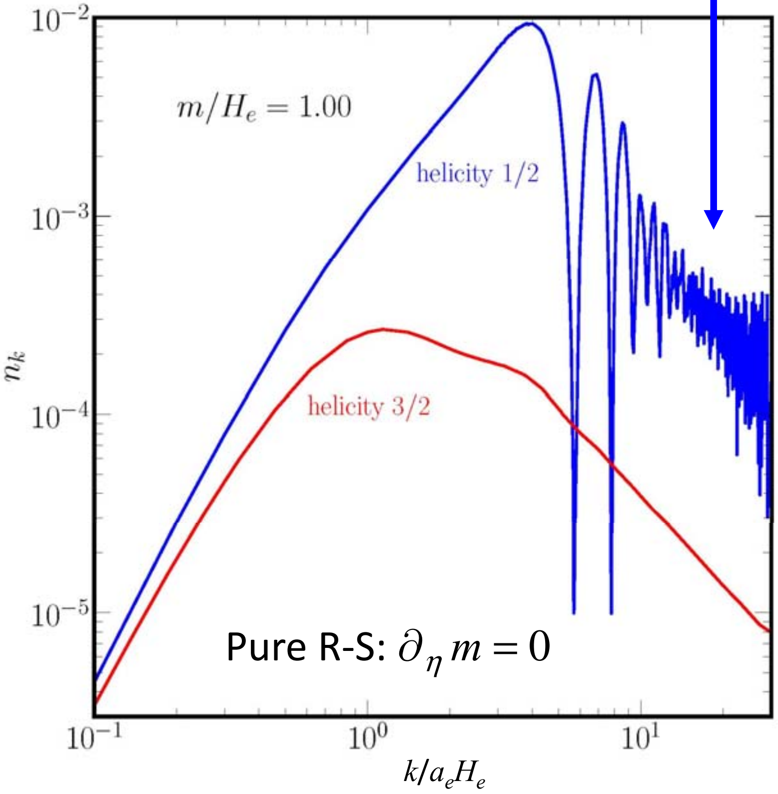
This is not noise!
(Basso & Chung 2108.01653)



Pure R-S: $\partial_\eta m = 0$

Runaway GPP of high-momentum modes

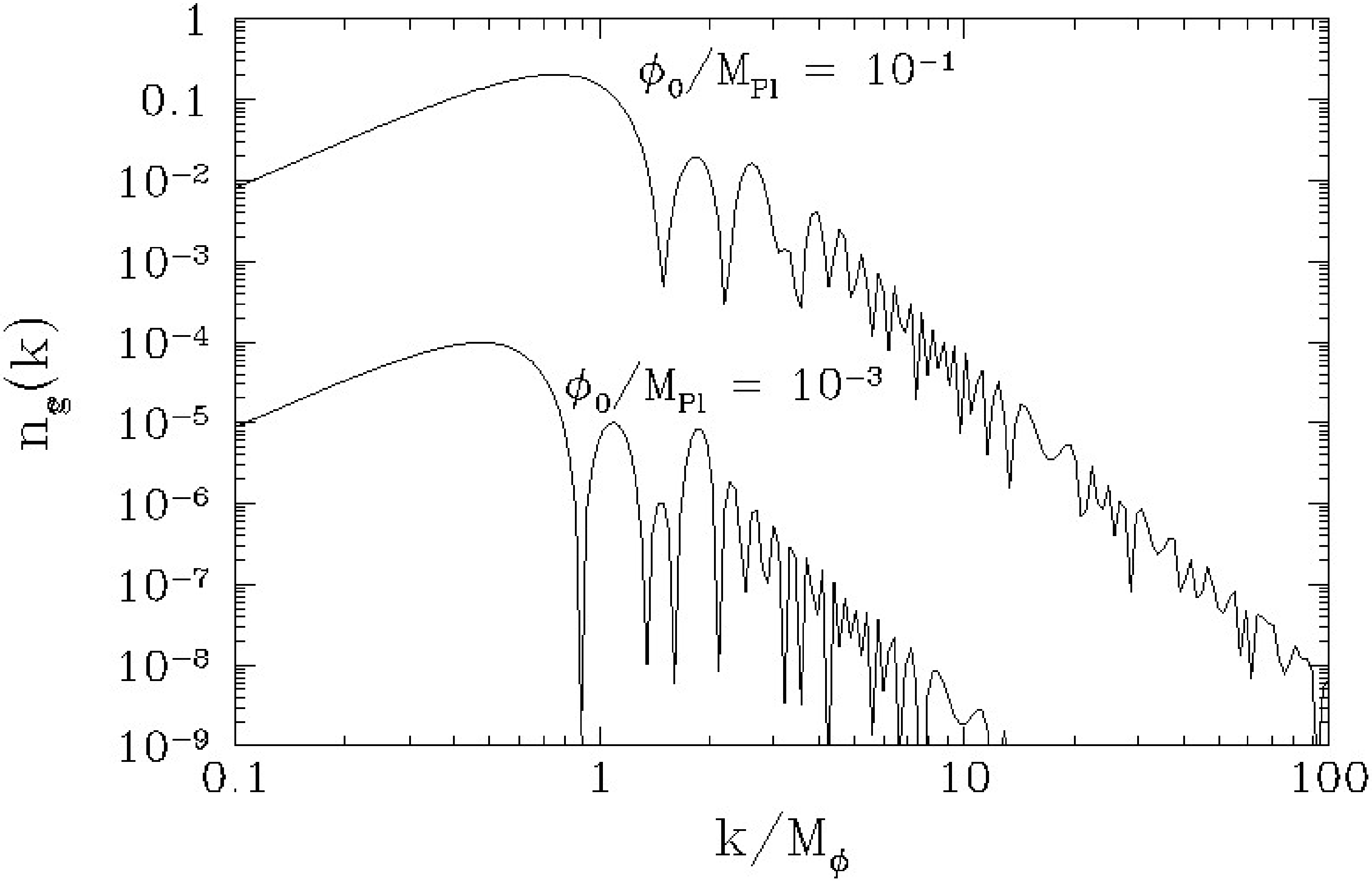
This is not noise!
(Basso & Chung 2108.01653)



Pure R-S: $\partial_\eta m = 0$

No Runaway GPP, but enhanced production

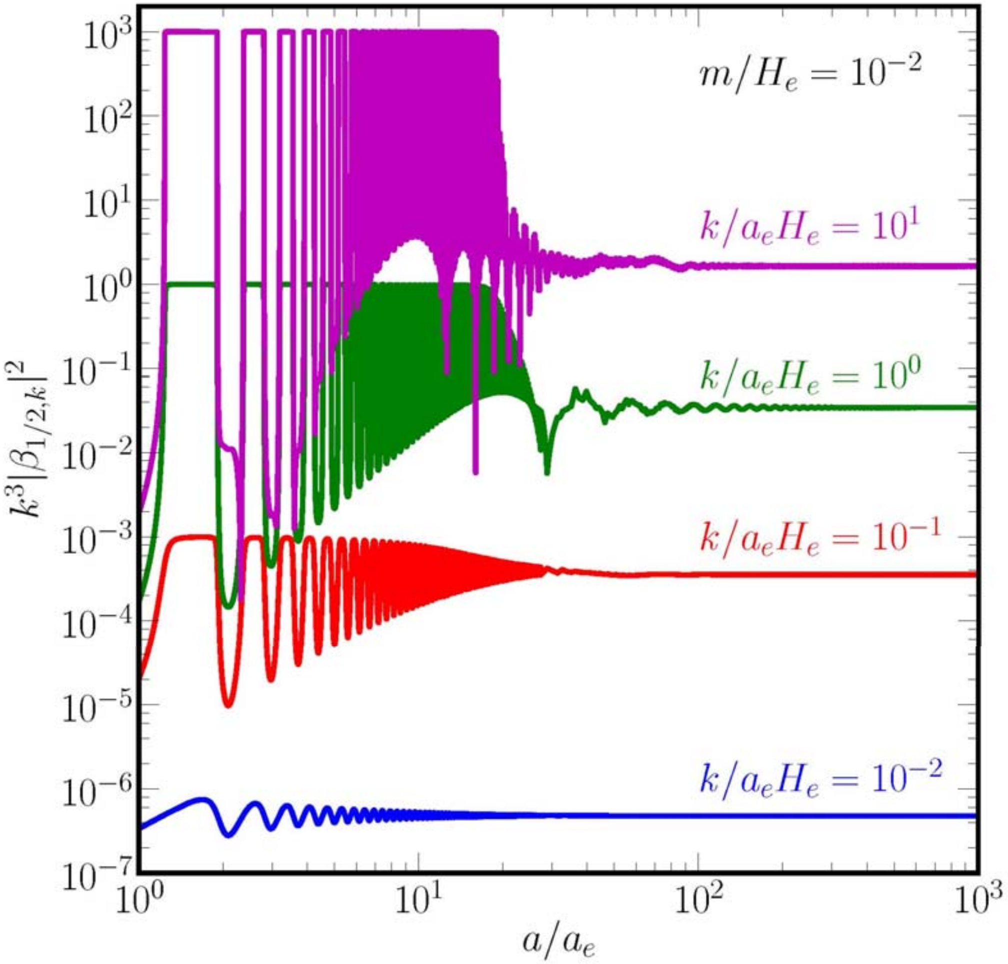
Thermal and nonthermal production of gravitinos in the early universe
Giudice, Riotto, Tkachev *JHEP* 11 (1999) 036

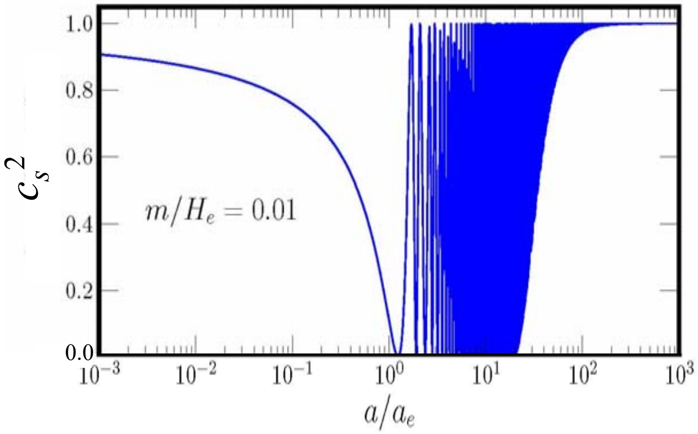


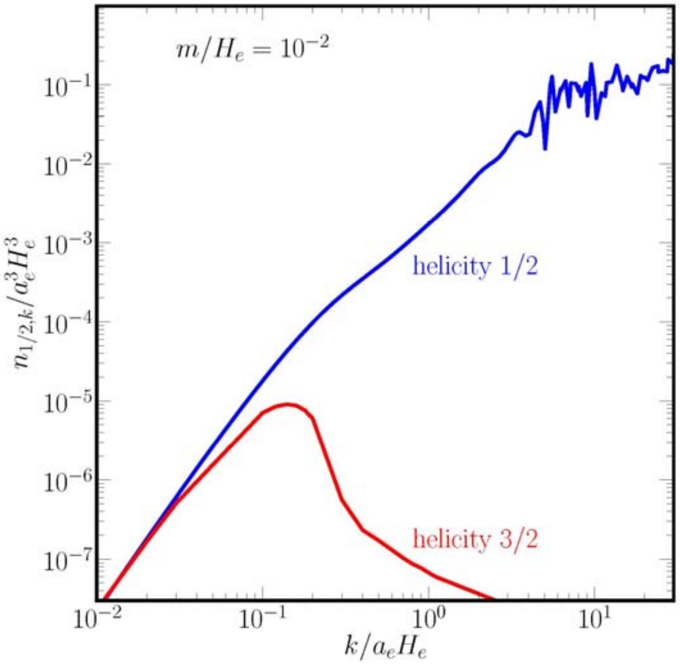
Vanishing sound speed and runaway production—pure RS

- Equation of motion: $\chi_k''(\eta)+\omega_k^2(\eta)\chi_k(\eta)=0$ $\qquad \omega_k^2(\eta)=c_s^2k^2+a^2(\eta)m^2$
- Adiabaticity parameter: $A_k=\dfrac{\partial_\eta\omega_k(\eta)}{\omega_k^2(\eta)}=\dfrac{a^3Hm^2+c_s(\partial_\eta c_s)k^2}{(c_s^2k^2+a^2m^2)^{3/2}}=\dfrac{H}{m}$ $\left(c_s\to 0 \text{ and } \partial_\eta c_s\to 0\right)$
- A_k independent of k if c_s (and $\partial_\eta c_s$) vanishes!!!
- If $m < H$, expect efficient particle production when c_s (and $\partial_\eta c_s$) vanishes!!!
- **Independent of *k*!**
- If sound speed vanishes, no energy cost to produce momentum modes of arbitrarily large k

$$k^3 \left|\beta_{1/2,k}\right|^2 \Big/ 2\pi^2 = n_{1/2,k} \Big/ a_e^3 \, H_e^3$$







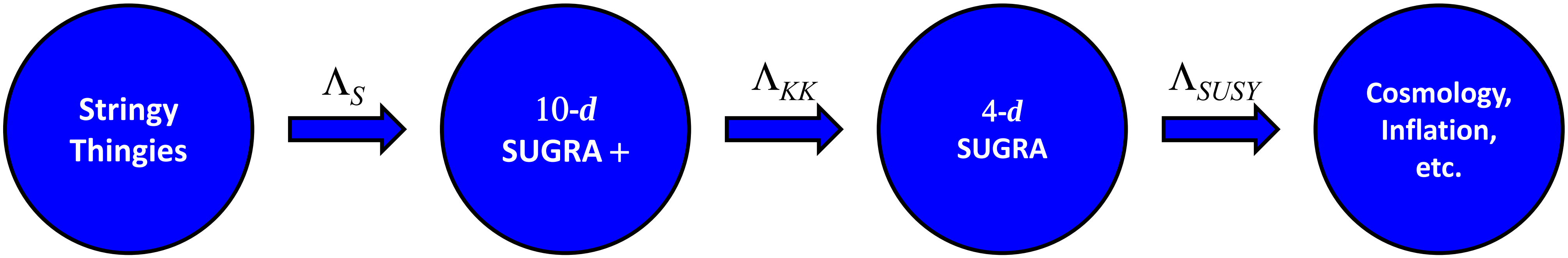
Vanishing sound speed and runaway production—pure RS

- Production of modes with arbitrarily high momentum
  $\longrightarrow$ produce infinite number density of particles if $m \lesssim H$, **unless**
- There is a cutoff and R-S is an EFT
  - There is an infinite tower of irrelevant operators important near the cutoff Λ

$$\mathcal{O}_n = c_n m_{3/2} \frac{\partial^n}{\Lambda^n} \left(\bar{\psi}^\mu \psi_\mu \right) \sim c_n \int d^3k \left(\frac{k}{\Lambda} \right)^n \bar{\psi}_k^\mu \psi_{\mu k}$$

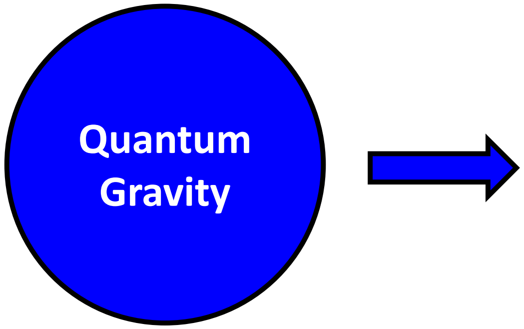
  - Breakdown of EFT for $k \sim \Lambda$
- So if $m \lesssim H$, must impose *ad hoc* UV cutoff on R-S model and RS model not consistent EFT
- But UV completion in hand: Supergravity (SUGRA) $\psi_\mu =$ gravitino
- Does SUGRA tame runaway production? **It depends!**
- Runaway production $\longrightarrow$ EFT in the swampland; No runaway production $\longrightarrow$ EFT in Landscape

Textbook $\mathcal{N}=1, D=4$ SUGRA



Stringy Thingies $\xrightarrow{\Lambda_S}$ 10-d SUGRA + $\xrightarrow{\Lambda_{KK}}$ 4-d SUGRA $\xrightarrow{\Lambda_{SUSY}}$ Cosmology, Inflation, etc.

- … are there 4-d SUGRA models In the swampland?



Quantum Gravity

Landscape

Swampland

Landscape: EFTs that are low-energy limits of Quantum Gravity.

Swampland: EFTs that are not.

Textbook $\mathcal{N} = 1$, $D = 4$ SUGRA*

- SUSY relates graviton e_μ^a and gravitino ψ_μ :
$$\delta_\xi \psi_\mu = D_\mu \xi \equiv \partial_\mu \xi + \tfrac{1}{4} \omega_{\mu ab} \gamma^{ab} \xi$$
$$\delta_\xi e_\mu^a = \tfrac{1}{2} \bar{\xi} \gamma^a \psi_\mu$$
- Chiral Superfields: $\mathbf{\Phi}^I$ contains { complex scalar Φ^I ; chiral fermion χ^I ; auxiliary field F^I }
- Antichiral Superfields: $\bar{\mathbf{\Phi}}^I$
- Action specified by Kähler potential $K = K(\Phi^I, \bar{\Phi}^I)$ and superpotential $W(\Phi^I)$
- Goldstino: $\upsilon = \sum_I (D_I W) \chi^I \qquad D_I = \partial/\partial\Phi^I + \partial K/\partial\Phi^I$
- In SUSY breaking background ($DW \neq 0$) gravitino eats goldstino
- Gravitino mass: $m_{3/2}(\Phi) = e^{K/2} |W|$ is generally time dependent

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* Everything I know about SUGRA I learned from *Supergravity* (Freedman and Van Proeyen) and Evan McDonough

Textbook $\mathcal{N}=1$, $D=4$ SUGRA

- Number of chiral superfields
- Superpotential W
- Kähler potential K

- In general, $\partial_\eta m_{3/2} \neq 0$
- In general, ρ and p depend on $m_{3/2}$
- Many models on the market

- SUGRA circa 1999, one chiral superfield (Giudice et al., Kallosh et al.)

$$K = \Phi\,\bar{\Phi} \qquad W = M_{\mathrm{Pl}} m_\phi \Phi$$

$$c_s^2 = \frac{\left(p - 3m_{3/2}^2 M_{\mathrm{Pl}}^2\right)^2}{\left(\rho + 3m_{3/2}^2 M_{\mathrm{Pl}}^2\right)^2} + \frac{4a^{-2} M_{\mathrm{Pl}}^4 \left(\partial_\eta m_{3/2}\right)^2}{\left(\rho + 3m_{3/2}^2 M_{\mathrm{Pl}}^2\right)^2} = 1$$

Seeming miraculous cancellation
<u>No runaway!</u>

Time dependence of $m_{3/2}$ compensates time-dependence of first “pressure” term and $\mathrm{c}_s{}^2 = 1$

- 21^{st}-century SUGRA, several superfields

  runaway or not depends on
    - number of superfields
    - other fields in EFT (and inflatino—Dudas’s talk)
    - $m_{3/2}/H_e$

- Hasegawa et al., first paper to notice runaway with two superfields. Introduced UV cutoff Λ.

Textbook $\mathcal{N} = 1$, $D = 4$ SUGRA

- Criteria for sound speed = 1

$$D_I W = \partial W \big/ \partial \Phi^I + M_{\rm Pl}^{-2}\, \partial K \big/ \partial \Phi^I \qquad c_s^2 = 1 - \frac{4 e^{K/M_{\rm Pl}^2}}{\left(\rho + 3 M_{\rm Pl}^2 m_{3/2}^2\right)^2}\left[\left|\sum\nolimits_I \dot{\Phi}^I D_I W\right|^2 - \left(\sum\nolimits_I \left|\dot{\Phi}^I\right|^2\right)\left(\sum\nolimits_J \left|D_J W\right|^2\right)\right]$$

- ${c_s}^2 = 1$ if square of sum = sum of squares (i.e., one superfield) …. or $m_{3/2} \gtrsim H_e$

- Otherwise gravitino "slow" (Benakli, Damé, Oz 1407.8321)

- Geometric view

$F^I \equiv \exp(K/2{\rm M_{Pl}}^2)\, D_I W$ direction in field space of SUSY breaking & $\dot{\Phi}^I$ field space trajectory

$$\vec{\dot{\Phi}} \cdot \vec{F} = \left|\vec{\dot{\Phi}}\right|\left|\vec{F}\right| \cos\theta$$

$$c_s^2 = 1 - \frac{4\left|\vec{\dot{\Phi}}\right|^2 \left|\vec{F}\right|^2}{\left(\left|\vec{\dot{\Phi}}\right|^2 + \left|\vec{F}\right|^2\right)^2}\left(1 - \cos^2\theta\right)$$

Field space trajectory $\perp$ SUSY breaking → cos $\theta = 0$

and $\left|\vec{\dot{\Phi}}\right| = \left|\vec{F}\right|$ sound speed vanishes

SUGRA Models with a Lonely Gravitino

- Lonely gravitino: gravitino is only particle with mass below cutoff of 4-d SUGRA
  Integrate out other particles, e.g., inflatino, irrelevant operators ….

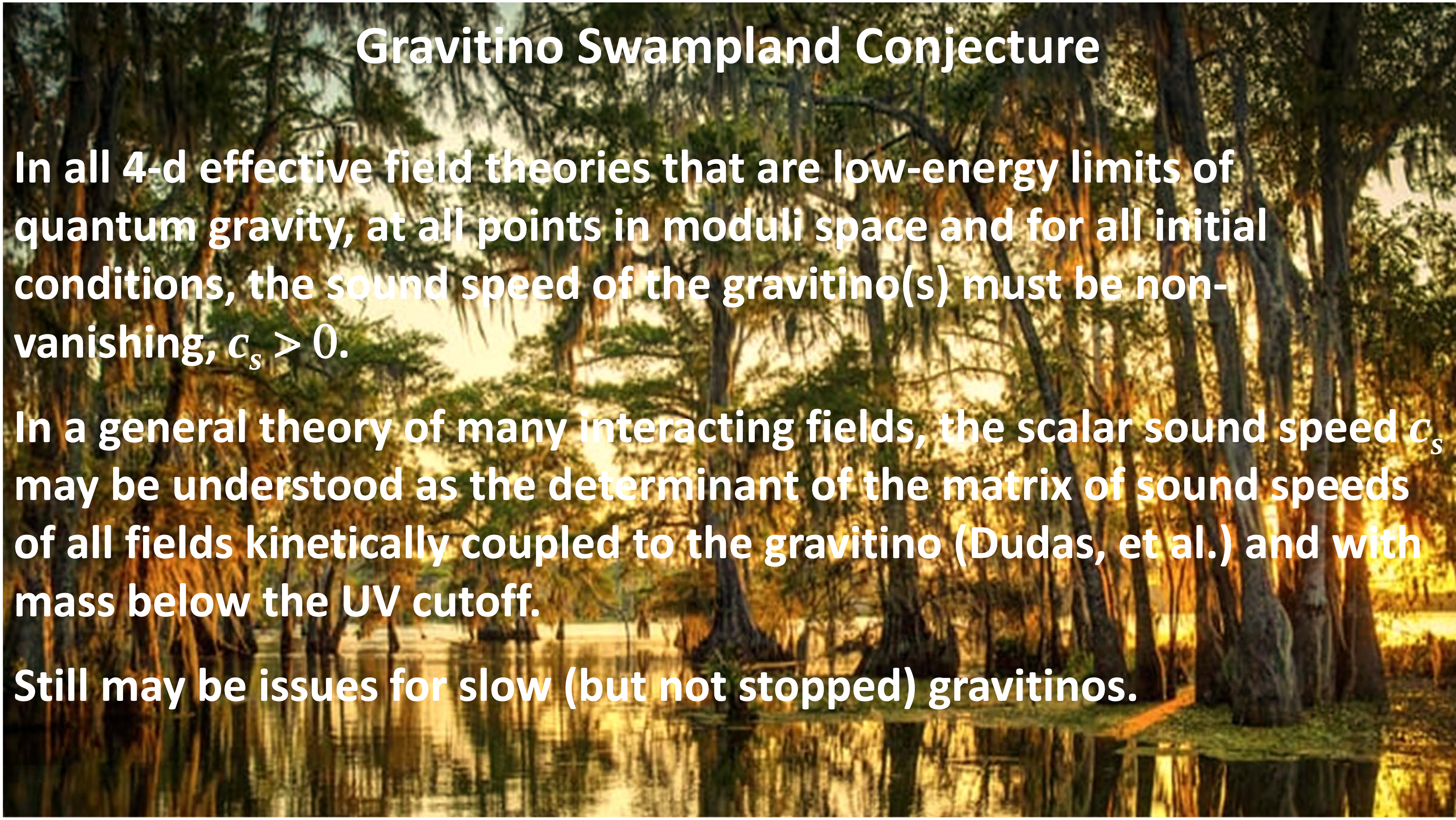
- Look at some popular (at least to the people proposing them) SUGRA models

Nilpotent superfield models $\boldsymbol{S}^{2} = 0$ (EFT of KKLT, α attractors for inflation Kallosh & Linde)

inflatino mass at end of inflation $3m_{3/2}\,\alpha\,\mathrm{M}_{\mathrm{Pl}}{}^{2}/2\mathrm{v}^{2}$ heavy and usually integrated out if $\left|\vec{F}\right| \leq H_e M_{\mathrm{Pl}}$, c_s^2 will vanish if $m \lesssim H_e$.

Orthogonal constrained nilpotent superfield models $\boldsymbol{S} \cdot \boldsymbol{(\Phi - \Phi)} = 0$

depending on parameters of model, $c_s{}^2$ can vanish.



Gravitino Swampland Conjecture

In all 4-d effective field theories that are low-energy limits of quantum gravity, at all points in moduli space and for all initial conditions, the sound speed of the gravitino(s) must be non-vanishing, $c_s > 0$.

In a general theory of many interacting fields, the scalar sound speed c_s may be understood as the determinant of the matrix of sound speeds of all fields kinetically coupled to the gravitino (Dudas, et al.) and with mass below the UV cutoff.

Still may be issues for slow (but not stopped) gravitinos.

Implications: Theory/Model Building

Rarita-Schwinger fields must have $m \gtrsim H_e$

SUGRA EFTs with lonely, constant-mass gravitino must have $m \gtrsim H_e$

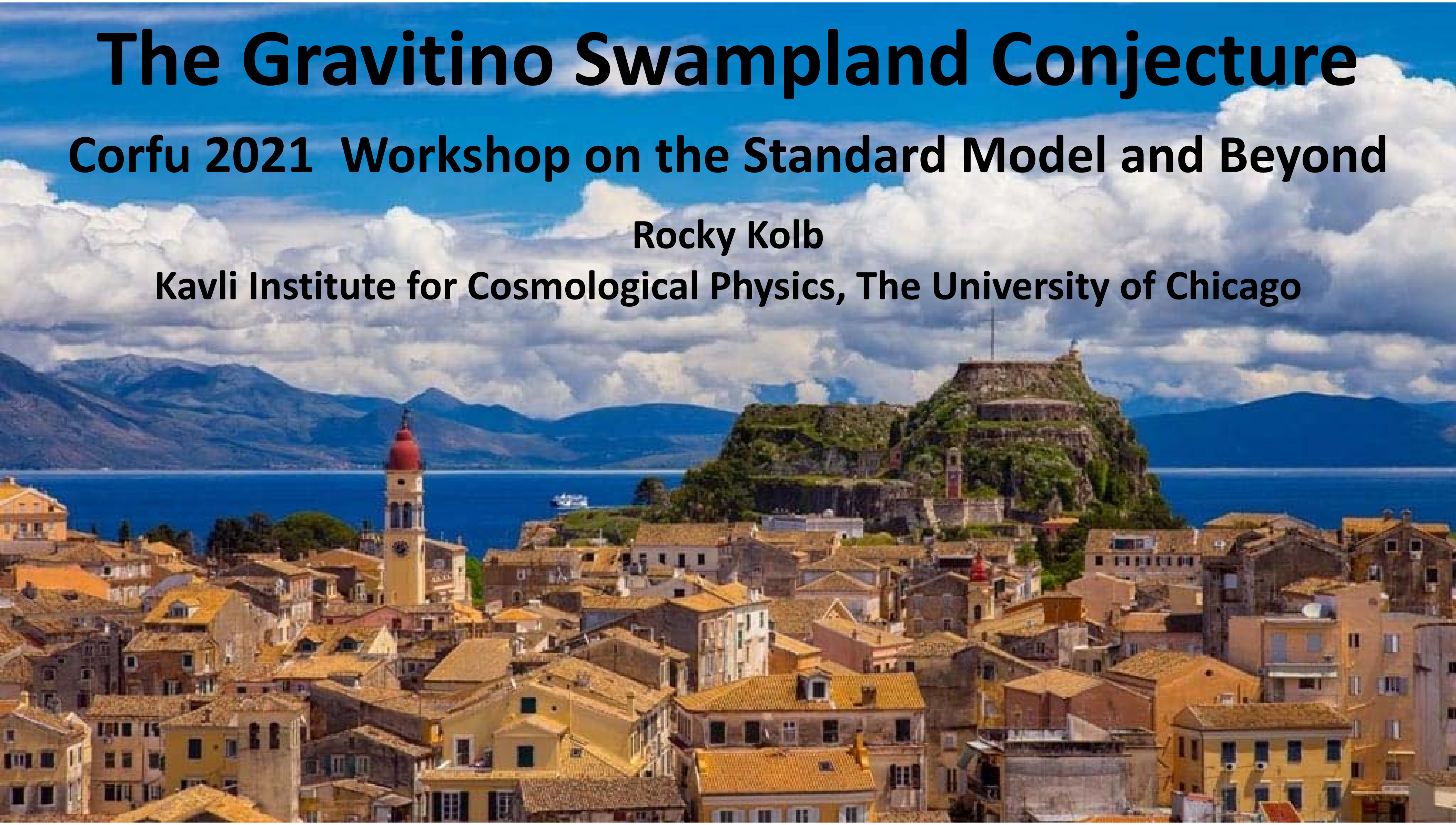
Implications: Observations/Experiments

(Assume lonely, constant-mass gravitino, conventional thermal history)

$$m \gtrsim H_e \rightarrow$$

1. If a gravitino is observed at terrestrial particle collider ($m \lesssim \mathrm{TeV}$), then cosmological experiments will never observe B-mode polarization of the CMB generated by gravitational waves.

2. If B-mode polarization from primordial gravitational waves is observed, then collider experiments will never see a gravitino.



The Gravitino Swampland Conjecture

Corfu 2021 Workshop on the Standard Model and Beyond

Rocky Kolb
Kavli Institute for Cosmological Physics, The University of Chicago

Work presented here based on

Catastrophic Production of Slow Gravitinos
arXiv:2102.10113 Phys. Rev. D, to appear

With more on the way!

The Gravitino Swampland Conjecture
arxiv :2103.10437 Phys. Rev. Lett., to appear

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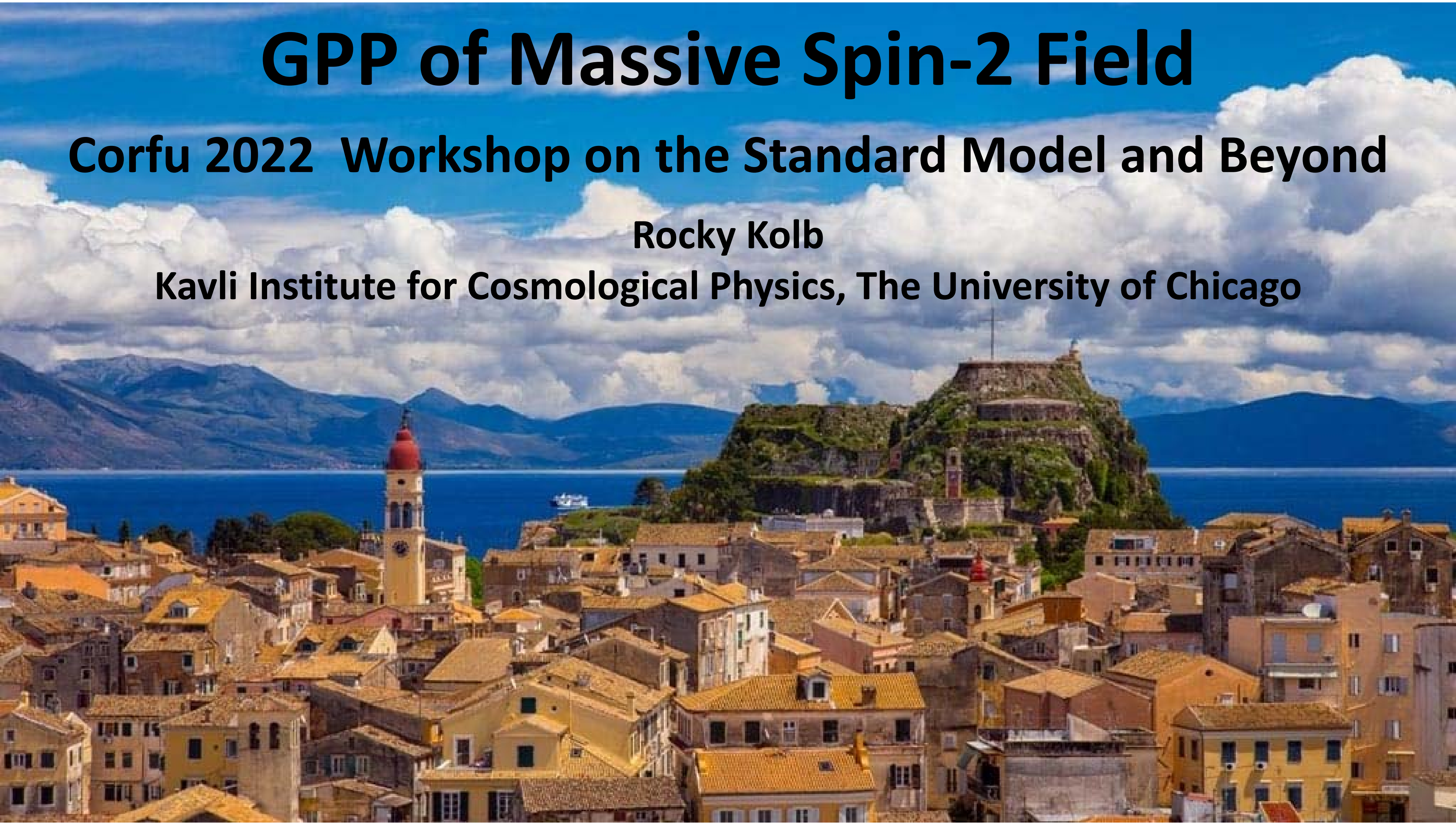

GPP of Massive Spin-2 Field

Corfu 2022 Workshop on the Standard Model and Beyond

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