Theory and Phenomenology of Continuous Spin Particles

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Particle Physics Then and Now

Testing the Standard Model
- Electroweak
- QCD
- etc.

Beyond the Standard Model
- Technicolor
- Supersymmetry
- Grand Unification
- etc.

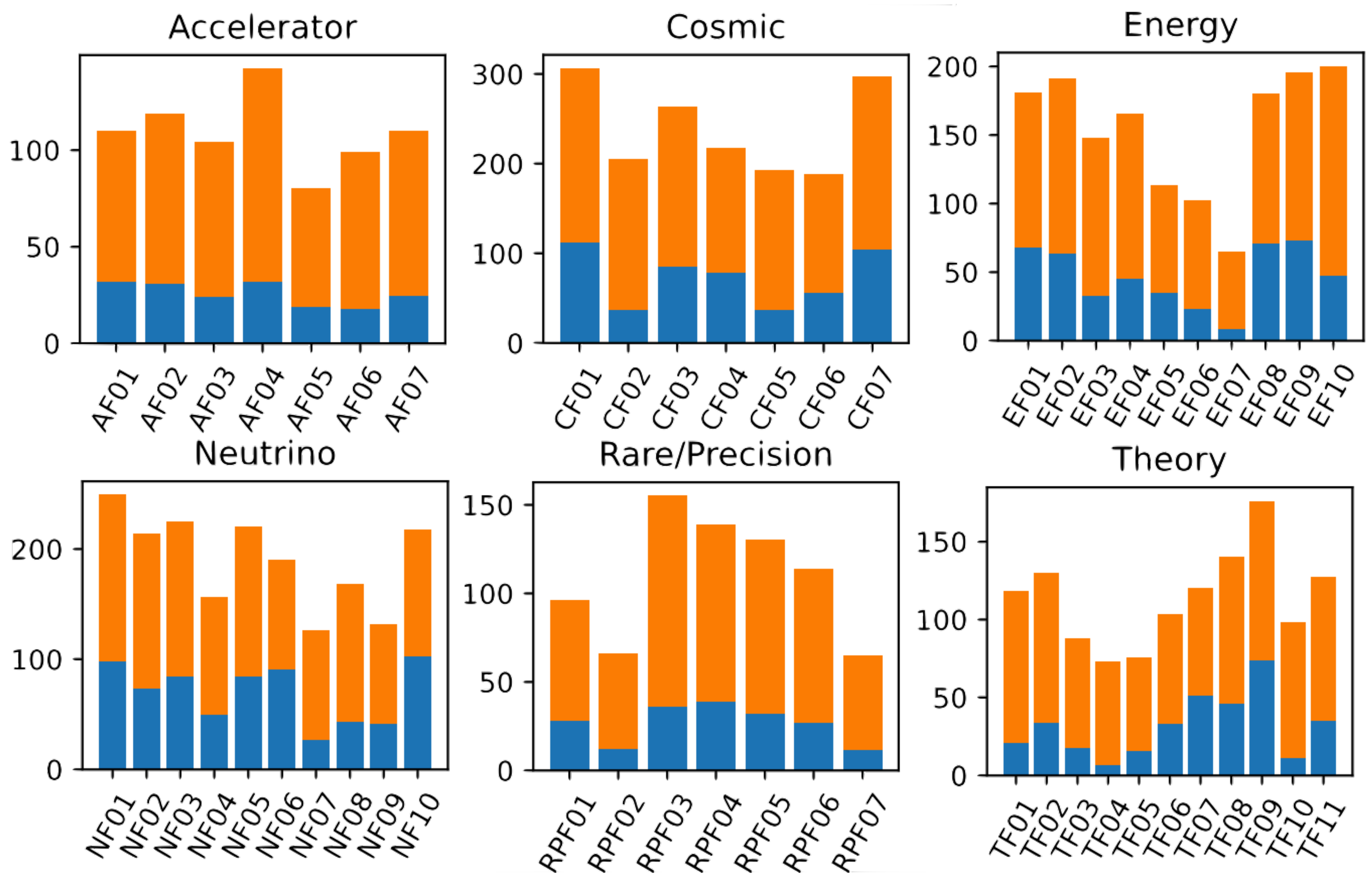
Limits of Accelerator Technology and Novel Accelerator Ideas

Novel Detector Ideas

Snowmass 1982 Summary

DISCOVERY	COMMENTS	ODDS*
Standard Model Higgs	As good as discovered, some say	2–1
Big surprises	Expect the unexpected	2–1
Supersymmetry	Too beautiful to be wrong?	5–1

2007 Fermilab survey



Snowmass 2021 Interest Survey (2203.07328)

Particle Physics Then and Now

How does a young scientist choose what to work on?

Testing the Standard Model Electroweak QCD etc.
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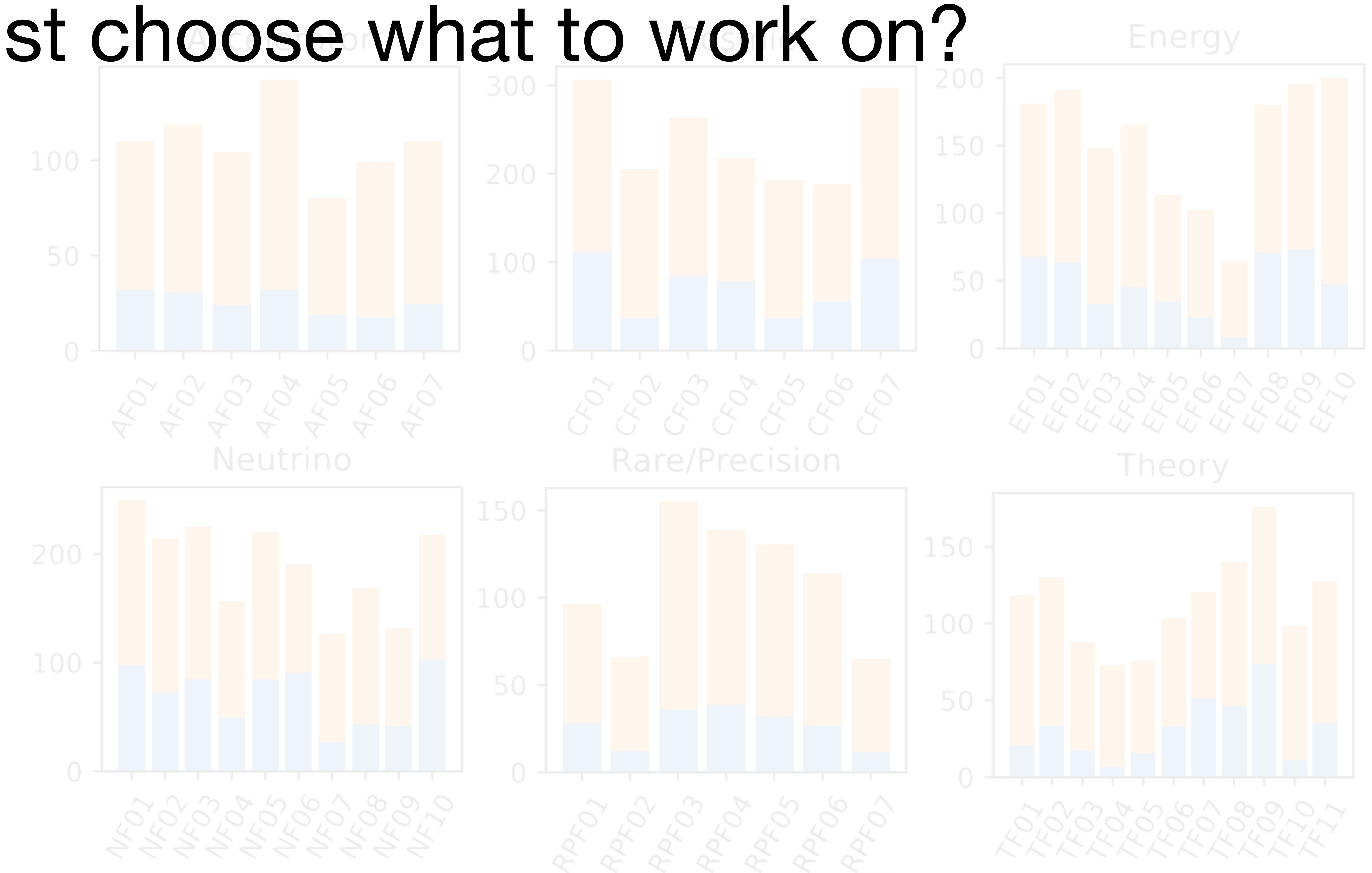

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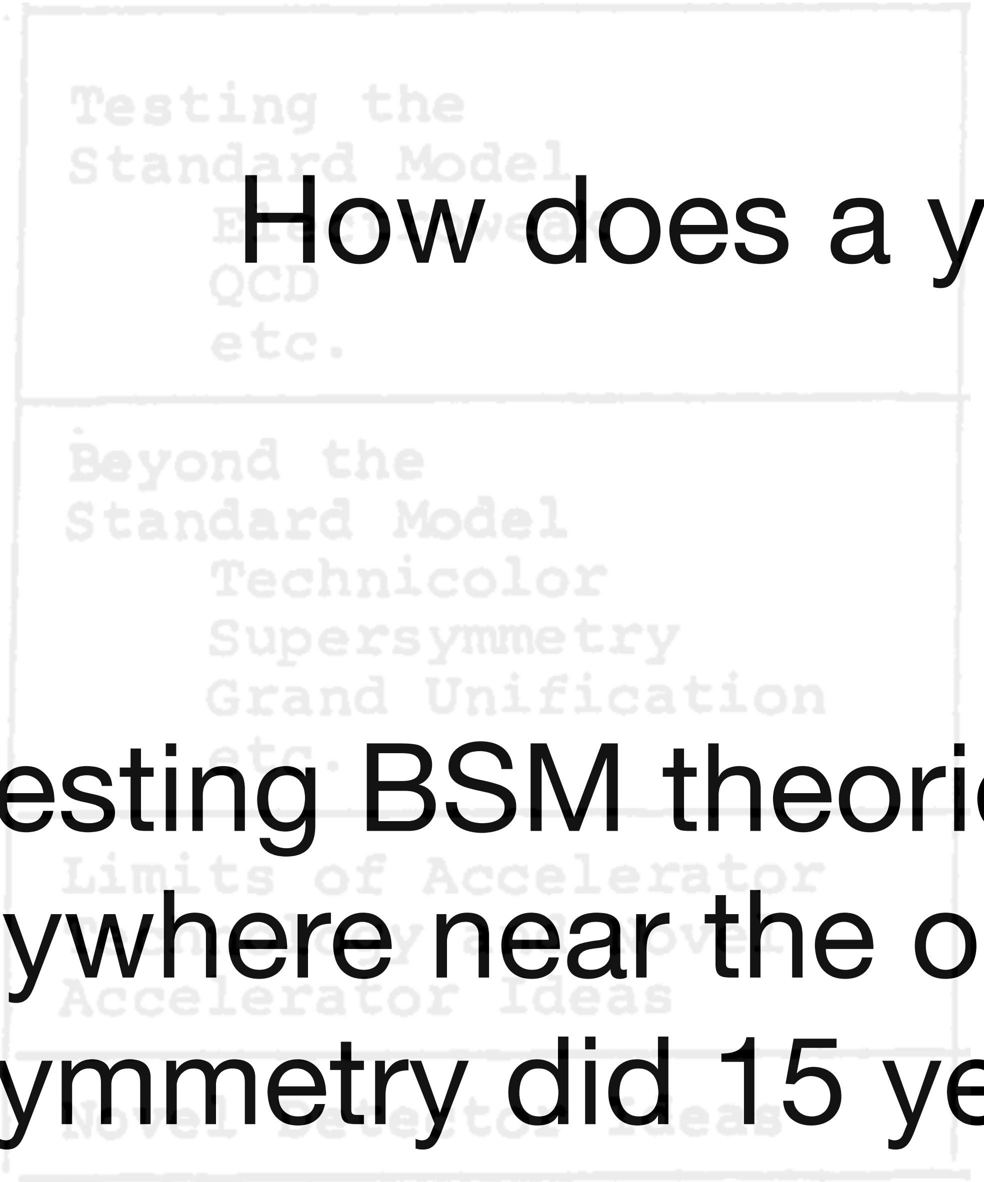
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Many interesting BSM theories, but none has anywhere near the odds that supersymmetry did 15 years ago!

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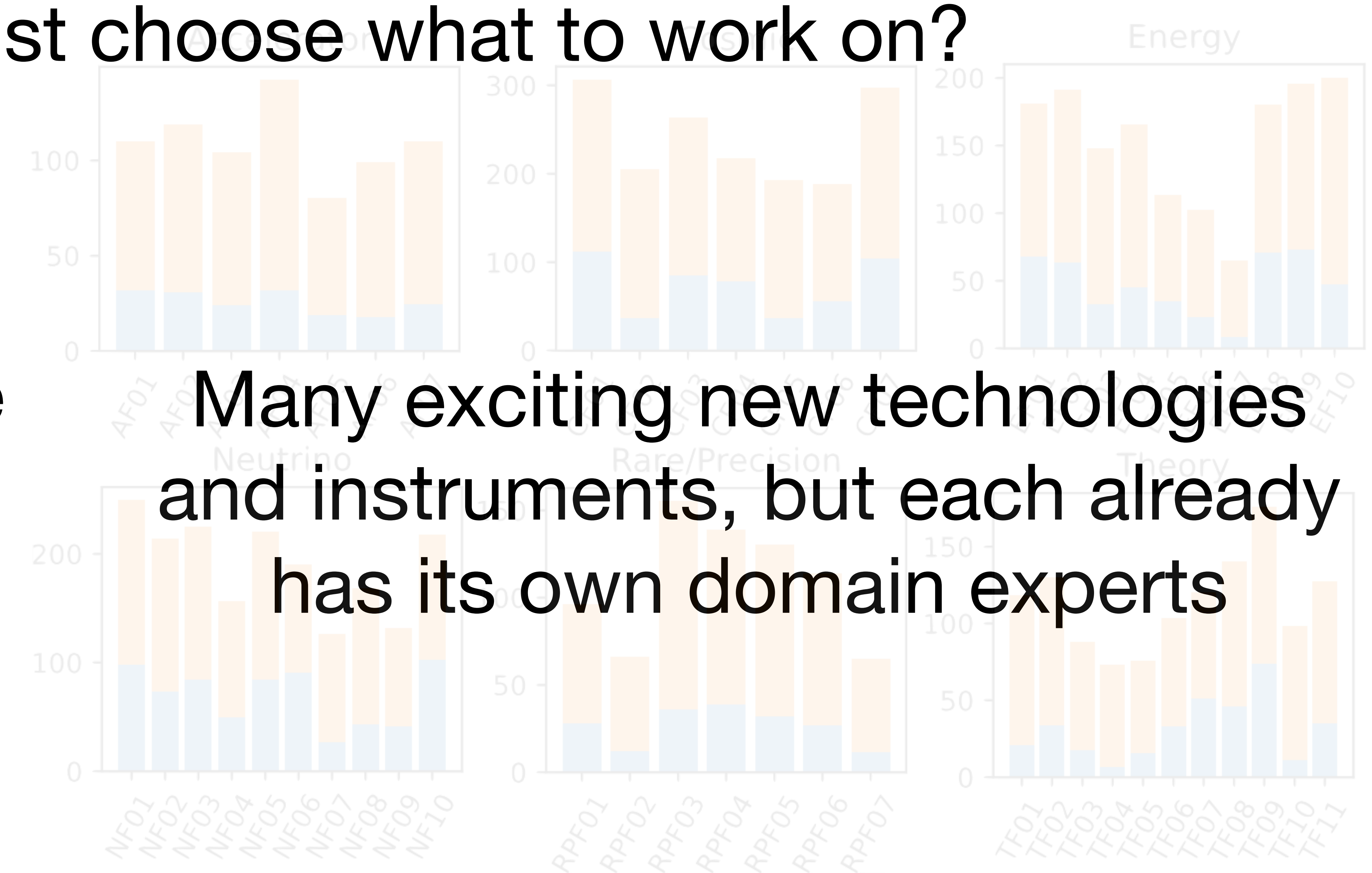

Many exciting new technologies and instruments, but each already has its own domain experts

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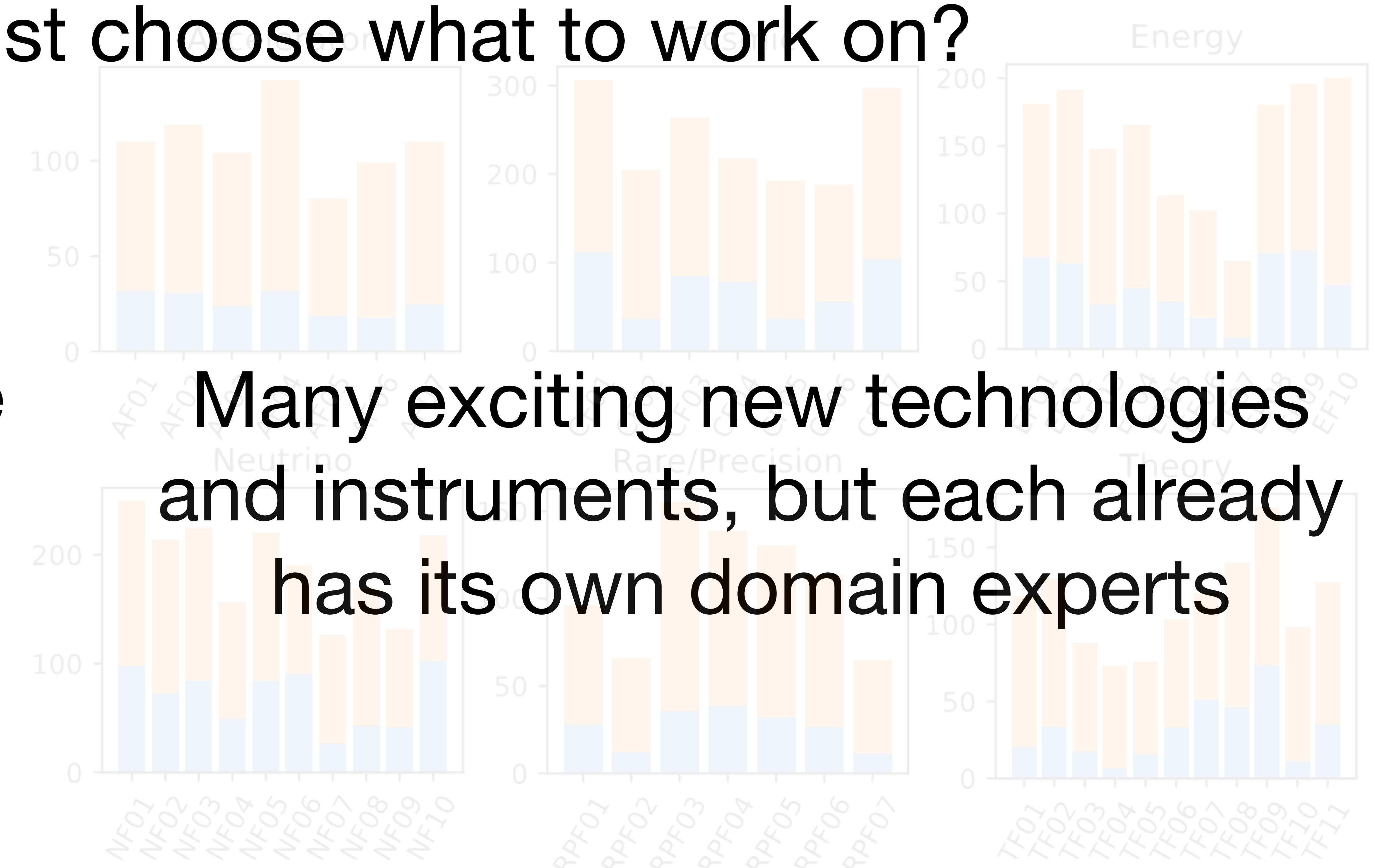
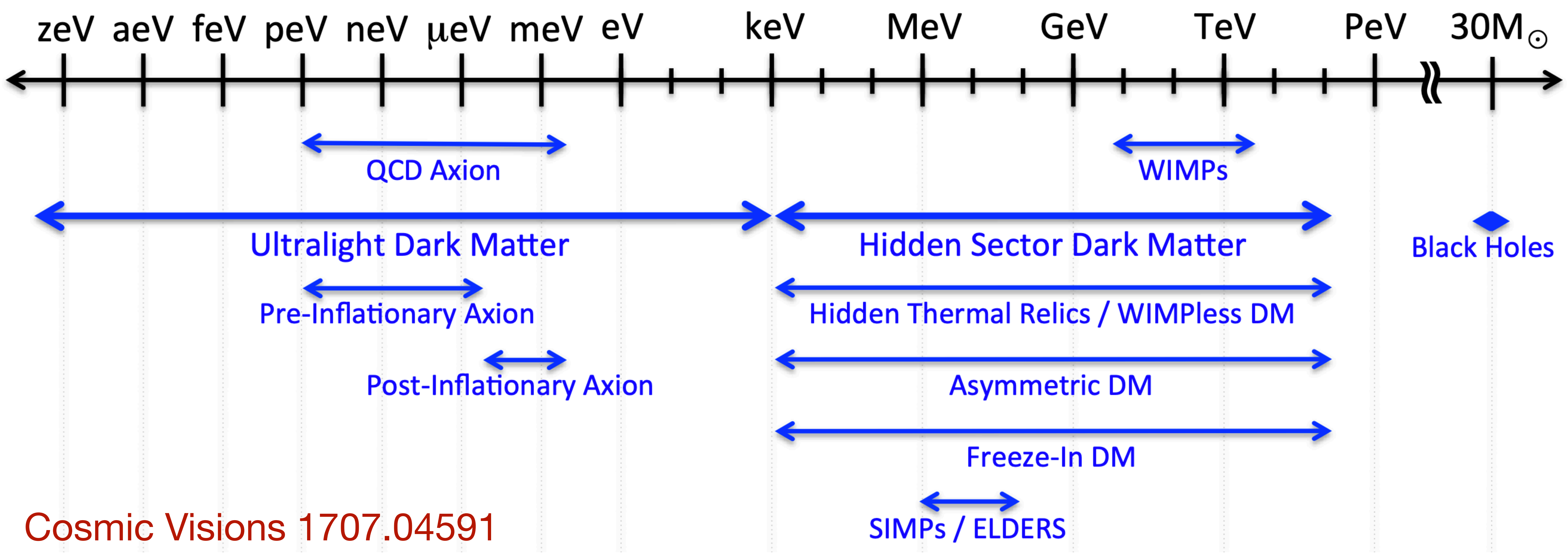


Another path: linking theories and the technologies that can test them, across fields

Physics is a big place — many exciting connections have not been made!

Case Study: Dark Matter



In current situation, we would like to both decisively test canonical models, and probe broadly into underexplored classes of models

New experimental programs can help do both!

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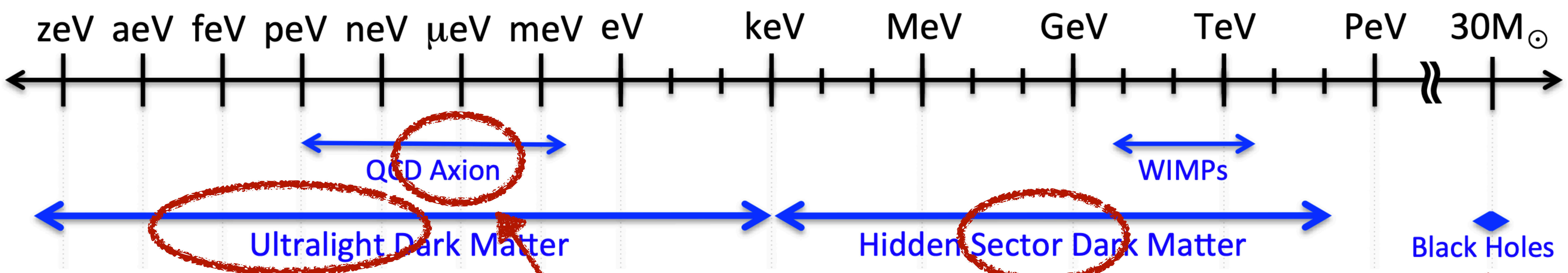
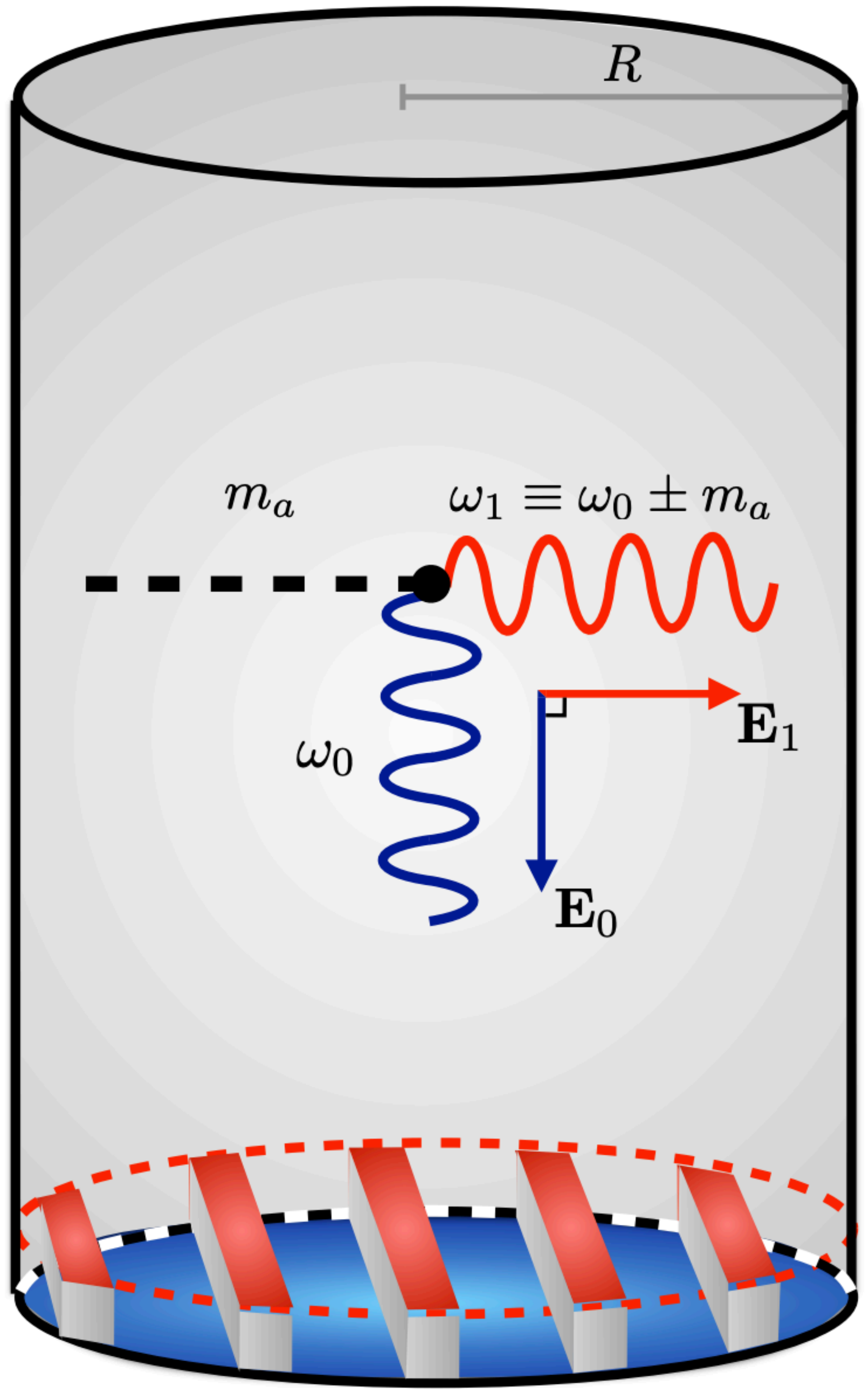
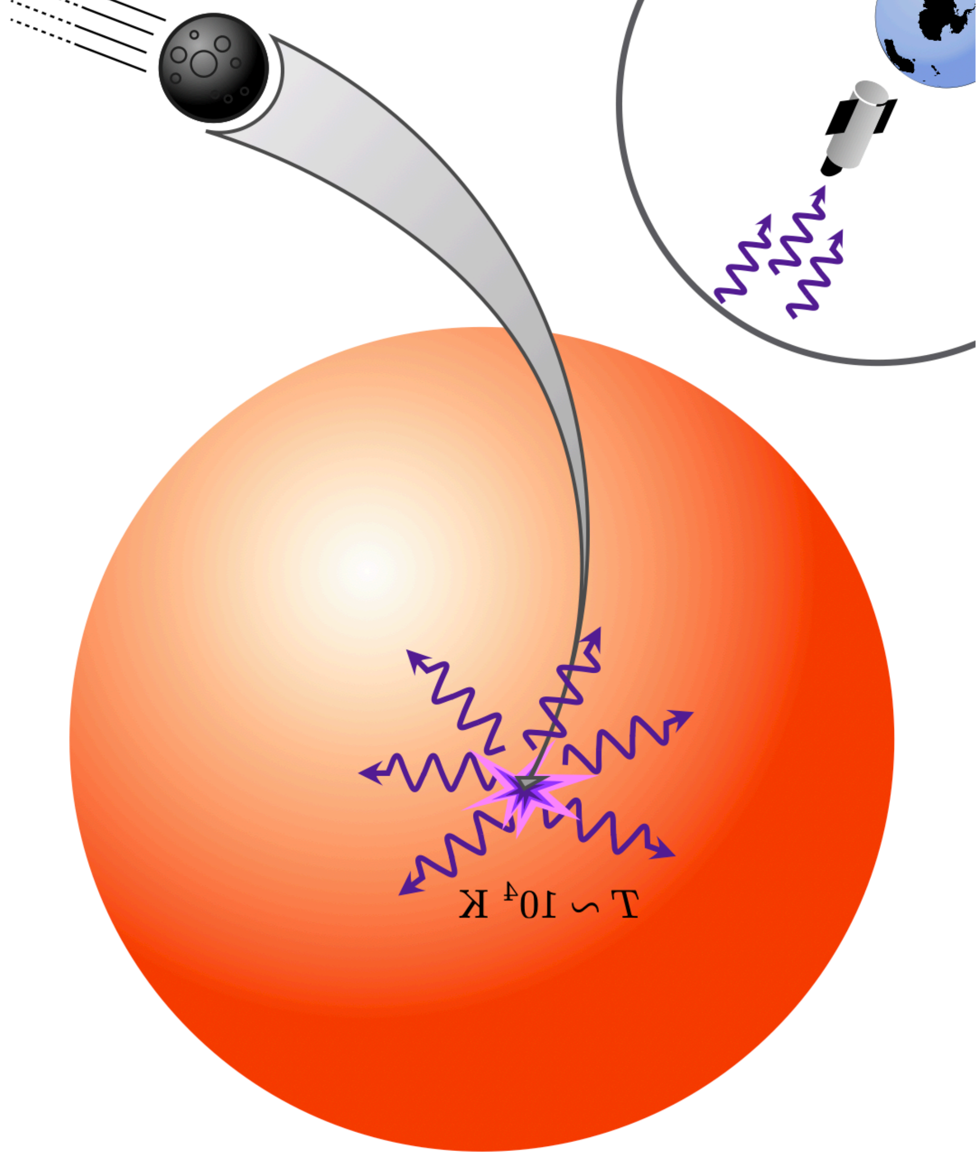




axion upconversion

1912.11048, 2007.15656

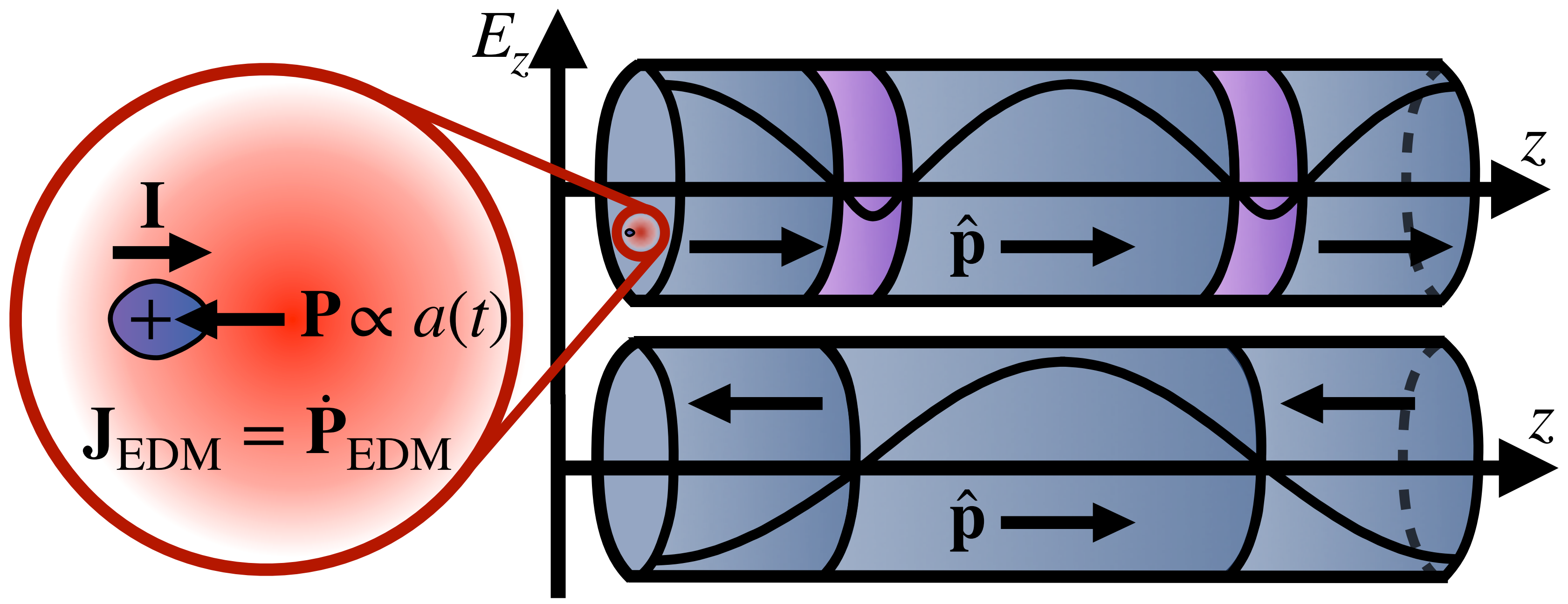


stellar shock transients

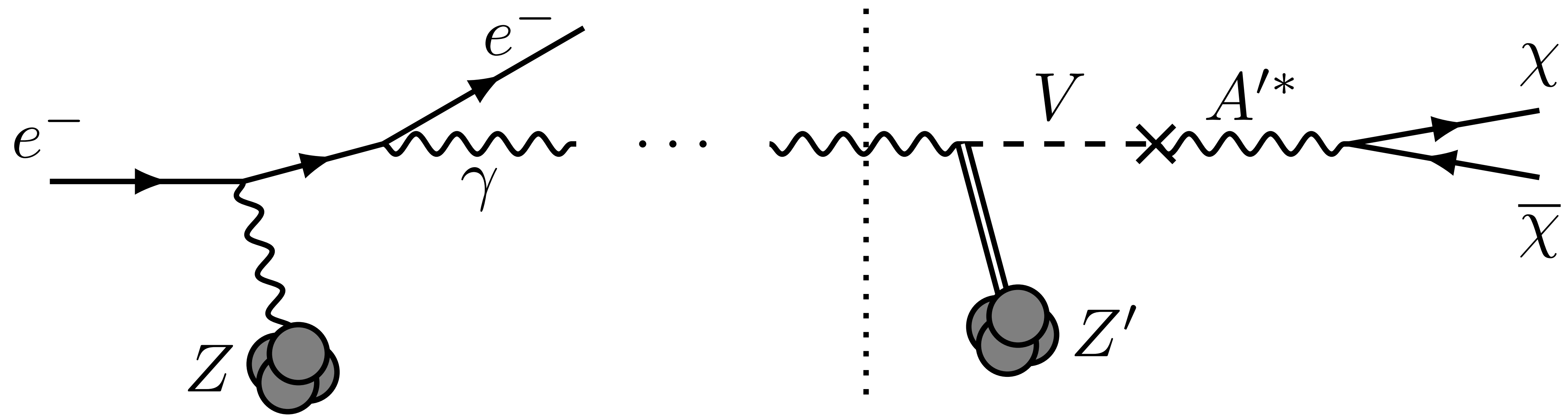
2106.09033

polarization haloscopes

invisible meson decays



2209.12901



2112.02104

Today’s talk is **not** about dark matter.
It’s about how to experimentally resolve a foundational open question in relativistic quantum field theory.

Same spirit of making new links between theory and experiment, but here the challenge was developing the formalism far enough to make predictions

Massless Particles

Quantum mechanics and special relativity strongly restrict the types of particles which can exist in our world

Wigner's classification (1939)

$p^\mu = 0$ vacuum expectation value

$p^2 < 0$ tachyon (instability)

$p^2 = 0$ massless particle

$p^2 > 0$ massive particle (m, J)

Massless Particles

Massless bosons mediate long-range forces, but are highly constrained

Weinberg's soft theorems (1965)

$p^2 = 0$ massless particle

$h = 0$ fine-tuned (not seen)

$|h| = 1$ couples to conserved charge (photon)

$|h| = 2$ couples to stress-energy (graviton)

$|h| > 2$ cannot interact (not seen)

Massless Particles

This is an elegant story: everything allowed by general principles plays a role

However, in the **generic** massless particle representation, historically called a “continuous spin particle” (CSP), helicity states mix under Lorentz transformations

$\dots$

$h = 2$

$h = 1$

$h = 0$

$h = -1$

$h = -2$

$\dots$

bosonic CSP

$\dots$

$h = 3/2$

$h = 1/2$

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fermionic CSP
(not covered here)

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<u>Why doesn't the CSP appear in textbooks?</u>

History, technical difficulty

<u>Why doesn't the CSP appear in nature?</u>

We **don't know** if it does!

Continuous Spin Particles

Previous work at Perimeter has shown CSP physics is potentially well-defined:

Weinberg soft theorems?

assume Lorentz invariant h

generalizes to well-behaved CSP soft factors

Schuster and Toro, JHEP (2013) 104

Incompatible with field theory?

Simple free field action found

Schuster and Toro, PRD (2015)

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No, for small enough ρ

(in prep)

Experimentally irrelevant?

Only three classes of CSP interactions, like scalars/gauge bosons/gravitons as $\rho \to 0$

Suggests known massless particles could be CSPs!

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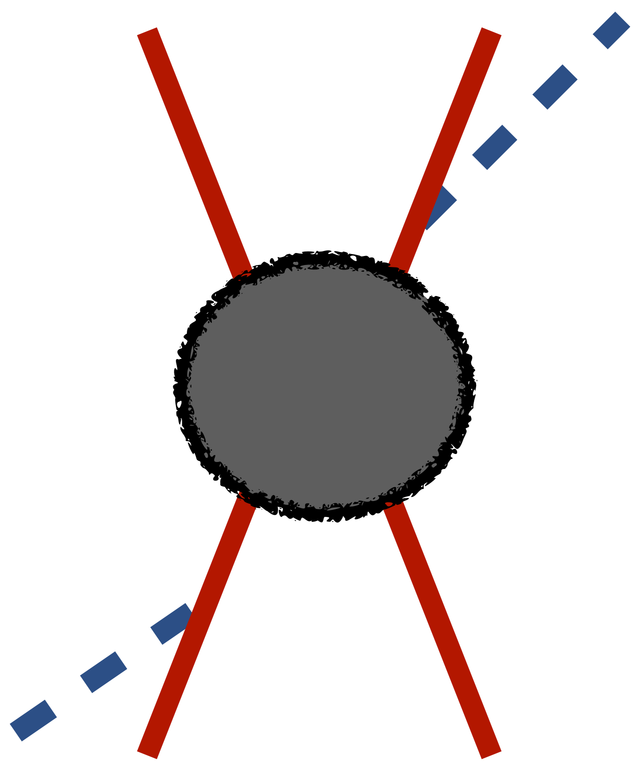
Strange and unfamiliar?

Absolutely!

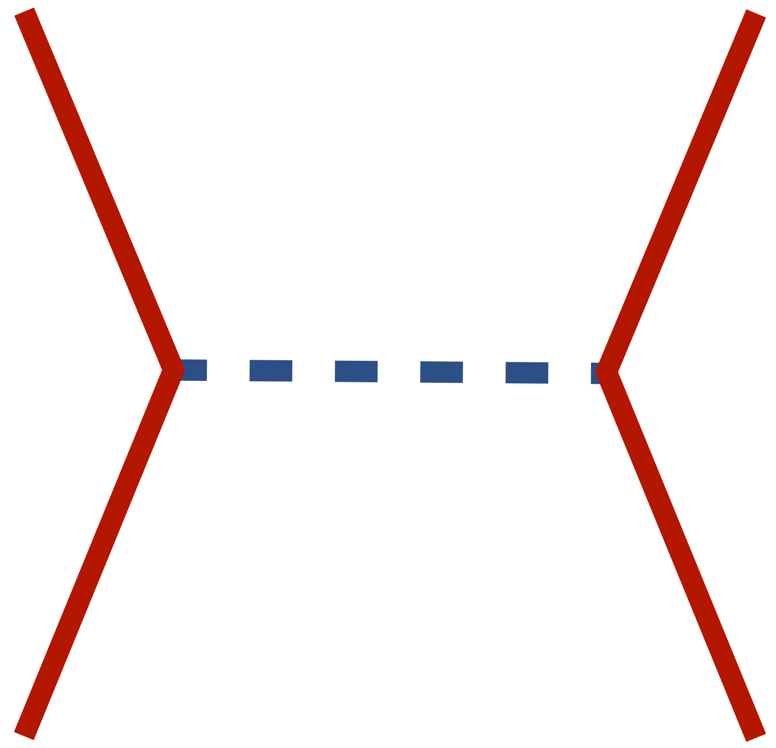
But CSPs are a theoretically motivated **infrared** deformation of familiar gauge theories, which may play a role in the resolution of long-standing puzzles

Continuous Spin Particles

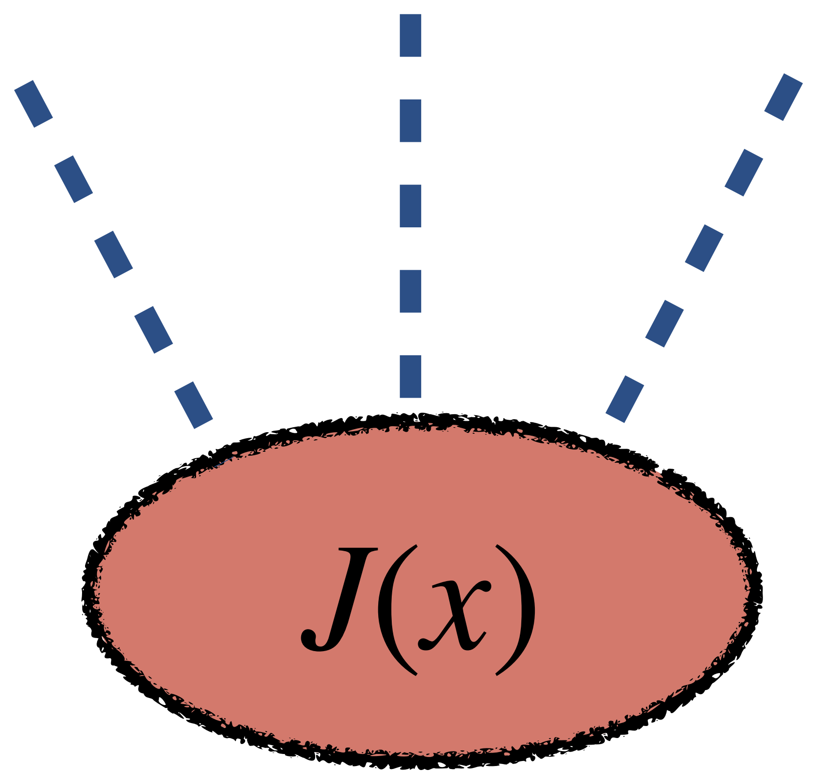
Until now, it has been unclear how to test if photons or gravitons are CSPs



Unique amplitudes for soft emission and absorption, but limited applicability



Consistent ansatzes for CSP exchange amplitudes, but not unique



Field theory can couple to current, but no dynamic sources of current known

Continuous Spin Particles

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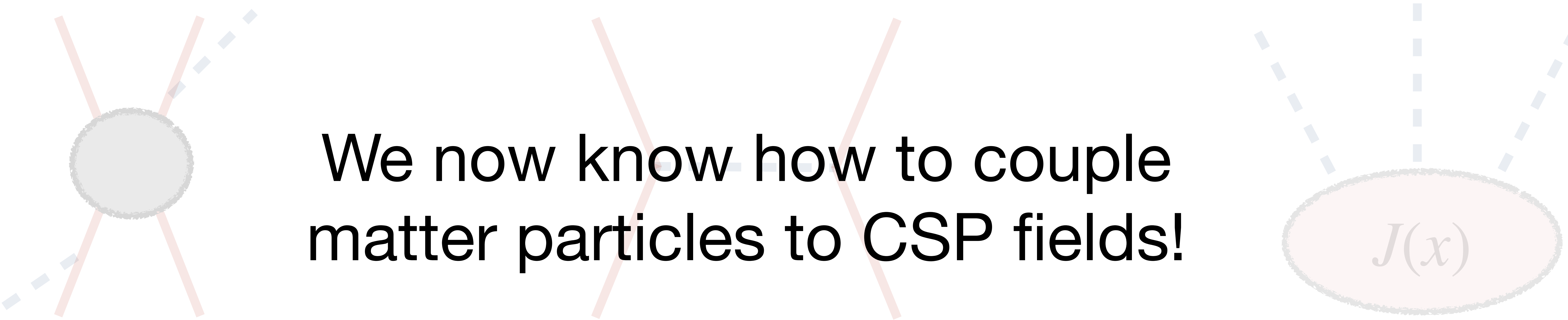
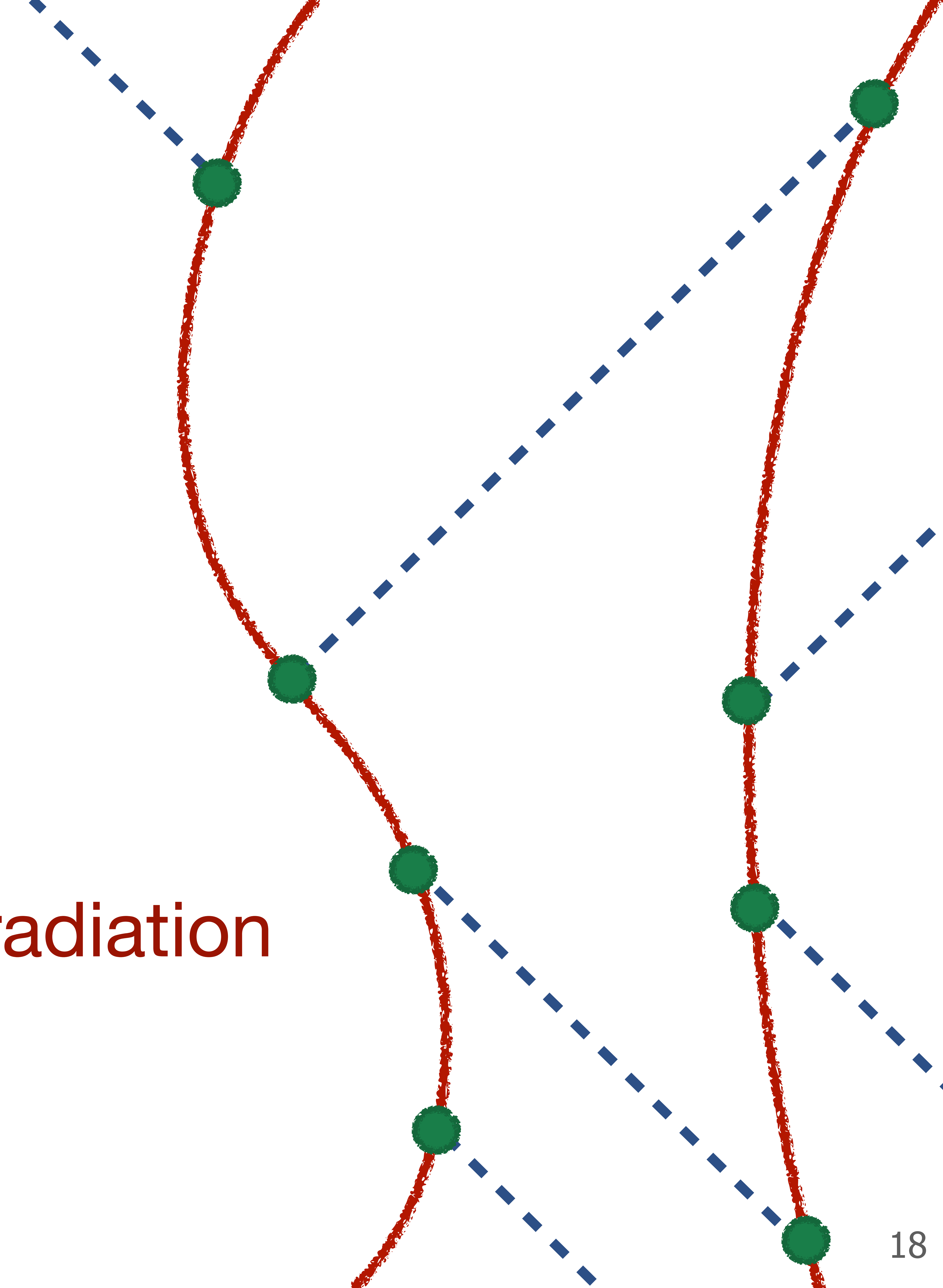


We now know how to couple matter particles to CSP fields!

Results for radiation emission or absorption are **unique**, leading to sharp predictions and specific tests

Outline

- **The free CSP field**
- Coupling matter particles to fields
- Emission and absorption of CSP radiation

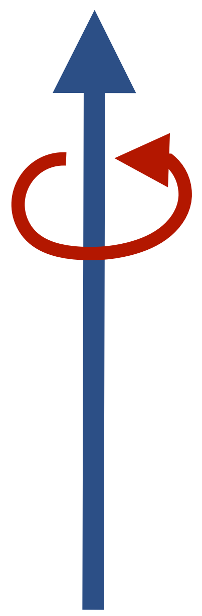


Massless Particles

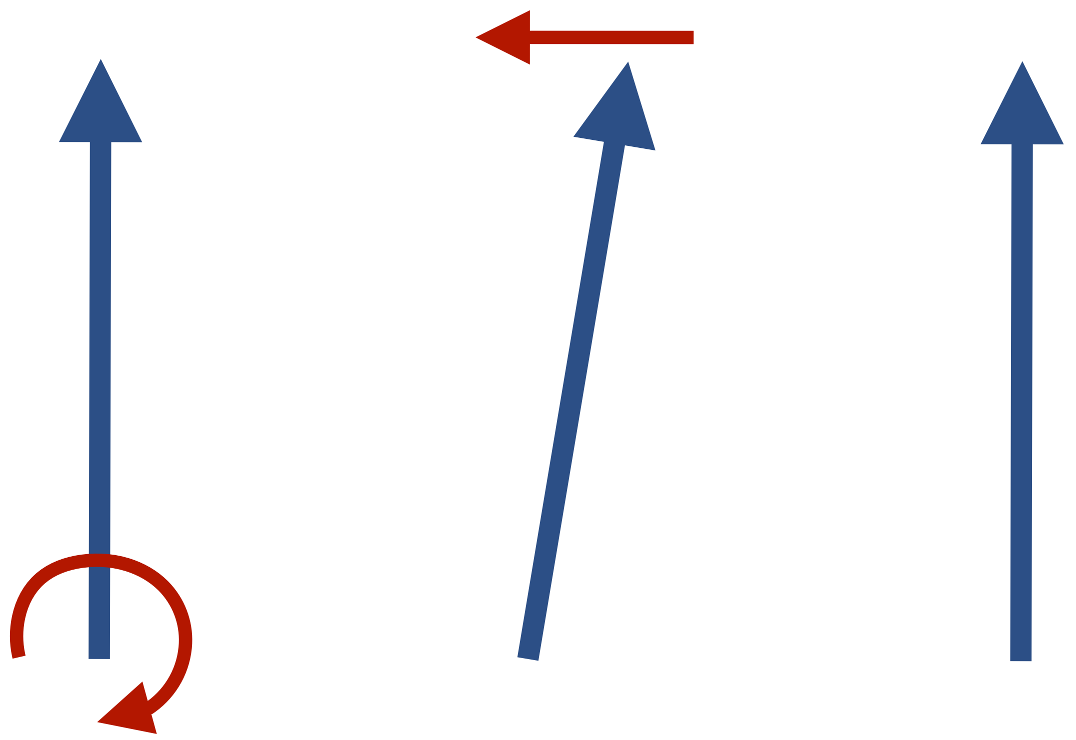
- Particles retain their identity when translated, boosted, or rotated (i.e. their state space is a representation of the Poincare group)

- A particle's internal degrees of freedom determined by action of Lorentz transformations that keep the particle momentum fixed (little group elements)

- For a massless particle, $k^\mu = (\omega, 0, 0, \omega)$, these are:



$$R = J_z$$



$$T_1 = J_x + K_y$$
$$T_2 = J_y - K_x$$
$$T_\pm = T_1 \pm iT_2$$

Massless Particles

- The eigenvalue of R is helicity, $R\,|\,h\rangle = h\,|\,h\rangle$, **always** integer or half-integer

- The $T_\pm$ operators must raise and lower helicity, $T_\pm\,|\,h\rangle = \rho\,|\,h \pm 1\rangle$

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    - Usual treatment assumes degenerate limit $\rho = 0$, only one helicity state
    - General case is CSP with spin scale ρ, all integer or half-integer helicities (focus on the integer case)

Actions for All Helicities

- Warm up: write a field that creates particles of any integer helicity, at $\rho = 0$
- For helicity h particles, simplest possible field is a rank h symmetric tensor
- Convenient way to package all h simultaneously uses auxiliary four-vector η^μ

$$\Psi(\eta, x) \sim \phi(x) + \eta^\mu A_\mu(x) + \eta^\mu \eta^\nu h_{\mu\nu}(x) + \dots$$

(with trace subtractions, normalizations)

- For $|h| \geq 1$, gauge symmetry required to get correct degrees of freedom

Actions for All Helicities

- The desired action turns out to be

$$S[\Psi] = \frac{1}{2}\int d^4x\,[d^4\eta]\,\left(\delta'(\eta^2+1)(\partial_x\Psi)^2 + \frac{1}{2}\,\delta(\eta^2+1)(\partial_x\cdot\partial_\eta\,\Psi)^2\right)$$

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- Integration over hyperboloid has geometric meaning, needs regularization:

$$\int [d^4\eta]\,\delta(\eta^2+1) = \int [d^4\eta]\,\delta'(\eta^2+1) \equiv 1$$

- Integrals of η-space functions just produce tensor contractions, e.g.

$$\int [d^4\eta]\,\delta(\eta^2+1)\,\eta^\mu\eta^\nu = -\frac{1}{4}g^{\mu\nu} \qquad \int [d^4\eta]\,\delta'(\eta^2+1)\,\eta^\mu\eta^\nu = -\frac{1}{2}g^{\mu\nu}$$

Actions for All Helicities

- To see how this works, consider the scalar component $\Psi(\eta, x) = \phi(x)$

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$$= \frac{1}{2}\int d^4x \, (\partial_x \phi)^2$$

- Trivially recovers massless scalar field action

Actions for All Helicities

- As another example, consider the vector component $\Psi(\eta, x) = \sqrt{2}\, \eta^\mu A_\mu(x)$

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$$= \int d^4x \left(-\frac{1}{2} (\partial_\mu A_\nu)^2 + \frac{1}{2} (\partial_\mu A^\mu)^2 \right) = -\frac{1}{4} \int d^4x\, F_{\mu\nu} F^{\mu\nu}$$

- Recovers massless vector field action; more generally, recovers linearized gravity at rank 2, and known Fronsdal action at general h, with appropriate gauge symmetries

Actions for All Helicities

- Dynamical content: plane wave radiation described by

$$\Psi_{\pm h,k} = e^{-ik\cdot x}\,(\eta \cdot \epsilon_{\pm})^{h}$$

  and annihilated by $T_{\pm}$ as expected

- Accounting for gauge redundancy, this is a complete basis for solutions

- Rank in η corresponds to helicity $|h|$, so one can easily go back to conventional tensor notation

The CSP Action

- The free CSP action is very similar:

$$S[\Psi] = \frac{1}{2} \int d^4x \, [d^4\eta] \, \left(\delta'(\eta^2 + 1)(\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1)((\partial_x \cdot \partial_\eta + \rho) \, \Psi)^2 \right)$$

Contains all helicities, has required gauge symmetries and right limit as $\rho \to 0$

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  Contains all helicities, has required gauge symmetries and right limit as $\rho \to 0$

- Harmonic gauge plane wave solutions indeed related by $T_\pm$, and take the form

$$\Psi_{\pm h,k} = e^{-ik\cdot x}\,e^{-i\rho\eta\cdot q}\,(\eta\cdot\epsilon_\pm)^h \qquad\qquad q\cdot k = 1$$

- No longer definite order in η! Tensor expansion not useful, η-space essential.

Outline

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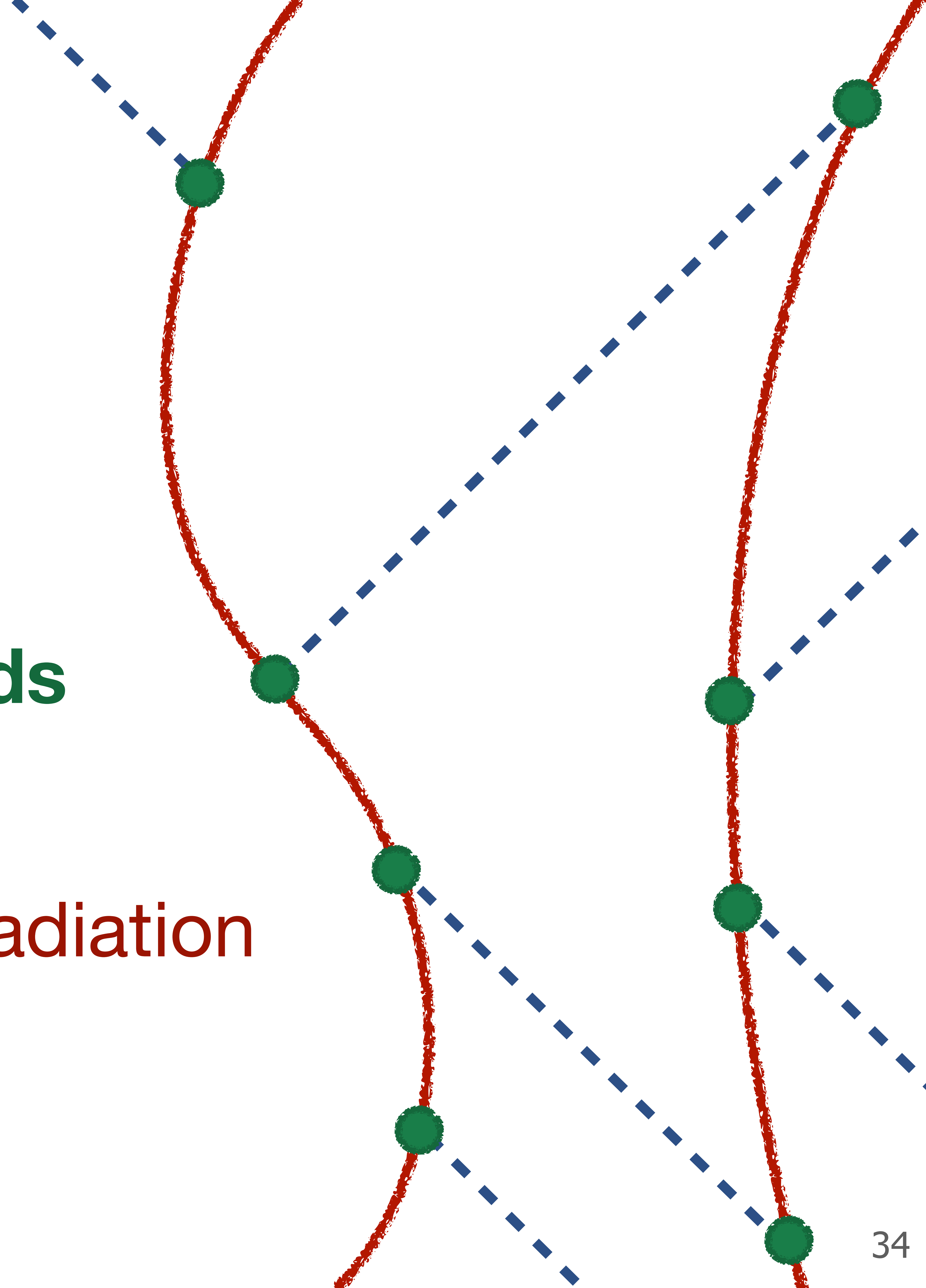
- **Coupling matter particles to fields**
- Emission and absorption of CSP radiation



Coupling Currents to Fields

- Scalar fields: $S_{\text{int}} = \int d^4x\, \phi(x)\, J(x)$ $\qquad$ $\partial_x^2\, \phi(x) = J(x)$

- Vector fields: $S_{\text{int}} = \int d^4x\, A_\mu(x)\, J^\mu(x)$ $\qquad$ $\partial_x^2\, A^\mu(x) = J^\mu(x)$

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- CSP fields: $S_{\text{int}} = \int d^4x\, [d^4\eta]\, \delta'(\eta^2 + 1)\, J(\eta, x)\, \Psi(\eta, x)$ $\qquad \partial_x^2\, \Psi(\eta, x) = J(\eta, x)$

  (includes scalar, vector, tensor, …)

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$$\partial_x^2 \, \phi(x) = J(x)$$

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$$\partial_x^2 \, A^\mu(x) = J^\mu(x)$$
$$\partial_\mu \, J^\mu = 0$$

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(includes scalar, vector, tensor, …)

- Gauge invariance of S_{int} implies continuity condition

$$(\partial_\eta \cdot \partial_x + \rho) \, J(\eta, x) = 0$$
$$\text{on } \eta^2 + 1 = 0$$

Currents From Particles

- For low-energy precision experiments, consider classical particle matter

- Current of particle must obey Poincare invariance and continuity condition

- Assuming leading currents are local to worldline and depend only on $z^\mu(\tau)$ and $\dot{z}^\mu(\tau)$ yields unique currents for scalars and vectors

$$J(x) = g \int d\tau \, \delta^4(x - z(\tau)) \qquad\qquad J^\mu(x) = e \int d\tau \, \frac{dz^\mu}{d\tau} \, \delta^4(x - z(\tau))$$

- Determines both how particles source field, and how they're acted on by field

$$\frac{dp^\mu}{d\tau} = g \, \partial^\mu \phi(z(\tau)) \qquad\qquad m \frac{d\dot{z}^\mu}{d\tau} = e \, \dot{z}_\nu F^{\mu\nu}(z(\tau))$$

Building CSP Currents

- The CSP current and (strong) continuity condition in Fourier space are

$$\tilde{J}(\eta, k) = \int d\tau \, e^{ik\cdot z(\tau)} f(\dot{z}, k, \eta) \qquad\qquad (-ik \cdot \partial_\eta + \rho) f = 0$$

- Implies f depends on k, so current not perfectly localized to worldline

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- Apparently many possibilities for f, such as

$$f = e^{-i\rho\eta\cdot V/k\cdot V} \qquad\qquad V = \begin{cases} \dot{z} & \text{temporal} \\ k - \dot{z}(\dot{z}\cdot k) & \text{spatial} \end{cases}$$

- Essential singularities at $k\cdot V = 0$ make evaluation in space tricky

Static Fields

- Computing static field requires regulating essential singularities at $\omega = 0$ (temporal current) or $|\overrightarrow{k}| = 0$ (spatial current), but result well-behaved:

$$\psi(\eta, \vec{r}, t) = \frac{1}{r} \times \begin{cases} J_0\left(\sqrt{2\rho\, \eta^0 t}\right) & \text{temporal current} \\ J_0\left(\sqrt{2\rho\, (|\overrightarrow{\eta}||\vec{r}| - \overrightarrow{\eta} \cdot \vec{r})}\right) & \text{spatial current} \end{cases}$$

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- Finding velocity-dependent forces is hard; unclear how general answers are

- Interestingly, currents seem to require substructure on scale $1/\rho$, yet still reduce to familiar localized currents as $\rho \to 0$

Radiation Fields

- An easier first question: emission and absorption of on-shell radiation ($k^2 = 0$)

- Spatial current simplifies to

$$f = \underbrace{\exp\left(-i\rho\frac{\eta\cdot\dot{z}}{k\cdot\dot{z}}\right)}_{\text{temporal current}} \underbrace{\exp\left(i\rho\frac{\eta\cdot k}{(k\cdot\dot{z})^2}\right)}_{1+\tilde{f}}$$

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- Harmonic gauge condition implies $\tilde{f}$ does not contribute to S_{int}!

Our core technical result: this phenomenon is **completely general**!

Radiation Fields

- For on-shell CSPs, **all** currents are equivalent to

$$f = h(k \cdot \dot{z}) \, \exp\left(-i\rho \frac{\eta \cdot \dot{z}}{k \cdot \dot{z}}\right)$$

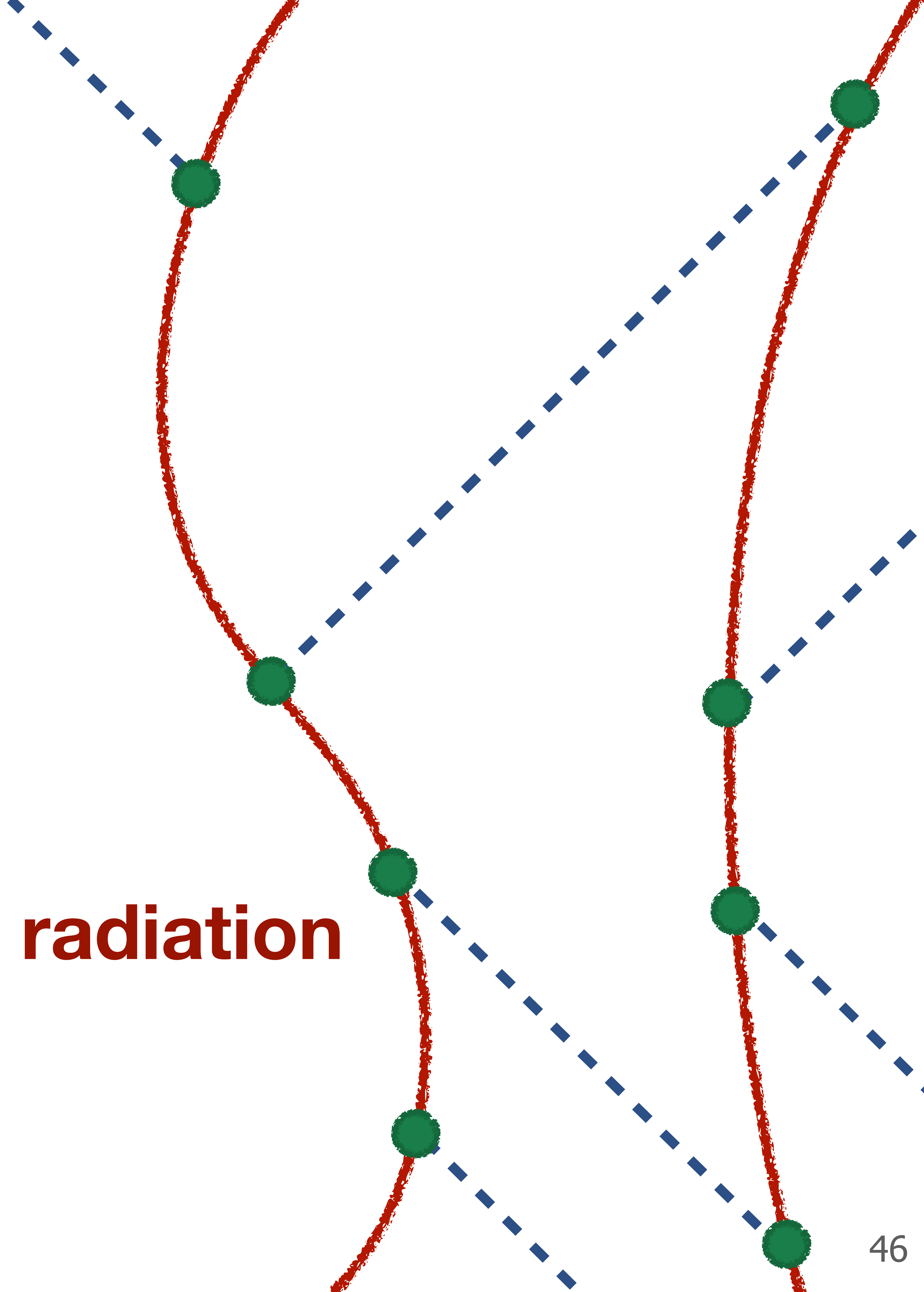
- Correspondence to ordinary massless particles at $\rho = 0$ gives three options

$$h \sim \begin{cases} g & \text{scalar CSP} \\ e \, k \cdot \dot{z} & \text{vector CSP} \\ m \, (k \cdot \dot{z})^2 & \text{graviton CSP} \end{cases}$$

- Motivates finding corrections to radiation emission and forces from radiation absorption, for vector CSP photons (focus of this talk) and graviton CSPs

Outline

- The free CSP field
- Coupling matter particles to fields
- **Emission and absorption of CSP radiation**



Emission of Vector CSPs

- Computing the harmonic n, helicity h radiation emitted from a non-relativistic charged particle in periodic motion is a straightforward exercise:

$$\frac{dP_{n,h}}{d\Omega} \propto q^2 \left| \int_0^T \frac{dt}{T} \, n^2 e^{in\omega_0 t} \, e^{-ih \arg(\epsilon_+ \cdot v_\perp)} J_h\!\left(\frac{\rho \, | \, v_\perp(t) \, |}{n\omega_0} \right) \right|^2$$

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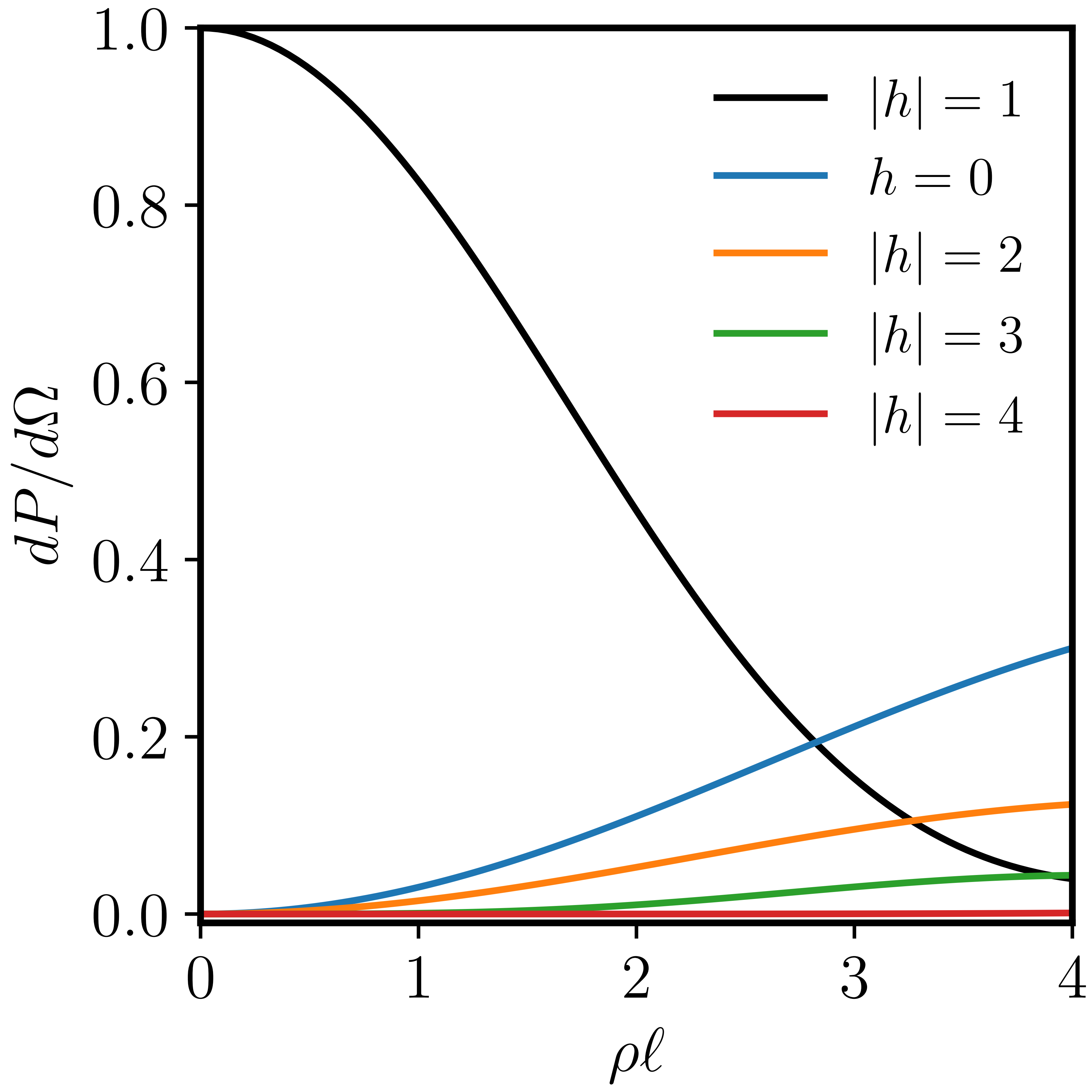

- Yields ordinary Larmor formula at $\rho = 0$
- Leading correction is $(\rho v_0/\omega)^2 = (\rho\ell)^2$ suppressed emission of $h = 0, 2$ modes
- Corrections negligible in UV, $\ell \ll 1/\rho$

Forces From Vector CSPs

- Computing the dynamics of a particle in helicity h CSP radiation background is another straightforward exercise:

$$L_{\text{int}}[\mathbf{z}(\tau), \mathbf{v}(\tau)] \propto \underbrace{\psi_{h,k}(\mathbf{z}, \tau)}_{\text{field amplitude}} \underbrace{(1 - \hat{\mathbf{u}} \cdot \mathbf{v})\, \tilde{J}_h\left(\frac{\rho}{\omega} \frac{\epsilon_\pm \cdot \mathbf{v}}{(1 - \hat{\mathbf{u}} \cdot \mathbf{v})}\right)}_{\text{series in } \rho \mathbf{v}}$$

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- Contains Lorentz force law, with distinctive velocity-dependent corrections:
  - $O(\rho v)$ forces from $h = 0$ (parallel to $\mathbf{v}_\perp$) and $h = 2$ (like grav. wave)
  - $O((\rho v)^2)$ forces from $h = 1$ (parallel to $\mathbf{v}$, violating Lorentz force law)

Open Questions

Core experimental question: most effective probes of the photon/graviton spin scale ρ

Cosmological and astrophysical bounds, CSP radiation background

Light shining through wall and helioscope searches

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Understanding CSP currents off-shell (near field) → Velocity-dependent modifications of force laws

Quantizing CSP-coupled matter → Atomic absorption/emission

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Non-Abelian structure (Yang—Mills, general relativity)? Higgs mechanism?

Deeper understanding of the origin of CSP-coupled currents?

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Much more physics to consider and discover!