Title: Particle Physics Seminar Series - TBA

Speakers: Rebecca Leane

Series: Particle Physics

Date: February 27, 2024 - 1:00 PM

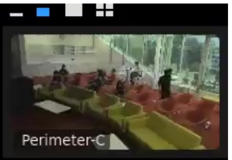
URL: https://pirsa.org/24020096

Abstract: Abstract and Zoom link TBA

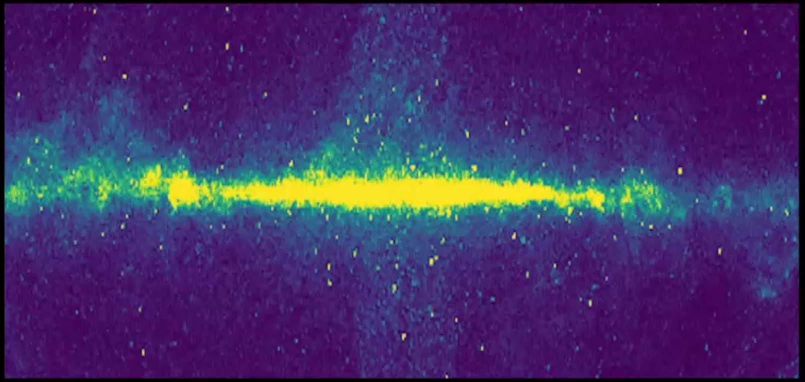
NEW ASTROPHYSICAL SEARCHES FOR DARK MATTER

REBECCA LEANE
SLAC NATIONAL ACCELERATOR LABORATORY

PERIMETER INSTITUTE
FEBRUARY 27TH 2024



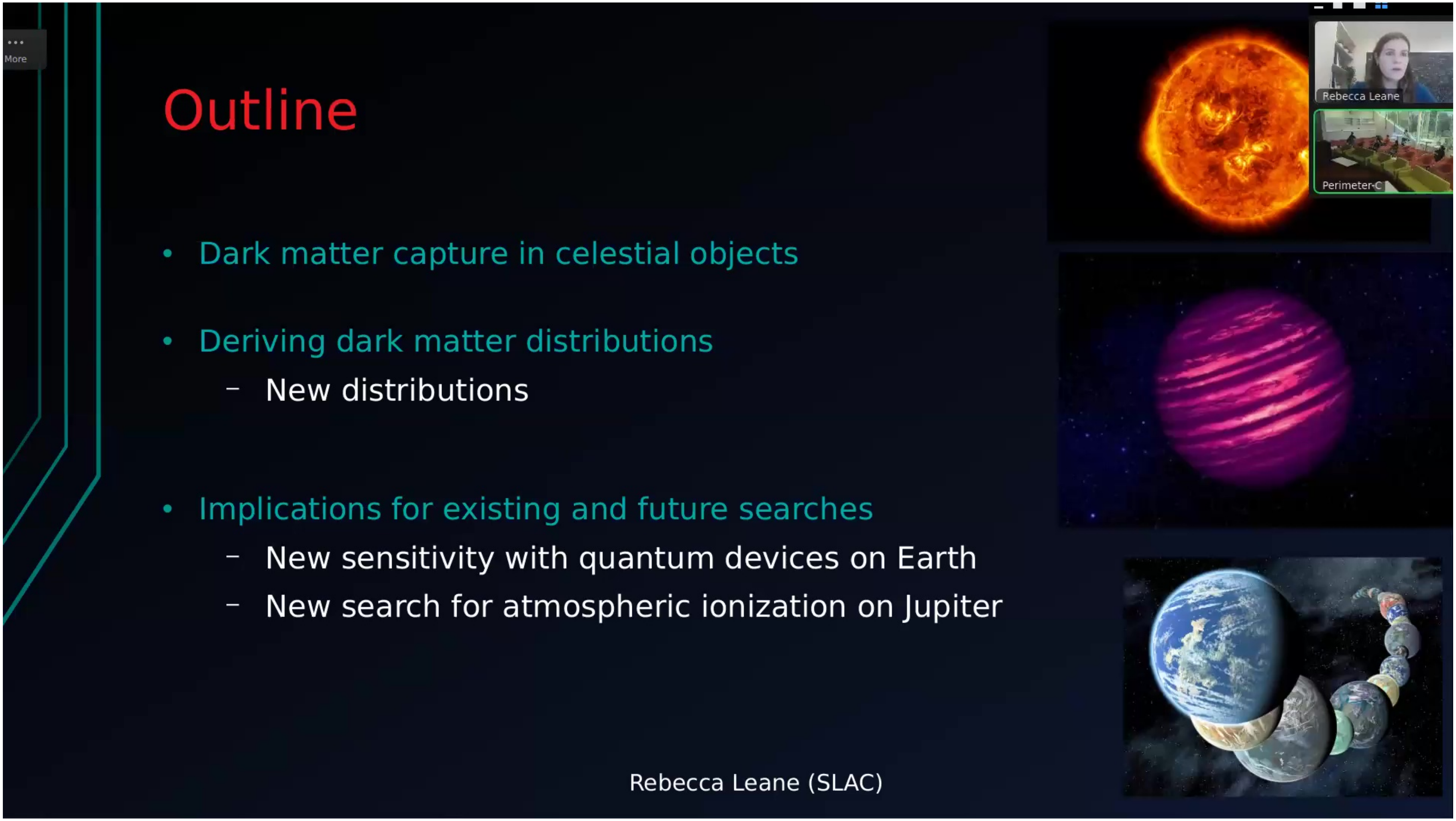
Finding Particle Dark Matter



New searches with astrophysical systems

Use **astrophysical datasets** to discover new particles

Rebecca Leane (SLAC)



Outline

- Dark matter capture in celestial objects
- Deriving dark matter distributions
  - New distributions
- Implications for existing and future searches
  - New sensitivity with quantum devices on Earth
  - New search for atmospheric ionization on Jupiter

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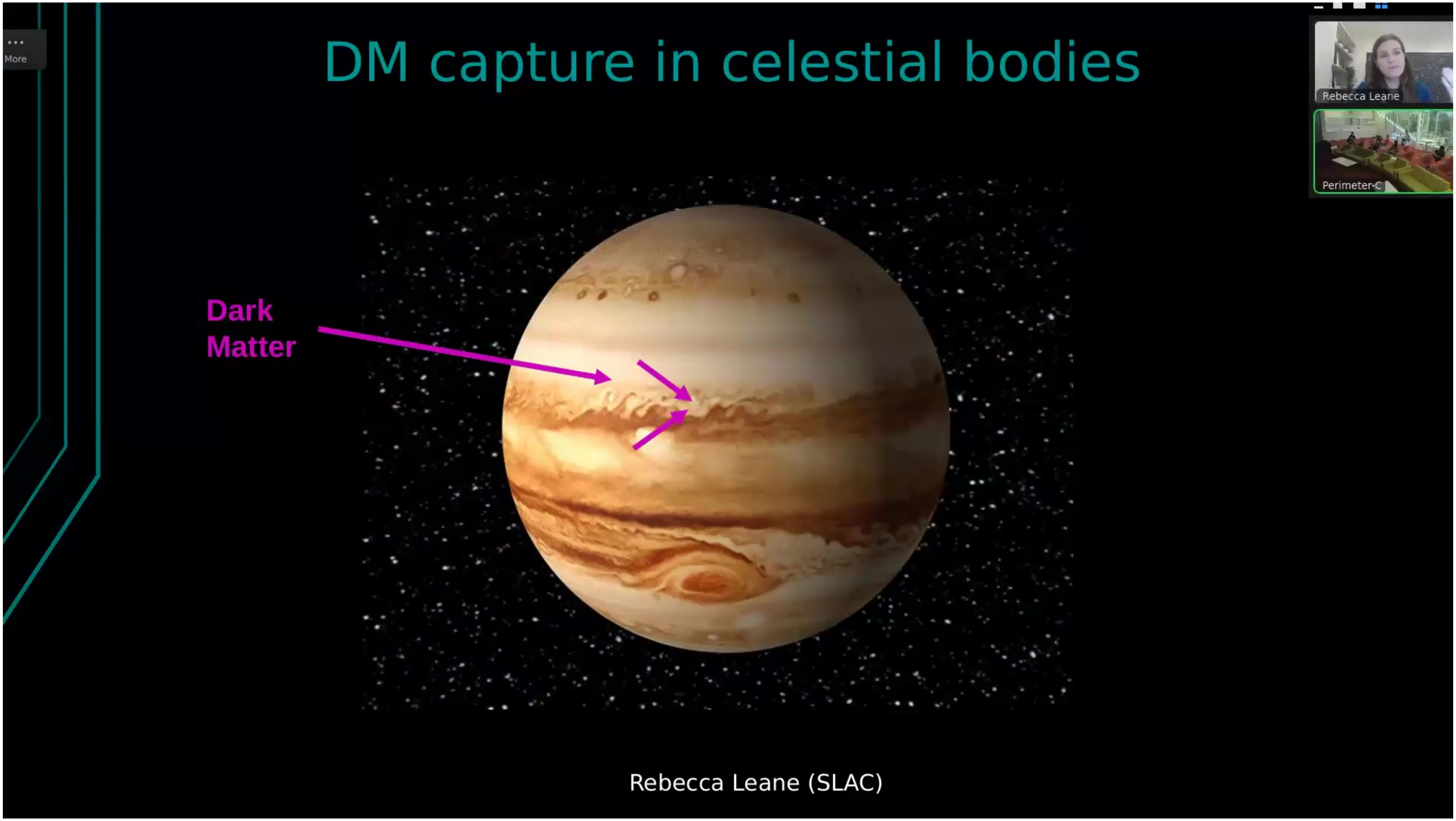

DM capture in celestial bodies

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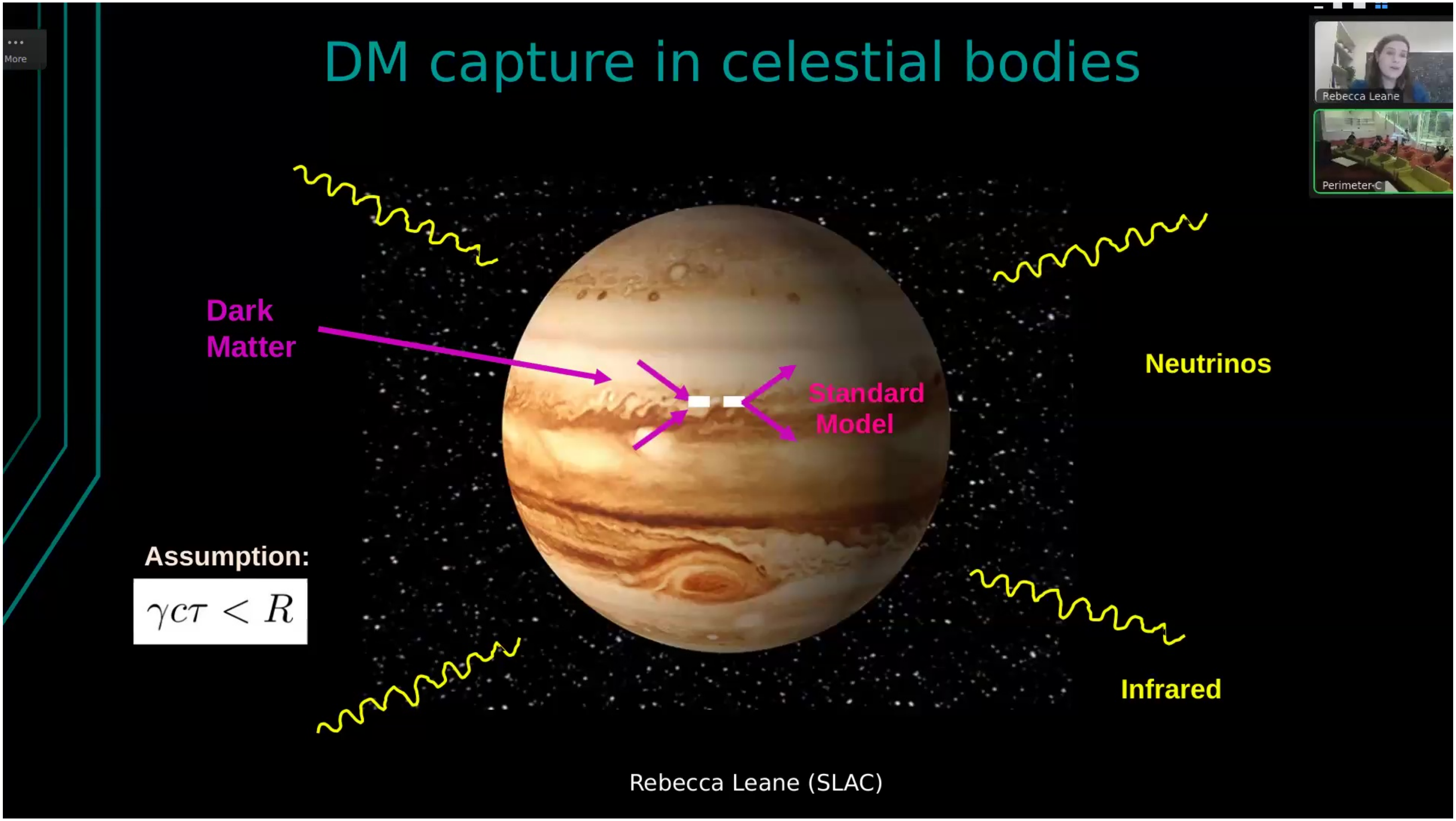

DM capture in celestial bodies

Assumption:

$$\gamma c \tau < R$$

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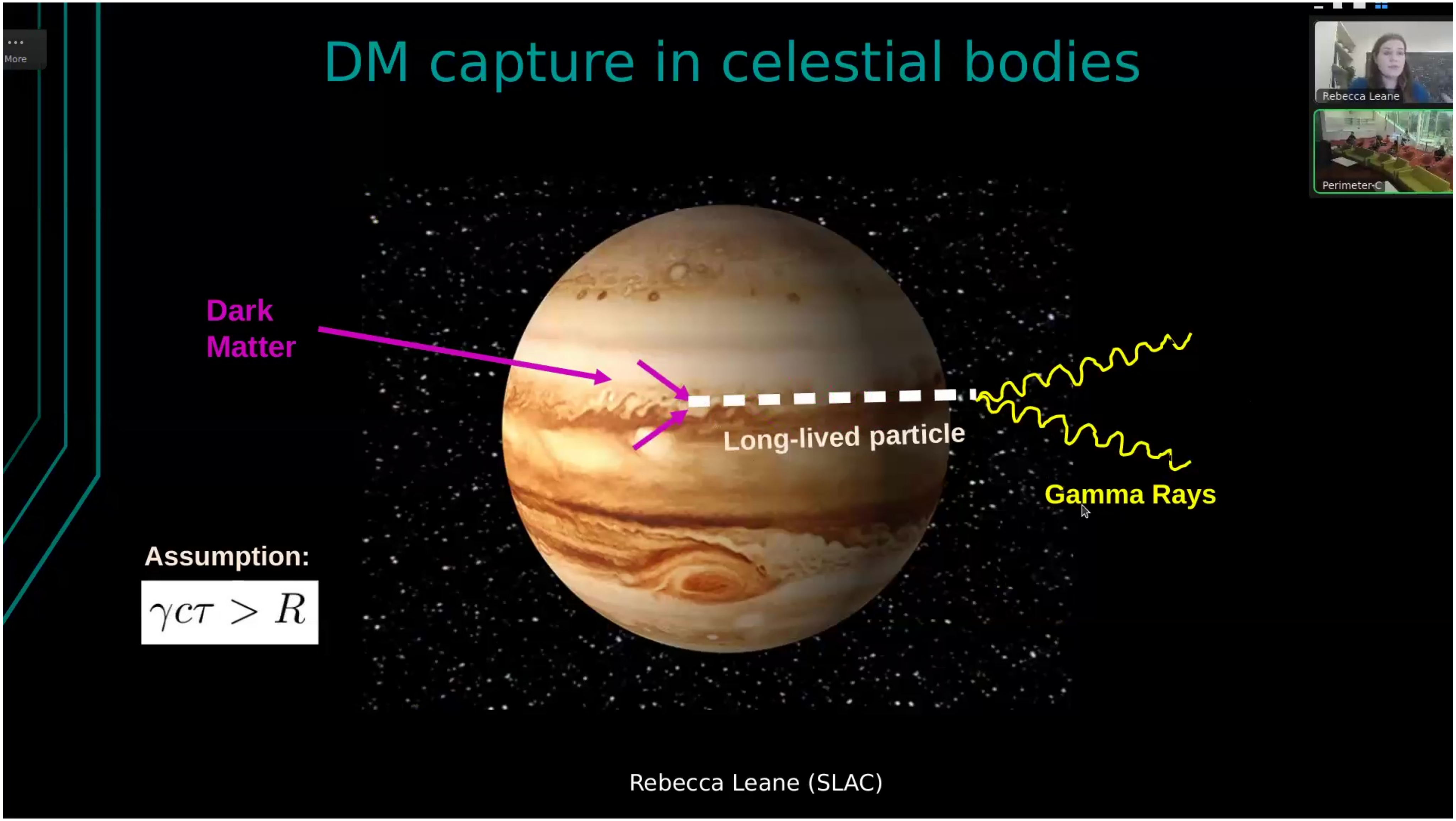

DM capture in celestial bodies

Dark Matter

Long-lived particle

Gamma Rays

Assumption:

$$\gamma c\tau > R$$

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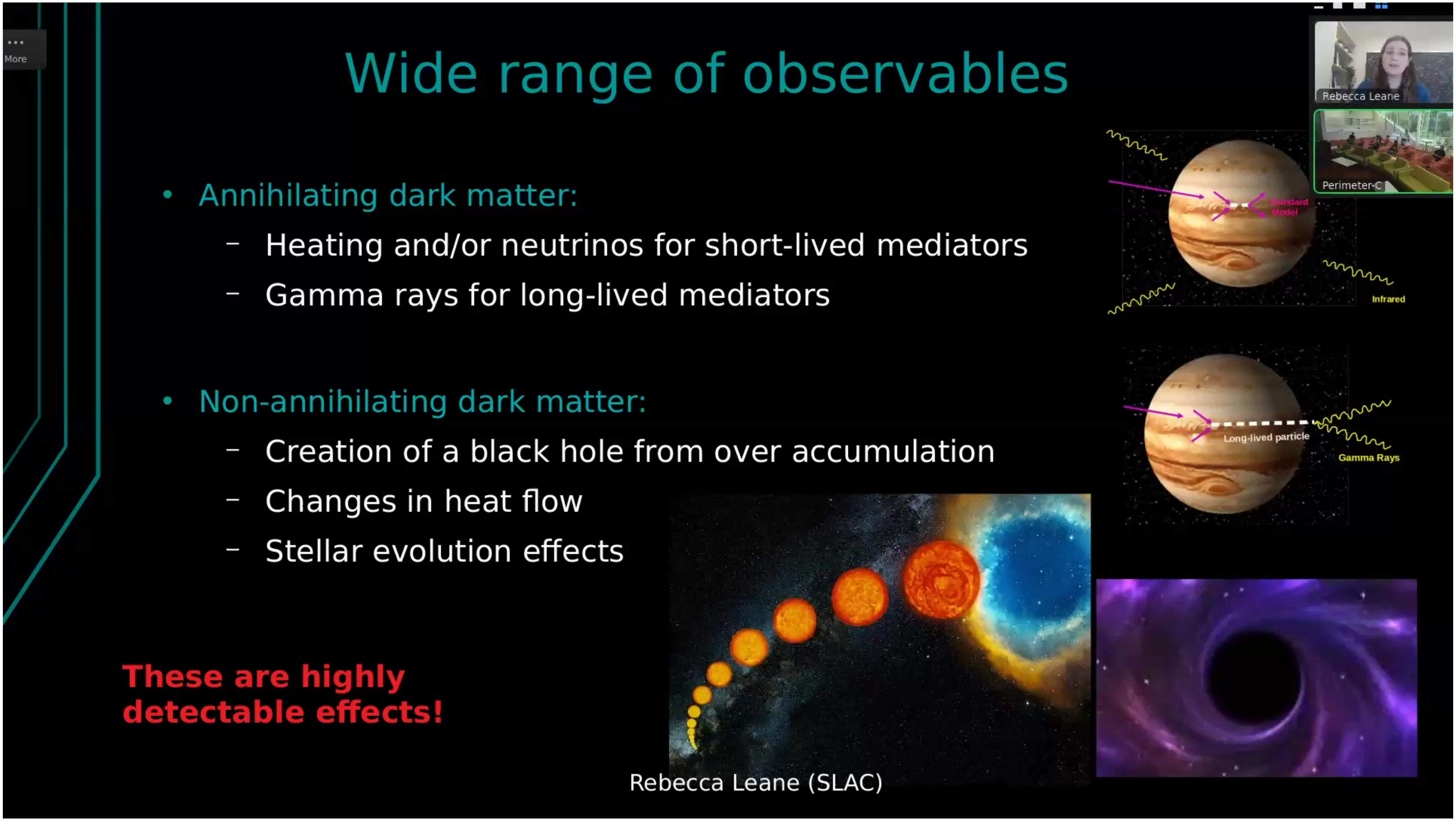

Wide range of observables

- Annihilating dark matter:
  - Heating and/or neutrinos for short-lived mediators
  - Gamma rays for long-lived mediators
- Non-annihilating dark matter:
  - Creation of a black hole from over accumulation
  - Changes in heat flow
  - Stellar evolution effects

These are highly detectable effects!

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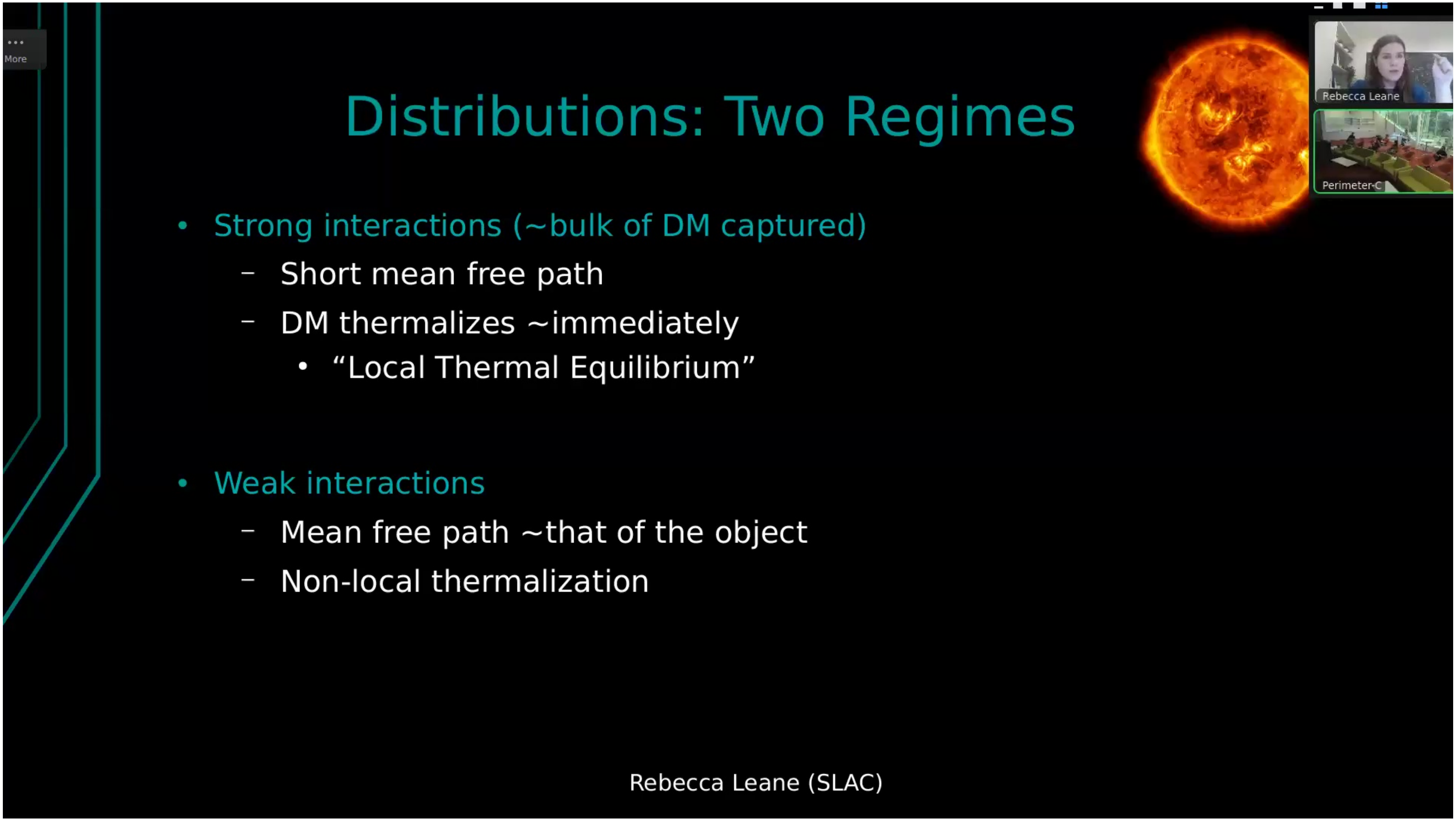

Distributions: Two Regimes

- Strong interactions (~bulk of DM captured)
  - Short mean free path
  - DM thermalizes ~immediately
    - "Local Thermal Equilibrium"

- Weak interactions
  - Mean free path ~that of the object
  - Non-local thermalization

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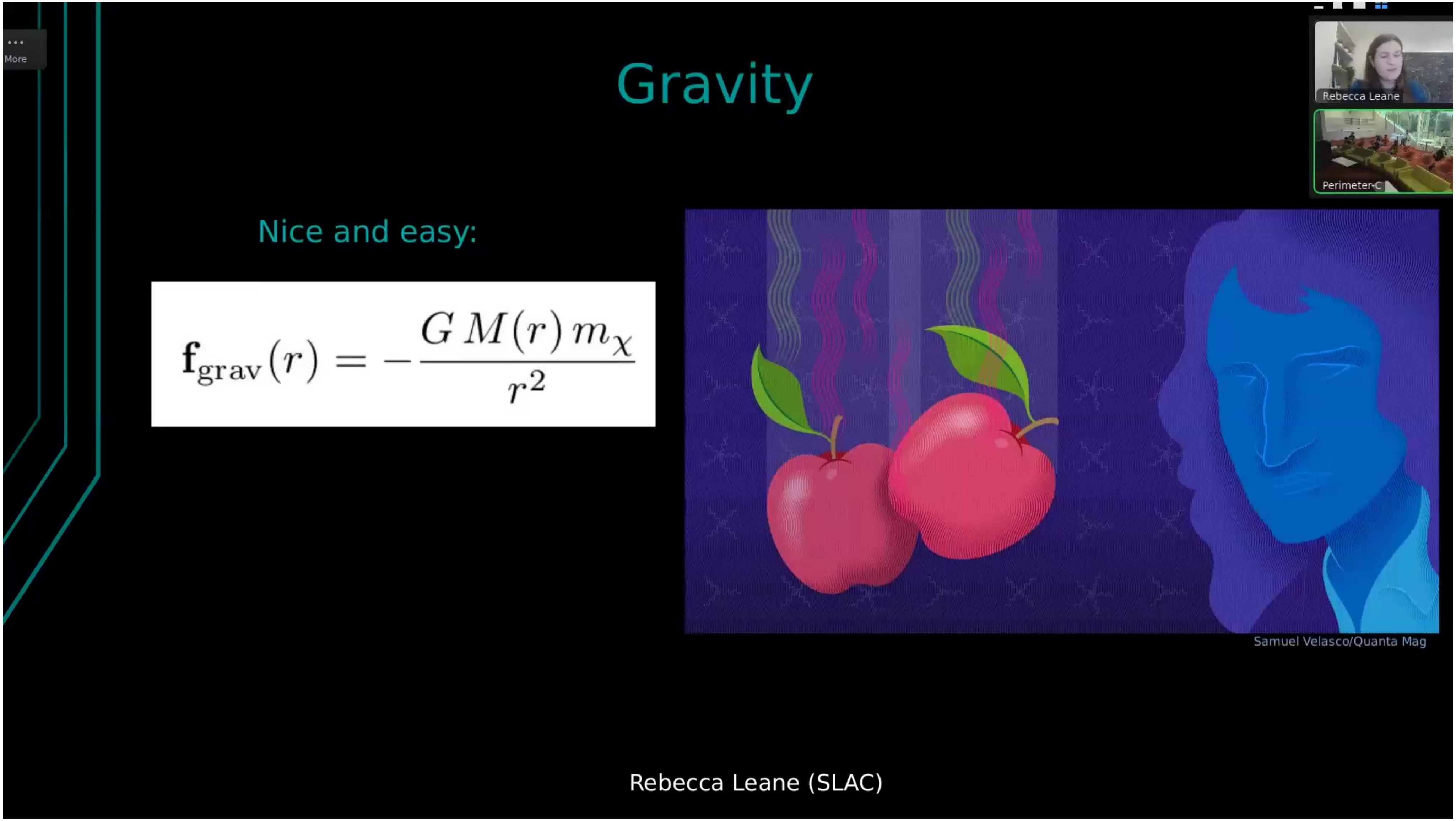

Gravity

Nice and easy:

$$\mathrm{f}_{\mathrm{grav}}(r) = -\frac{G\,M(r)\,m_\chi}{r^2}$$

Samuel Velasco/Quanta Mag

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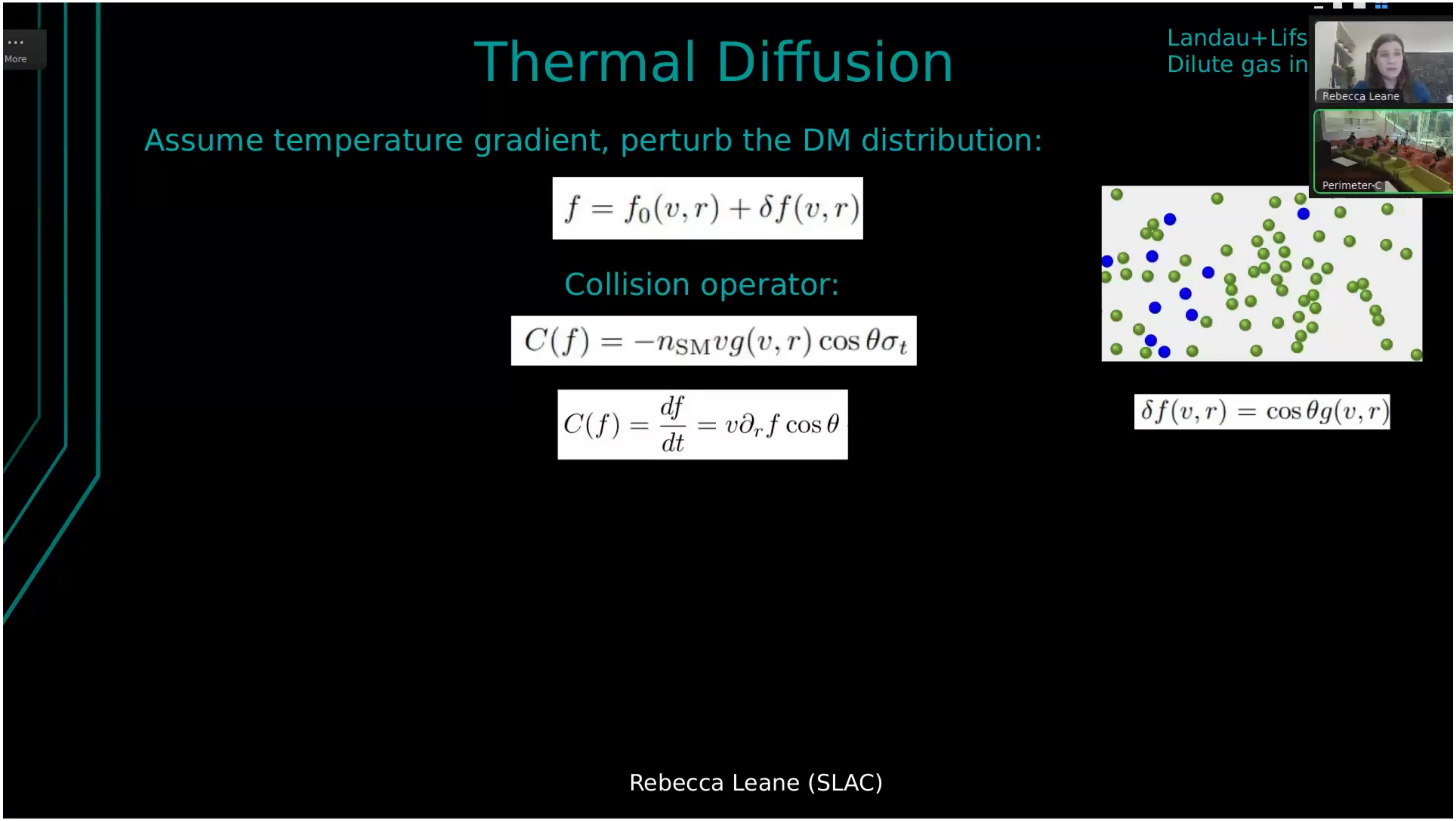

Thermal Diffusion

Landau+Lifs
Dilute gas in

Assume temperature gradient, perturb the DM distribution:

$$f = f_0(v,r) + \delta f(v,r)$$

Collision operator:

$$C(f) = -n_{\rm SM} v g(v,r) \cos\theta \sigma_t$$

$$C(f) = \frac{df}{dt} = v\partial_r f \cos\theta$$

$$\delta f(v,r) = \cos\theta g(v,r)$$

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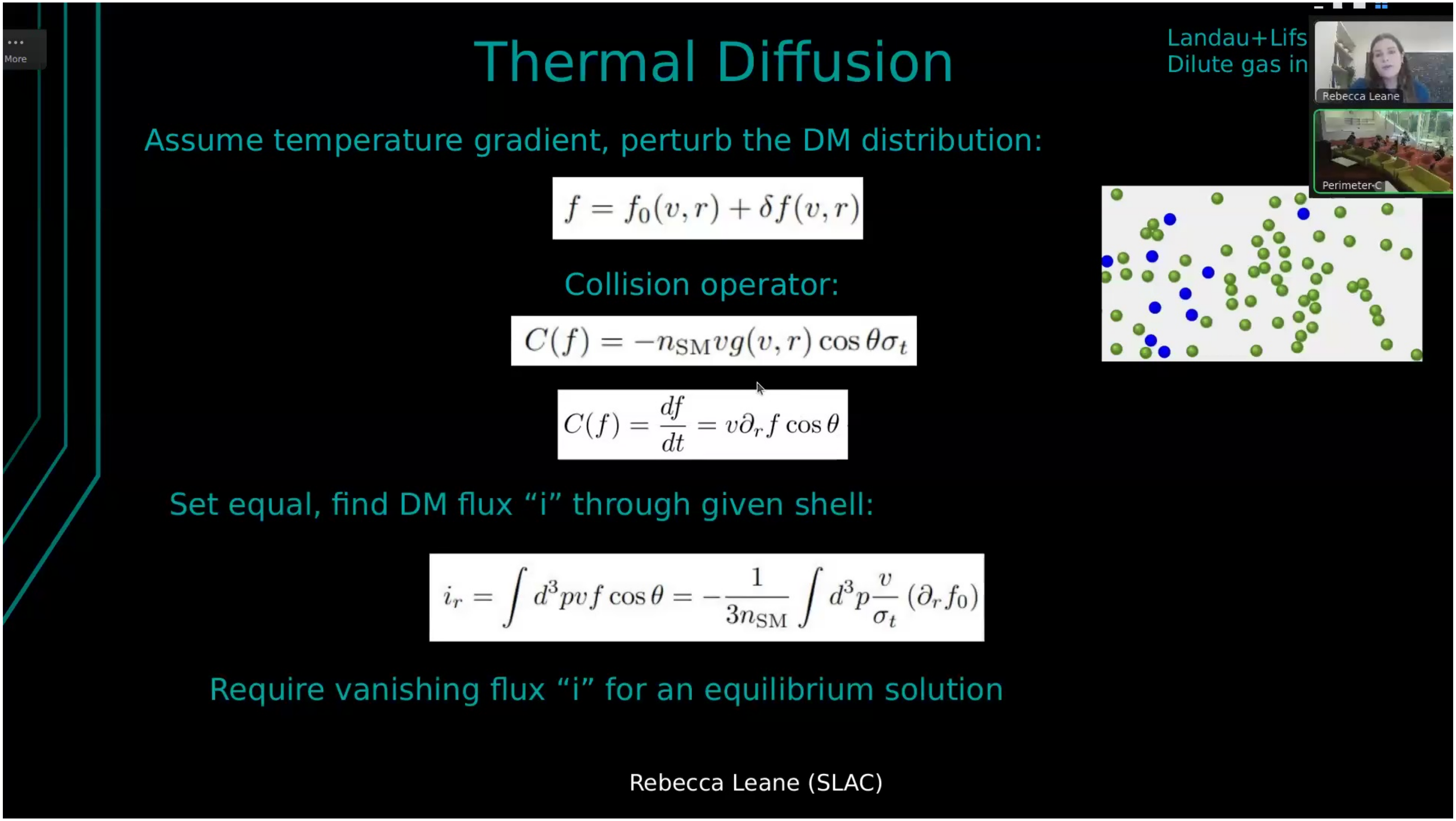

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$$C(f) = -n_{\rm SM} v g(v,r) \cos\theta \sigma_t$$

$$C(f) = \frac{df}{dt} = v \partial_r f \cos\theta$$

Set equal, find DM flux “i” through given shell:

$$i_r = \int d^3p v f \cos\theta = -\frac{1}{3 n_{\rm SM}} \int d^3p \frac{v}{\sigma_t} \left(\partial_r f_0\right)$$

Require vanishing flux “i” for an equilibrium solution

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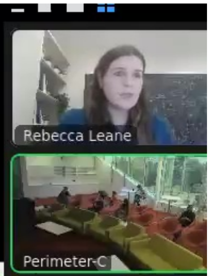
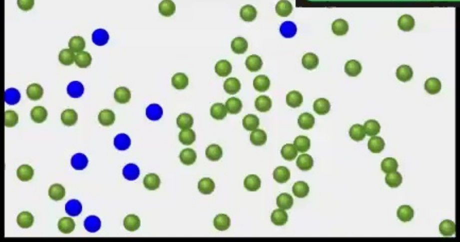
Thermal Diffusion



Rewrite:

$$\nabla_r \log\left(n_\chi T\right) = \frac{1}{2}\left(\frac{1}{1+\mu}\right)^{3/2} \nabla_r \log\left(T\right)$$



with $\mu = m_\chi / m_{\rm SM}$

Scaling of DM density with temperature:

$$\frac{n_\chi^{\rm LTE}(r)}{N_0^{\rm LTE}} = \left[\frac{T(r)}{T(0)}\right]^{-1+\frac{1}{2}(1+\mu)^{-3/2}}$$

- Not always same as background, despite equilibrium! Limiting cases:
  - Understandable from velocity and mass: $v \sim \sqrt{T/m_1}$
  - Light DM: density prop to T^-1/2
  - Heavy DM: density prop to T^-1

Light gas spends more time in regions where temperature is high

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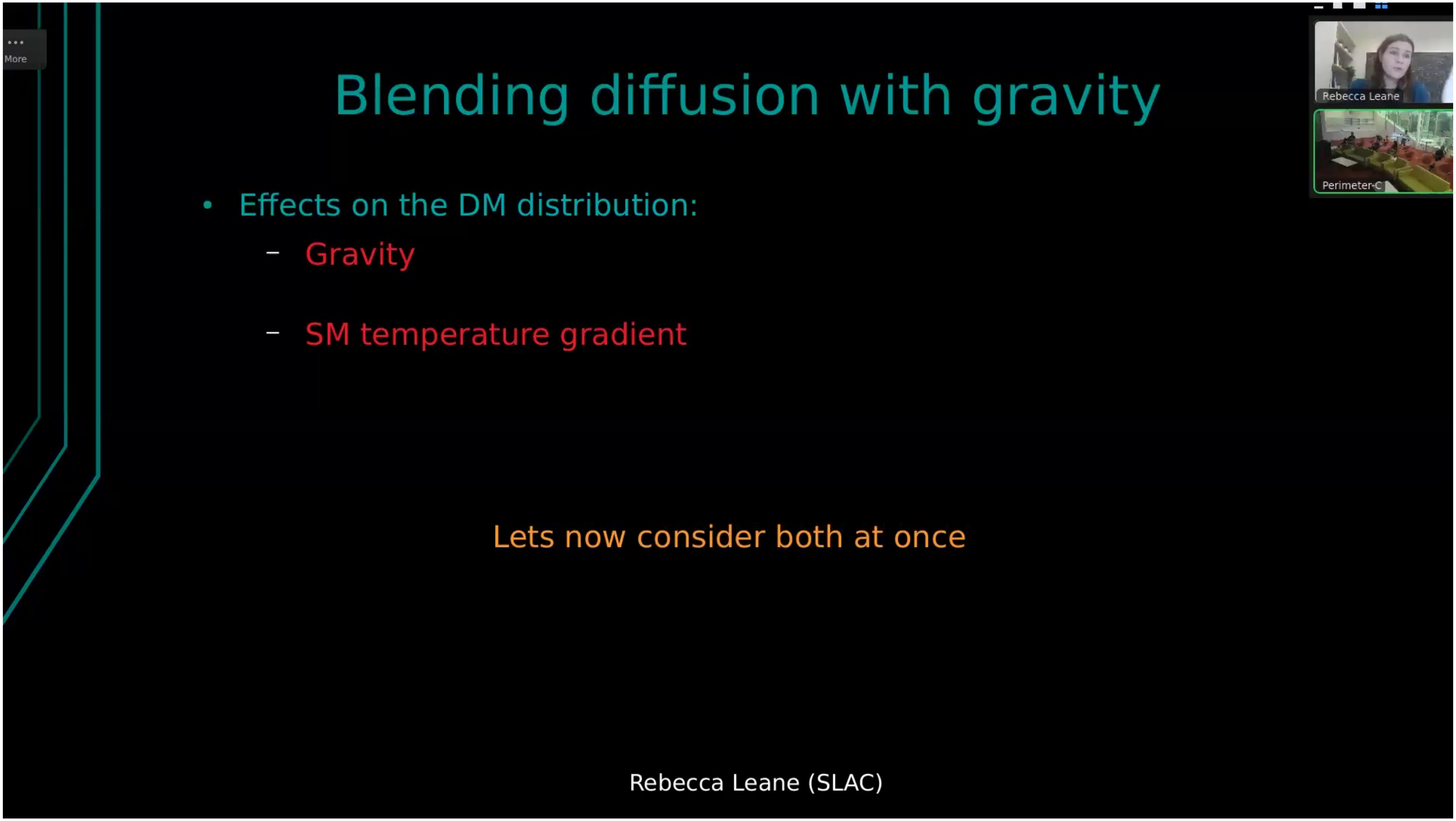

Blending diffusion with gravity

- Effects on the DM distribution:
    - Gravity
    - SM temperature gradient

Lets now consider both at once

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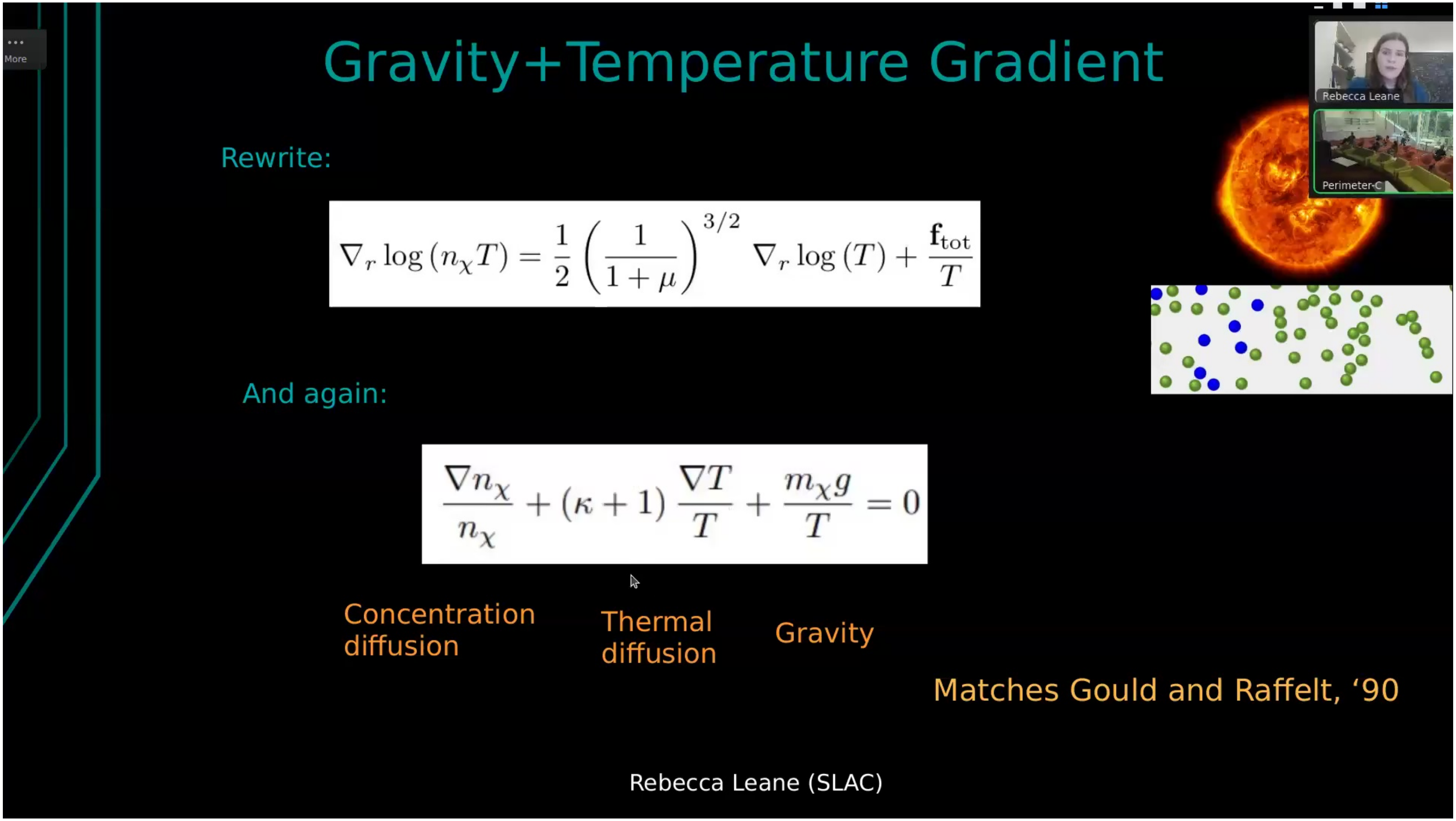

Gravity+Temperature Gradient

Rewrite:

$$\nabla_r \log(n_\chi T) = \frac{1}{2}\left(\frac{1}{1+\mu}\right)^{3/2} \nabla_r \log(T) + \frac{\mathbf{f}_{\mathrm{tot}}}{T}$$

And again:

$$\frac{\nabla n_\chi}{n_\chi} + (\kappa+1)\frac{\nabla T}{T} + \frac{m_\chi g}{T} = 0$$

Concentration diffusion

Thermal diffusion

Gravity

Matches Gould and Raffelt, ‘90

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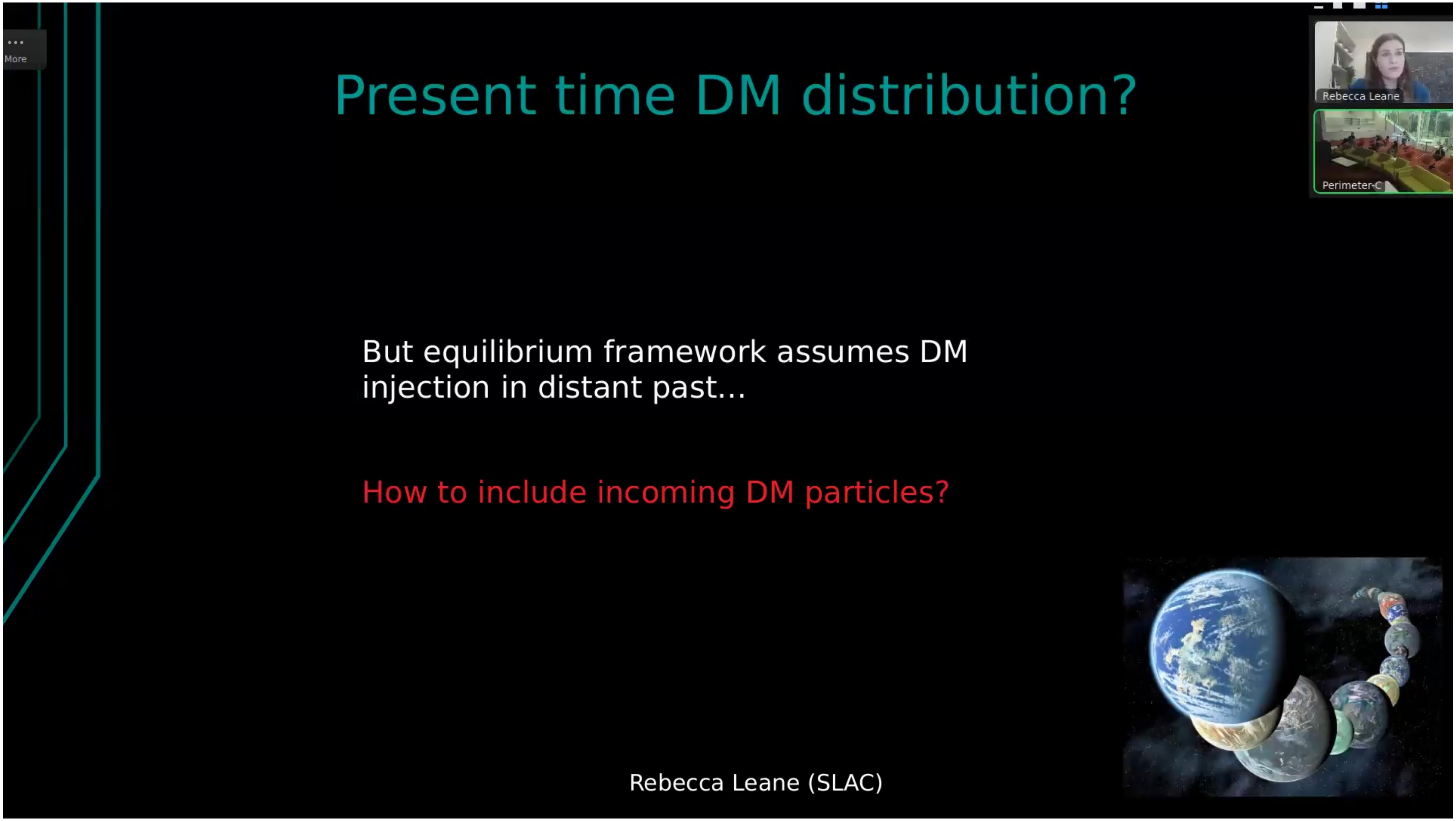

Present time DM distribution?

But equilibrium framework assumes DM injection in distant past…

How to include incoming DM particles?

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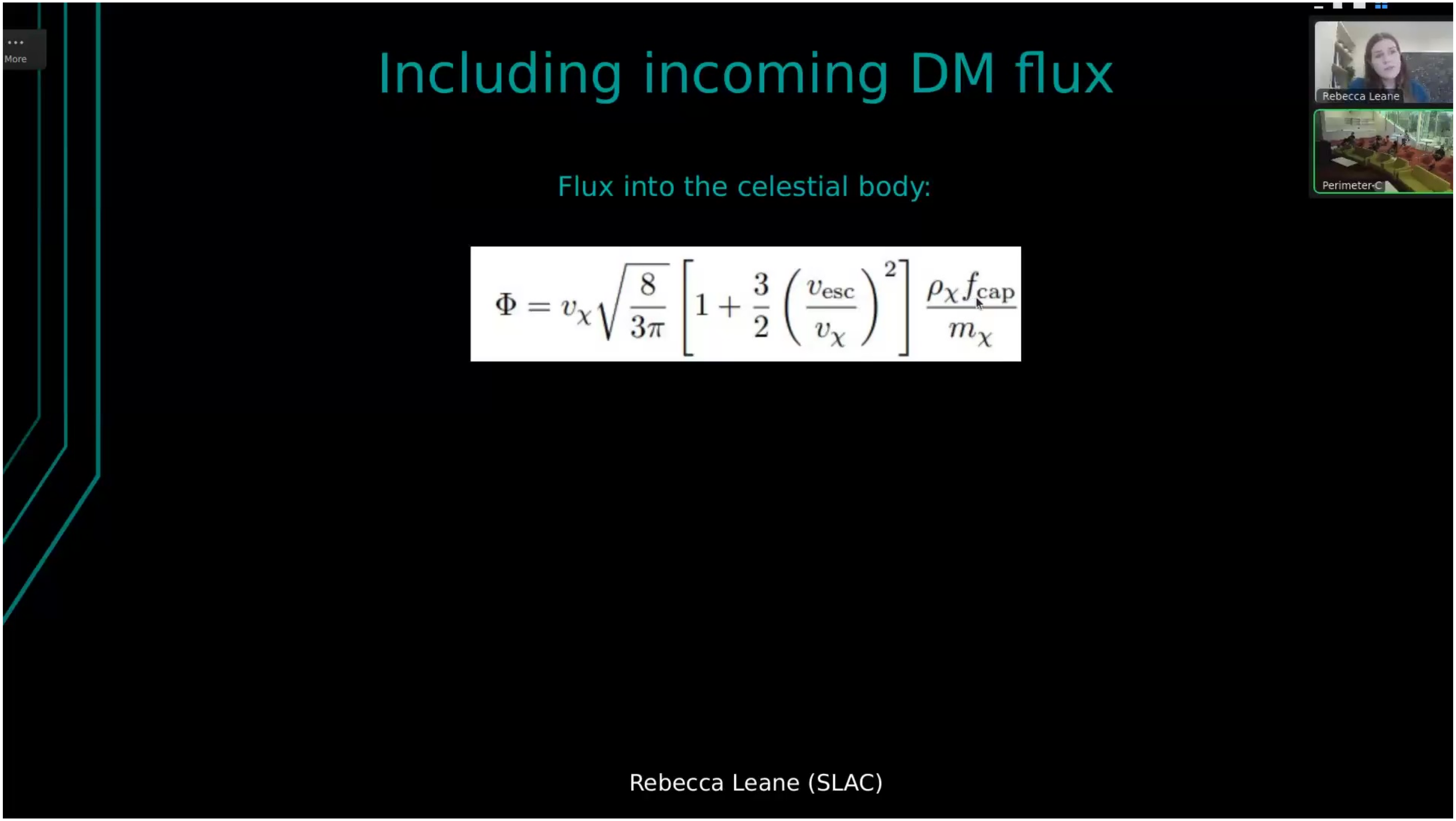

Including incoming DM flux

Flux into the celestial body:

$$\Phi = v_\chi \sqrt{\frac{8}{3\pi}} \left[1 + \frac{3}{2} \left(\frac{v_{\mathrm{esc}}}{v_\chi} \right)^2 \right] \frac{\rho_\chi f_{\mathrm{cap}}}{m_\chi}$$

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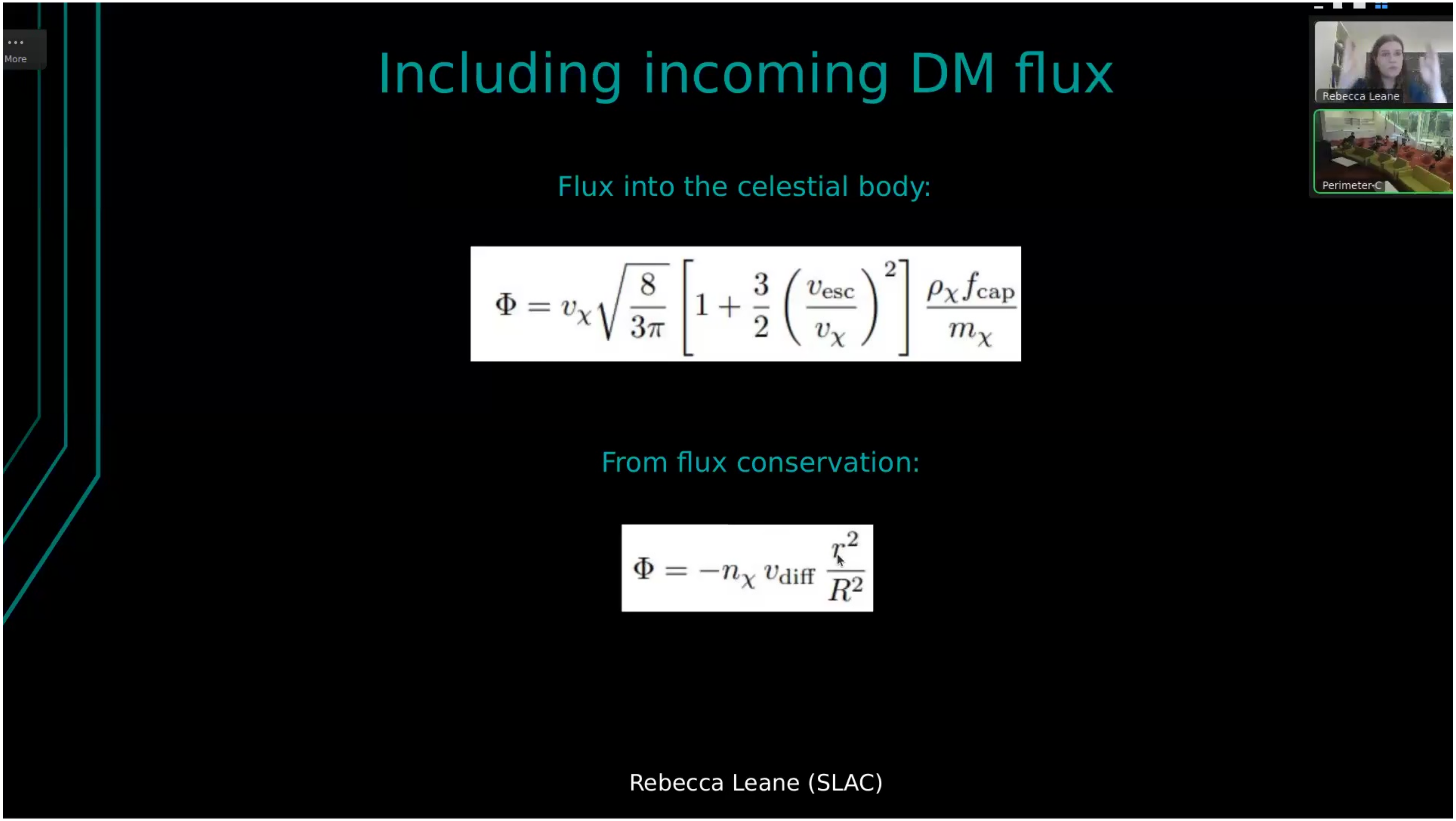

Including incoming DM flux

Flux into the celestial body:

$$\Phi = v_\chi \sqrt{\frac{8}{3\pi}} \left[1 + \frac{3}{2}\left(\frac{v_{\rm esc}}{v_\chi}\right)^2\right] \frac{\rho_\chi f_{\rm cap}}{m_\chi}$$

From flux conservation:

$$\Phi = -n_\chi \, v_{\rm diff} \, \frac{r^2}{R^2}$$

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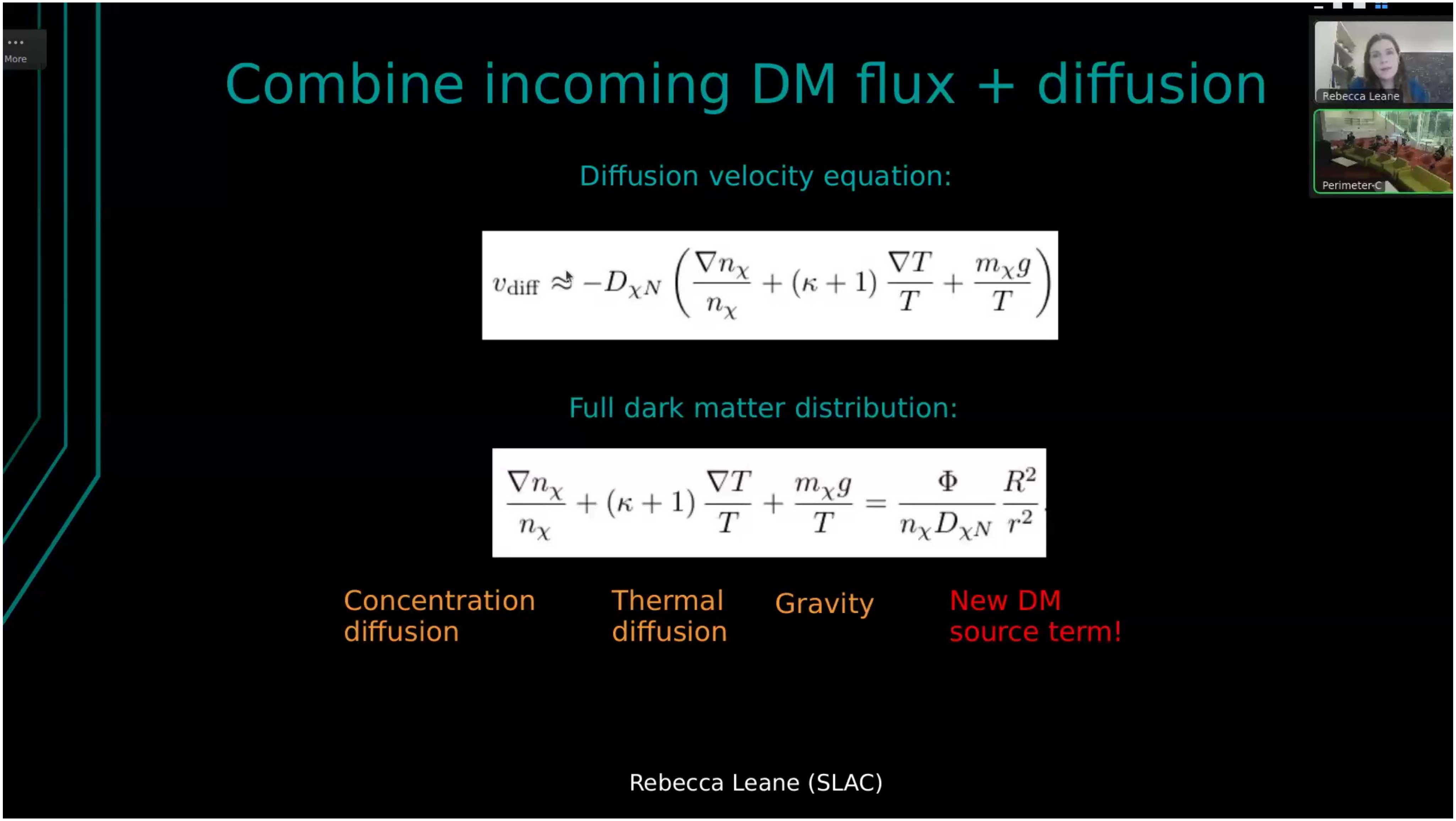

Combine incoming DM flux + diffusion

Diffusion velocity equation:

$$v_{\rm diff} \approx -D_{\chi N}\left(\frac{\nabla n_\chi}{n_\chi} + (\kappa+1)\frac{\nabla T}{T} + \frac{m_\chi g}{T}\right)$$

Full dark matter distribution:

$$\frac{\nabla n_\chi}{n_\chi} + (\kappa+1)\frac{\nabla T}{T} + \frac{m_\chi g}{T} = \frac{\Phi}{n_\chi D_{\chi N}}\frac{R^2}{r^2}$$

Concentration diffusion

Thermal diffusion

Gravity

New DM source term!

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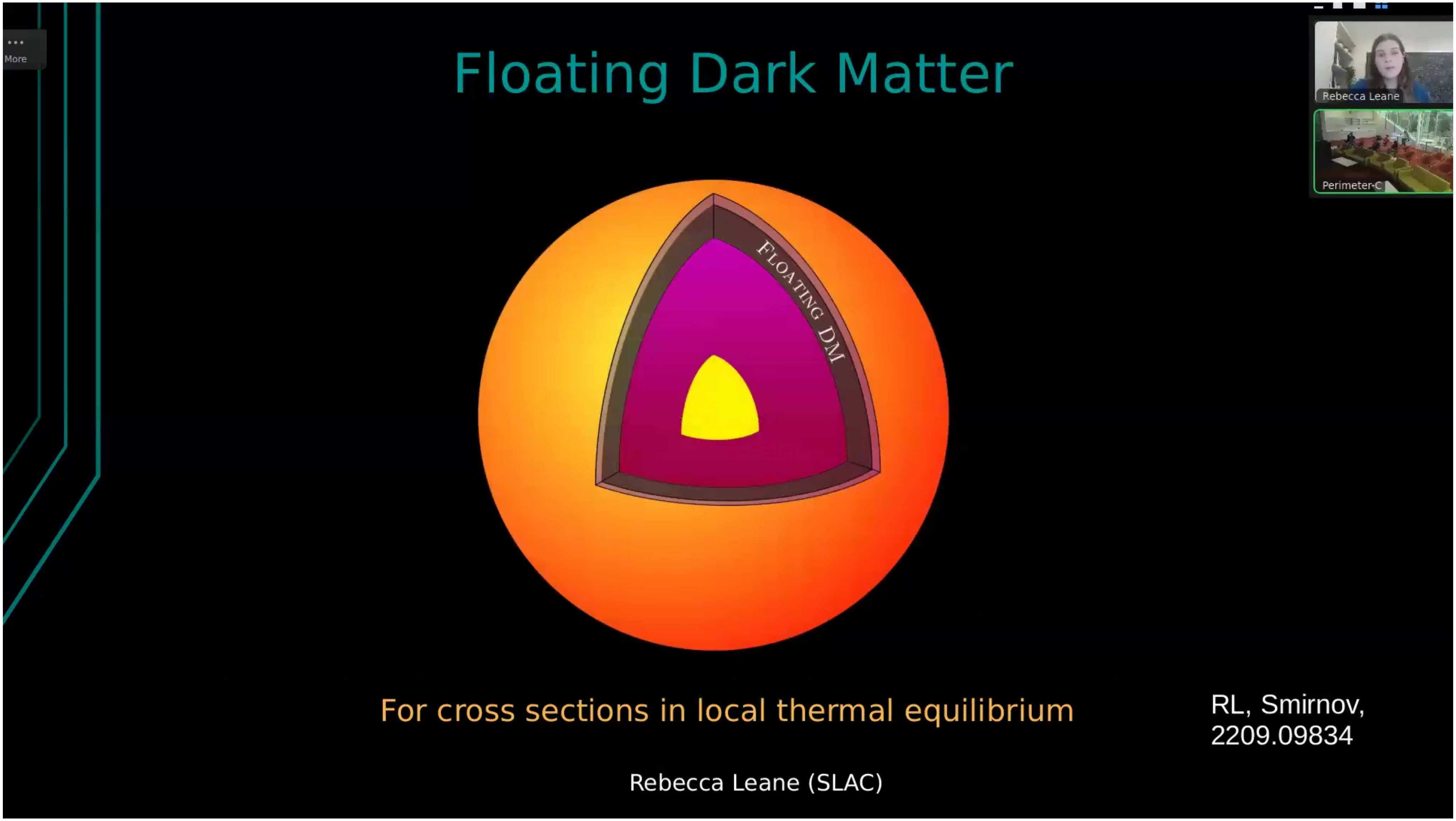

Floating Dark Matter

For cross sections in local thermal equilibrium

RL, Smirnov,
2209.09834

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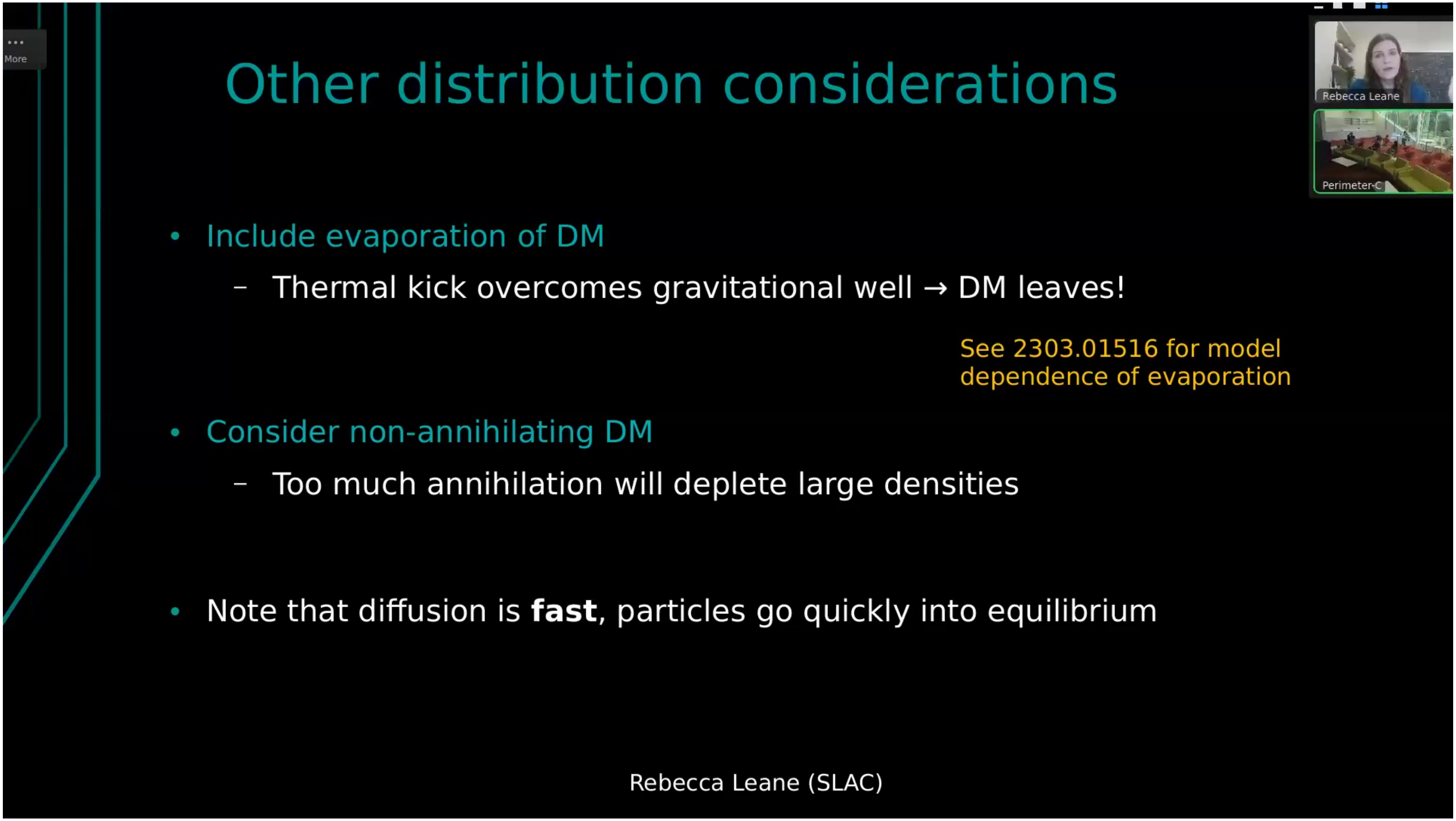

Other distribution considerations

- Include evaporation of DM
  - Thermal kick overcomes gravitational well → DM leaves!

See 2303.01516 for model dependence of evaporation

- Consider non-annihilating DM
  - Too much annihilation will deplete large densities

- Note that diffusion is **fast**, particles go quickly into equilibrium

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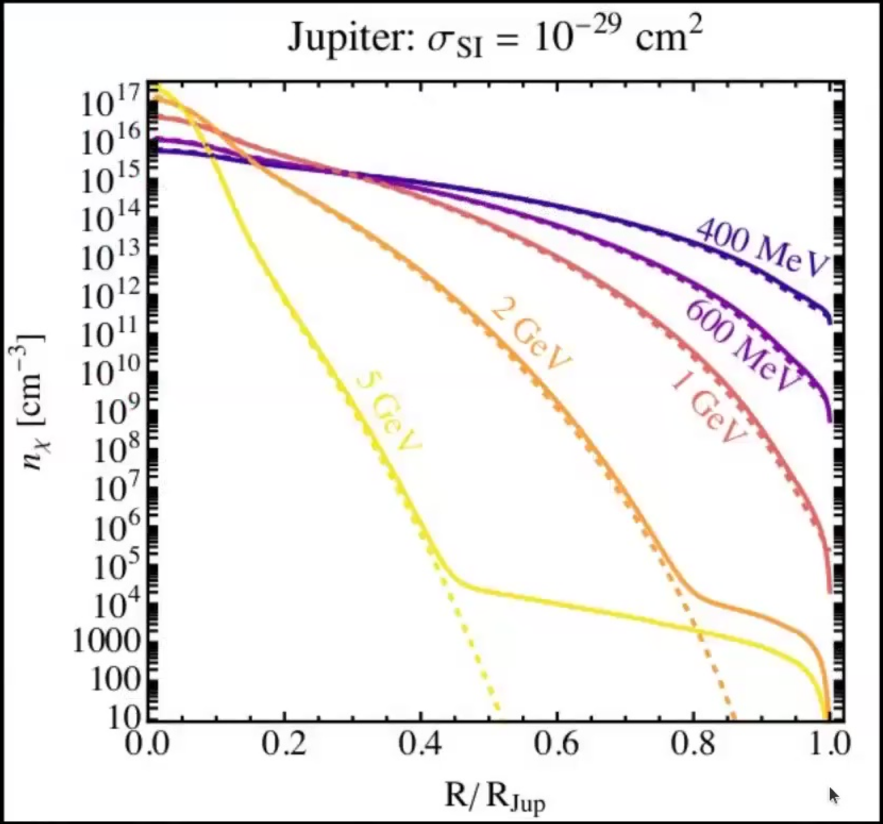
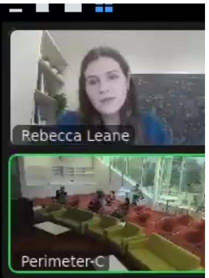
More

Floating dark matter: Jupiter



RL, Smirnov ‘22



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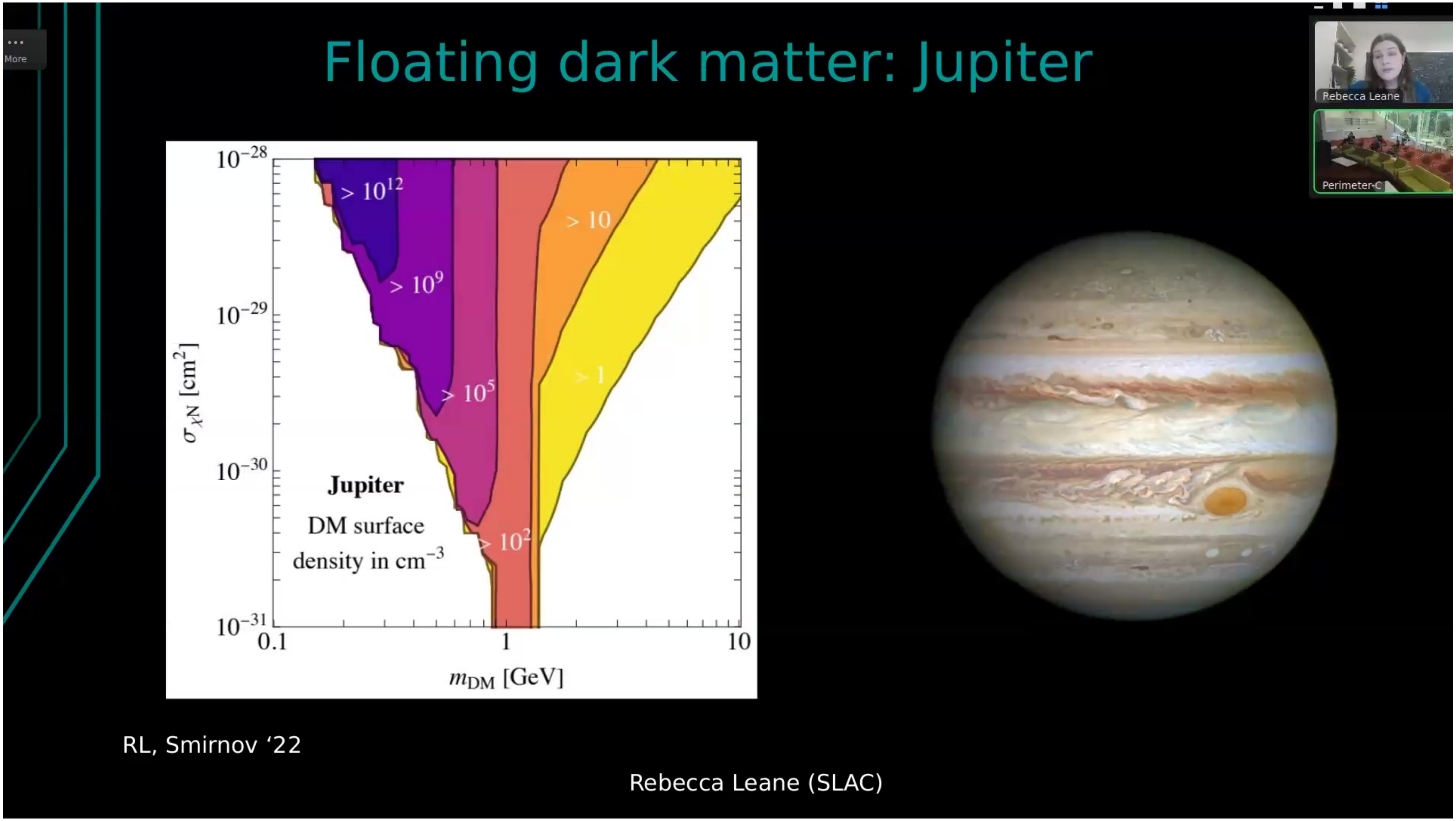

Floating dark matter: Jupiter

RL, Smirnov '22

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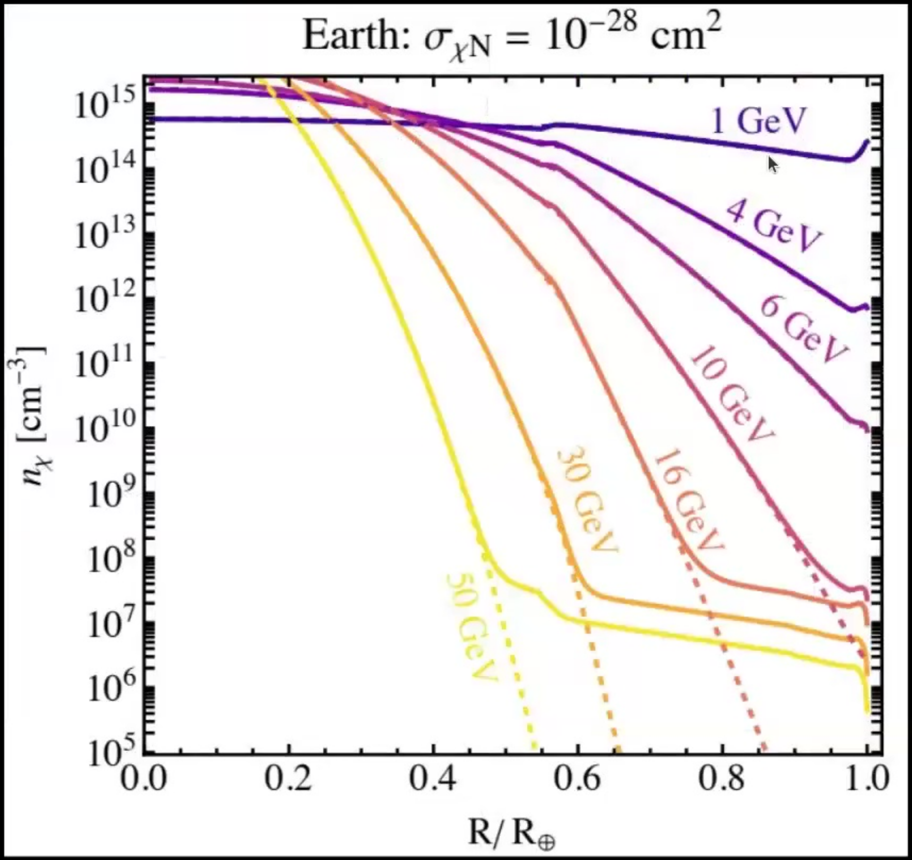
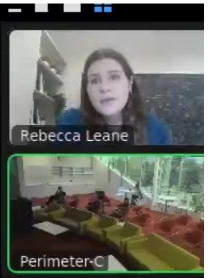
Floating dark matter: Earth



RL, Smirnov ‘22



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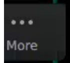
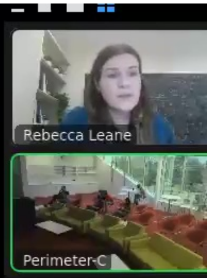
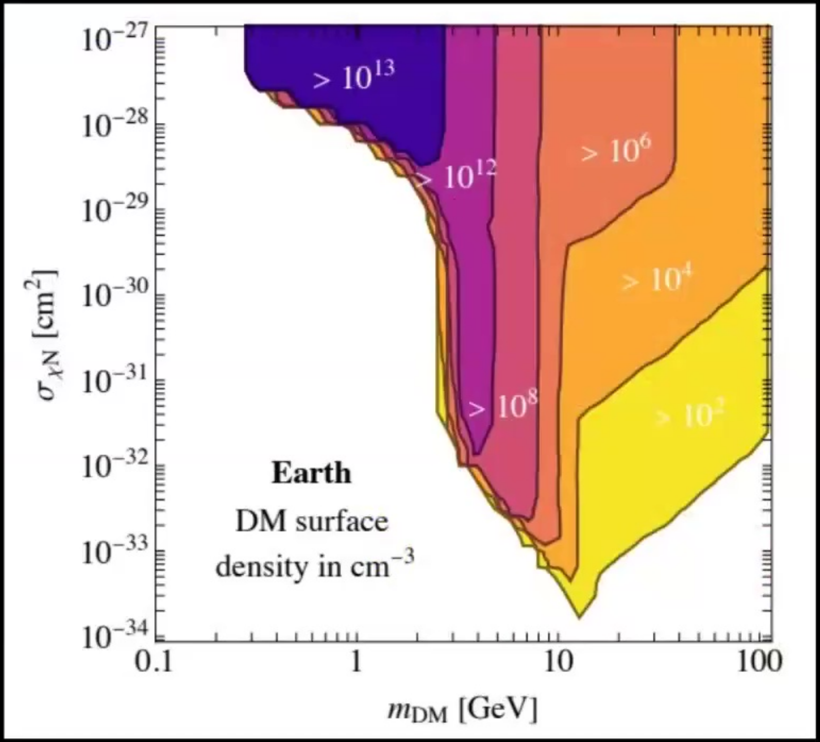


Floating dark matter: Earth





RL, Smirnov '22

See also e.g.
Neufeld, Farrar, McKee '18
Pospelov, Ramani '20

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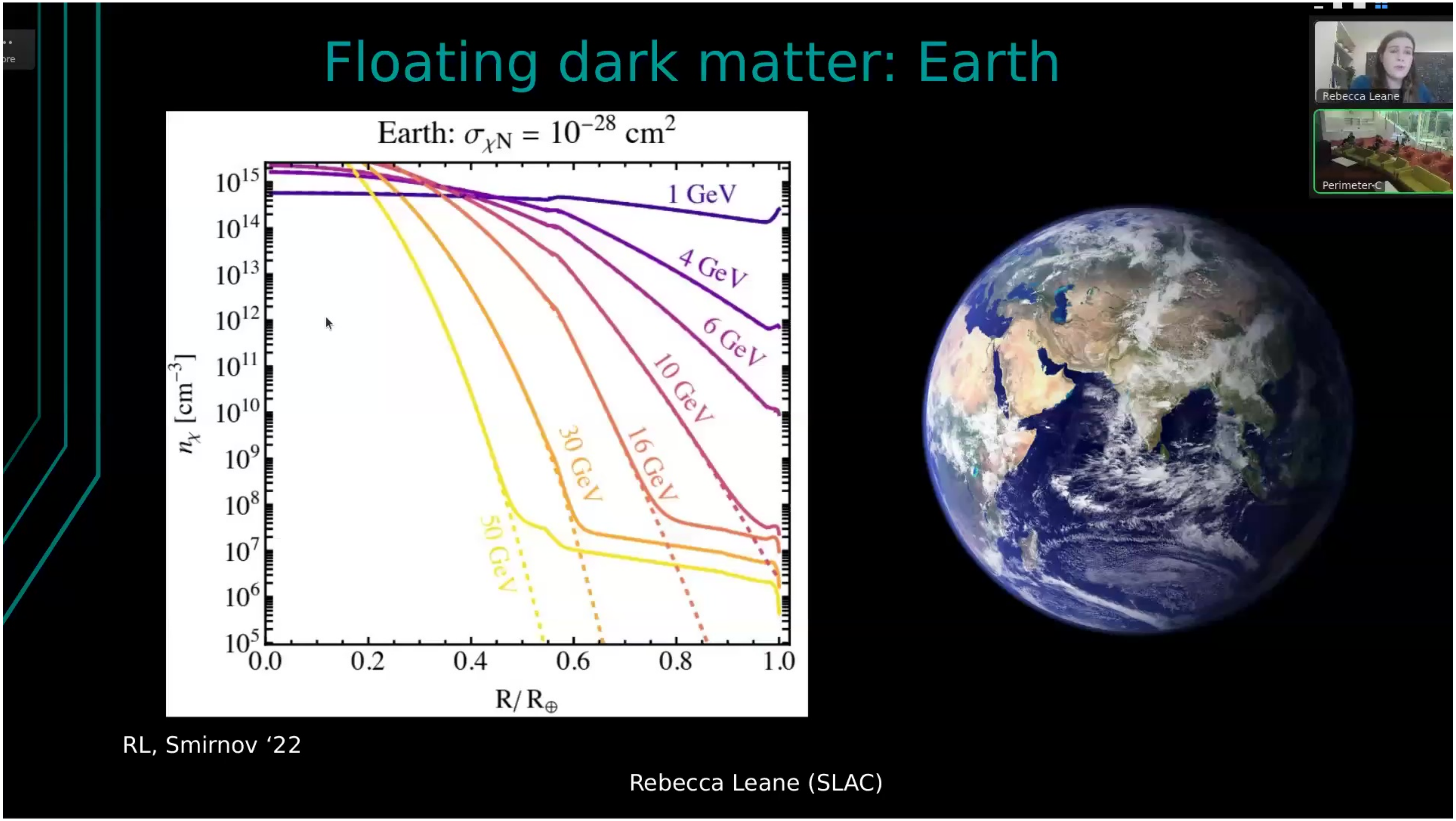

Floating dark matter: Earth

RL, Smirnov '22

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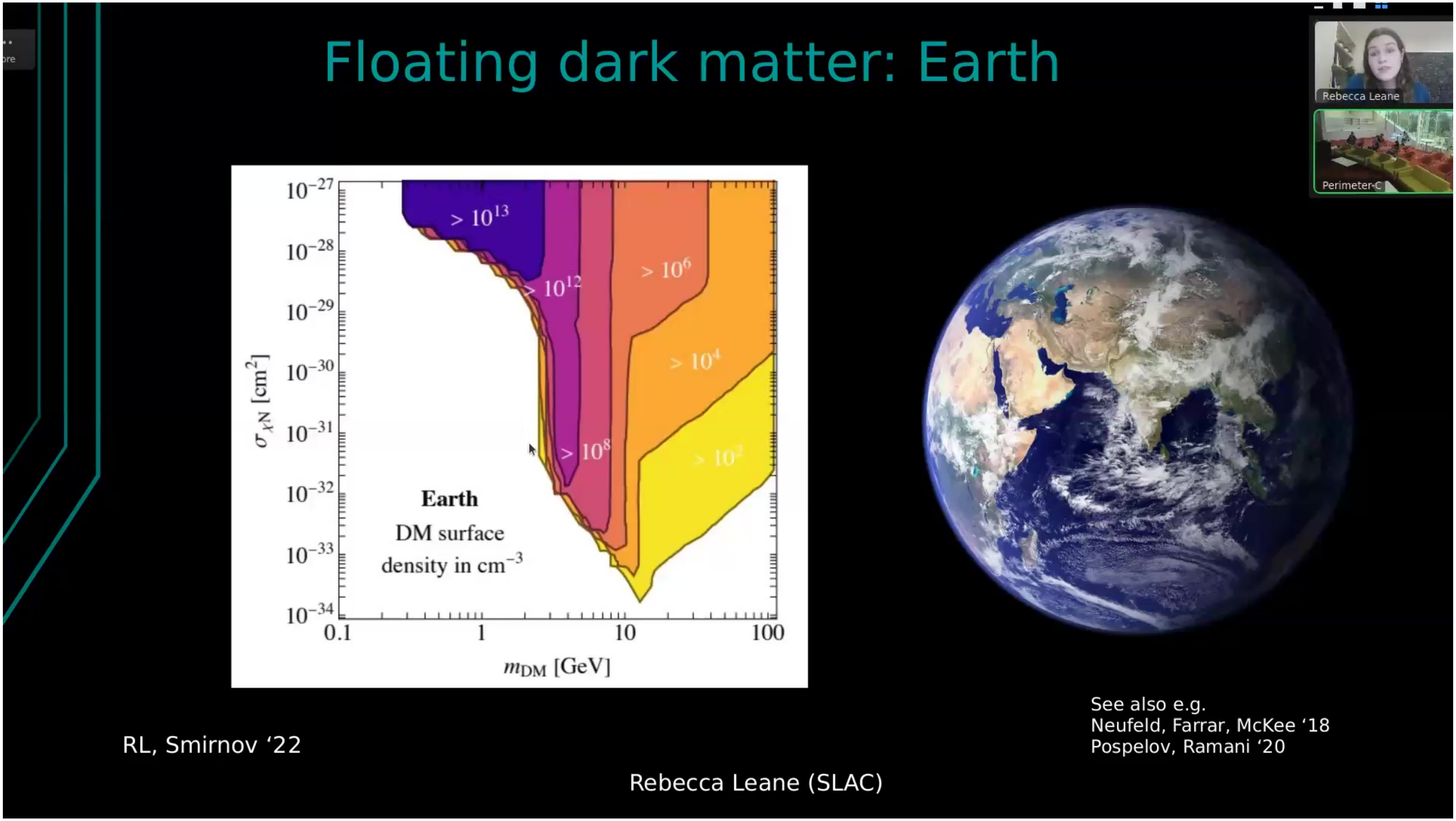

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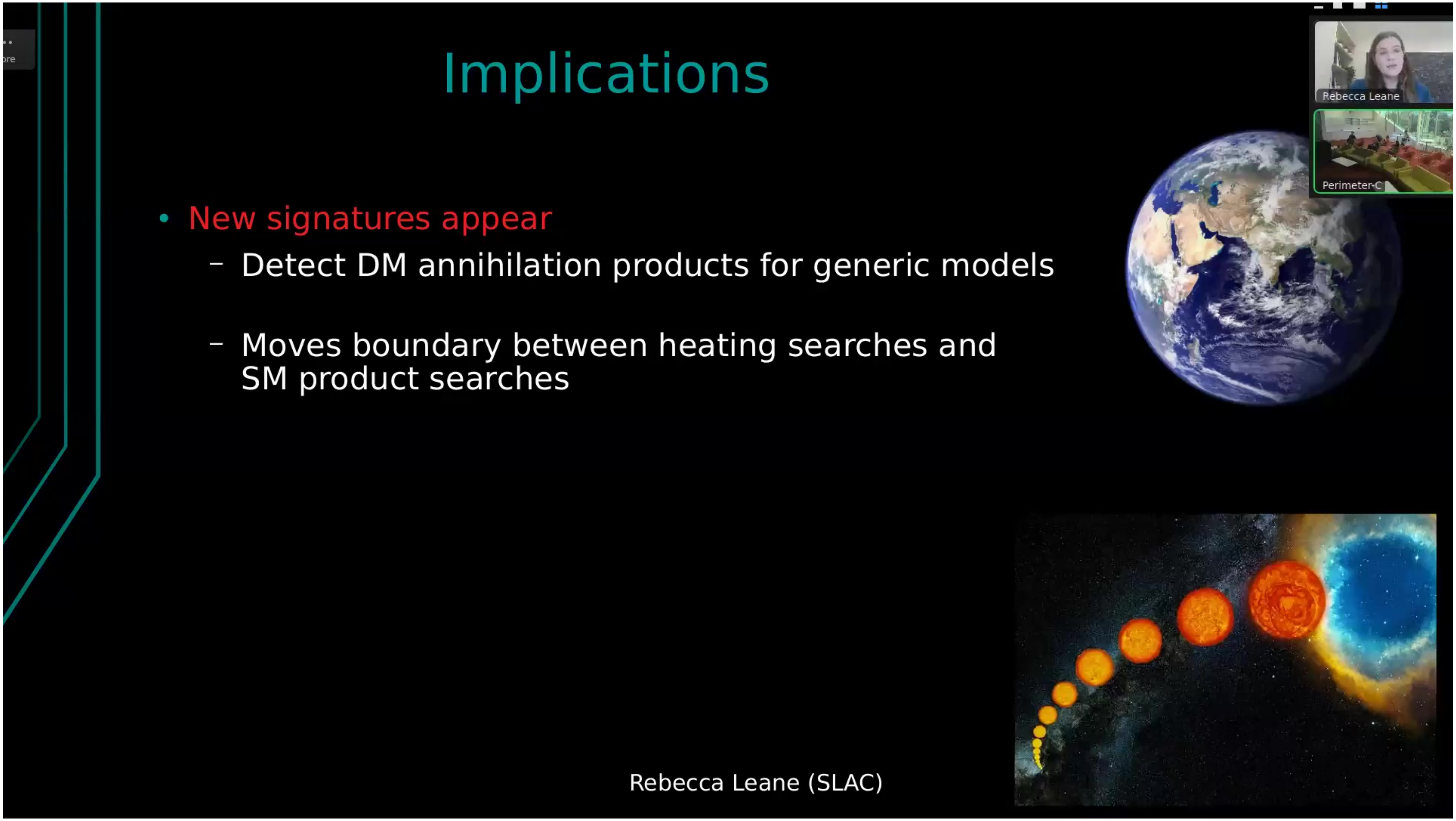

Implications

- New signatures appear
  - Detect DM annihilation products for generic models
  - Moves boundary between heating searches and SM product searches

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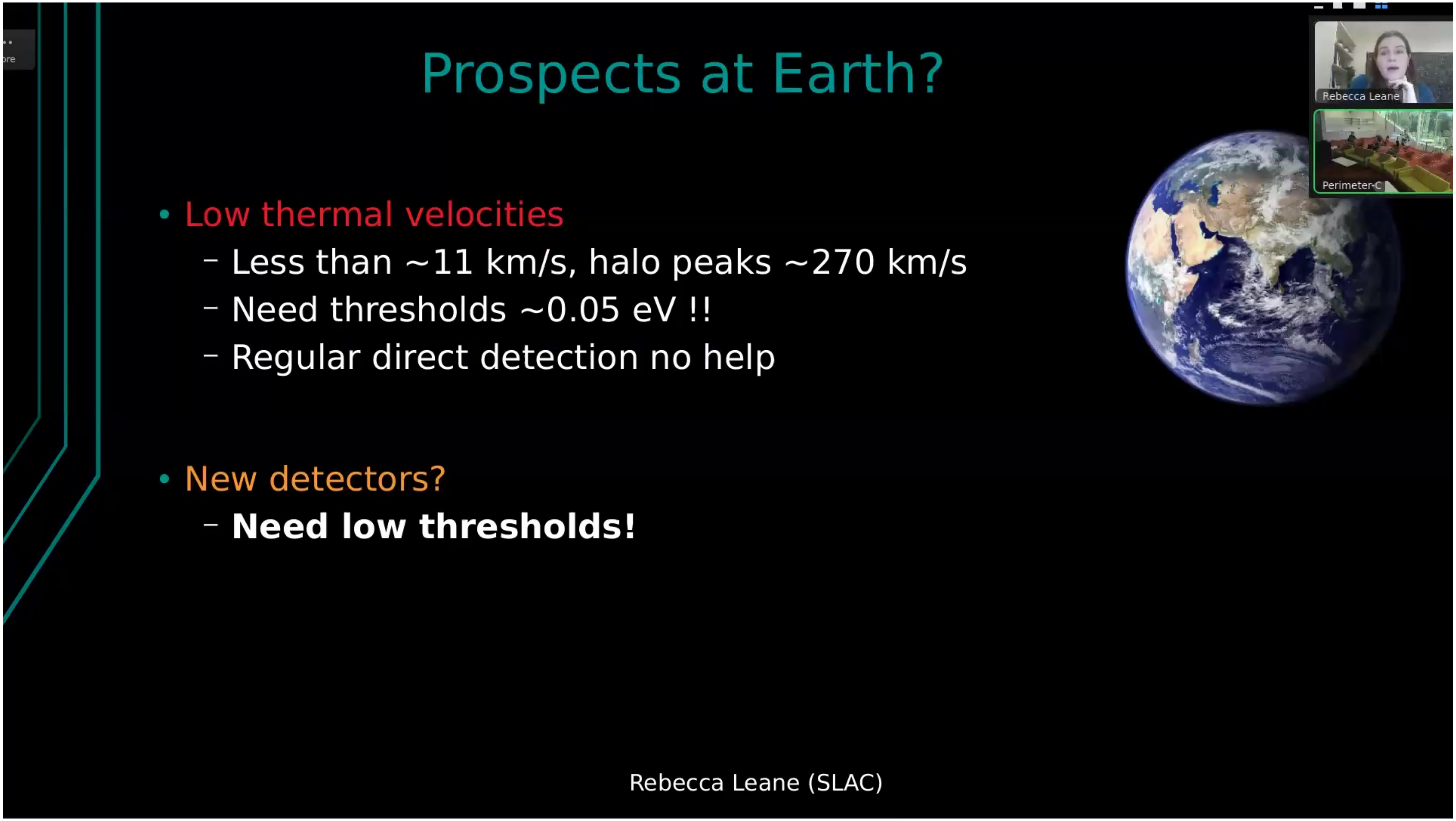

Prospects at Earth?

- Low thermal velocities
  - Less than ~11 km/s, halo peaks ~270 km/s
  - Need thresholds ~0.05 eV !!
  - Regular direct detection no help

- New detectors?
  - **Need low thresholds!**

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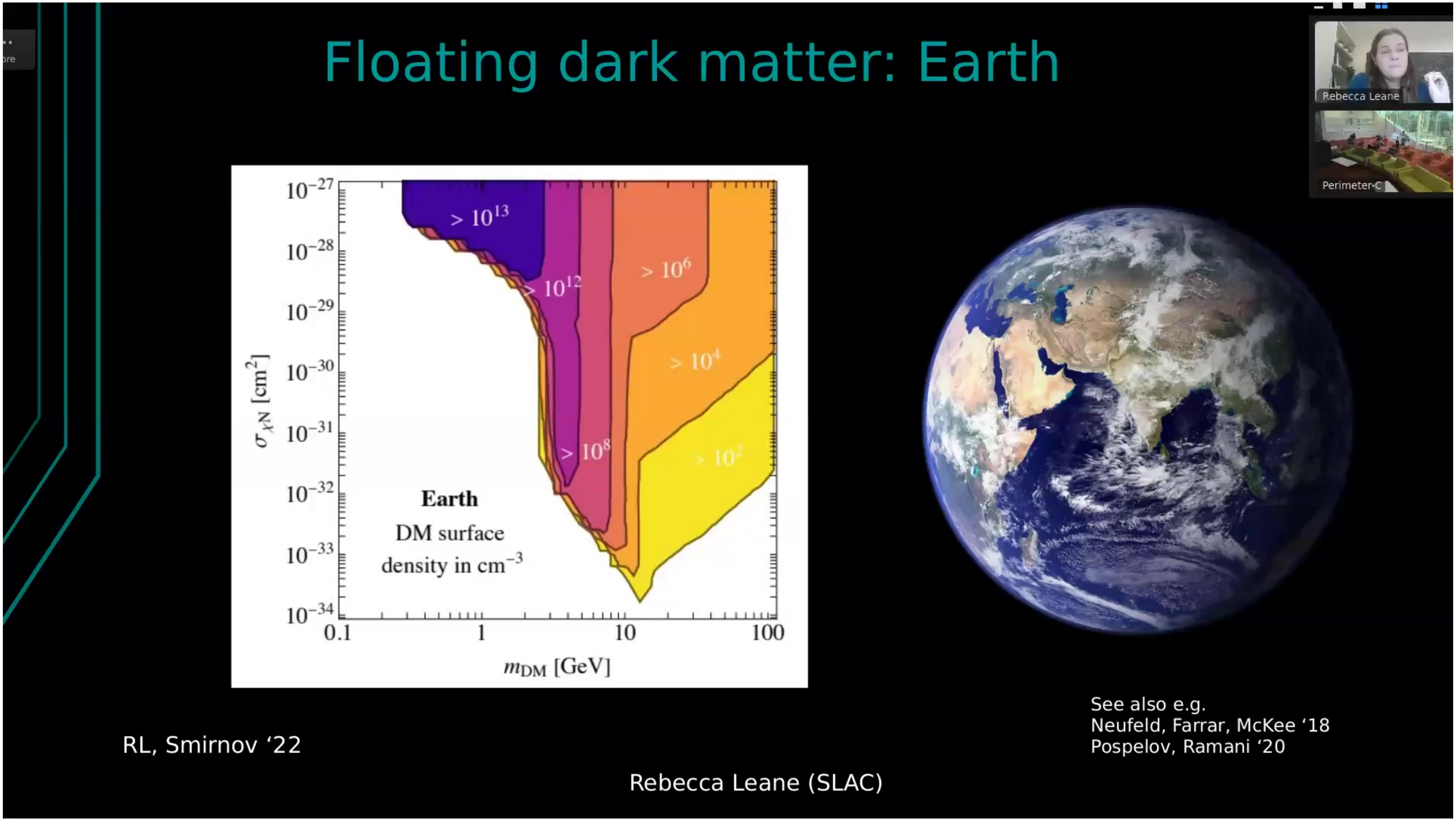

Floating dark matter: Earth

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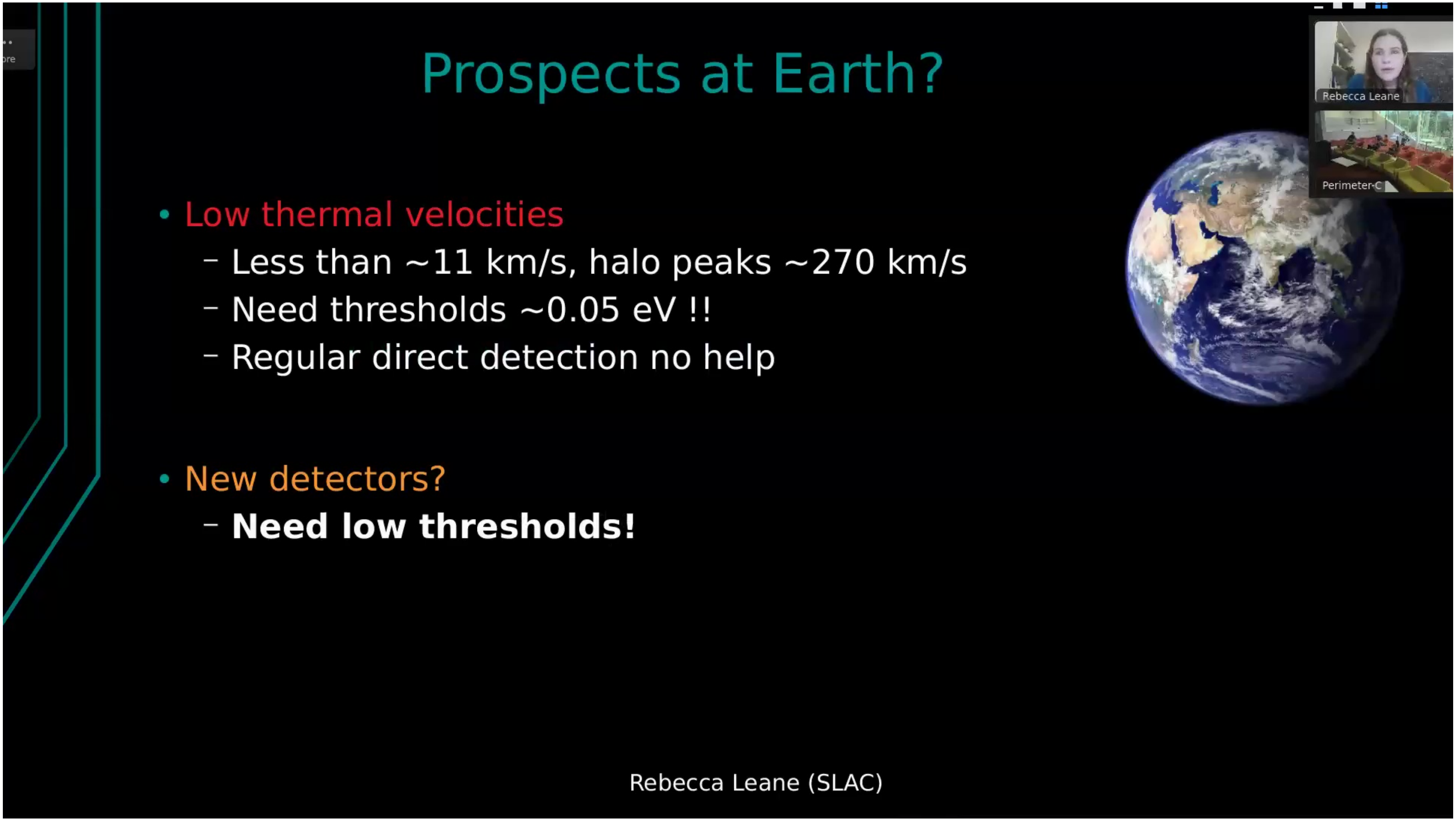

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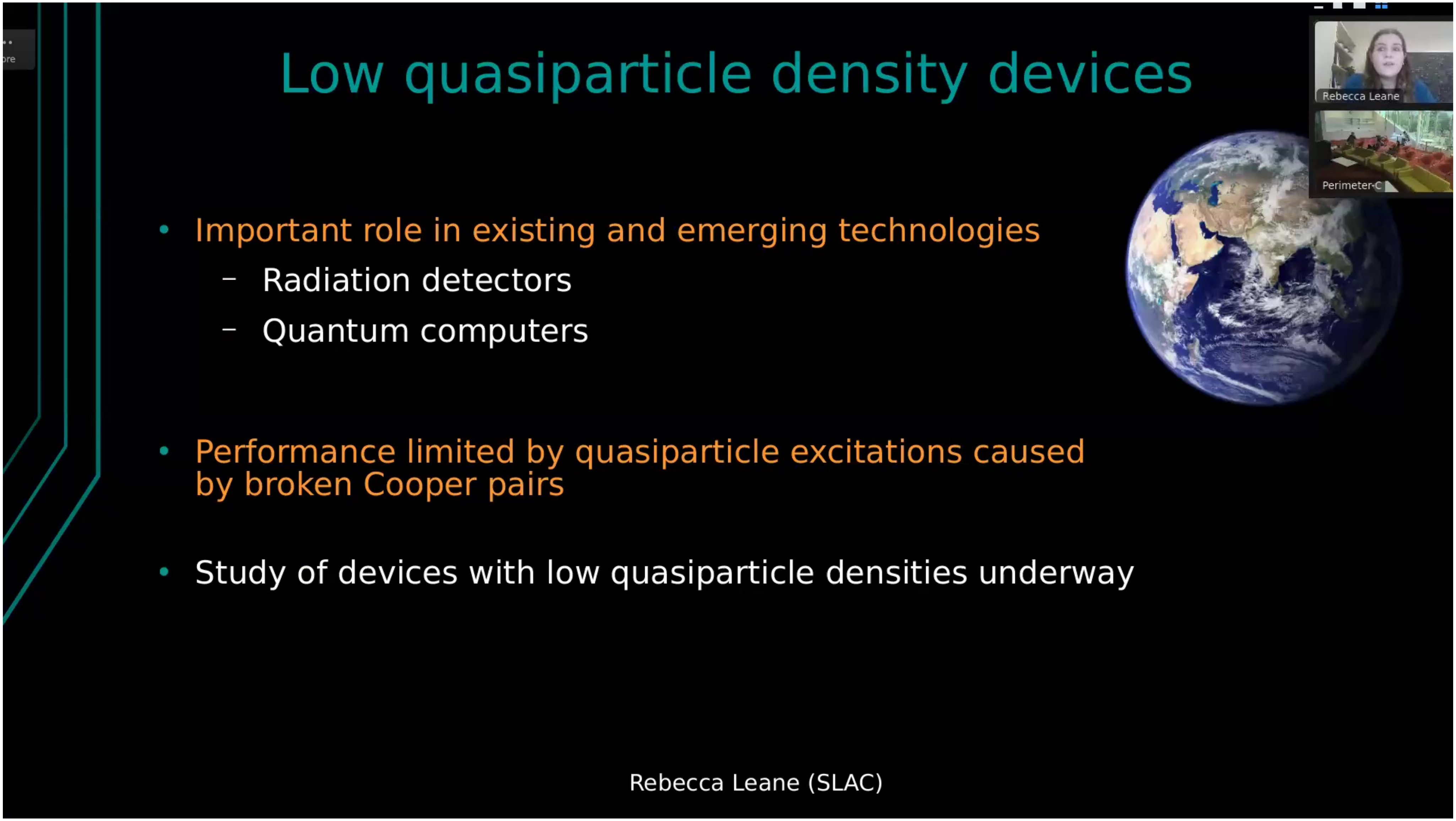

Low quasiparticle density devices

- Important role in existing and emerging technologies
  - Radiation detectors
  - Quantum computers
- Performance limited by quasiparticle excitations caused by broken Cooper pairs
- Study of devices with low quasiparticle densities underway

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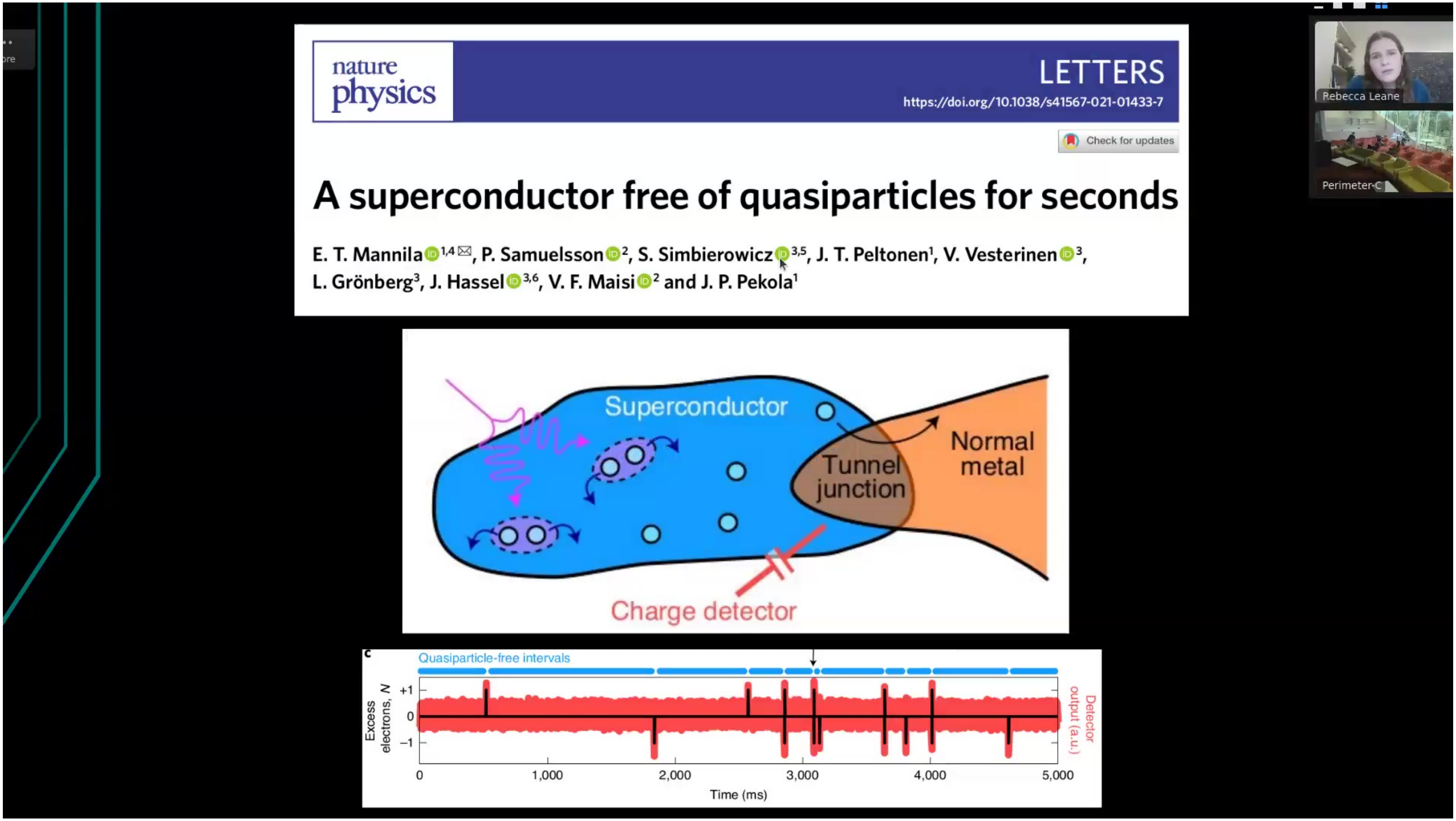


nature physics

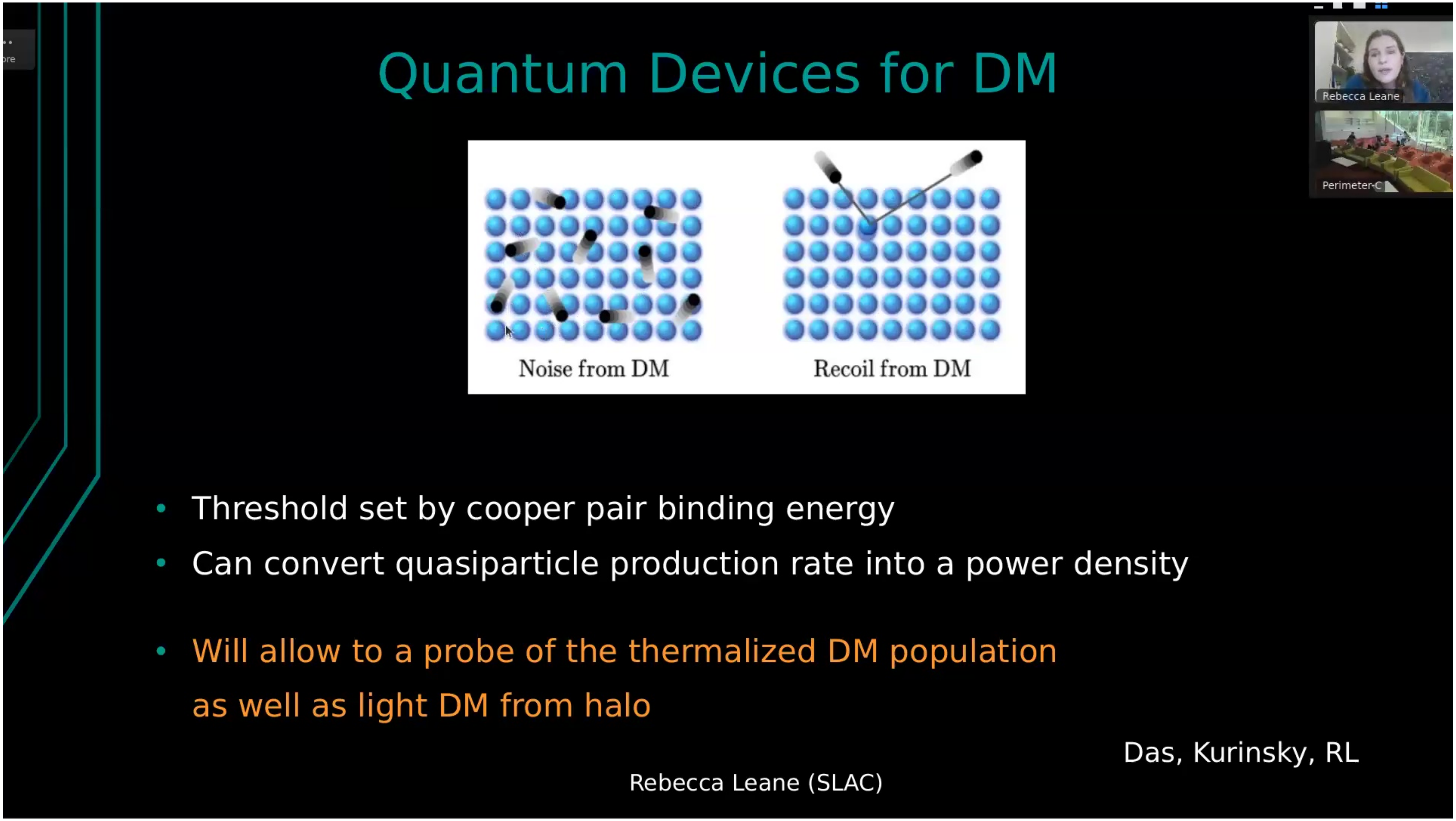
LETTERS

https://doi.org/10.1038/s41567-021-01433-7

Check for updates

A superconductor free of quasiparticles for seconds

E. T. Mannila[1,4], P. Samuelsson[2], S. Simbierowicz[3,5], J. T. Peltonen[1], V. Vesterinen[3], L. Grönberg[3], J. Hassel[3,6], V. F. Maisi[2] and J. P. Pekola[1]



Quantum Devices for DM

- Threshold set by cooper pair binding energy
- Can convert quasiparticle production rate into a power density

- Will allow to a probe of the thermalized DM population as well as light DM from halo

Das, Kurinsky, RL

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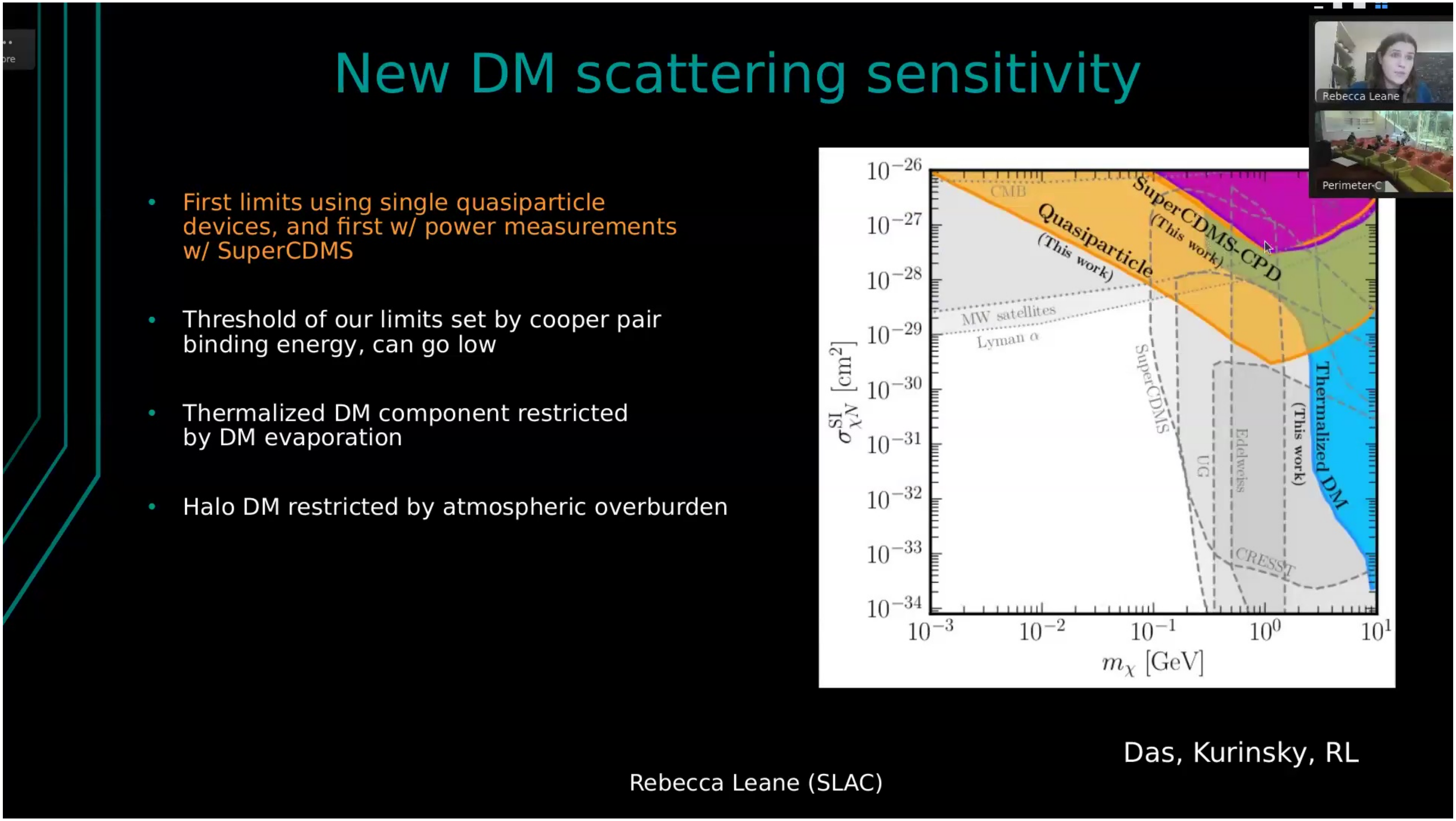

New DM scattering sensitivity

- First limits using single quasiparticle devices, and first w/ power measurements w/ SuperCDMS
- Threshold of our limits set by cooper pair binding energy, can go low
- Thermalized DM component restricted by DM evaporation
- Halo DM restricted by atmospheric overburden

Das, Kurinsky, RL

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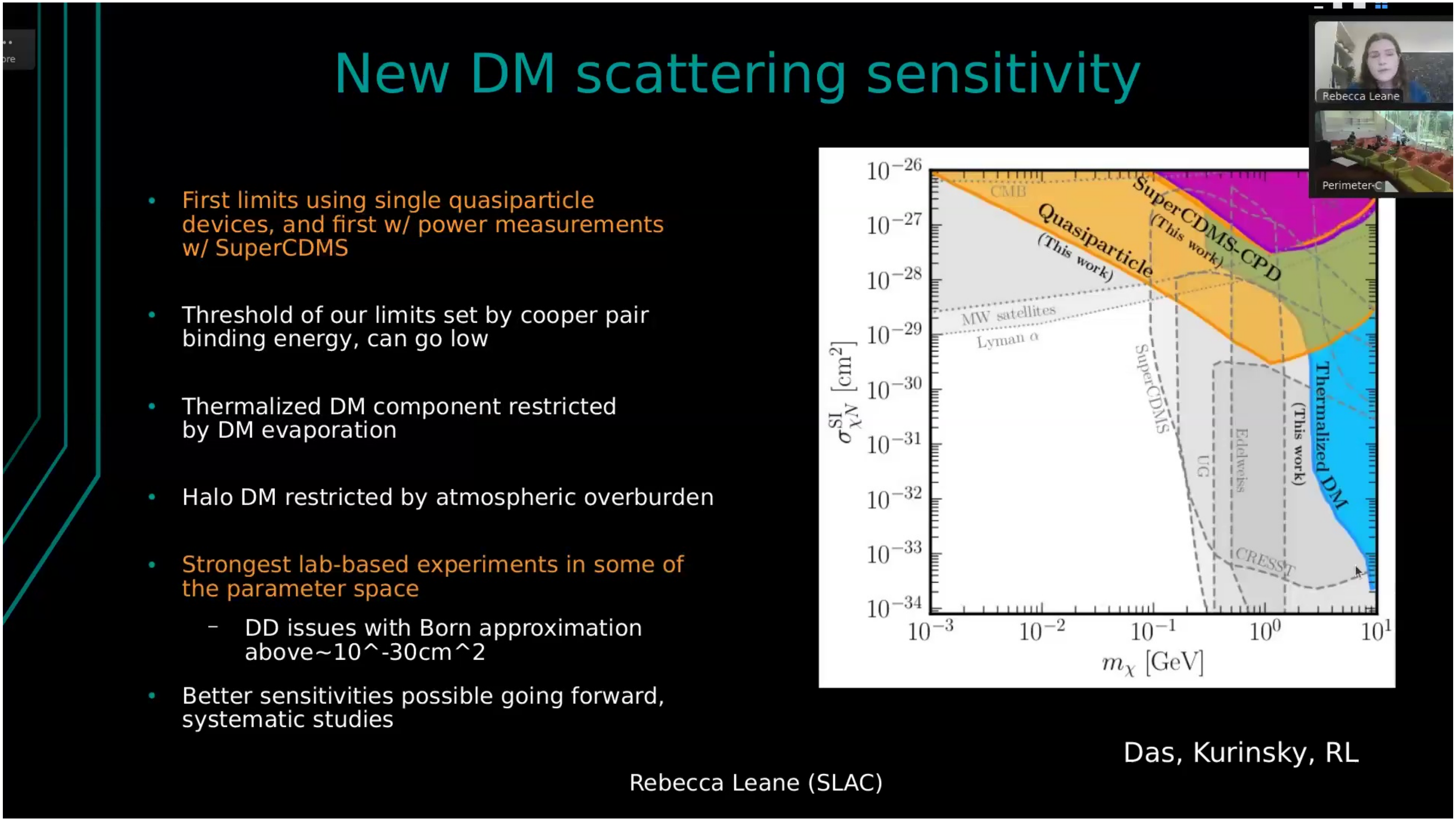

New DM scattering sensitivity

- First limits using single quasiparticle devices, and first w/ power measurements w/ SuperCDMS
- Threshold of our limits set by cooper pair binding energy, can go low
- Thermalized DM component restricted by DM evaporation
- Halo DM restricted by atmospheric overburden
- Strongest lab-based experiments in some of the parameter space
  - DD issues with Born approximation above~10^-30cm^2
- Better sensitivities possible going forward, systematic studies

Das, Kurinsky, RL

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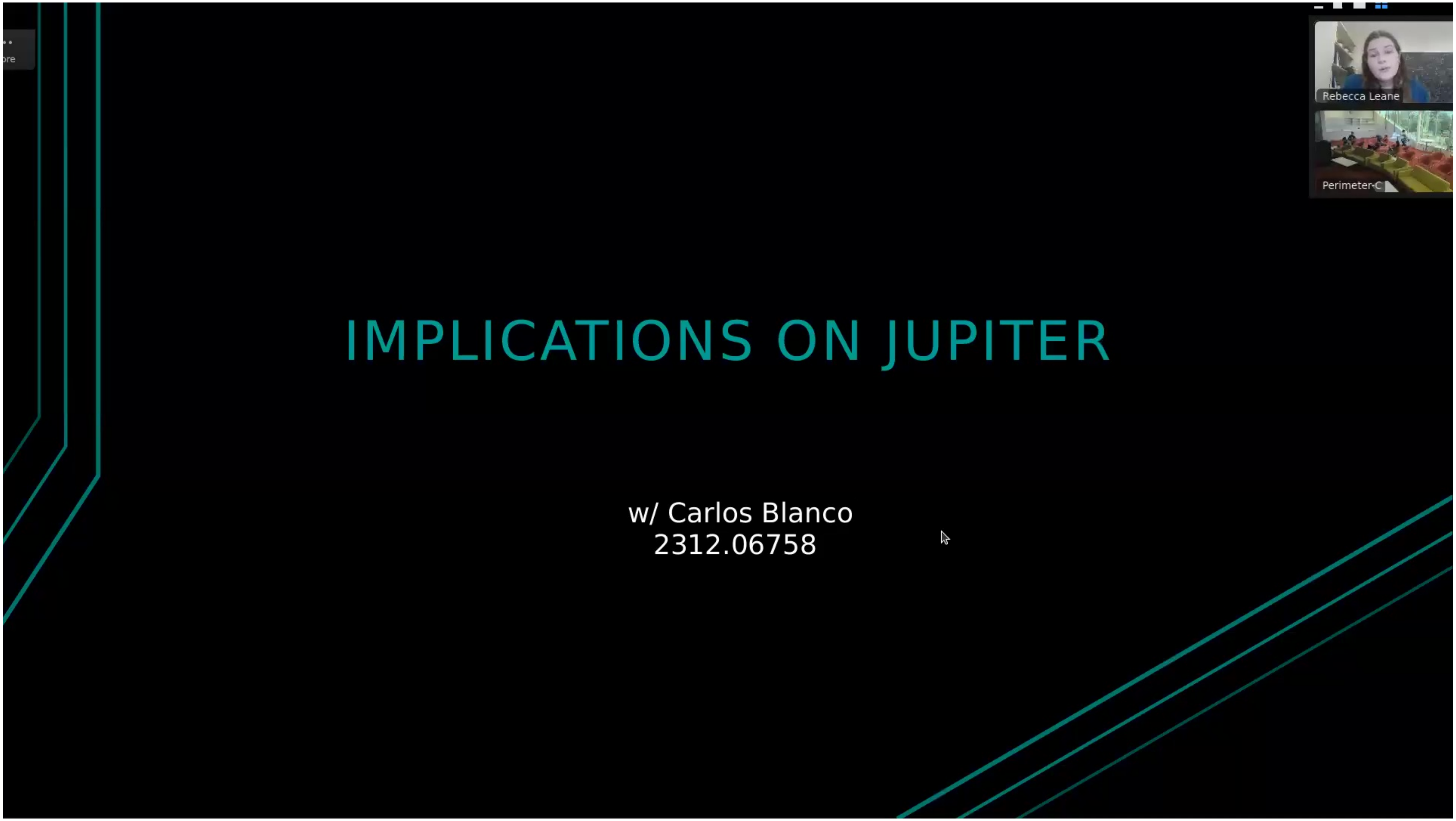
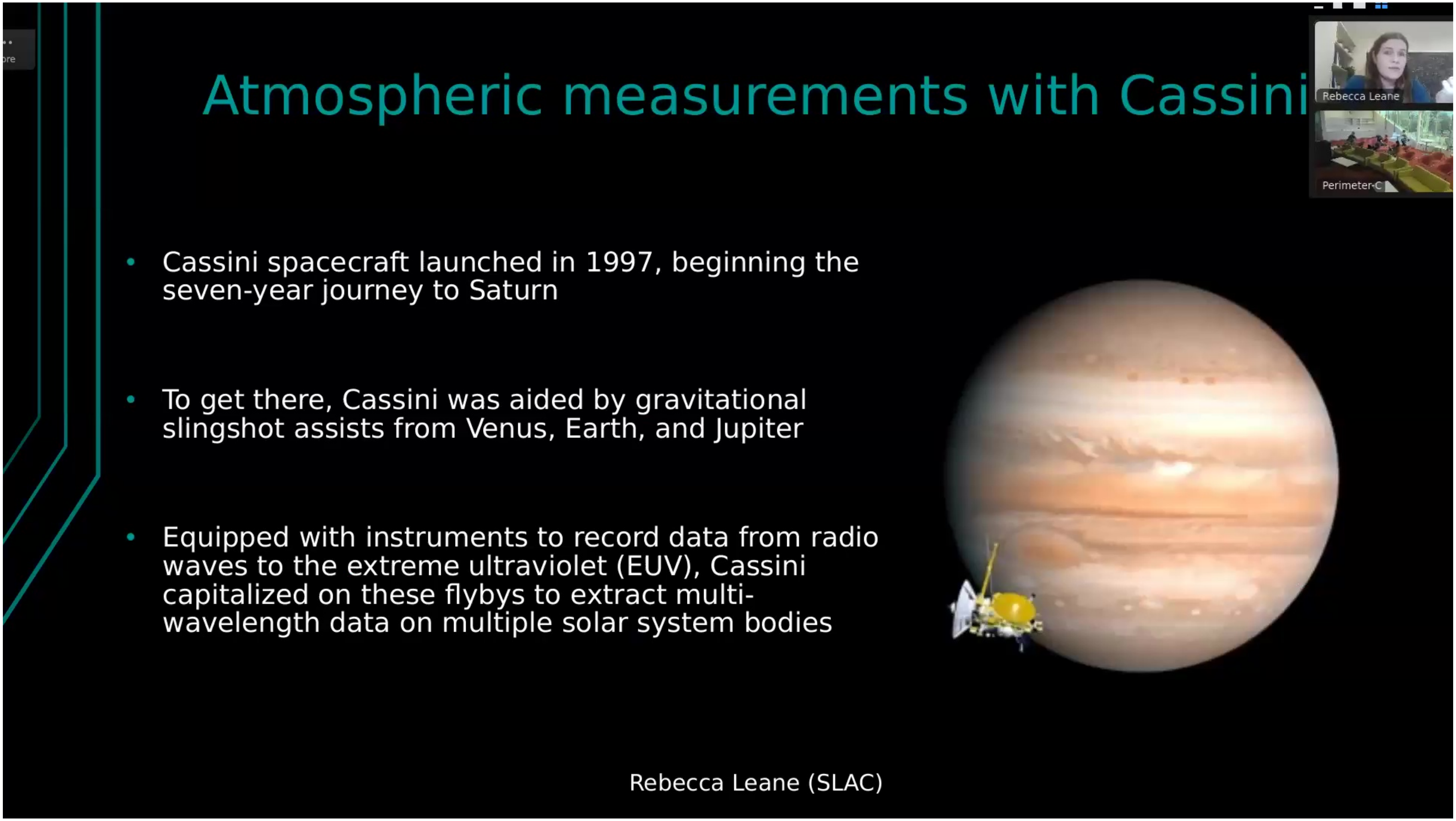


IMPLICATIONS ON JUPITER

w/ Carlos Blanco
2312.06758



Atmospheric measurements with Cassini

- Cassini spacecraft launched in 1997, beginning the seven-year journey to Saturn
- To get there, Cassini was aided by gravitational slingshot assists from Venus, Earth, and Jupiter
- Equipped with instruments to record data from radio waves to the extreme ultraviolet (EUV), Cassini capitalized on these flybys to extract multi-wavelength data on multiple solar system bodies

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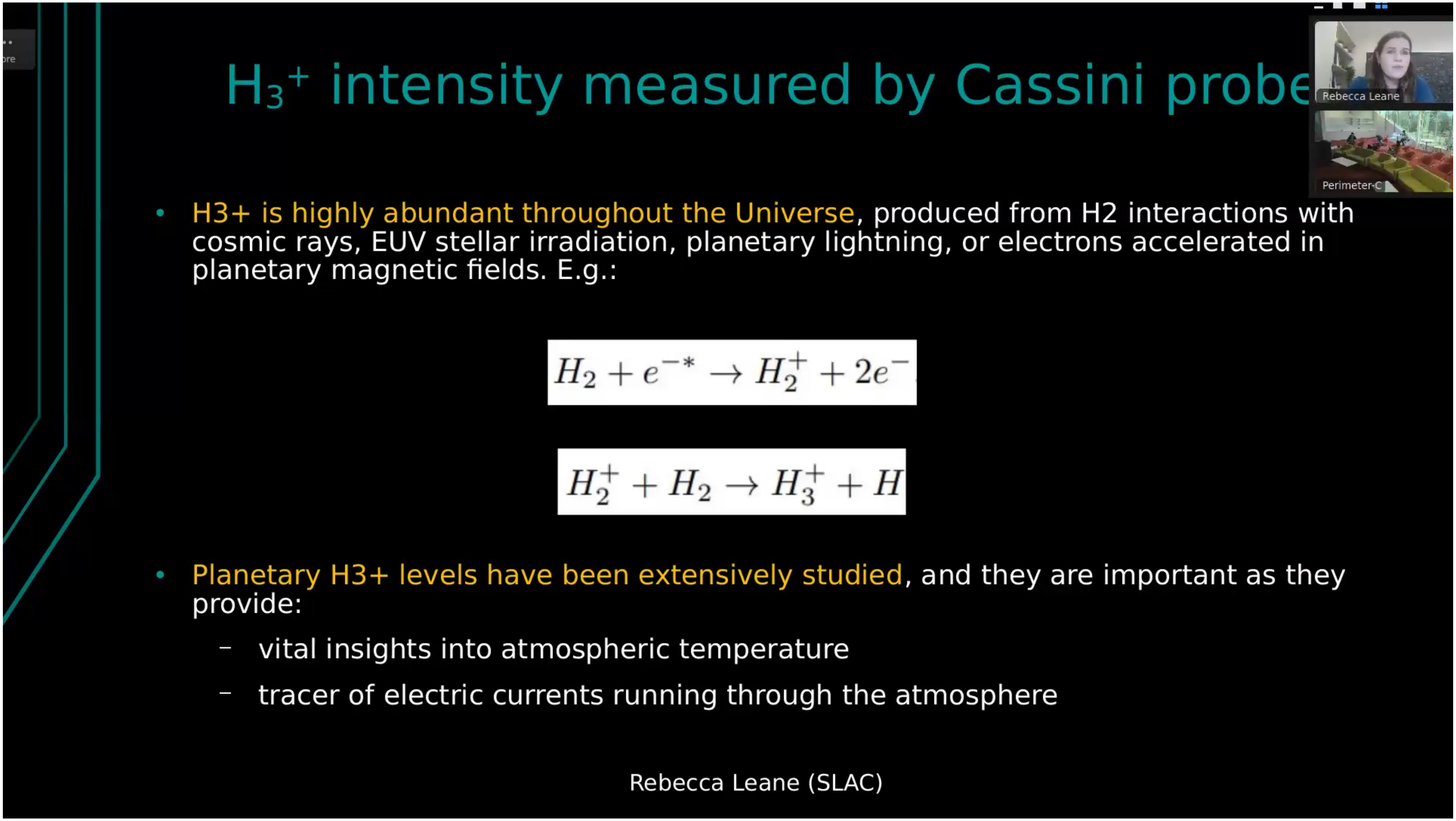

H_3^+ intensity measured by Cassini probe

- H3+ is highly abundant throughout the Universe, produced from H2 interactions with cosmic rays, EUV stellar irradiation, planetary lightning, or electrons accelerated in planetary magnetic fields. E.g.:

$$H_2 + e^{-*} \rightarrow H_2^+ + 2e^-$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

- Planetary H3+ levels have been extensively studied, and they are important as they provide:
  - vital insights into atmospheric temperature
  - tracer of electric currents running through the atmosphere

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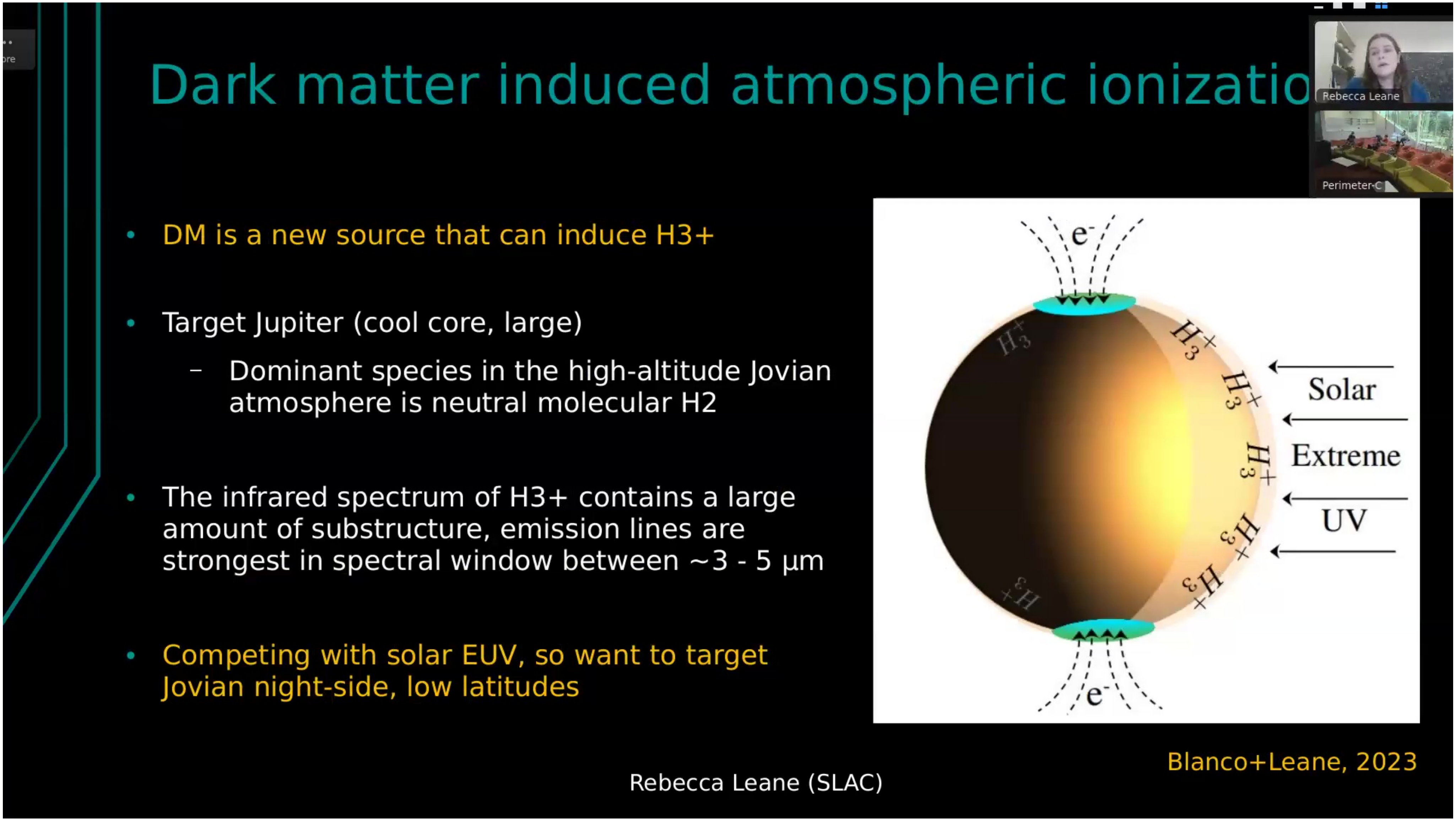
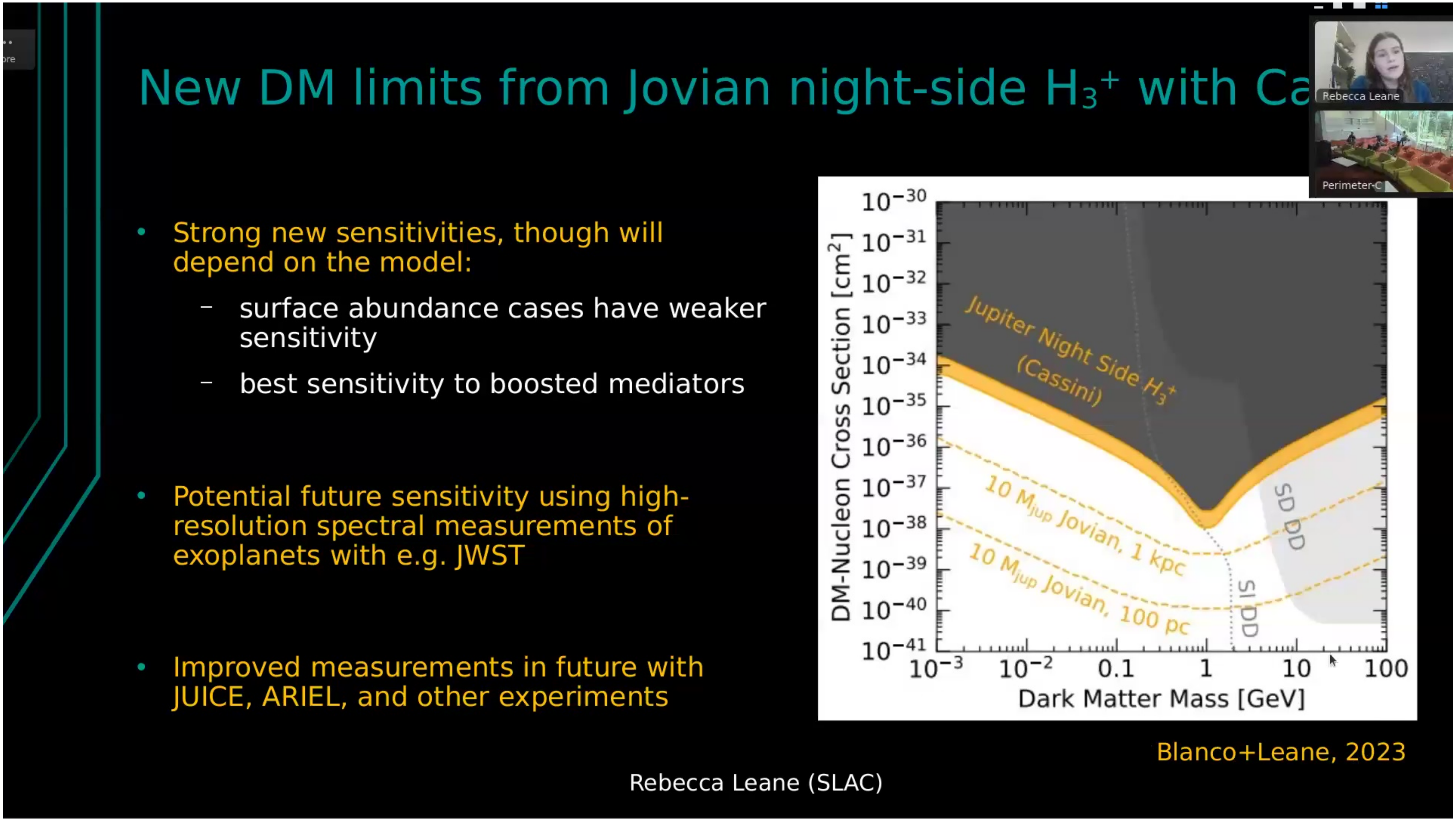


Dark matter induced atmospheric ionizatio

- DM is a new source that can induce H3+
- Target Jupiter (cool core, large)
  - Dominant species in the high-altitude Jovian atmosphere is neutral molecular H2
- The infrared spectrum of H3+ contains a large amount of substructure, emission lines are strongest in spectral window between ~3 - 5 µm
- Competing with solar EUV, so want to target Jovian night-side, low latitudes

Blanco+Leane, 2023

Rebecca Leane (SLAC)



New DM limits from Jovian night-side H_3^+ with Ca

- Strong new sensitivities, though will depend on the model:
  - surface abundance cases have weaker sensitivity
  - best sensitivity to boosted mediators
- Potential future sensitivity using high-resolution spectral measurements of exoplanets with e.g. JWST
- Improved measurements in future with JUICE, ARIEL, and other experiments

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Summary

- DM distributions important for signals in celestial bodies
- Derived general framework, including diffusion, gravity, non-equilibrium DM
- Observe large surface abundances, especially for light DM
  - More than about 14 orders of magnitude above halo densities
- New search strategies!
  - Low quasiparticle density devices for DM, improvement in future
  - H3+ atmospheric measurements for DM, improvement in future
- Lots of implications, plenty of new opportunities!

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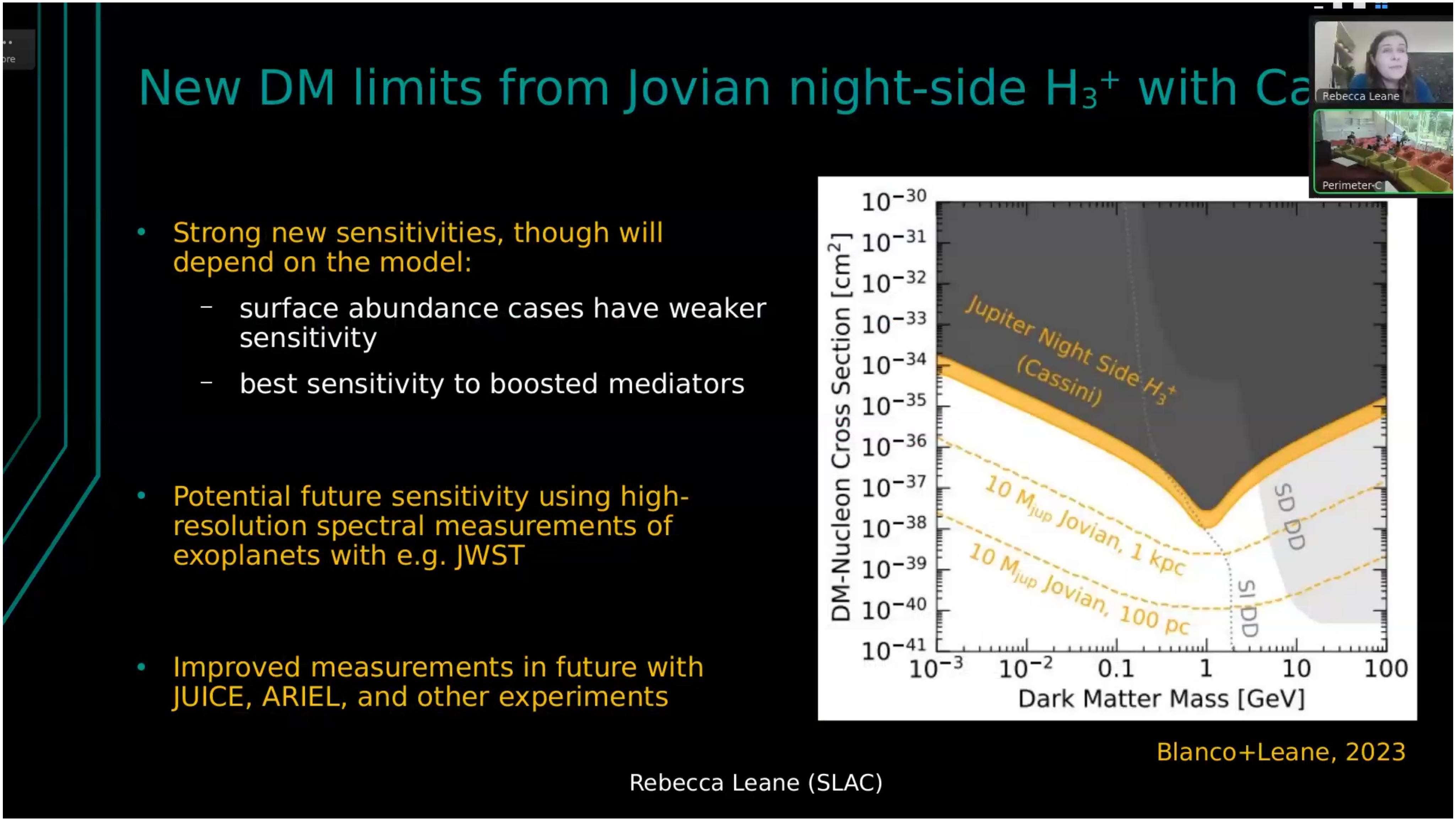

New DM limits from Jovian night-side H_3^+ with Ca

- Strong new sensitivities, though will depend on the model:
  - surface abundance cases have weaker sensitivity
  - best sensitivity to boosted mediators
- Potential future sensitivity using high-resolution spectral measurements of exoplanets with e.g. JWST
- Improved measurements in future with JUICE, ARIEL, and other experiments

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