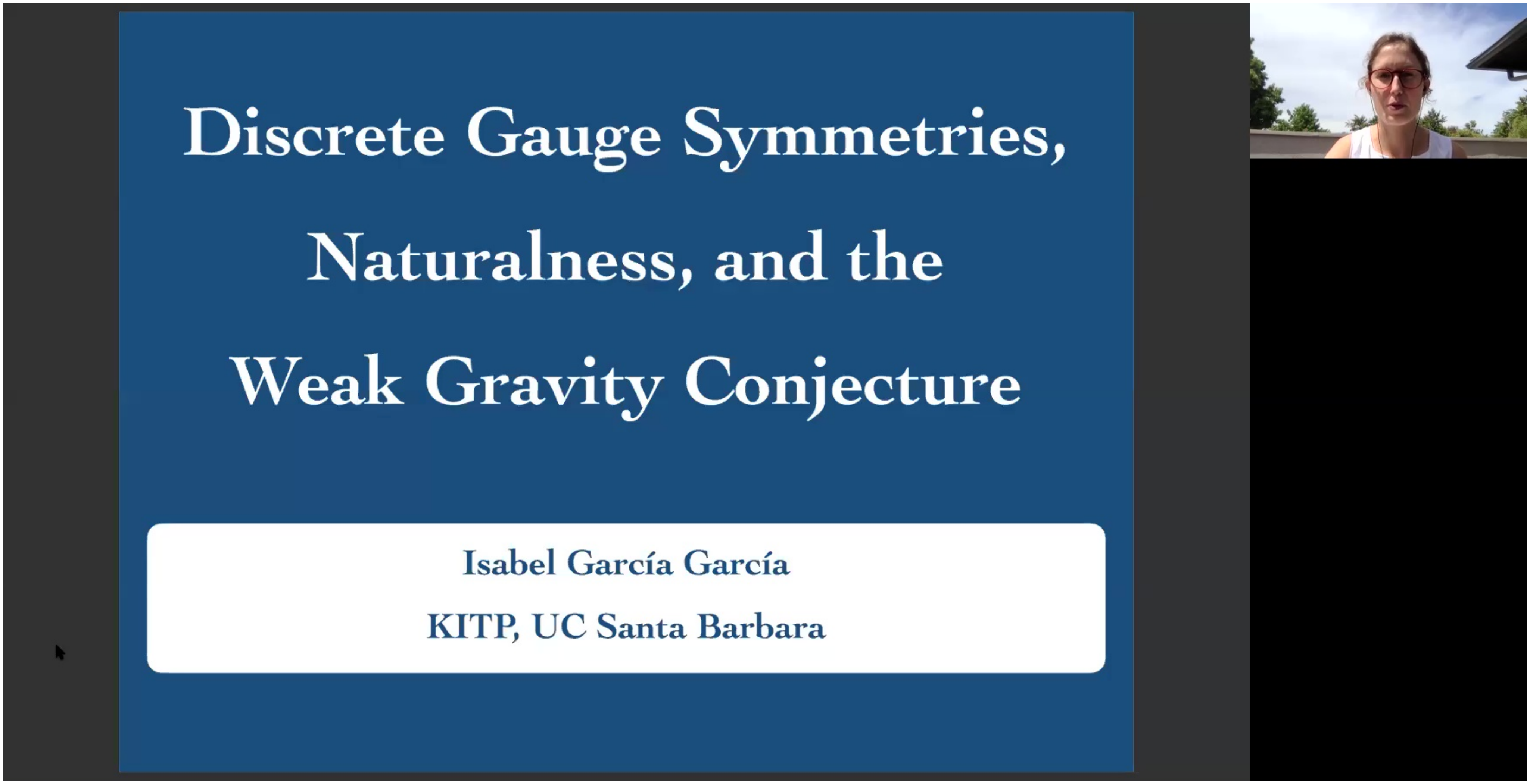
Title: The Weak Gravity Conjecture, Naturalness, and Discrete Gauge Symmetries

Speakers: Isabel Garcia Garcia

Series: Particle Physics

Date: June 02, 2020 - 2:00 PM

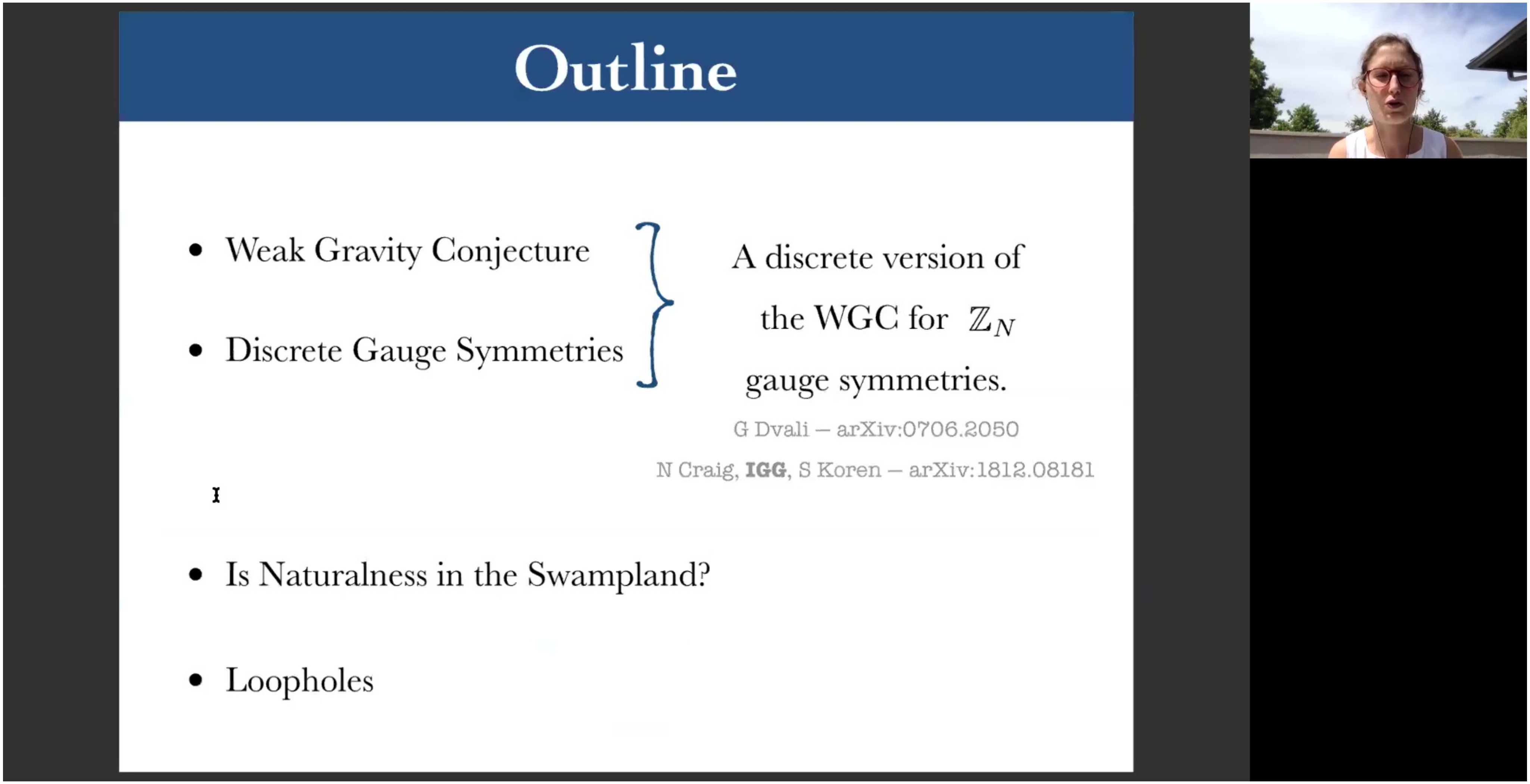
URL: http://pirsa.org/20030118



Discrete Gauge Symmetries, Naturalness, and the Weak Gravity Conjecture

Isabel García García

KITP, UC Santa Barbara



Outline

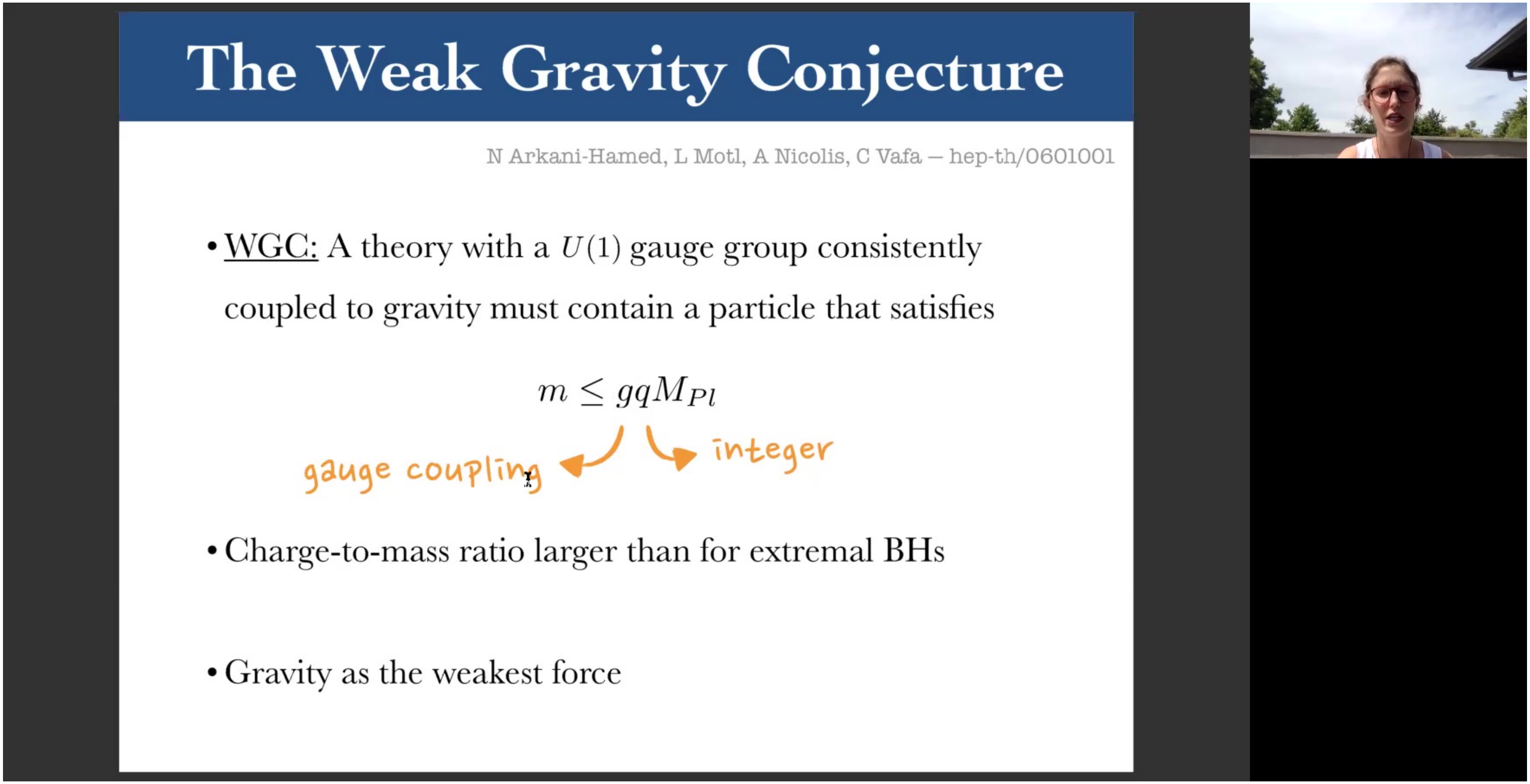
- Weak Gravity Conjecture
- Discrete Gauge Symmetries

A discrete version of the WGC for $\mathbb{Z}_N$ gauge symmetries.

G Dvali – arXiv:0706.2050

N Craig, **IGG**, S Koren – arXiv:1812.08181

- Is Naturalness in the Swampland?
- Loopholes



The Weak Gravity Conjecture

N Arkani-Hamed, L Motl, A Nicolis, C Vafa — hep-th/0601001

- WGC: A theory with a $U(1)$ gauge group consistently coupled to gravity must contain a particle that satisfies

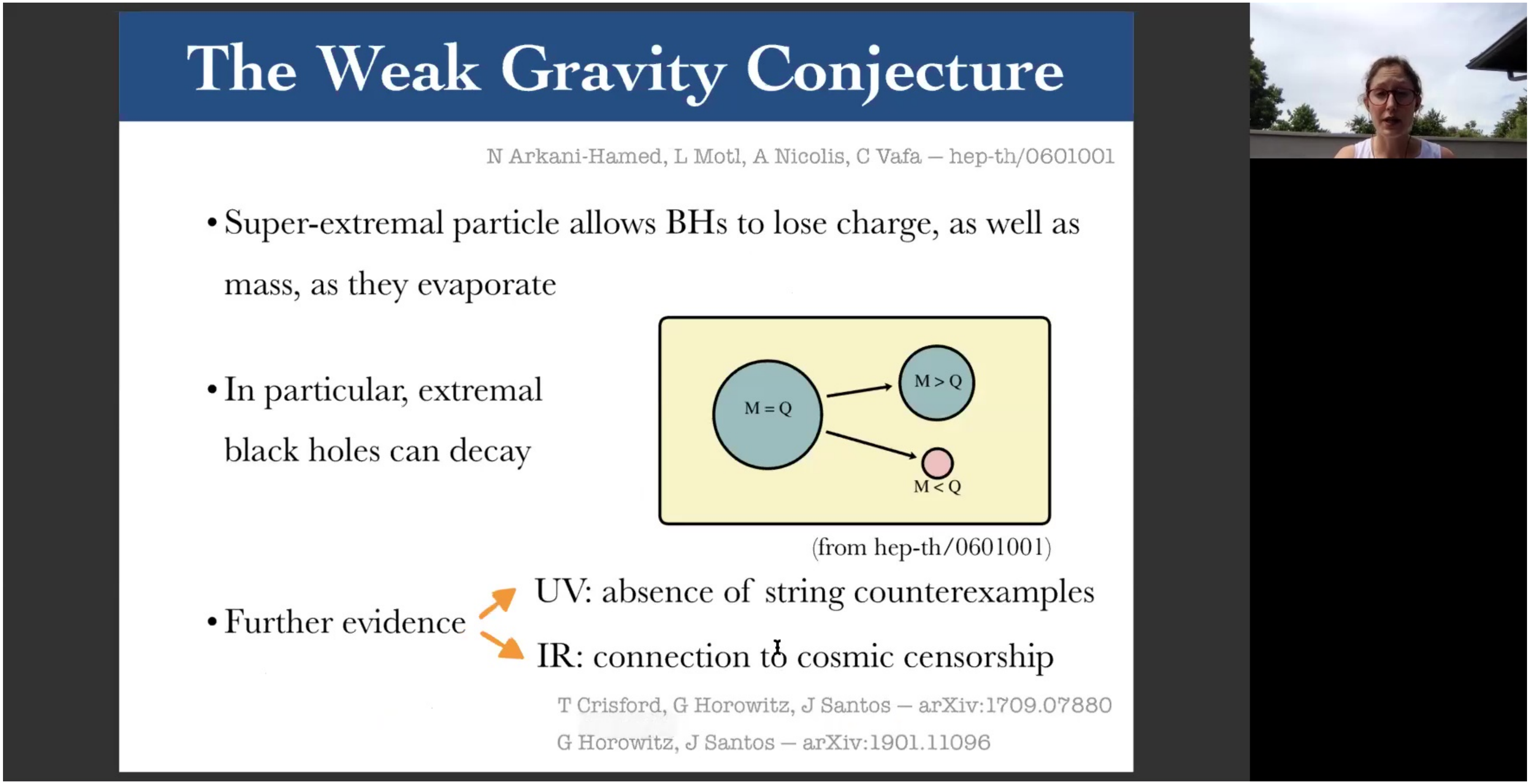
$$m \leq gqM_{Pl}$$

gauge coupling

integer

- Charge-to-mass ratio larger than for extremal BHs

- Gravity as the weakest force



The Weak Gravity Conjecture

N Arkani-Hamed, L Motl, A Nicolis, C Vafa — hep-th/0601001

- Super-extremal particle allows BHs to lose charge, as well as mass, as they evaporate

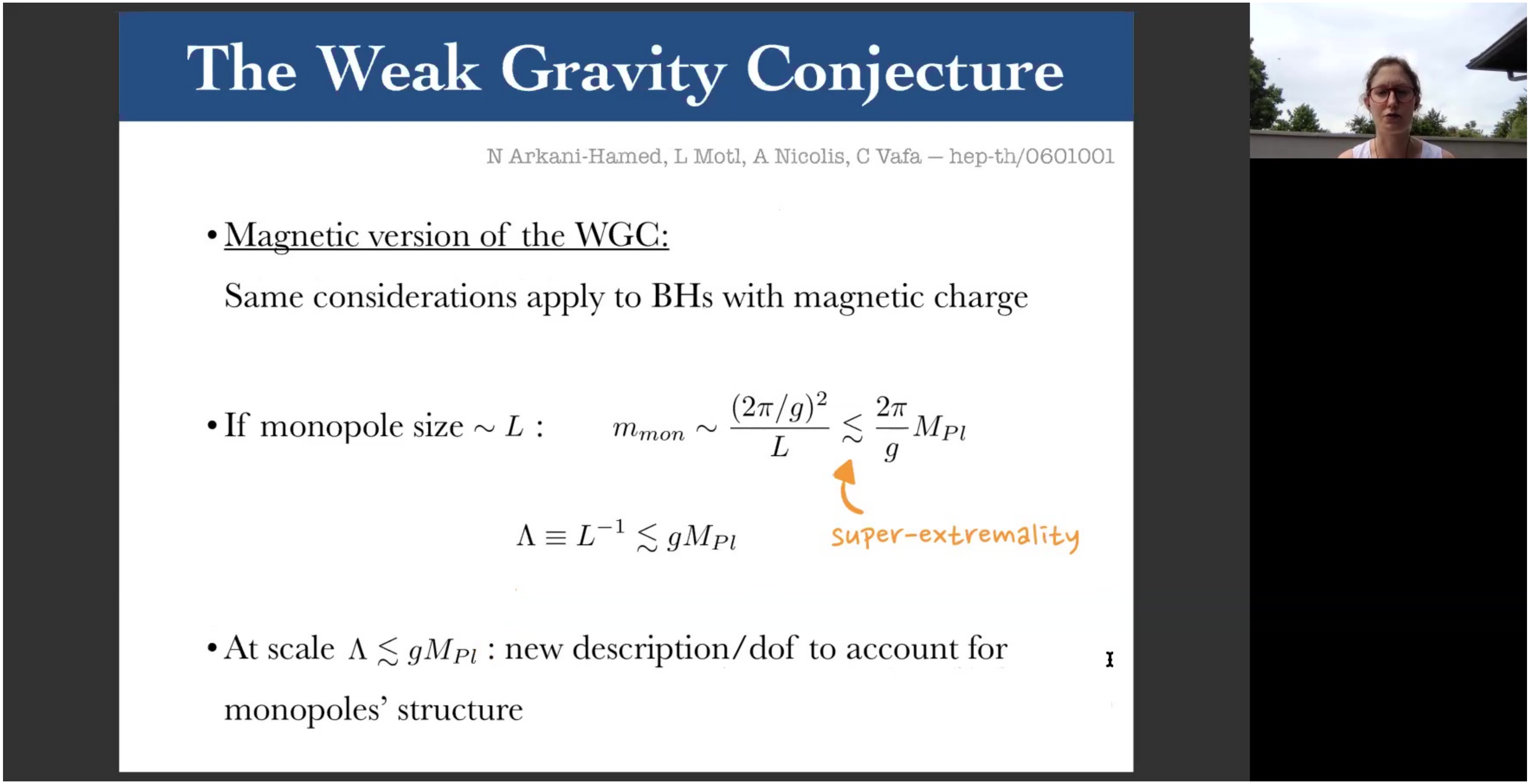
- In particular, extremal black holes can decay

(from hep-th/0601001)

- Further evidence
  - UV: absence of string counterexamples
  - IR: connection to cosmic censorship

T Crisford, G Horowitz, J Santos — arXiv:1709.07880

G Horowitz, J Santos — arXiv:1901.11096



The Weak Gravity Conjecture

N Arkani-Hamed, L Motl, A Nicolis, C Vafa — hep-th/0601001

- Magnetic version of the WGC:

  Same considerations apply to BHs with magnetic charge

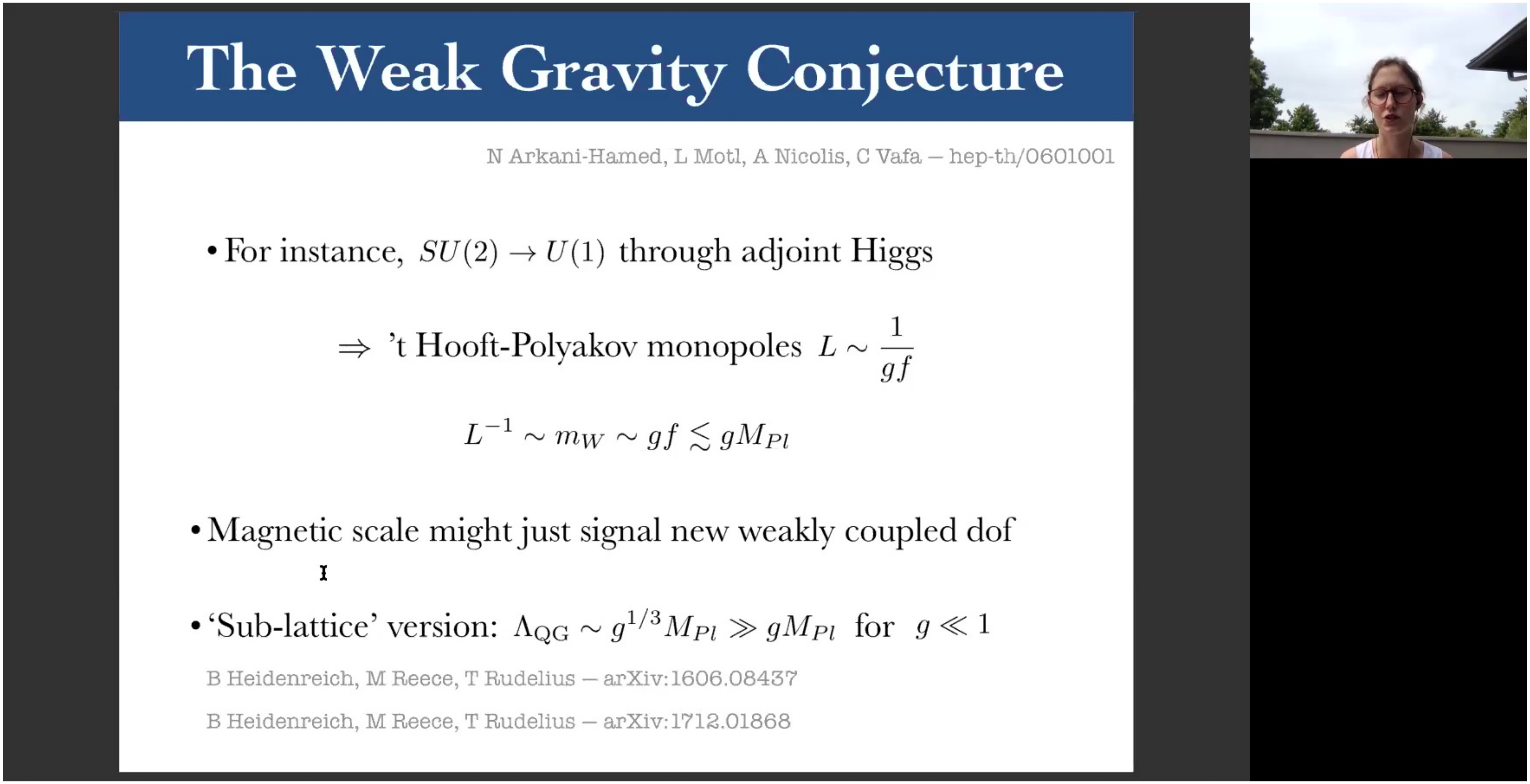
- If monopole size $\sim L$:

$$m_{mon} \sim \frac{(2\pi/g)^2}{L} \lesssim \frac{2\pi}{g} M_{Pl}$$

$$\Lambda \equiv L^{-1} \lesssim g M_{Pl}$$

super-extremality

- At scale $\Lambda \lesssim g M_{Pl}$: new description/dof to account for monopoles' structure



The Weak Gravity Conjecture

N Arkani-Hamed, L Motl, A Nicolis, C Vafa – hep-th/0601001

- For instance, $SU(2) \to U(1)$ through adjoint Higgs

$$\Rightarrow \text{ 't Hooft-Polyakov monopoles } L \sim \frac{1}{gf}$$

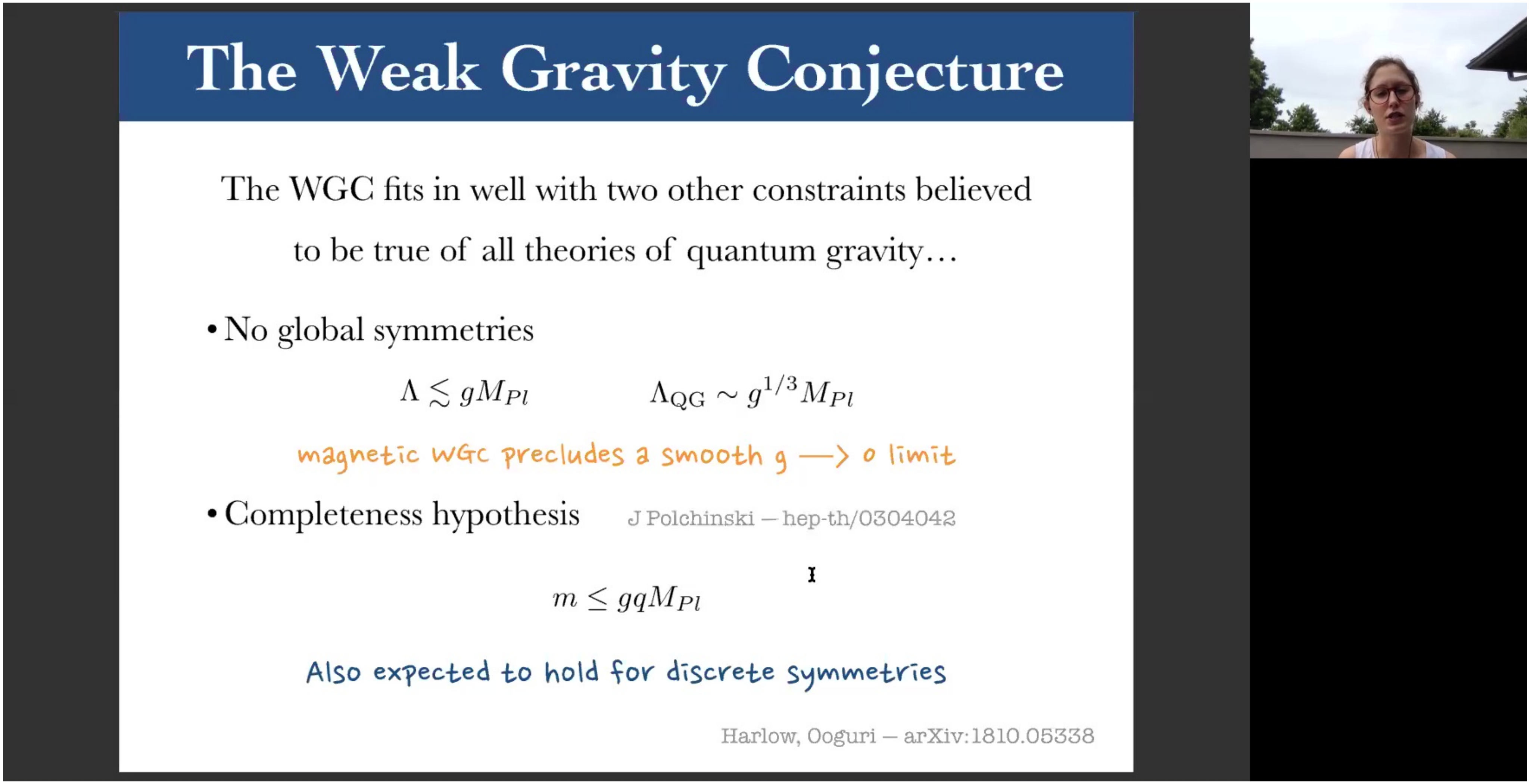
$$L^{-1} \sim m_W \sim gf \lesssim gM_{Pl}$$

- Magnetic scale might just signal new weakly coupled dof

- 'Sub-lattice' version: $\Lambda_{\mathrm{QG}} \sim g^{1/3} M_{Pl} \gg gM_{Pl}$ for $g \ll 1$

B Heidenreich, M Reece, T Rudelius – arXiv:1606.08437

B Heidenreich, M Reece, T Rudelius – arXiv:1712.01868



The Weak Gravity Conjecture

The WGC fits in well with two other constraints believed to be true of all theories of quantum gravity…

- No global symmetries

$$\Lambda \lesssim g M_{Pl} \qquad \Lambda_{\mathrm{QG}} \sim g^{1/3} M_{Pl}$$

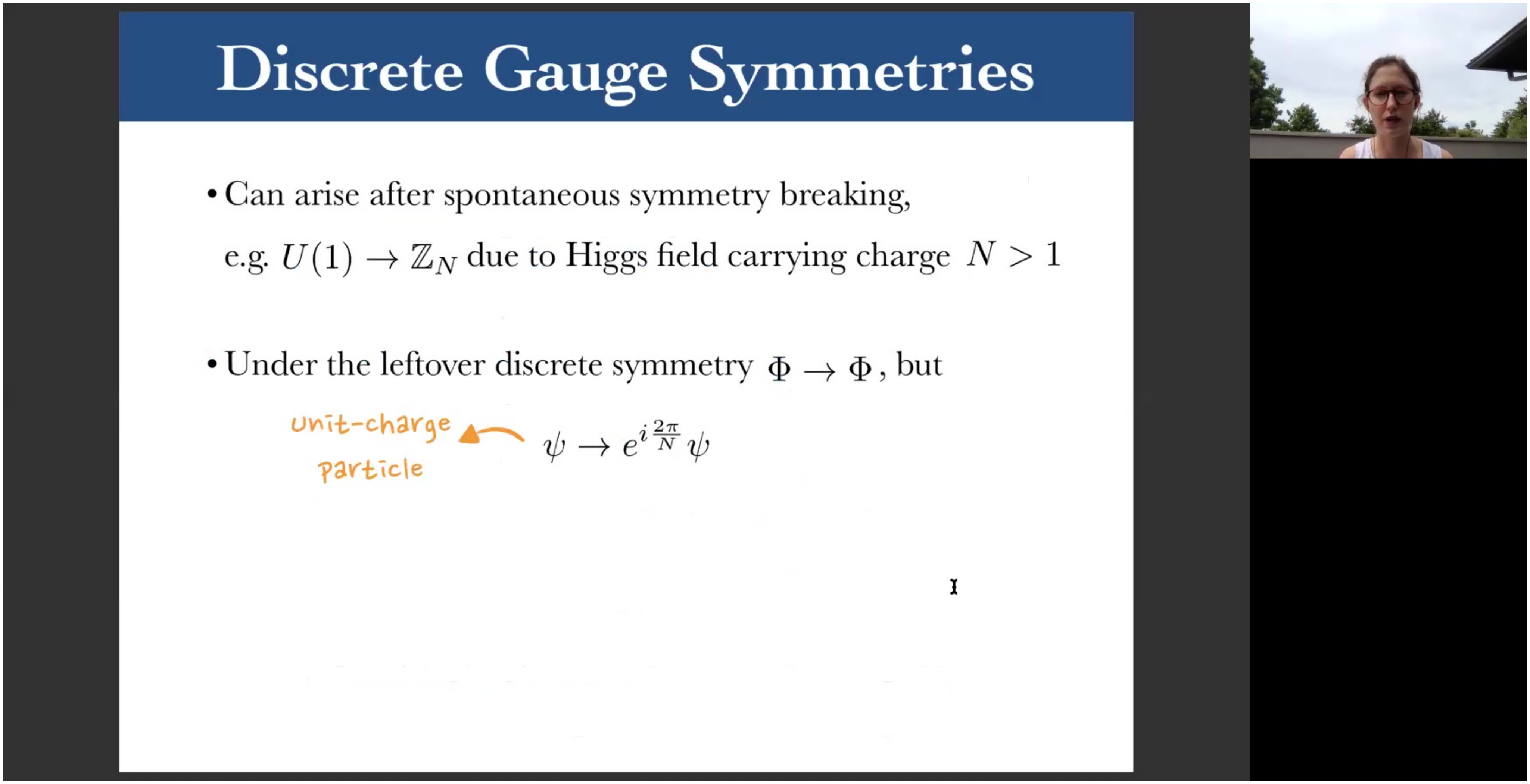
magnetic WGC precludes a smooth g —> 0 limit

- Completeness hypothesis J Polchinski – hep-th/0304042

$$m \leq g q M_{Pl}$$

Also expected to hold for discrete symmetries

Harlow, Ooguri – arXiv:1810.05338

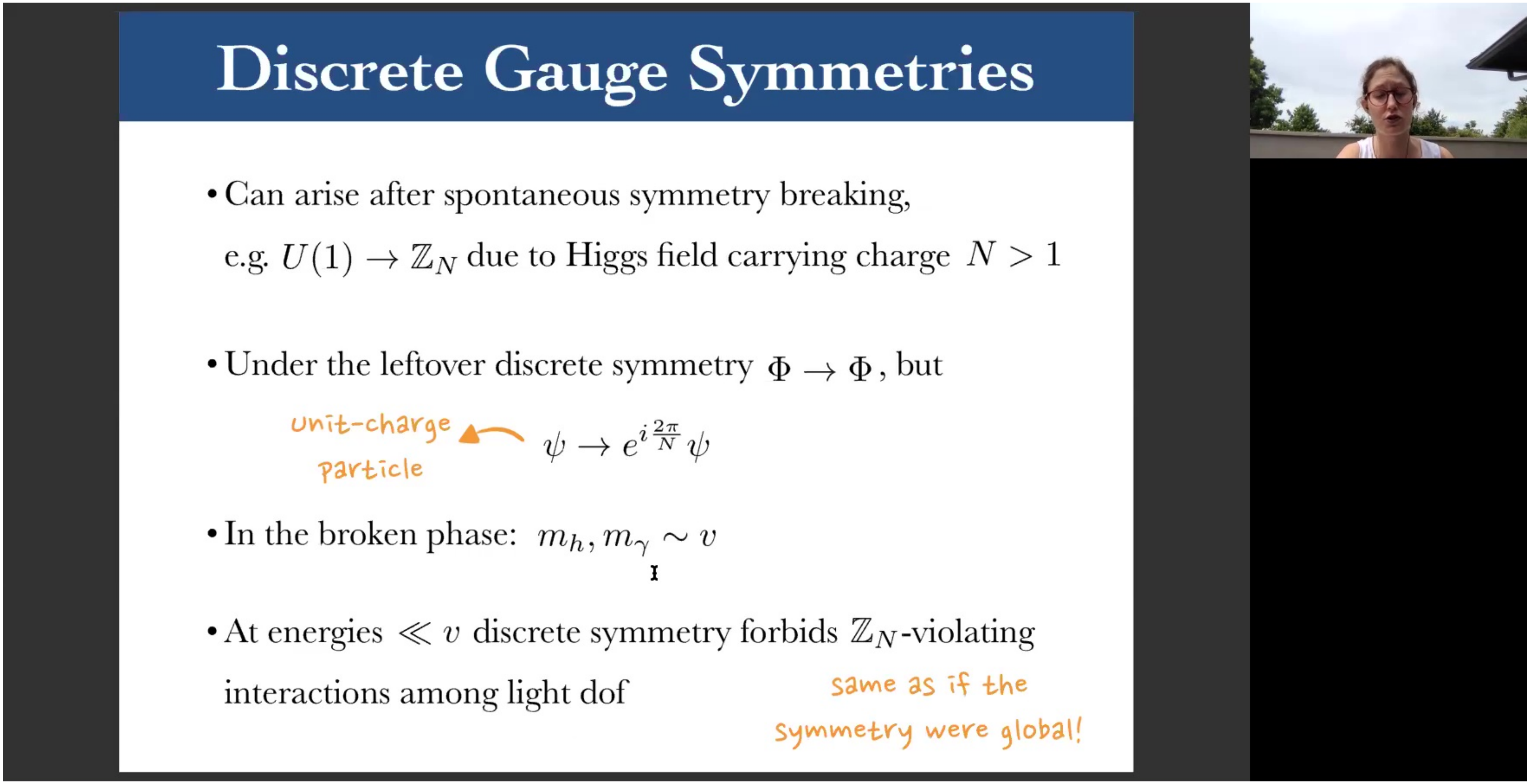


Discrete Gauge Symmetries

- Can arise after spontaneous symmetry breaking, e.g. $U(1) \rightarrow \mathbb{Z}_N$ due to Higgs field carrying charge $N > 1$

- Under the leftover discrete symmetry $\Phi \rightarrow \Phi$, but

unit-charge particle ← $\psi \rightarrow e^{i\frac{2\pi}{N}}\psi$



Discrete Gauge Symmetries

- Can arise after spontaneous symmetry breaking, e.g. $U(1) \to \mathbb{Z}_N$ due to Higgs field carrying charge $N > 1$

- Under the leftover discrete symmetry $\Phi \to \Phi$, but

unit-charge particle

$$\psi \to e^{i\frac{2\pi}{N}}\psi$$

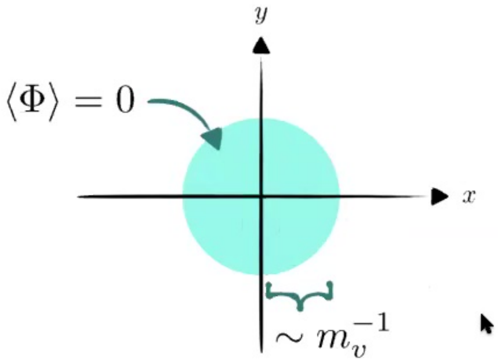
- In the broken phase: $m_h, m_\gamma \sim v$

- At energies $\ll v$ discrete symmetry forbids $\mathbb{Z}_N$-violating interactions among light dof

same as if the symmetry were global!

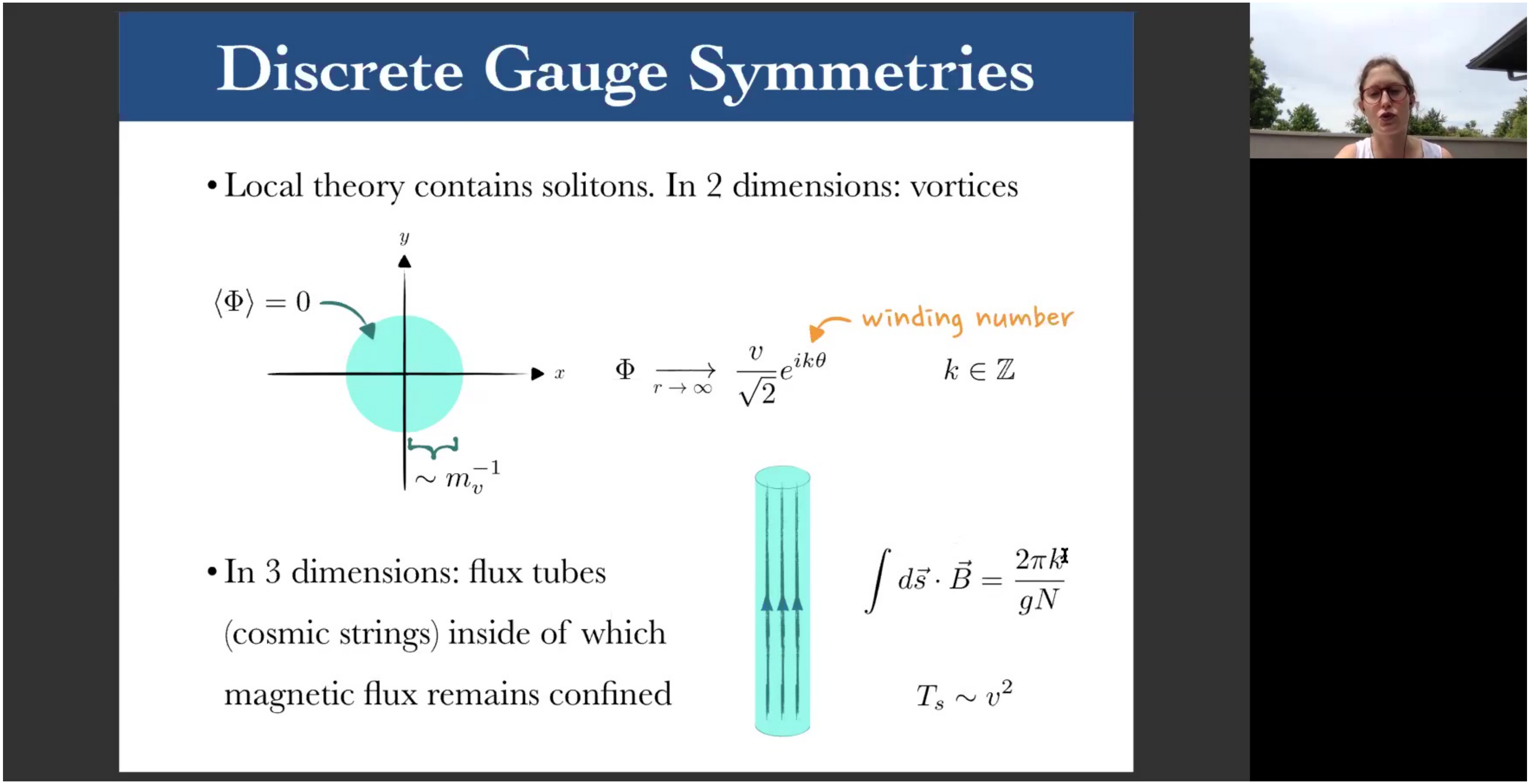
Discrete Gauge Symmetries

- Local theory contains solitons. In 2 dimensions: vortices



$$\Phi \xrightarrow[r\to\infty]{} \frac{v}{\sqrt{2}}e^{ik\theta} \qquad k \in \mathbb{Z}$$

winding number



Discrete Gauge Symmetries

- Local theory contains solitons. In 2 dimensions: vortices

$$\Phi \xrightarrow[r \to \infty]{} \frac{v}{\sqrt{2}} e^{ik\theta}$$

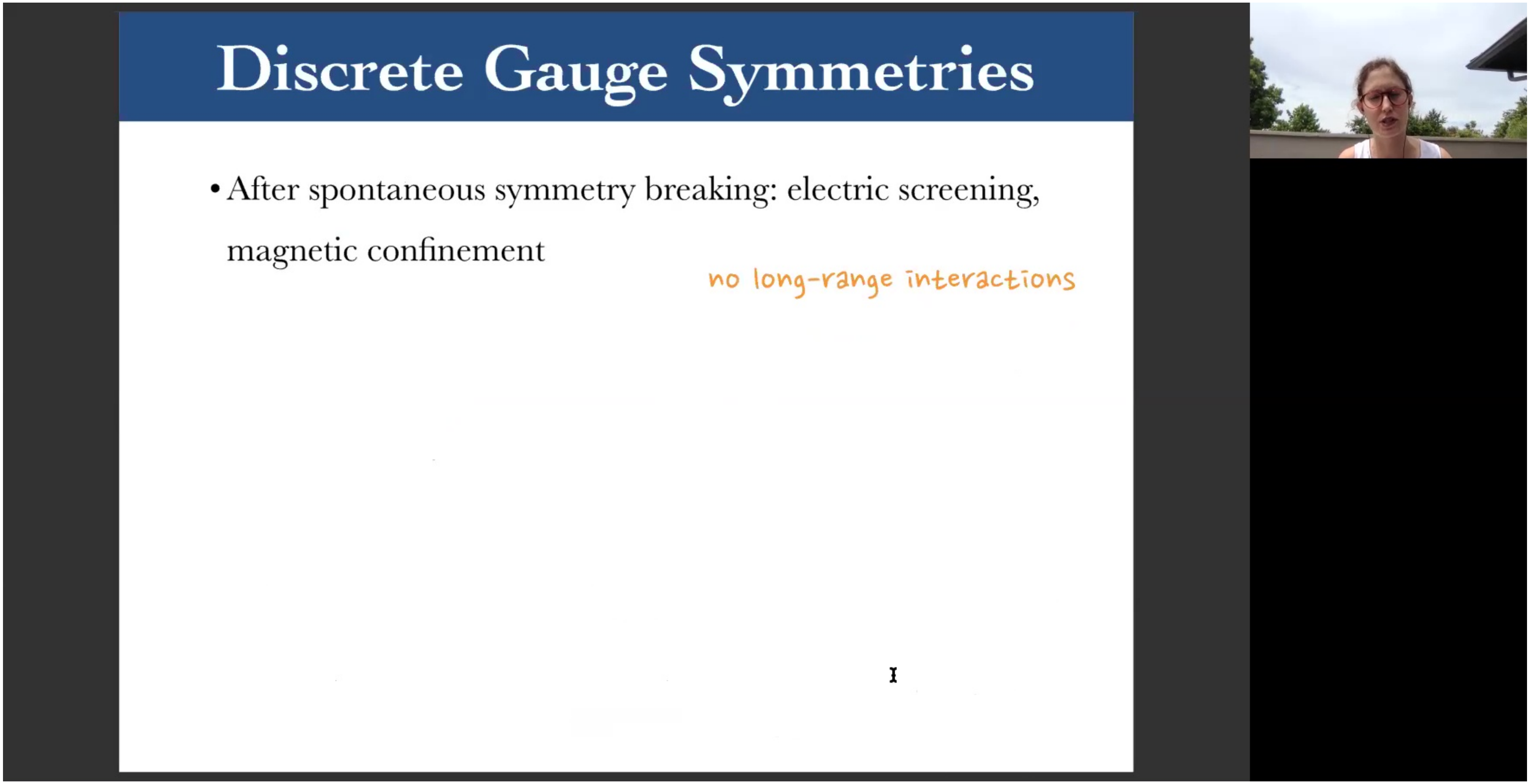
winding number

$k \in \mathbb{Z}$

- In 3 dimensions: flux tubes (cosmic strings) inside of which magnetic flux remains confined

$$\int d\vec{s} \cdot \vec{B} = \frac{2\pi k}{gN}$$

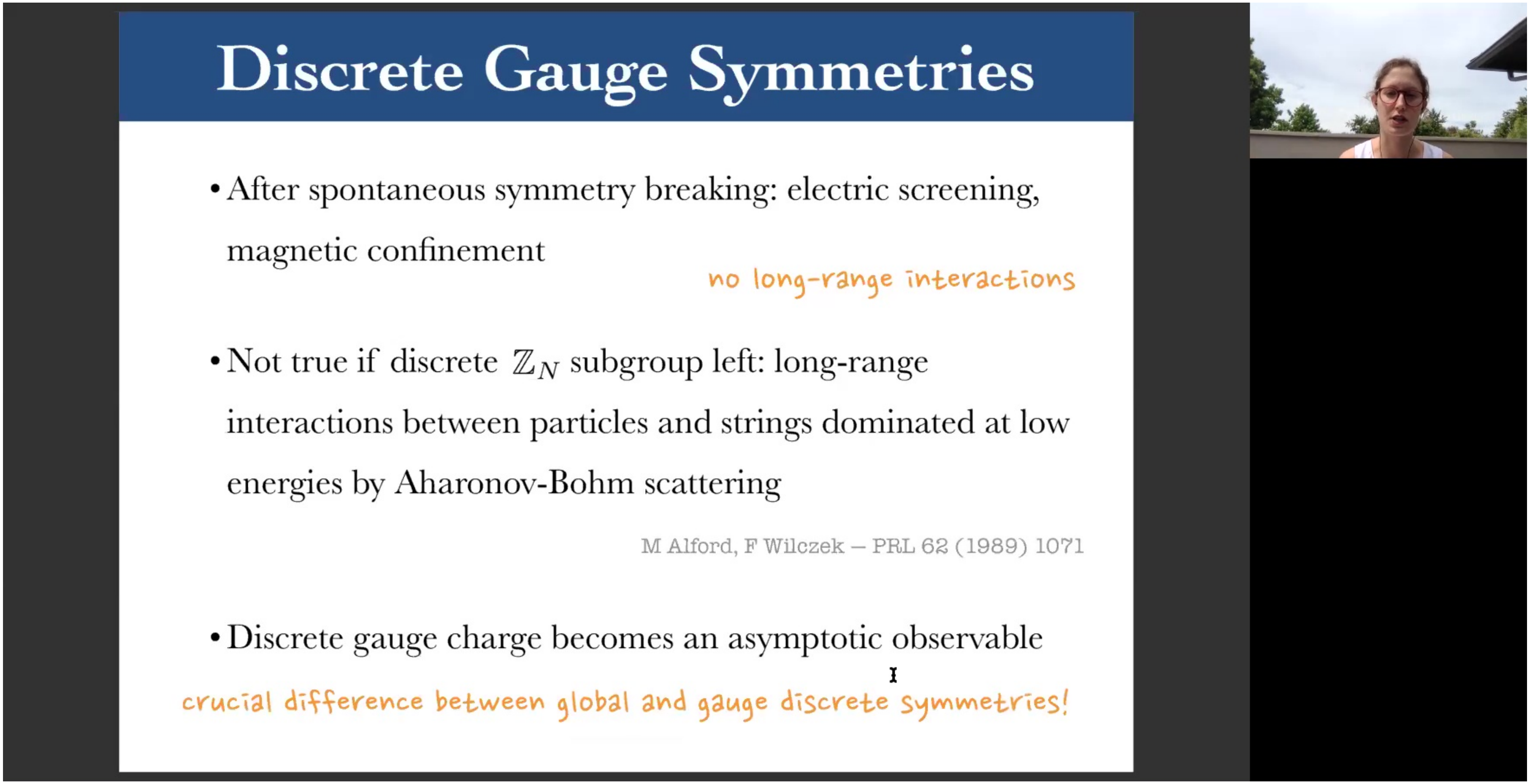
$$T_s \sim v^2$$



Discrete Gauge Symmetries

- After spontaneous symmetry breaking: electric screening, magnetic confinement

no long-range interactions



Discrete Gauge Symmetries

- After spontaneous symmetry breaking: electric screening, magnetic confinement

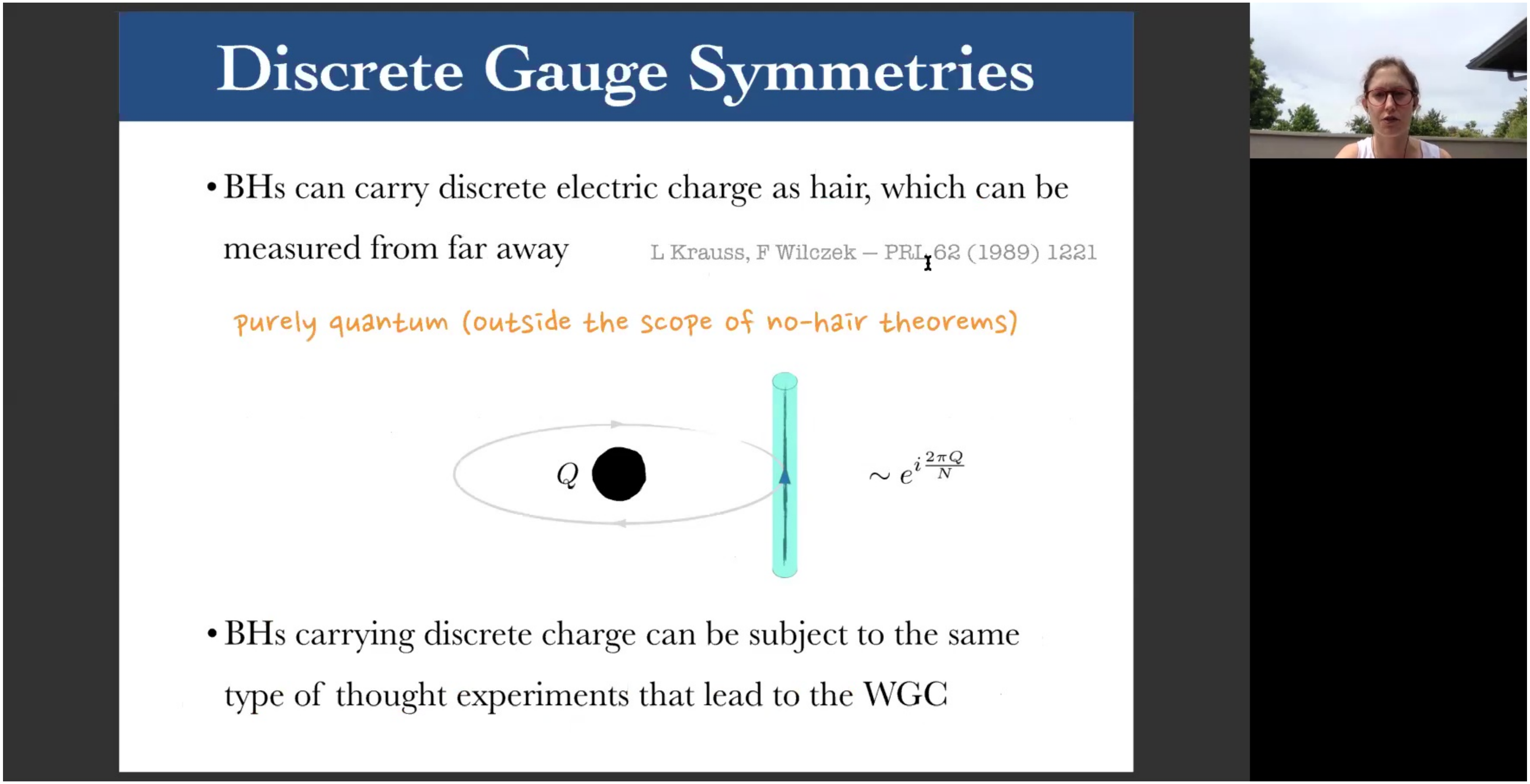
no long-range interactions

- Not true if discrete $\mathbb{Z}_N$ subgroup left: long-range interactions between particles and strings dominated at low energies by Aharonov-Bohm scattering

M Alford, F Wilczek – PRL 62 (1989) 1071

- Discrete gauge charge becomes an asymptotic observable

crucial difference between global and gauge discrete symmetries!



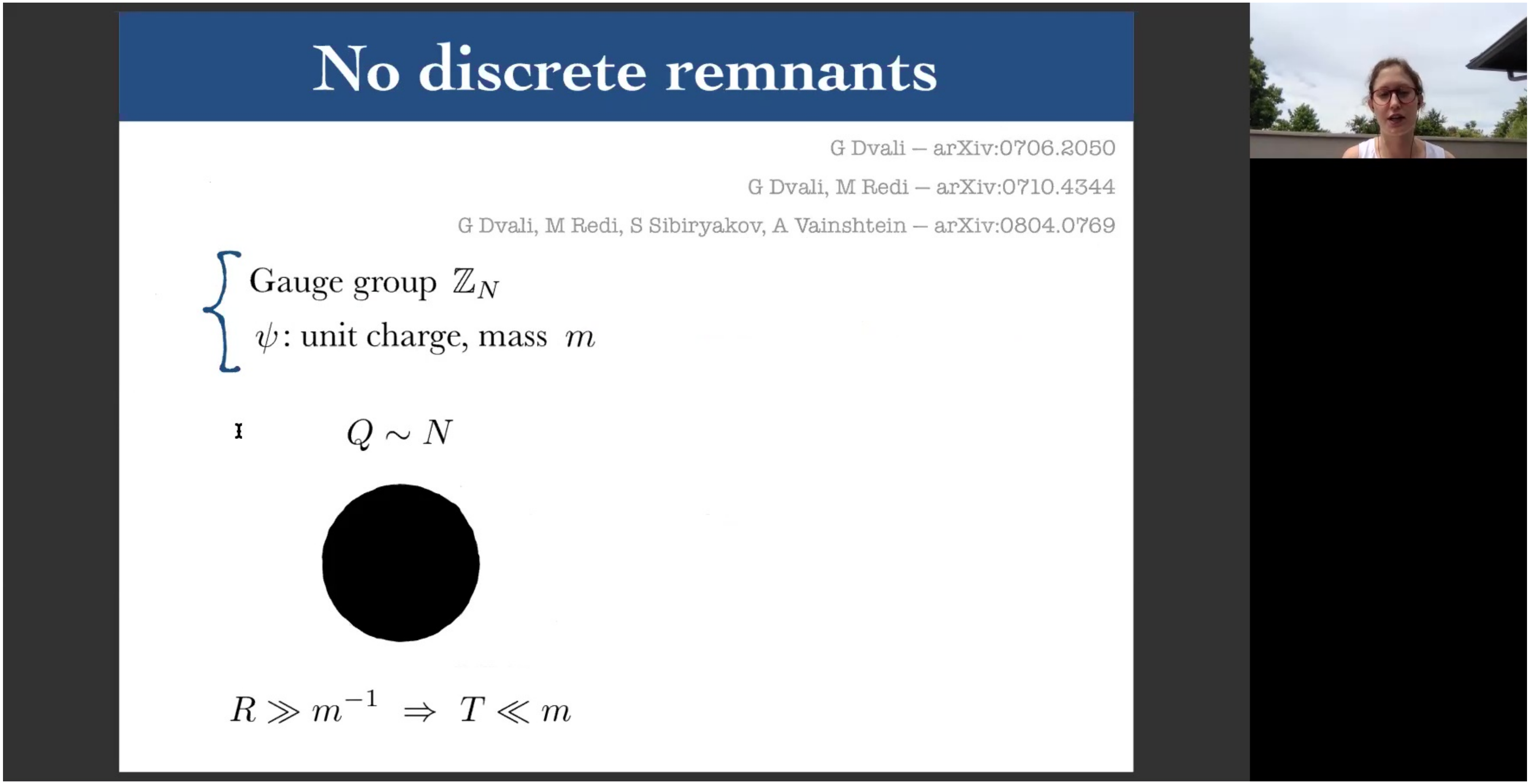
Discrete Gauge Symmetries

- BHs can carry discrete electric charge as hair, which can be measured from far away L Krauss, F Wilczek – PRL 62 (1989) 1221

purely quantum (outside the scope of no-hair theorems)

$\sim e^{i\frac{2\pi Q}{N}}$

- BHs carrying discrete charge can be subject to the same type of thought experiments that lead to the WGC



No discrete remnants

G Dvali – arXiv:0706.2050

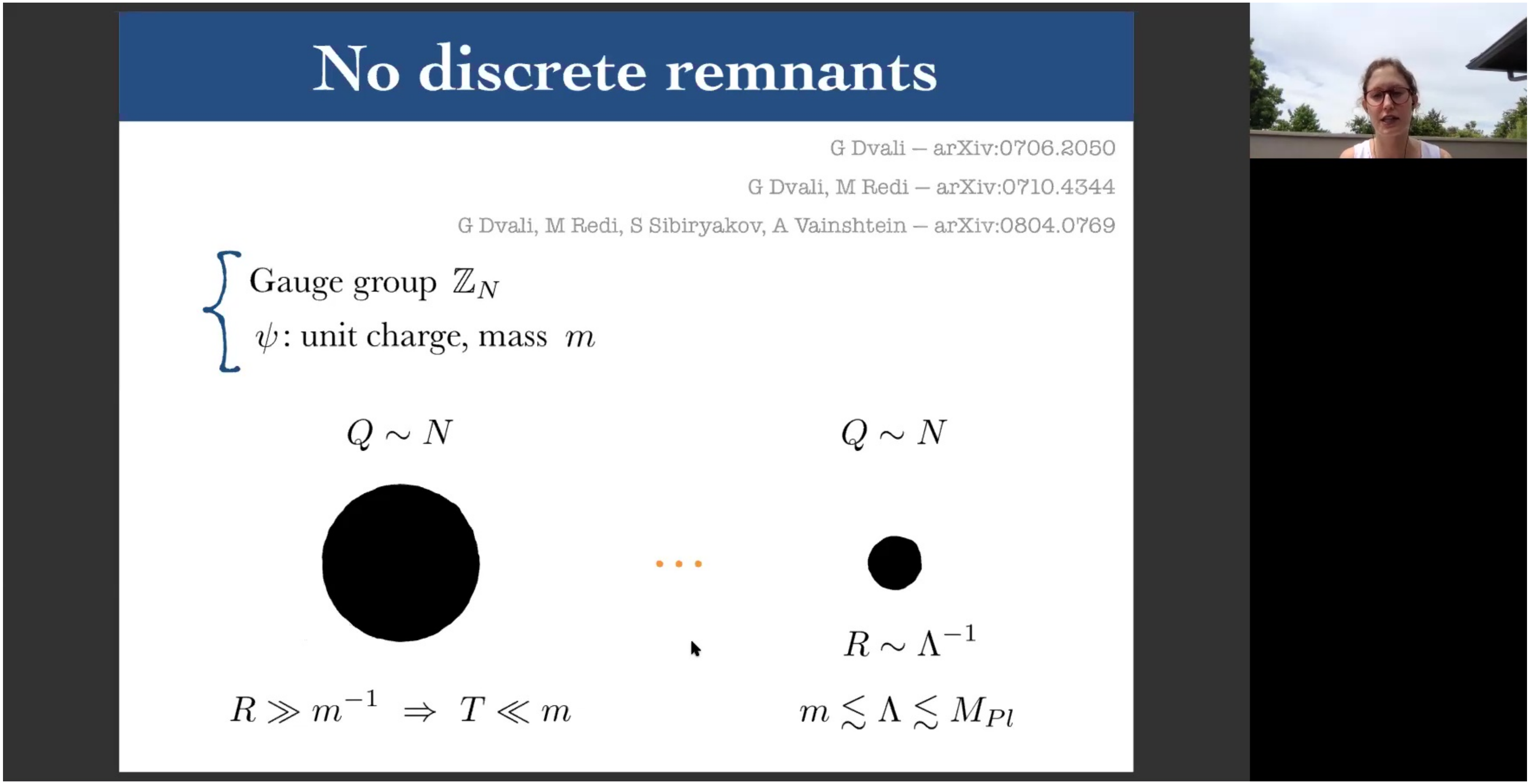
G Dvali, M Redi – arXiv:0710.4344

G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

$$\begin{cases} \text{Gauge group } \mathbb{Z}_N \\ \psi\text{: unit charge, mass } m \end{cases}$$

$$Q \sim N$$

$$R \gg m^{-1} \;\Rightarrow\; T \ll m$$



No discrete remnants

G Dvali – arXiv:0706.2050

G Dvali, M Redi – arXiv:0710.4344

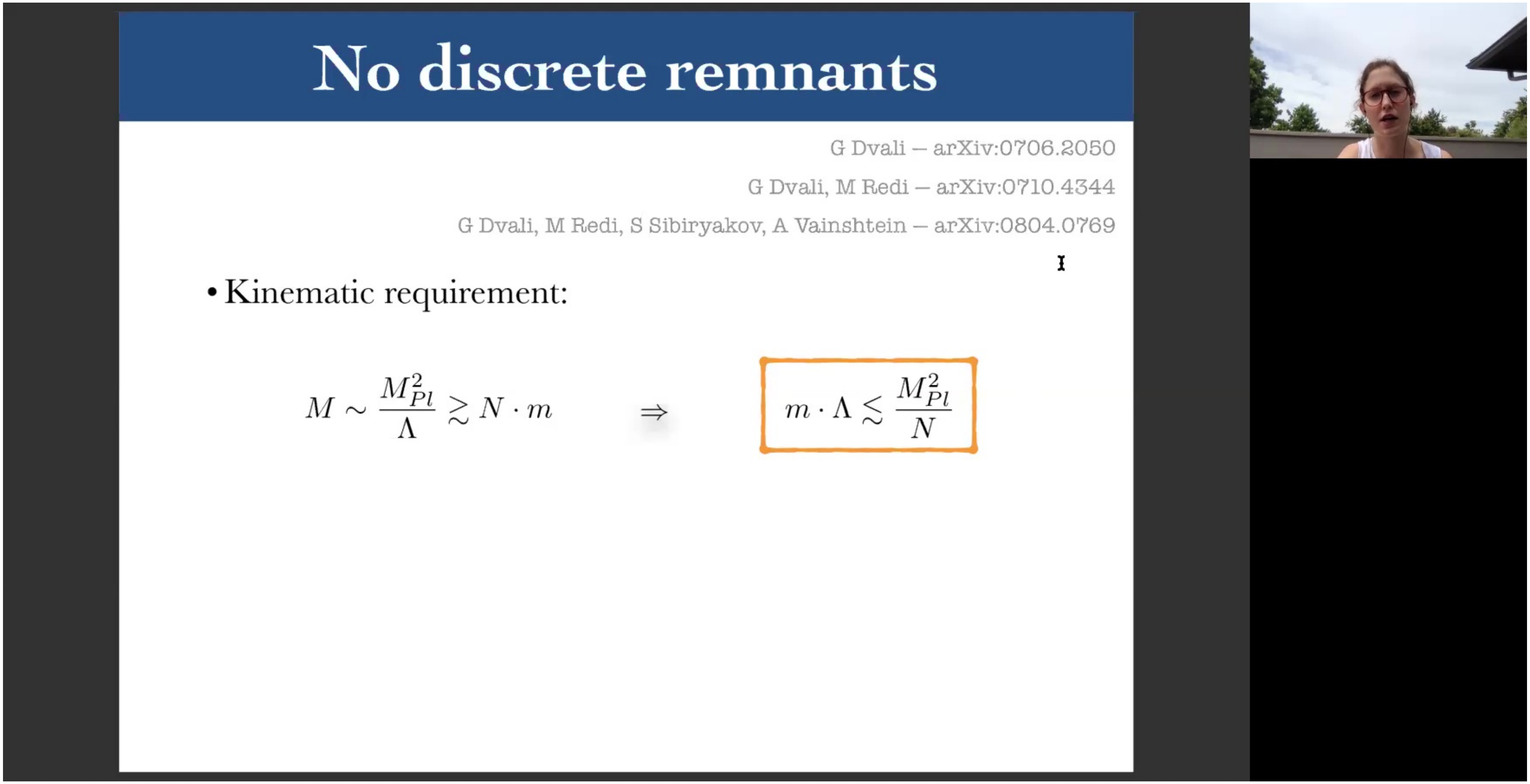
G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

$$\begin{cases} \text{Gauge group } \mathbb{Z}_N \\ \psi\text{: unit charge, mass } m \end{cases}$$

$Q \sim N$ $\qquad$ $Q \sim N$

$R \sim \Lambda^{-1}$

$R \gg m^{-1} \ \Rightarrow \ T \ll m$ $\qquad$ $m \lesssim \Lambda \lesssim M_{Pl}$



No discrete remnants

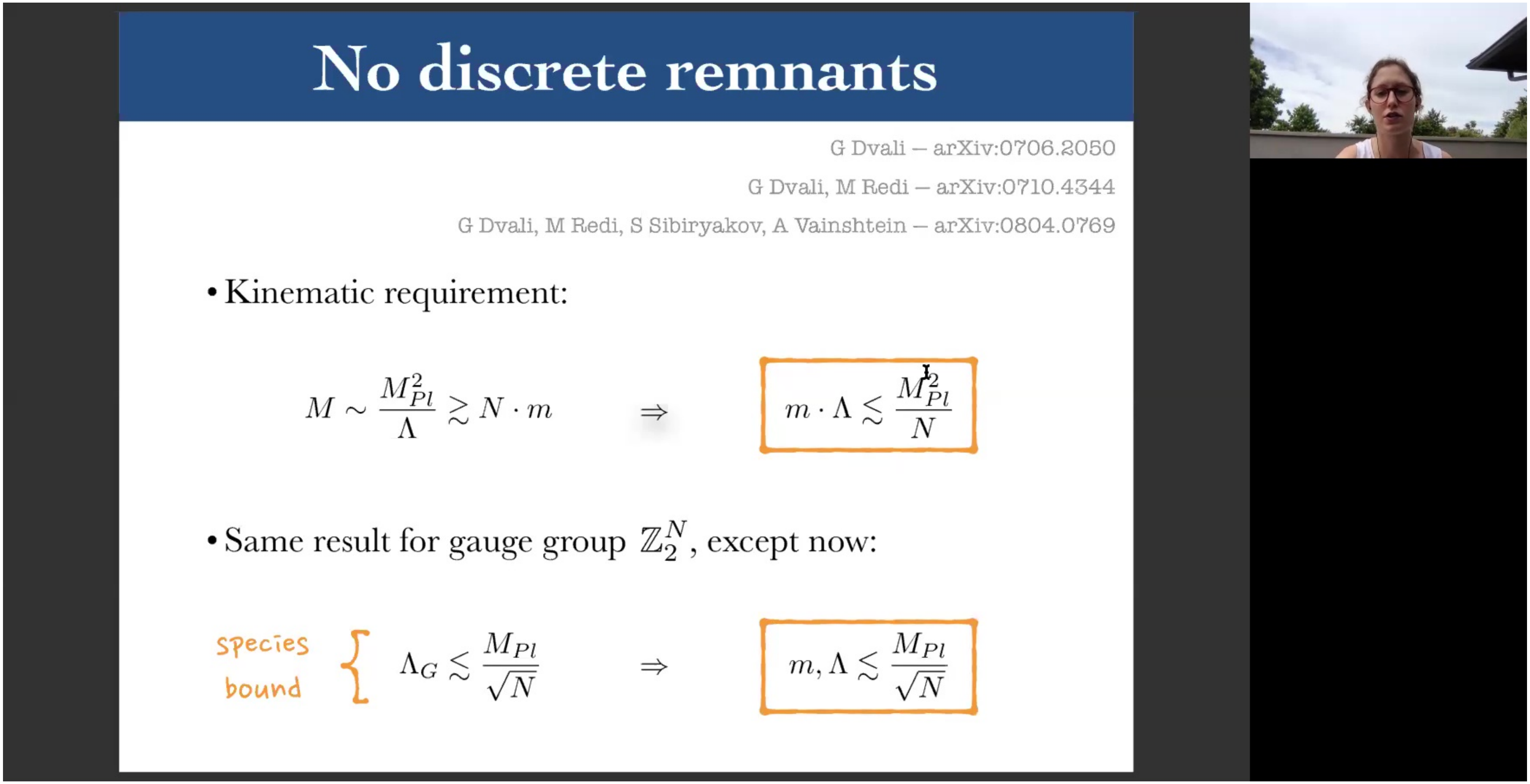
G Dvali – arXiv:0706.2050

G Dvali, M Redi – arXiv:0710.4344

G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

- Kinematic requirement:

$$M \sim \frac{M_{Pl}^2}{\Lambda} \gtrsim N \cdot m \qquad \Rightarrow \qquad \boxed{m \cdot \Lambda \lesssim \frac{M_{Pl}^2}{N}}$$



No discrete remnants

G Dvali – arXiv:0706.2050

G Dvali, M Redi – arXiv:0710.4344

G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

- Kinematic requirement:

$$M \sim \frac{M_{Pl}^2}{\Lambda} \gtrsim N \cdot m \qquad \Rightarrow \qquad \boxed{m \cdot \Lambda \lesssim \frac{M_{Pl}^2}{N}}$$

- Same result for gauge group $\mathbb{Z}_2^N$, except now:

species bound

$$\left\{ \Lambda_G \lesssim \frac{M_{Pl}}{\sqrt{N}} \right. \qquad \Rightarrow \qquad \boxed{m, \Lambda \lesssim \frac{M_{Pl}}{\sqrt{N}}}$$

No discrete remnants

G Dvali – arXiv:0706.2050

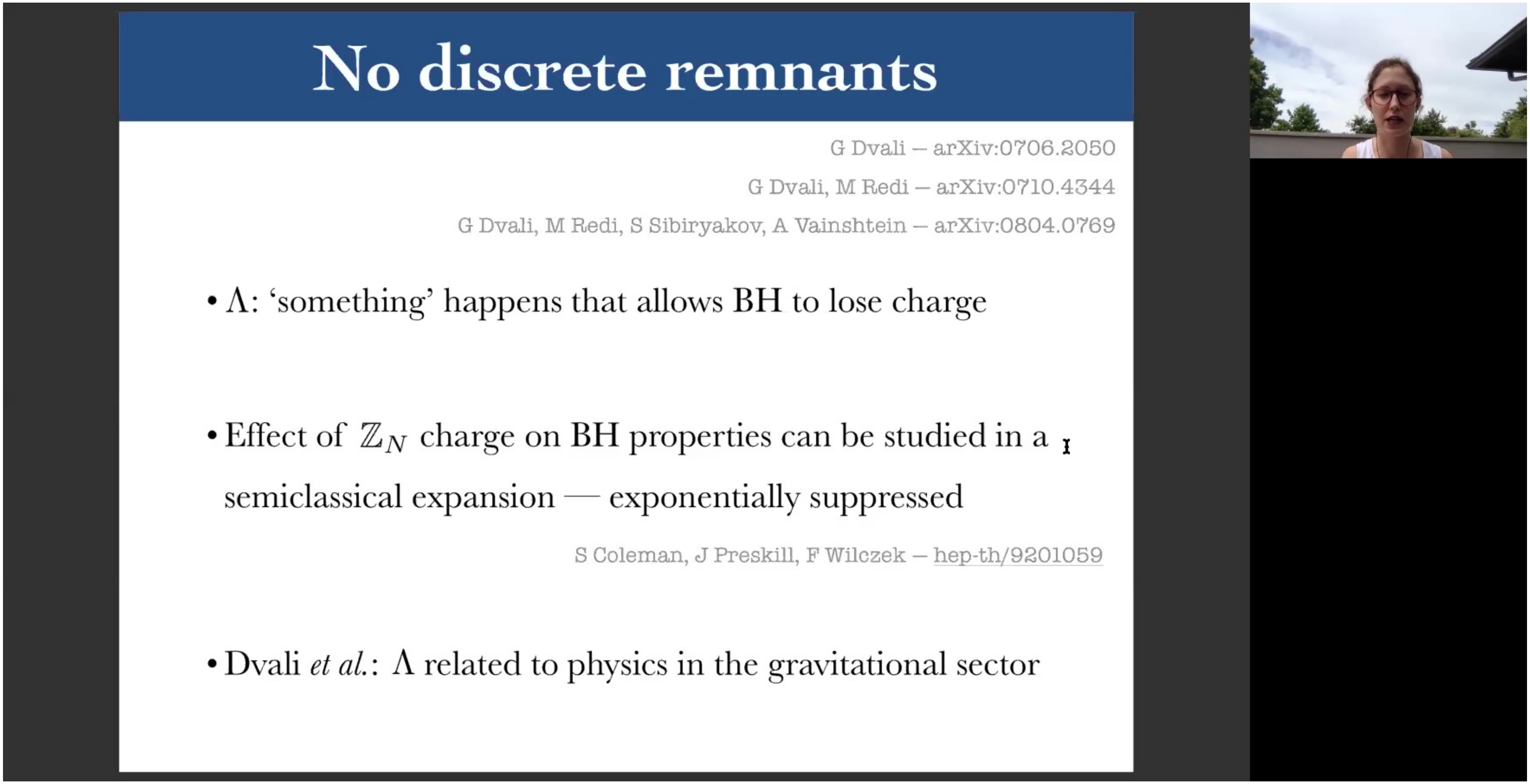
G Dvali, M Redi – arXiv:0710.4344

G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

- Λ: 'something' happens that allows BH to lose charge
- Effect of $\mathbb{Z}_N$ charge on BH properties can be studied in a semiclassical expansion — exponentially suppressed

S Coleman, J Preskill, F Wilczek – hep-th/9201059

- Dvali *et al.*: Λ related to physics in the gravitational sector



No discrete remnants

G Dvali – arXiv:0706.2050

G Dvali, M Redi – arXiv:0710.4344

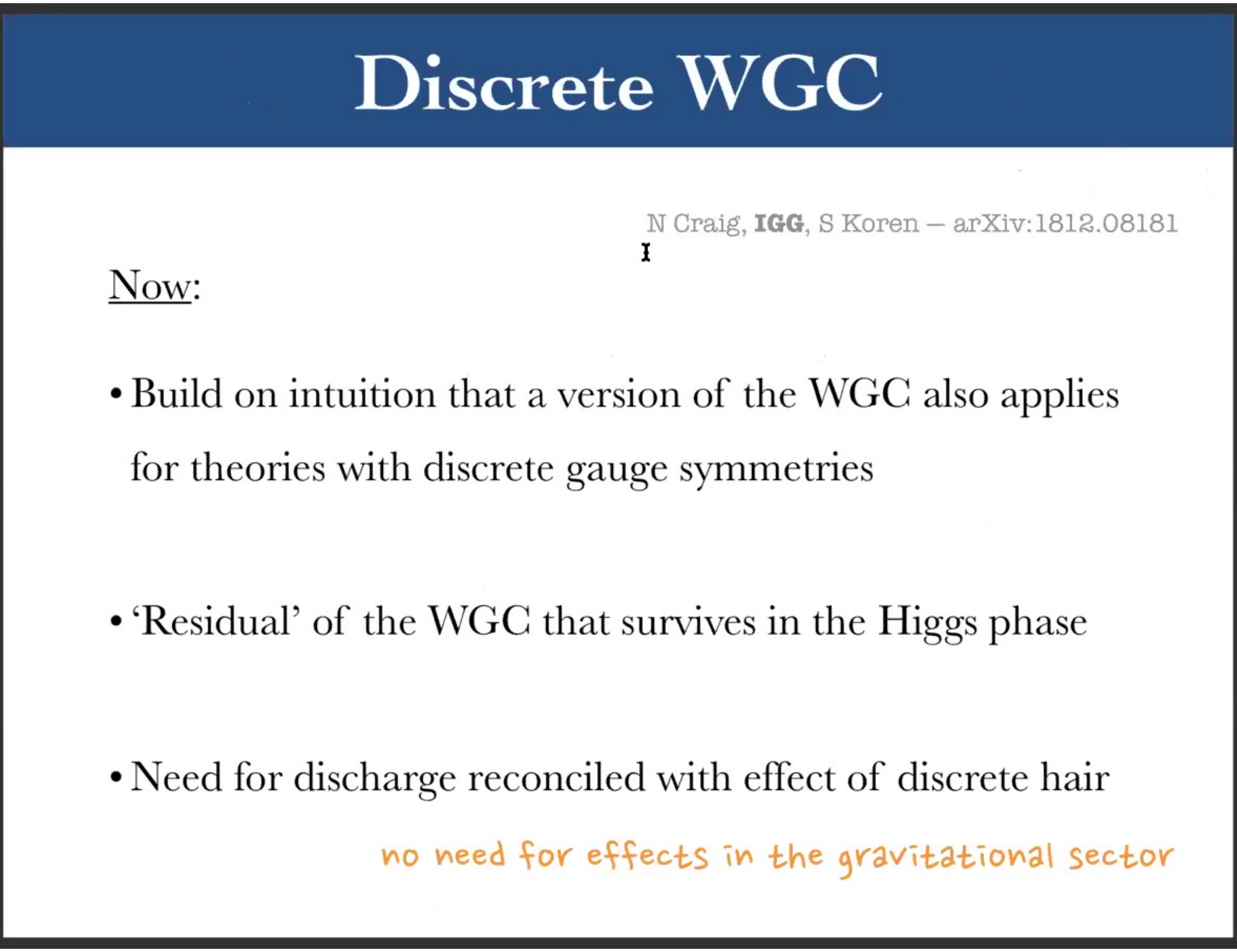
G Dvali, M Redi, S Sibiryakov, A Vainshtein – arXiv:0804.0769

- Λ: ‘something’ happens that allows BH to lose charge

- Effect of $\mathbb{Z}_N$ charge on BH properties can be studied in a semiclassical expansion — exponentially suppressed

S Coleman, J Preskill, F Wilczek – hep-th/9201059

- Dvali *et al.*: Λ related to physics in the gravitational sector



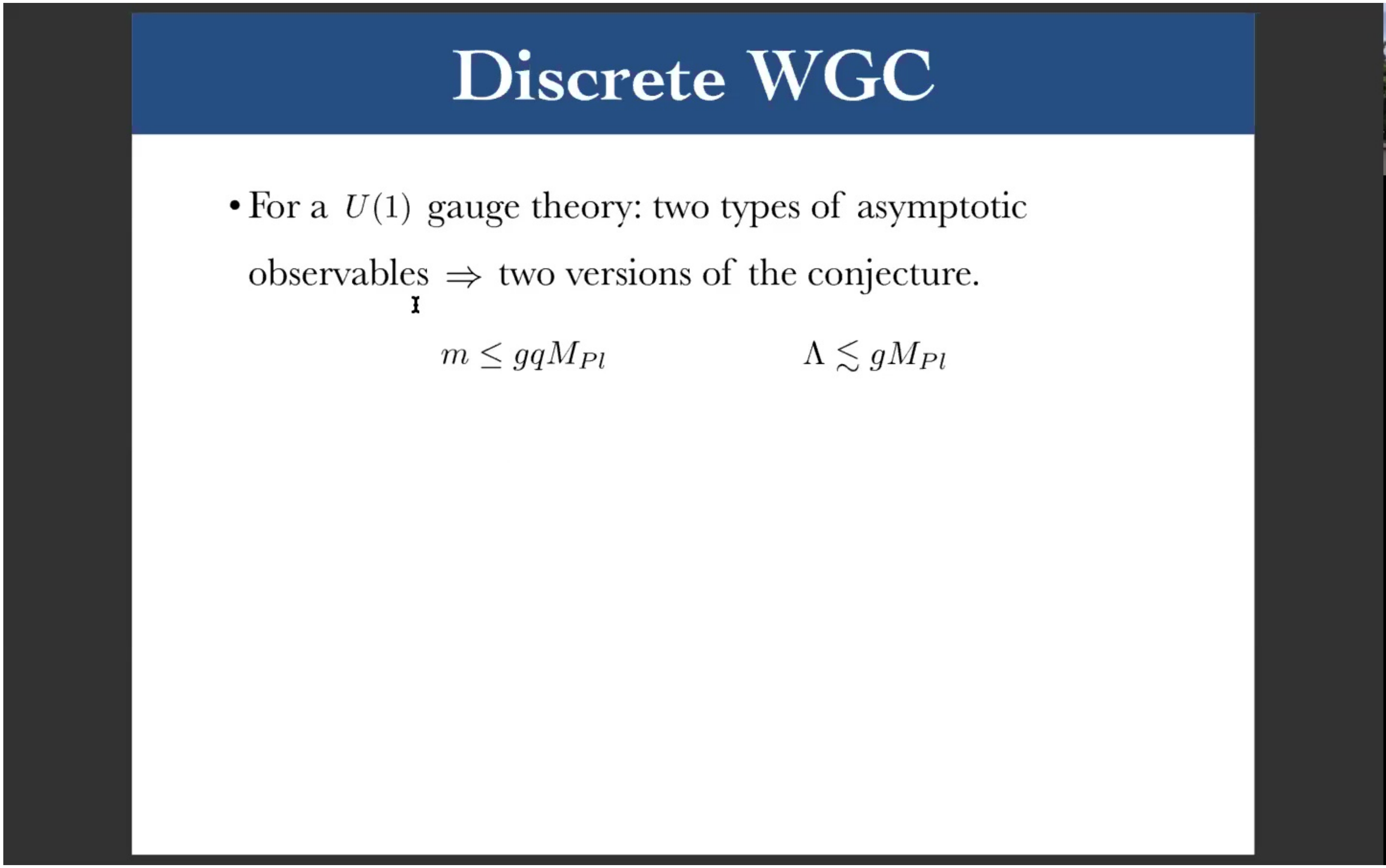
Discrete WGC

N Craig, **IGG**, S Koren – arXiv:1812.08181

Now:

- Build on intuition that a version of the WGC also applies for theories with discrete gauge symmetries
- 'Residual' of the WGC that survives in the Higgs phase
- Need for discharge reconciled with effect of discrete hair

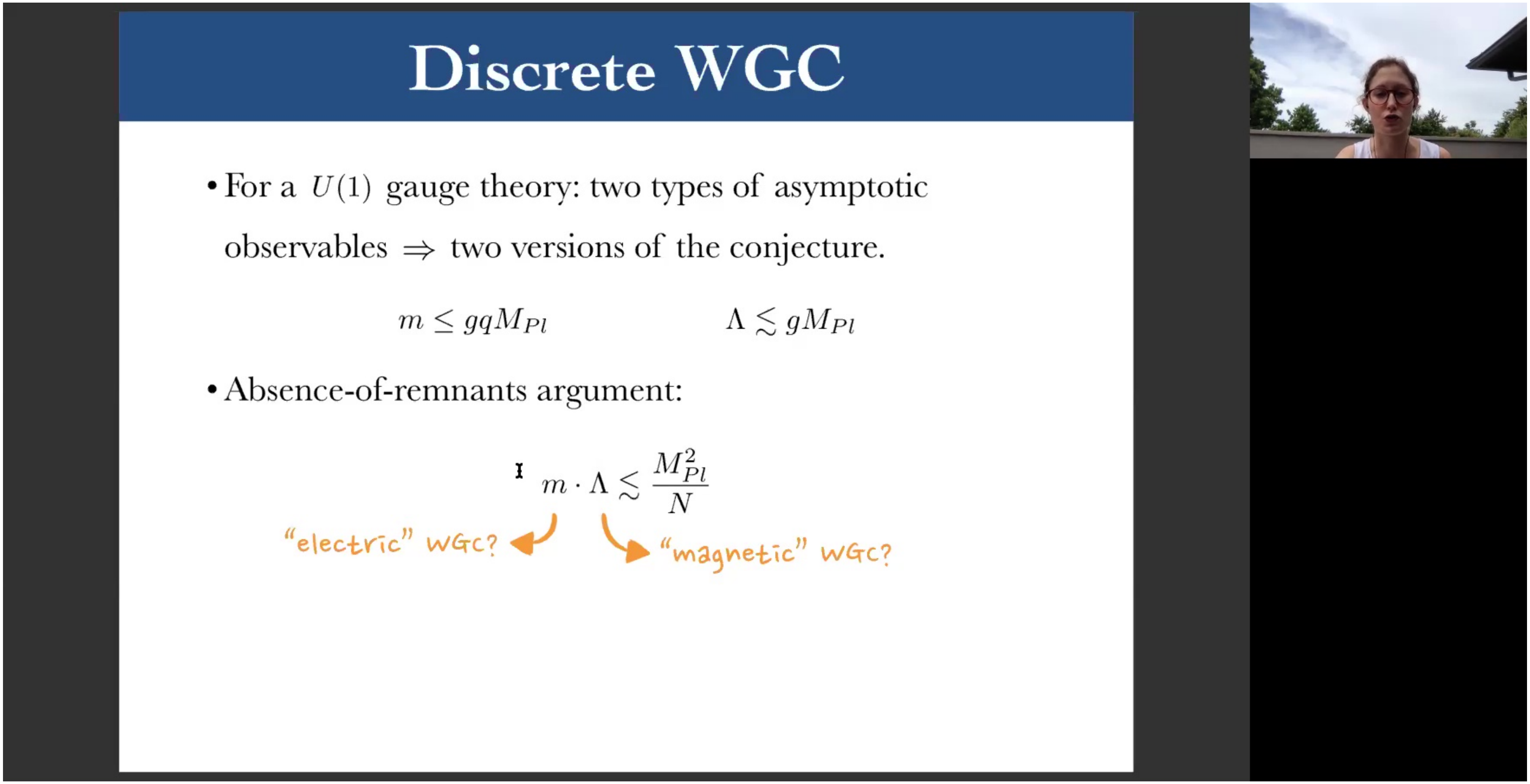
no need for effects in the gravitational sector



Discrete WGC

- For a $U(1)$ gauge theory: two types of asymptotic observables $\Rightarrow$ two versions of the conjecture.

$$m \leq gqM_{Pl} \qquad\qquad \Lambda \lesssim gM_{Pl}$$



Discrete WGC

- For a $U(1)$ gauge theory: two types of asymptotic observables $\Rightarrow$ two versions of the conjecture.

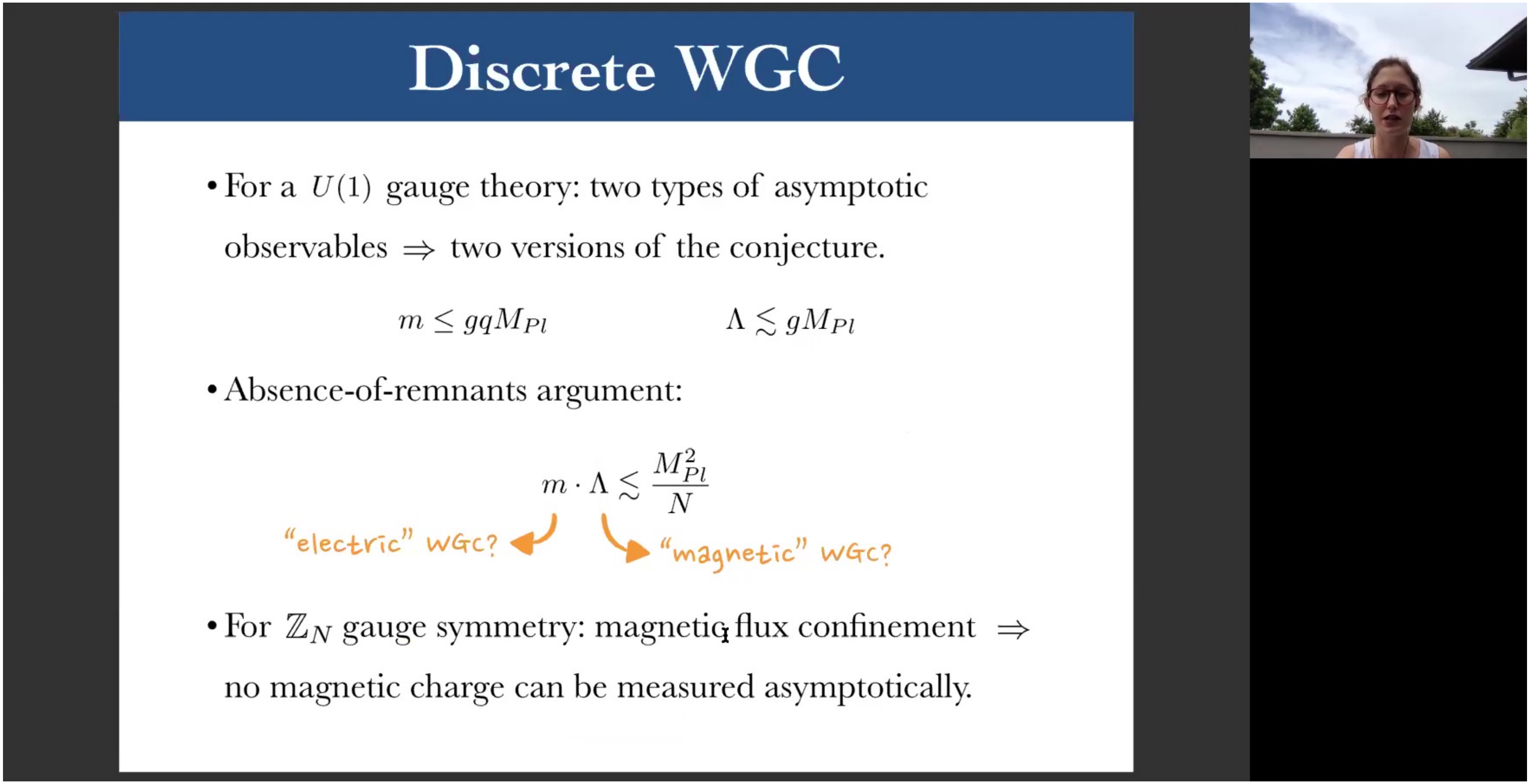
$$m \leq g q M_{Pl} \qquad \qquad \Lambda \lesssim g M_{Pl}$$

- Absence-of-remnants argument:

$$m \cdot \Lambda \lesssim \frac{M_{Pl}^2}{N}$$

“electric” WGC?

“magnetic” WGC?



Discrete WGC

- For a $U(1)$ gauge theory: two types of asymptotic observables $\Rightarrow$ two versions of the conjecture.

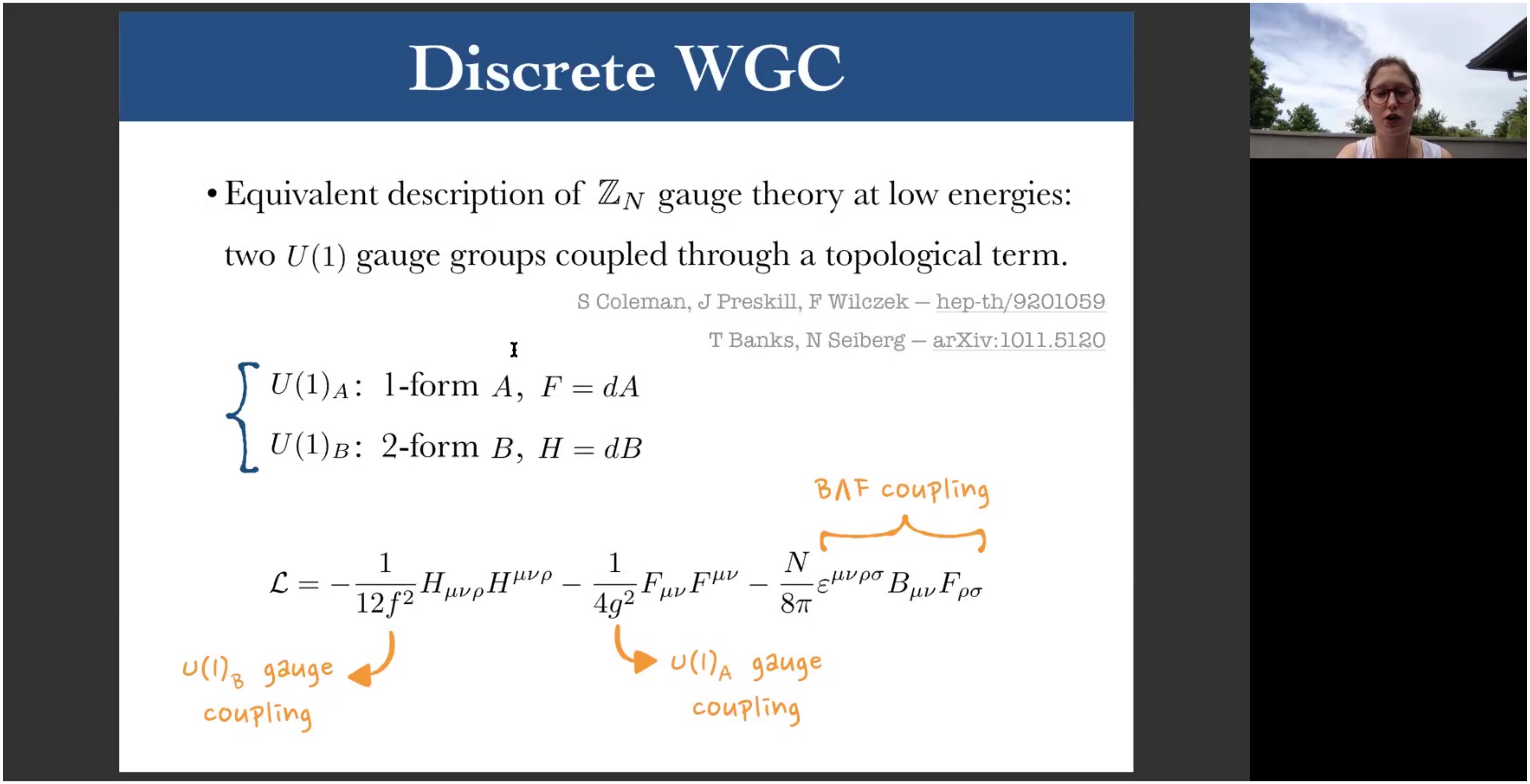
$$m \leq gqM_{Pl} \qquad\qquad \Lambda \lesssim gM_{Pl}$$

- Absence-of-remnants argument:

$$m \cdot \Lambda \lesssim \frac{M_{Pl}^2}{N}$$

"electric" WGC? "magnetic" WGC?

- For $\mathbb{Z}_N$ gauge symmetry: magnetic flux confinement $\Rightarrow$ no magnetic charge can be measured asymptotically.



Discrete WGC

- Equivalent description of $\mathbb{Z}_N$ gauge theory at low energies: two $U(1)$ gauge groups coupled through a topological term.

S Coleman, J Preskill, F Wilczek – hep-th/9201059

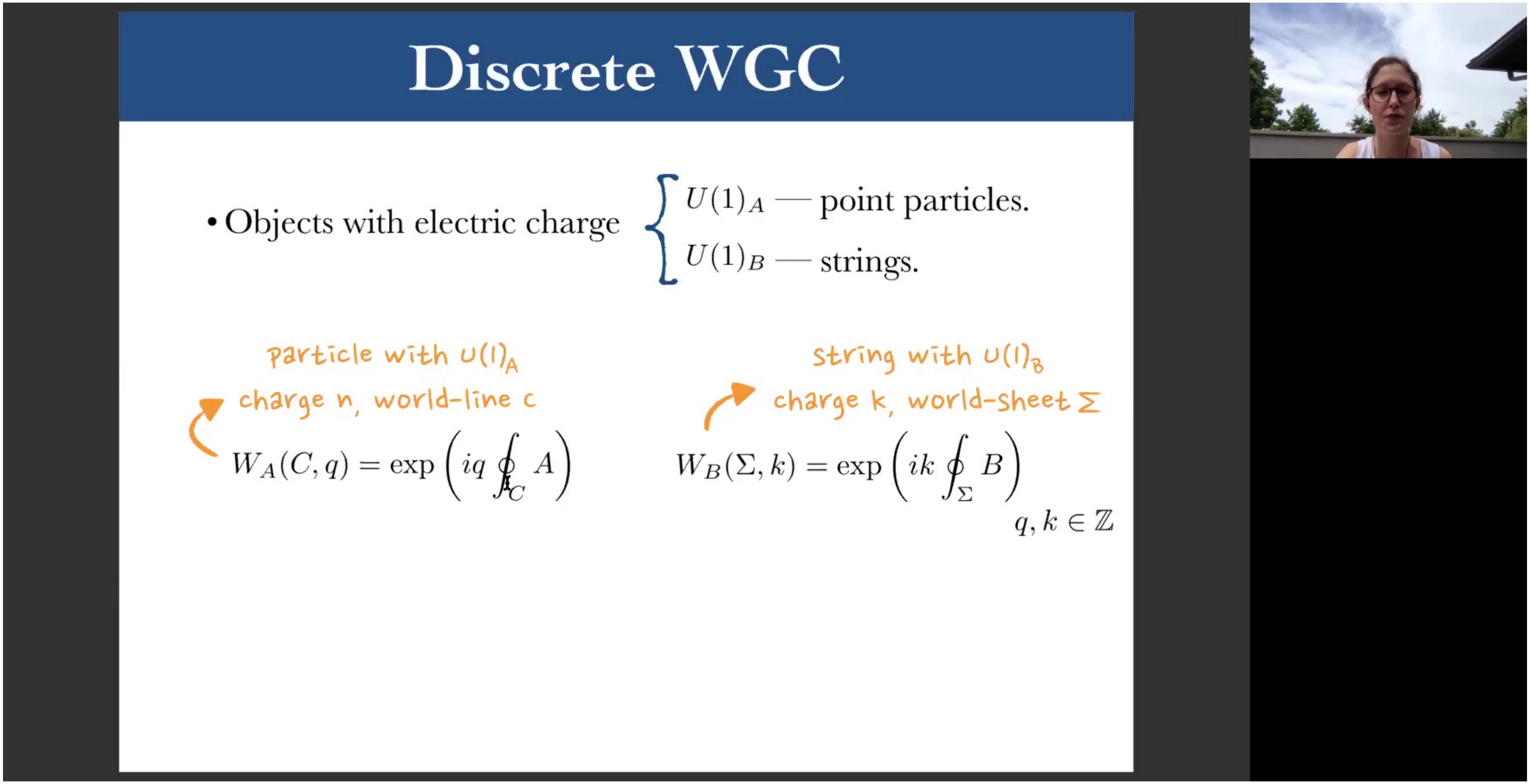
T Banks, N Seiberg – arXiv:1011.5120

$$\begin{cases} U(1)_A: \ \text{1-form } A, \ F = dA \\ U(1)_B: \ \text{2-form } B, \ H = dB \end{cases}$$

$$\mathcal{L} = -\frac{1}{12f^2} H_{\mu\nu\rho} H^{\mu\nu\rho} - \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} - \frac{N}{8\pi} \overbrace{\varepsilon^{\mu\nu\rho\sigma} B_{\mu\nu} F_{\rho\sigma}}^{B\wedge F \text{ coupling}}$$

$U(1)_B$ gauge coupling

$U(1)_A$ gauge coupling



Discrete WGC

- Objects with electric charge $\begin{cases} U(1)_A \text{ — point particles.} \\ U(1)_B \text{ — strings.} \end{cases}$

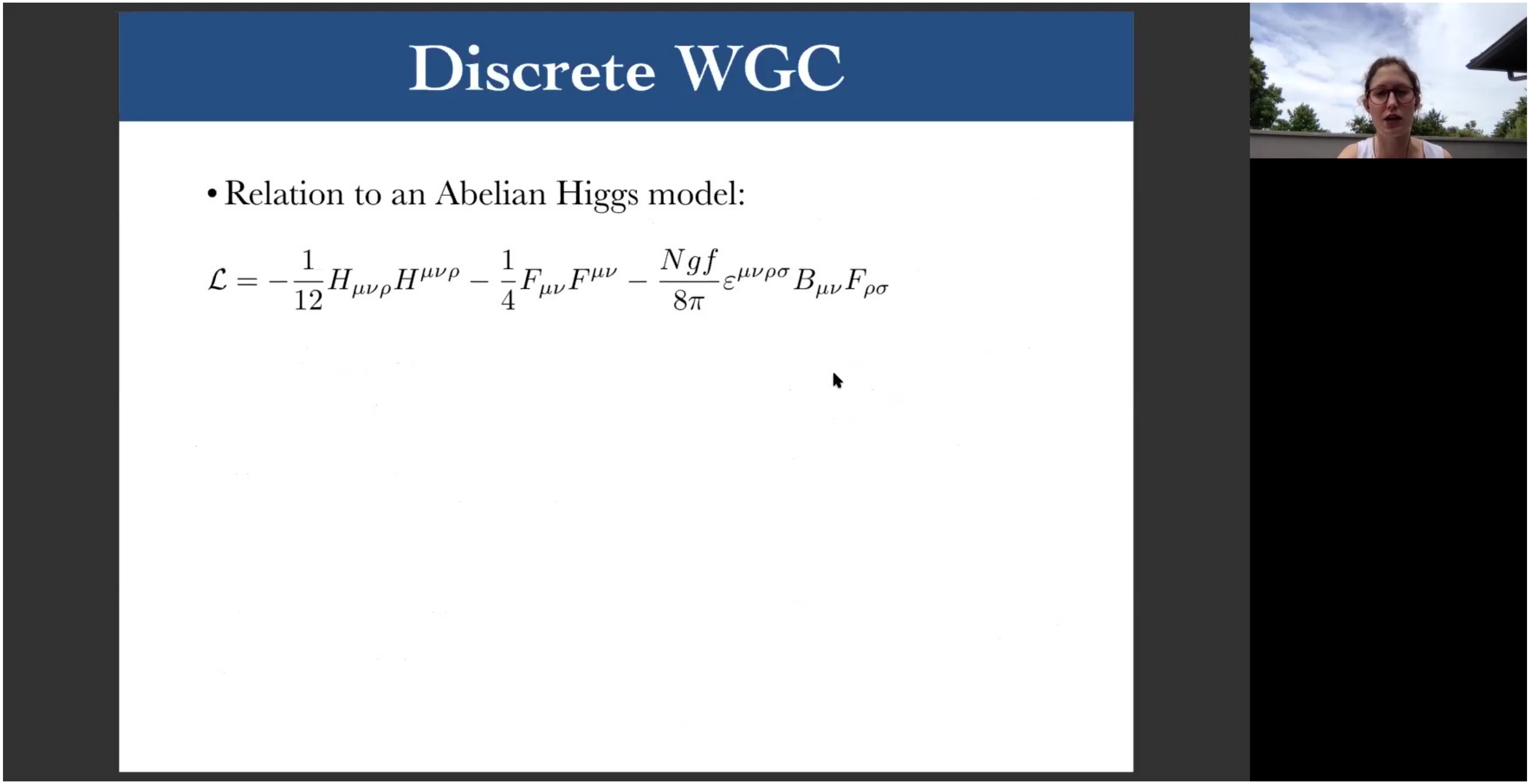
particle with $U(1)_A$
charge n, world-line c

$$W_A(C,q) = \exp\left(iq\oint_C A\right)$$

string with $U(1)_B$
charge k, world-sheet Σ

$$W_B(\Sigma,k) = \exp\left(ik\oint_\Sigma B\right)$$

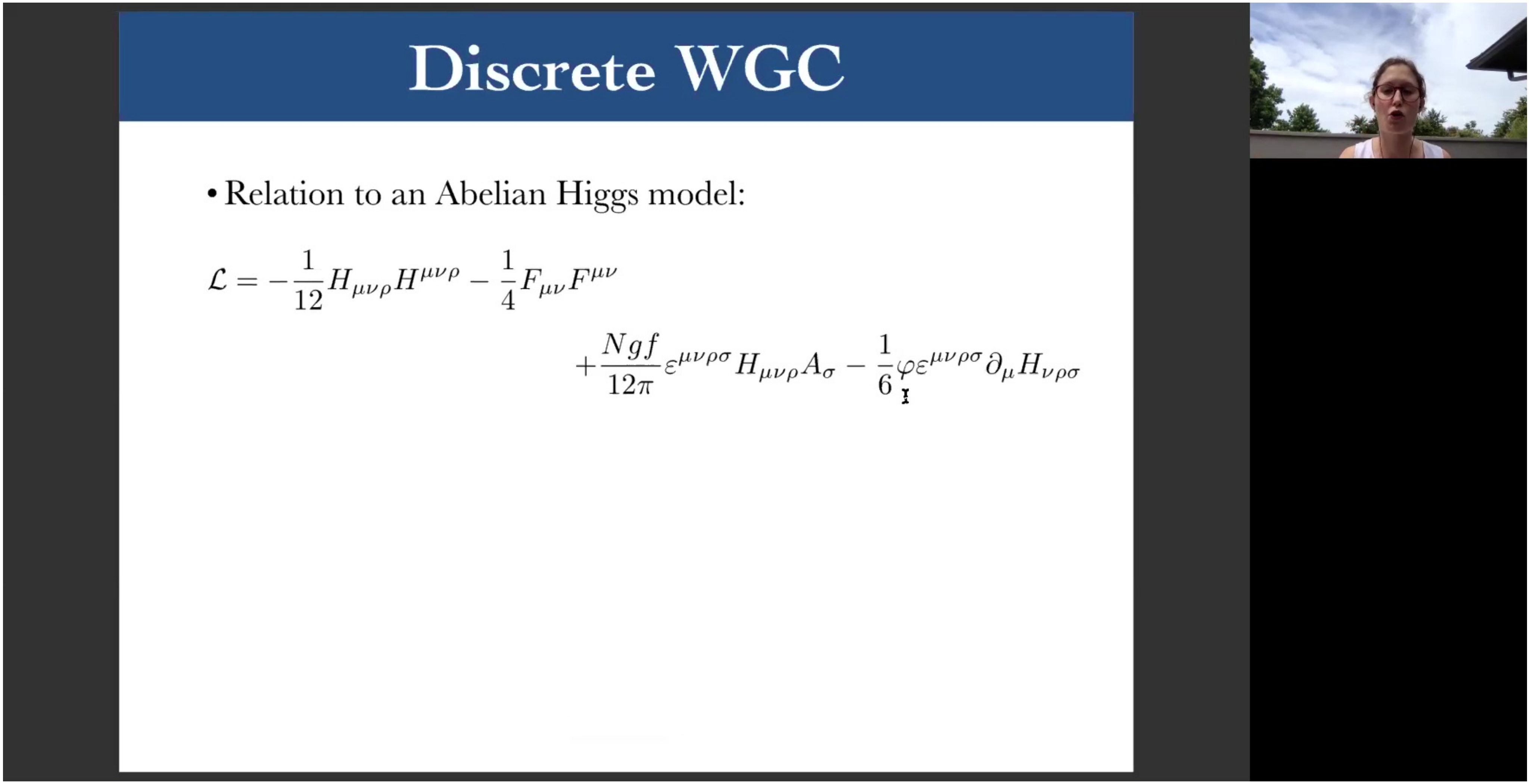
$$q,k \in \mathbb{Z}$$



Discrete WGC

- Relation to an Abelian Higgs model:

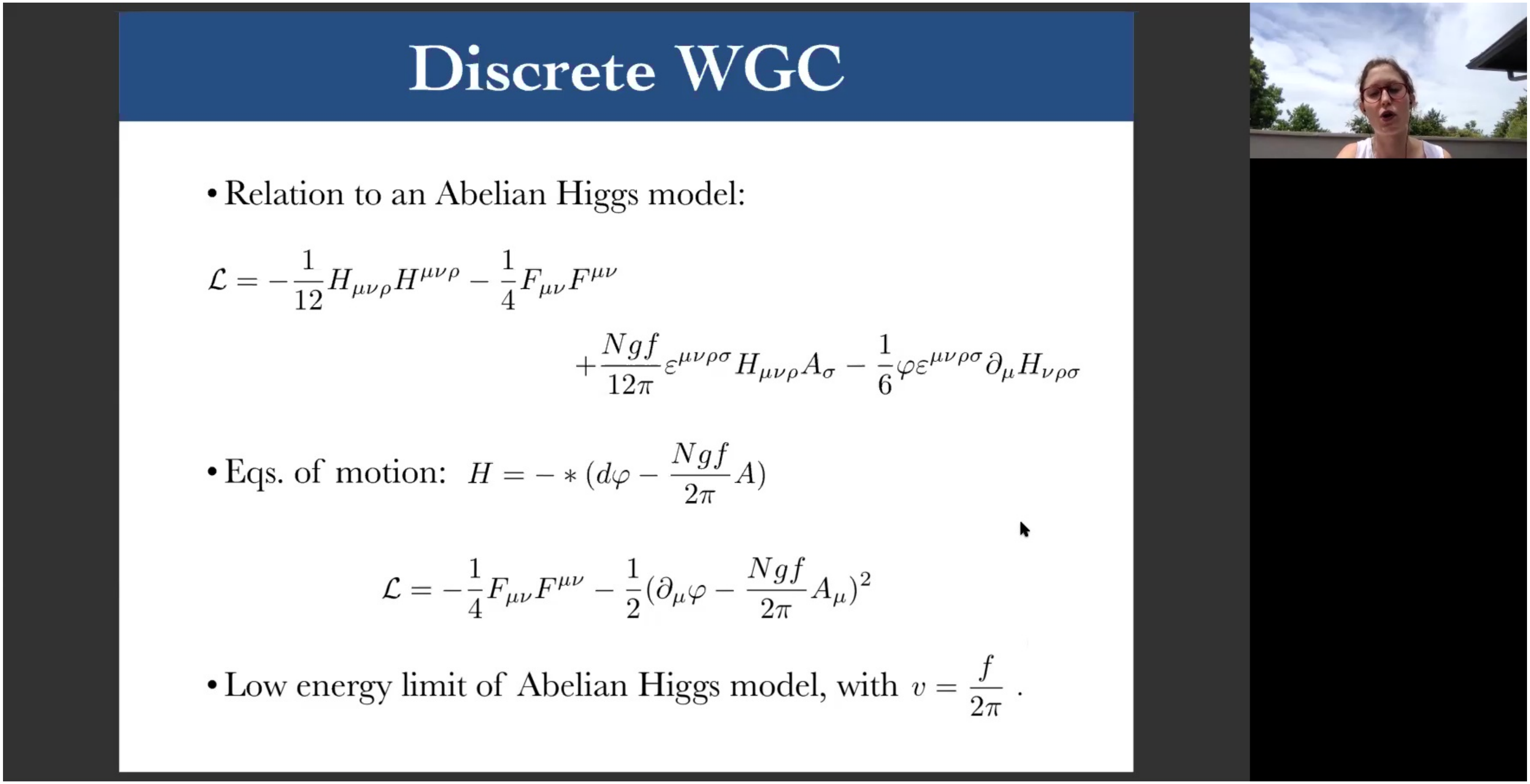
$$\mathcal{L} = -\frac{1}{12}H_{\mu\nu\rho}H^{\mu\nu\rho} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{Ngf}{8\pi}\varepsilon^{\mu\nu\rho\sigma}B_{\mu\nu}F_{\rho\sigma}$$



Discrete WGC

- Relation to an Abelian Higgs model:

$$\mathcal{L} = -\frac{1}{12}H_{\mu\nu\rho}H^{\mu\nu\rho} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{Ngf}{12\pi}\varepsilon^{\mu\nu\rho\sigma}H_{\mu\nu\rho}A_\sigma - \frac{1}{6}\varphi\varepsilon^{\mu\nu\rho\sigma}\partial_\mu H_{\nu\rho\sigma}$$



Discrete WGC

- Relation to an Abelian Higgs model:

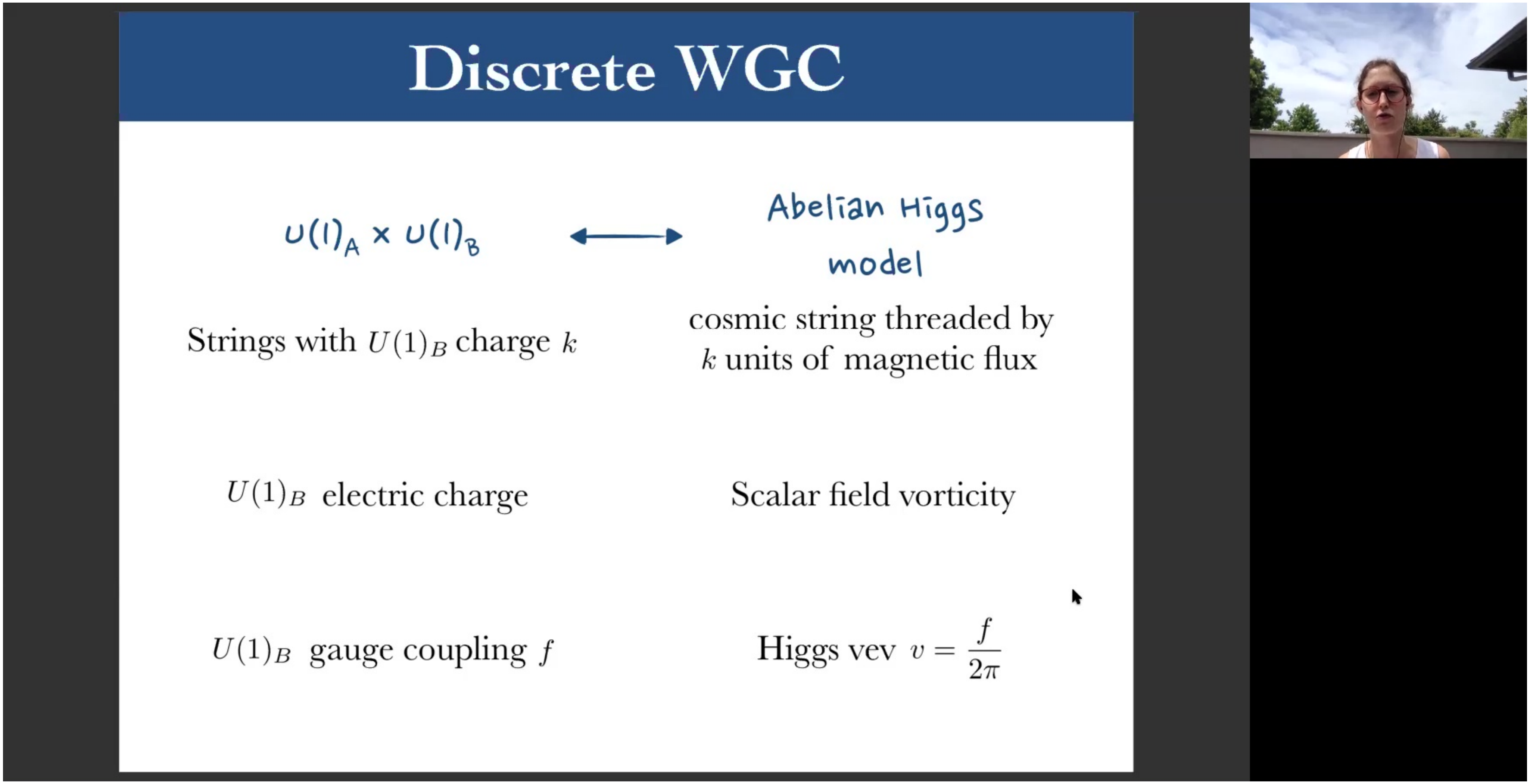
$$\mathcal{L} = -\frac{1}{12}H_{\mu\nu\rho}H^{\mu\nu\rho} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$+\frac{Ngf}{12\pi}\varepsilon^{\mu\nu\rho\sigma}H_{\mu\nu\rho}A_\sigma - \frac{1}{6}\varphi\varepsilon^{\mu\nu\rho\sigma}\partial_\mu H_{\nu\rho\sigma}$$

- Eqs. of motion: $H = - * (d\varphi - \frac{Ngf}{2\pi}A)$

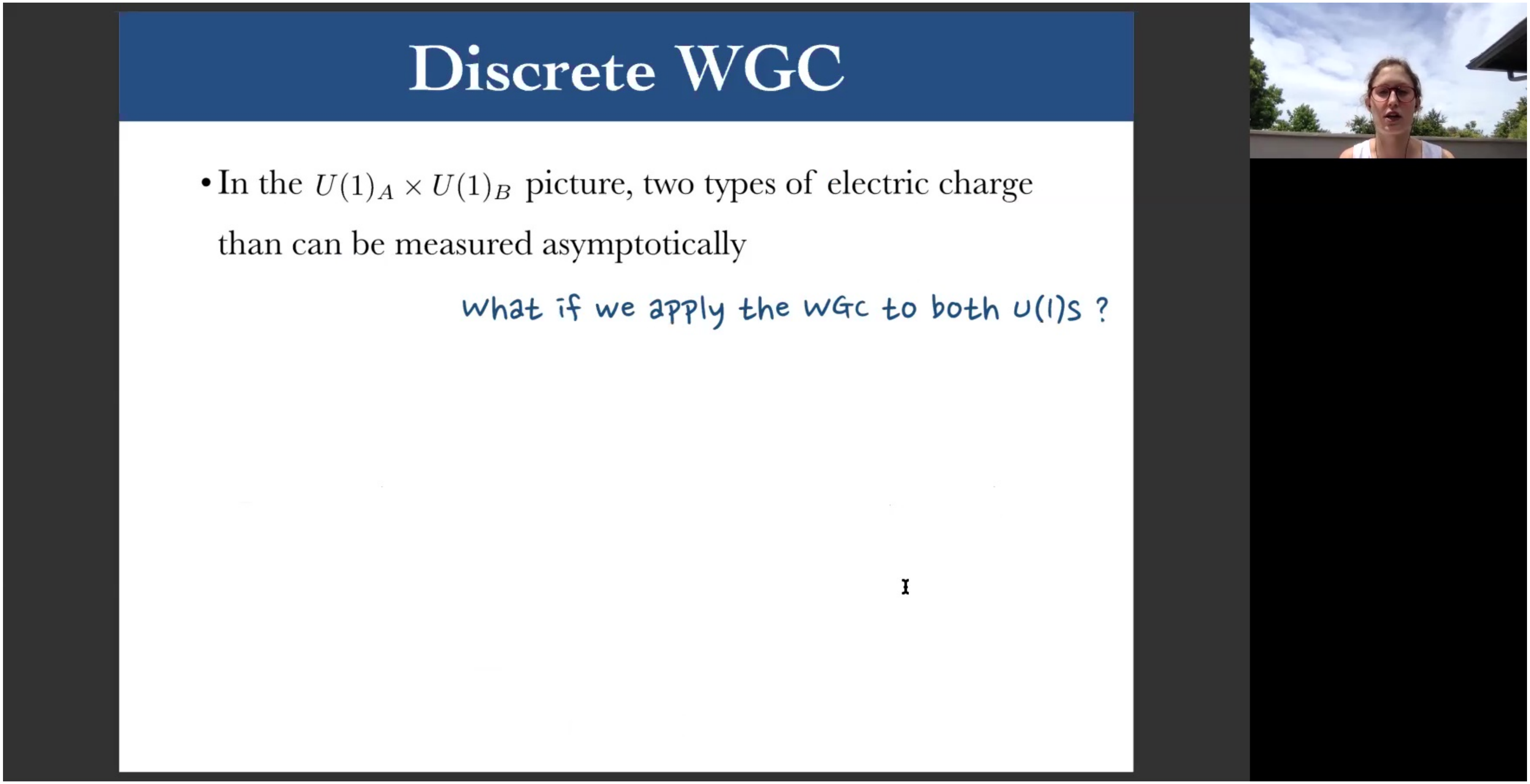
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(\partial_\mu\varphi - \frac{Ngf}{2\pi}A_\mu)^2$$

- Low energy limit of Abelian Higgs model, with $v = \frac{f}{2\pi}$.



Discrete WGC

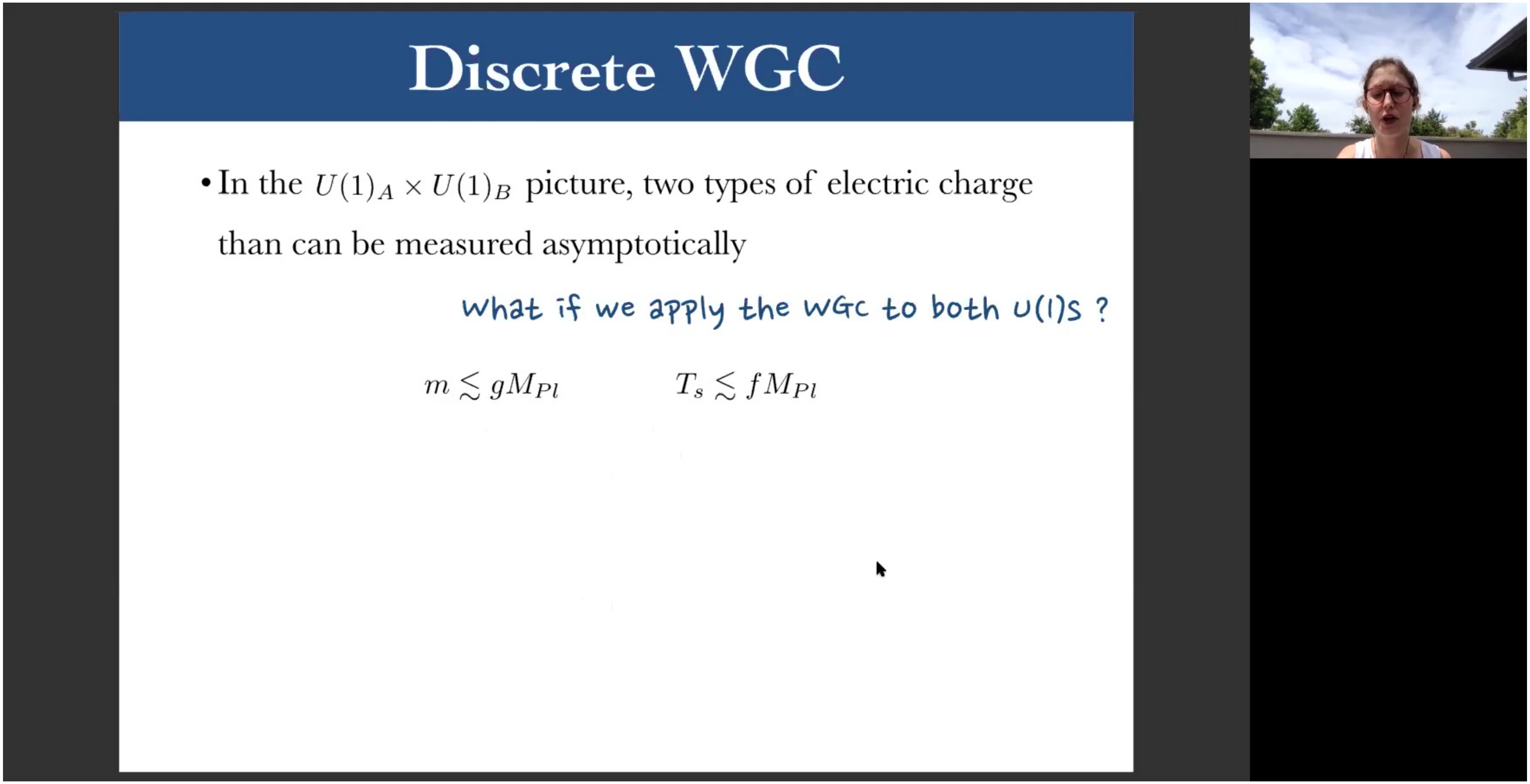
$U(1)_A \times U(1)_B$ ⟷	Abelian Higgs model
Strings with $U(1)_B$ charge k	cosmic string threaded by k units of magnetic flux
$U(1)_B$ electric charge	Scalar field vorticity
$U(1)_B$ gauge coupling f	Higgs vev $v = \frac{f}{2\pi}$



Discrete WGC

- In the $U(1)_A \times U(1)_B$ picture, two types of electric charge than can be measured asymptotically

What if we apply the WGC to both U(1)s ?

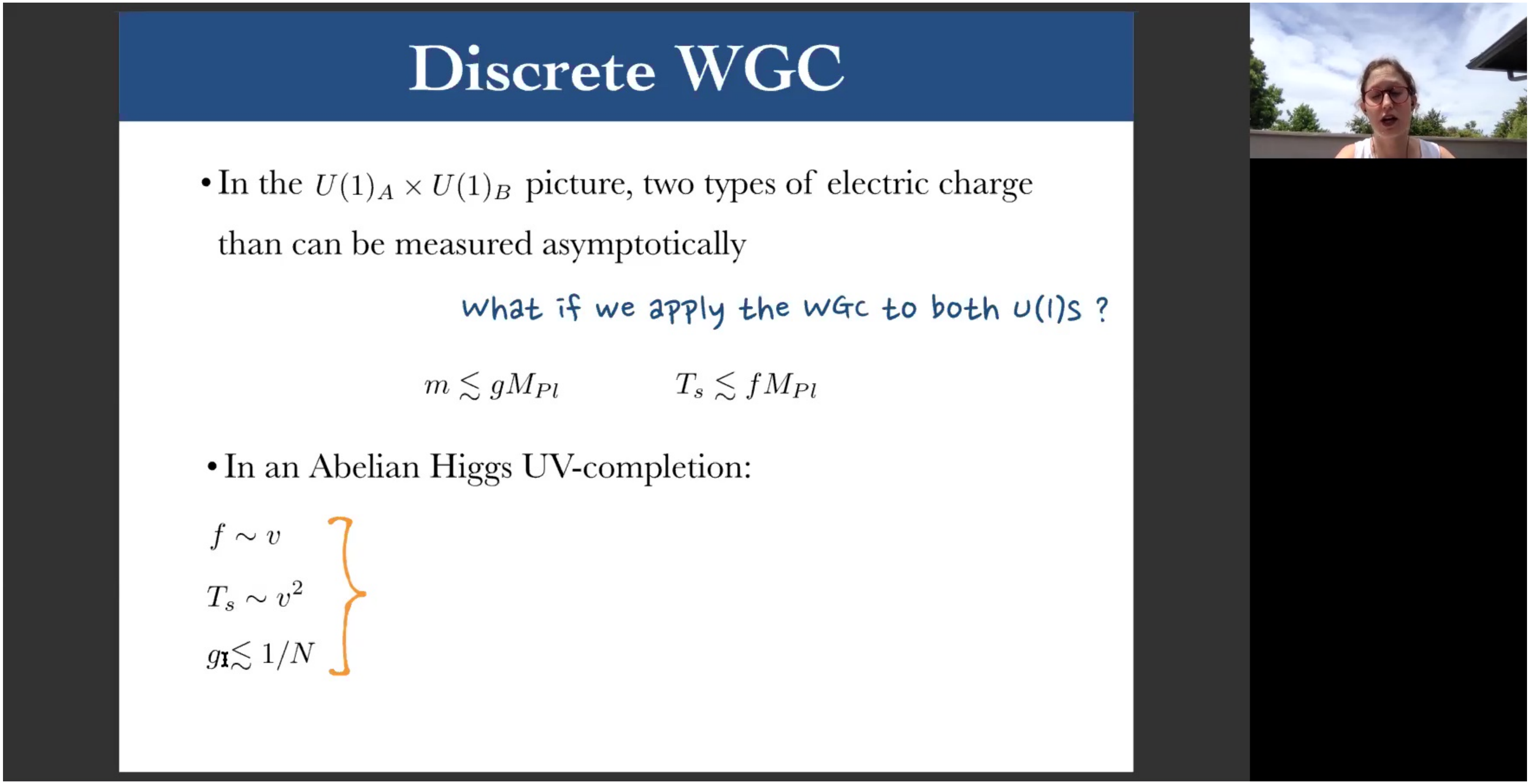


Discrete WGC

- In the $U(1)_A \times U(1)_B$ picture, two types of electric charge than can be measured asymptotically

what if we apply the WGC to both U(1)s ?

$$m \lesssim g M_{Pl} \qquad T_s \lesssim f M_{Pl}$$



Discrete WGC

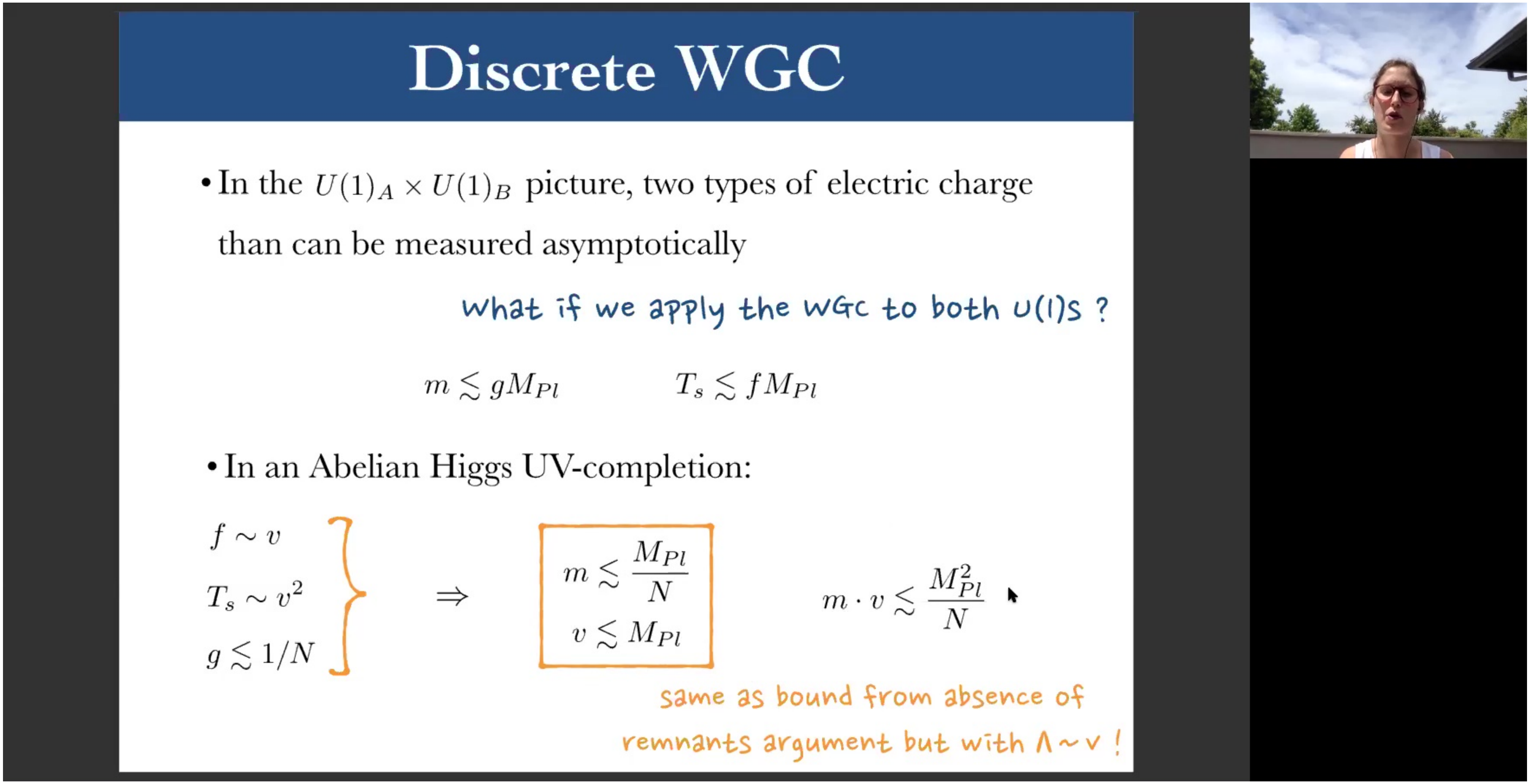
- In the $U(1)_A \times U(1)_B$ picture, two types of electric charge than can be measured asymptotically

what if we apply the WGC to both U(1)s ?

$$m \lesssim g M_{Pl} \qquad\qquad T_s \lesssim f M_{Pl}$$

- In an Abelian Higgs UV-completion:

$$\left.\begin{aligned} f &\sim v \\ T_s &\sim v^2 \\ g &\lesssim 1/N \end{aligned}\right\}$$



Discrete WGC

- In the $U(1)_A \times U(1)_B$ picture, two types of electric charge than can be measured asymptotically

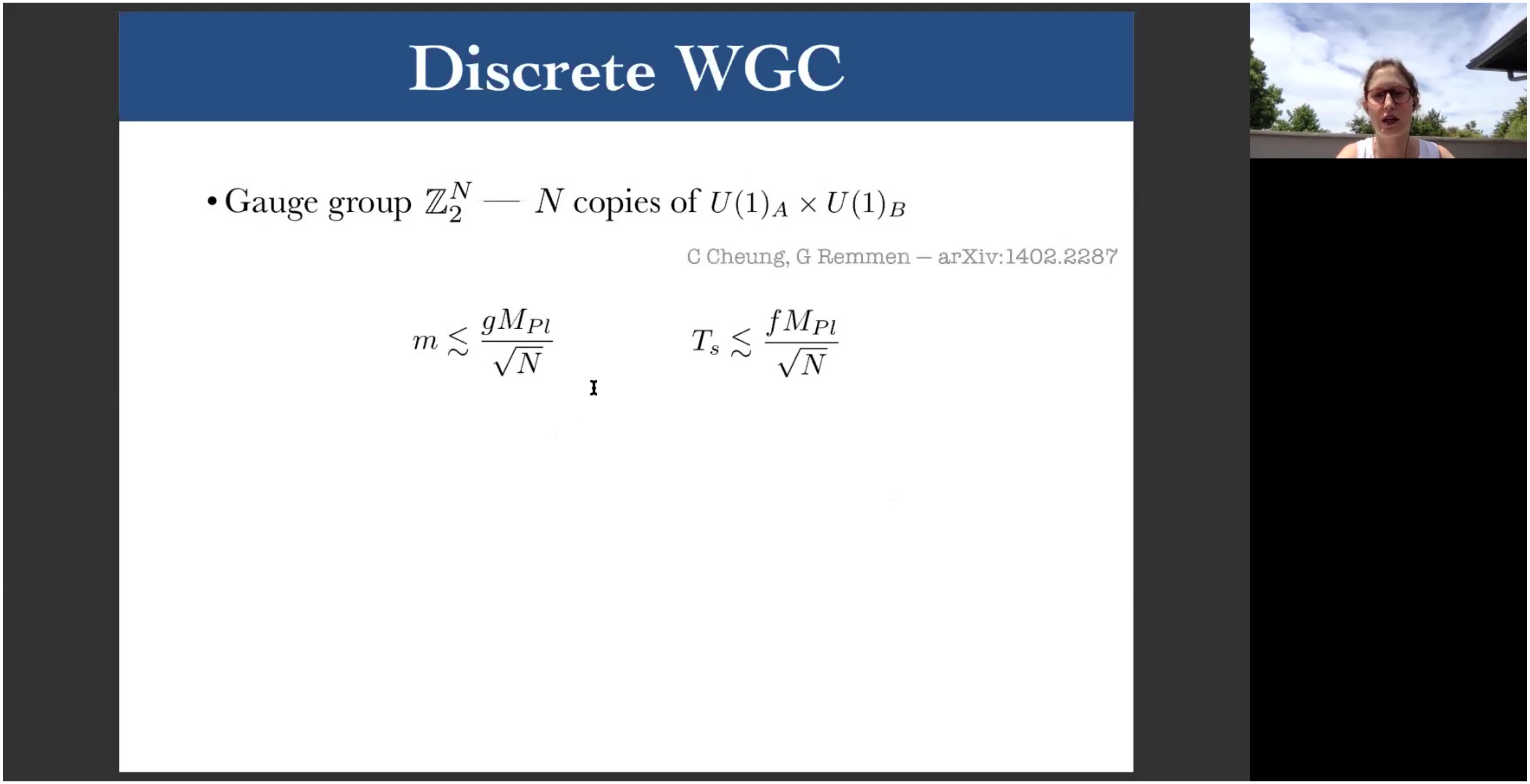
what if we apply the WGC to both U(1)s ?

$$m \lesssim g M_{Pl} \qquad T_s \lesssim f M_{Pl}$$

- In an Abelian Higgs UV-completion:

$$\left.\begin{array}{l} f \sim v \\ T_s \sim v^2 \\ g \lesssim 1/N \end{array}\right\} \Rightarrow \boxed{\begin{array}{c} m \lesssim \dfrac{M_{Pl}}{N} \\ v \lesssim M_{Pl} \end{array}} \qquad m \cdot v \lesssim \frac{M_{Pl}^2}{N}$$

same as bound from absence of remnants argument but with $\Lambda \sim v$!

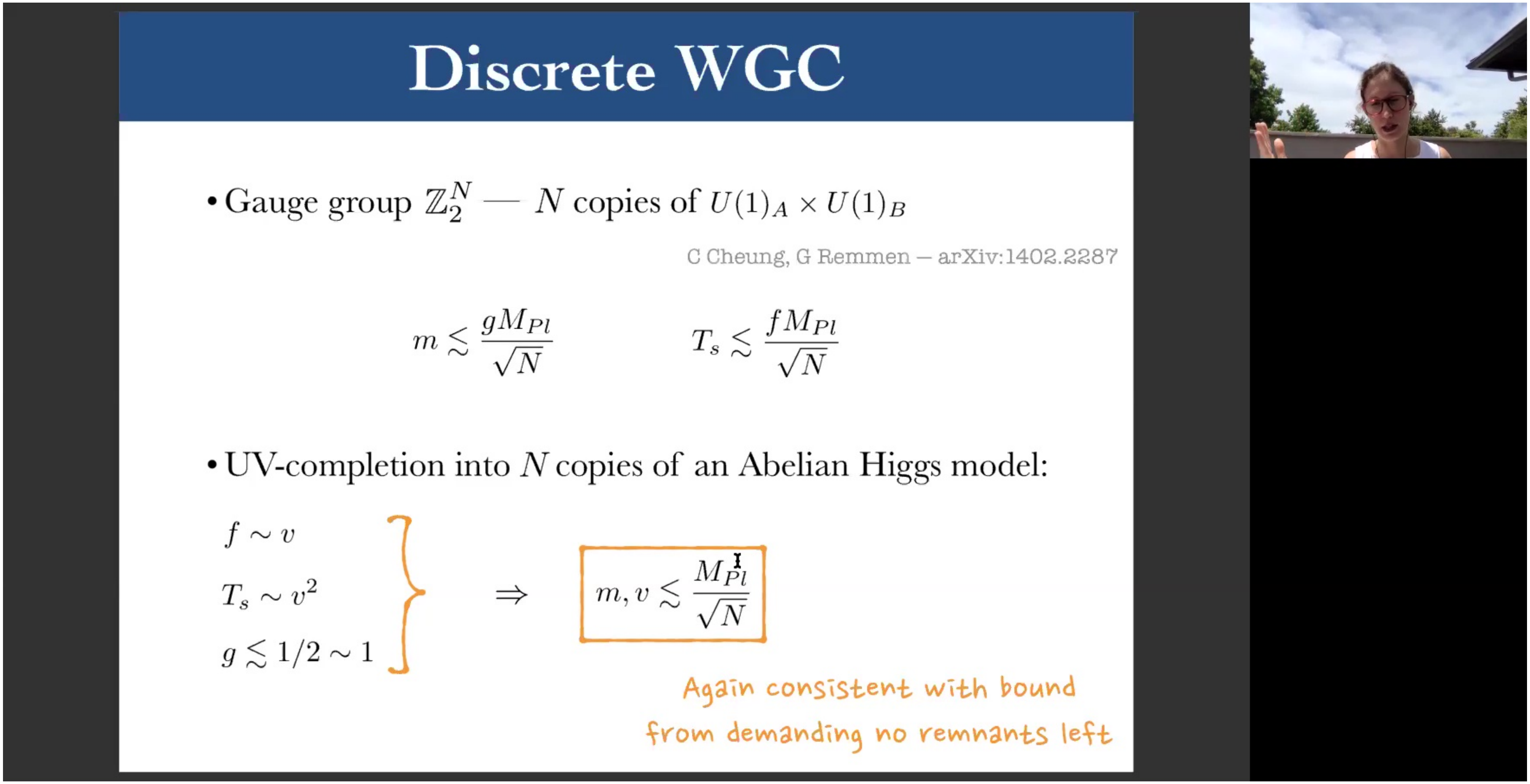


Discrete WGC

- Gauge group $\mathbb{Z}_2^N$ — N copies of $U(1)_A \times U(1)_B$

C Cheung, G Remmen – arXiv:1402.2287

$$m \lesssim \frac{g M_{Pl}}{\sqrt{N}} \qquad T_s \lesssim \frac{f M_{Pl}}{\sqrt{N}}$$



Discrete WGC

- Gauge group $\mathbb{Z}_2^N$ — N copies of $U(1)_A \times U(1)_B$

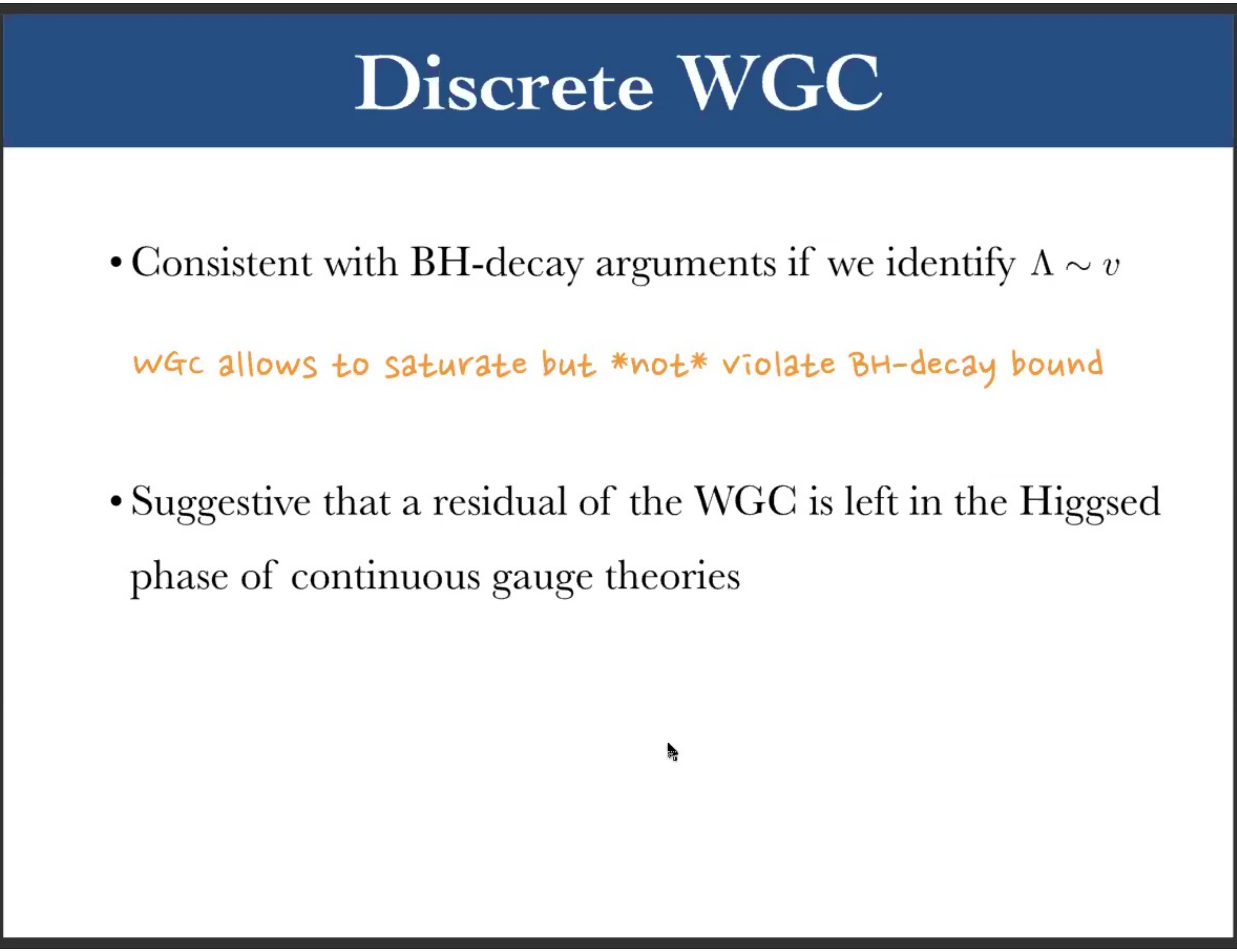
C Cheung, G Remmen – arXiv:1402.2287

$$m \lesssim \frac{g M_{Pl}}{\sqrt{N}} \qquad T_s \lesssim \frac{f M_{Pl}}{\sqrt{N}}$$

- UV-completion into N copies of an Abelian Higgs model:

$$\left.\begin{array}{l} f \sim v \\ T_s \sim v^2 \\ g \lesssim 1/2 \sim 1 \end{array}\right\} \Rightarrow \boxed{m, v \lesssim \frac{M_{Pl}}{\sqrt{N}}}$$

Again consistent with bound
from demanding no remnants left

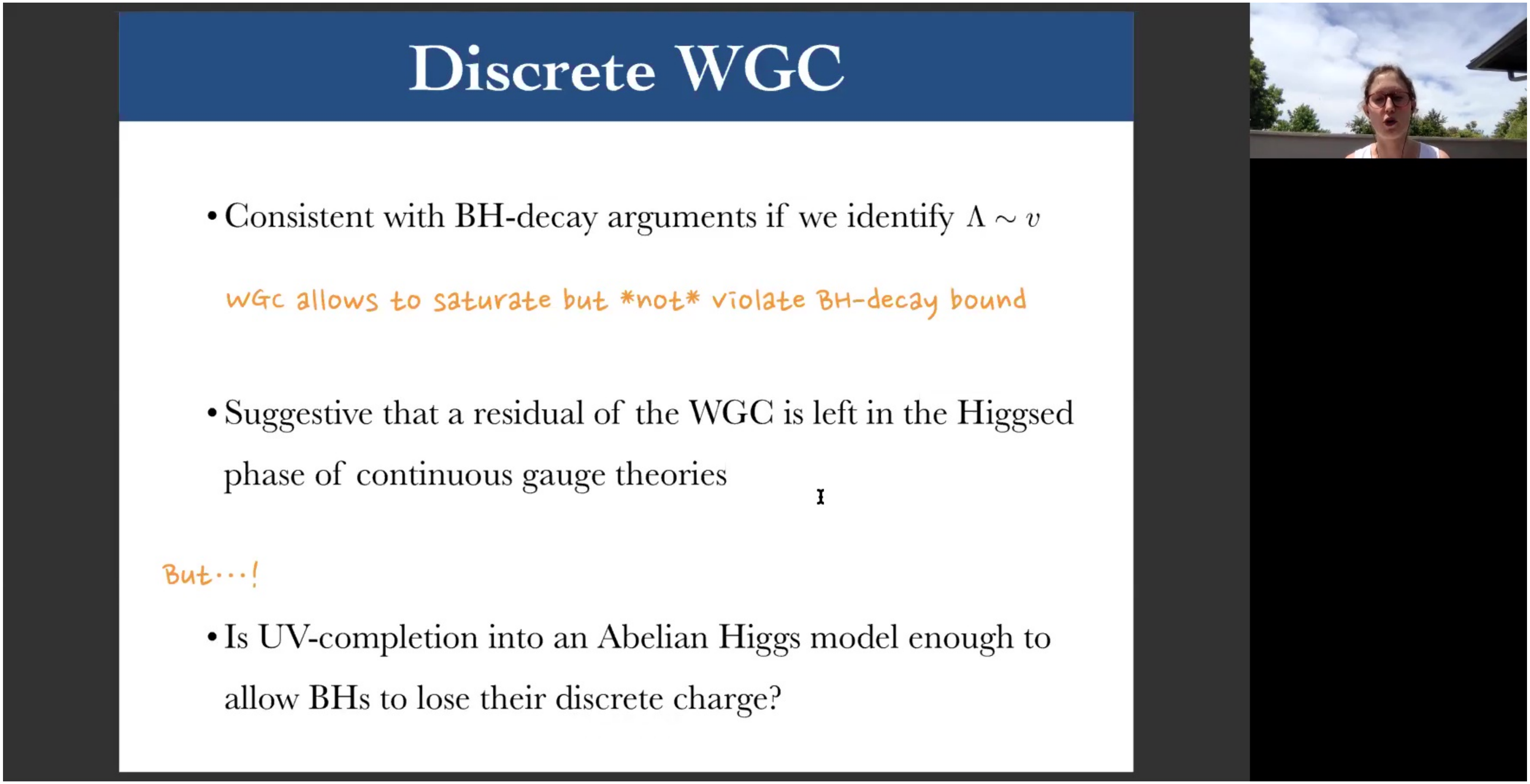


Discrete WGC

- Consistent with BH-decay arguments if we identify $\Lambda \sim v$

WGC allows to saturate but *not* violate BH-decay bound

- Suggestive that a residual of the WGC is left in the Higgsed phase of continuous gauge theories



Discrete WGC

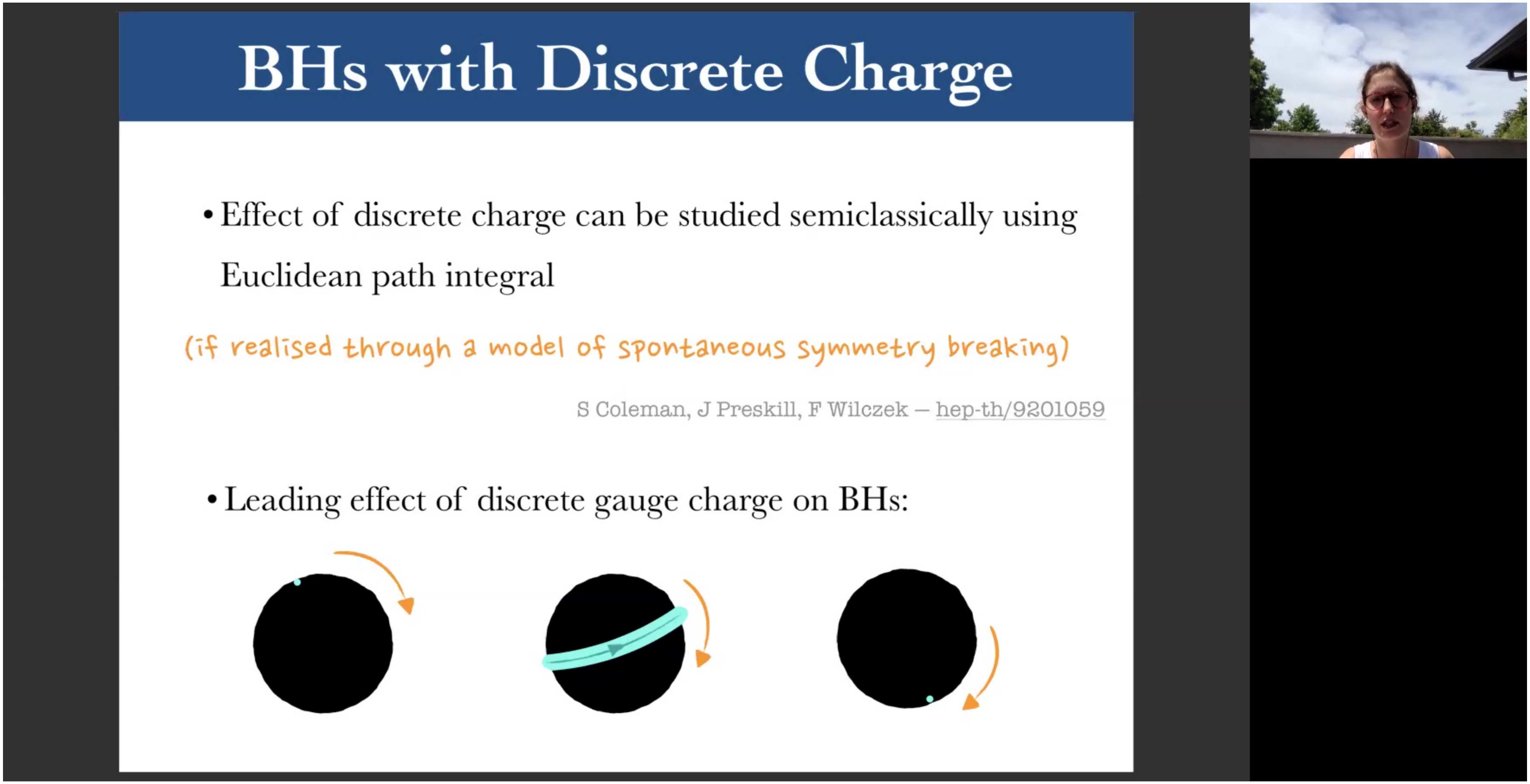
- Consistent with BH-decay arguments if we identify $\Lambda \sim v$

WGC allows to saturate but *not* violate BH-decay bound

- Suggestive that a residual of the WGC is left in the Higgsed phase of continuous gauge theories

But···!

- Is UV-completion into an Abelian Higgs model enough to allow BHs to lose their discrete charge?



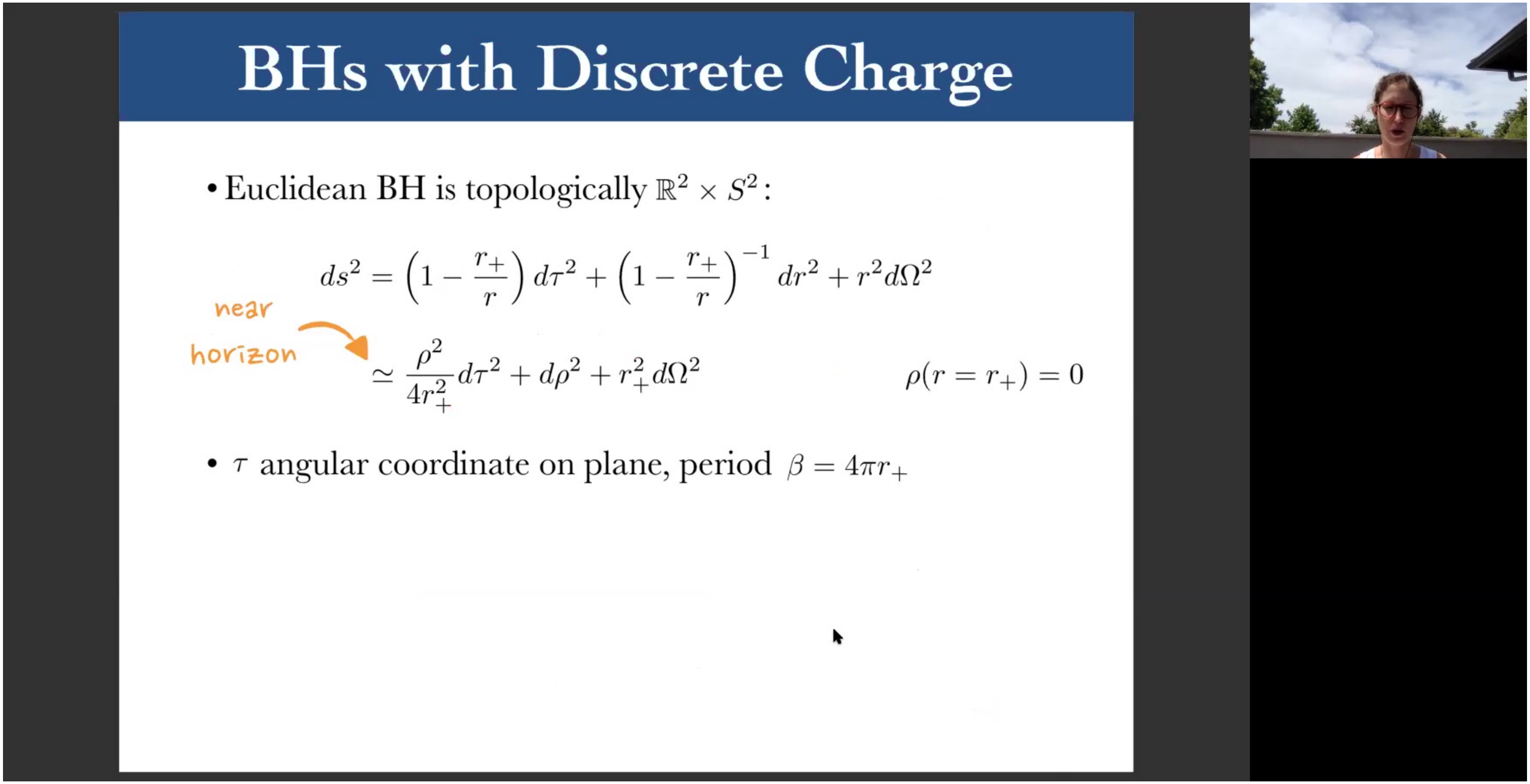
BHs with Discrete Charge

- Effect of discrete charge can be studied semiclassically using Euclidean path integral

(if realised through a model of spontaneous symmetry breaking)

S Coleman, J Preskill, F Wilczek – hep-th/9201059

- Leading effect of discrete gauge charge on BHs:



BHs with Discrete Charge

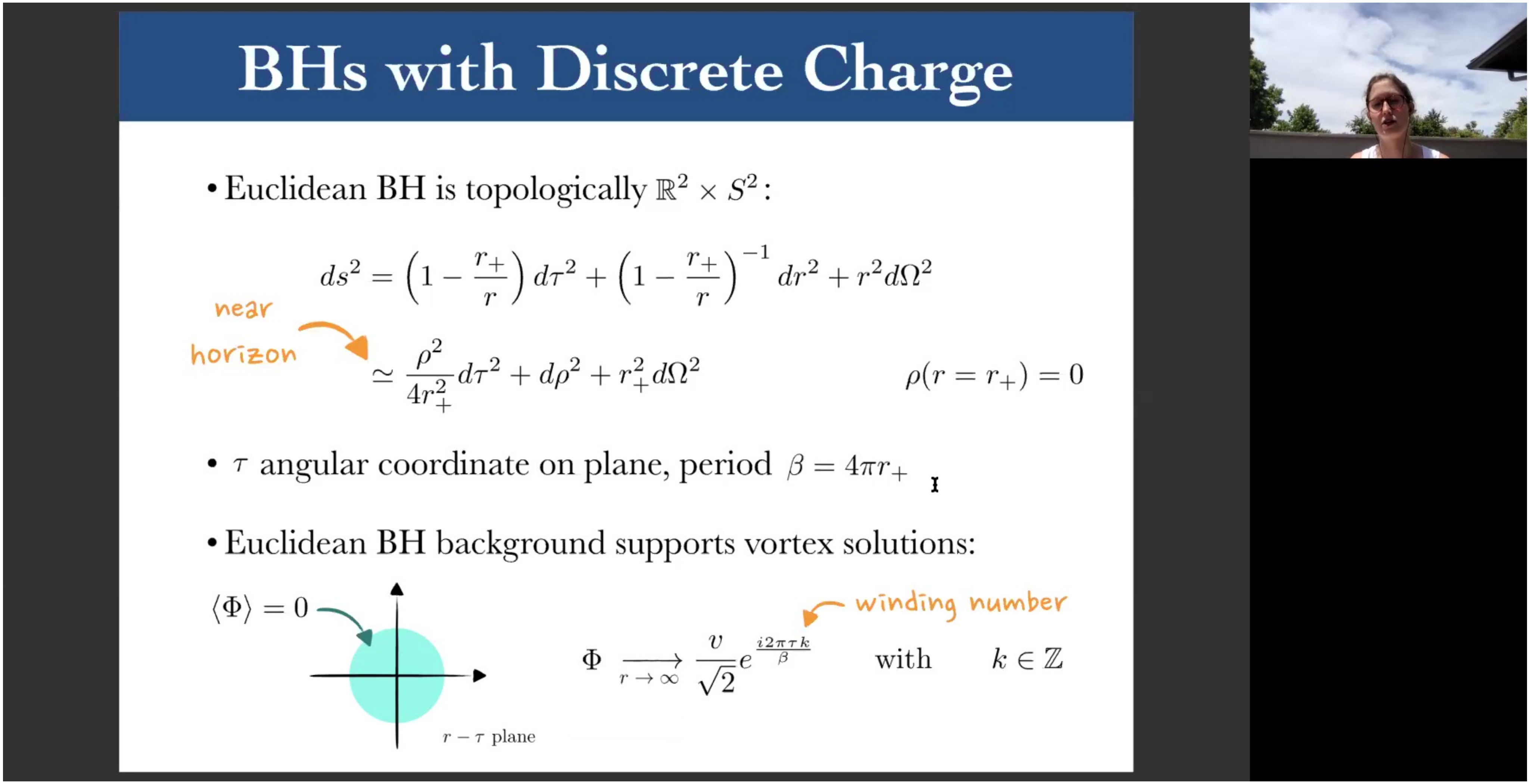
- Euclidean BH is topologically $\mathbb{R}^2 \times S^2$:

$$ds^2 = \left(1 - \frac{r_+}{r}\right) d\tau^2 + \left(1 - \frac{r_+}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

near horizon

$$\simeq \frac{\rho^2}{4r_+^2} d\tau^2 + d\rho^2 + r_+^2 d\Omega^2 \qquad \rho(r = r_+) = 0$$

- τ angular coordinate on plane, period $\beta = 4\pi r_+$



BHs with Discrete Charge

- Euclidean BH is topologically $\mathbb{R}^2 \times S^2$:

$$ds^2 = \left(1 - \frac{r_+}{r}\right) d\tau^2 + \left(1 - \frac{r_+}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

near horizon

$$\simeq \frac{\rho^2}{4r_+^2} d\tau^2 + d\rho^2 + r_+^2 d\Omega^2 \qquad \rho(r = r_+) = 0$$

- τ angular coordinate on plane, period $\beta = 4\pi r_+$

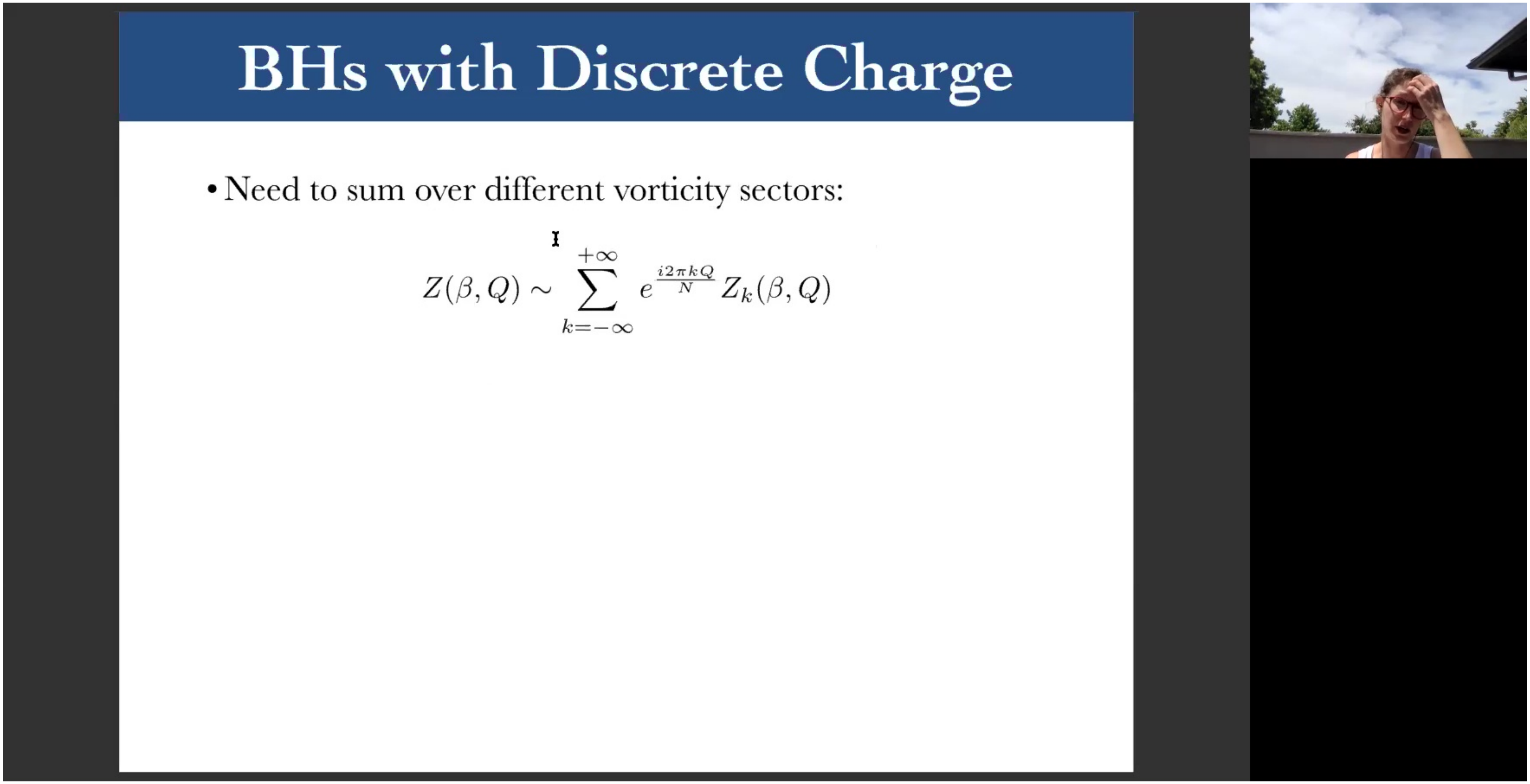
- Euclidean BH background supports vortex solutions:

$\langle \Phi \rangle = 0$

$r - \tau$ plane

winding number

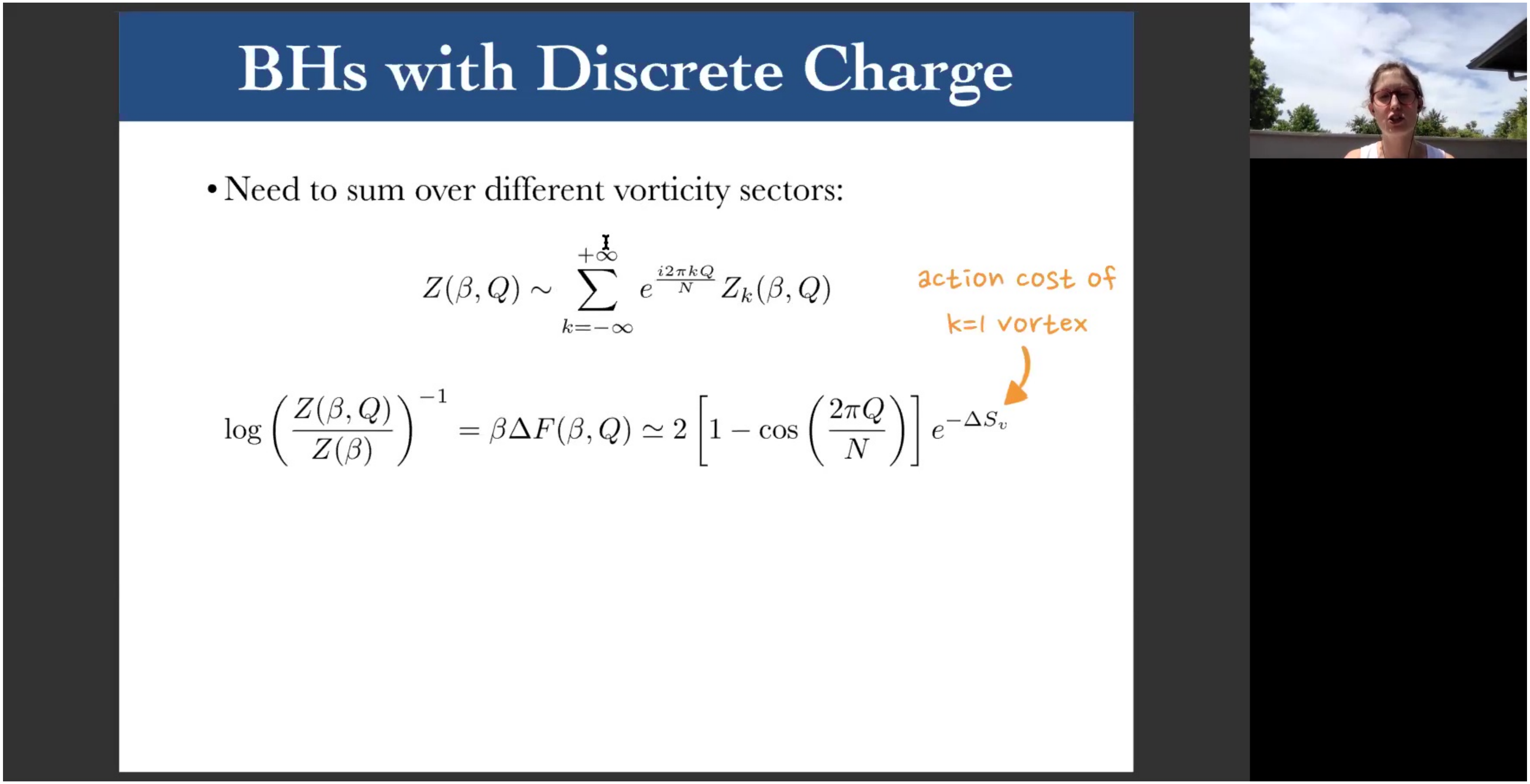
$$\Phi \xrightarrow[r \to \infty]{} \frac{v}{\sqrt{2}} e^{\frac{i 2\pi \tau k}{\beta}} \qquad \text{with} \qquad k \in \mathbb{Z}$$



BHs with Discrete Charge

- Need to sum over different vorticity sectors:

$$Z(\beta, Q) \sim \sum_{k=-\infty}^{+\infty} e^{\frac{i2\pi kQ}{N}} Z_k(\beta, Q)$$



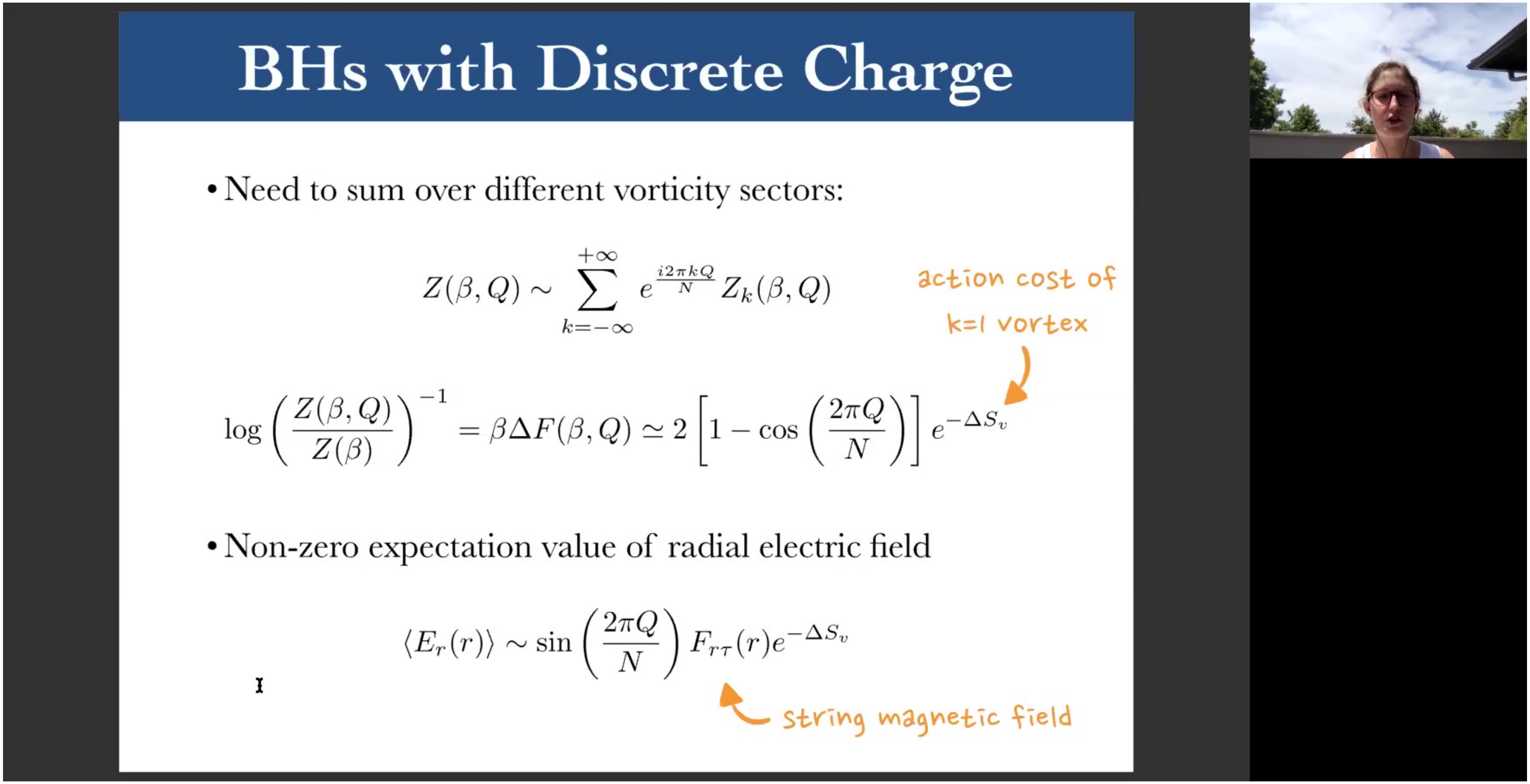
BHs with Discrete Charge

- Need to sum over different vorticity sectors:

$$Z(\beta, Q) \sim \sum_{k=-\infty}^{+\infty} e^{\frac{i2\pi kQ}{N}} Z_k(\beta, Q)$$

action cost of k=1 vortex

$$\log\left(\frac{Z(\beta, Q)}{Z(\beta)}\right)^{-1} = \beta\Delta F(\beta, Q) \simeq 2\left[1 - \cos\left(\frac{2\pi Q}{N}\right)\right] e^{-\Delta S_v}$$



BHs with Discrete Charge

- Need to sum over different vorticity sectors:

$$Z(\beta, Q) \sim \sum_{k=-\infty}^{+\infty} e^{\frac{i2\pi kQ}{N}} Z_k(\beta, Q)$$

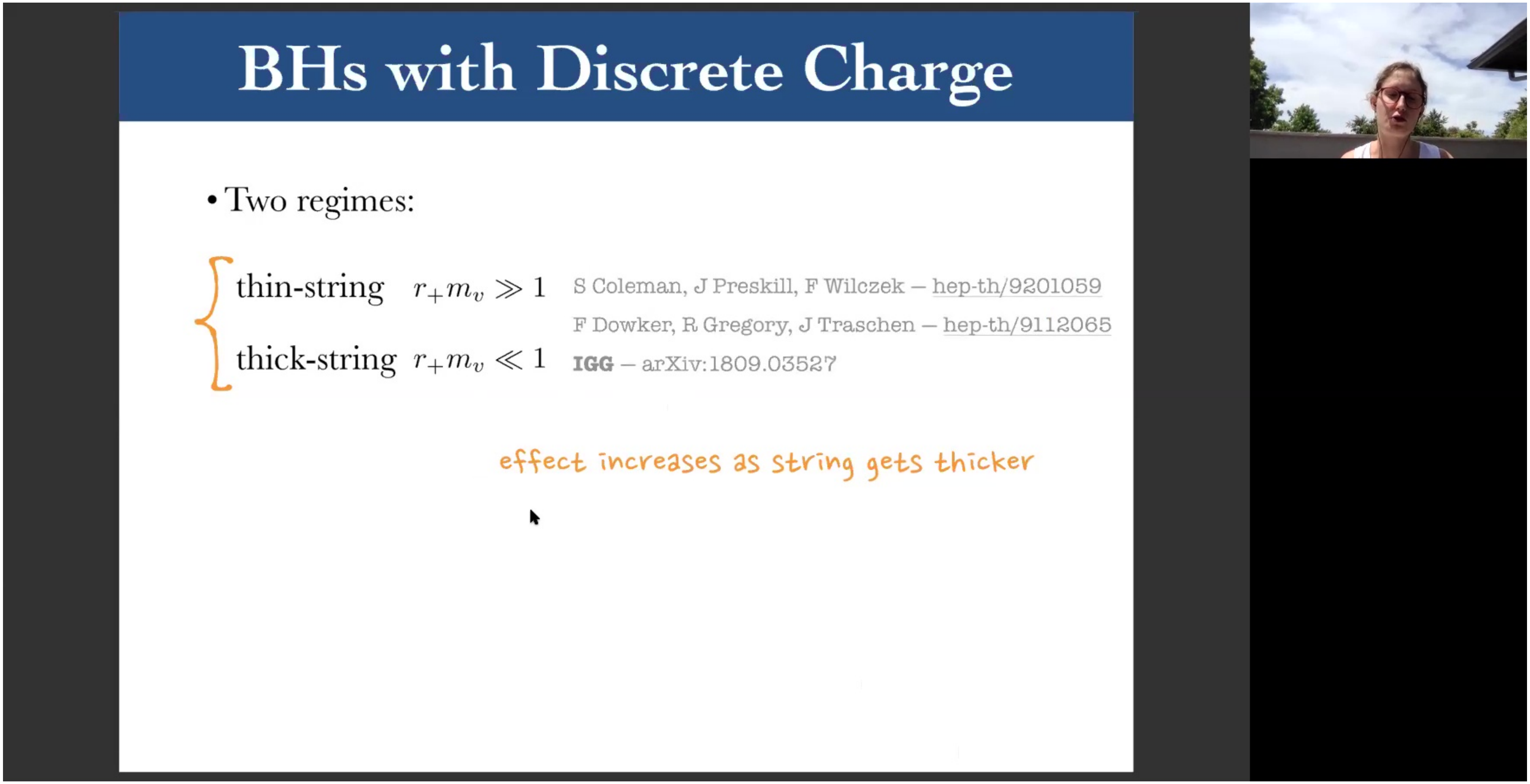
action cost of
k=1 vortex

$$\log\left(\frac{Z(\beta,Q)}{Z(\beta)}\right)^{-1} = \beta \Delta F(\beta, Q) \simeq 2\left[1 - \cos\left(\frac{2\pi Q}{N}\right)\right] e^{-\Delta S_v}$$

- Non-zero expectation value of radial electric field

$$\langle E_r(r) \rangle \sim \sin\left(\frac{2\pi Q}{N}\right) F_{r\tau}(r) e^{-\Delta S_v}$$

string magnetic field



BHs with Discrete Charge

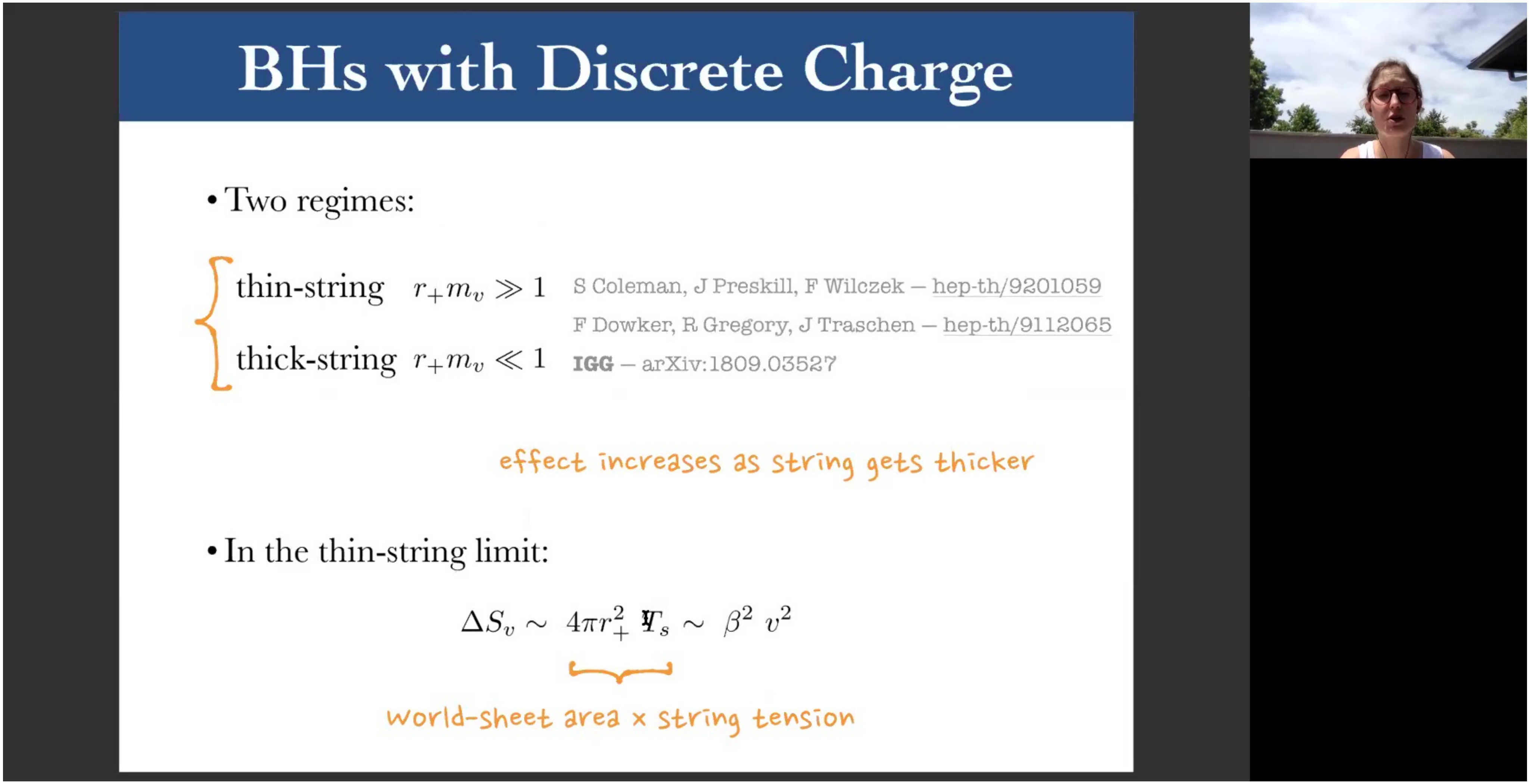
- Two regimes:

thin-string $r_+ m_v \gg 1$ S Coleman, J Preskill, F Wilczek – hep-th/9201059

F Dowker, R Gregory, J Traschen – hep-th/9112065

thick-string $r_+ m_v \ll 1$ **IGG** – arXiv:1809.03527

effect increases as string gets thicker



BHs with Discrete Charge

- Two regimes:

thin-string $r_+ m_v \gg 1$

thick-string $r_+ m_v \ll 1$

S Coleman, J Preskill, F Wilczek – hep-th/9201059

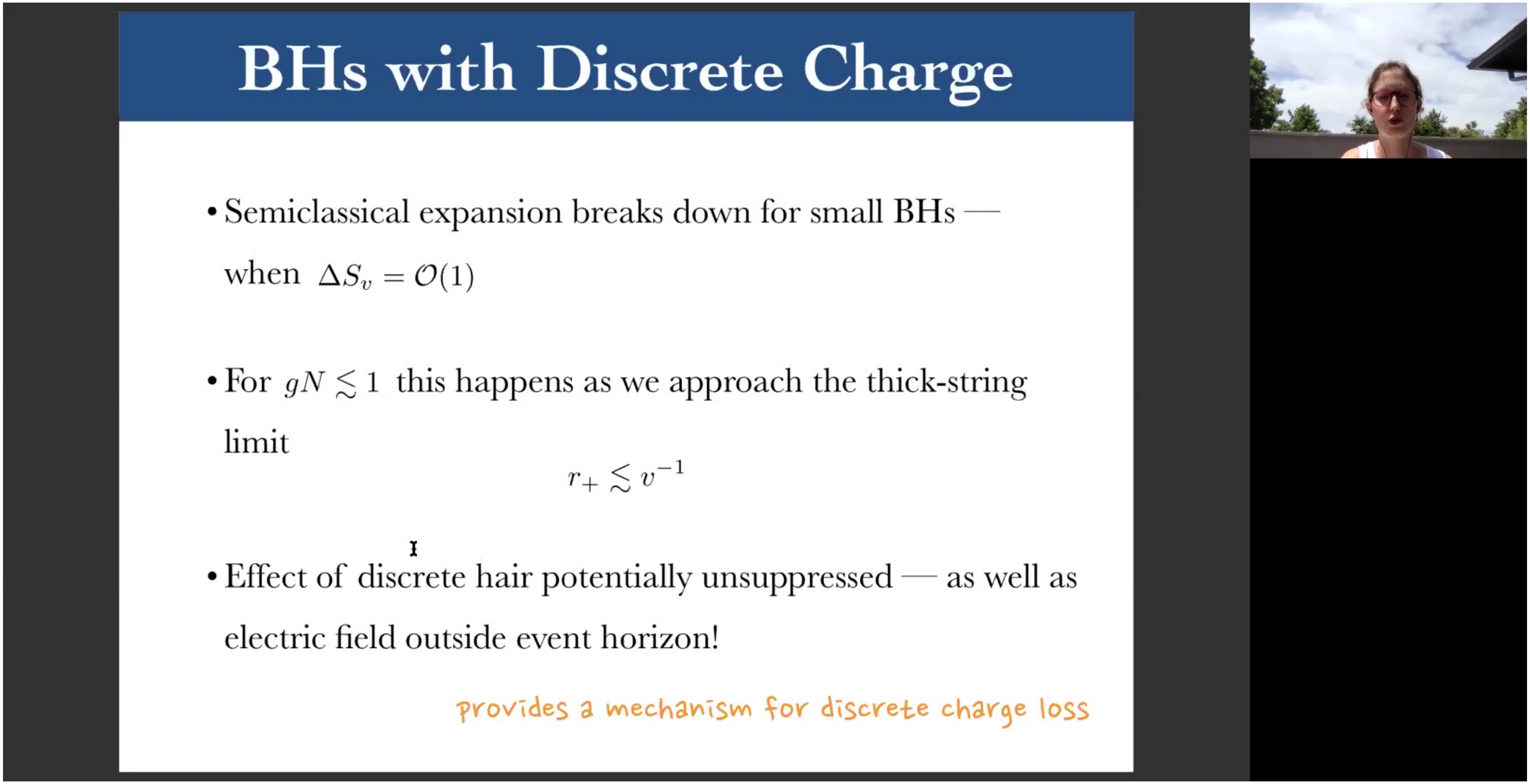
F Dowker, R Gregory, J Traschen – hep-th/9112065

IGG – arXiv:1809.03527

effect increases as string gets thicker

- In the thin-string limit:

$$\Delta S_v \sim \underbrace{4\pi r_+^2 \, T_s}_{\text{world-sheet area x string tension}} \sim \beta^2 \, v^2$$



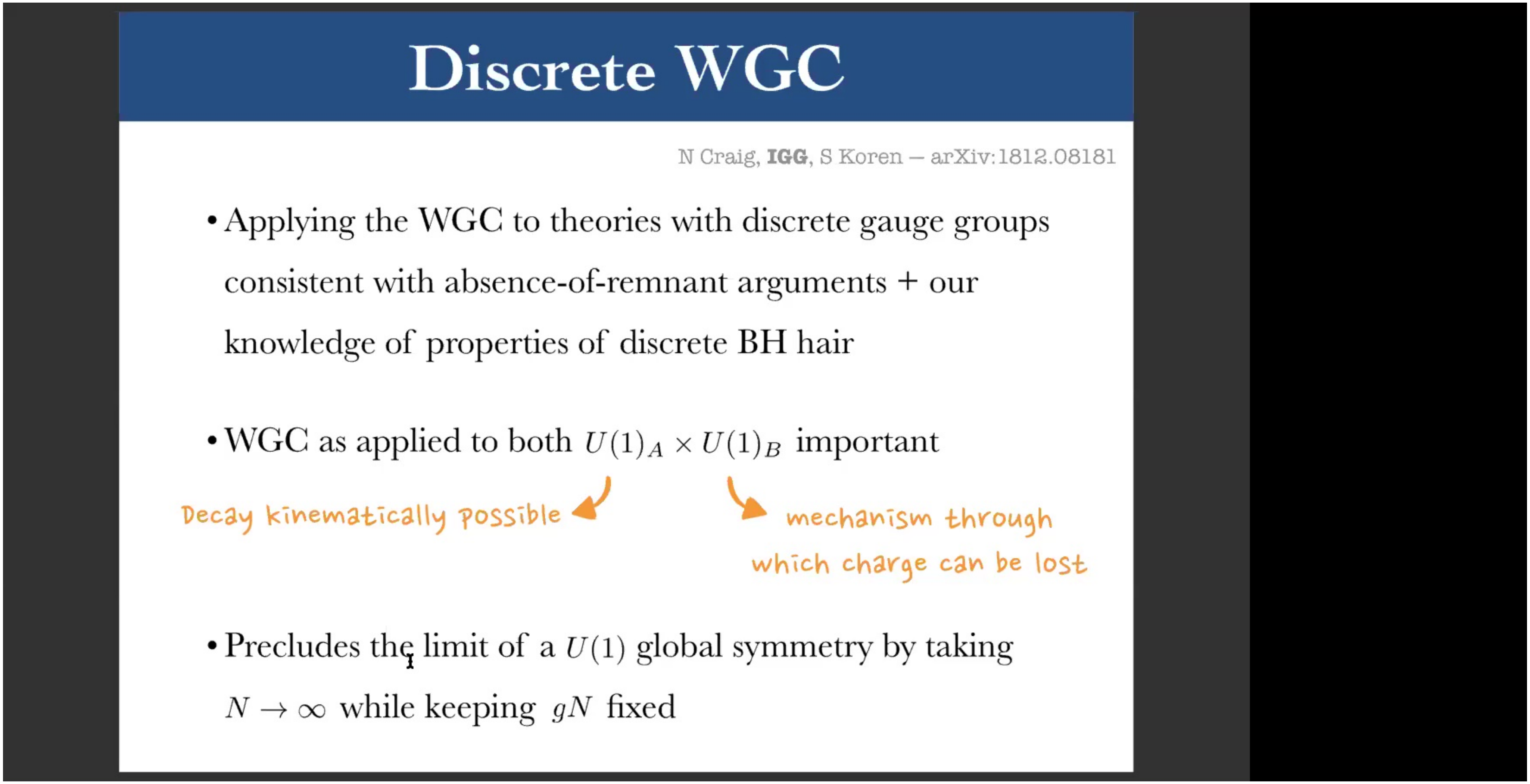
BHs with Discrete Charge

- Semiclassical expansion breaks down for small BHs — when $\Delta S_v = \mathcal{O}(1)$
- For $gN \lesssim 1$ this happens as we approach the thick-string limit

$$r_+ \lesssim v^{-1}$$

- Effect of discrete hair potentially unsuppressed — as well as electric field outside event horizon!

provides a mechanism for discrete charge loss



Discrete WGC

N Craig, **IGG**, S Koren — arXiv:1812.08181

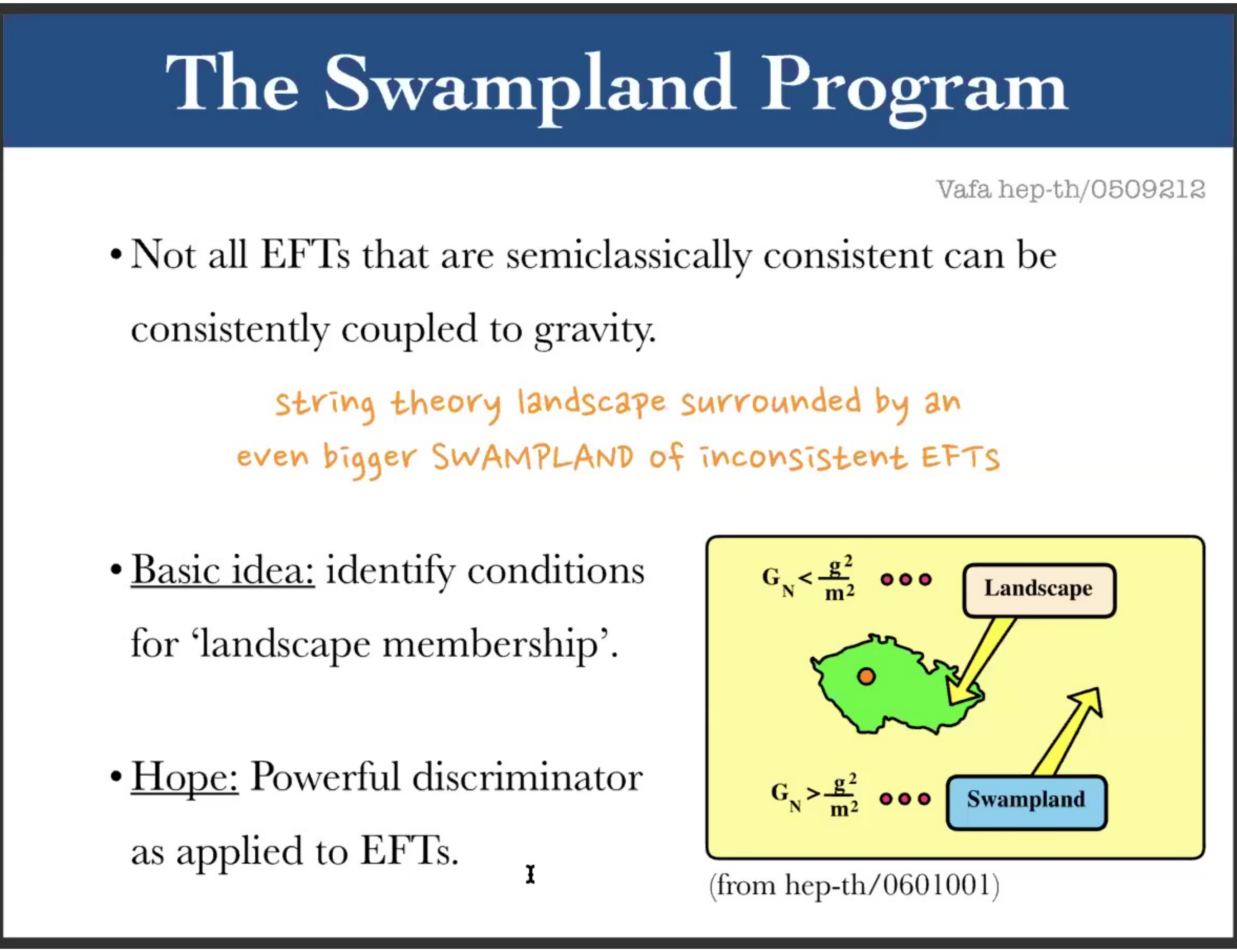
- Applying the WGC to theories with discrete gauge groups consistent with absence-of-remnant arguments + our knowledge of properties of discrete BH hair

- WGC as applied to both $U(1)_A \times U(1)_B$ important

Decay kinematically possible

mechanism through which charge can be lost

- Precludes the limit of a $U(1)$ global symmetry by taking $N \to \infty$ while keeping gN fixed



The Swampland Program

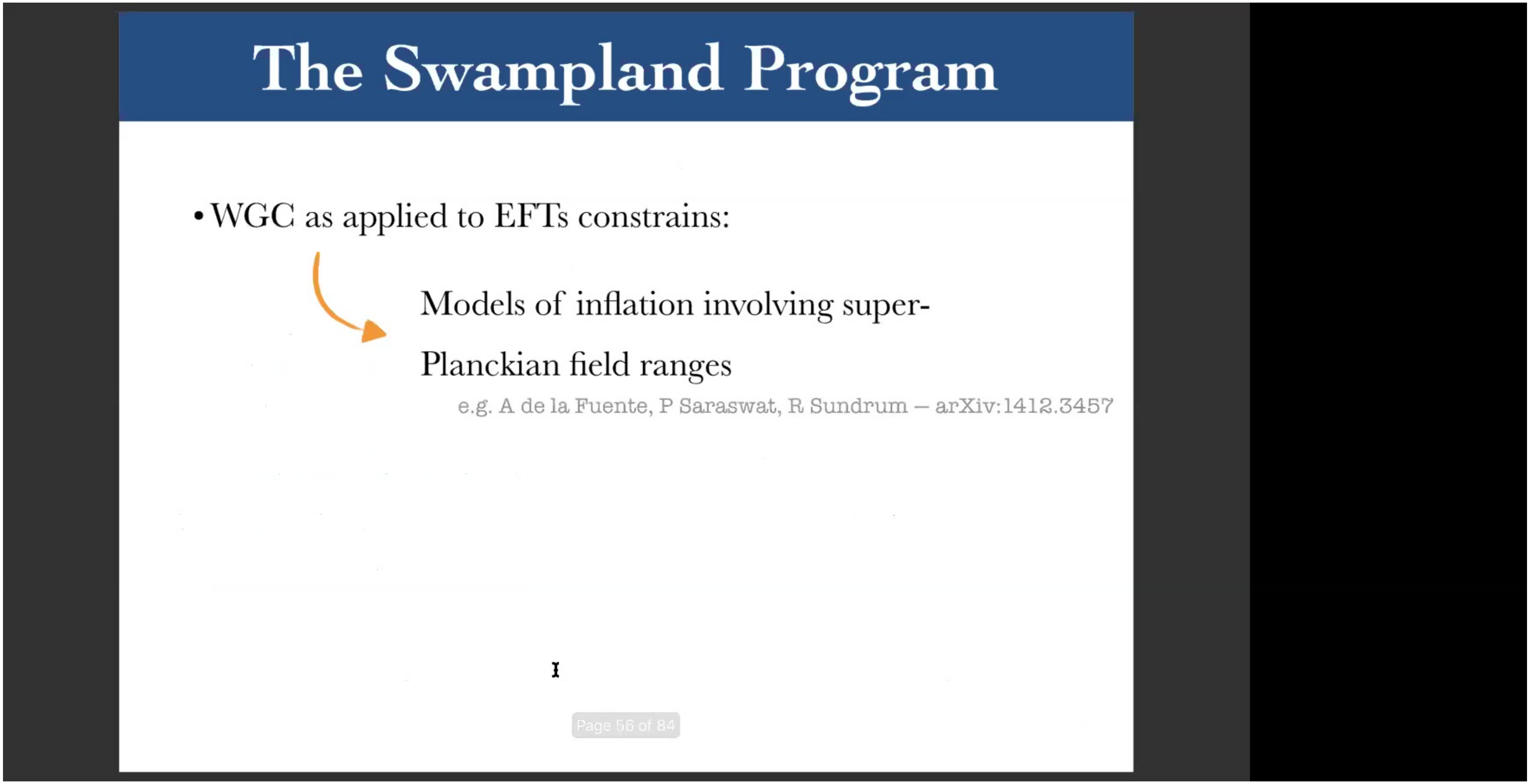
Vafa hep-th/0509212

- Not all EFTs that are semiclassically consistent can be consistently coupled to gravity.

string theory landscape surrounded by an
even bigger SWAMPLAND of inconsistent EFTs

- Basic idea: identify conditions for 'landscape membership'.
- Hope: Powerful discriminator as applied to EFTs.

(from hep-th/0601001)



The Swampland Program

- WGC as applied to EFTs constrains:

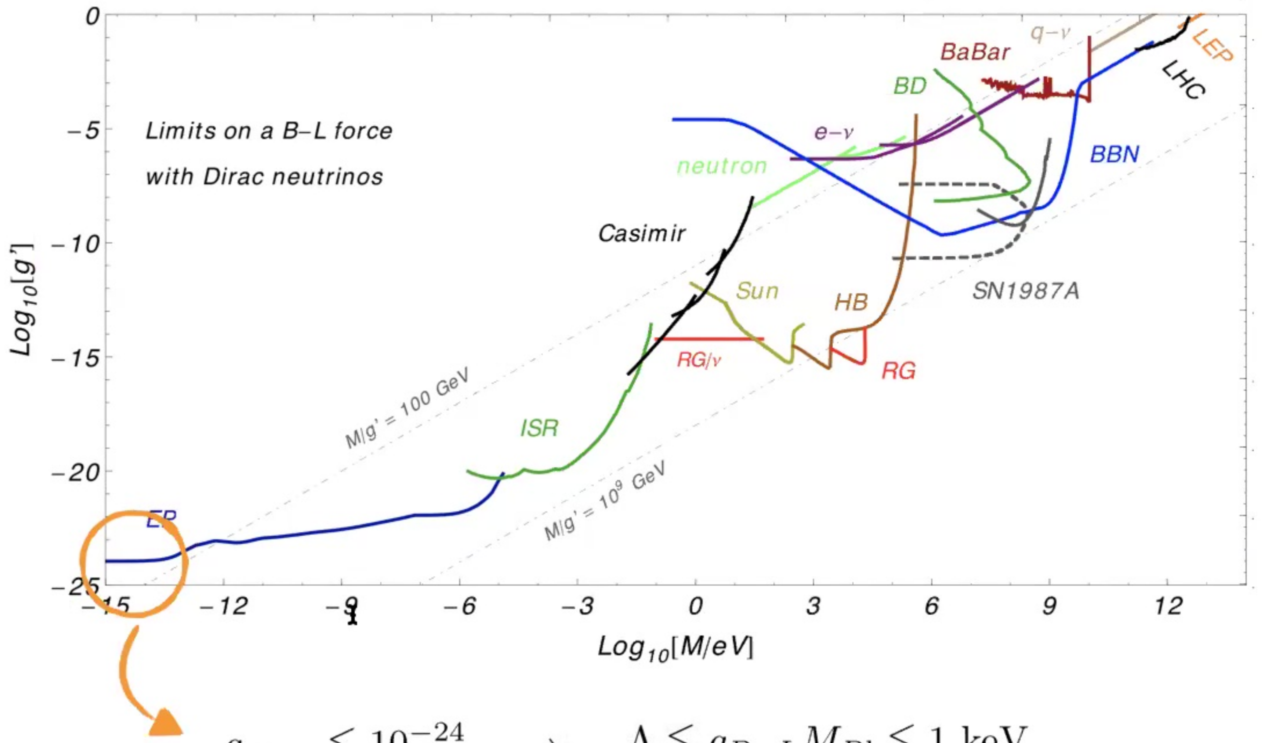
Models of inflation involving super-Planckian field ranges

e.g. A de la Fuente, P Saraswat, R Sundrum – arXiv:1412.3457

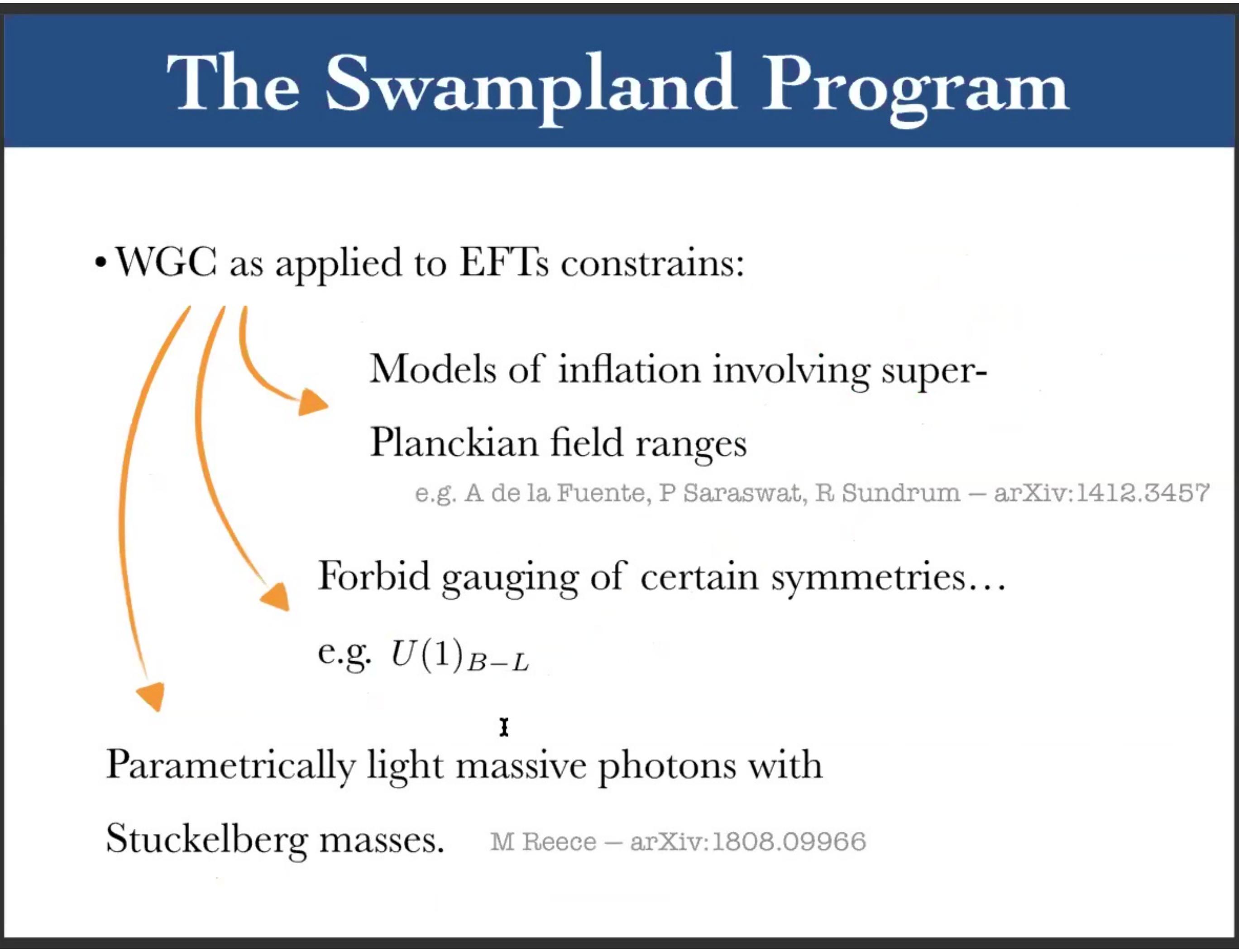
Page 56 of 84

The Swampland Program

(from arXiv:1408.6845)



$$g_{B-L} \lesssim 10^{-24} \quad \Rightarrow \quad \Lambda \lesssim g_{B-L} M_{Pl} \lesssim 1 \text{ keV}$$



The Swampland Program

- WGC as applied to EFTs constrains:

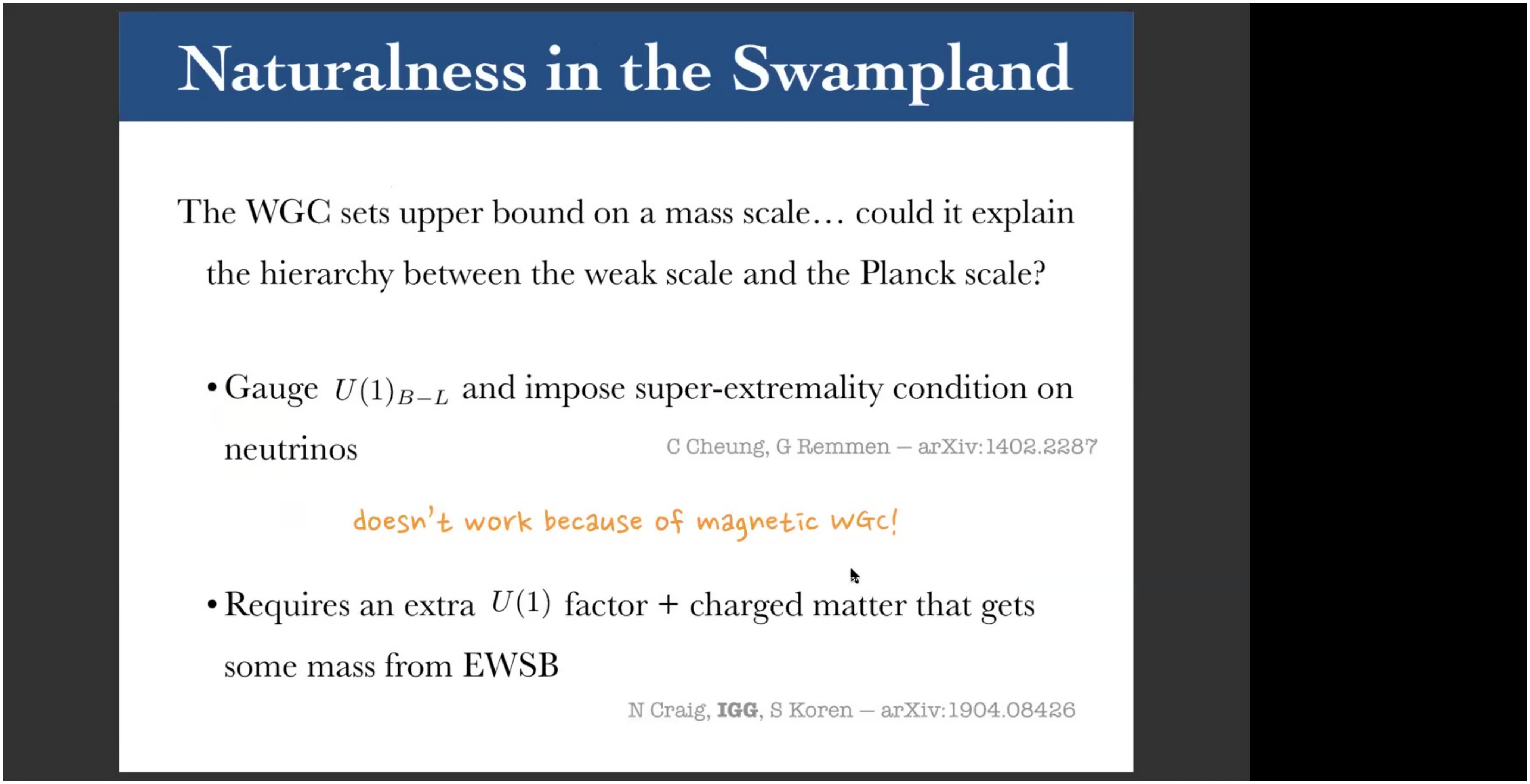
Models of inflation involving super-Planckian field ranges

e.g. A de la Fuente, P Saraswat, R Sundrum – arXiv:1412.3457

Forbid gauging of certain symmetries…

e.g. $U(1)_{B-L}$

Parametrically light massive photons with Stuckelberg masses. M Reece – arXiv:1808.09966



Naturalness in the Swampland

The WGC sets upper bound on a mass scale… could it explain the hierarchy between the weak scale and the Planck scale?

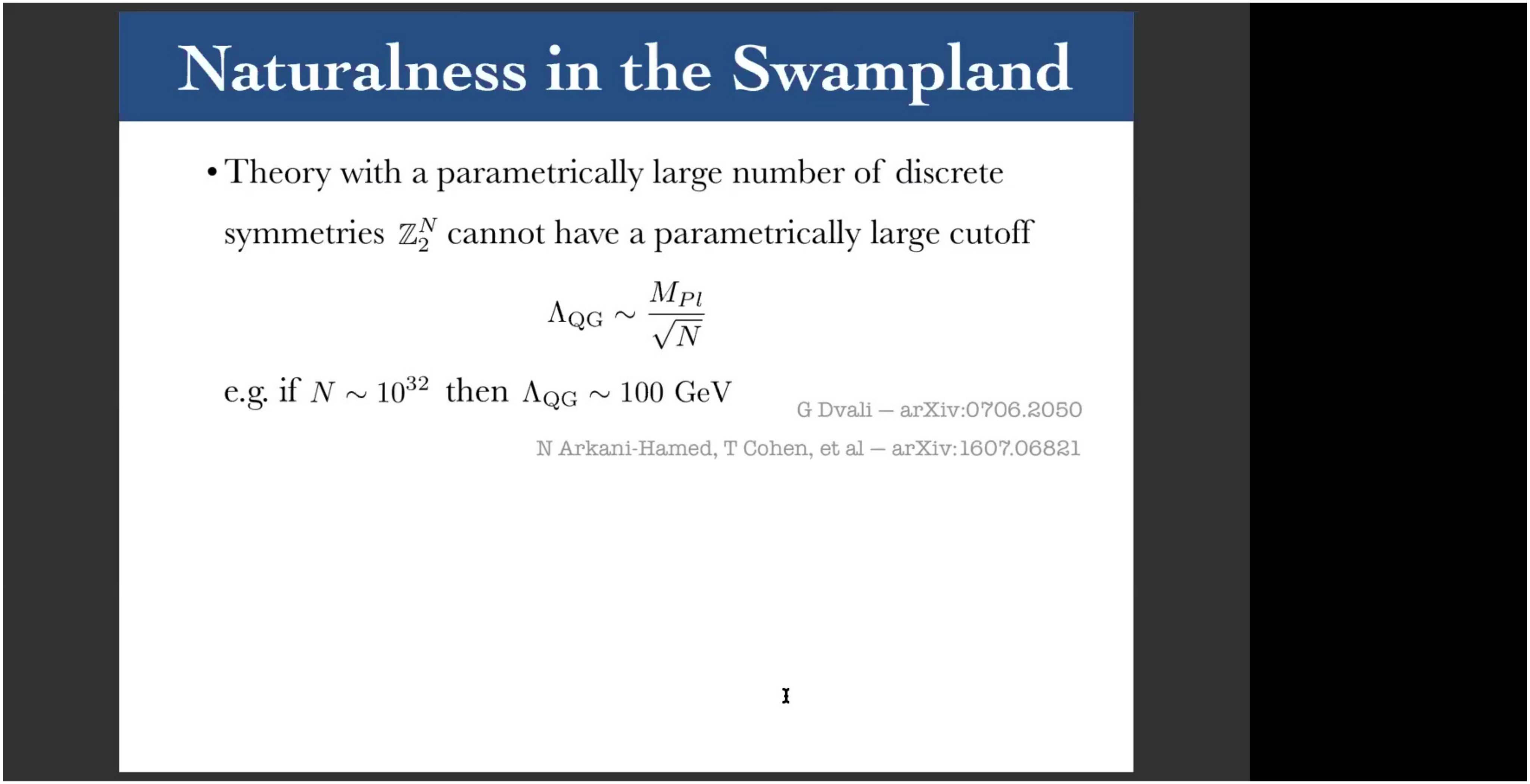
- Gauge $U(1)_{B-L}$ and impose super-extremality condition on neutrinos

C Cheung, G Remmen – arXiv:1402.2287

doesn't work because of magnetic WGC!

- Requires an extra $U(1)$ factor + charged matter that gets some mass from EWSB

N Craig, **IGG**, S Koren – arXiv:1904.08426



Naturalness in the Swampland

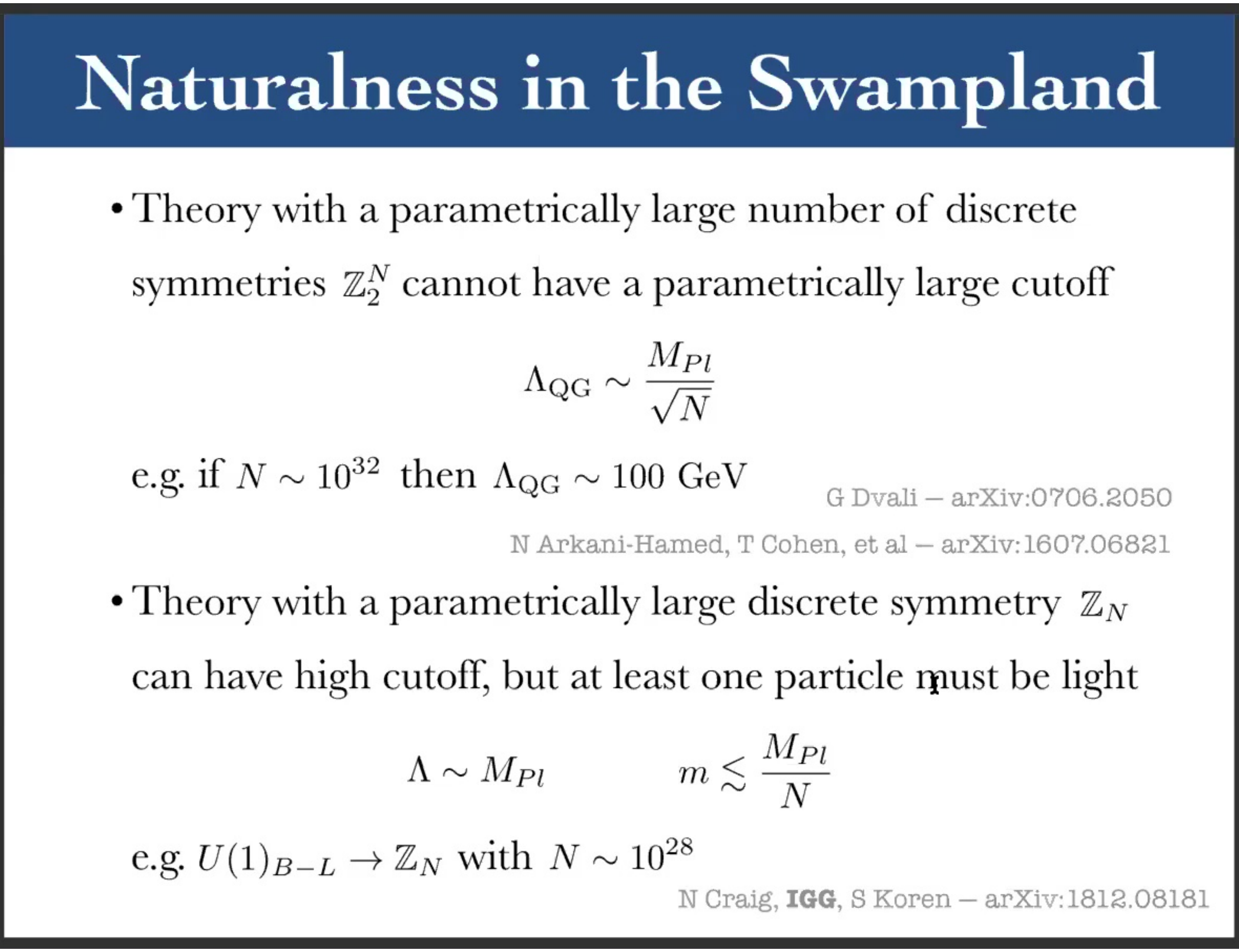
- Theory with a parametrically large number of discrete symmetries $\mathbb{Z}_2^N$ cannot have a parametrically large cutoff

$$\Lambda_{\mathrm{QG}} \sim \frac{M_{Pl}}{\sqrt{N}}$$

e.g. if $N \sim 10^{32}$ then $\Lambda_{\mathrm{QG}} \sim 100\ \mathrm{GeV}$

G Dvali – arXiv:0706.2050

N Arkani-Hamed, T Cohen, et al – arXiv:1607.06821



Naturalness in the Swampland

- Theory with a parametrically large number of discrete symmetries $\mathbb{Z}_2^N$ cannot have a parametrically large cutoff

$$\Lambda_{\mathrm{QG}} \sim \frac{M_{Pl}}{\sqrt{N}}$$

e.g. if $N \sim 10^{32}$ then $\Lambda_{\mathrm{QG}} \sim 100$ GeV

G Dvali – arXiv:0706.2050

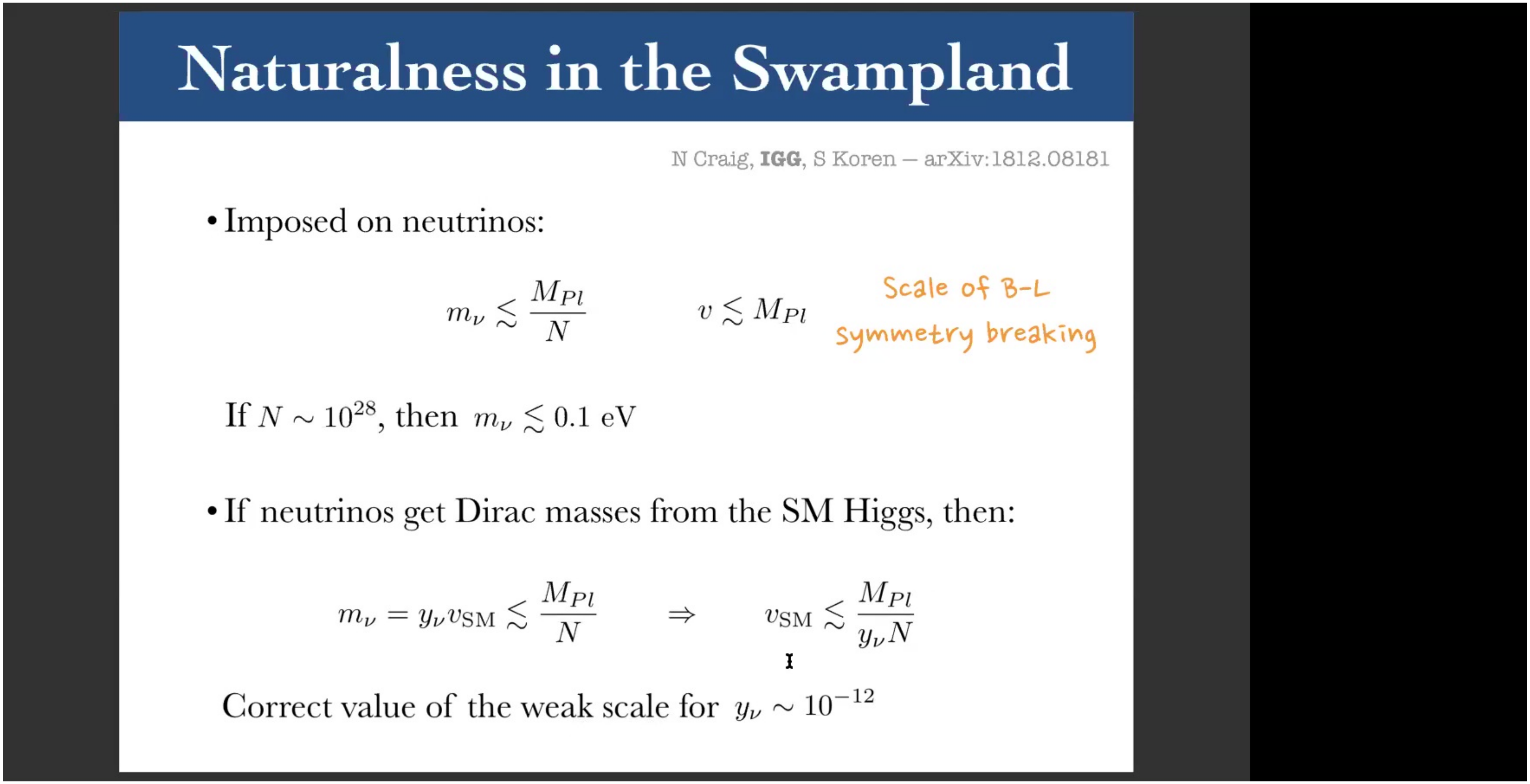
N Arkani-Hamed, T Cohen, et al – arXiv:1607.06821

- Theory with a parametrically large discrete symmetry $\mathbb{Z}_N$ can have high cutoff, but at least one particle must be light

$$\Lambda \sim M_{Pl} \qquad\qquad m \lesssim \frac{M_{Pl}}{N}$$

e.g. $U(1)_{B-L} \to \mathbb{Z}_N$ with $N \sim 10^{28}$

N Craig, **IGG**, S Koren – arXiv:1812.08181



Naturalness in the Swampland

N Craig, **IGG**, S Koren — arXiv:1812.08181

- Imposed on neutrinos:

$$m_\nu \lesssim \frac{M_{Pl}}{N} \qquad\qquad v \lesssim M_{Pl}$$

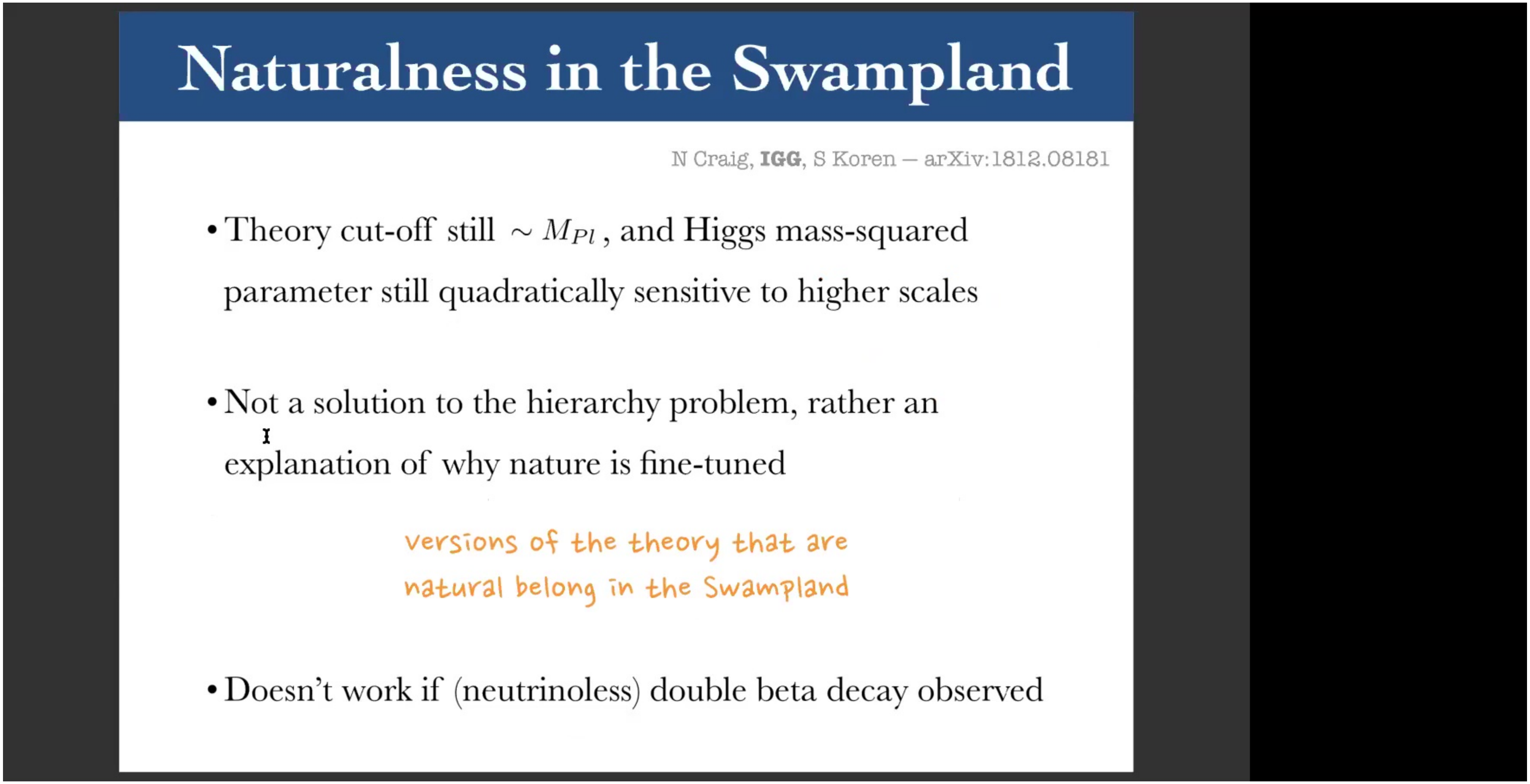
Scale of B-L
symmetry breaking

If $N \sim 10^{28}$, then $m_\nu \lesssim 0.1$ eV

- If neutrinos get Dirac masses from the SM Higgs, then:

$$m_\nu = y_\nu v_{\text{SM}} \lesssim \frac{M_{Pl}}{N} \qquad \Rightarrow \qquad v_{\text{SM}} \lesssim \frac{M_{Pl}}{y_\nu N}$$

Correct value of the weak scale for $y_\nu \sim 10^{-12}$



Naturalness in the Swampland

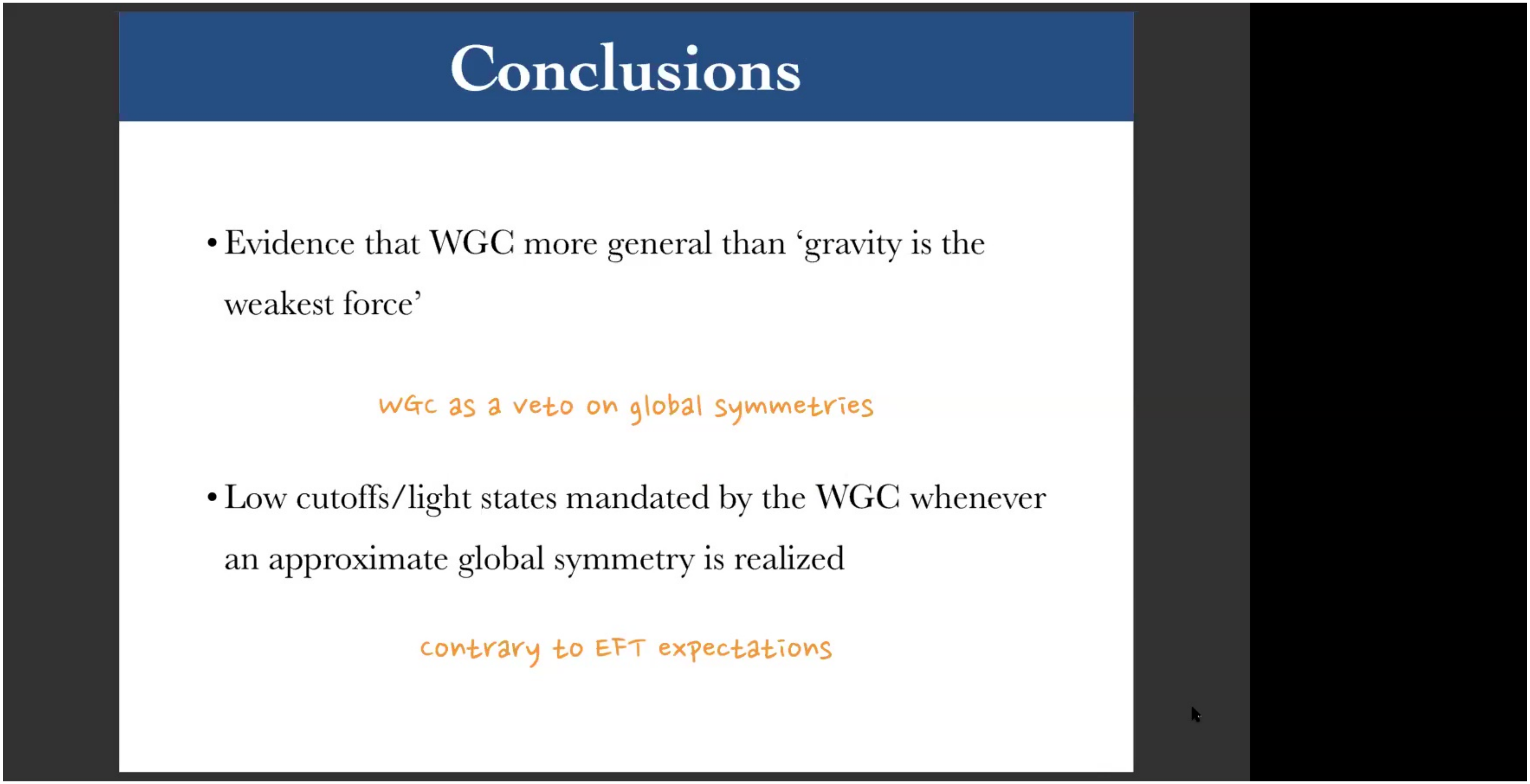
N Craig, **IGG**, S Koren — arXiv:1812.08181

- Theory cut-off still $\sim M_{Pl}$, and Higgs mass-squared parameter still quadratically sensitive to higher scales

- Not a solution to the hierarchy problem, rather an explanation of why nature is fine-tuned

versions of the theory that are
natural belong in the Swampland

- Doesn't work if (neutrinoless) double beta decay observed



Conclusions

- Evidence that WGC more general than 'gravity is the weakest force'

WGC as a veto on global symmetries

- Low cutoffs/light states mandated by the WGC whenever an approximate global symmetry is realized

contrary to EFT expectations