Title: Multimessenger signals from electromagnetic decay of axion stars - VIRTUAL

Speakers: Eugene Lim

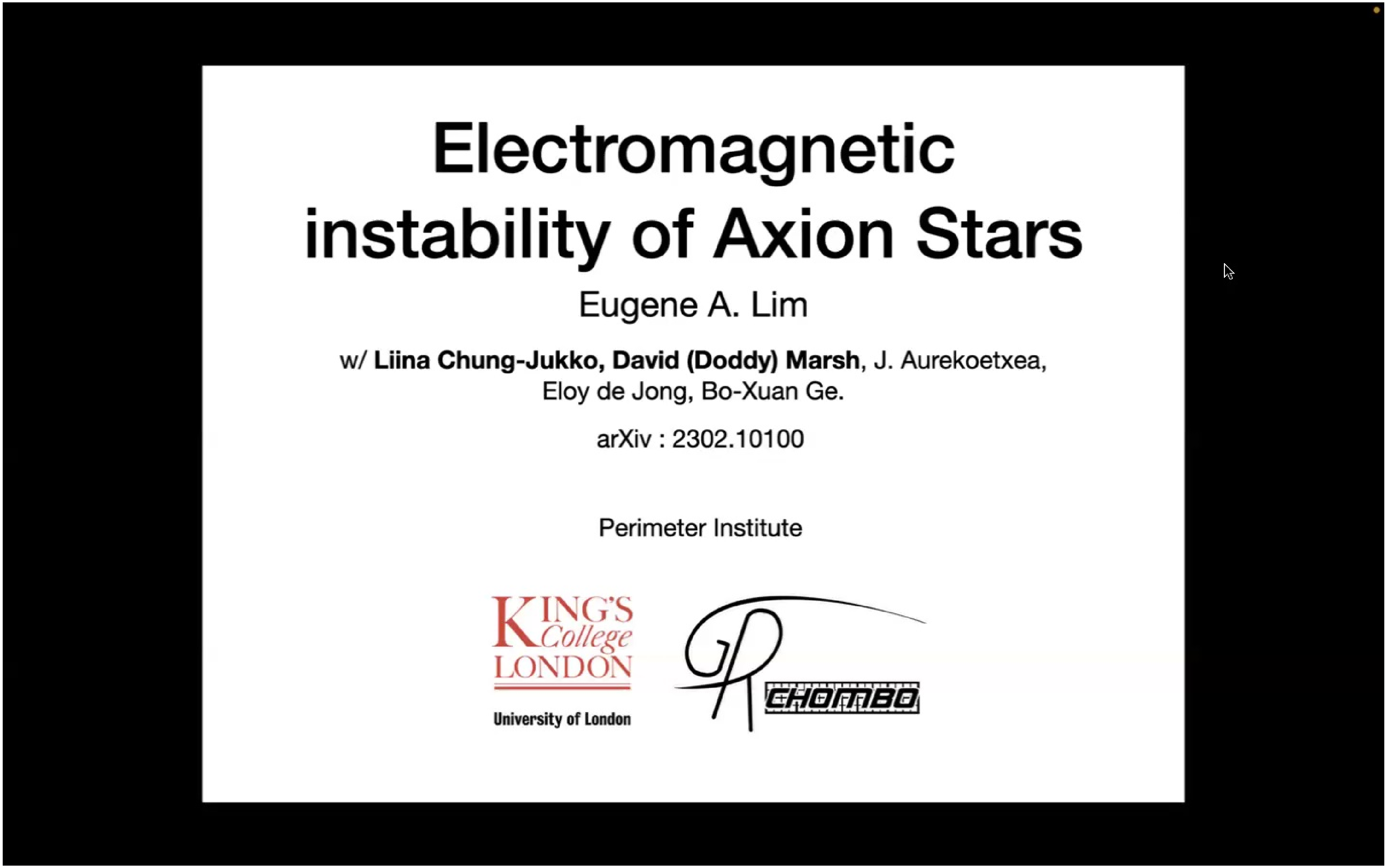
Series: Strong Gravity

Date: November 02, 2023 - 1:00 PM

URL: https://pirsa.org/23110045

Abstract: If axion Dark Matter exists, then they can collapse to form self-gravitating exotic compact objects known as axion stars. As mergers of such compact objects can potentially yield detectable gravititational waves which are correlated with a burst of electromagnetic radiation, much effort have been expended to compute these signals. I will discuss both the technical and theoretical challenges of this endeavour, and demonstrate such decays. I will show that axion stars may not be stable to electromagnetic decay, raising the question on whether we should expect to see these objects in the first place.

Zoom link https://pitp.zoom.us/j/98298572209?pwd=WVFZUFJqQzZQdU8vcjhQRVpzVHZDdz09



Electromagnetic instability of Axion Stars

Eugene A. Lim

w/ **Liina Chung-Jukko, David (Doddy) Marsh**, J. Aurekoetxea,
Eloy de Jong, Bo-Xuan Ge.

arXiv : 2302.10100

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GR CHOMBO

Ultra Light Dark matter

DM gravitationally detected, but what are they?

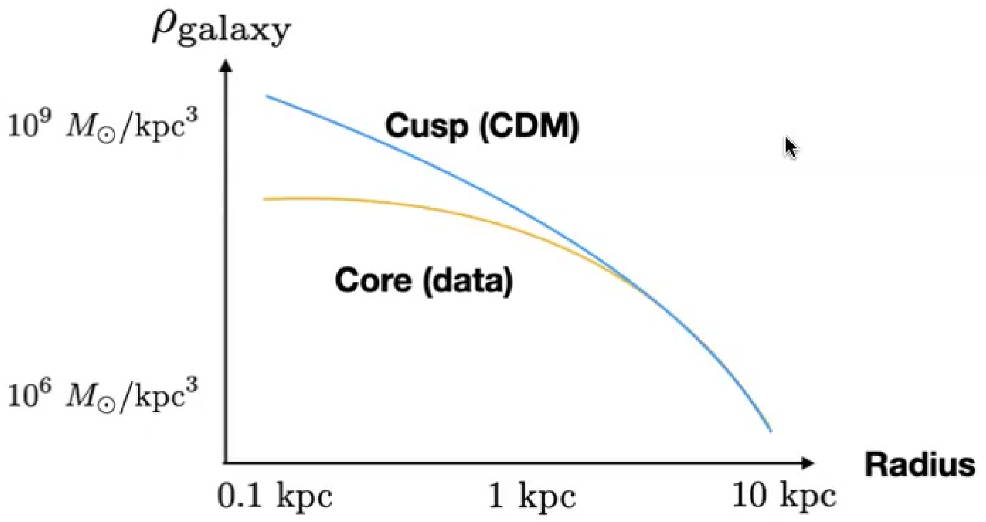
credit : HST

Gravitational lensing

Bullet Cluster

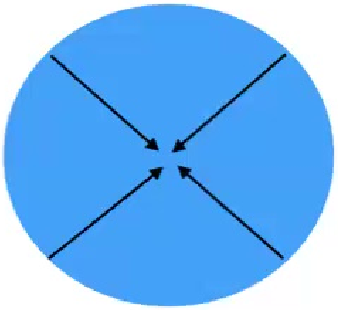
Ultra Light Dark matter

Cold DM (e.g. WIMP) has “small scale problems”.

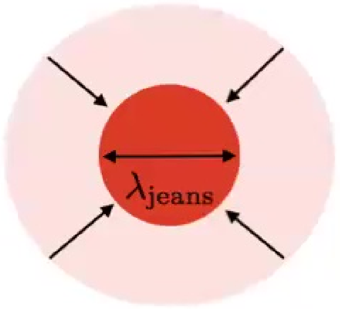


Ultra Light Dark matter

CDM is pressureless, so forms small scale structures.

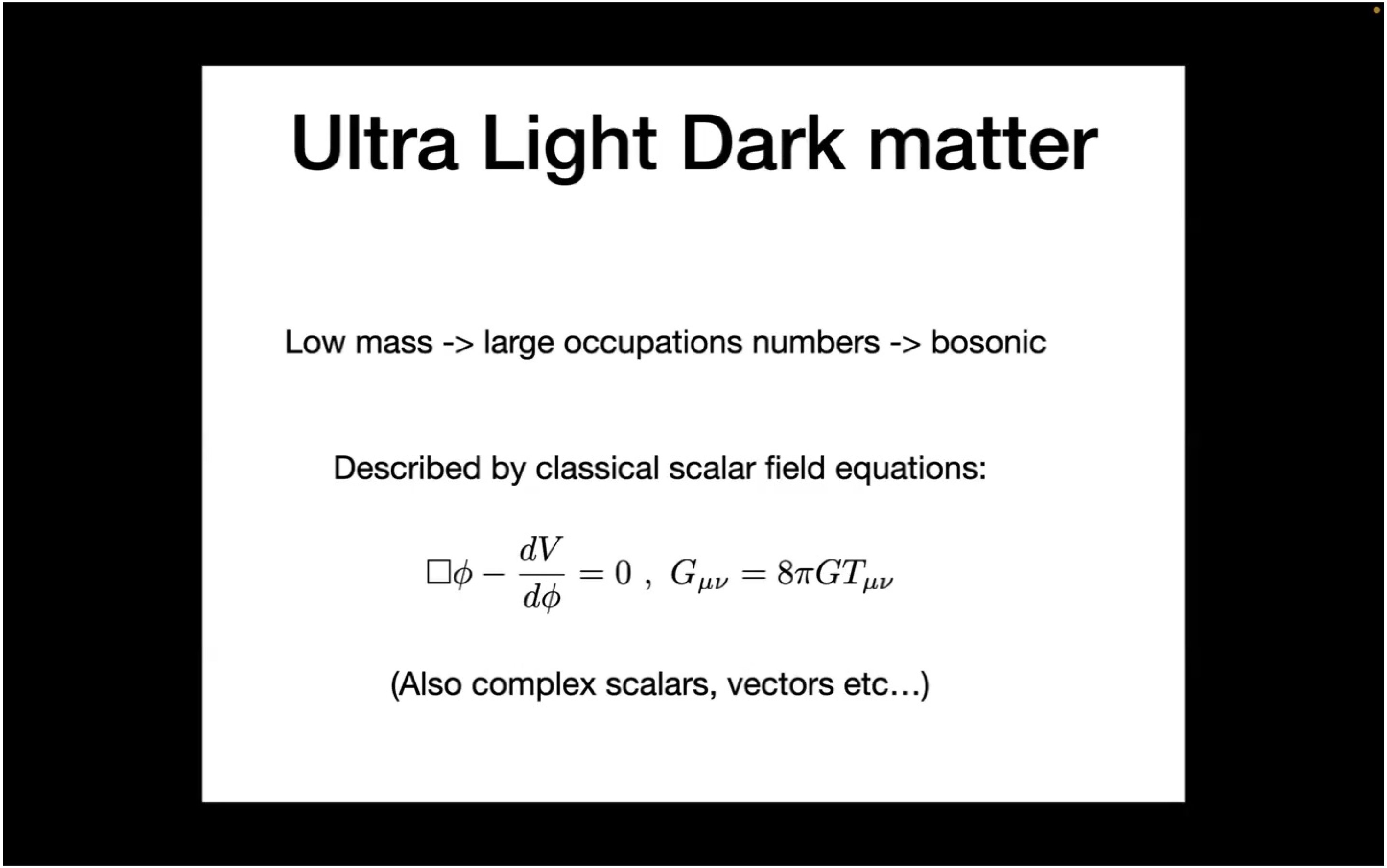


CDM



Outward pressure around 1 kpc

Some kind of “pressure support” must kick in around 1 kpc scale.



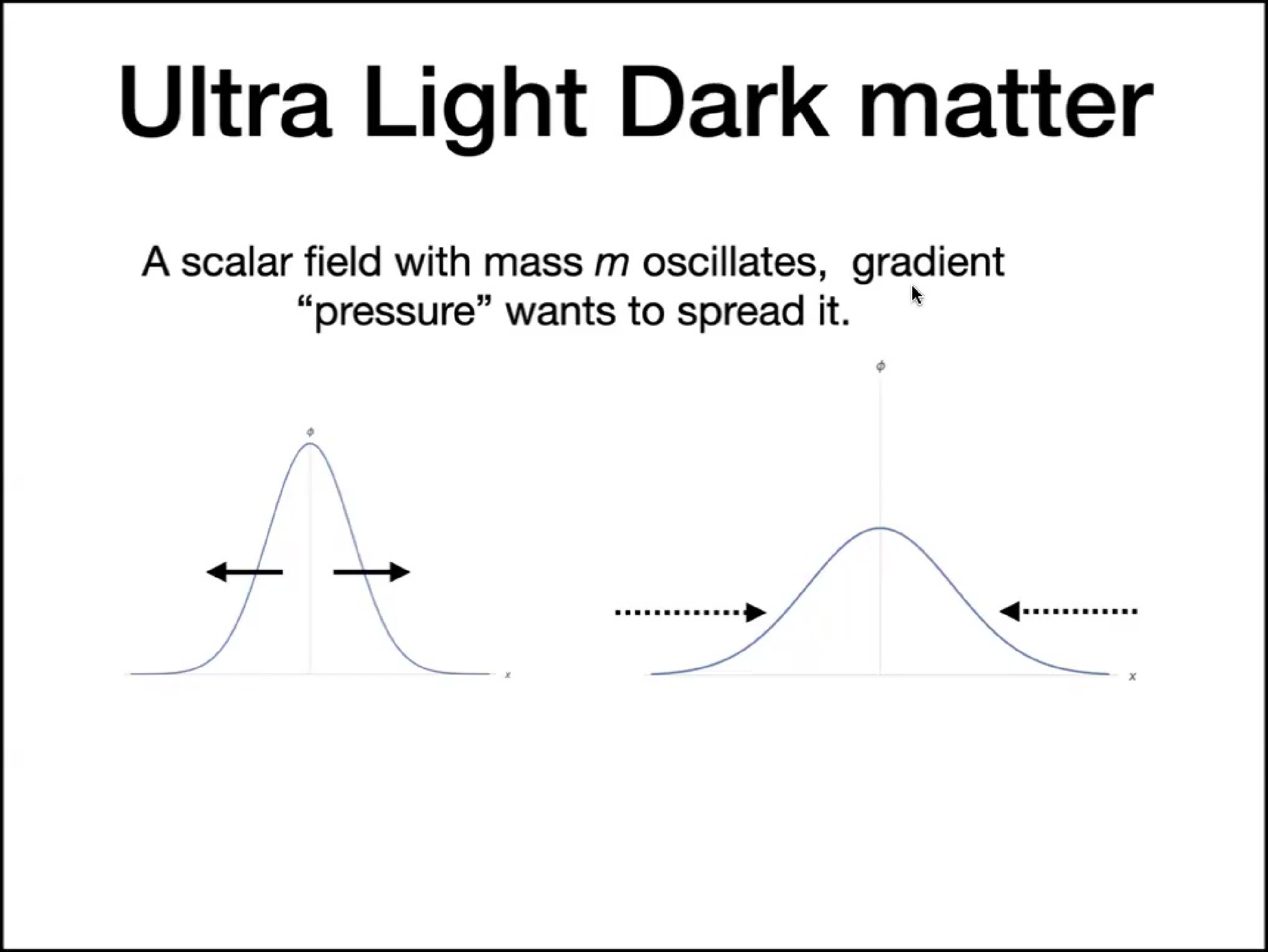
Ultra Light Dark matter

Low mass -> large occupations numbers -> bosonic

Described by classical scalar field equations:

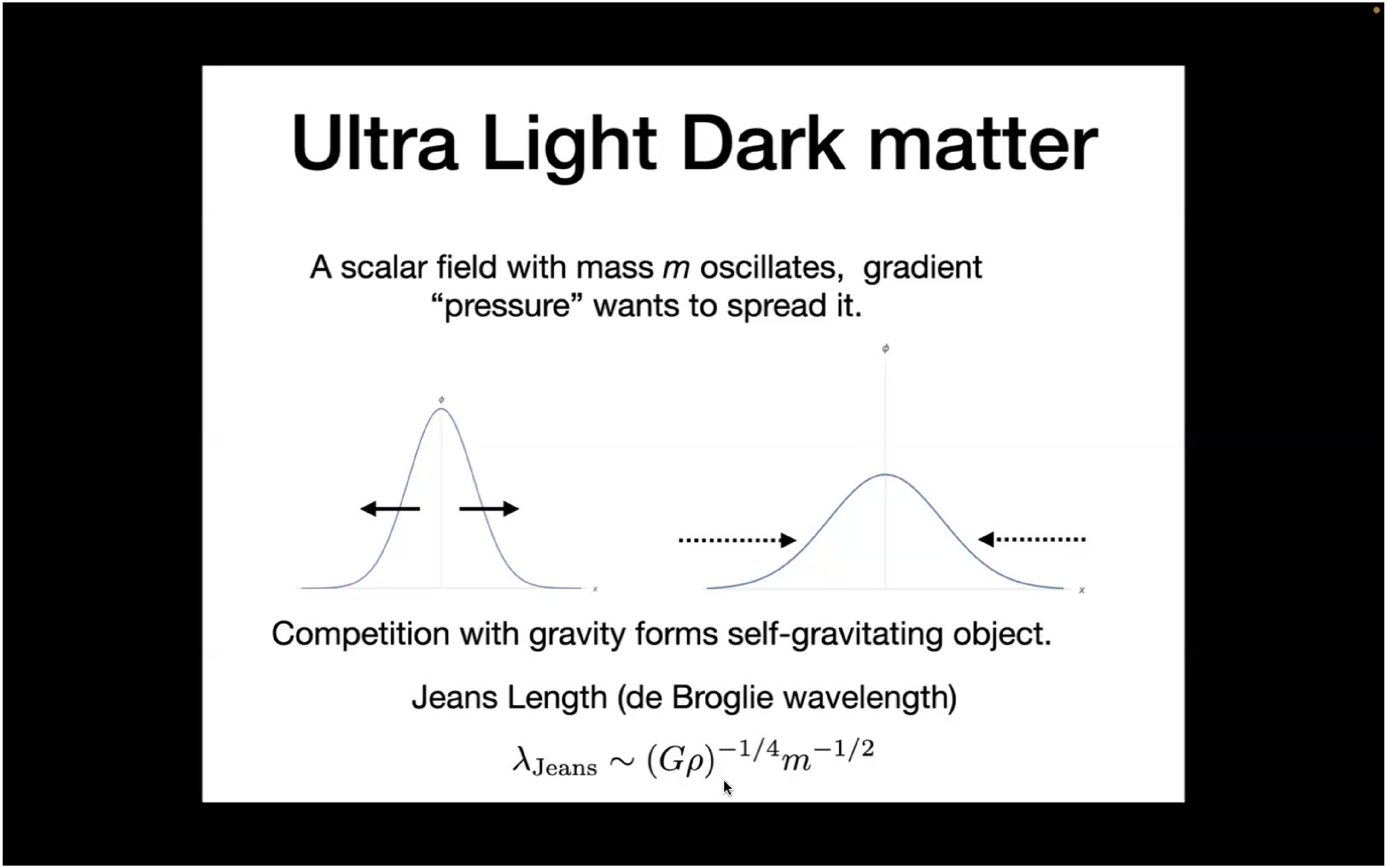
$$\Box\phi - \frac{dV}{d\phi} = 0 \ , \ G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(Also complex scalars, vectors etc…)



Ultra Light Dark matter

A scalar field with mass m oscillates, gradient "pressure" wants to spread it.



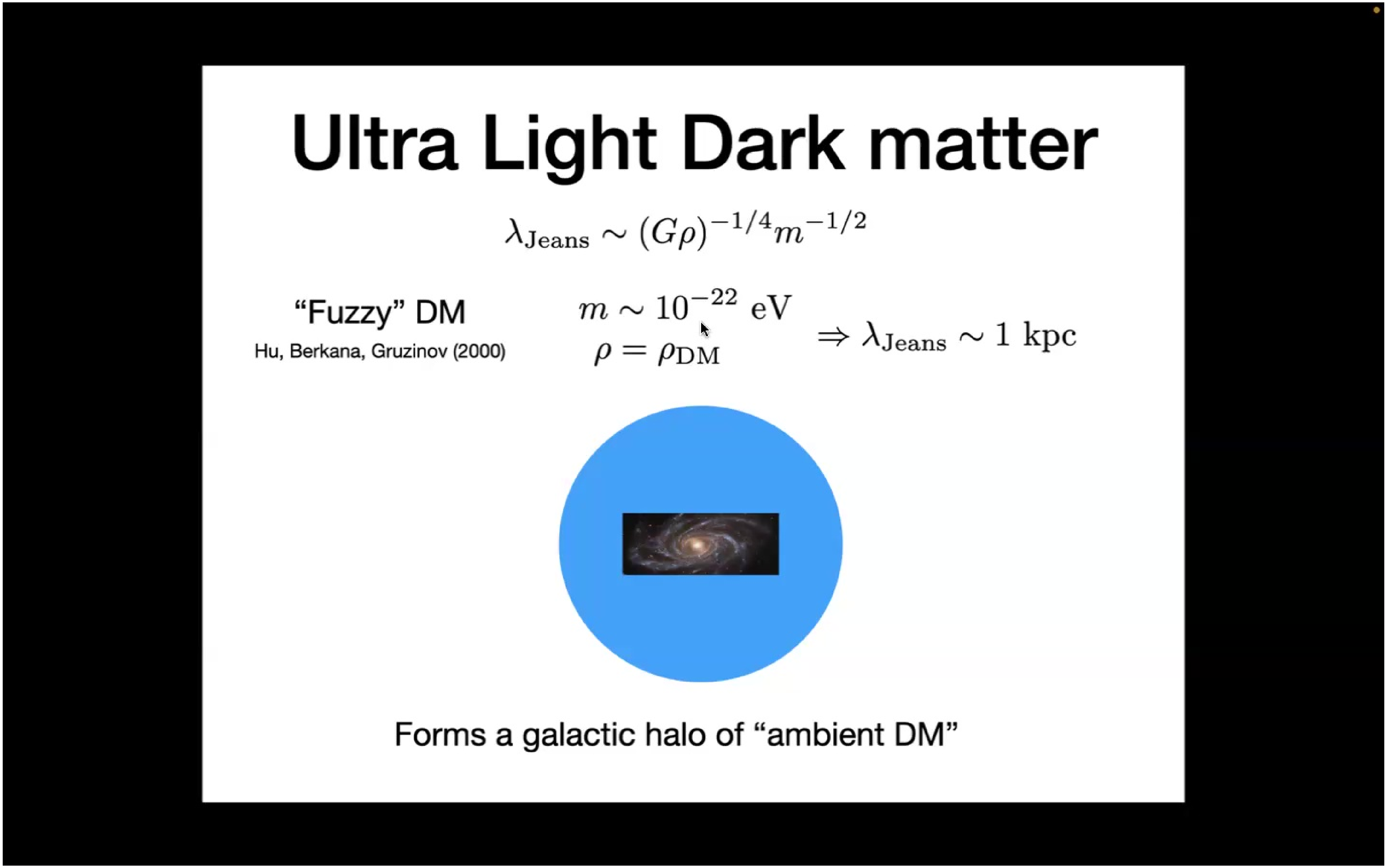
Ultra Light Dark matter

A scalar field with mass *m* oscillates, gradient “pressure” wants to spread it.

Competition with gravity forms self-gravitating object.

Jeans Length (de Broglie wavelength)

$$\lambda_{\text{Jeans}} \sim (G\rho)^{-1/4} m^{-1/2}$$



Ultra Light Dark matter

$$\lambda_{\text{Jeans}} \sim (G\rho)^{-1/4} m^{-1/2}$$

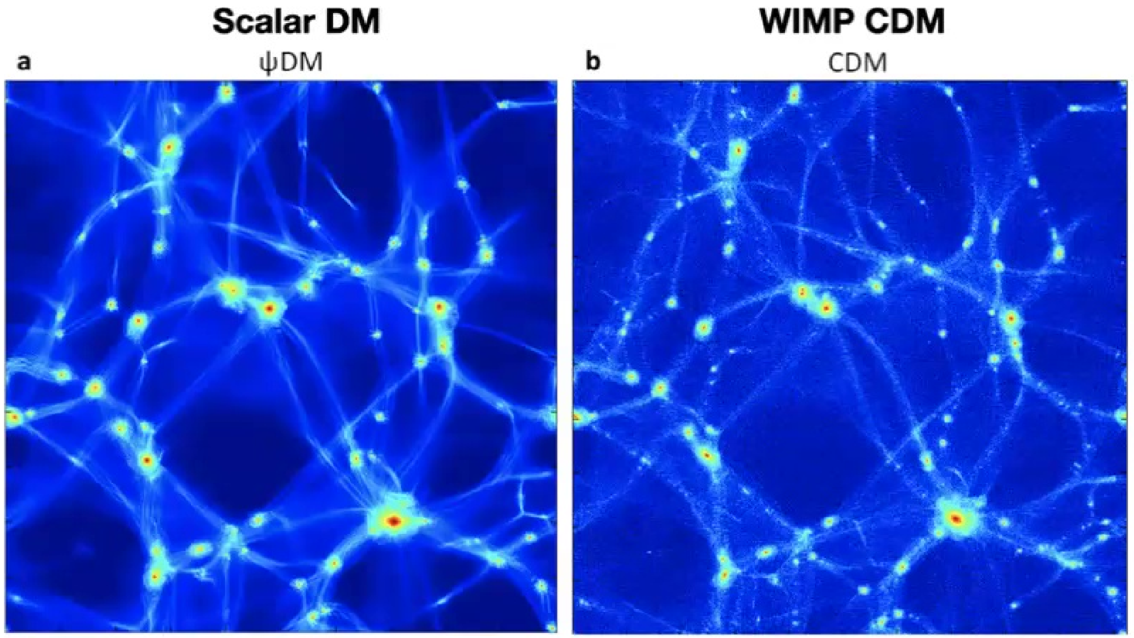
"Fuzzy" DM

Hu, Berkana, Gruzinov (2000)

$$m \sim 10^{-22}\ \text{eV}$$
$$\rho = \rho_{\text{DM}}$$
$$\Rightarrow \lambda_{\text{Jeans}} \sim 1\ \text{kpc}$$

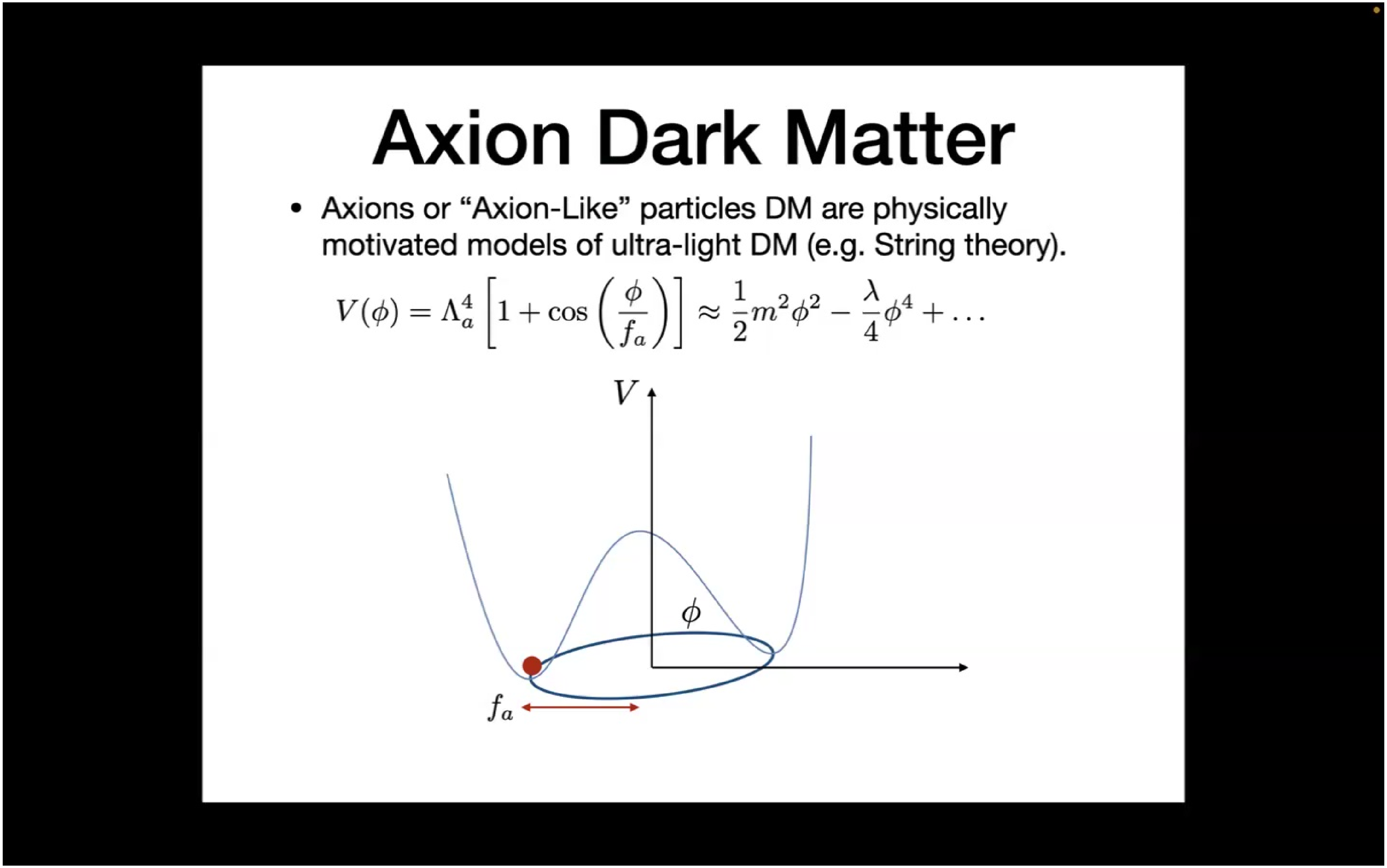
Forms a galactic halo of "ambient DM"

Ultra Light Dark matter



Schive et al (2014)

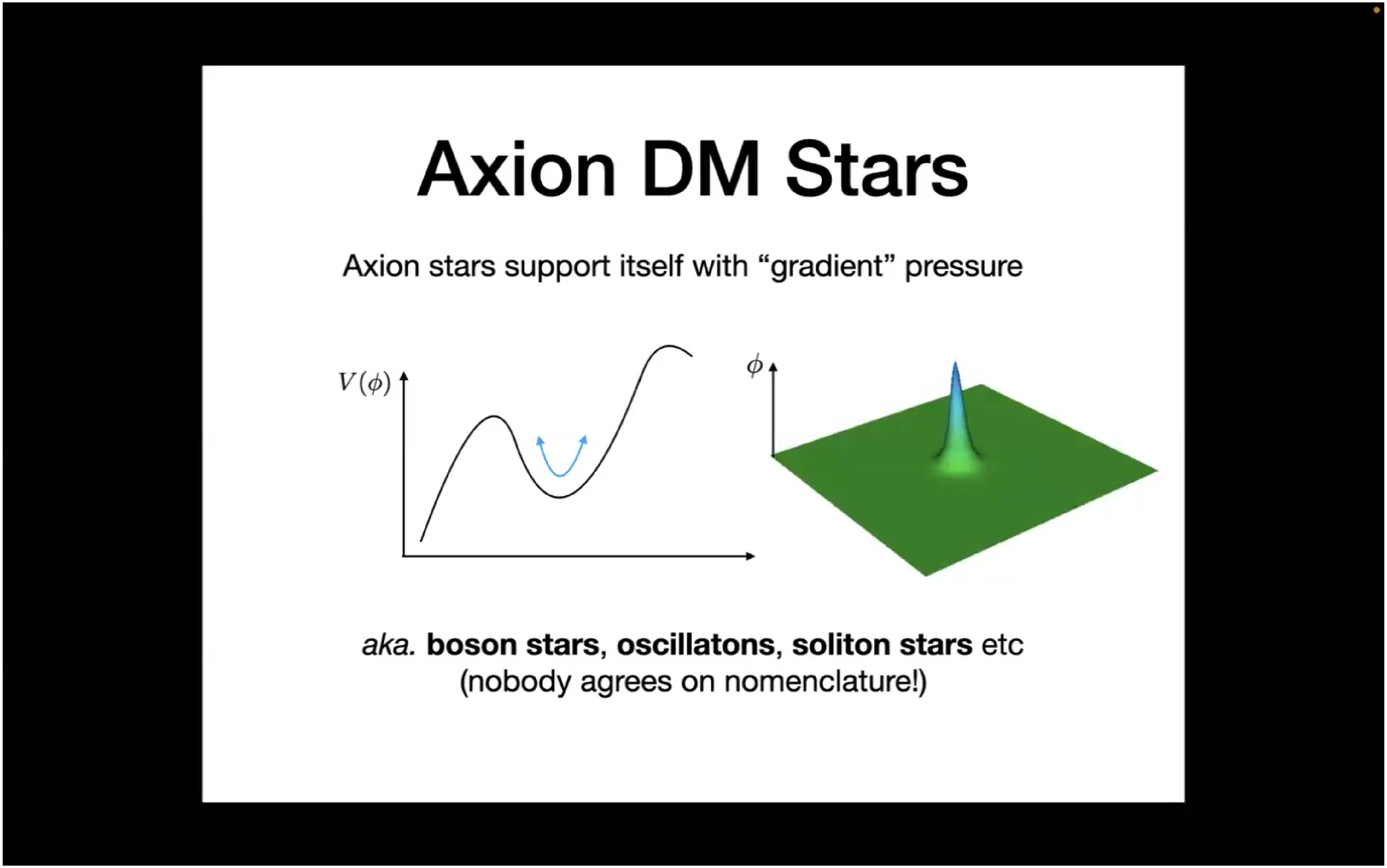
Numerical simulations reproduced large scale WIMP CDM structures.



Axion Dark Matter

- Axions or "Axion-Like" particles DM are physically motivated models of ultra-light DM (e.g. String theory).

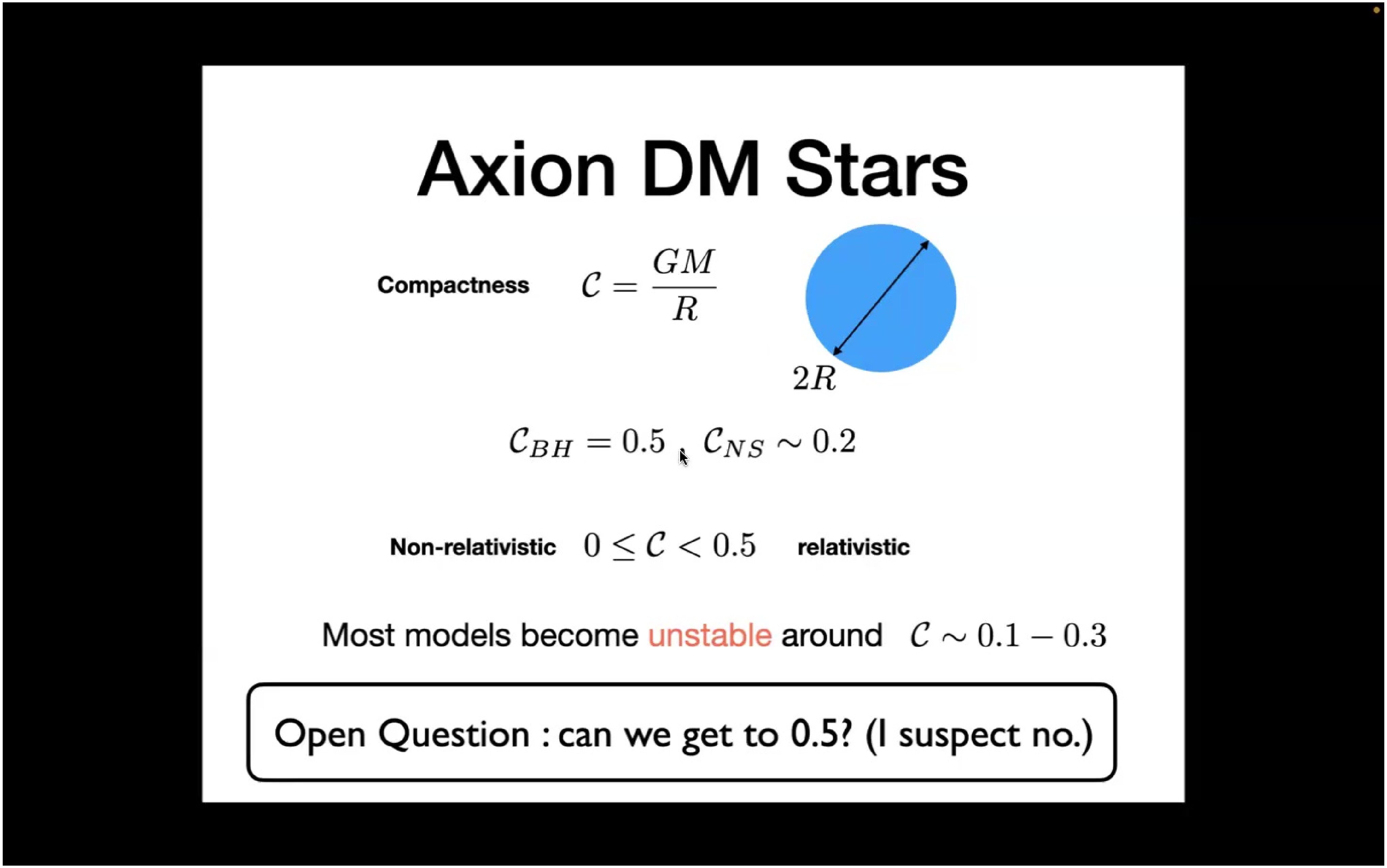
$$V(\phi) = \Lambda_a^4 \left[1 + \cos\left(\frac{\phi}{f_a}\right)\right] \approx \frac{1}{2} m^2 \phi^2 - \frac{\lambda}{4} \phi^4 + \ldots$$



Axion DM Stars

Axion stars support itself with “gradient” pressure

aka. **boson stars, oscillatons, soliton stars** etc
(nobody agrees on nomenclature!)



Axion DM Stars

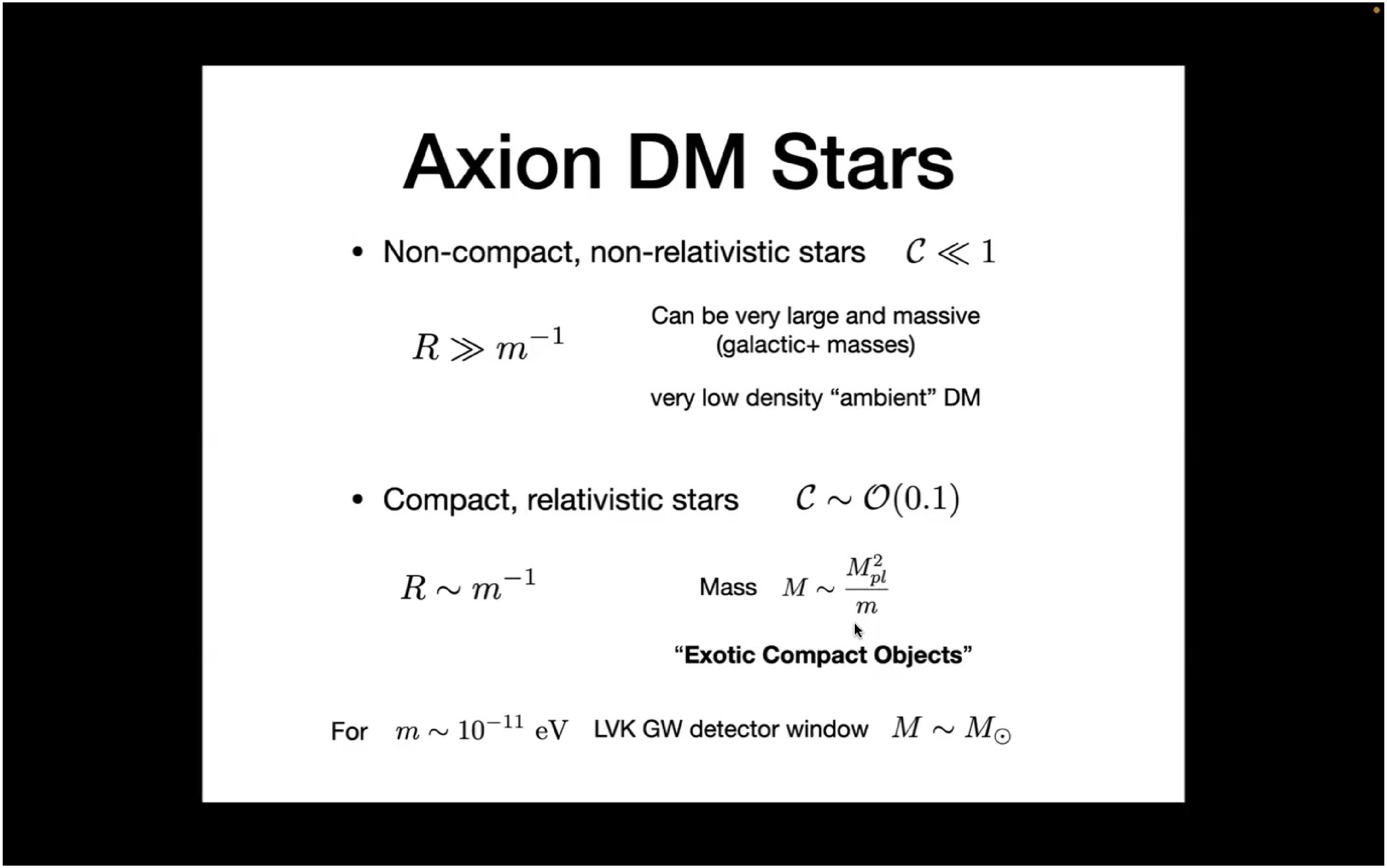
Compactness $\mathcal{C} = \frac{GM}{R}$

$\mathcal{C}_{BH} = 0.5$, $\mathcal{C}_{NS} \sim 0.2$

Non-relativistic $0 \leq \mathcal{C} < 0.5$ **relativistic**

Most models become unstable around $\mathcal{C} \sim 0.1 - 0.3$

Open Question : can we get to 0.5? (I suspect no.)



Axion DM Stars

- Non-compact, non-relativistic stars $\mathcal{C} \ll 1$

$R \gg m^{-1}$

Can be very large and massive
(galactic+ masses)

very low density “ambient” DM

- Compact, relativistic stars $\mathcal{C} \sim \mathcal{O}(0.1)$

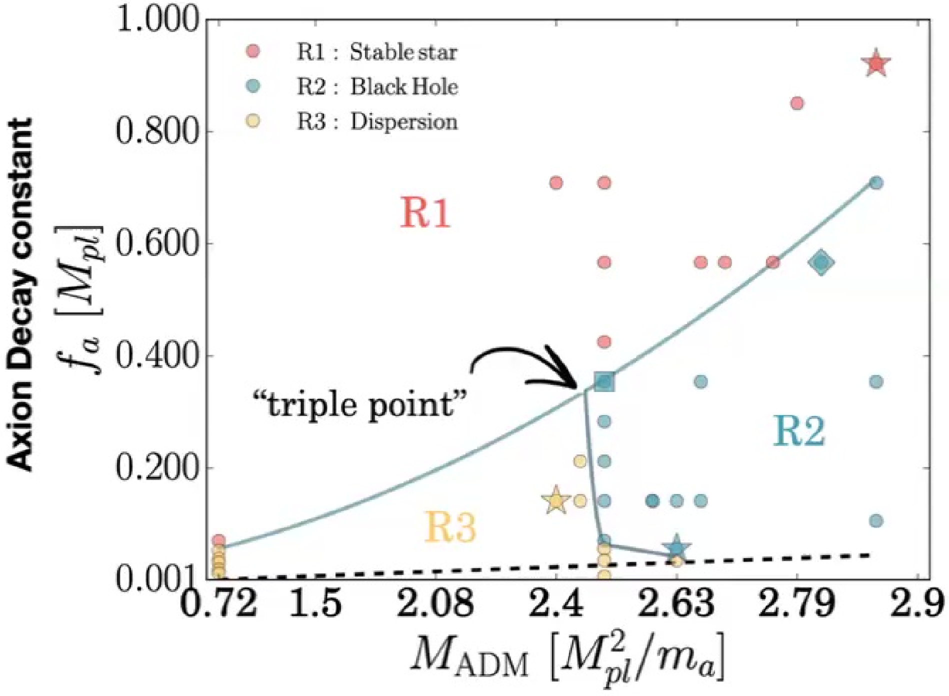
$R \sim m^{-1}$

Mass $M \sim \frac{M_{pl}^2}{m}$

“Exotic Compact Objects”

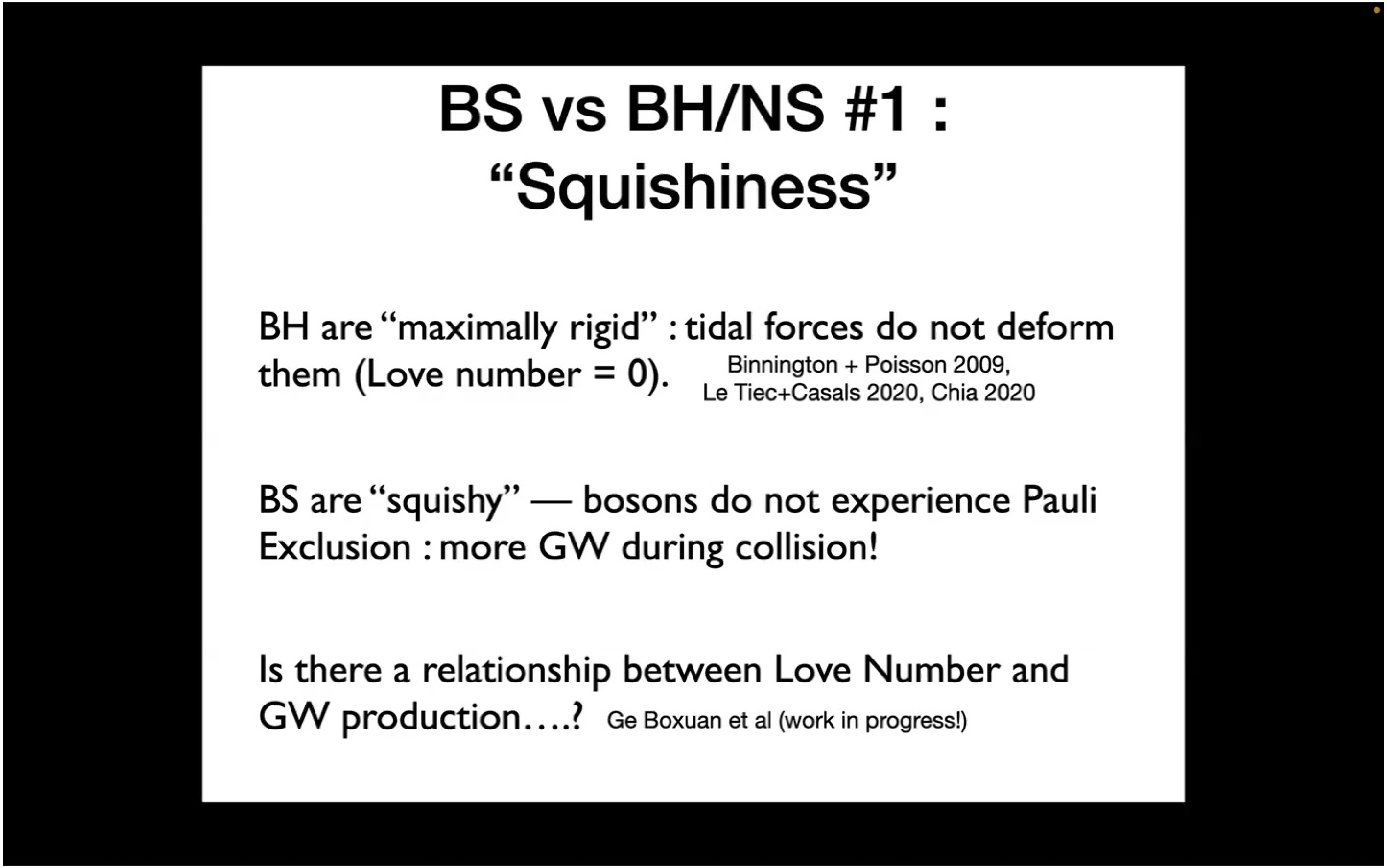
For $m \sim 10^{-11}$ eV LVK GW detector window $M \sim M_\odot$

Stability of Axion Stars



(Helfer, Clough, Marsh, Lim, Fairbairn, Becceril 2016)

Axion/Boson Stars
vs
Black Holes/Neutron Stars



BS vs BH/NS #1 : “Squishiness”

BH are “maximally rigid” : tidal forces do not deform them (Love number = 0). Binnington + Poisson 2009, Le Tiec+Casals 2020, Chia 2020

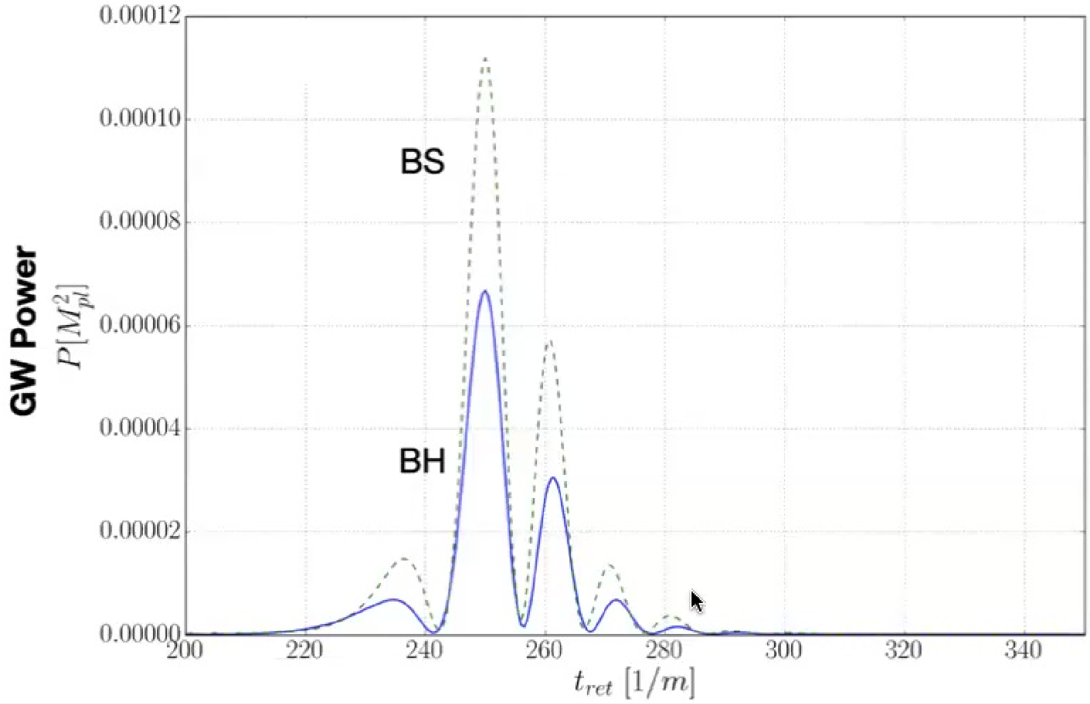
BS are “squishy” — bosons do not experience Pauli Exclusion : more GW during collision!

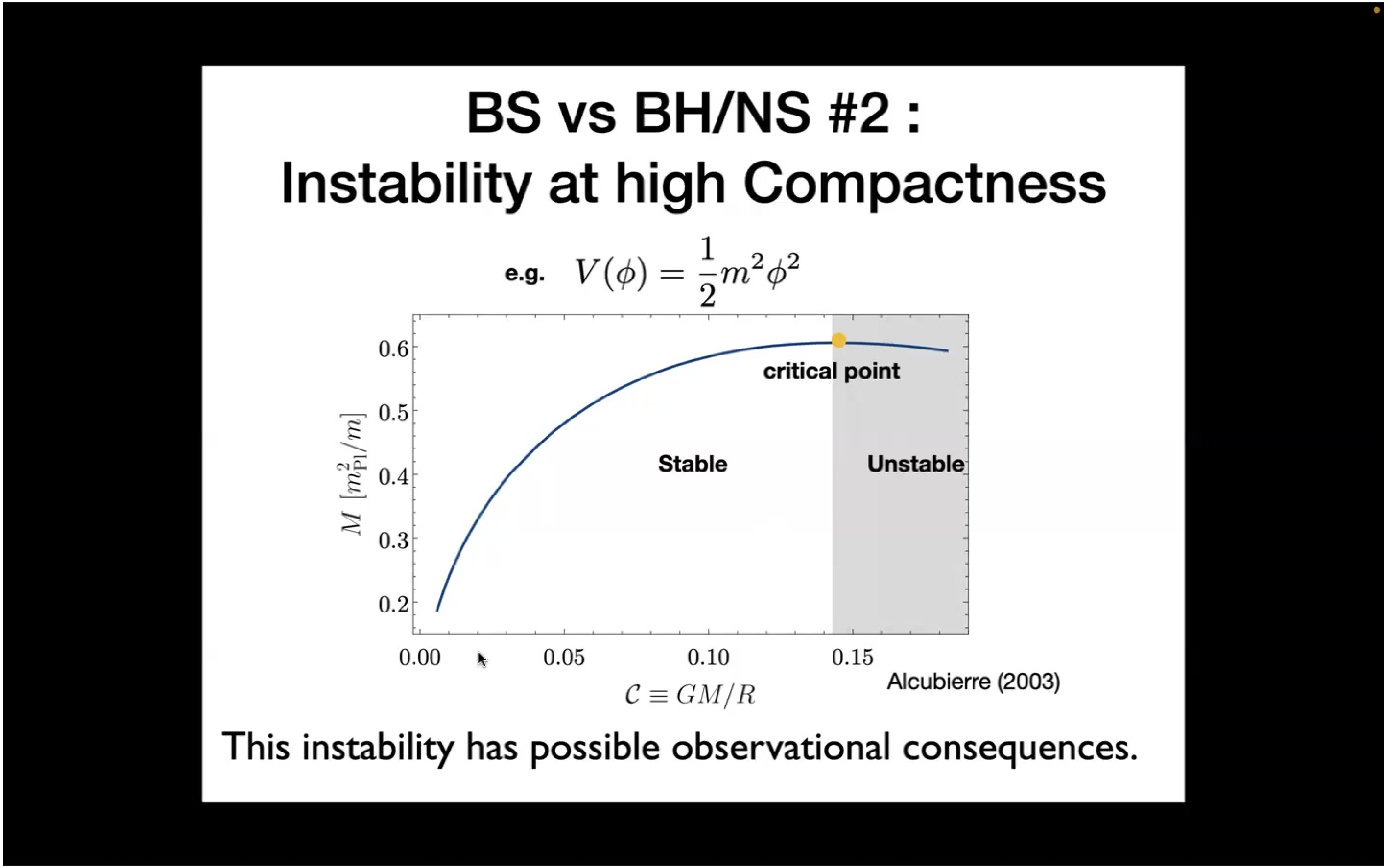
Is there a relationship between Love Number and GW production….? Ge Boxuan et al (work in progress!)

BS vs BH/NS #1 : “Squishiness”

More GW power from equal mass BS collisions vs BH collisions

(Helfer, Lim, Amin, Garcia 2018)





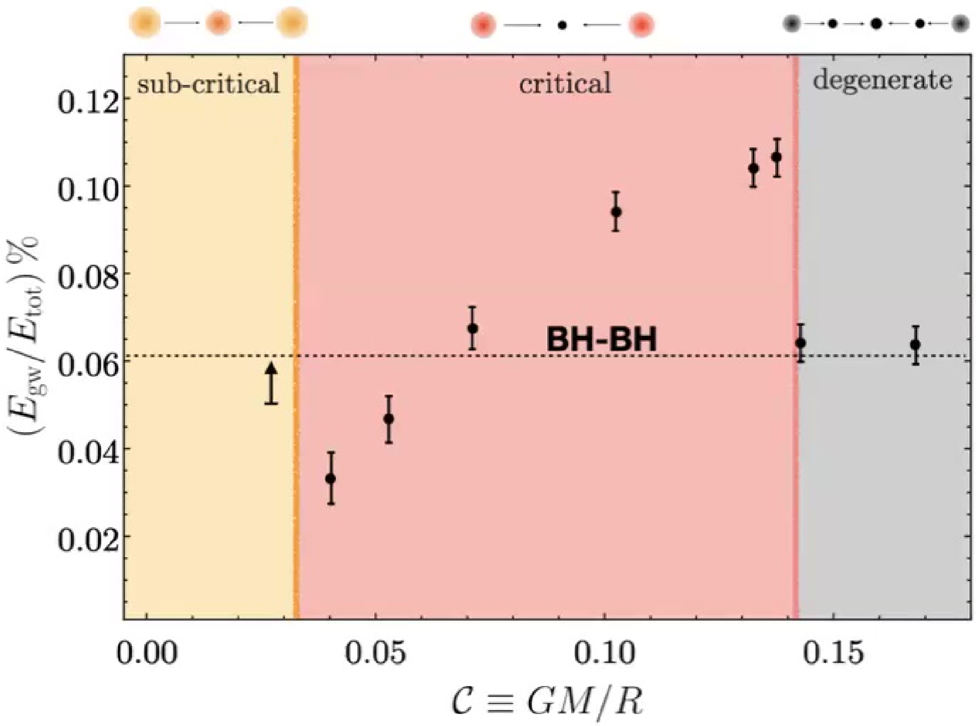
BS vs BH/NS #2 :
Instability at high Compactness

e.g. $V(\phi) = \frac{1}{2} m^2 \phi^2$

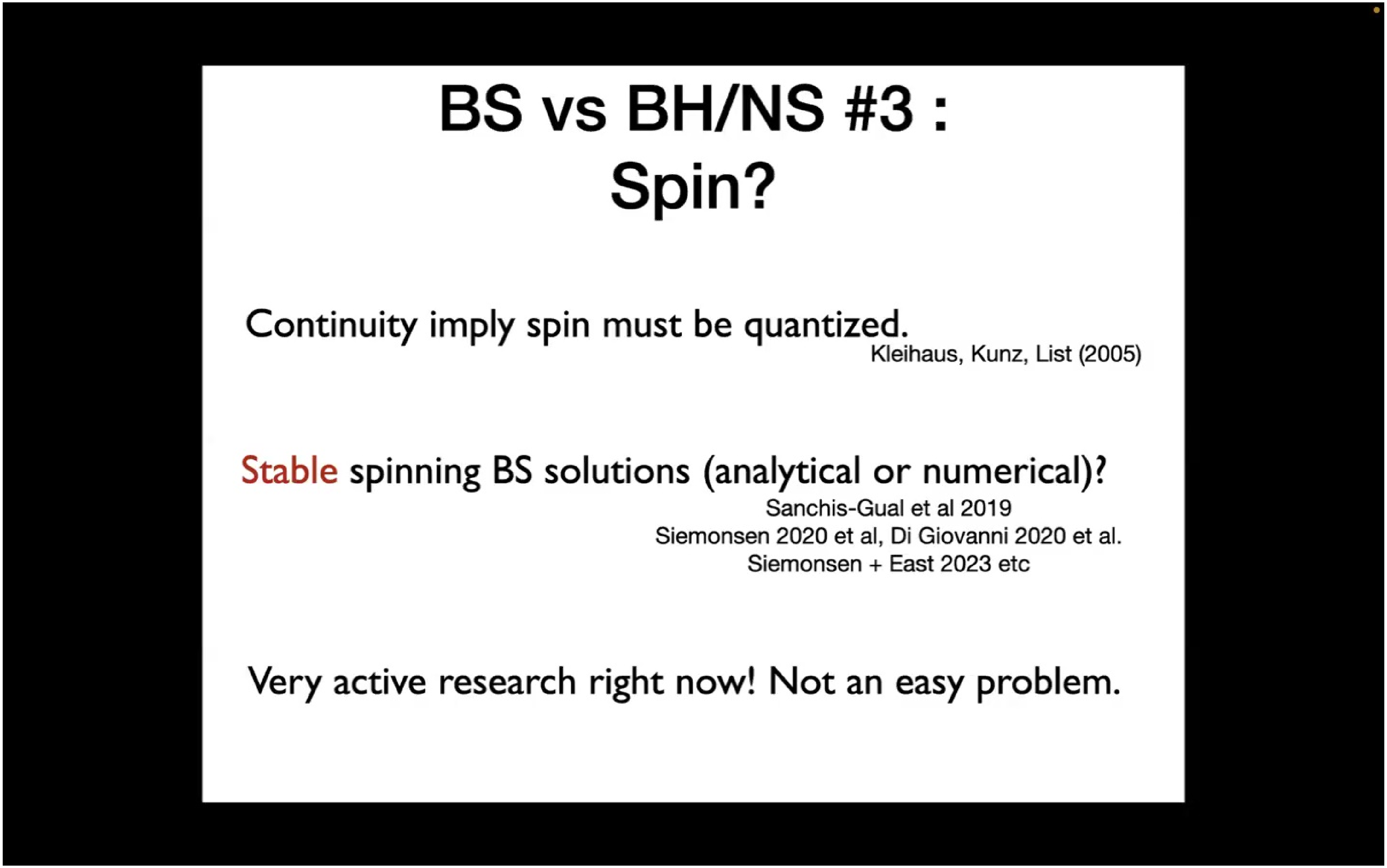
Alcubierre (2003)

This instability has possible observational consequences.

BS vs BH/NS #2 :
Instability at high Compactness



(Helfer, Lim, Amin, Garcia 2018)



BS vs BH/NS #3 : Spin?

Continuity imply spin must be quantized.

Kleihaus, Kunz, List (2005)

Stable spinning BS solutions (analytical or numerical)?

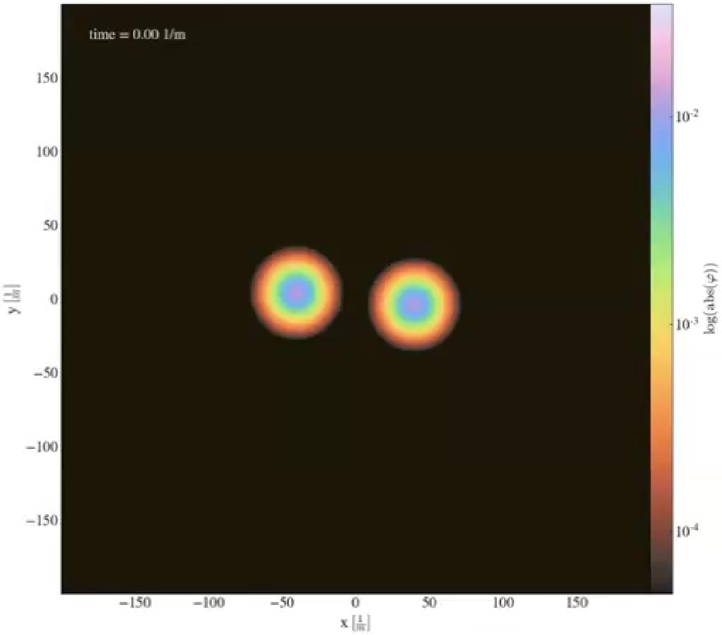
Sanchis-Gual et al 2019
Siemonsen 2020 et al, Di Giovanni 2020 et al.
Siemonsen + East 2023 etc

Very active research right now! Not an easy problem.

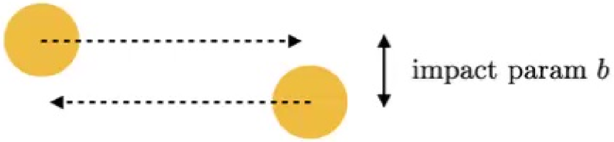
BS vs BH/NS #4 :
Post-merger signals

BH end states are boring, BS end states are exciting!

Croft, Helfer, Ge, Lim, Sperhake,
Radia, Clough (2022)



Colliding 2 boosted BS with non-zero impact parameter.



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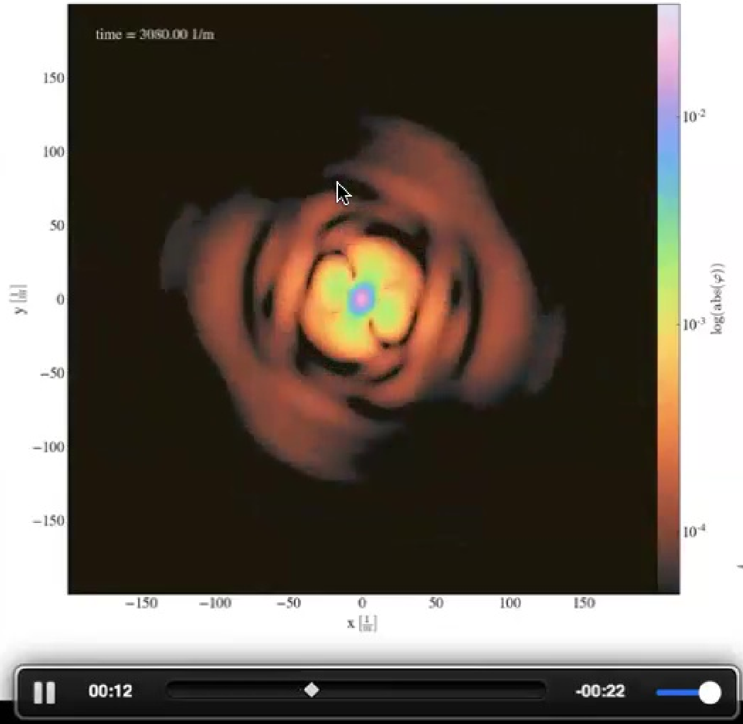

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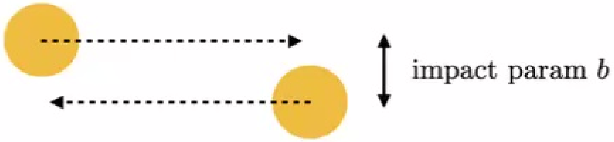

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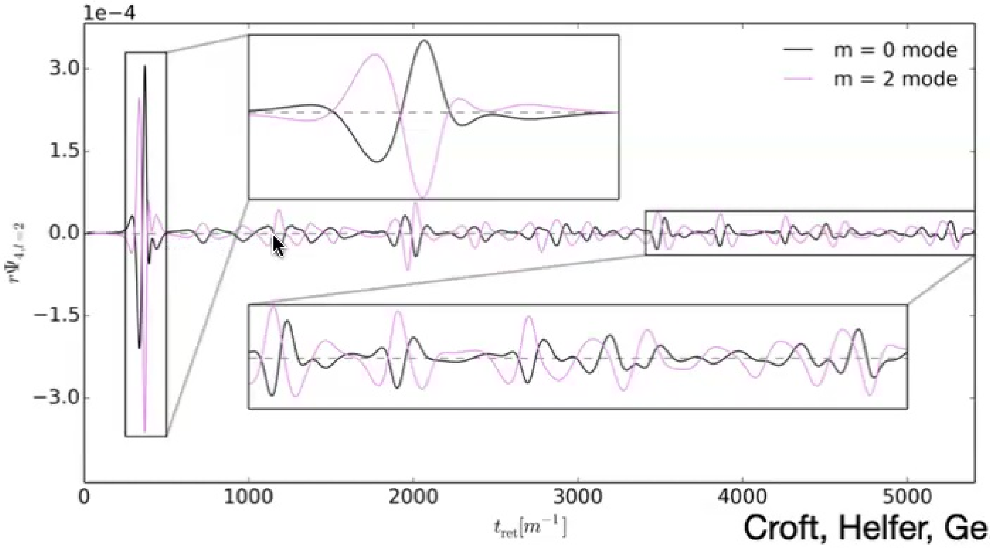
BS vs BH/NS #4 : Post-merger signals

If post-collision remnant is a highly perturbed BS, we get long lived GW signal.



Croft, Helfer, Ge, Lim, Sperhake, Radia, Clough (2022)

GW signatures for *post-collision* BS with spin.

Axion-Photon couplings and its consequences

Axion-Photon Coupling

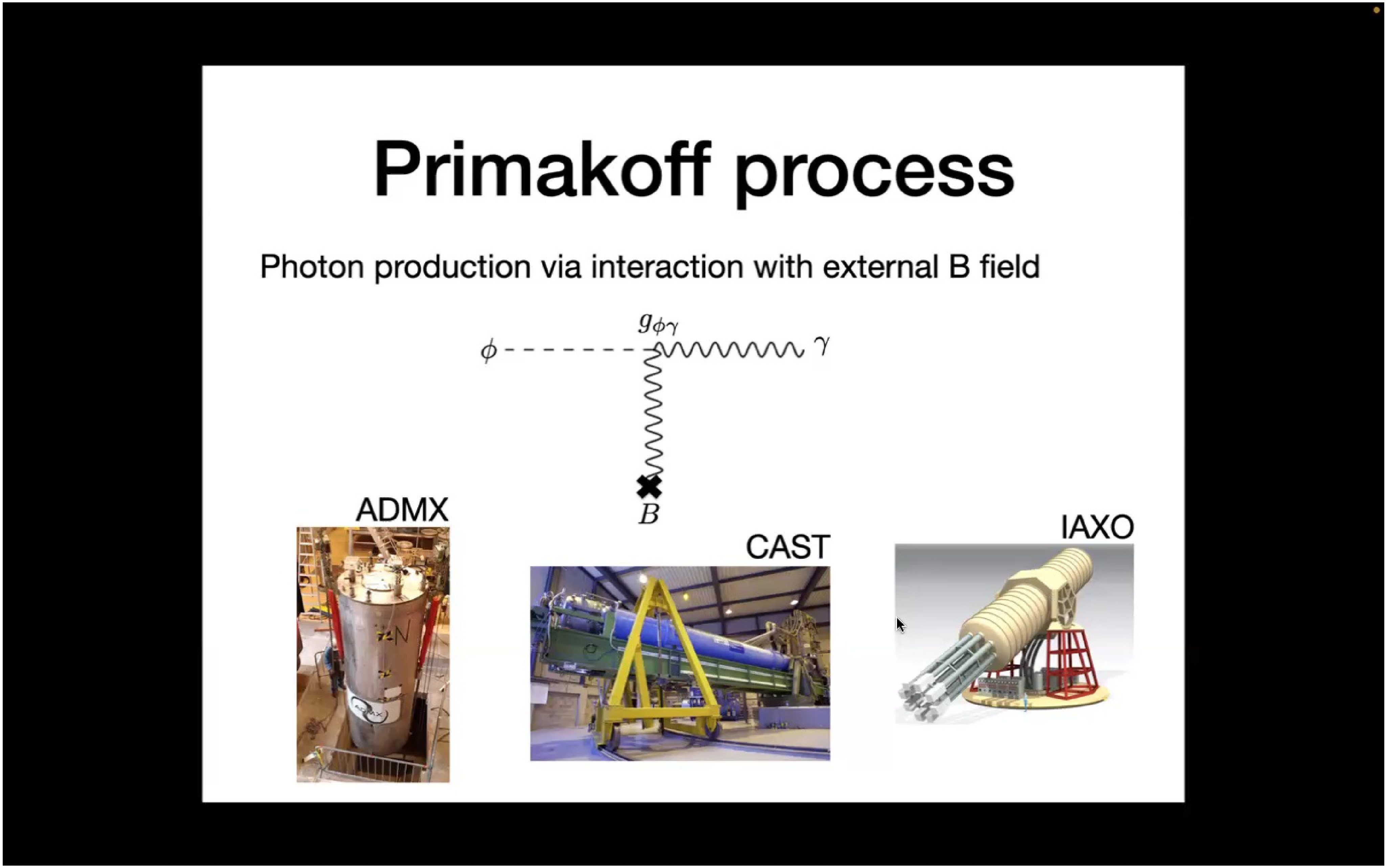
Chern-Simons coupling to Electromagnetic fields:

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{EM} - \frac{g_{a\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

QCD axions : induced through axion mixing with pions.

Exotic axions : coupling is a free parameter but computable in explicit models e.g. string axions.

Primary channel for Direct Detection Experiments (CAST, CasPER, ADMX, IAXO etc.)

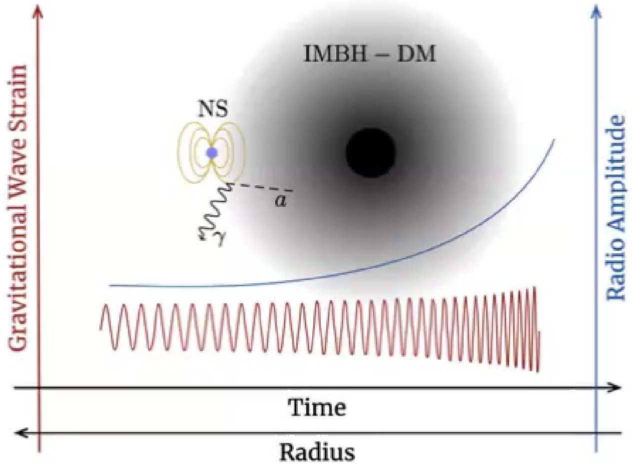


Primakoff process

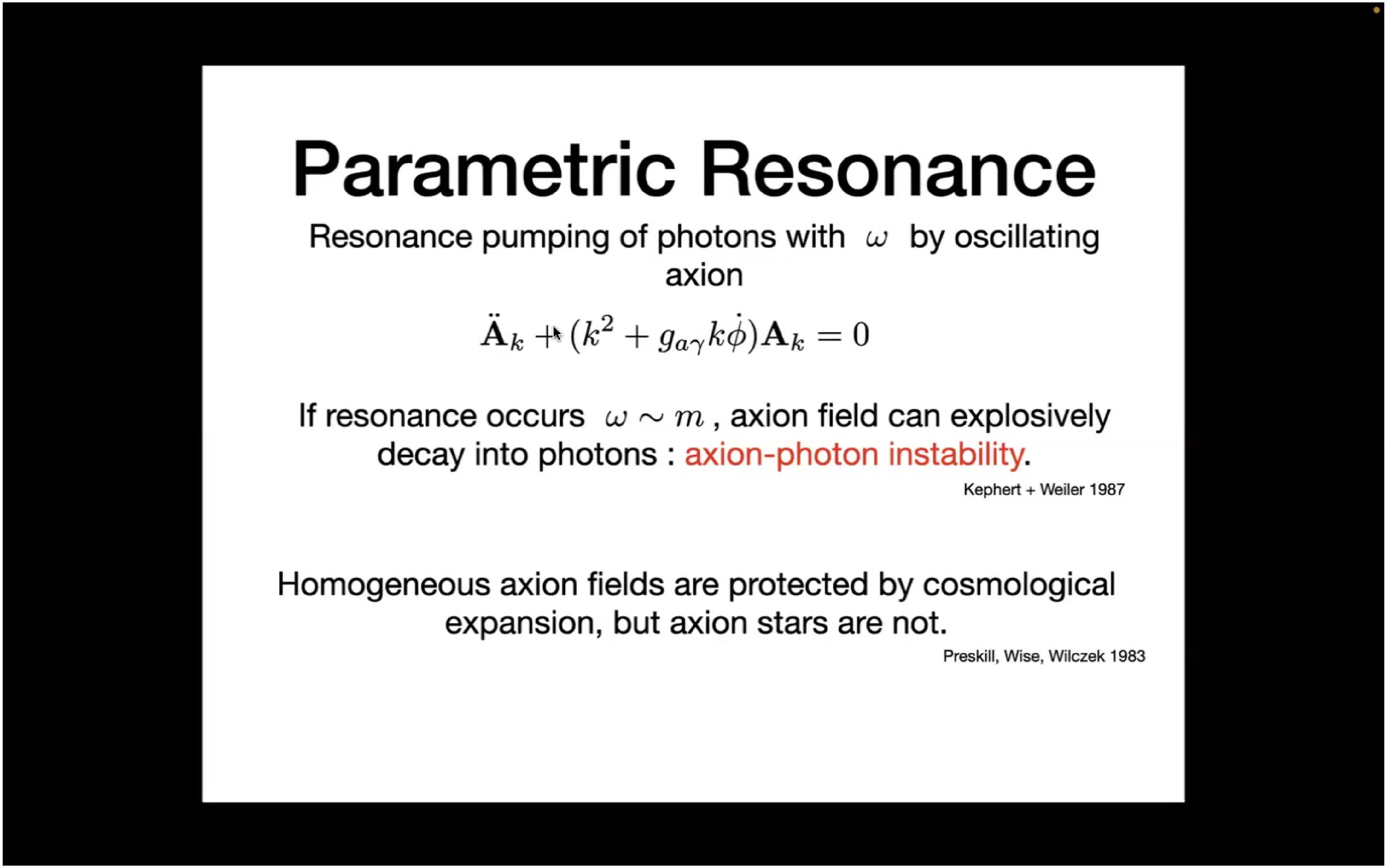
Photon production via interaction with external B field

Primakoff process

Multi-messenger signals from NS-BH interactions



Edwards et al (2020)



Parametric Resonance

Resonance pumping of photons with ω by oscillating axion

$$\ddot{\mathbf{A}}_k + (k^2 + g_{a\gamma} k \dot{\phi})\mathbf{A}_k = 0$$

If resonance occurs $\omega \sim m$, axion field can explosively decay into photons : axion-photon instability.

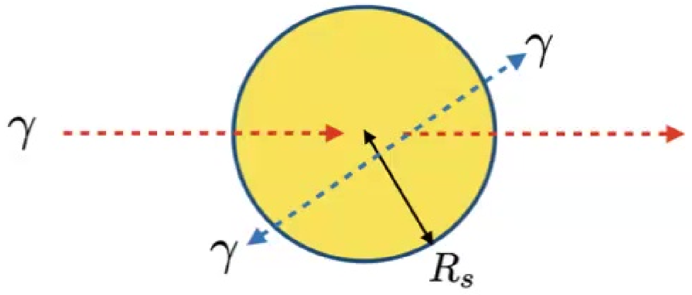
Kephert + Weiler 1987

Homogeneous axion fields are protected by cosmological expansion, but axion stars are not.

Preskill, Wise, Wilczek 1983

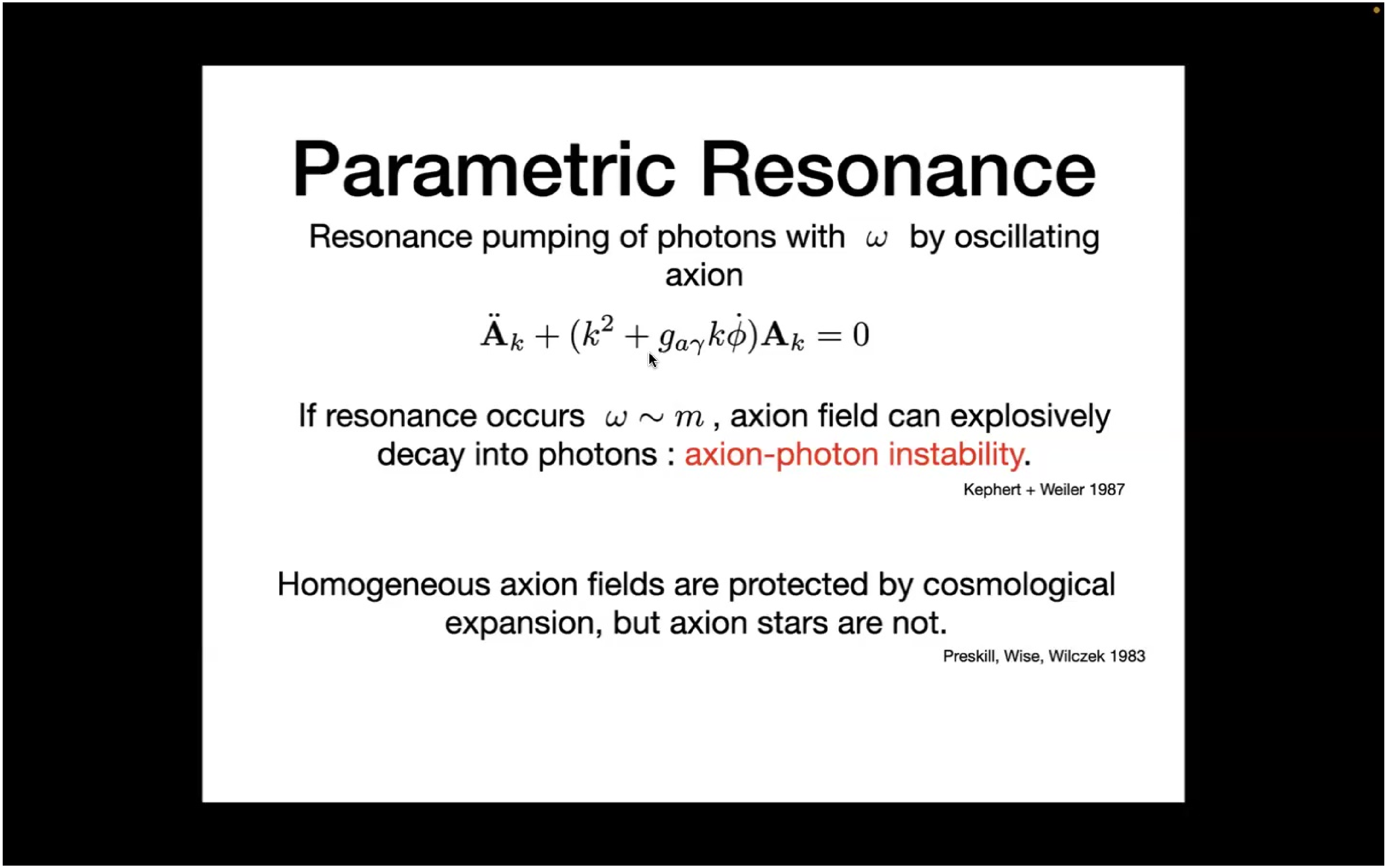
Axion Star Decay?

Similar to stimulated emission : Axion star radio bursts?



$$\gamma + \phi \to \gamma + \gamma + \gamma$$

$$2kR_s \sim 1 \Rightarrow k \sim m \quad \text{since} \quad R_s \sim m^{-1}$$



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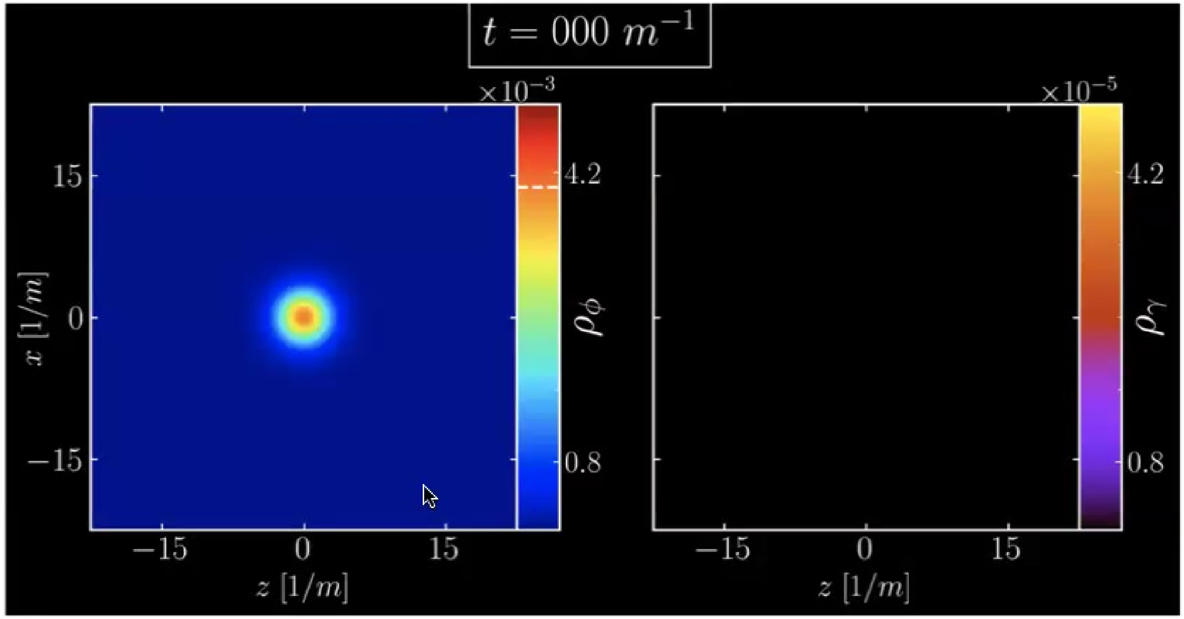
Axion Star Decay!

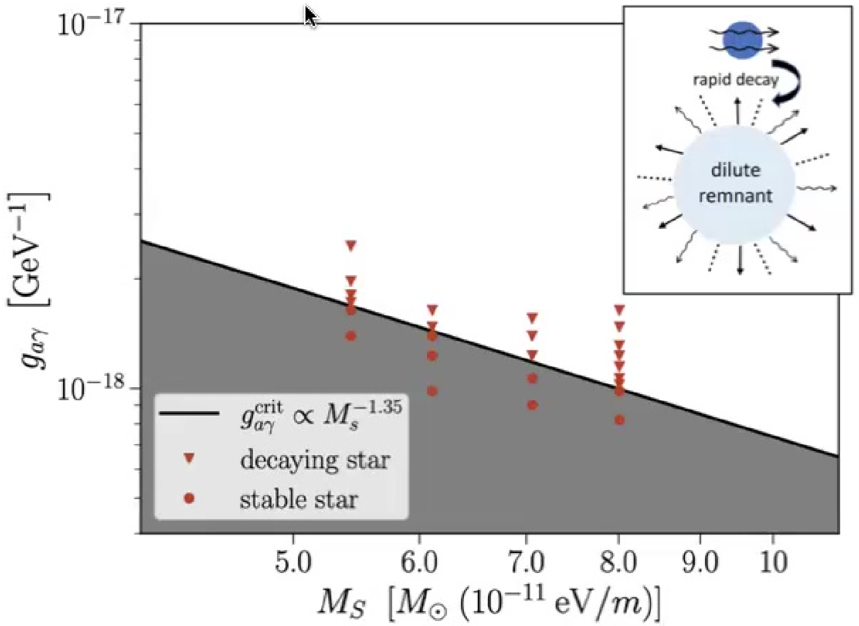
(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)



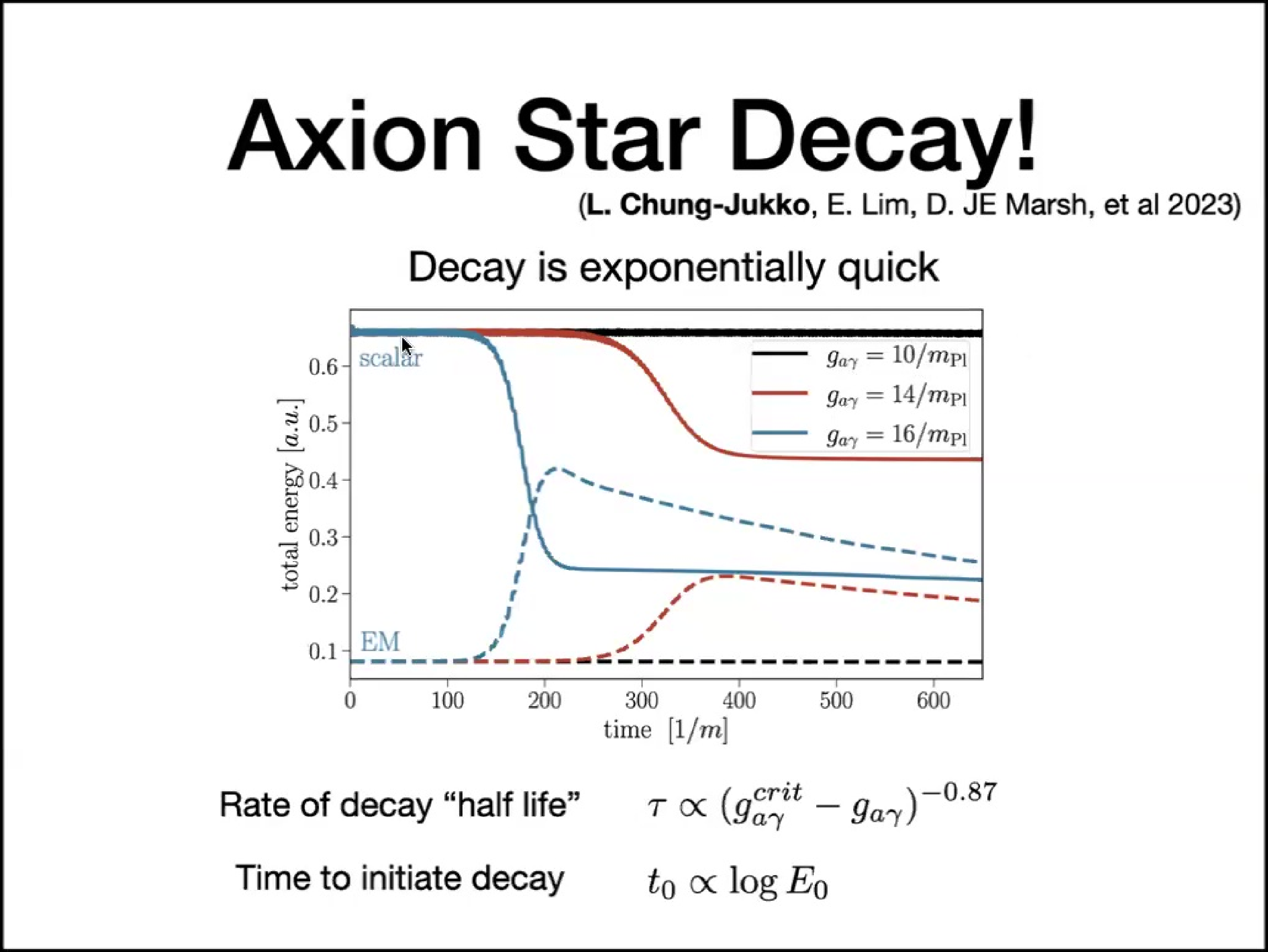
Axion Star Decay!

(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)

Unstable when $g_{a\gamma} > g_{a\gamma}^{crit} \sim M_s^{-1.35}$ independent of m



Actual formula: $g_{a\gamma}^{\rm crit} \approx \frac{1.66 \times 10^{-17}}{\rm GeV}\left[\left(\frac{M_s}{M_\odot}\right)\left(\frac{m}{10^{-11}\rm eV}\right)\right]^{-1.35}$



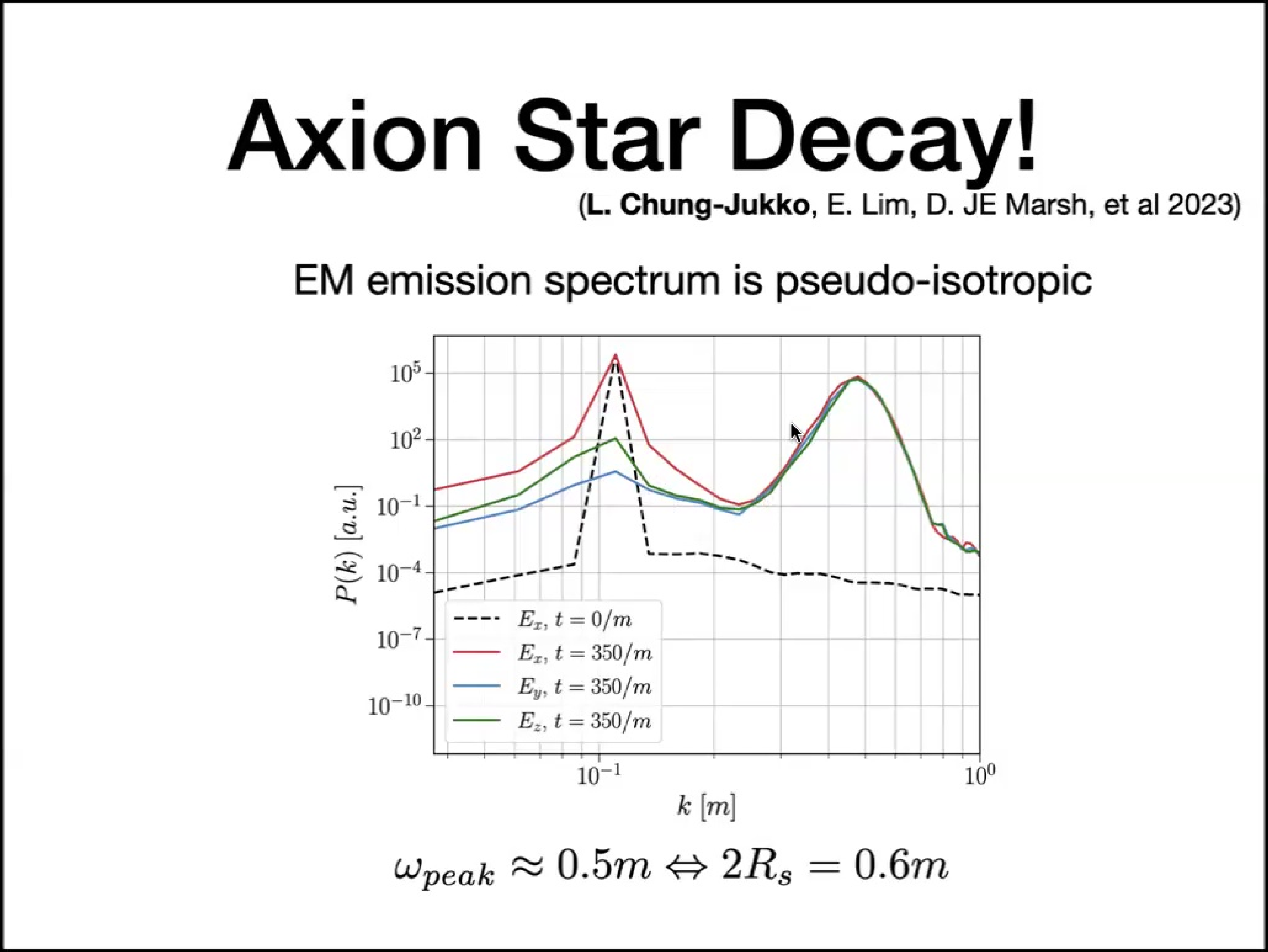
Axion Star Decay!

(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)

Decay is exponentially quick

Rate of decay "half life" $\tau \propto (g_{a\gamma}^{crit} - g_{a\gamma})^{-0.87}$

Time to initiate decay $t_0 \propto \log E_0$

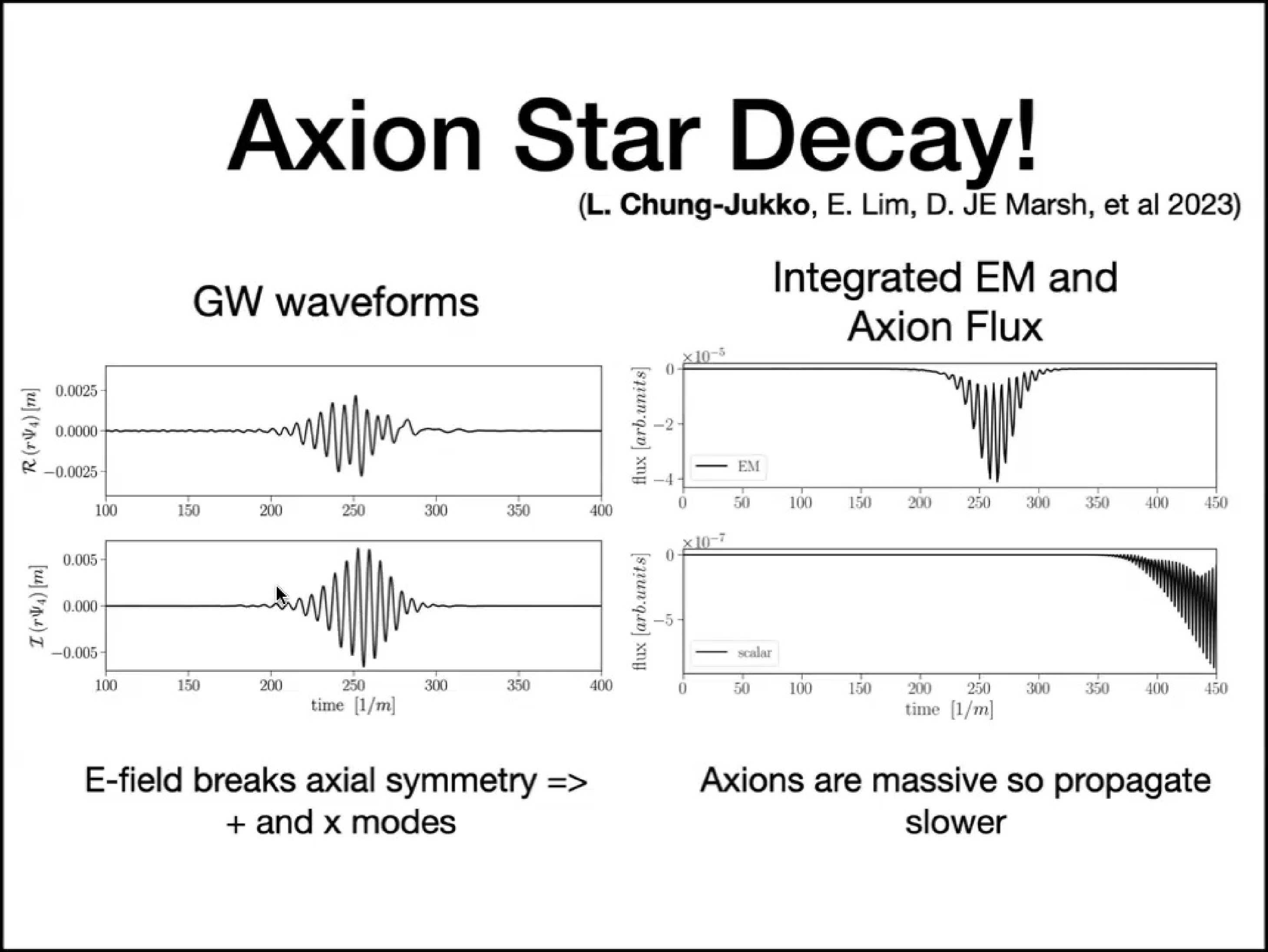


Axion Star Decay!

(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)

EM emission spectrum is pseudo-isotropic

$$\omega_{peak} \approx 0.5m \Leftrightarrow 2R_s = 0.6m$$



Axion Star Decay!

(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)

GW waveforms

Integrated EM and Axion Flux

E-field breaks axial symmetry =>
+ and x modes

Axions are massive so propagate slower

The end of Axion Stars?

(**L. Chung-Jukko**, E. Lim, D. JE Marsh, et al 2023)

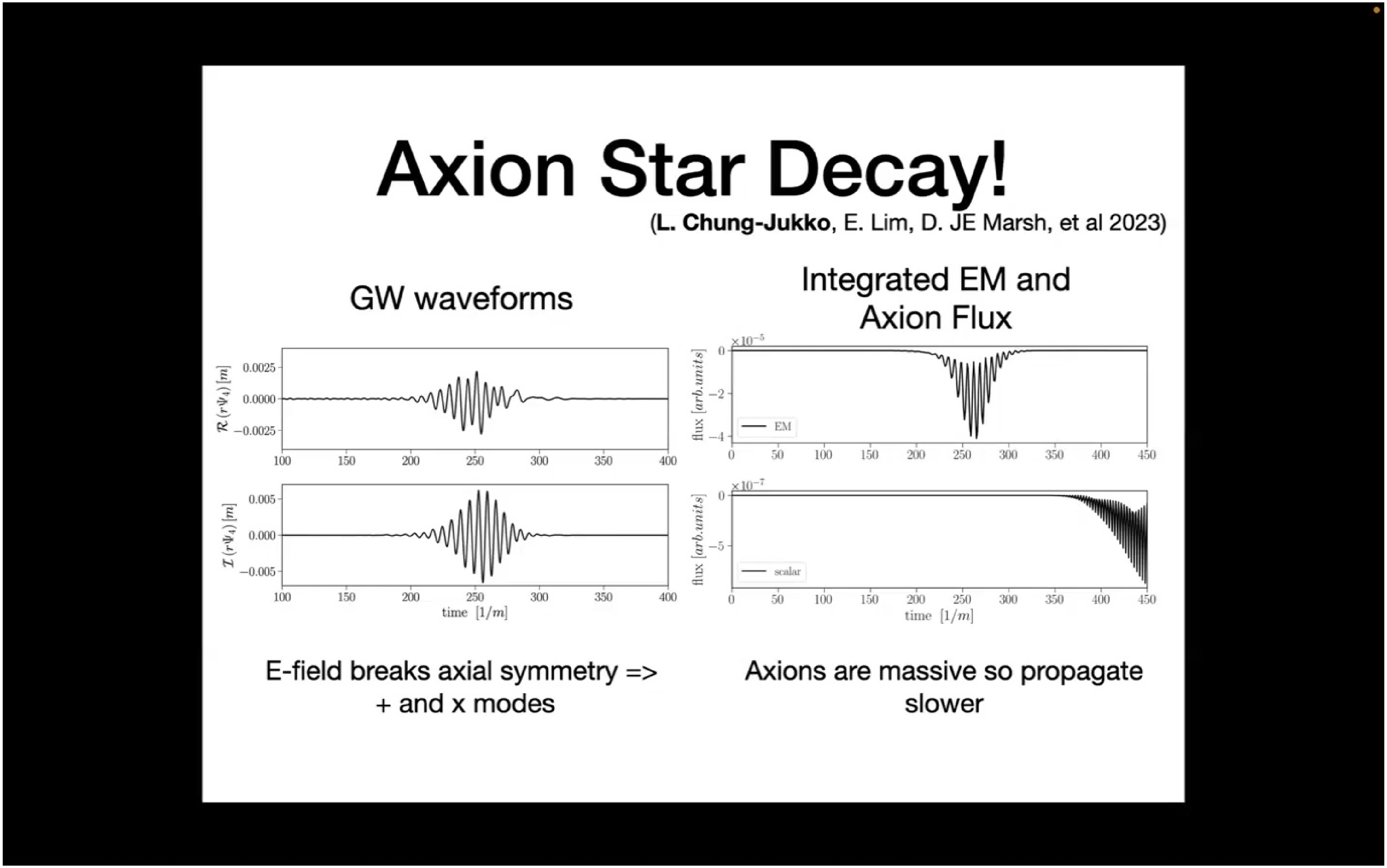
If $g_{a\gamma} > g_{g\gamma}^{crit}$ axion stars will decay within a Hubble time from CMB photons alone.

e.g. for $m = 10^{-11}\ \mathrm{eV}$ such that $M_s \sim \mathcal{O}(M_\odot)$

then $t_0 \sim 0.05\mathrm{s}$ for $g_{a\gamma} = 16 m_{\mathrm{pl}}^{-1}$

=> no compact axion stars in LVK sensitivity range.

🙁



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GW waveforms

Integrated EM and Axion Flux

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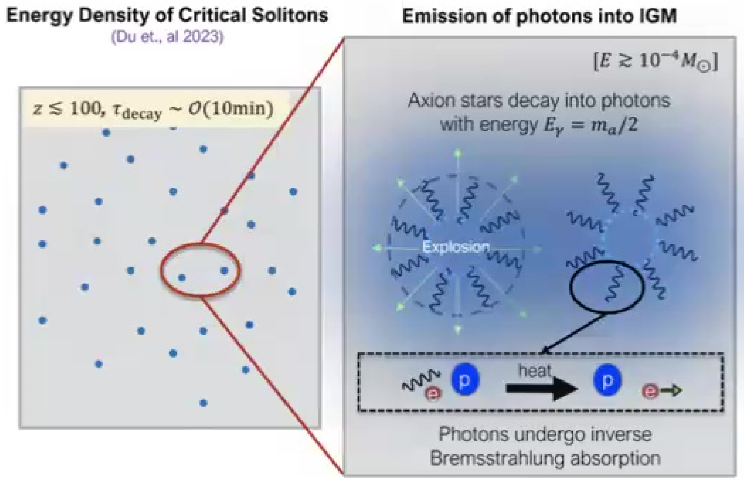
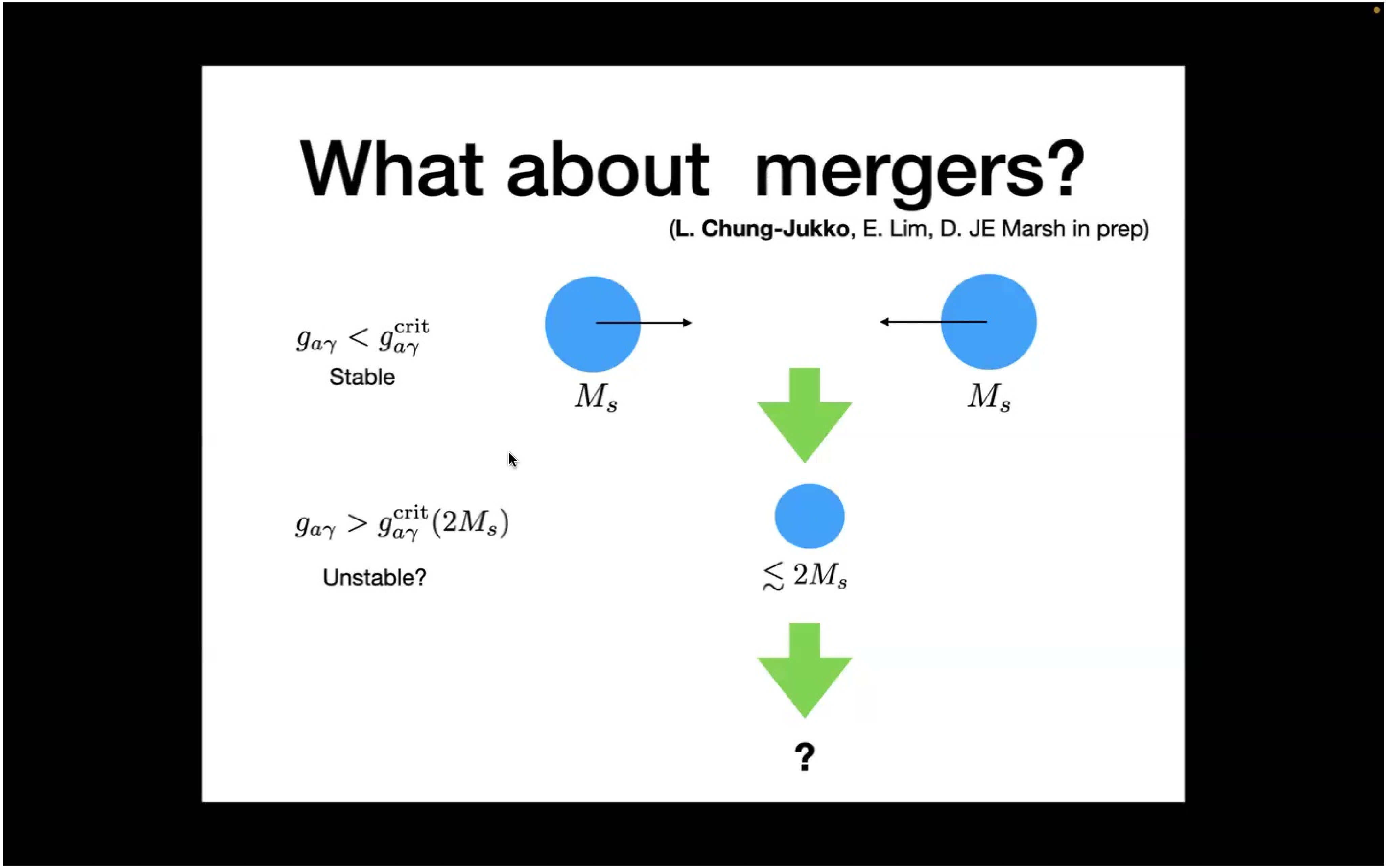
The end of Axion Stars?

Axion stars decaying into photons is a lot of energy into the intergalactic medium…

Observable? Constraints?



e.g. Heat up integalactic medium and change CMB optical depth. (Escudero et al 2023)



What about mergers?

(**L. Chung-Jukko**, E. Lim, D. JE Marsh in prep)

$g_{a\gamma} < g_{a\gamma}^{\mathrm{crit}}$

Stable

M_s M_s

$g_{a\gamma} > g_{a\gamma}^{\mathrm{crit}}(2M_s)$

Unstable?

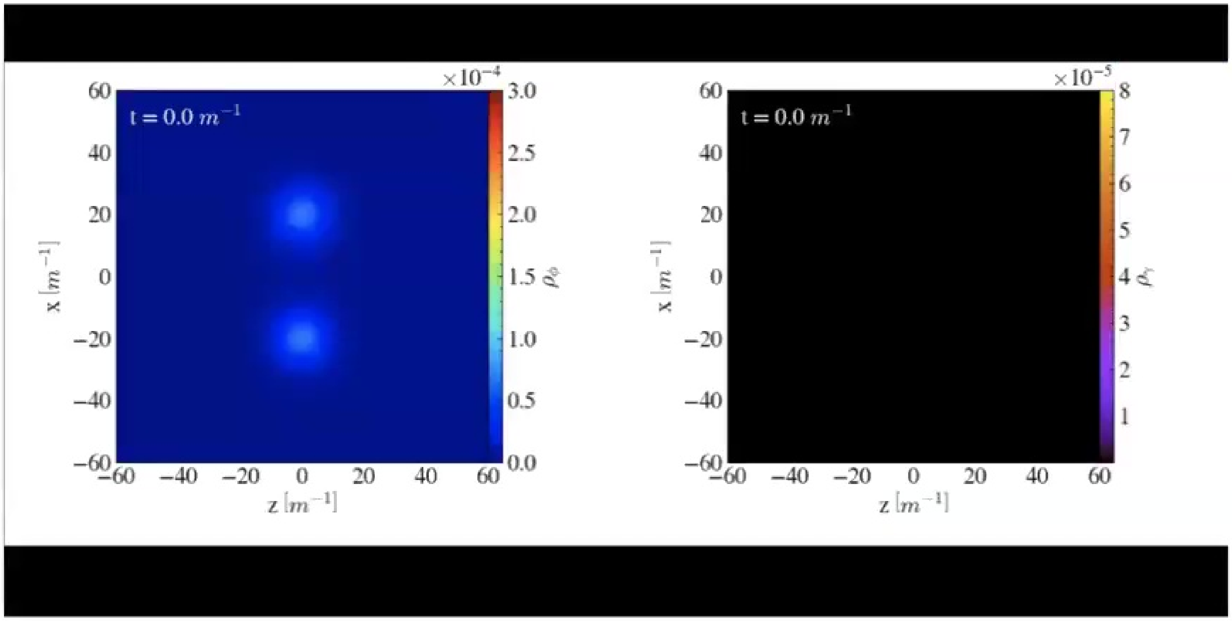
$\lesssim 2M_s$

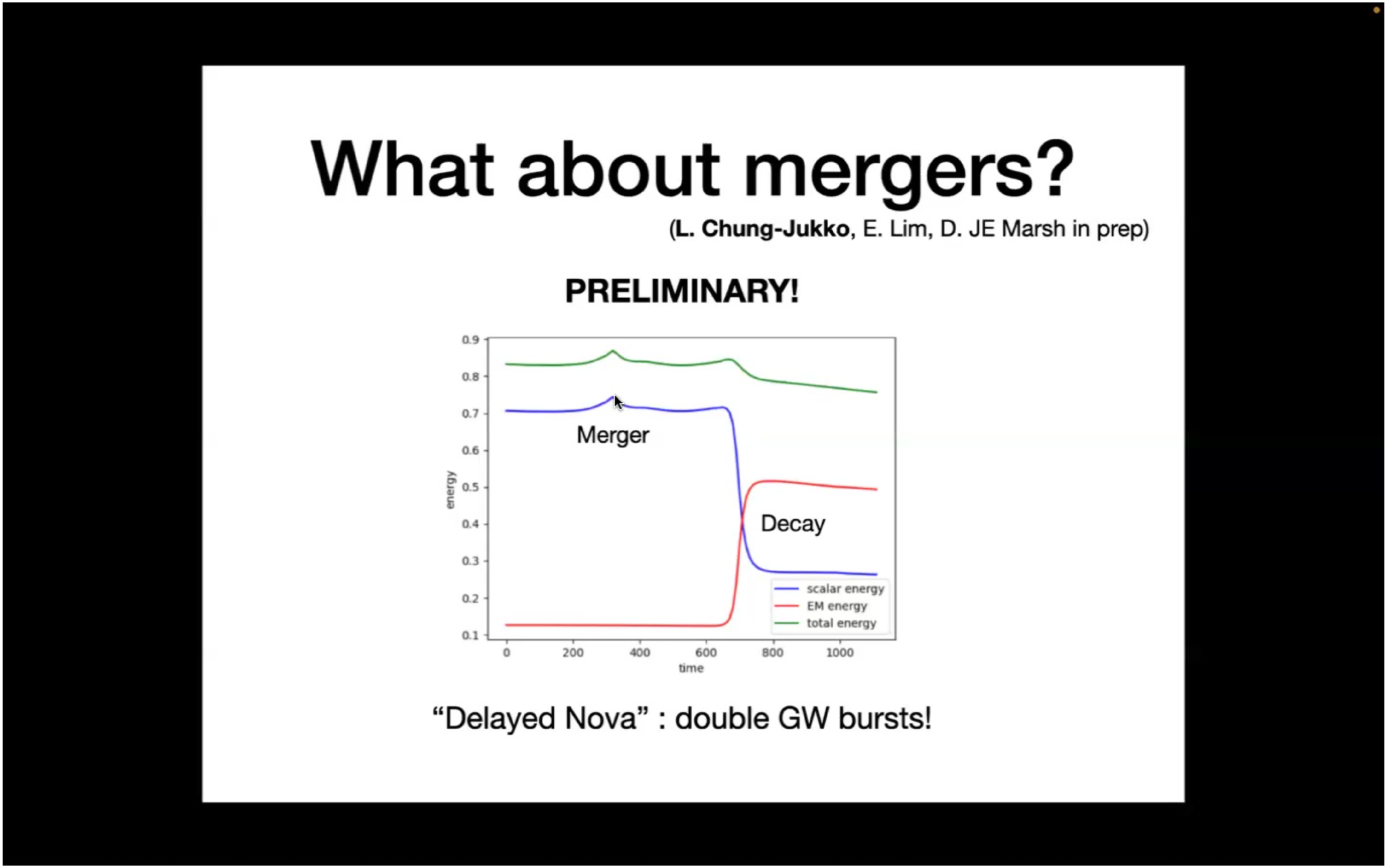
?

What about mergers?

(**L. Chung-Jukko**, E. Lim, D. JE Marsh in prep)

PRELIMINARY!





What about mergers?

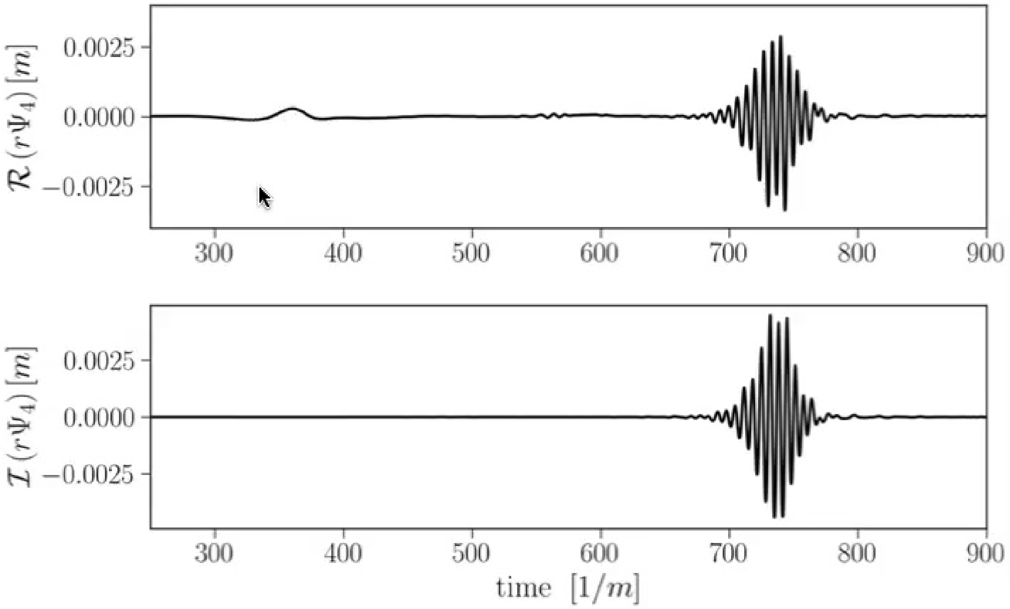
(**L. Chung-Jukko**, E. Lim, D. JE Marsh in prep)

PRELIMINARY!

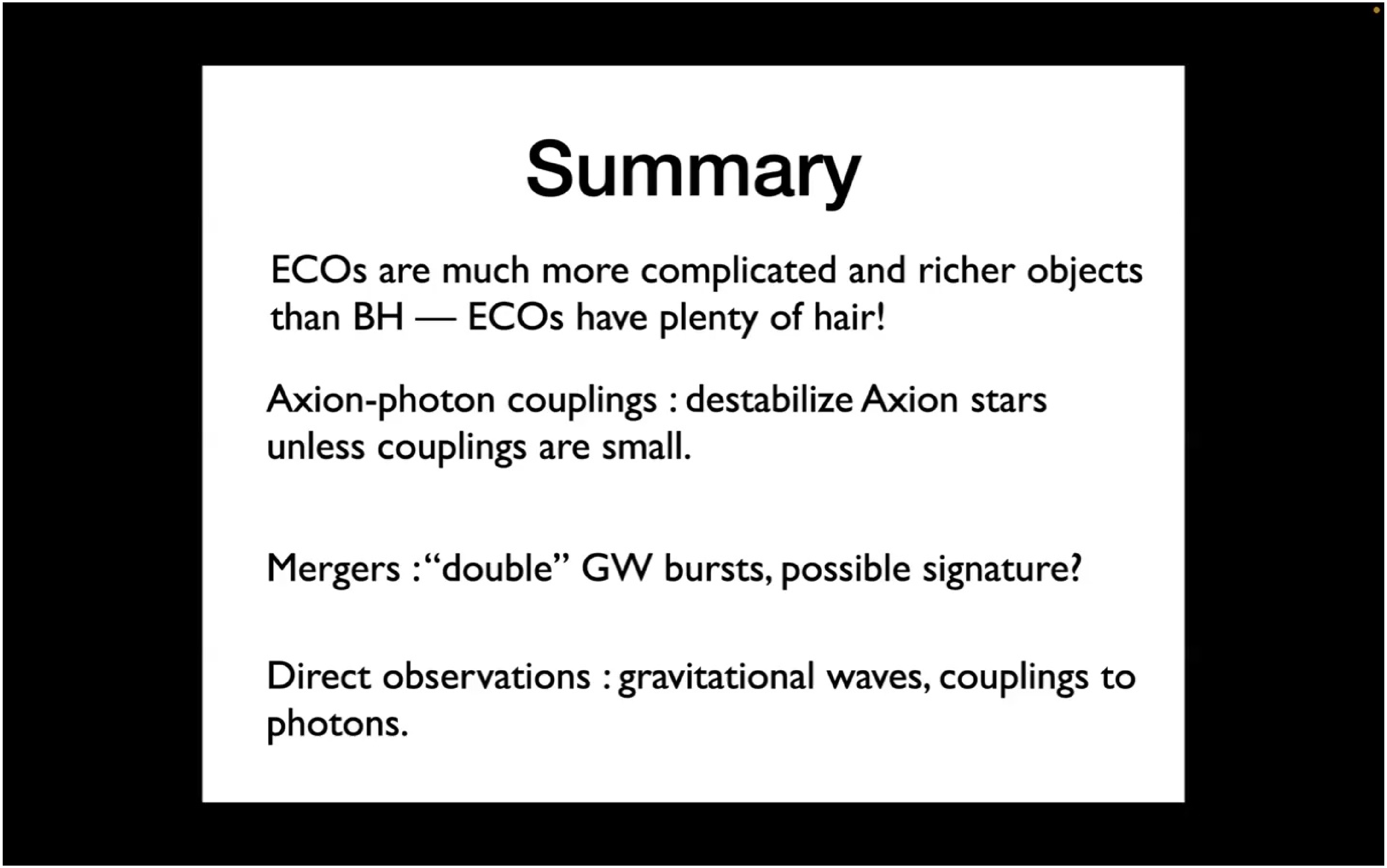
"Delayed Nova" : double GW bursts!

What about mergers?

(**L. Chung-Jukko**, E. Lim, D. JE Marsh in prep)



$$E_{GW,decay} \sim \mathcal{O}(10) \times E_{GW,merger}$$



Summary

ECOs are much more complicated and richer objects than BH — ECOs have plenty of hair!

Axion-photon couplings : destabilize Axion stars unless couplings are small.

Mergers :“double” GW bursts, possible signature?

Direct observations : gravitational waves, couplings to photons.