Transient Targets for Dark Matter Searches Using Quantum Sensors

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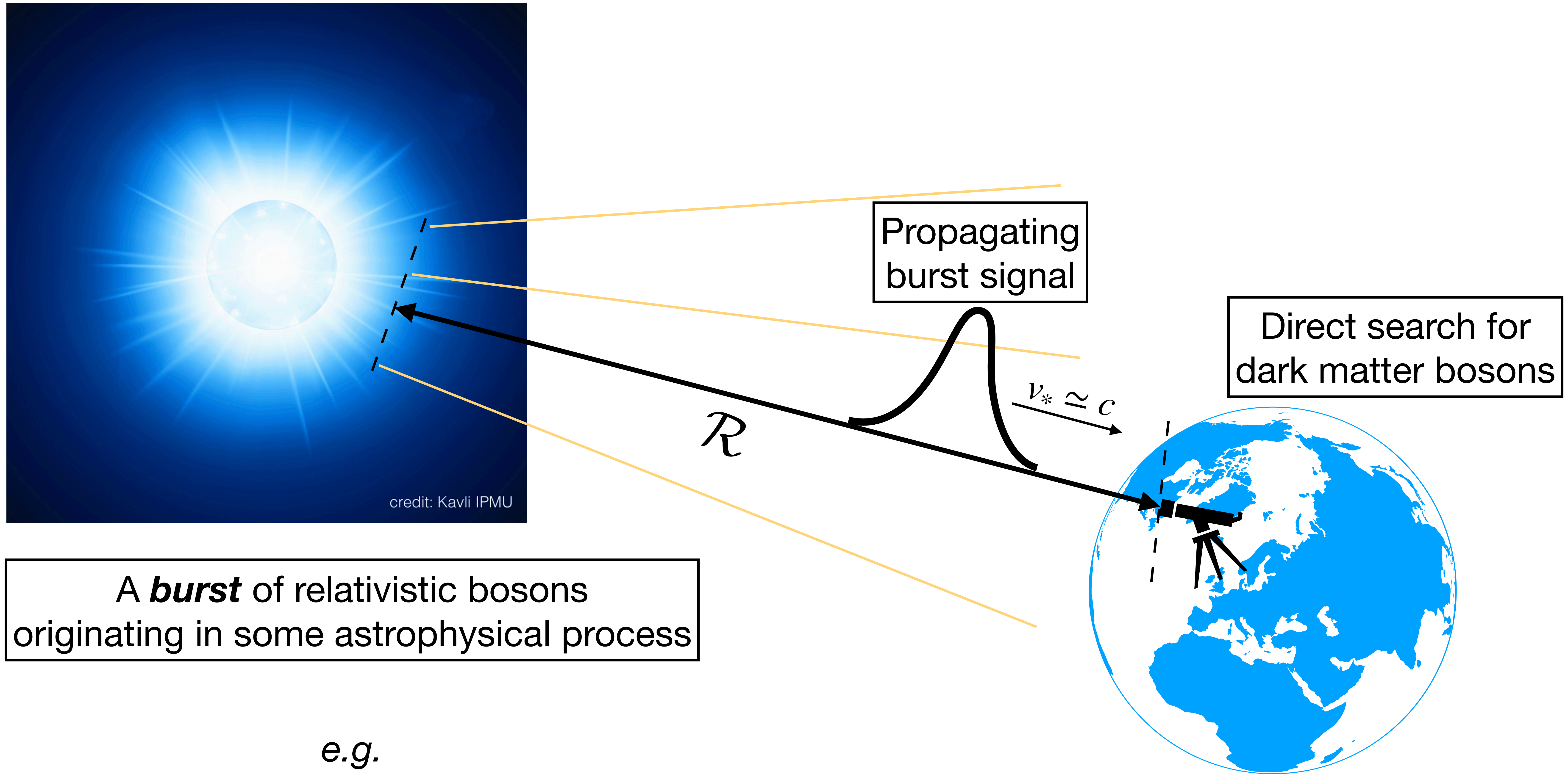
Oskar Klein Centre
Stockholm University

2nd Terrestrial Very-Long-Baseline Atom Interferometer Workshop
03/04/2024

Based on

J Eby, Shirai, Stadnik, Takhistov (2106.14893)
Arakawa, **J Eby**, Safronova, Takhistov, Zaheer (2306.16468)
Arakawa, Zaheer, **J Eby**, Takhistov, Safronova (2402.06736)

The Basic Picture



A ***burst*** of relativistic bosons originating in some astrophysical process

e.g.

- *Bosenovae* from collapse of boson stars **[this talk]**
- Dark sector emission
- Astrophysical merger events
- [etc.]

Outline

1. Ultralight dark matter

2. Relativistic ULDM ***bursts***

3. Experimental sensitivity

Natural units used throughout:

$1\,\text{eV} \simeq 10^{-32}\,\text{g} \simeq 10^{-66} M_\odot$

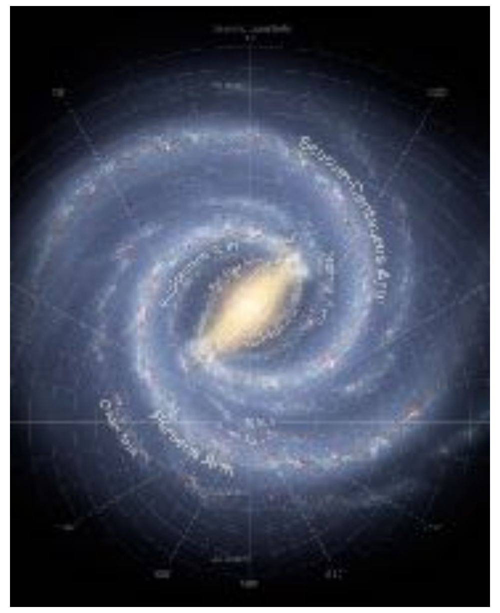
$1\,\text{eV} \simeq (10^{-7}\,\text{m})^{-1}$

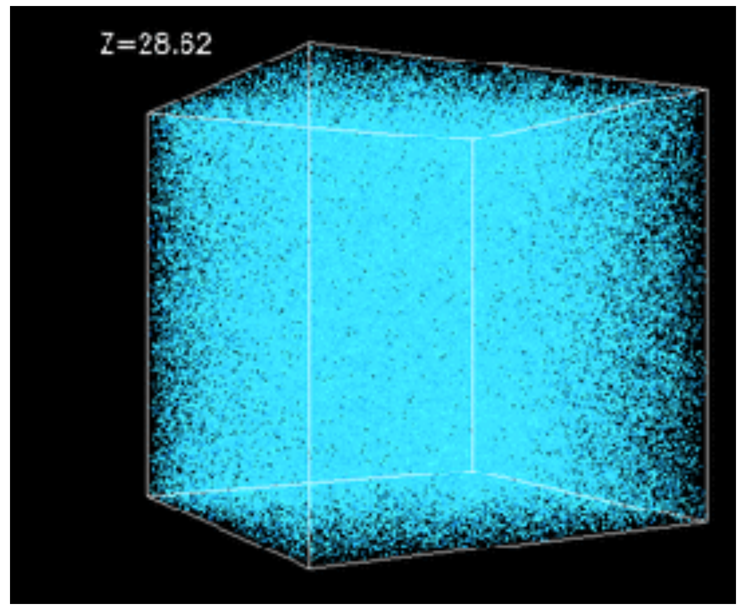
$1\,\text{eV} \simeq (10^{-15}\,\text{sec})^{-1}$

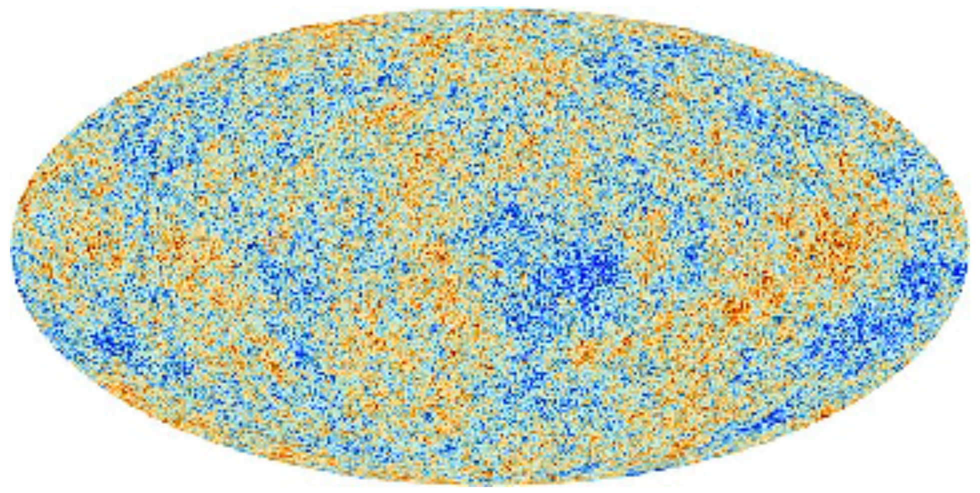
Ultralight Dark Matter

Dark Matter

galaxies — *galaxy clusters* — *structure formation* — *cosmic microwave background* → distance scale







evidence for Dark Matter

Local DM Properties:

Density of DM in our neighborhood

$$\rho_{\rm dm} = 0.4\,{\rm GeV/cm^3}$$

"local density"

DM velocities

~Maxwell-Boltzmann

$$v_{\rm dm} \simeq 240\,{\rm km/sec} \simeq 10^{-3}$$

mean velocity

Concordance model of Cosmology:

ΛCDM

6 parameters
fit all* observations
at %-level precision!

Λ: Dark Energy

CDM: Cold Dark Matter

Dark Matter

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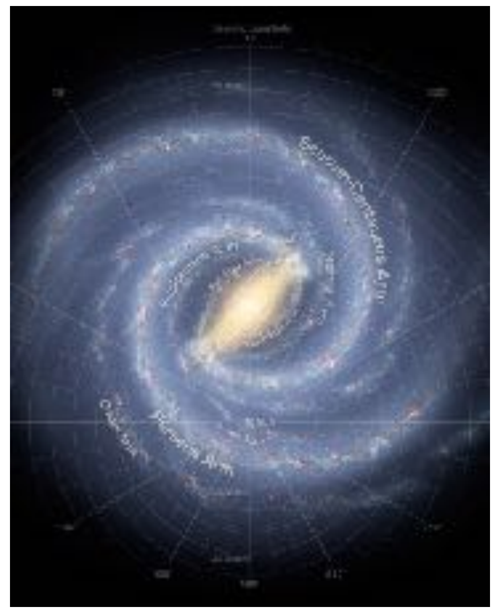

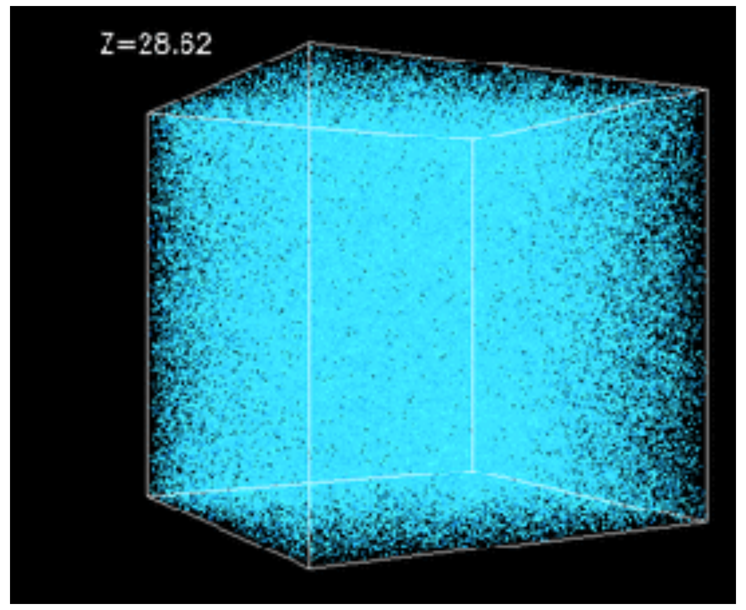
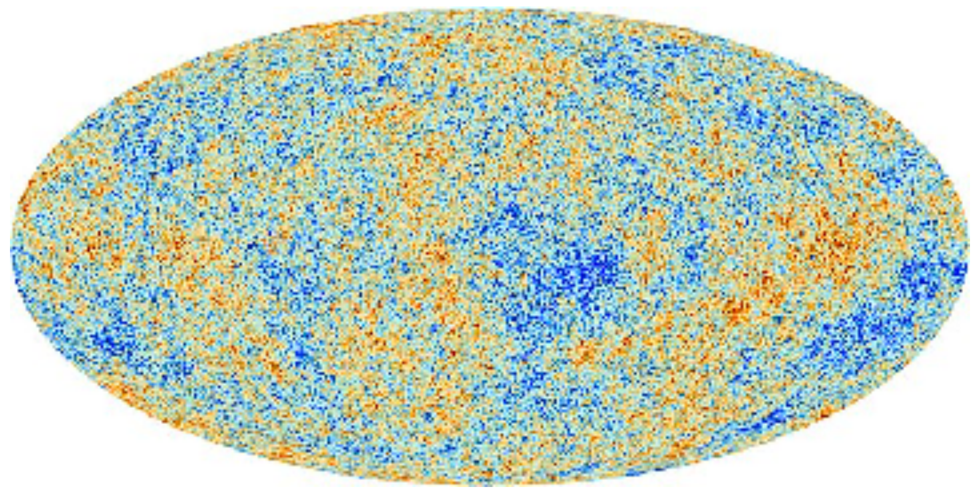

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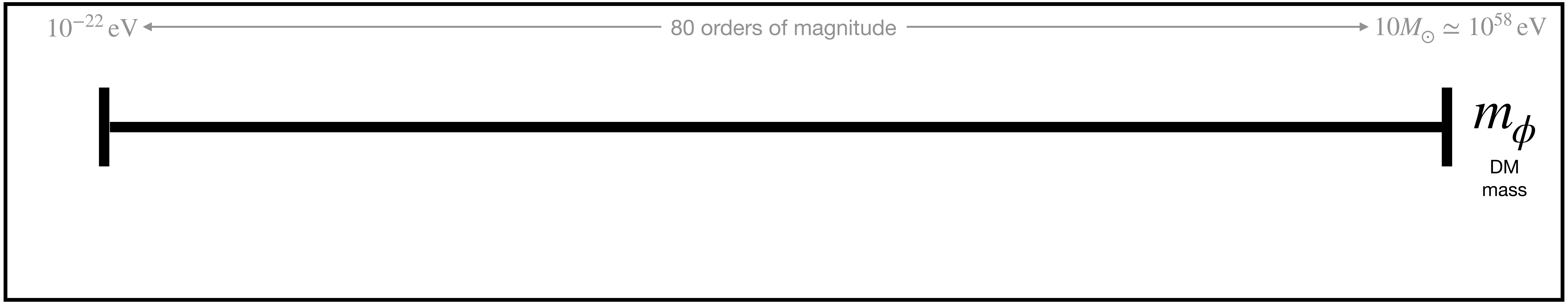
The Dark Matter Mystery

Models of Dark Matter



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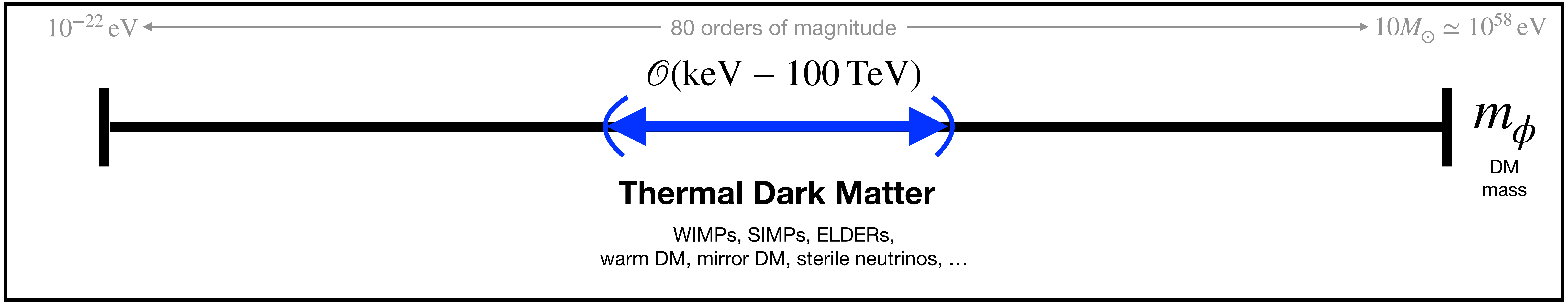

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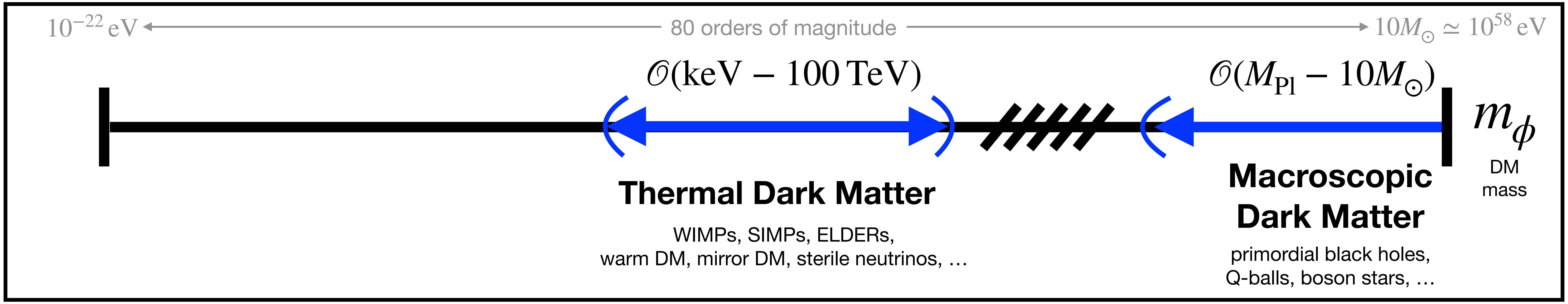

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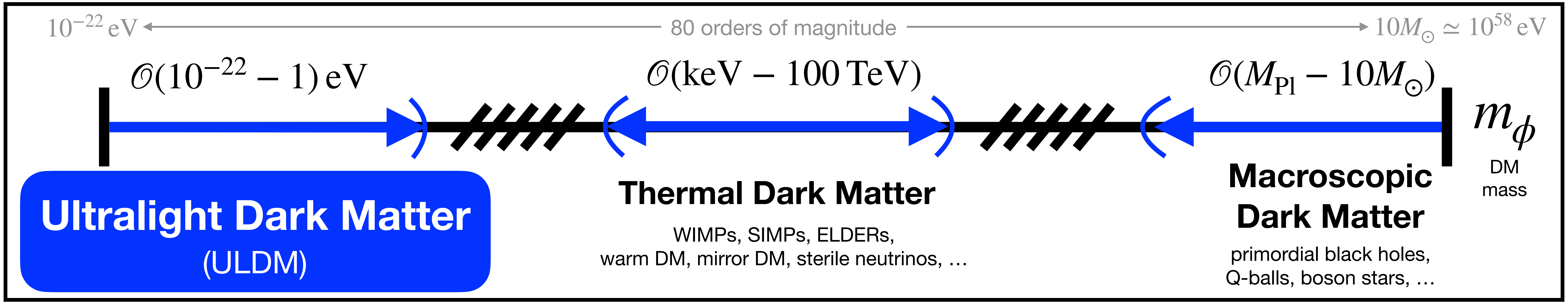


The Dark Matter Mystery

Models of Dark Matter

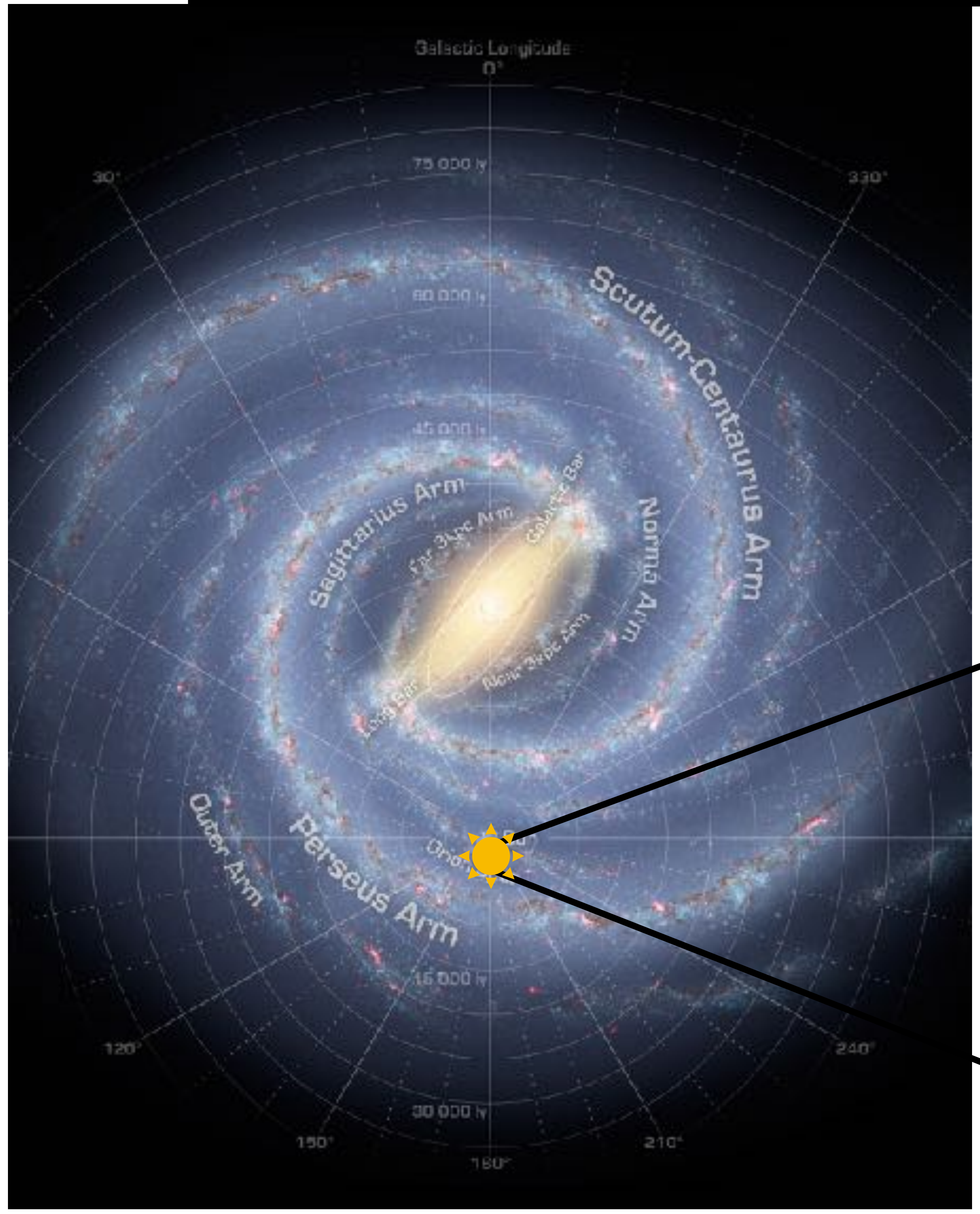
$10^{-22}\,\text{eV}$ ← 80 orders of magnitude → $10 M_\odot \simeq 10^{58}\,\text{eV}$

$\mathcal{O}(10^{-22} - 1)\,\text{eV}$ | $\mathcal{O}(\text{keV} - 100\,\text{TeV})$ | $\mathcal{O}(M_{\text{Pl}} - 10 M_\odot)$ | m_ϕ DM mass

Ultralight Dark Matter (ULDM)

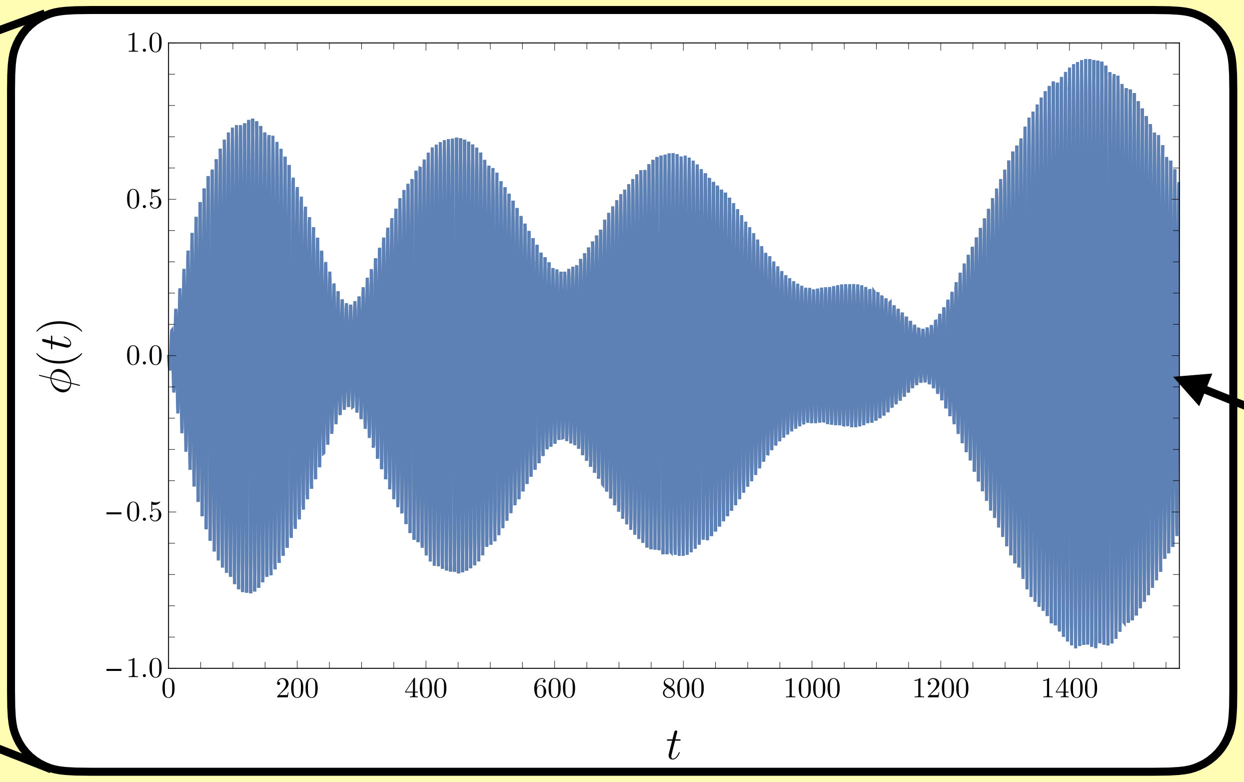
Thermal Dark Matter
WIMPs, SIMPs, ELDERs, warm DM, mirror DM, sterile neutrinos, …

Macroscopic Dark Matter
primordial black holes, Q-balls, boson stars, …



Long wavelength

$$\lambda_{\text{dB}} \equiv \frac{2\pi}{m_\phi v_{\text{dm}}} \sim 10^4\,\text{AU}\left(\frac{10^{-15}\,\text{eV}}{m_\phi}\right)$$



Oscillation frequency

$$\omega_\phi \sim m_\phi \simeq 1\,\text{Hz} \times \left(\frac{10^{-15}\,\text{eV}}{m_\phi}\right)$$

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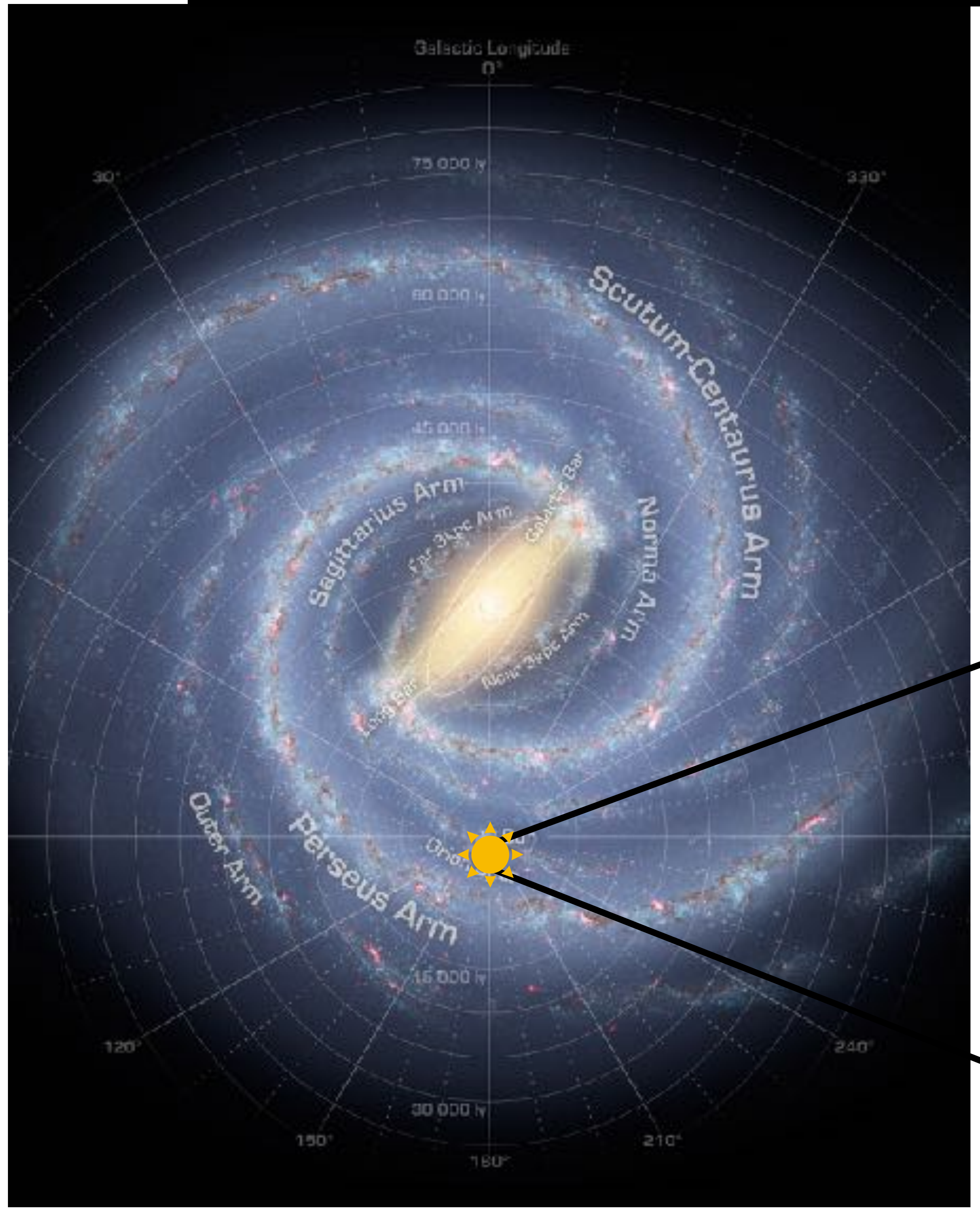

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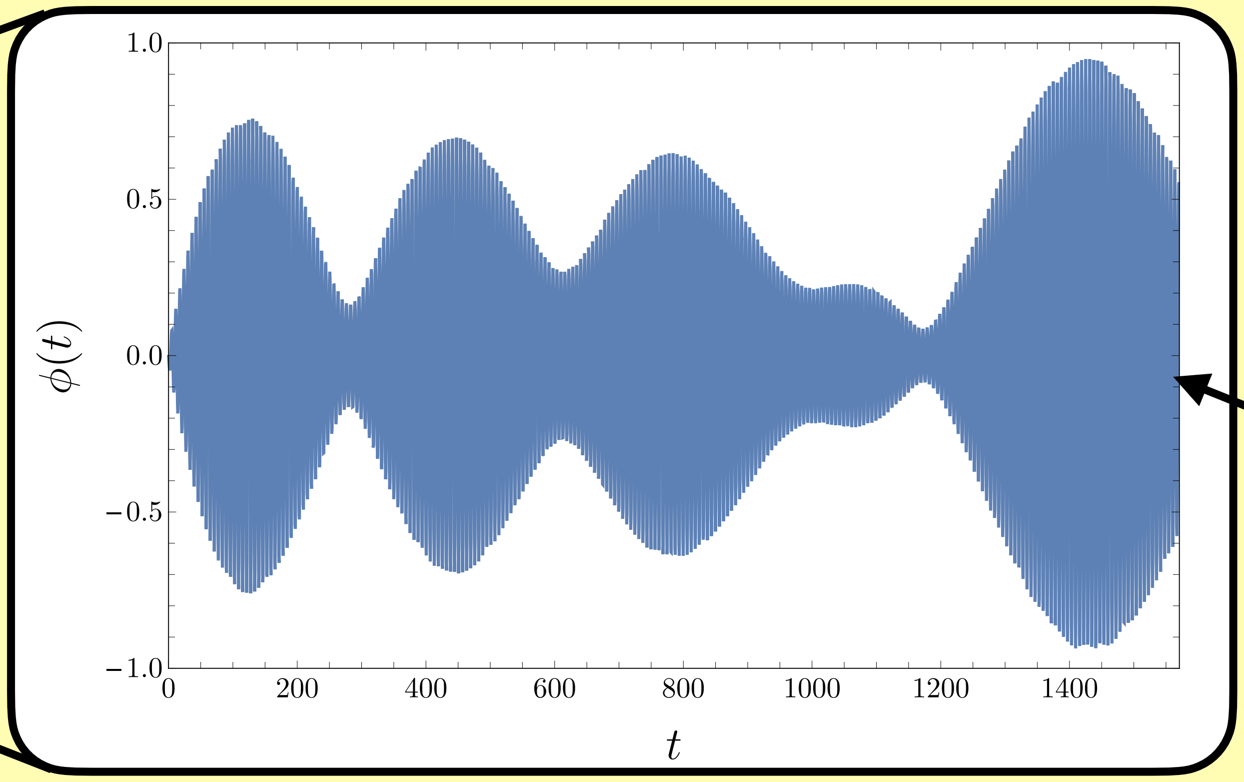
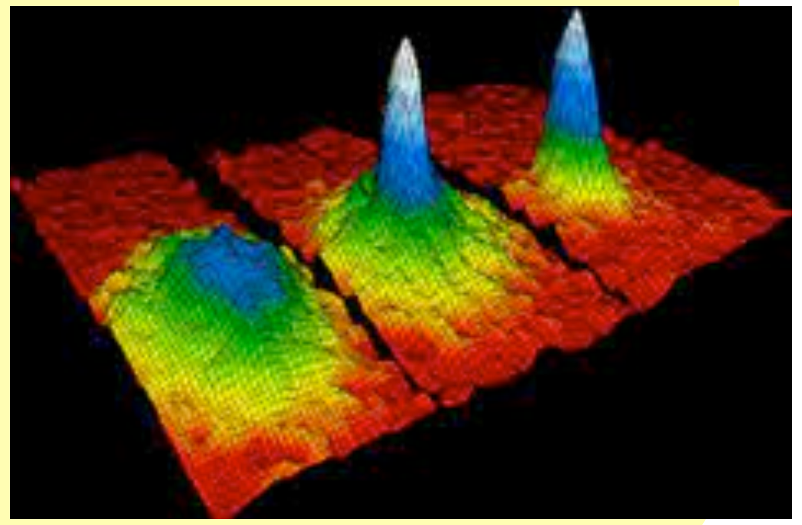


Large state occupation

$$\mathcal{N} \simeq (\rho_{\mathrm{dm}}/m_\phi)\lambda_{\mathrm{dB}}^3 \simeq 10^{68} \times \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)^4$$



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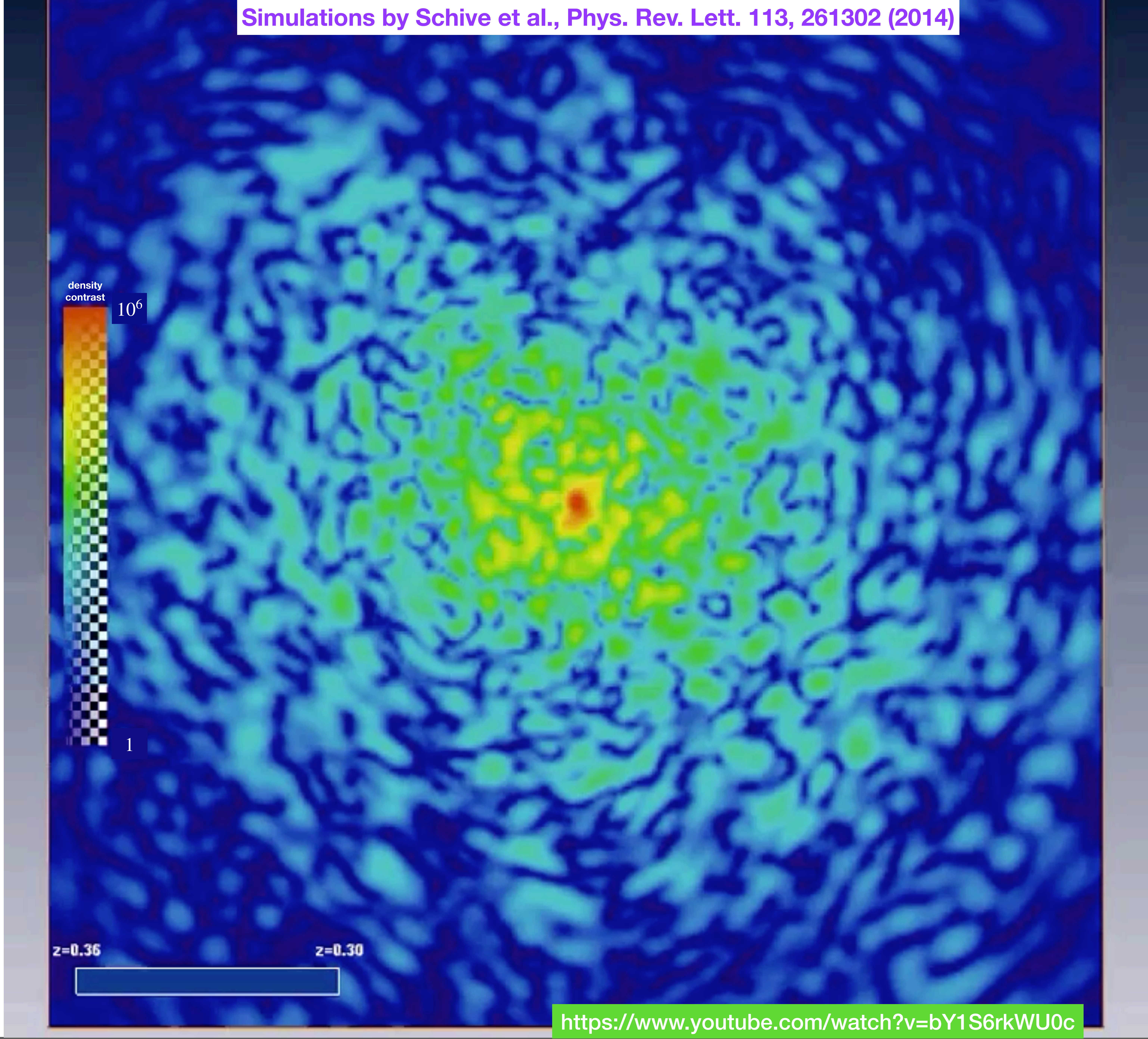
ULDM Waves

Example with $m_\phi \simeq 10^{-22}\,\mathrm{eV}$



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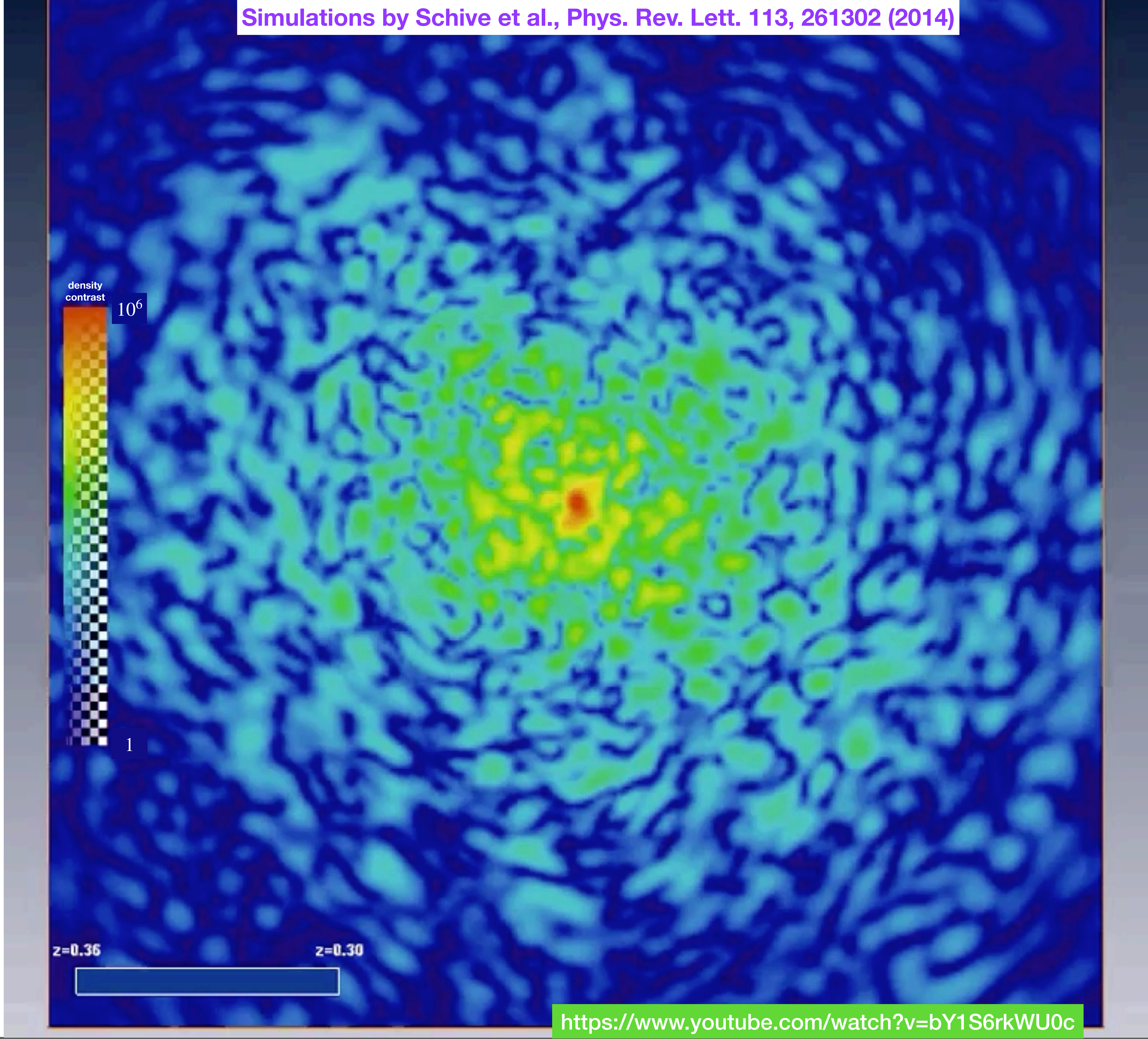

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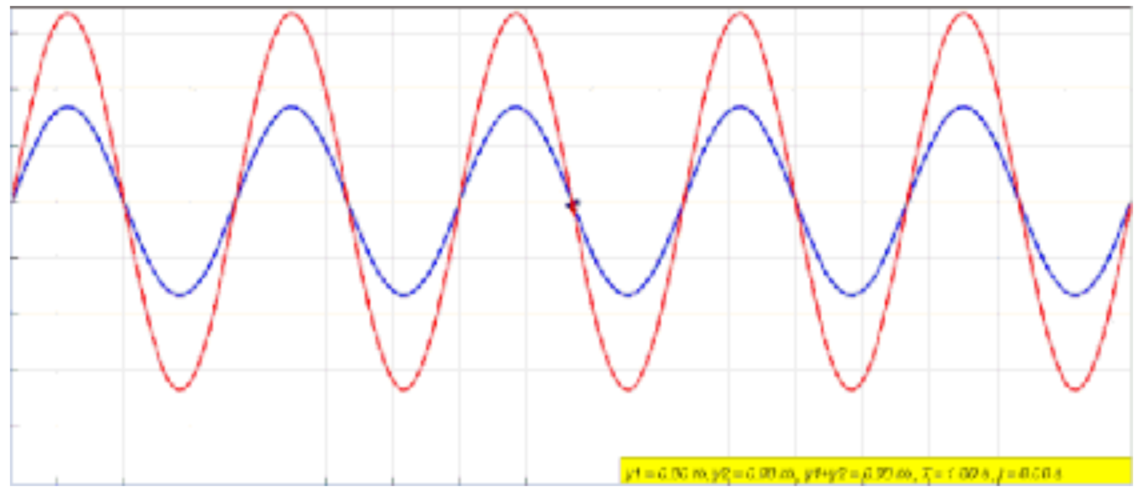

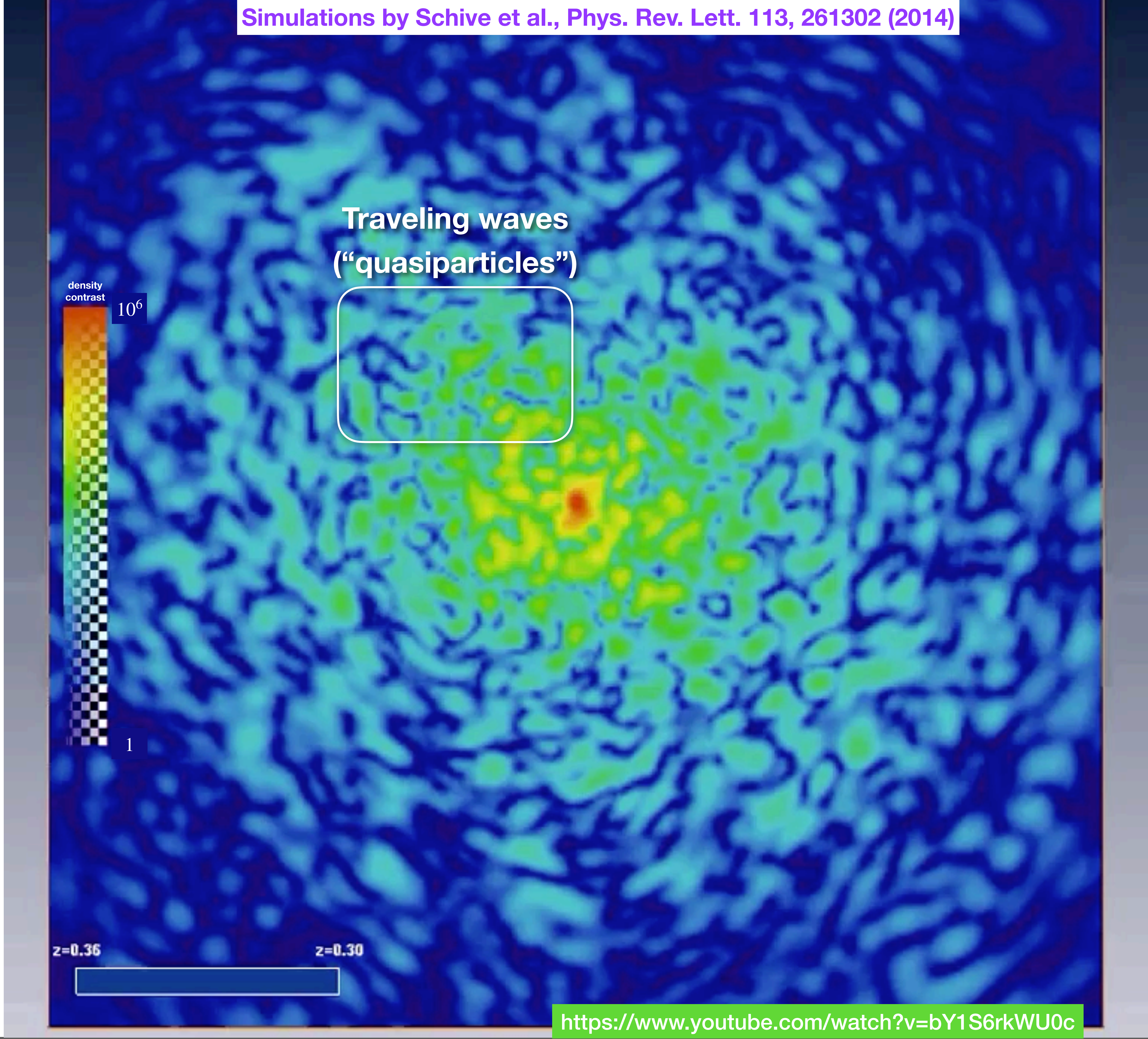

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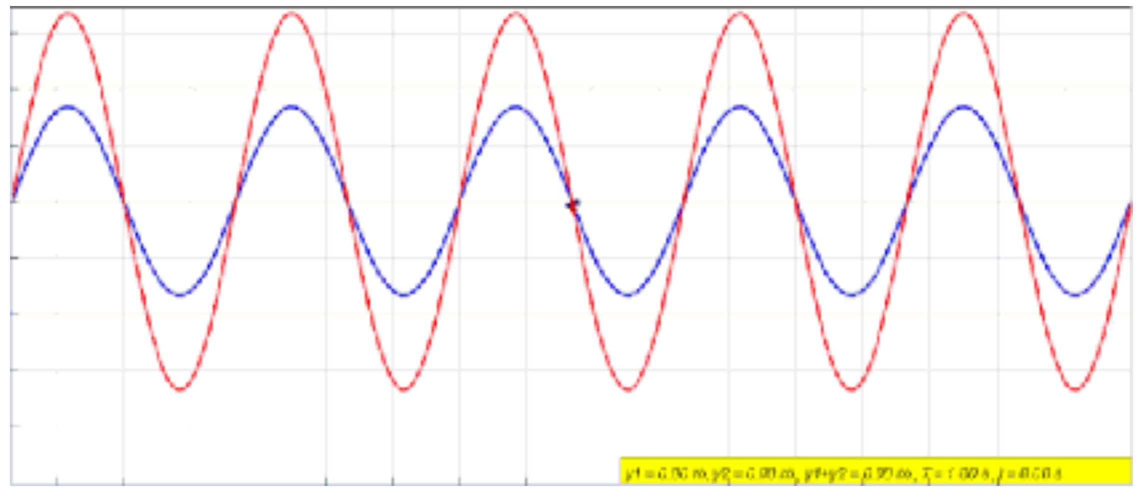

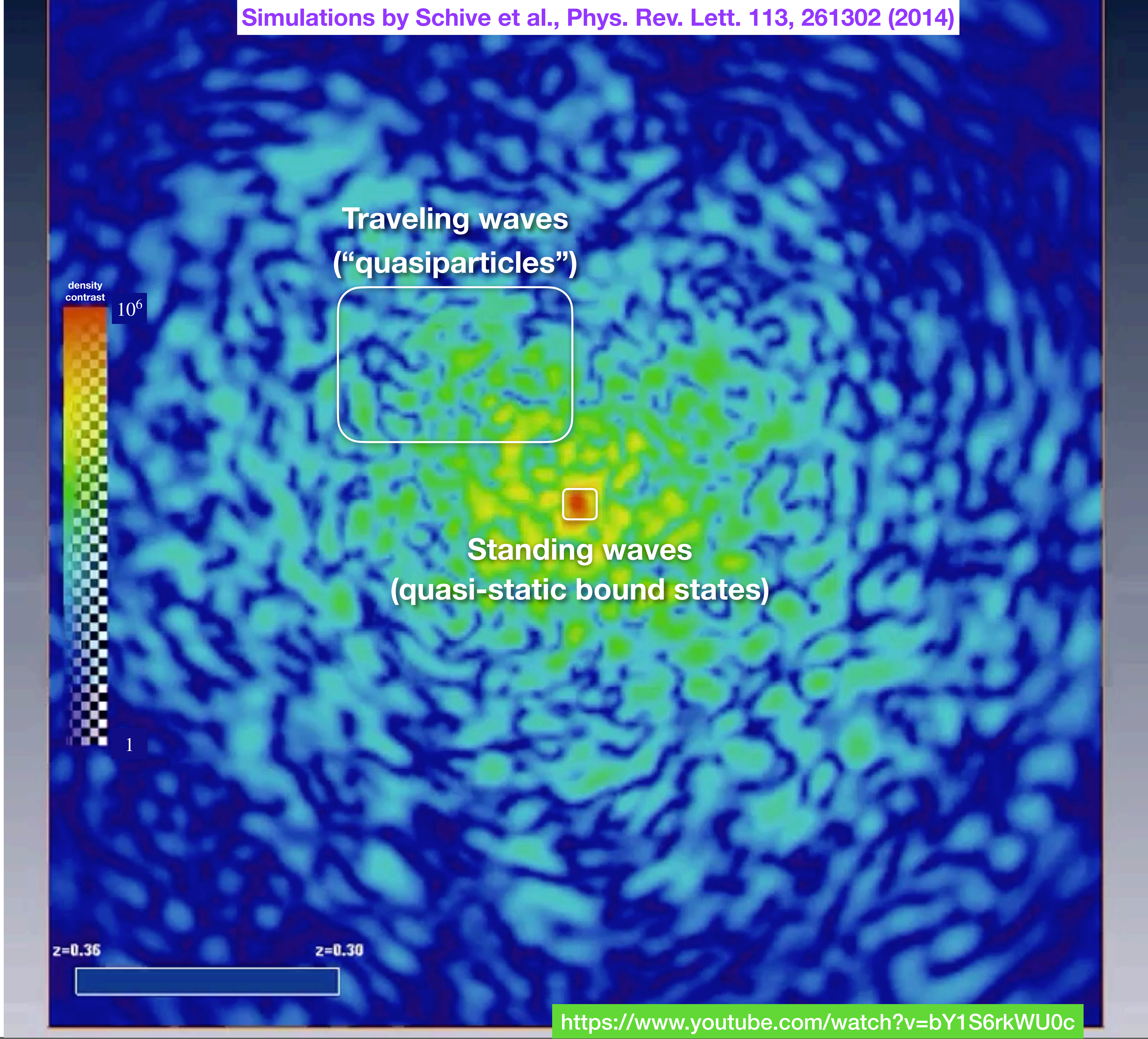

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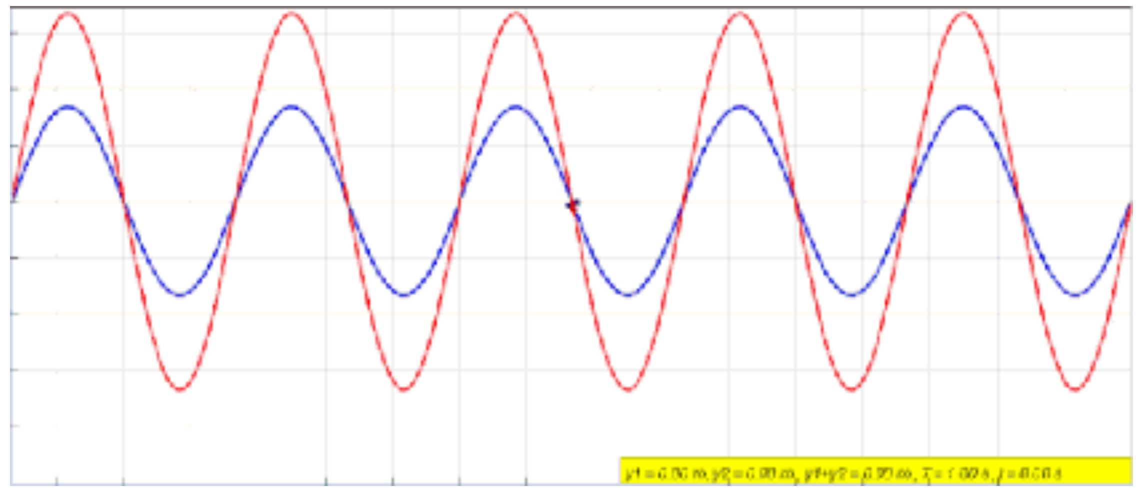
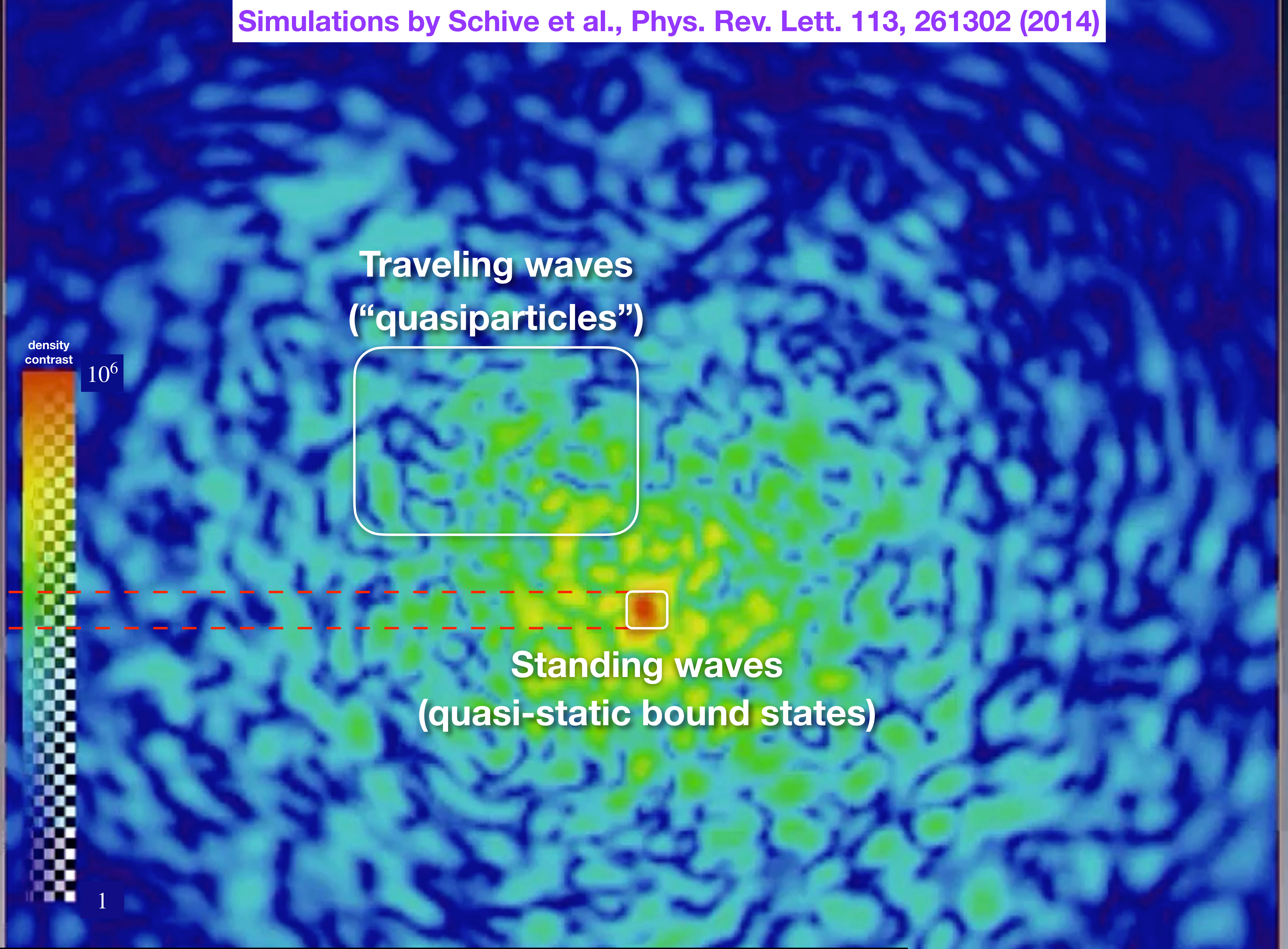
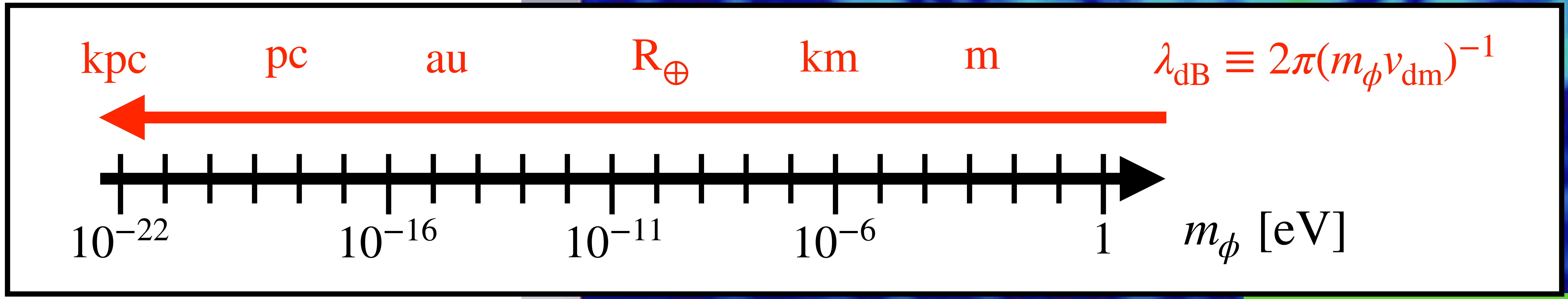


$\lambda_{\rm dB}$

Wave amplitude $\Longleftrightarrow$ DM density

Variations of $\rho_{\rm dm}$
on scales of order $\lambda_{\rm dB}$



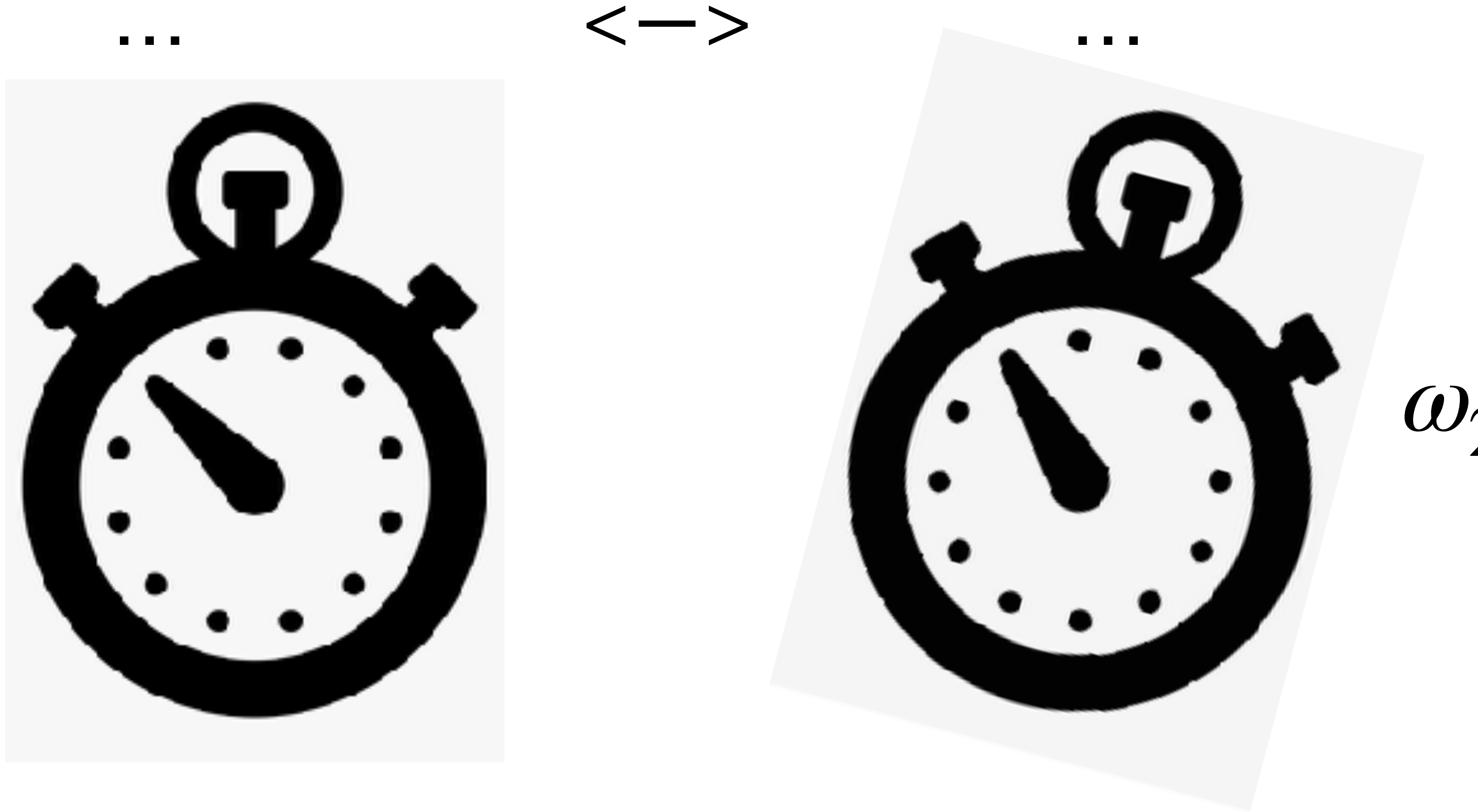


Basics of Quantum Sensor Searches

Basic procedure: Compare two "clocks" with different couplings to ULDM field

Atom 1	<—>	Atom 2
Atomic transition 1	<—>	Atomic transition 2
Atomic transition	<—>	Cavity
…	<—>	…

ω_1

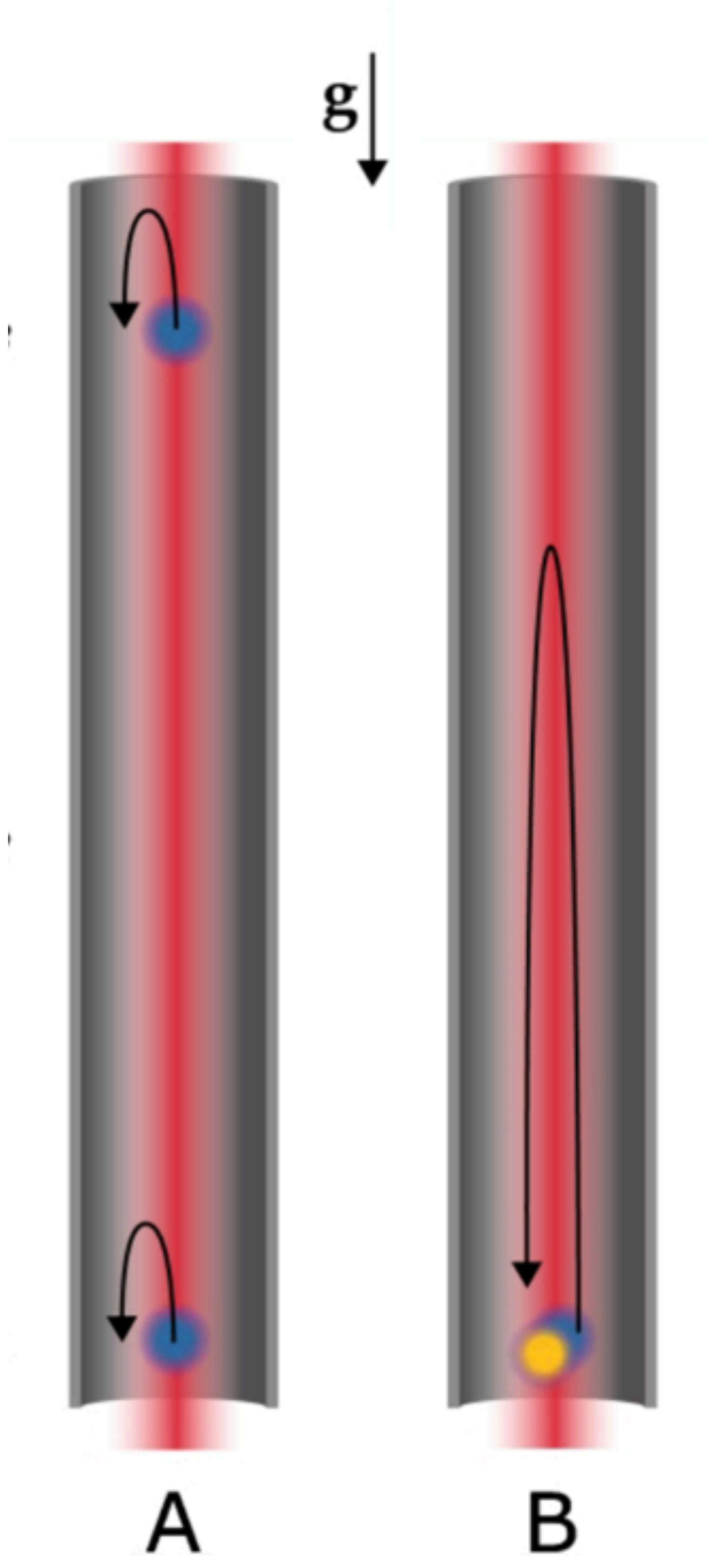


ω_2

Look for peak in Fourier spectrum at DM Compton frequency

$$\omega_\phi \simeq m_\phi \simeq \text{few Hz}\left(\frac{m_\phi}{10^{-15}\,\text{eV}}\right)$$

Derevianko + Pospelov (1311.1244)
Arvanitaki, Huang, Van Tilburg (1405.2925)
Stadnik + Flambaum (1412.7801, 1503.08540)



"New Horizons: Scalar and Vector Ultralight Dark Matter" (2203.14915)

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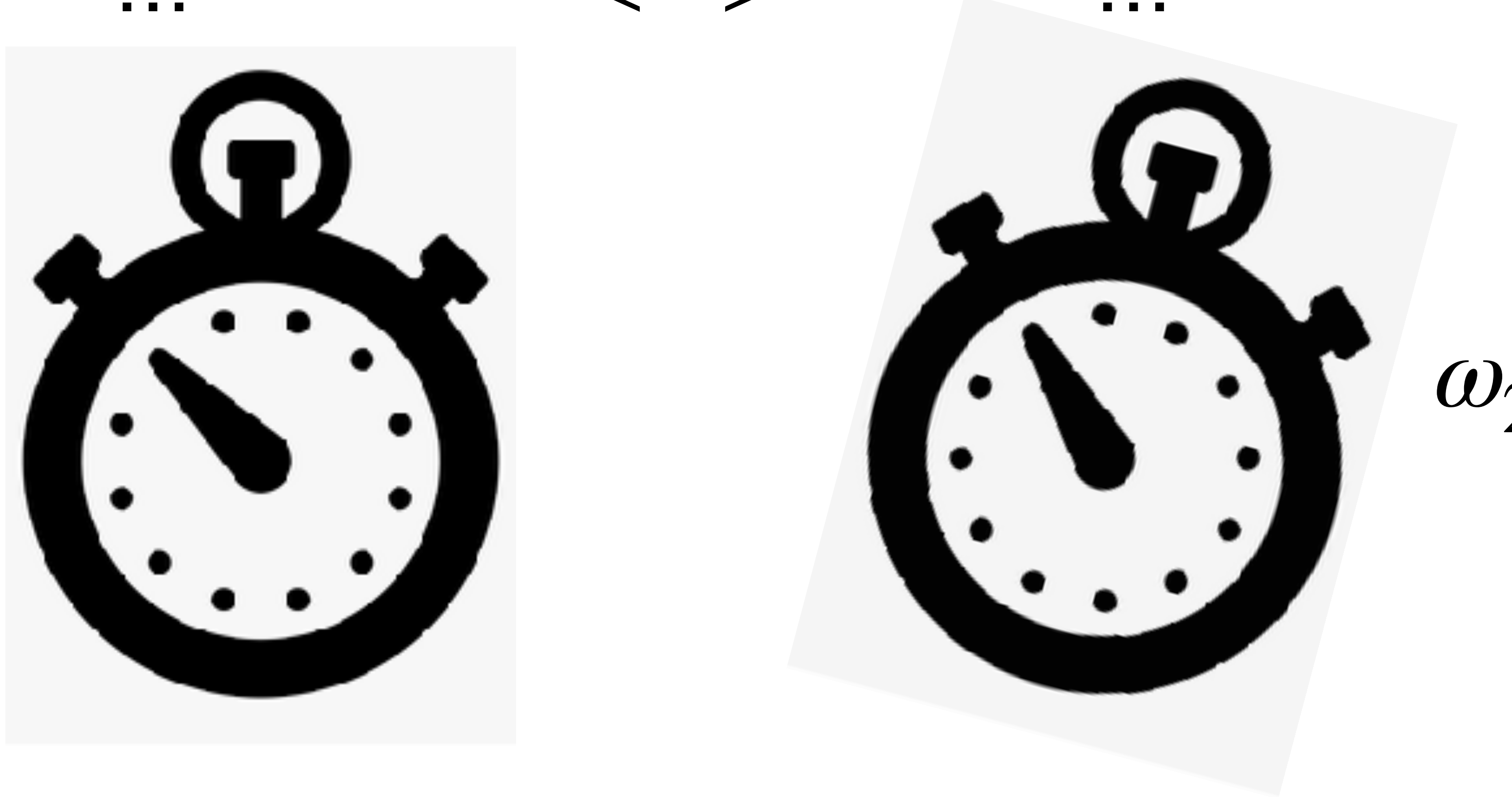
ω_1  ω_2

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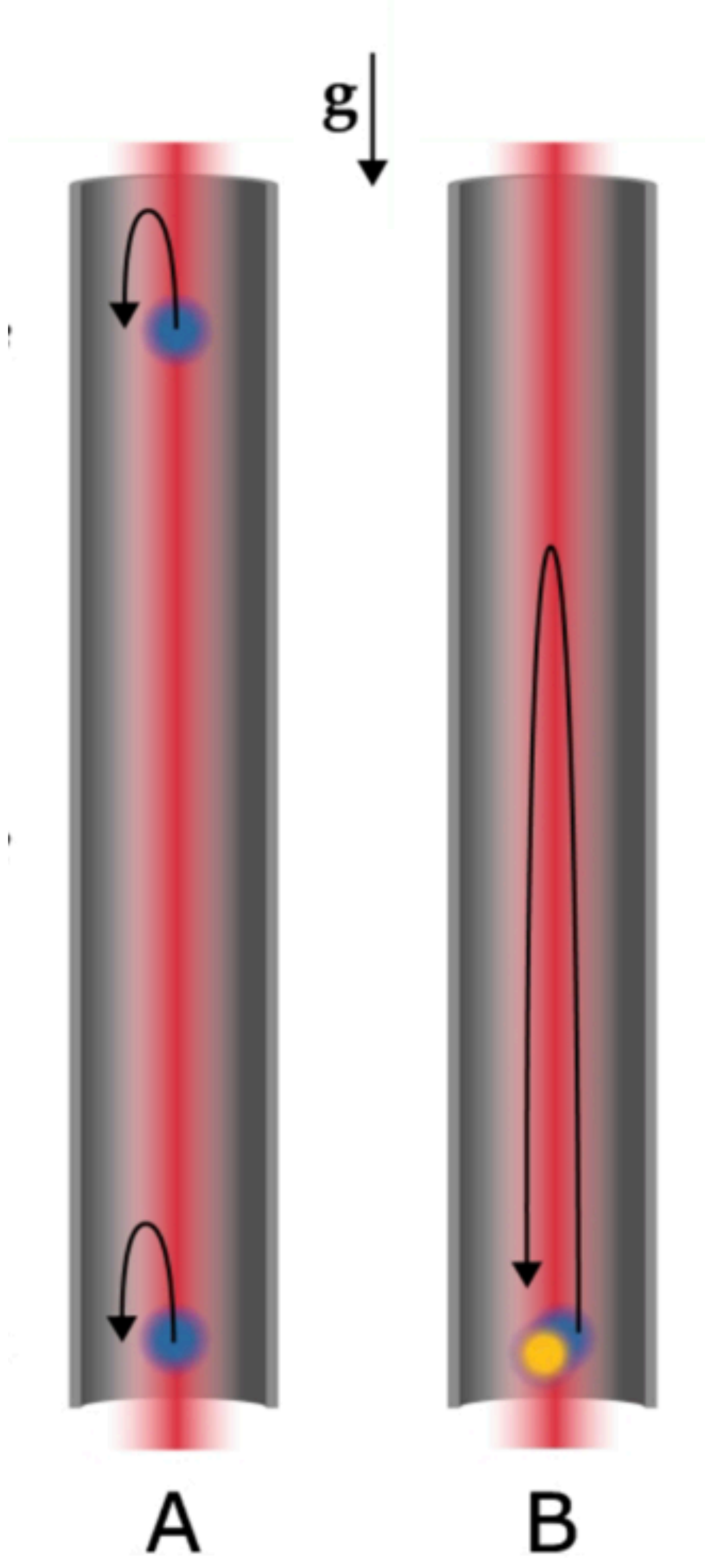


"New Horizons: Scalar and Vector Ultralight Dark Matter" (2203.14915)

(e.g.) ULDM-photon interaction

$$\mathscr{L} \supset d_e \frac{\phi}{2M_{\rm Pl}} F^{\mu\nu} F_{\mu\nu}$$

c.f. $\mathscr{L}_{\rm EM} \supset \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$

Leads to effective oscillation of fine-structure constant

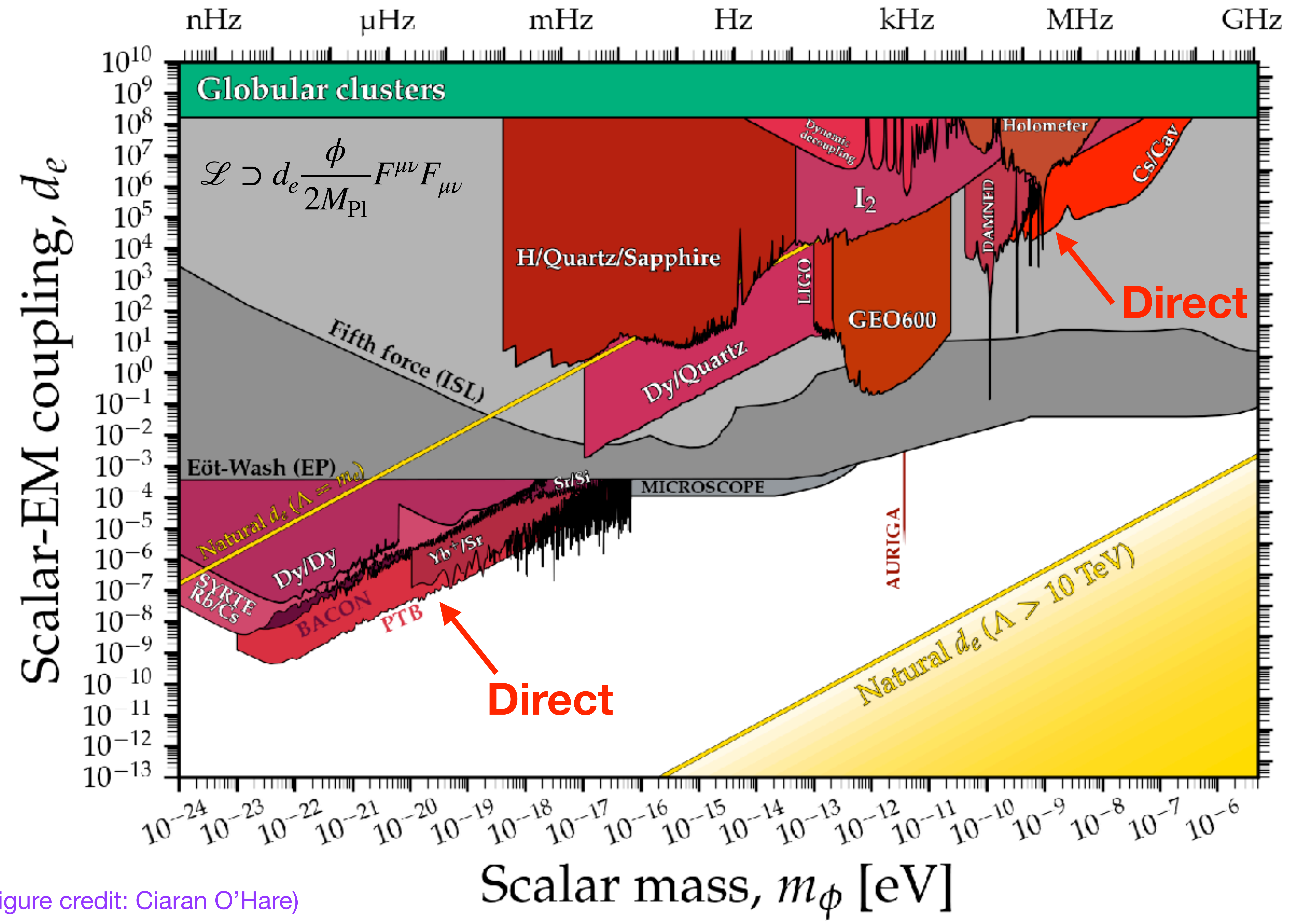
$$\alpha \rightarrow \alpha + \delta\alpha$$

with

$$\frac{\delta\alpha}{\alpha} \simeq \frac{d_e \phi}{M_{\rm Pl}}$$

$$\simeq 10^{-18} \left(\frac{d_e}{10^{-2}} \right) \left(\frac{\rho}{\rho_{\rm dm}} \right)^{1/2} \left(\frac{10^{-15}\,\text{eV}}{m_\phi} \right)$$

Current Status



(figure credit: Ciaran O'Hare)

Direct searches depend critically on DM properties near Earth: density $\rho_{\rm dm}$ and velocity dispersion $v_{\rm dm}$

along with the frequency of the incoming ULDM field ω_ϕ

Many such searches ongoing, well-established techniques

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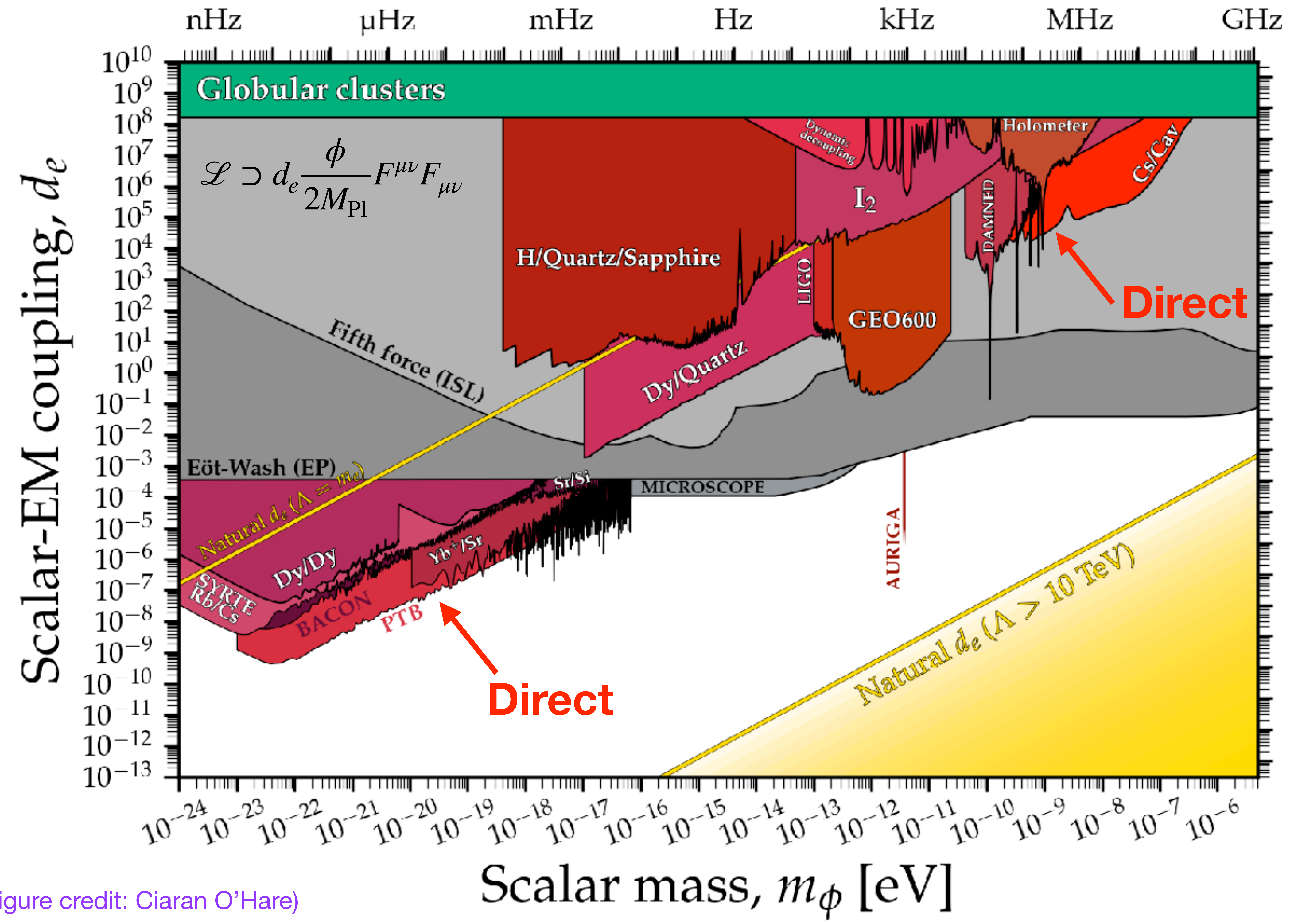

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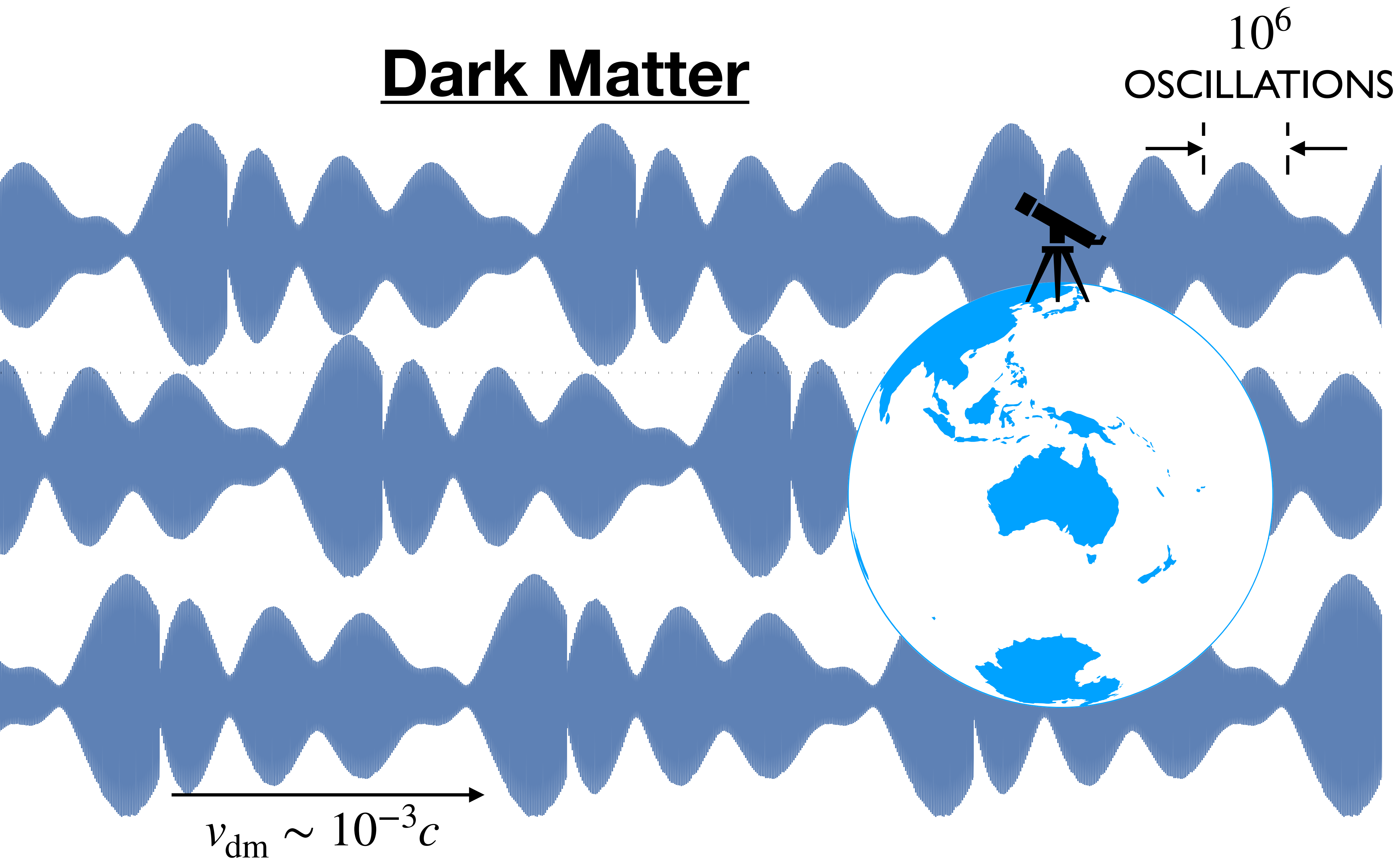
Can we use these techniques to probe ULDM with even greater sensitivity, including at high frequency $\gtrsim$ mHz ?

Beyond (mere) cold DM:

Relativistic bursts of ULDM

Dark Matter

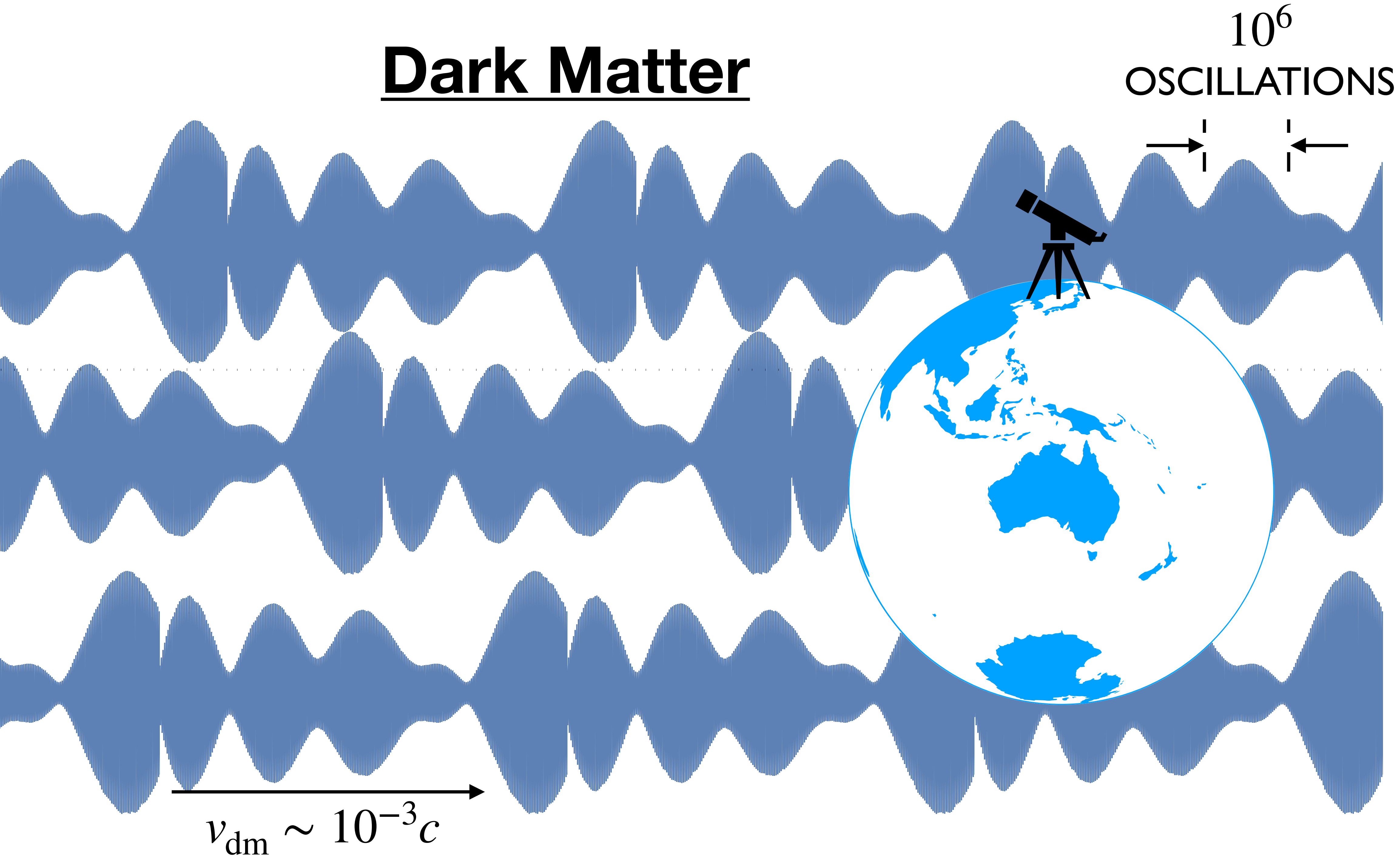


Local DM density: $\rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$

Ultralight scalars are high 'quality' oscillators: $v_{\rm dm} \simeq 10^{-3}c$

$\tau_{\rm dm} \sim 2\pi v_{\rm dm}^{-2} m_\phi^{-1} \sim 10^6/m_\phi$

Dark Matter



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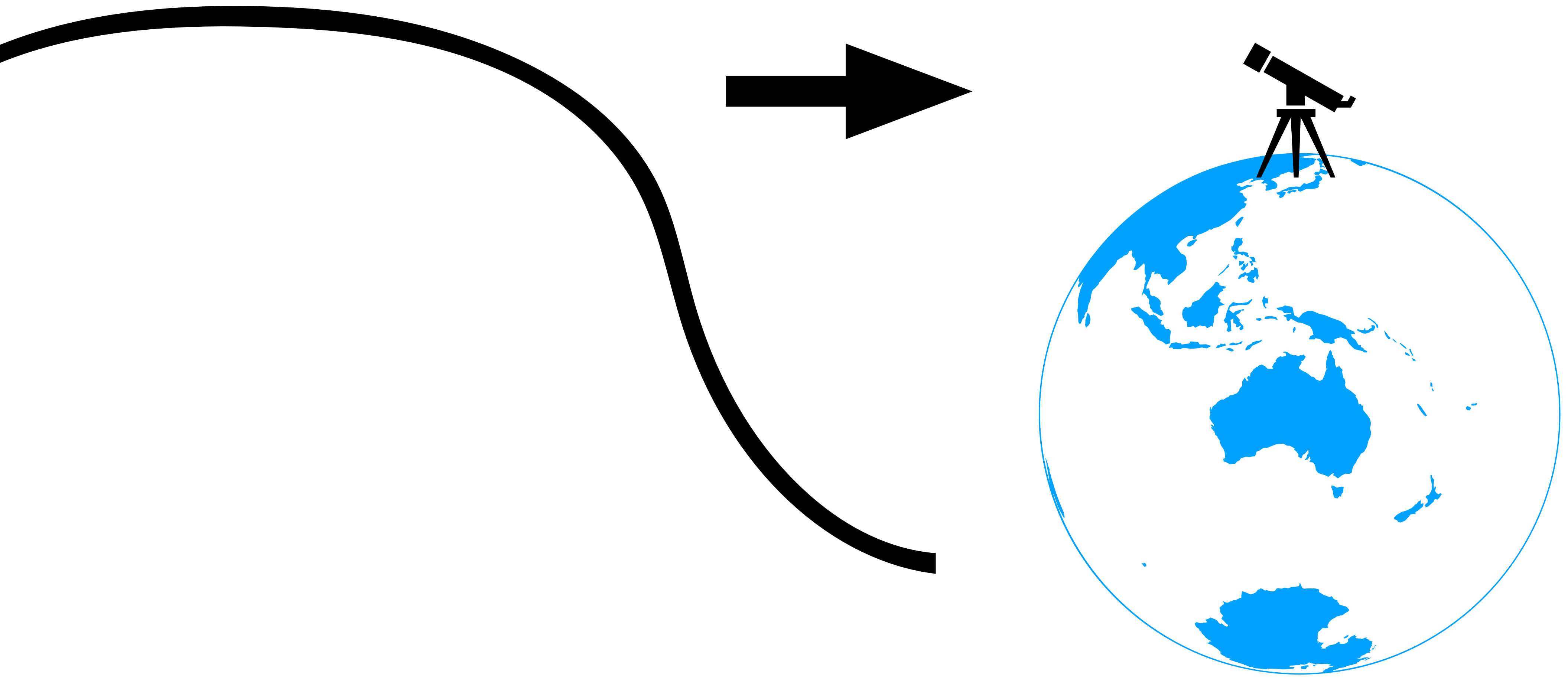
Relativistic Burst



Burst density: $\rho_* \sim ?$

Relativistic velocity: $v_* \simeq c$

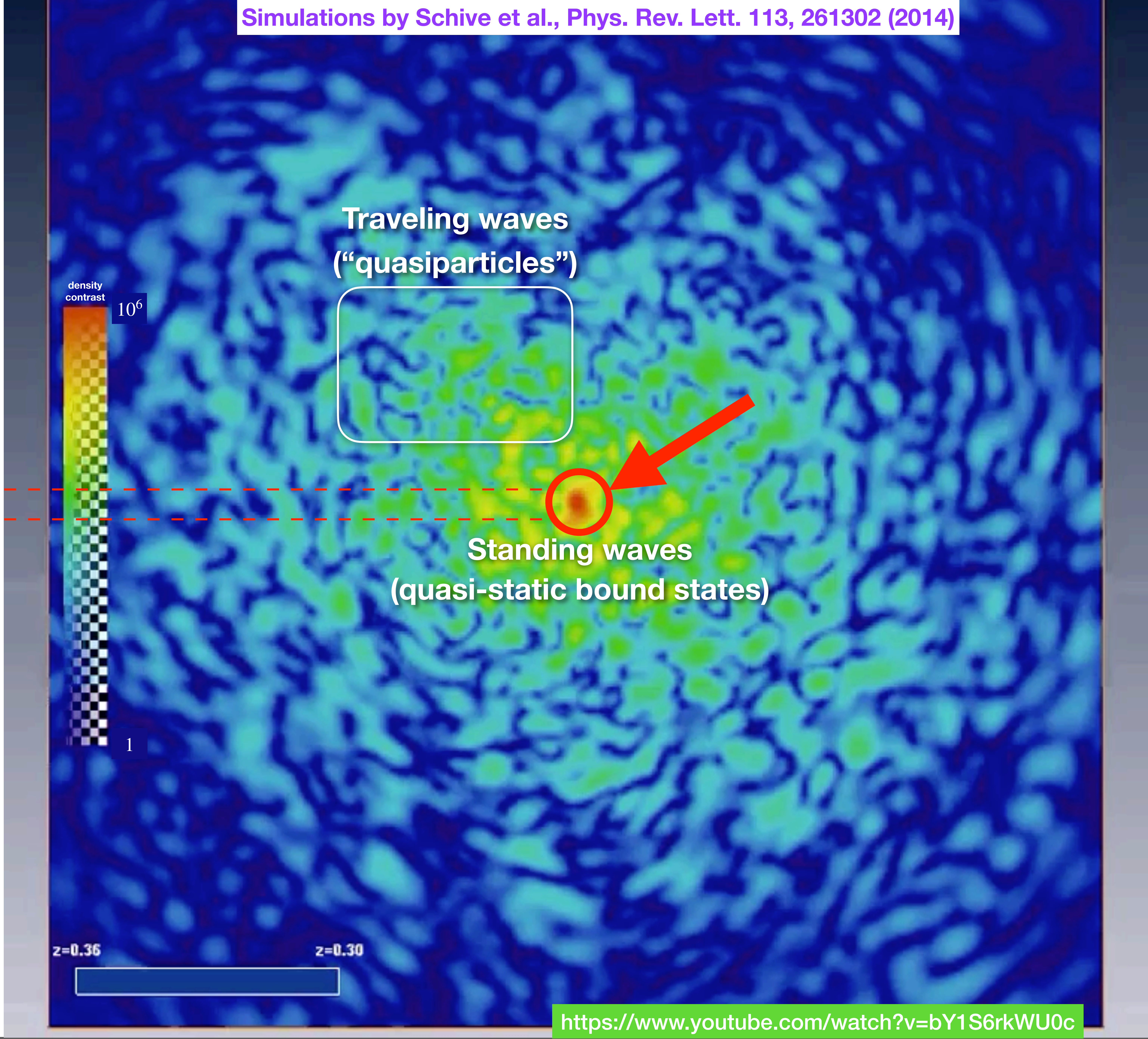
$\tau_* \sim ?$
coherence?

$\delta t \sim ?$
duration?

Sensitivity?

Bound States

$\lambda_{\rm dB}$



The standing wave patterns correspond to extremely dense configurations, $\rho \gg \rho_{\rm dm}$

Can source novel signals!

Bound States

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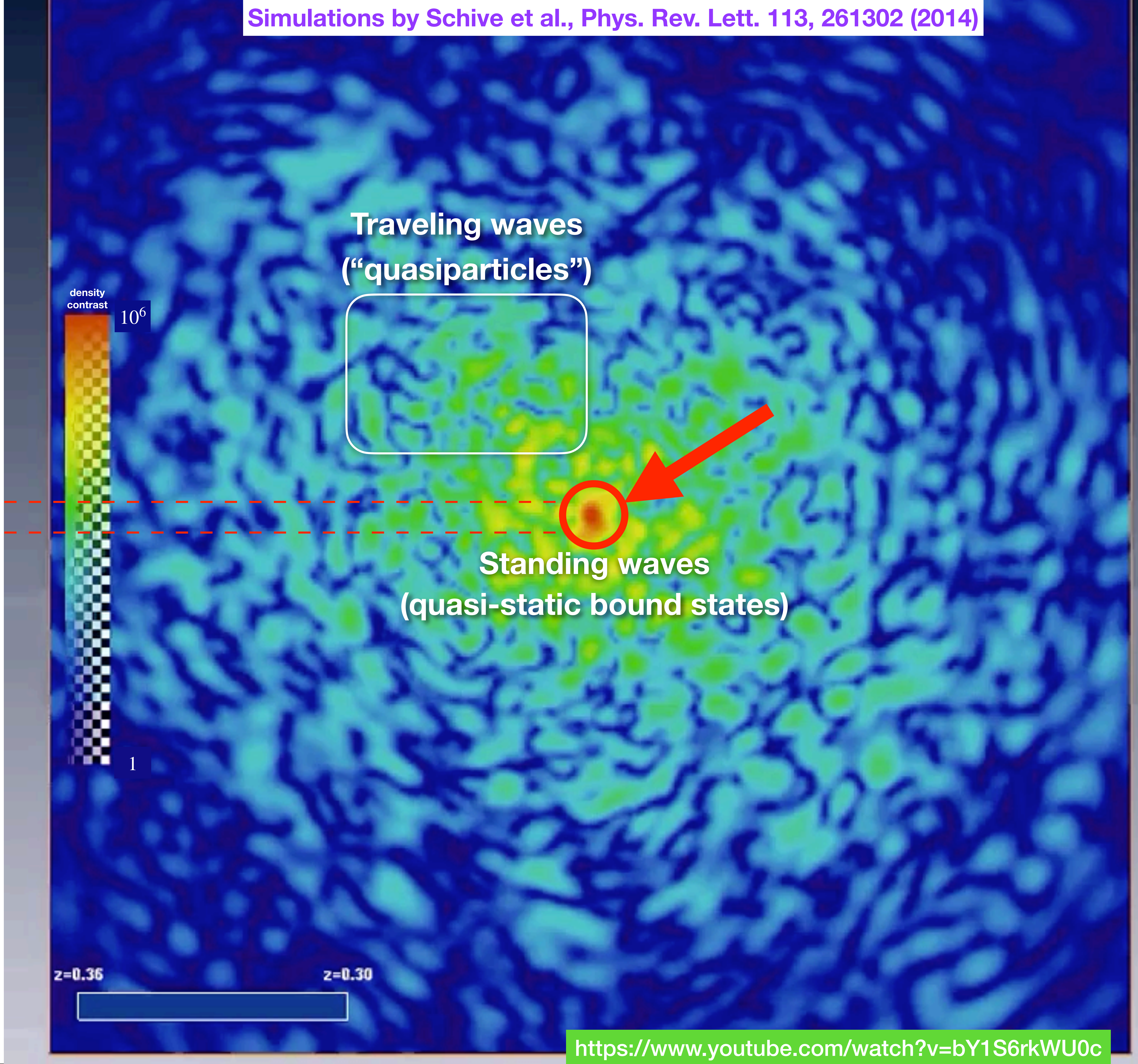

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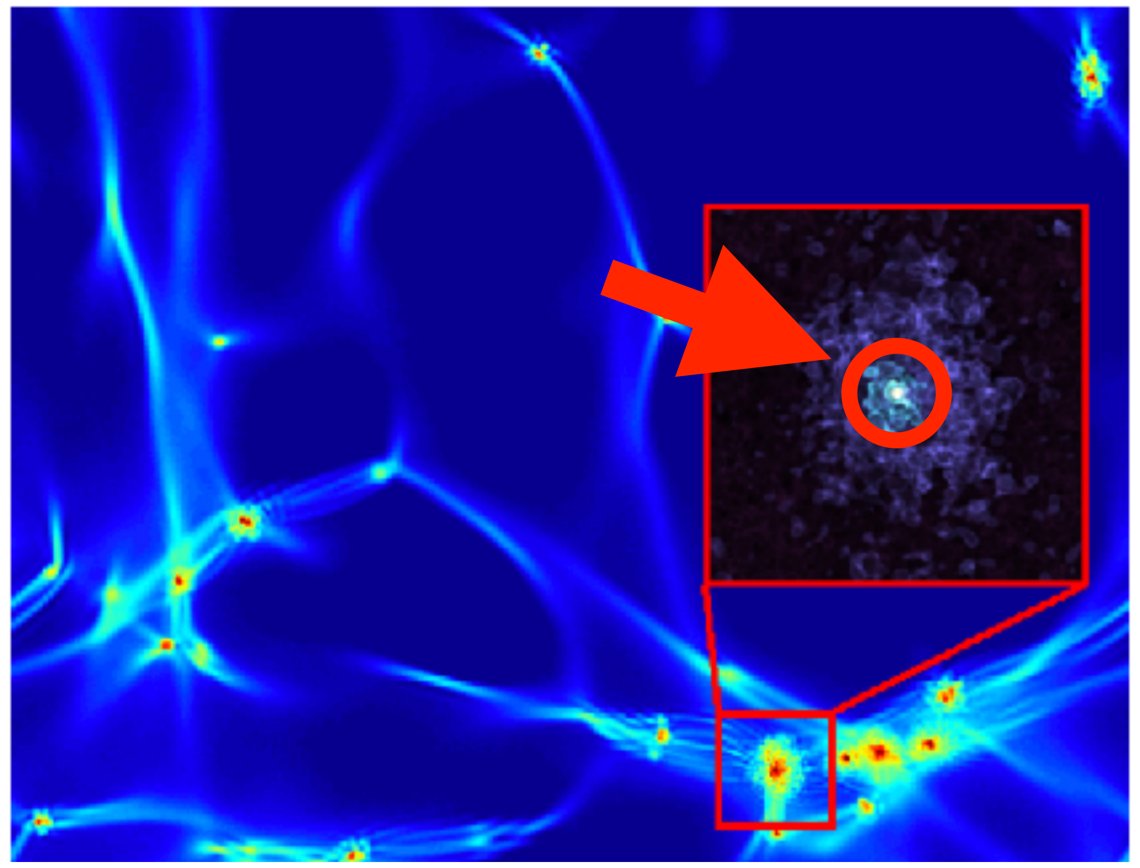
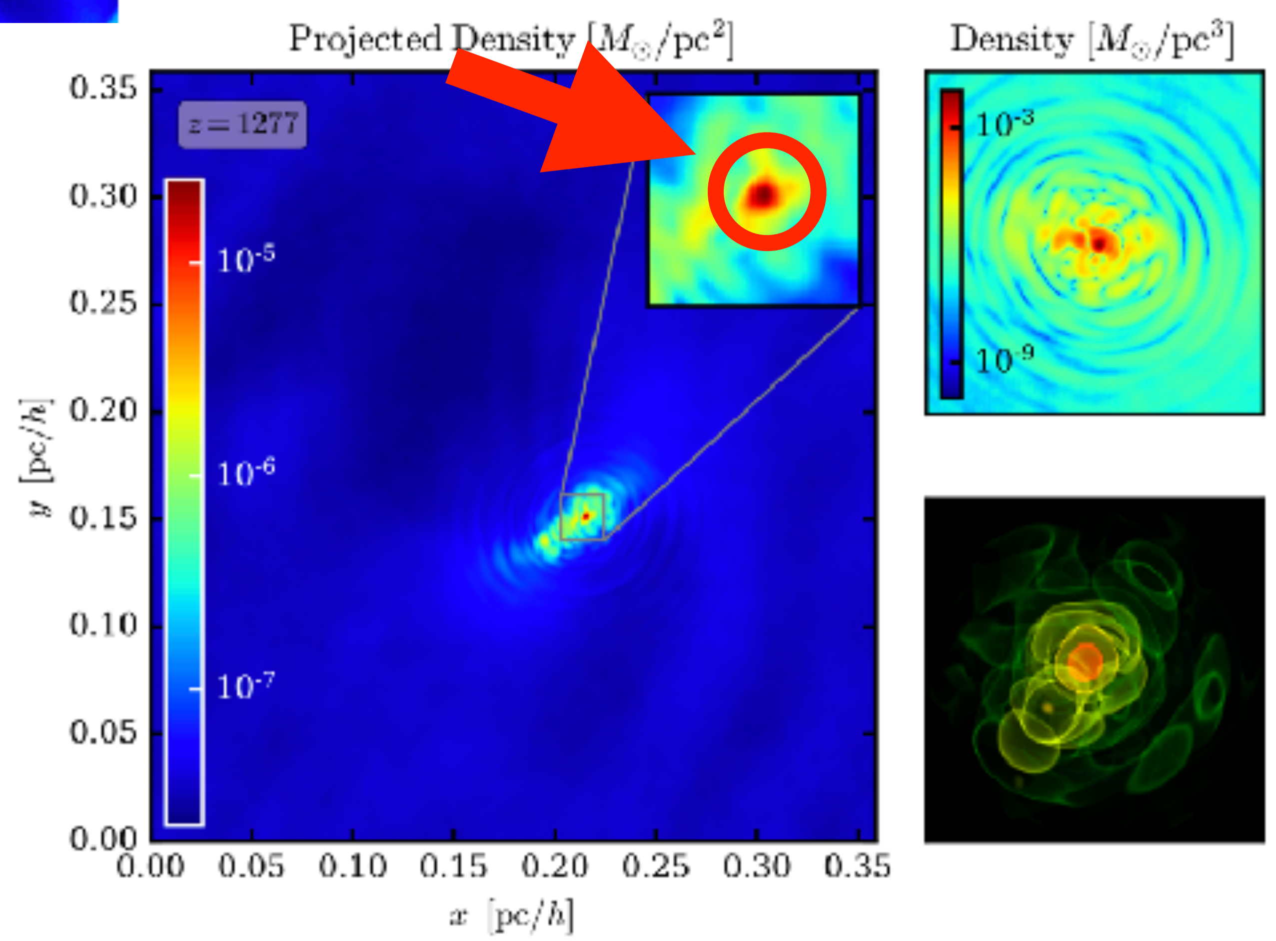


Mocz et al. (1705.05845)

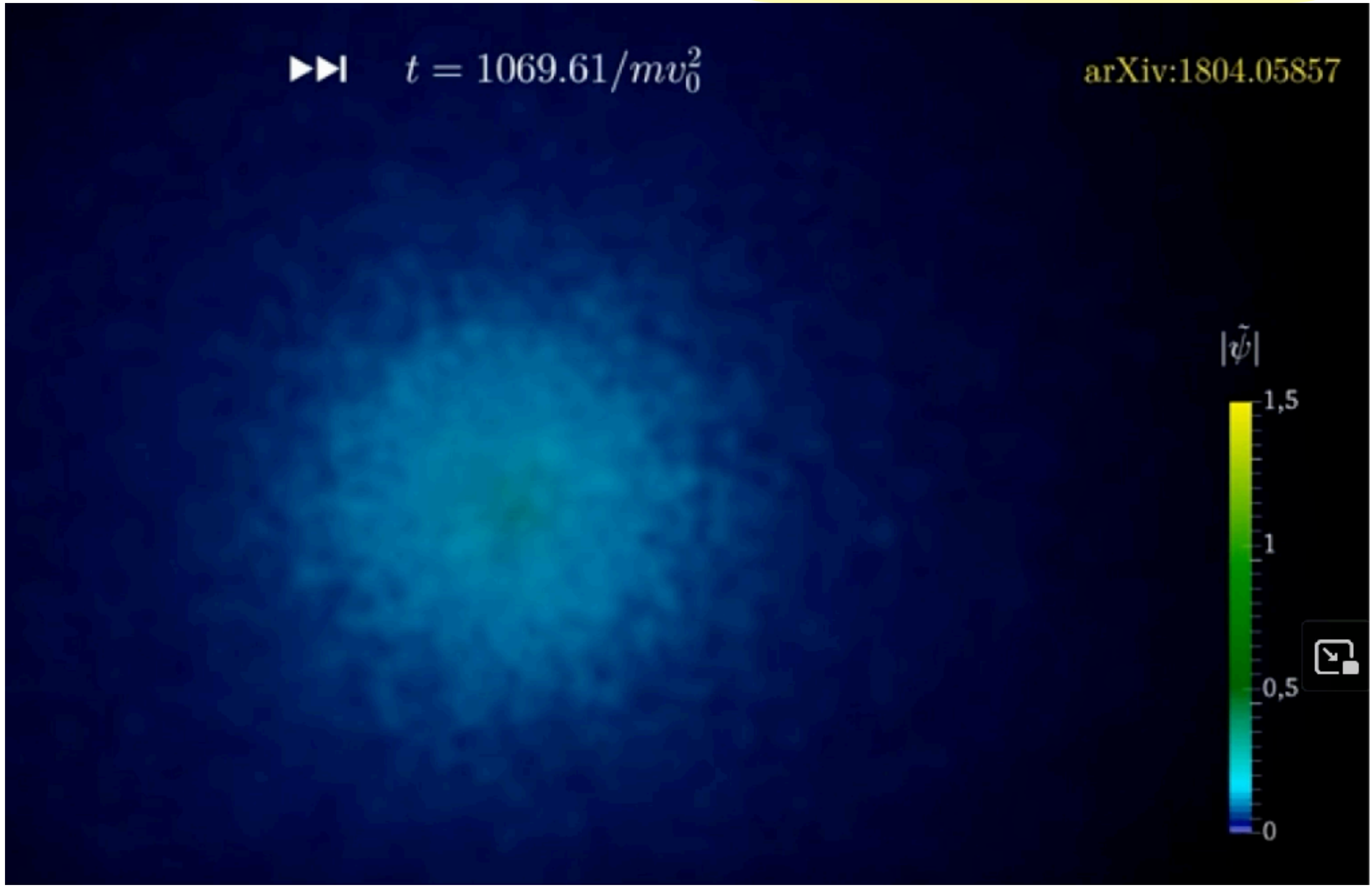
Boson Stars

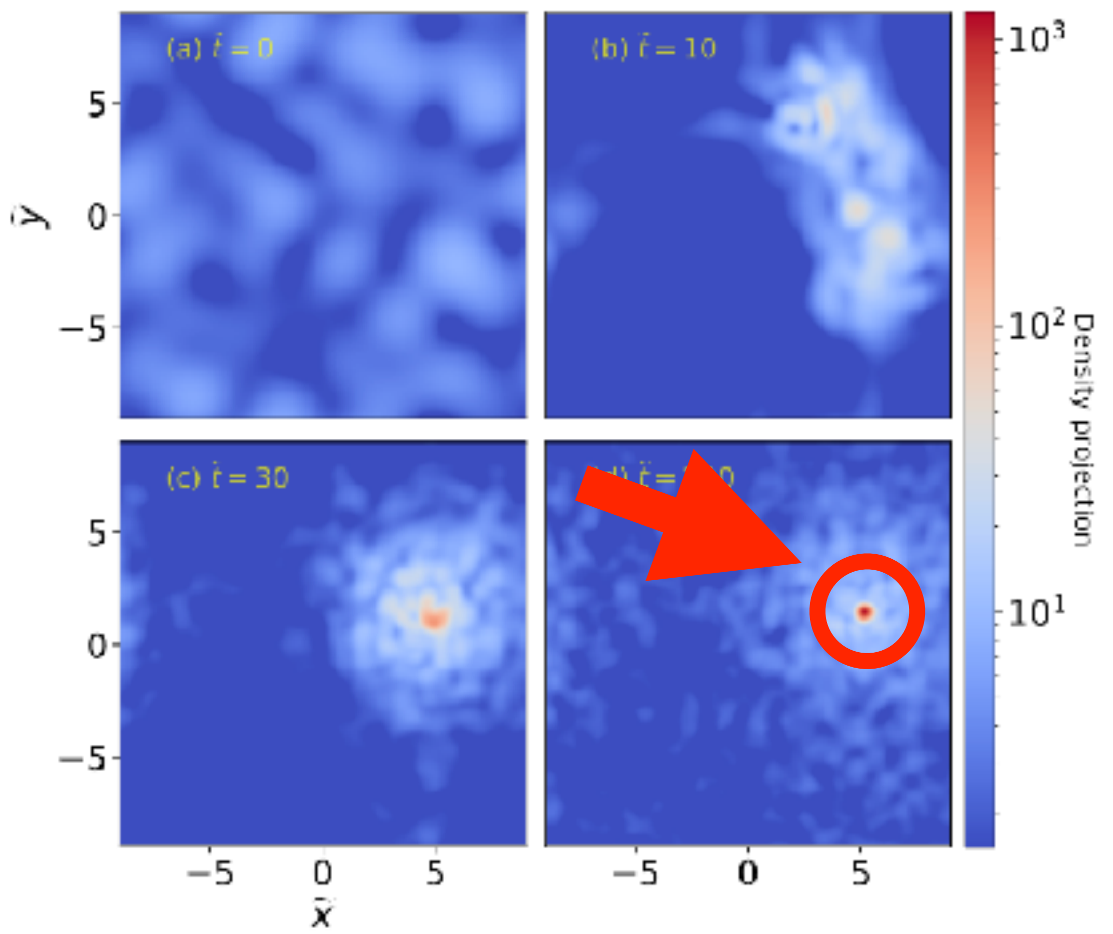
Gravitationally-bound, dense configuration formed from $N \gg 1$ ULDM particles

Can also be understood as…
- ***standing wave pattern***
- ***ground state of eq. of motion***
- ***Bose-Einstein condensate***



Eggemeier and Niemeyer (1906.01348)





Chen et al. (2011.01333)

(among others!)

Levkov, Panin, Tkachev (1804.05857)
Video via Alexander Panin on YouTube

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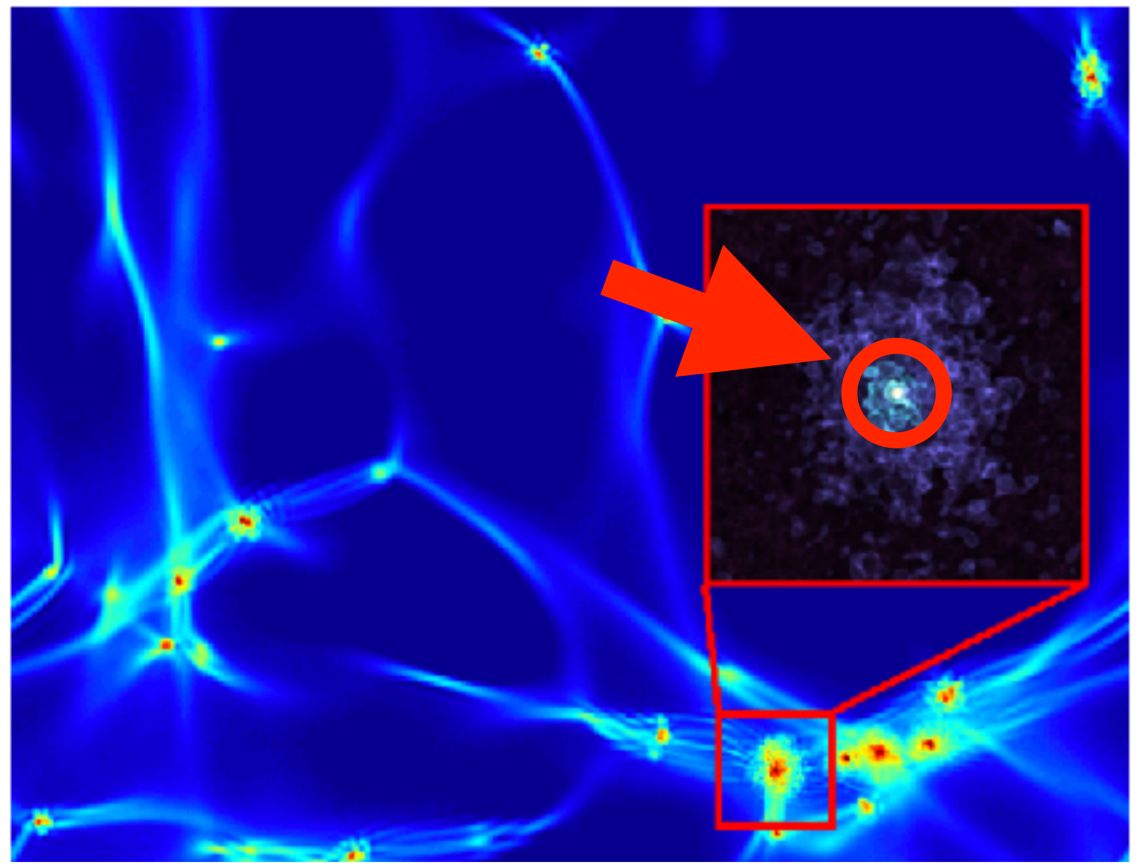

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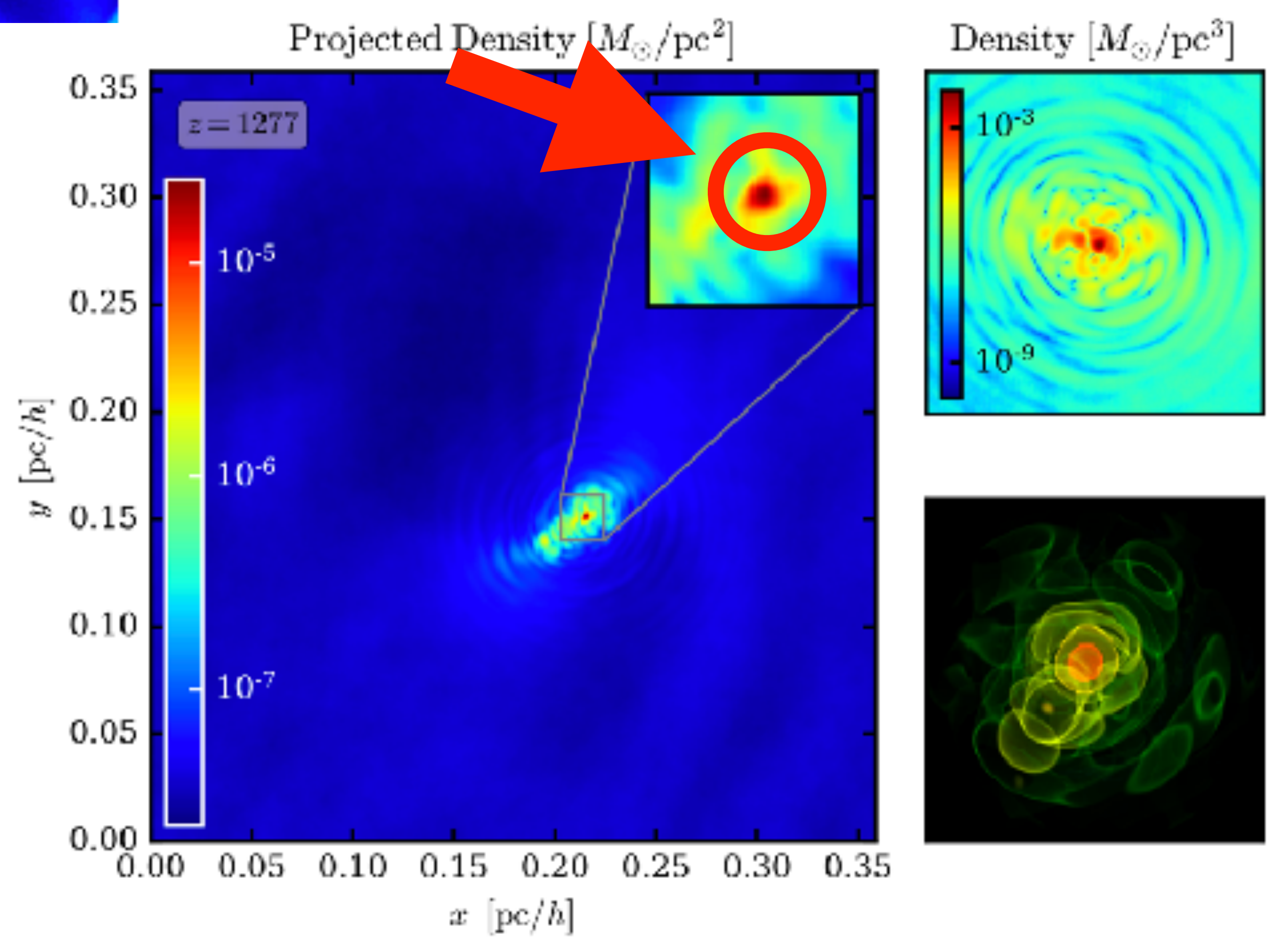

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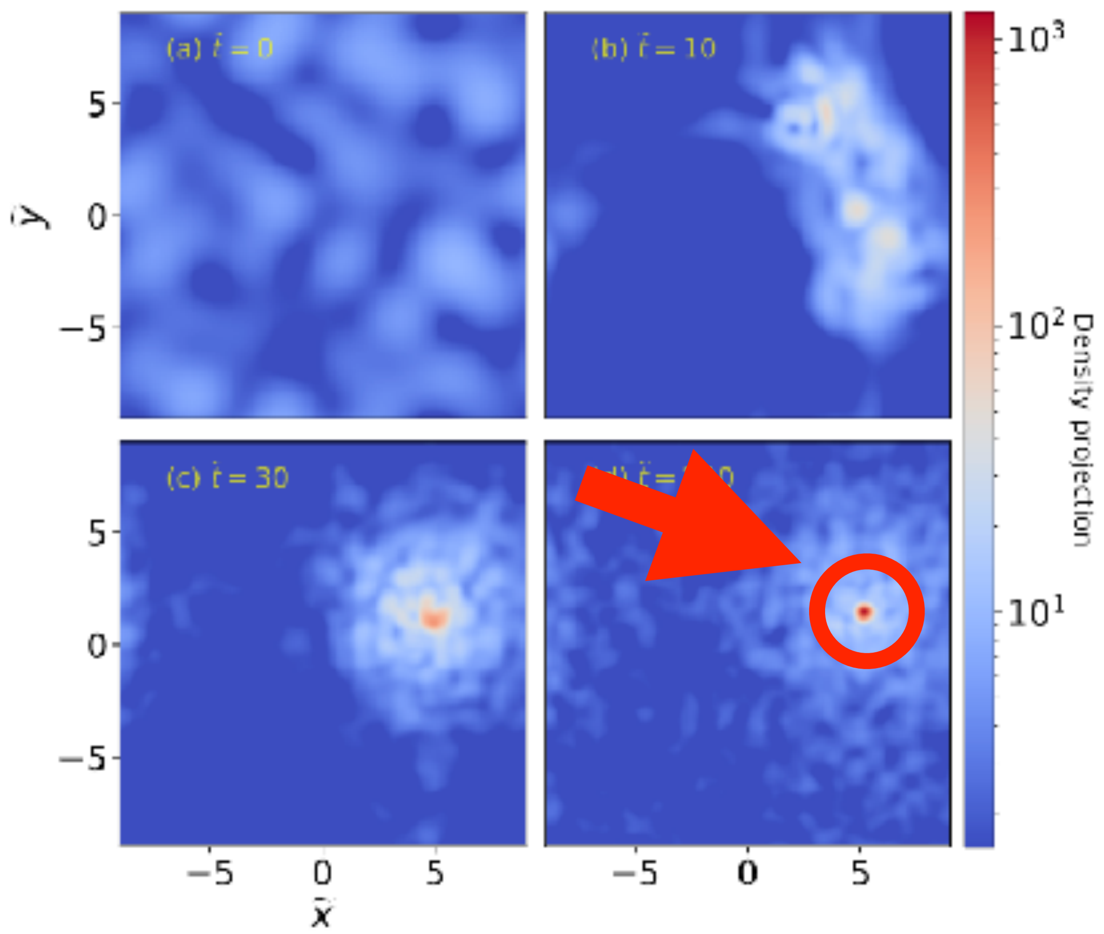

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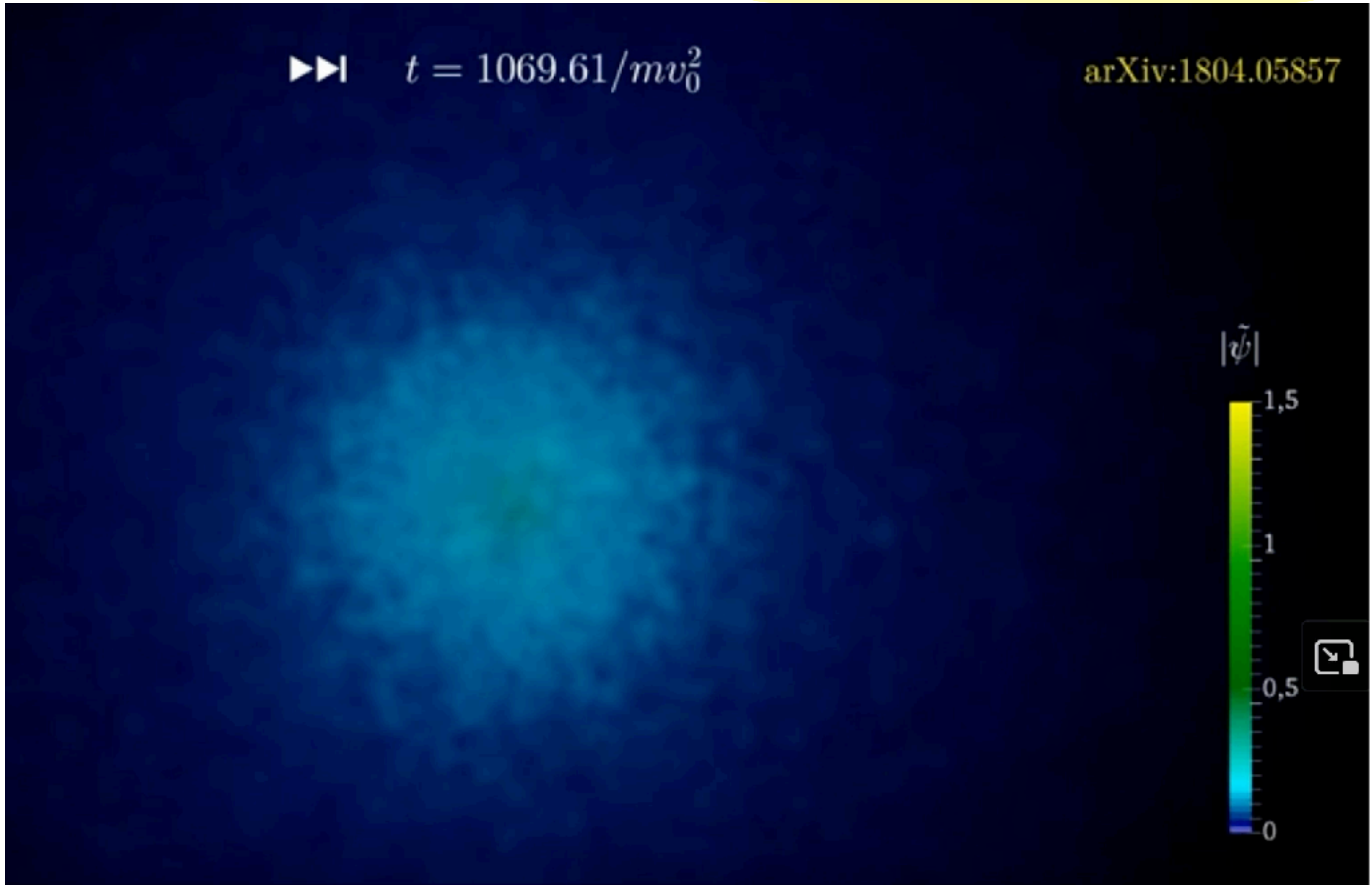

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Equations of Motion

$$\mathscr{L}_\phi \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda}{4!}\phi^4 - \ldots$$

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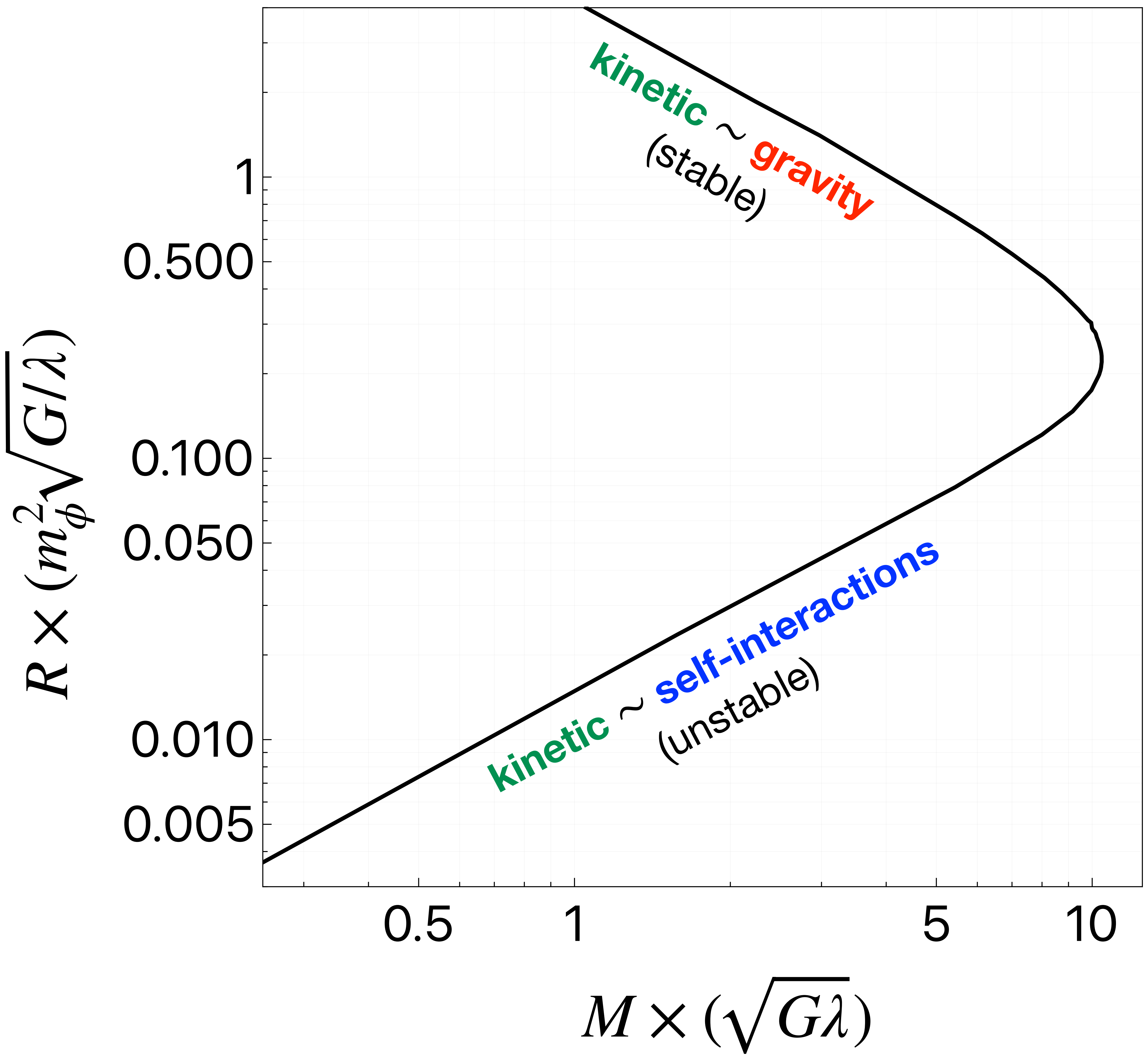
ULDM is
- non-relativistic
- classical field
- gravitating

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + V_g\left(|\psi|^2\right) + V_{int}\left(|\psi|^2\right)\right]\psi$$

Boson star:
ground state of Schrödinger eq. with self-gravity

kinetic	gravity	self-interactions
$\propto \frac{1}{m_\phi R^2}$	$\propto -\frac{G m_\phi M}{R}$	$\propto -\frac{\lambda M}{m_\phi^3 R^3} + \dots$



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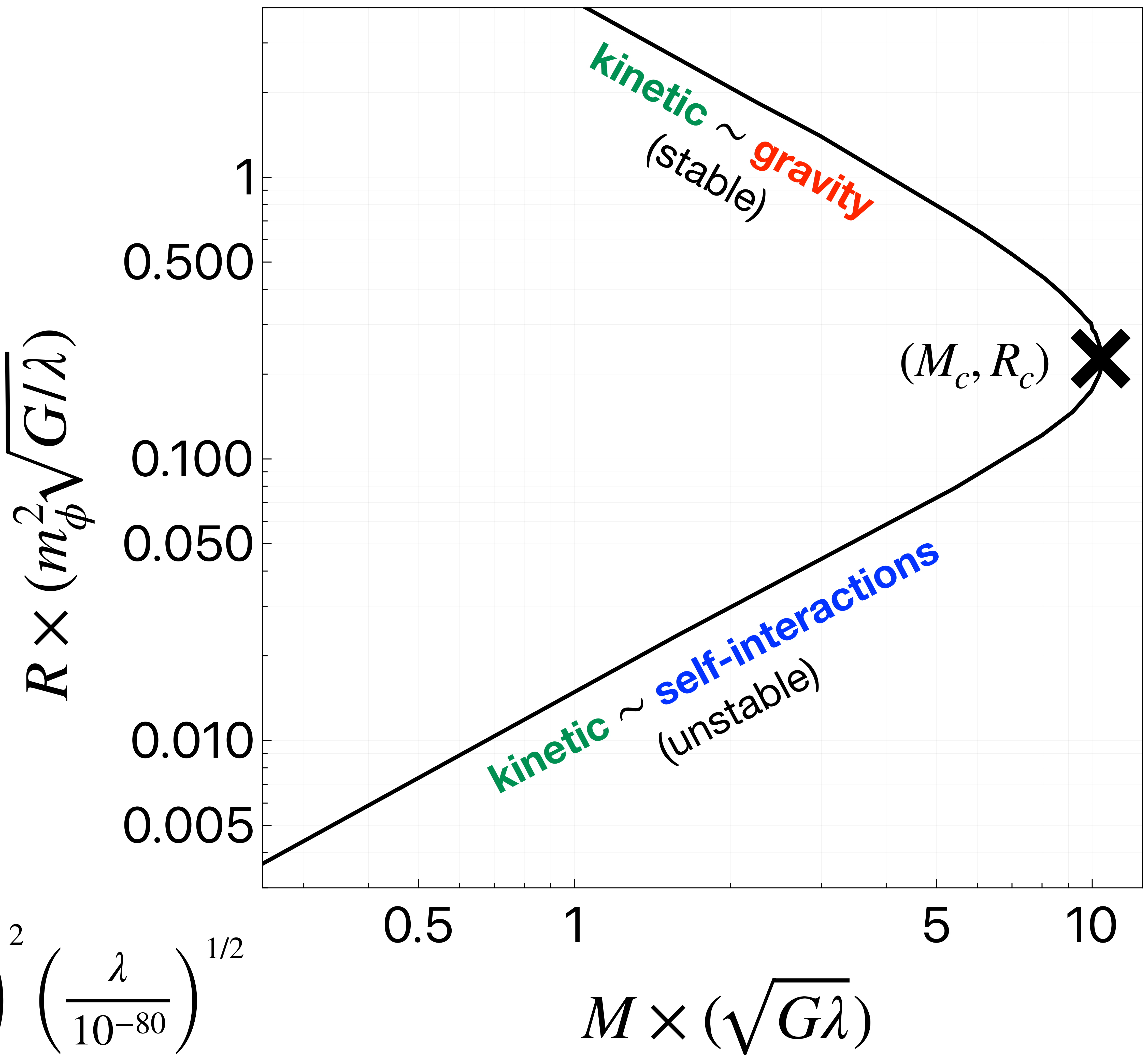
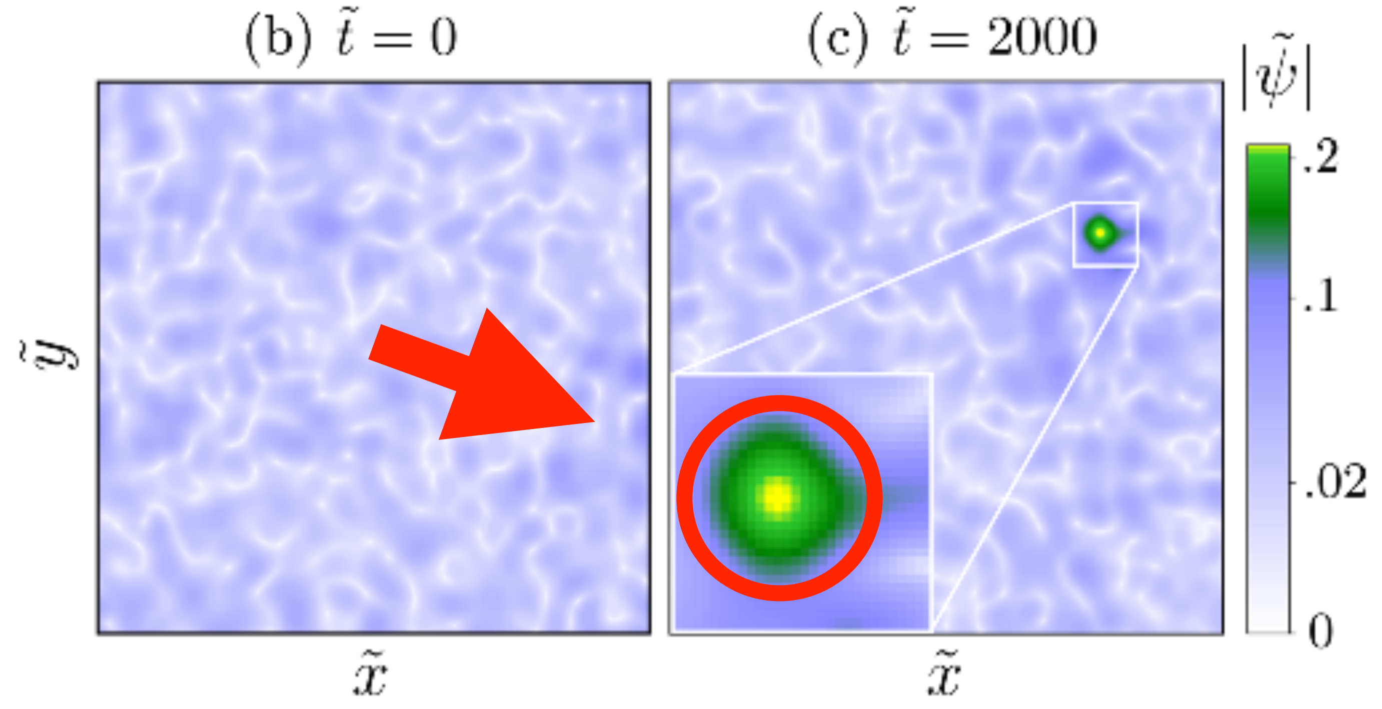
$$M_c \simeq \frac{10}{\sqrt{G\lambda}} \simeq 10^3 M_\odot \left(\frac{10^{-80}}{\lambda}\right)^{1/2}$$

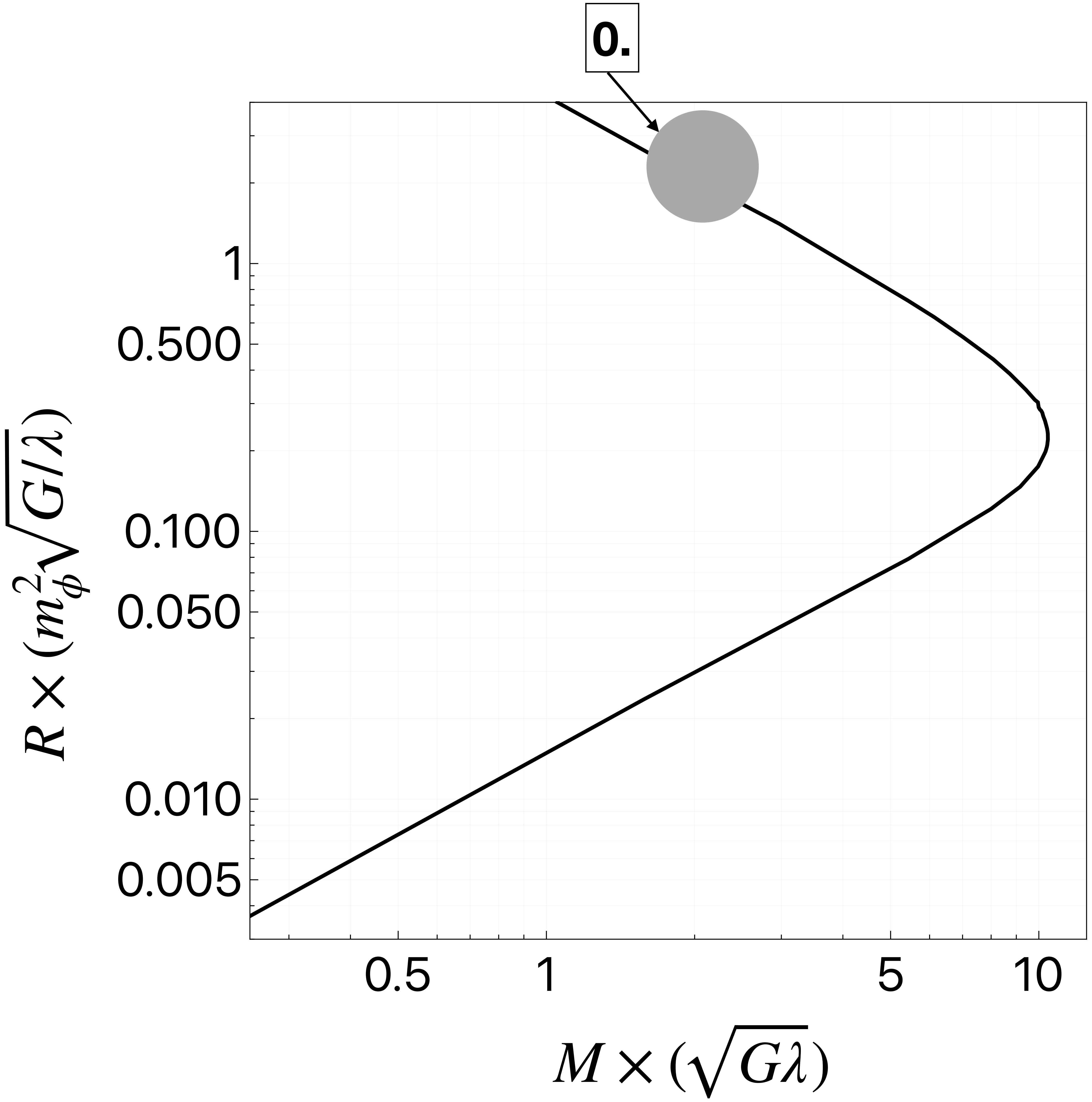
$$R_c \simeq \frac{0.2}{m_\phi^2}\sqrt{\frac{\lambda}{G}} \simeq 70\,R_\odot \left(\frac{10^{-15}\,\text{eV}}{m_\phi}\right)^2 \left(\frac{\lambda}{10^{-80}}\right)^{1/2}$$



Life Cycle of a Boson Star

0. Birth





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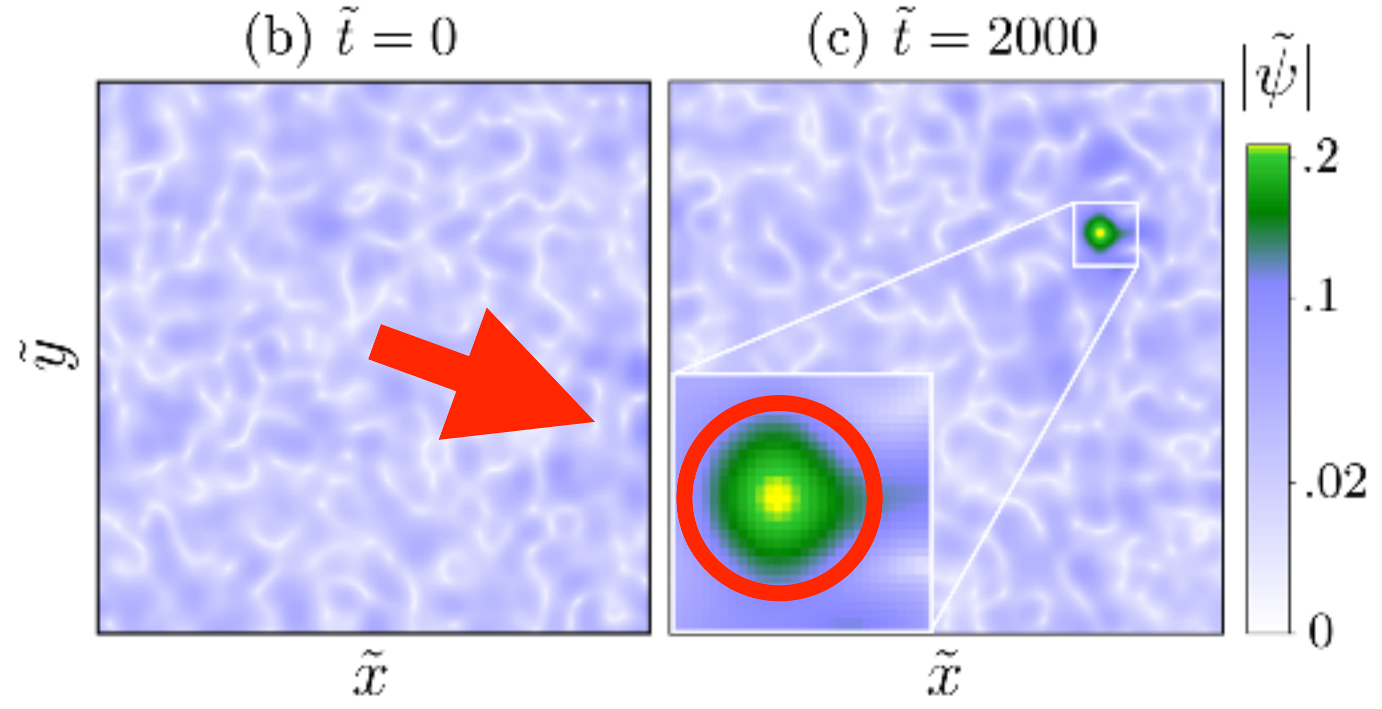
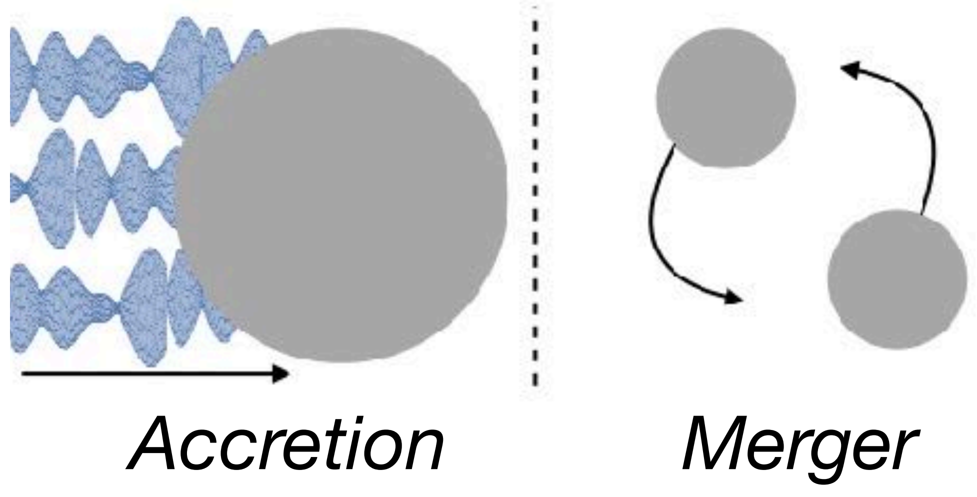
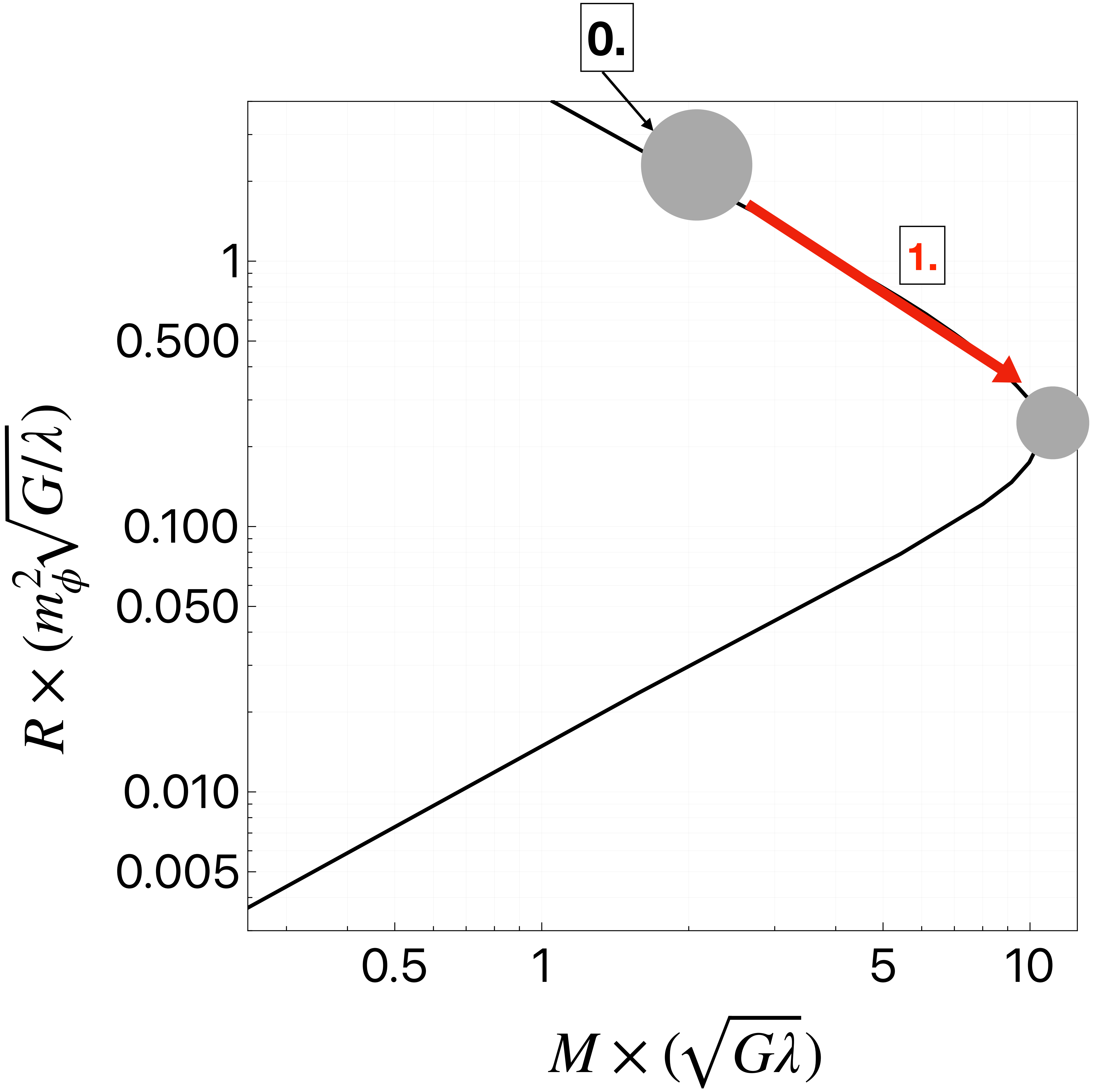


1. Growing up





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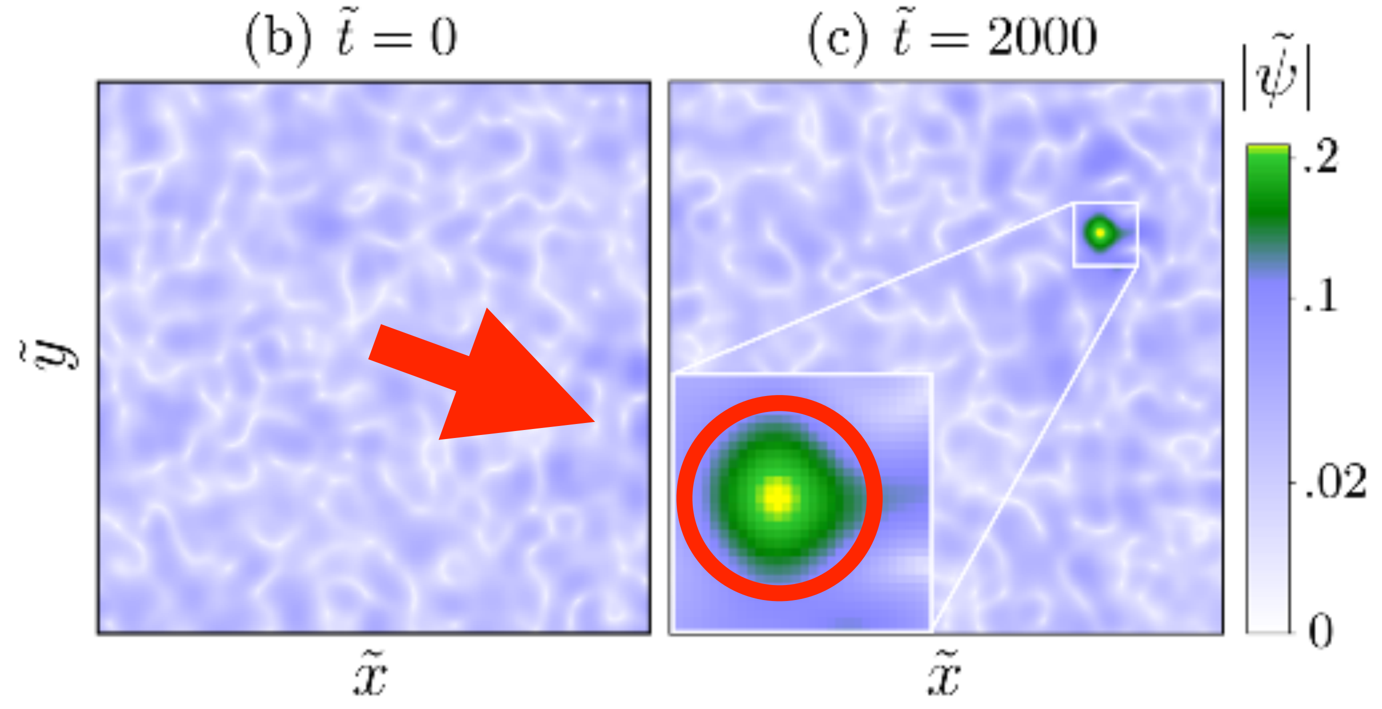

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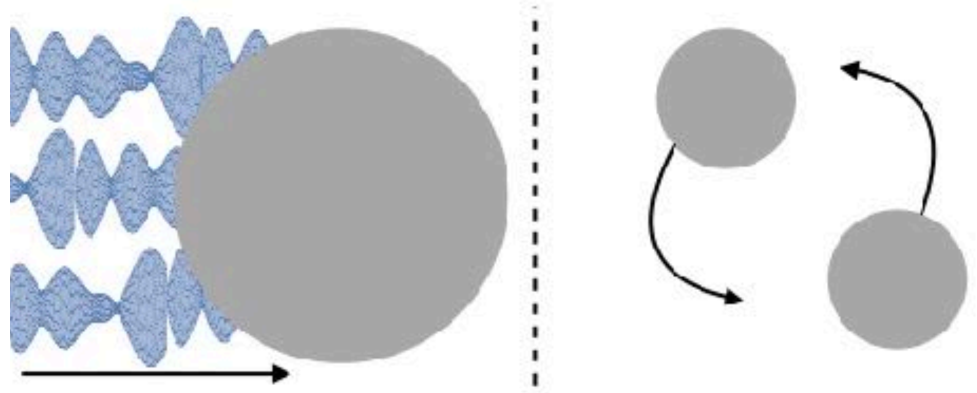
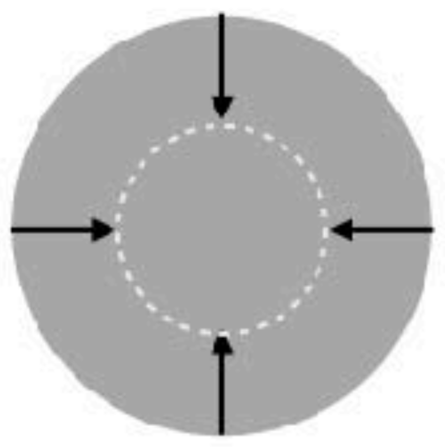
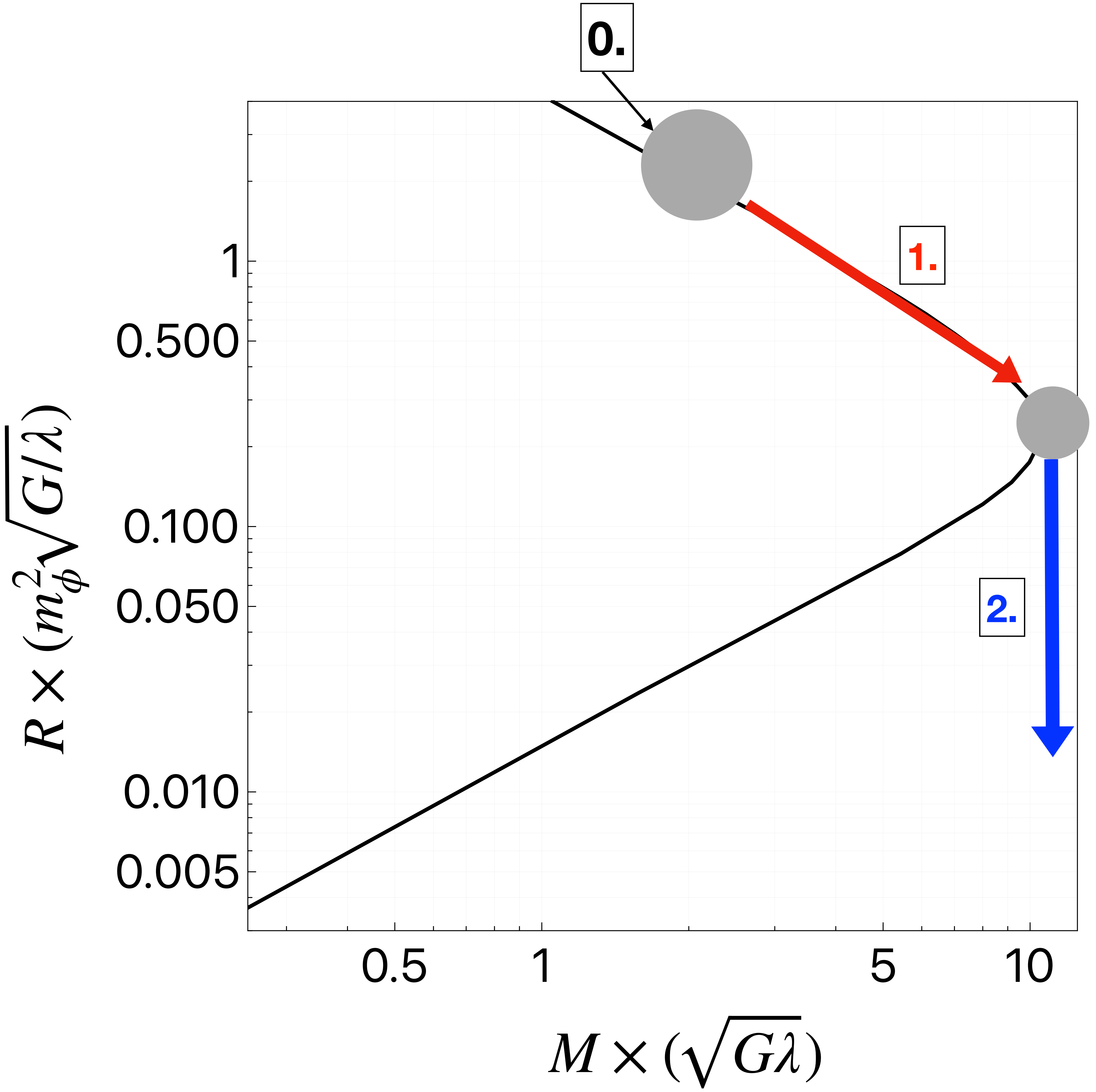


2. Gravitational collapse





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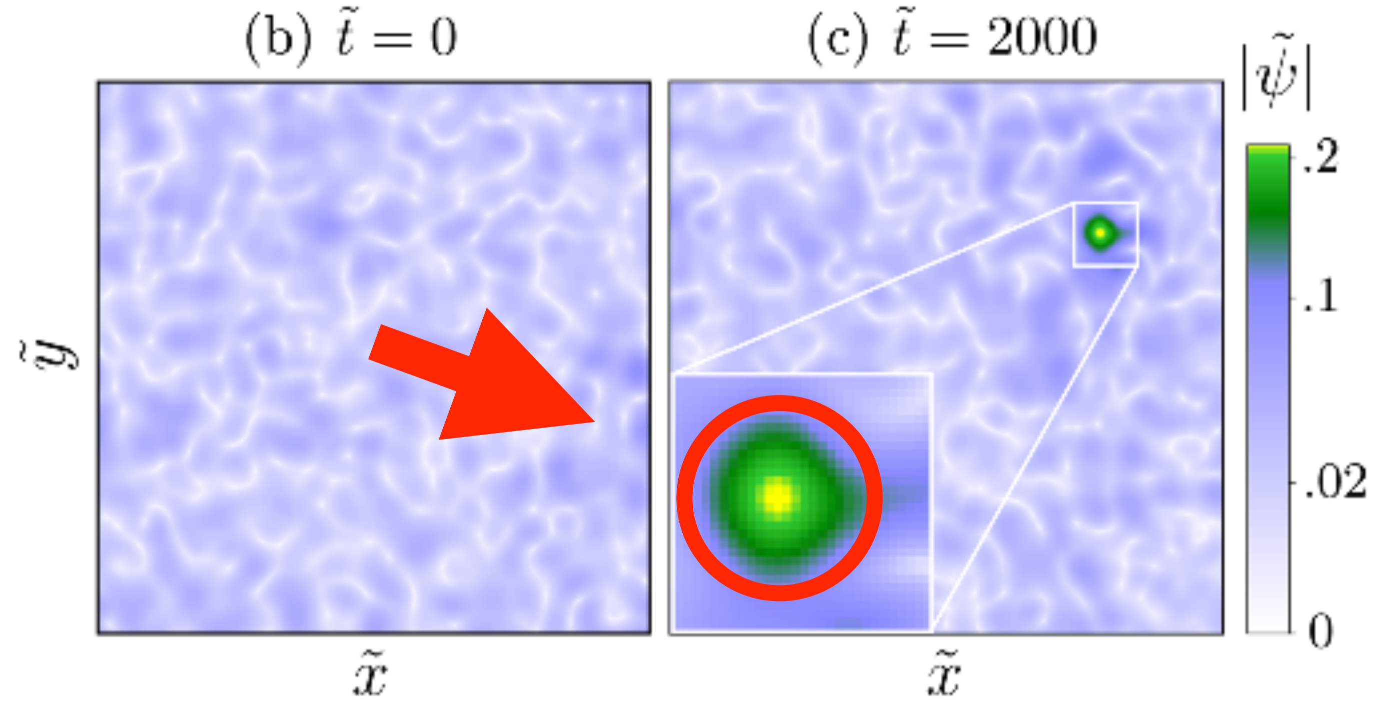

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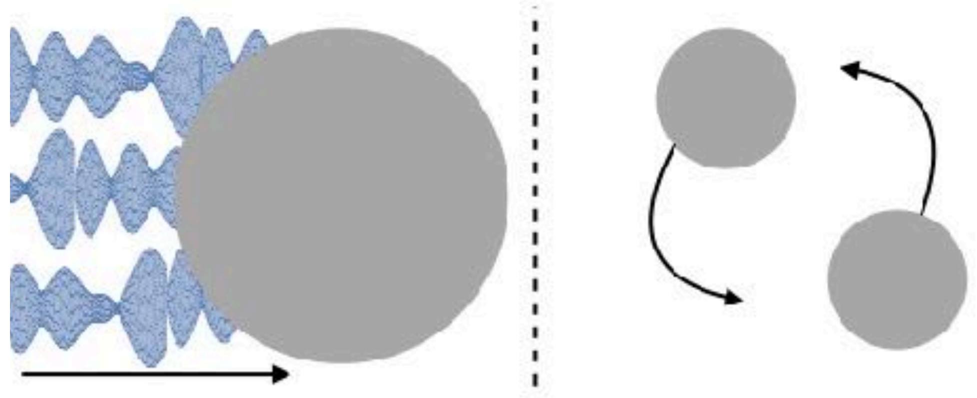

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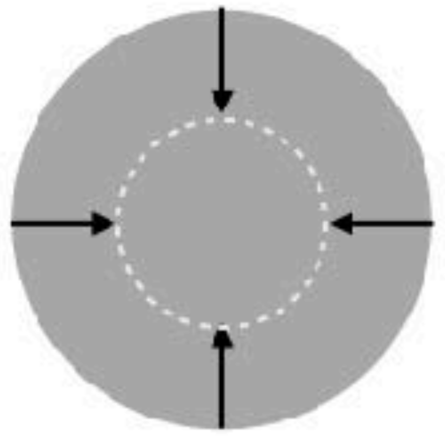
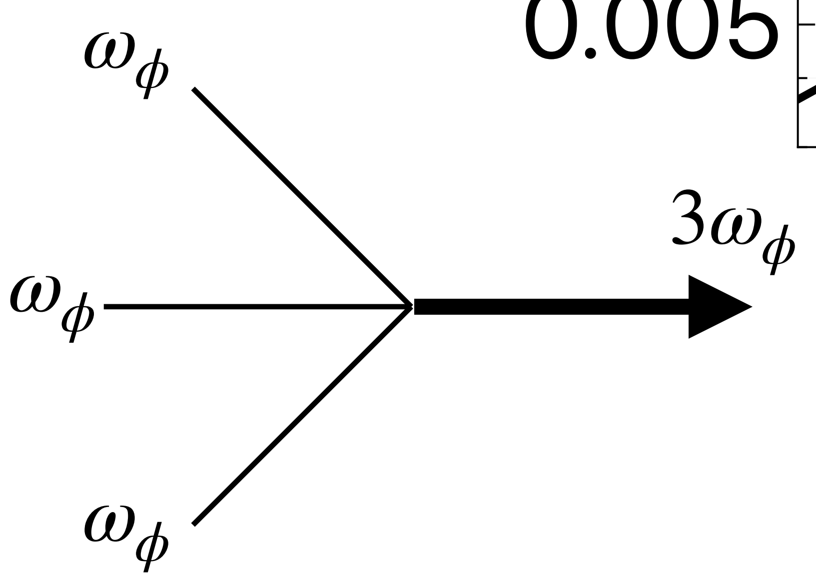
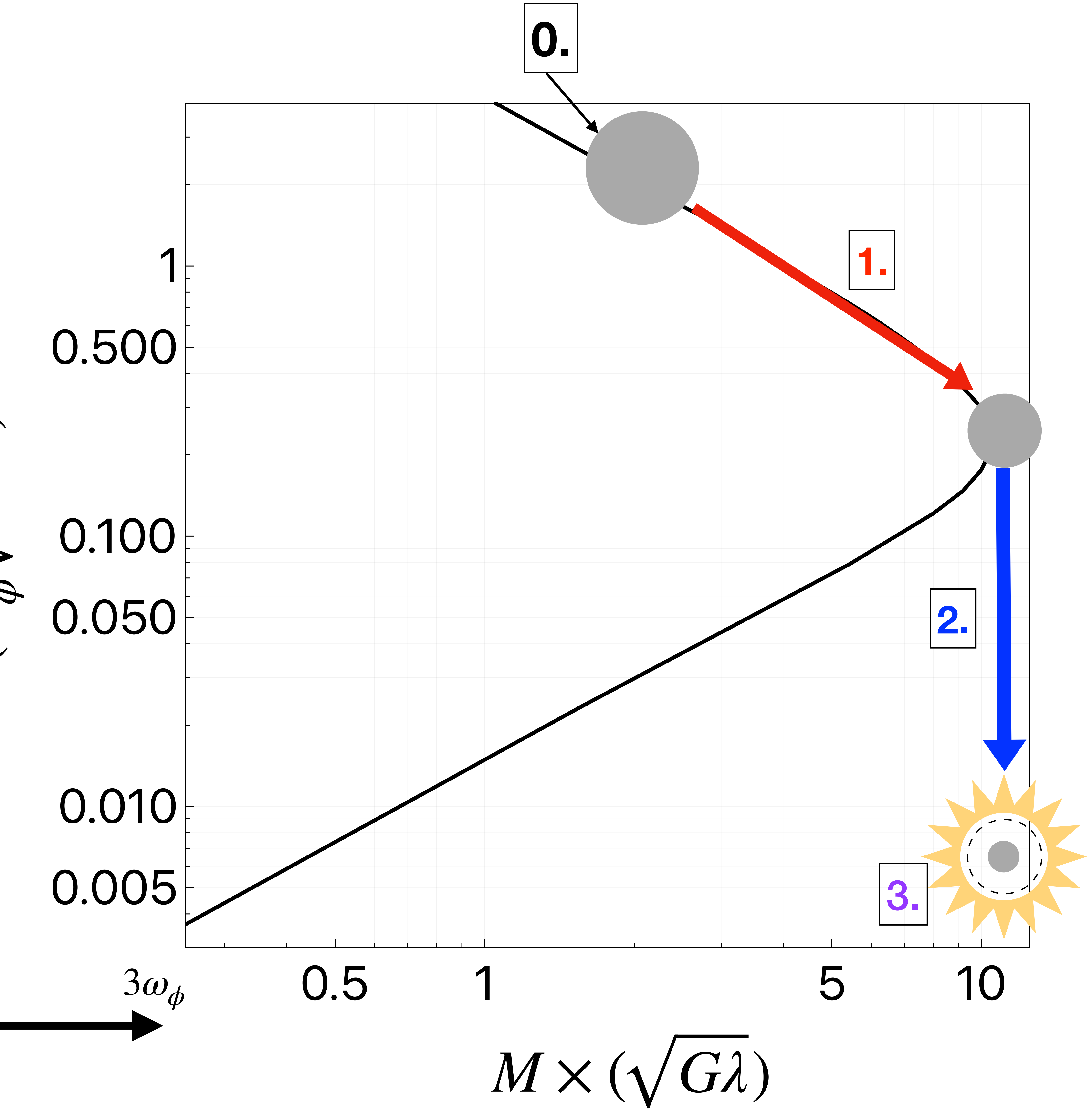


3. "Bosenova" explosion

Annihilations in core of collapsing boson star rapidly expel energy





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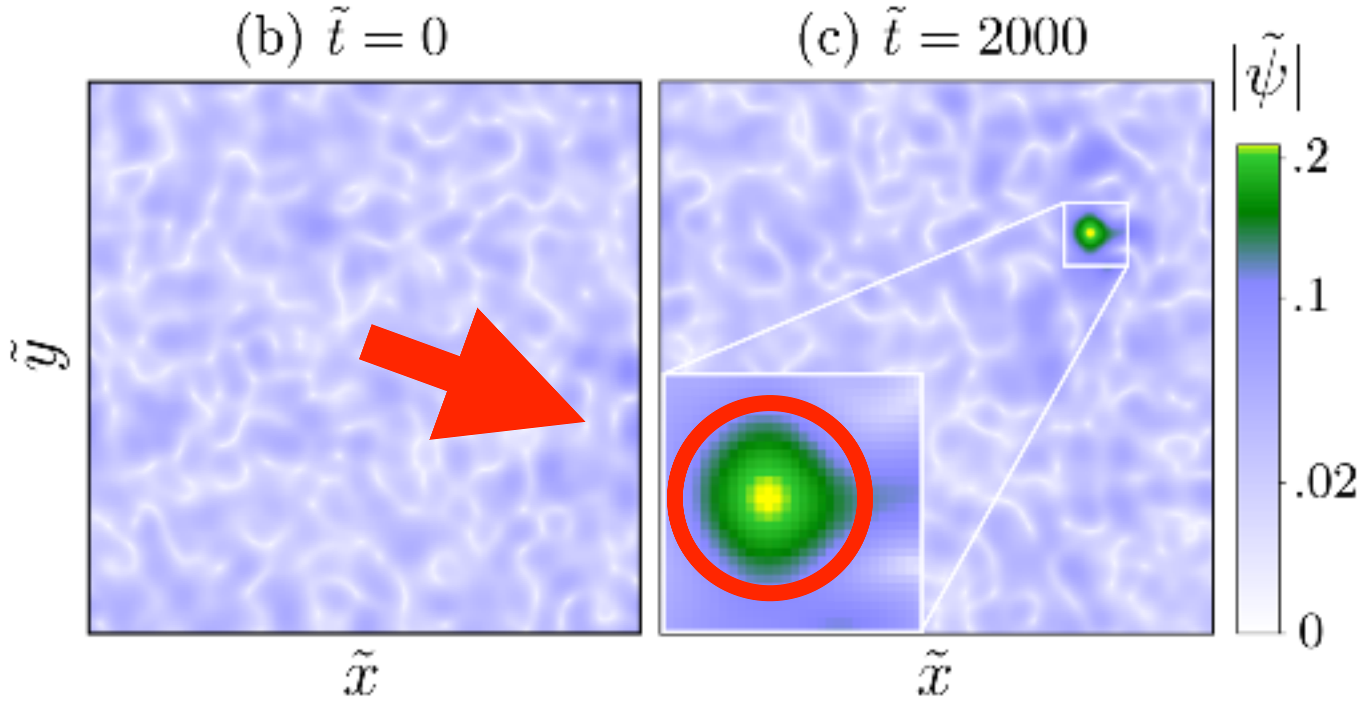

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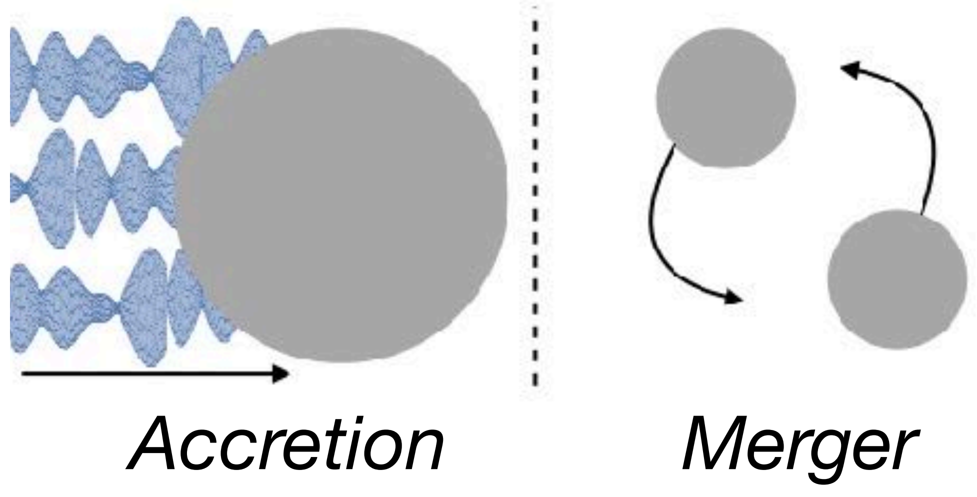

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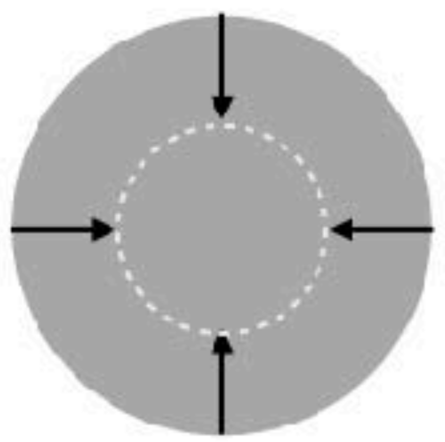

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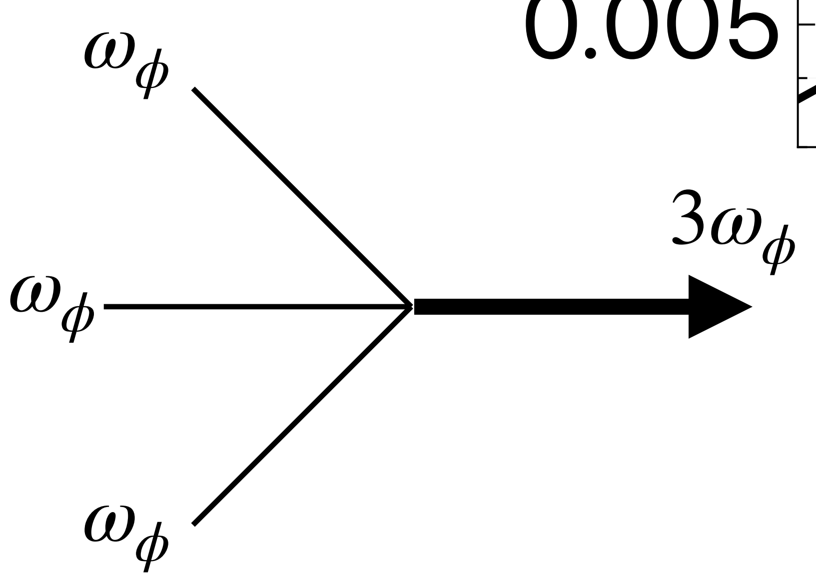
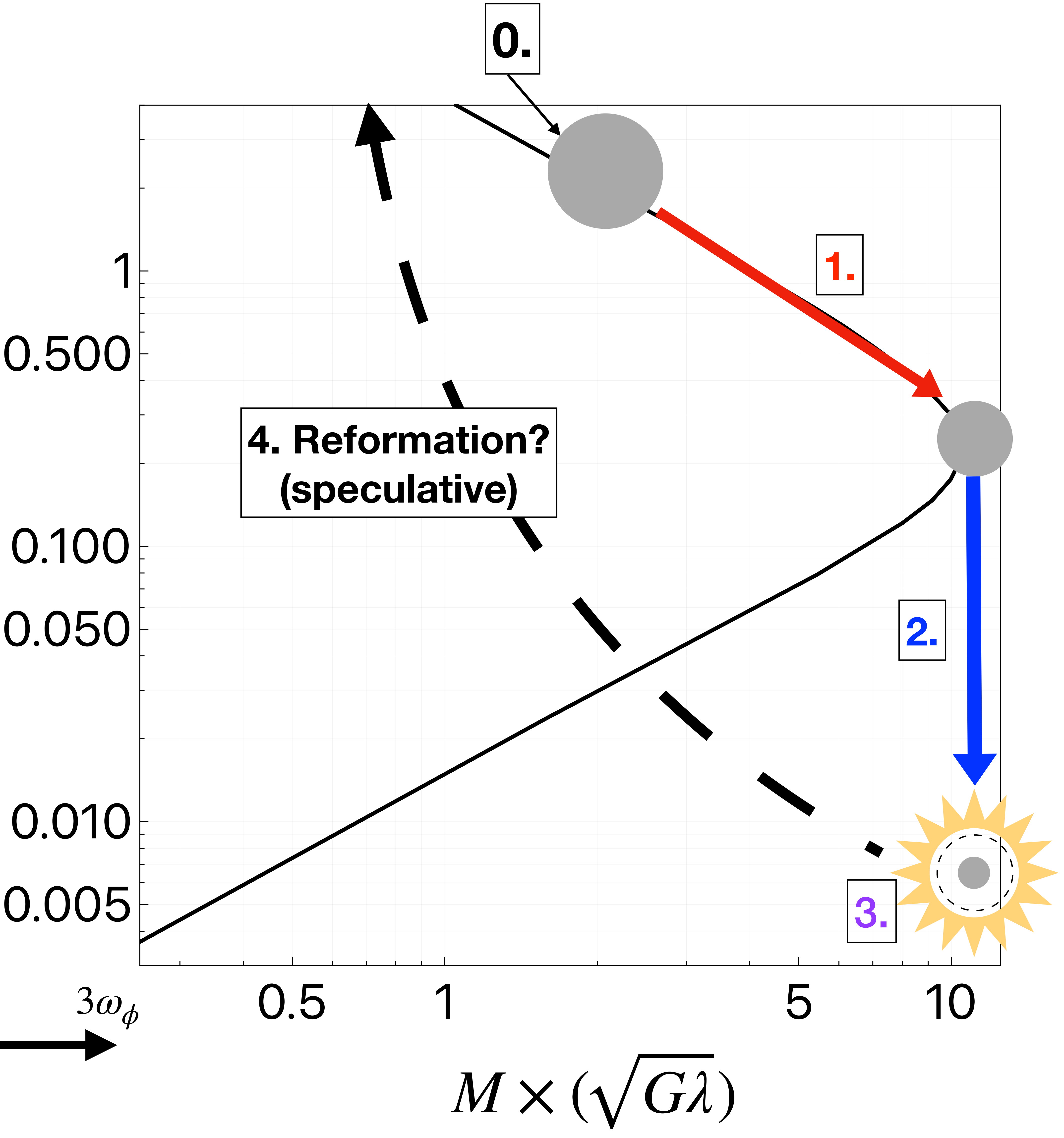
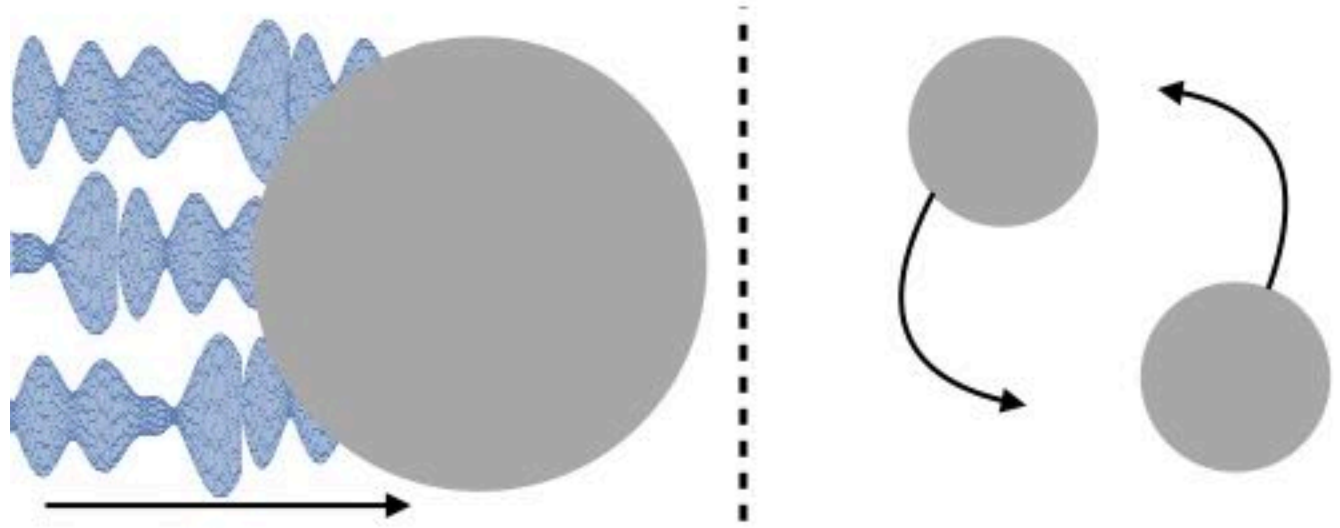




Event Rate vs Burst Signal

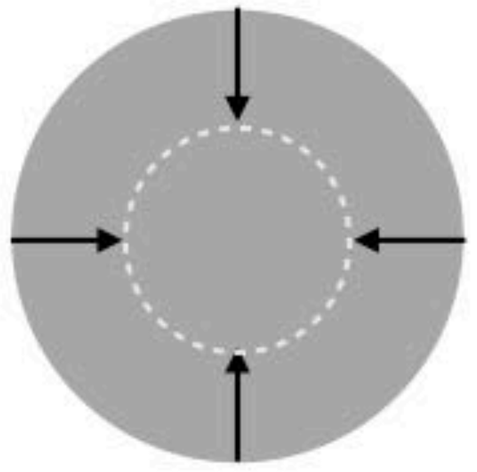
1. Boson Star Mass Growth



$M \uparrow$, $R \downarrow$

Either accretion of scalar field or merger events

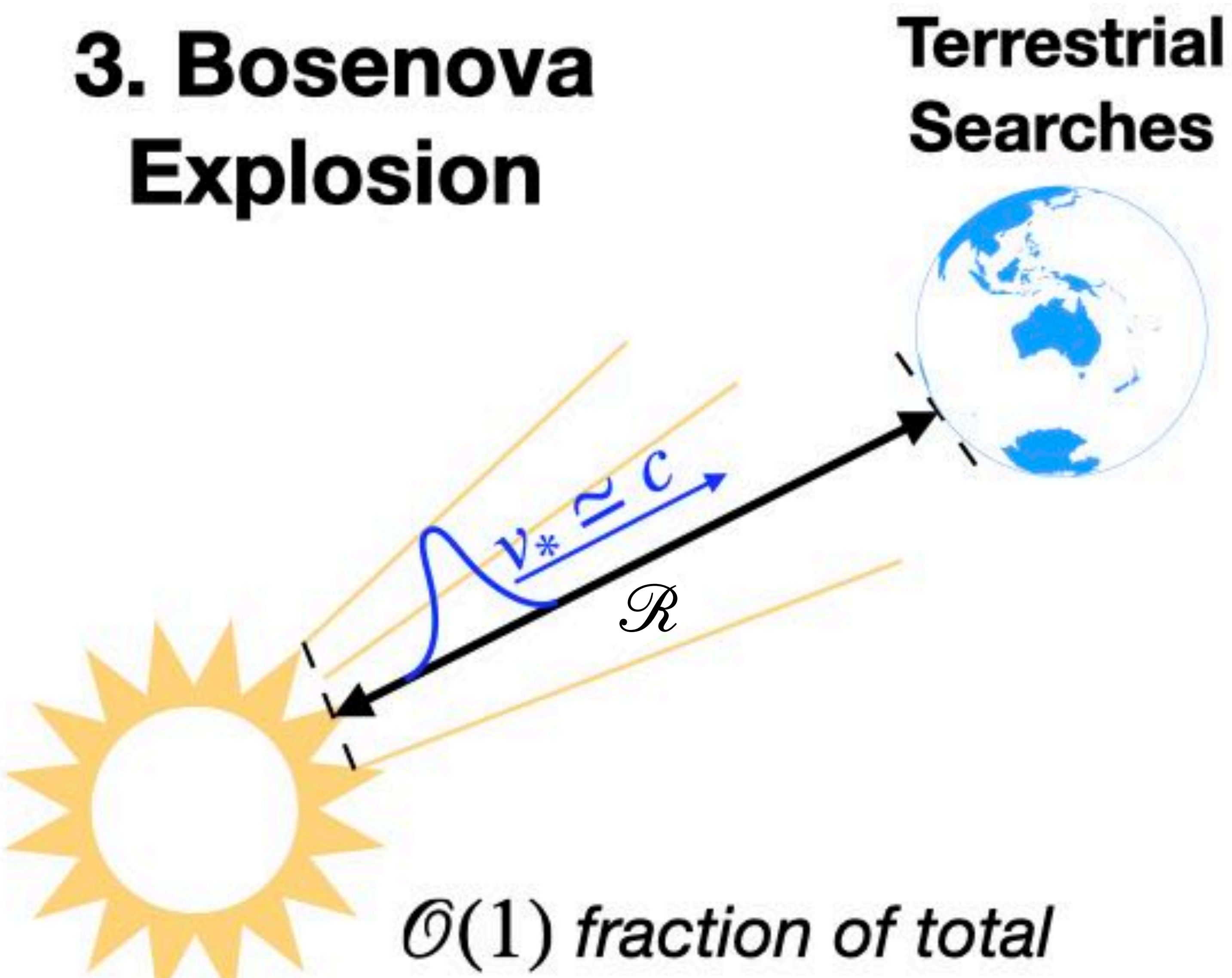
2. Gravitational Collapse



Collapse when mass reaches critical

$M \simeq M_c$

3. Bosenova Explosion

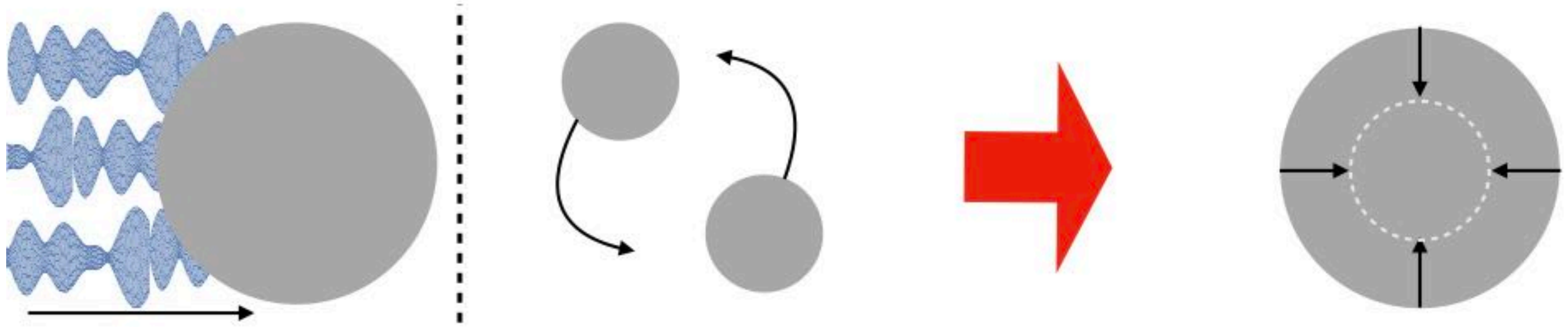


$\mathcal{O}(1)$ *fraction of total boson star energy is emitted*

Event Rate vs Burst Signal

1. Boson Star Mass Growth

2. Gravitational Collapse



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***Highly* model-dependent:**

- *Cosmology (formation history)*
- *Astrophysics (mass growth, merger history)*
- *Particle physics (interactions→relaxation rate)*

Given a fraction f_{bs} of DM in boson stars, the number within radius r is approximately:

$$N_{bs}(r) \sim \frac{f_{bs}\rho_{dm}r^3}{M_c} \sim 10^7 f_{bs}\left(\frac{r}{10\,\mathrm{kpc}}\right)^3\sqrt{\frac{\lambda}{10^{-80}}}$$

Compare with the total mass-energy inside each boson stars when it collapses:

$$M_c \simeq \frac{10}{\sqrt{G\lambda}} \simeq 10^3 M_\odot\sqrt{\frac{10^{-80}}{\lambda}}$$

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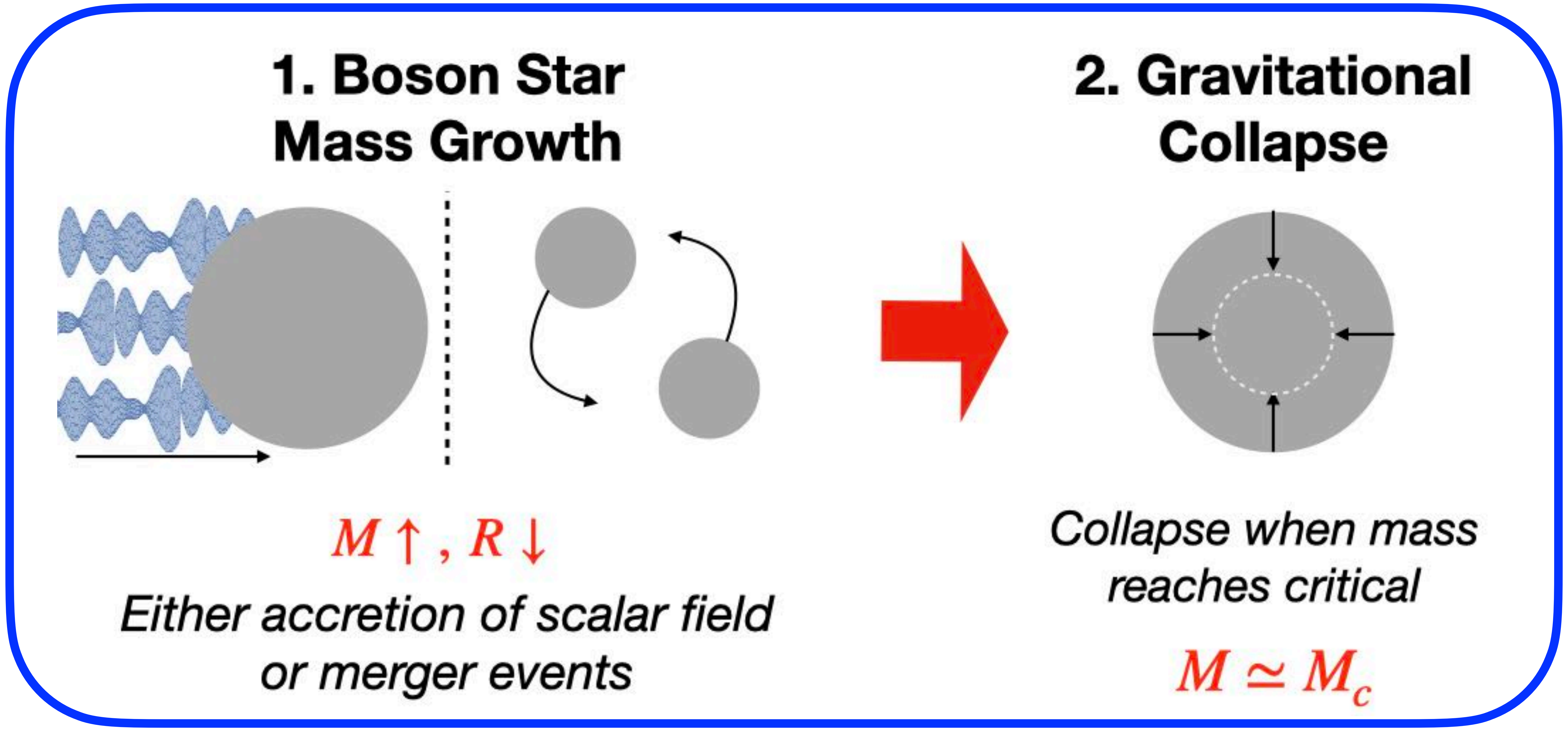

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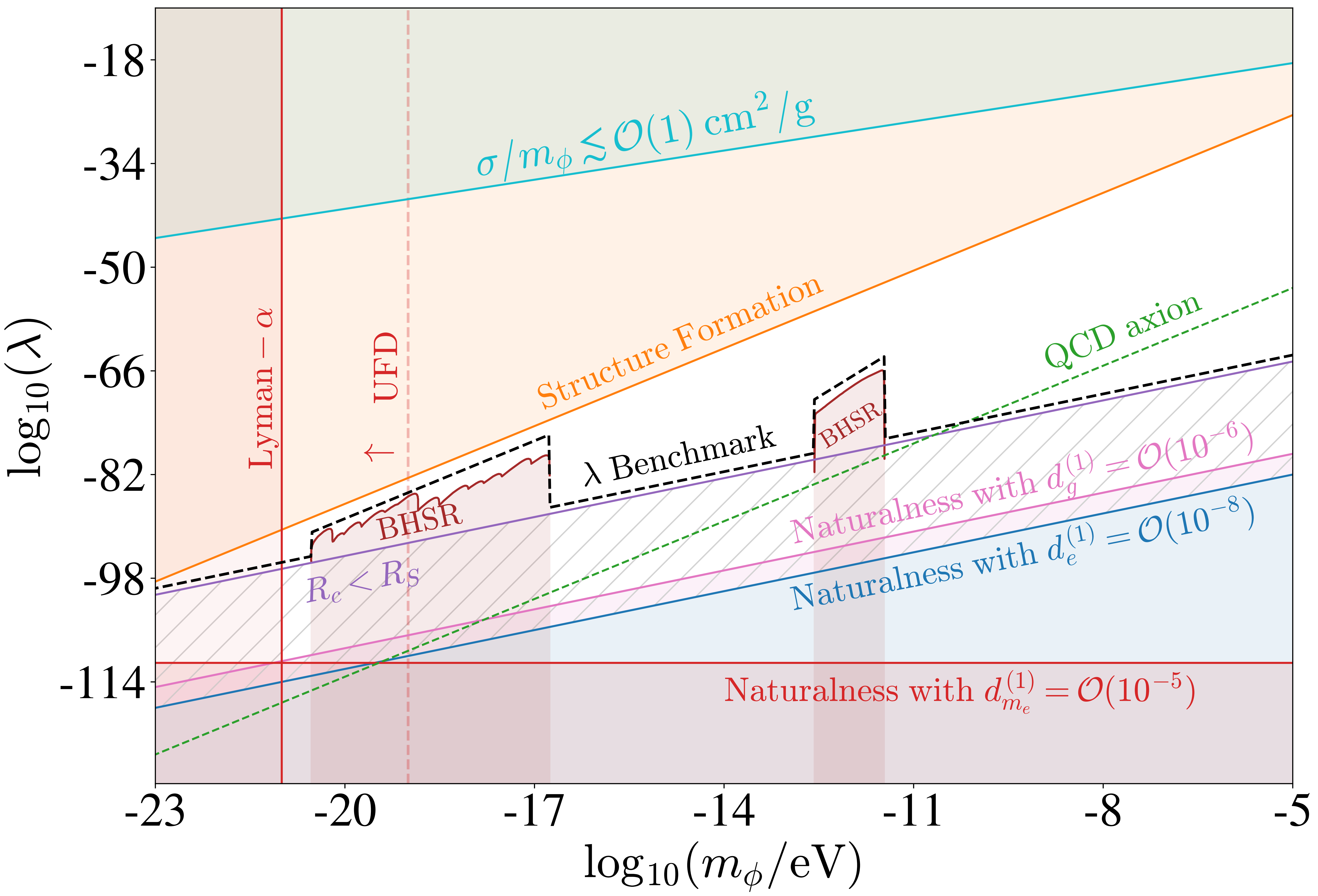
Strong self-interactions ↔ large λ →
- **Larger $N_{bs}(r)$ → Larger burst rate**
- **Smaller M_c → Smaller signal strength**

Event Rate vs Burst Signal

Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468)



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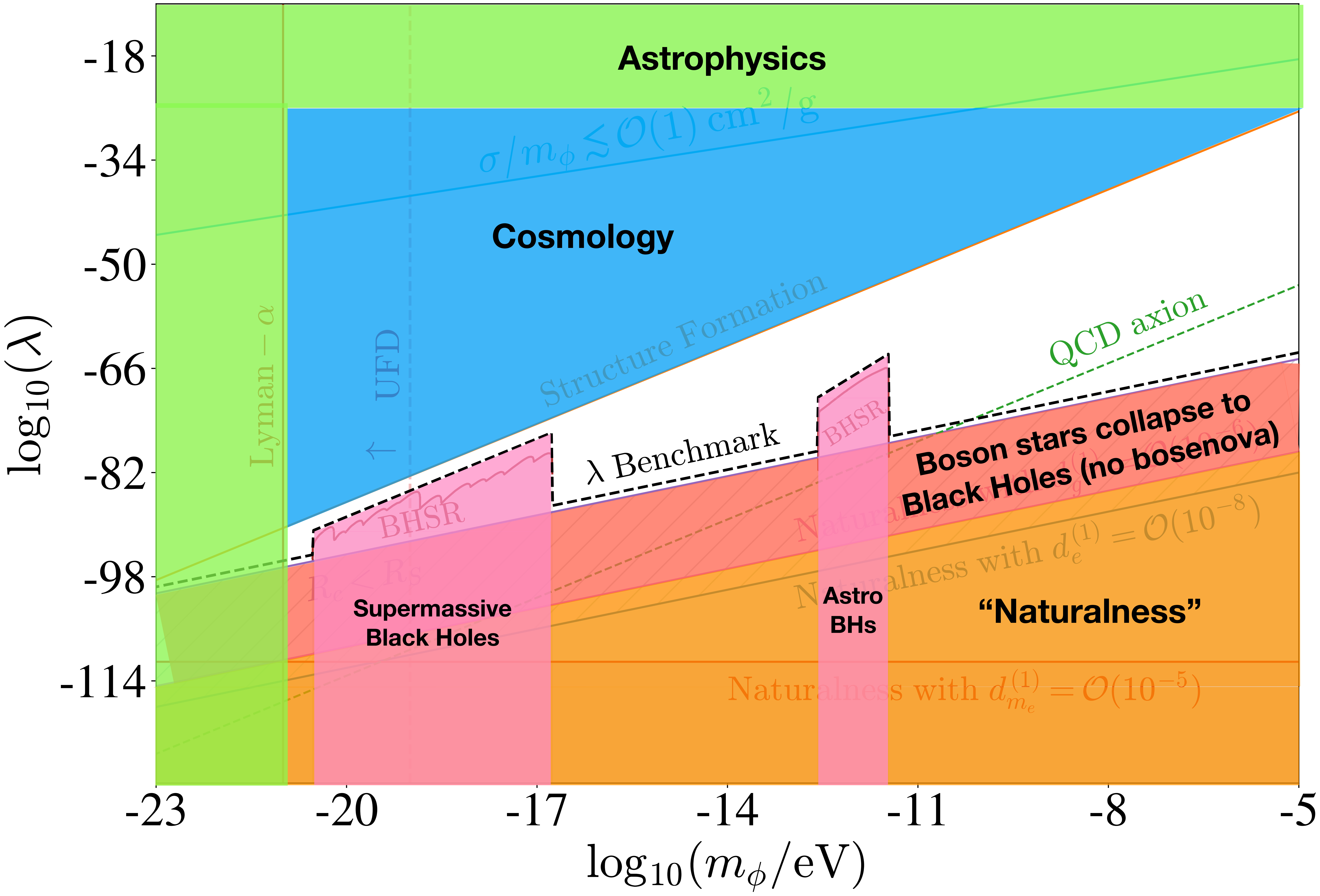

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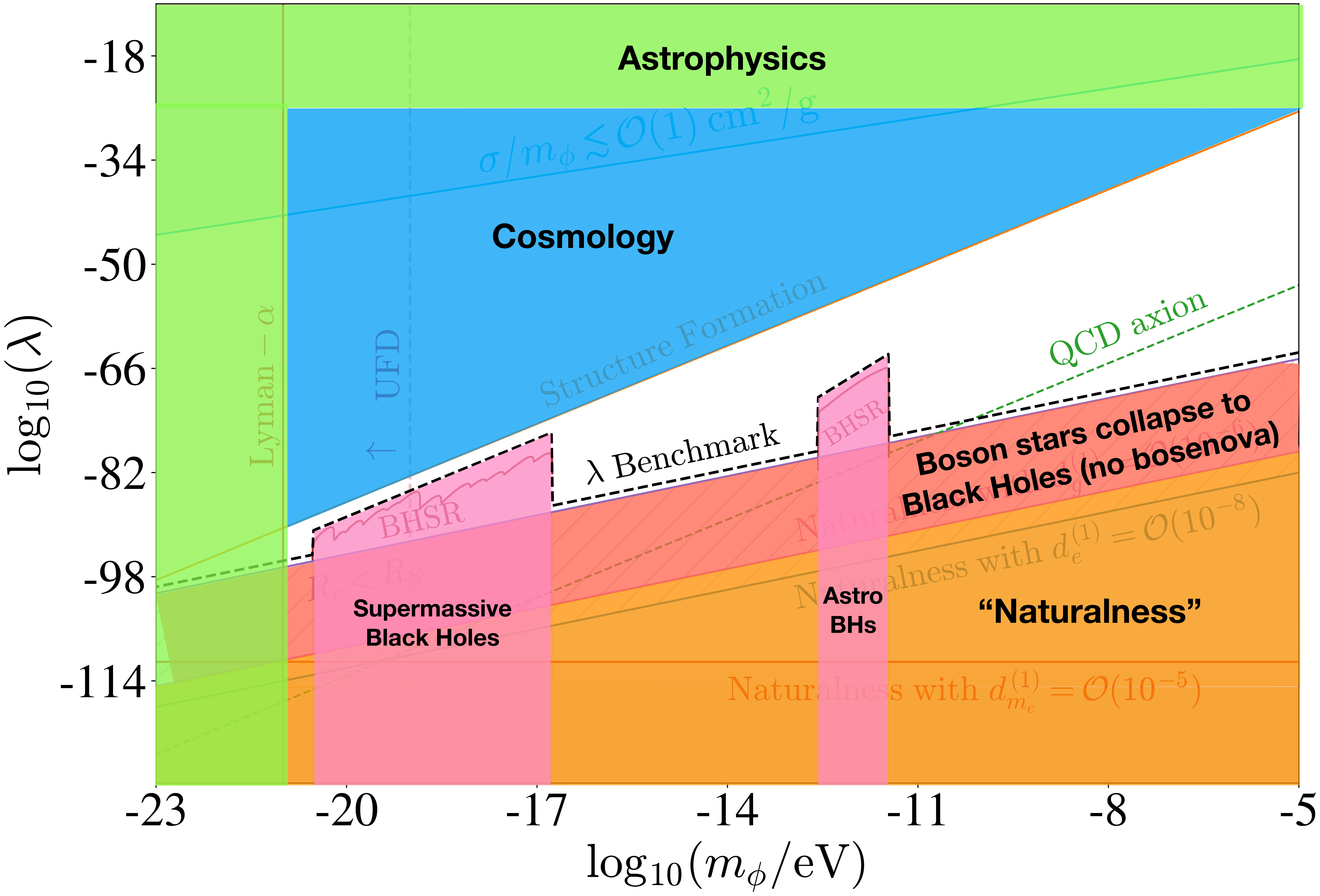


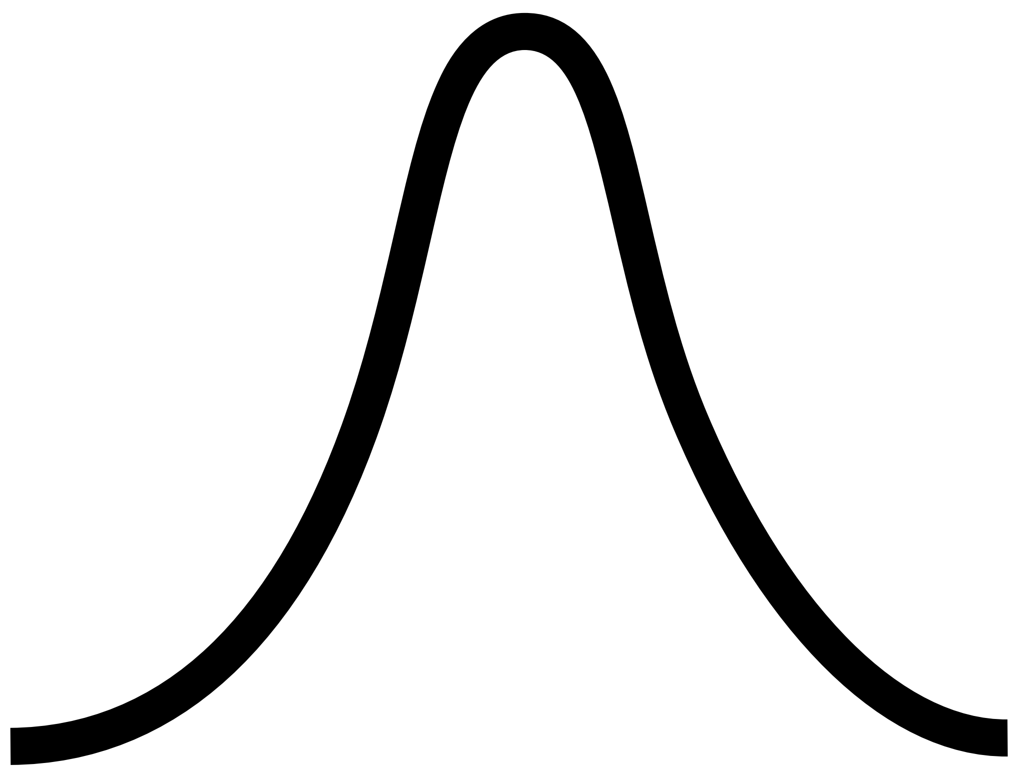
Smaller M_c (signal)
Larger Γ (rate)

Larger M_c (signal)
Smaller Γ (rate)

Future work is needed to fully estimate the rate across range of models

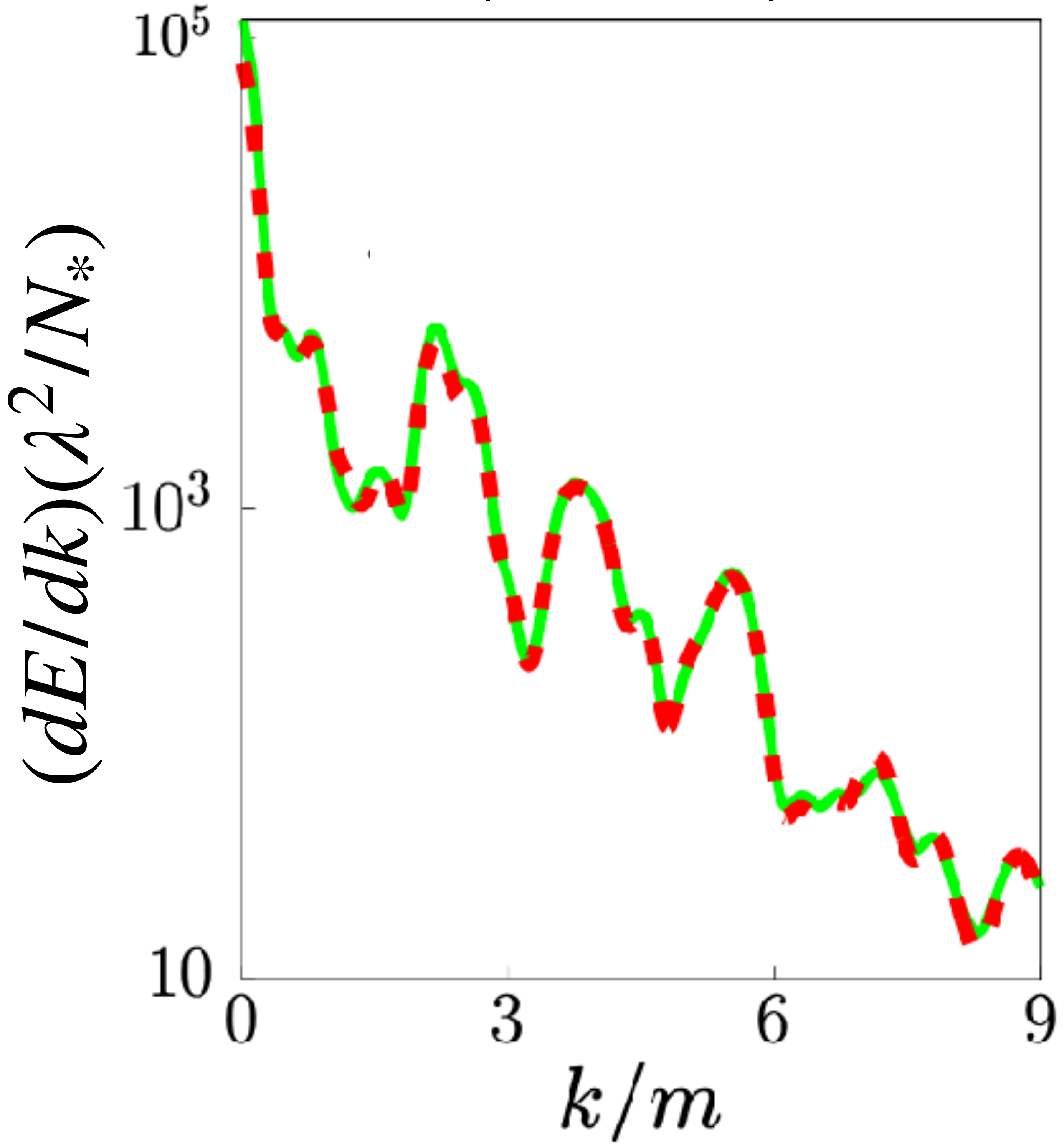
Event Rate vs Burst Signal

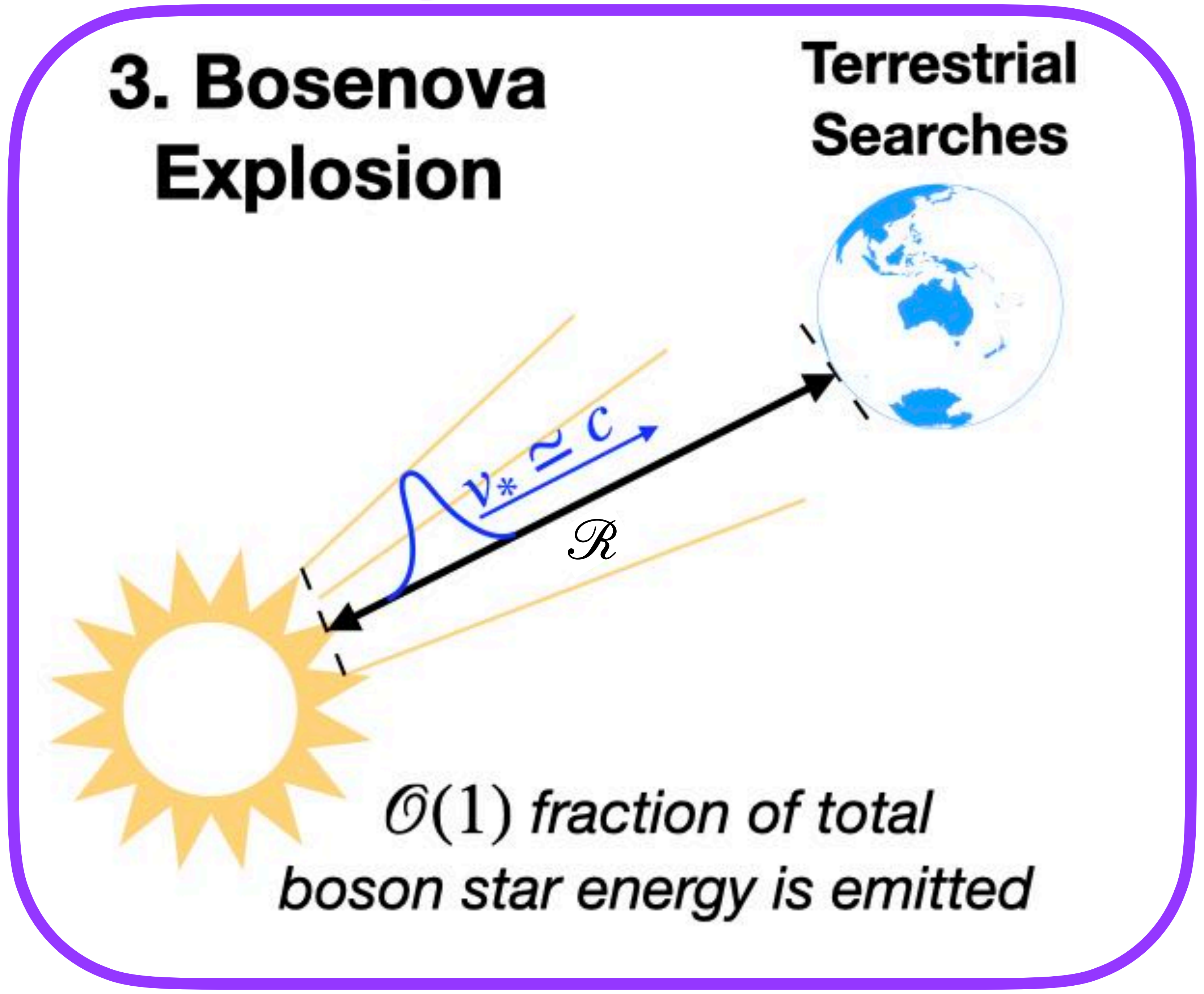
Burst properties:



momentum spectrum of emission:
peaked at $k_0 \sim \text{few} \times m_\phi$
with width $\delta k \sim m_\phi$

Emission Spectrum (simulation):





Simulations of collapse+explosion process

Levkov, Panin, Tkachev (1609.03611)

Bosenova predicted by

JE, Leembruggen, Suranyi, Wijewardhana (1608.06911)

Event Rate vs Burst Signal

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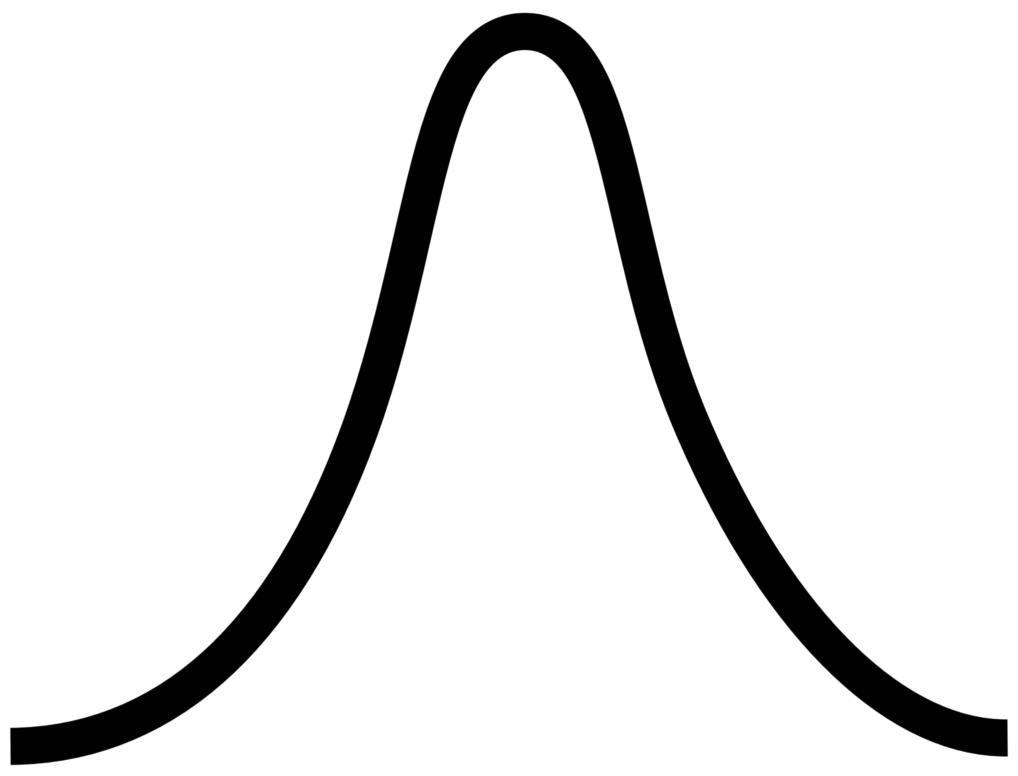

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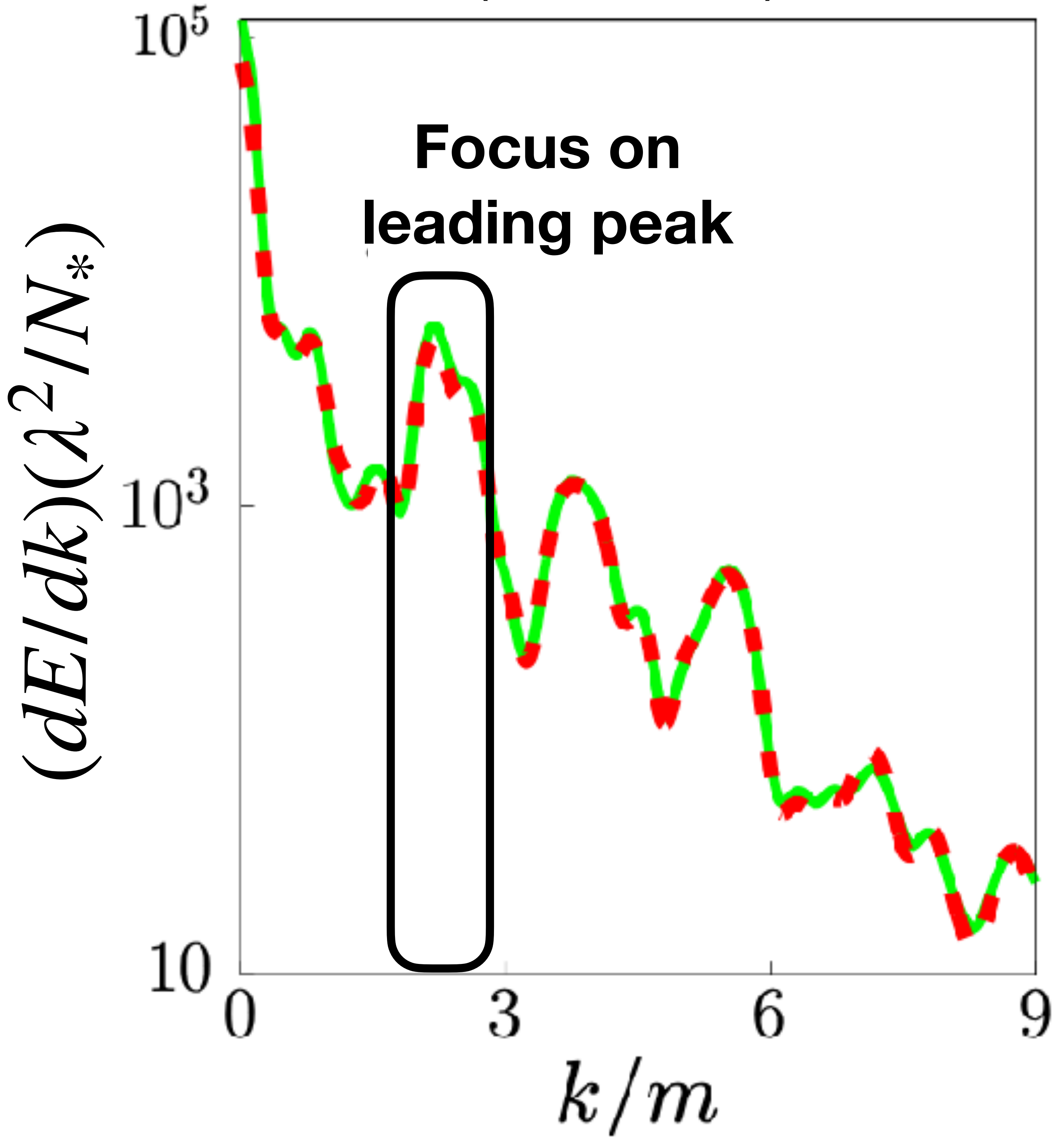
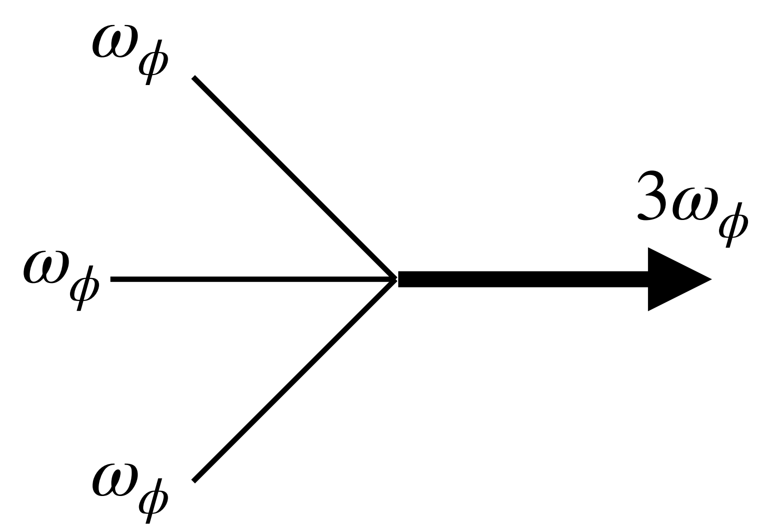
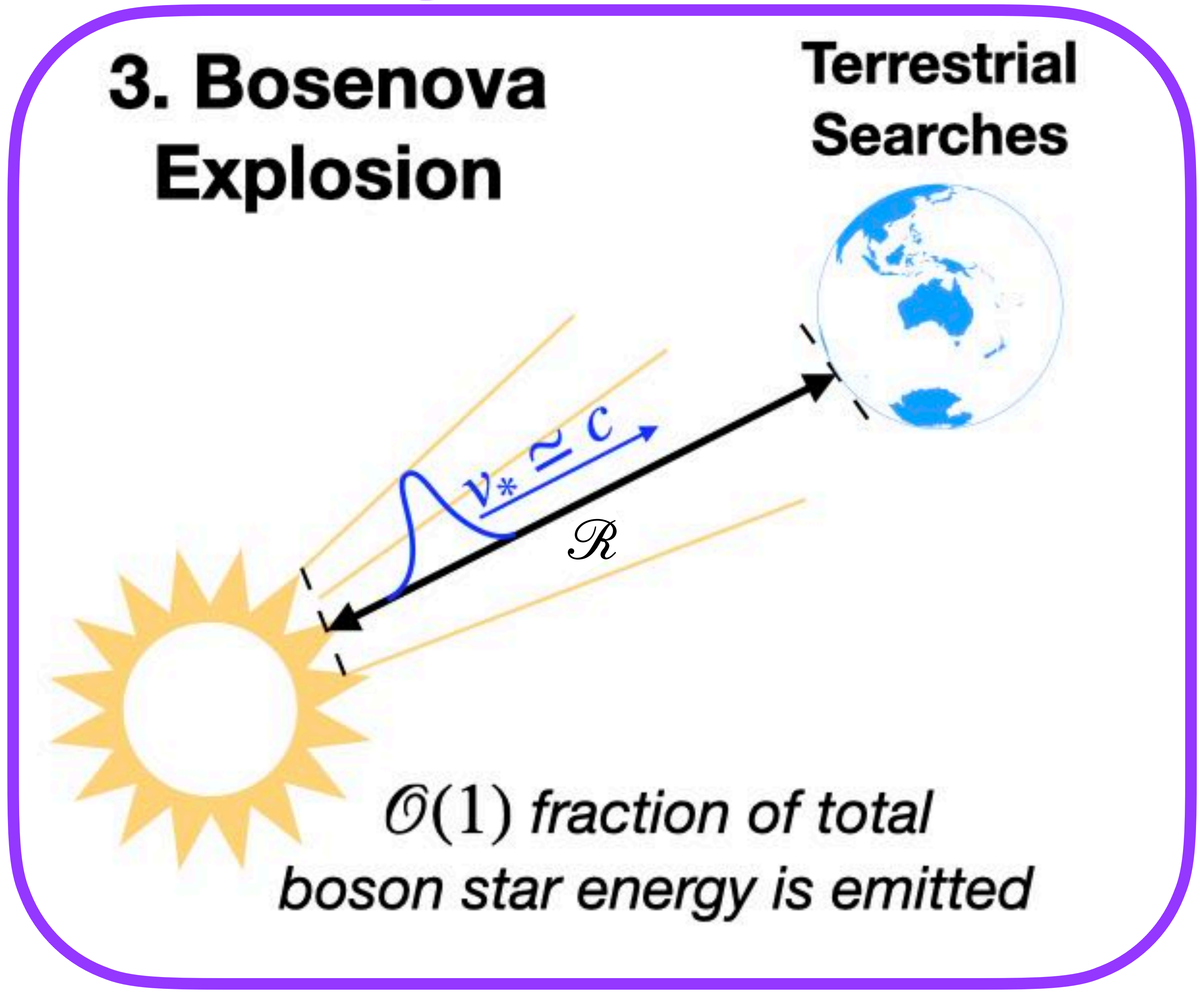


e.g.





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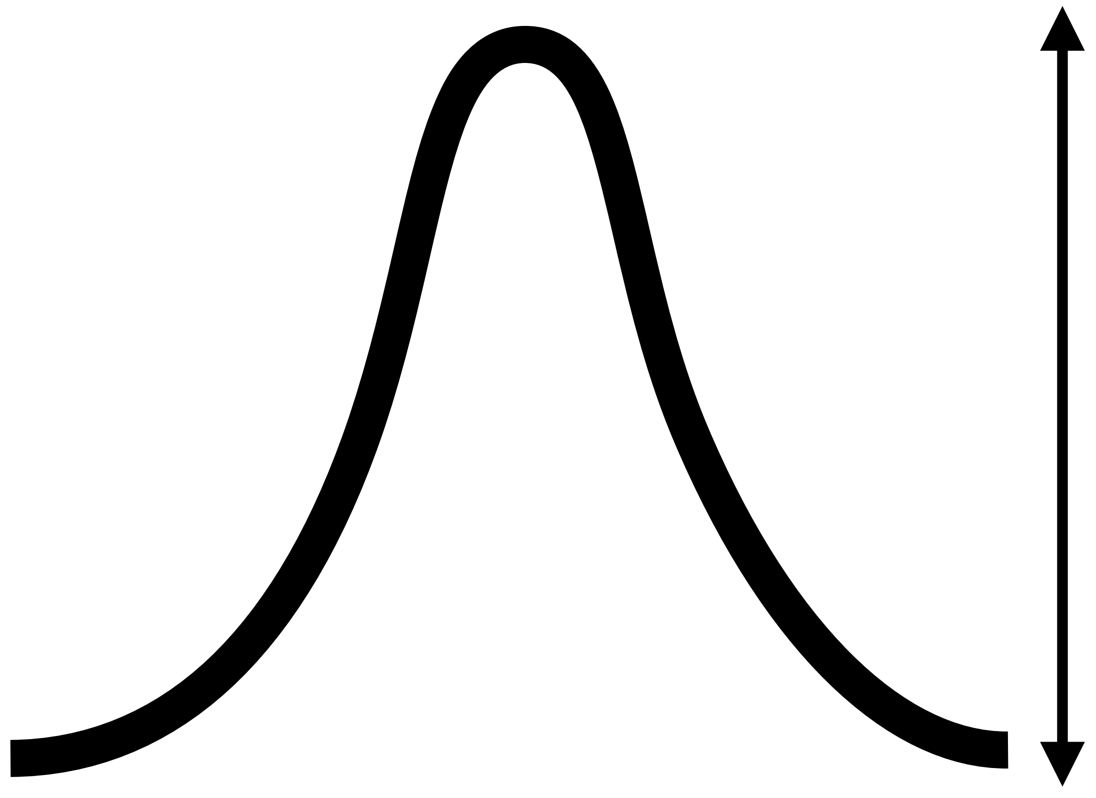

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with width $\delta k \sim m_\phi$

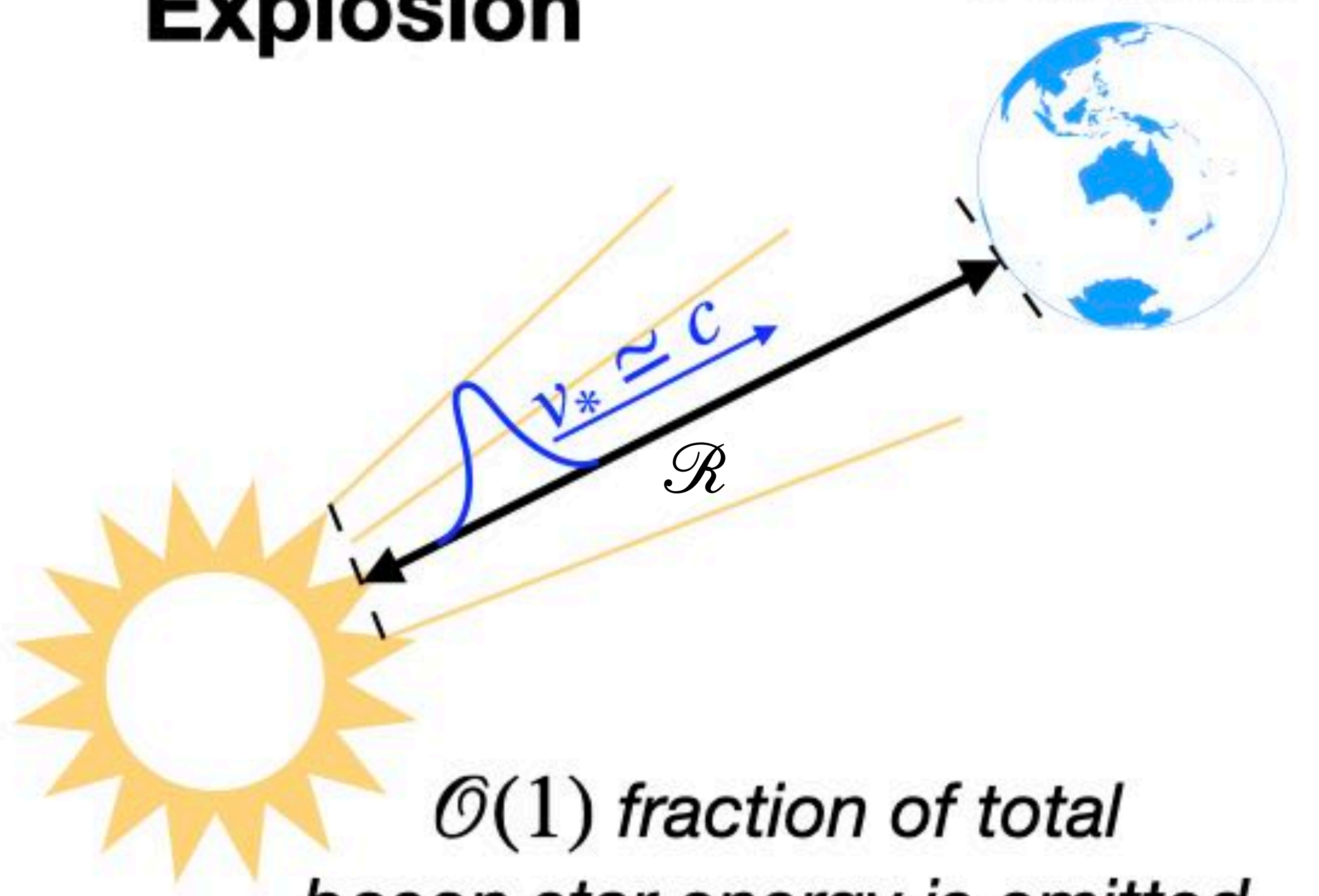
Energy density in burst

total emitted energy, $\sim M_c$

$$\rho_* \sim \frac{\mathcal{E}_{\text{emitted}}}{4\pi\mathcal{R}^2\delta x}$$

burst distance

burst 'size'



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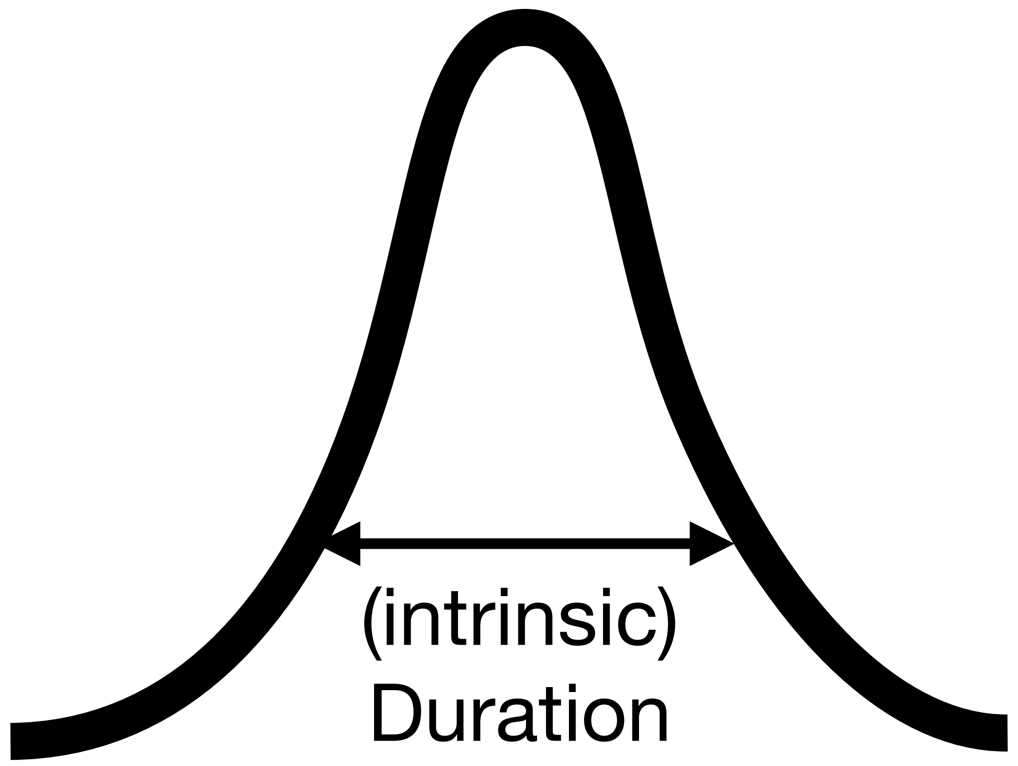
JE, Shirai, Stadnik, Takhistov (2106.14893)

Wave Spreading in Flight

At Source



δt_*

momentum spectrum of emission:

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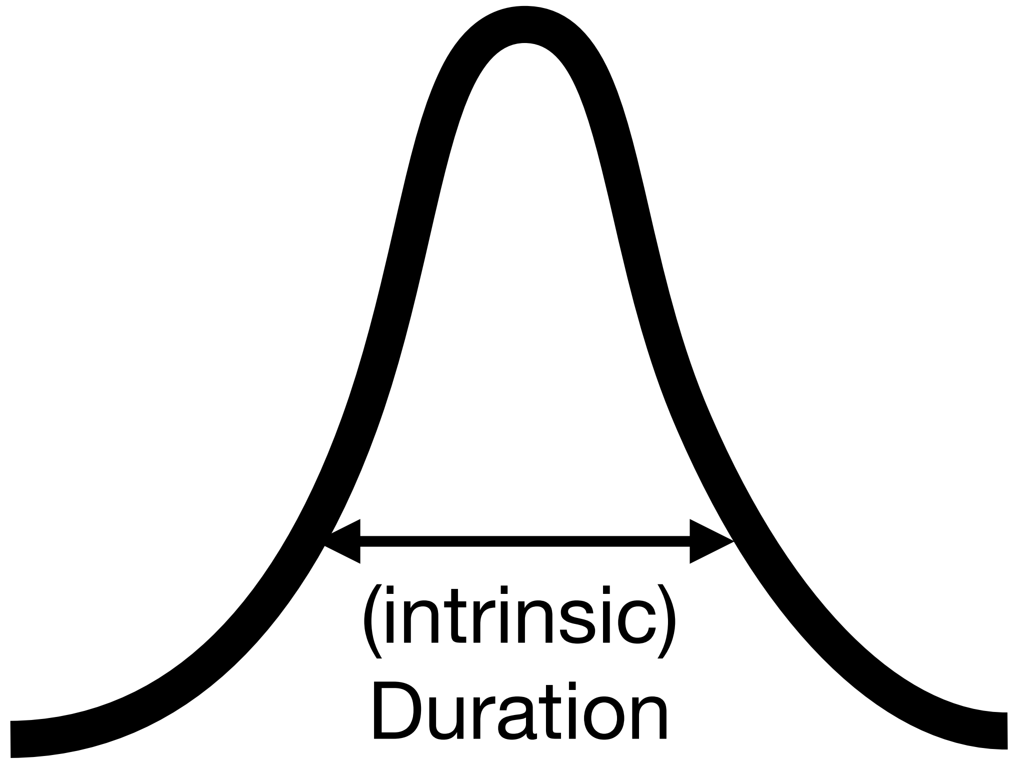
JE, Shirai, Stadnik, Takhistov (2106.14893)

Wave Spreading in Flight

At Source

Fastest momentum modes
move away from
slower ones during propagation

At Detector



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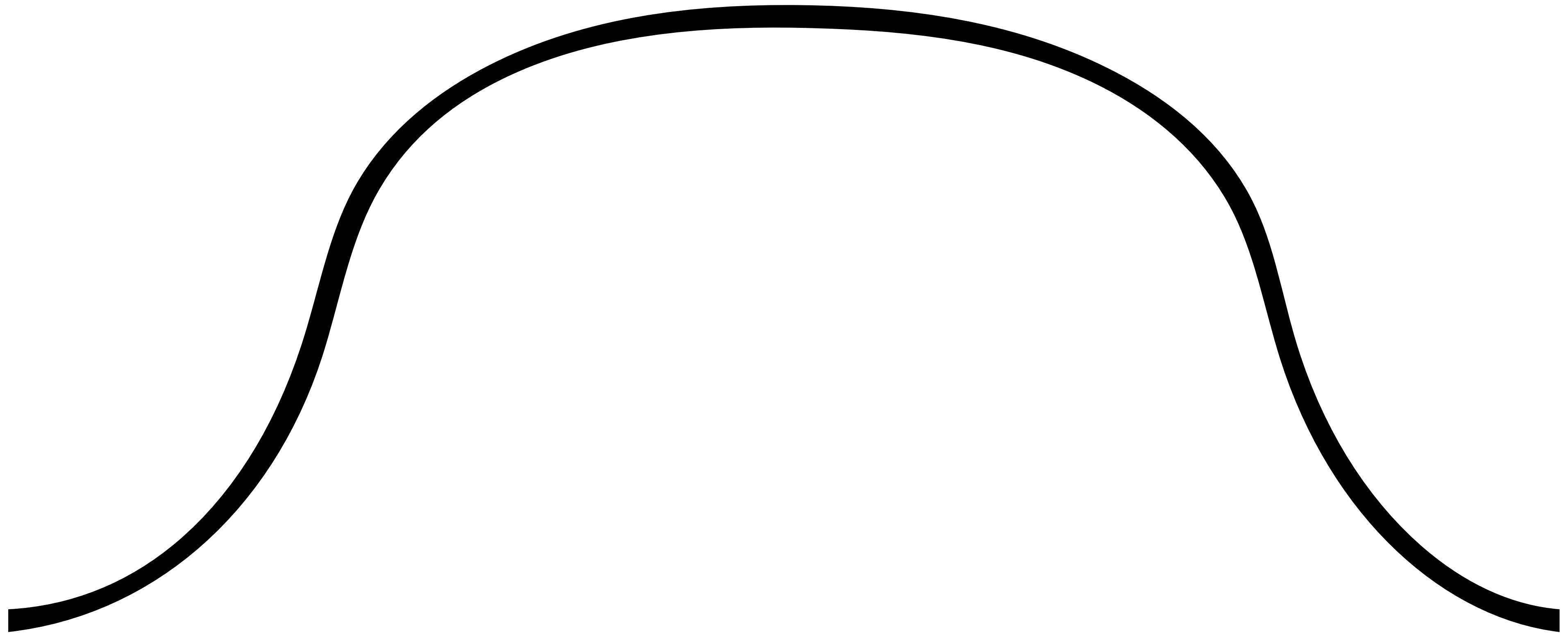

$\mathscr{R}$

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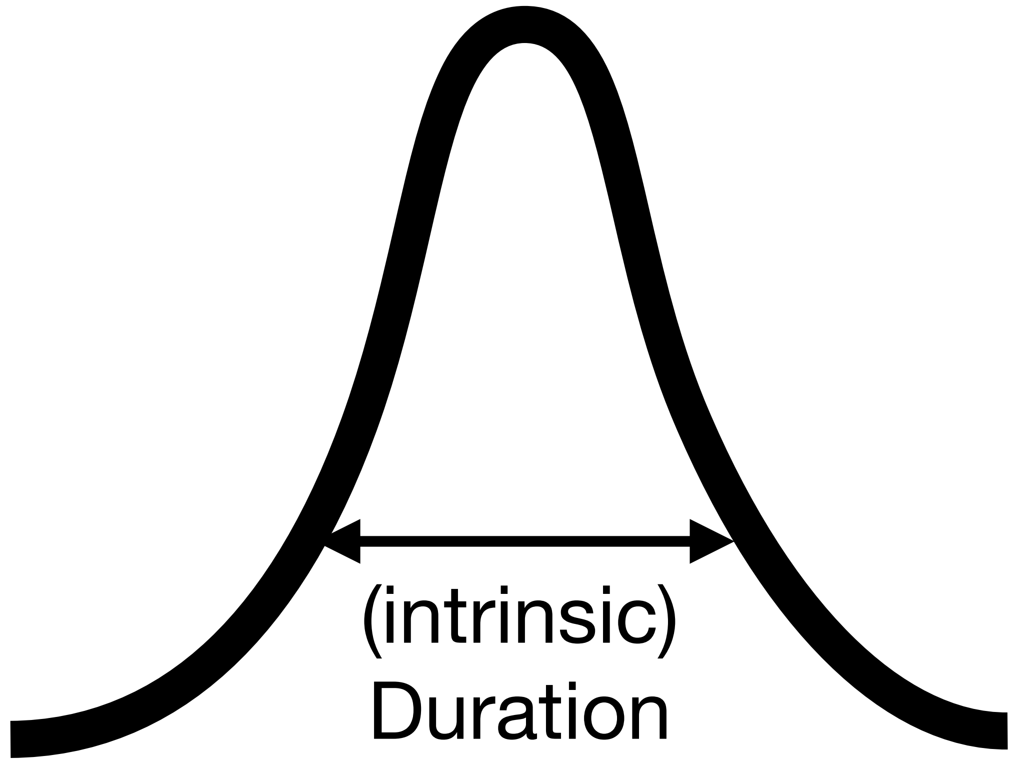

(intrinsic)
Duration

δt_*

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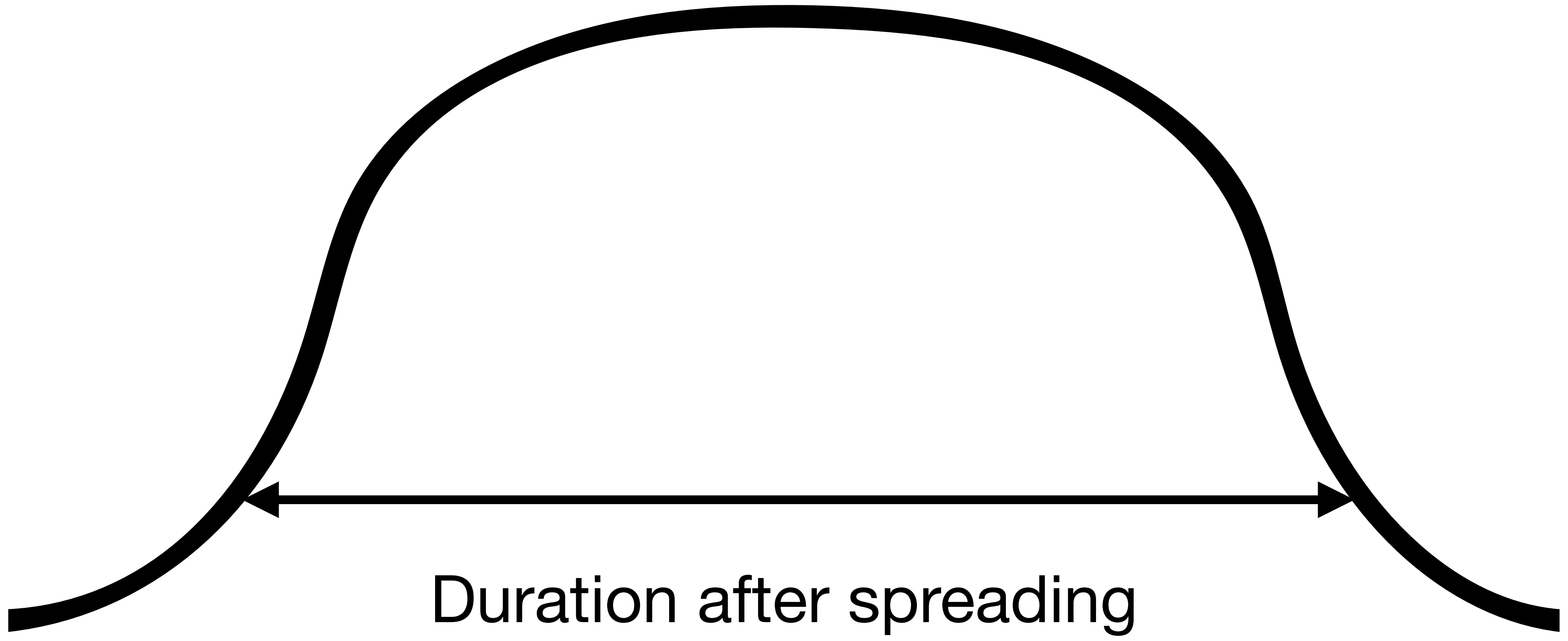
$\mathscr{R}$



Duration after spreading

$$\delta t \sim \mathscr{R}$$

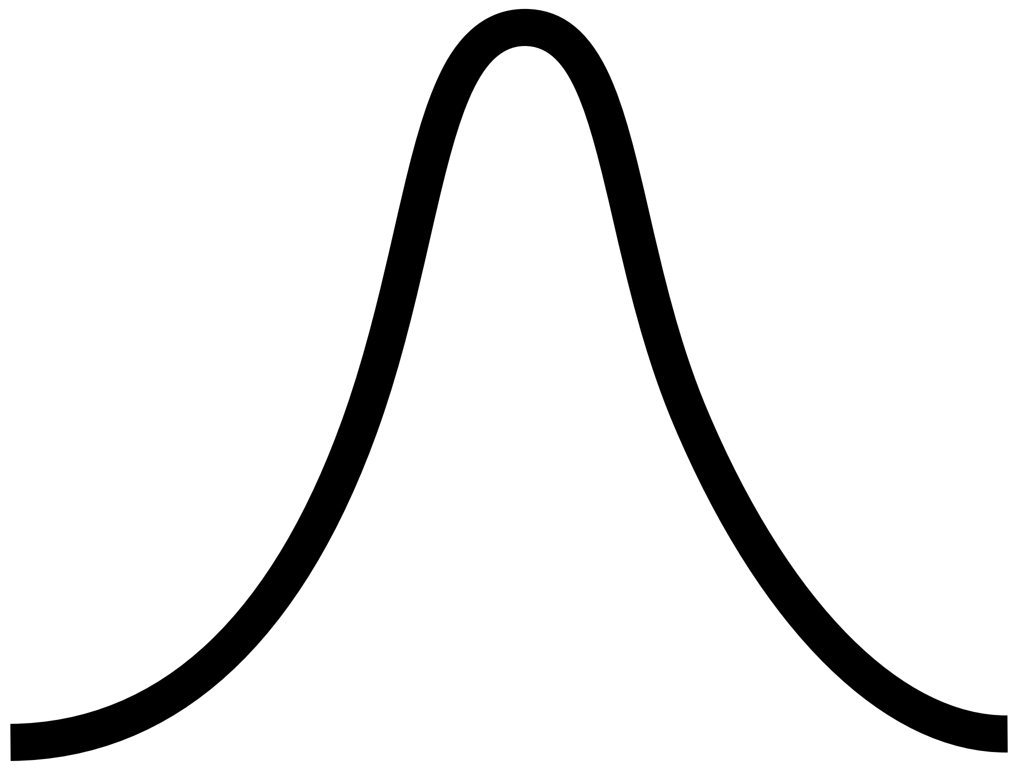
$$\sim \text{months} \left(\frac{\mathscr{R}}{\text{pc}} \right)$$

This is the length of time during which the burst contributes to a signal in the detector!

JE, Shirai, Stadnik, Takhistov (2106.14893)

Coherence Time

At Source



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imagine discrete momentum modes

$k_1, k_2, k_3, \ldots$

Fastest momentum modes
move away from
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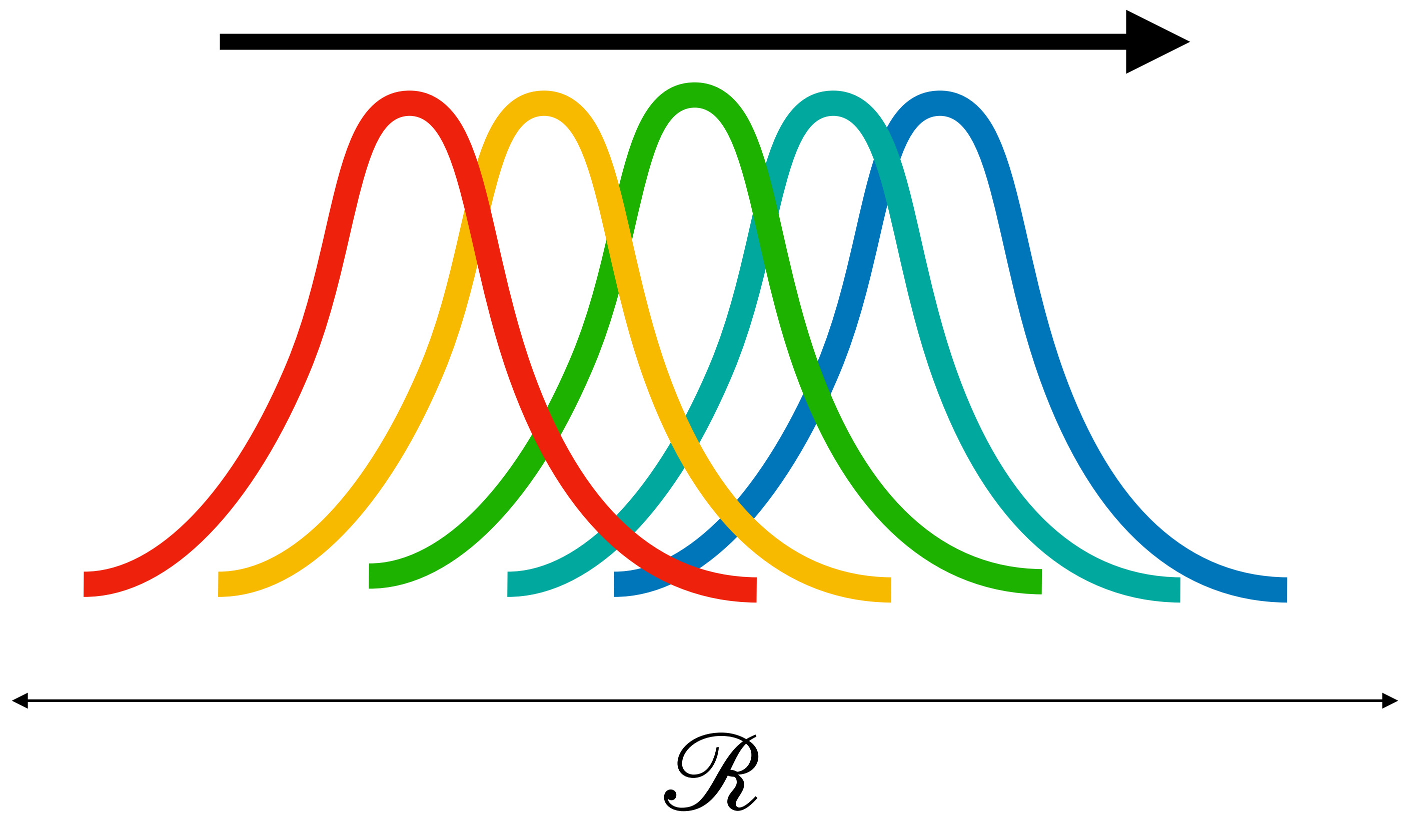
$k_1 < k_2 < k_3, \ldots$



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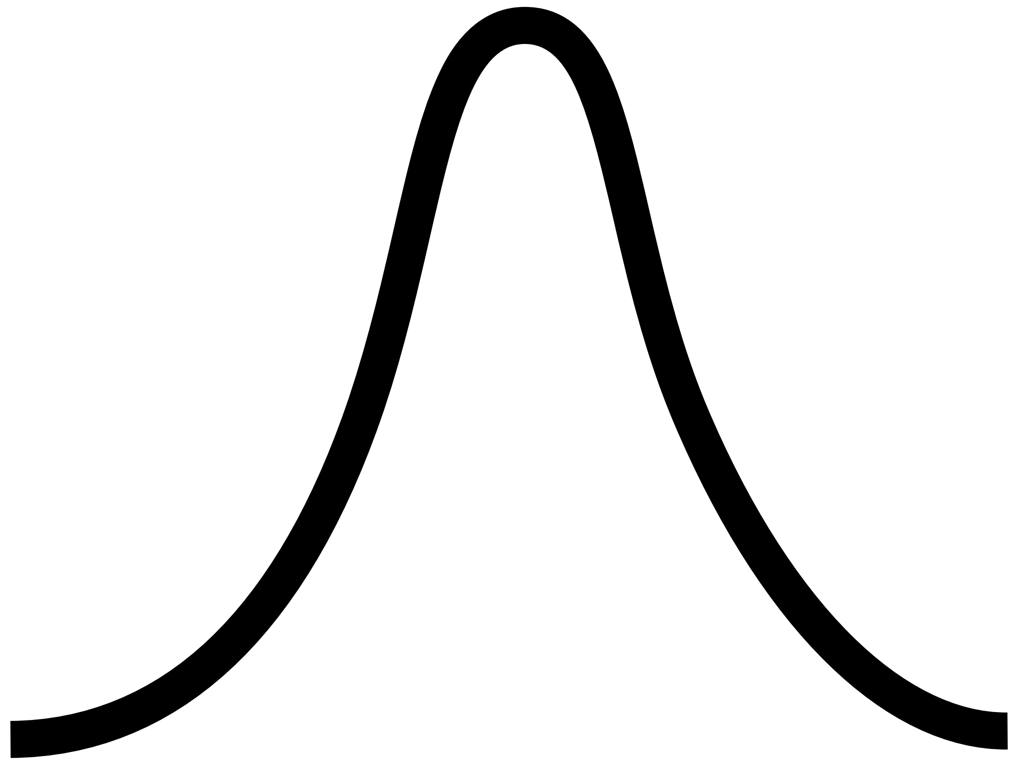

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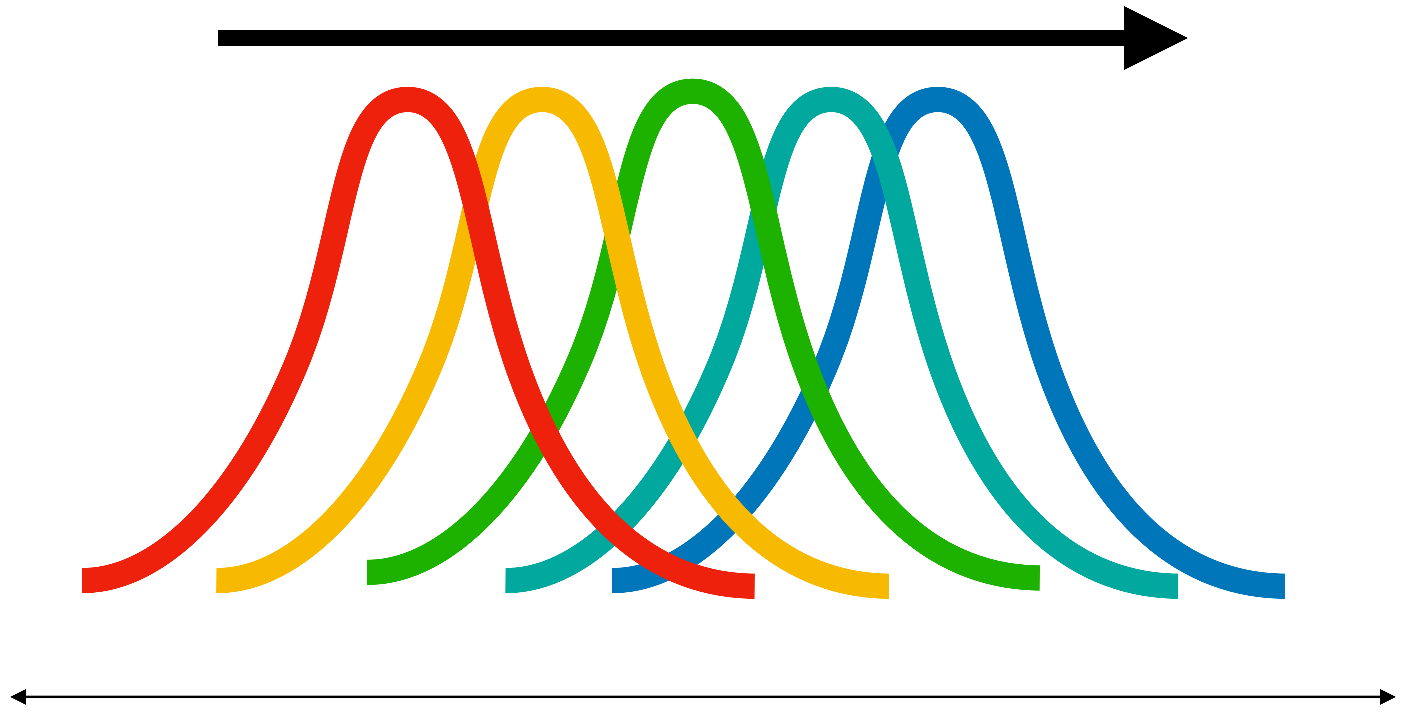

$\mathscr{R}$

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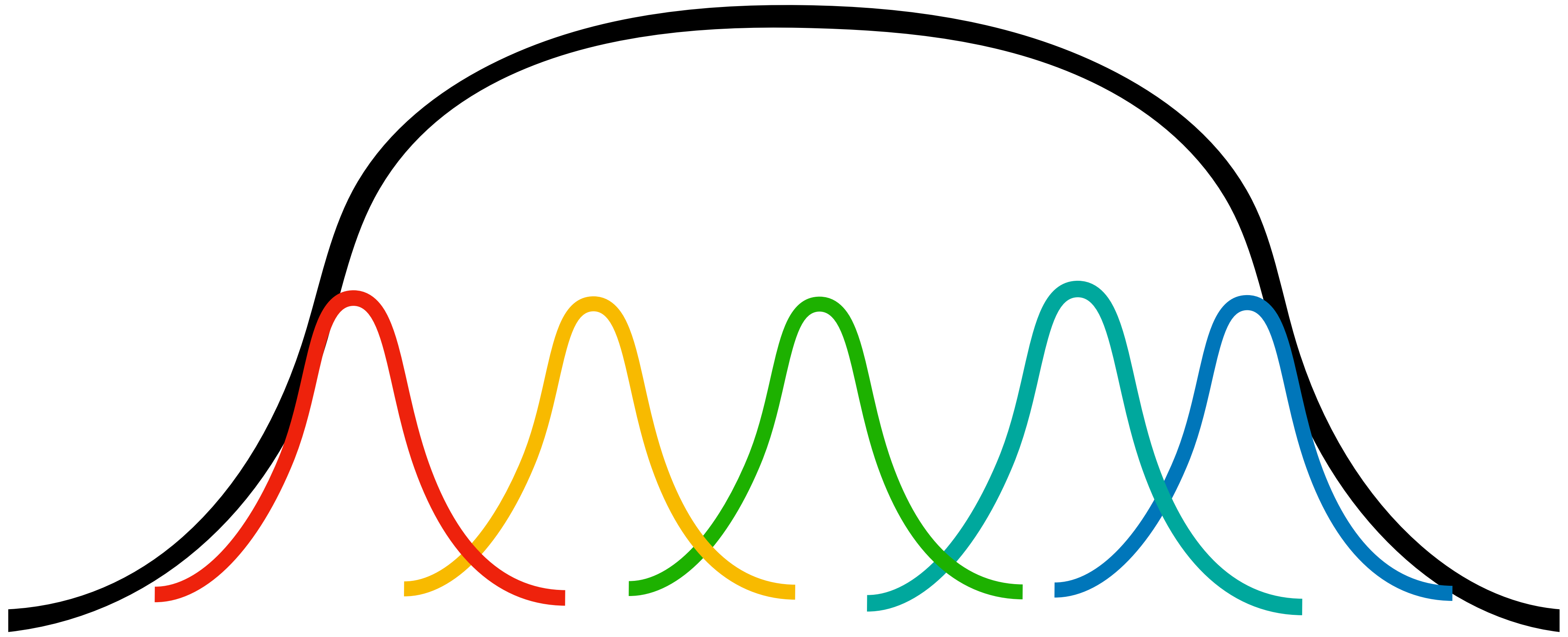

modes arrive at different times

At any given moment in the detector, one sees a **narrow** distribution of momentum / energy

"effective coherence time" $\tau_* \sim 10^{-2}\mathscr{R}$

JE, Shirai, Stadnik,
Takhistov (2106.14893)

Sensitivity Estimation

Sensitivity Ratio at fixed frequency ω_0

$$\frac{d^{\text{(burst)}}_{i,*}(\omega_0)}{d^{\text{(DM)}}_{i,\text{DM}}(\omega_0)} \sim \left(\frac{\rho_{\text{dm}}}{\rho_*}\right)^n \frac{t_{\text{int}}^{1/4} \min\left(\tau_{\text{dm}}^{1/4}, t_{\text{int}}^{1/4}\right)}{\min\left(\delta t^{1/4}, t_{\text{int}}^{1/4}\right) \min\left(\tau_*^{1/4}, t_{\text{int}}^{1/4}\right)}$$

"Is a given DM experiment equally/more sensitive to relativistic bursts compared to cold DM search?"

Timescales:

Interrogation time†	t_{int}
DM coherence time	τ_{dm}
Burst coherence time	τ_*
Burst duration	δt

†laser coherence, natural linewidth, …

JE, Shirai, Stadnik, Takhistov (2106.14893)

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usual scaling of DM signal

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$n = 1/2$ (linear coupling)

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$$\frac{d_{i,*}^{\text{(burst)}}(\omega_0)}{d_{i,\mathrm{DM}}^{\text{(DM)}}(\omega_0)} \sim \left(\frac{\rho_{\mathrm{dm}}}{\rho_*}\right)^n \frac{t_{\mathrm{int}}^{1/4} \min\left(\tau_{\mathrm{dm}}^{1/4}, t_{\mathrm{int}}^{1/4}\right)}{\min\left(\delta t^{1/4}, t_{\mathrm{int}}^{1/4}\right) \min\left(\tau_*^{1/4}, t_{\mathrm{int}}^{1/4}\right)}$$

energy density in the burst

"did we catch all/most of the signal?"

"is the signal coherent for the whole integration time?"

"Is a given DM experiment equally/more sensitive to relativistic bursts compared to cold DM search?"

Timescales:

Interrogation time†	t_{int}
DM coherence time	τ_{dm}
Burst coherence time	τ_*
Burst duration	δt

†laser coherence, natural linewidth, …

Current and Future Experimental Sensitivity

For axion-like particles (pseudoscalar couplings)

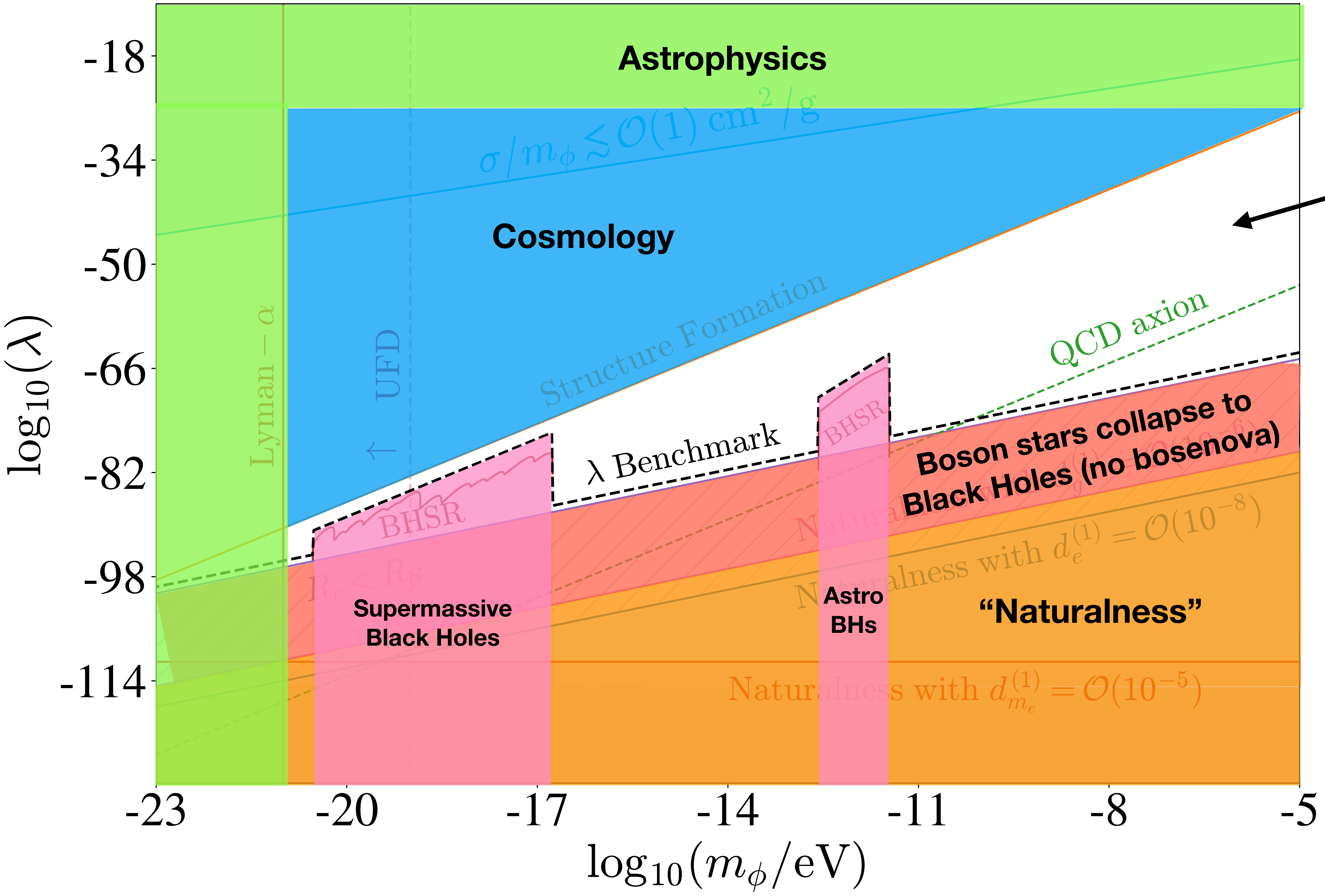
JE, Shirai, Stadnik, Takhistov (2106.14893)

For dilaton-like particles (scalar couplings)

Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468, 2402.06736)

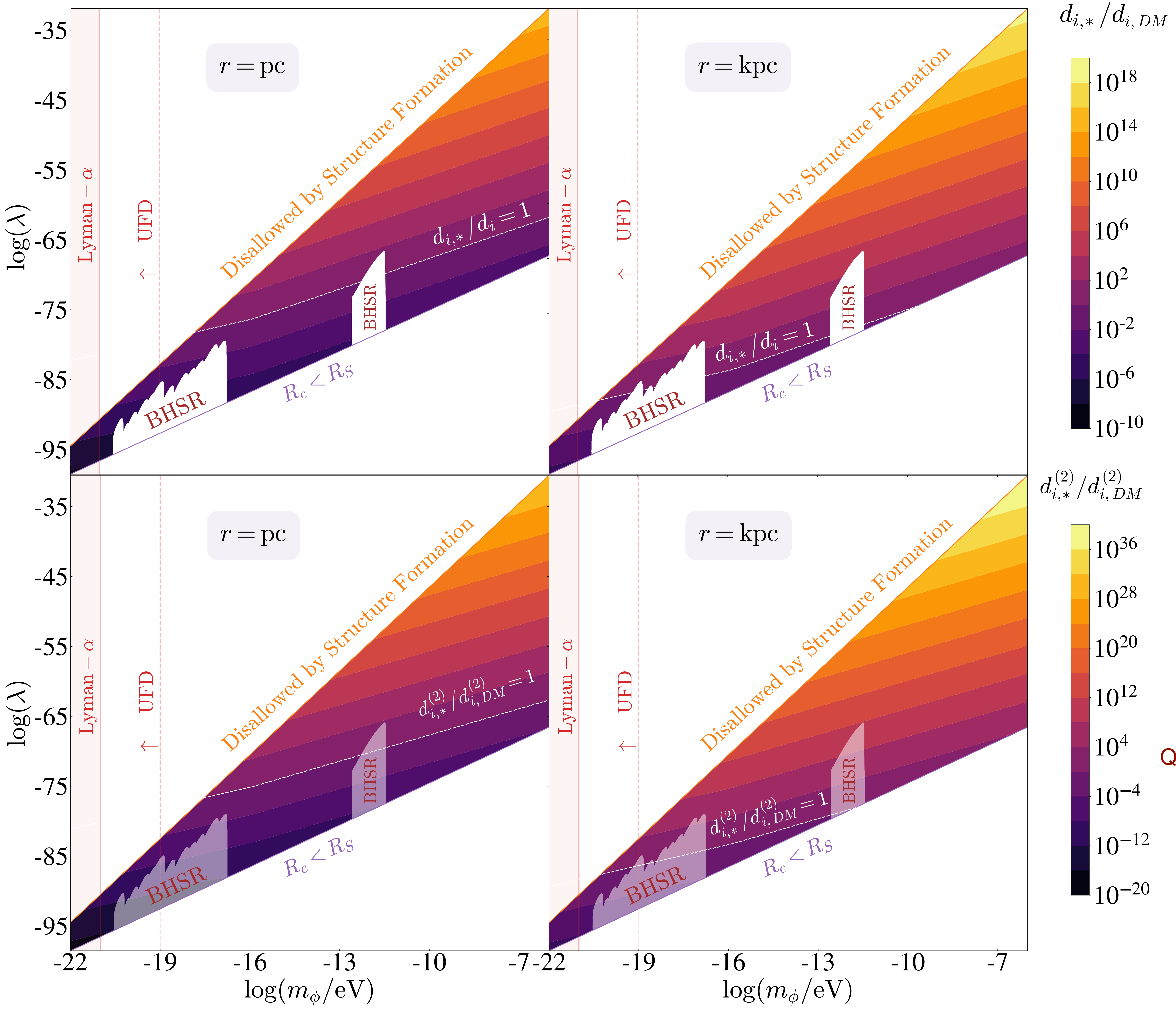
more relevant for atomic clocks, interferometers, and other quantum sensors

Recall (self-interactions)



Compute $\frac{d_*}{d_{\mathrm{DM}}}$ in this space

as a function of burst distance r



Sensitivity Ratio

Linear couplings (2306.16468) e.g. $\mathcal{L} \supset d_e \frac{\phi}{2M_{\text{Pl}}} F^{\mu\nu}F_{\mu\nu}$

Below the dotted line:

In a given quantum sensing experiment,

The signal from a nearby bosenova would be **as strong or stronger than** that of DM in the same parameter space

Quadratic couplings (2402.06736) e.g. $\mathcal{L} \supset d_e^{(2)} \left(\frac{\phi}{2M_{\text{Pl}}}\right)^2 F^{\mu\nu}F_{\mu\nu}$

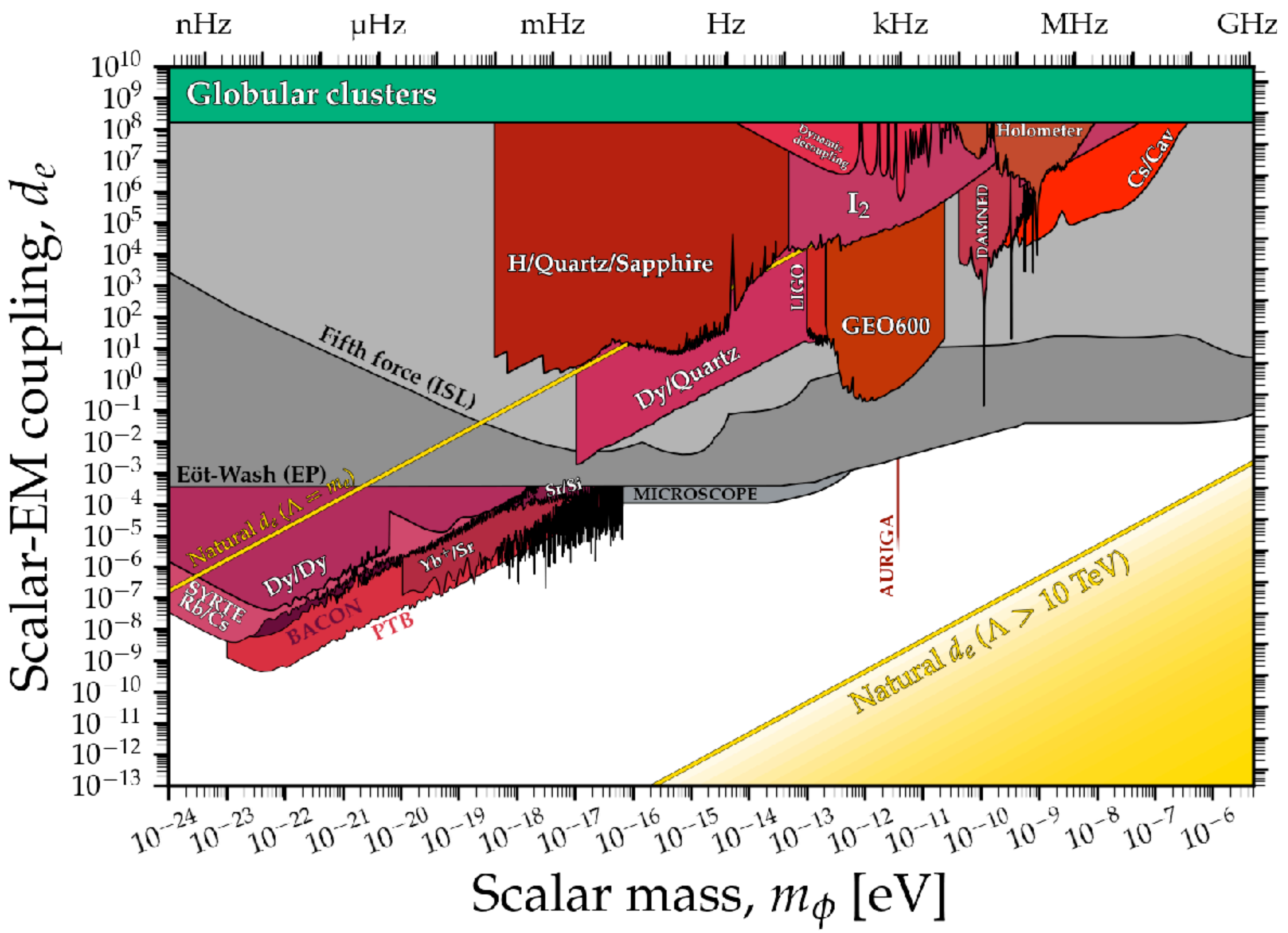
Interrogation time: $t_{\text{int}} = 1$ year

Observables

Coupling to photons

Oscillation of fine-structure constant

$$\mathscr{L} \supset d_e \frac{\phi}{2M_{\rm Pl}} F^{\mu\nu} F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$



Observables

Coupling to photons

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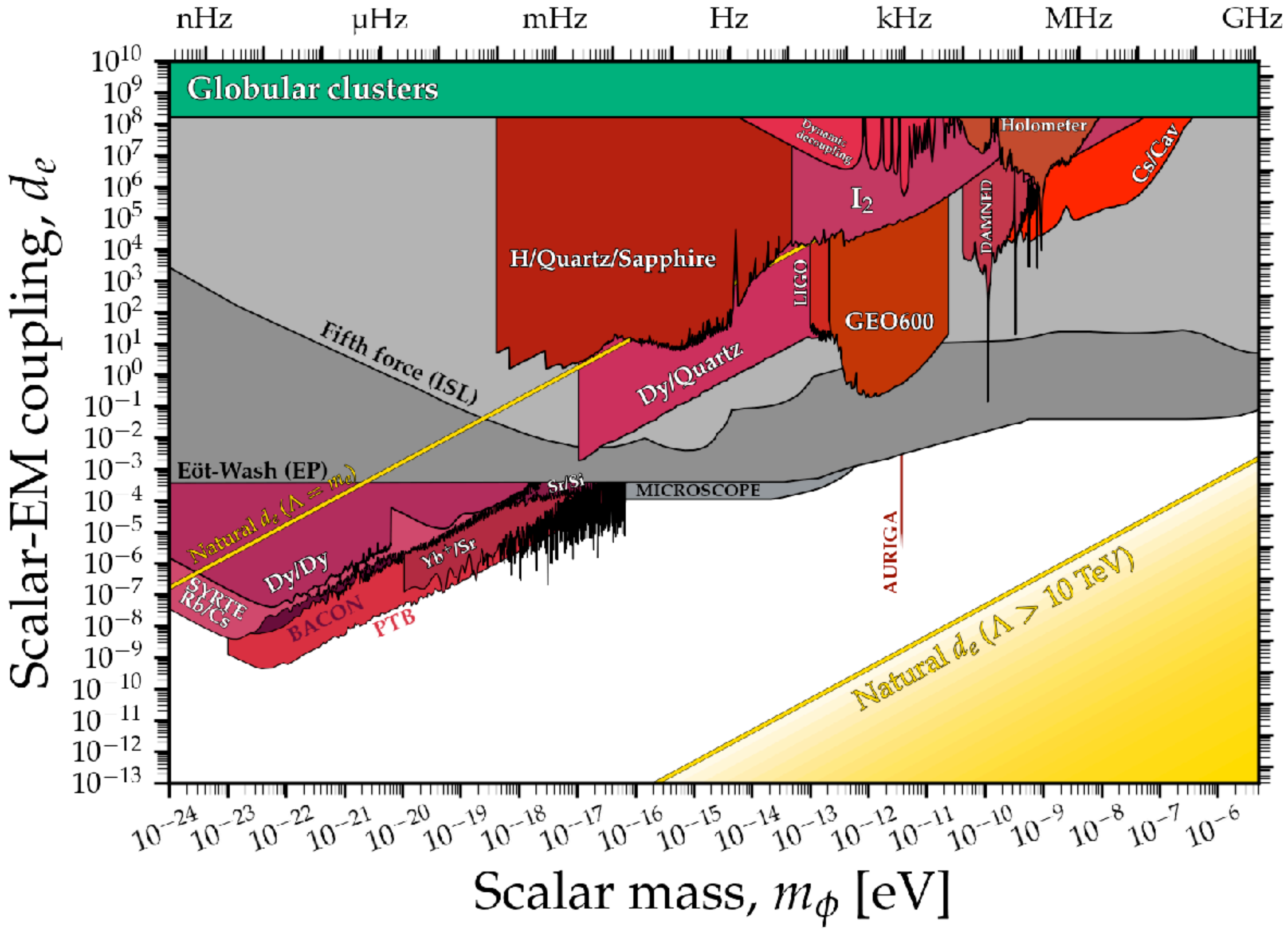
Oscillation of fine-structure constant



Coupling to electrons

$$\mathcal{L} \supset d_{m_e} \frac{\phi}{2M_{\rm Pl}} \bar{e}e \longrightarrow \frac{m_e}{m_p} \to \frac{m_e}{m_p} + \frac{\delta m_e(d_{m_e}, \rho, m_\phi)}{m_p}$$

Oscillation of electron-proton mass ratio

Coupling to gluons

$$\mathcal{L} \supset d_g \frac{\phi}{2M_{\rm Pl}} G^{a\mu\nu}G^a_{\mu\nu}$$

Coupling to quarks

$$\mathcal{L} \supset d_{m_q} \frac{\phi}{2M_{\rm Pl}} \bar{q}q$$

$$\frac{m_q}{\Lambda_{\rm QCD}} \to \frac{m_q}{\Lambda_{\rm QCD}} + \delta\left(\frac{m_q}{\Lambda_{\rm QCD}}\right)(d_{m_q}, d_g, \rho, m_\phi)$$

Oscillation of ratio of quark mass to QCD scale

Observables

This talk

Coupling to photons

$$\mathscr{L} \supset d_e \frac{\phi}{2M_{\rm Pl}} F^{\mu\nu} F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$

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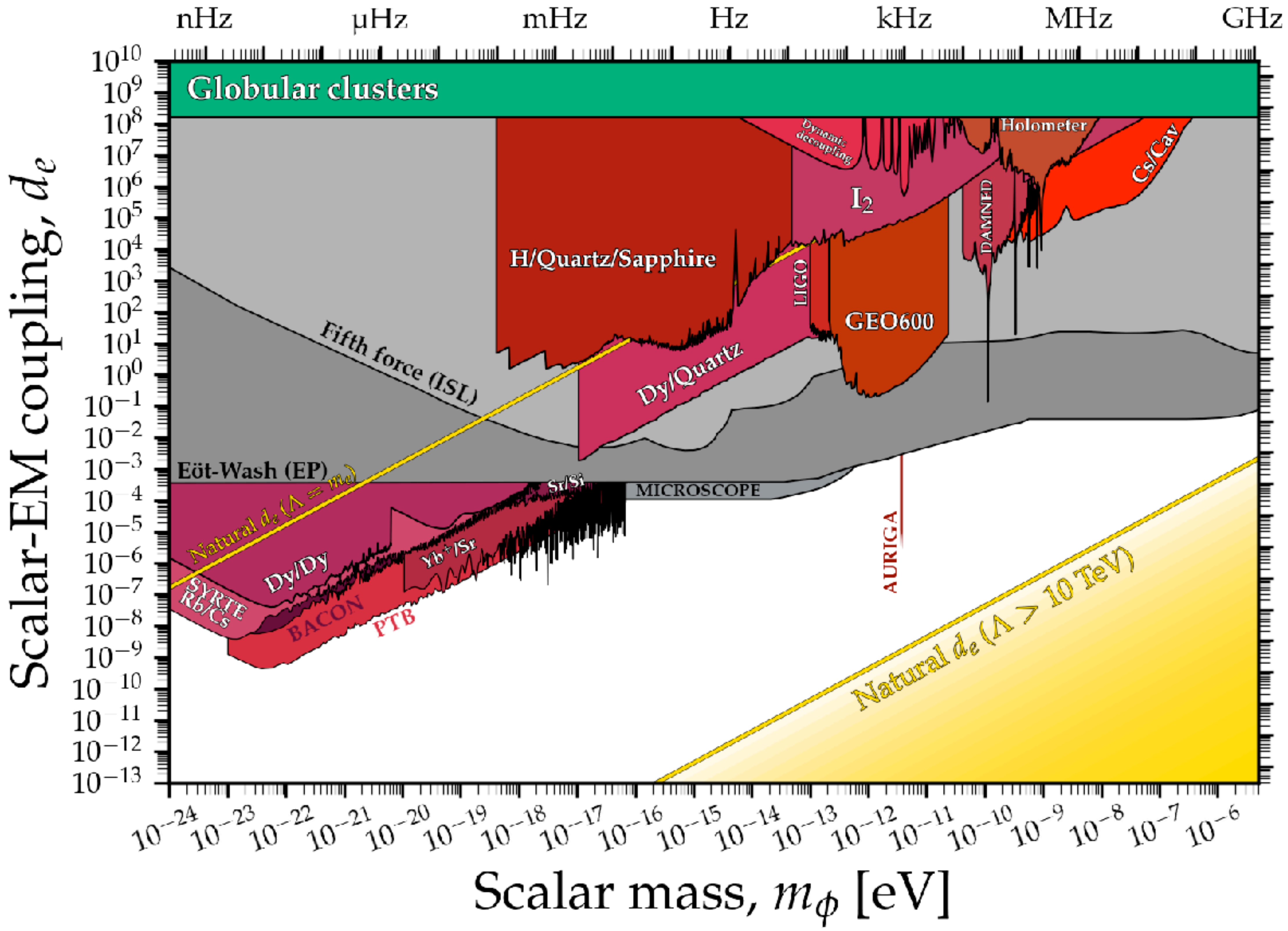

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Oscillation of ratio of quark mass to QCD scale

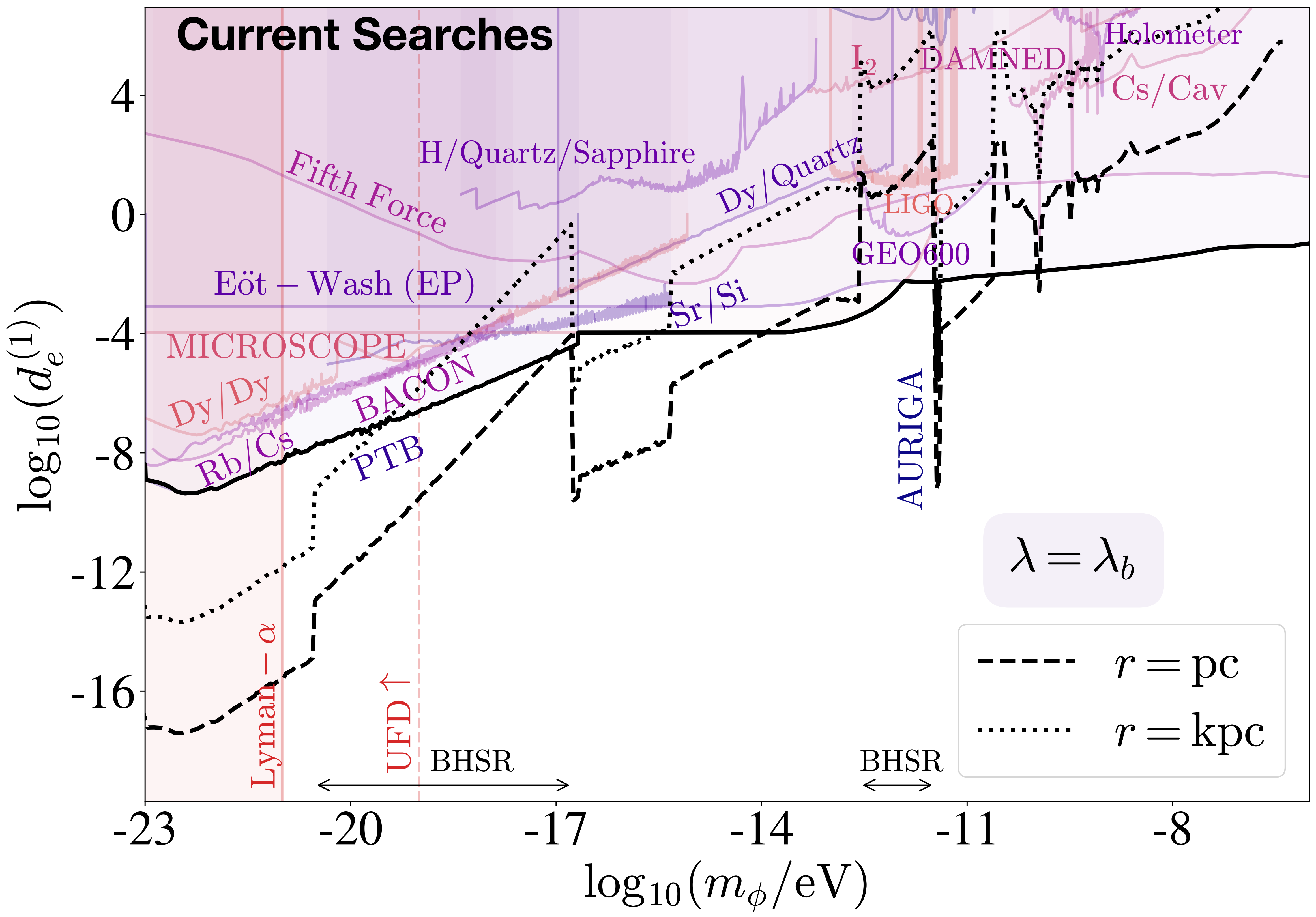
Searches for Photon Couplings

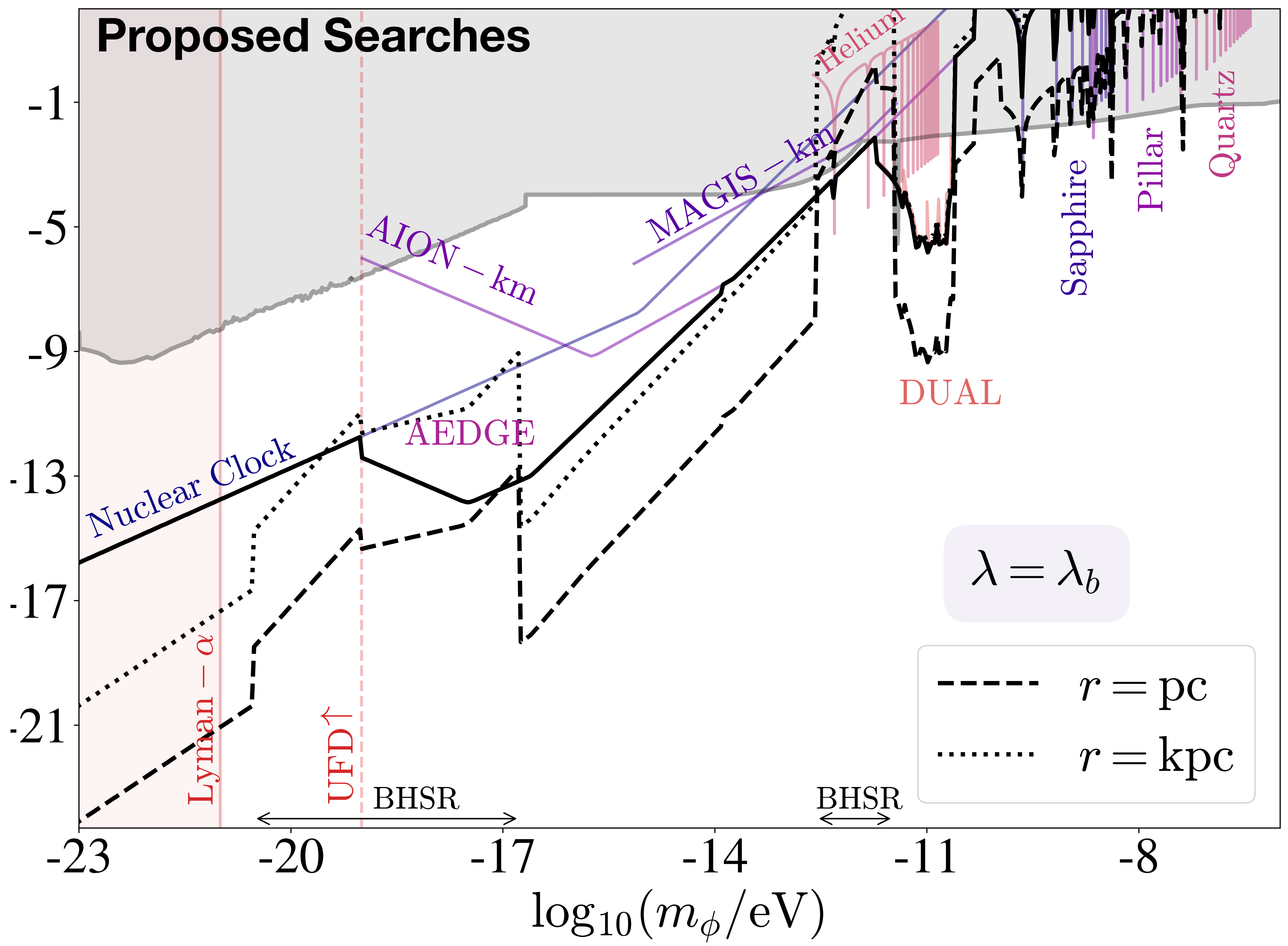
Coupling to photons

(linear)

Oscillation of fine-structure constant

$$\mathscr{L} \supset d_e \frac{\phi}{2M_{\mathrm{Pl}}} F^{\mu\nu}F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$





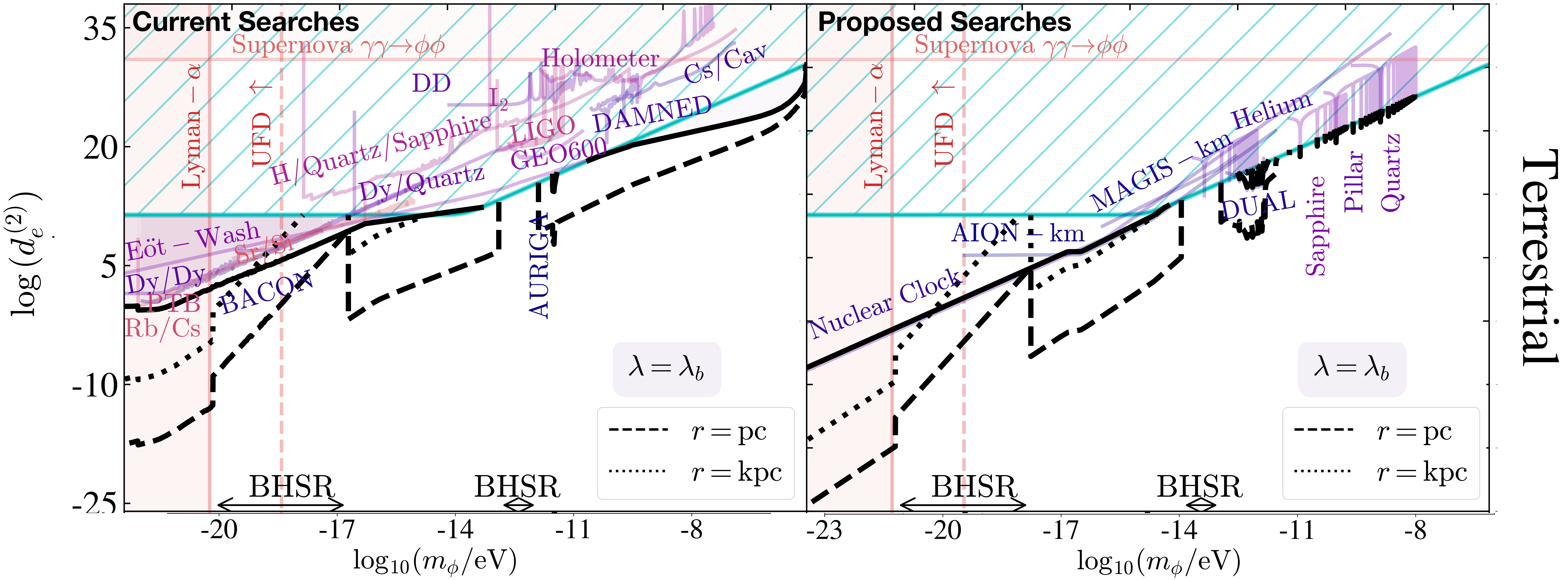
Searches for Photon Couplings

Coupling to photons

(quadratic)

Oscillation of fine-structure constant

$$\mathscr{L} \supset d_e^{(2)} \left(\frac{\phi}{2M_{\rm Pl}} \right)^2 F^{\mu\nu} F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$



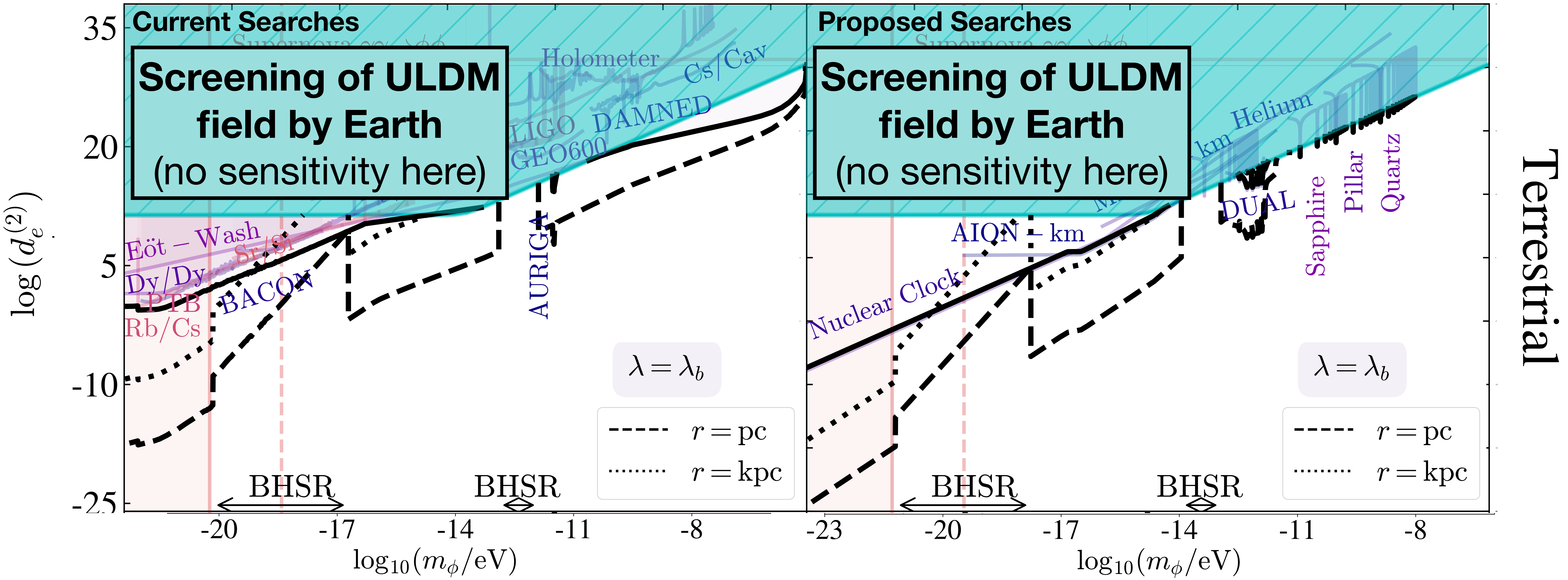
Searches for Photon Couplings

Coupling to photons

(quadratic)

Oscillation of fine-structure constant

$$\mathscr{L} \supset d_e^{(2)} \left(\frac{\phi}{2M_{\rm Pl}}\right)^2 F^{\mu\nu}F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$



Conclusions

- Ultralight dark matter fields induce oscillation of fundamental constants, leading to world-leading constraints on ULDM couplings to the Standard Model from quantum sensing experiments

- Relativistic bursts of ULDM particles, originating in astrophysical processes (like *bosenovae* from boson star collapse) lead to signals in the very same experiments. A long-baseline atom interferometer would be extremely useful for detection of such signals!

- Bosenova signals allow sensitivity to extremely weakly-coupled fields beyond current EP limits, even for masses up to $m_\phi \sim 10^{-11}\,\mathrm{eV}$ (kHz); can push to $m_\phi \sim 10^{-8}\,\mathrm{eV}$ (MHz) in the future

- At present, detection is viable but exclusion is difficult; need stronger prediction of burst rate

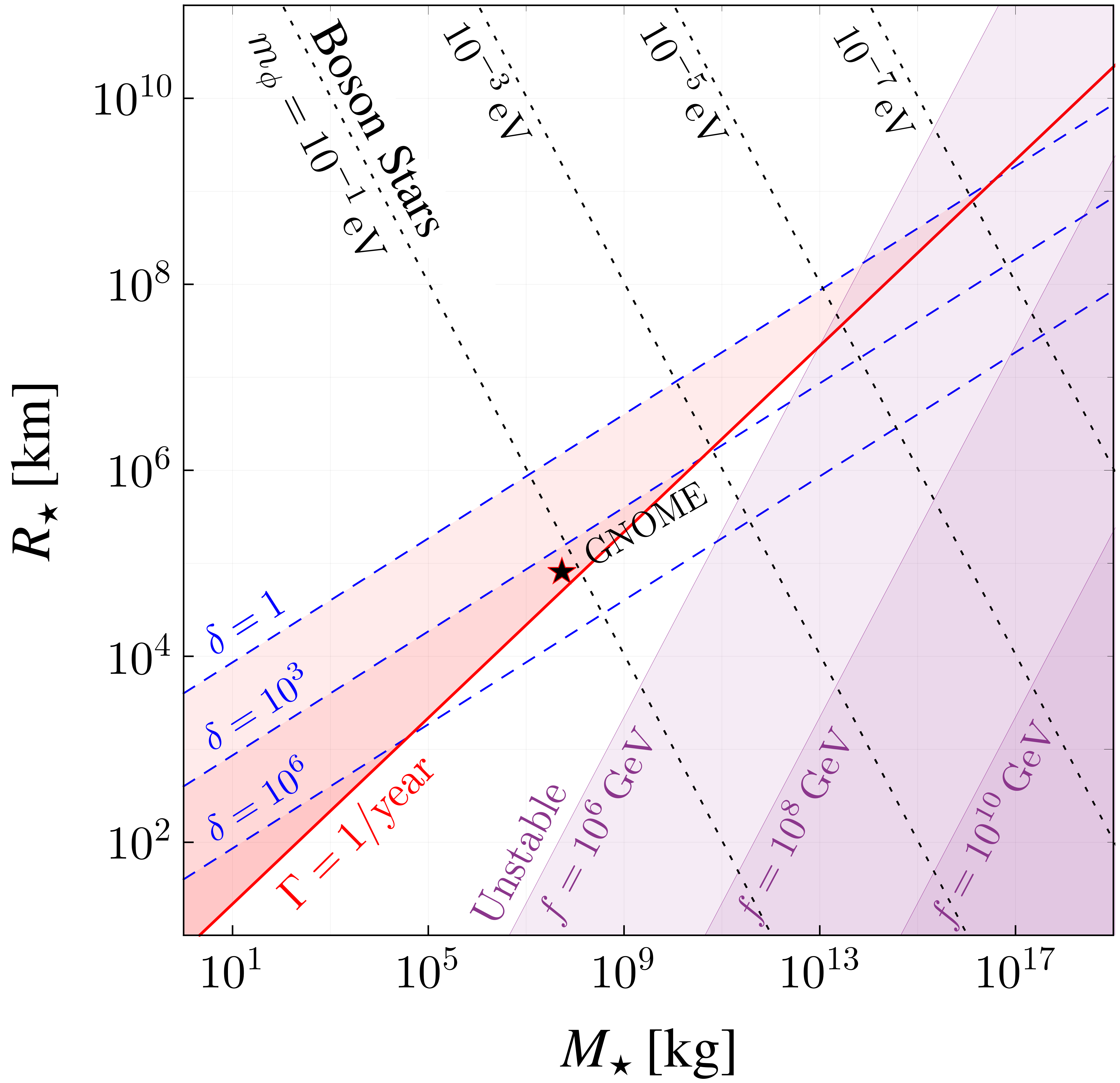
- Future experiments (including a TVLBAI!) will be able to set strict limits on ULDM self-interactions and thereby probe underlying fundamental models far beyond what is possible with DM searches

Thank you for your attention!

Backup Slides

Banerjee, Budker, **JE**, Kim, Perez (1902.08212)

Boson Star Encounters



Overdensity

$$\delta \equiv \frac{\rho_\star}{\rho_{\rm dm}} \propto \rho_{local}^{-1} R_\star^{-4} m_\phi^{-2}$$

Encounter rate

$$\Gamma \equiv \frac{\rho_{\rm dm}}{M_\star} \sigma_\star v_\star \propto \rho_{local} R_\star^3 m_\phi^2$$

Both parameters are only significant when

$$m_\phi \gtrsim 10^{-7}\,\text{eV}$$

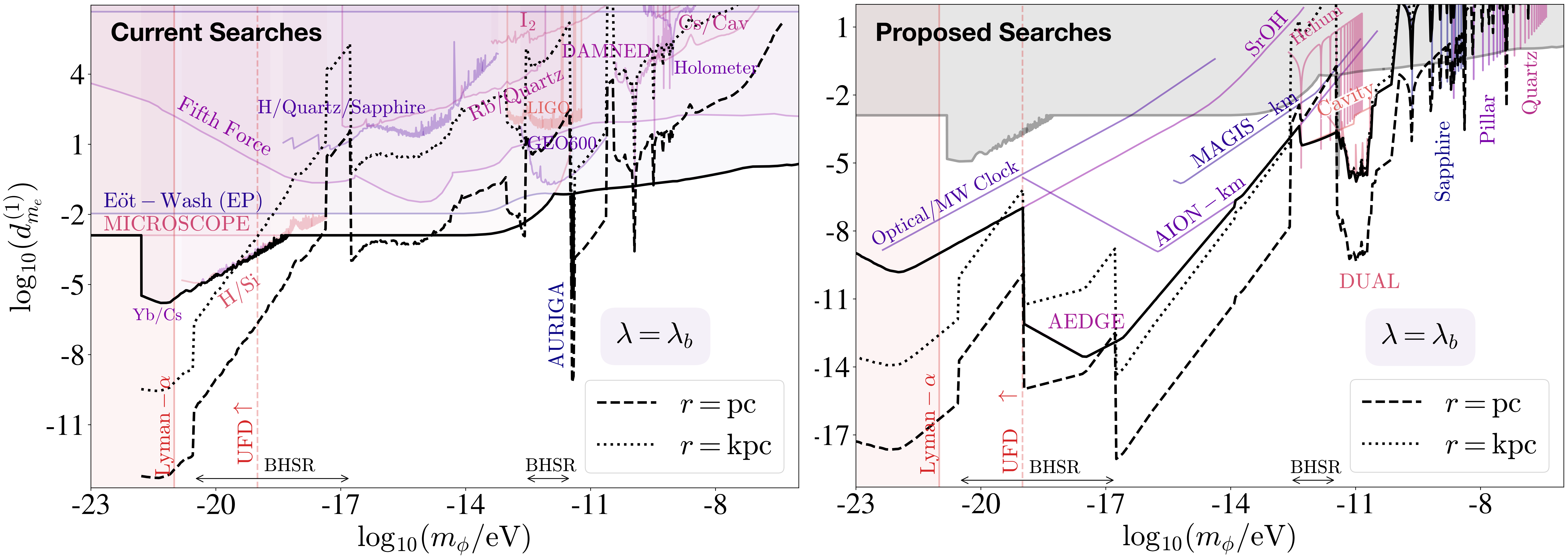
Searches for Electron Couplings

Coupling to electrons

$$\mathscr{L} \supset d_{m_e} \frac{\phi}{2M_{\rm Pl}} \bar{e}e \longrightarrow$$

Oscillation of electron-proton mass ratio

$$\frac{m_e}{m_p} \to \frac{m_e}{m_p} + \frac{\delta m_e(d_{m_e}, \rho, m_\phi)}{m_p}$$



Searches for Gluon Couplings

Coupling to gluons

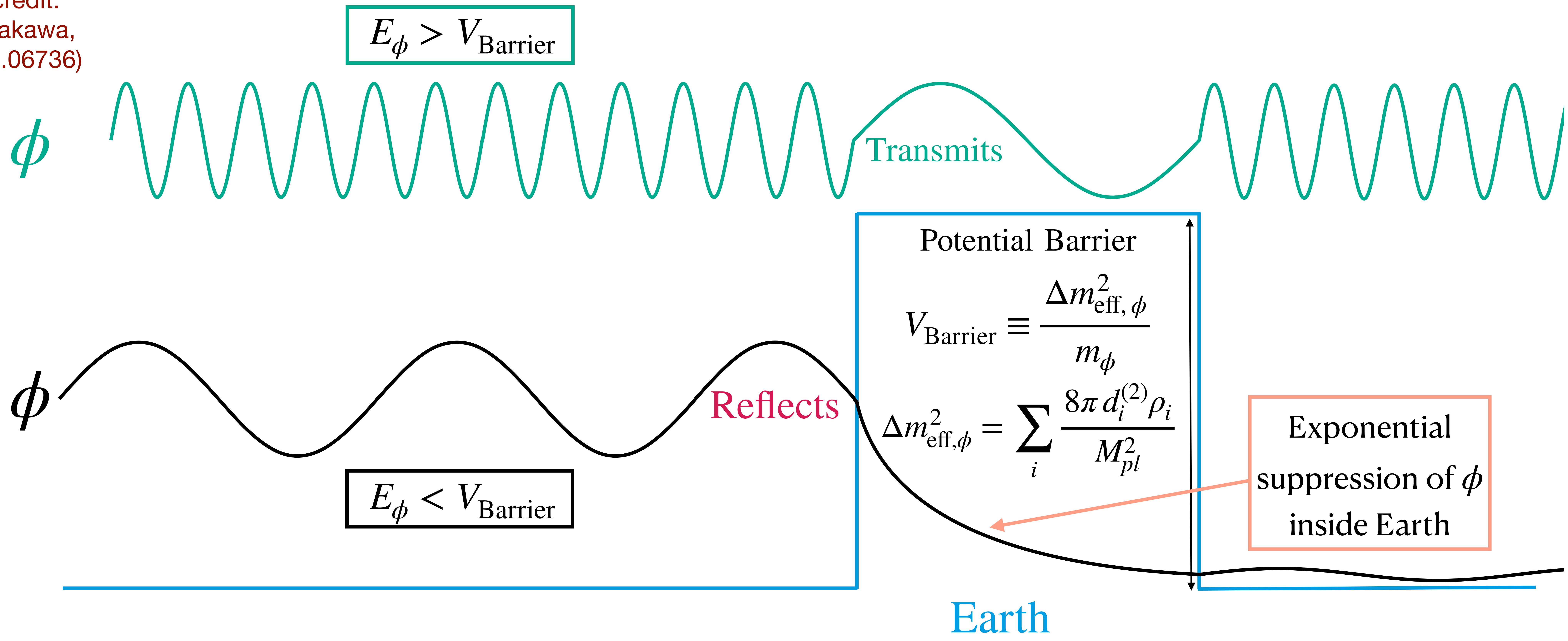
$$\mathscr{L} \supset d_g \frac{\phi}{2M_{\rm Pl}} G^{a\mu\nu} G^a_{\mu\nu}$$

Oscillation of ratio of quark mass to QCD scale

$$\frac{m_q}{\Lambda_{\rm QCD}} \to \frac{m_q}{\Lambda_{\rm QCD}} + \delta\left(\frac{m_q}{\Lambda_{\rm QCD}}\right)(d_g, \rho, m_\phi)$$

Screening (Quadratic Couplings)

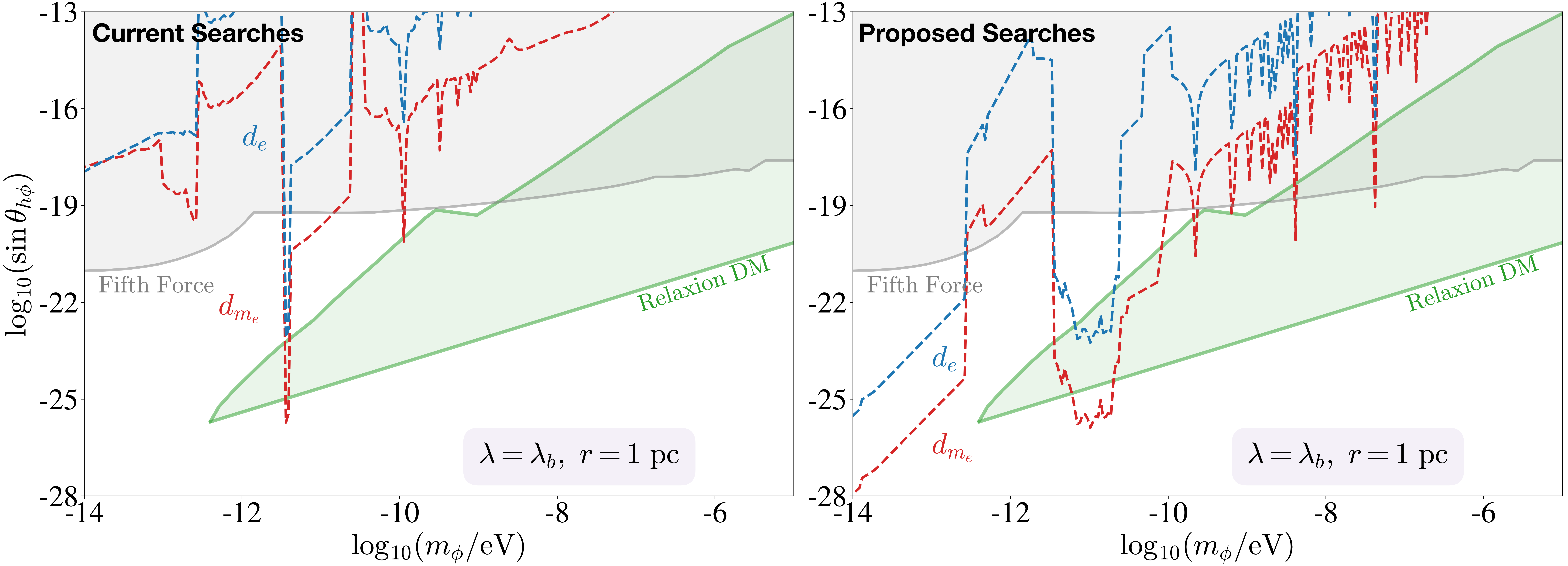
Image credit:
Jason Arakawa,
see (2402.06736)



$$\mathscr{L} \supset \frac{m_\phi^2}{2}\phi^2 + d_{m_e}^{(2)}\left(\frac{\phi}{2M_{\rm Pl}}\right)^2 m_e \bar{e} e \simeq \frac{m_\phi^2}{2}\phi^2 + d_{m_e}^{(2)}\left(\frac{\phi}{2M_{\rm Pl}}\right)^2 \rho_e \simeq \frac{m_\phi^2 + \Delta m_\phi^2}{2}\phi^2$$

Banerjee, Kim, Perez (1810.01889)
Chatrchyan, Servant (2211.15694)

Search for Relaxion DM

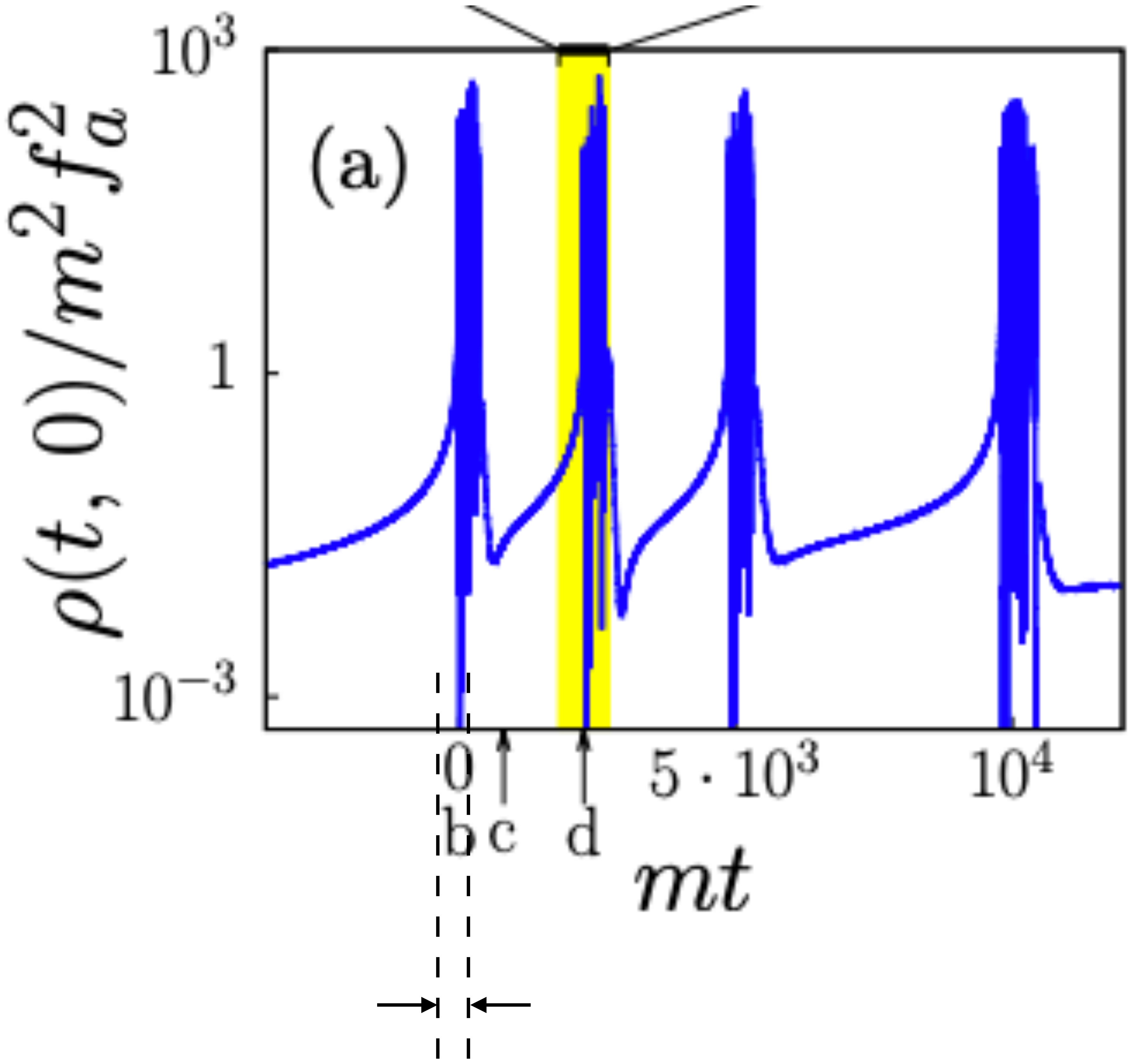


Levkov, Panin, Tkachev
(1609.03611)

Simulation Results

Levkov, Panin, Tkachev (1609.03611)

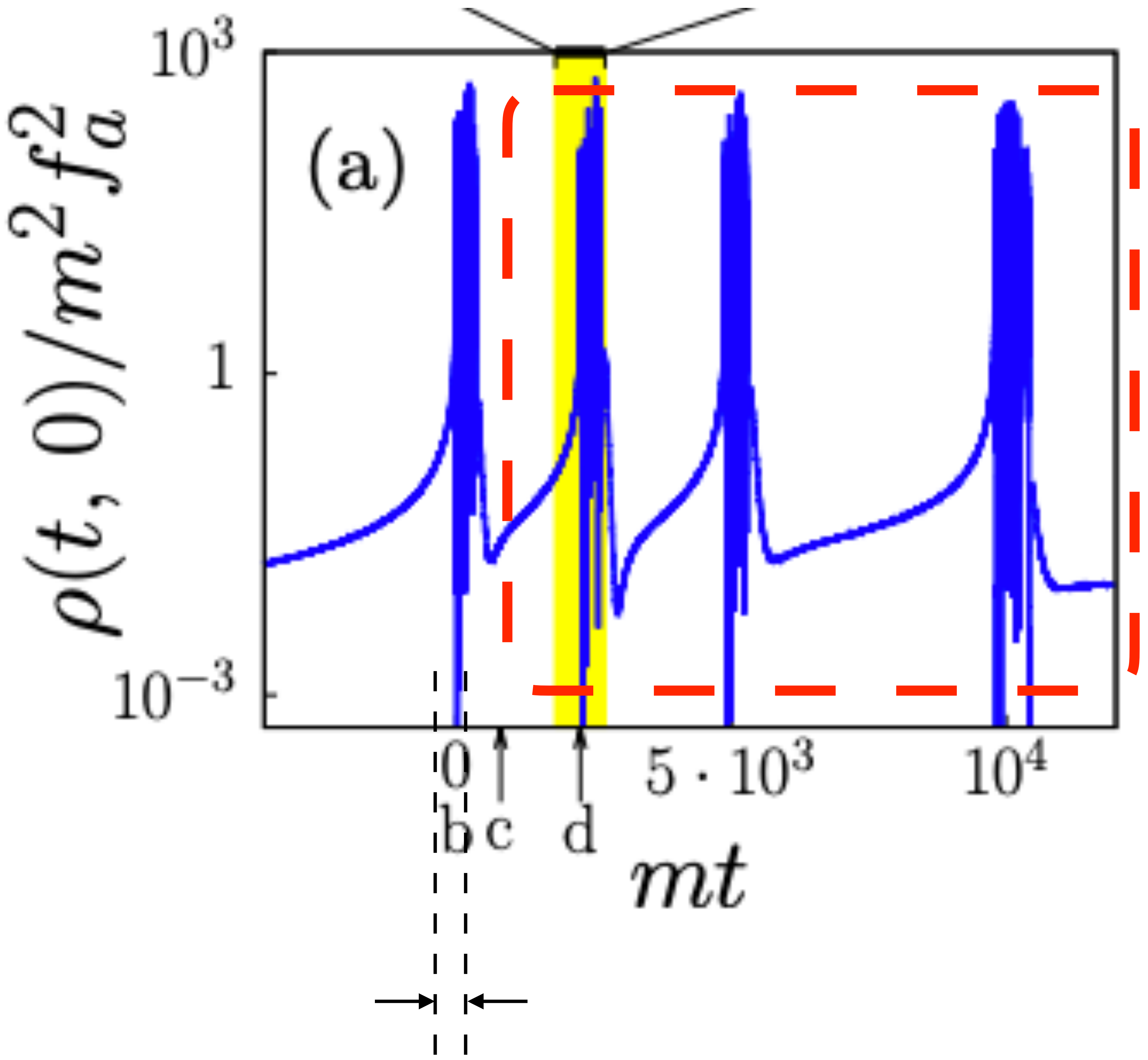
Simulation Results



Short duration $\delta t_{\rm burst} \sim \mathcal{O}(400)/m$

Levkov, Panin, Tkachev (1609.03611)

Simulation Results



Multiple explosions per collapse! (Ignored here)

Short duration $\delta t_{\rm burst} \sim \mathcal{O}(400)/m$

Levkov, Panin, Tkachev
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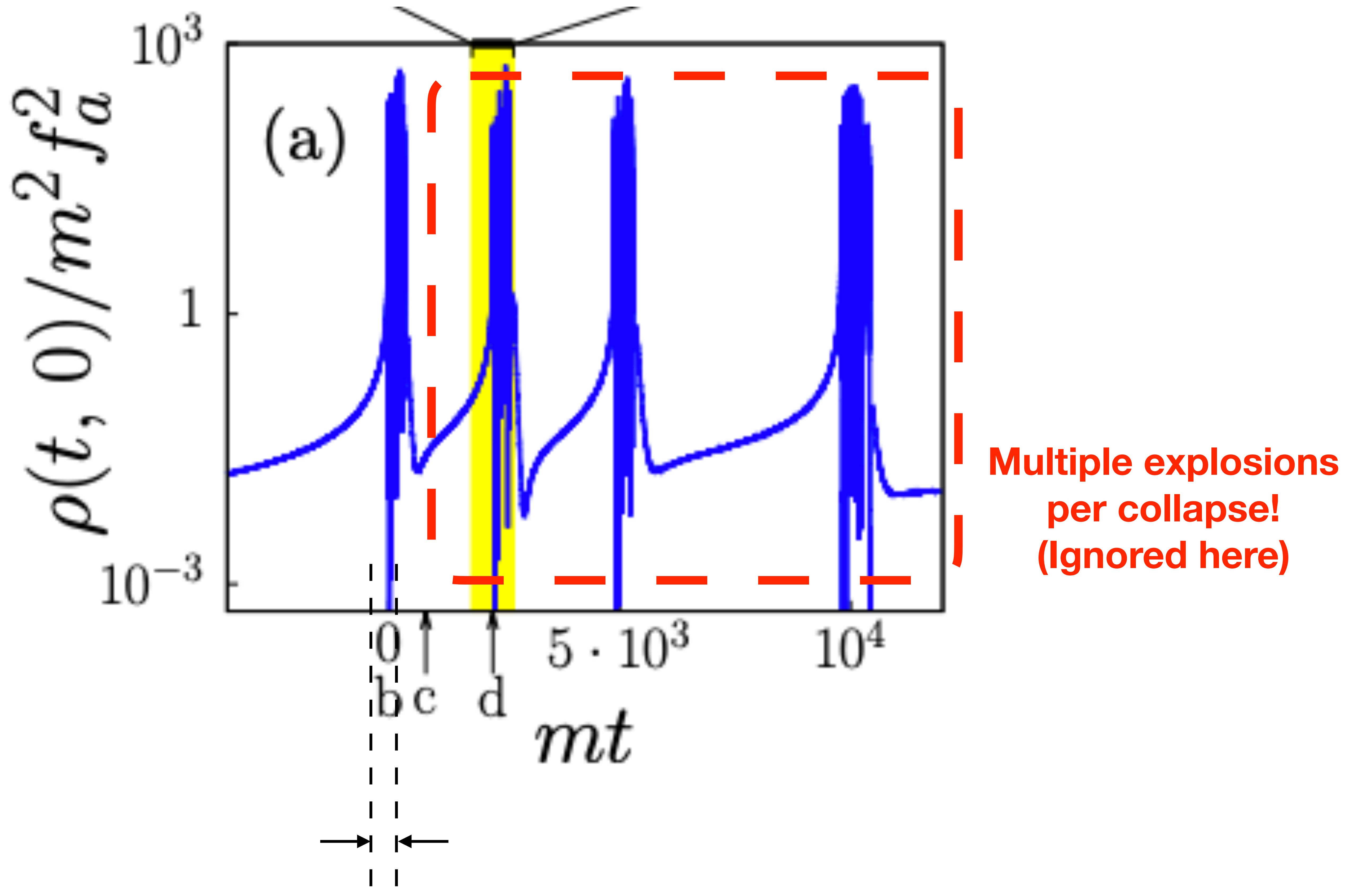
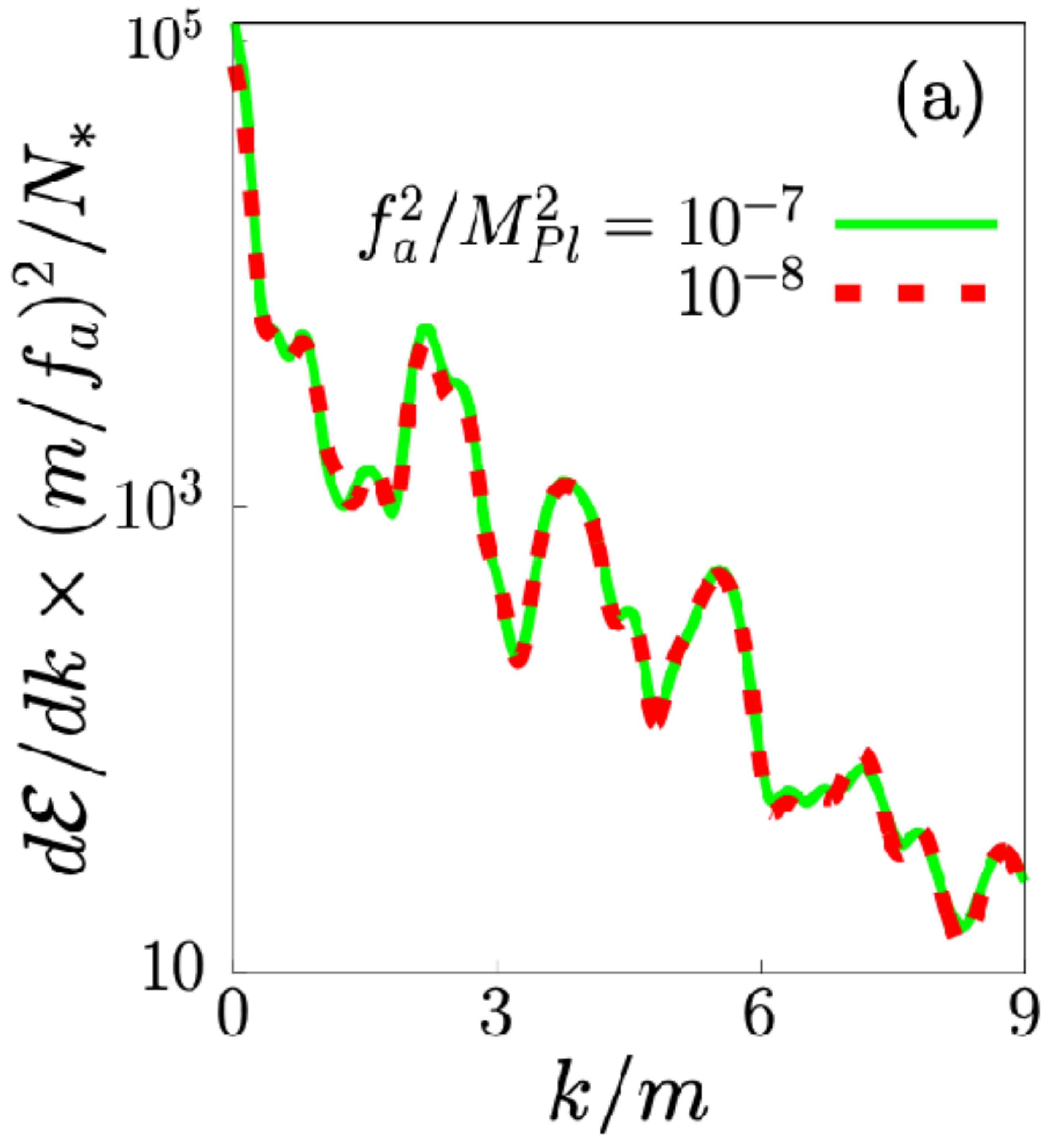
Simulation Results





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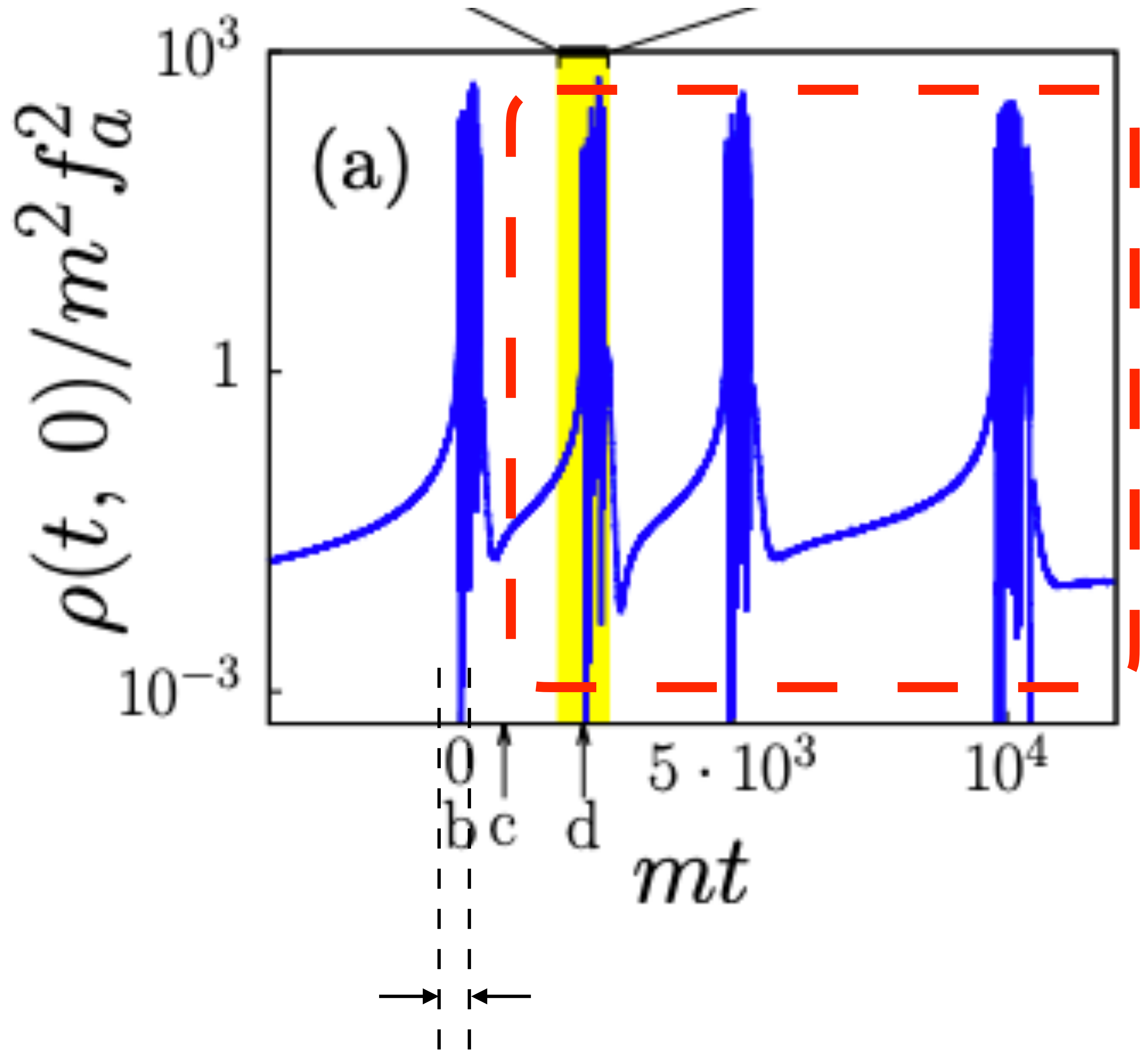
Levkov, Panin, Tkachev (1609.03611)

Simulation Results

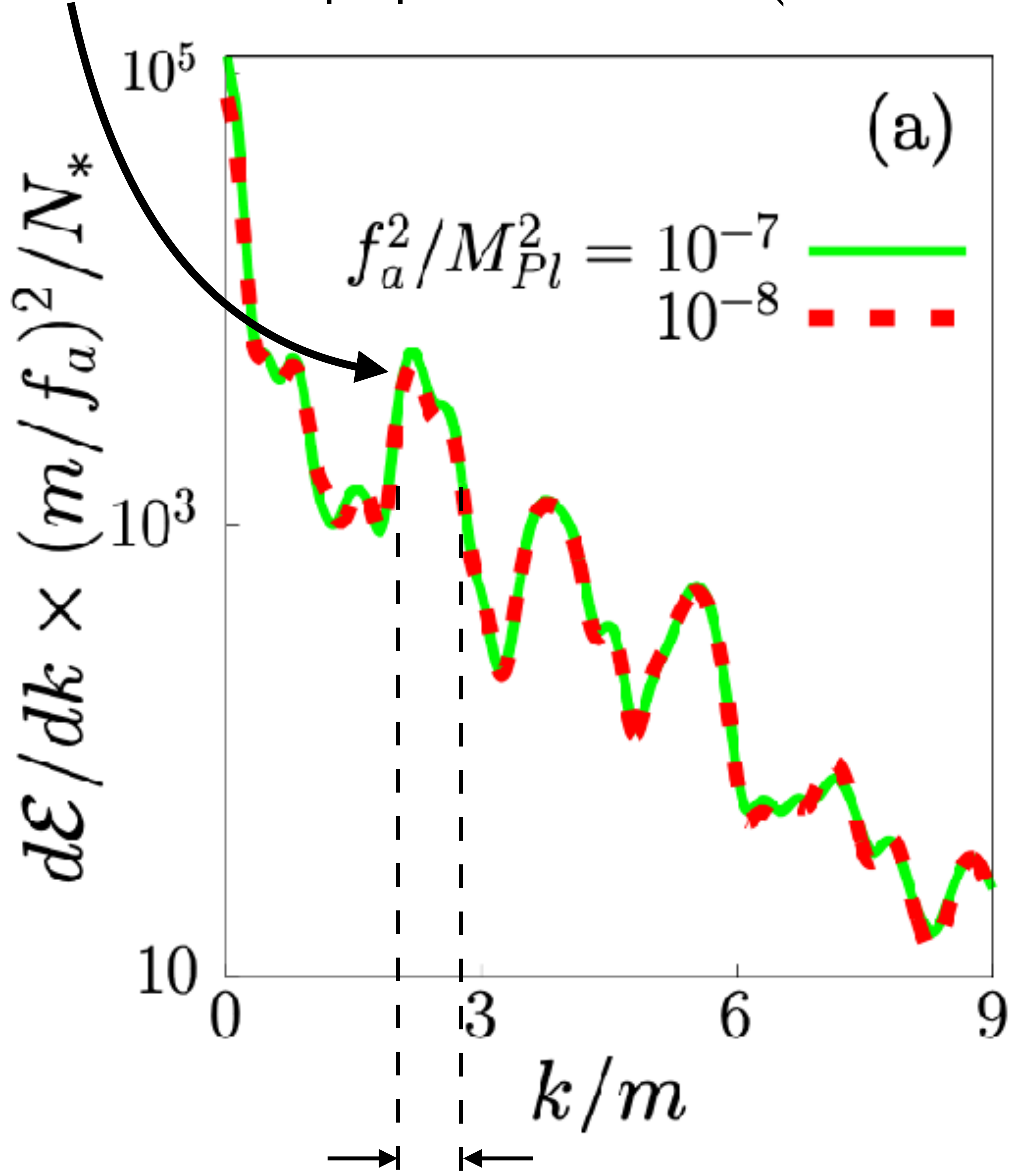


Short duration $\delta t_{\text{burst}} \sim \mathcal{O}(400)/m$

Multiple explosions per collapse! (Ignored here)

Large integrated energy! In first peak alone,

$$\mathcal{E}_{\text{peak}} \approx 3400\frac{m}{|\lambda|} \simeq 10^2 M_\odot \left(\frac{f}{10^{16}\,\text{GeV}}\right)^2 \frac{10^{-15}\,\text{eV}}{m}$$

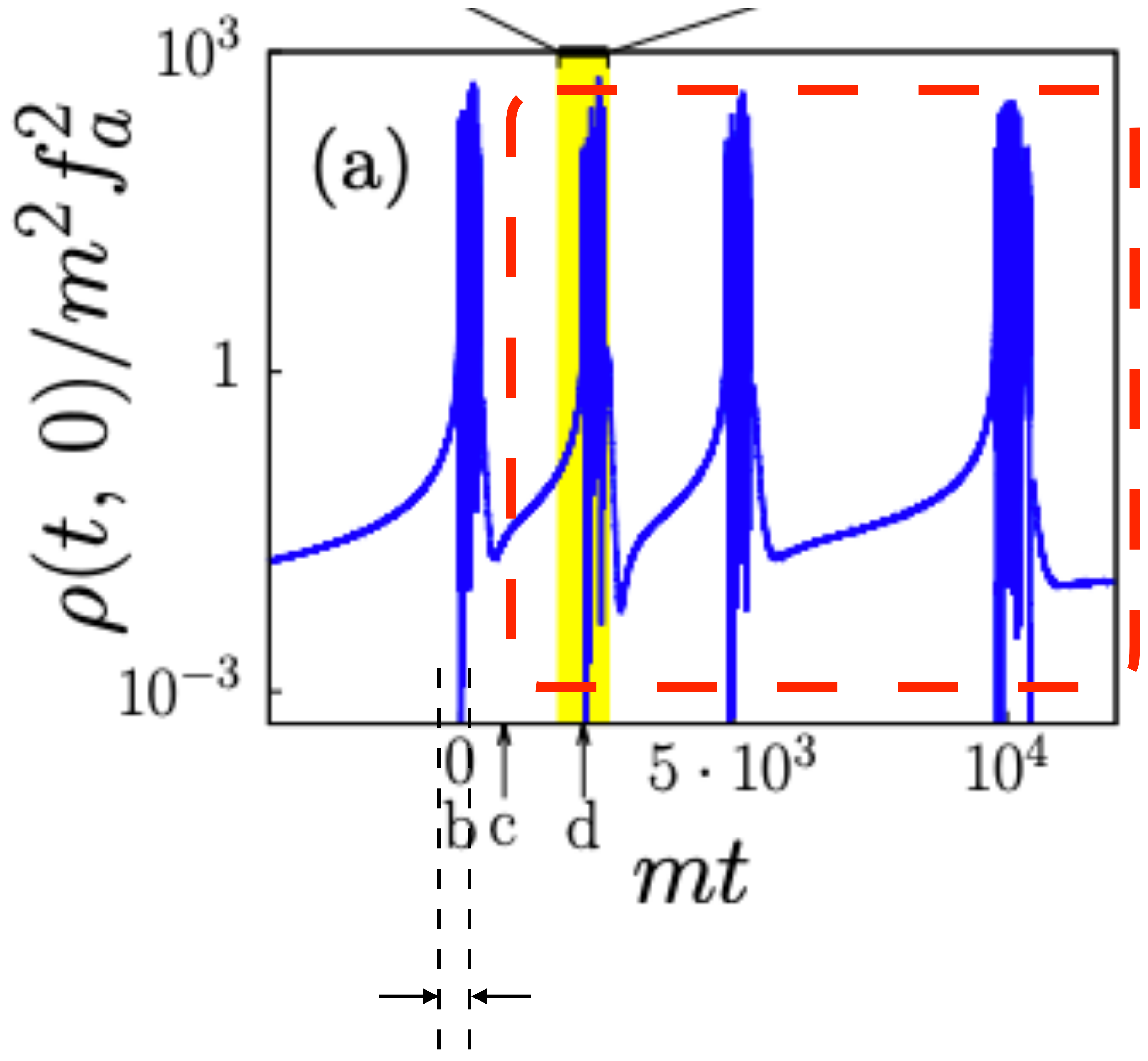


Momentum peak $k_0 \simeq 2.4\,m$

with spread of $\delta k \sim m$

Levkov, Panin, Tkachev (1609.03611)

Simulation Results



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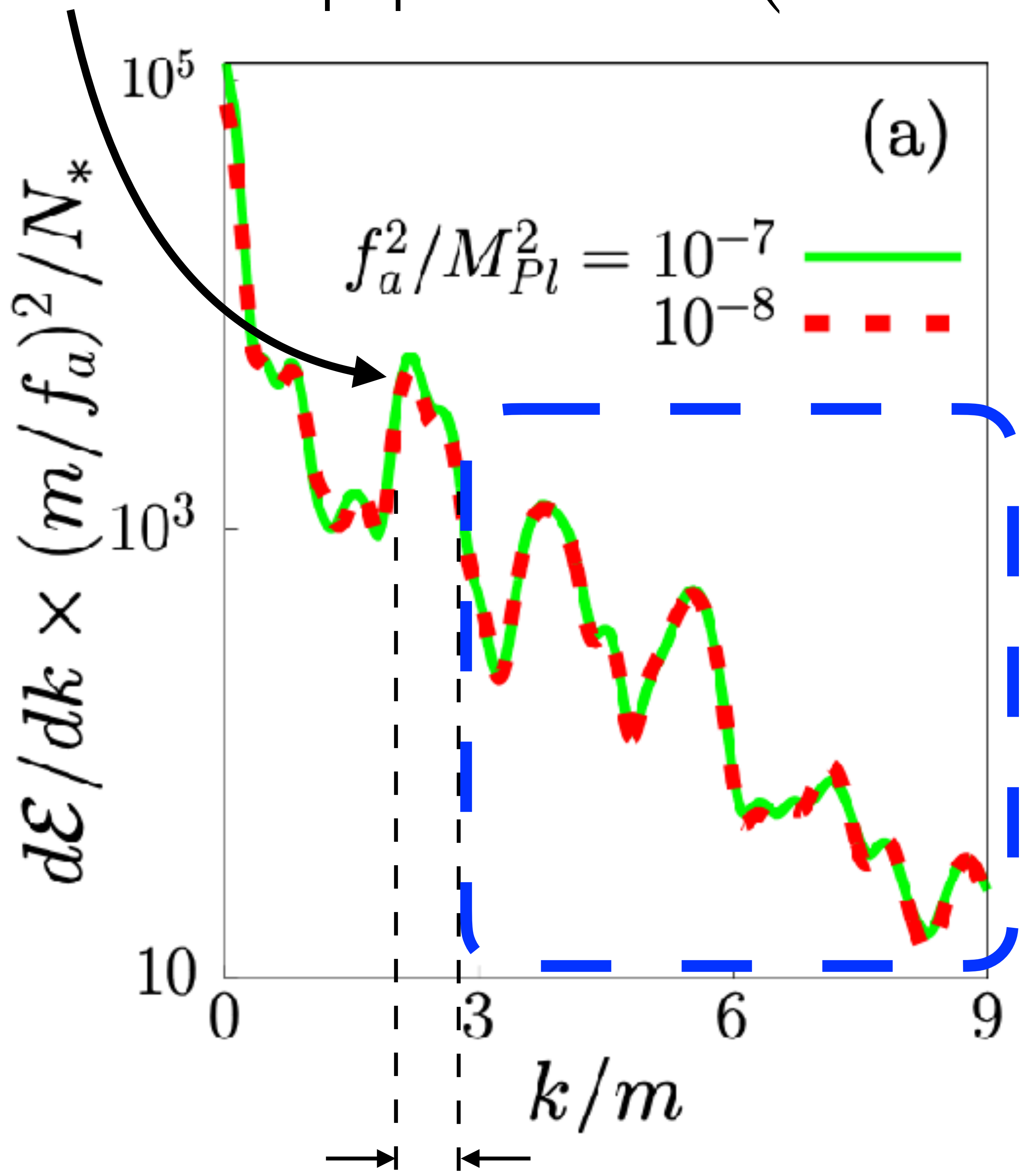


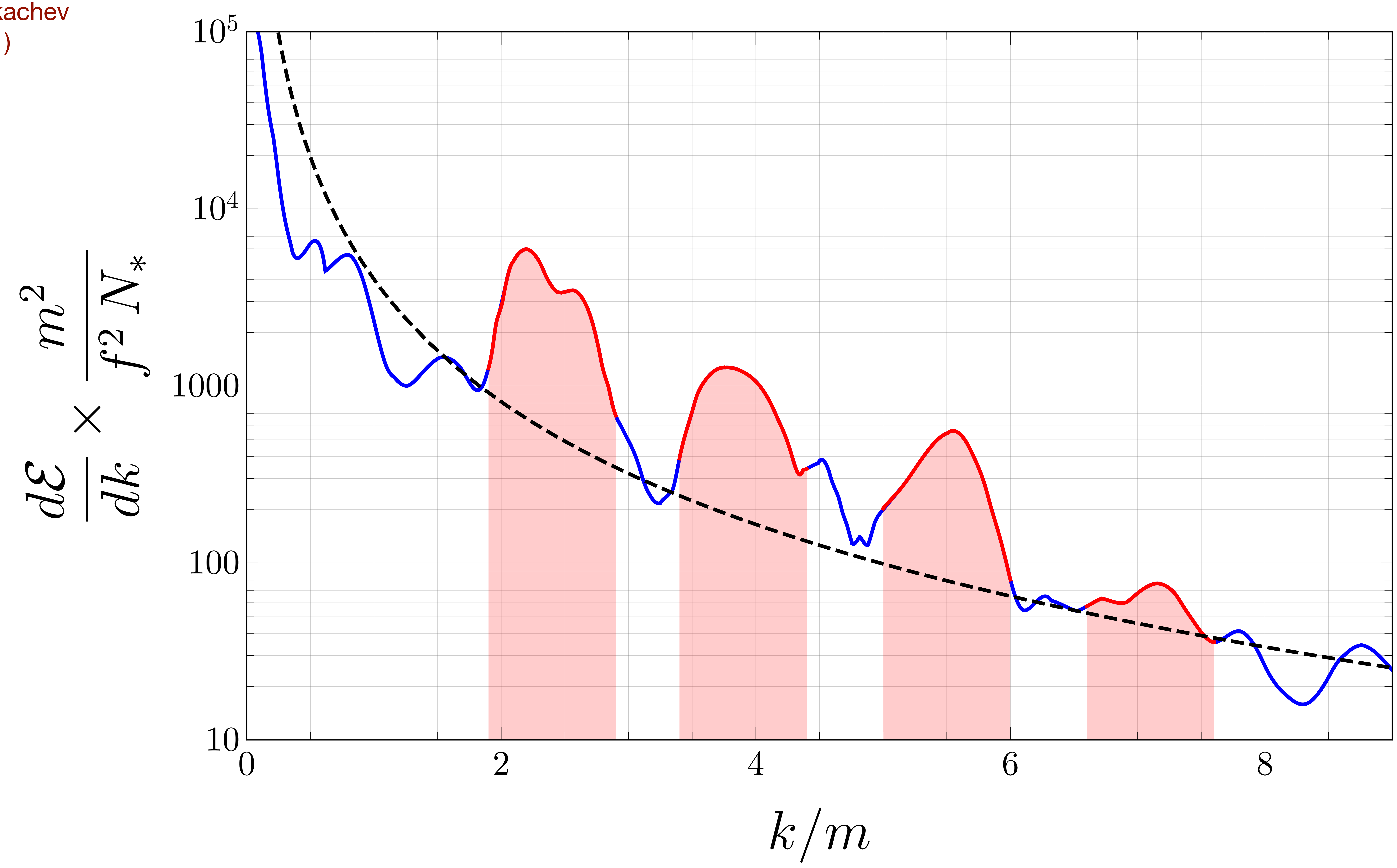
Higher-energy peaks! (Ignored here)

Momentum peak $k_0 \simeq 2.4\,m$

with spread of $\delta k \sim m$

Emission Spectrum from Boson Star Collapse

Levkov, Panin, Tkachev
(1609.03611)



JE, Takhistov (2402.00100)

Other Sources of Bursts