

# What the Stars Tell us About Dark Matter

Joachim Kopp (CERN & JGU Mainz)  
NOW 2018 | Ostuni, Italy | September 2018

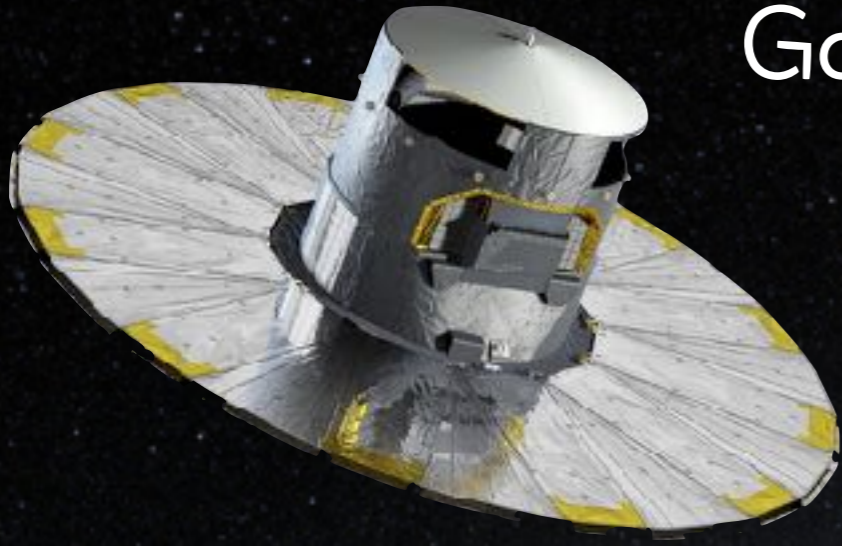


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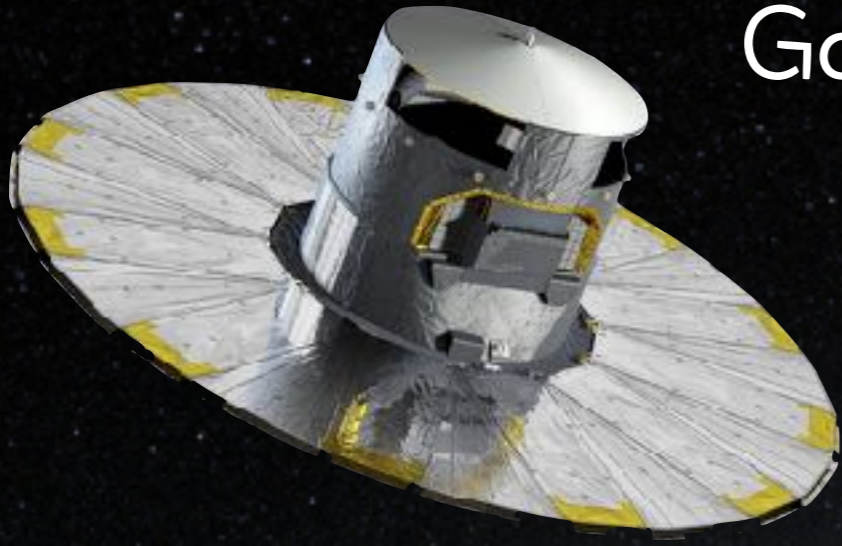




Gaia

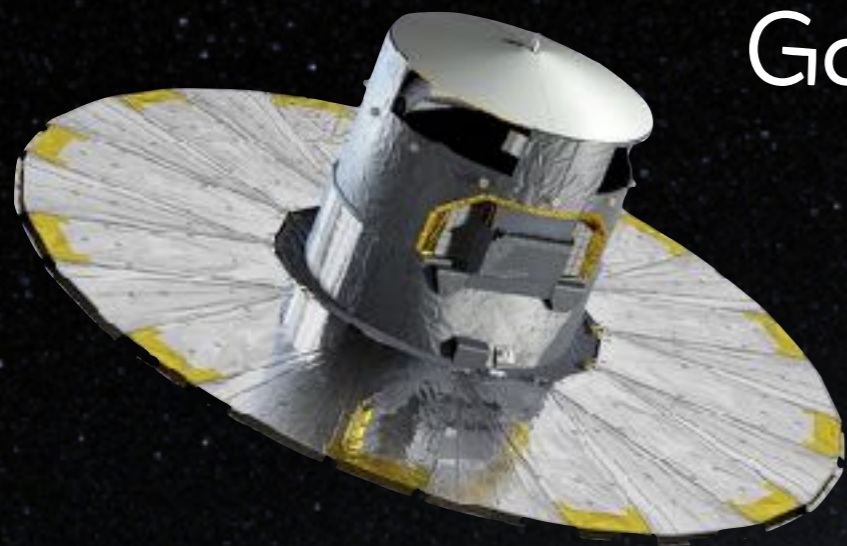


Gaia



Fermi





Gaia



LIGO



Fermi

# In this Talk

- ☑ **Gaia: Stellar Wakes**
  - Probing DM halo substructure
- ☑ **Fermi-LAT / GBM: Femtolensing of GRBs**
  - Constraints on Primordial Black Holes
- ☑ **LIGO / VIRGO: Modified Binary Inspirals**
  - Can dark sector forces cause deviations from GR predictions?

# Gaia

“Stellar Wakes” Probe the DM Halo



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**1600 kpc**

**via lactea II**

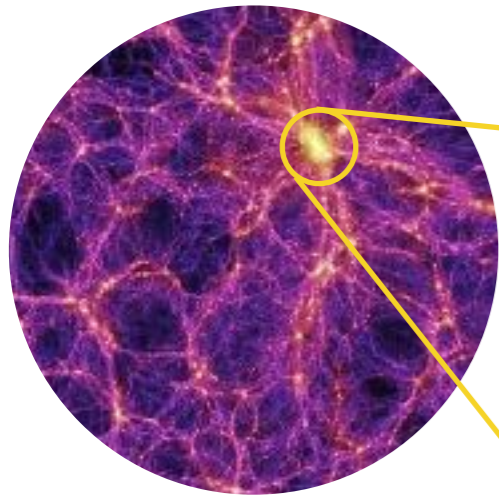
**Diemand, Kuhlen, Madau, Zemp, Moore, Potter, Stadel, 2008**

**1600 kpc**

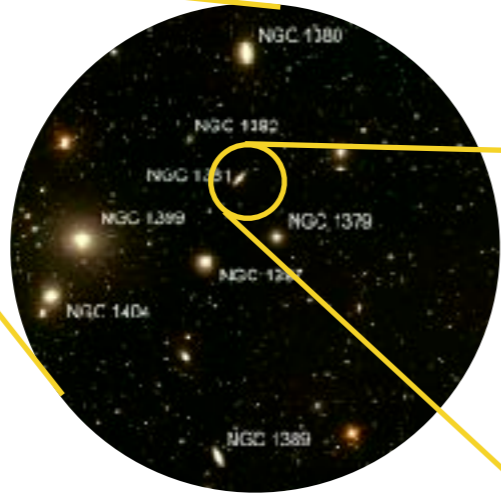
**via lactea II**

**Diemand, Kuhlen, Madau, Zemp, Moore, Potter, Stadel, 2008**

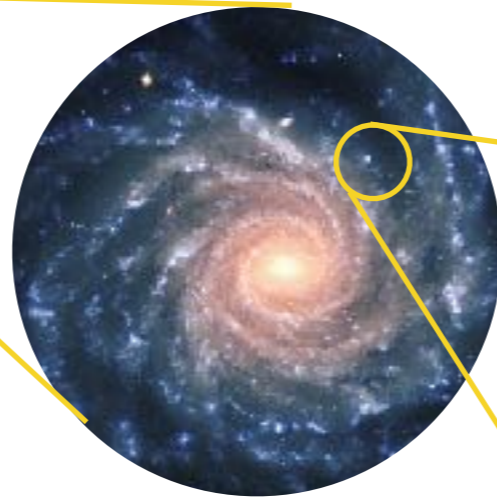
# Dark Matter Clustering Across the Scales



Cosmic Web  
~ Gpc



Galaxy Cluster  
~ Mpc



Galaxy  
~ 100 kpc



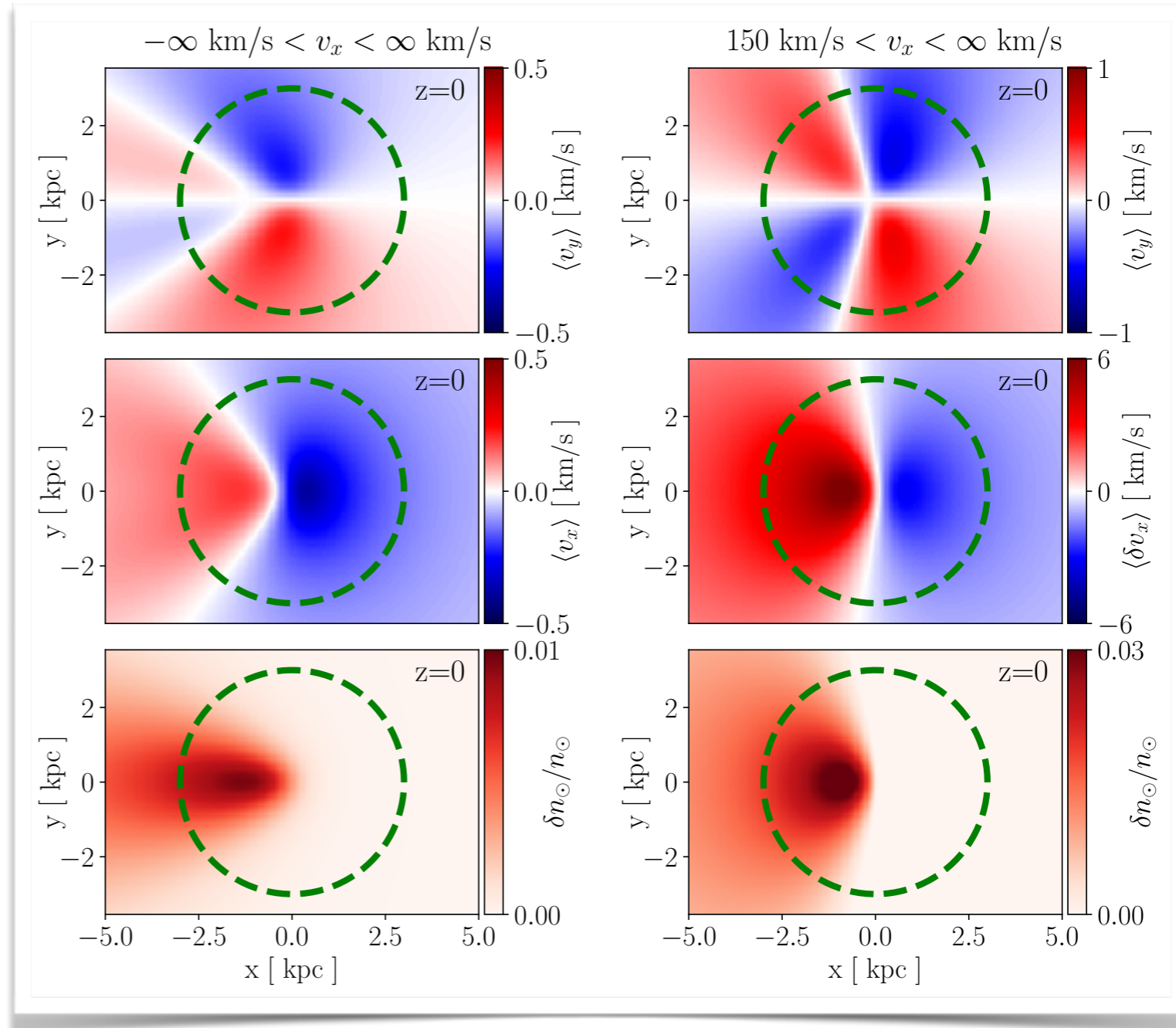
Dwarf Galaxy  
~kpc,  $\sim 10^9 M_{\odot}$



Unknown  
 $\ll 10^9 M_{\odot}$

# Stellar Wakes

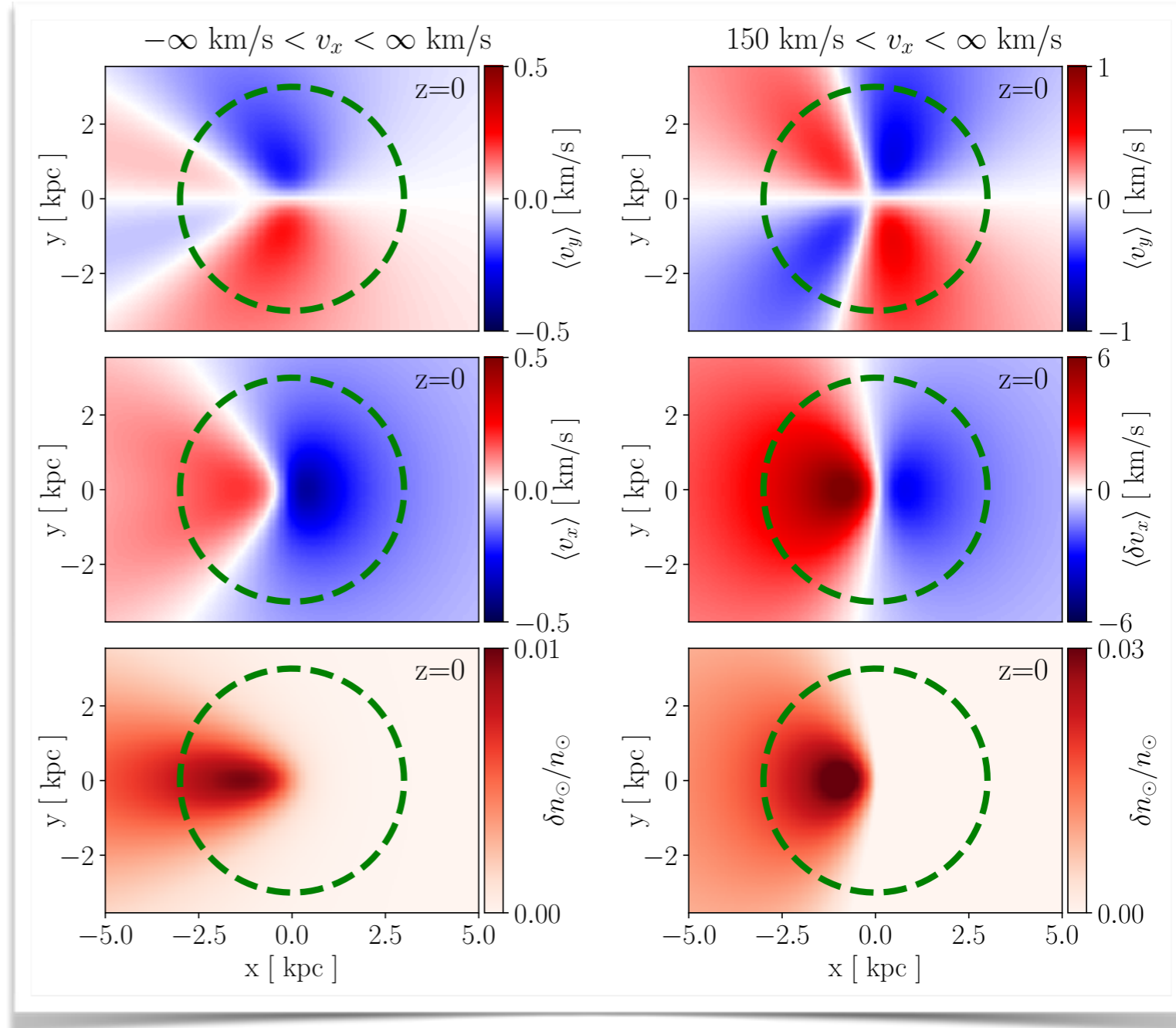
- ☑ Perturbations of stellar phase space distribution by passing DM subhalo
- ☑ Detectable in Gaia



# Stellar Wakes

- ☑ Perturbations of stellar phase space distribution by passing DM subhalo
- ☑ Detectable in Gaia

Buschmann JK Safdi Wu  
arXiv:1711.03554



- ☑ Collisionless Boltzmann Equation for 6D phase space distribution

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f - \vec{\nabla}_x \Phi \cdot \vec{\nabla}_v f = 0$$

- ☑ Perturbative treatment

$$f(\vec{x}, \vec{v}, t) = f_0(\vec{v}) + f_1(\vec{x}, \vec{v}, t)$$

- ☑ Leading order Boltzmann Equation:

$$\frac{\partial f_1}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f_1 = \vec{\nabla}_x \Phi \cdot \vec{\nabla}_v f_0$$

# Analytic Treatment

- ☑ Leading order Boltzmann Equation:

$$\frac{\partial f_1}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f_1 = \vec{\nabla}_x \Phi \cdot \vec{\nabla}_v f_0$$

- ☑ Solution (proof via Fourier Transformation)

$$f_1(\vec{x}, \vec{v}) = \int_0^\infty \frac{du}{u^2} \vec{\nabla}_y \Phi(\vec{y}) \cdot \vec{\nabla}_v f_0(\vec{v}) \Big|_{\vec{y}=\vec{x}-\vec{v}/u}$$

- ☑ Closed form solution for
  - Maxwell-Boltzmann-like  $f_0(\vec{v})$
  - Plummer sphere potential for  $\Phi(\vec{y})$

# Statistical Analysis



## ☑ Likelihood function

$$p(d|\mathcal{M}, \Theta) = e^{-N_{\text{star}}(\Theta)} \prod_{k=1}^{\bar{N}_{\text{star}}} f(\vec{x}_k, \vec{v}_k)(\Theta)$$

## ☑ Likelihood function

$$p(d|\mathcal{M}, \Theta) = e^{-N_{\text{star}}(\Theta)} \prod_{k=1}^{\bar{N}_{\text{star}}} f(\vec{x}_k, \vec{v}_k)(\Theta)$$

**Model and  
Model Parameters**

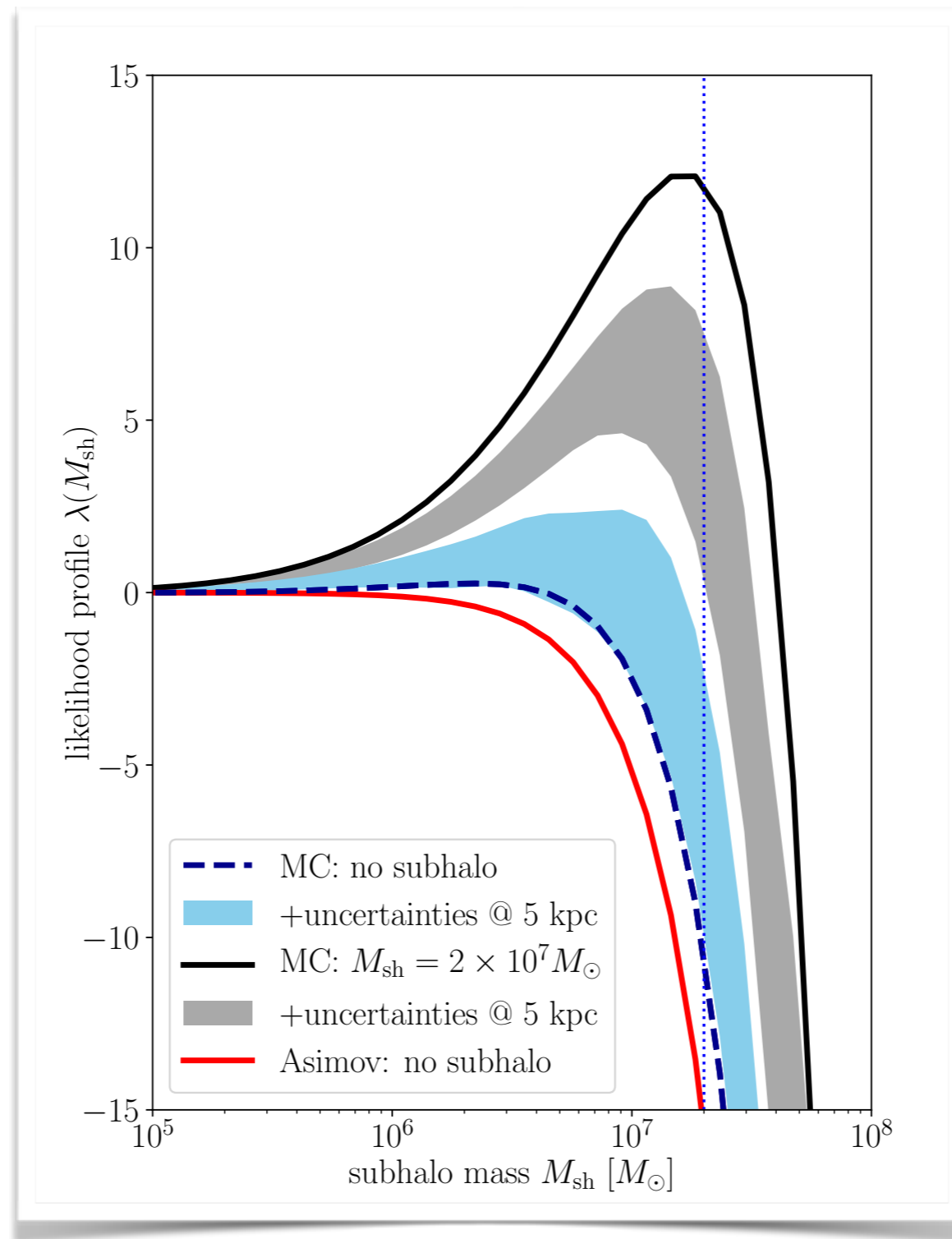
## ✓ Likelihood function

$$p(d|\mathcal{M}, \Theta) = e^{-N_{\text{star}}(\Theta)} \prod_{k=1}^{\bar{N}_{\text{star}}} f(\vec{x}_k, \vec{v}_k)(\Theta)$$

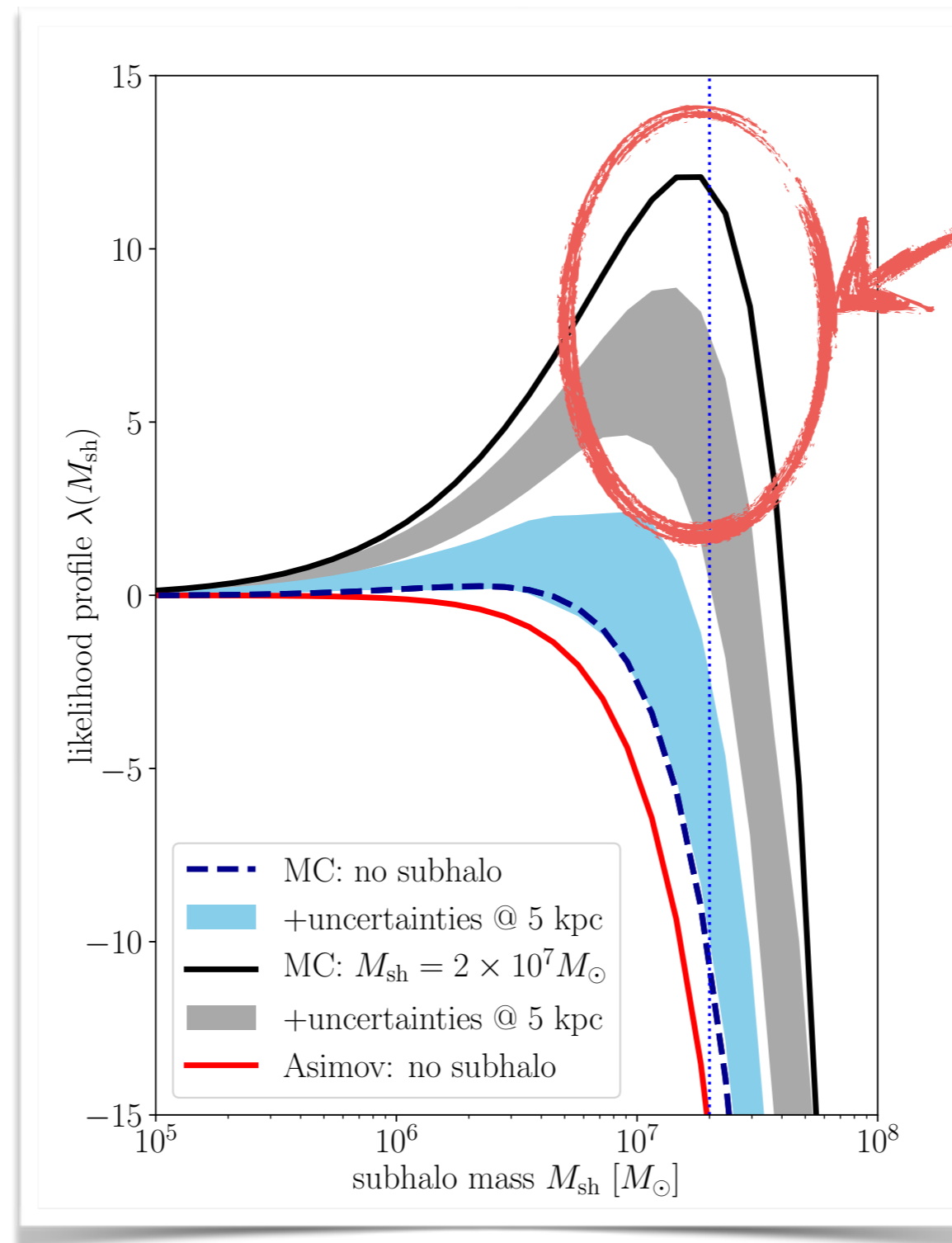
## ✓ Test Statistic

$$\lambda(M_{\text{sh}}) = 2 \left[ \max_{\Theta_{\text{nuis}}} \log p(d|\mathcal{M}, \theta) - \max_{\Theta} \log p(d|\mathcal{M}, \Theta) \right]$$

# Results



# Results



**Significant  
Discovery Potential**  
even at  $M_{\text{sh}} \sim 10^7 M_{\odot}$

Buschmann JK Safdi Wu  
arXiv:1711.03554

# Fermi-LAT / GBM

## GRB Femtolensing by Primordial Black Holes



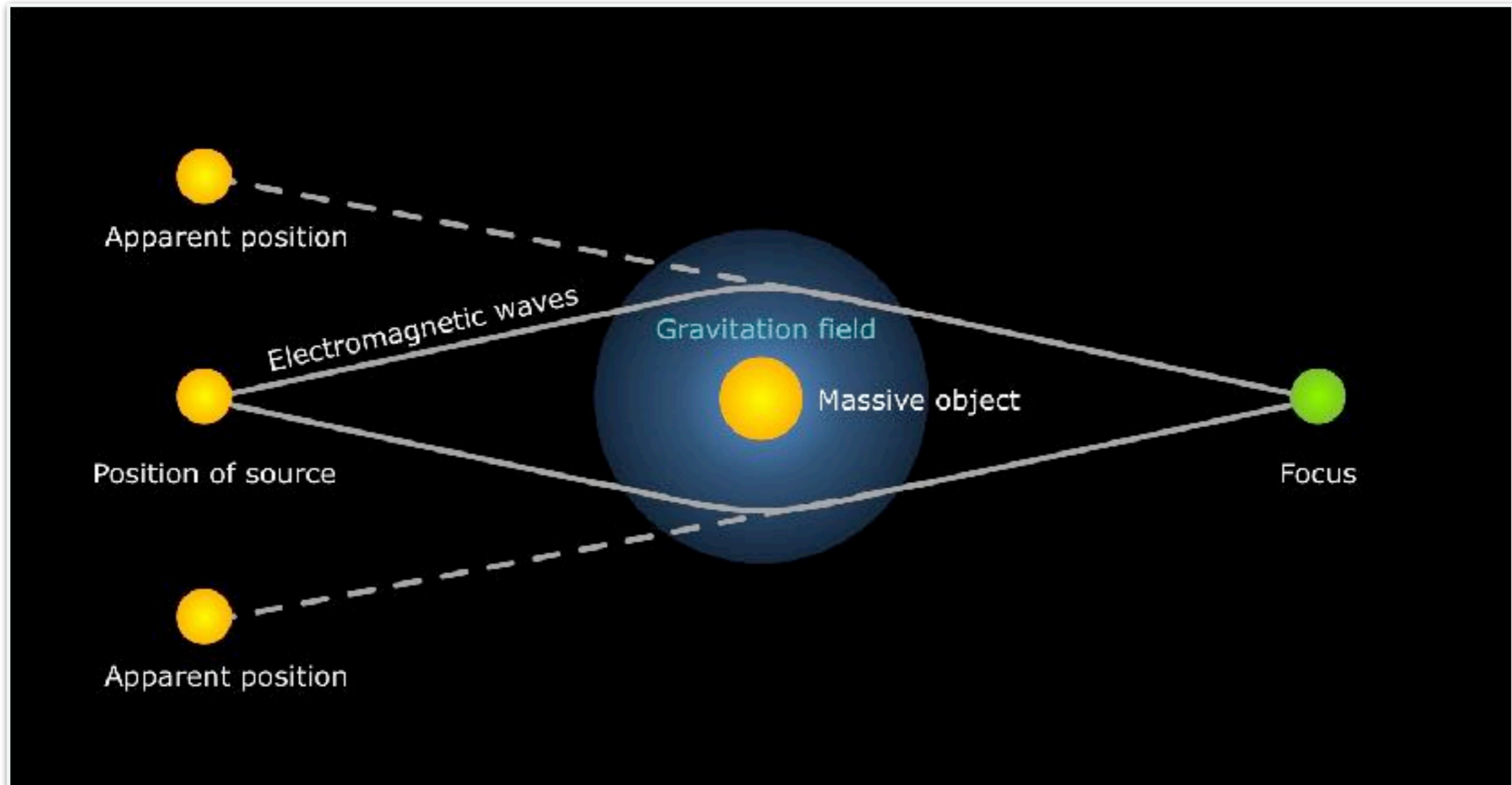
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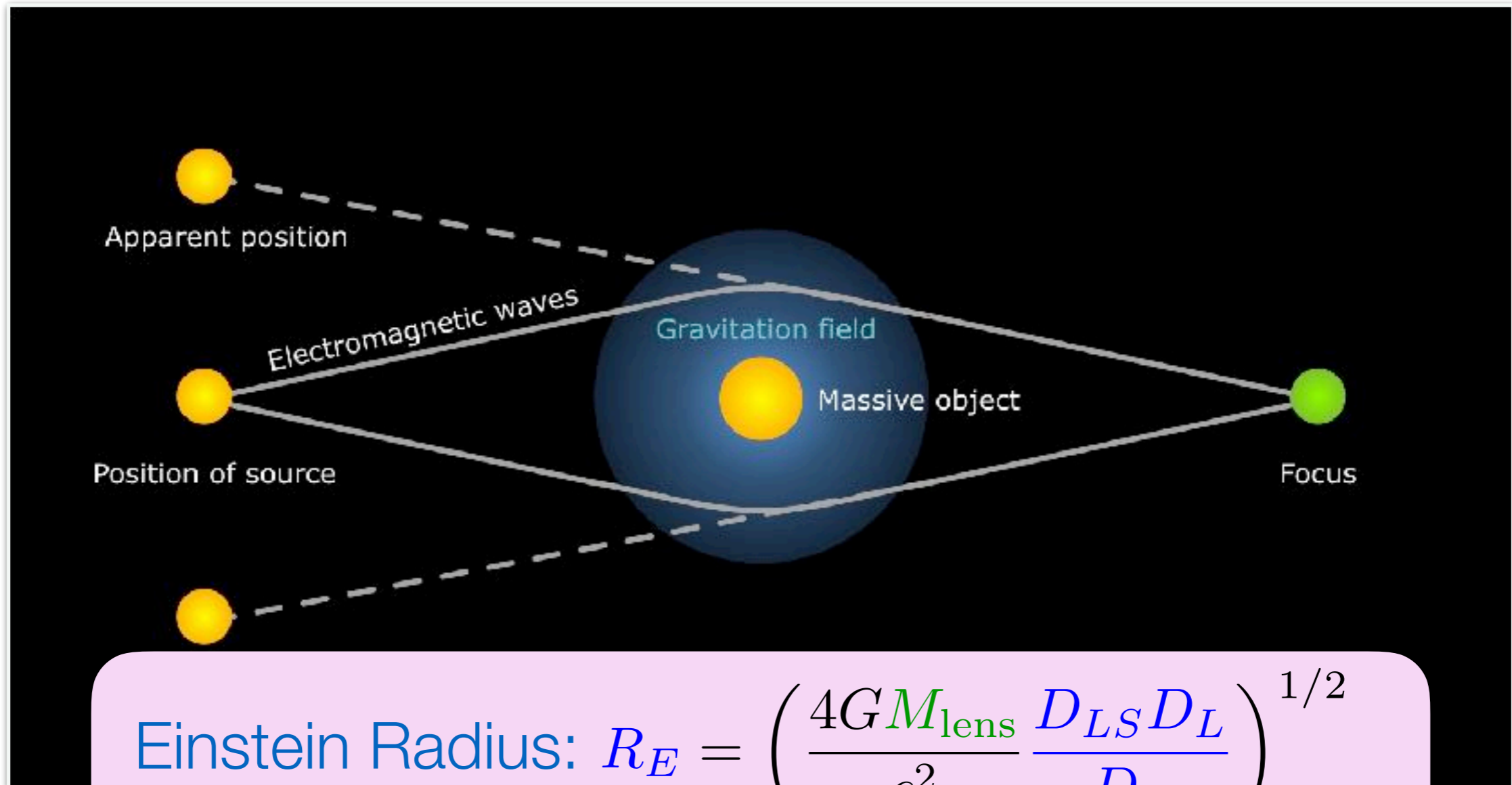




# Gravitational Lensing



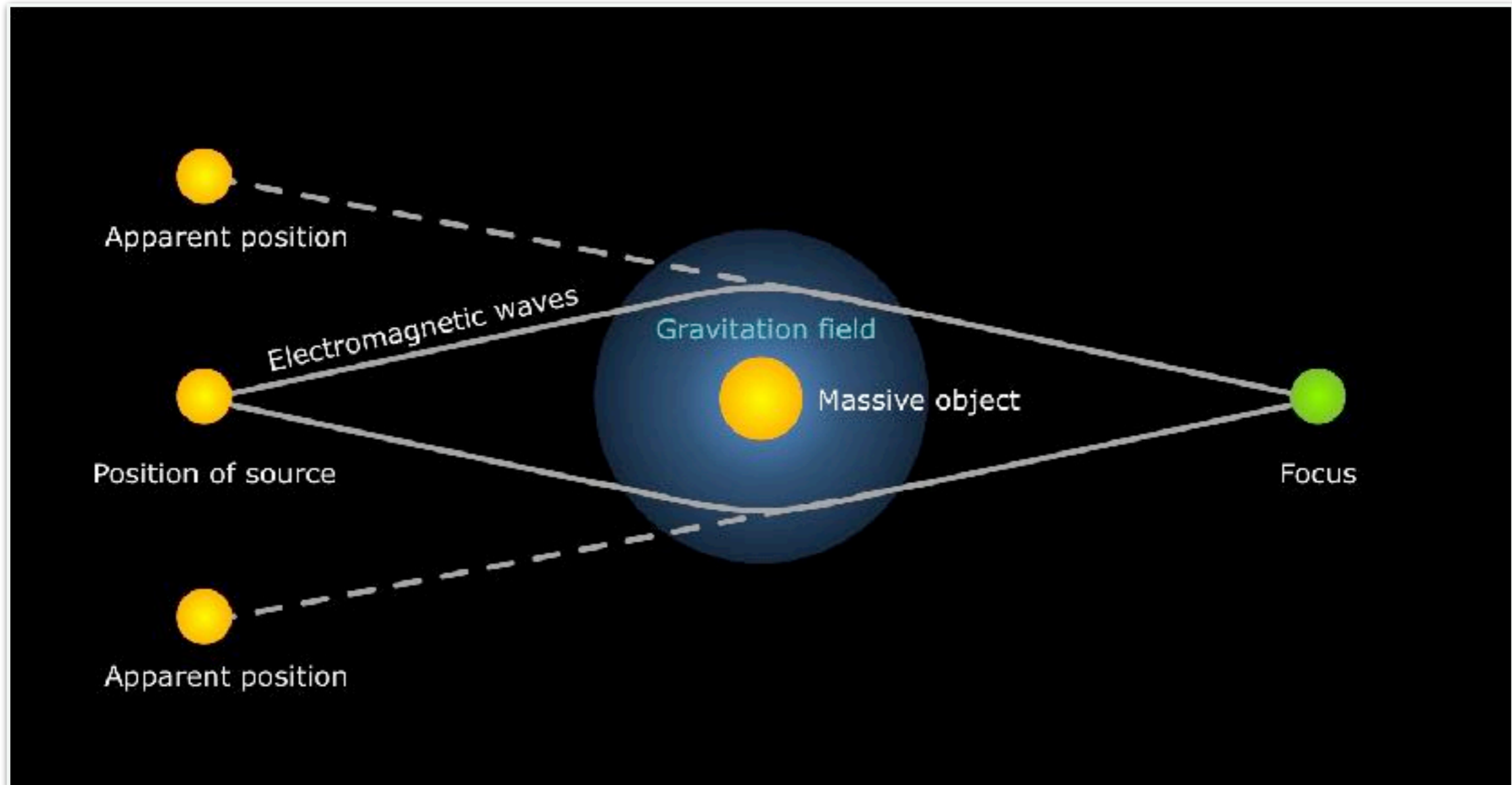
# Gravitational Lensing



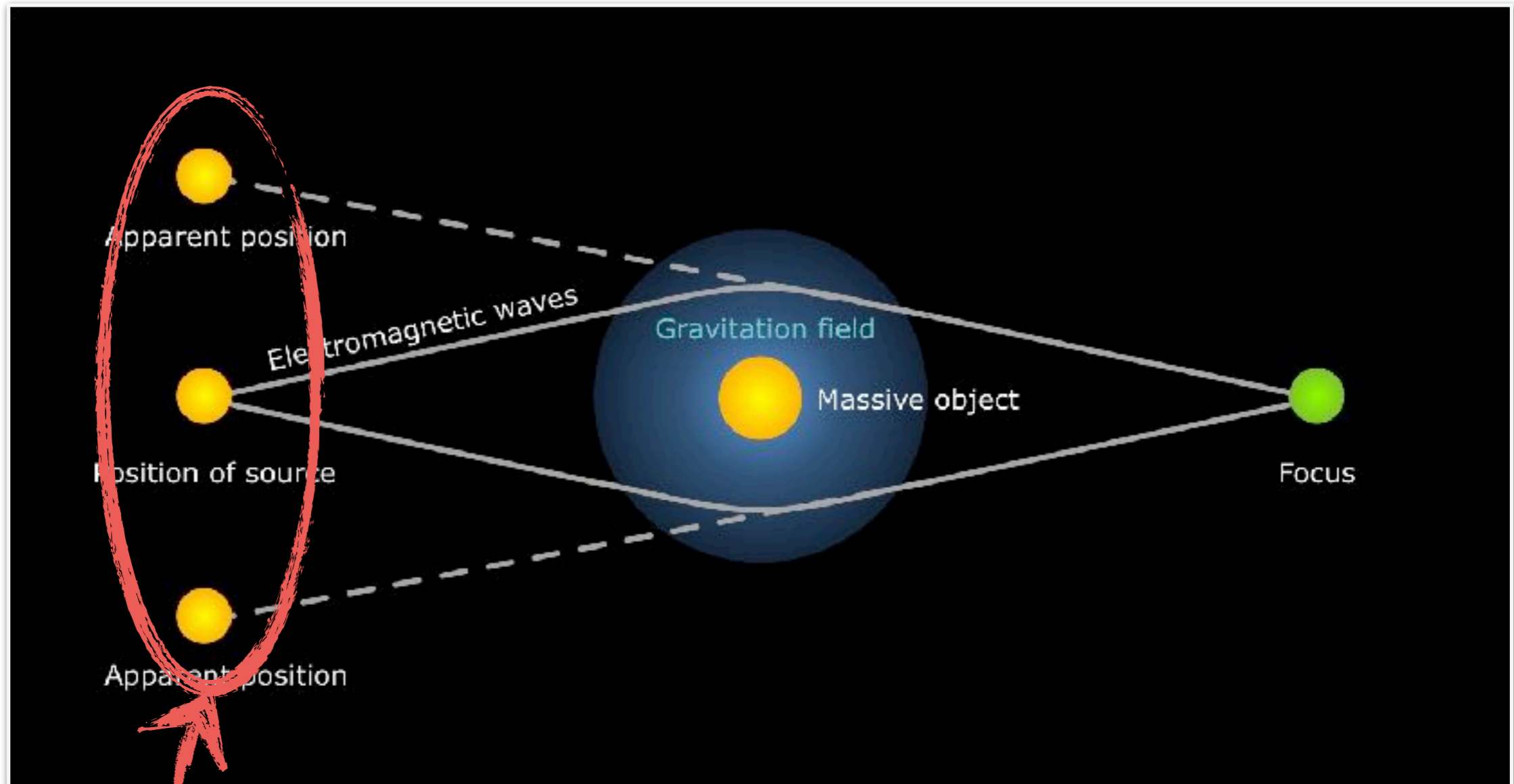
$$\text{Einstein Radius: } R_E = \left( \frac{4GM_{\text{lens}}}{c^2} \frac{D_{LS}D_L}{D_S} \right)^{1/2}$$

(typical distance between lensed /and unlensed images)

# Femtolensing

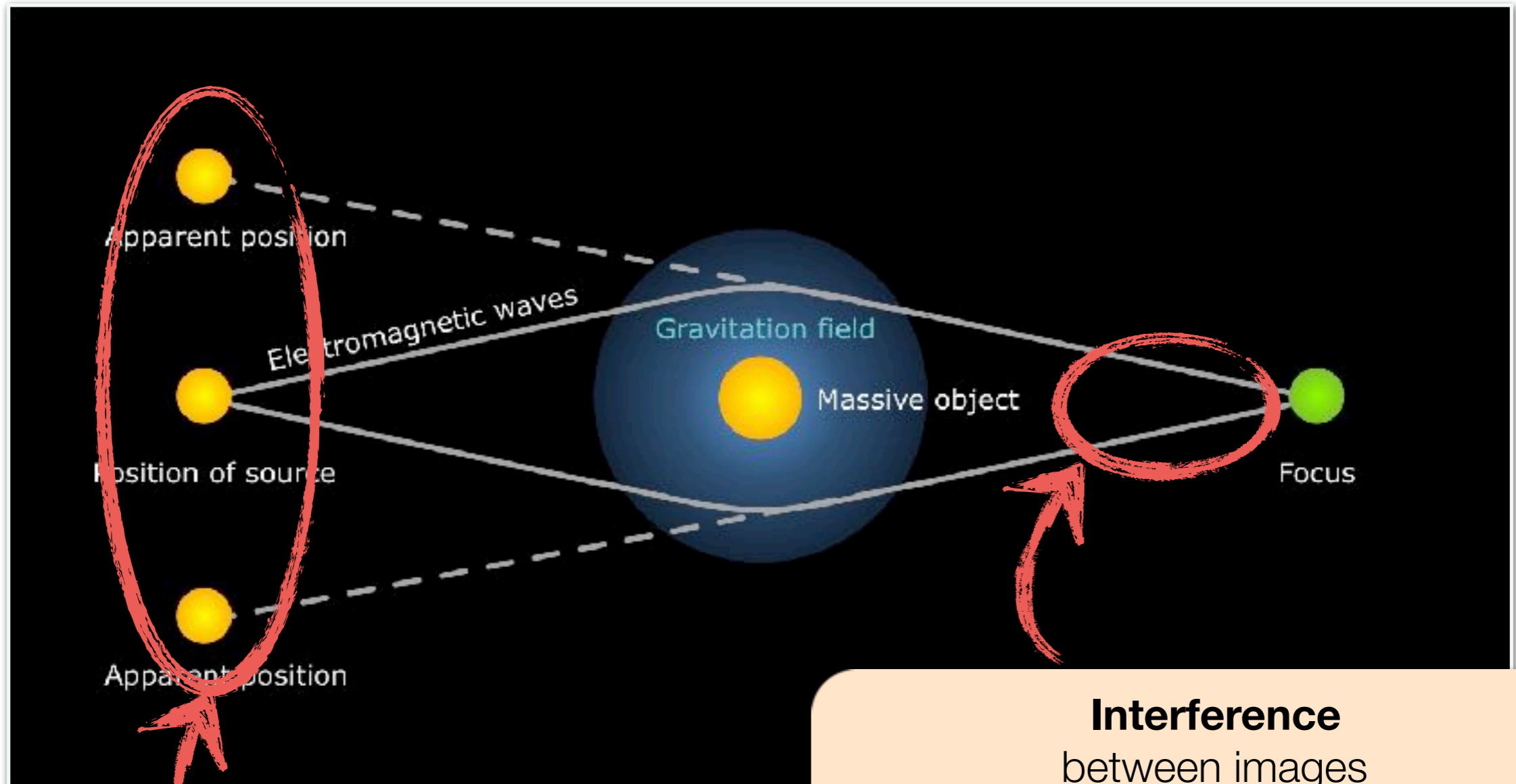


# Femtolensing



Images not resolved

# Femtolensing



**Images not resolved**

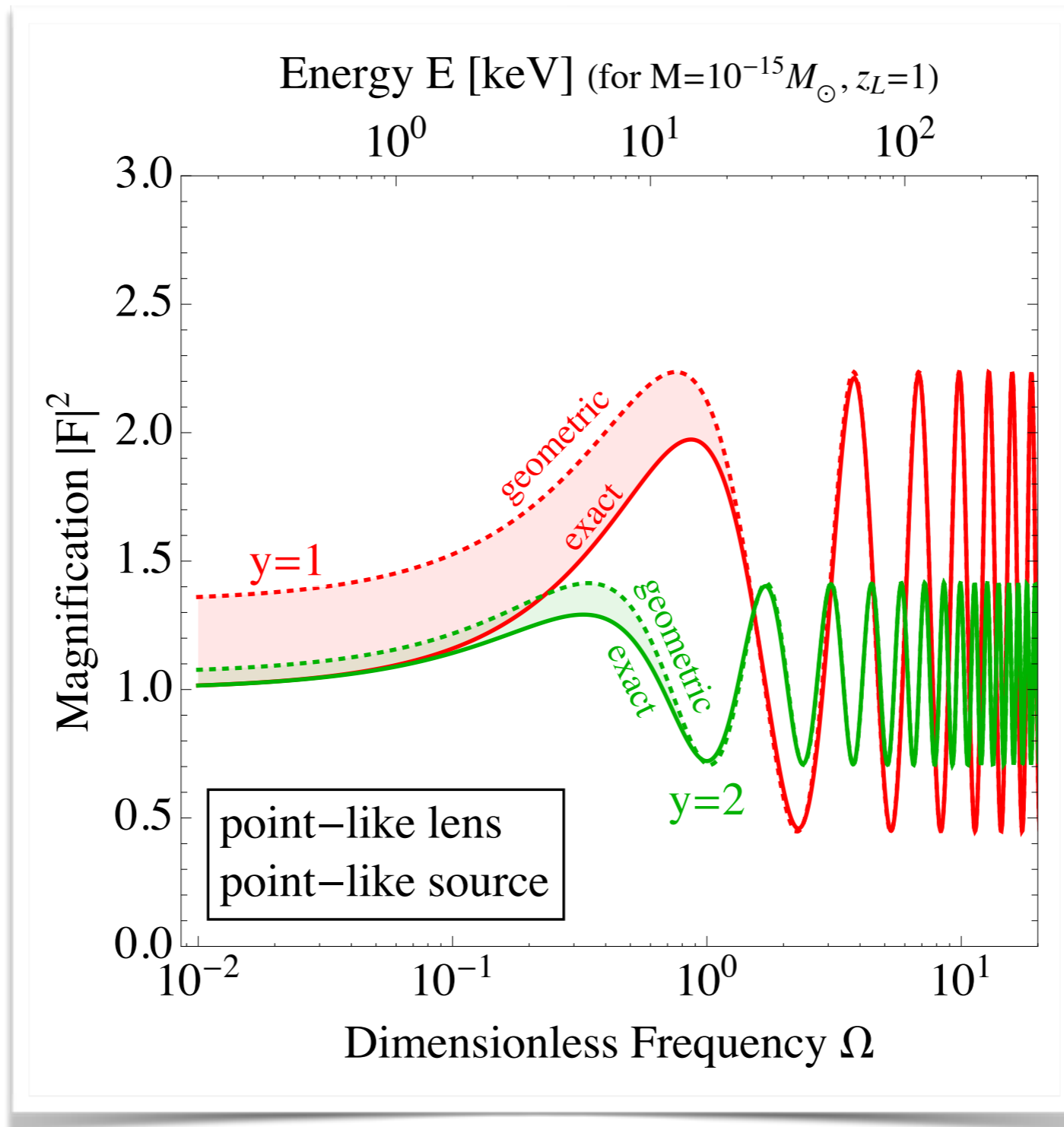
## Interference

between images

$$A = A_1 e^{iEt_1} + A_2 e^{iEt_2}$$

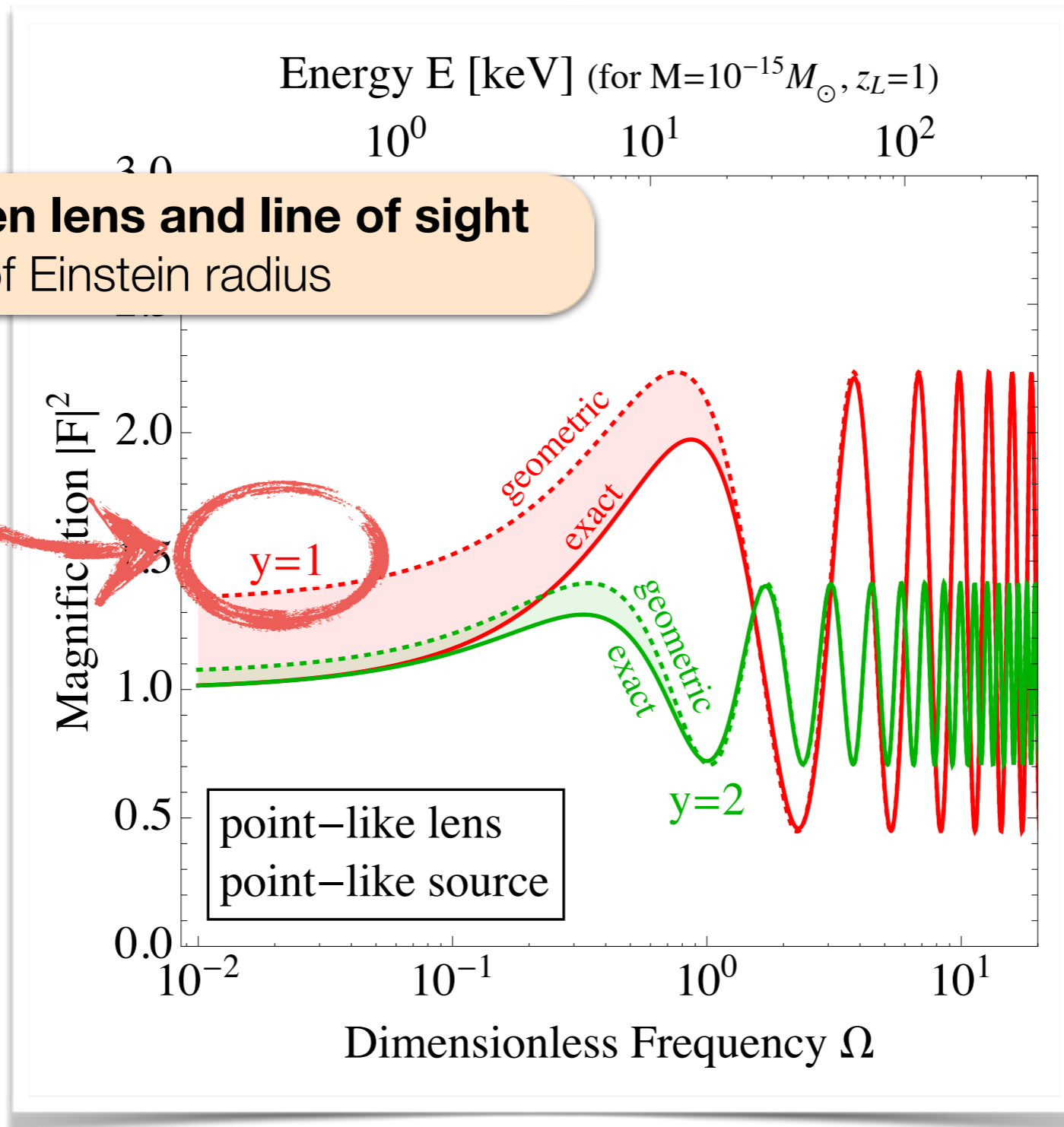
expect wiggles in energy spectrum

# Femtolensing



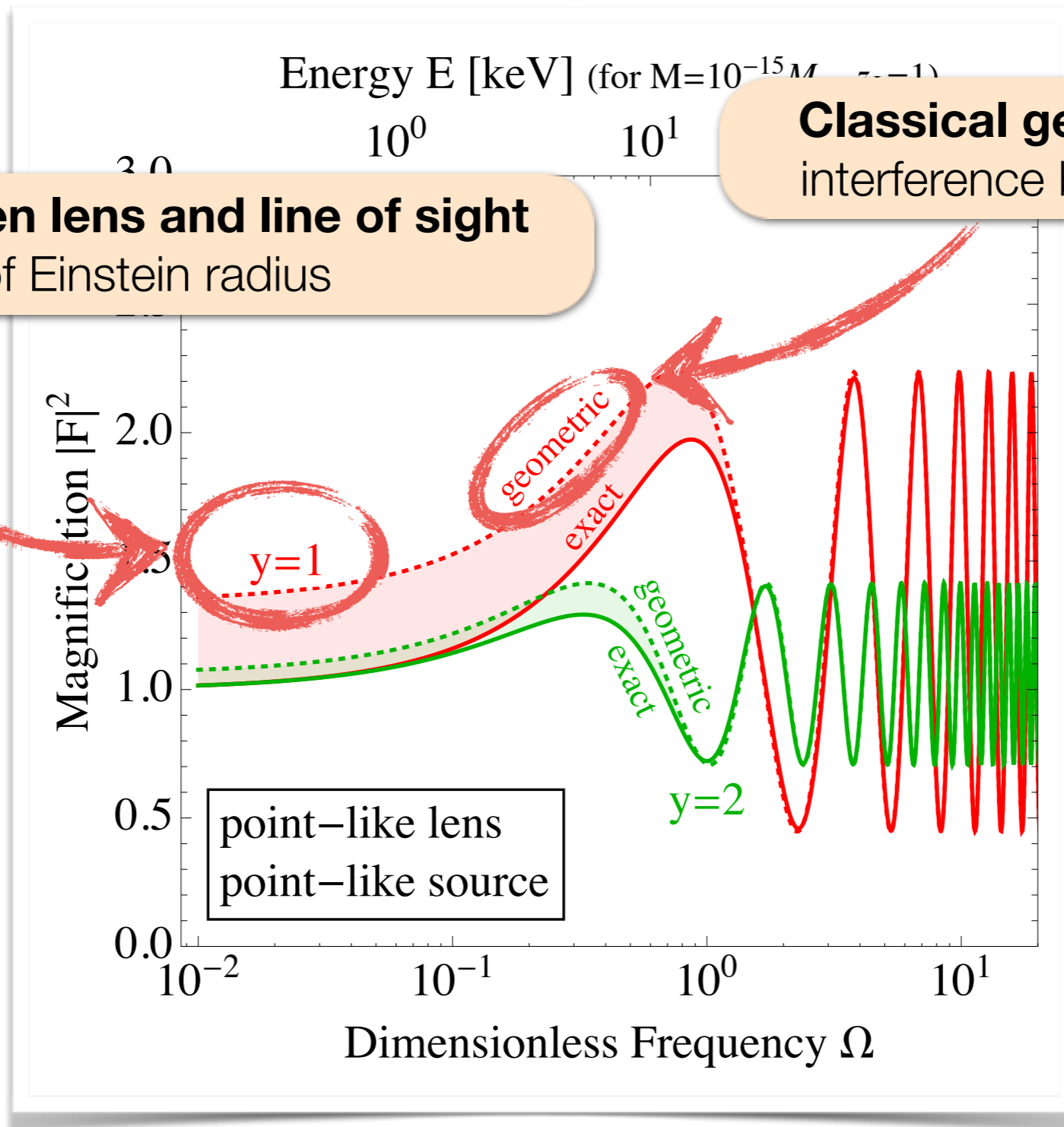
Katz JK Sibiryakov Xue  
arXiv:1807.11495

# Femtolensing



Katz JK Sibiryakov Xue  
arXiv:1807.11495

# Femtolensing

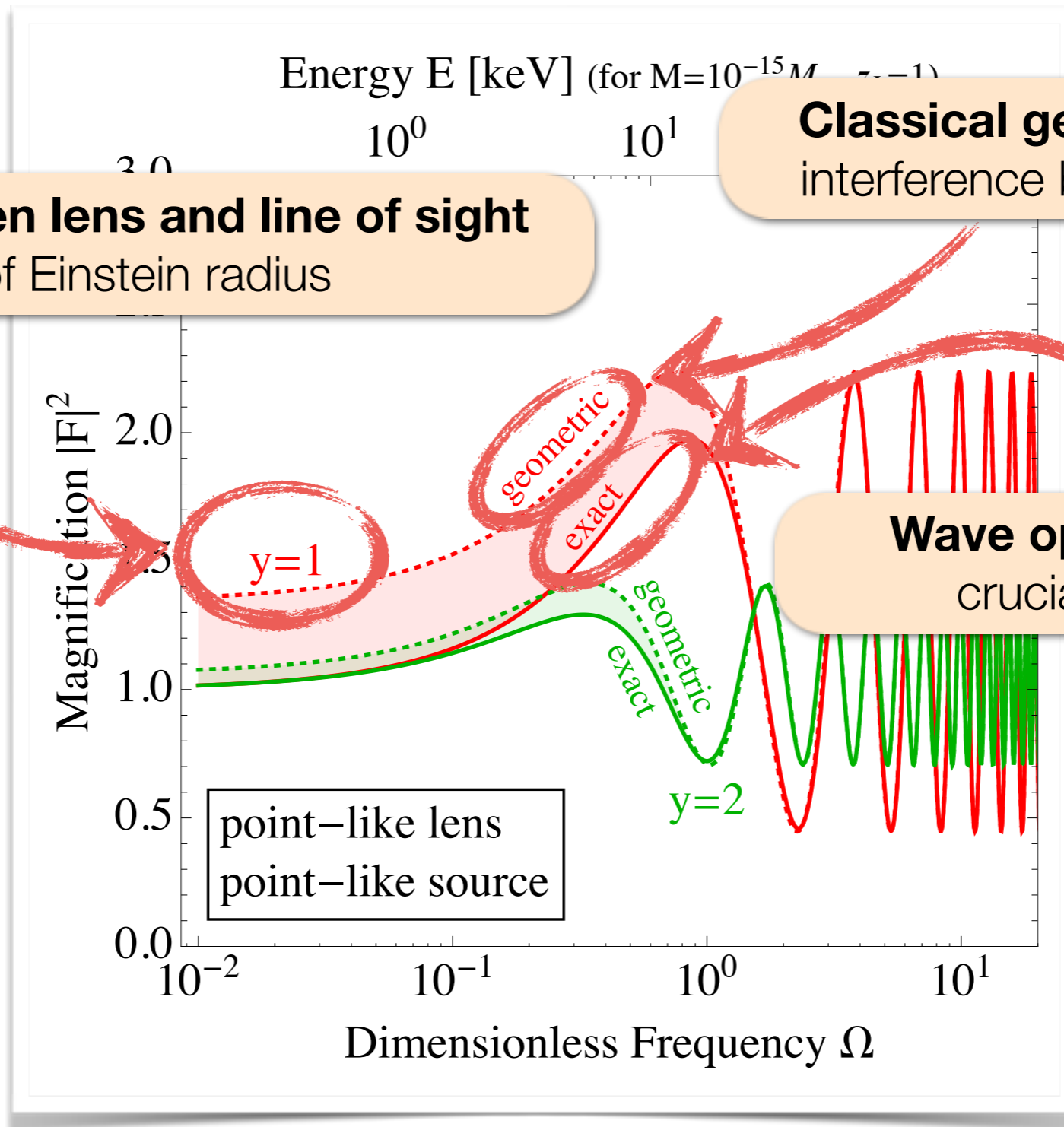


**Distance between lens and line of sight**  
in units of Einstein radius

**Classical geometric picture**  
interference between two rays

Katz JK Sibiryakov Xue  
arXiv:1807.11495

# Femtolensing



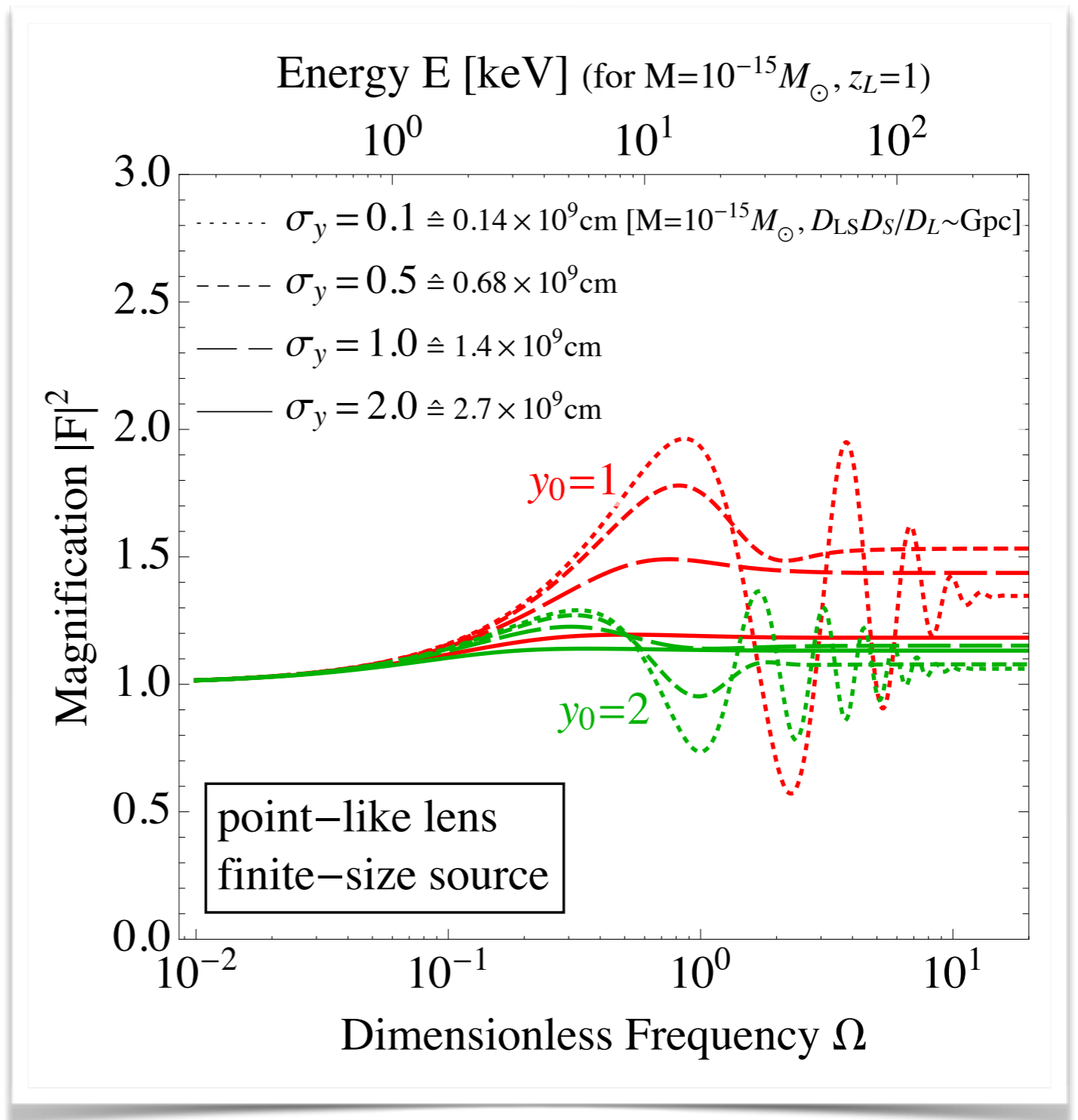
**Distance between lens and line of sight**  
in units of Einstein radius

**Classical geometric picture**  
interference between two rays

**Wave optics corrections**  
crucial if  $\lambda \gtrsim G_N M_{\text{lens}}$

Katz JK Sibiryakov Xue  
arXiv:1807.11495

# Further Corrections

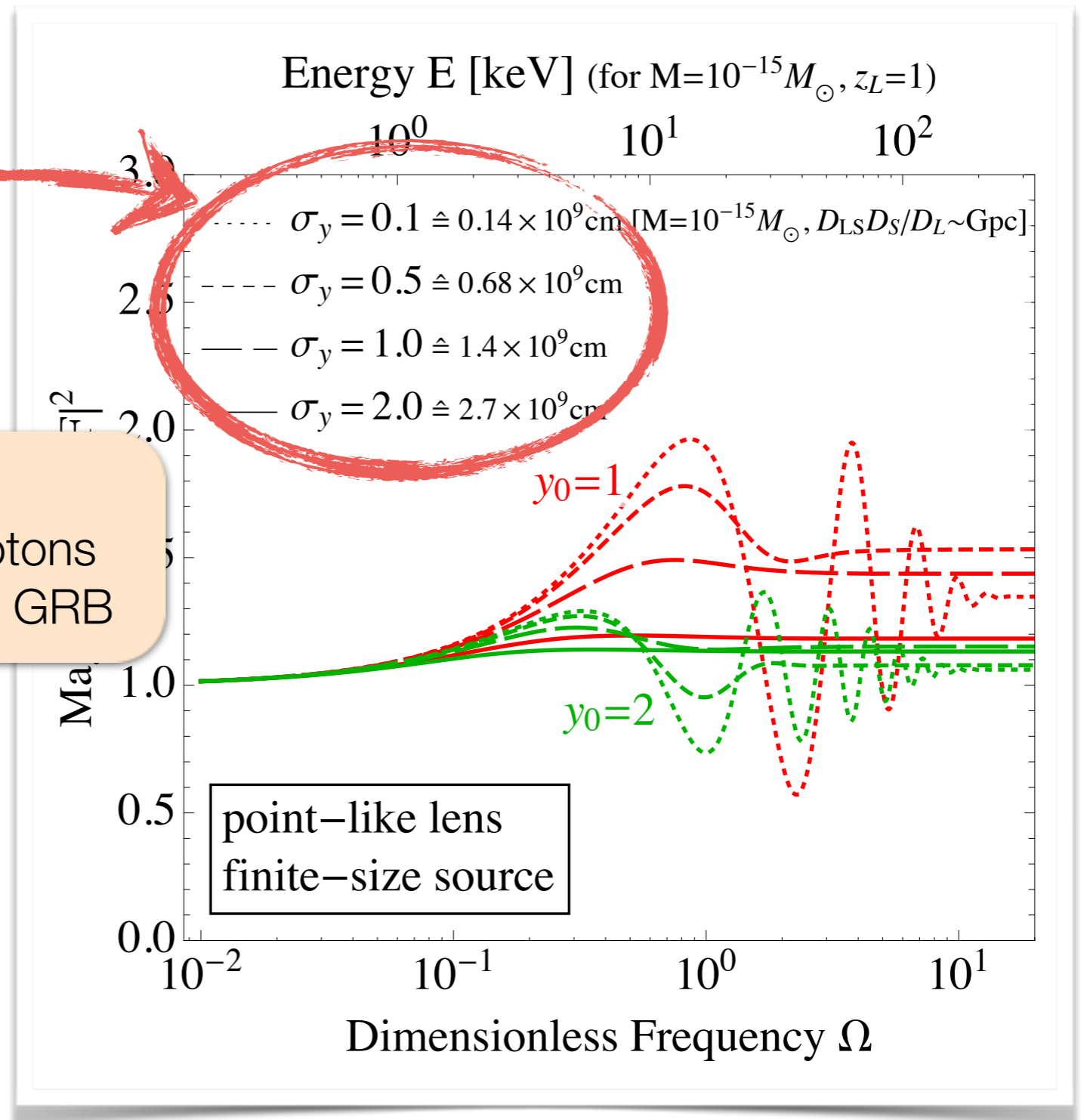


Katz JK Sibiryakov Xue  
arXiv:1807.11495

# Further Corrections

## GRBs are not pointlike

small phase difference between photons emitted at different points across the GRB



Katz JK Sibiryakov Xue  
arXiv:1807.11495

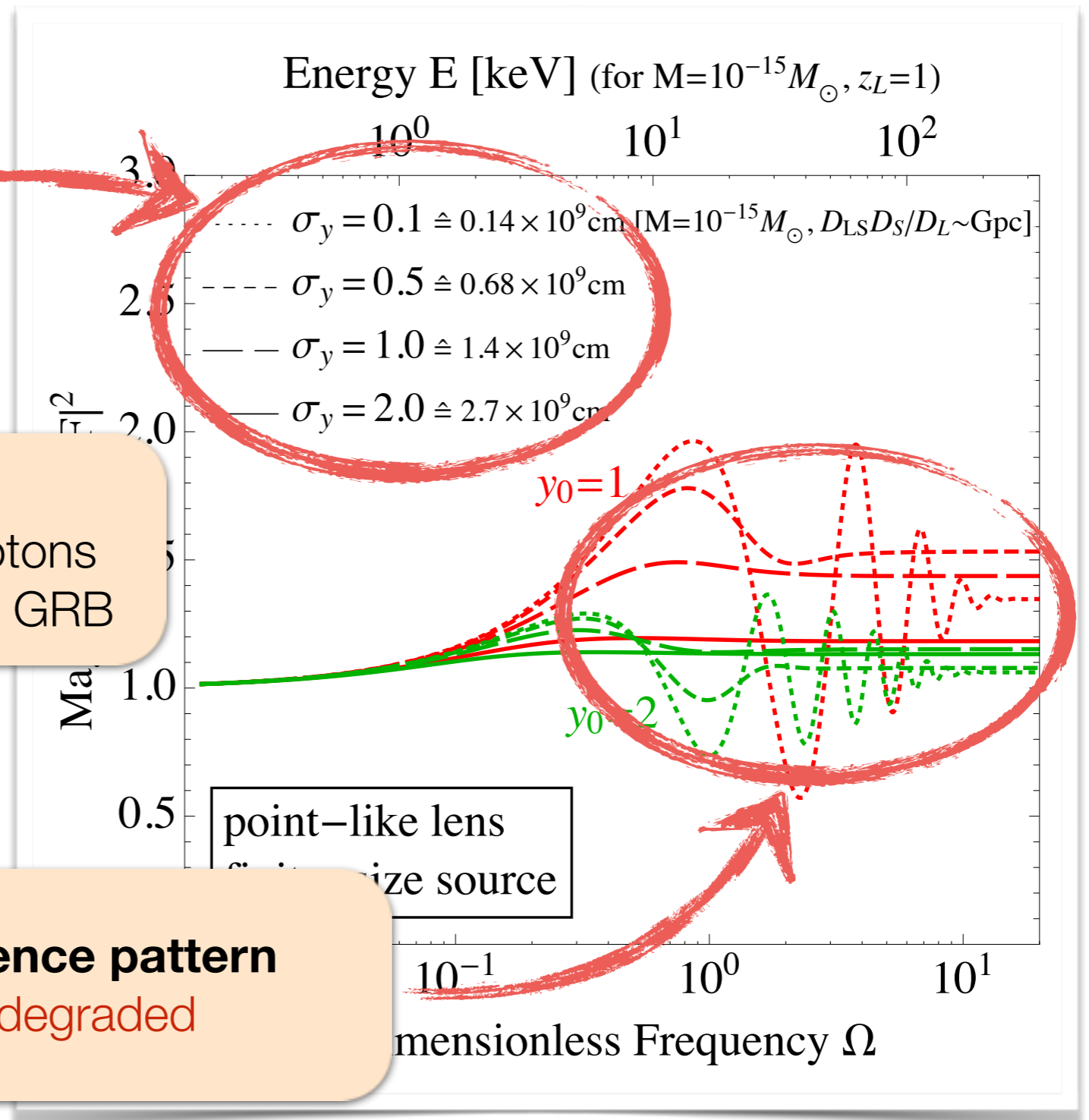
# Further Corrections

## GRBs are not pointlike

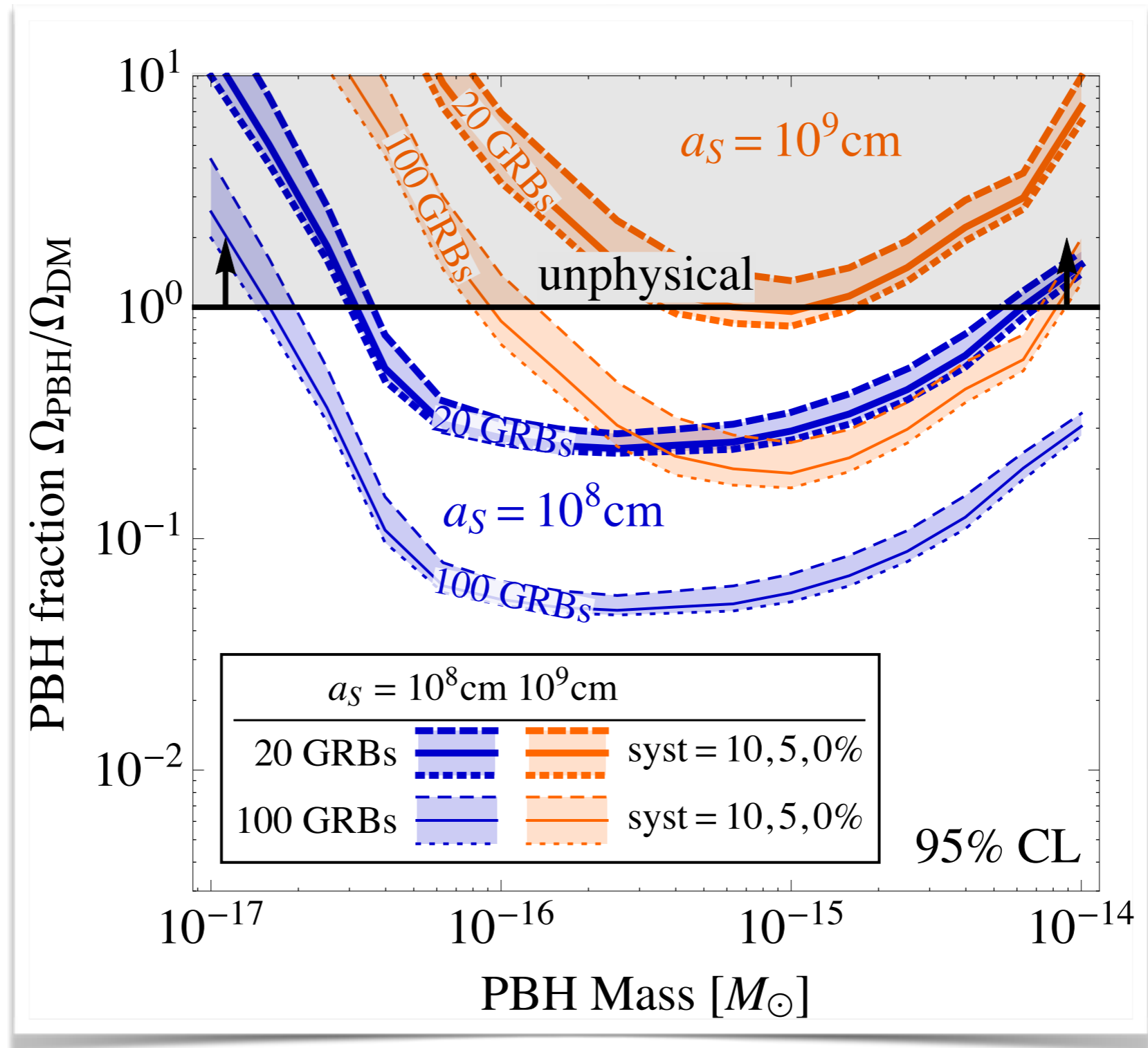
small phase difference between photons emitted at different points across the GRB

## Wash-out of interference pattern

sensitivity severely degraded

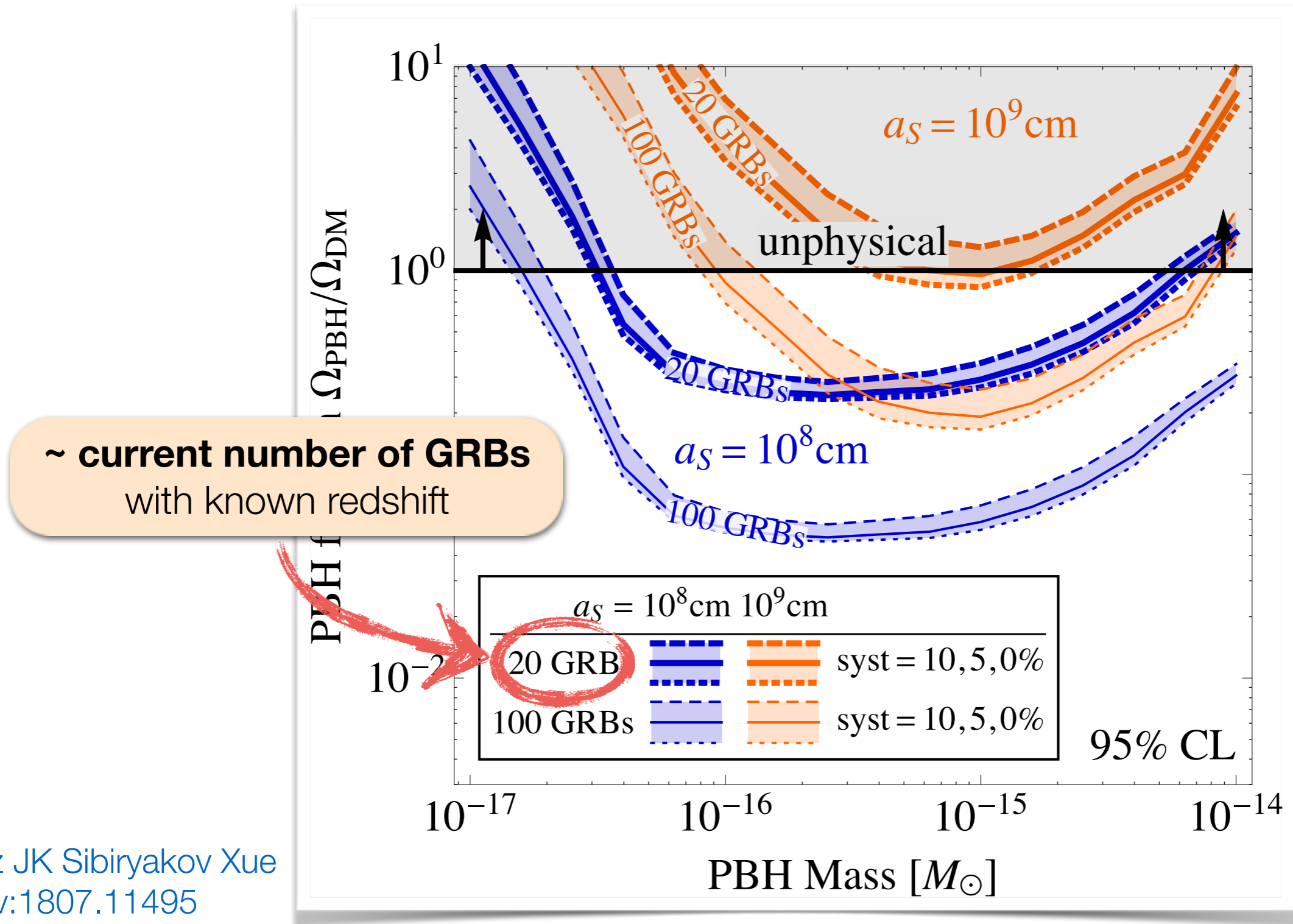


# Sensitivity Estimates



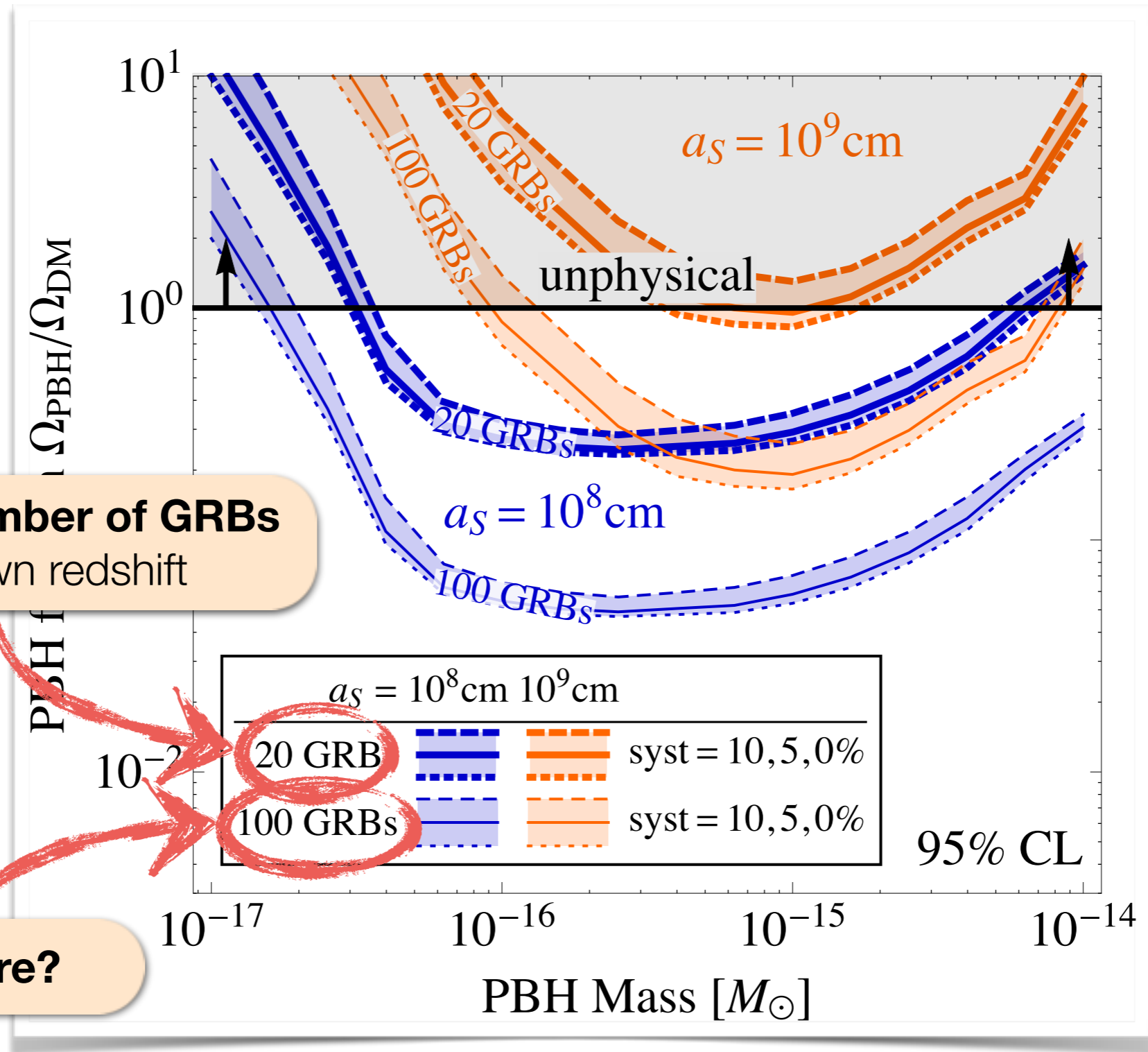
Katz JK Sibiryakov Xue  
arXiv:1807.11495

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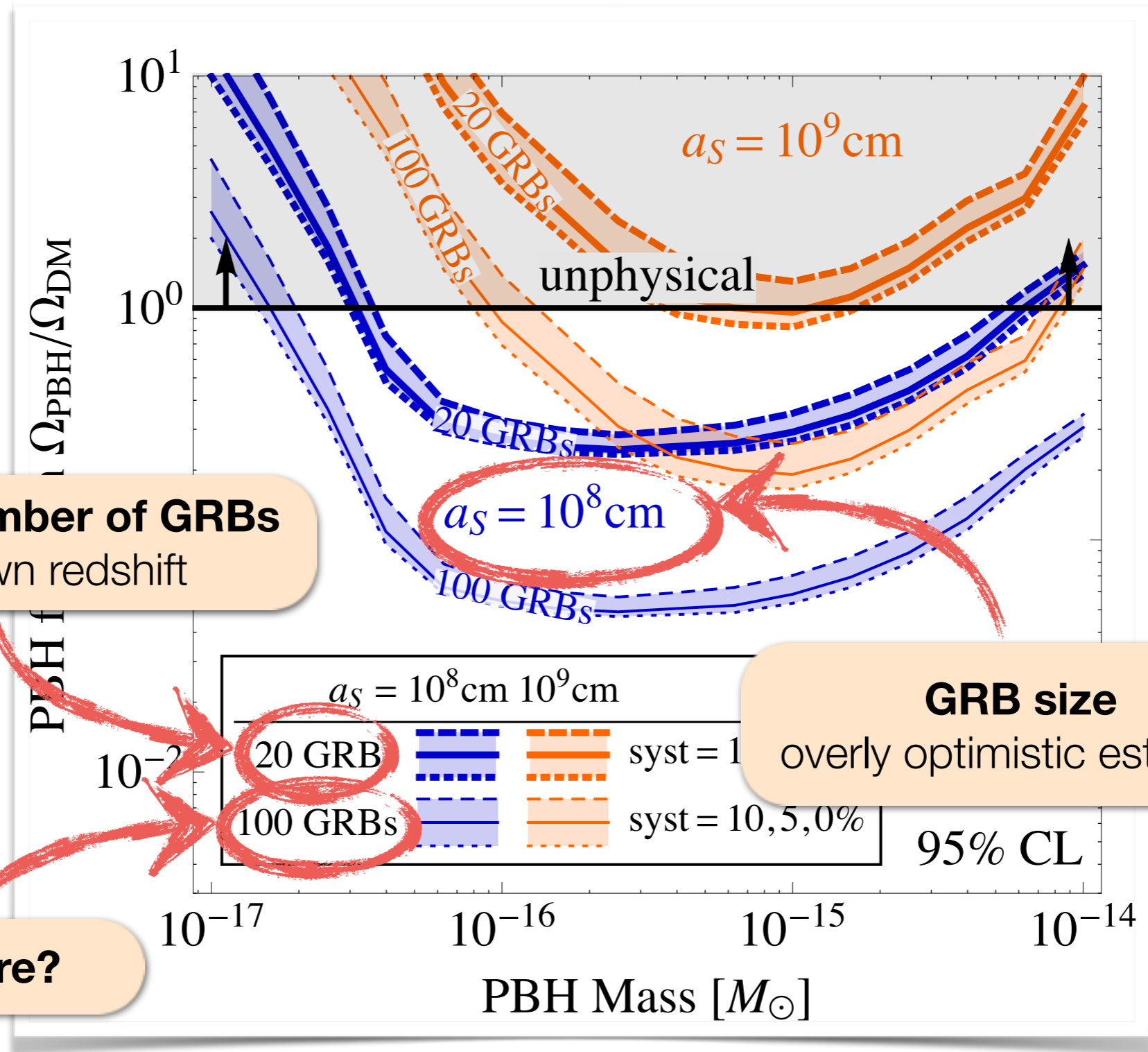
Katz JK Sibiryakov Xue  
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# Sensitivity Estimates



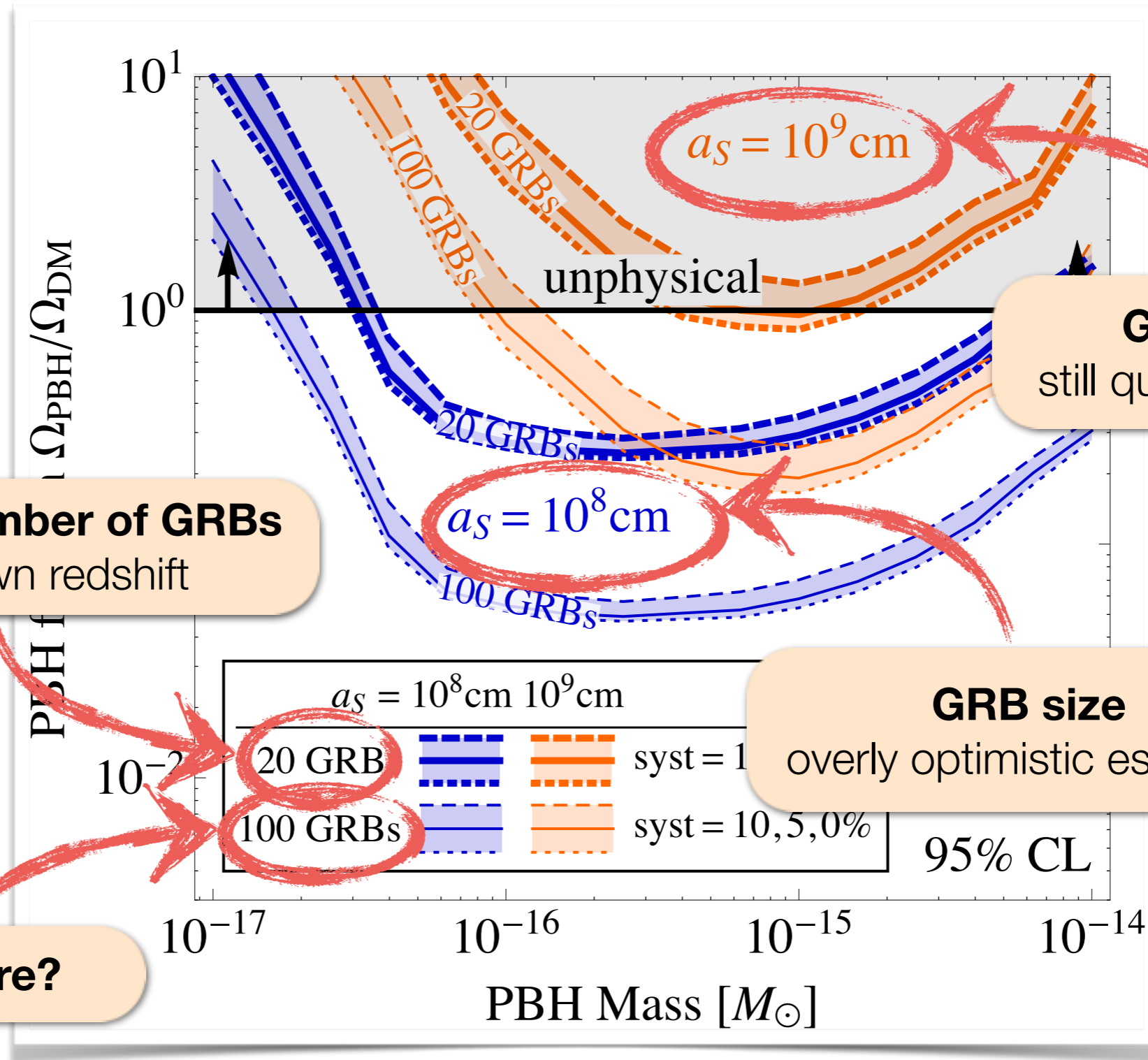
Katz JK Sibiryakova  
arXiv:1807.11495

# Sensitivity Estimates



Katz JK Sibirsky  
arXiv:1807.11495

# Sensitivity Estimates



~ current number of GRBs with known redshift

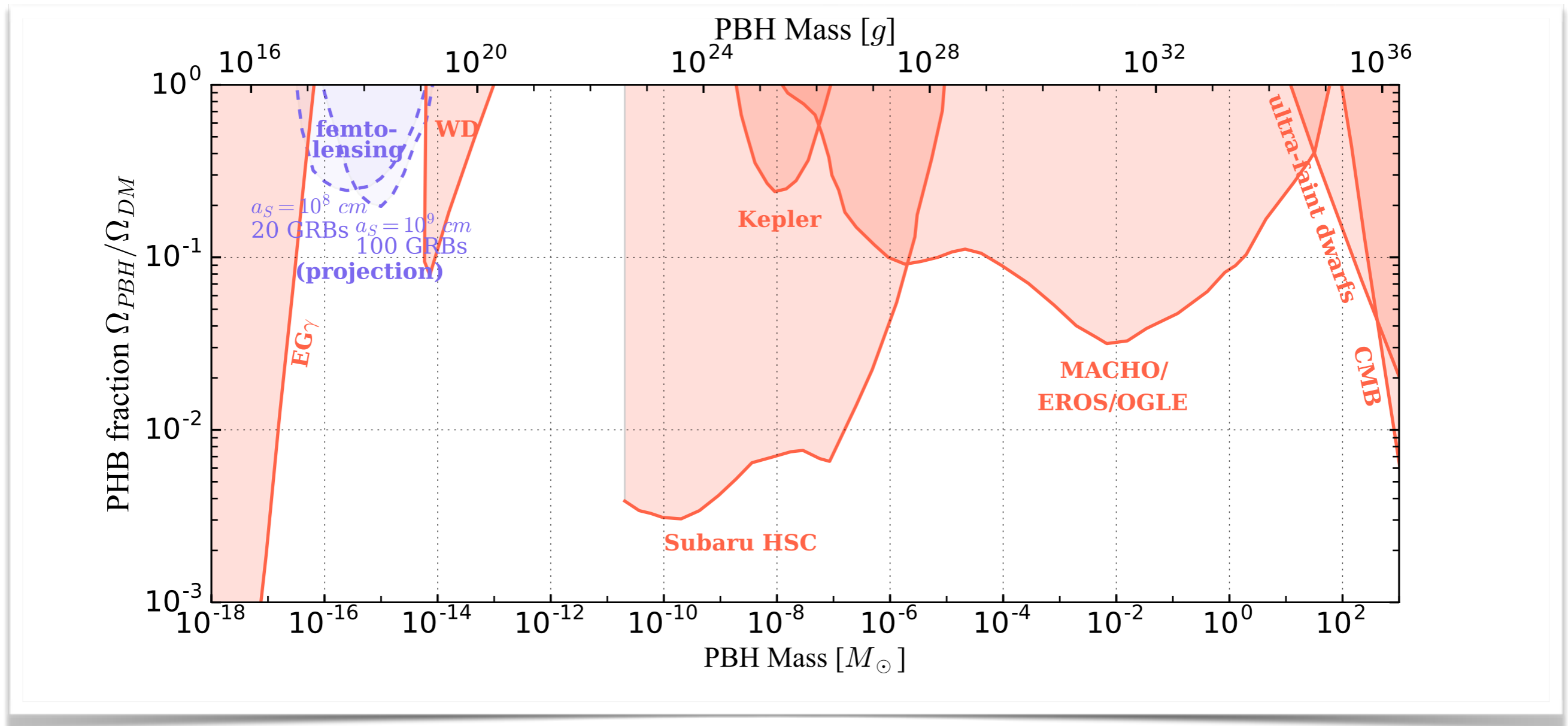
GRB size still quite optimistic

GRB size overly optimistic estimate

Future?

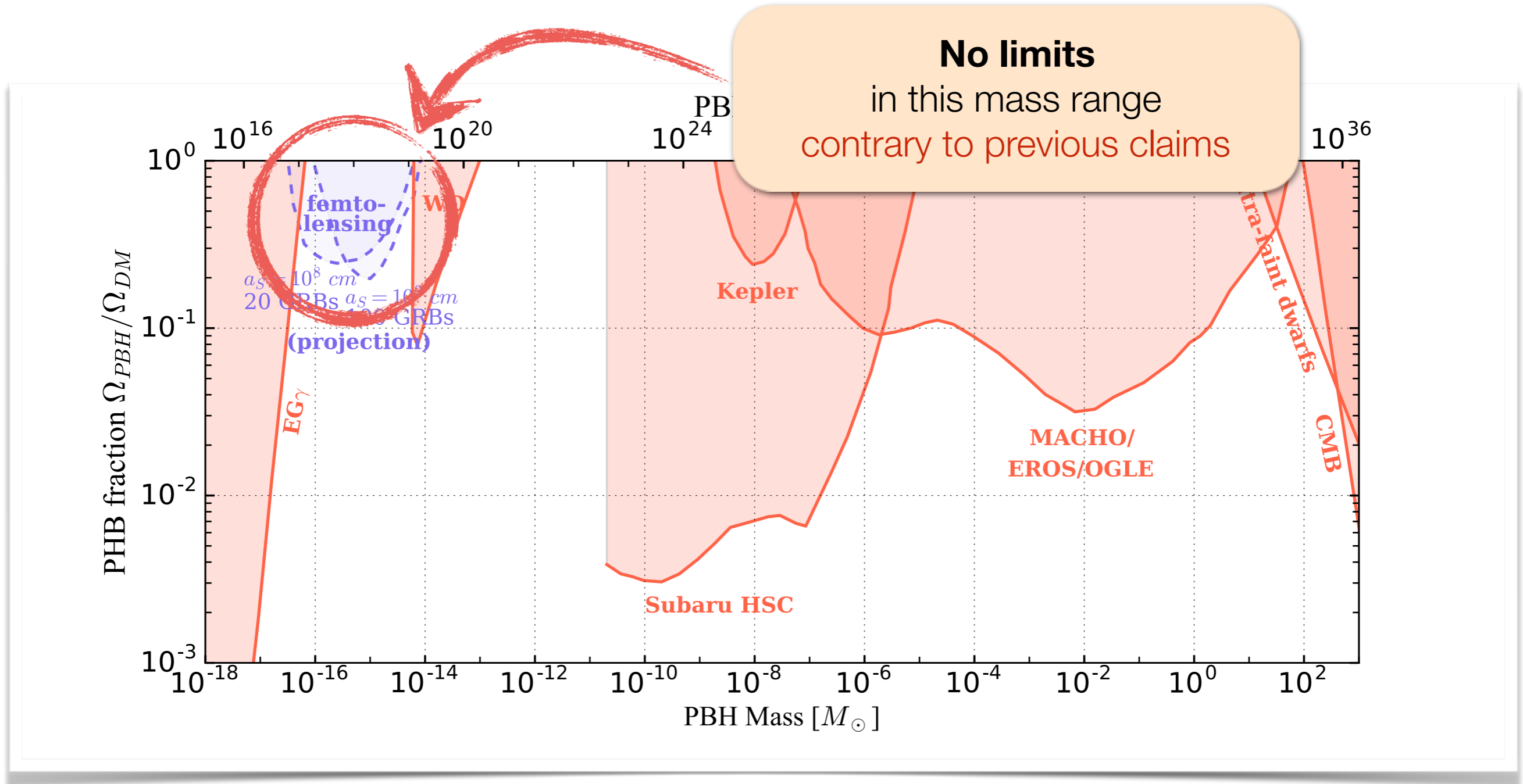
Katz JK Sibiryakova  
arXiv:1807.11495

# PBH Parameter Space



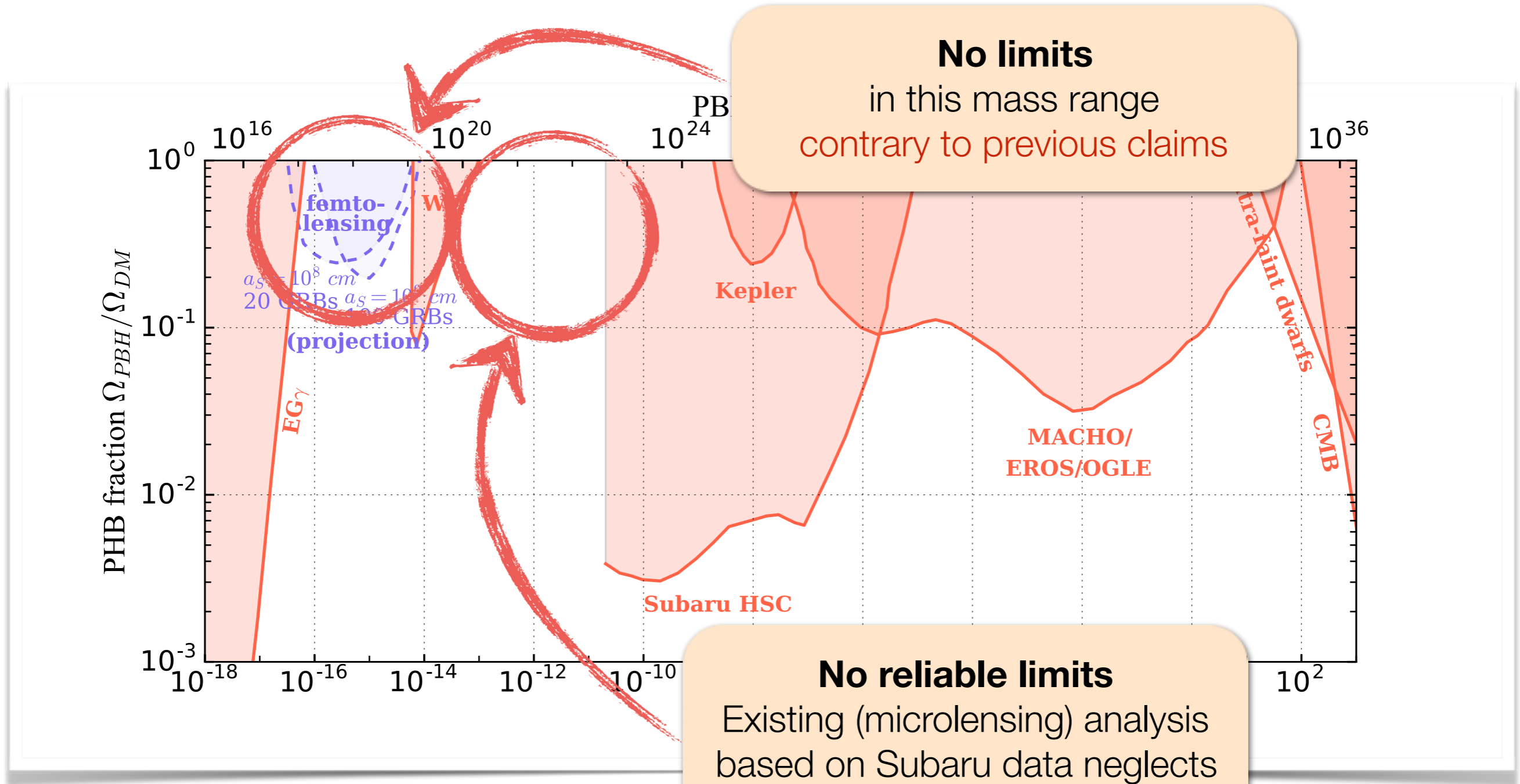
Katz JK Sibiryakov Xue  
arXiv:1807.11495

# PBH Parameter Space



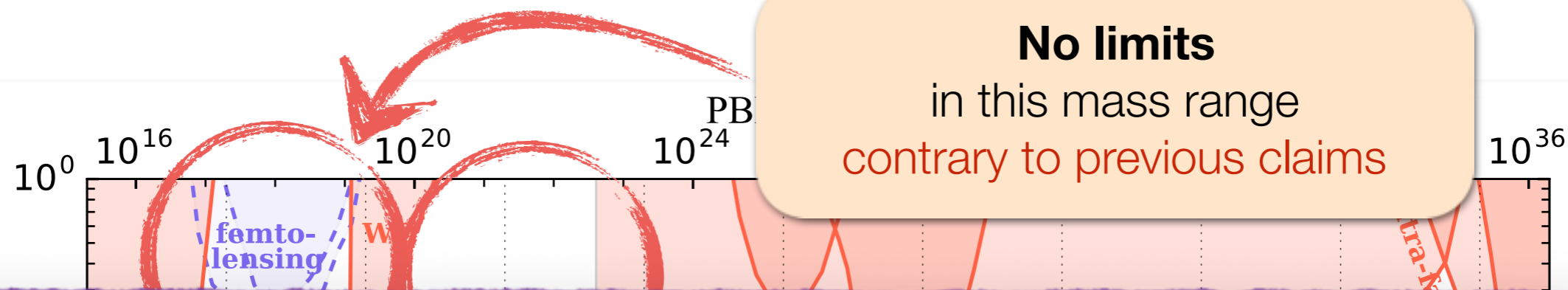
Katz JK Sibiryakov Xue  
arXiv:1807.11495

# PBH Parameter Space



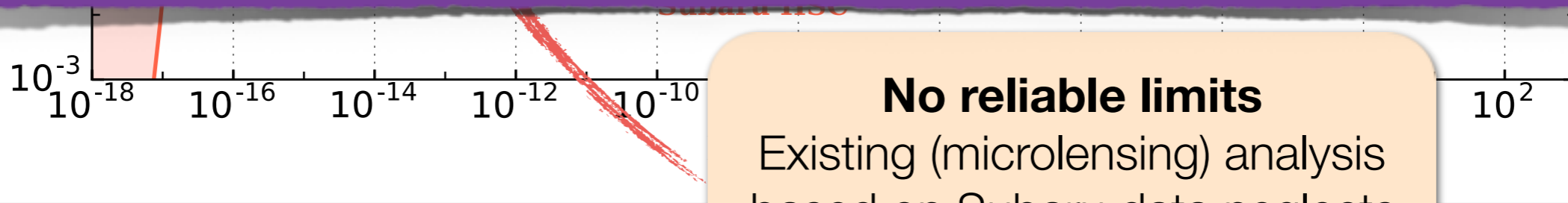
Katz JK Sibiryakov Xue  
arXiv:1807.11495

# PBH Parameter Space



**No limits**  
in this mass range  
contrary to previous claims

Parameter space for  
**Primordial Black Hole Dark Matter**  
is again wide open!



**No reliable limits**  
Existing (microlensing) analysis  
based on Subaru data neglects  
wave optics effects

Katz JK Sibiryakov Xue  
arXiv:1807.11495

# LIGO / VIRGO

Probing Dark Sector Forces in Binary Inspirals

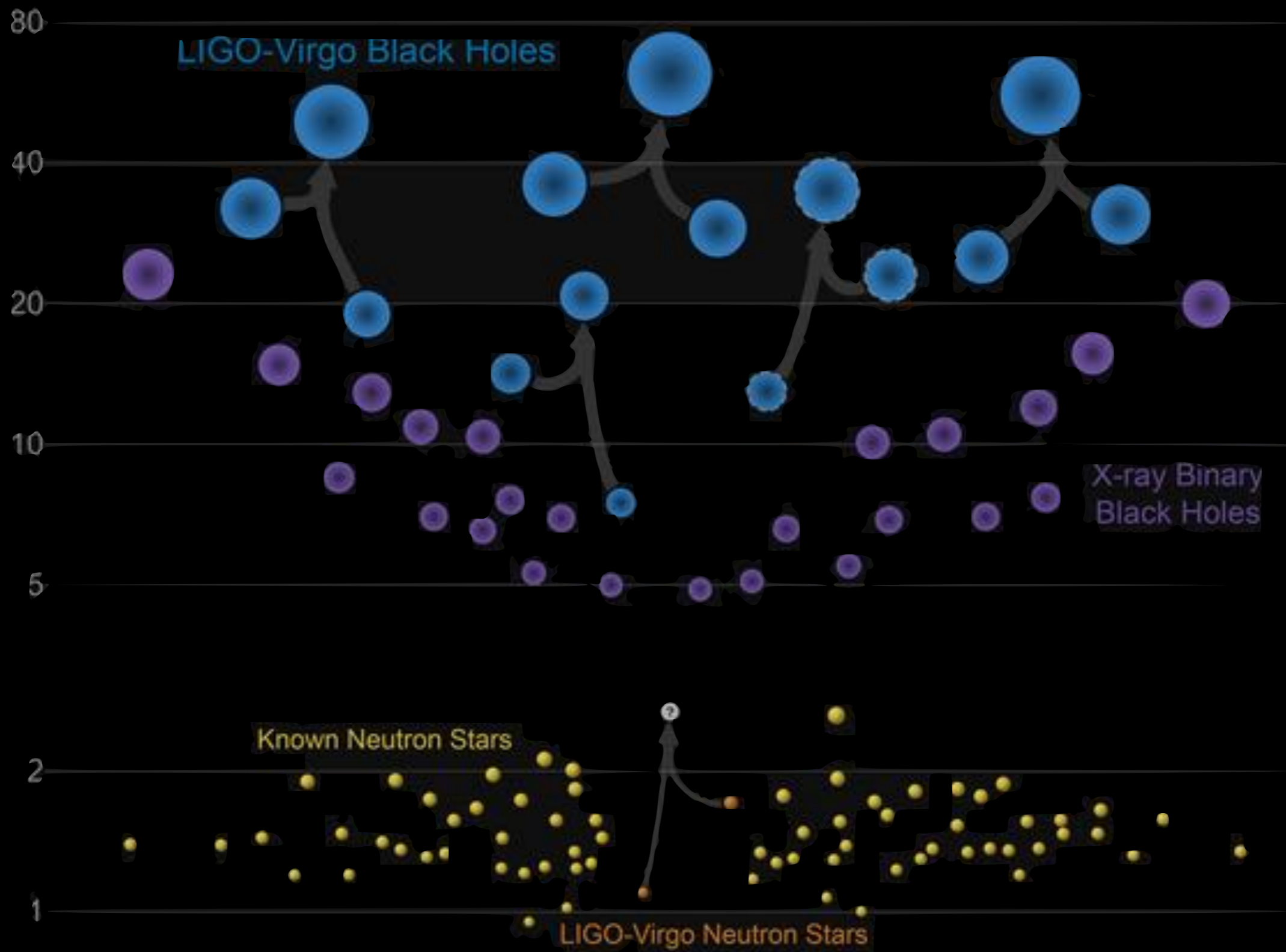


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# Masses in the Stellar Graveyard

*in Solar Masses*



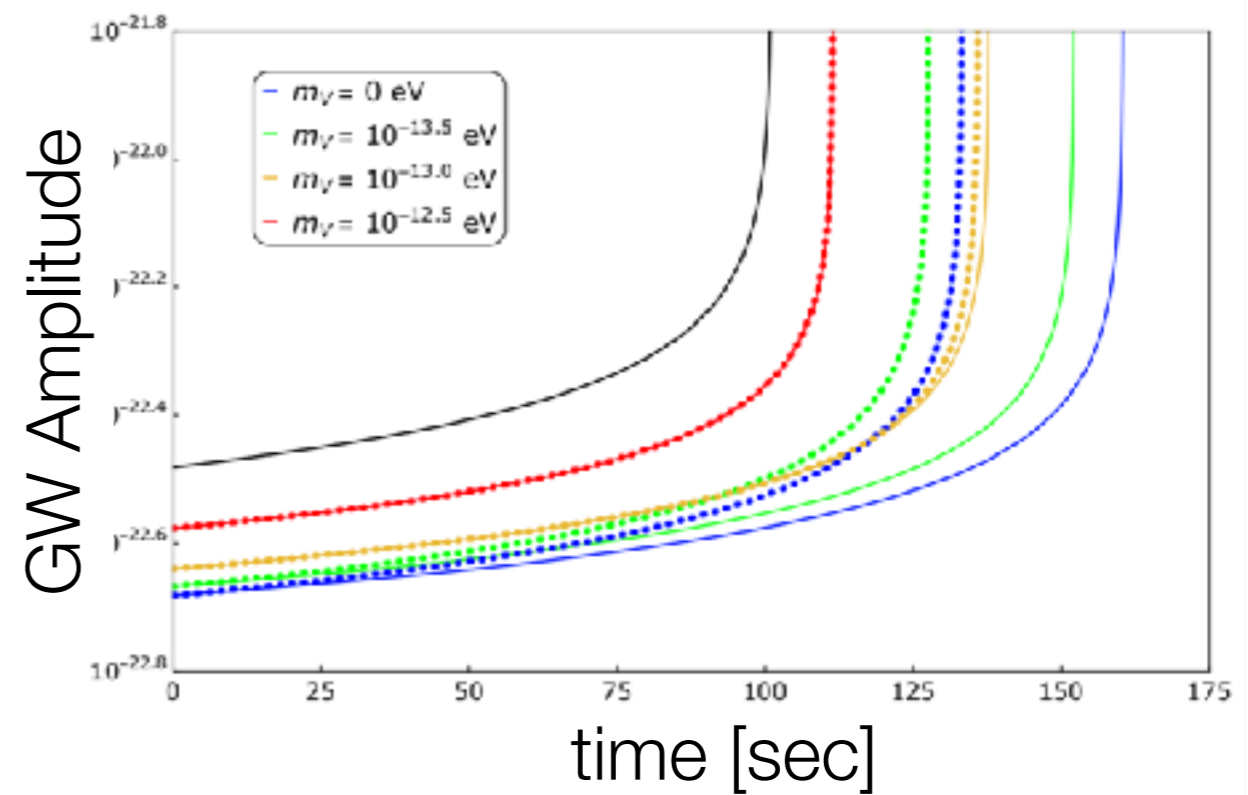
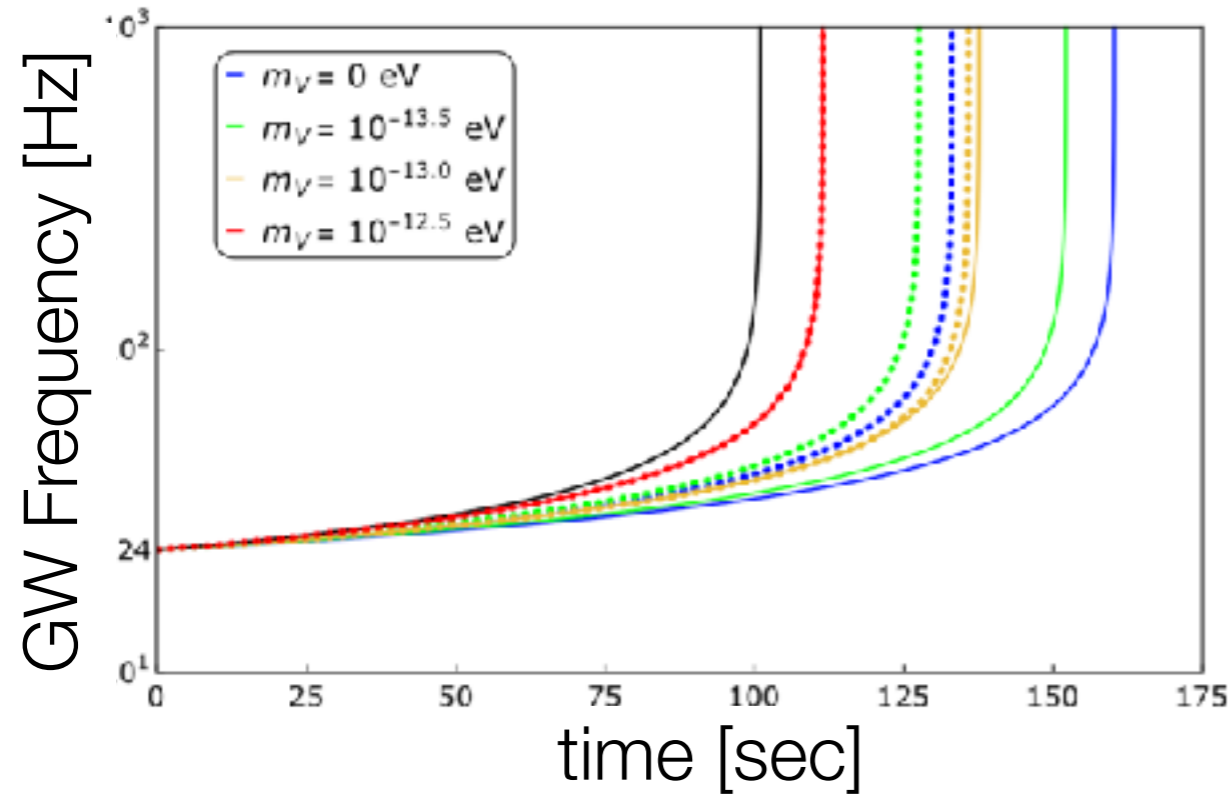
# Gravitational Wave Astronomy has finally begun!

# Probing Dark Sectors in Binary Inspirals

- ☑ GW waveform predicted precisely by GR
- ☑ Imagine **dark gauge boson  $A'$**  coupled to neutron stars
  - Either to neutrons (e.g.  $U(1)_B$ )
  - or to **Dark Matter** inside the neutron star
- ☑ Expect modified force once  $d < 1/M_{A'}$
- ☑ Moreover: energy loss due to  $A'$  radiation

Croon Nelson Sun Walker Xianyu  
arXiv:1711.02096

# Probing Dark Sectors in Binary Inspirals



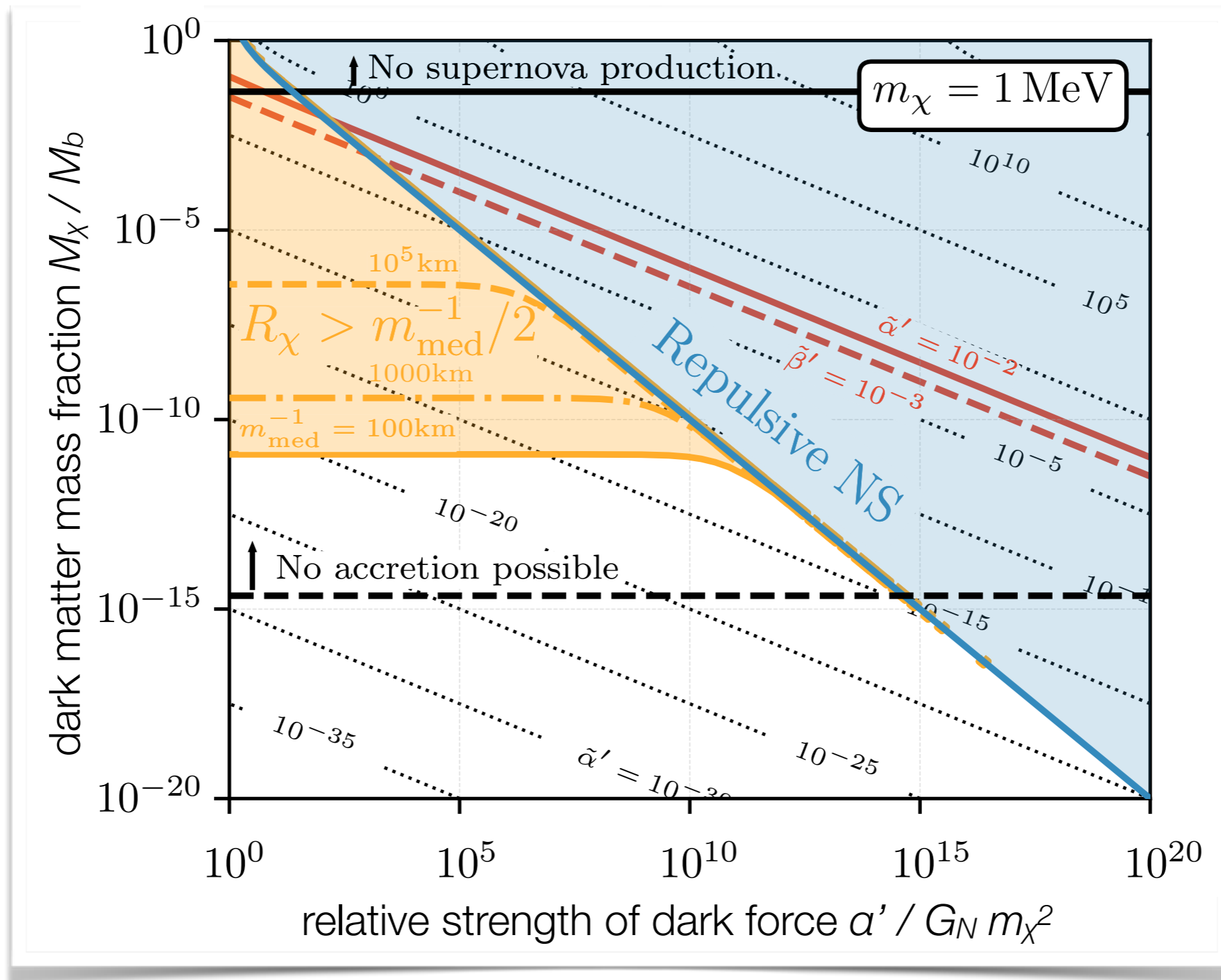
Croon Nelson Sun Walker Xianyu  
arXiv:1711.02096

# Questions

- Can **neutron stars** contain enough **dark matter**?
- Will it **stay inside** during the inspiral?

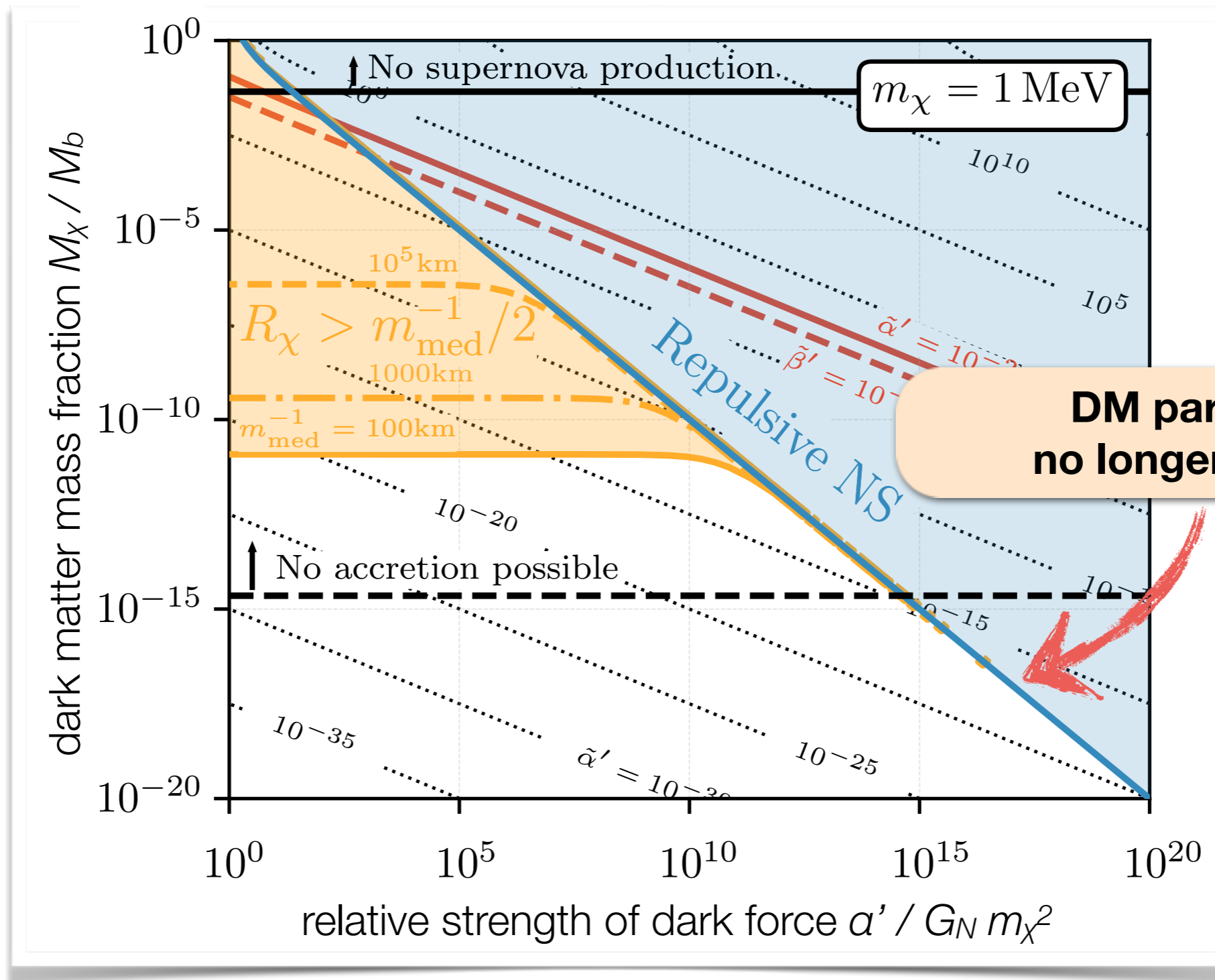
Laha JK Opferkuch Shepherd  
arXiv:1807.02527

# Case 1: Repulsive Force



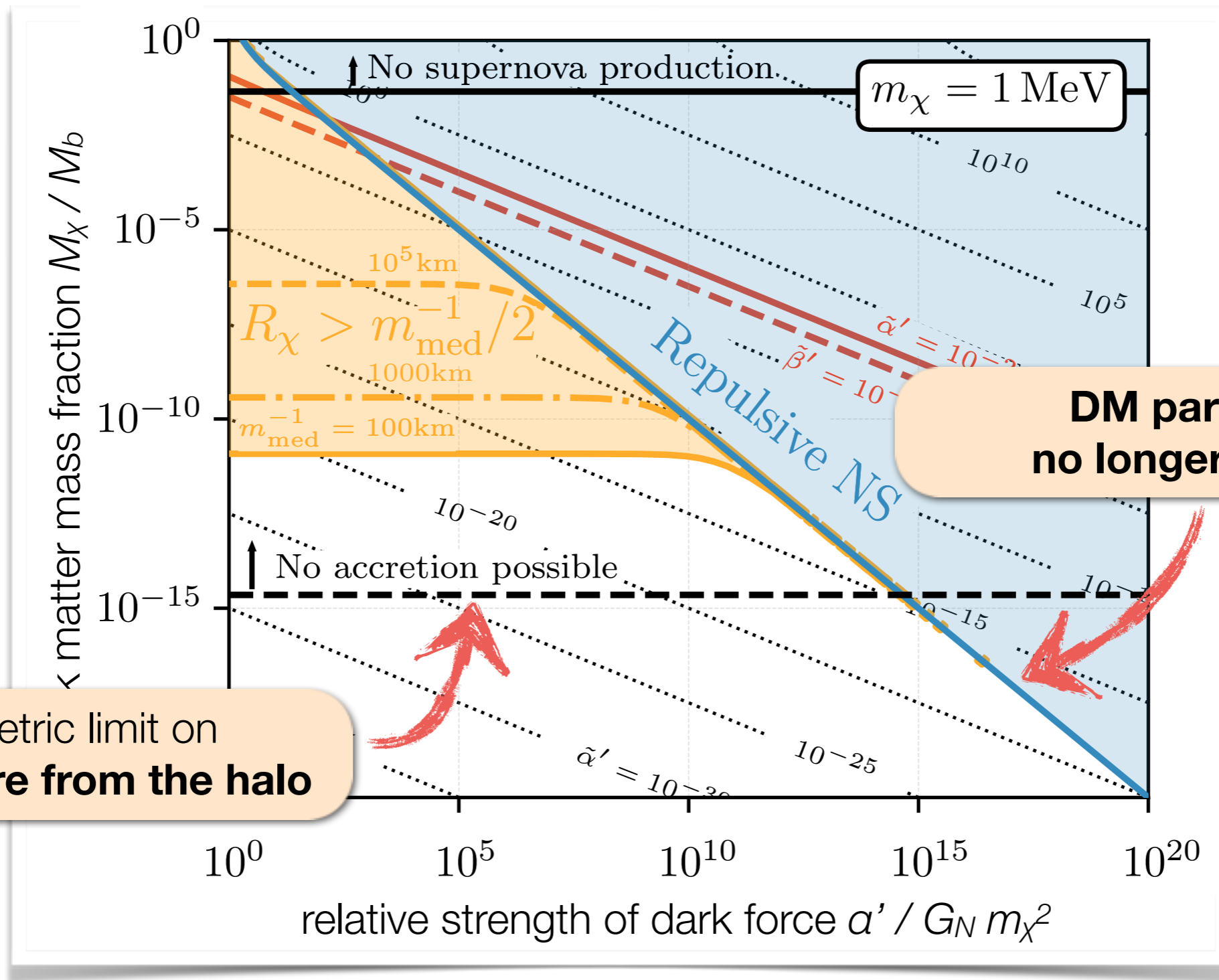
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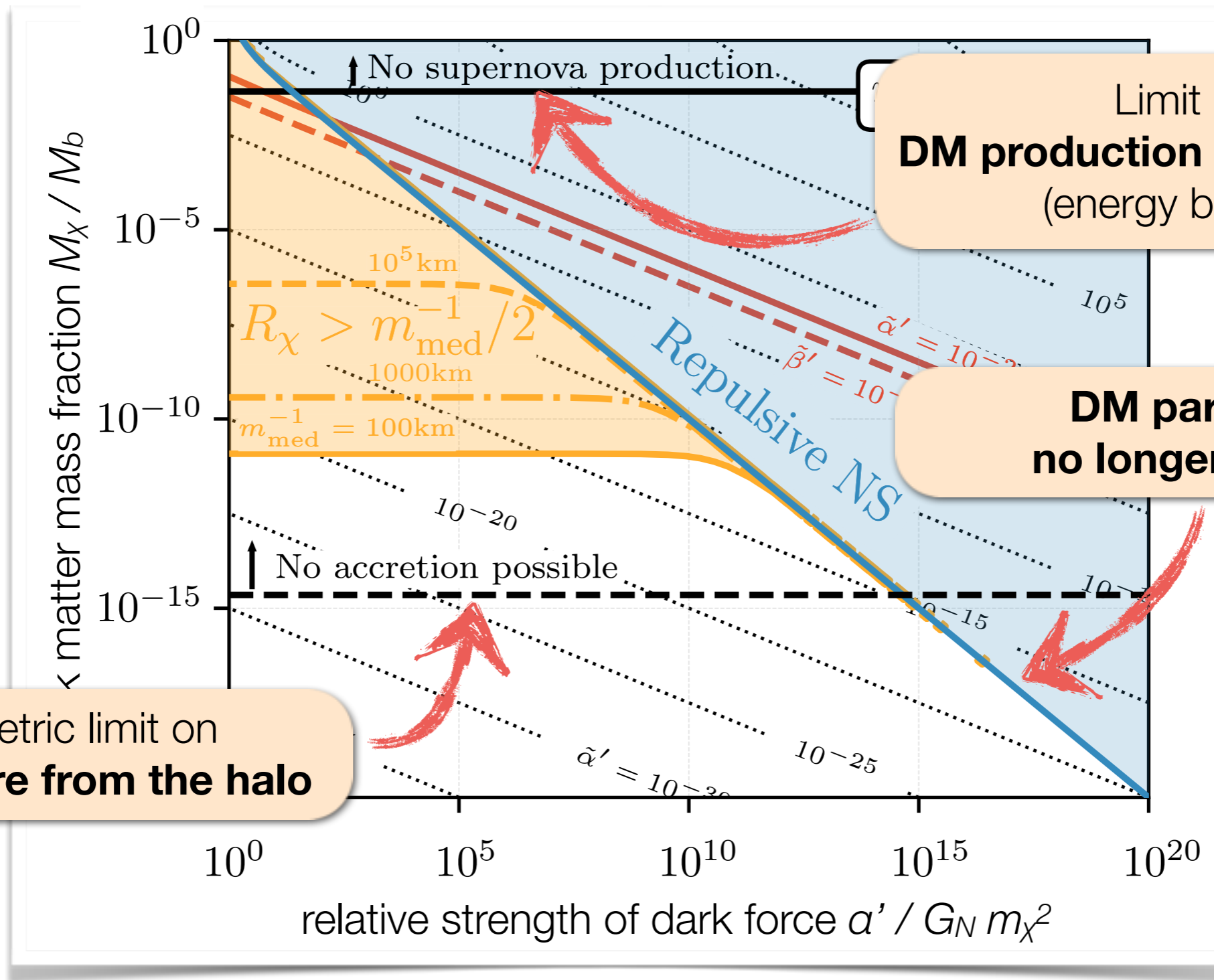
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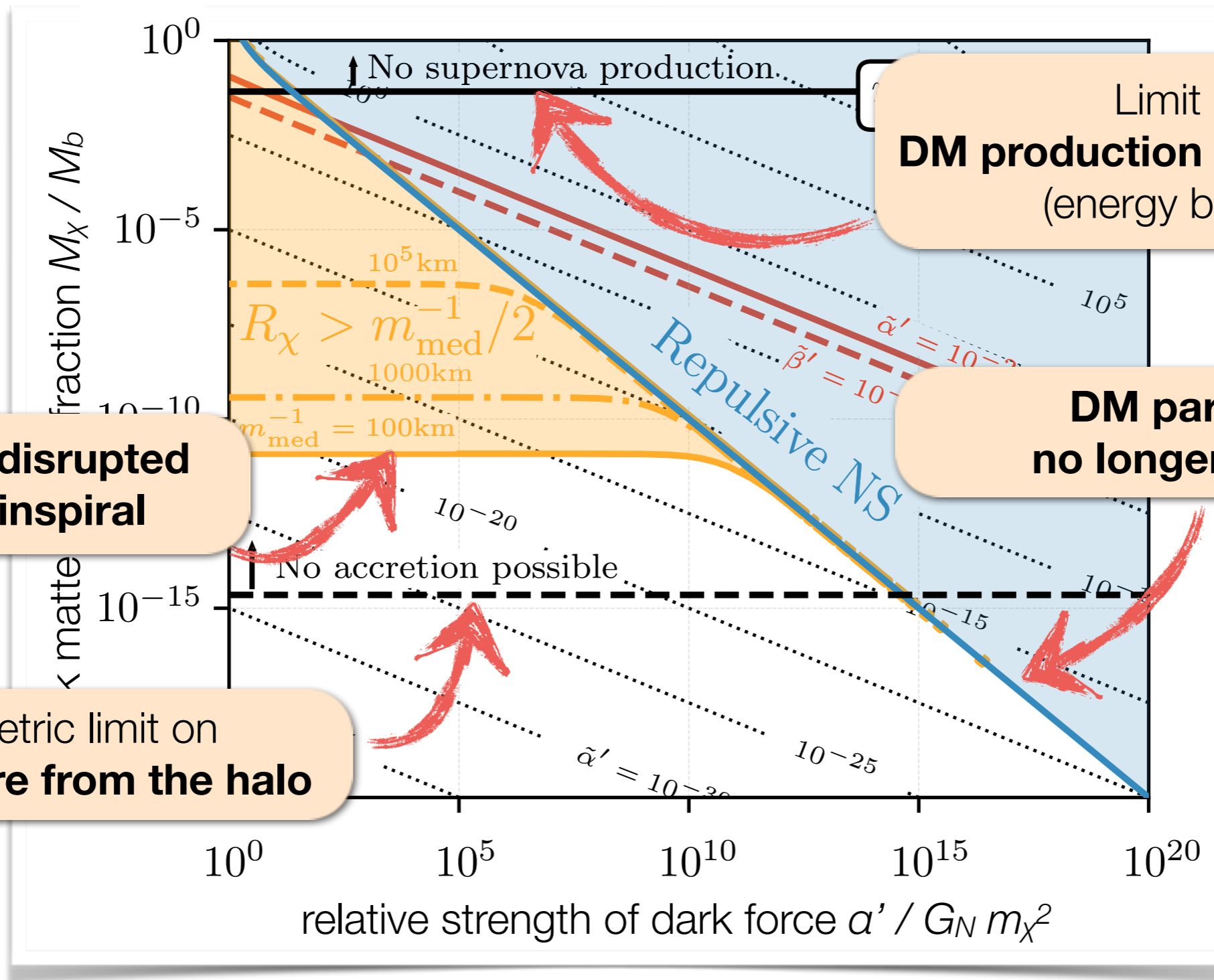
Limit on  
**DM production in supernova**  
(energy budget)

**DM particles  
no longer bound**

Geometric limit on  
**DM capture from the halo**

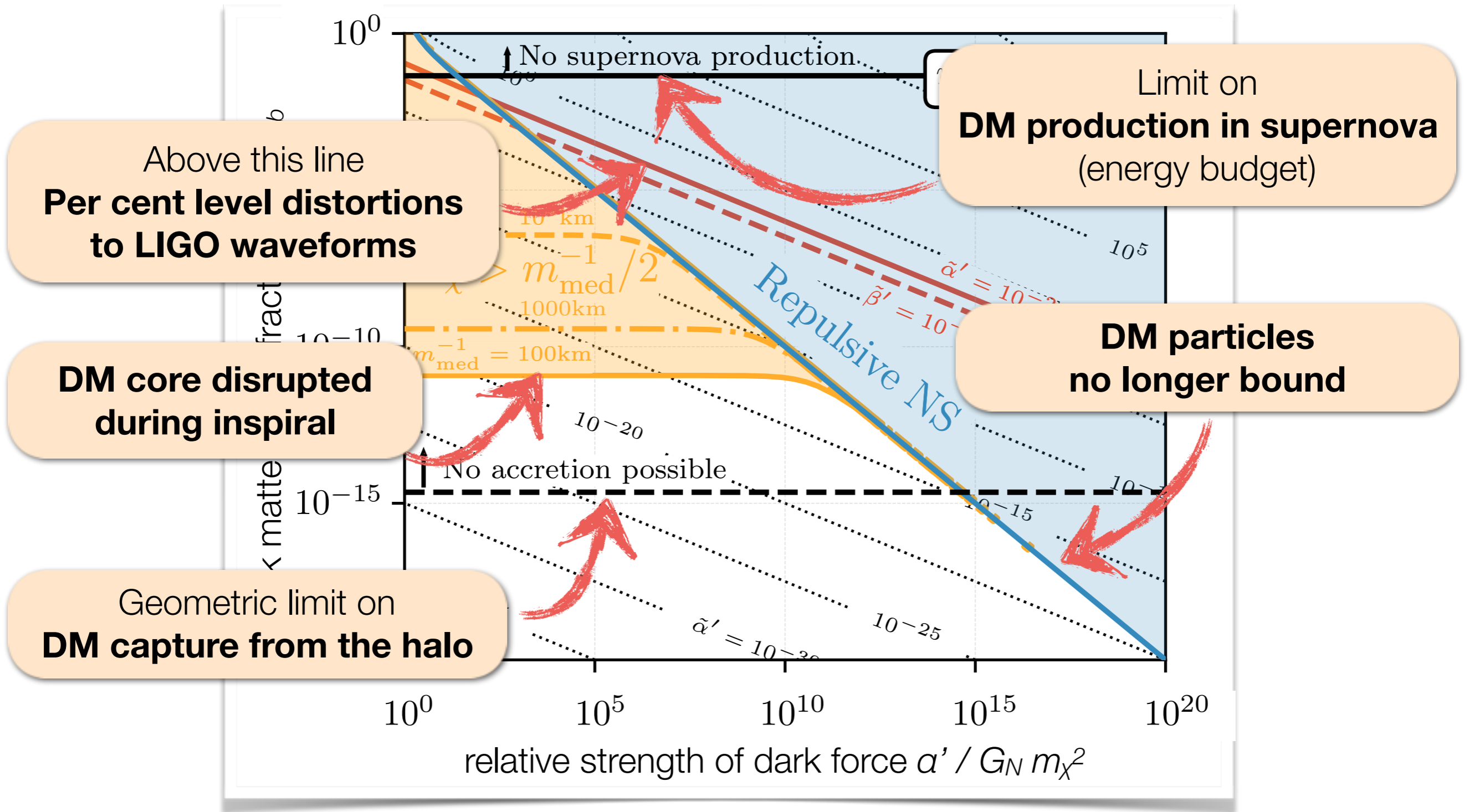
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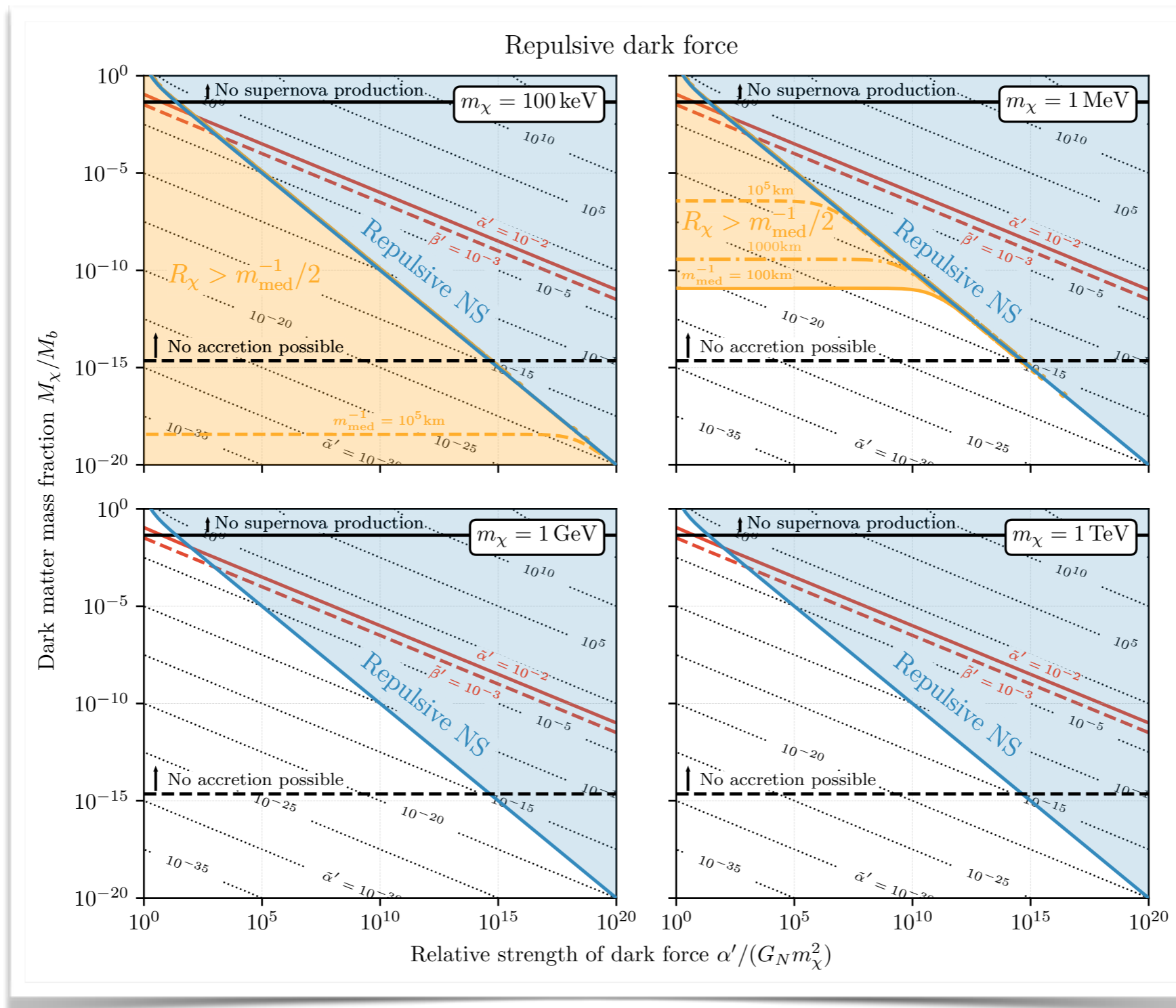
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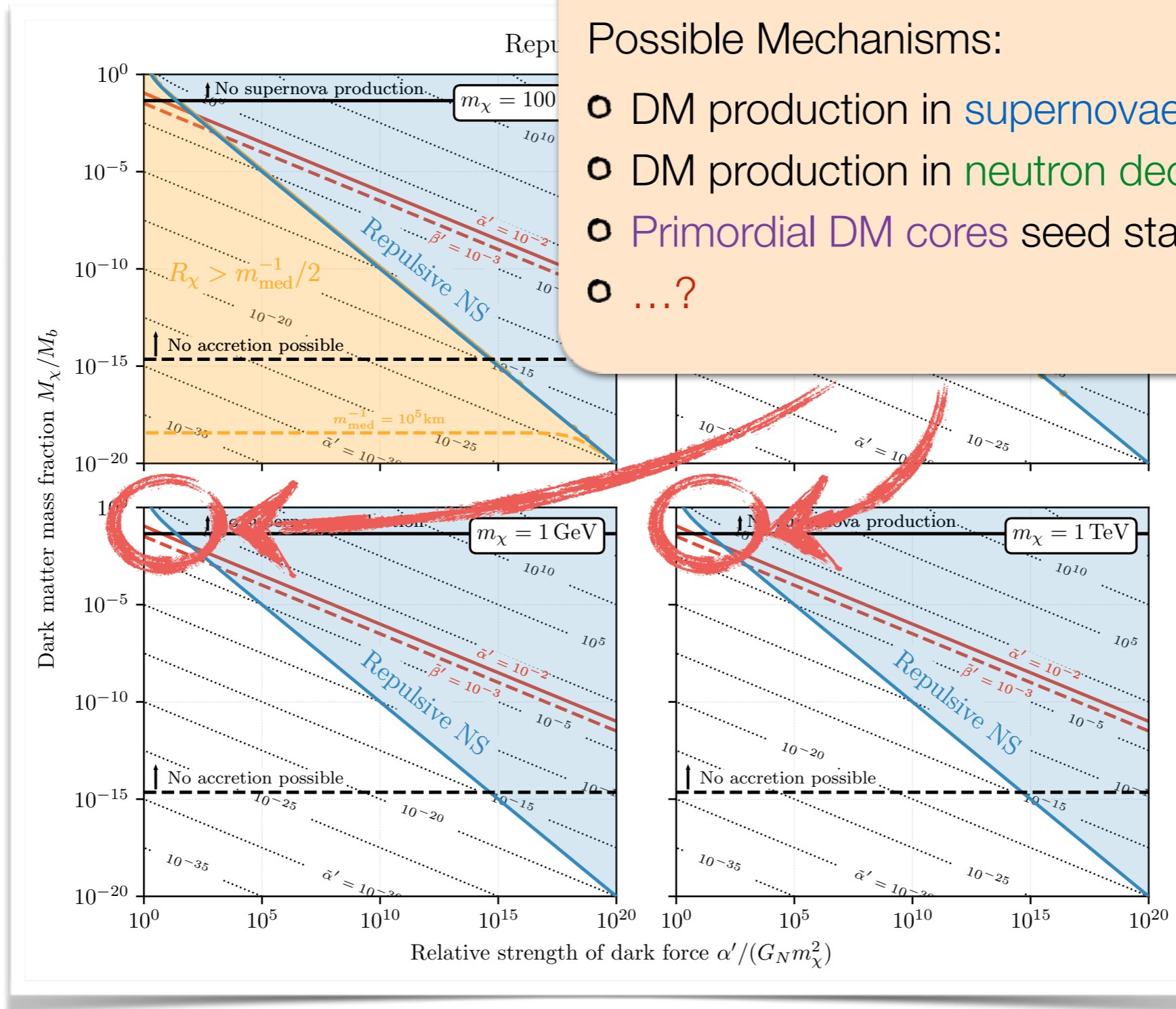
Laha JK Opferkuch Shepherd arXiv:1807.02527

# Case 1: Repulsive Force

tiny windows of opportunity

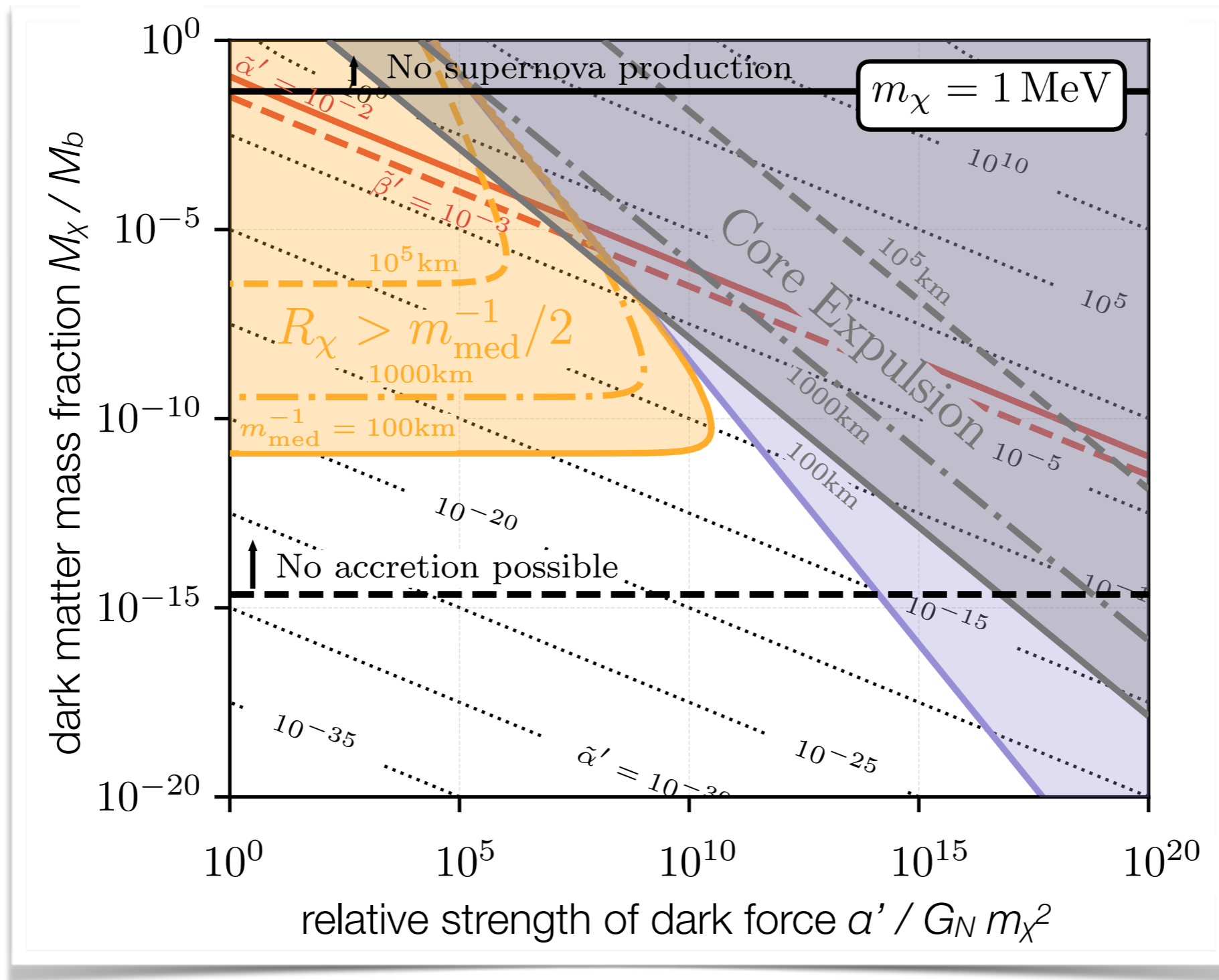
Possible Mechanisms:

- DM production in **supernovae**
- DM production in **neutron decay**
- **Primordial DM cores** seed star formation
- ...?



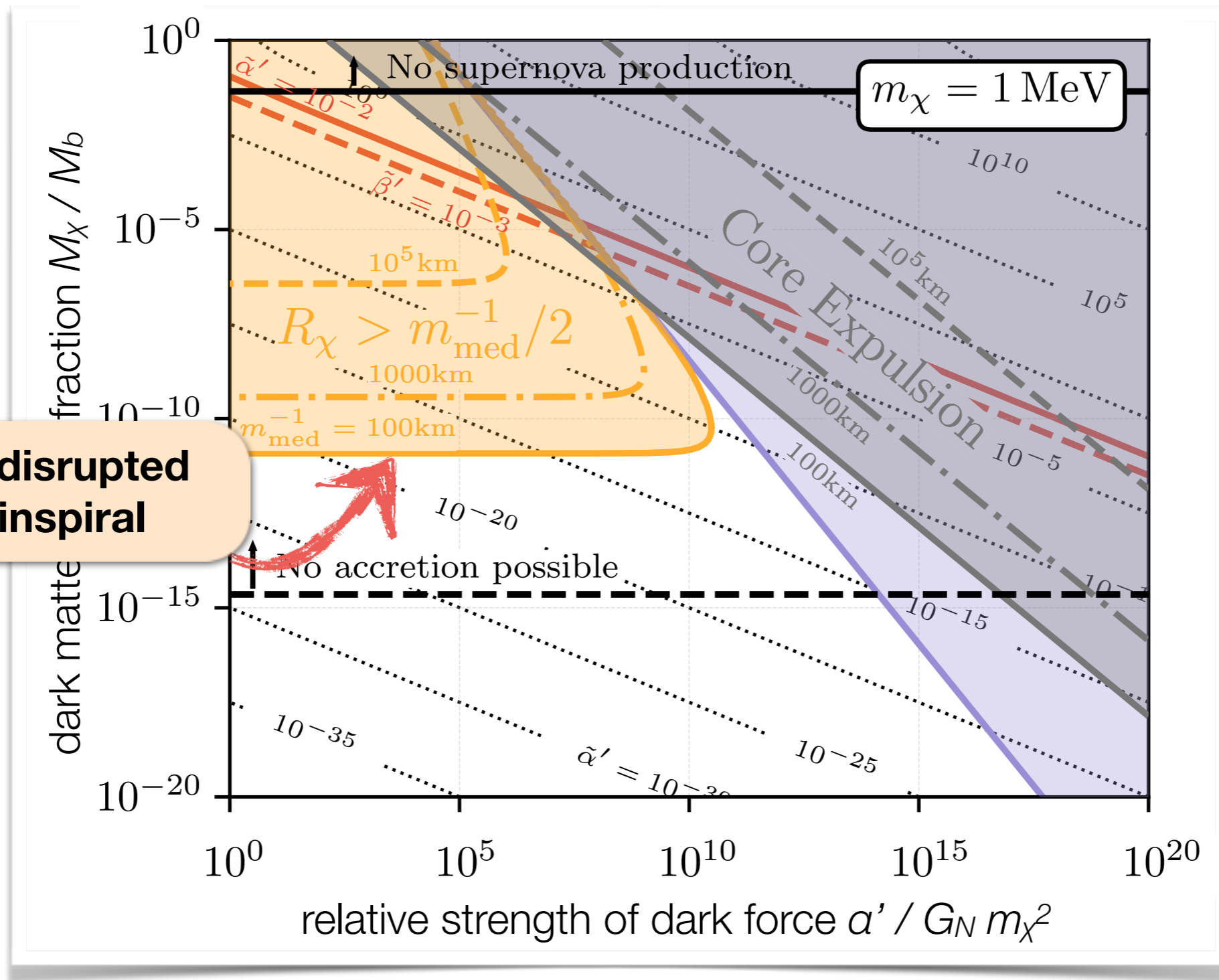
Laha JK Opferkuch Shepherd arXiv:1807.02527

# Case 2: Attractive Force



Laha JK Opferkuch Shepherd arXiv:1807.02527

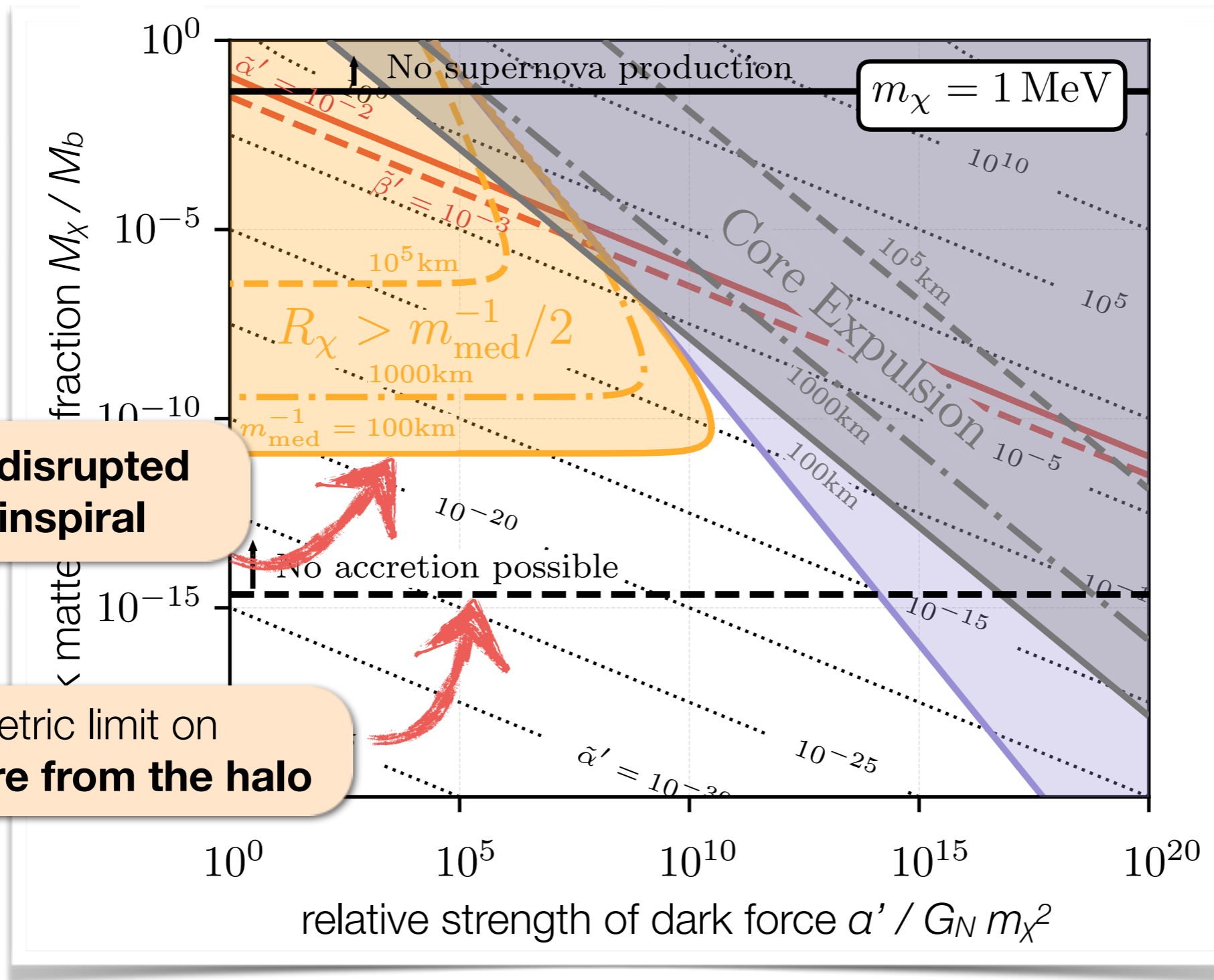
# Case 2: Attractive Force



**DM core disrupted during inspiral**

Laha JK Opferkuch Shepherd arXiv:1807.02527

# Case 2: Attractive Force

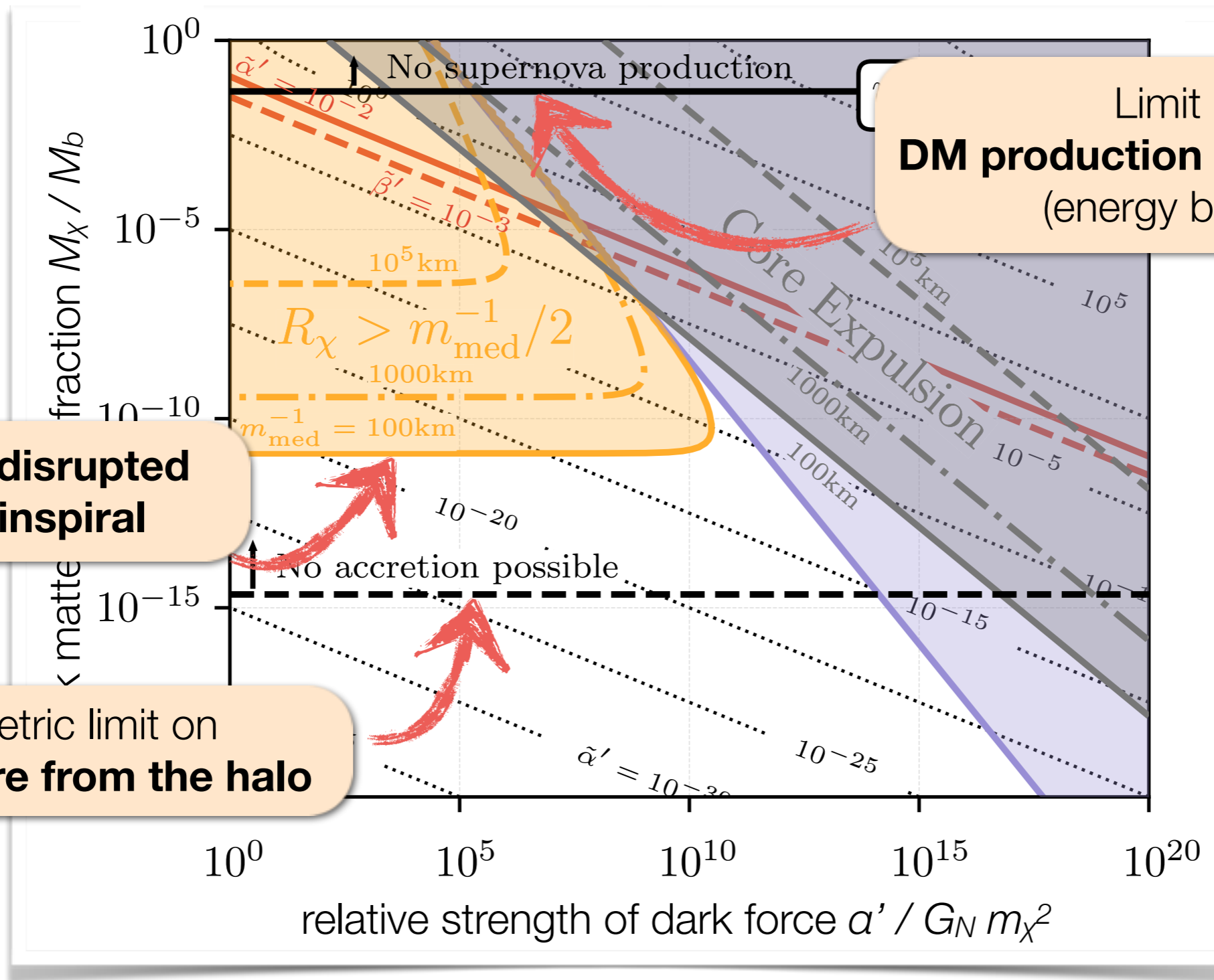


**DM core disrupted during inspiral**

Geometric limit on **DM capture from the halo**

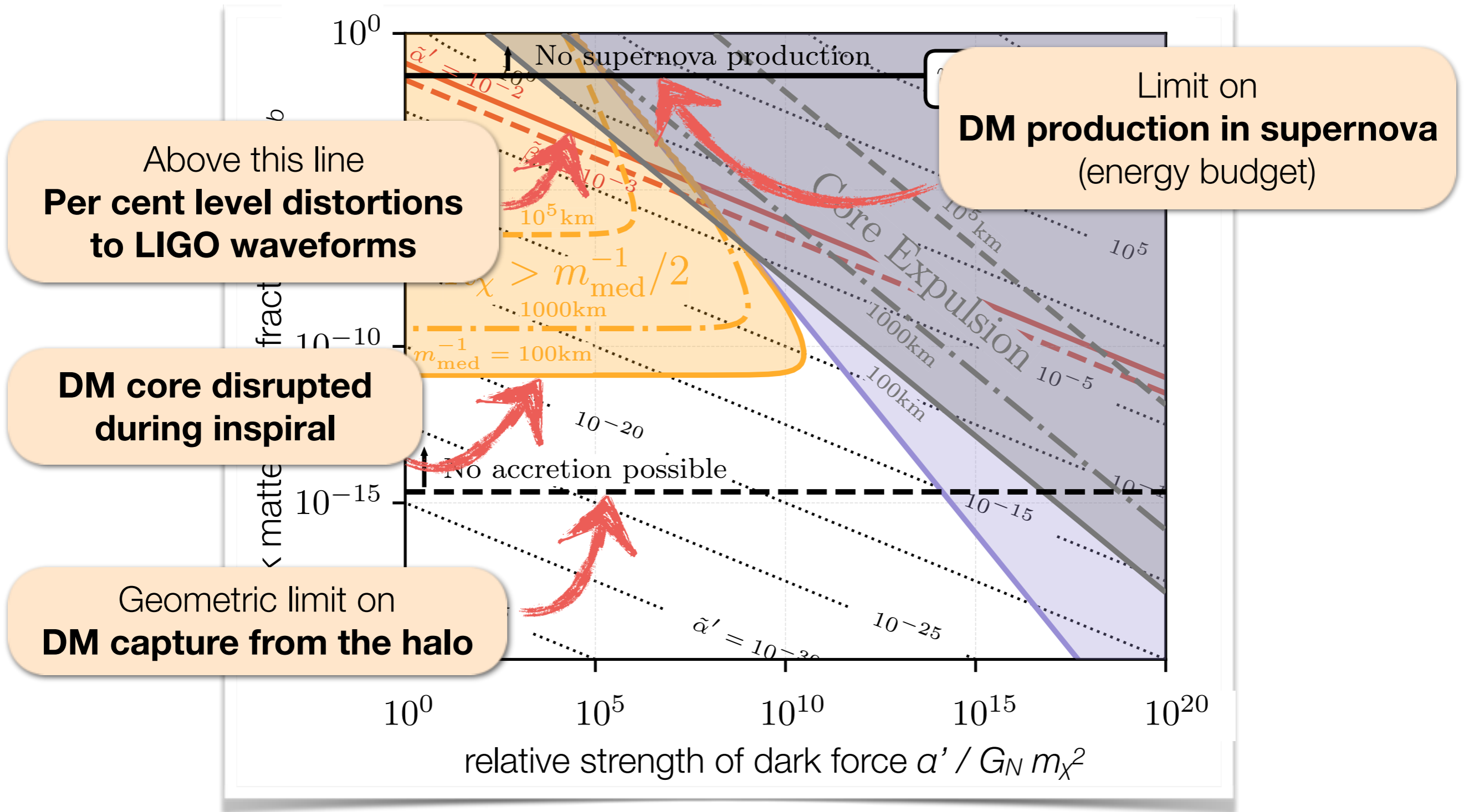
Laha JK Opferkuch Shepherd arXiv:1807.02527

# Case 2: Attractive Force



Laha JK Opferkuch Shepherd arXiv:1807.02527

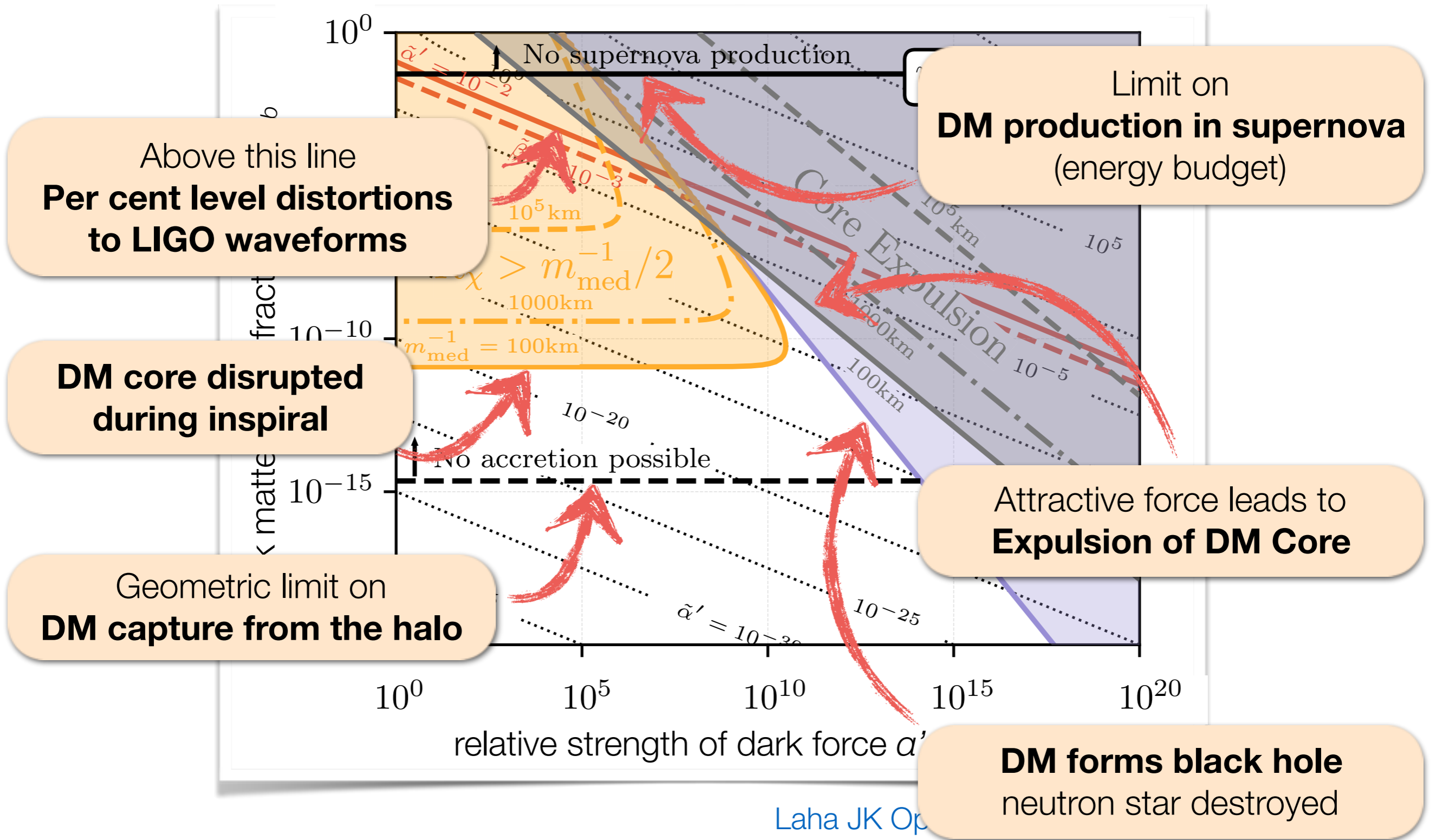
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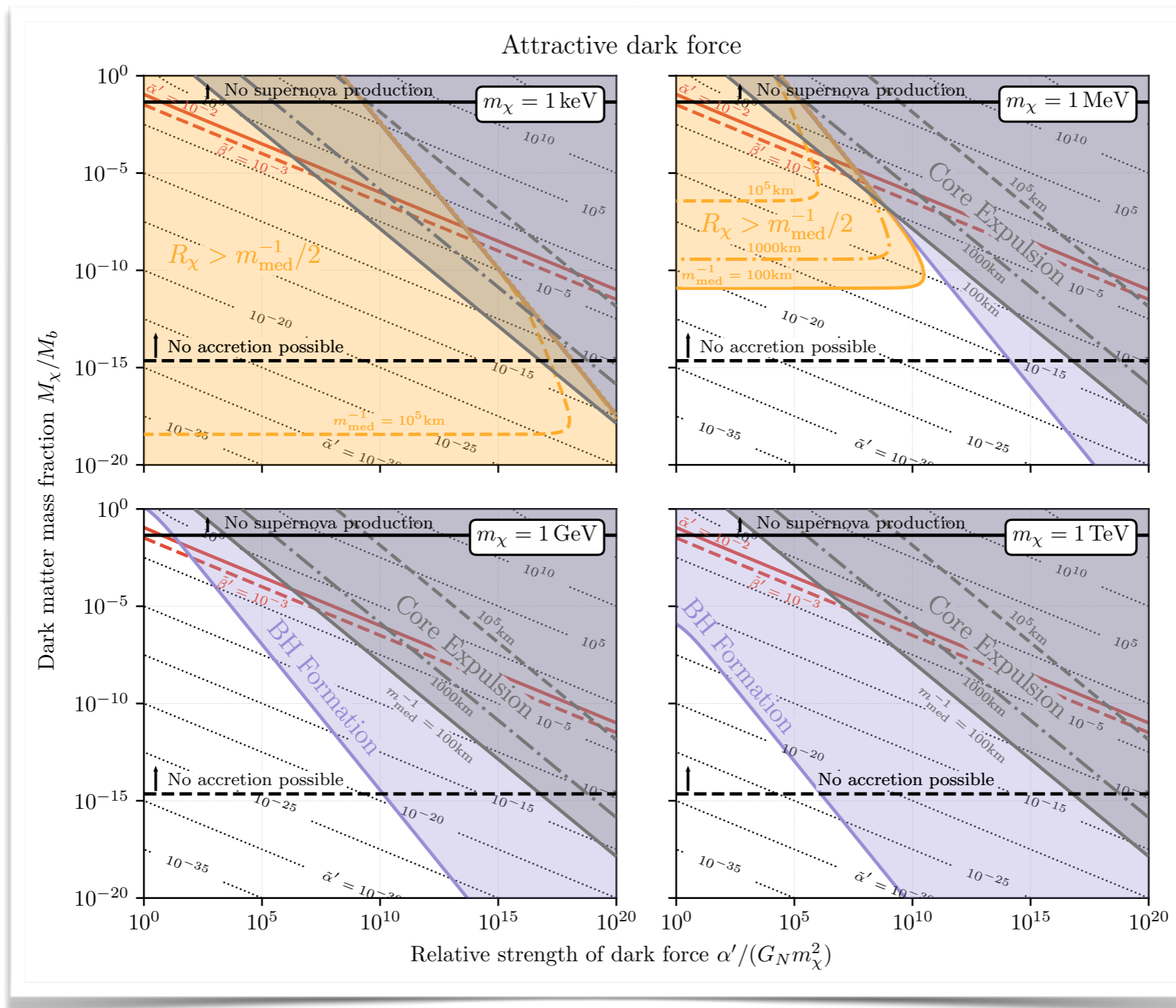


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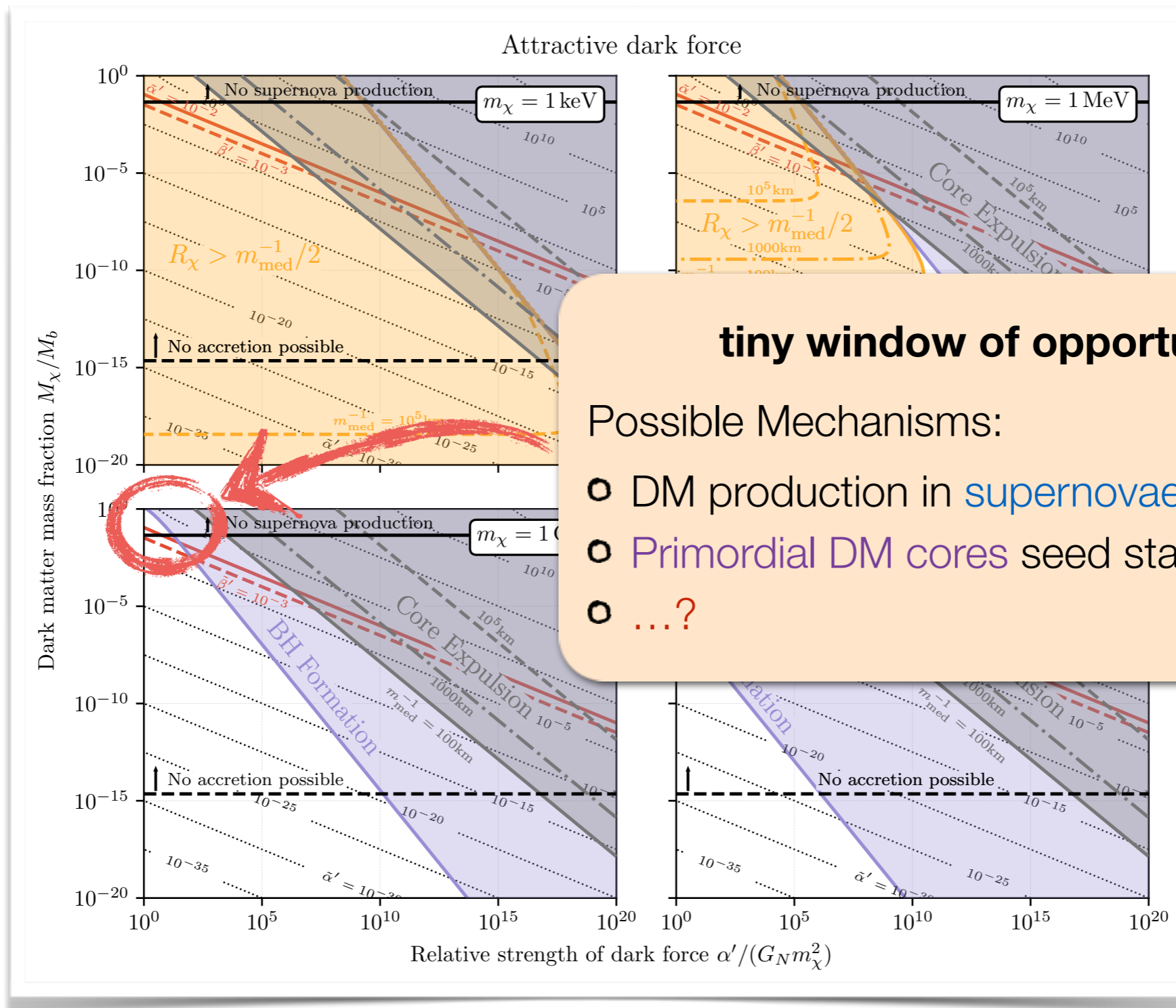
Laha JK Op

# Case 1: Repulsive Force



Laha JK Opferkuch Shepherd arXiv:1807.02527

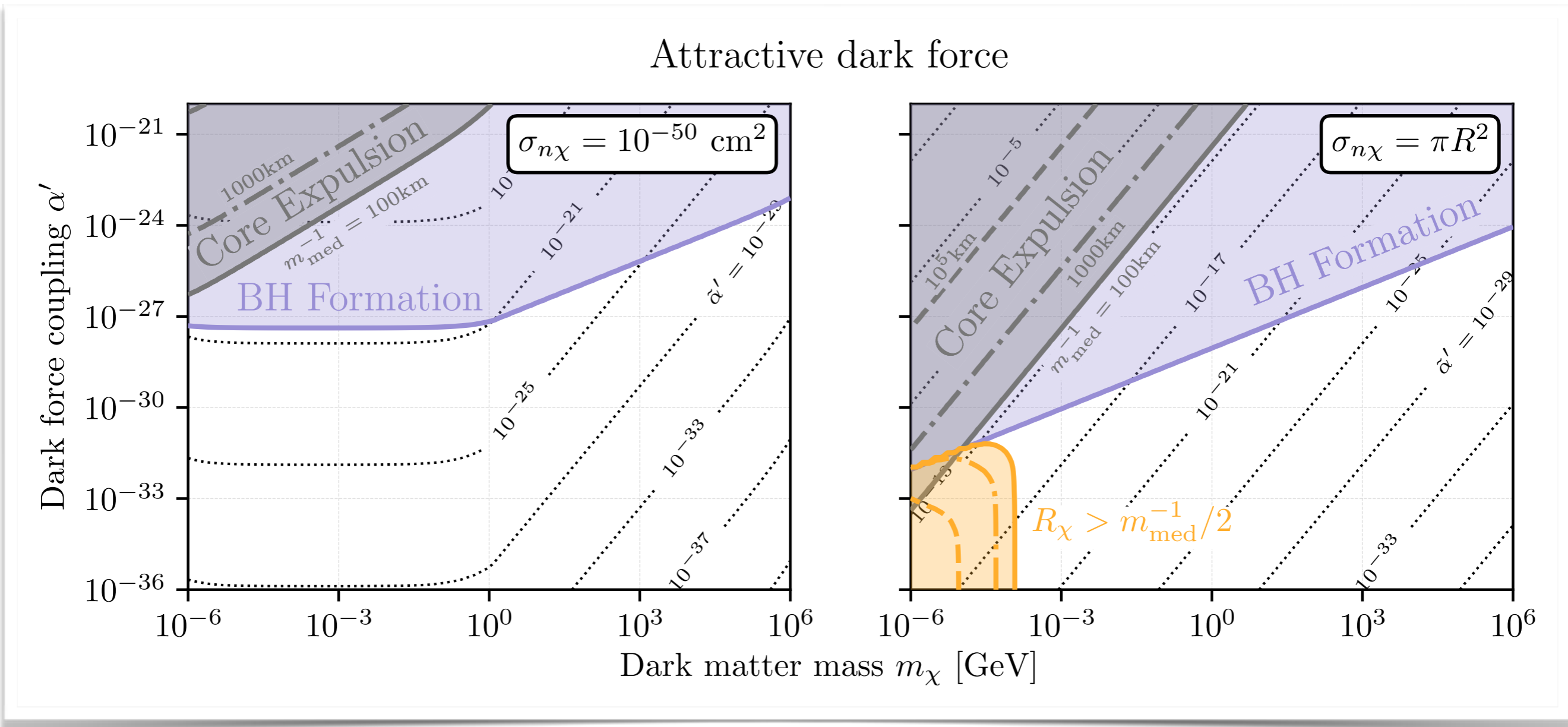
# Case 1: Repulsive Force



Laha JK Opferkuch Shepherd arXiv:1807.02527

# Constraints on Particle Physics Parameters

- Assuming DM capture from the halo



Laha JK Opferkuch Shepherd arXiv:1807.02527

# Summary



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## ☑ Gaia: Stellar Wakes

- Passing **DM subhalos** perturb **stellar phase space distribution**
- Potentially observable down to  $M_{\text{sh}} \sim 10^7 M_{\odot}$

## ☑ Fermi-LAT / GBM: Femtolensing of GRBs

- Passing **PBH** causes **interference pattern** in GRB spectrum
- *no current bounds* because GRBs are not pointlike

## ☑ LIGO / VIRGO: Modified Binary Inspirals

- Probably *no observable signals* from **dark sector forces**
- except for **exotic DM core** production mechanisms

# Thank You !



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