Dark Matter

Joachim Kopp (CERN & JGU Mainz)
EuCAPT Colloquium | March 3rd, 2020

In this Talk

- ☑ WIMP Dark Matter
- ☑ Primordial Black Holes
- ☑ Dark Photons

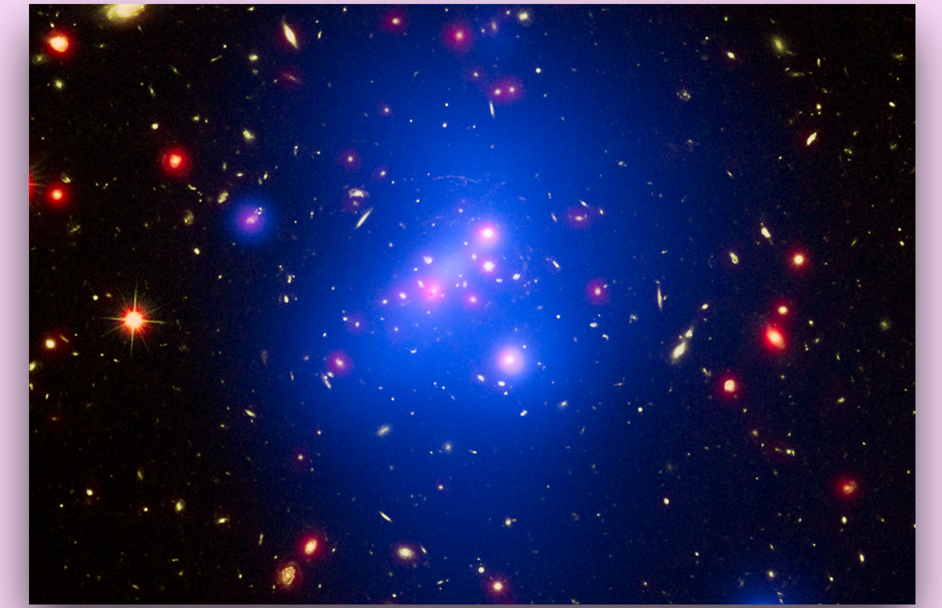
Not in this Talk

- ☑ Axions
- ☑ Sterile Neutrinos
- ☑ ...

Evidence for Dark Matter

Evidence for Dark Matter

Galaxy Clusters



Virial Theorem: $E_{\rm kin} = -\frac{1}{2} E_{\rm pot}$

Zwicky, 1930s: $E_{\rm kin} = -\frac{1}{2} E_{\rm pot} \times 170$

Evidence for Dark Matter

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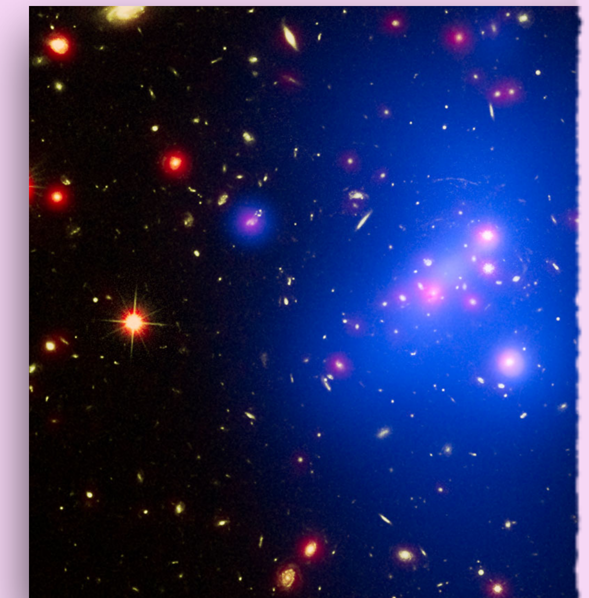
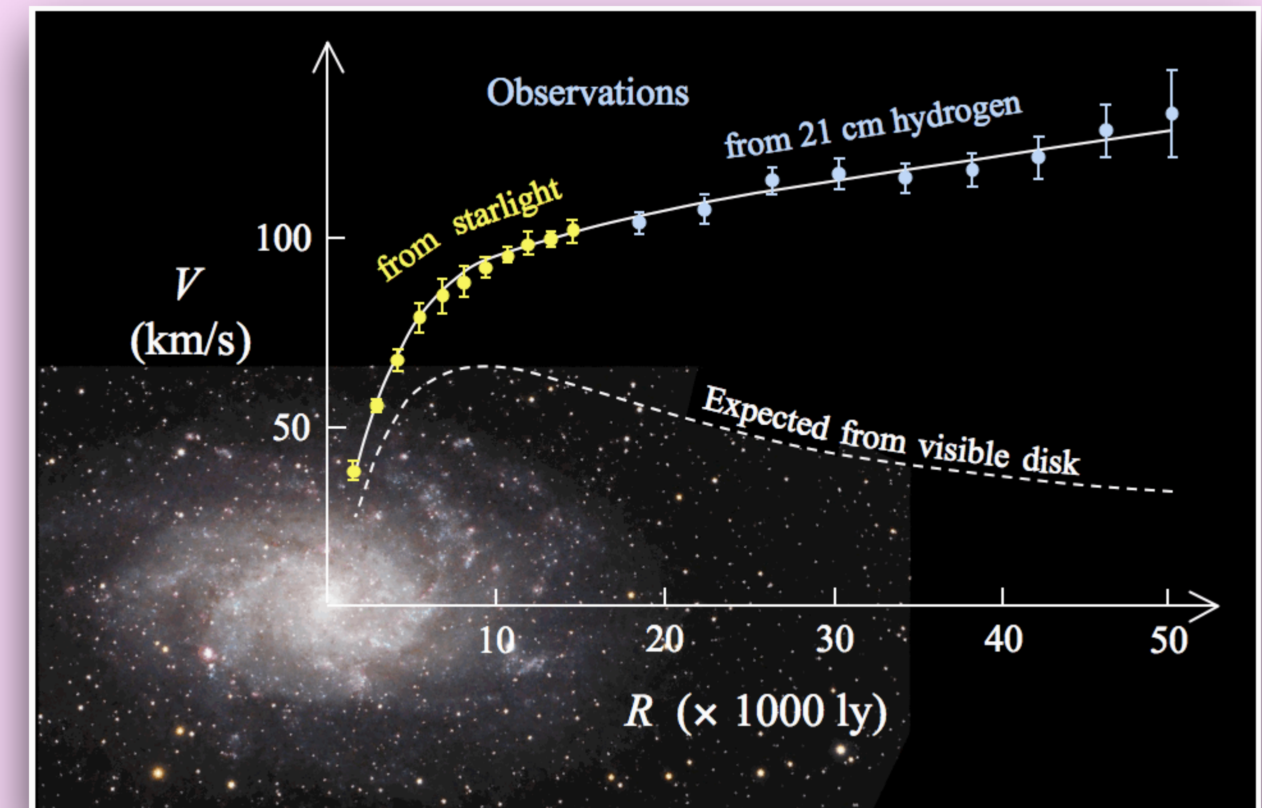


Virial Theorem: $E_{\mathrm{kin}} =$

Zwicky, 1930s: $E_{\mathrm{kin}} =$

Galaxy Rotation Curves



Evidence for Dark Matter

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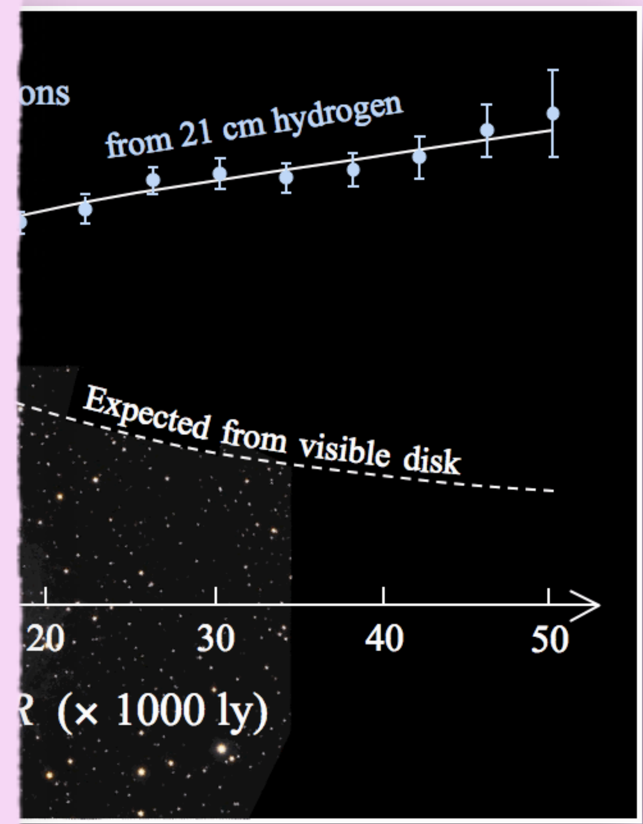
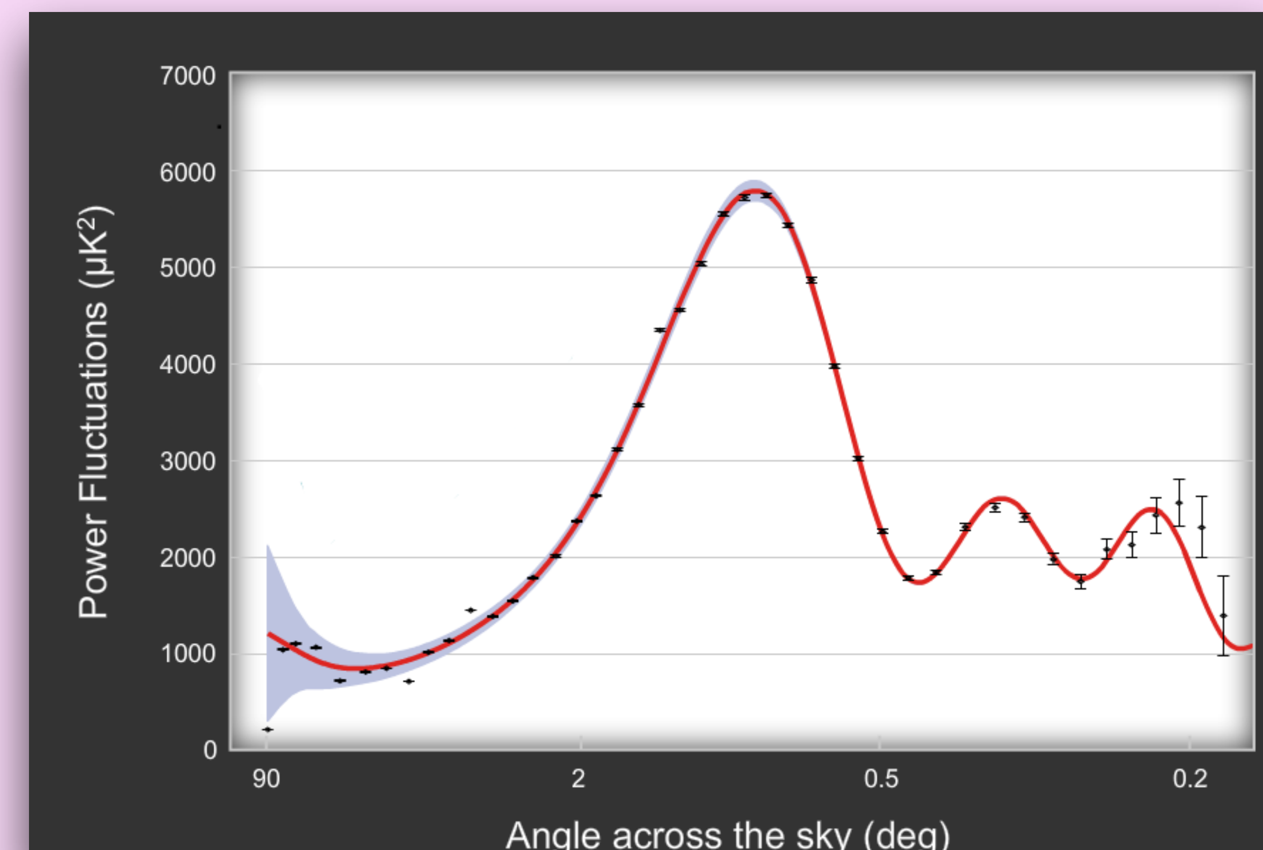


Cosmic Microwave Background



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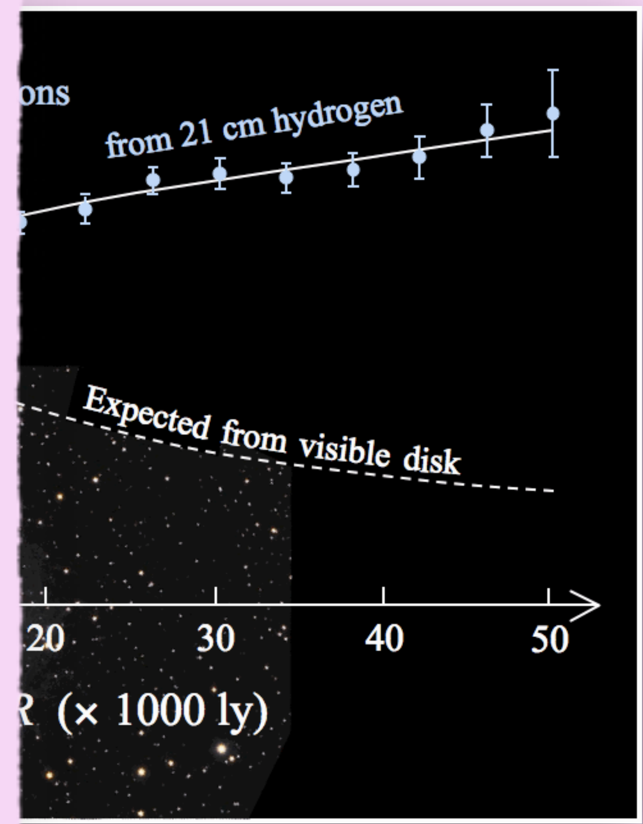

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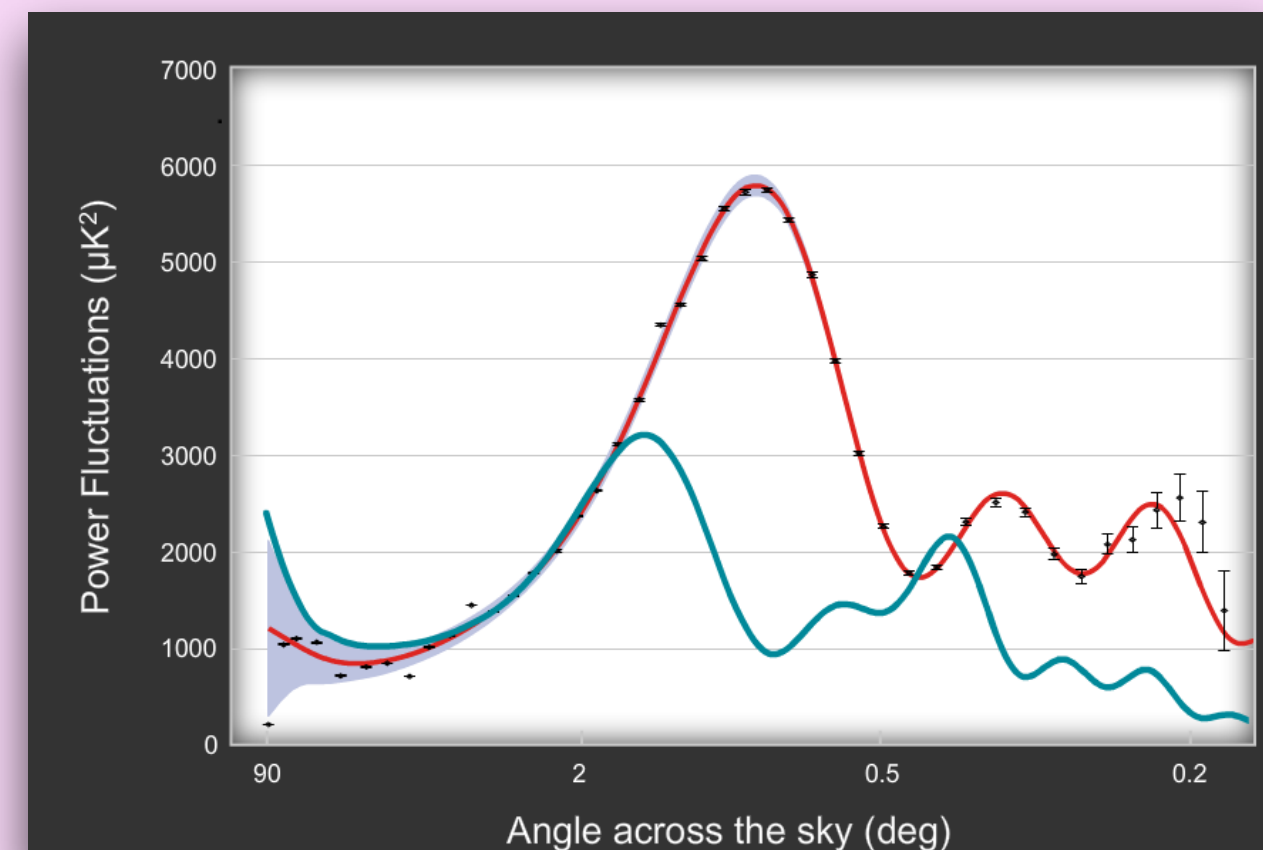

Evidence for Dark Matter

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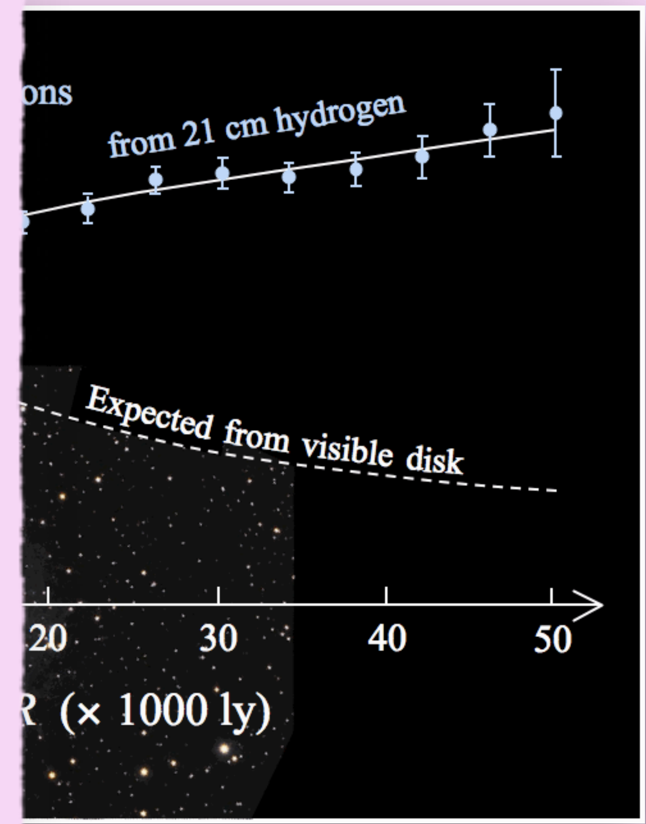

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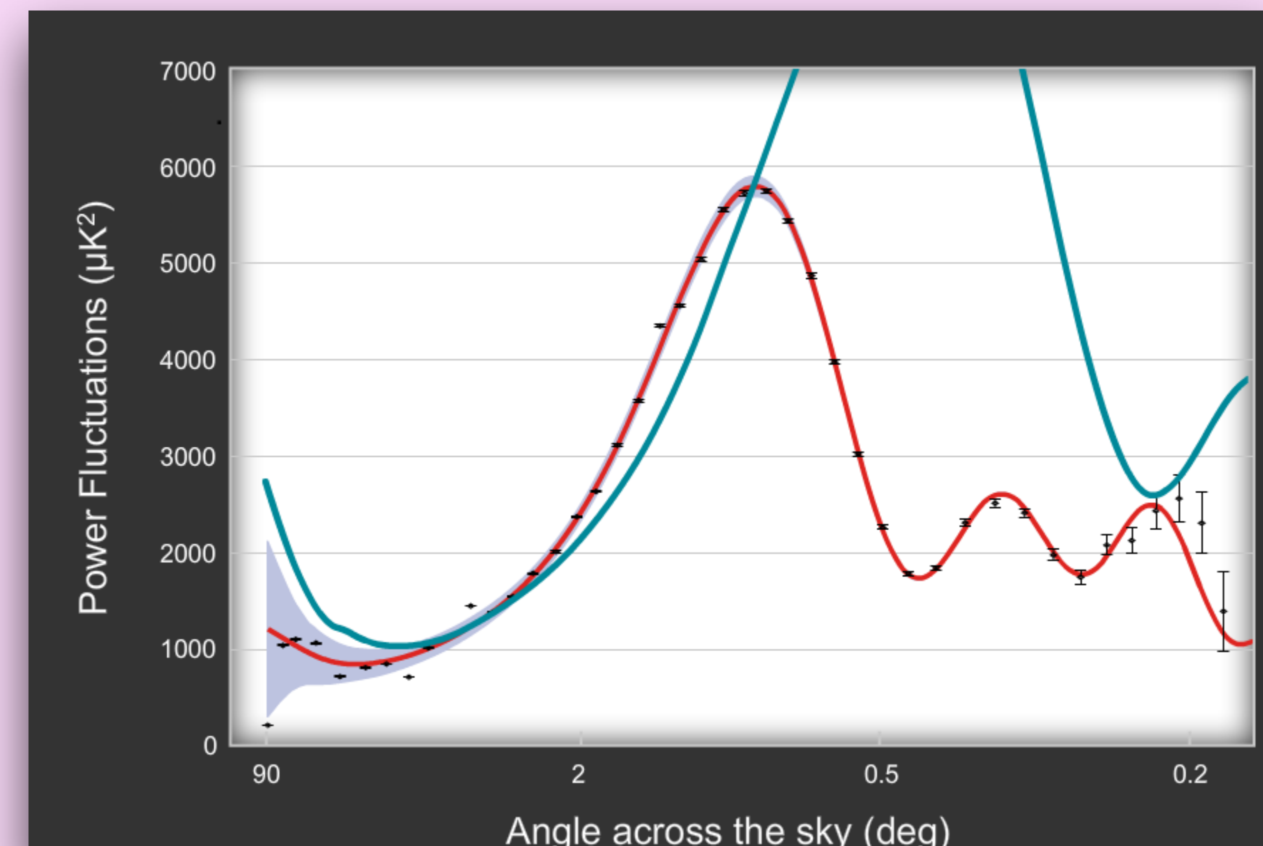
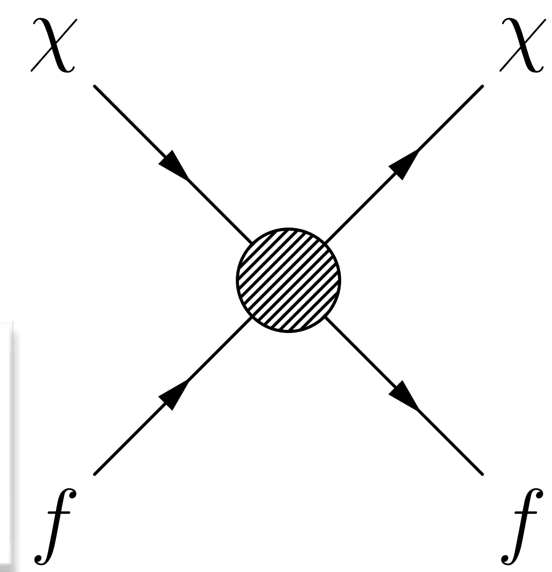


WIMP Dark Matter

Standard Lore: Thermal Freeze-Out

- Early on: DM in thermal equilibrium with SM

  e.g. via $\bar{\chi}\chi \longleftrightarrow \bar{f}f$



- Number density: $n_{\chi,\mathrm{eq}} = \int \frac{d^3p}{(2\pi)^3} \exp\left[-E_\chi(\vec{p})/T\right]$

- T drops, interactions freeze out

- Described by Boltzmann equation

$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\left(n_\chi^2 \langle \sigma(\chi\chi \to \bar{f}f) v_{\mathrm{rel}} \rangle - n_f^2 \langle \sigma(\bar{f}f \to \chi\chi) v_{\mathrm{rel}} \rangle\right)$$

Thermal Freeze-Out

$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\left(n_\chi^2 \langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle - n_f^2 \langle \sigma(\bar{f}f \to \chi\chi) v_{\rm rel} \rangle \right)$$

- ☑ Detailed balance: $n_f^2 \langle \sigma(\bar{f}f \to \chi\chi) v_{\rm rel} \rangle = n_{\chi,\rm eq}^2 \langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle$
- ☑ Final Boltzmann equation

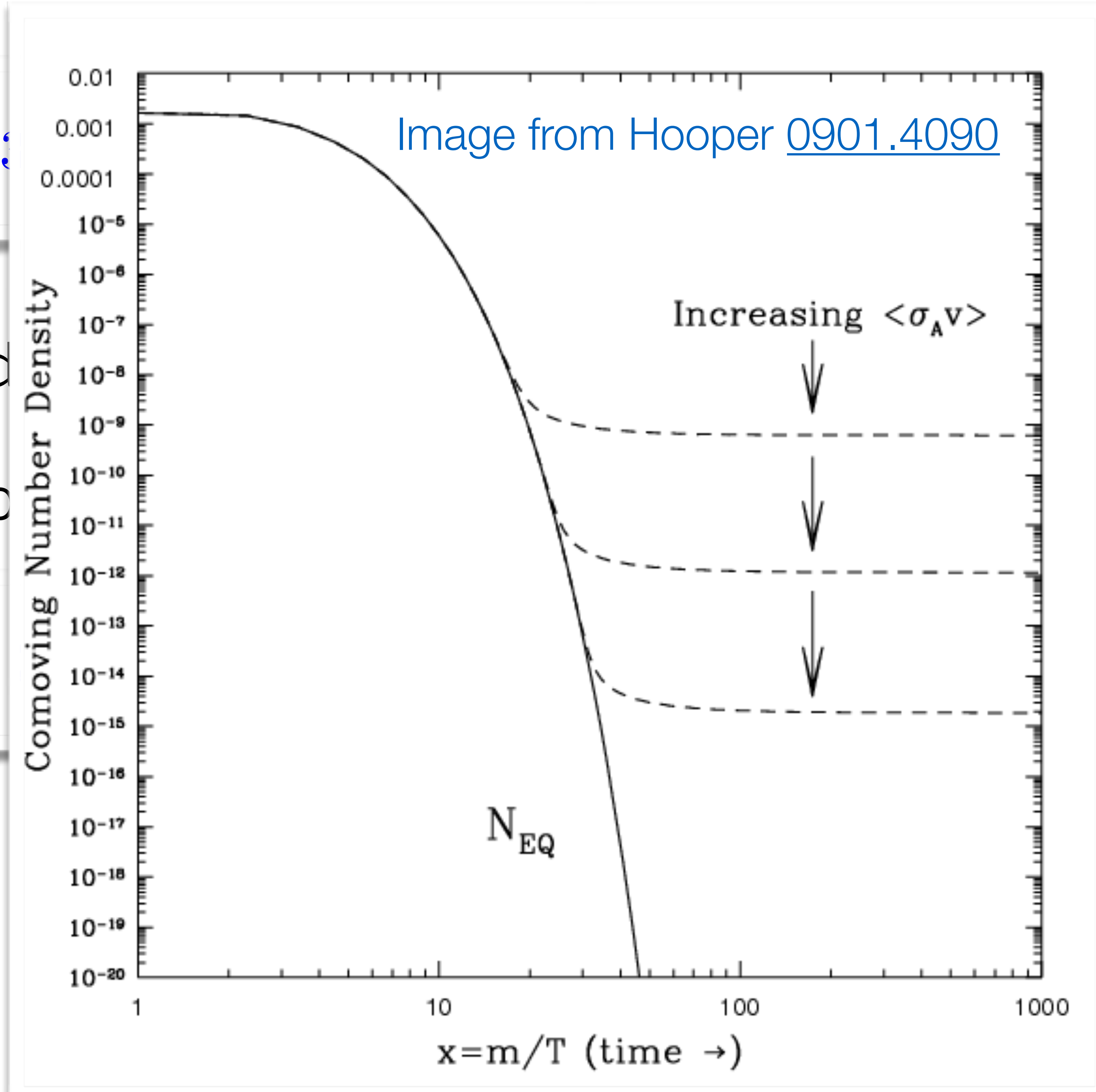
$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle \left(n_\chi^2 - n_{\chi,\rm eq}^2 \right)$$

Thermal Freeze-Out

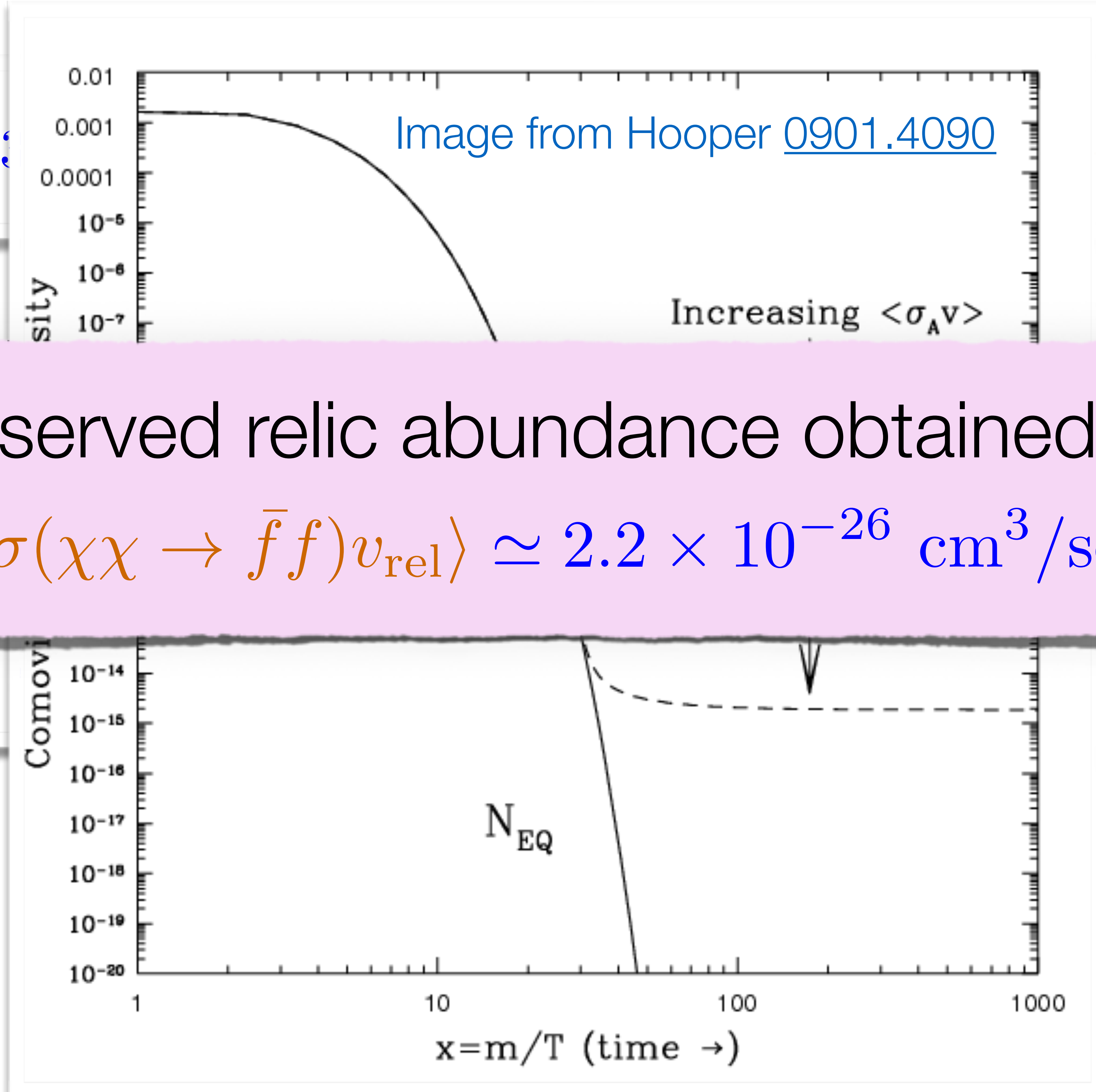
$$\frac{dn_\chi}{dt} + \ldots \to \chi\chi)v_{\rm rel}\rangle\Big)$$

- Detailed ... $(\chi\chi \to \bar{f}f)v_{\rm rel}\rangle$
- Final Bo...

$$\frac{dn_\chi}{dt} + \ldots$$



Thermal Freeze-Out



observed relic abundance obtained for

$$\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq 2.2 \times 10^{-26}\ {\rm cm}^3/{\rm sec}$$

Standard Lore: Thermal Freeze-Out

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- ☑ Expect new particles at ~ 100 GeV
- ☑ SM-like couplings ~ α_{em} ~ 0.01
- ☑ Expect $\langle \sigma(\chi\chi \to \bar{f}f) v_{\mathrm{rel}} \rangle \simeq \mathrm{few} \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$

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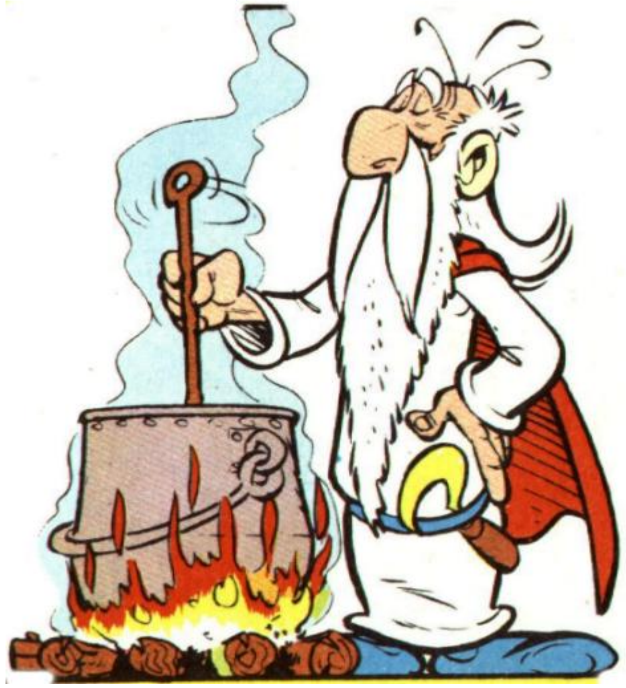
WIMP Miracle



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DM annihilation today

observed relic abundance obtained for

$$\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq 2.2 \times 10^{-26}\ {\rm cm}^3/{\rm sec}$$

If this is mechanism is responsible for setting the DM abundance in the early Universe,

annihilations should still be happening today

in regions of high DM density

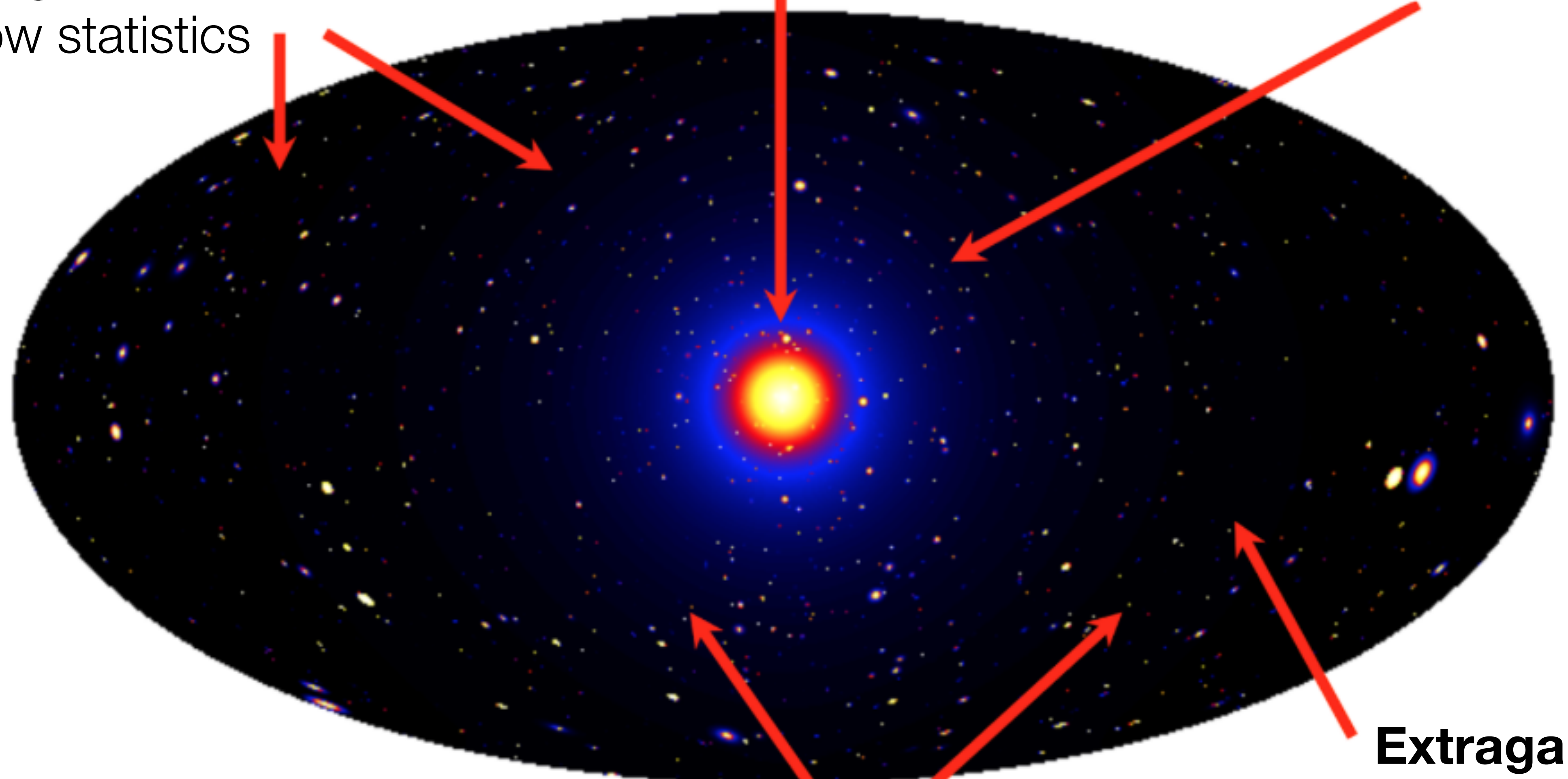
WIMP Dark Matter: Indirect Detection

Where to look for DM Annihilation?

Galactic Center
good statistics, but source confusion and diffuse background

Dwarf Satellite Galaxies
low BG and good source ID, but low statistics

Milky Way Halo
good statistics, but diffuse background



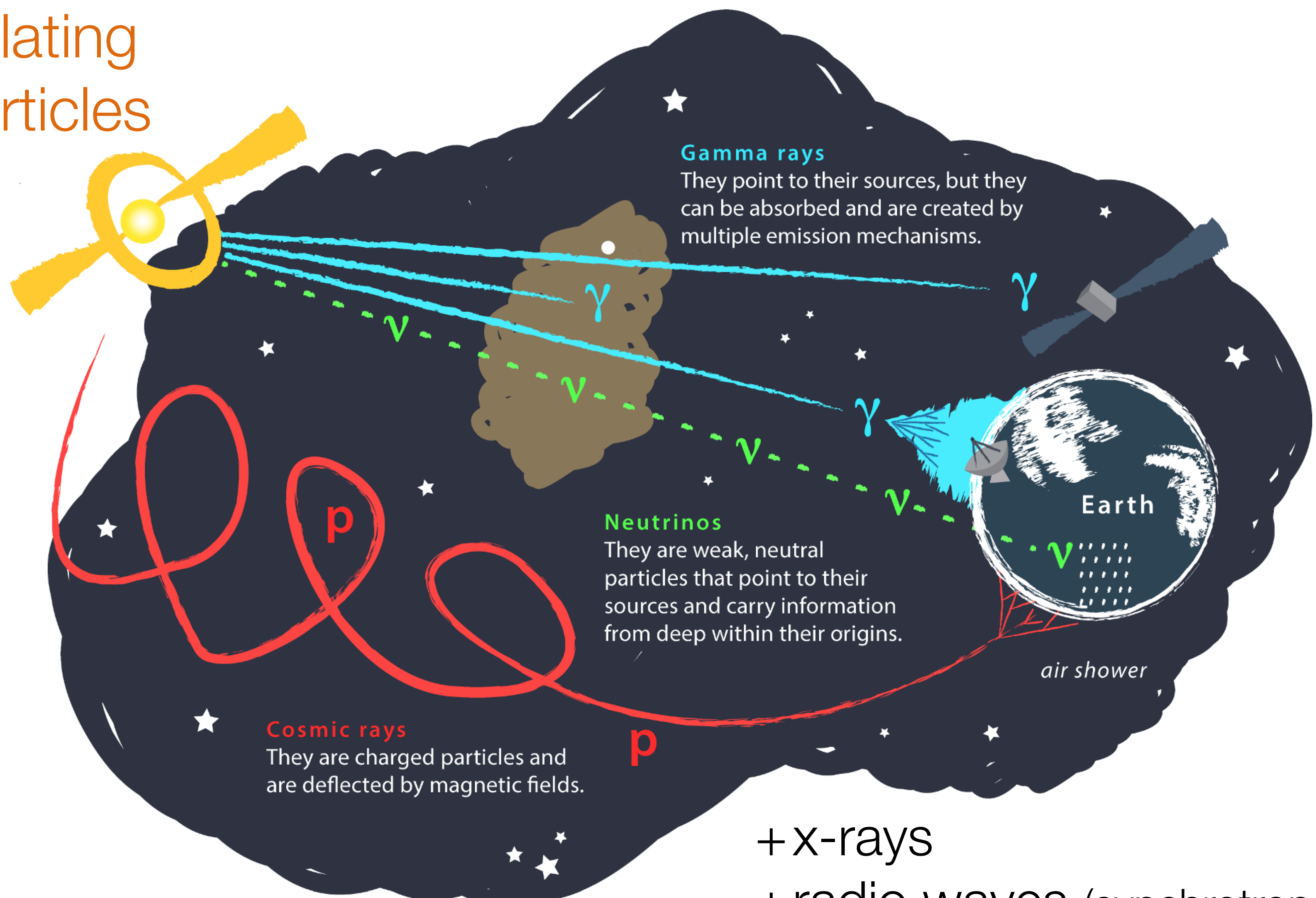
Extragalactic
large statistics, but astrophysical foregrounds and Galactic diffuse background

Galaxy Clusters
low background, but low statistics

arXiv:0908.0195, Fermi-LAT, KIPAC/Stanford

Messengers of DM Annihilation

Annihilating DM particles



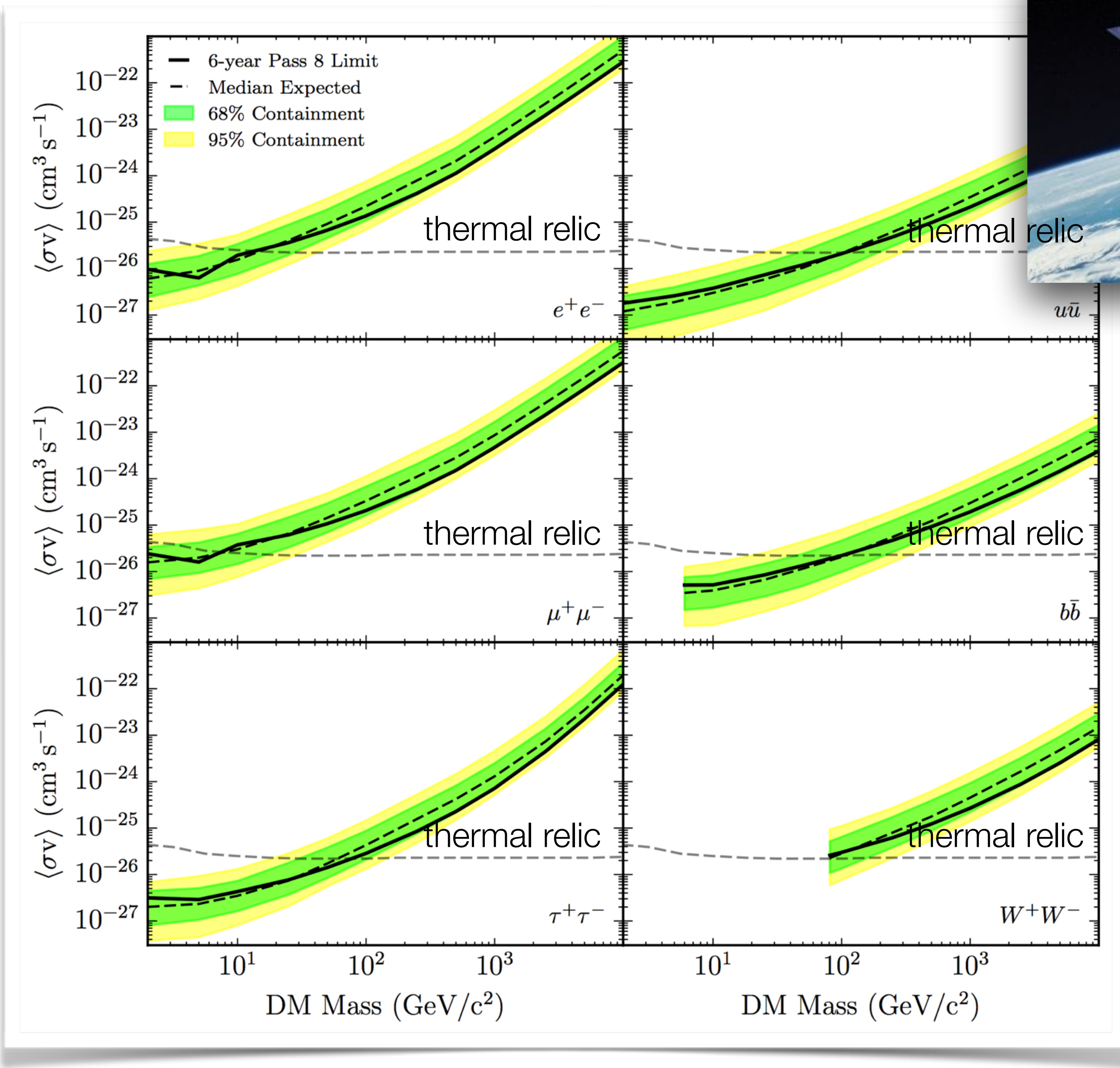
+x-rays

+radio waves (synchrotron emission)

+…

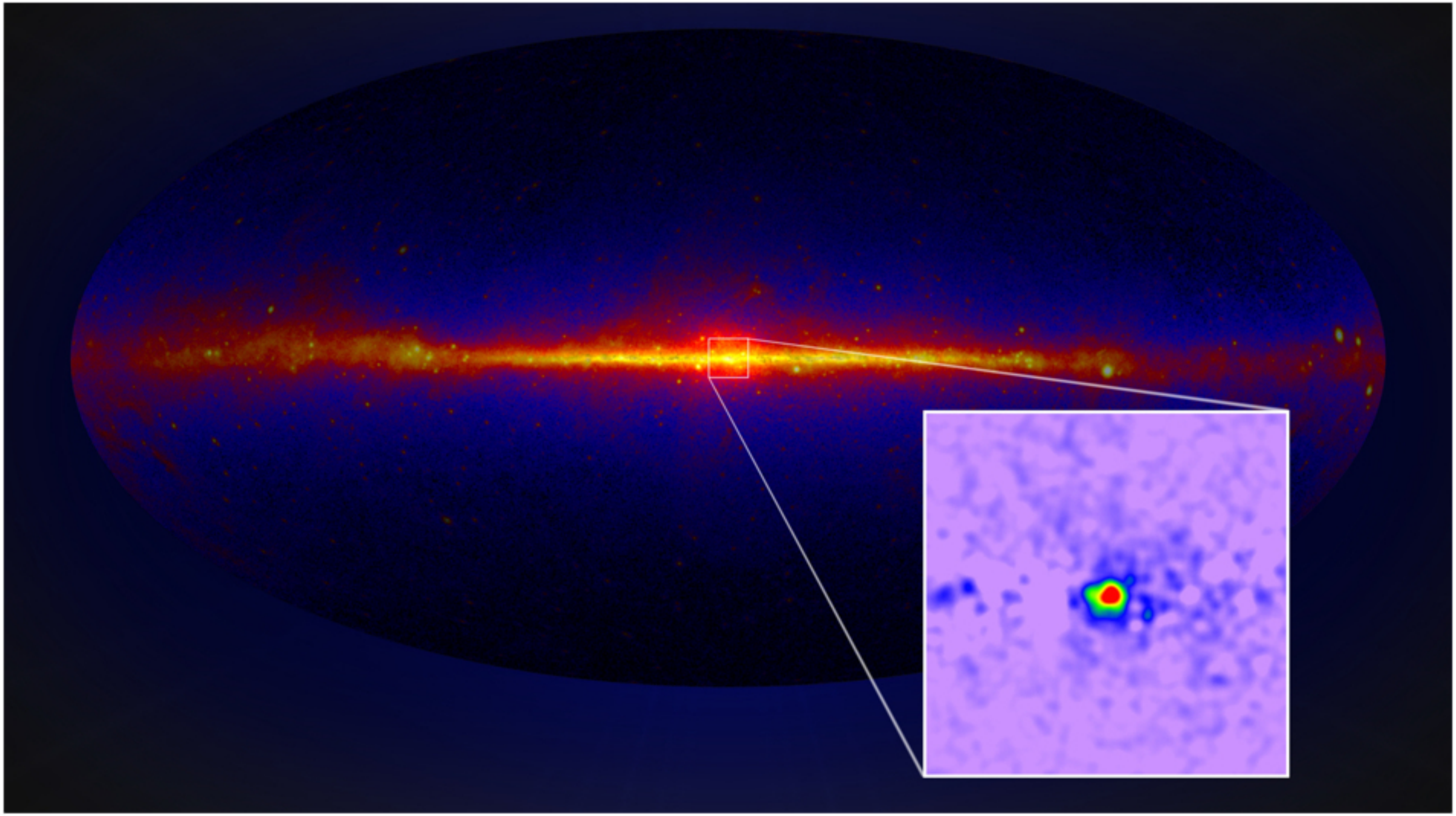
Image: J.A. Aguilar and J. Yang, IceCube/WIPAC

Fermi-LAT Limits from Dwarf Galaxies



Credit: Fermi-LAT

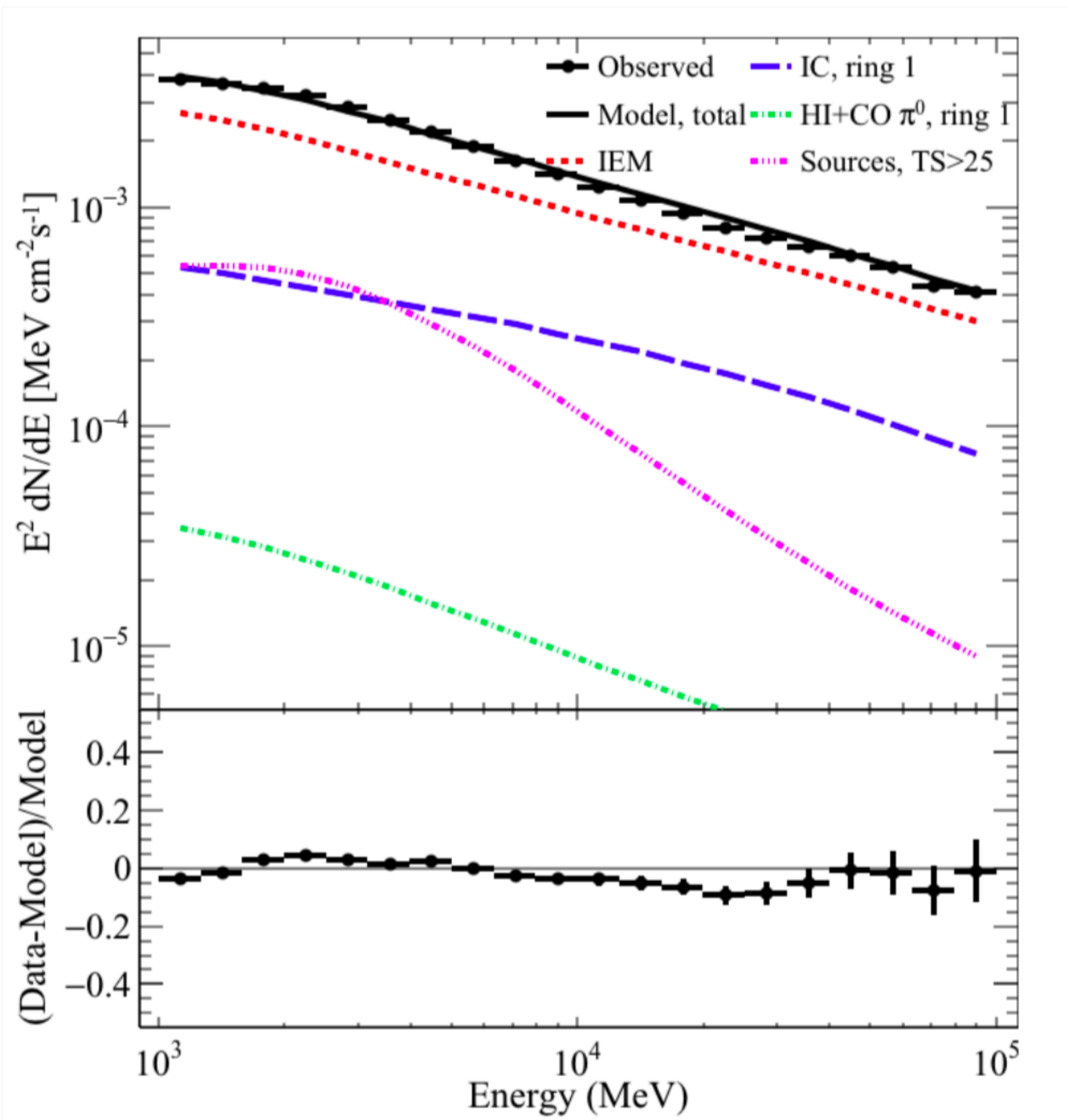
The Galactic Center Excess



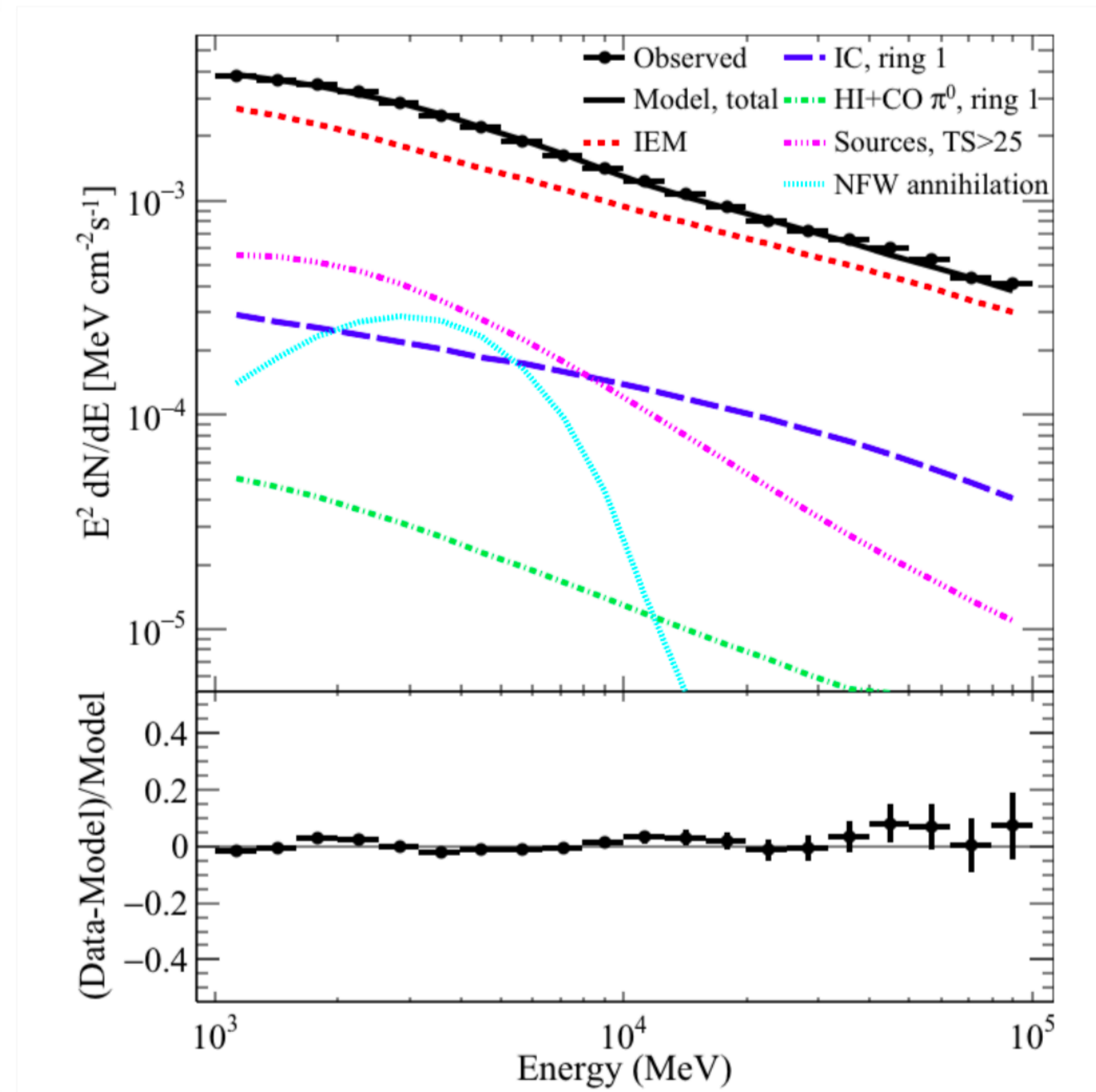
Credit: Tim Linden & NASA

Dark Matter or Astrophysics?

no DM



including DM annihilation

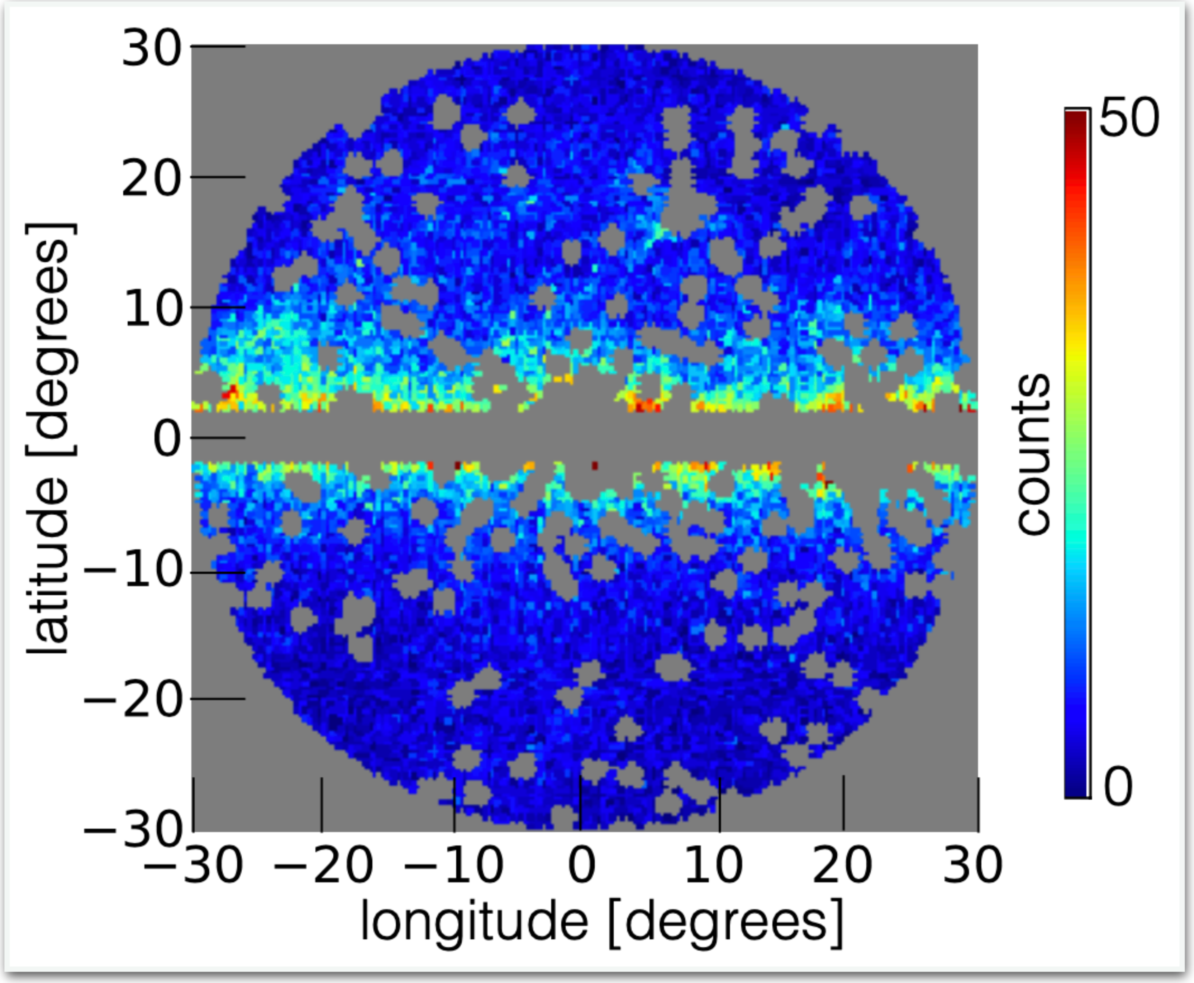


Fermi-Lat, arXiv:1511.02938

Non-Poissonian Template Fit

Fit the morphology of the excess using 7 templates:

- ☑ diffuse background
- ☑ Fermi Bubbles
- ☑ isotropic background
- ☑ isotropic point sources
- ☑ disk-correlated point sources
- ☑ NFW-distributed point sources
- ☑ NFW-distributed dark matter



"Non-Poissonian" = probability for finding a point source with a given flux in a given pixel follows a power law
➠ photon count in each pixel not Poisson-distributed

Lee *et al.*, arXiv:1506.05124

Non-Poissonian Template Fit

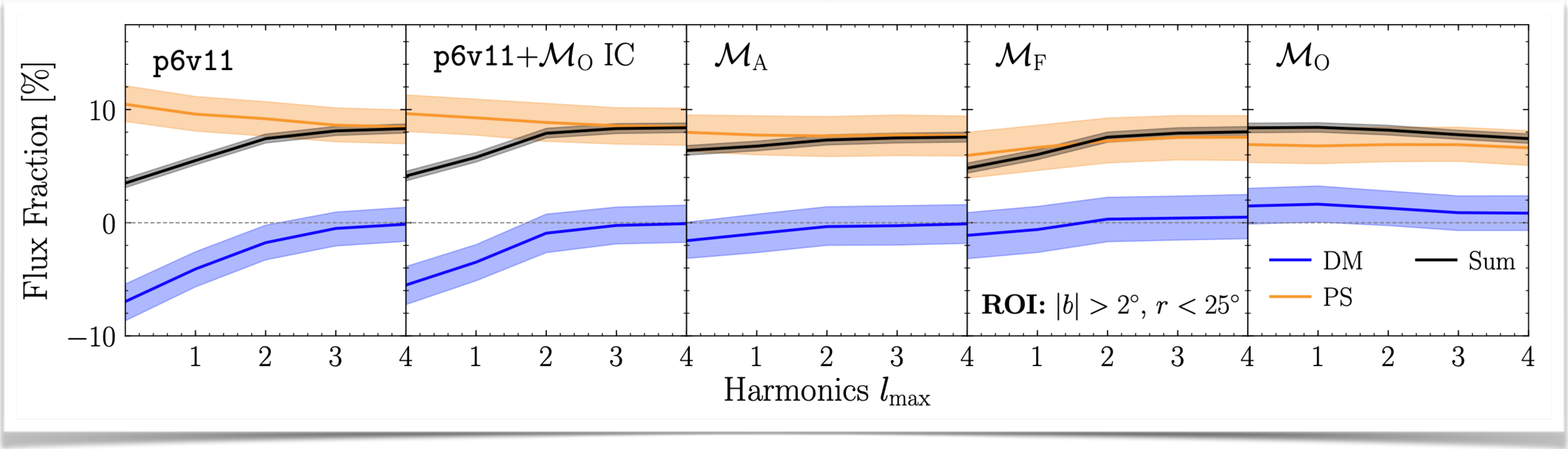
- ☑ Initial Result (2015): strong preference for point sources
- ☑ Update (2019): original method not robust
  (misses injected DM signal when applied to simulated data)
- ☑ Most recently (2020):

  Leane, Slatyer: spurious preference for point sources due to unmodeled North—South asymmetry of the excess

  Buschmann *et al.*: with more conservative modelling of large-scale asymmetries in the Galactic diffuse emission (spherical harmonics expansion), preference for point sources remains.

Lee Lisanti Safdi Slatyer Xue, arXiv:1506.05124
Leane Slatyer, arXiv:1904.08430, arXiv:1908.10874
Leane Slatyer, arXiv:2002.12370, arXiv:2002.12371
Buschmann *et al.*, arXiv:2002.12373

Non-Poissonian Template Fit



Buschmann *et al.*, arXiv:2002.12373

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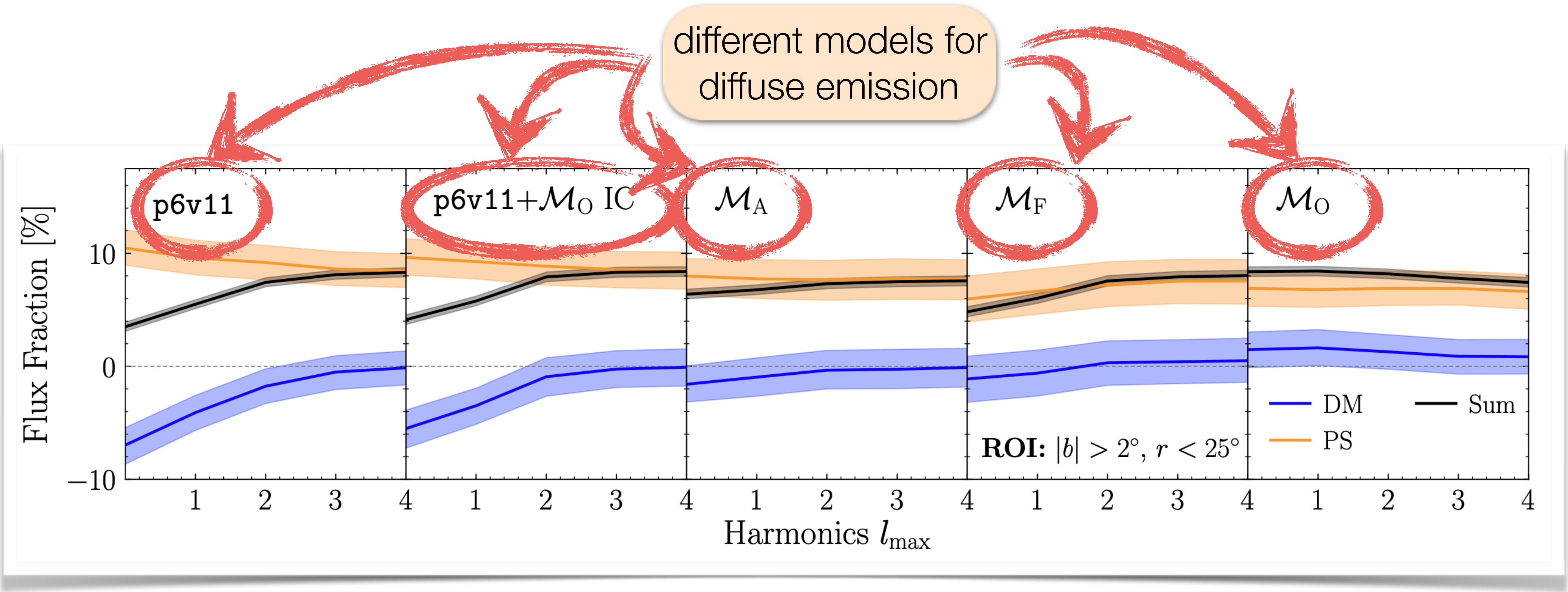

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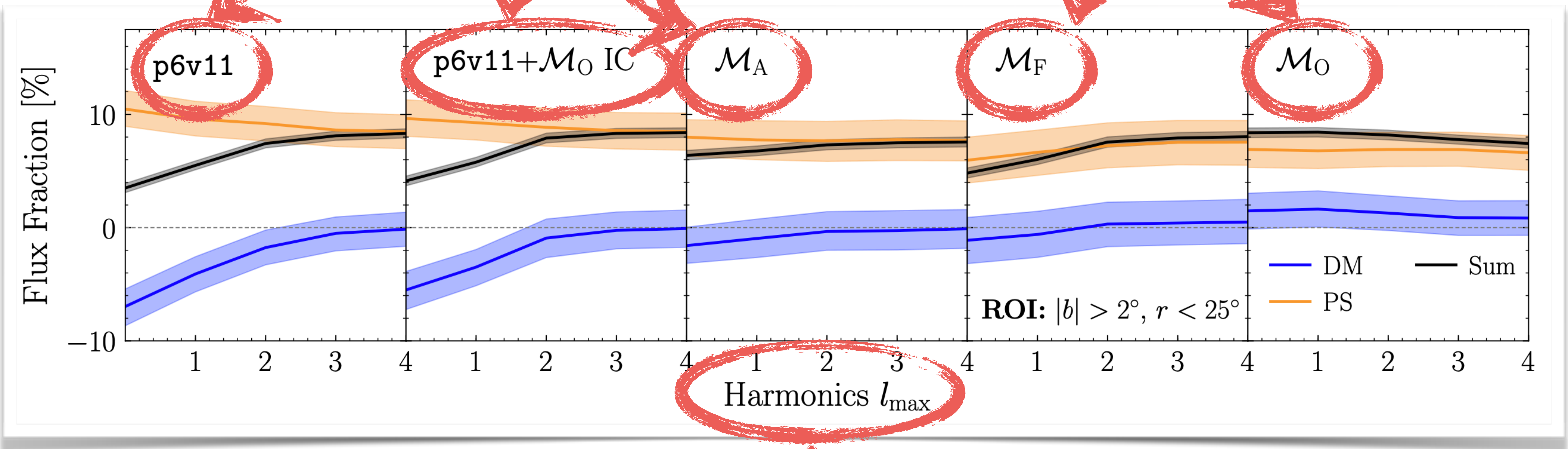
Non-Poissonian Template Fit

different models for diffuse emission



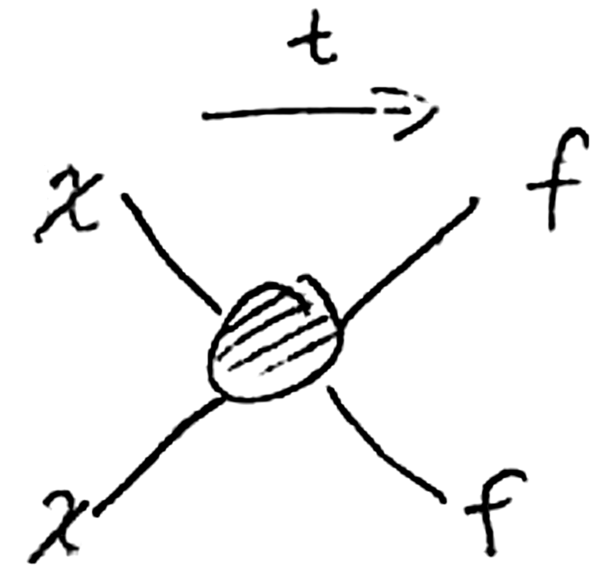
max. degree of spherical harmonics

Buschmann *et al.*, arXiv:2002.12373

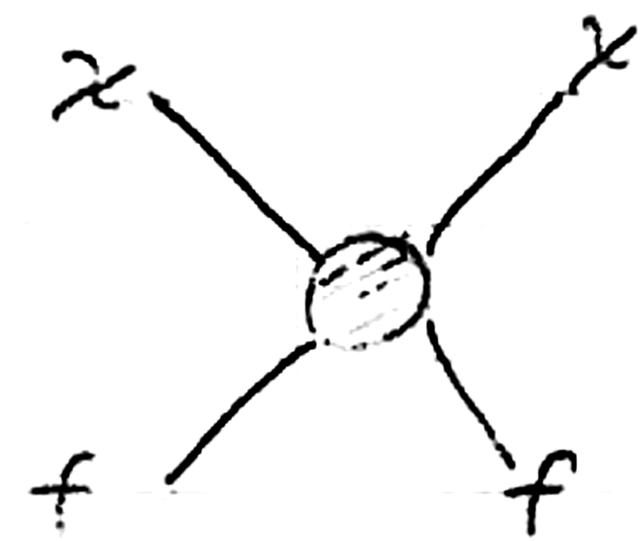
WIMP Dark Matter: Direct Detection

Direct Detection of WIMP Dark Matter

- Annihilation:

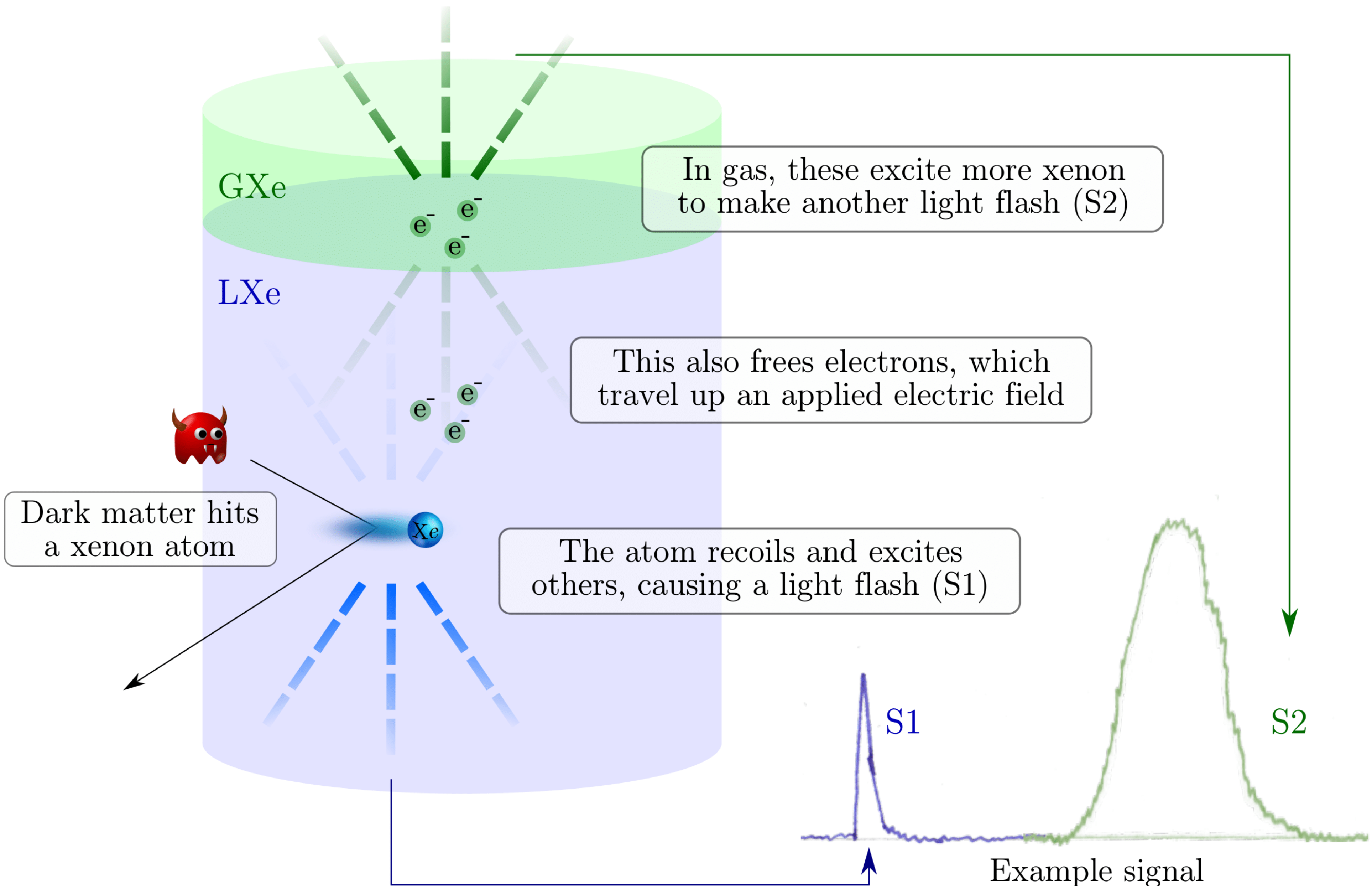


- Turn diagram around
  ➠ DM scattering



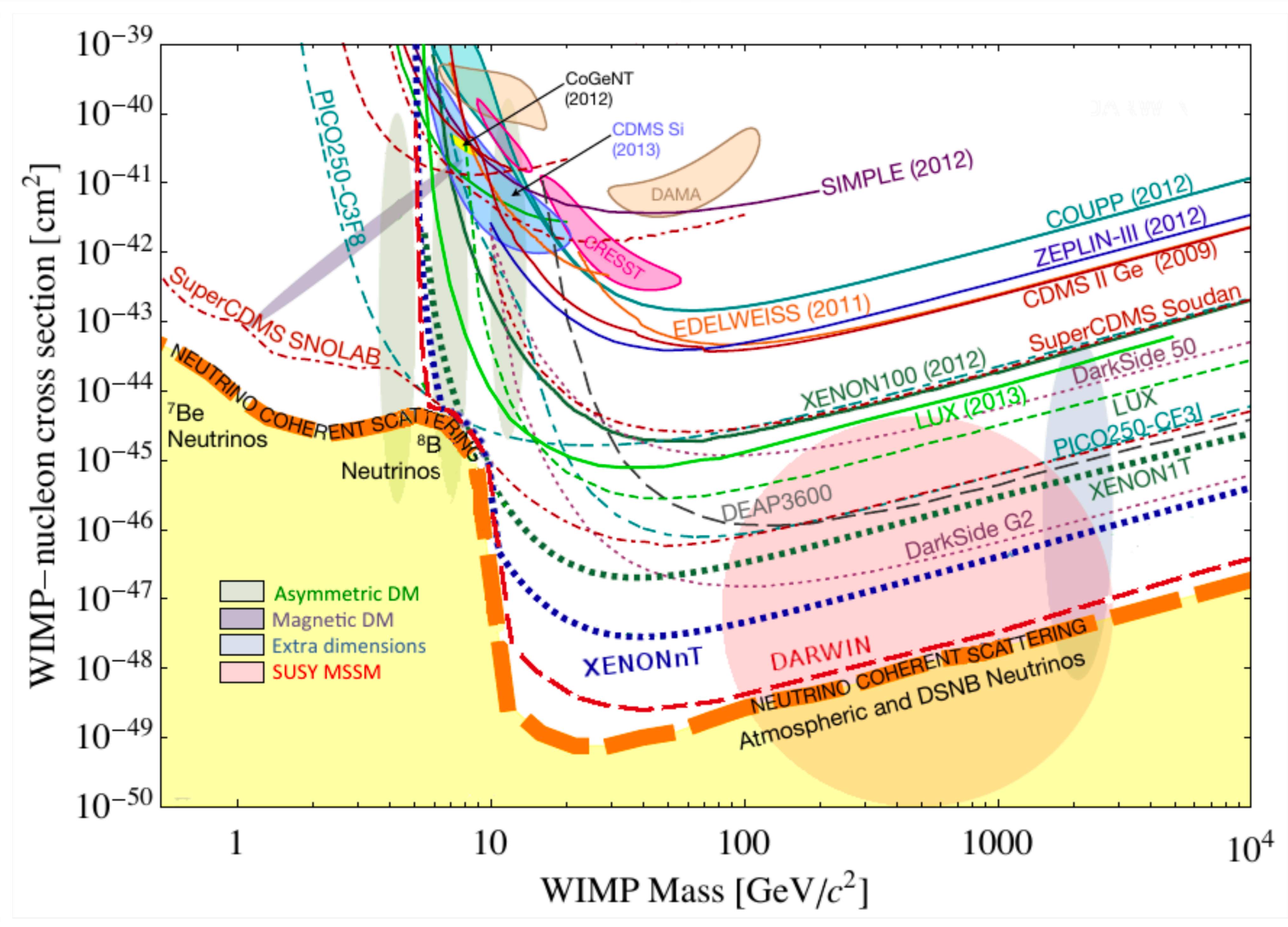
- Galactic WIMPs detectable by scattering
  (preferentially on nuclei for kinematic reasons)

Direct Detection Experiments



XENON collaboration

Direct Detection Results

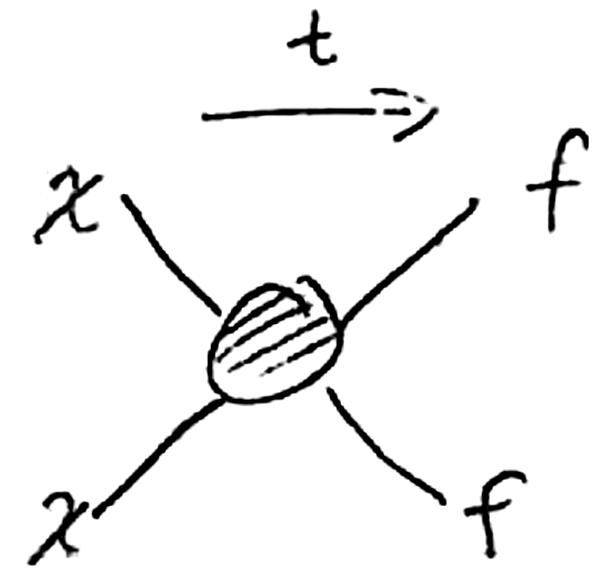


Klasen Pohl Sigl arXiv:1507.03800

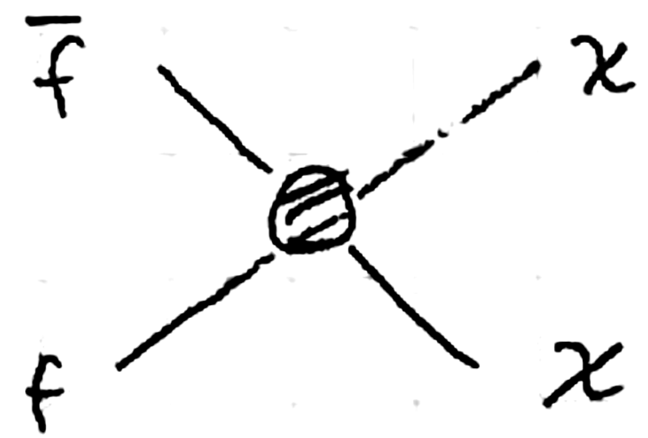
WIMP Dark Matter:
Collider Searches

WIMP Production at Colliders

- Annihilation:



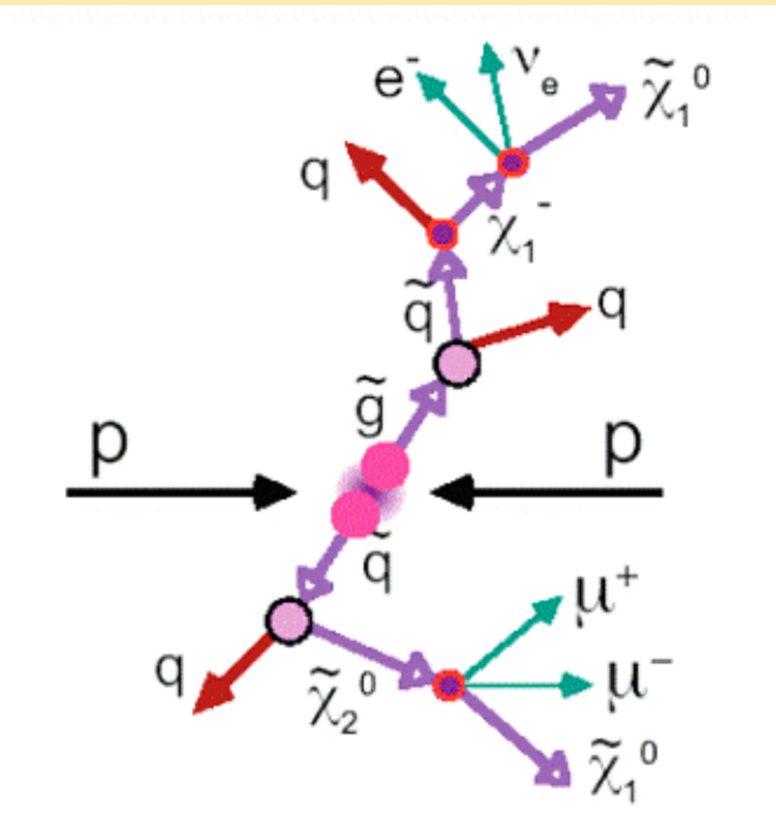
- Rotate diagram by 180°
  ➠ DM production



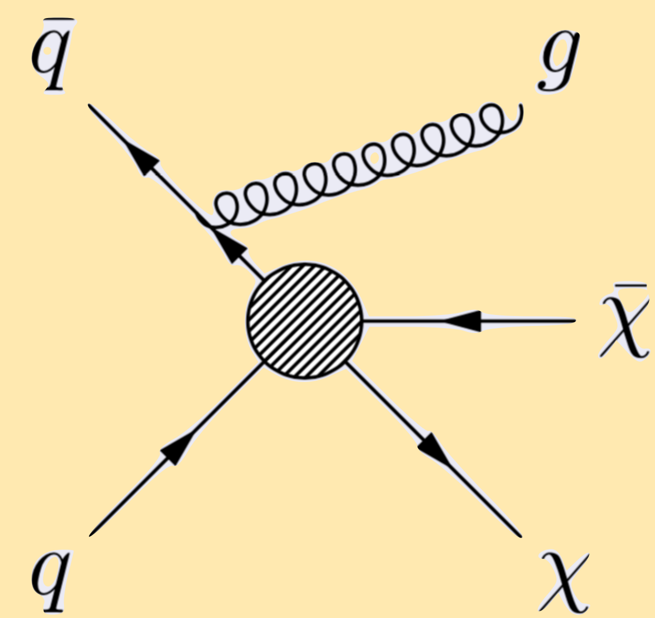
- WIMP Production could be possible at the LHC
  But: WIMPs are invisible to the detectors

WIMP Detection at Colliders

Cascade Decays

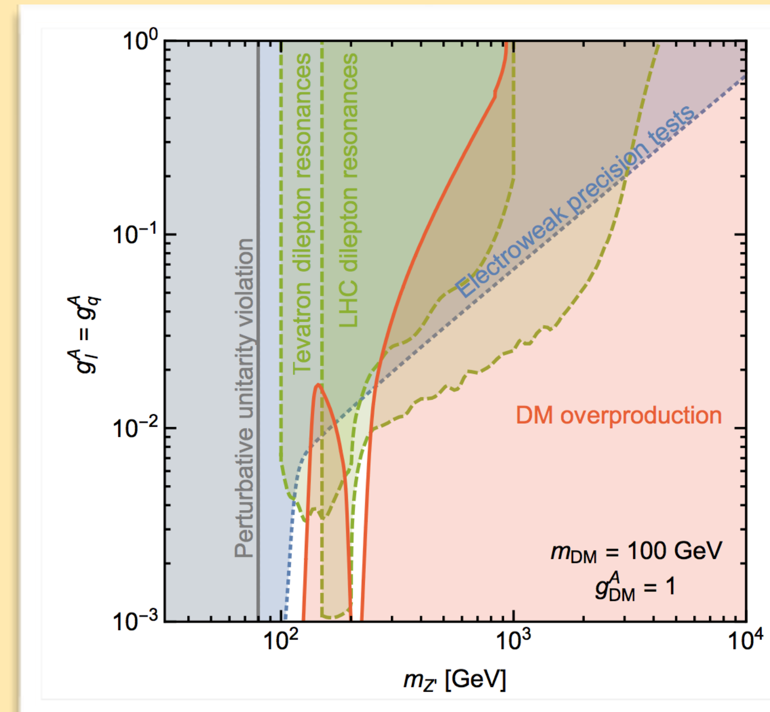


mono-X signatures

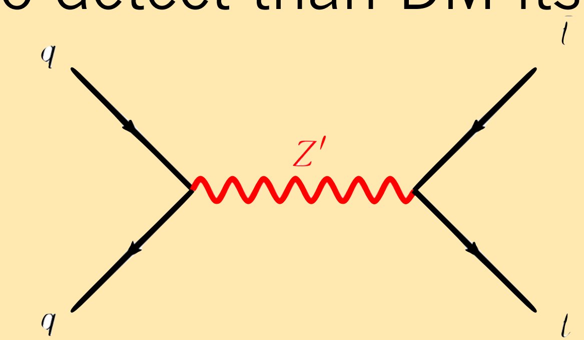


- X = gluon, photon, ...
- more model-independent
- large background

mediator searches

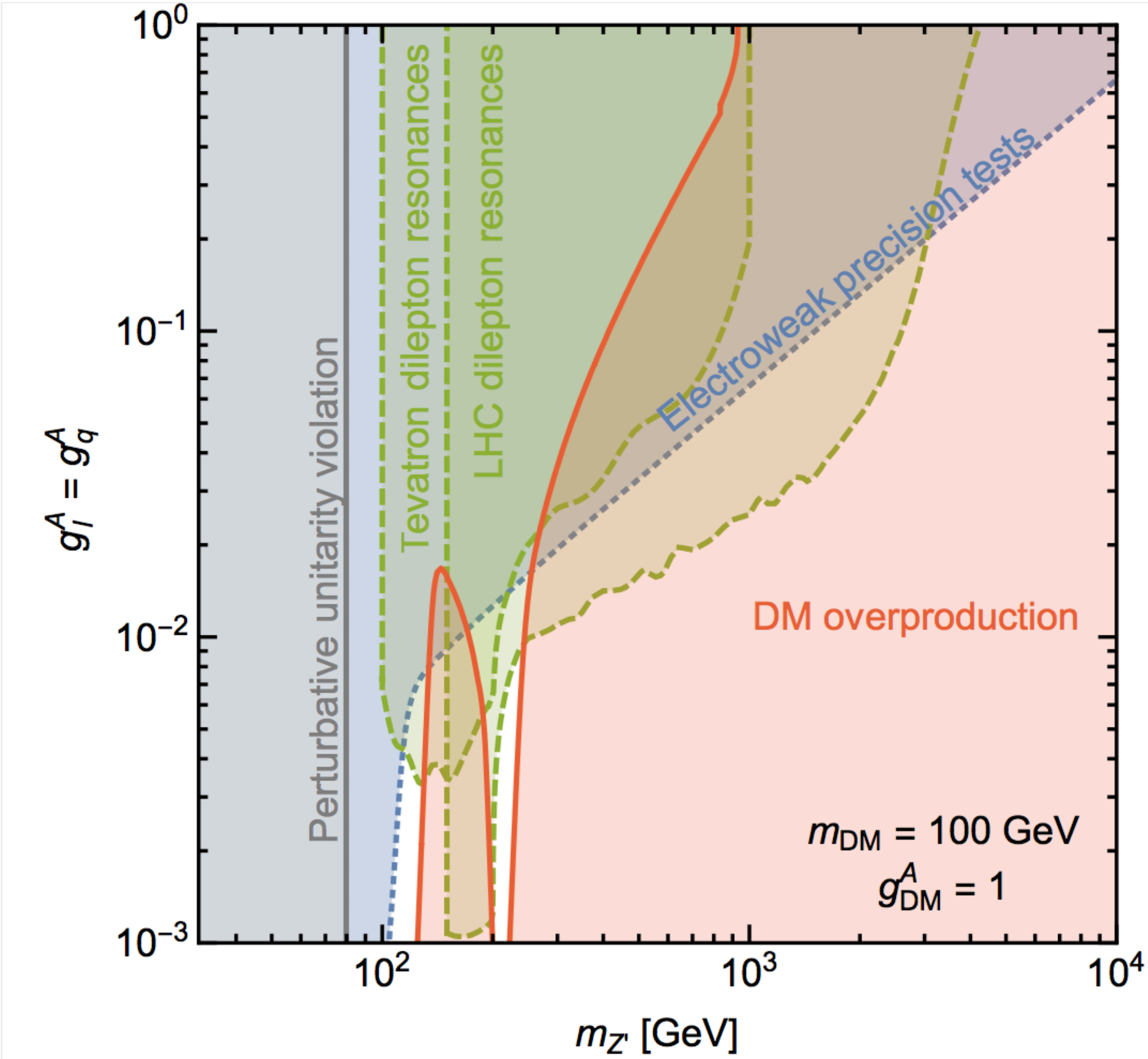


- Mediators of DM–SM interactions often easier to detect than DM itself



WIMP Detection at Colliders

Ca ... ediator searches



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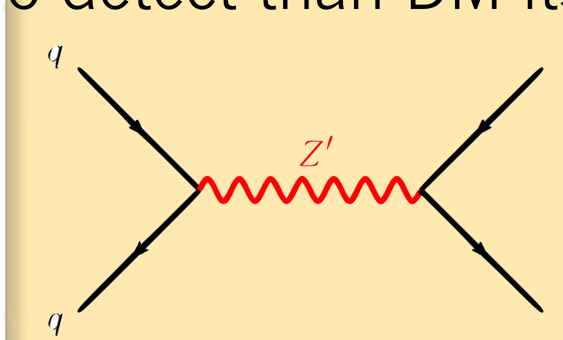

WIMPs — Take-Home Messages

- ☑ Many ways of probing WIMPs
  - indirect (charged & neutral cosmic rays)
  - direct (scattering on nuclei or electrons)
  - collider (production of DM particles)
- ☑ Each individual method has shortcomings
  (backgrounds, foregrounds, ...)
- ☑ To convince the community, we need
  - detections with different methods/messengers
  - for indirect detection: signals from different source regions

Primordial Black Holes as Dark Matter

Basic Idea

- Upward fluctuations of the plasma density in the early Universe may gravitationally collapse into black holes.
- Criterion:
  "collapse should happen faster than rebound"
  - Collapse timescale: $1/(G\,\delta\rho)^{1/2}$ (from $R \sim G M t^2/R^2$)
  - Rebound timescale: $R/c_{sound} = R/w^{1/2}$
  - where w is the equation of state parameter ($p = w\,\rho$)
  - ➟ $R > (w/G\,\delta\rho)^{1/2}$
  - Set $R \sim 1/H \sim M_{Pl}/T^2$ (Hubble horizon) and use $G \sim 1/M_{Pl}^2$
  - ➟ $\delta\rho/T^4 > w$

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relative overdensity

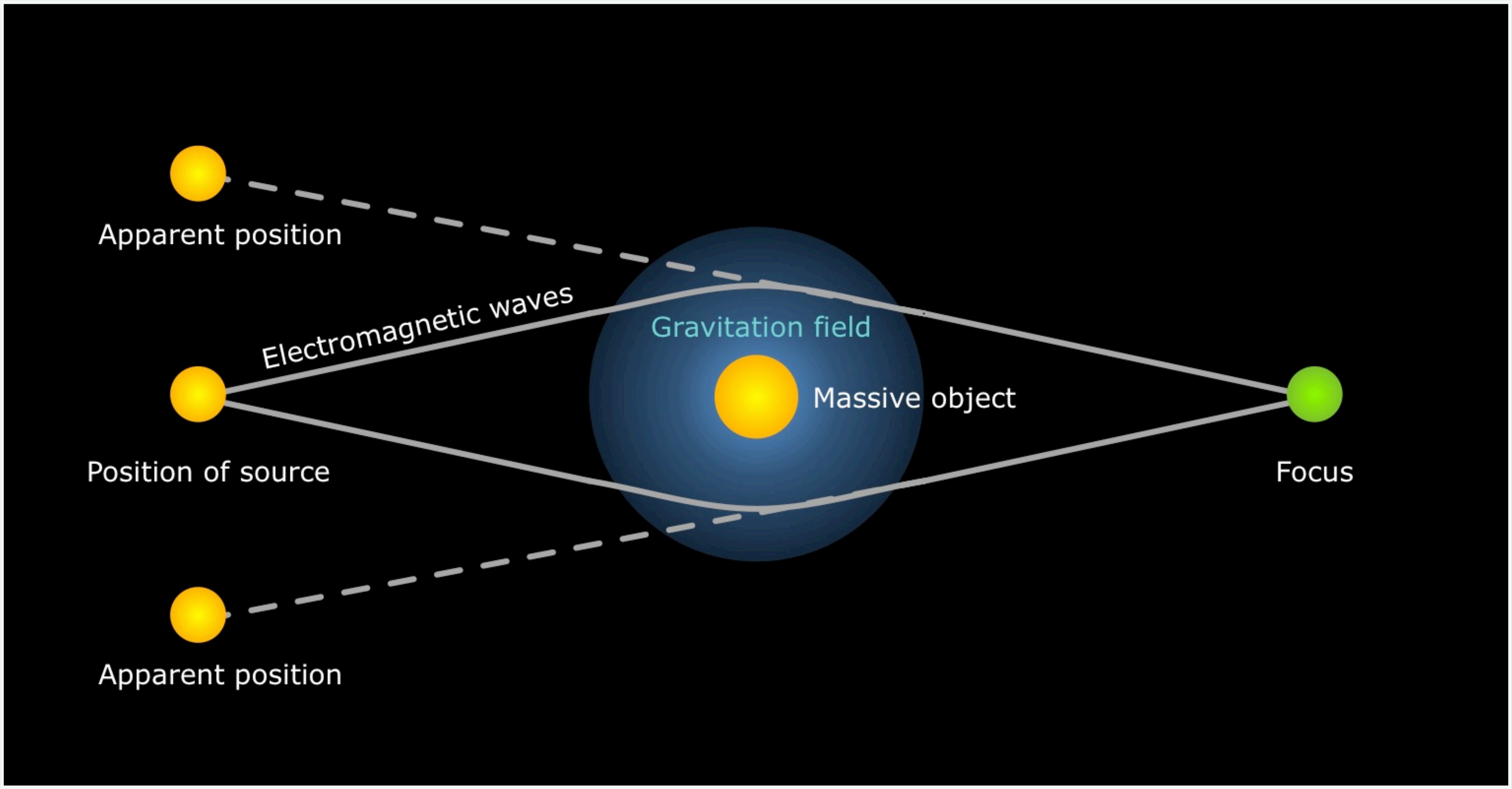
Gravitational Lensing

- Basic idea:
  PBH intersecting our line of sight to a distant source distorts the image of that source

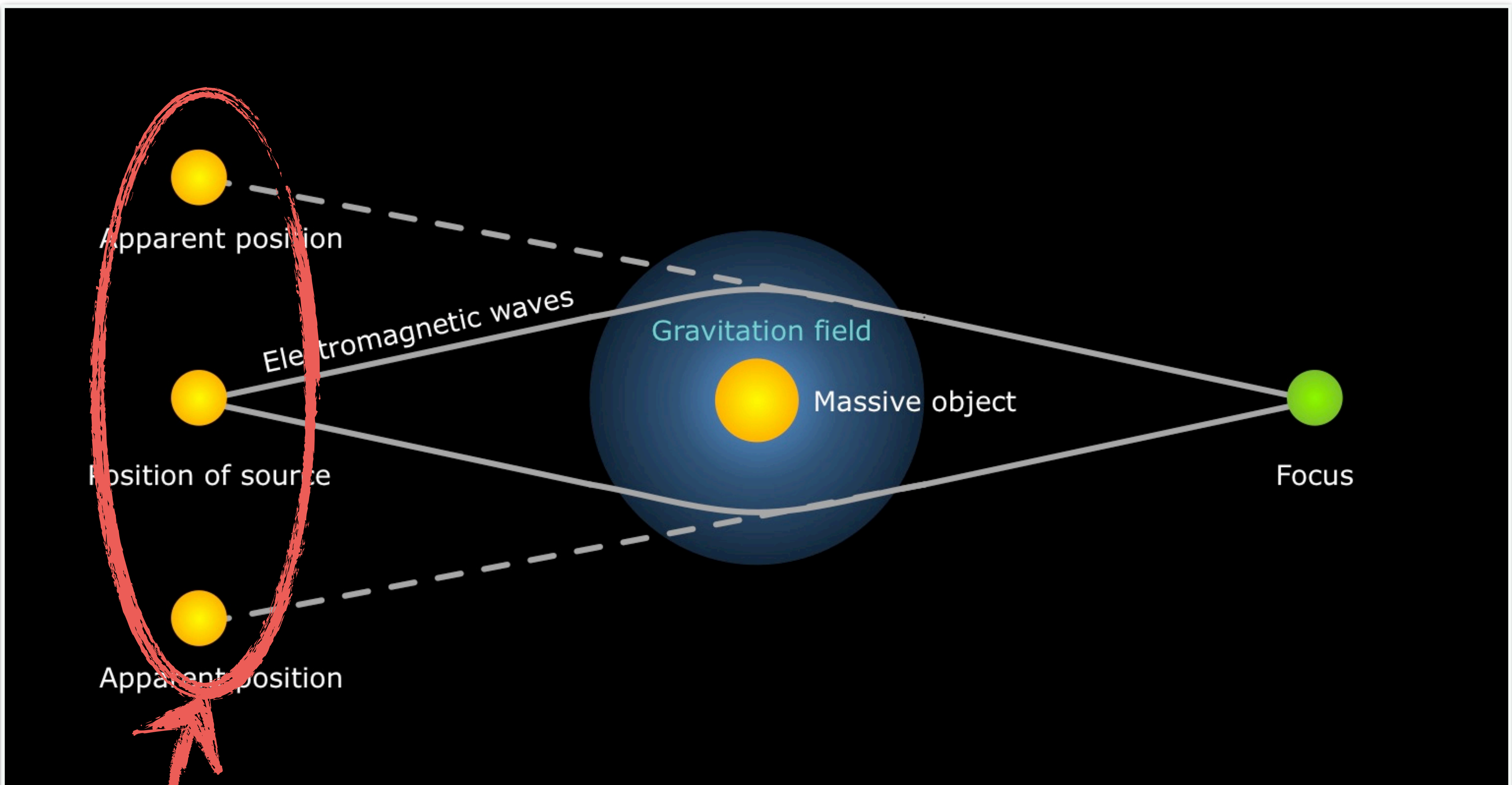
www.spacetelescope.org

www.spacetelescope.org

Microlensing

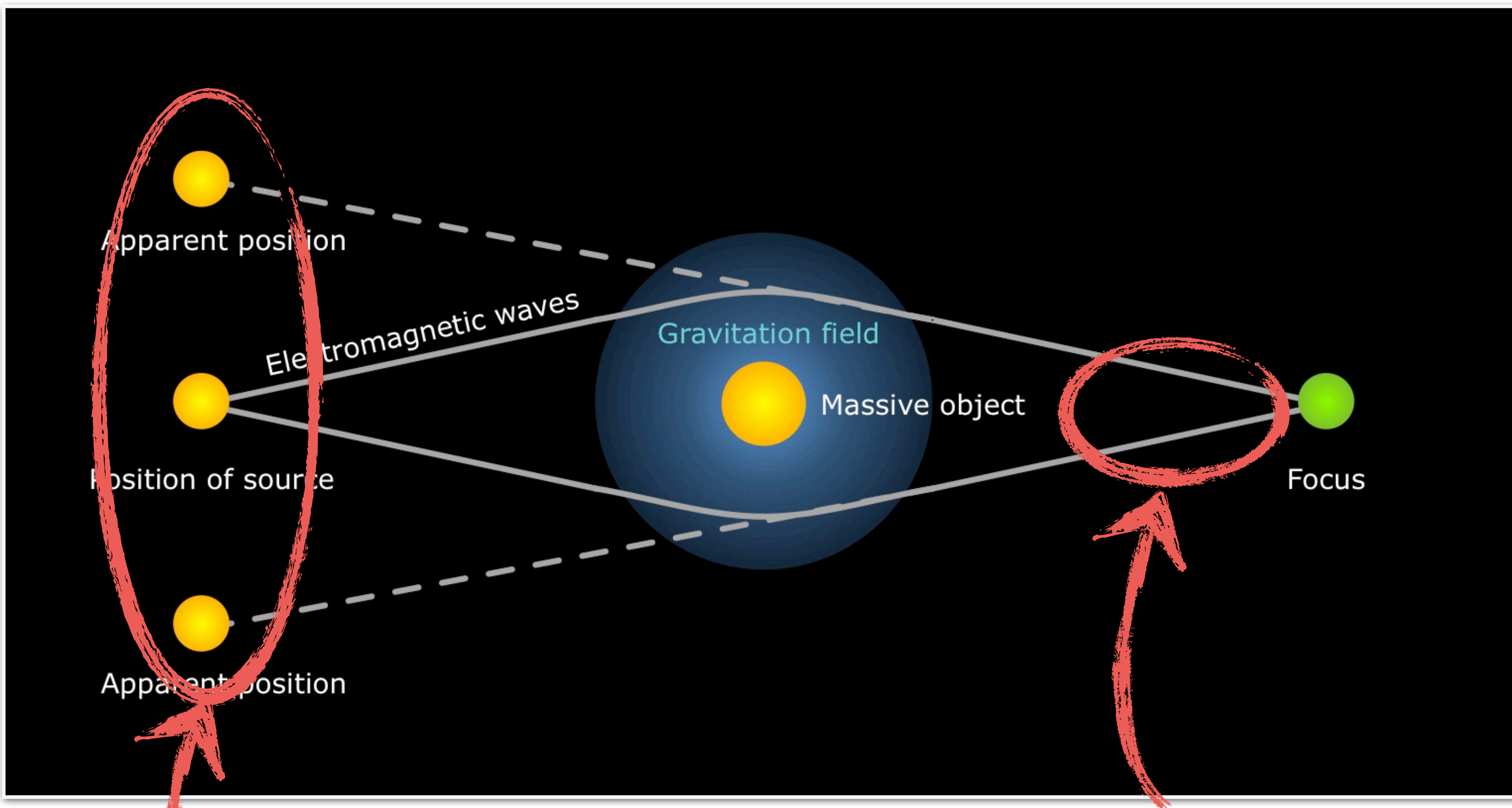


Microlensing



Images not resolved

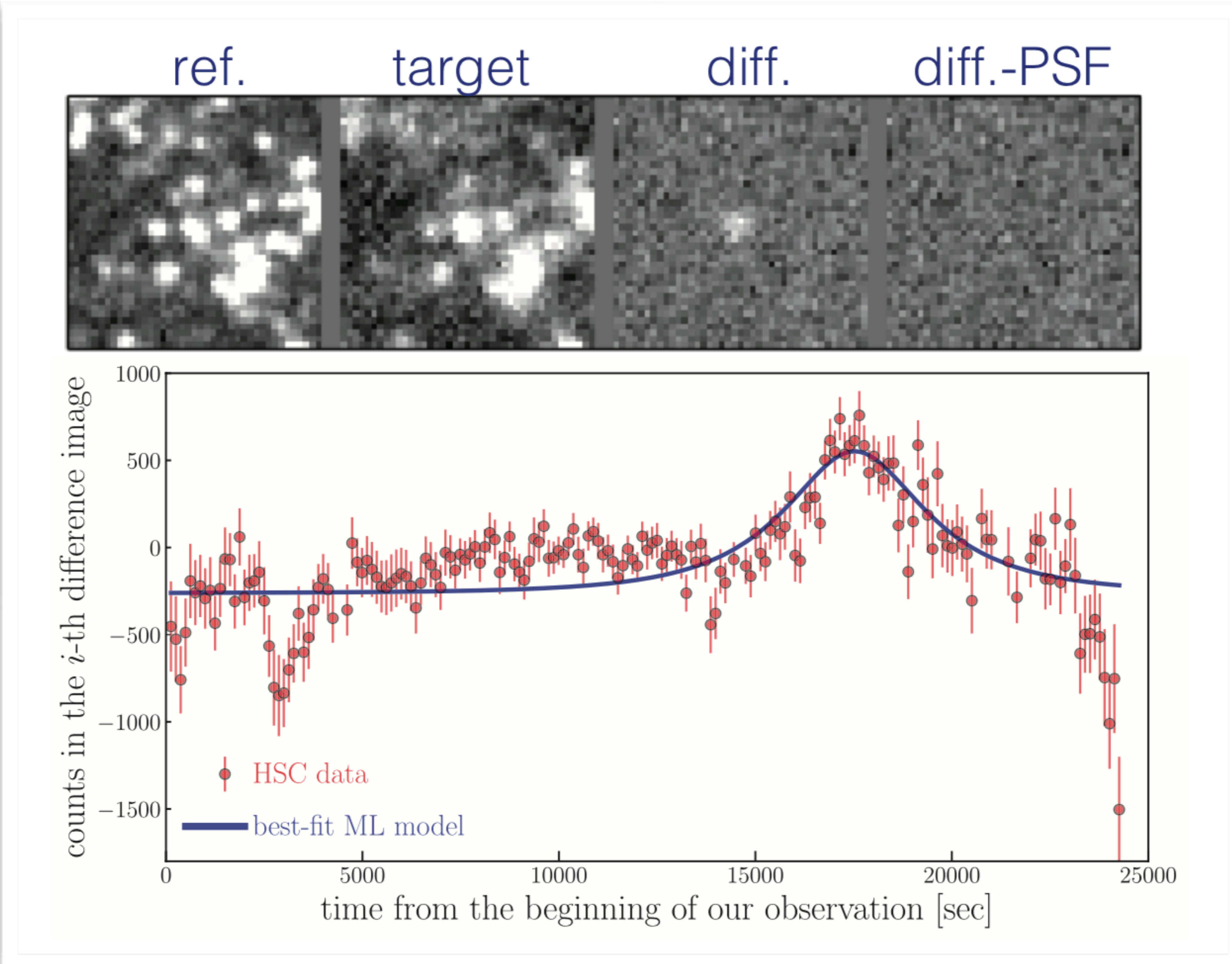
Microlensing



Images not resolved

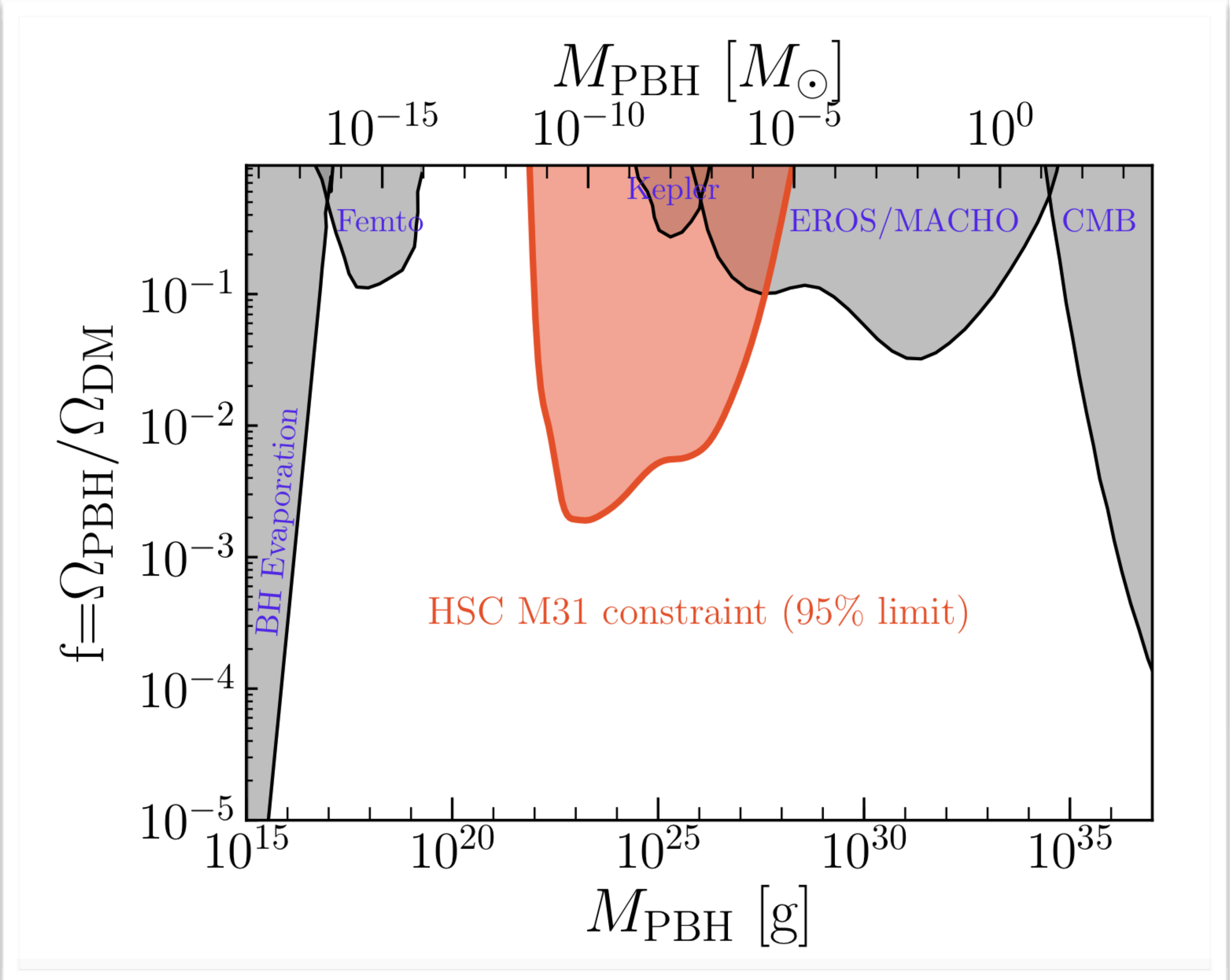
focusing effect
➠ transient brightening of the source

Data Analysis



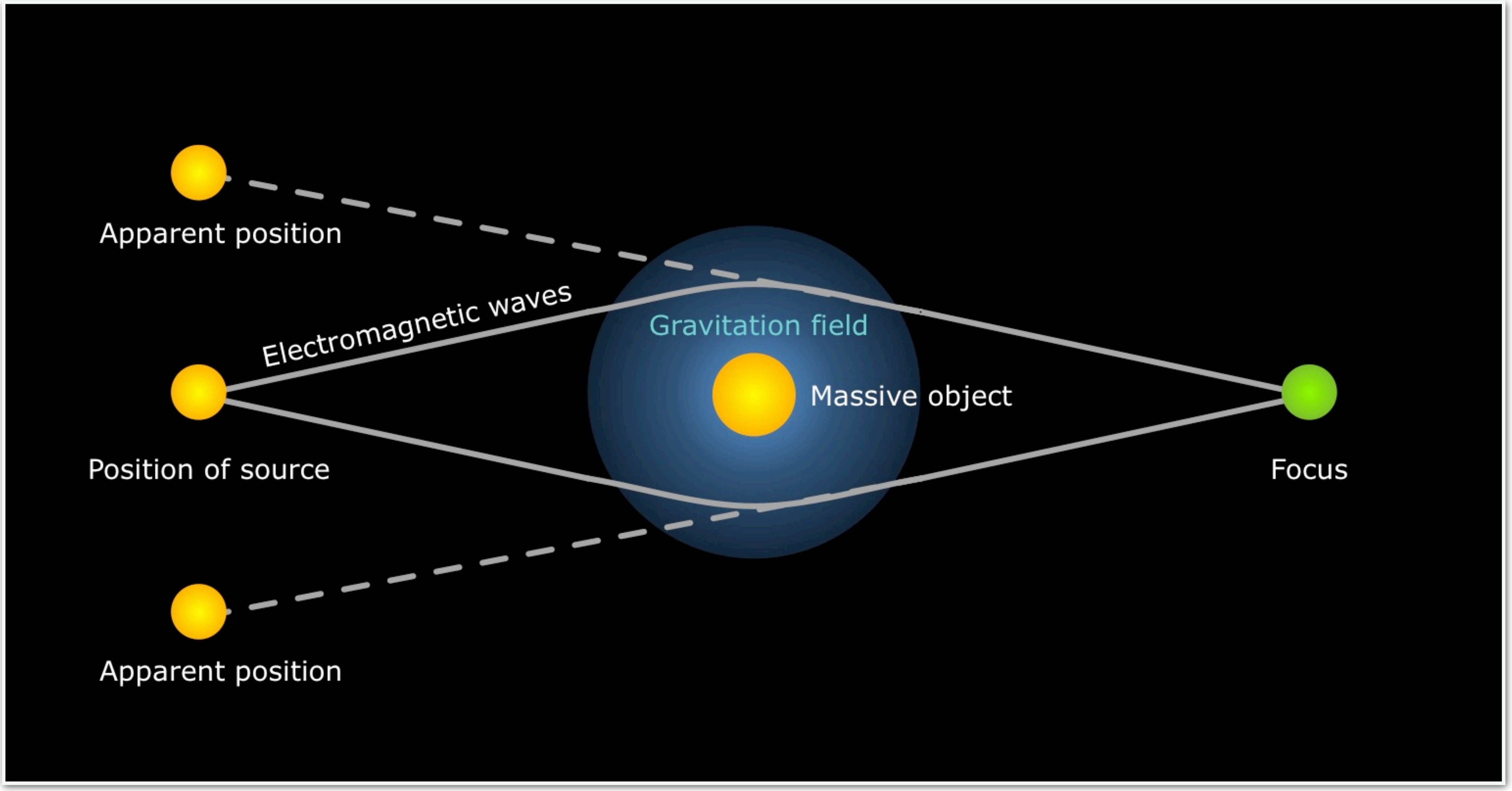
Niikura et al. arXiv:1701.02151

Resulting Limits

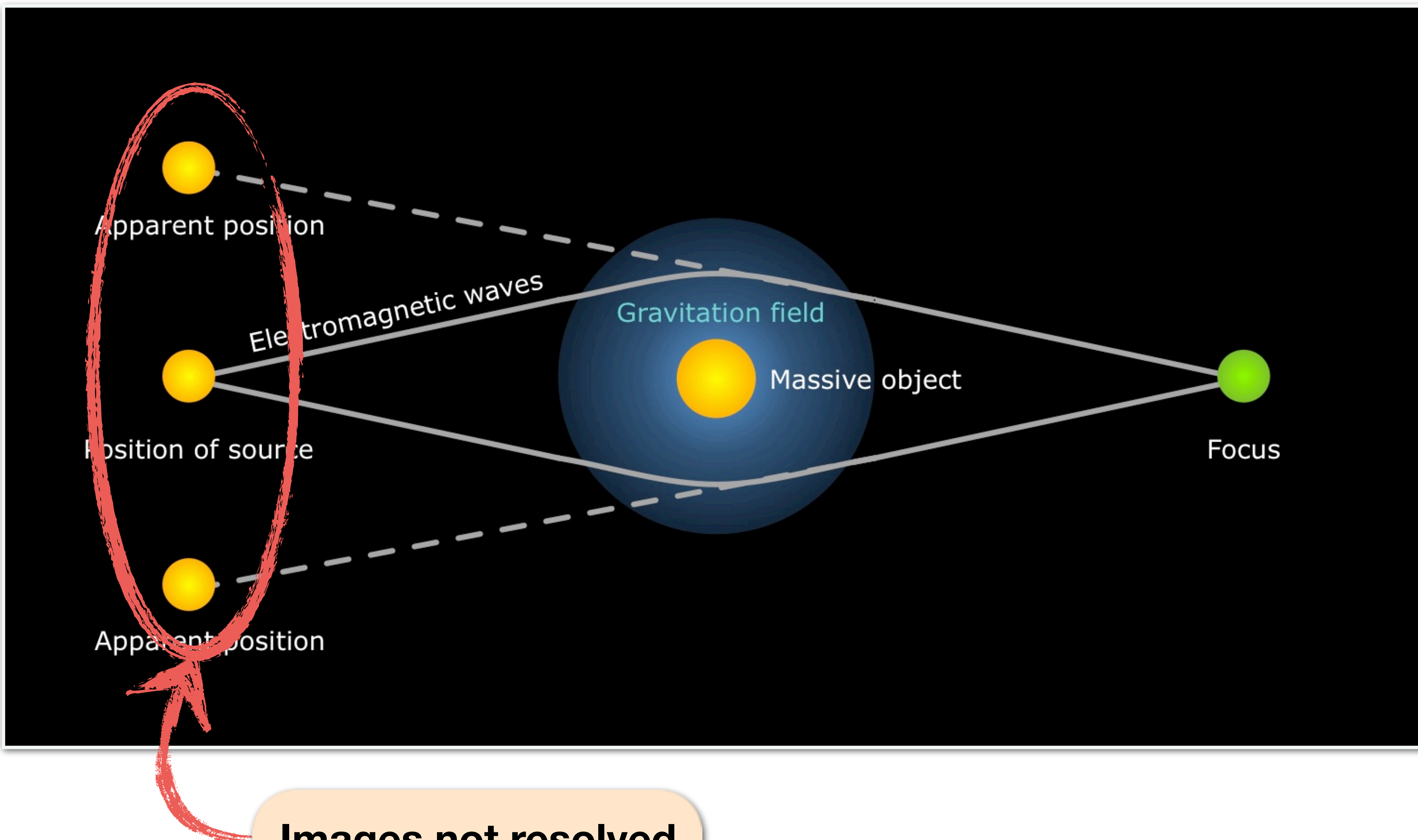


Niikura et al. arXiv:1701.02151

Femtolensing



Femtolensing



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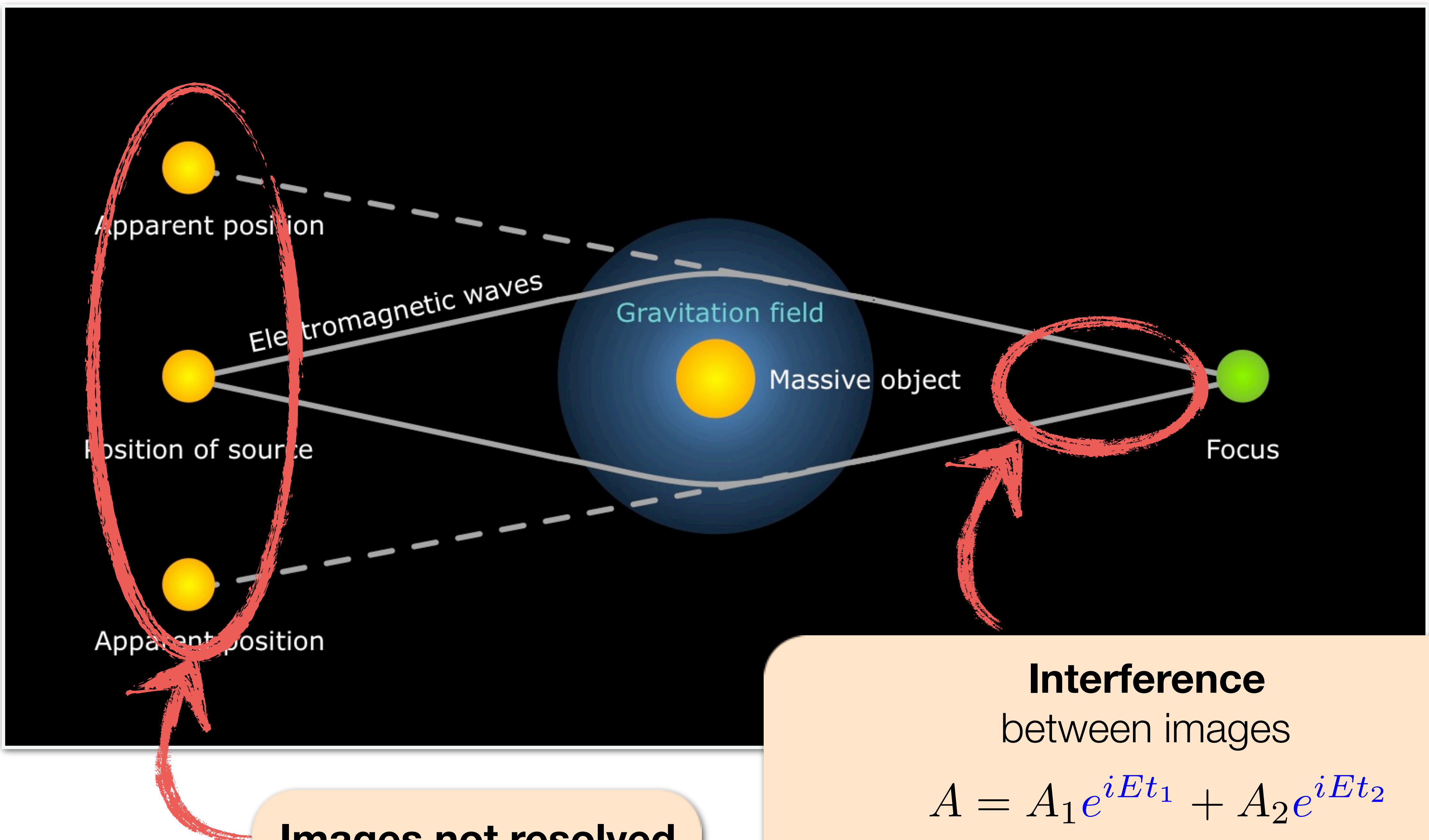


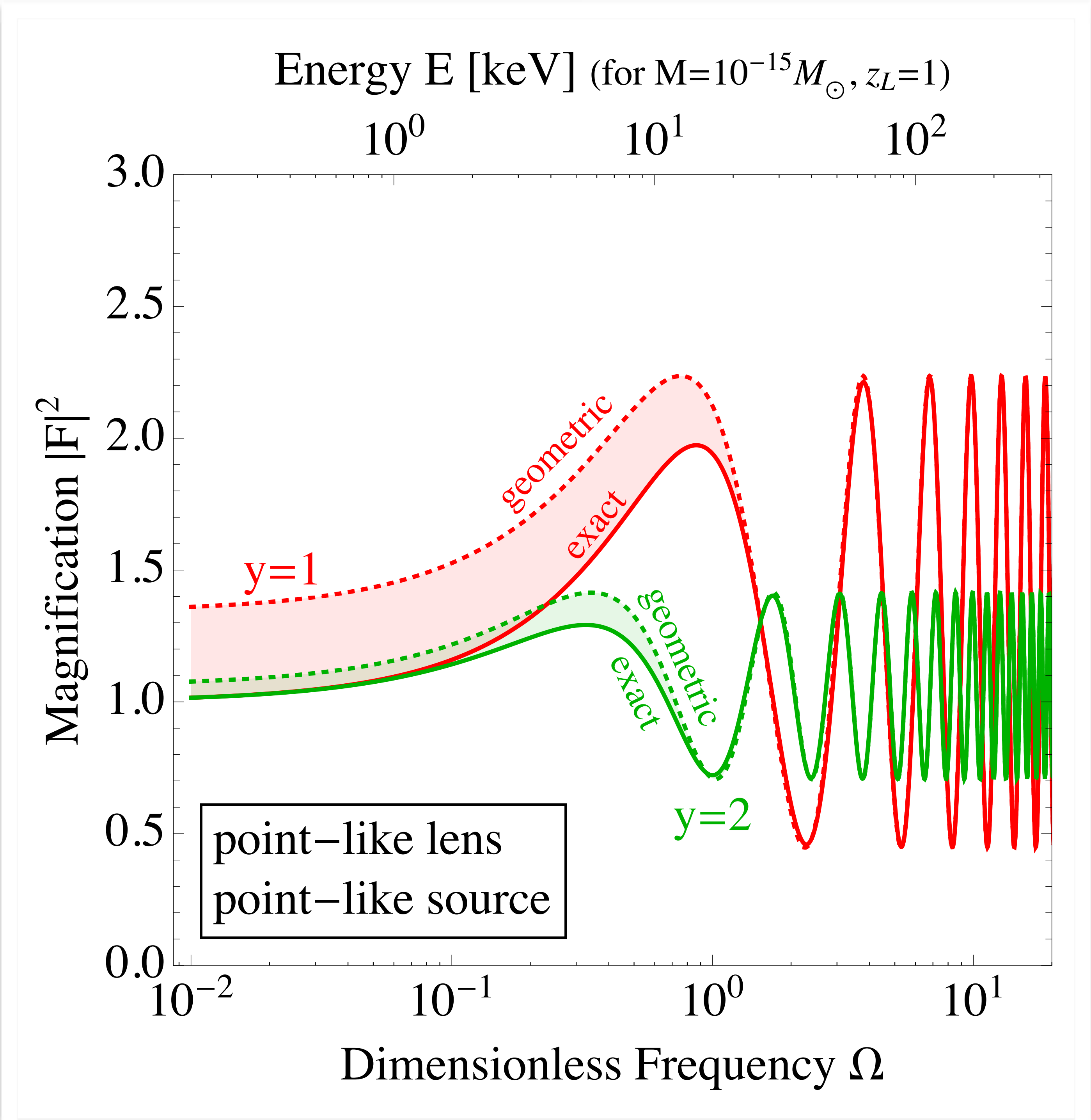
Images not resolved

Interference
between images

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

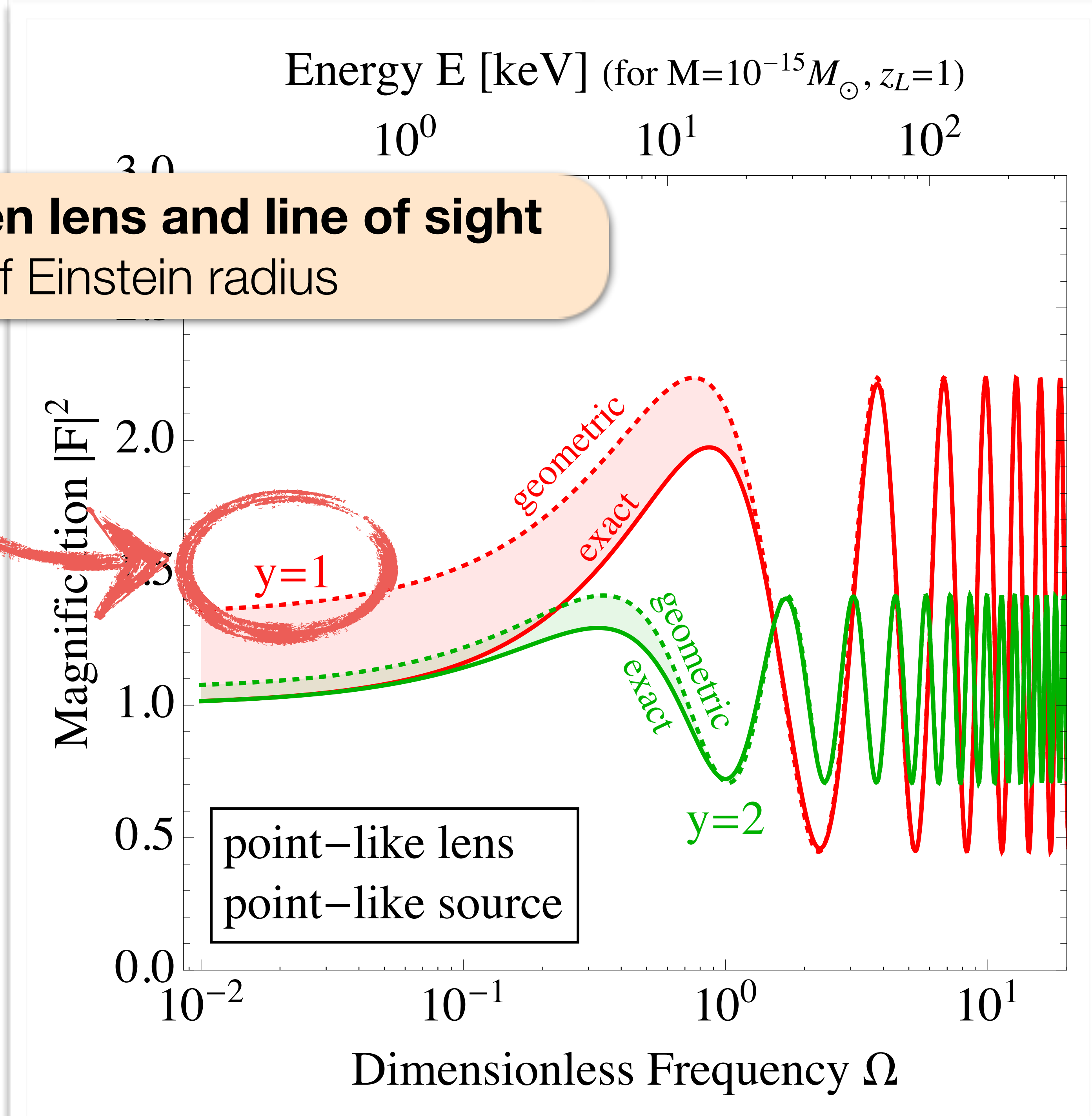
expect wiggles in energy spectrum

Magnification Function



Katz JK Sibiryakov Xue
arXiv:1807.11495

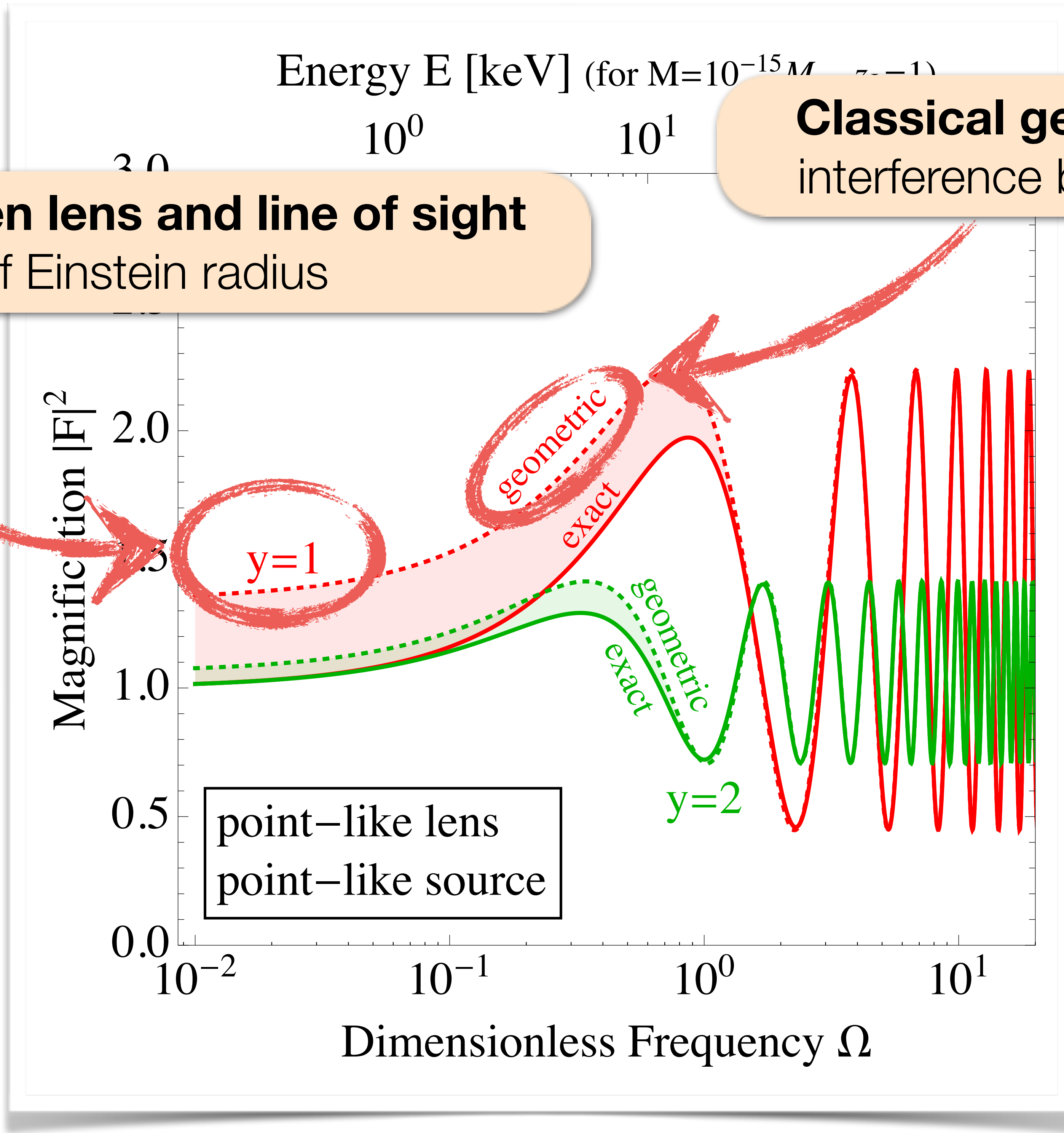
Magnification Function



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

Katz JK Sibiryakov Xue
arXiv:1807.11495

Magnification Function



Distance between lens and line of sight
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Classical geometric picture
interference between two rays

Katz JK Sibiryakov Xue
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Magnification Function

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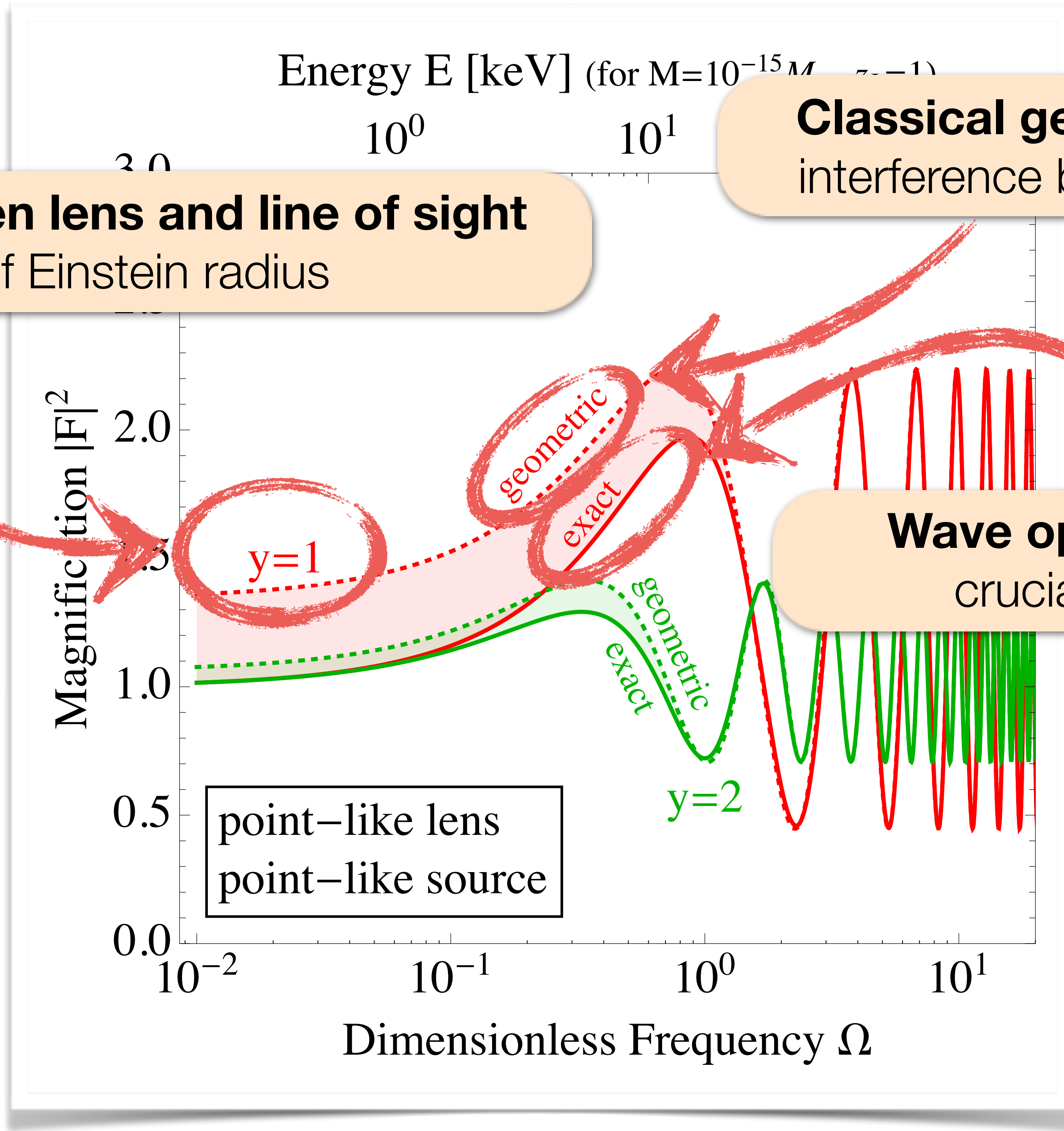
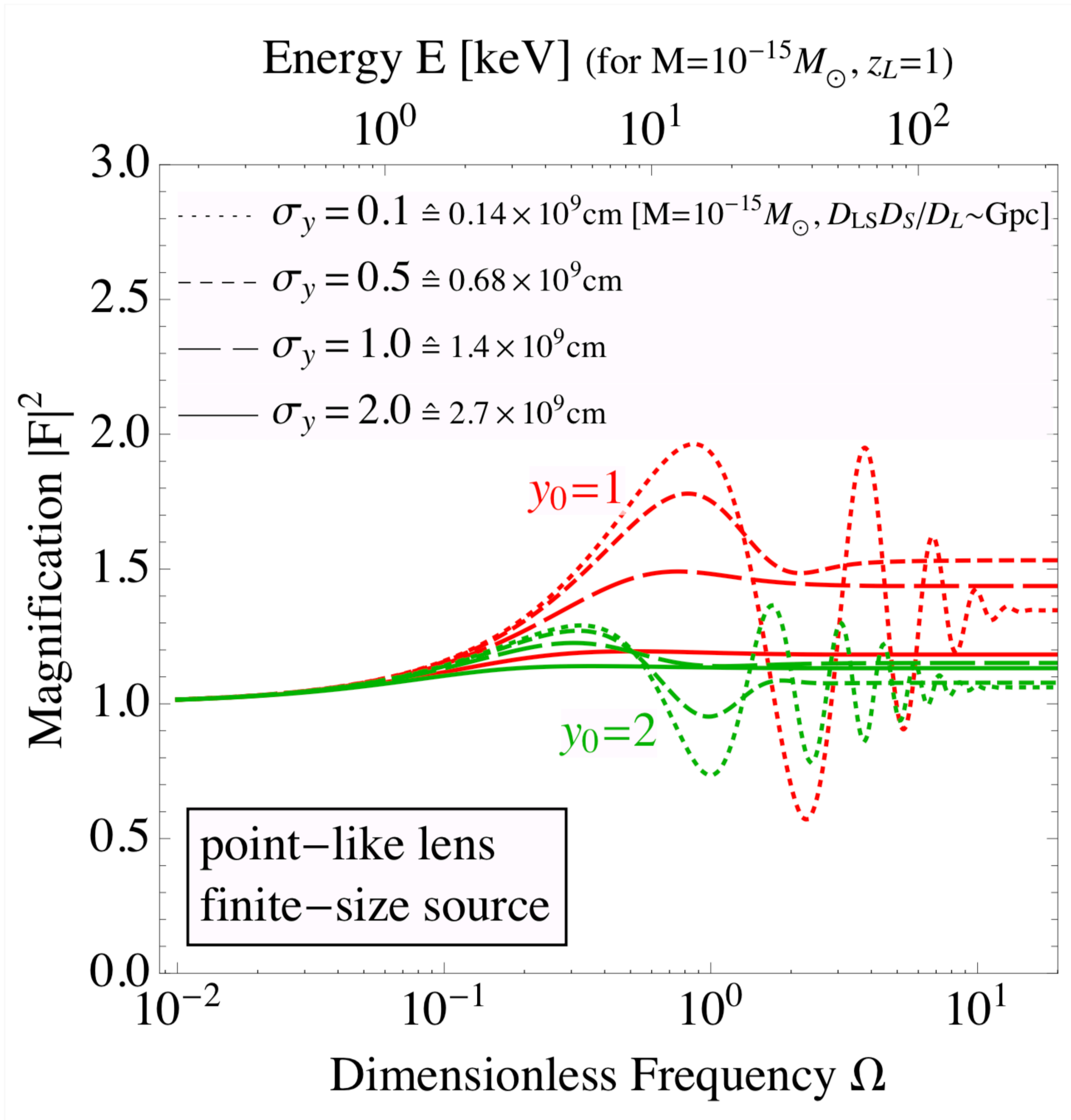


Wave optics corrections
crucial if $\lambda \gtrsim G_N M_{lens}$

Katz JK Sibiryakov Xue
arXiv:1807.11495

Including Finite Source Size



Katz JK Sibiryakov Xue
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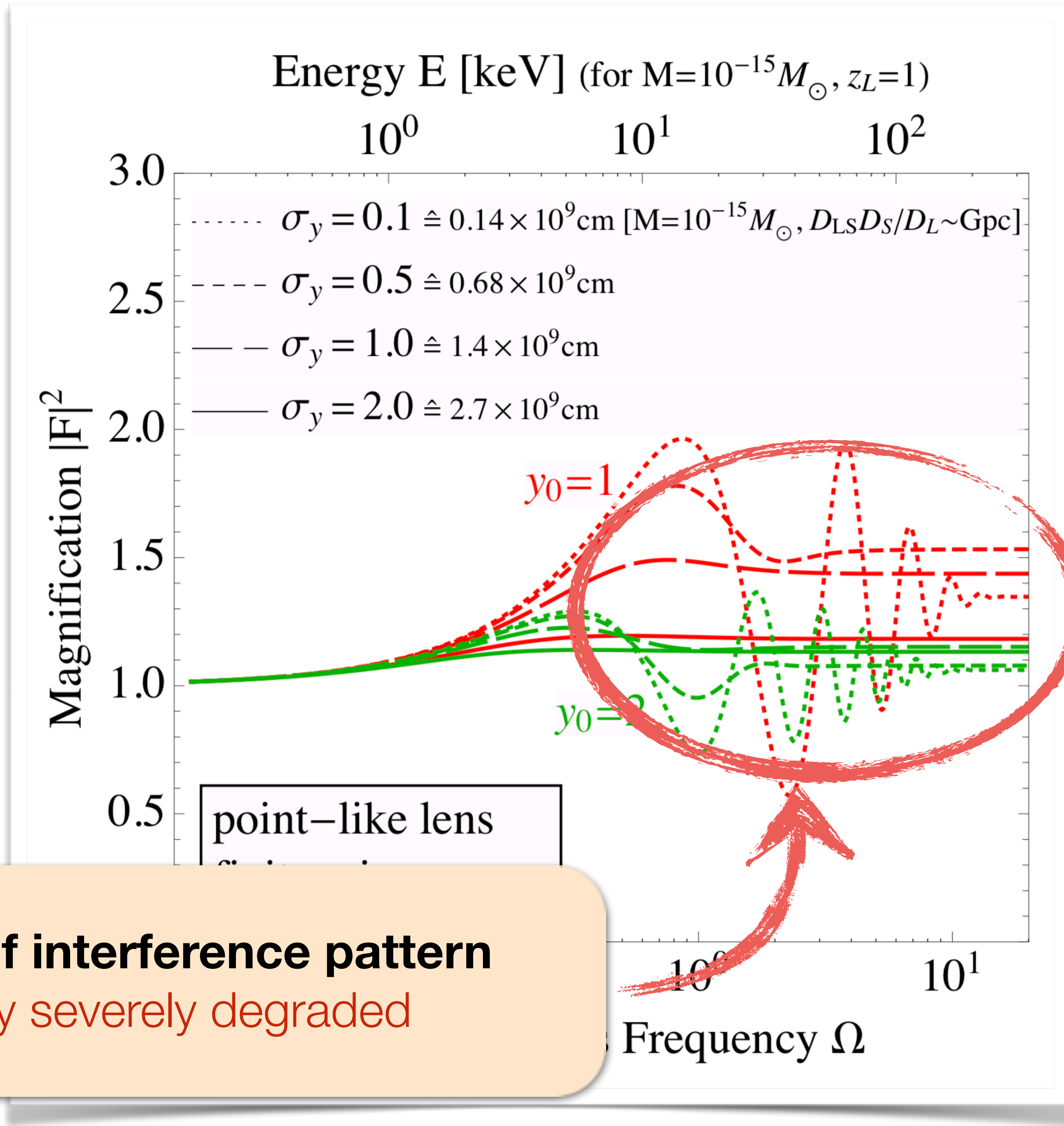

Katz
arXiv

Wash-out of interference pattern

sensitivity severely degraded

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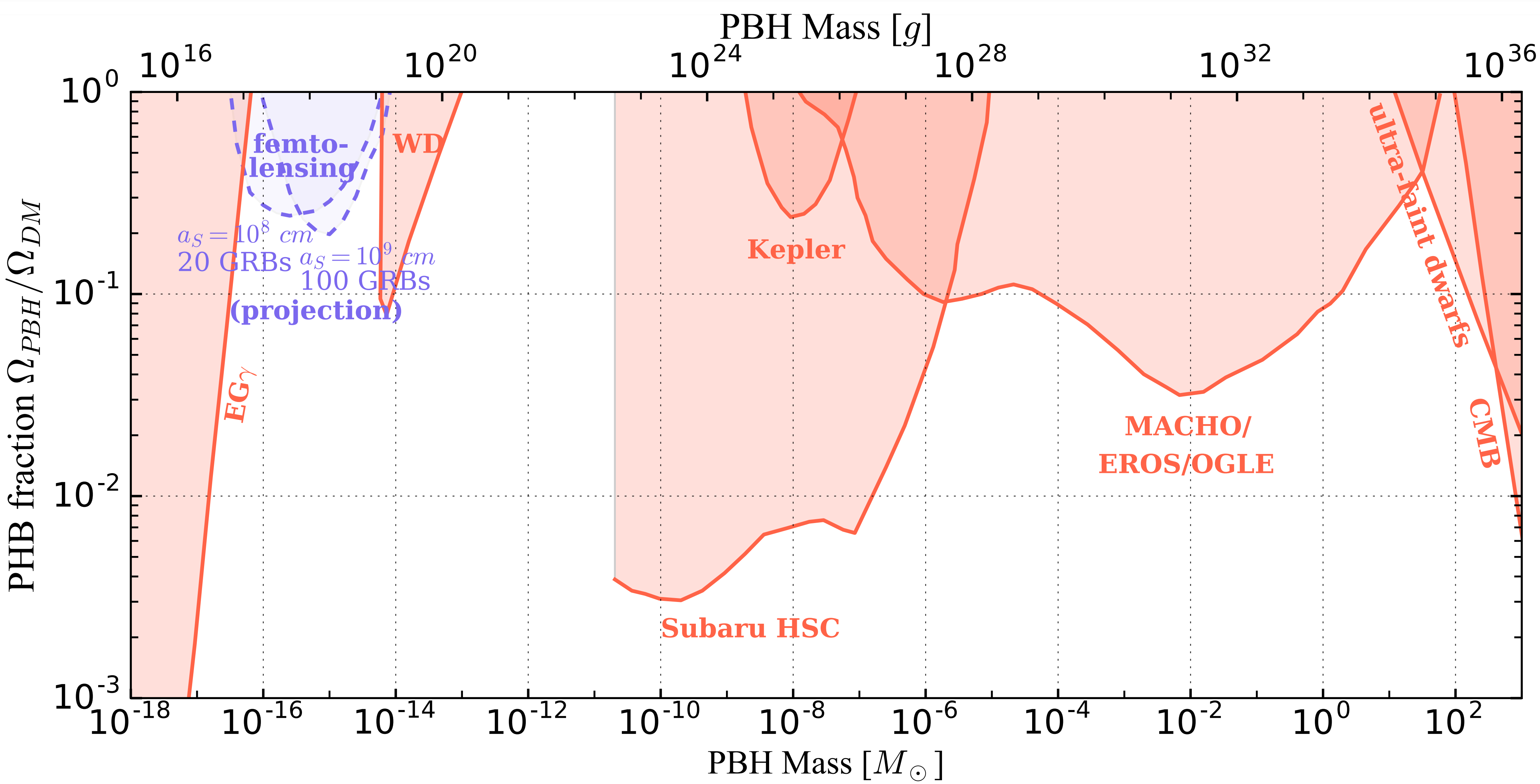
Femtolensing of Gamma Ray Bursts



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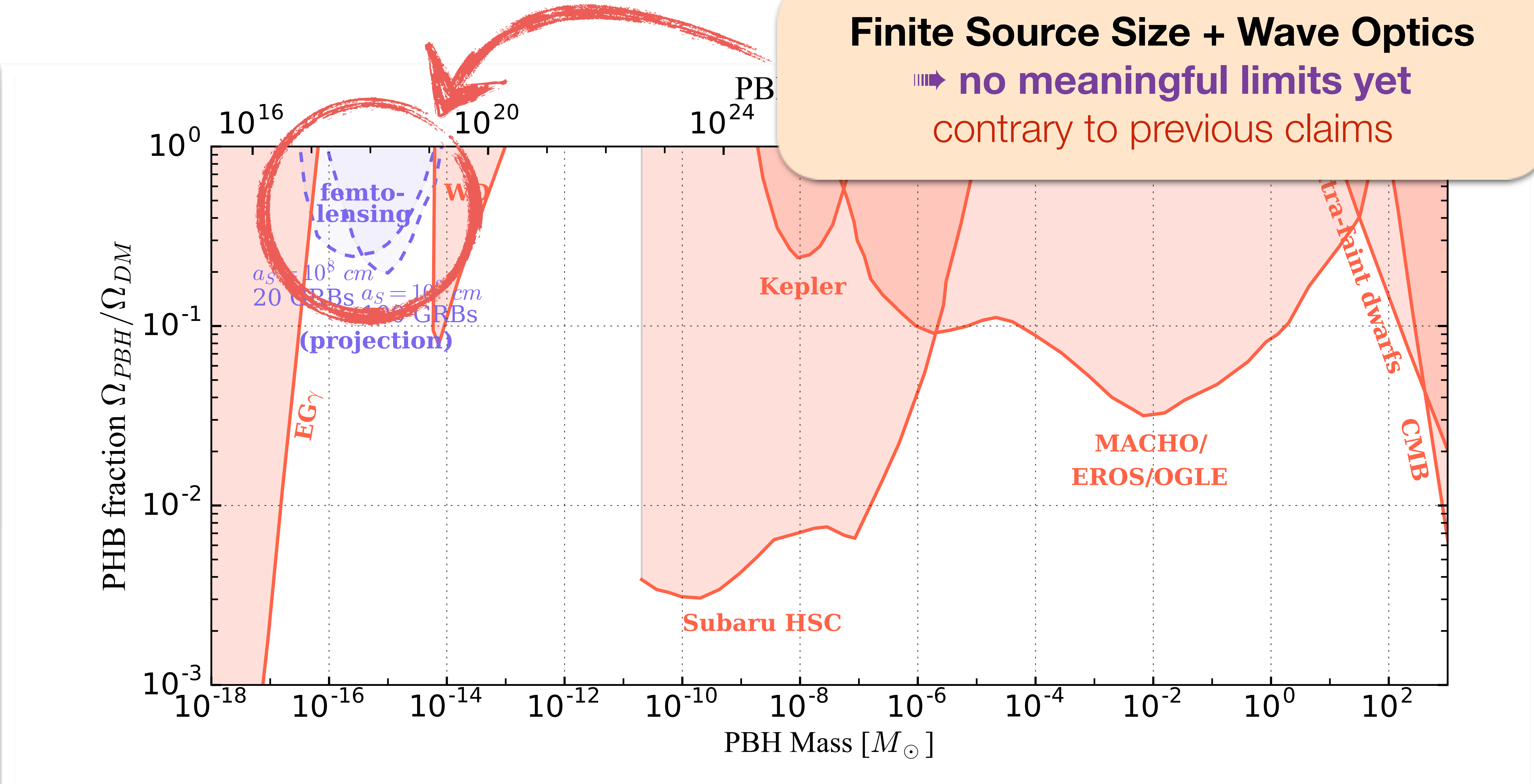
Assuming δ-like PBH mass distribution

Femtolensing of Gamma Ray Bursts



Finite Source Size + Wave Optics

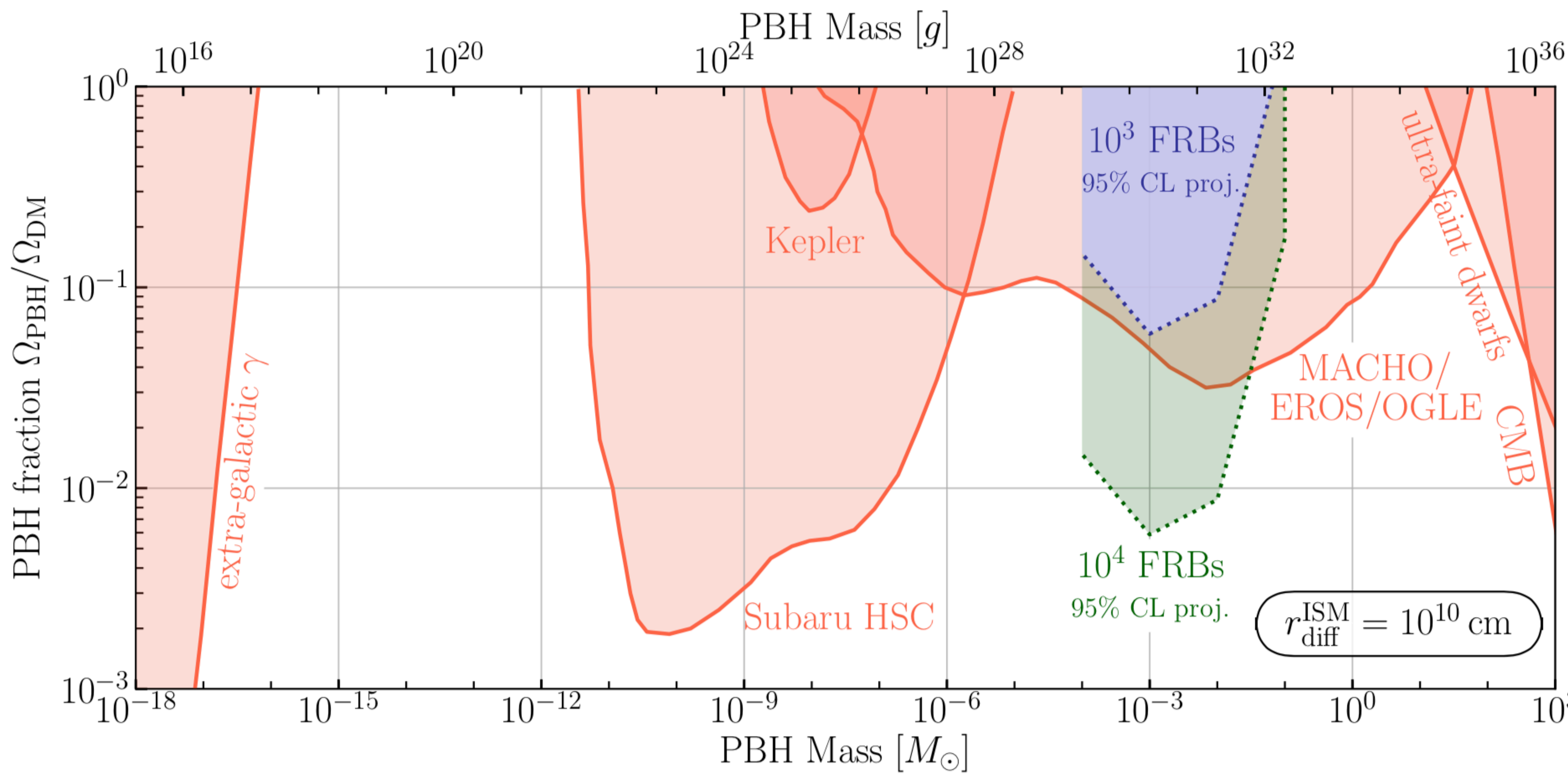
➠ **no meaningful limits yet**

contrary to previous claims

Katz JK Sibiryakov Xue
arXiv:1807.11495

Assuming δ-like PBH mass distribution

Femtolensing of Fast Radio Bursts

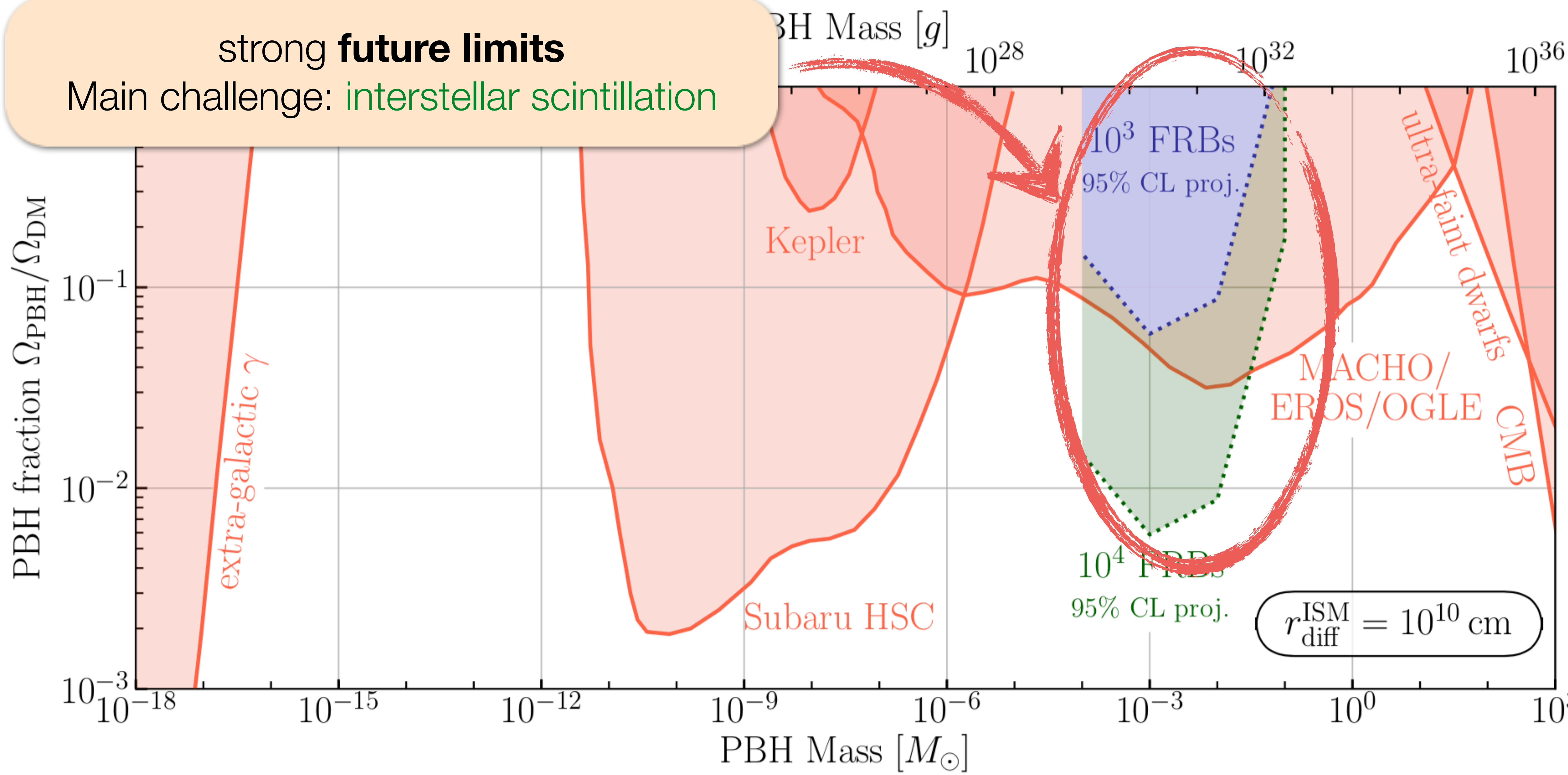


Katz JK Sibiryakov Xue, arXiv:1912.07620

Assuming δ-like PBH mass distribution

Femtolensing of Fast Radio Bursts

strong **future limits**
Main challenge: interstellar scintillation



Katz JK Sibiryakov Xue, arXiv:1912.07620

Assuming δ-like PBH mass distribution

Dark Photons

Motivation

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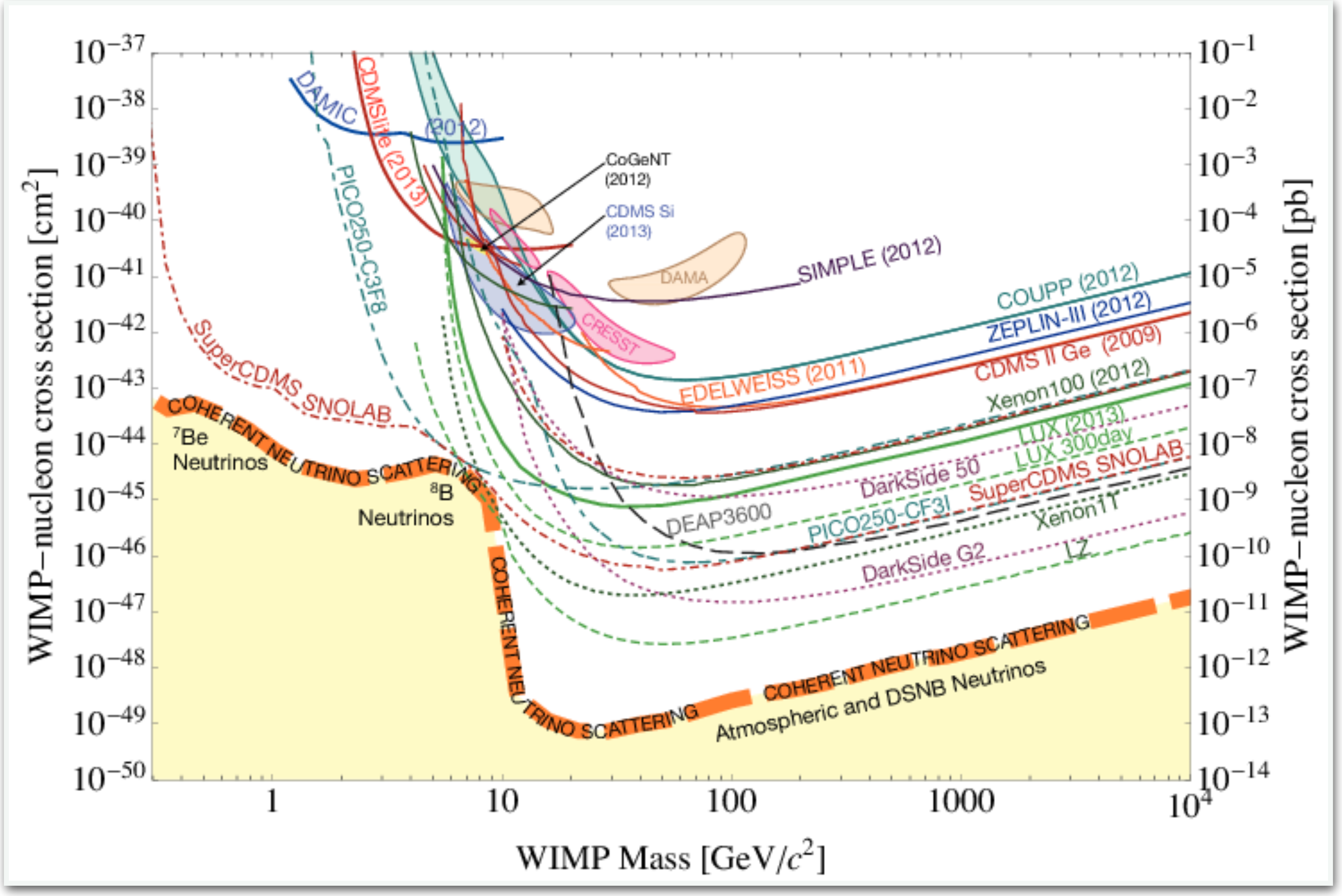

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  below energy threshold of Fermi-LAT (γ), AMS-02 (e^+e^-), ...
  below threshold for annihilation into γ-rich final states ($\bar{b}b$, $\tau^+\tau^-$, ...)

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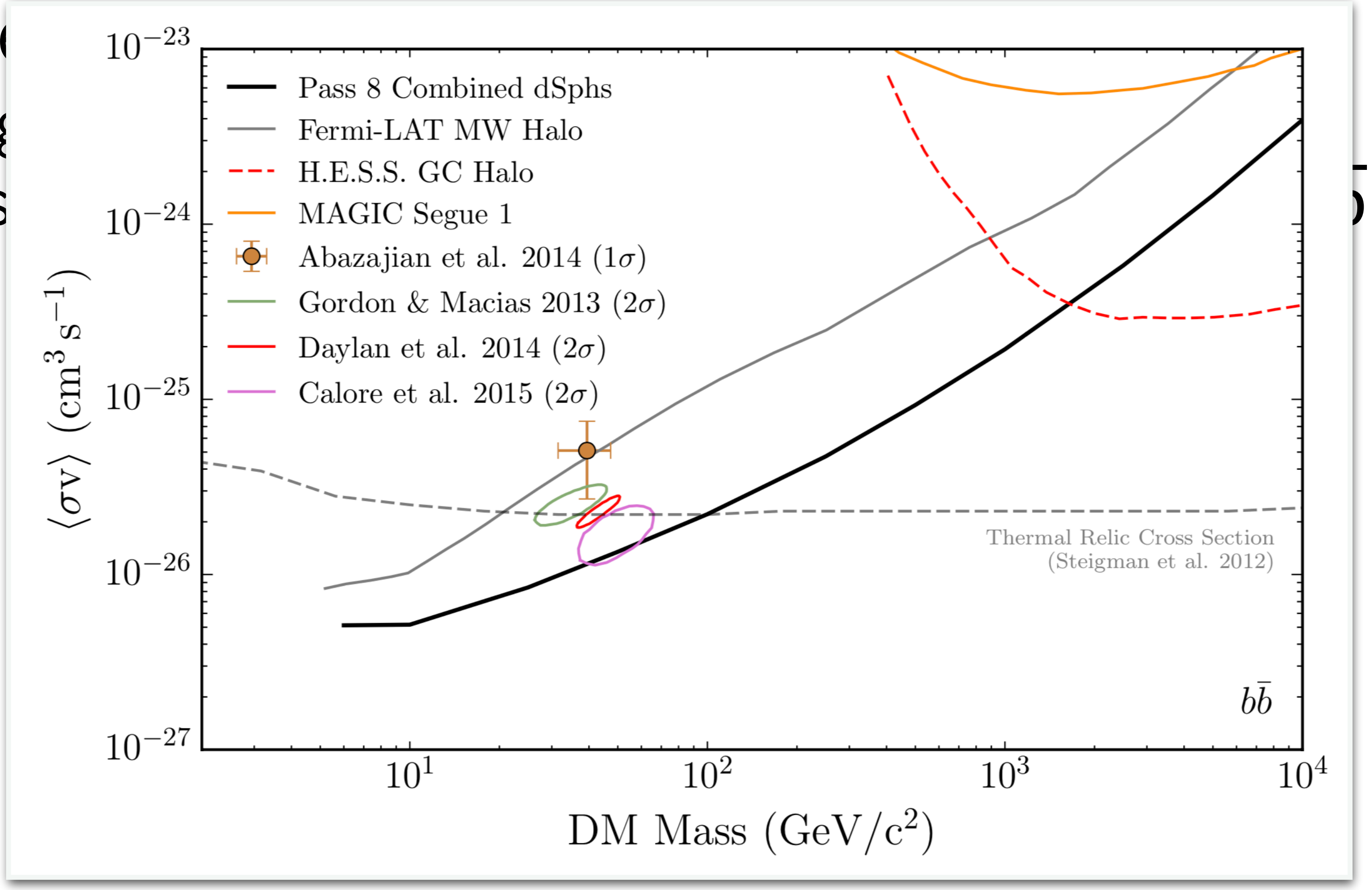
  below thres… b, τ⁺τ⁻, …)



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  below energy threshold of Fermi-LAT (γ), AMS-02 (e^+e^-), ...
  below threshold for annihilation into γ-rich final states ($\bar{b}b$, $\tau^+\tau^-$, ...)
- ☑ For light mediator particles, colliders are at relative disadvantage (cross section $\sigma \sim 1/E_{cm}^2$)

Motivation

- Only three possibilities for coupling a total gauge singlet to SM particles through a renormalizable interaction
  - Singlet scalar *S*: Higgs portal $\mathcal{L} \supset \lambda (H^\dagger H) S^\dagger S$
    (typically implies $m_S \sim m_H$ ➟ back at the electroweak scale)
  - Singlet fermion *N*: Neutrino portal $\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$
    (relevant for instance for sterile neutrino DM)
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Hypercharge (B_μ) field strength tensor

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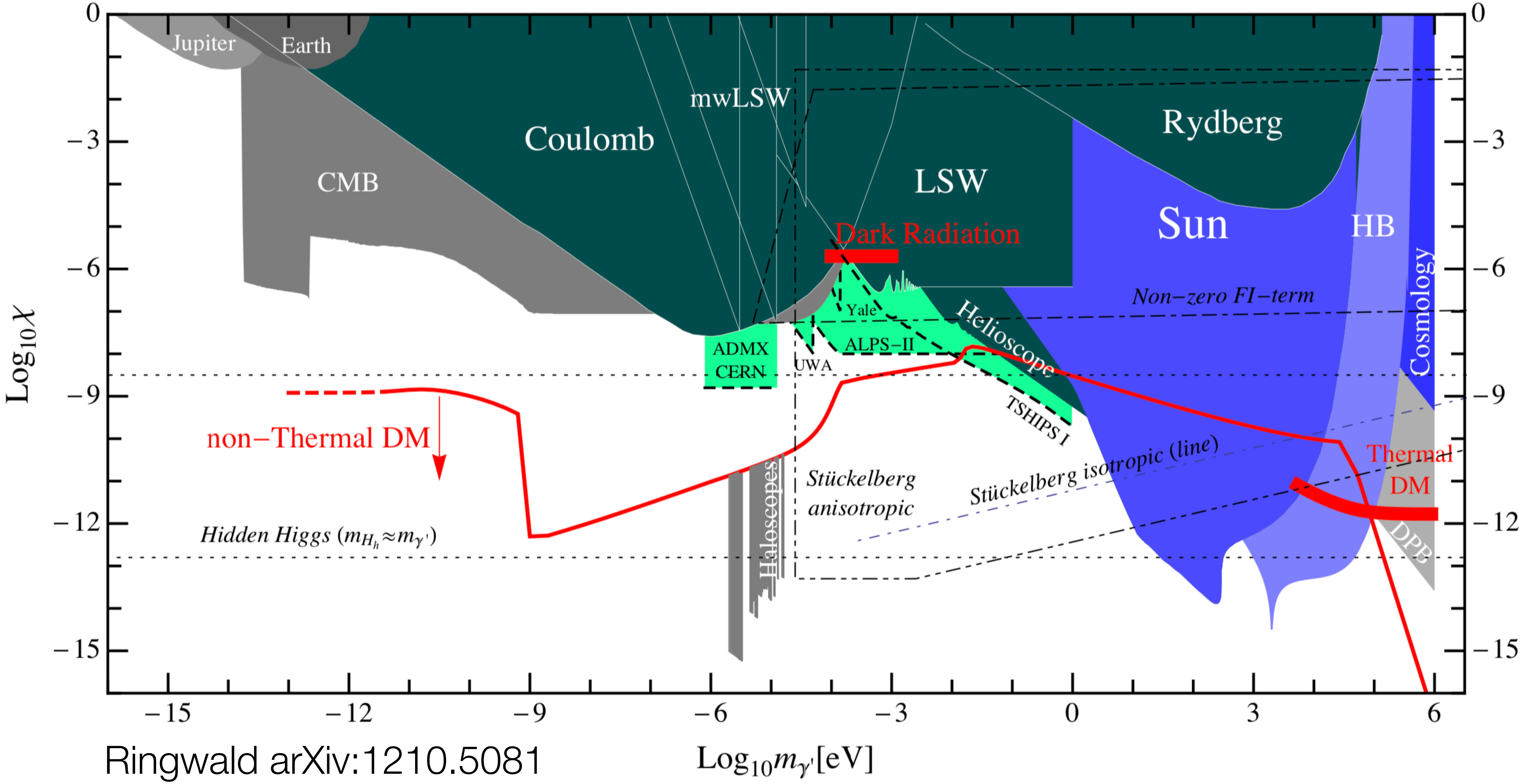
Hypercharge (B_μ) field strength tensor

B'_μ field strength tensor

Dark Photons and Dark Matter

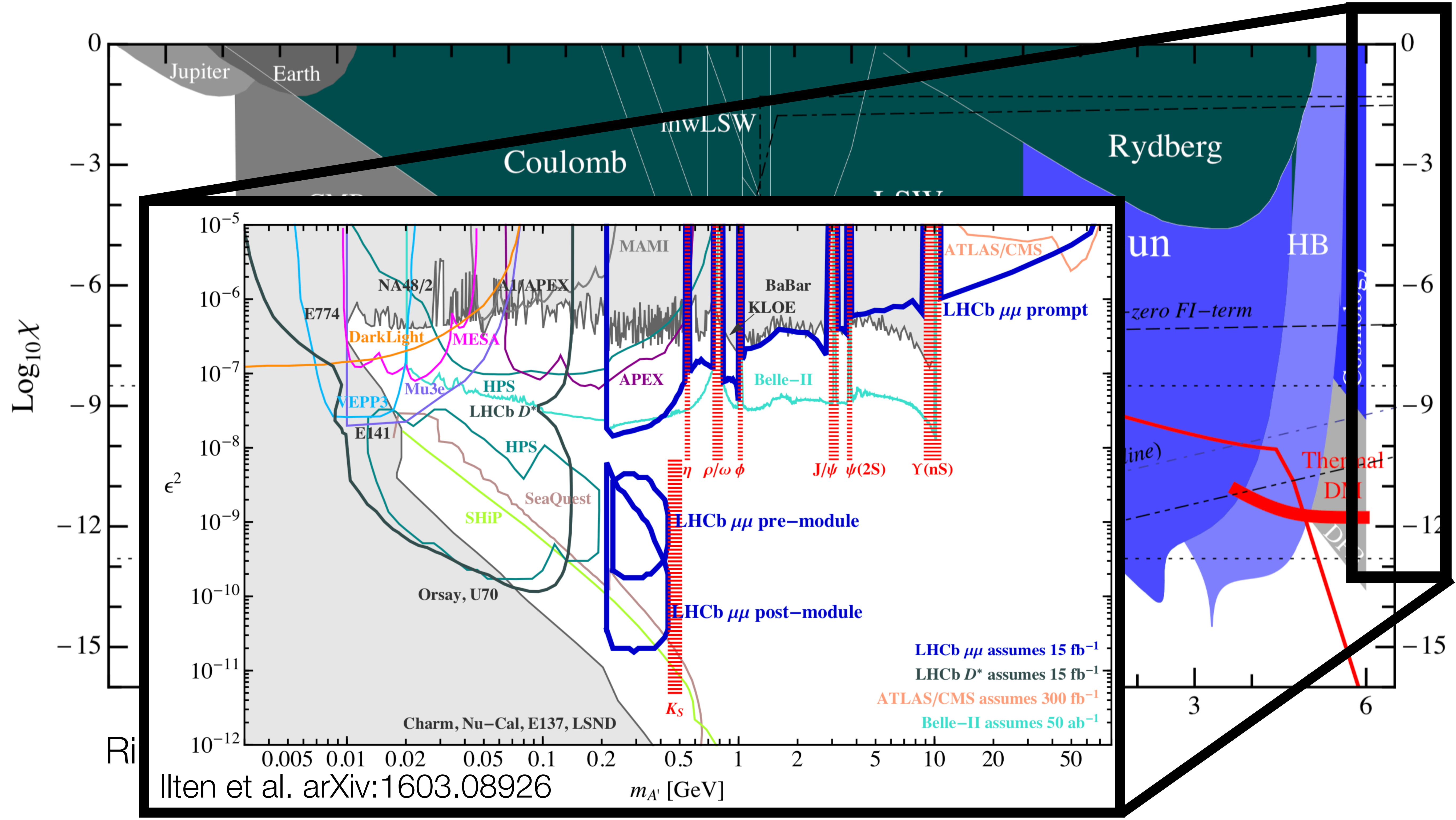
- ☑ Dark Photons could either make up the dark matter ...
- ☑ ... or act as mediator of DM—SM couplings

Dark Photon Constraints



Ringwald arXiv:1210.5081

Dark Photon Constraints



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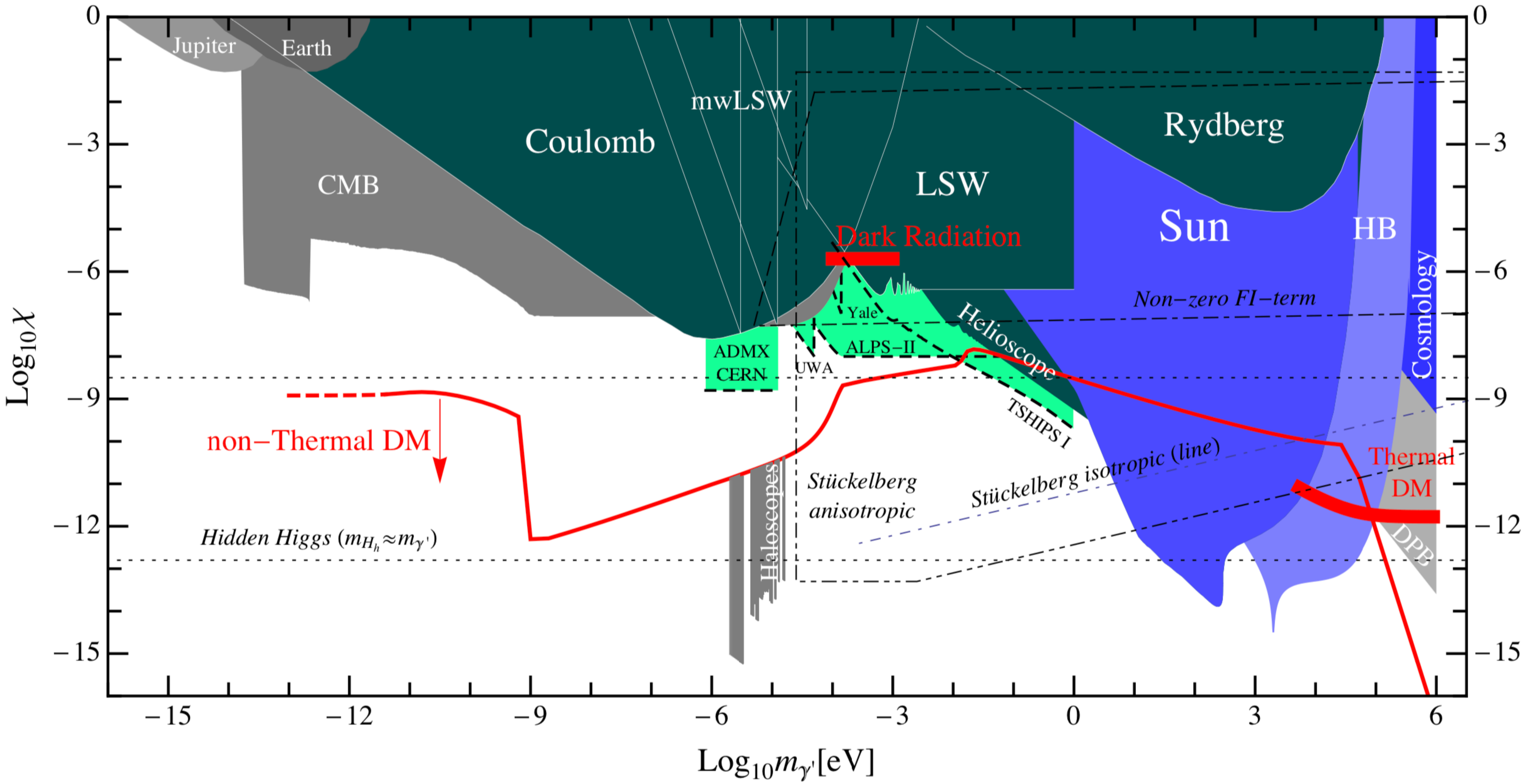
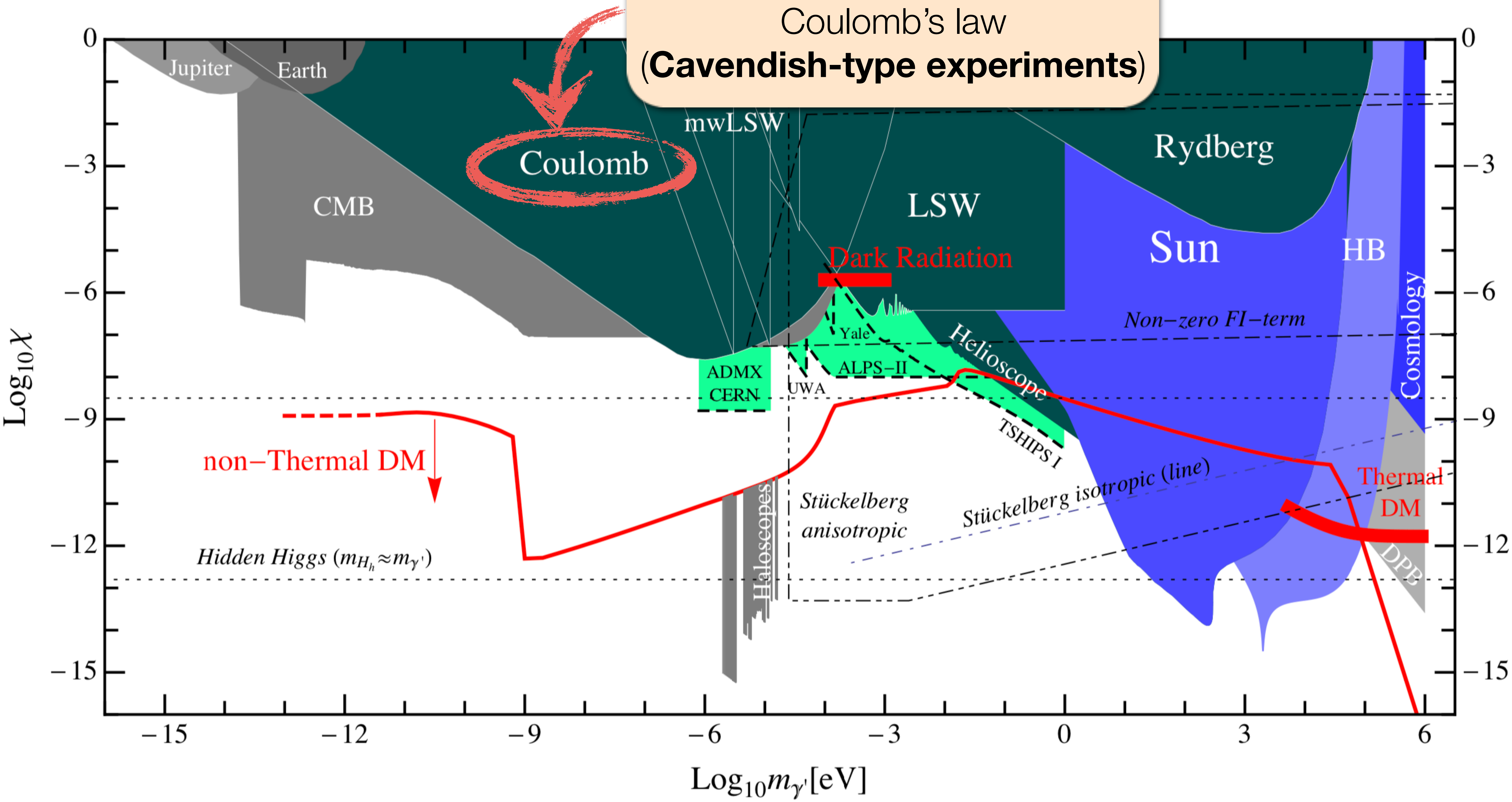


Dark Photon Constraints

Modification to the 1/r behavior of Coulomb's law (**Cavendish-type experiments**)



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Dark Photon Constraints

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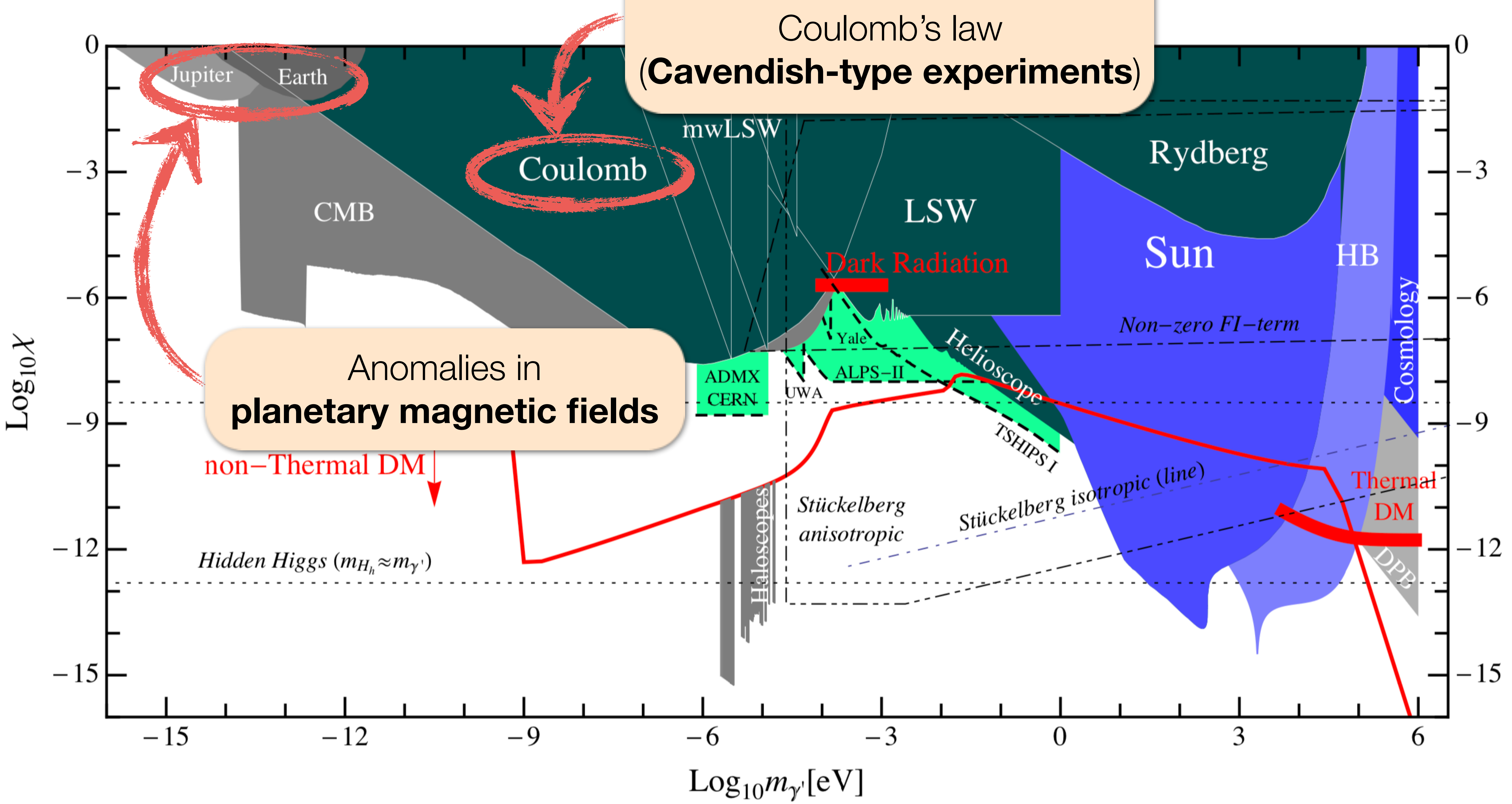

Anomalies in **planetary magnetic fields**

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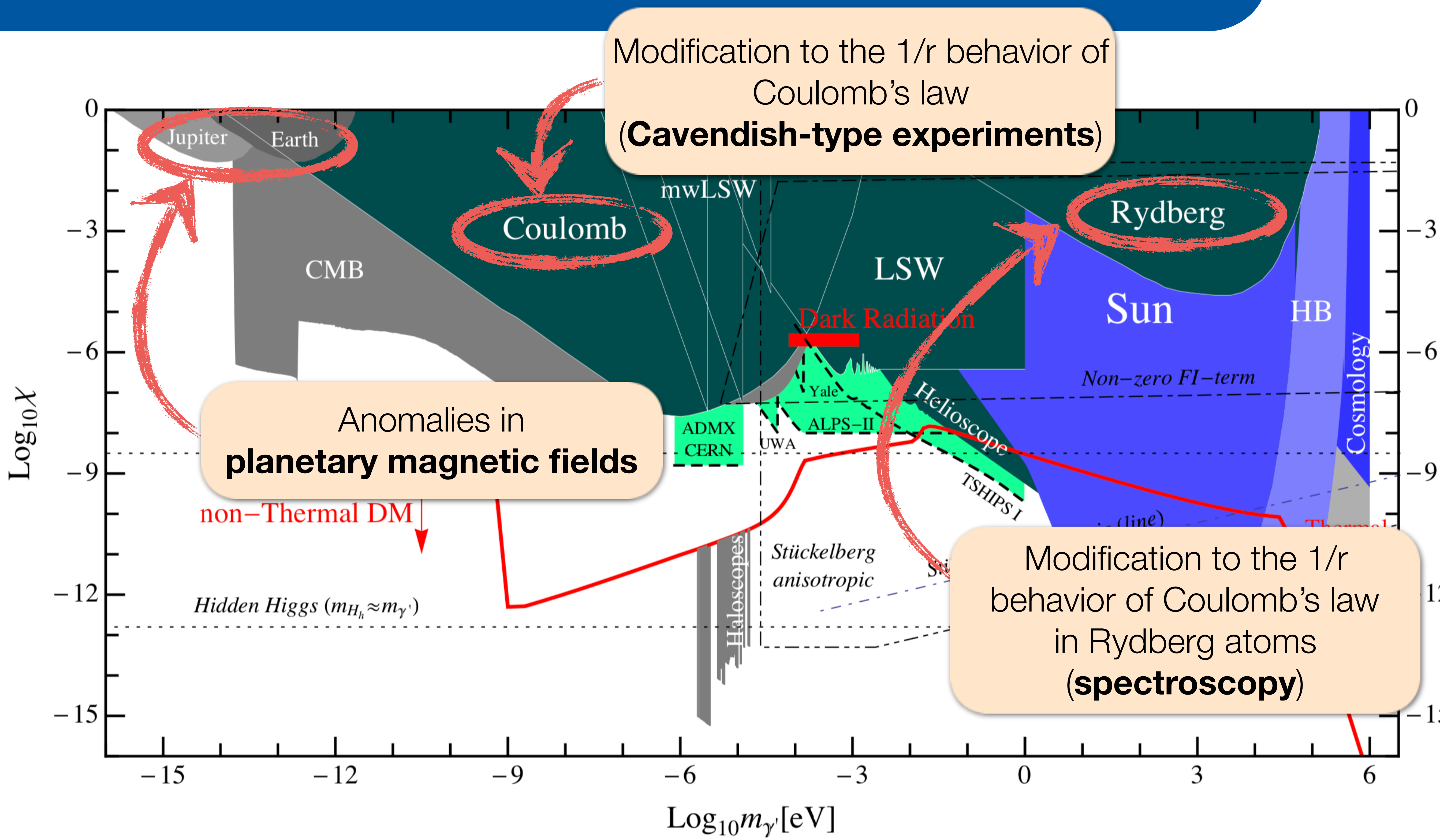
Dark Photon Constraints



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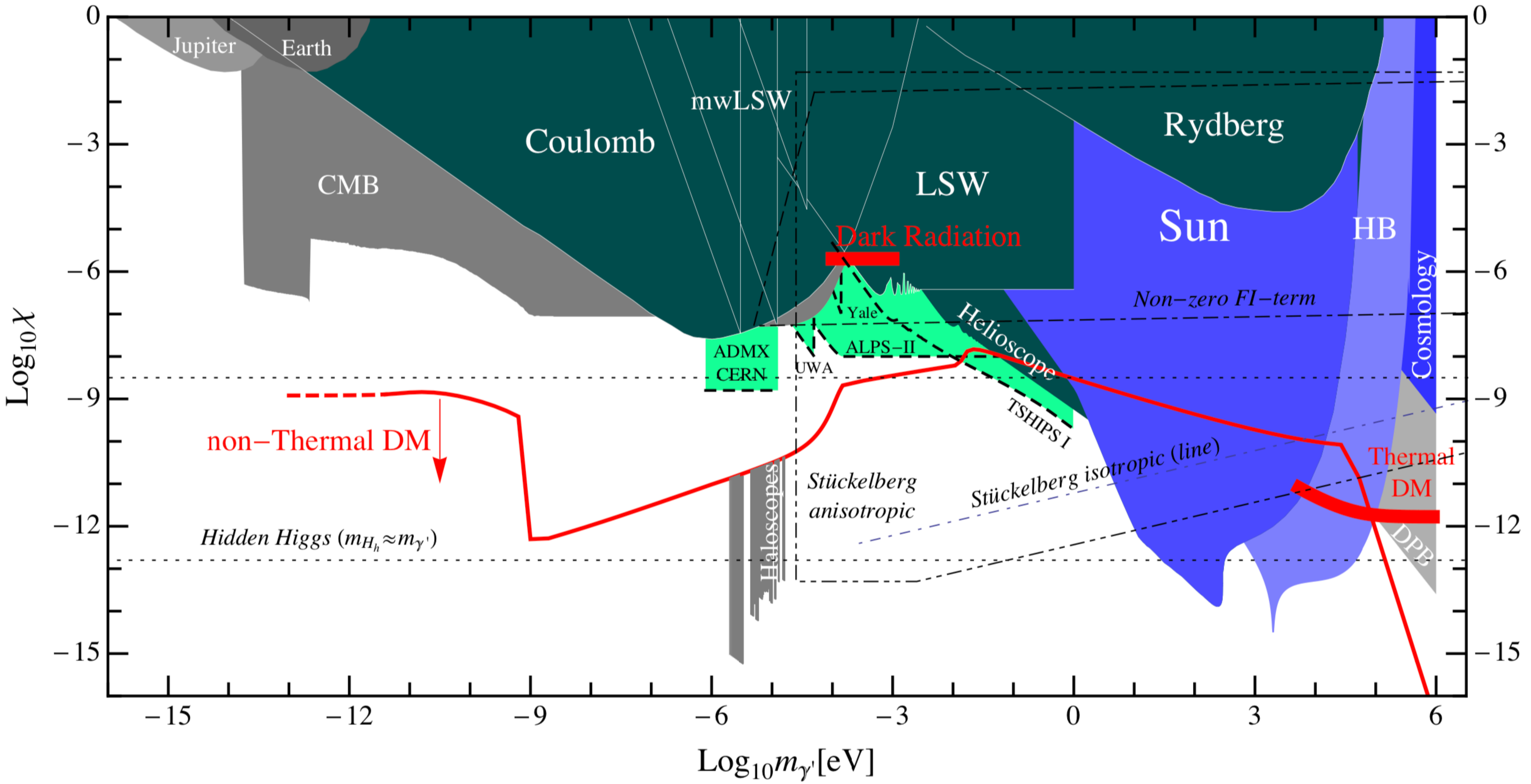
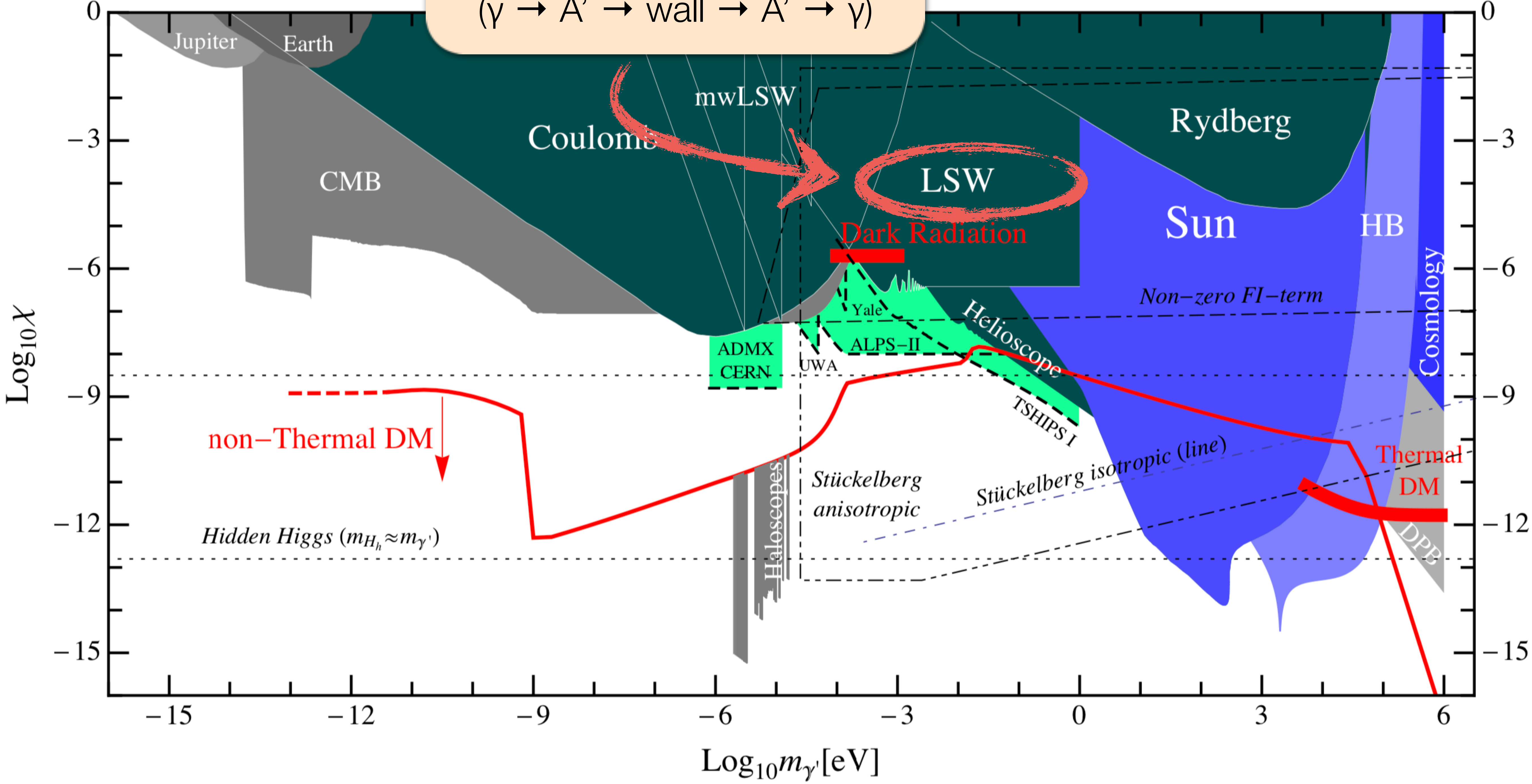


Dark Photon Constraints

Light shining through wall
experiments
(γ → A' → wall → A' → γ)



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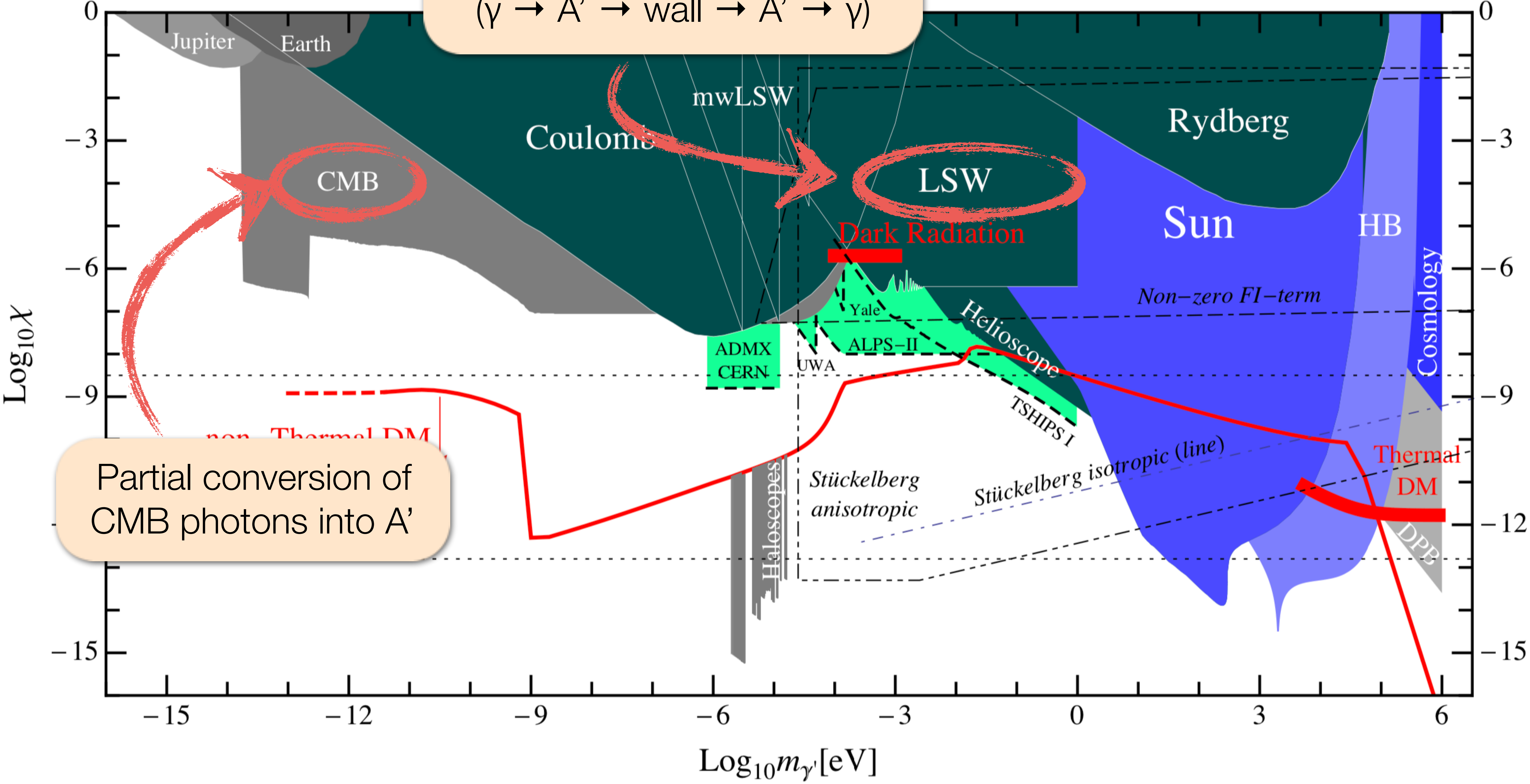
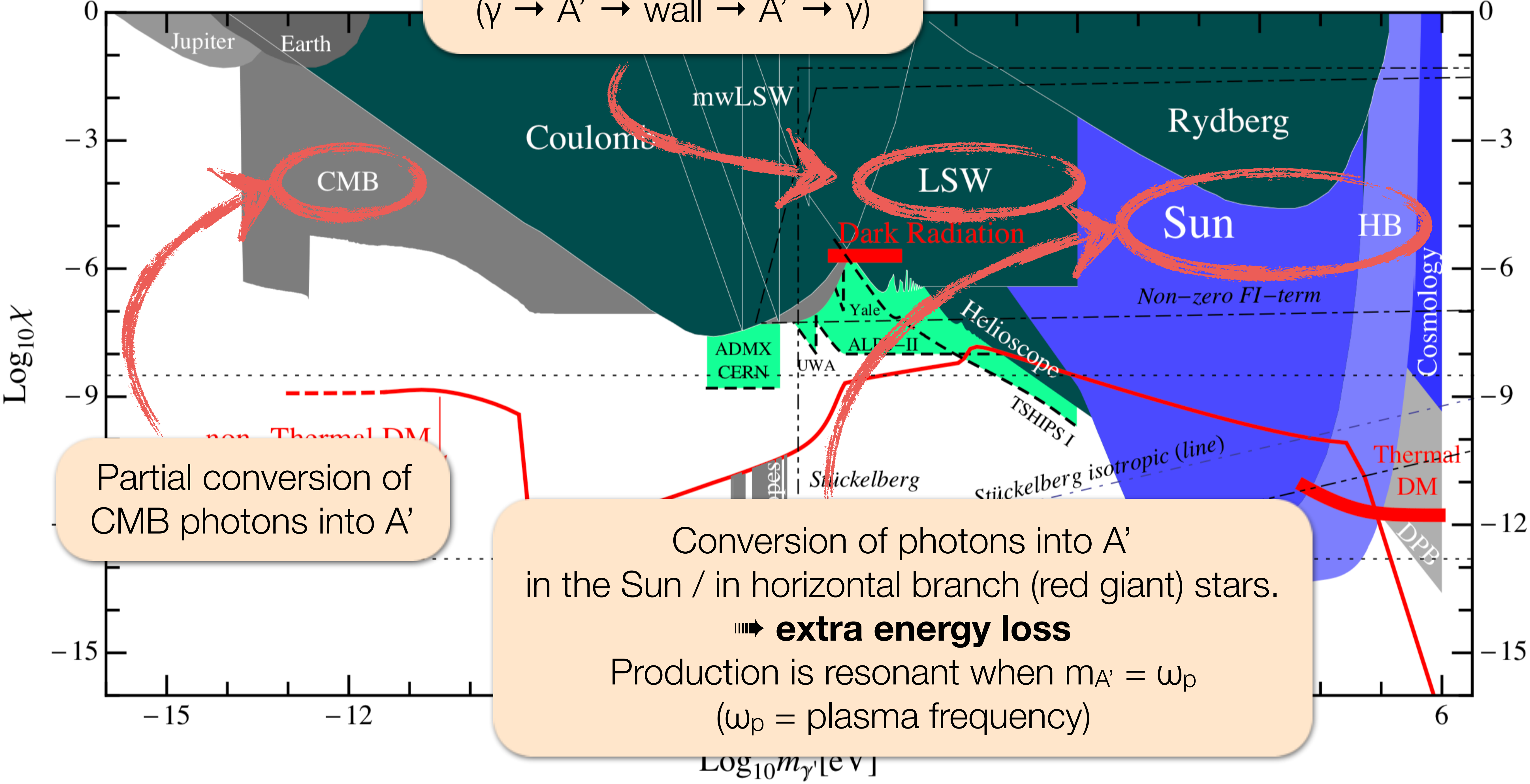


Partial conversion of CMB photons into A’

Dark Photon Constraints



Light shining through wall experiments ($\gamma \to A' \to$ wall $\to A' \to \gamma$)

Partial conversion of CMB photons into A'

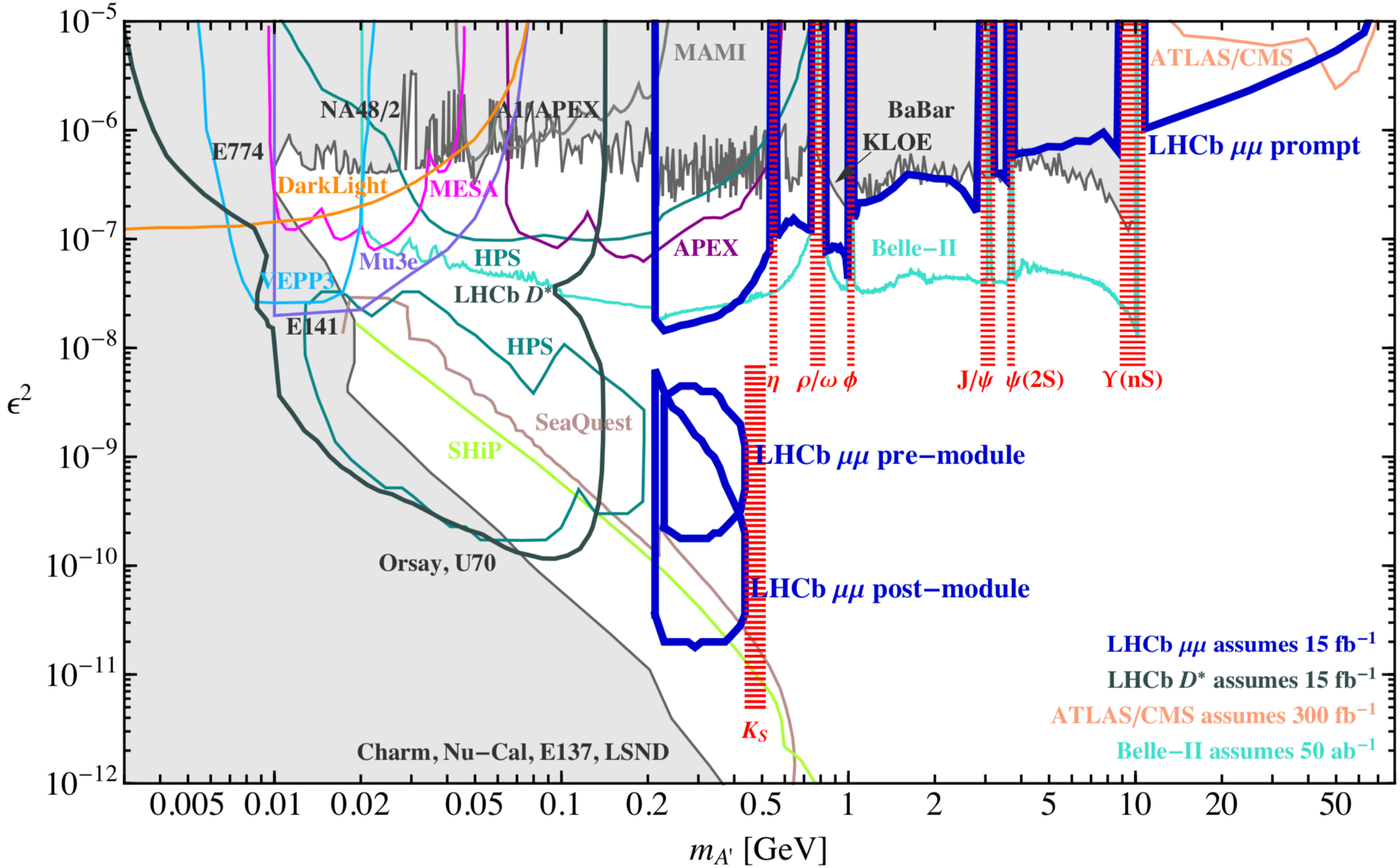
Conversion of photons into A' in the Sun / in horizontal branch (red giant) stars.

➠ **extra energy loss**

Production is resonant when $m_{A'} = \omega_p$

(ω_p = plasma frequency)

Dark Photon Constraints



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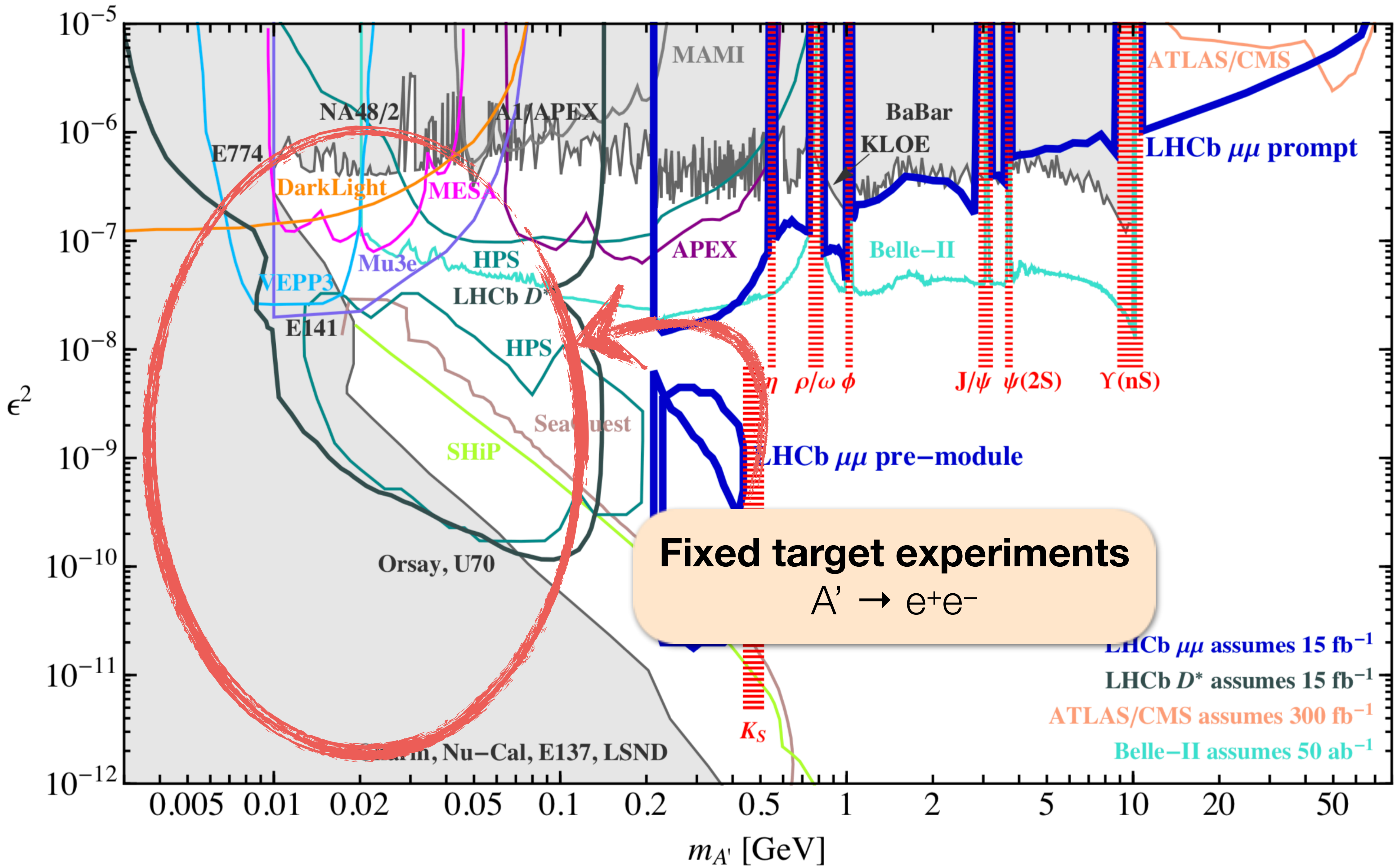

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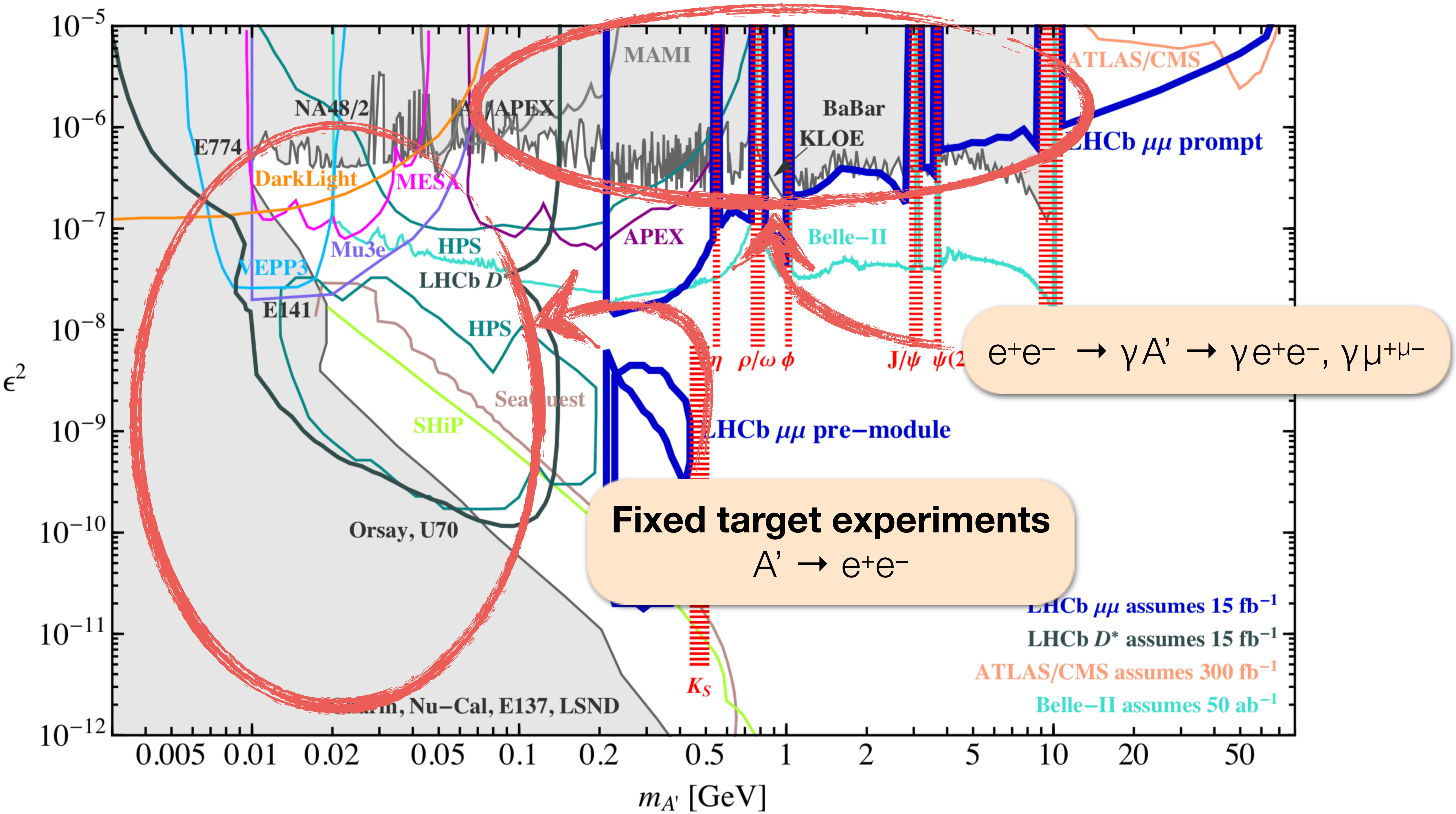

Summary

Summary

WIMP Dark Matter

- annihilation today leads to various types of cosmic rays
- for individual messengers: confusion with astrophysical sources

Primordial Black Holes

- interesting DM candidate that doesn't require new particles
- interesting astrophysical constraints
- but lots of open parameter space

Dark Photons

- generically appear in low-scale ($\lesssim$ GeV) DM models
- potpourri of constraints (both terrestrial & astro)

Thank You !

Bonus Slides on WIMPs

Gamma Ray Flux at Earth

$$\phi_\gamma = \frac{\Delta\Omega}{4\pi} \left[\frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int d\ell(\psi)\, \rho_{\rm DM}^2(\ell, \psi) \right] \frac{\langle \sigma v_{\rm rel} \rangle}{2 m_\chi^2} \frac{dN_\gamma}{dE_\gamma}$$

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line of sight
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DM mass density

Gamma Ray Flux at Earth

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line of sight
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DM mass density

injection spectrum

Gamma Ray Flux at Earth

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J-factor
contains all dependencies on astrophysics

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particle physics factor
factor 2 in denominator only for self-conjugate DM

Cosmic Ray Transport — Leaky Box Model

Galactic Disk
gas, stars: CR sources
thickness ~ 100 pc

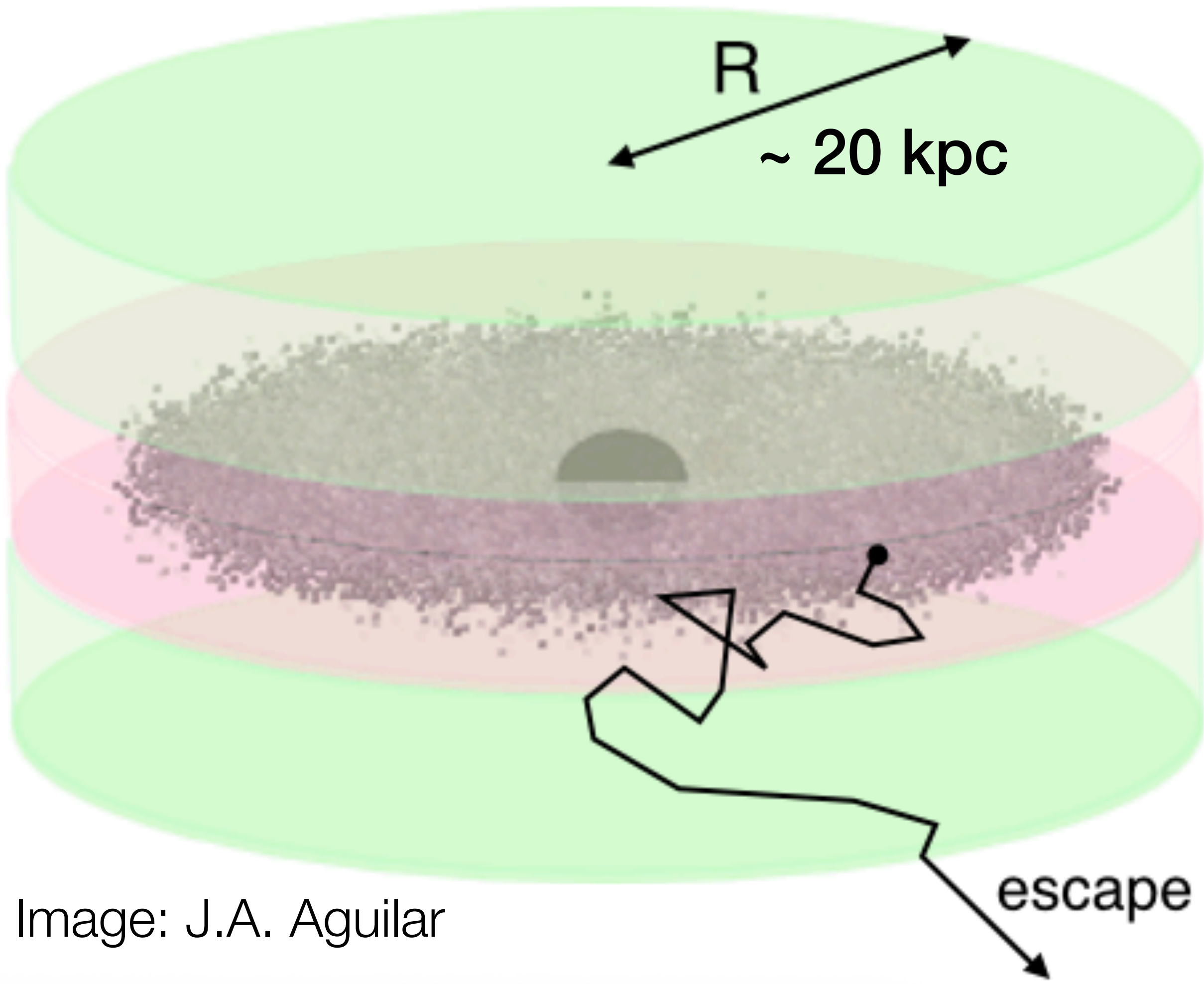

Image: J.A. Aguilar

Confinement Layer
turbulent magnetic fields
thickness 1–15 kpc??

Master equation (diffusion–loss equation)

$$\frac{\partial f(t,\vec{x},E)}{\partial t} - K \cdot \Delta f + \frac{\partial}{\partial E}[b(e)\cdot f] + \frac{\partial}{\partial z}[v_c f]\cdot \operatorname{sgn} z = Q(t,\vec{x},E)$$

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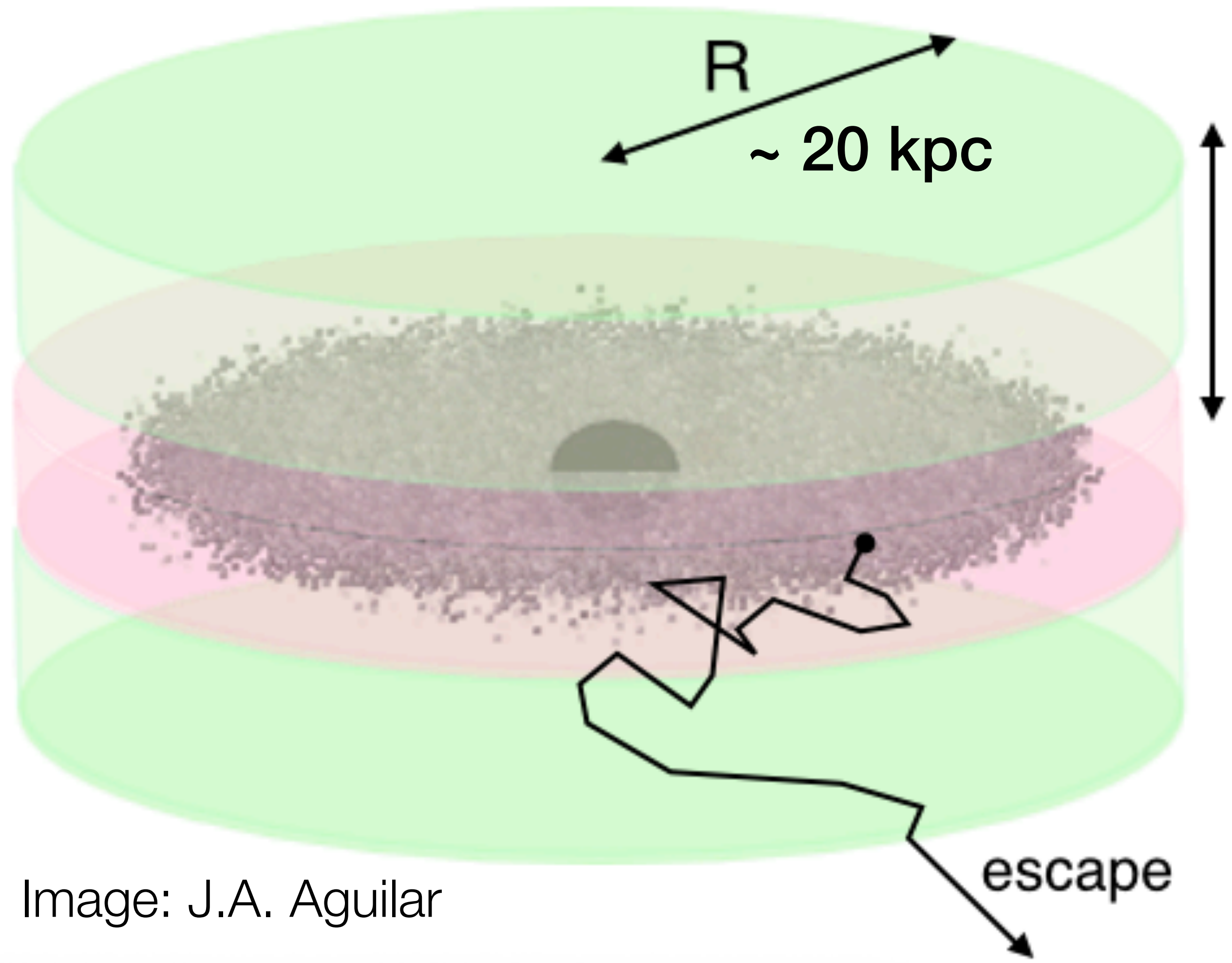

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per unit energy

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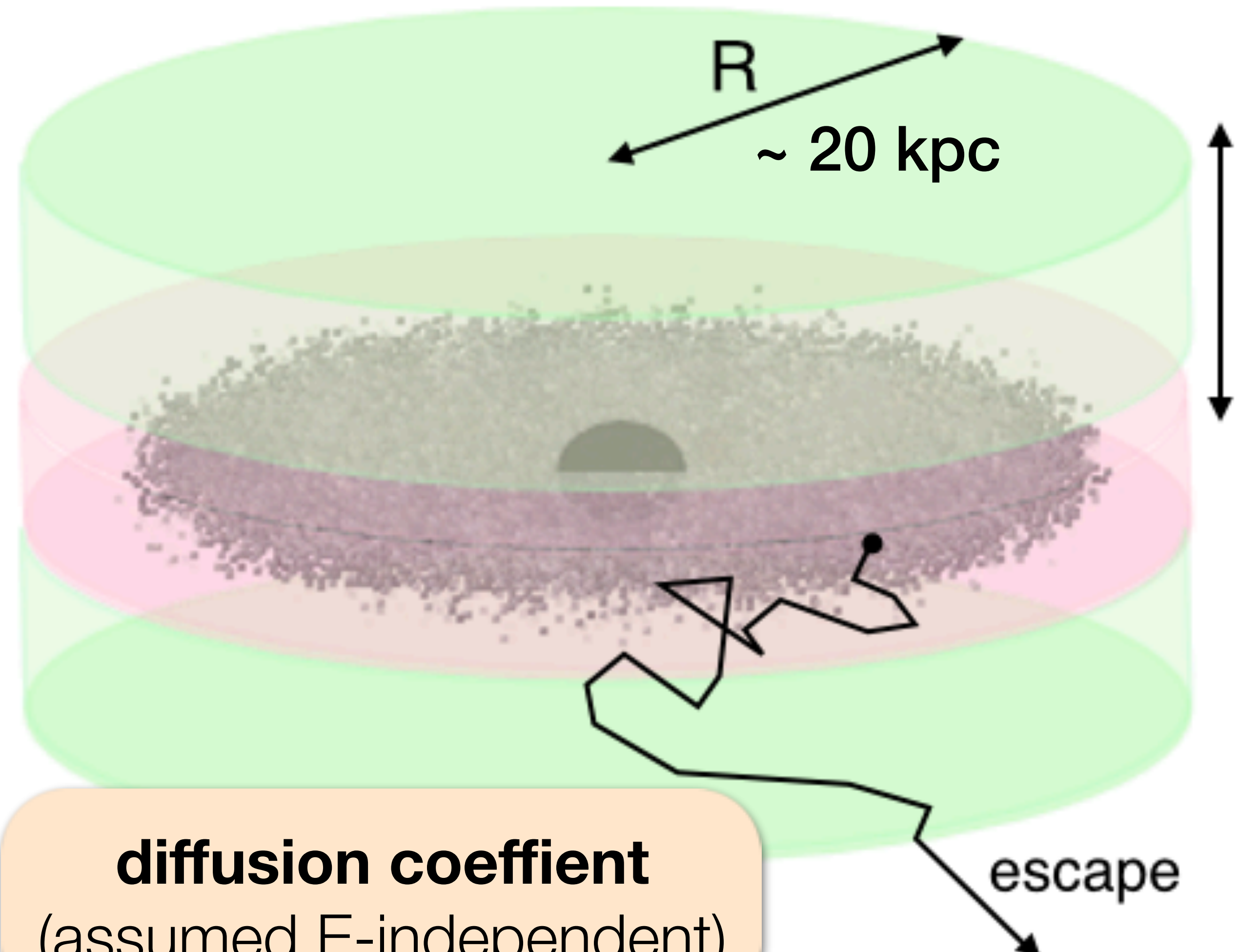

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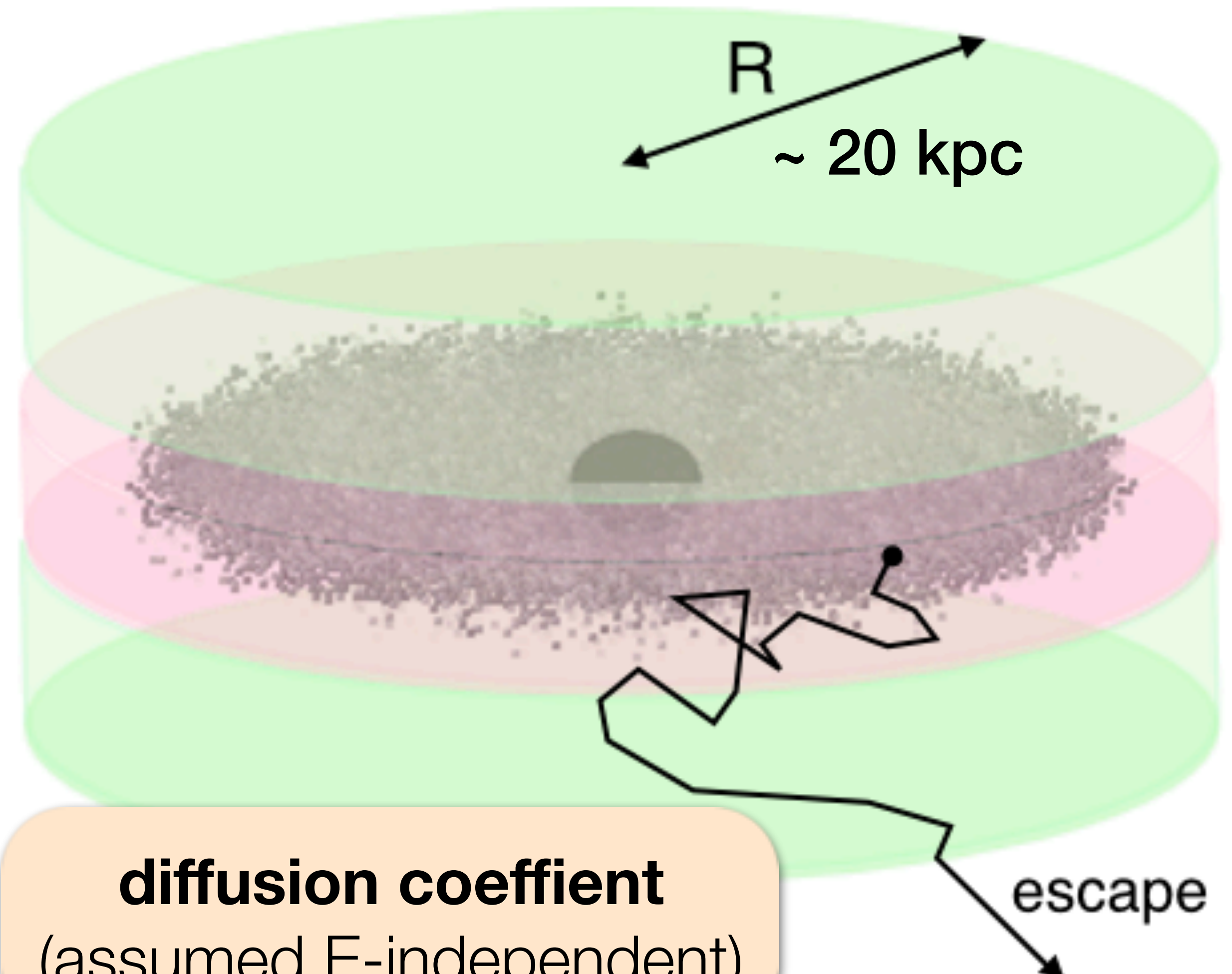

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loss function

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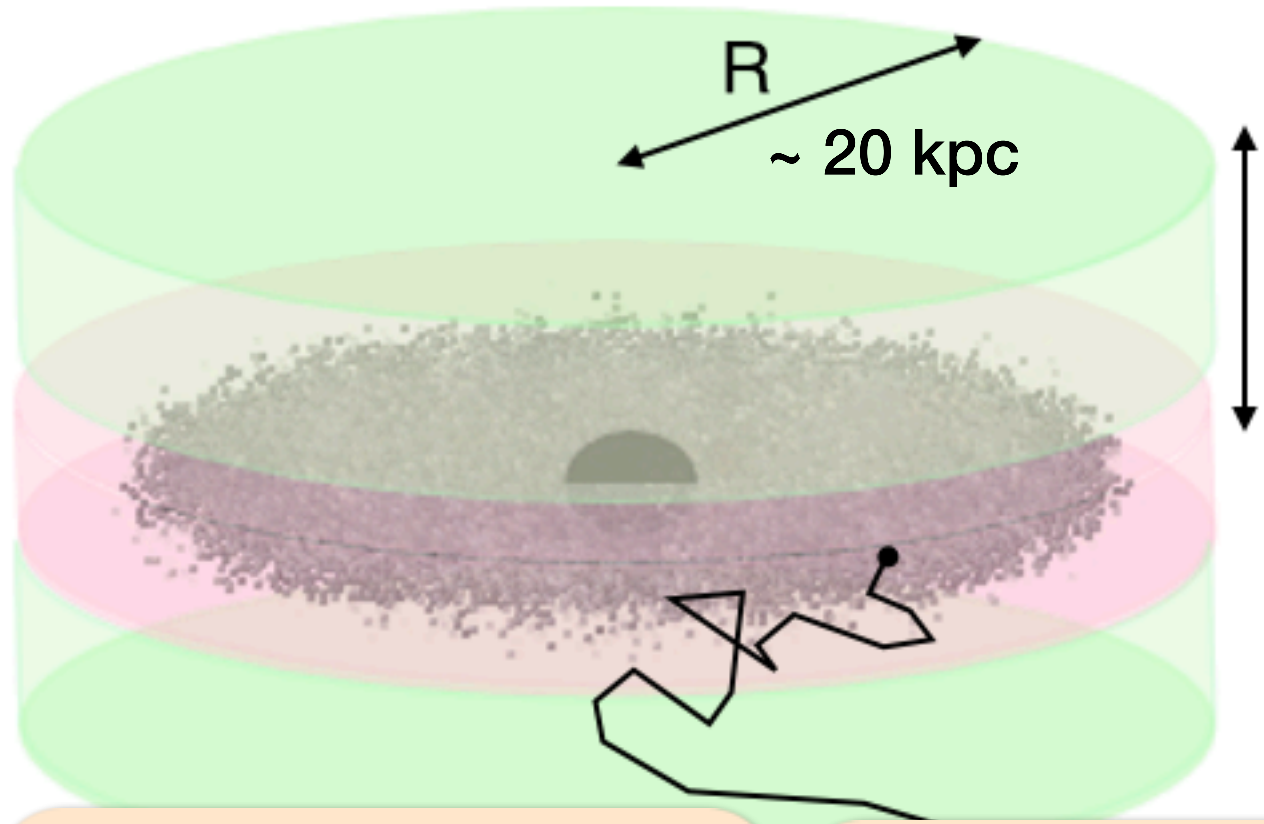
Cosmic Ray Transport — Leaky Box Model



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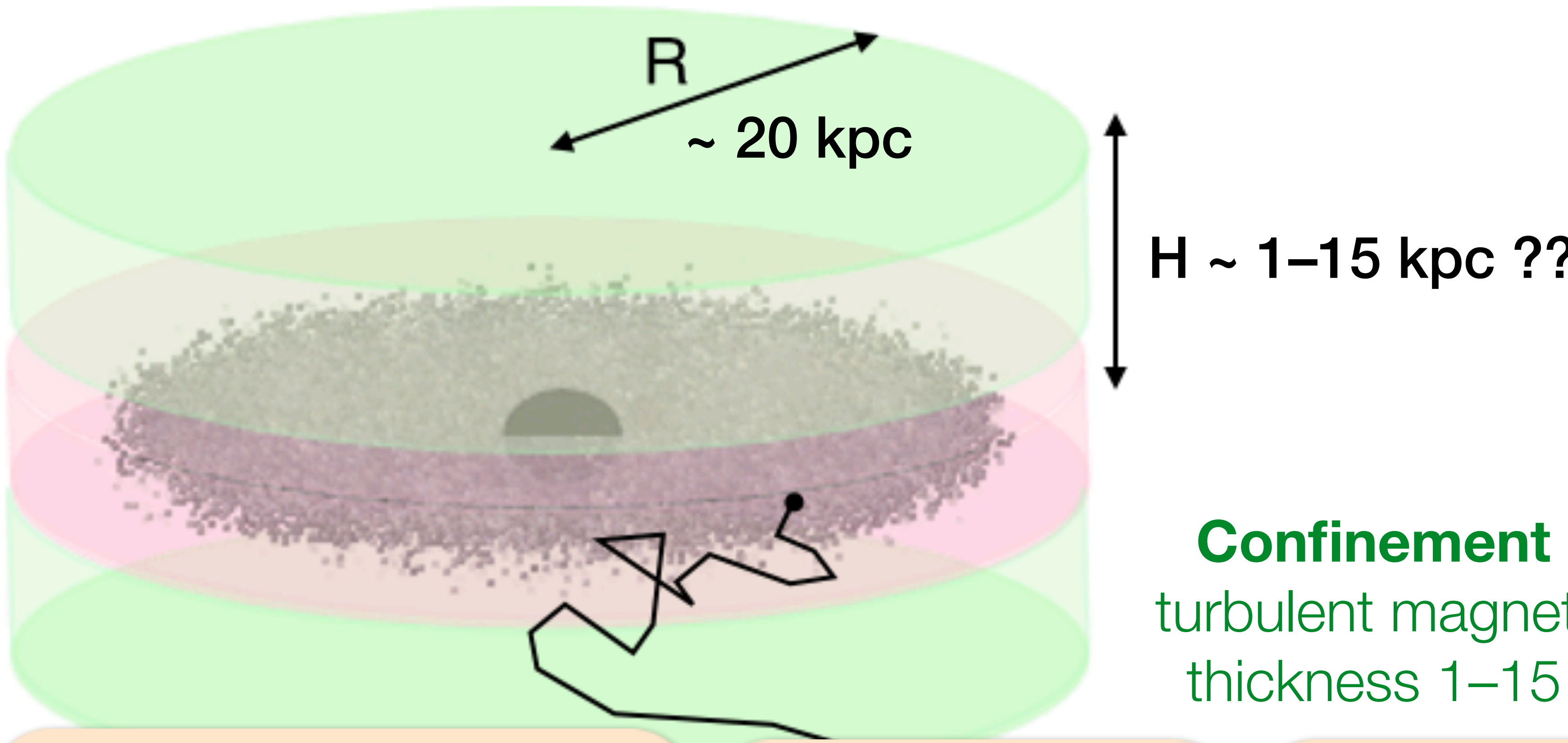
loss function

Cosmic Ray Transport — Leaky Box Model



Galactic Disk
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Confinement Layer
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diffusion coeffient (assumed E-independent)

convective wind

source term

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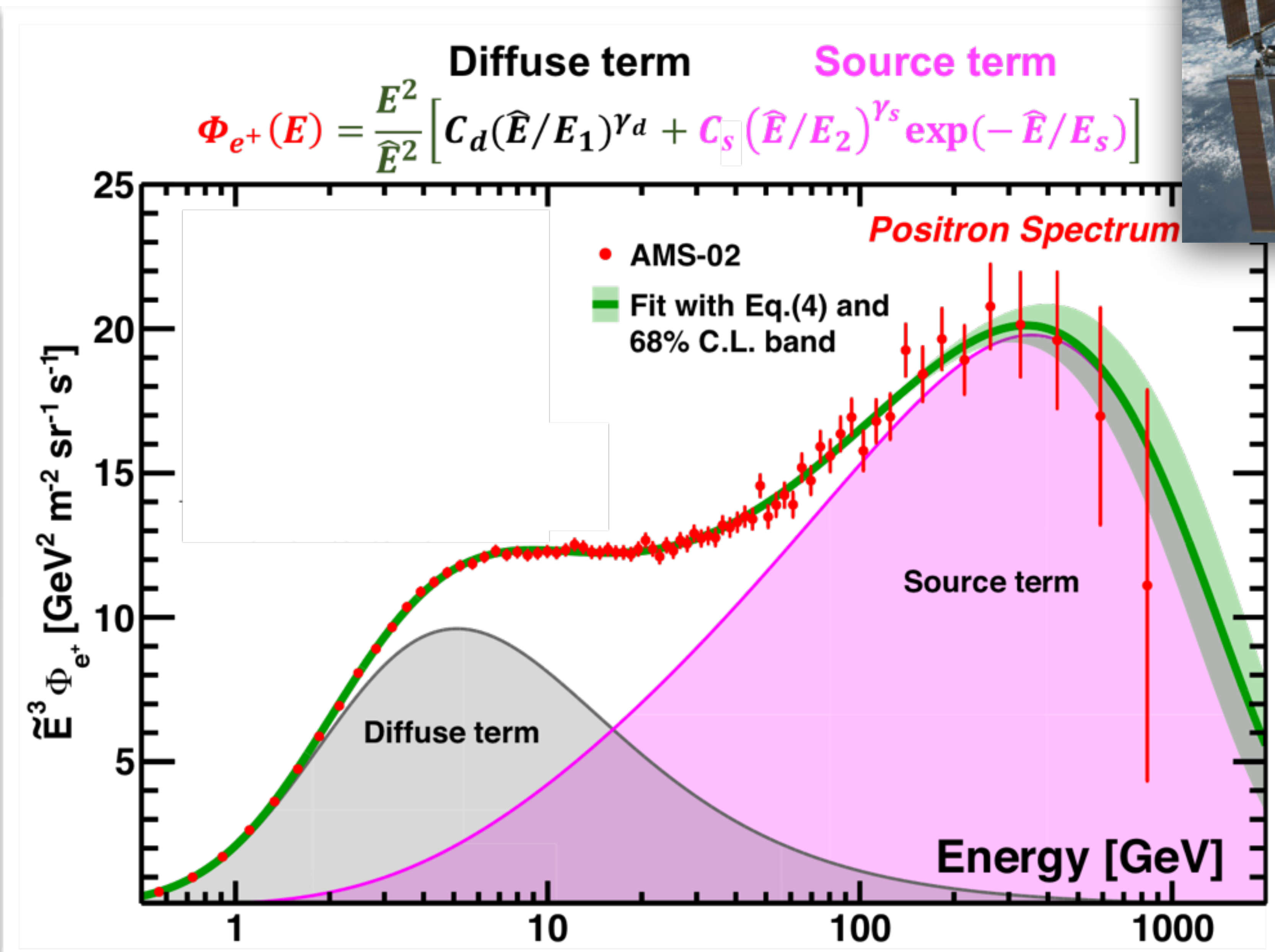
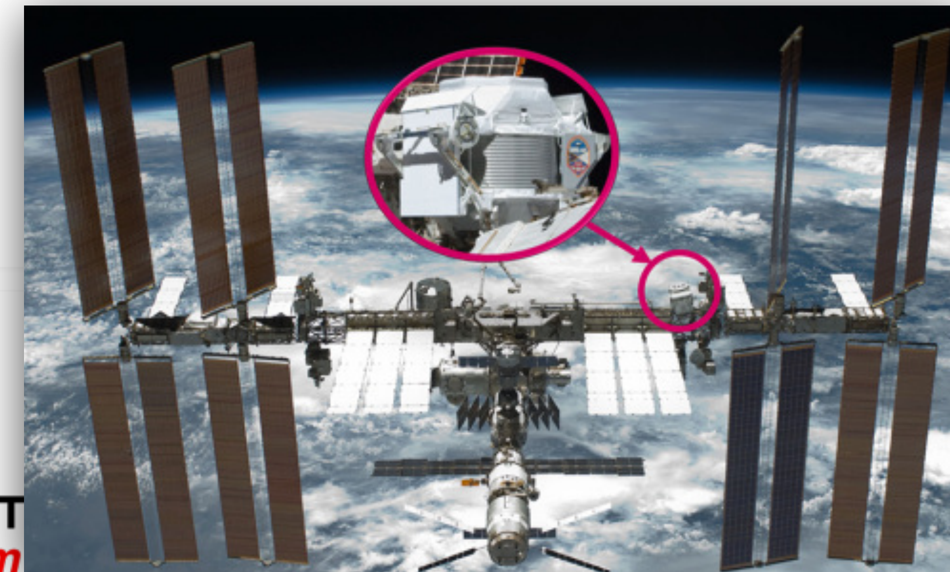
loss function

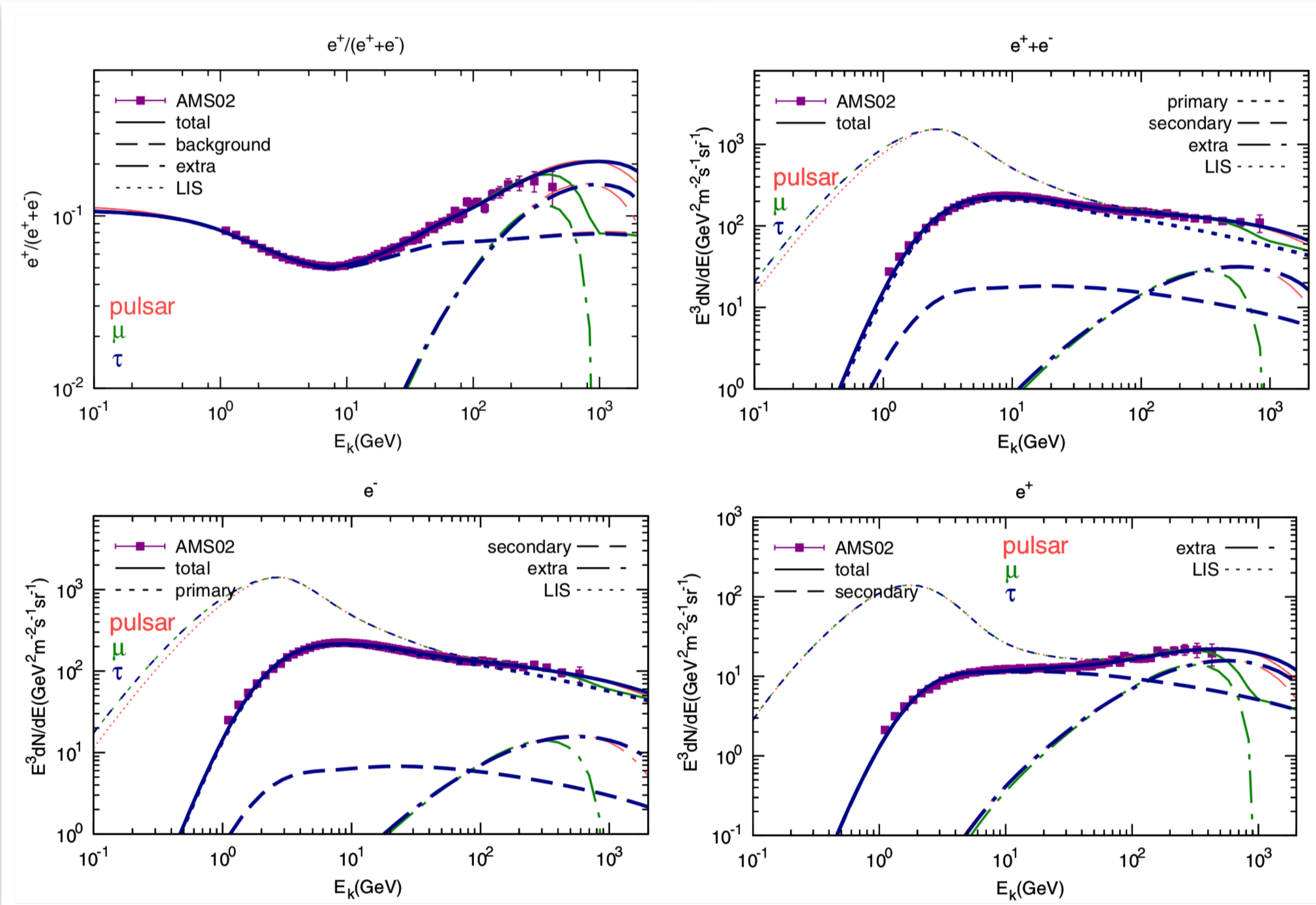
AMS-02 Positron Excess





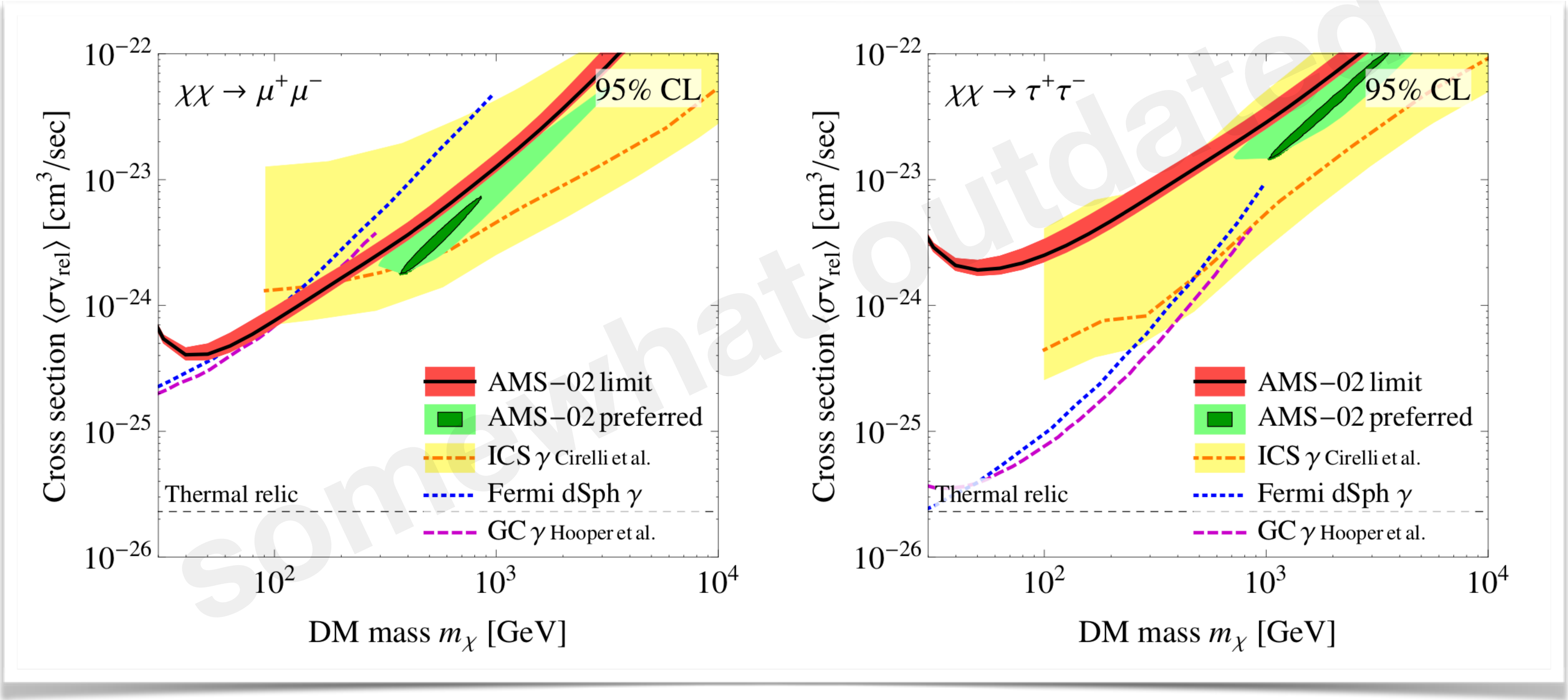
Source: AMS-02

Dark Matter or Pulsars?



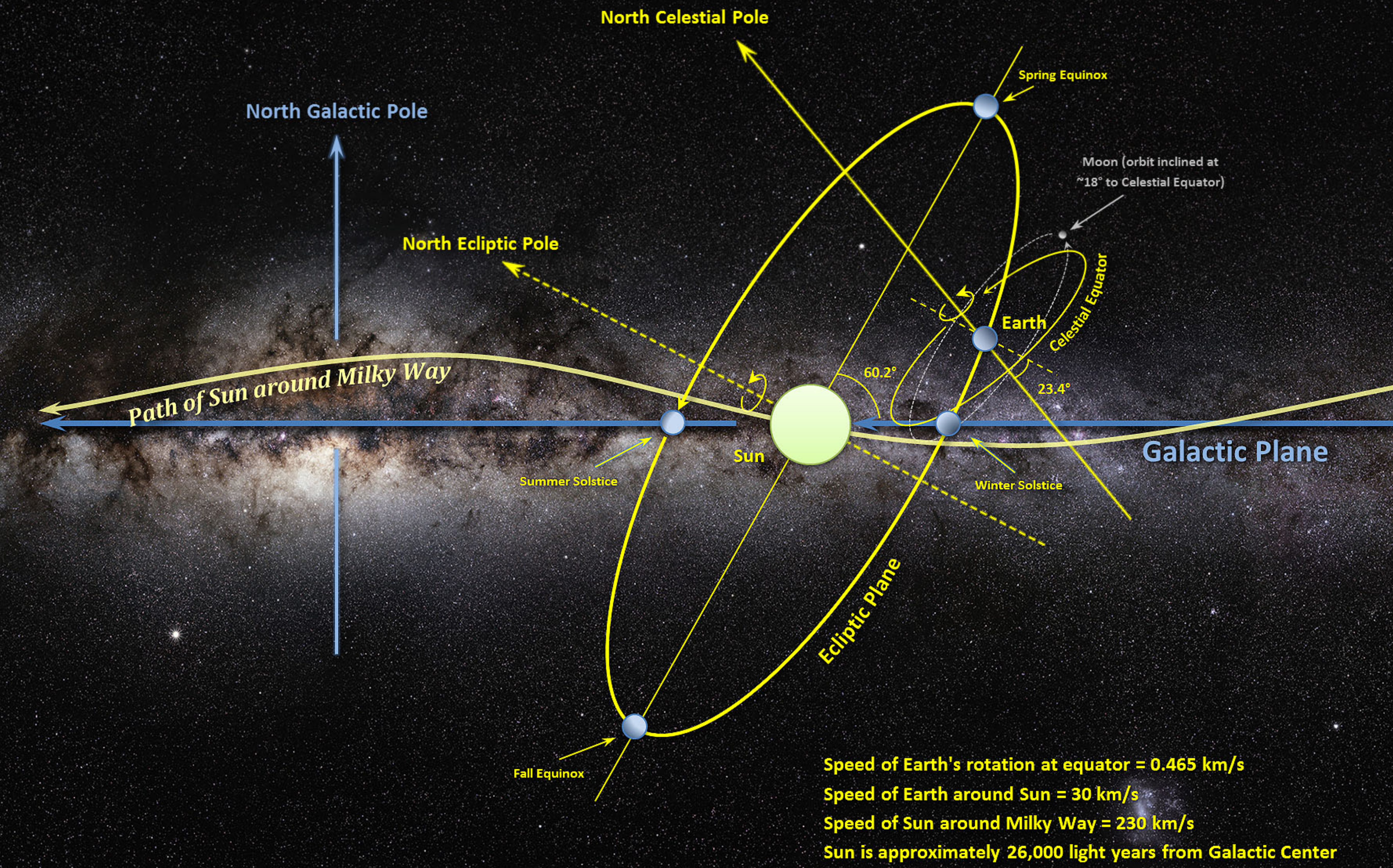
Lin Yuan Bi, arXiv:1409.6248

AMS-02 Dark Matter Constraints



JK arXiv:1304.1184

MOTION OF EARTH AND SUN AROUND THE MILKY WAY

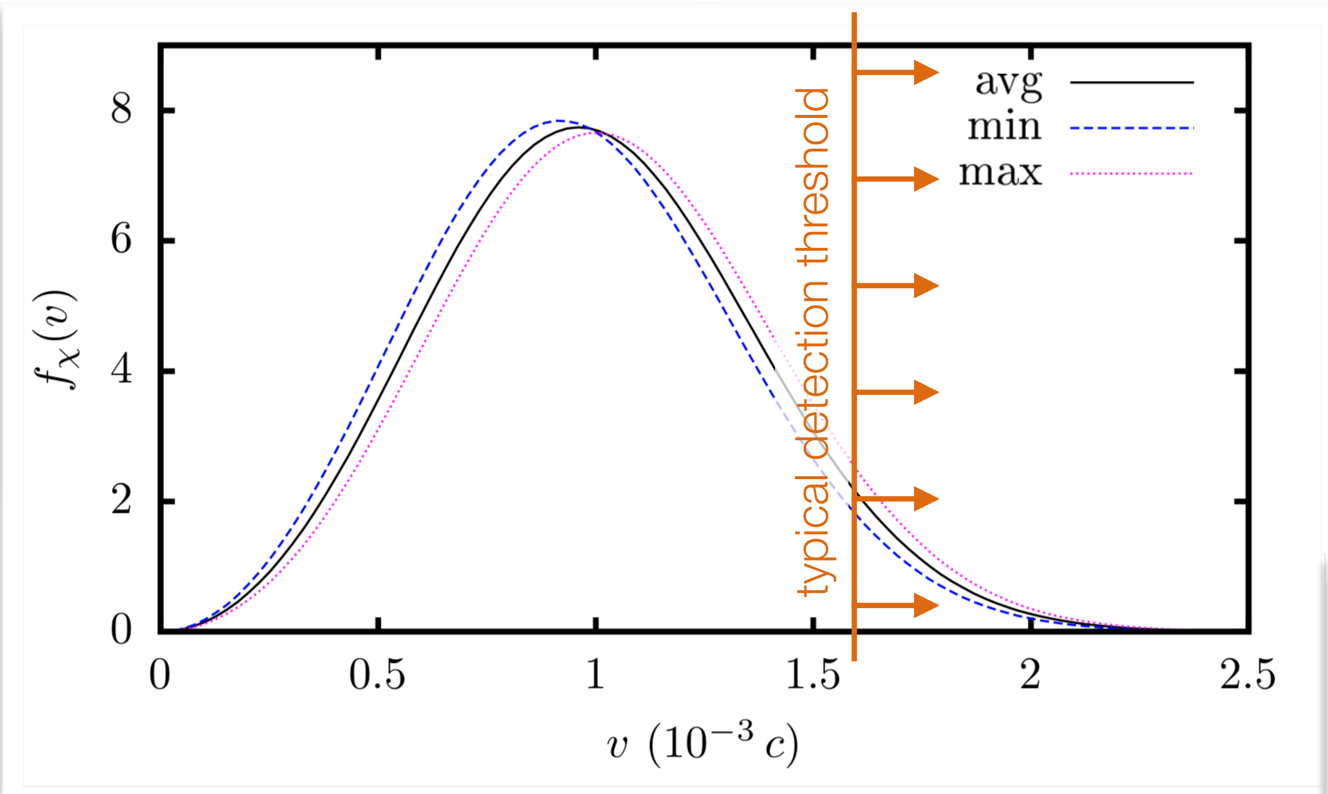


Source: Wikimedia Commons

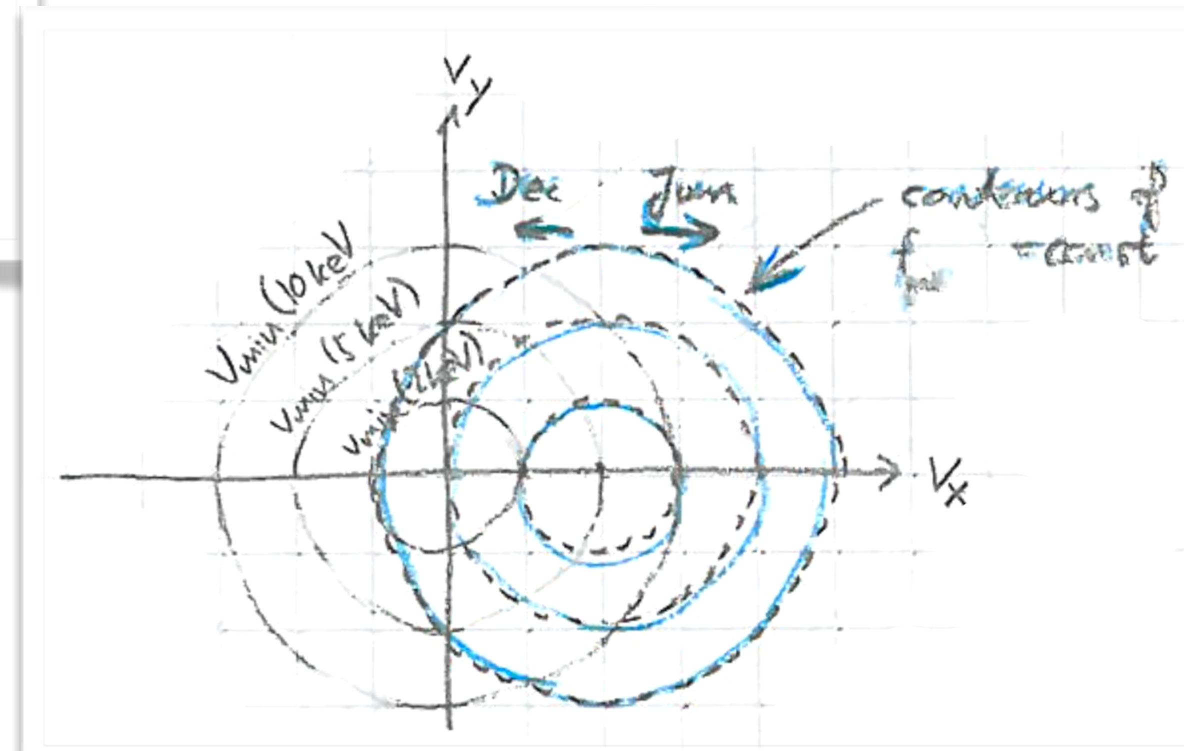
Diagram not to scale

Background Image Credit: ESO/S. Brunier

DM Velocity Distribution: Annual Modulation



Roberts *et al.* arXiv:1604.04559



Bonus Slides on PBHs

PBH Evaporation

- Hawking 1974: black holes emit thermal radiation at temperature $T_{\rm BH} = 1/(8\pi G_N M)$ (*"Hawking radiation"*)

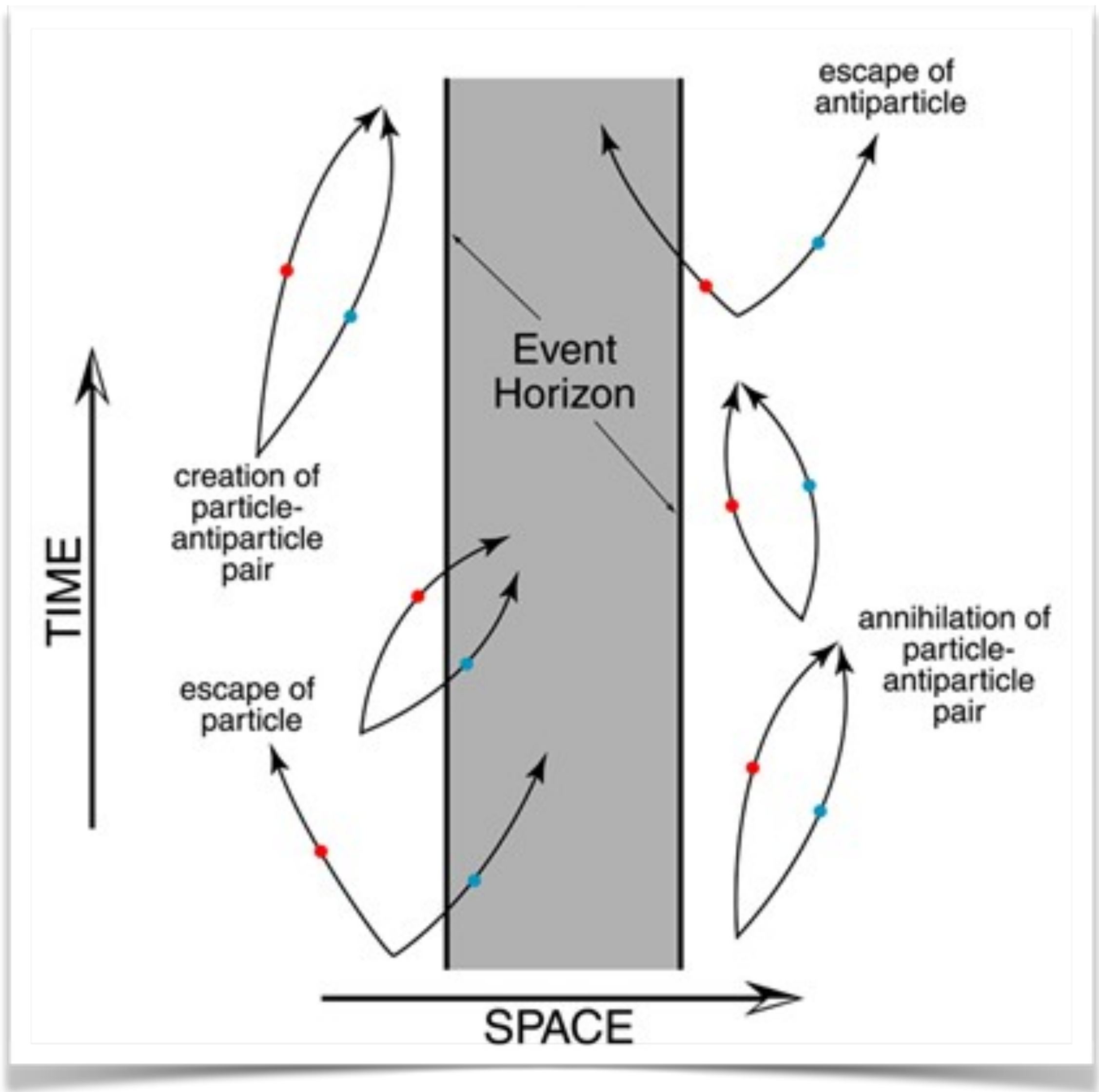


image by Stephen Dilorio

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- Mass loss per unit area per unit time (Stefan Boltzmann law):

$$\frac{dM_{\mathrm{BH}}}{dt\,dA} = \sigma T_{\mathrm{BH}}^4$$

- Consequently, they eventually evaporate.

$$\frac{dM_{\mathrm{BH}}}{dt} = \sigma T_{\mathrm{BH}}^4 \cdot 4\pi R^2 = \frac{1}{2^{10}\pi \cdot 15} \frac{1}{G_N^2 M^2}$$

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Stefan-Boltzmann constant:
$\sigma = \pi^2/60$

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Stefan-Boltzmann constant: $\sigma = \pi^2/60$

Schwarzschild radius $R = 2 G_N M$

PBH Evaporation

$$\frac{dM_{\rm BH}}{dt} = \sigma T_{\rm BH}^4 \cdot 4\pi R^2 = \frac{1}{2^{10}\pi \cdot 15} \frac{1}{G_N^2 M^2}$$

- Solve this differential equation by separation of variables

$$t = 5 \cdot 2^{10} \pi G_N^2 M^3 = 2 \times 10^{67}\,\text{yrs} \times \left(\frac{M}{M_\odot}\right)^3$$

- Conclusions:
  - PBH with mass $\lesssim 10^{-20} M_\odot$ have already evaporated
  - Even for somewhat larger masses (up to $10^{-16} M_\odot$), their Hawking radiation would contribute significantly to extragalactic background light

Gravitational Lensing: Formalism

- Starting from the Minkowski metric

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

we add a weak gravitational potential

$$\eta_{\mu\nu} \rightarrow g_{\mu\nu} = \begin{pmatrix} 1+\frac{2\Phi}{c^2} & 0 & 0 & 0 \\ 0 & -(1-\frac{2\Phi}{c^2}) & 0 & 0 \\ 0 & 0 & -(1-\frac{2\Phi}{c^2}) & \\ 0 & 0 & 0 & -(1-\frac{2\Phi}{c^2}) \end{pmatrix}$$

- Corresponding line element:

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \left(1+\frac{2\Phi}{c^2}\right) c^2 \mathrm{d}t^2 - \left(1-\frac{2\Phi}{c^2}\right) (\mathrm{d}\vec{x})^2$$

- Light travels along null geodesic (*ds* = 0):

$$\left(1+\frac{2\Phi}{c^2}\right) c^2 \mathrm{d}t^2 = \left(1-\frac{2\Phi}{c^2}\right) (\mathrm{d}\vec{x})^2$$

based on lecture notes by Massimo Meneghetti

Gravitational Lensing: Formalism

$$\left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2=\left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

- Speed of light in gravitational field

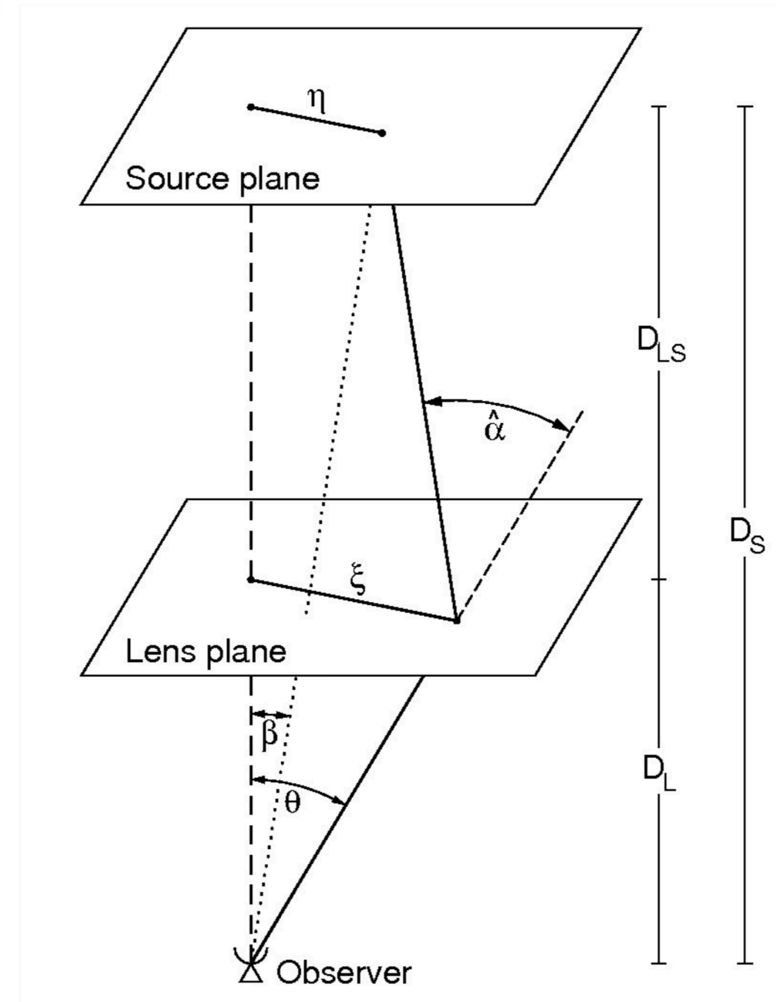
$$c'=\frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t}=c\sqrt{\frac{1+\frac{2\Phi}{c^2}}{1-\frac{2\Phi}{c^2}}}\approx c\left(1+\frac{2\Phi}{c^2}\right)$$

- Corresponding index of refraction

$$n=c/c'=\frac{1}{1+\frac{2\Phi}{c^2}}\approx 1-\frac{2\Phi}{c^2}$$

- Light travel time is increased by

$$\Delta t_{\mathrm{grav}}=\int_S^O\frac{dl}{c}\,n[\vec{x}(l)]=\int_S^O\frac{dl}{c}\,\frac{2G_NM}{c^2\sqrt{l^2+\xi^2}}\simeq-\frac{4G_NM}{c^2}\log\theta$$



based on lecture notes by Massimo Meneghetti

Gravitational Lensing: Formalism

$$\left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 = \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

- ☑ Speed of light in gravitational field

$$c' = \frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t} = c\sqrt{\frac{1+\frac{2\Phi}{c^2}}{1-\frac{2\Phi}{c^2}}} \approx c\left(1+\frac{2\Phi}{c^2}\right)$$

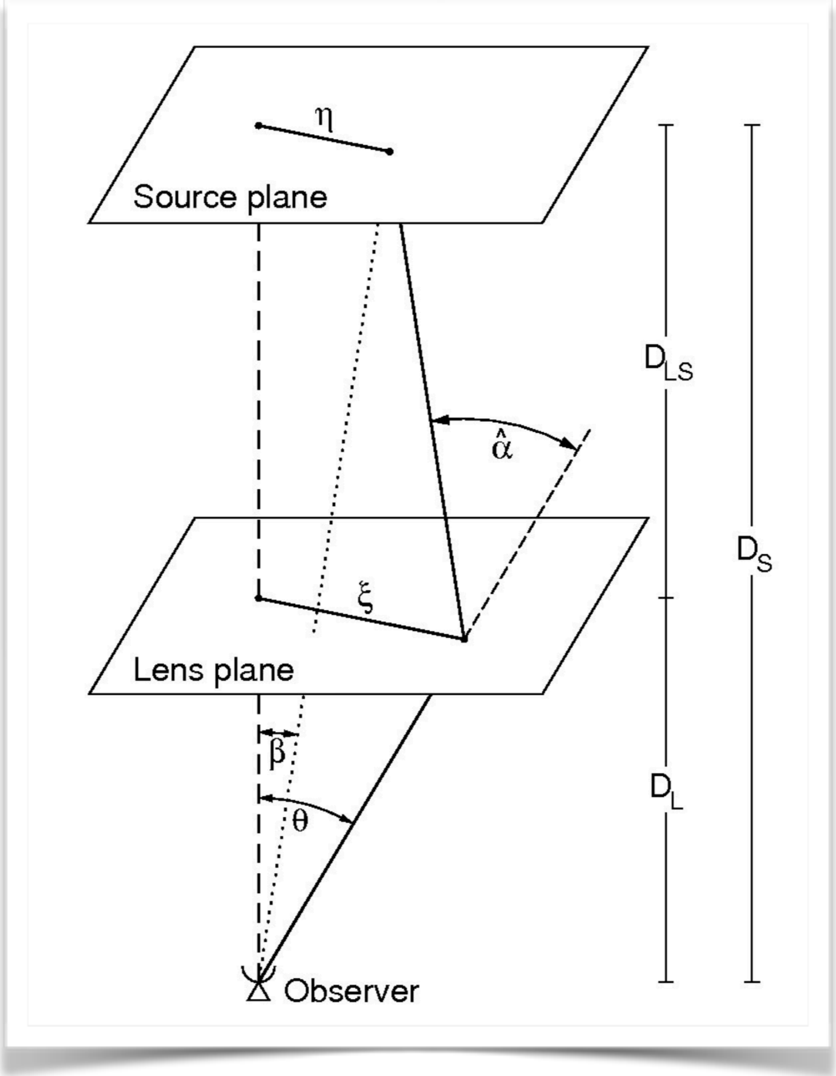
- ☑ Corresponding index of refraction

$$n = c/c' = \frac{1}{1+\frac{2\Phi}{c^2}} \approx 1-\frac{2\Phi}{c^2}$$

- ☑ Light travel time is increased by

$$\Delta t_{\rm grav} = \int_S^O \frac{dl}{c}\, n[\vec{x}(l)] = \int_S^O \frac{dl}{c}\frac{2G_N M}{c^2\sqrt{l^2+\xi^2}} \simeq -\frac{4G_N M}{c^2}\log\theta$$

Integral from source to observer



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Gravitational Lensing: Formalism

$$\left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 = \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

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$$c' = \frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t} = c\sqrt{\frac{1+\frac{2\Phi}{c^2}}{1-\frac{2\Phi}{c^2}}} \approx c\left(1+\frac{2\Phi}{c^2}\right)$$

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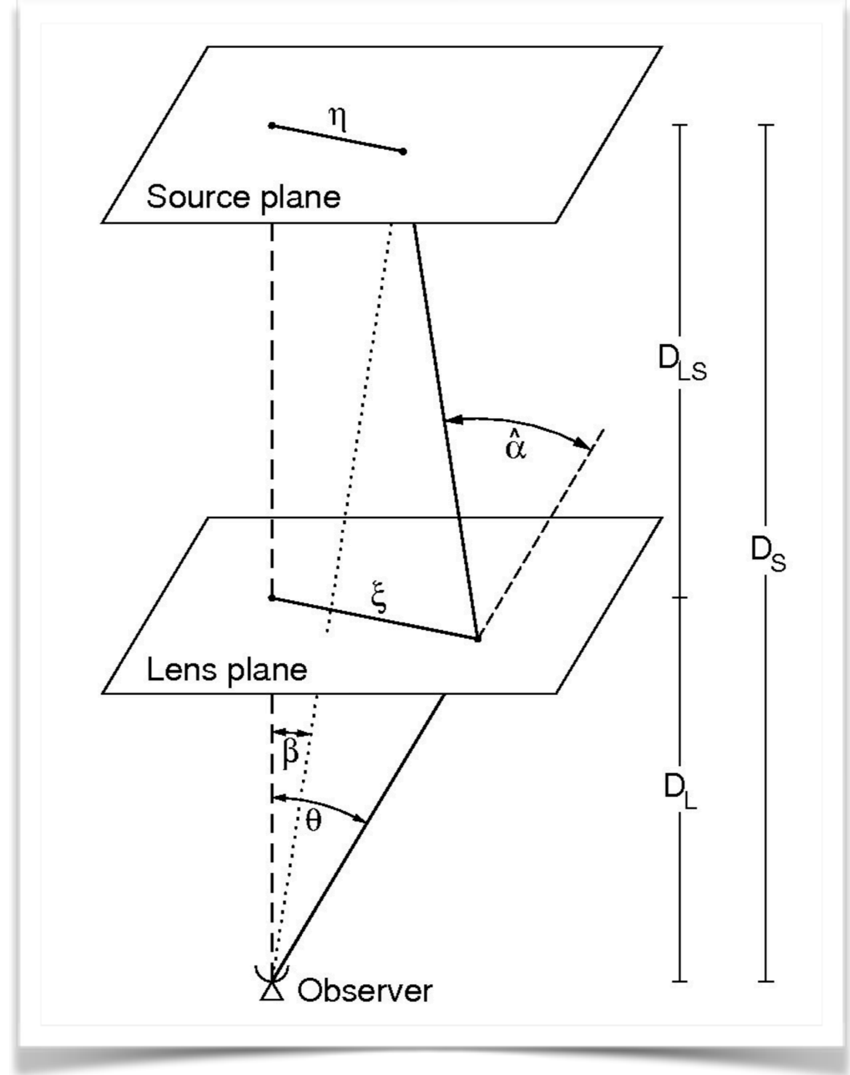
Integral from source to observer

Impact parameter (min. distance to lens)



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Gravitational Lensing: Formalism

$$\left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 = \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

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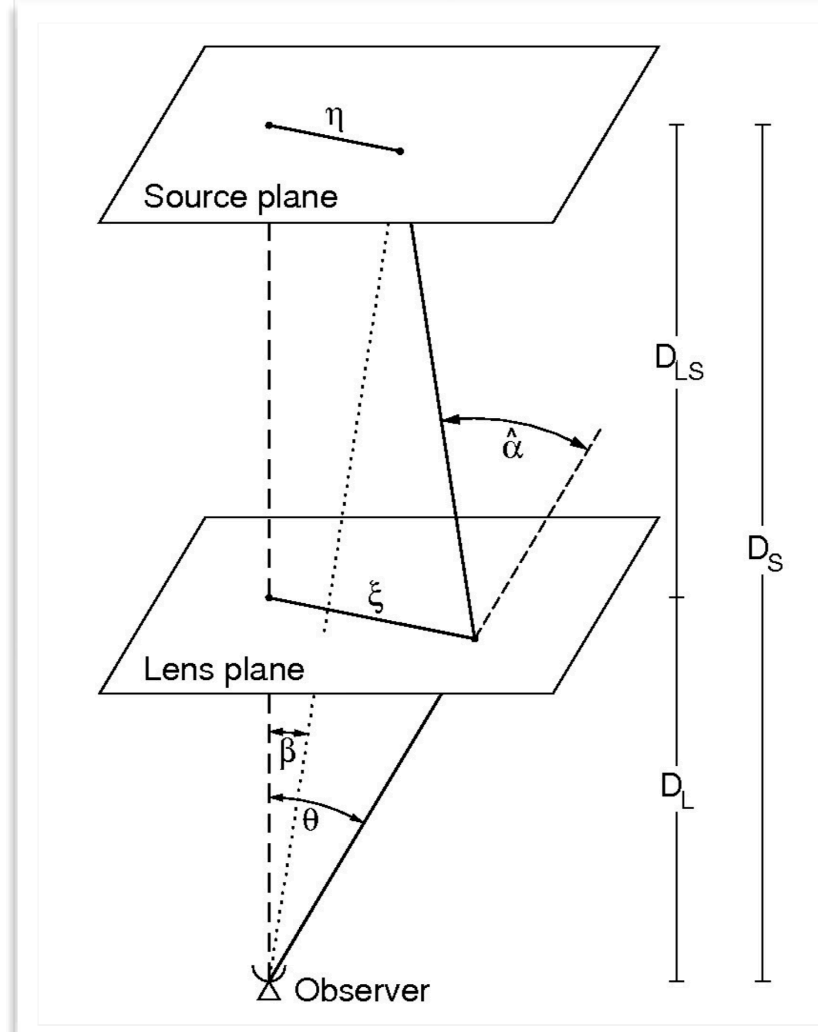


Integral from source to observer

Impact parameter (min. distance to lens)

lensing angle $\theta = \xi/D_S$

based on lecture notes by Massimo Meneghetti

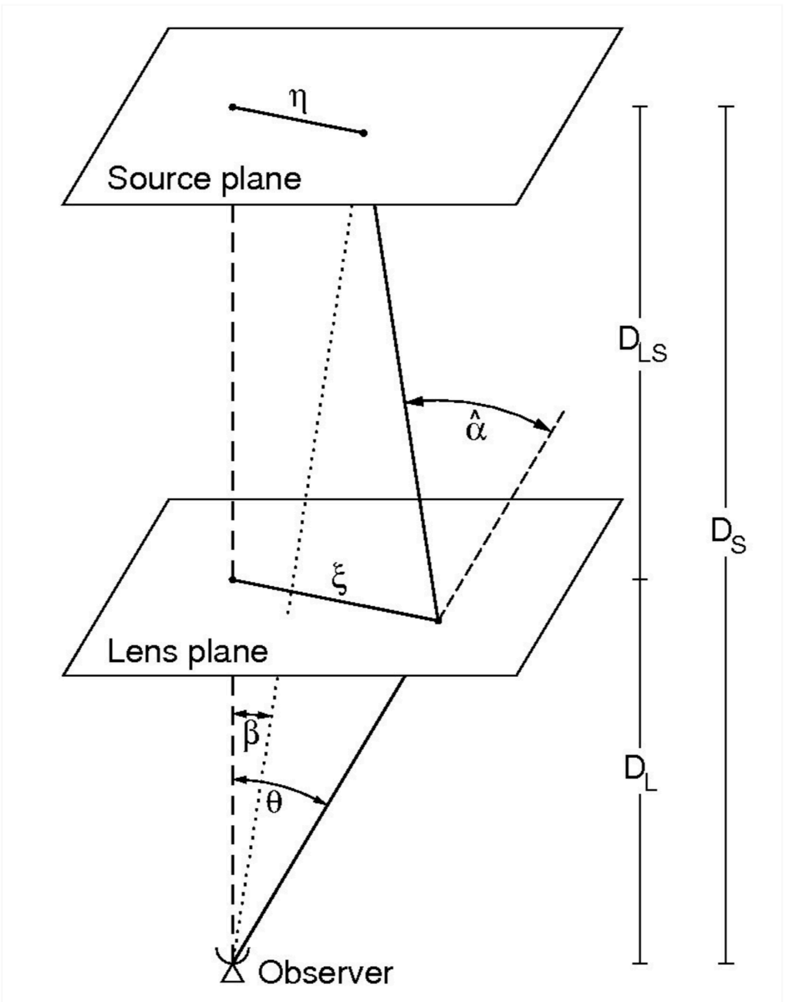
Gravitational Lensing: Formalism

- In addition: geometric time delay

$$\Delta t_{\text{geom}} = \left[\frac{D_L}{c\,\cos(\theta-\beta)} - D_L\right] + \left[\frac{D_{LS}}{c\,\cos[(\theta-\beta)D_L/D_{LS}]} - D_{LS}\right]$$
$$\simeq \frac{D_L}{2c}(\theta-\beta)^2 + \frac{D_{LS}}{2c}\frac{(\theta-\beta)^2 D_L^2}{D_{LS}^2}$$
$$= \frac{D_L D_S}{2cD_{LS}}(\theta-\beta)^2$$

- Overall:

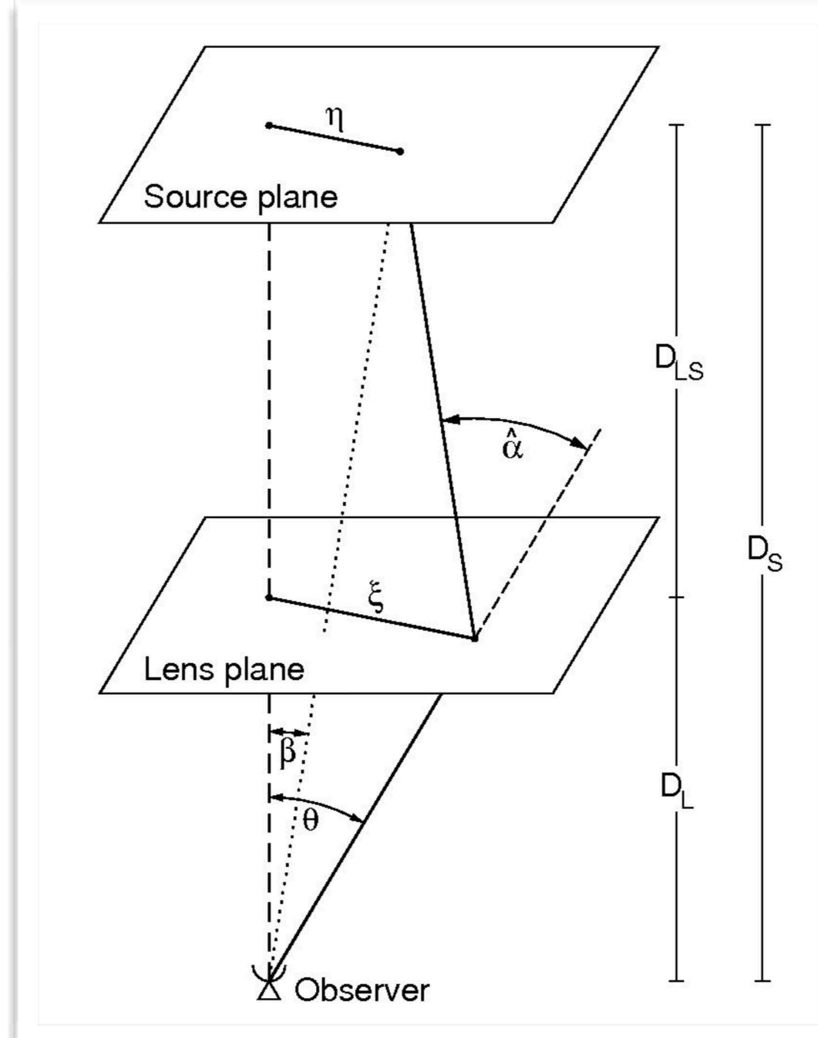
$$\Delta t = \frac{D_L D_S}{cD_{LS}}\left[\frac{(\theta-\beta)^2}{2} - \frac{4G_N M D_{LS}}{c^2 D_L D_S}\log\theta\right]$$



Gravitational Lensing: Formalism

- In addition: geometric time delay

$$\begin{aligned}\Delta t_{\text{geom}} &= \left[\frac{D_L}{c\,\cos(\theta-\beta)} - D_L\right] + \left[\frac{D_{LS}}{c\,\cos[(\theta-\beta)D_L/D_{LS}]} - D_{LS}\right] \\ &\simeq \frac{D_L}{2c}(\theta-\beta)^2 + \frac{D_{LS}}{2c}\frac{(\theta-\beta)^2 D_L^2}{D_{LS}^2} \\ &= \frac{D_L D_S}{2cD_{LS}}(\theta-\beta)^2\end{aligned}$$



- Overall:

$$\Delta t = \frac{D_L D_S}{cD_{LS}}\left[\frac{(\theta-\beta)^2}{2} - \frac{4G_N M D_{LS}}{c^2 D_L D_S}\log\theta\right]$$

Square of the **Einstein angle**:

$$\theta_E^2 \equiv \frac{4G_N M D_{LS}}{c^2 D_L D_S}$$

Gravitational Lensing: Formalism

$$\Delta t = \frac{D_L D_S}{c D_{LS}} \left[\frac{(\theta - \beta)^2}{2} - \frac{4 G_N M D_{LS}}{c^2 D_L D_S} \log \theta \right]$$

- Light waves travelling from the source to the observer along different paths (different θ) acquire different phase: $e^{i\omega\Delta t}$.
- Fermat's principle: if $\omega \Delta t \gg 1$, contributions with different θ will interfere destructively, except at stationary points of Δt.

$$\frac{d\,\Delta t}{d\theta} = \frac{D_L D_S}{c\, D_{LS}} \left[(\theta - \beta) - \frac{\theta_E^2}{\theta} \right] \stackrel{!}{=} 0$$

- Leads to the lens equation:

$$\theta - \beta = \frac{\theta_E^2}{\theta}$$

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Gravitational Lensing: Formalism

$$\theta - \beta = \frac{\theta_E^2}{\theta}$$

- The solutions are the angular positions of the lensed images

$$\theta_{\pm} = \frac{1}{2}\left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2}\right)$$

- We see that the Einstein angle is a measure for the angular deviation between the lensed and (hypothetical) unlensed images. This interpretation is exact for **β** = 0 (lens along the line of sight).

- One can also compute the magnification (intensity relative to the unperturbed source) of the two images:

$$\mu_{\pm} = \frac{y^2 + 2}{2y\sqrt{y^2 + 4}} \pm \frac{1}{2} \qquad \text{with} \qquad y \equiv \beta/\theta_E$$

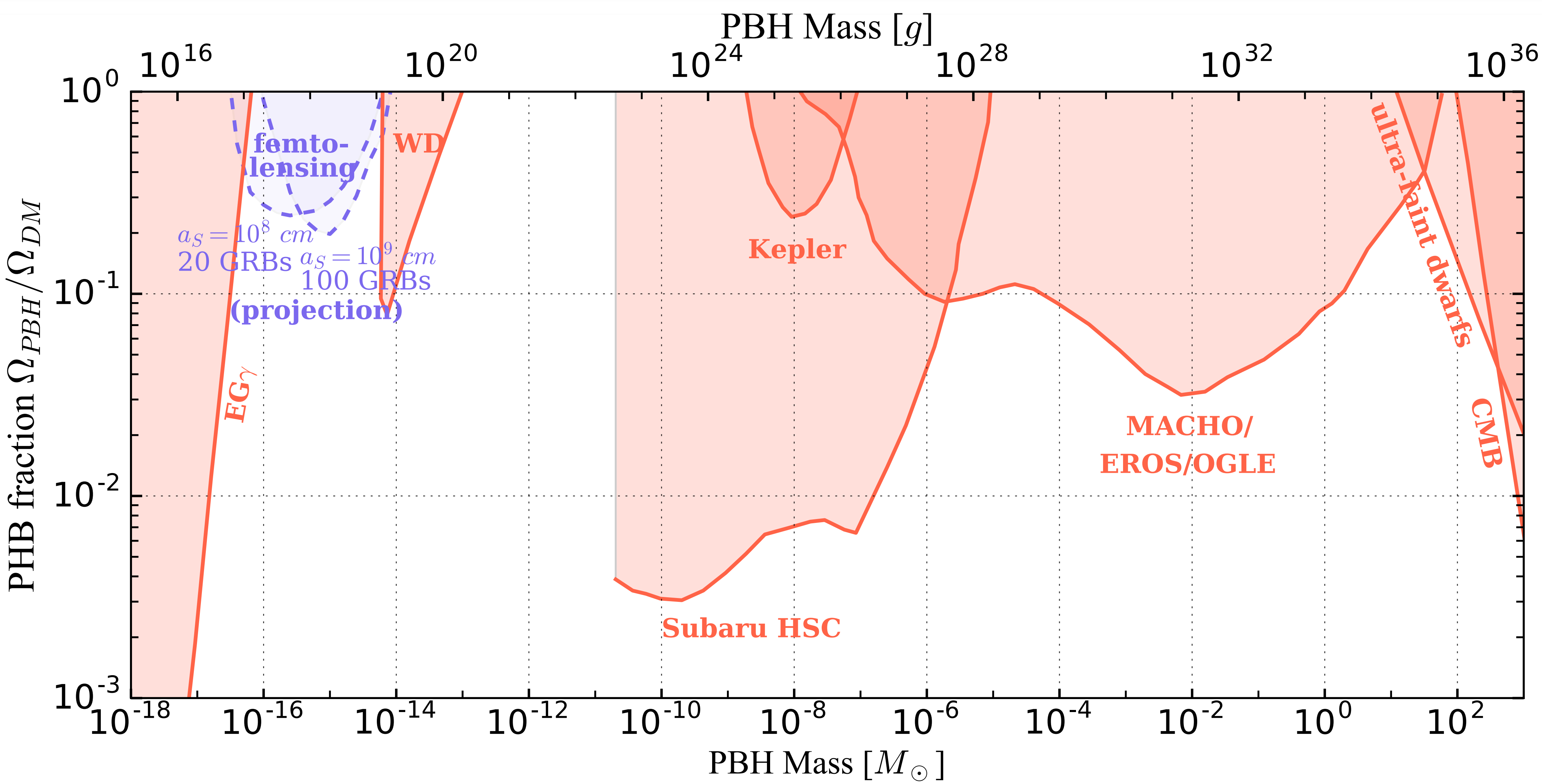
Microlensing

- For a 1 $M_\odot$ lens at $\mathcal{O}$(kpc) distance (typical scale within the Milky Way):
  $\theta_E \sim 0.003$ arcsec
- For comparison:
  angular resolution of the Hubble telescope: 0.05 arcsec
- However: can still observe overall brightening of the source

$$\mu_\pm = \frac{y^2+2}{2y\sqrt{y^2+4}} \pm \frac{1}{2} \quad \Rightarrow \text{total magnification:} \quad \mu = \frac{y^2+2}{y\sqrt{y^2+4}}$$

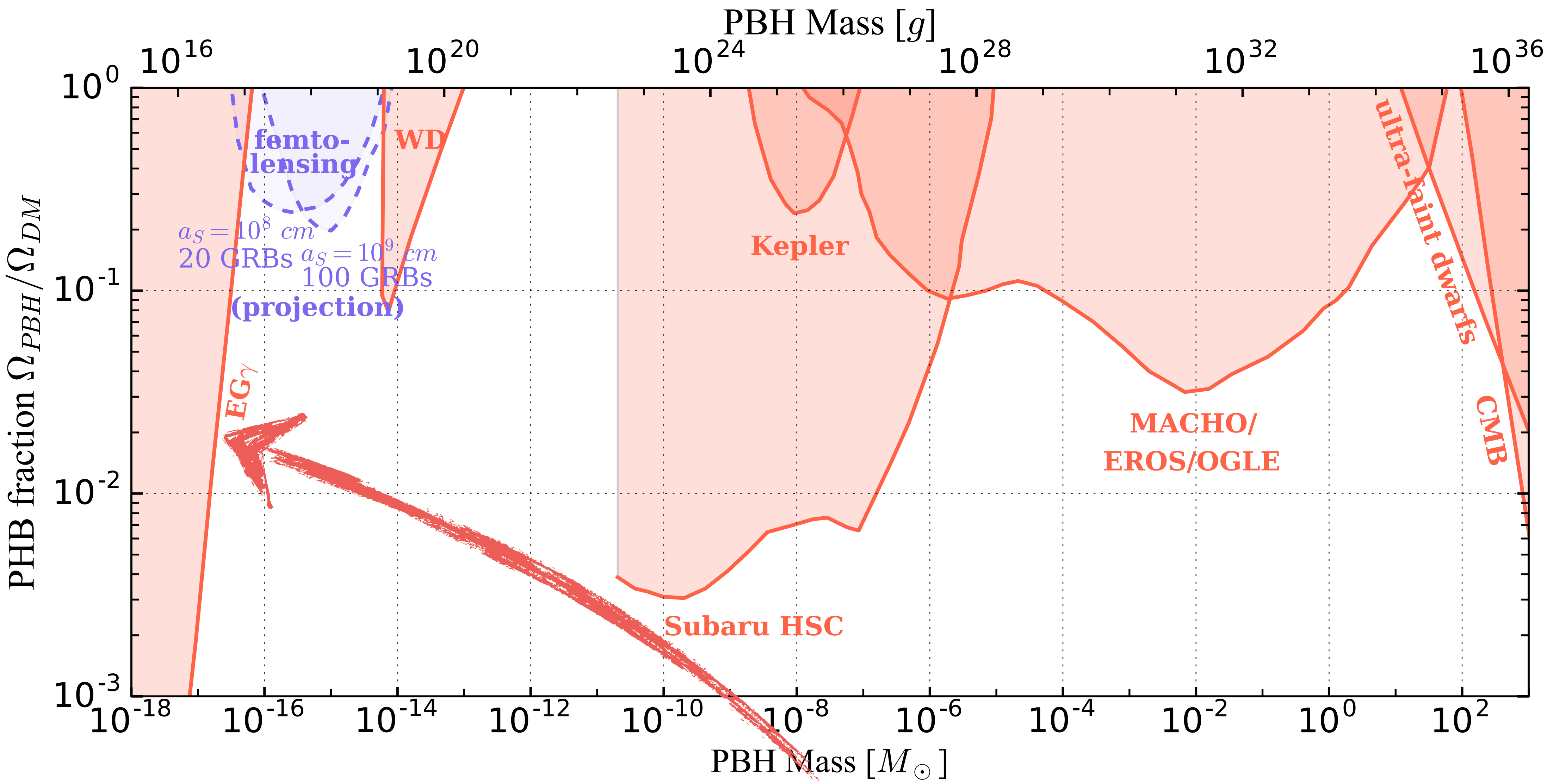
- This effect is called microlensing.
- Observable because of time dependence: a PBH passing in front of a background star leads to transient magnification of that star.

PBH Parameter Space



Katz JK Sibiryakov Xue
arXiv:1807.11495

PBH Parameter Space



Katz JK Sibiryakov Xue
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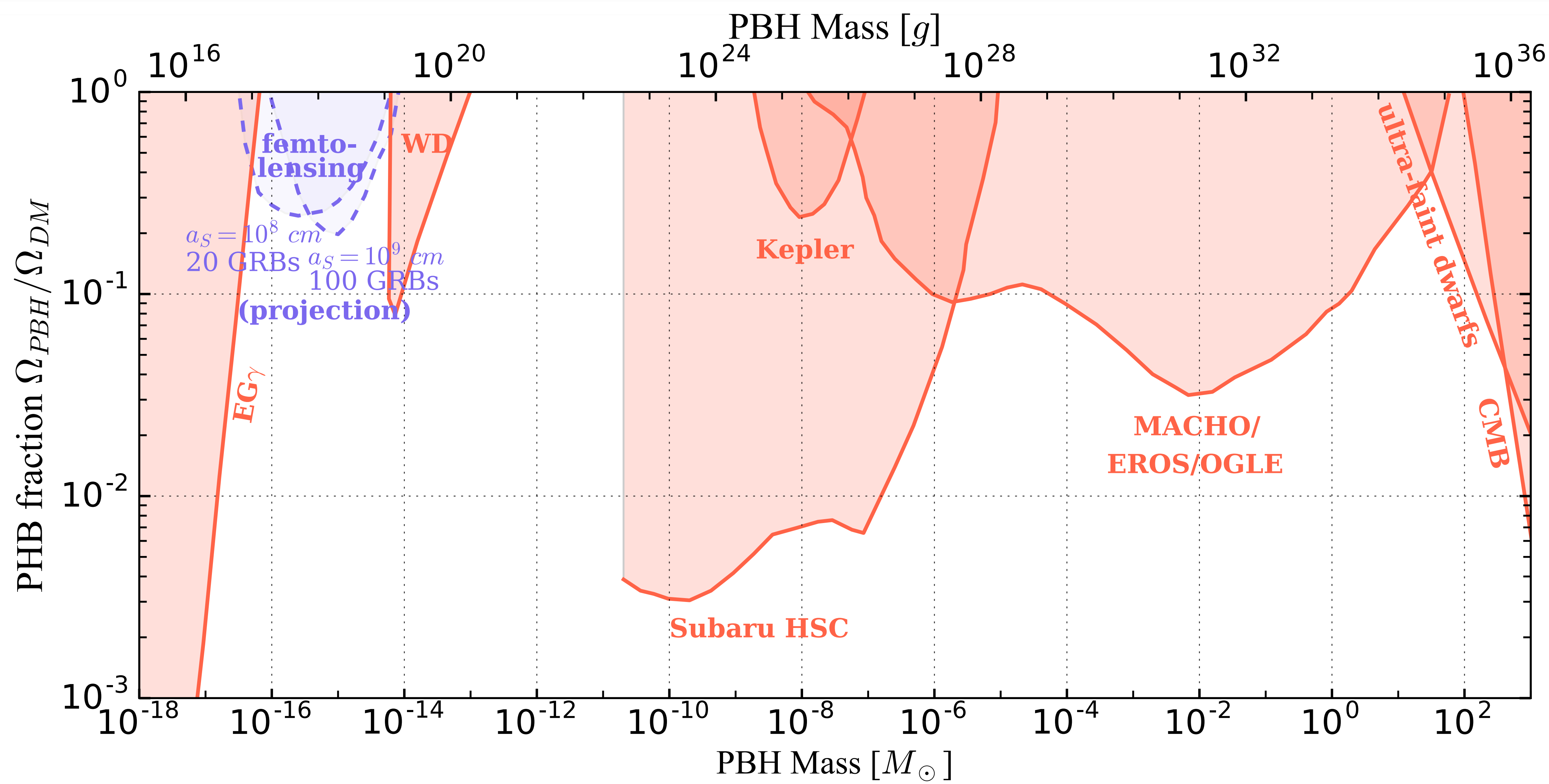
Extragalactic background light
constraint on Hawking radiation
from PBH evaporation

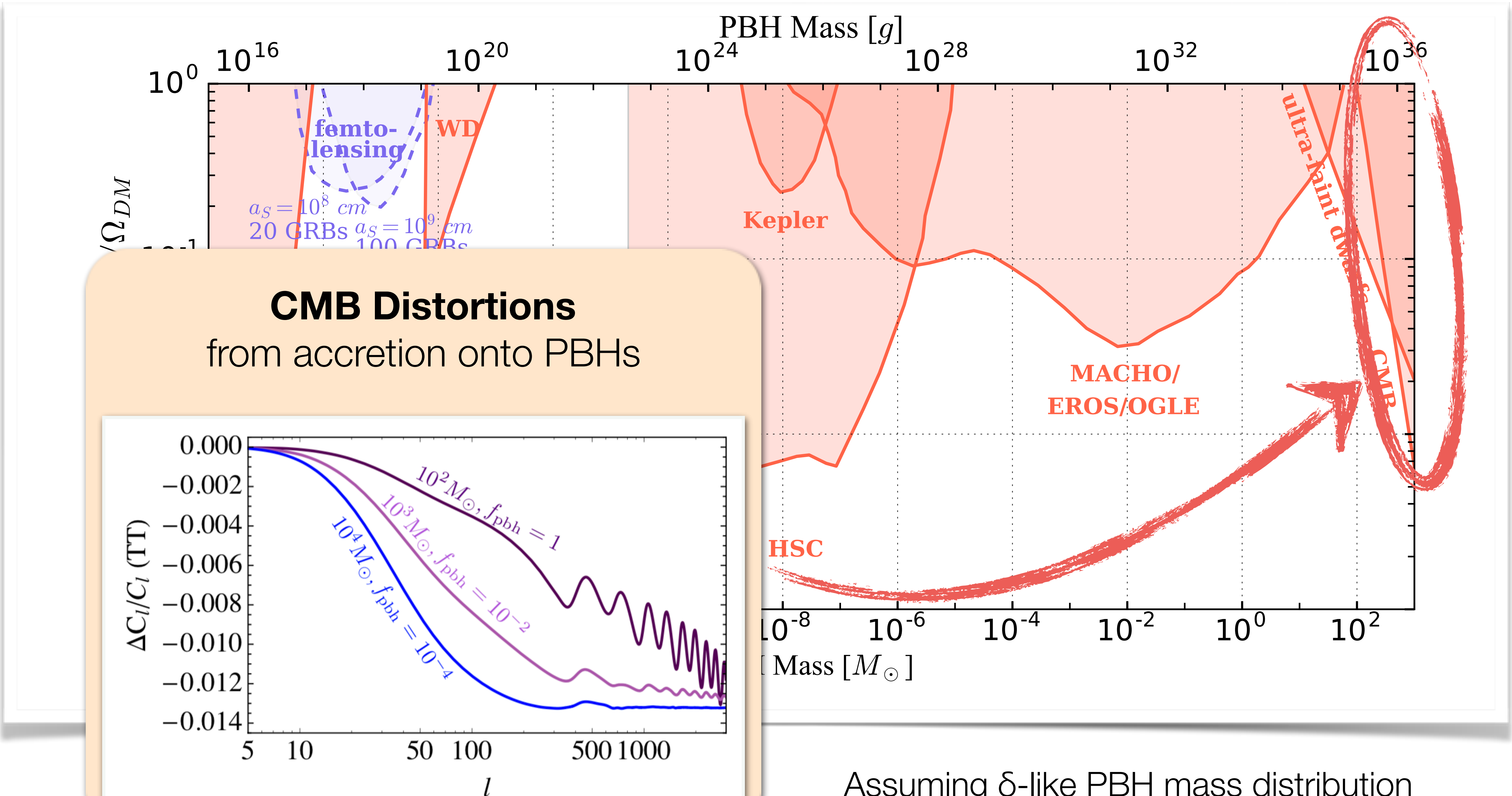
PBH Parameter Space



Assuming δ-like PBH mass distribution

PBH Parameter Space

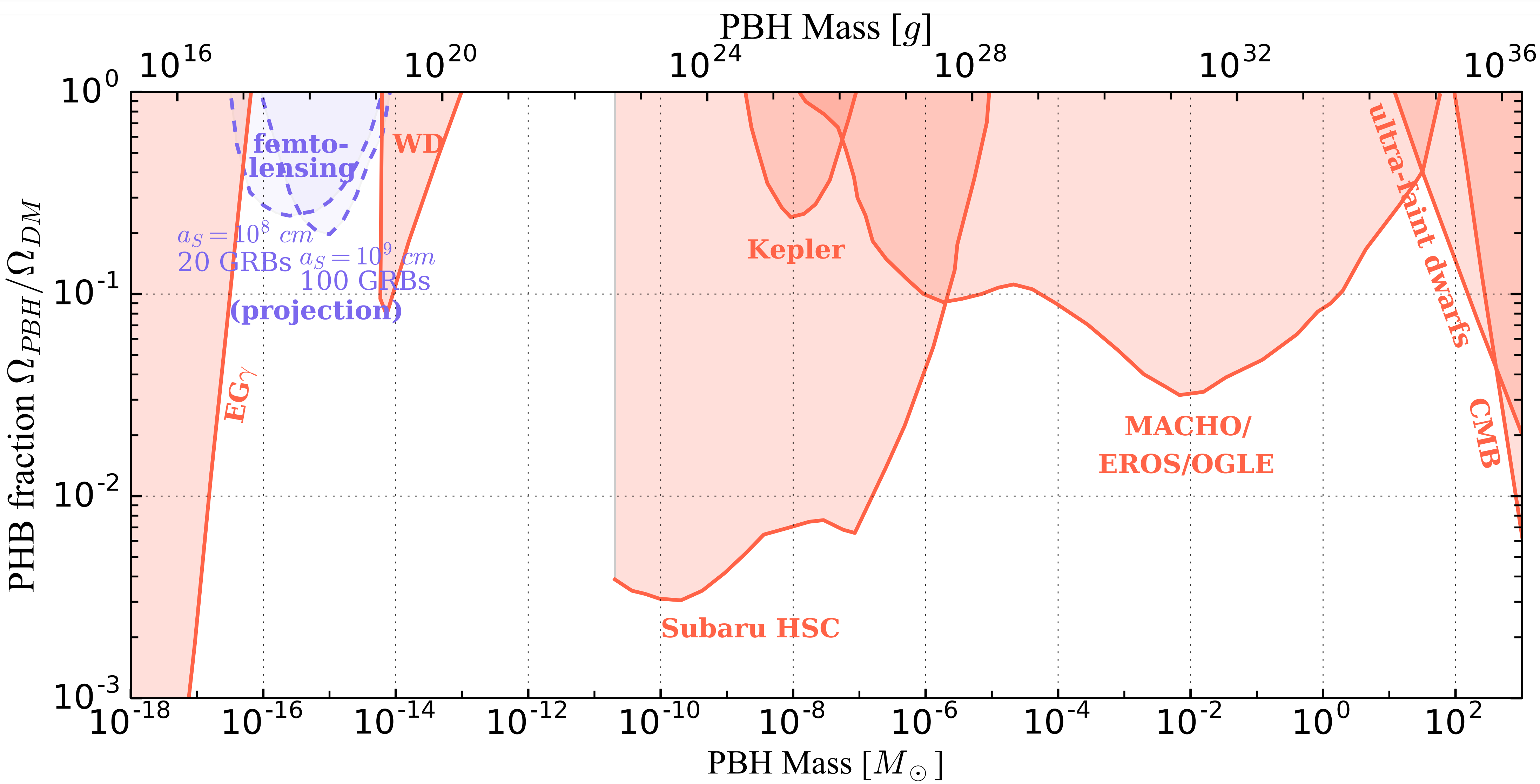
Ali-Haïmoud Kamionkowski arXiv:1612.05644



CMB Distortions
from accretion onto PBHs

Assuming δ-like PBH mass distribution

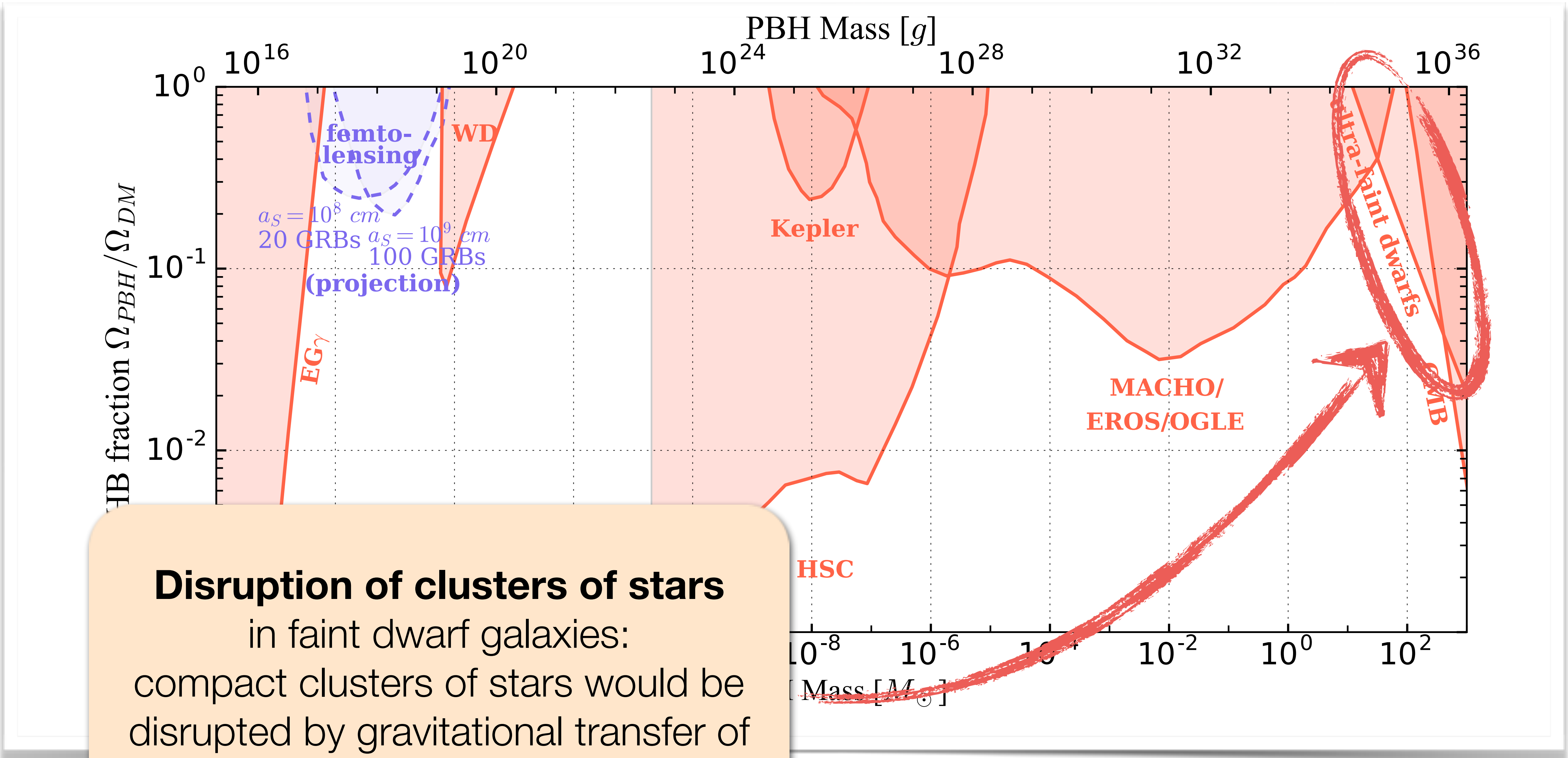
PBH Parameter Space



Assuming δ-like PBH mass distribution

PBH Parameter Space

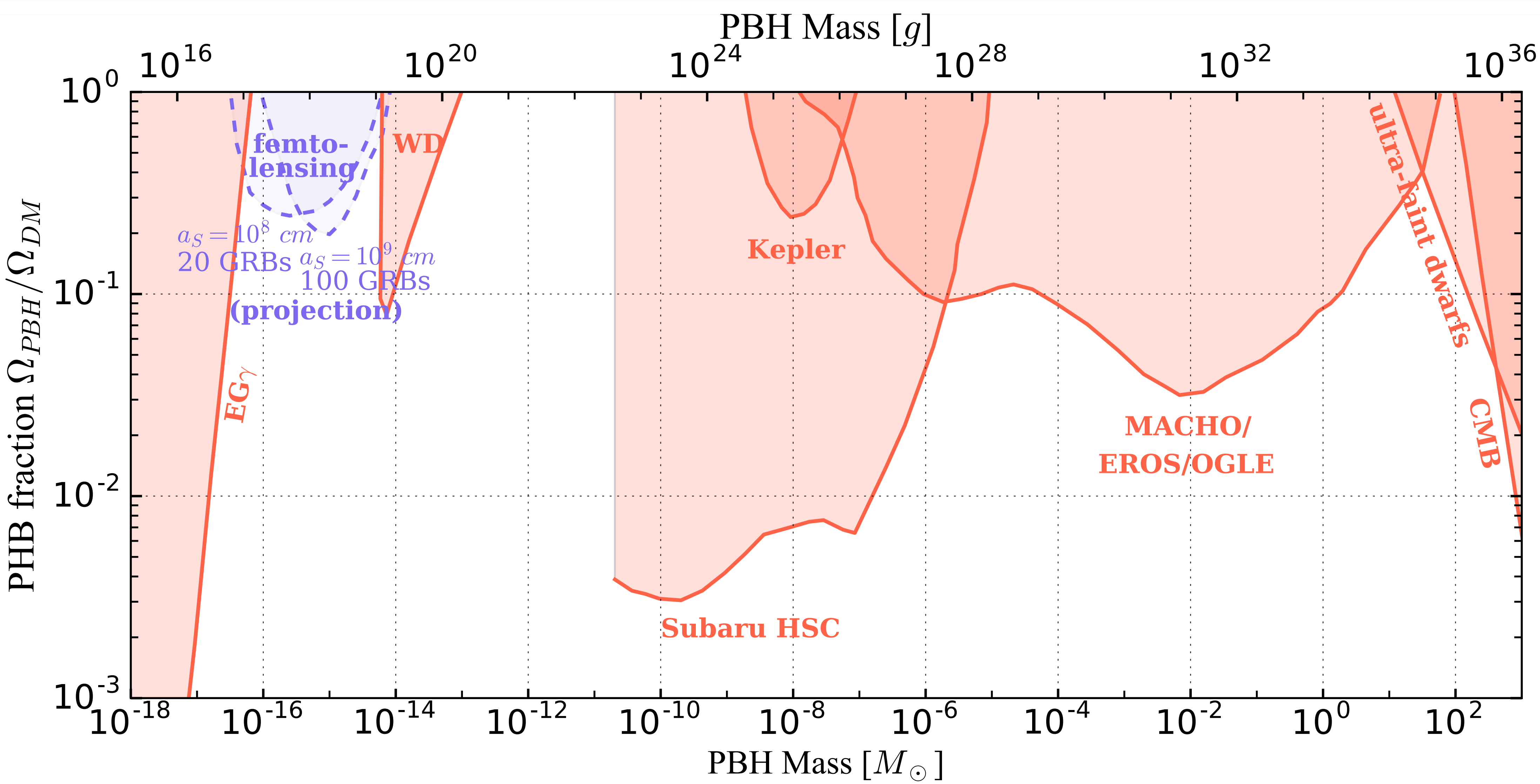
Brandt arXiv:1605.03665



Disruption of clusters of stars
in faint dwarf galaxies:
compact clusters of stars would be disrupted by gravitational transfer of kinetic energy from massive PBHs.

Assuming δ-like PBH mass distribution

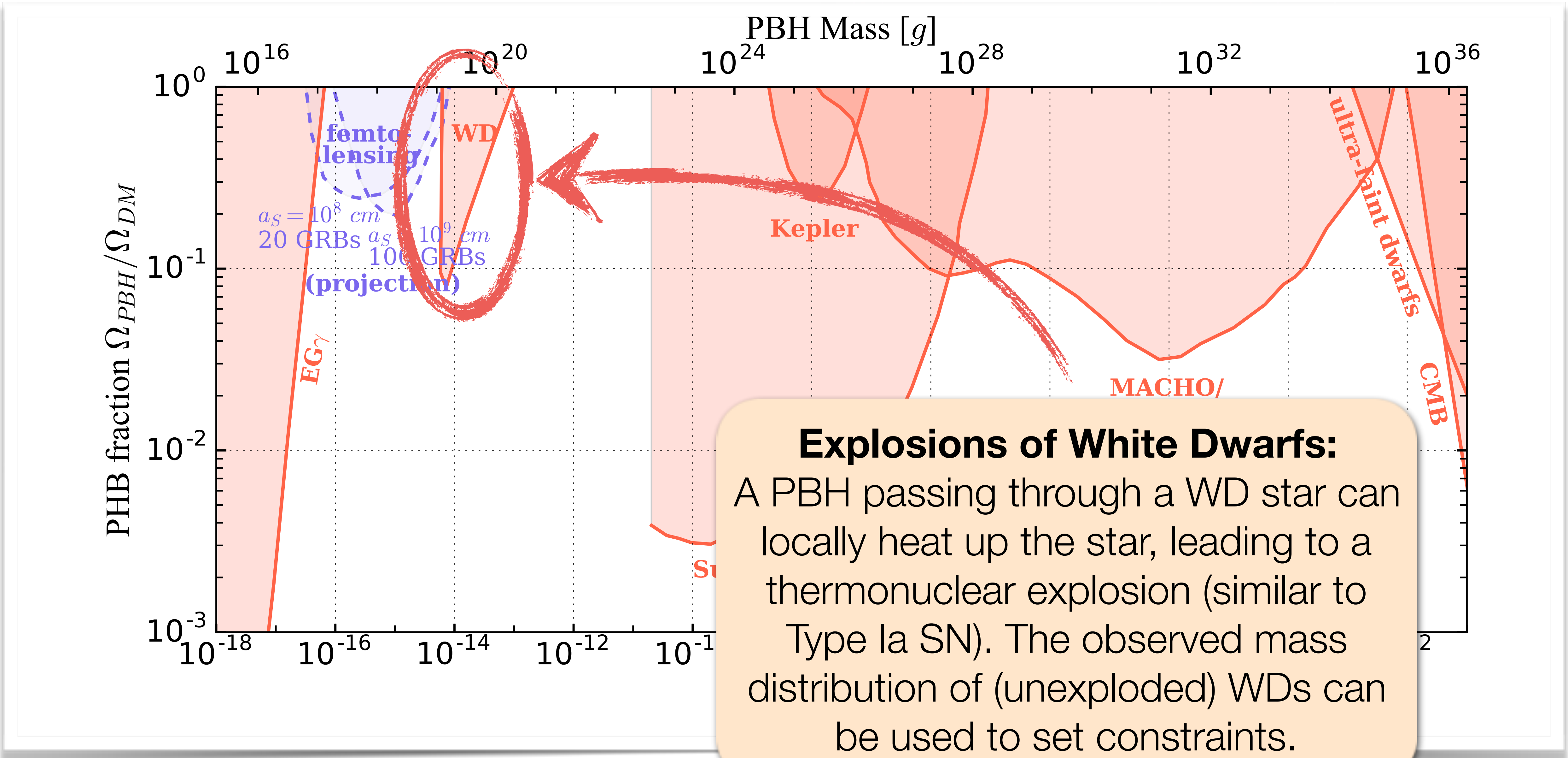
PBH Parameter Space



Assuming δ-like PBH mass distribution

PBH Parameter Space

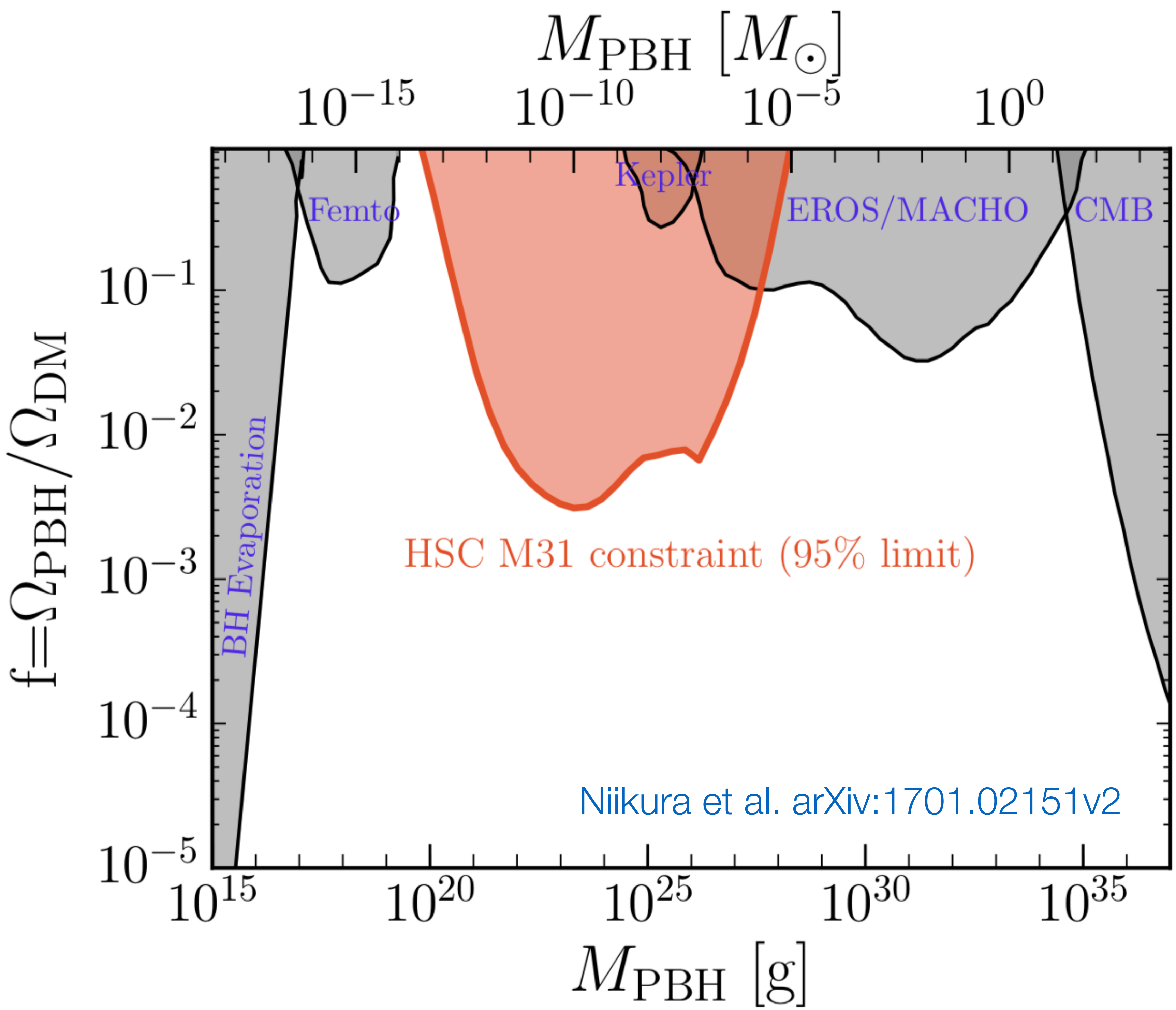
Graham Rajendran Veral arXiv:1505.04444



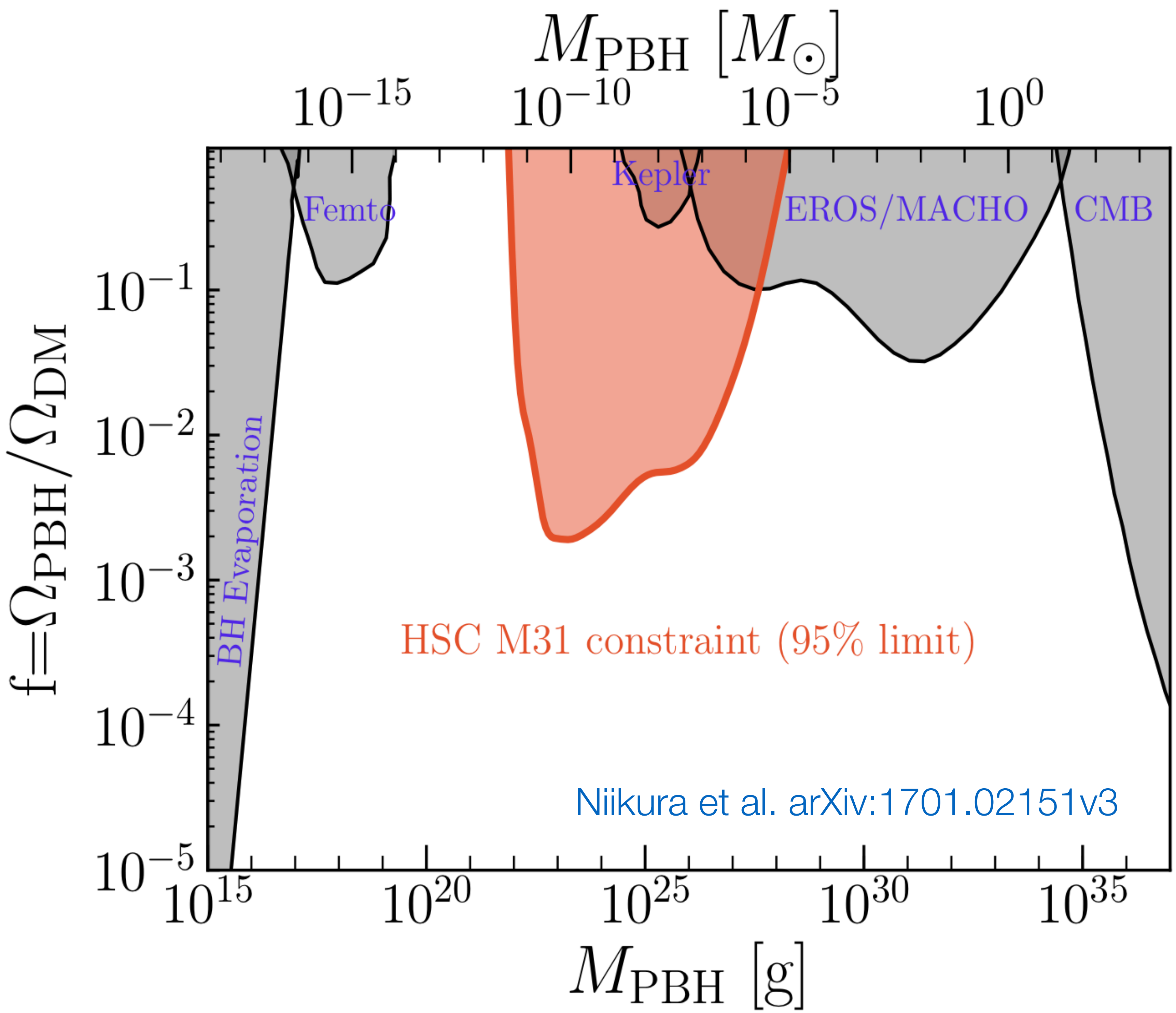
Explosions of White Dwarfs:
A PBH passing through a WD star can locally heat up the star, leading to a thermonuclear explosion (similar to Type Ia SN). The observed mass distribution of (unexploded) WDs can be used to set constraints.

Assuming δ-like PBH mass distribution

Effect of Wave Optics + Finite Source Size



Effect of Wave Optics + Finite Source Size



Time Delay (Geometric Optics)

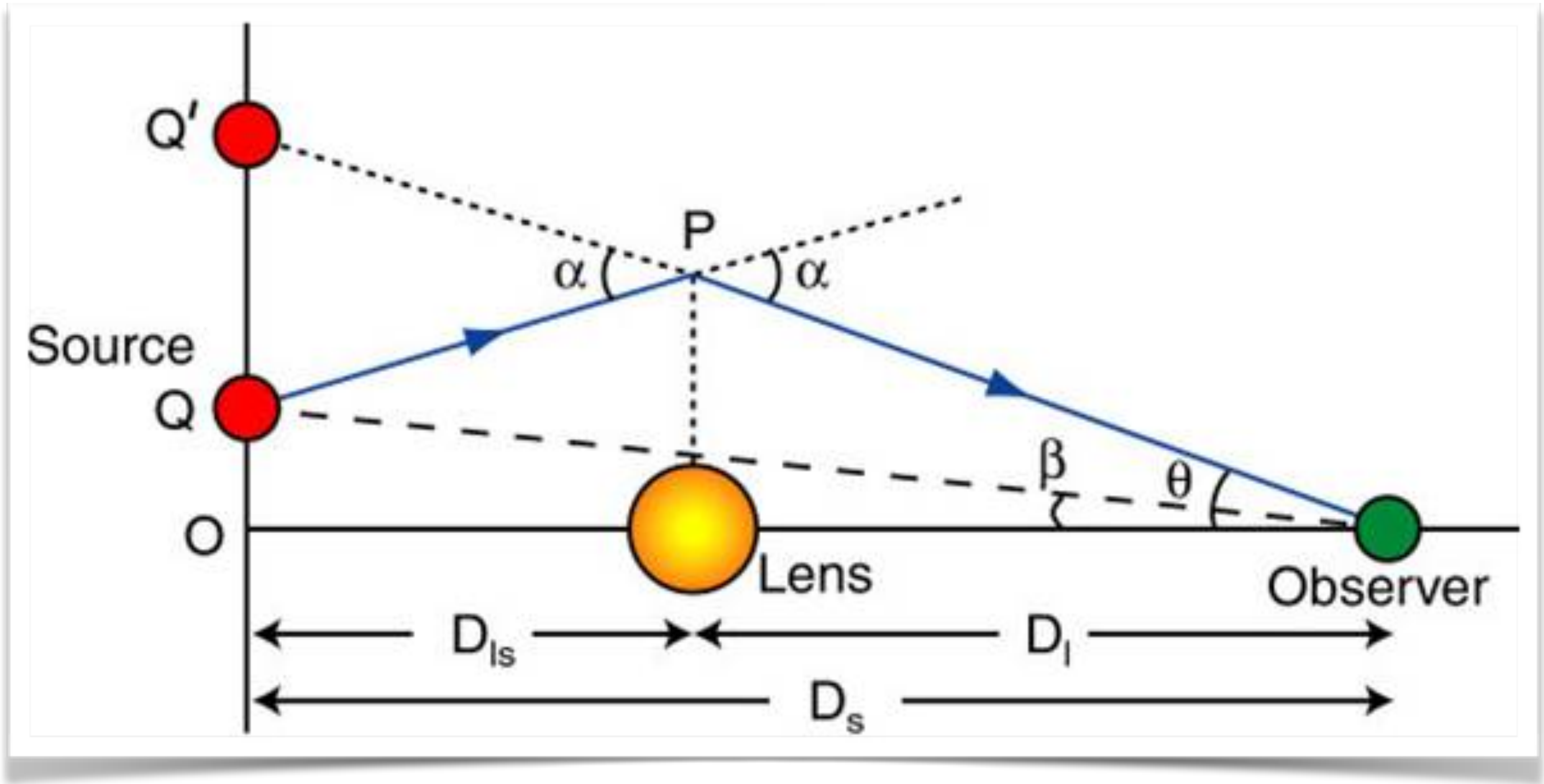
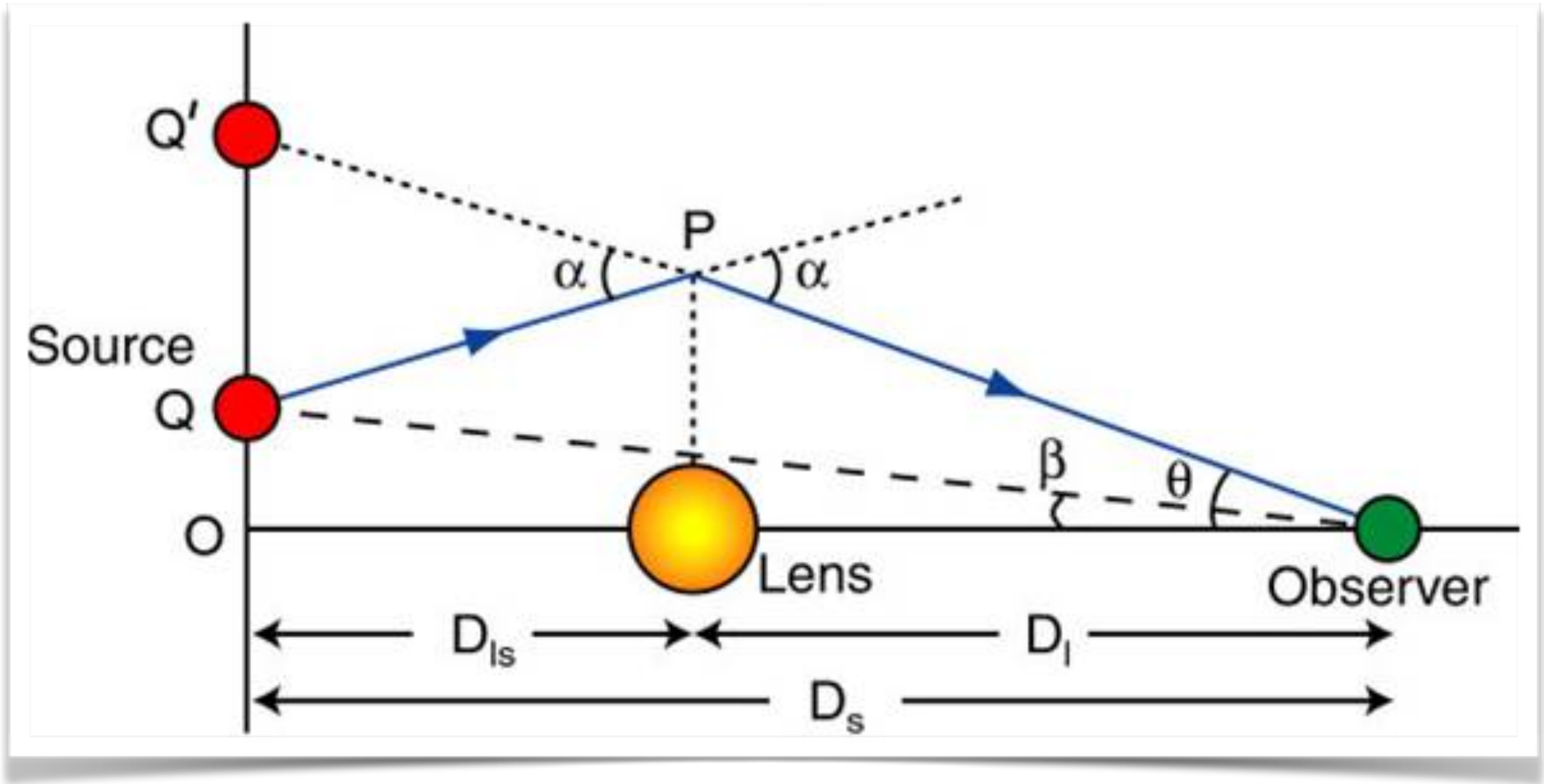


Image: University of Manchester

Time Delay:

$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

Time Delay (Geometric Optics)



niversity of Manchester

Geometric Time Delay

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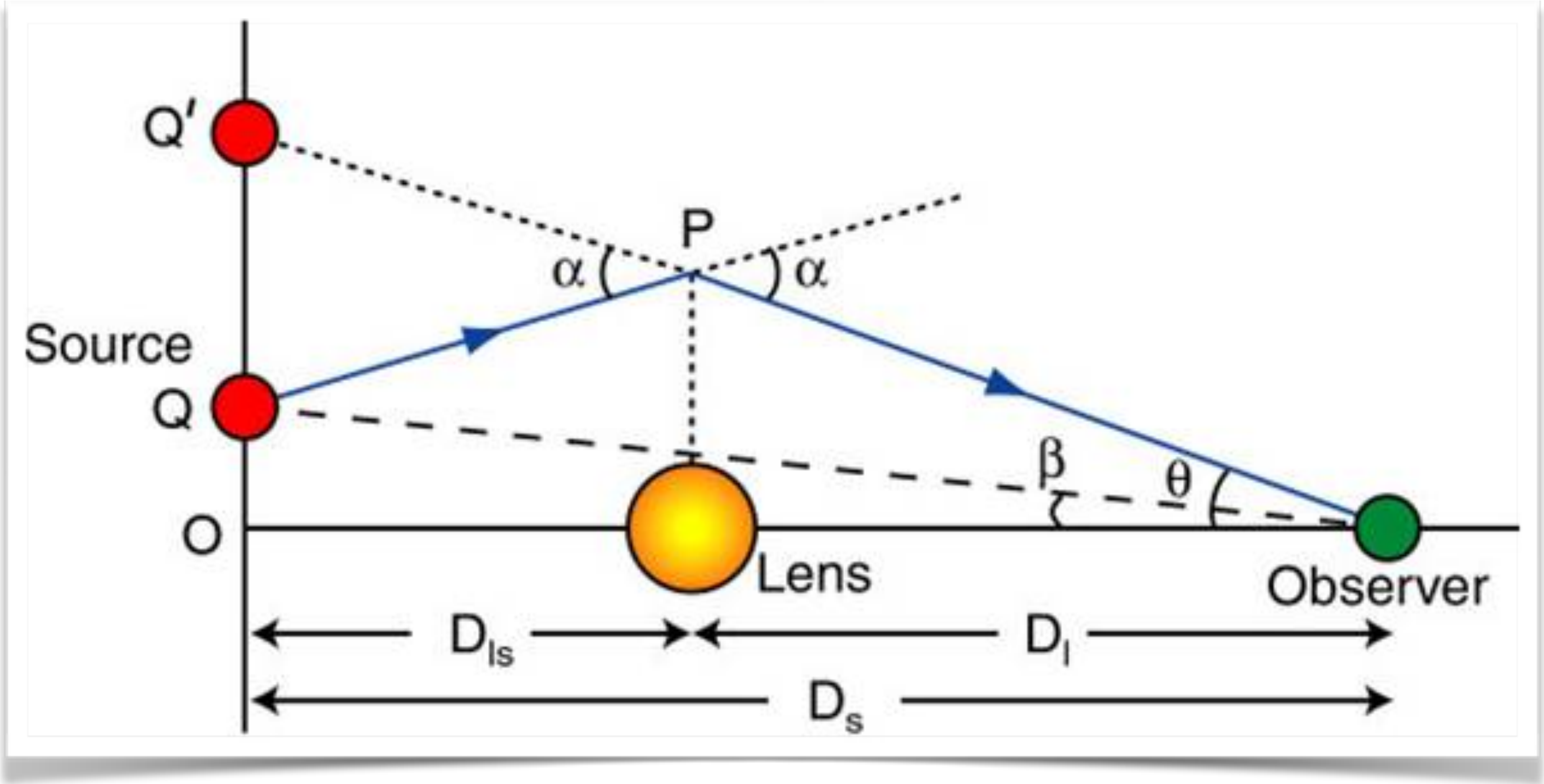
$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

Time Delay (Geometric Optics)



University of Manchester

Geometric Time Delay

Time Delay: $$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

Lensing Potential

for point-like lens: $\psi(\theta) = \theta_E^2 \log\theta$

Time Delay (Geometric Optics)

$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

- If $\omega\,\Delta t \lesssim 1$, expect interference between the two images
- Oscillatory features in magnification function

Caveat 1: Wave Optics

- Our calculations so far relied on Fermat's principle: if $\omega\Delta t \gg 1$, contributions with different θ will interfere destructively, except at stationary points of Δt.
- Leads to the lens equation

$$\theta - \beta = \frac{\theta_E^2}{\theta}$$

- What if $\omega\Delta t \lesssim 1$?
- Need to evaluate full Fresnel integral

$$\mu \propto \left| \int d^2\vec{\theta}\, e^{i\omega\Delta t(\vec{\theta},\vec{\beta})} \right|^2$$

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Caveat 1: Wave Optics

$$\mu \propto \left| \int d^2\vec{\theta}\, e^{i\omega \Delta t(\vec{\theta},\vec{\beta})} \right|^2$$

☑ Can be evaluated analytically for point-like lens

$$F(y,\Omega)_{\rm BH} = e^{i\Omega|\vec{y}|^2/2} \left(-\frac{i\Omega}{2}\right)^{i\Omega/2} \Gamma\left(1-\frac{i\Omega}{2}\right) L_{-1+\frac{i\Omega}{2}} \left(-\frac{i|\vec{y}|^2\Omega}{2}\right)$$

with

$$\Omega \equiv \frac{4GM(1+z_L)}{c^3}\,\omega \qquad\qquad y \equiv \beta/\theta_E$$

☑ Tends to reduce magnification
(more destructive interference)

Caveat 1: Wave Optics

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Laguerre polynomial

with

$$\Omega \equiv \frac{4GM(1+z_L)}{c^3}\,\omega \qquad y \equiv \beta/\theta_E$$

☑ Tends to reduce magnification
(more destructive interference)

Caveat 2: Finite Size of the Source

- Different points on the source are magnified differently
- Remember: total magnification in geometric optics:

$$\mu = \frac{y^2 + 2}{y\sqrt{y^2+4}} \,.$$

- Now need to evaluate

$$\int d\vec{y}\, \frac{\vec{y}^2 + 1}{|\vec{y}|\sqrt{\vec{y}^2+4}}$$

- Tends to reduce the magnification

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Required Source Properties for Femtolensing

- ☑ How to realize $\omega \Delta t \lesssim 1$?

$$\Delta t = \frac{D_L D_S}{c\, D_{LS}} \left[\frac{(\theta - \beta)^2}{2} - \frac{4 G_N M D_{LS}}{c^2 D_L D_S} \log \theta \right]$$
$$\sim \frac{4 G_N M}{c^2} = 2 \times 10^{-5}\,\mathrm{sec} \left(\frac{M}{M_\odot} \right)$$

or, equivalently

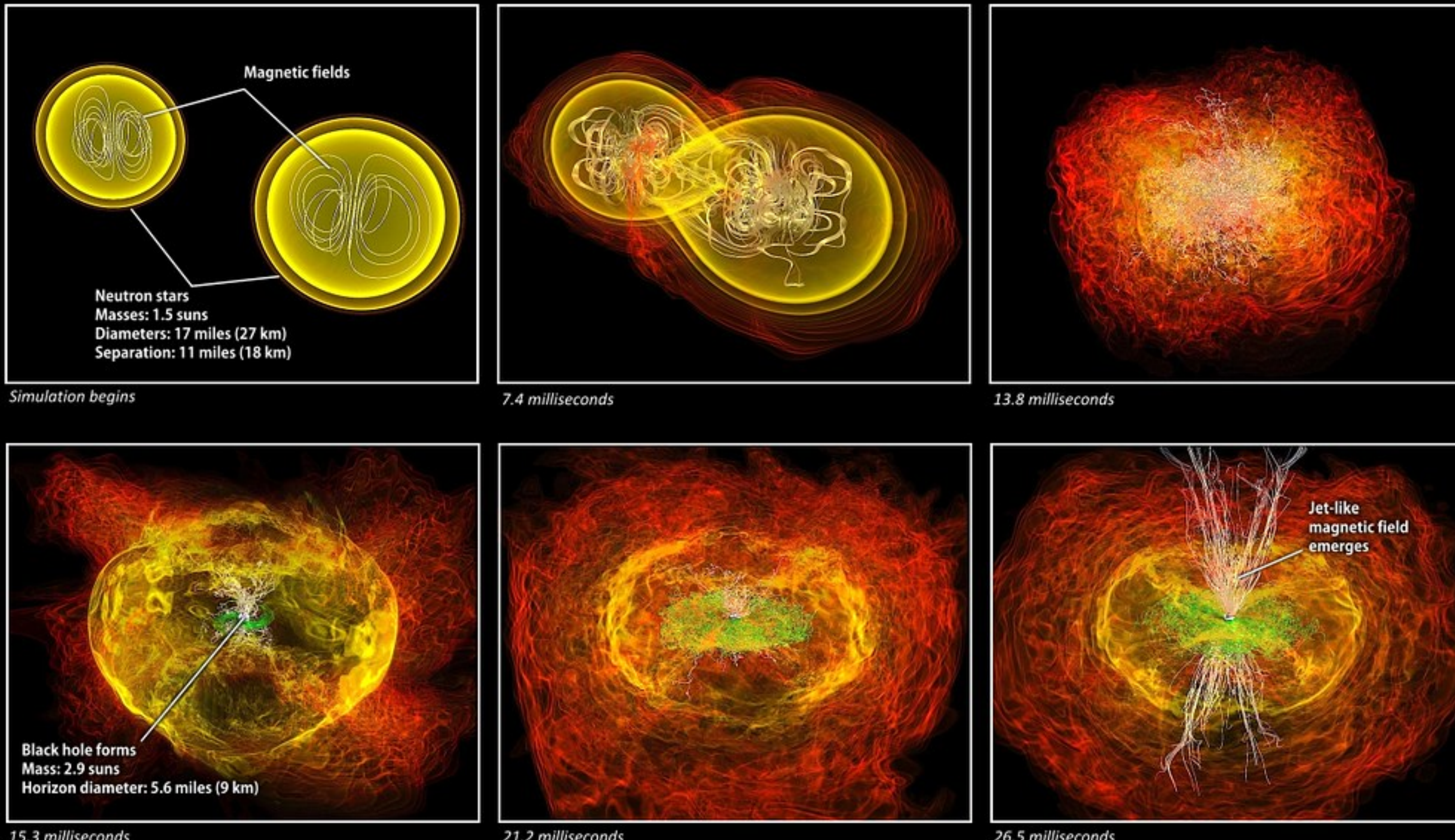
$$\frac{1}{\Delta t} \sim 0.3\,\mathrm{MeV} \left(\frac{10^{-16} M_\odot}{M} \right)$$

- ☑ Satisfied for instance for *gamma rays*

Possible Source: Gamma Ray Bursts (GRBs)

- ☑ Brightest electromagnetic events in the Universe
  - Can be observed far, far away (~ Gpc, z ~ few)
  - large probability of finding a lens in between
- ☑ Duration: ~100 ms to tens of seconds
- ☑ Proposed mechanisms
  - Supernova explosion of massive star (long GRB, duration ≳ 2 sec)
  - Binary neutron star merger (short GRB, duration ≲ 2 sec)

Crashing neutron stars can make gamma-ray burst jets

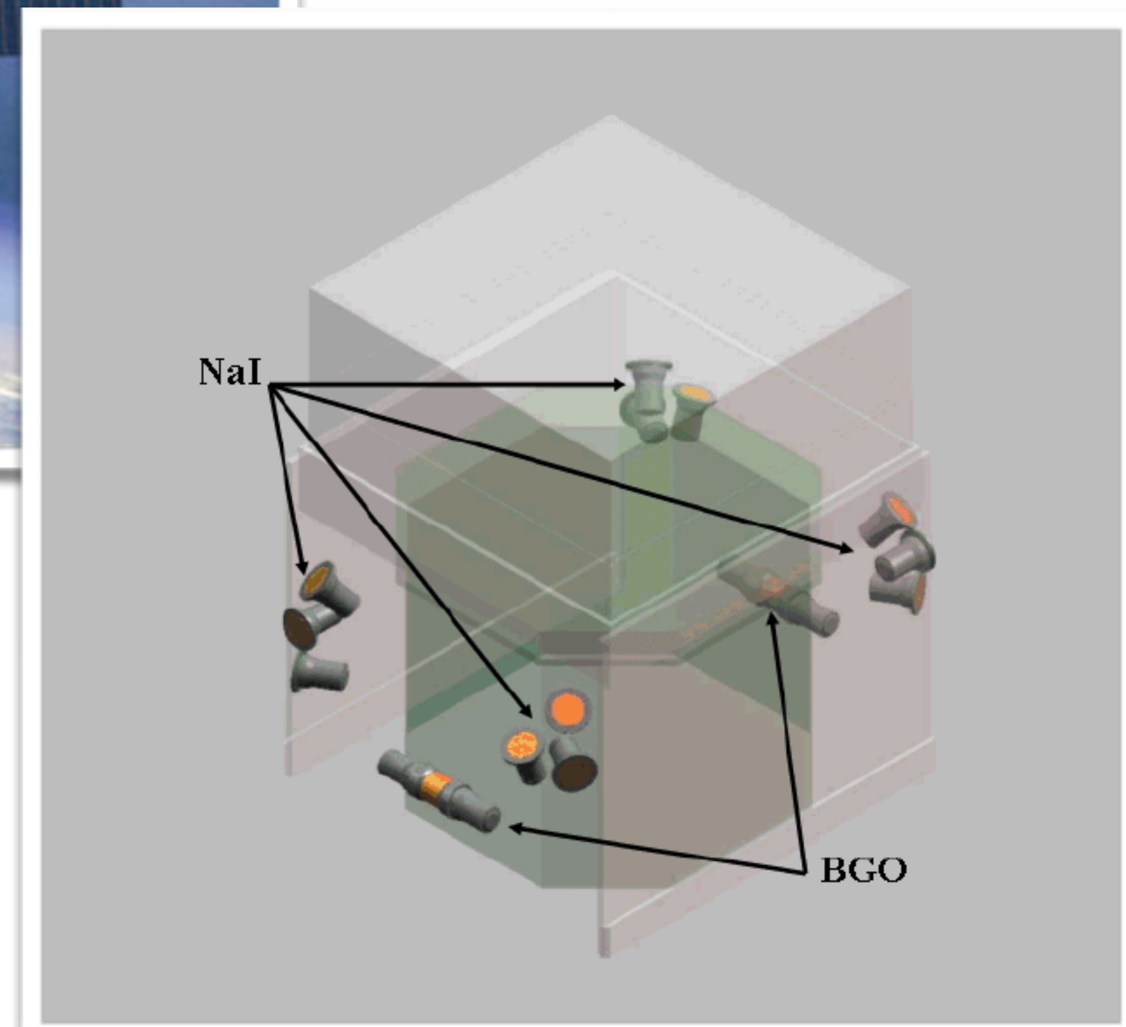


Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

GRB Observations

Fermi Satellite

Fermi Gamma Ray Burst Monitor



GRB Observations

GBM Specifications & Performance

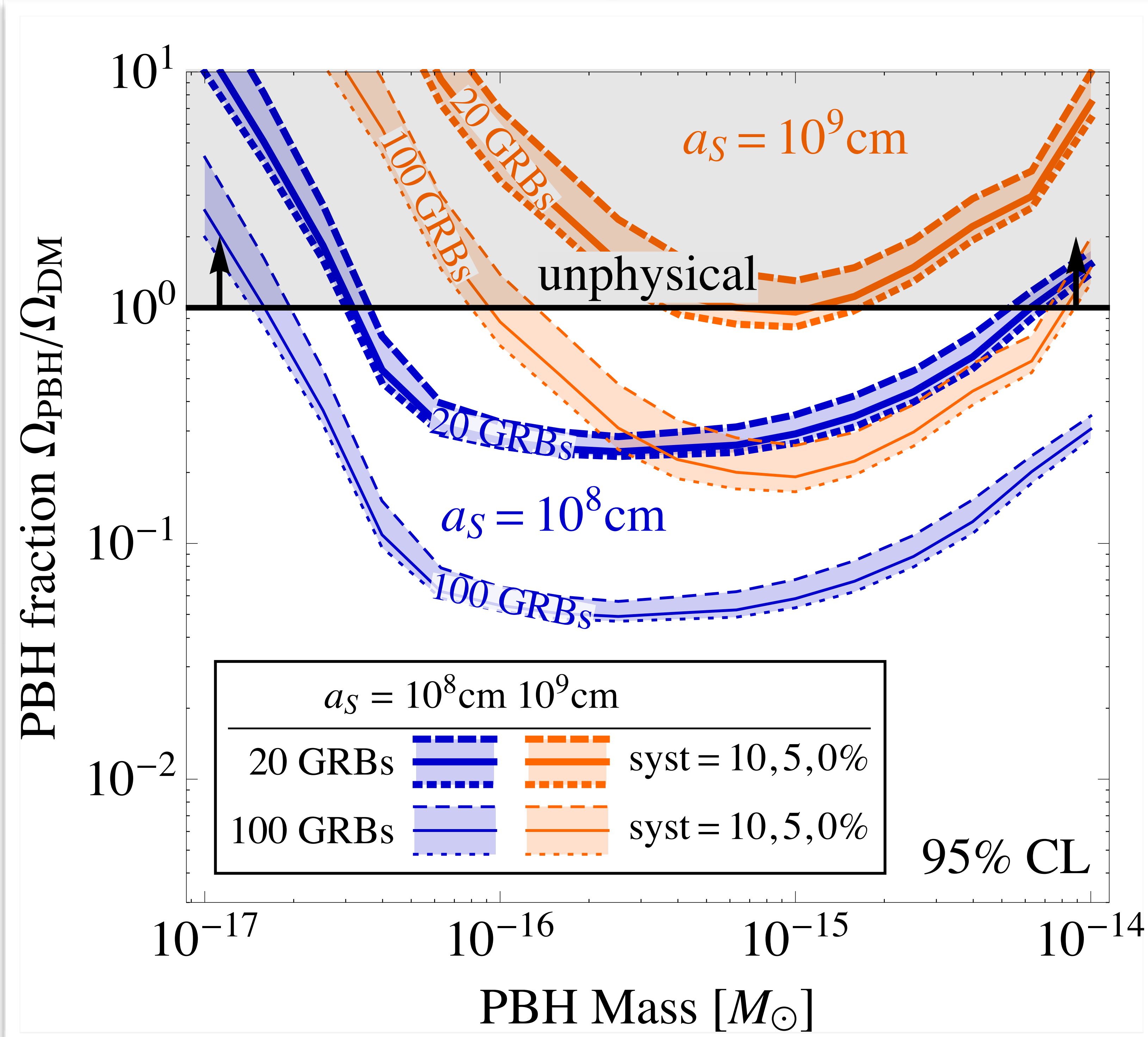
Quantity	GBM (Minimum Spec.)
Energy Range	< 10 keV - > 25 MeV
Field of View	all sky not occulted by the Earth
Energy Resolution [1]	< 10%
Deadtime per Event	< 15 μs
Burst Sensitivity [2]	< 0.5 cm^{-2} s^{-1}
Alert GRB Location [3]	~ 15°
Final GRB Location [4]	~ 3°

[1] 1-σ, 0.1 - 1 MeV
[2] 50 - 300 keV
[3] Calculated on-board; 1 second burst of 10 photons cm^{-2} s^{-1}, 50 - 300 keV
[4] Final ground computed locations; 1 second burst of 10 photons cm^{-2} s^{-1}, 50 - 300 keV

GRB Caveats

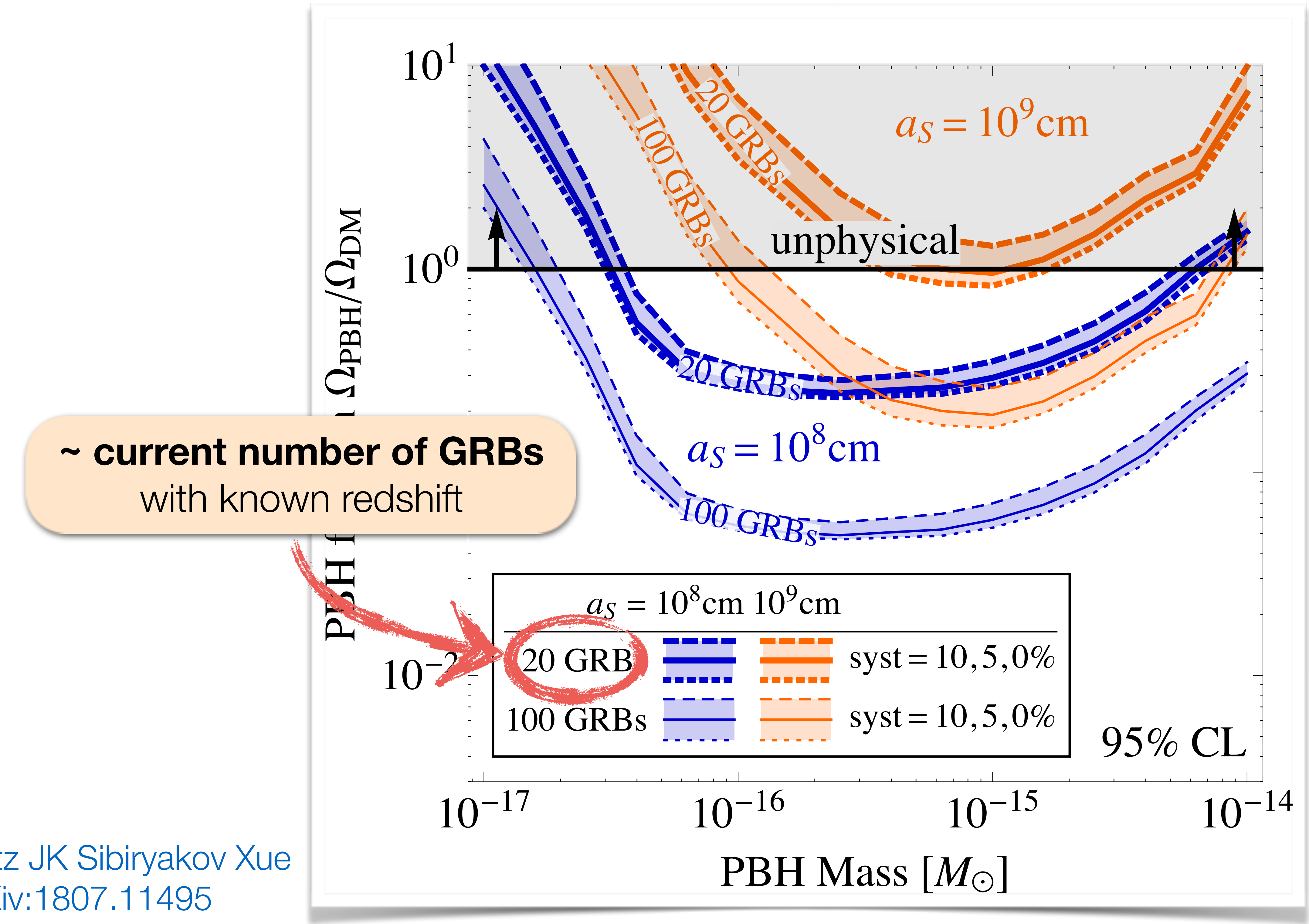
- ☑ To constrain the PBH density using (non-)observation of femtolensing, we need to know the distance to the GRB
  - Requires optical counterpart
  - Only ~20 GRBs with known distance so far
- ☑ Wave optics effects
- ☑ Finite size of GRB source

Sensitivity Estimates



Katz JK Sibiryakov Xue
arXiv:1807.11495

Sensitivity Estimates



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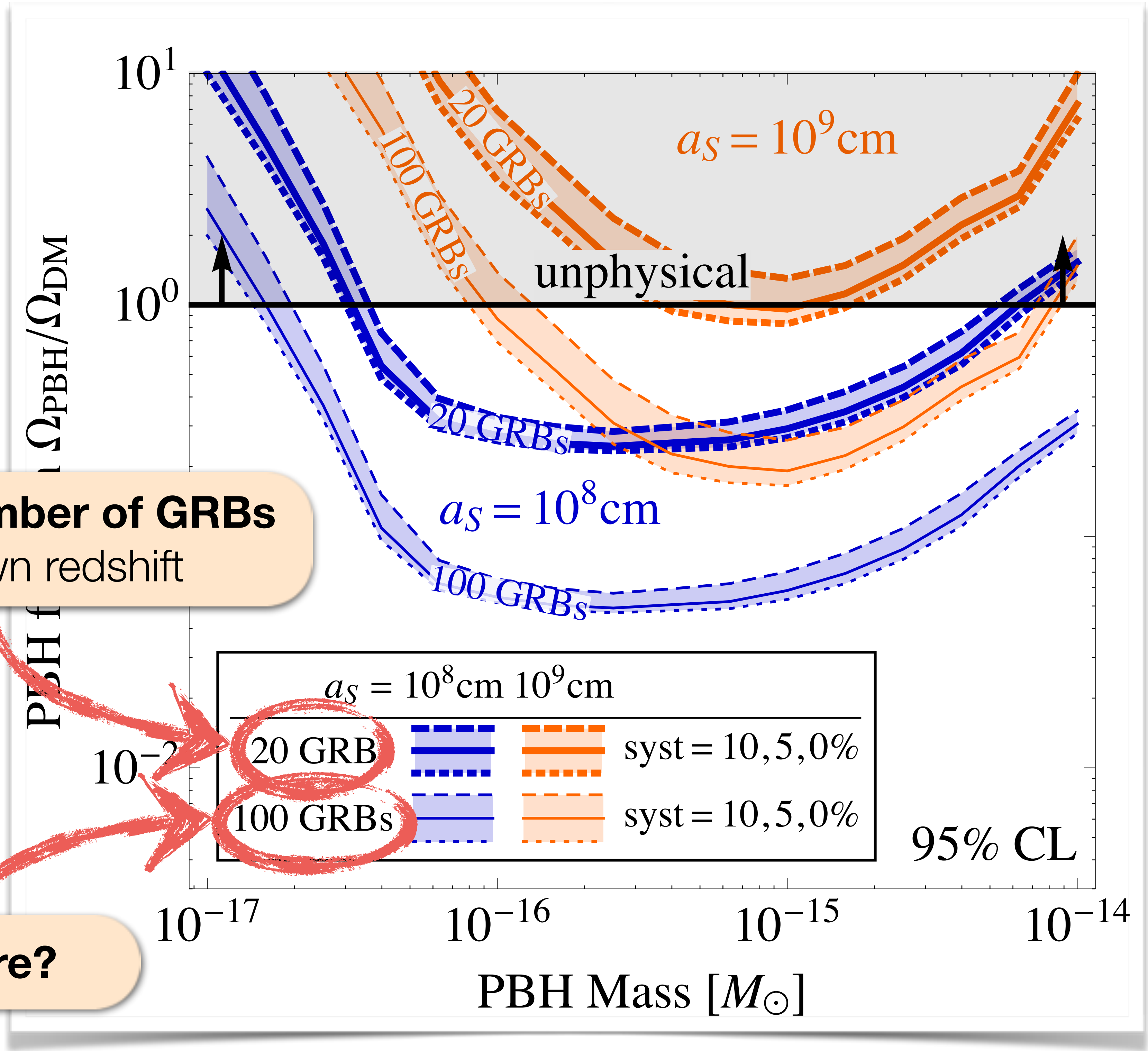
Sensitivity Estimates

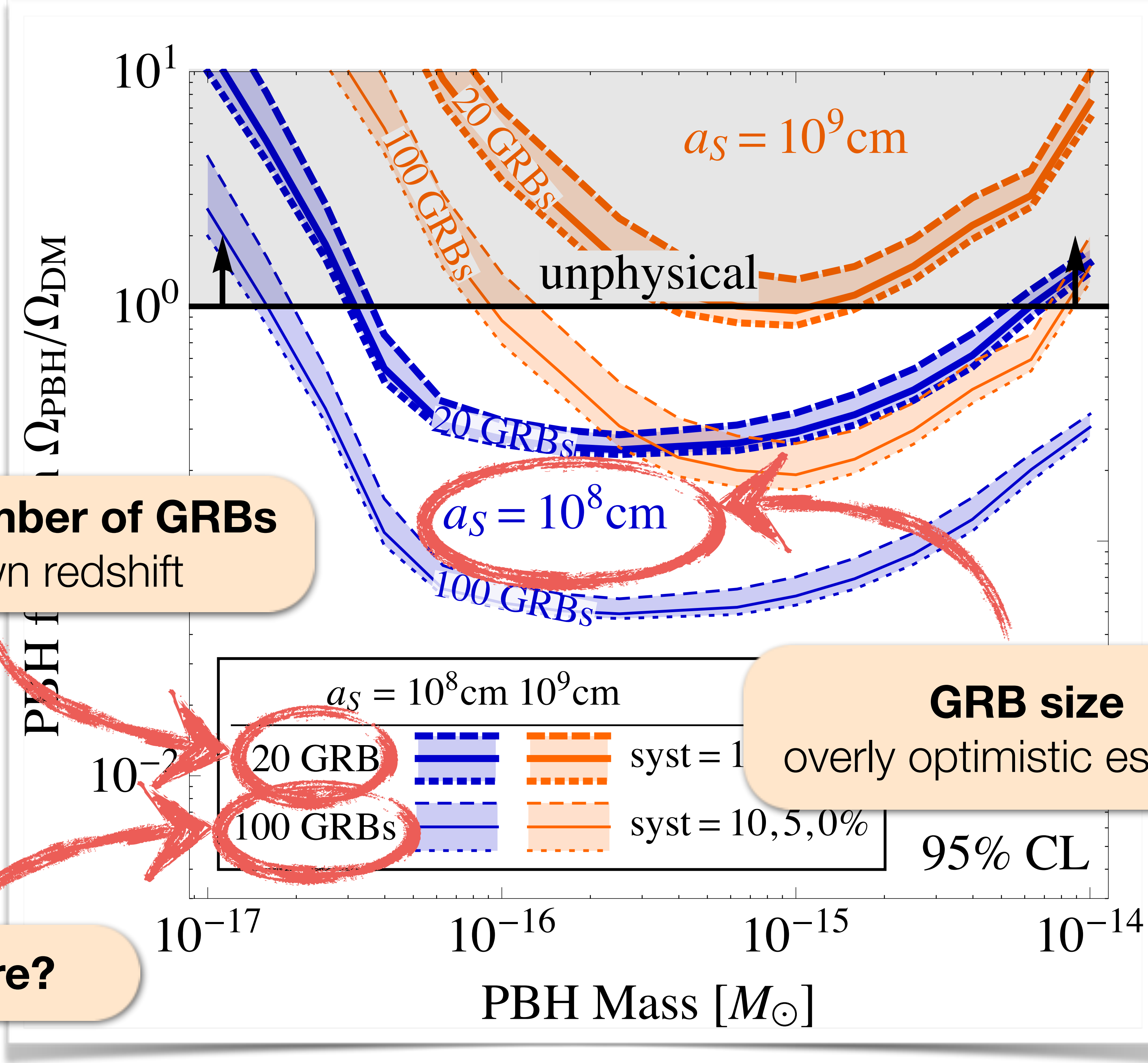


~ current number of GRBs with known redshift

Future?

Katz JK Sibir...
arXiv:1807.11495

Sensitivity Estimates



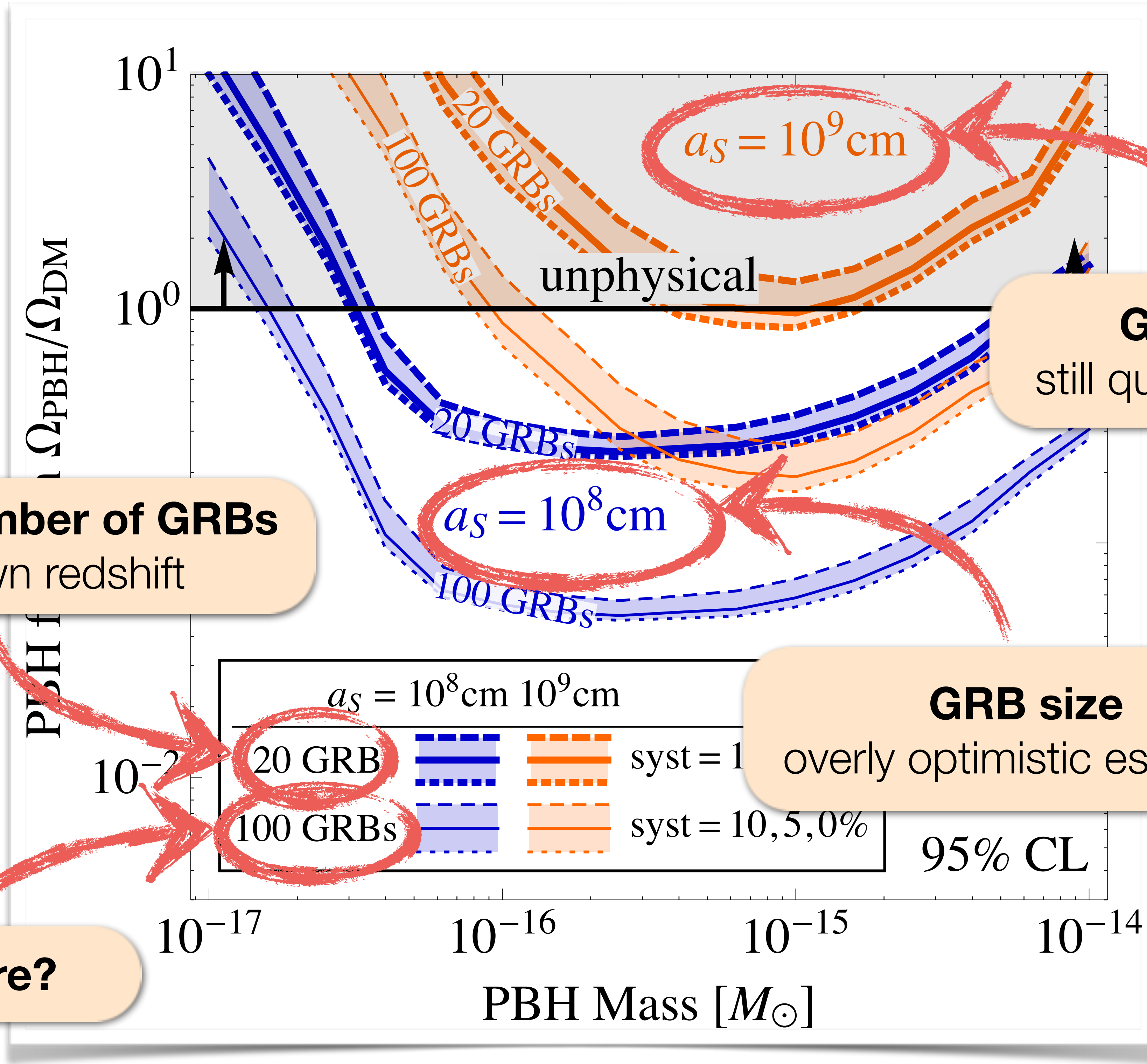
~ current number of GRBs
with known redshift

GRB size
overly optimistic estimate

Future?

Katz JK Sibir...
arXiv:1807.11495

Sensitivity Estimates



GRB size
still quite optimistic

~ current number of GRBs
with known redshift

GRB size
overly optimistic estimate

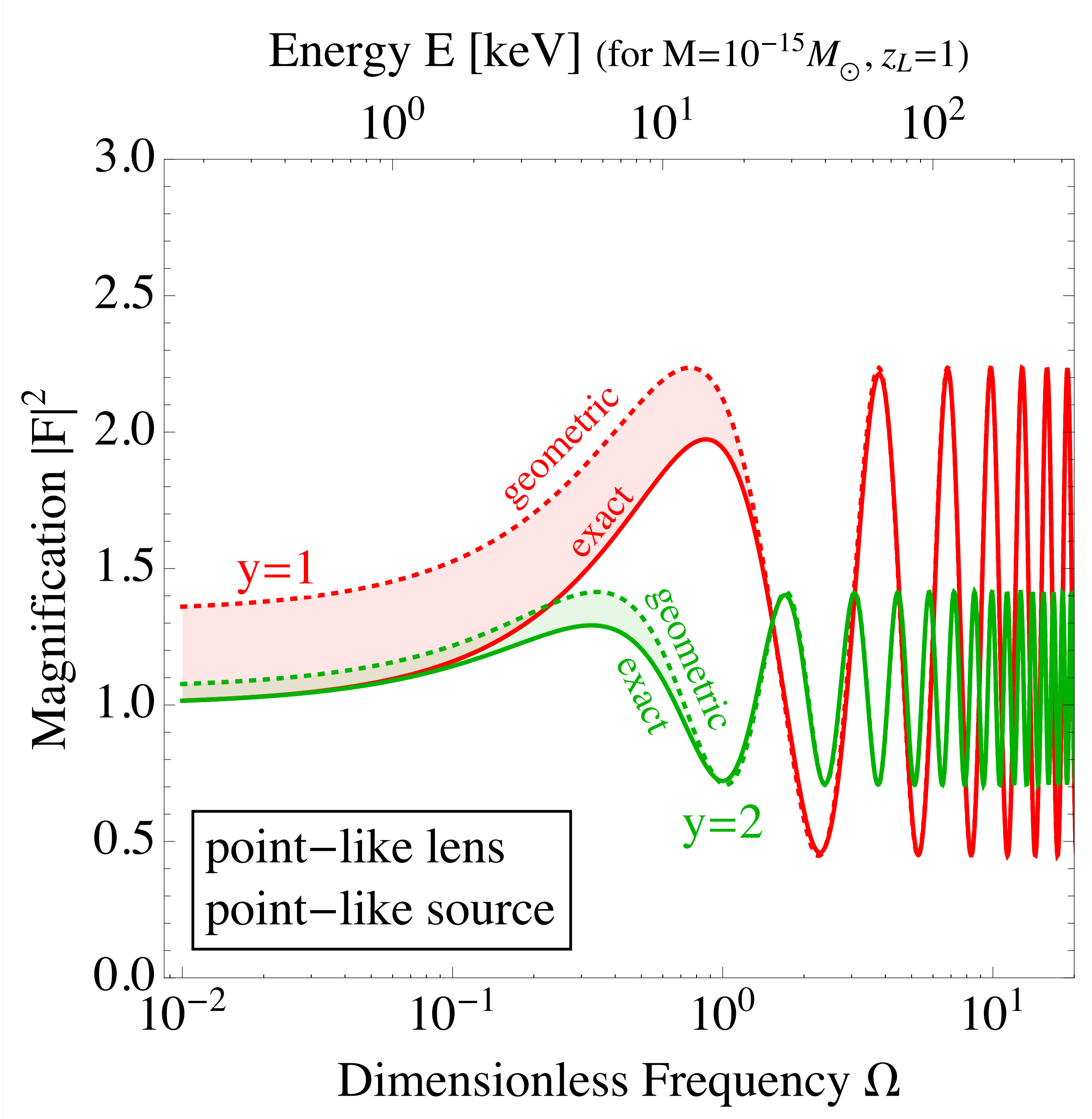
Future?

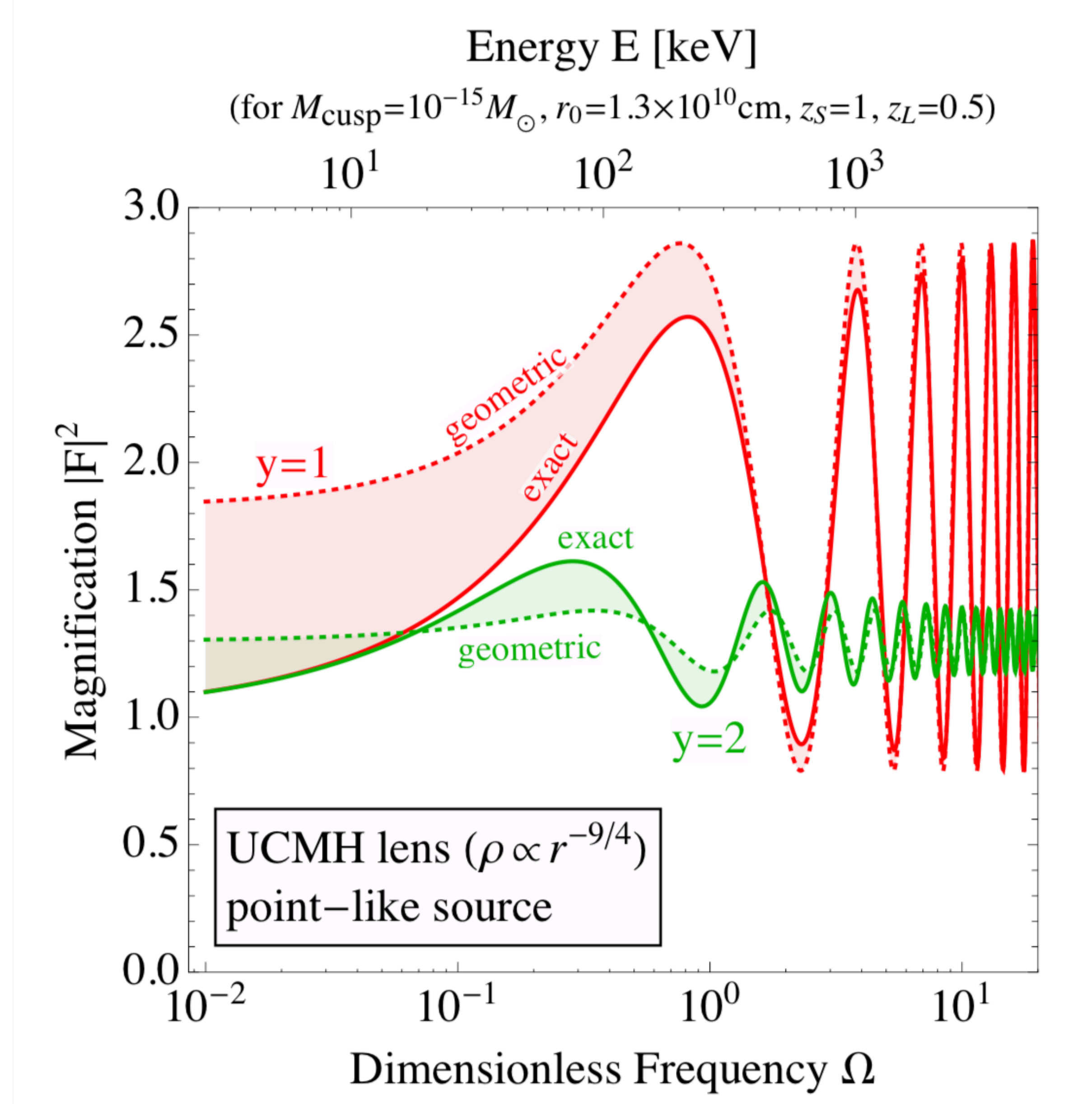
Katz JK Sibir[...]
arXiv:1807.11495

Excursion: Finite Size Lenses

Non-pointlike compact DM candidates: ultra-compact (axion) minihalos

large uncertainty in mass distribution and density profile





Finite Size of GRB Sources

- γ production in GRBs: Katz JK Sibiryakov Xue, arXiv:1807.11495
  - e^+, e^- acceleration in relativistic shock waves
- Variability time scale in rest frame for source size a_S:

$$t_{\rm var} \sim a_S/c$$

- Relativistic boost γ:

$$t_{\rm var} \sim (1 + z_S)\left(1 - \frac{v}{c}\cos\theta_{\rm obs}\right)\gamma\, a_S/c$$

- Observation angle $\theta_{\rm obs} \sim 1/\gamma$
- Observed $t_{\rm var} \gtrsim 0.01$ sec (short GRB); $\gtrsim 0.1$ sec (long GRB)

$$a_S \simeq \frac{10^{11}\,\text{cm}}{1 + z_S} \times \left(\frac{t_{\rm var}}{0.03\,\text{sec}}\right)\left(\frac{\gamma}{100}\right)$$

Finite Size of GRB Sources: Caveats

- Some GRBs with shorter variability time scale $t_{var} \lesssim 10^{-3}$ sec
  - t_{var} distribution could have a long tail → use tail for femtolensing
- Intrinsic variability might be too fast to be resolved
- Conservative estimate: require optical depth $\tau < 1$:

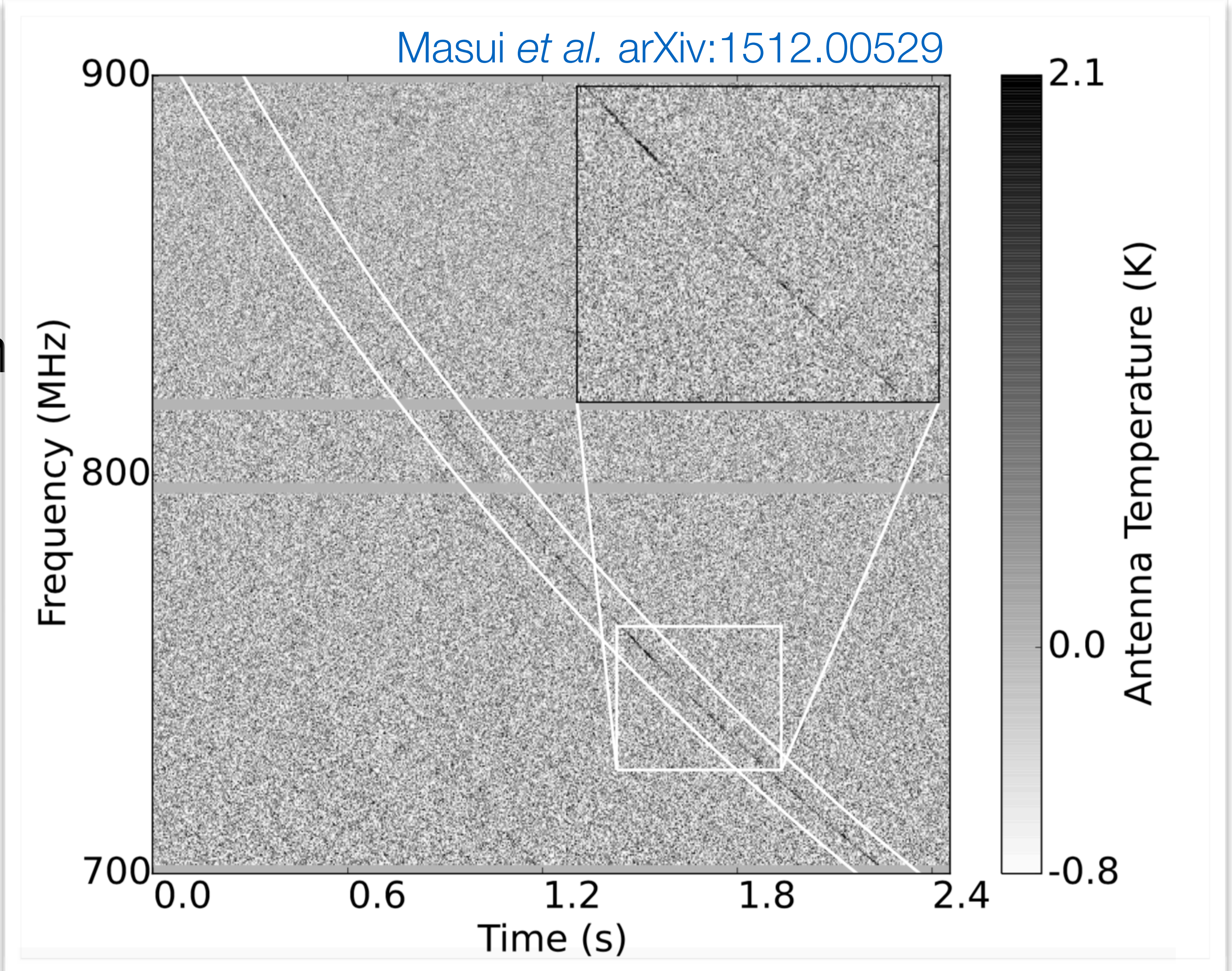
$$a_S > 1.8 \times 10^9 \left(\frac{d_S}{7\text{Gpc}}\right)^2 \left(\frac{f_{500}}{10^{-3}\text{sec}^{-1}\text{cm}^{-2}\,\text{keV}^{-1}}\right) \left(\frac{\gamma}{1000}\right)^{-4} \text{cm}\,.$$

- Assumptions:
  - Power law spectrum with $\alpha = -2$
  - Thomson scattering (non-relativistic in rest frame of ejecta)
  - Target e^+, e^- from pair production by γ rays
  - ...

Katz JK Sibiryakov Xue, arXiv:1807.11495

Fast Radio Bursts

- Short (~ ms) burst of radio waves
- At $\mathcal{O}$(Gpc) distance (inferred from dispersion)
- Some repeaters
- Mechanism unknown



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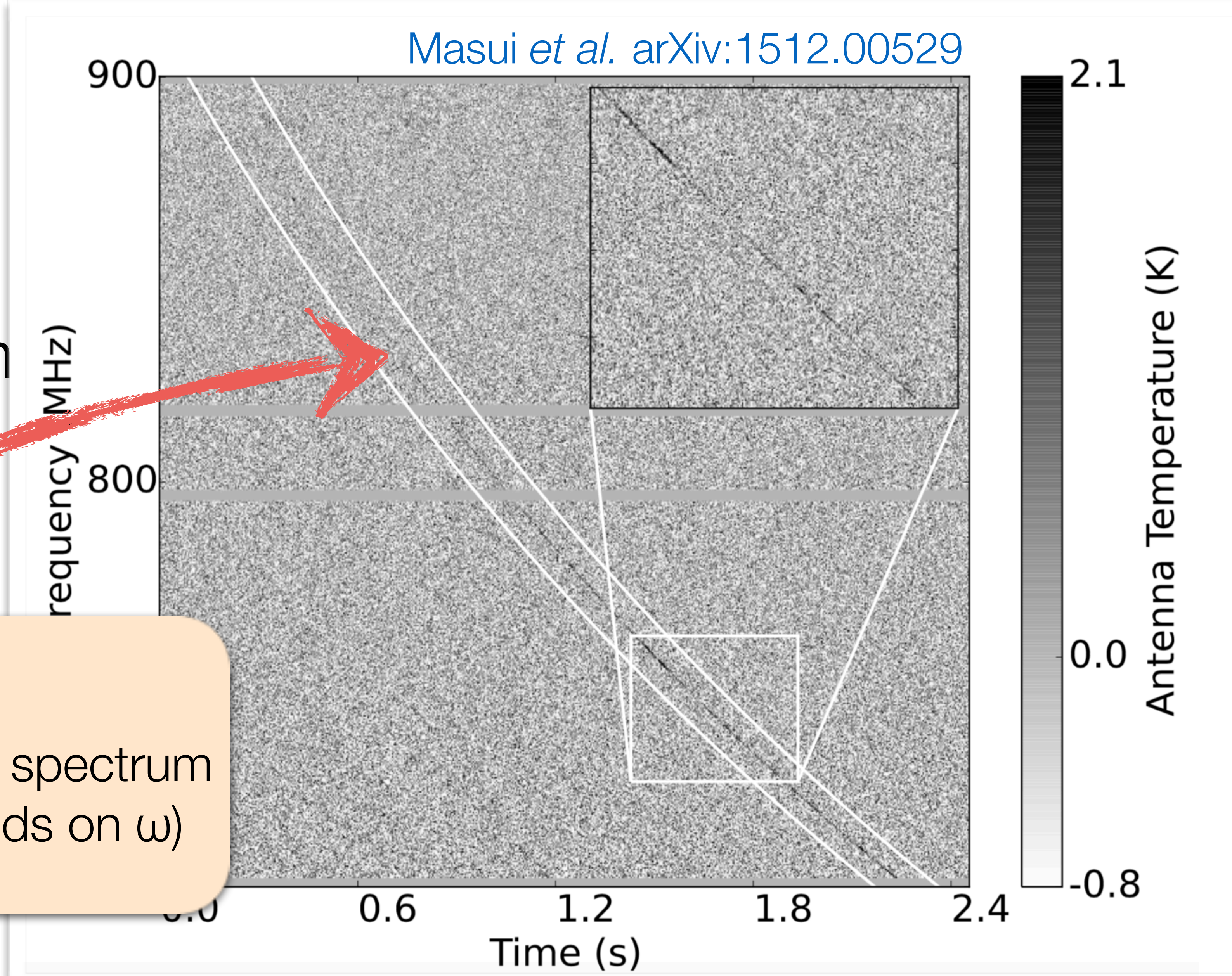

Dispersion
Burst moves through the frequency spectrum
(speed of light in ISM / IGM depends on ω)

Fast Radio Bursts

Scintillation
interference between waves traveling
along different paths through turbulent ISM / IGM.

- ☑ Short (~ ms) burst of radio waves
- ☑ At $\mathcal{O}$(Gpc) distance
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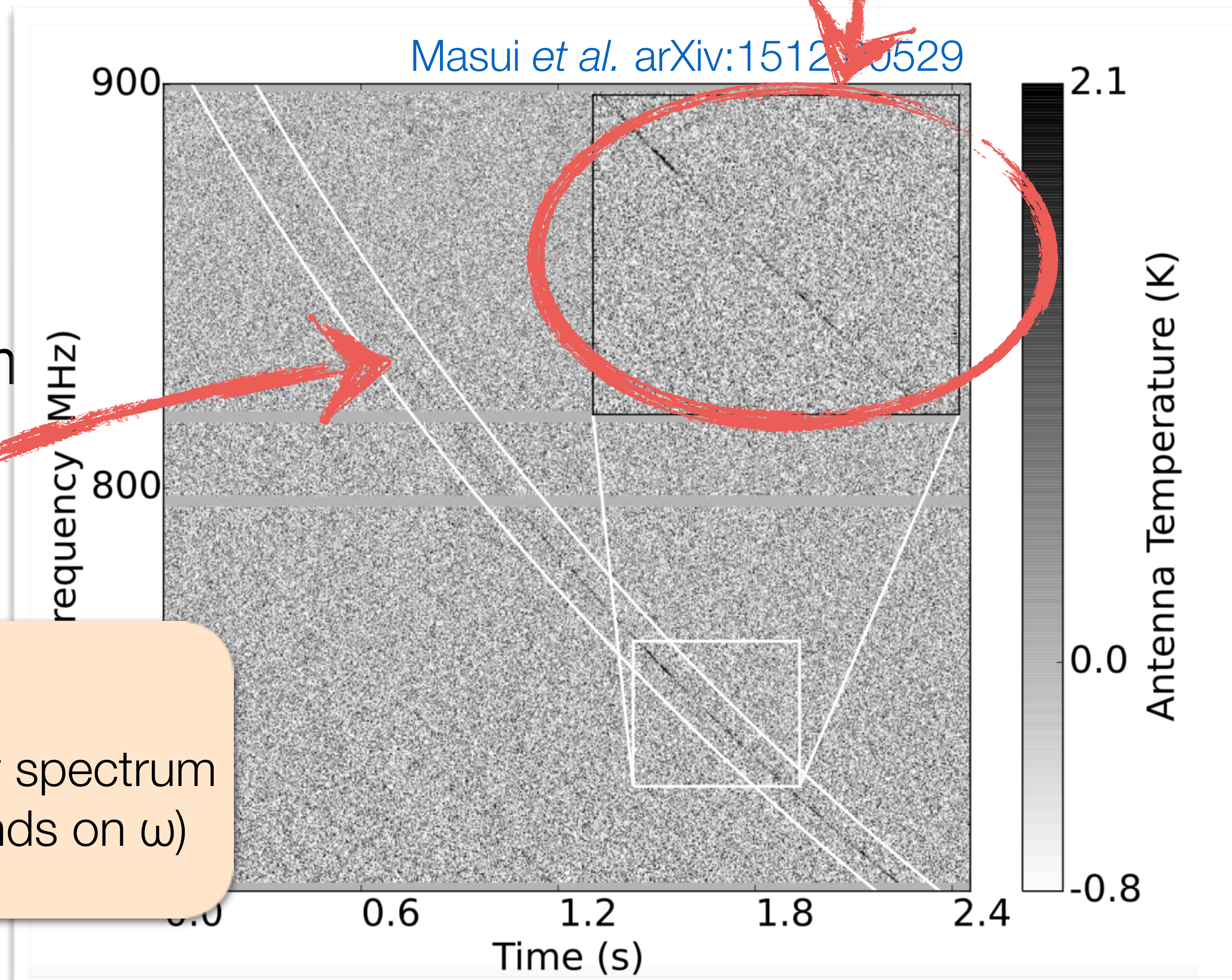
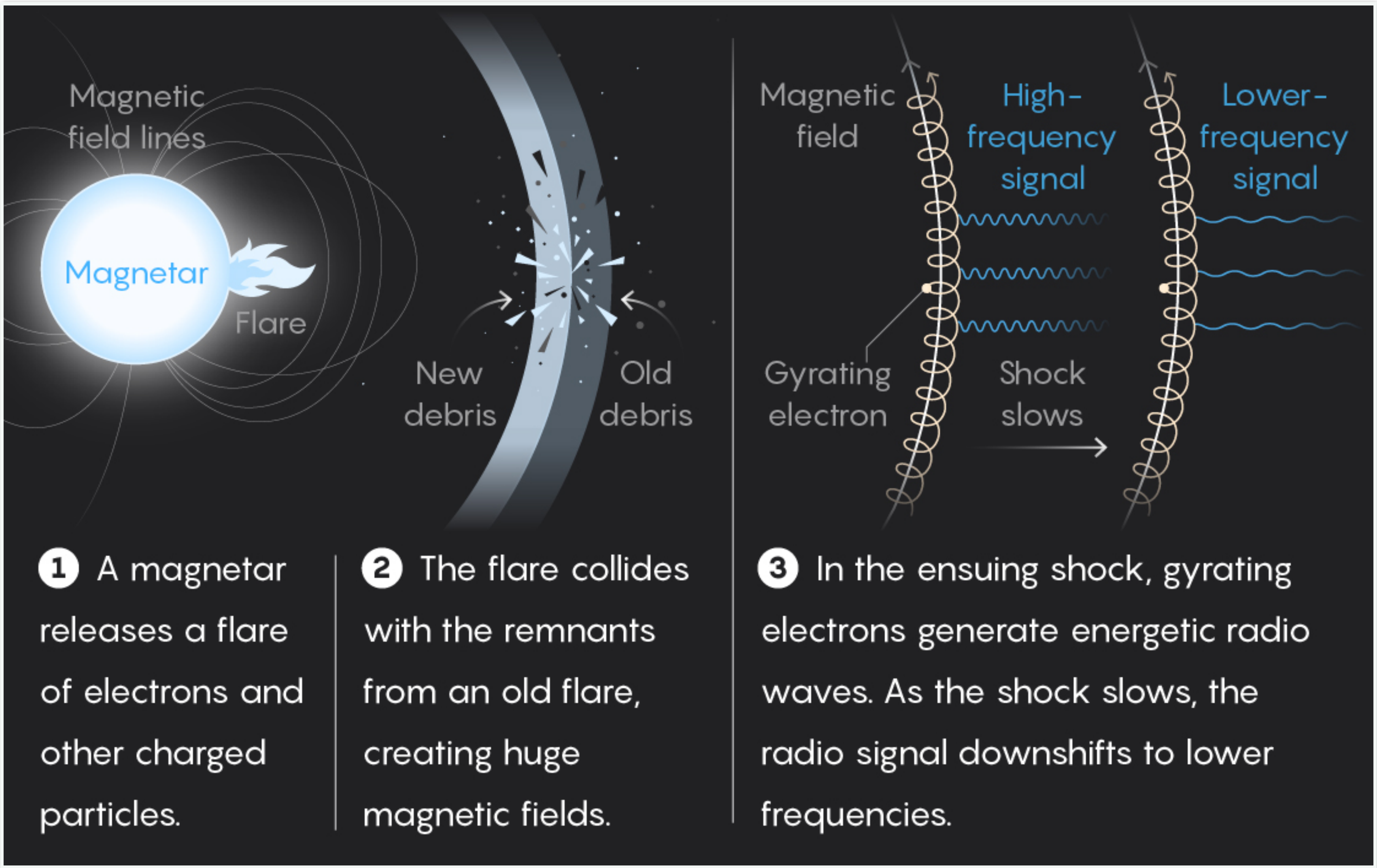


Dispersion
Burst moves through the frequency spectrum
(speed of light in ISM / IGM depends on ω)

One of $\mathcal{O}(50)$ proposed FRB mechanisms



see arXiv:1810.05836
for a review of mechanisms

Image: Quanta Magazine
based on Metzger Margalit Sironi arXiv:1902.01866

Femtolensing of FRBs

- Remember:

$$\Delta t \simeq \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\theta_E^2\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2}-\psi(\vec{\theta})\right) \sim 4G_N M_{\mathrm{lens}}$$

- Leads to O(2π) phase shifts for f ~ GHz if $M_{\mathrm{lens}} \sim 10^{-4} M_{\mathrm{sun}}$
- Many new FRBs expected from SKA → high statistics
- But: easily confused with *scintillation*
-

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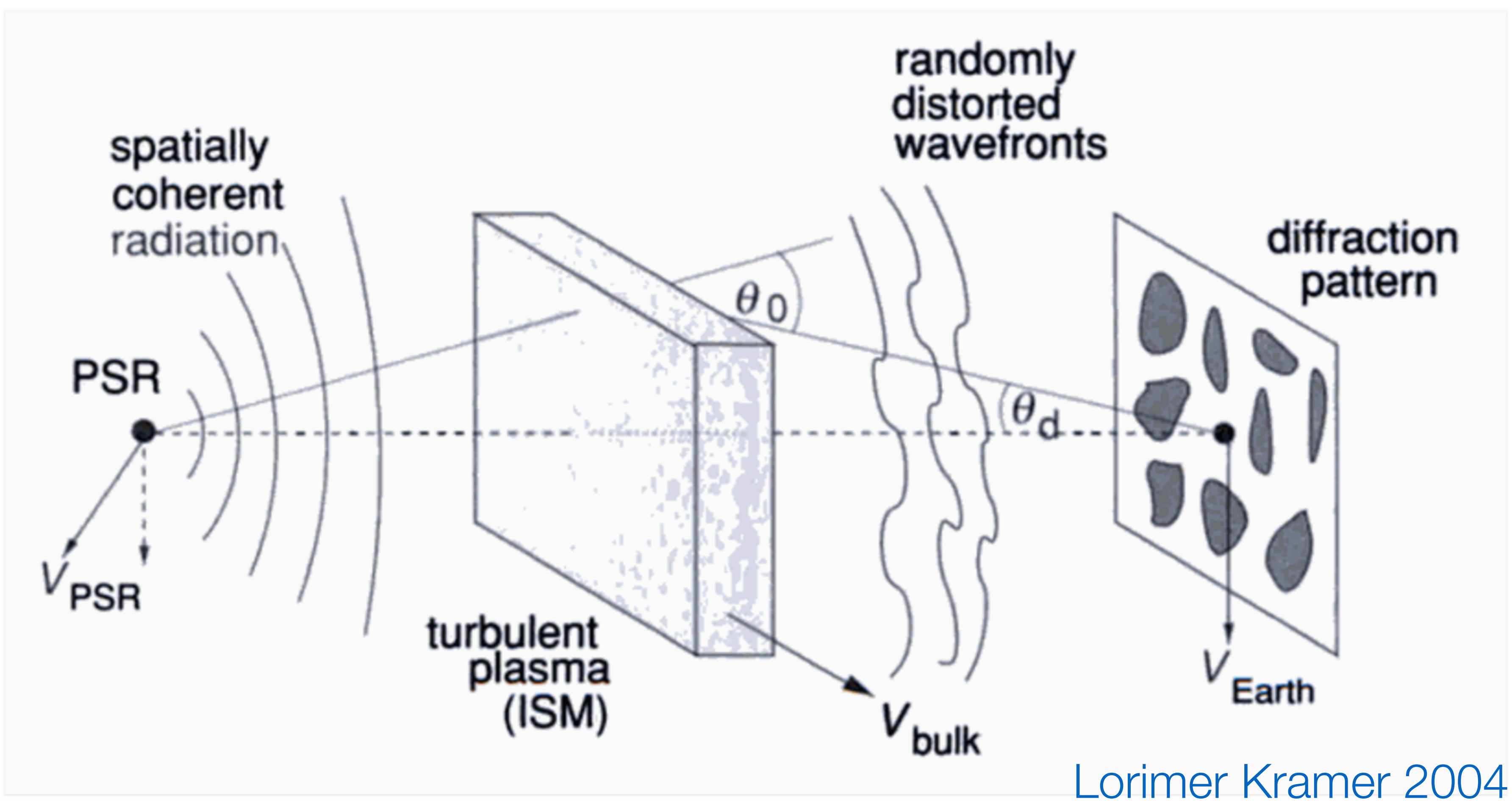
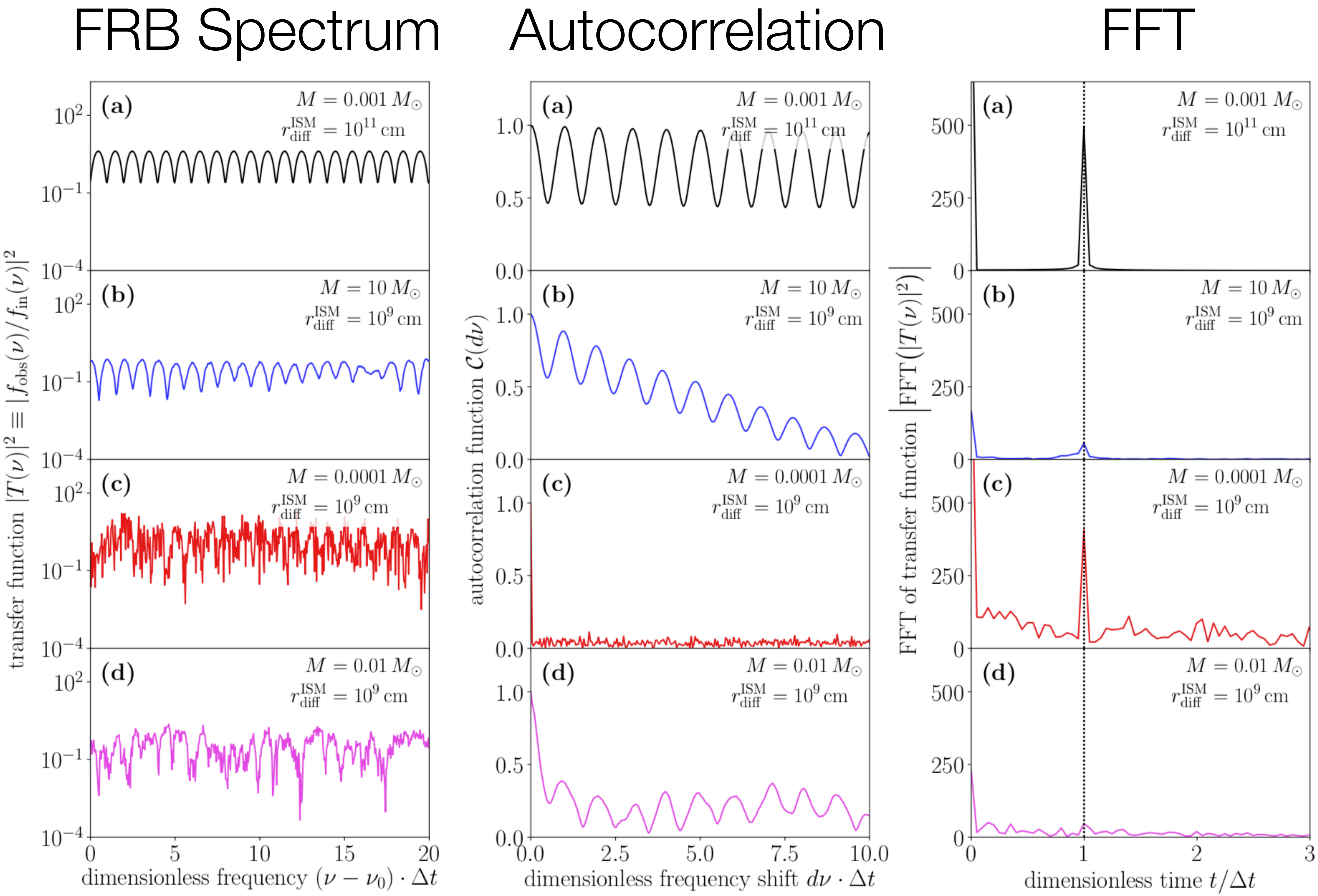
Scintillation

- many different lines of sight to the source because of refraction / diffraction in turbulent ISM / IGM
- leads to random interference patterns



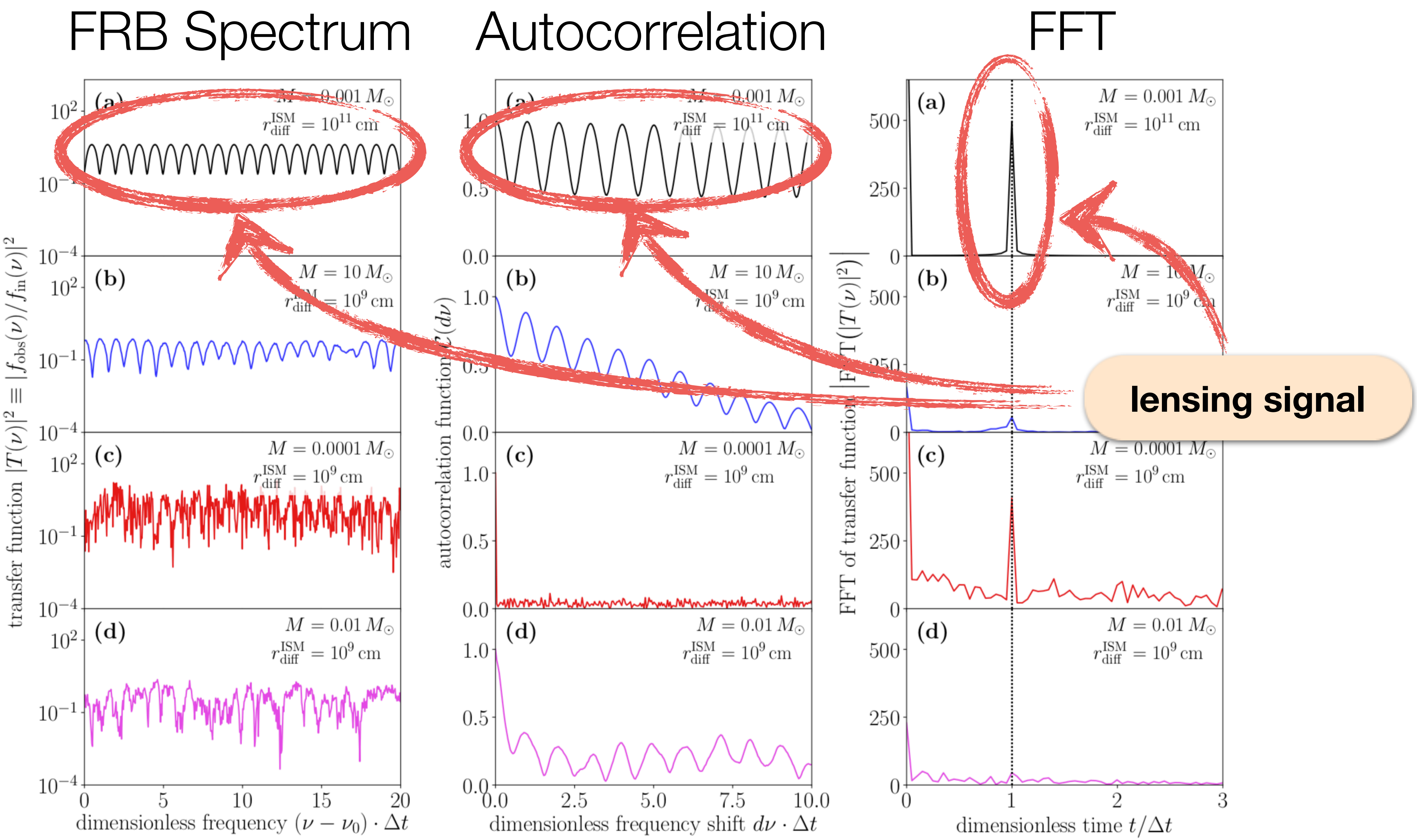
Lorimer Kramer 2004

Scintillation



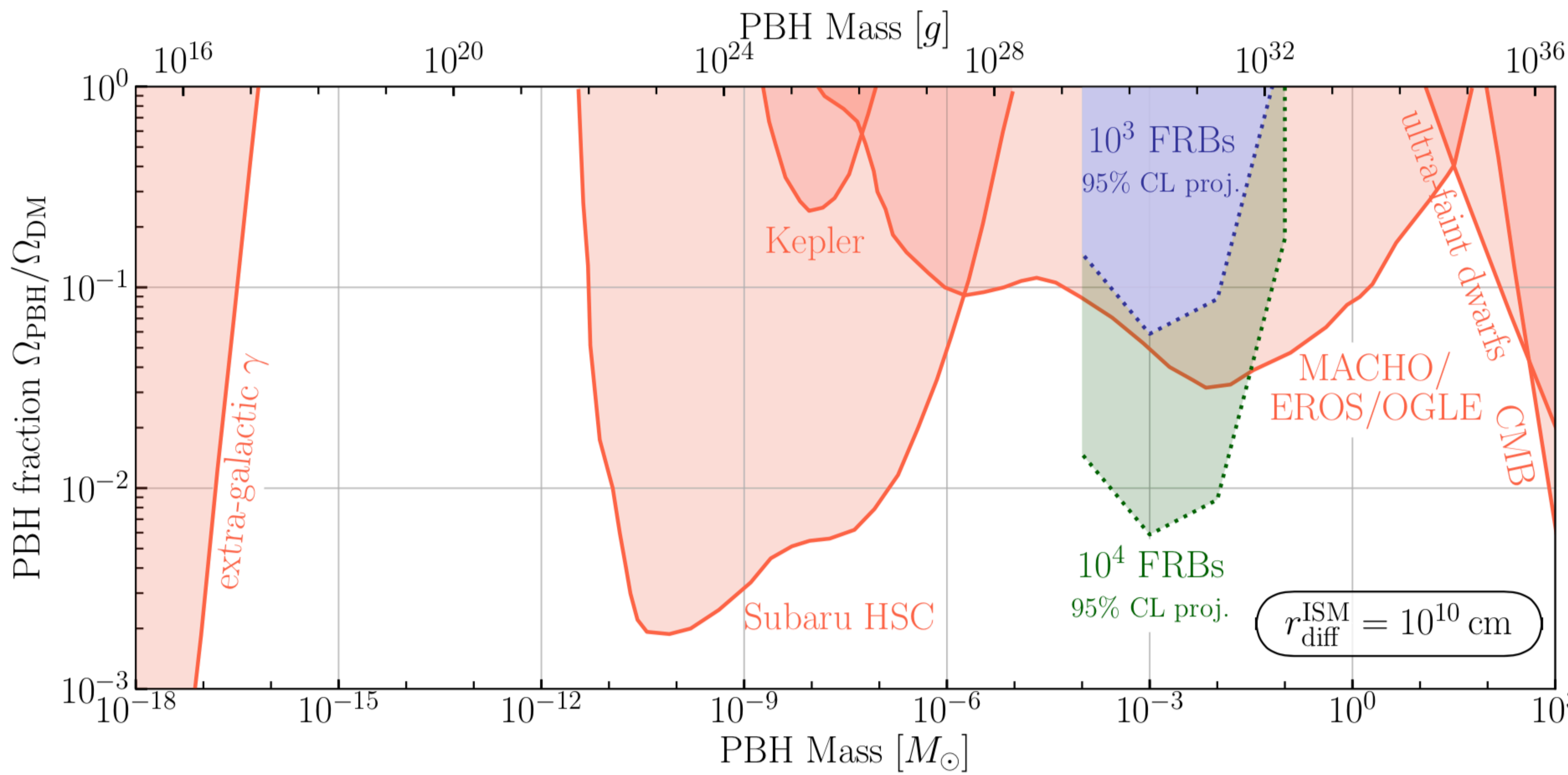
Katz JK Sibiryakov Xue, arXiv:1912.07620

Scintillation



Katz JK Sibiryakov Xue, arXiv:1912.07620

PBH Parameter Space



Katz JK Sibiryakov Xue, arXiv:1912.07620

Assuming δ-like PBH mass distribution

Bonus Slides on Dark Photons

Dark Photons: Formalism

$$\mathcal{L} \supset -\frac{1}{2} \sin\chi F_Y^{\mu\nu} F'_{\mu\nu}$$

- Remove kinetic mixing term by transformation

$$\begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & \sec\chi \end{pmatrix} \begin{pmatrix} \tilde{B}_\mu \\ \tilde{B}'_\mu \end{pmatrix}$$

to ensure *B* and *B'* have standard kinetic terms
(necessary for proper definition and normalization of 1-particle states)
Note: this trafo does not change the SM hypercharge couplings.

- Electroweak symmetry breaking mixes *B* and *W*:

$$\begin{pmatrix} \tilde{A}_\mu \\ \tilde{Z}_\mu \\ \tilde{Z}'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w & \cos\theta_w & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{B}_\mu \\ W^3_\mu \\ \tilde{B}'_\mu \end{pmatrix}$$

see for instance arXiv:0903.1118

Dark Photons: Formalism

$$\mathcal{L} \supset -\frac{1}{2}\sin\chi F_Y^{\mu\nu} F'_{\mu\nu}$$

$$\begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & \sec\chi \end{pmatrix} \begin{pmatrix} \tilde{B}_\mu \\ \tilde{B}'_\mu \end{pmatrix} \qquad \begin{pmatrix} \tilde{A}_\mu \\ \tilde{Z}_\mu \\ \tilde{Z}'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w & \cos\theta_w & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{B}_\mu \\ W^3_\mu \\ \tilde{B}'_\mu \end{pmatrix}$$

- ☑ θ_w is defined such that Ã is massless.
- ☑ Ž and Ž' have mass term of the form

$$\frac{1}{2}\begin{pmatrix} \tilde{Z}_\mu & \tilde{Z}'_\mu \end{pmatrix} \begin{pmatrix} m^2 & -\Delta \\ -\Delta & M^2 \end{pmatrix} \begin{pmatrix} \tilde{Z}^\mu \\ \tilde{Z}'^\mu \end{pmatrix}$$

- ☑ Diagonalized by rotation

$$\begin{pmatrix} Z_- \\ Z_+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} \tilde{Z}^\mu \\ \tilde{Z}'^\mu \end{pmatrix}$$

see for instance arXiv:0903.1118

Dark Photons: Formalism

$$\mathcal{L} \supset -\frac{1}{2}\sin\chi F_Y^{\mu\nu} F'_{\mu\nu}$$

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$$\begin{pmatrix} Z_- \\ Z_+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} \tilde{Z}^\mu \\ \tilde{Z}'^\mu \end{pmatrix}$$

- Couplings to SM currents in the new basis:

$$\begin{pmatrix} J_A \\ J_Z \\ J_{Z'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -\cos\theta_w \tan\chi \sin\zeta & \sin\theta_w \tan\chi \sin\zeta + \cos\zeta & \sec\chi \sin\zeta \\ -\cos\theta_w \tan\chi \cos\zeta & \sin\theta_w \tan\chi \cos\zeta - \sin\zeta & \sec\chi \cos\zeta \end{pmatrix} \begin{pmatrix} J^{\mathrm{SM}}_{\mathrm{EM}} \\ J^{\mathrm{SM}}_Z \\ J' \end{pmatrix}$$

- Note: photon couplings unchanged (related to unbroken $U(1)_{em}$)