Multimessenger Astronomy and Fundamental Physics

Joachim Kopp (CERN & JGU Mainz)
"Physics of the Universe" School | Asiago, Italy | January 16th, 2020

In this Talk

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

WIMP Dark Matter:
Cosmology

Evidence for Dark Matter

Evidence for Dark Matter

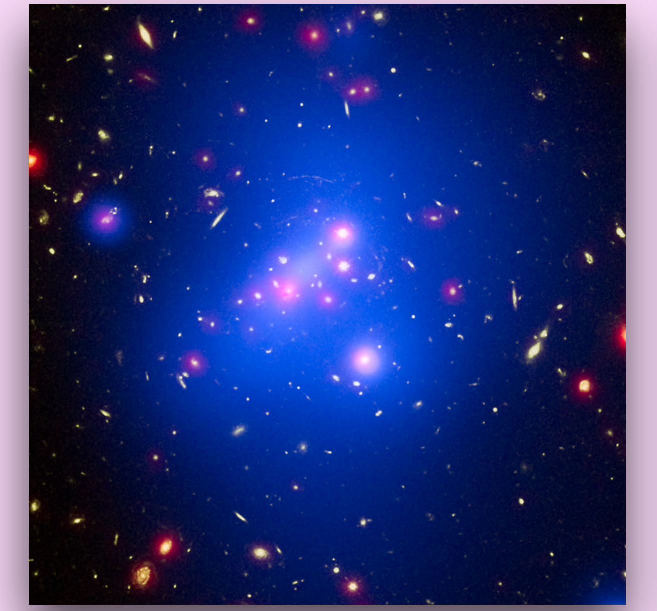
Galaxy Clusters

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

Galaxy Clusters



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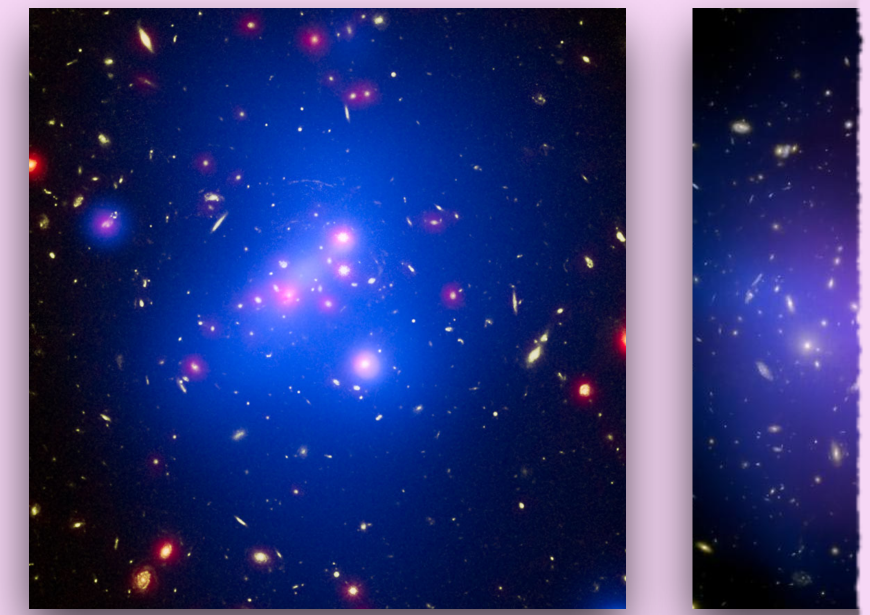

Virial Theorem: $E_{\mathrm{kin}} =$

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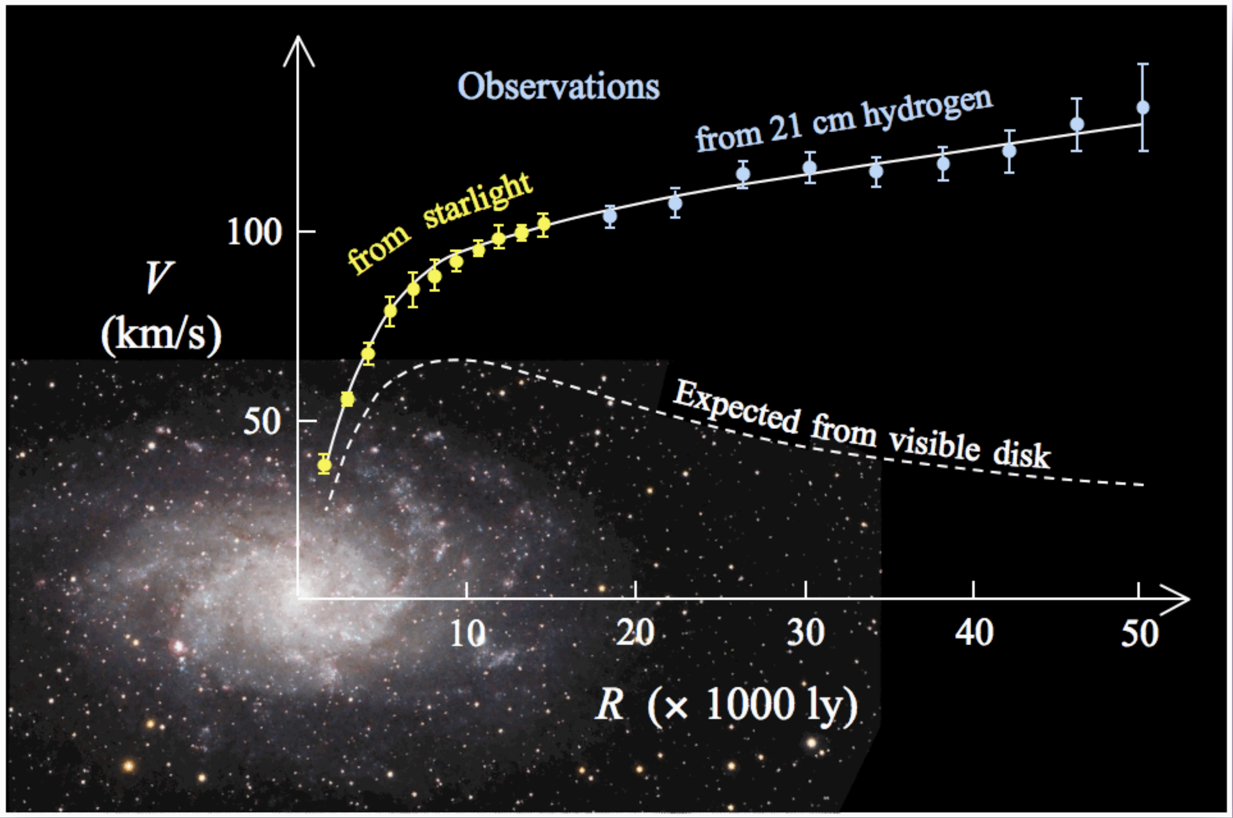
Galaxy Rotation Curves



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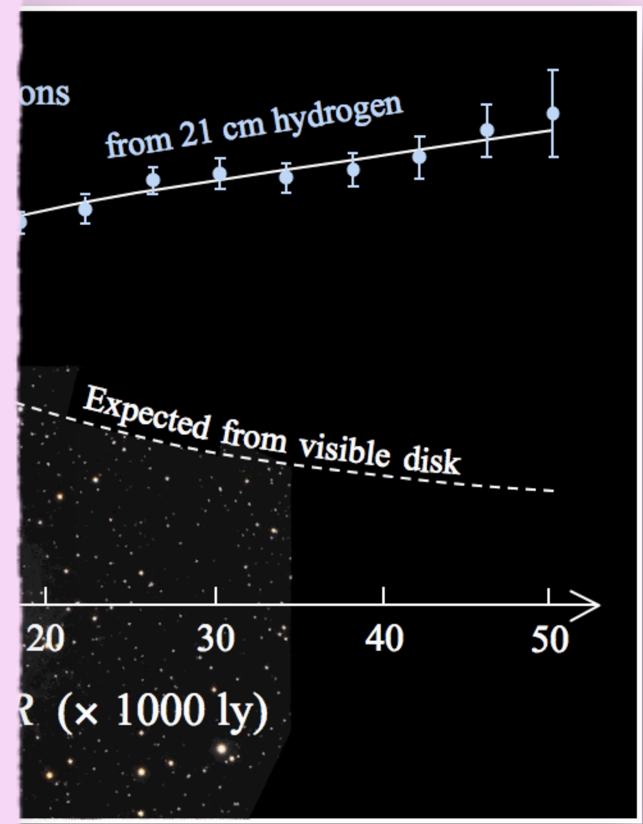
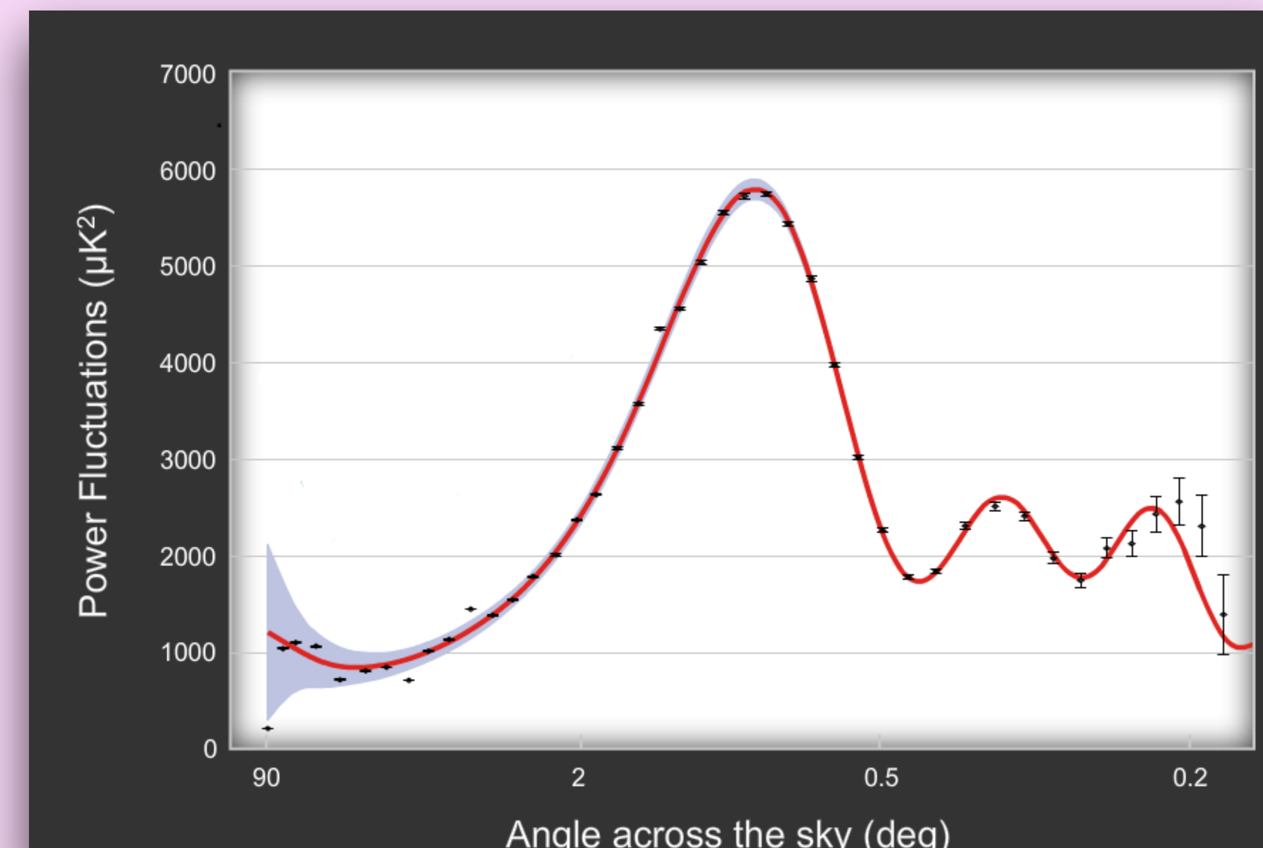


Cosmic Microwave Background



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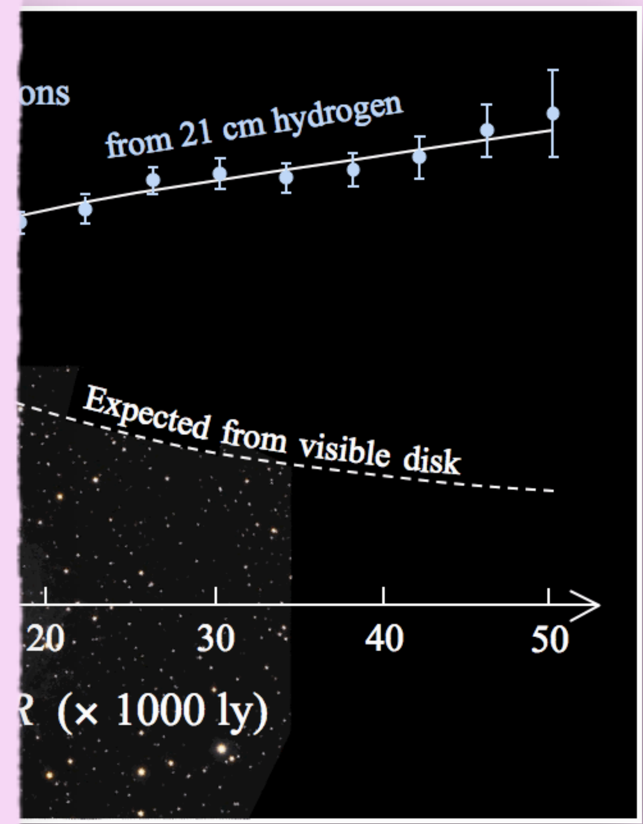

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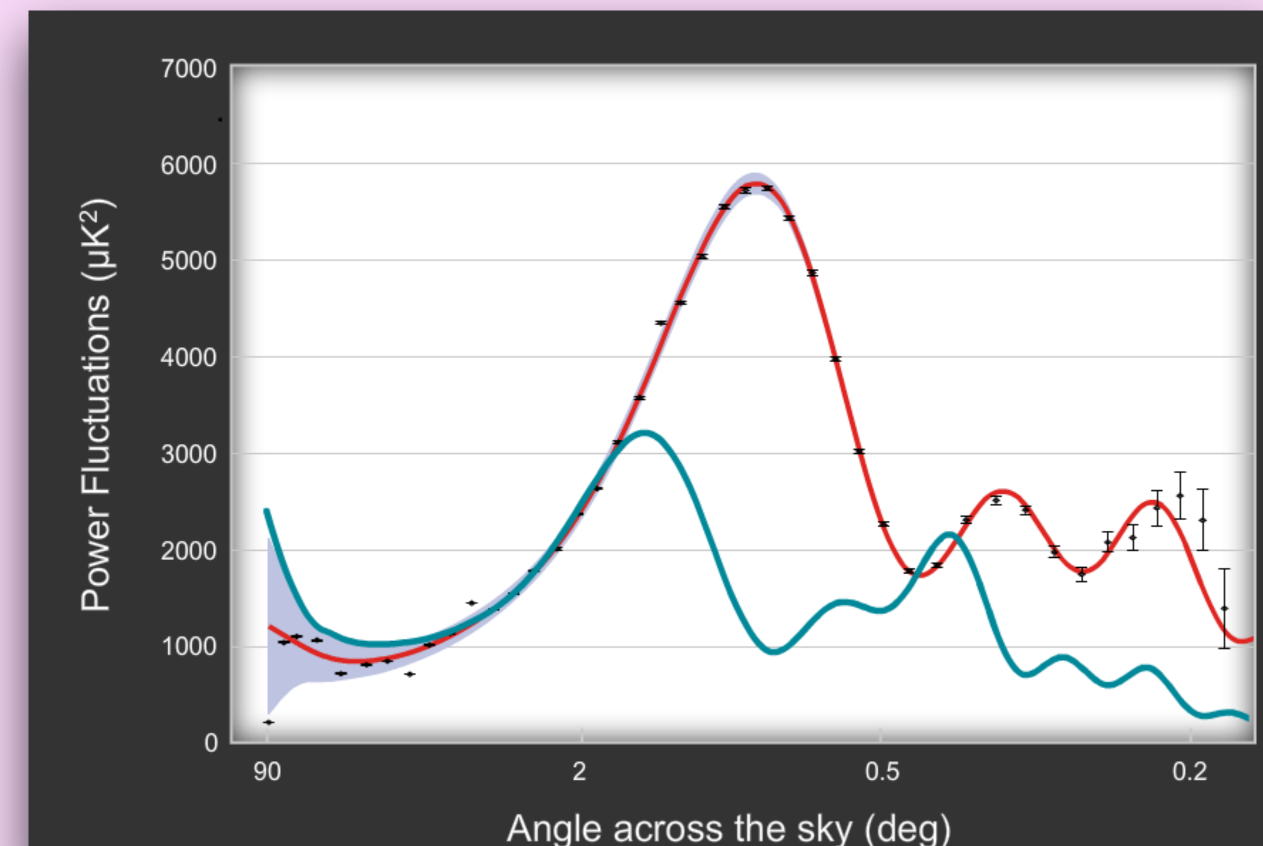

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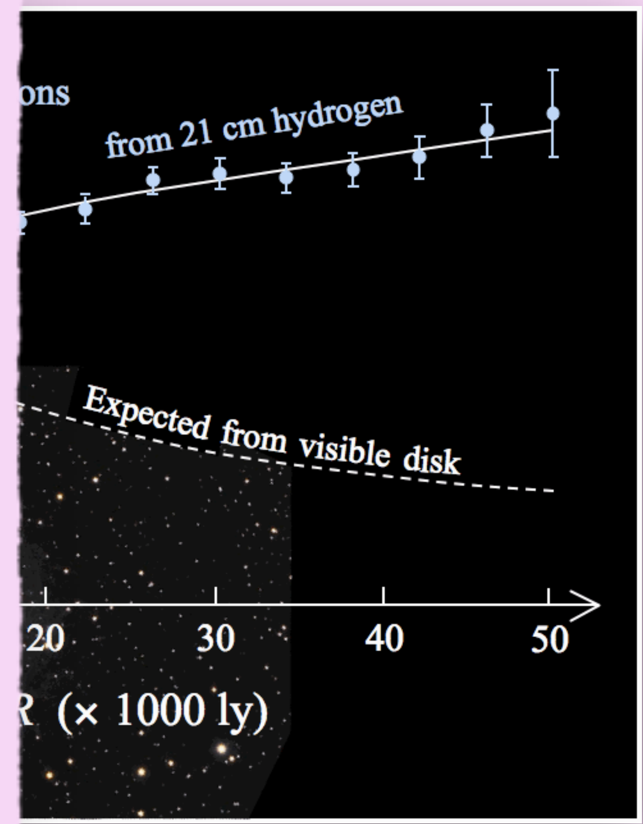

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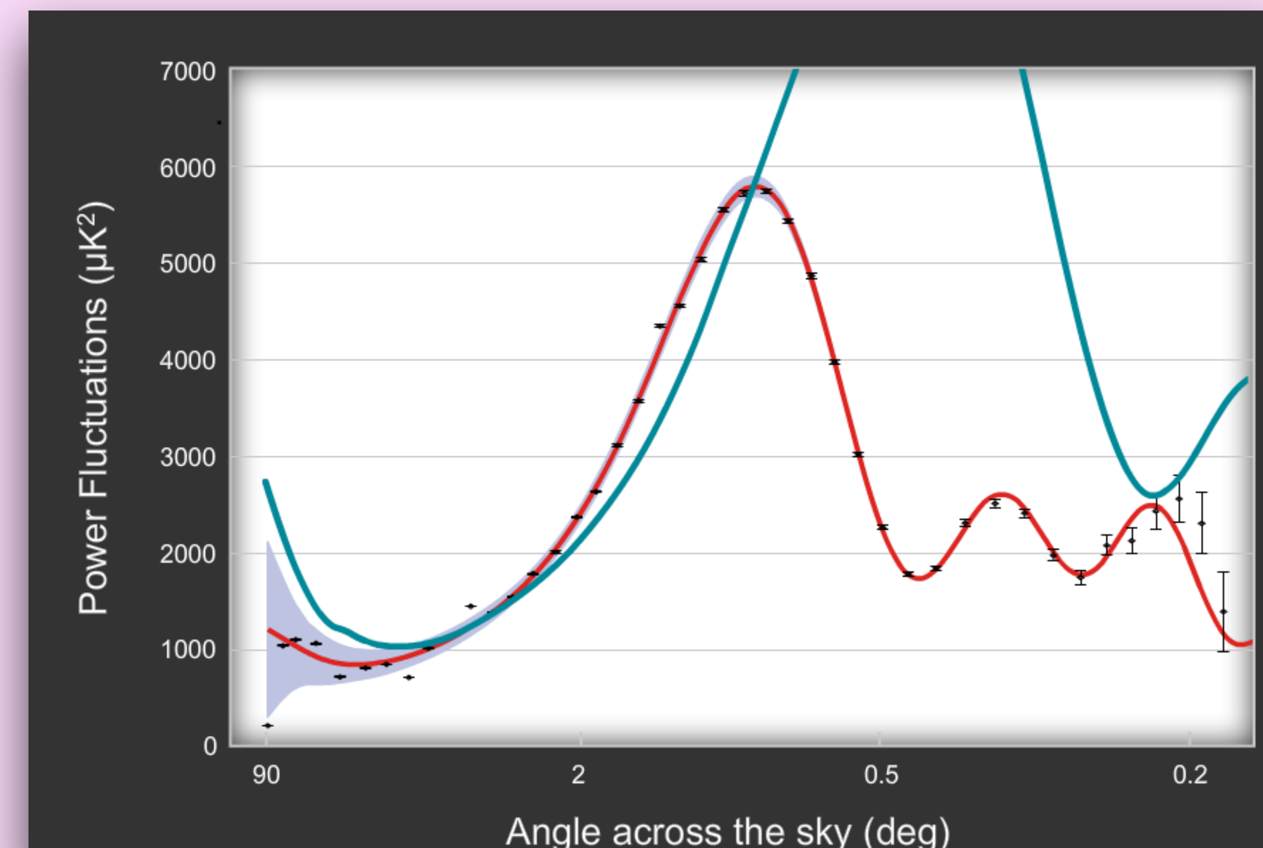
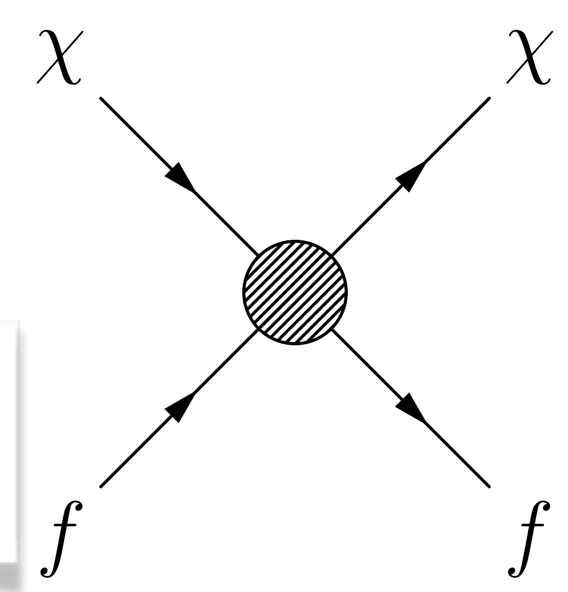


Standard Lore: Thermal Freeze-Out

- 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

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

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Standard Lore: Thermal Freeze-Out

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- ☑ 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

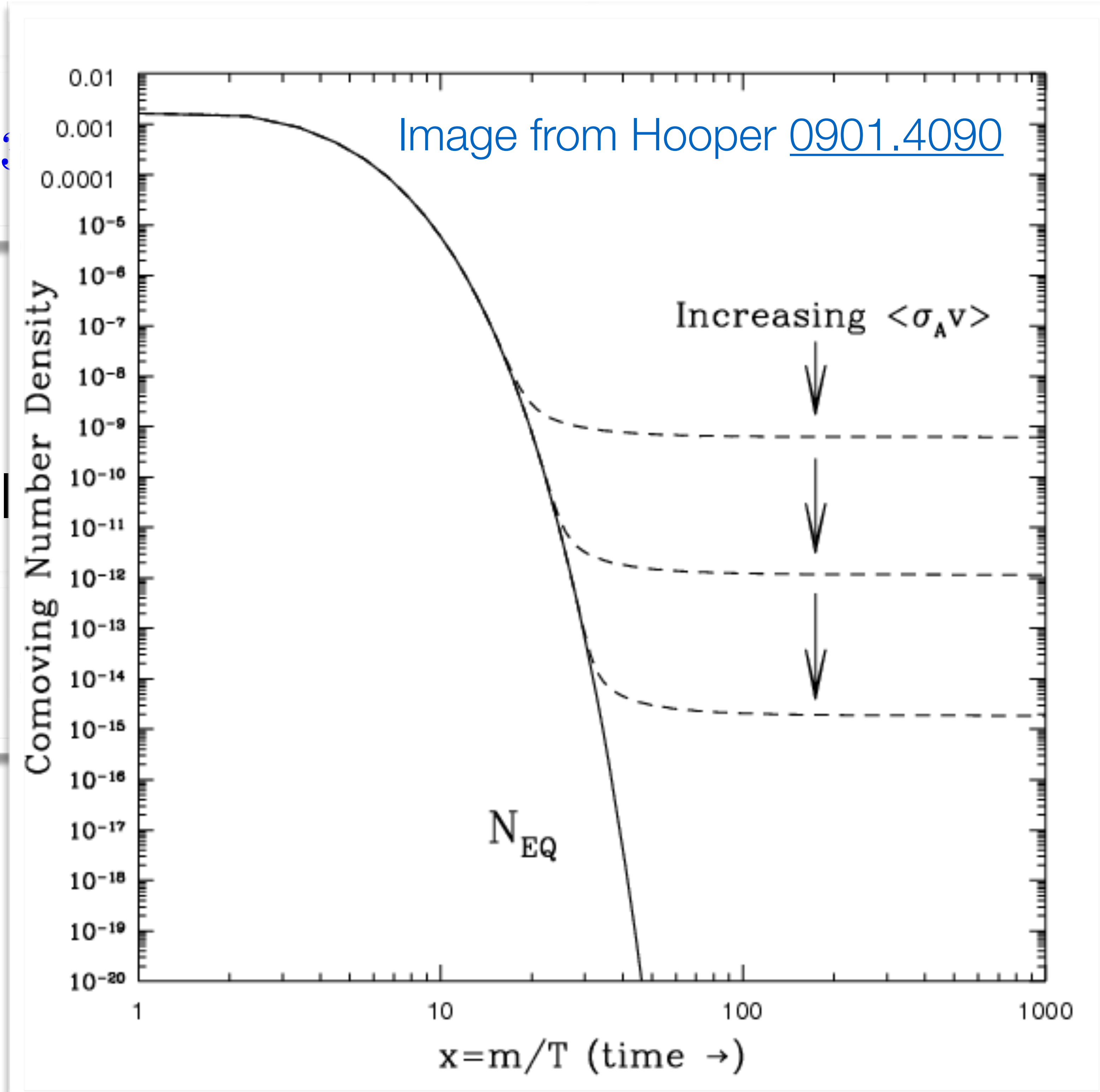
$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle \left(n_\chi^2 - n_{\chi,\rm eq}^2 \right)$$

Standard Lore: Thermal Freeze-Out

$\frac{dn_\chi}{dt} + 3$ … $\to \chi\chi) v_{\rm rel}\rangle \Big)$

- ☑ Detailed … $\chi\chi \to \bar{f} f) v_{\rm rel}\rangle$
- ☑ Final Bol…

$\frac{dn_\chi}{dt} +$ …



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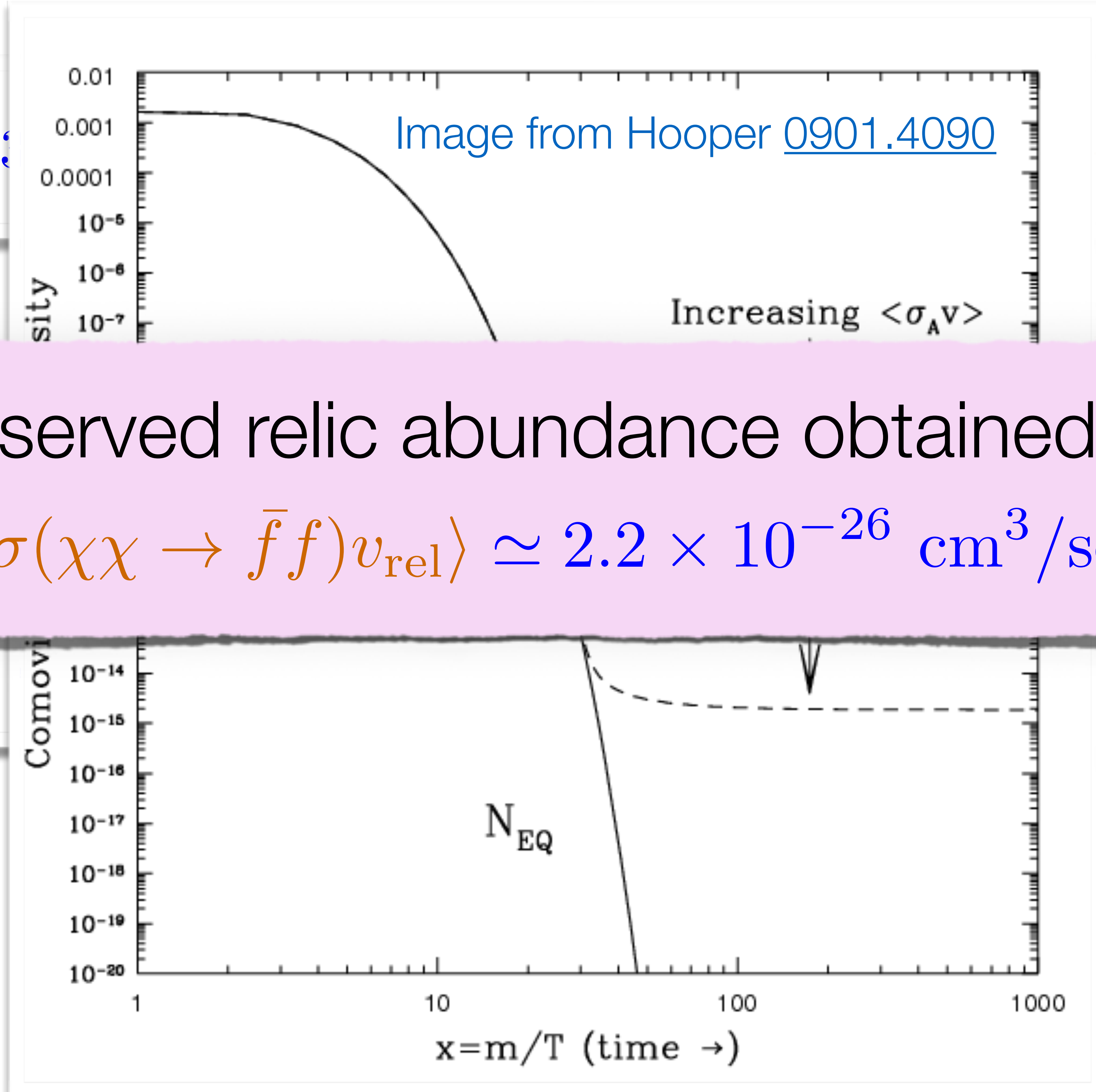
Standard Lore: Thermal Freeze-Out



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 ~ $\alpha_{\rm em}$ ~ 0.01
- ☑ Expect $\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq \text{few} \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$

Standard Lore: Thermal Freeze-Out

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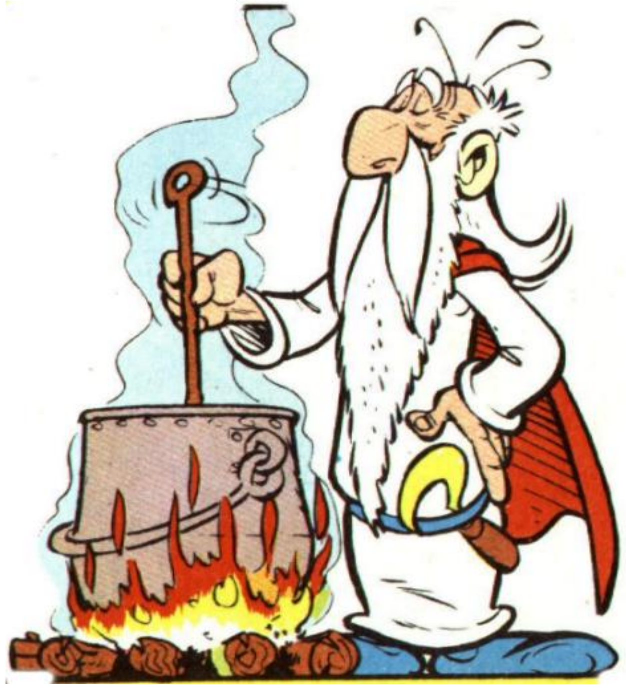
WIMP Miracle



DM annihilation today

observed relic abundance obtained for

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

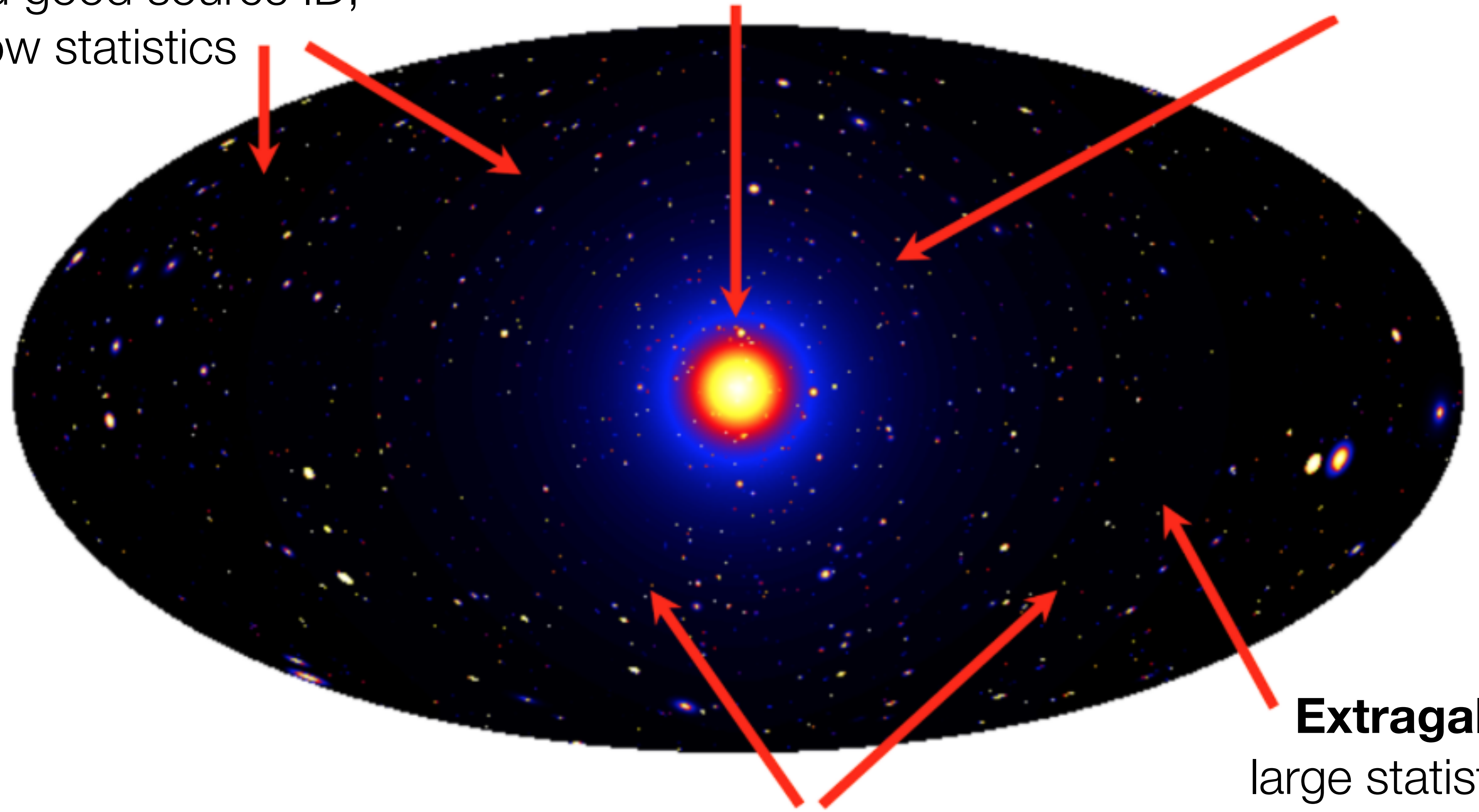
If this is mechanism is responsible for setting the DM abundance in the early Universe,

annihilations should still be happening today

in regions of high DM density

WIMP Dark Matter:
Indirect Detection

Where to look for DM Annihilation?



arXiv:0908.0195,
Fermi-LAT,
KIPAC/Stanford

Messengers of DM Annihilation

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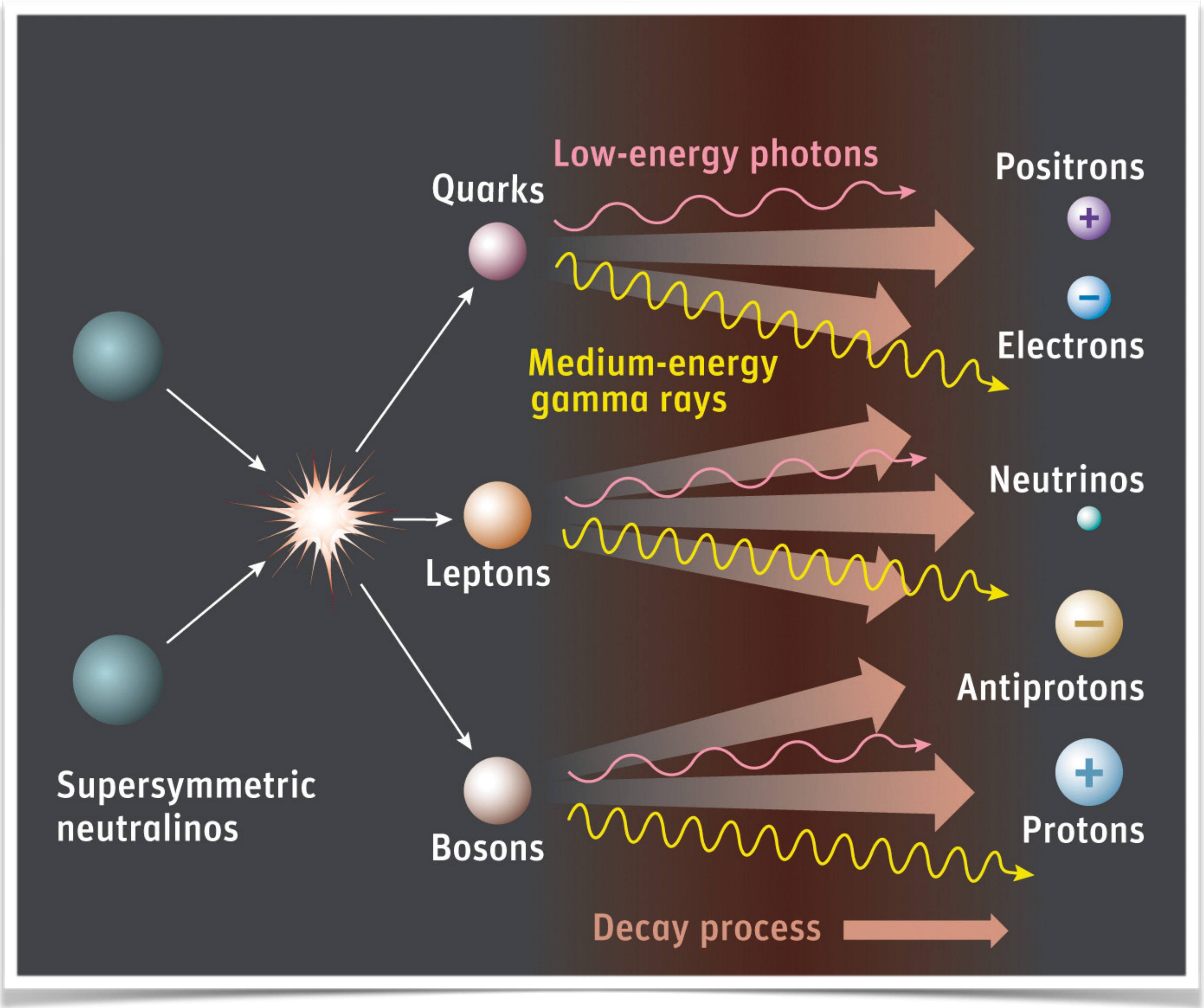

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Messengers of DM Annihilation

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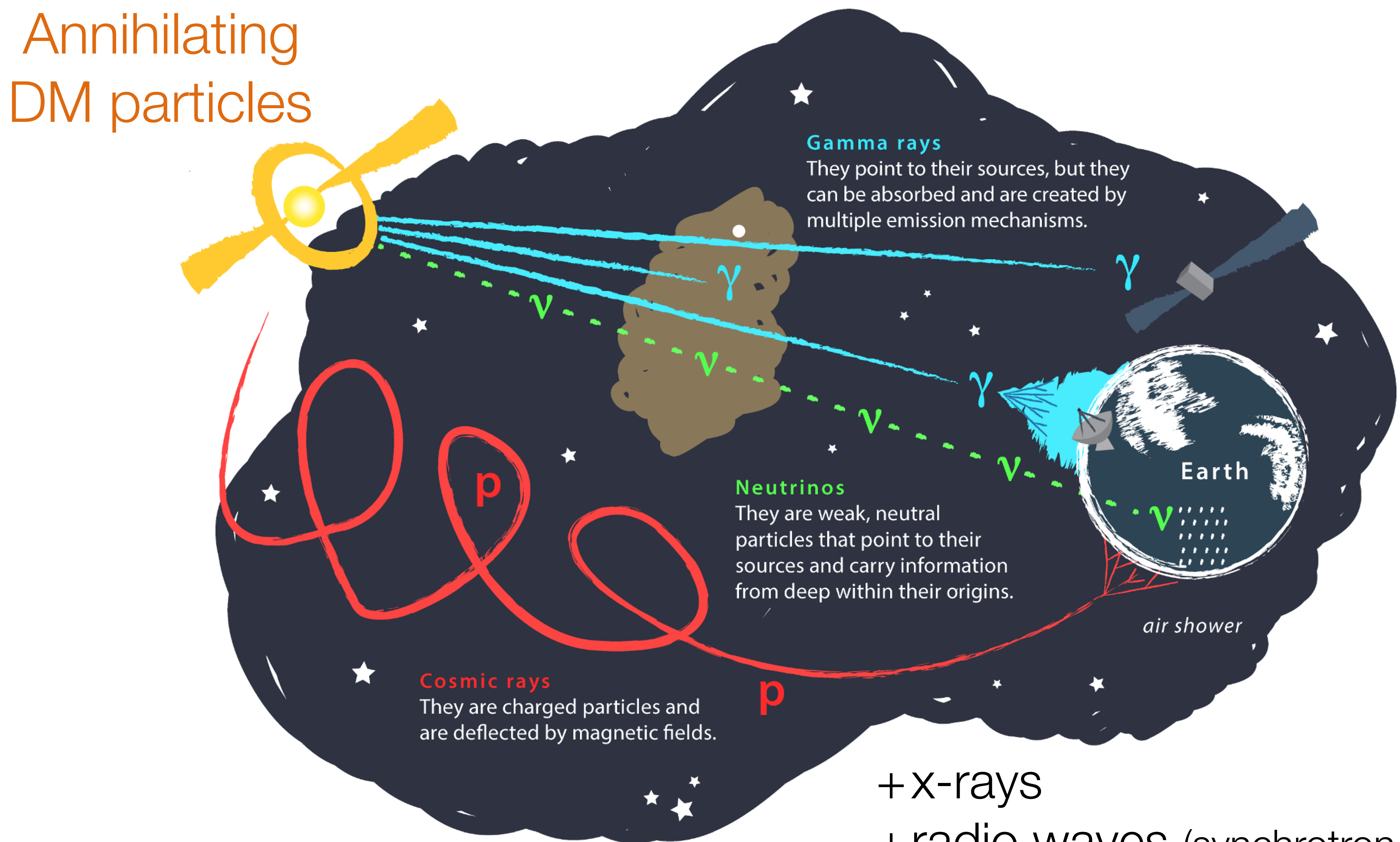
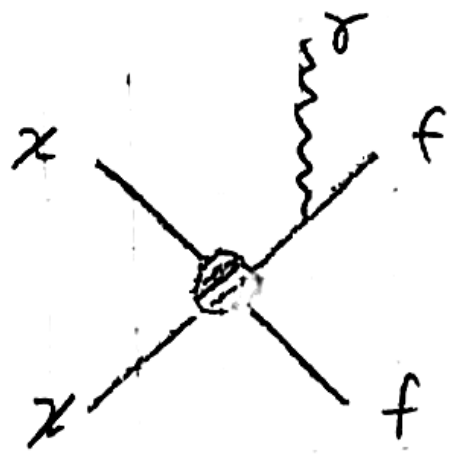


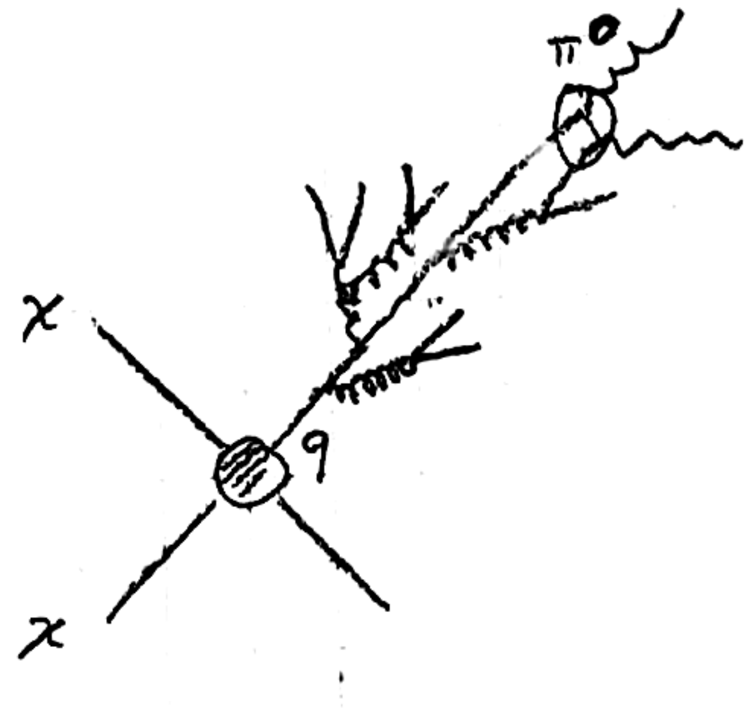
+x-rays
+radio waves (synchrotron emission)
+…

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

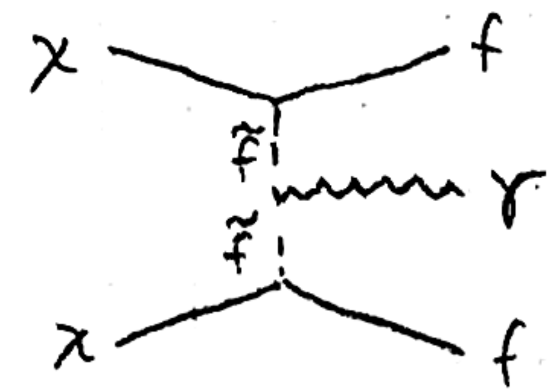
Prompt Gamma Rays from DM Annihilation



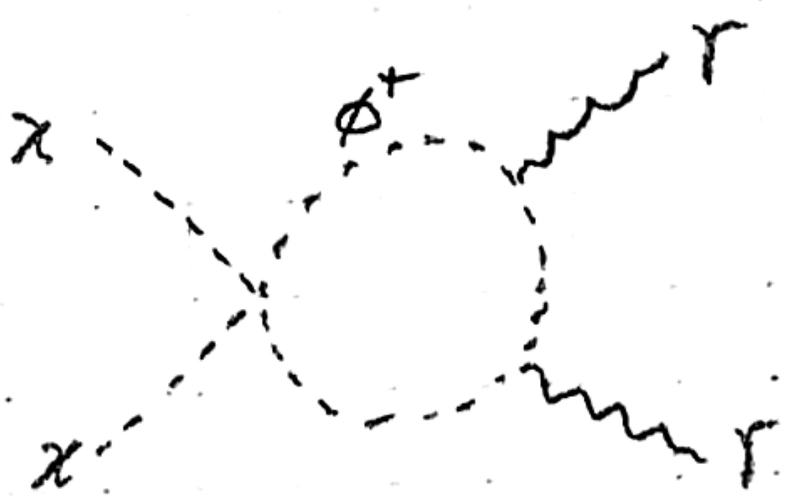
final state radiation



π^0 decay
(for hadronic final states)

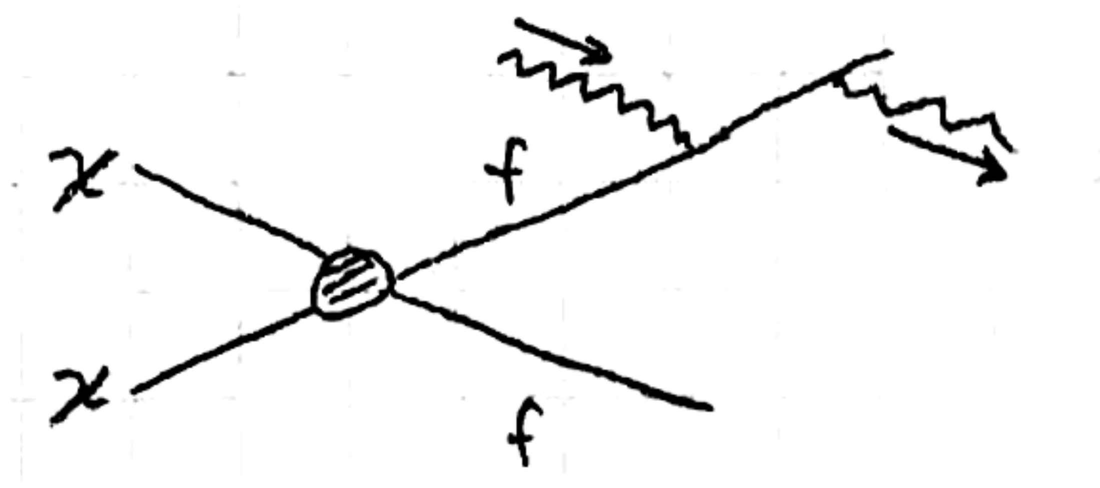


internal bremsstrahlung
(for charged mediators)



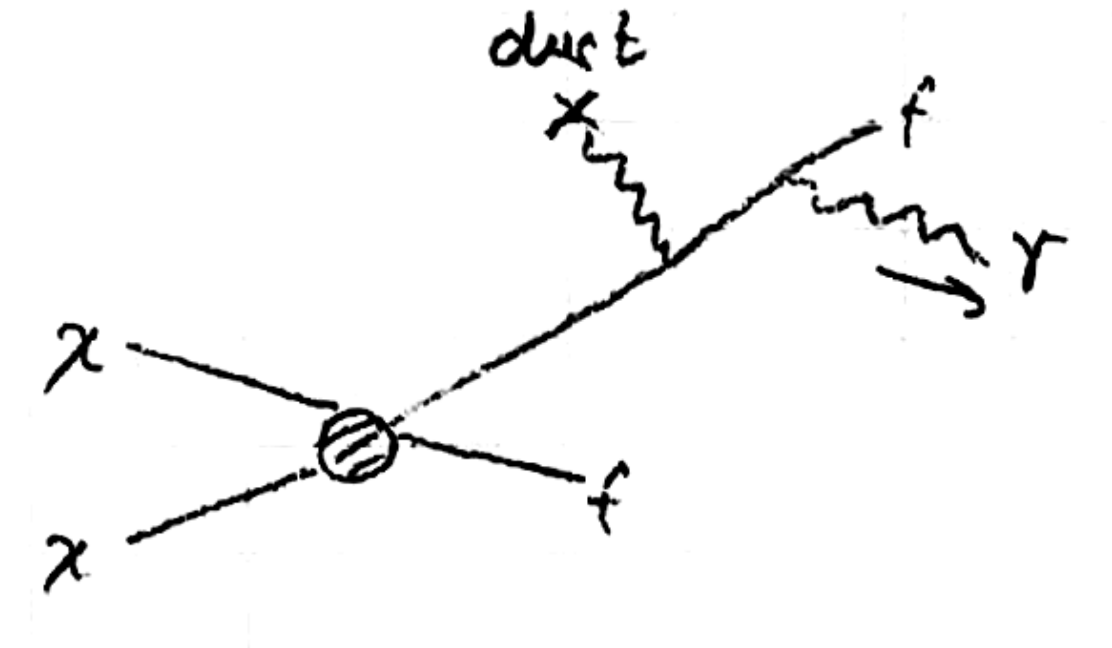
direct annihilation
(via loops of charged particles)

Secondary Gamma Rays from DM Annihilation



inverse Compton scattering

on starlight or the CMB



bremsstrahlung

(less important)

Gamma Ray Flux at Earth

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

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line of sight
in direction ψ

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DM mass density

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DM mass density

injection spectrum

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J-factor
contains all dependencies on astrophysics

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J-factor
contains all dependencies on astrophysics

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

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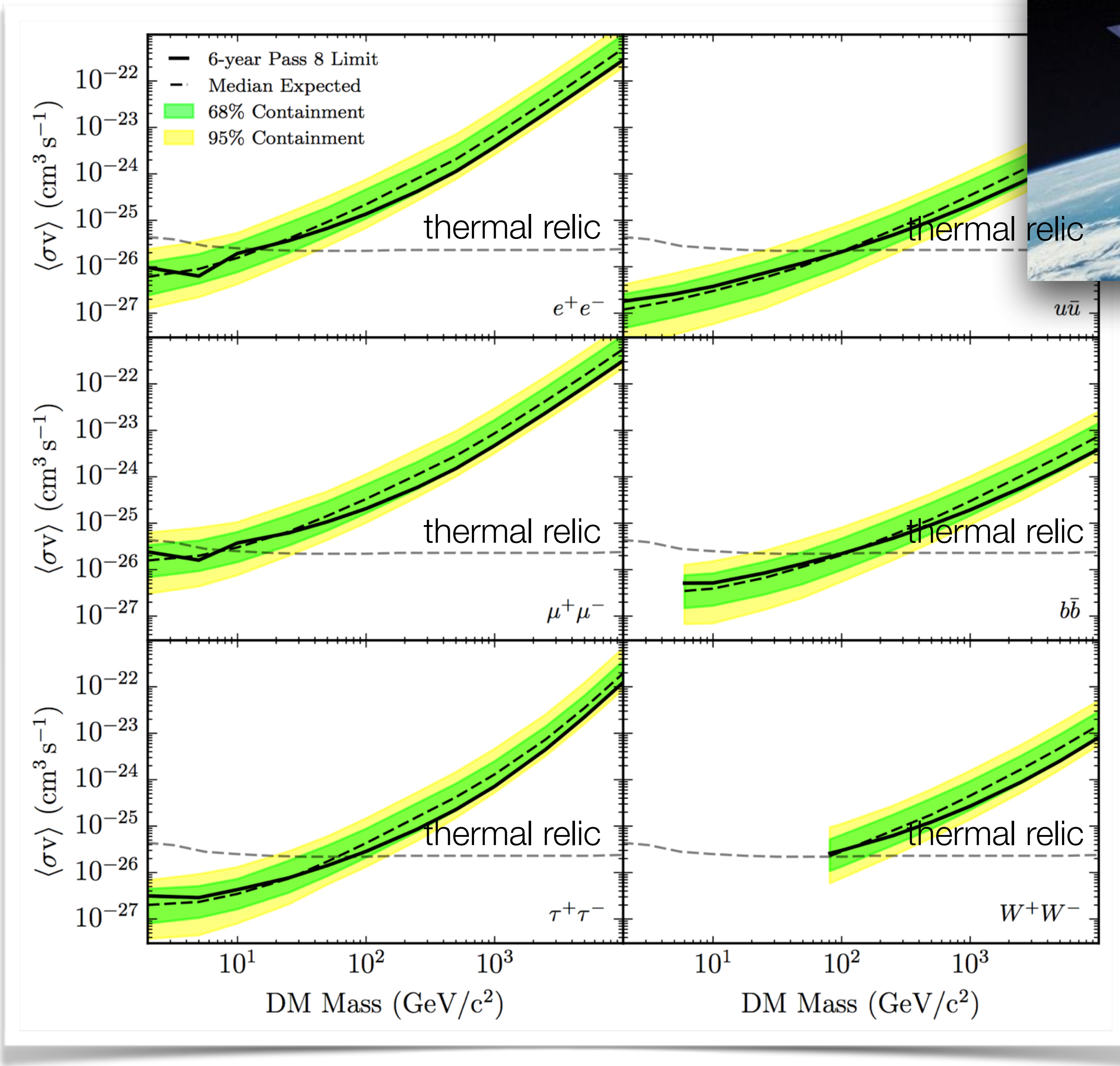
Fermi-LAT Limits from Dwarf Galaxies



Credit: Fermi-LAT

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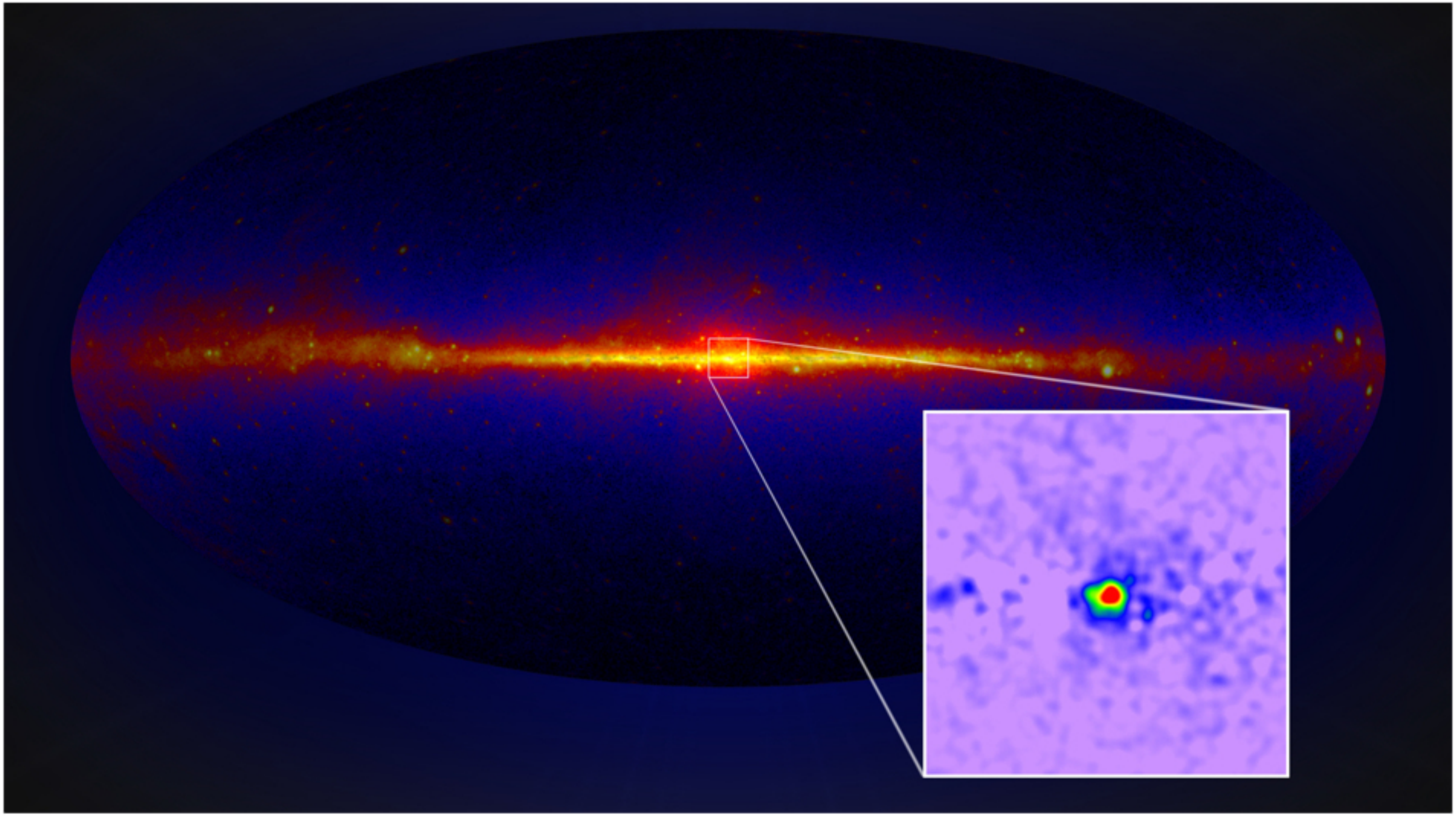
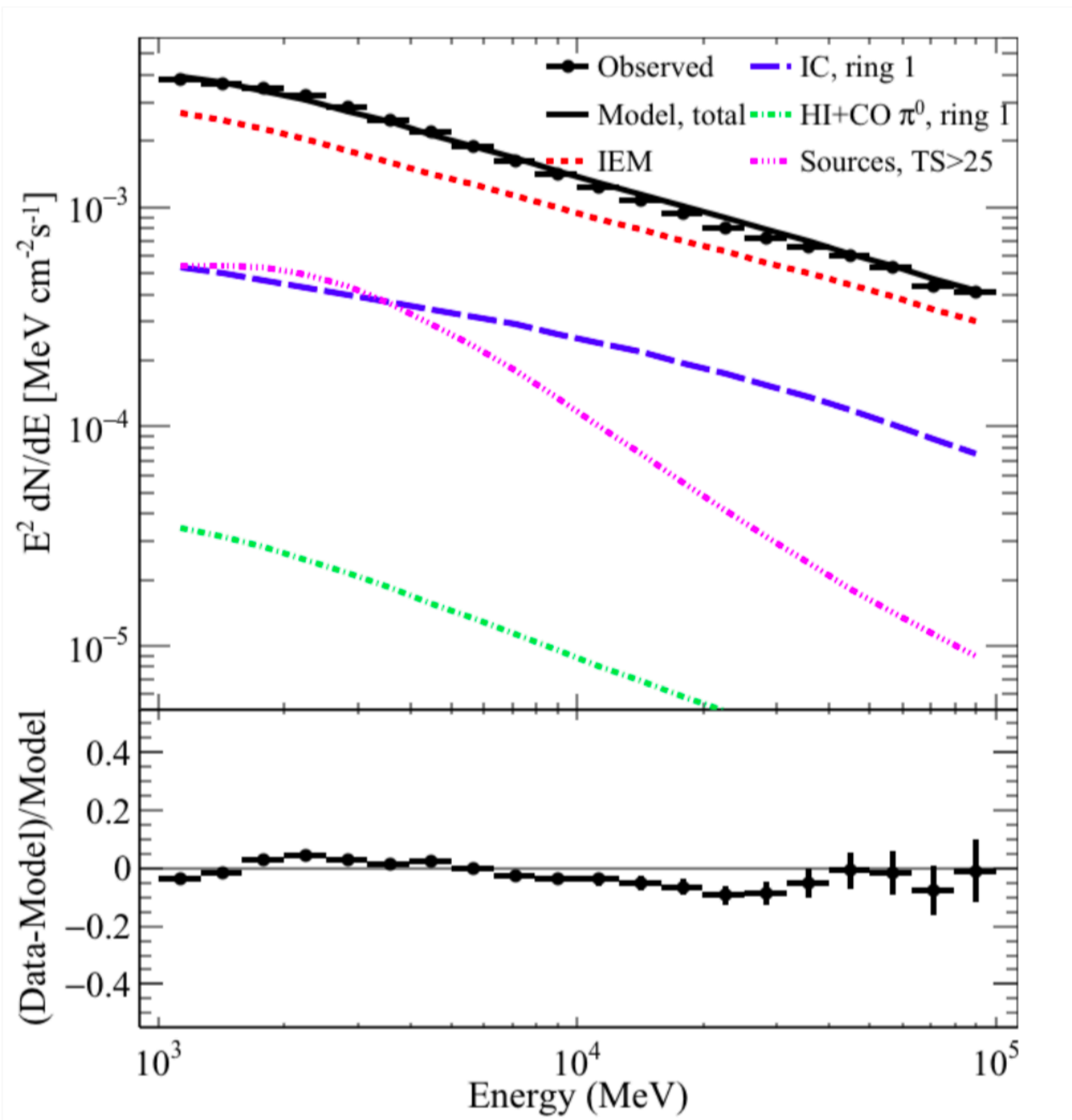
The Galactic Center Excess



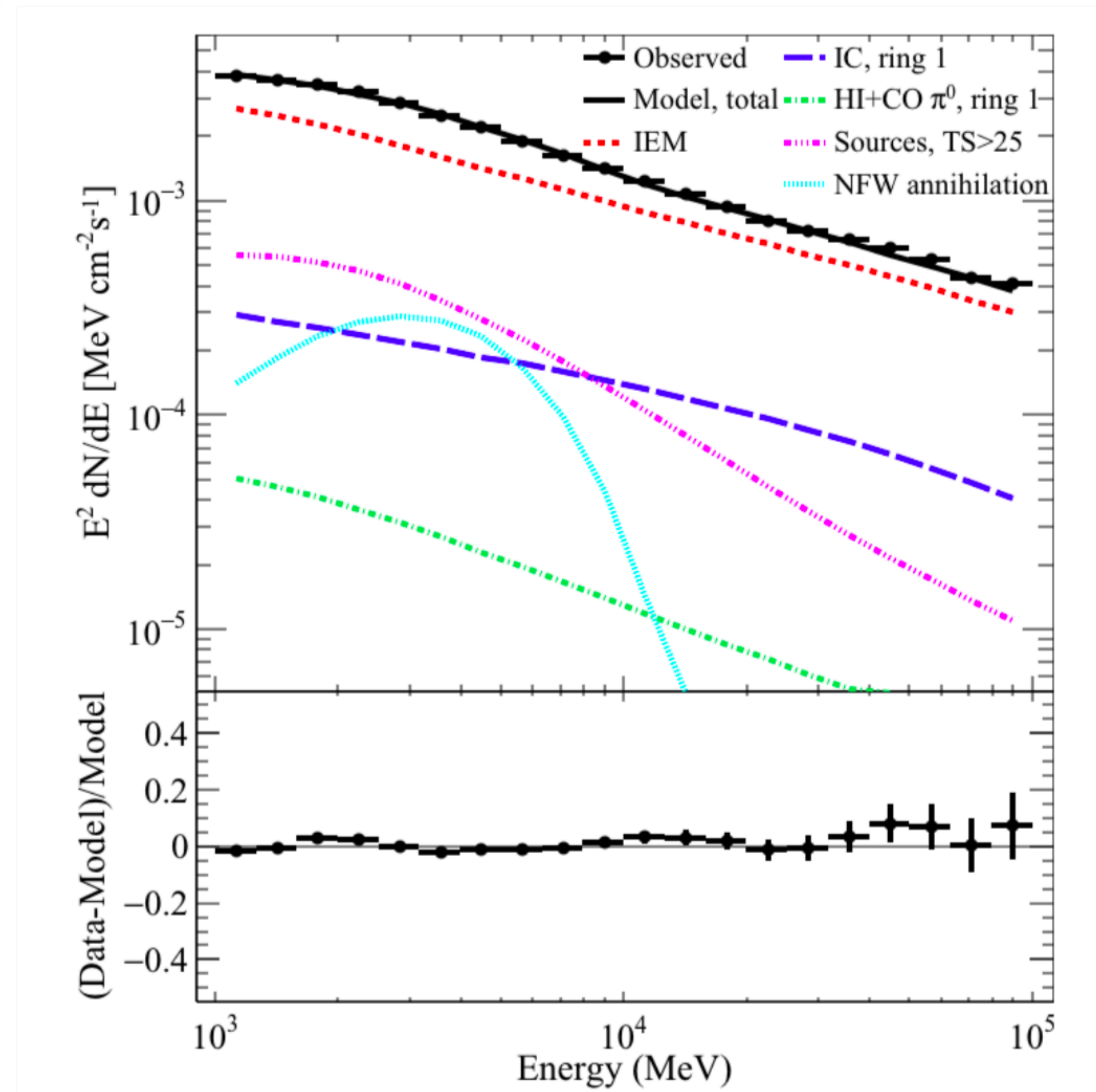
Credit: Tim Linden & NASA

Dark Matter or Astrophysics?

no DM



including DM annihilation



Fermi-Lat, arXiv:1511.02938

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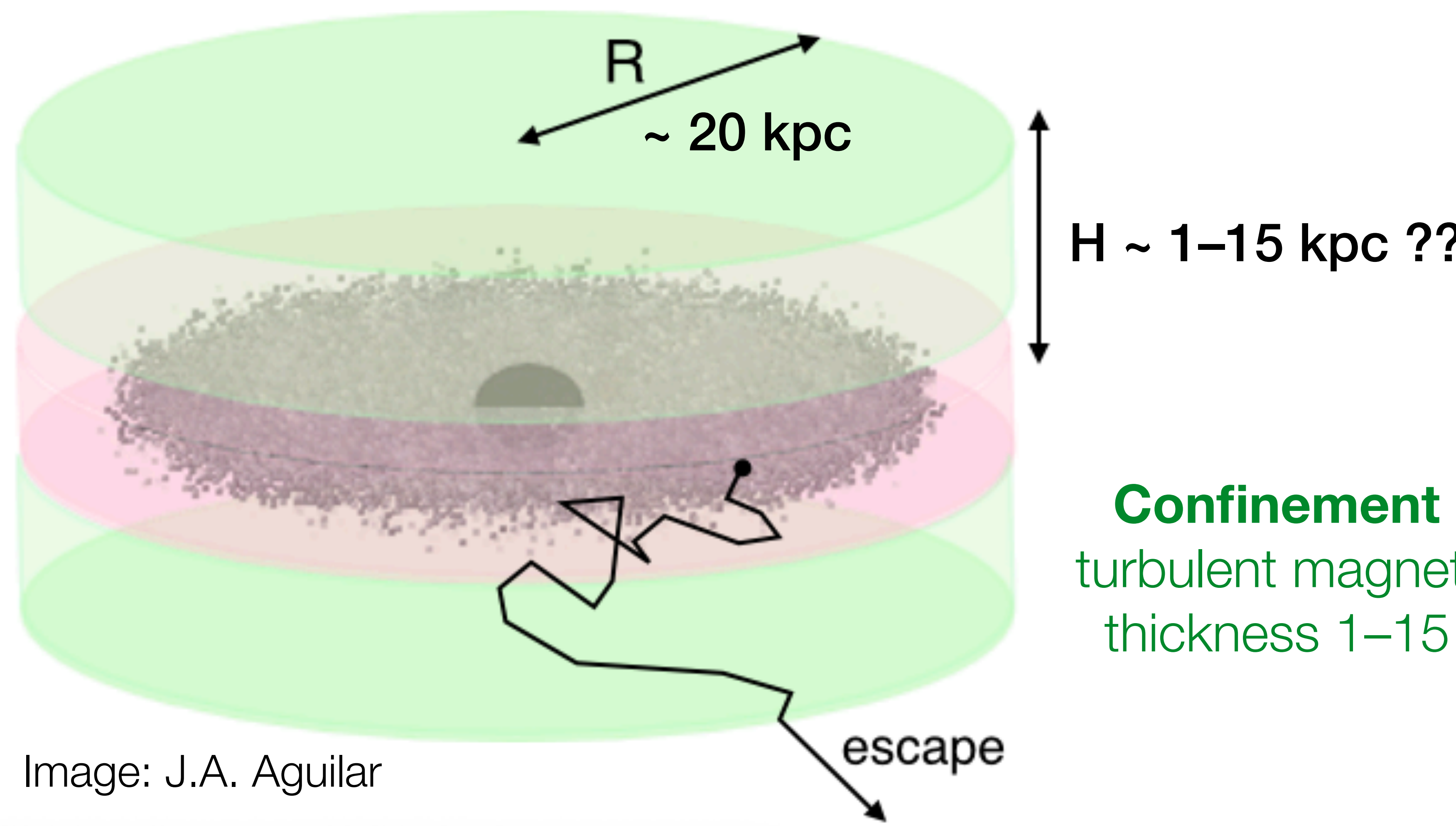
Cosmic Ray Transport — Leaky Box Model

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



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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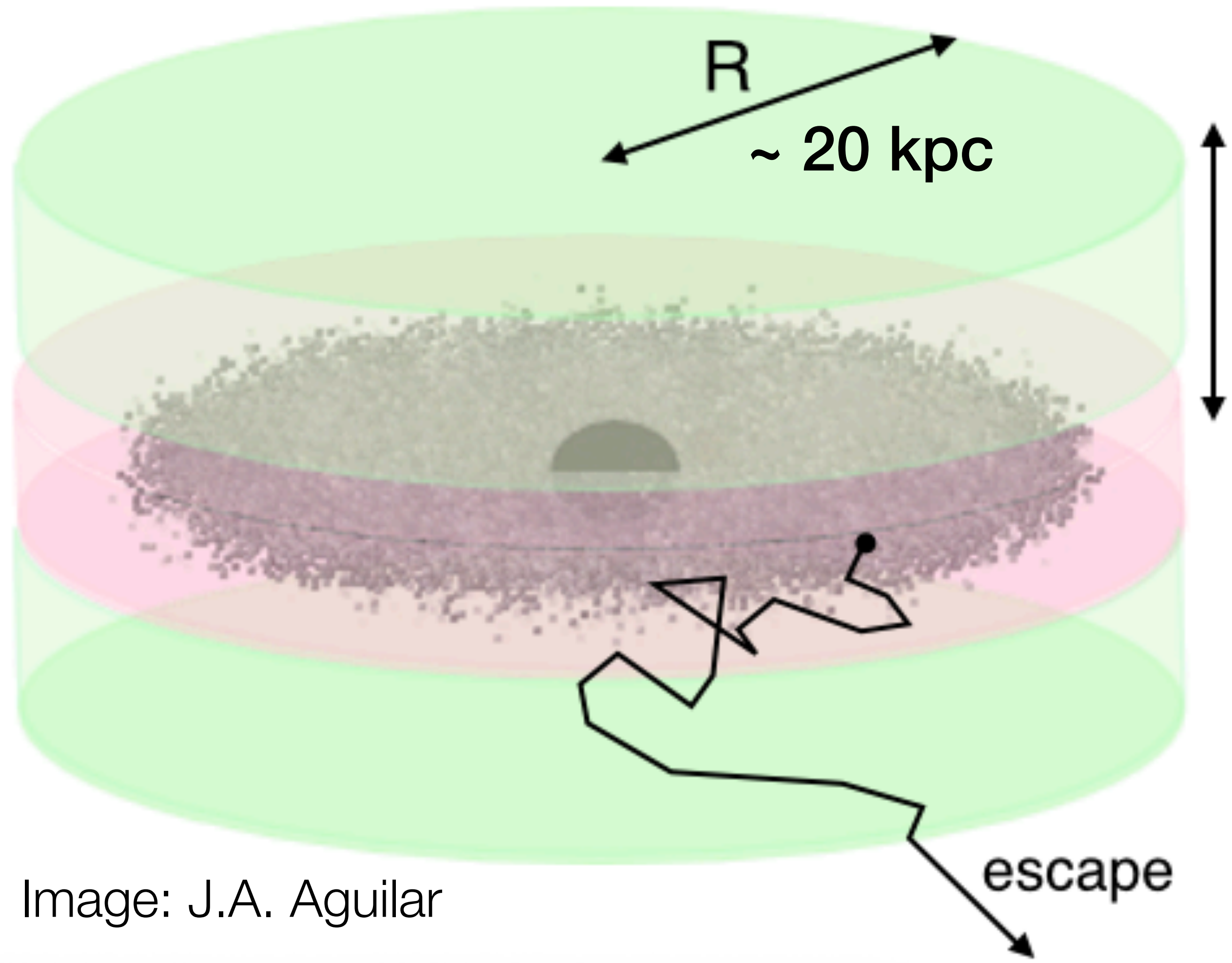

Image: J.A. Aguilar

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density of particles
per unit energy

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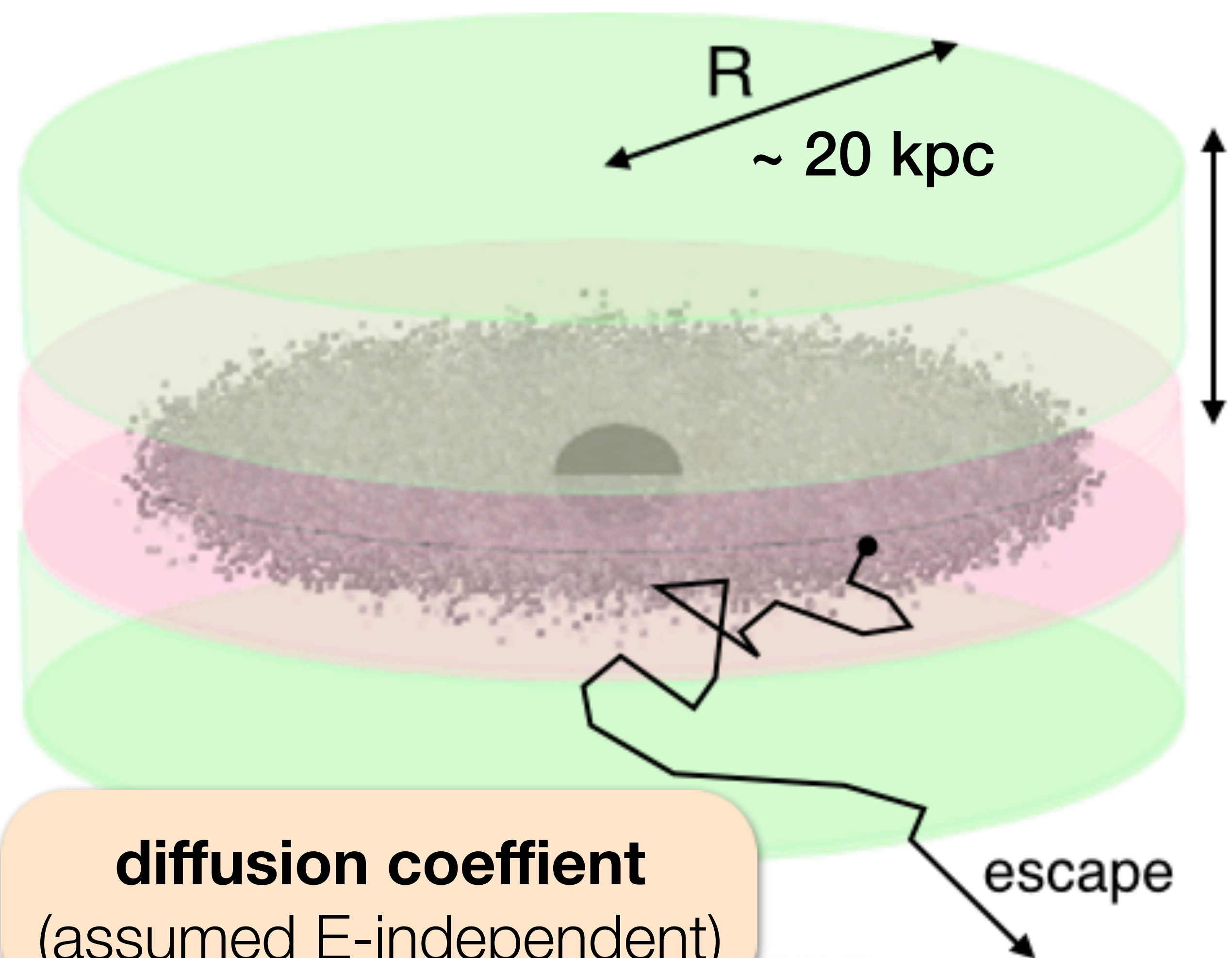

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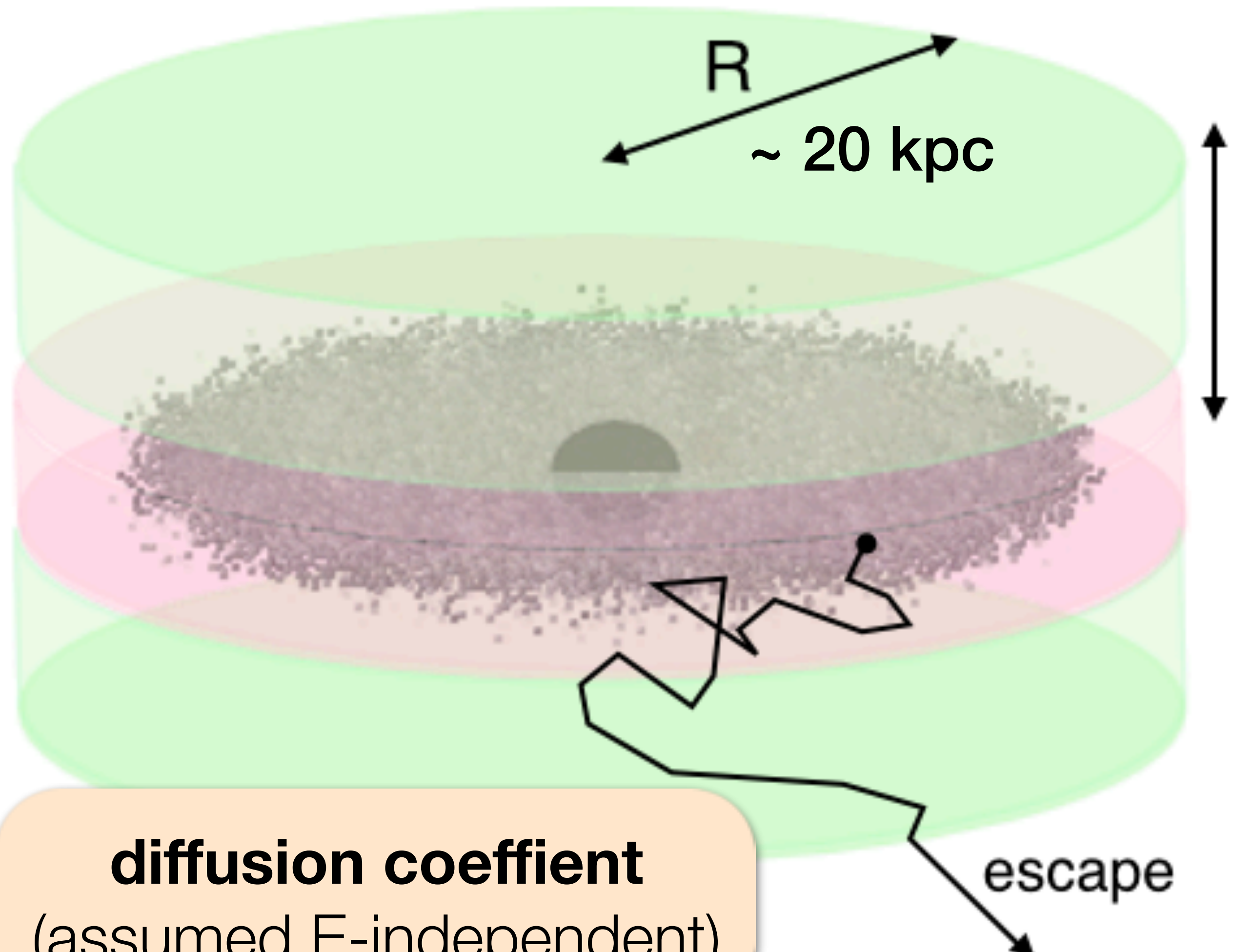
Cosmic Ray Transport — Leaky Box Model



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loss function

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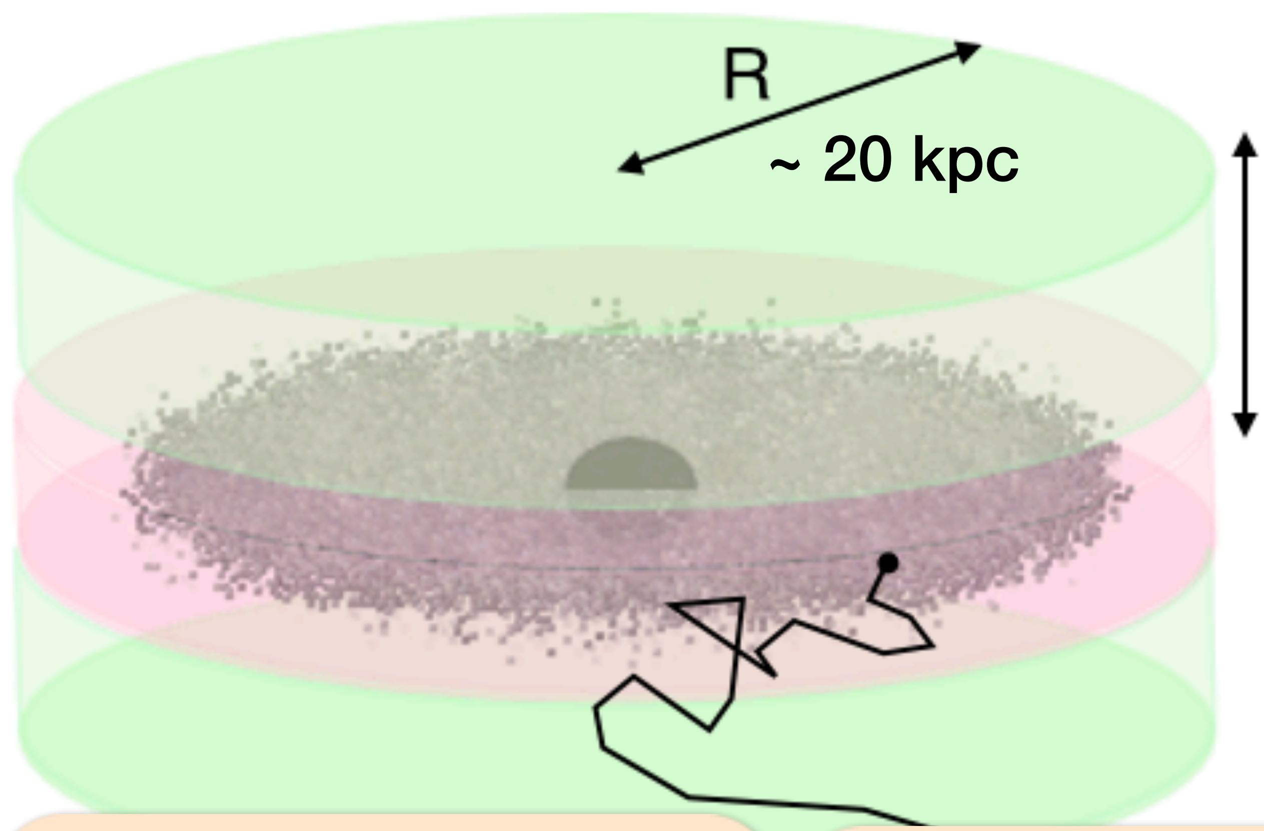
Cosmic Ray Transport — Leaky Box Model



Galactic Disk
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Confinement Layer
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density of particles
per unit energy

diffusion coeffient
(assumed E-independent)

convective wind

Master equation (diffusion–loss equation)

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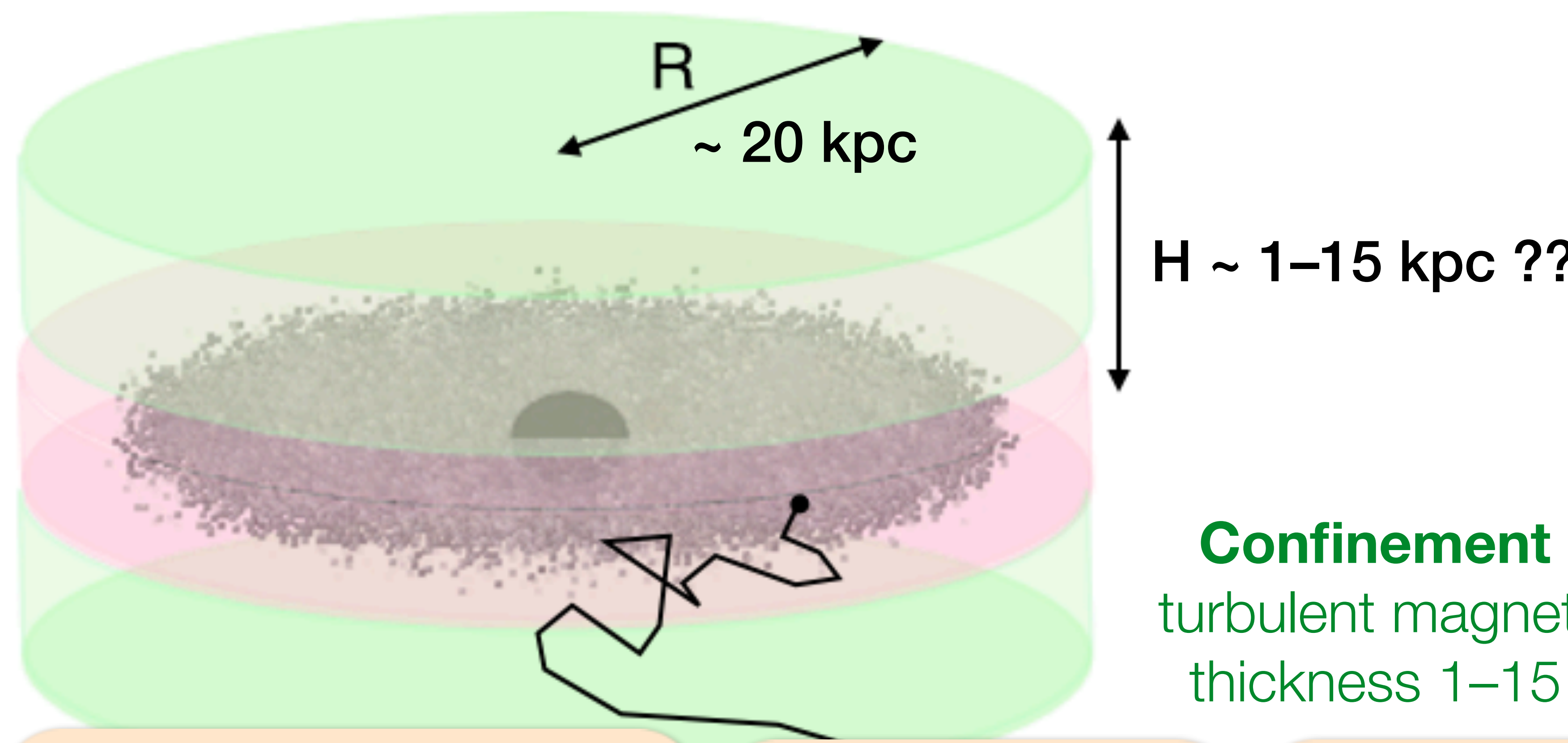
loss function

Cosmic Ray Transport — Leaky Box Model



Galactic Disk
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density of particles
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convective wind

source term

Master equation (diffusion–loss equation)

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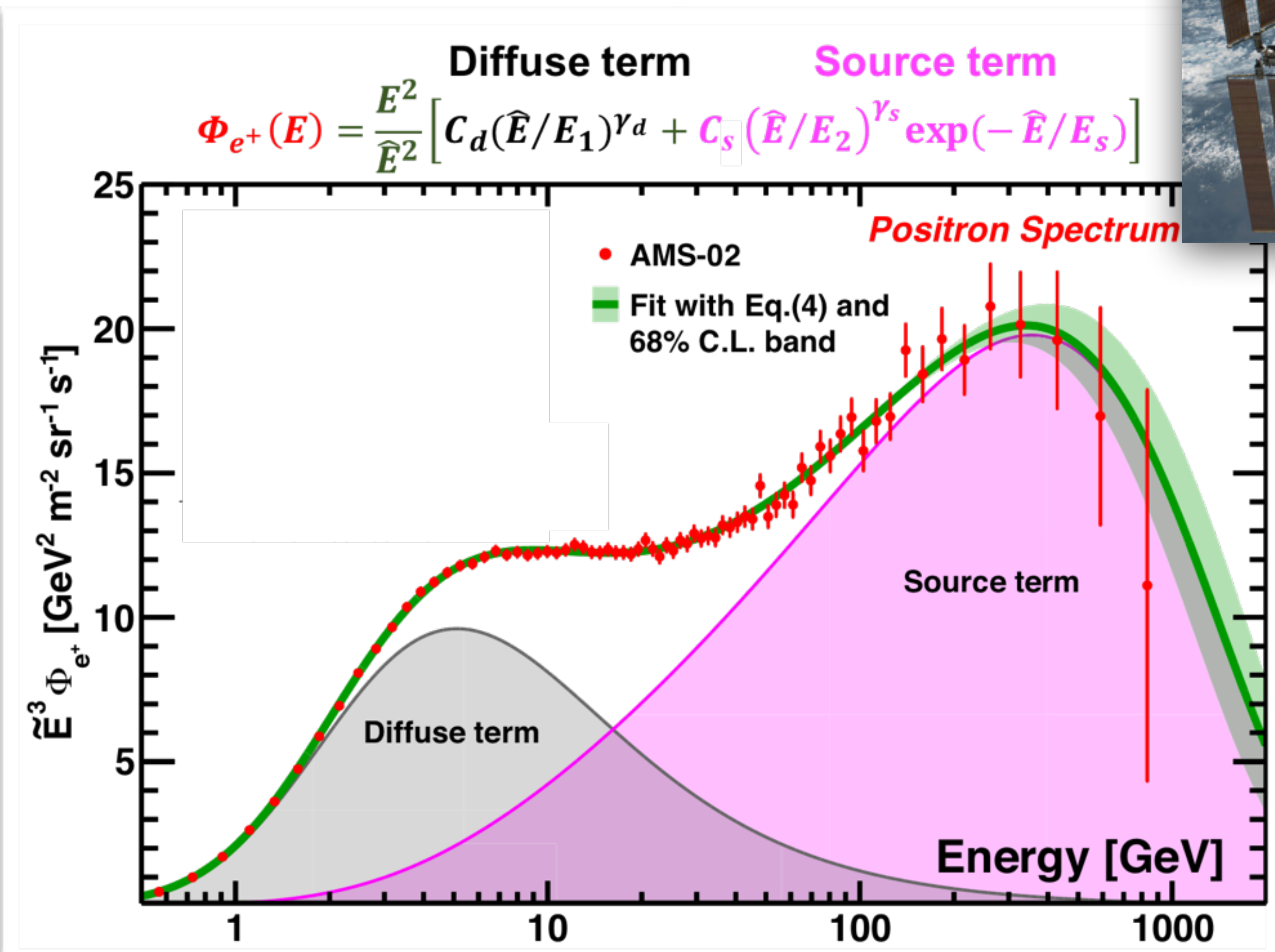
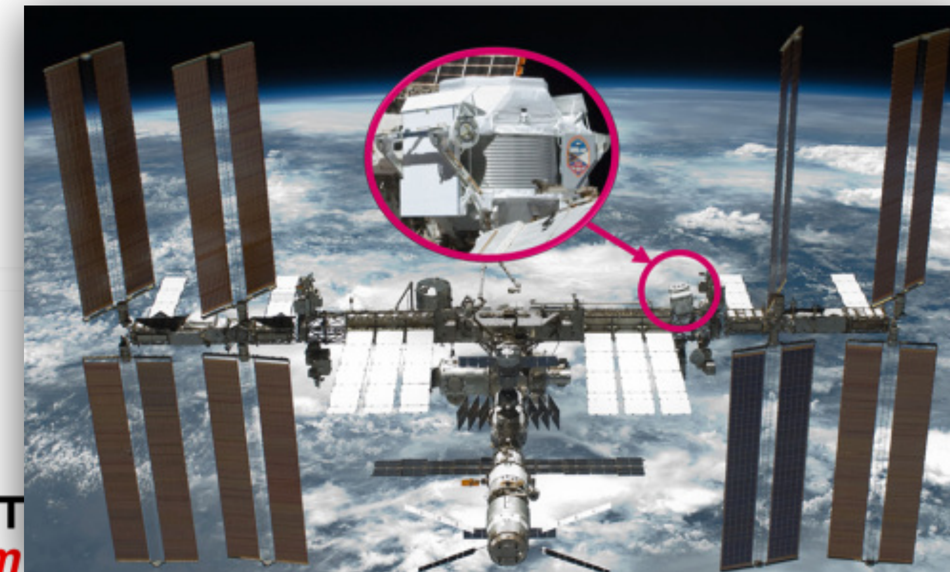
loss function

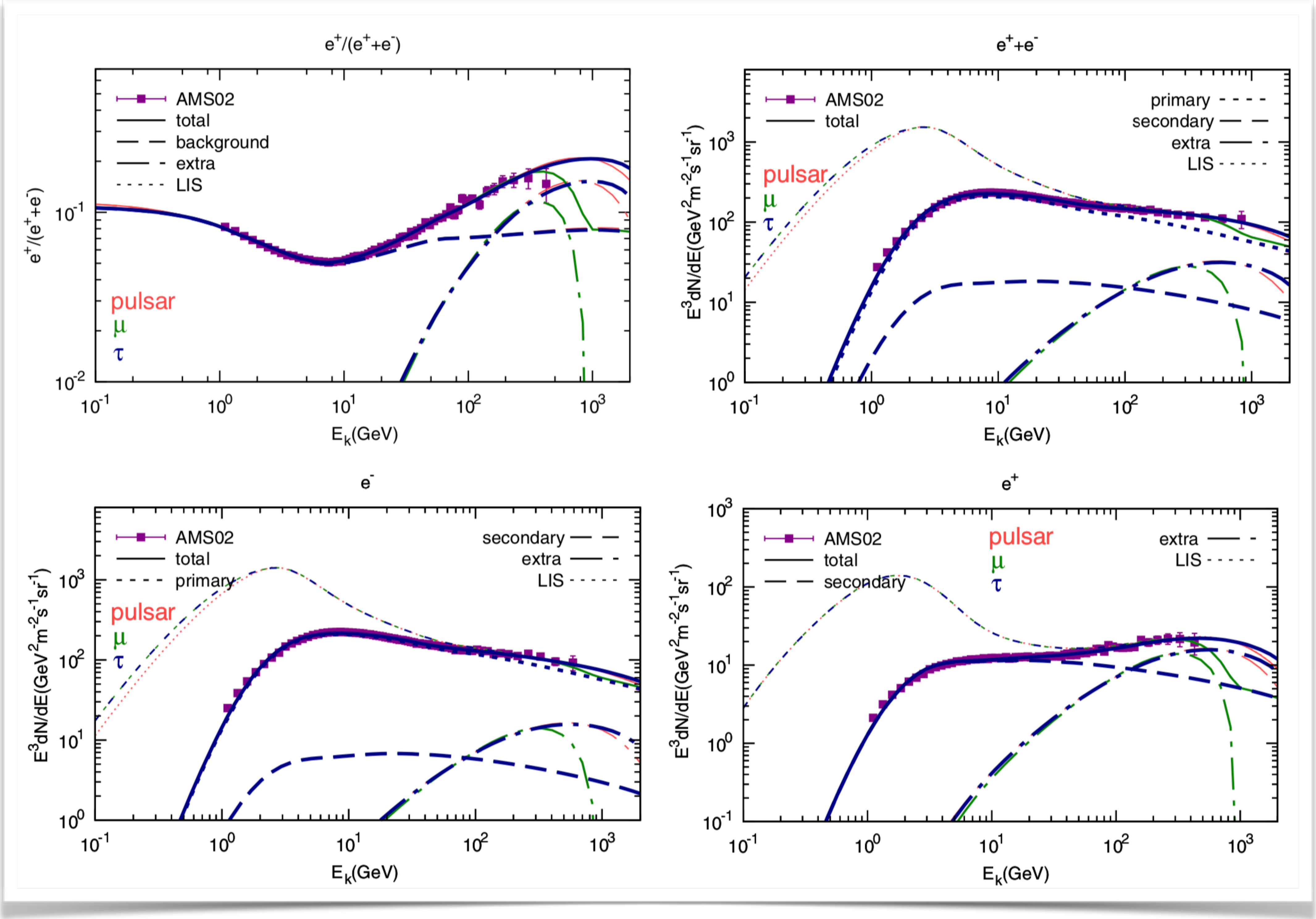
AMS-02 Positron Excess





Source: AMS-02

Dark Matter or Pulsars?



Lin Yuan Bi, arXiv:1409.6248

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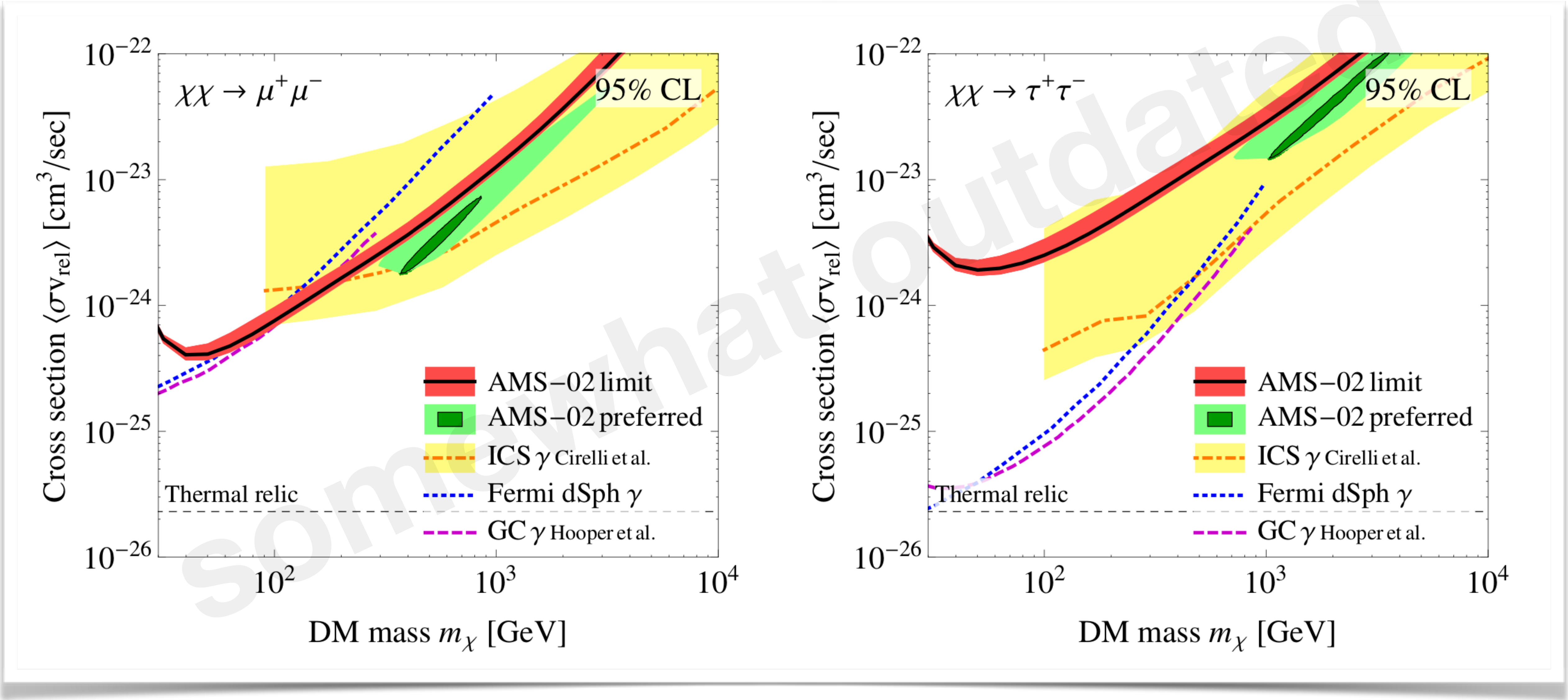
AMS-02 Dark Matter Constraints

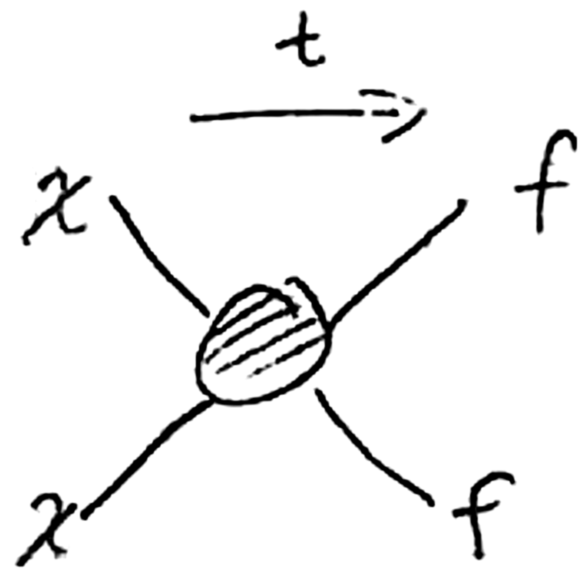


JK arXiv:1304.1184

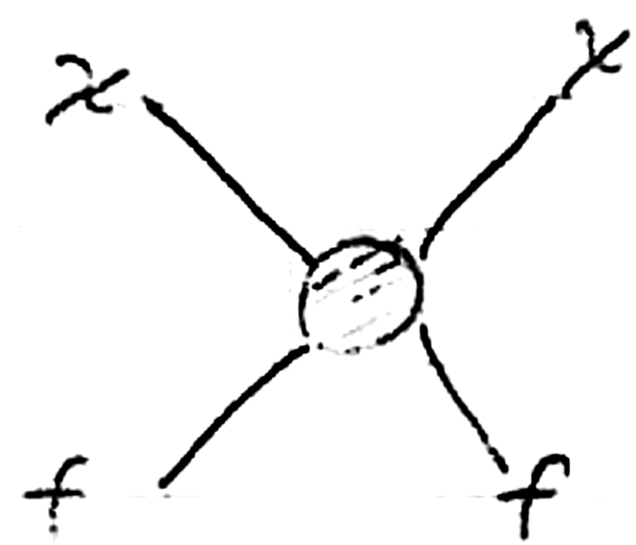
WIMP Dark Matter:
Direct Detection

Direct Detection of WIMP Dark Matter

- ☑ Annihilation:



- ☑ Turn diagram around
  ➠ DM scattering



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

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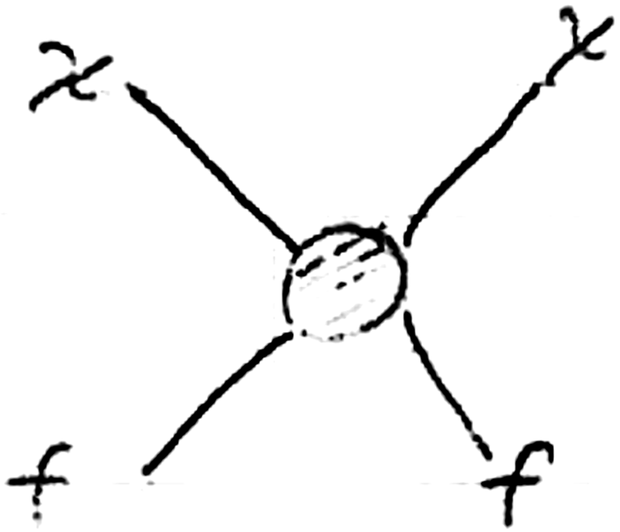
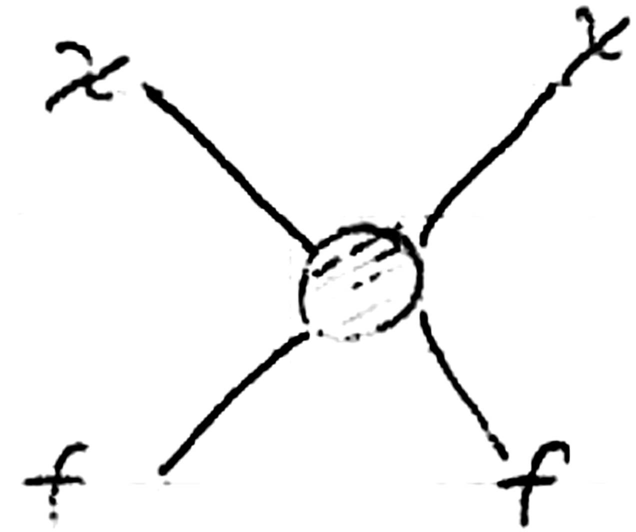
Direct Detection in a Toy Model



Direct Detection in a Toy Model

- Toy Model: scalar- (e.g. Higgs-) mediated DM interactions

$$\mathcal{L} \supset \sum_q \frac{m_q}{\Lambda^3} (\bar{\chi}\chi)(\bar{q}q)$$



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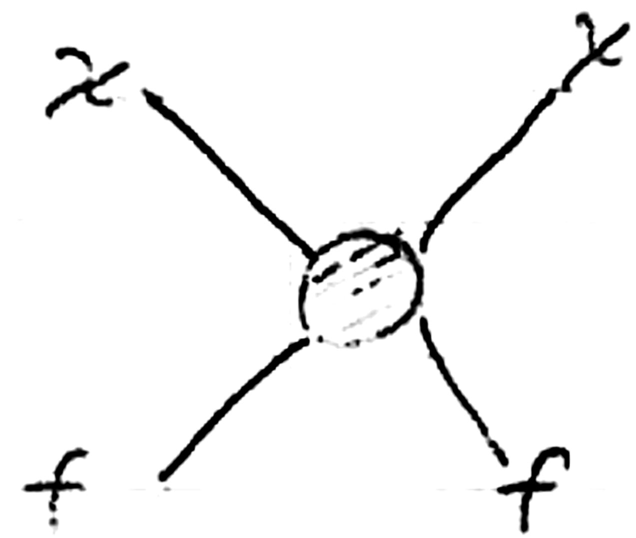
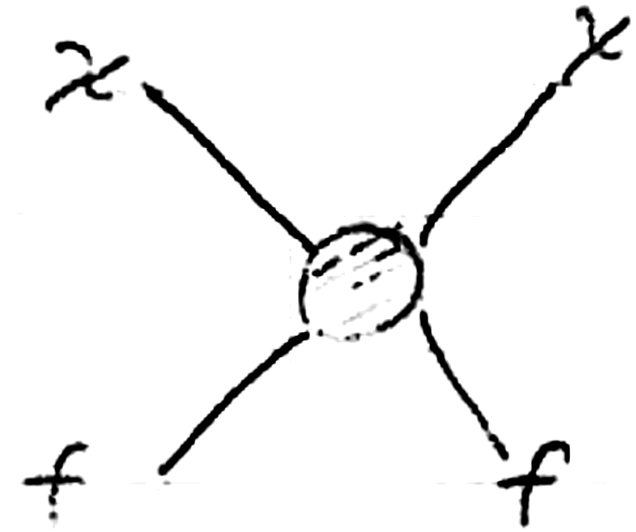
EFT cutoff scale



Direct Detection in a Toy Model

- ☑ Toy Model: scalar- (e.g. Higgs-) mediated DM interactions



$$\mathcal{L} \supset \sum_q \frac{m_q}{\Lambda^3} (\bar{\chi}\chi)(\bar{q}q)$$

EFT cutoff scale

DM fields

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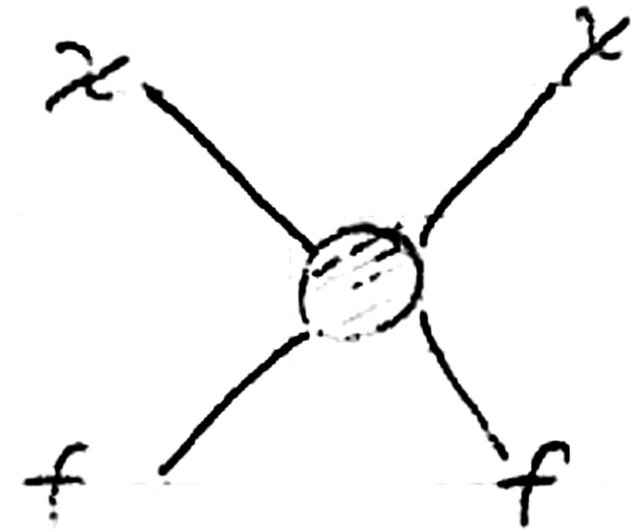

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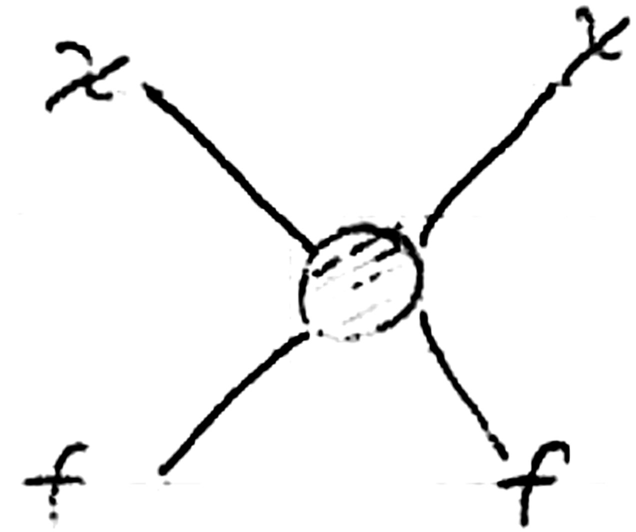

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EFT cutoff scale

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SM quark fields

Idea: new scalar mixes with the SM Higgs boson
➠ couplings to fermions ∝ mass

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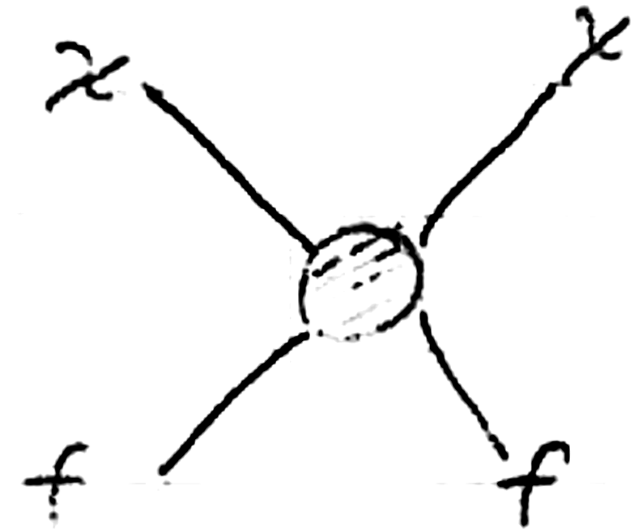

$$\mathcal{L} \supset \sum_q \frac{m_q}{\Lambda^3} (\bar{\chi}\chi)(\bar{q}q)$$

- ☑ Non-relativistic matrix element:

$$\frac{1}{4}\overline{|\mathcal{M}|^2} = \frac{16 m_N^2 m_\chi^2}{\Lambda^6} \left[\sum_q m_q \langle N|\bar{q}q|N\rangle \right]^2$$

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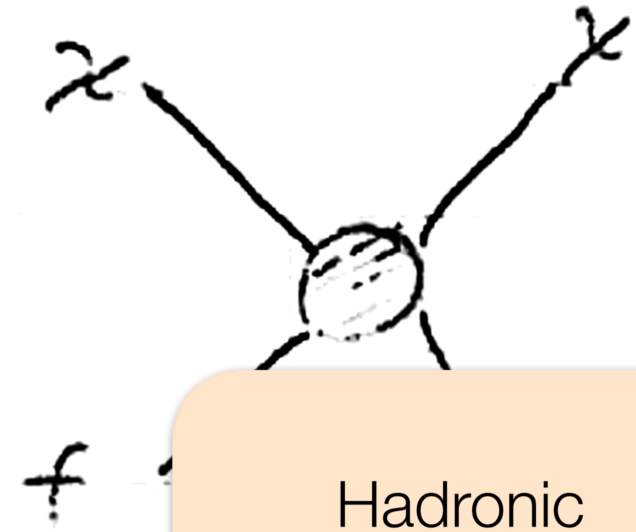

Hadronic
Matrix Elements
… there be dragons

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Cross Section and Rates

Cross Section and Rates

- Differential WIMP–nucleon cross section
  (per unit recoil energy interval)

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recoil energy

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$$\frac{dR_{\chi N}}{dE_r} = \int_{v_{\min}}^{\infty} dv_\chi\, v_\chi^2\, d\Omega_{v_\chi}\, f_\oplus(\vec{v}_\chi)\, n_\chi v_\chi \,\frac{1}{m_N}\,\frac{d\sigma_{\chi N}}{dE_r}$$

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DM velocity distribution
in Earth rest frame

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coherent scattering on all nucleons

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coherent scattering
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nuclear form factor
loss of coherence at
large momentum transfer

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coherent scattering on all nucleons

nuclear form factor loss of coherence at large momentum transfer

kinematic correction factor

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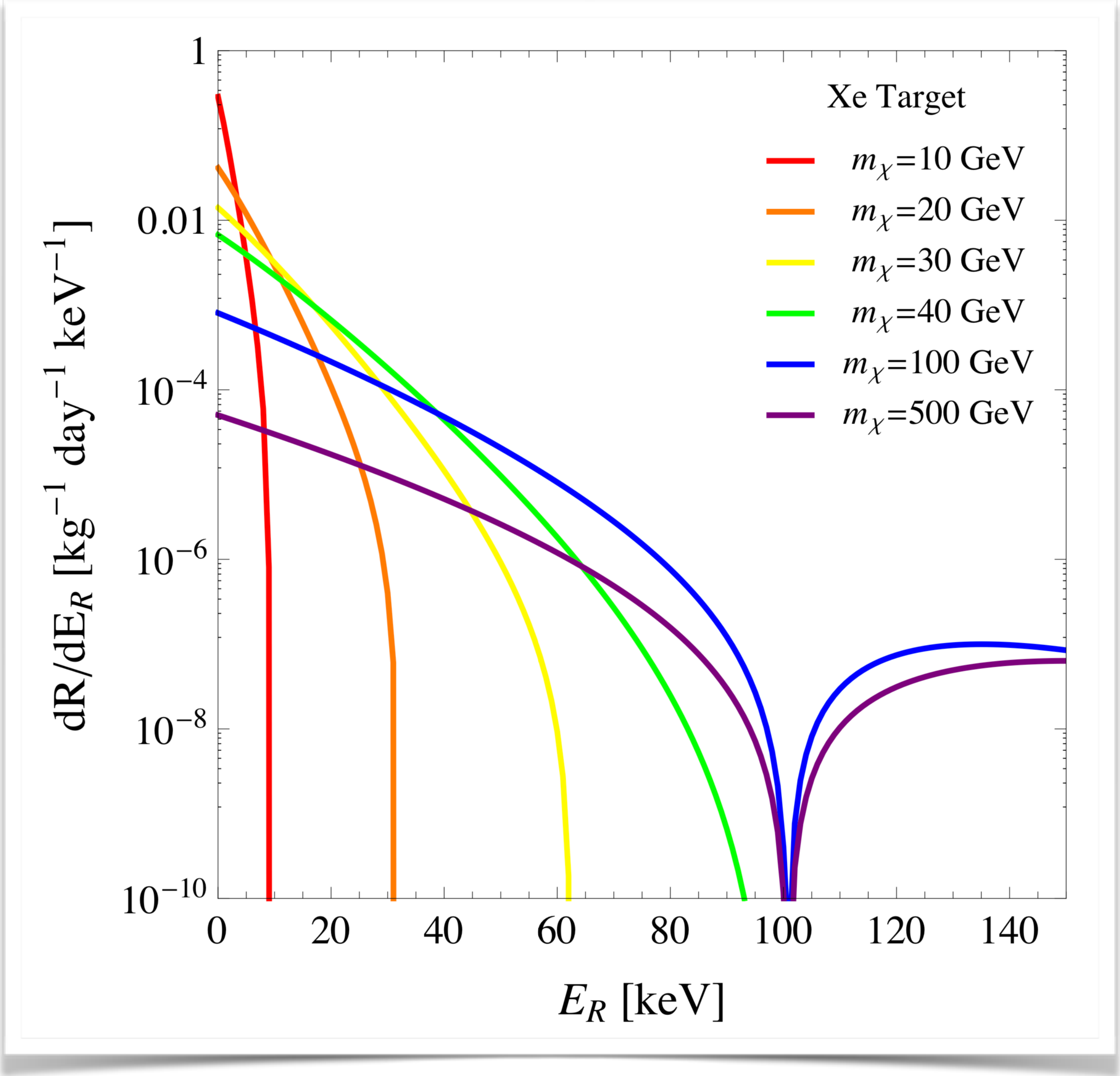
Recoil Spectrum



Dienes Kumar Thomas, arXiv:1208.0336

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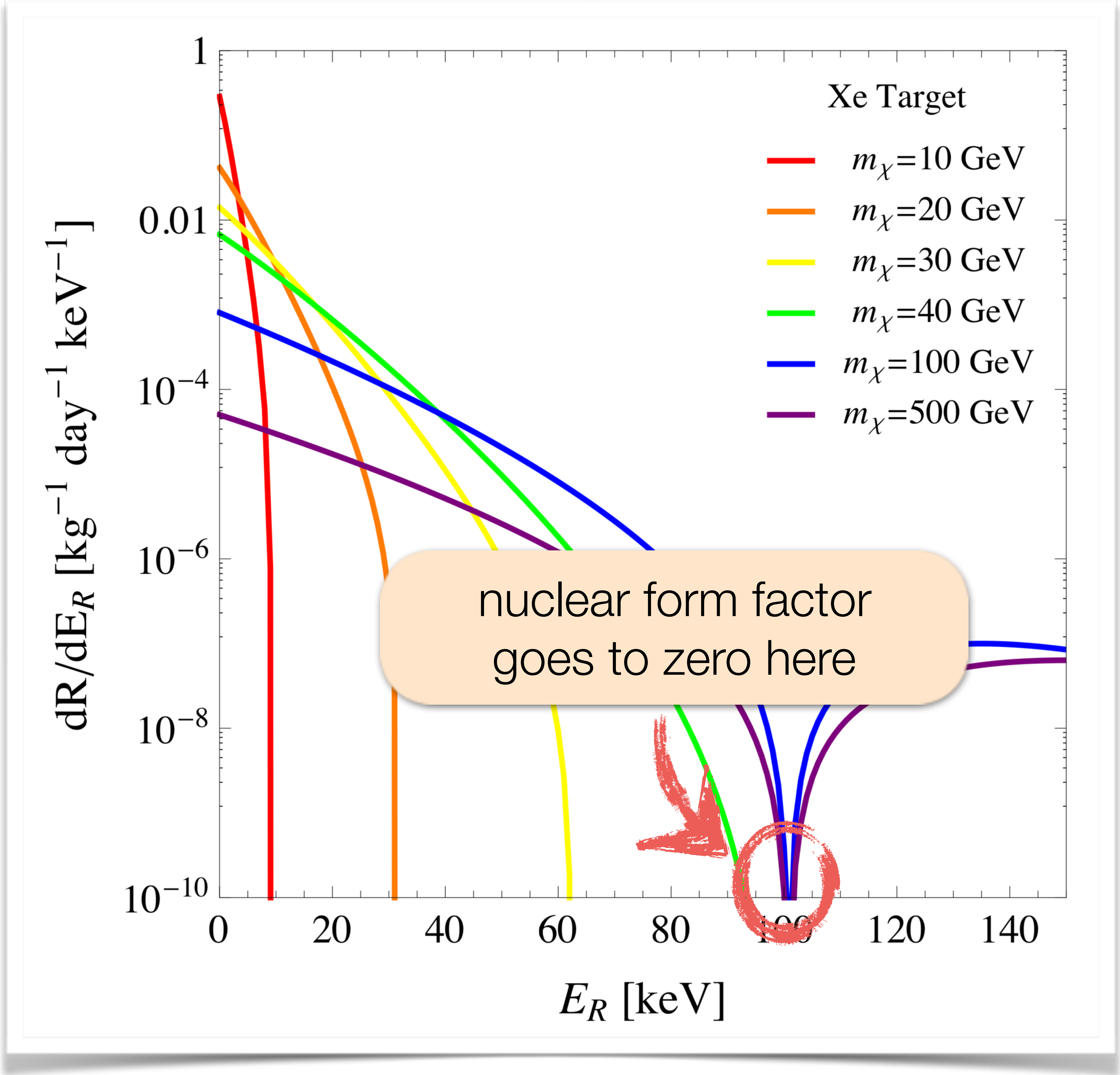
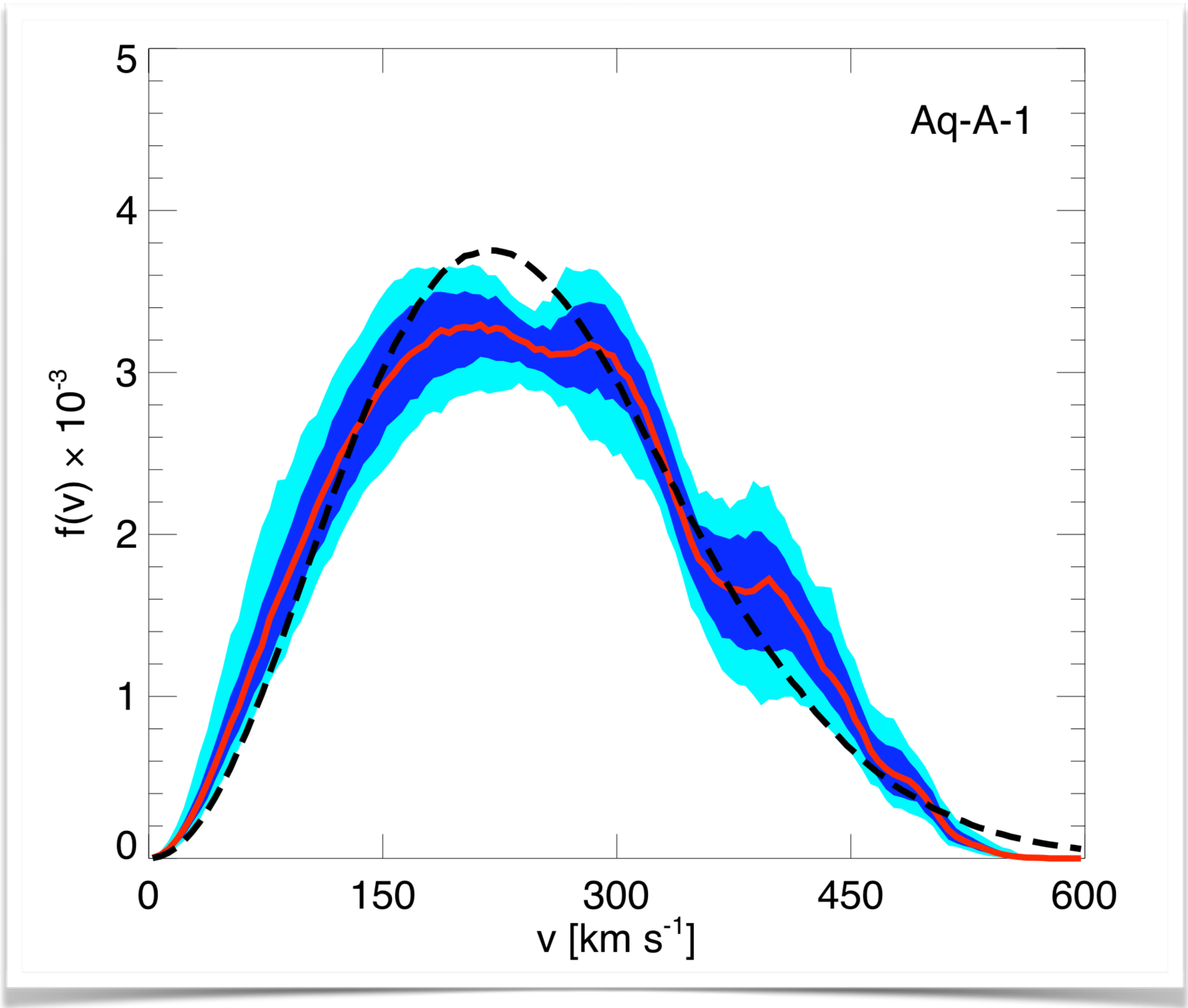


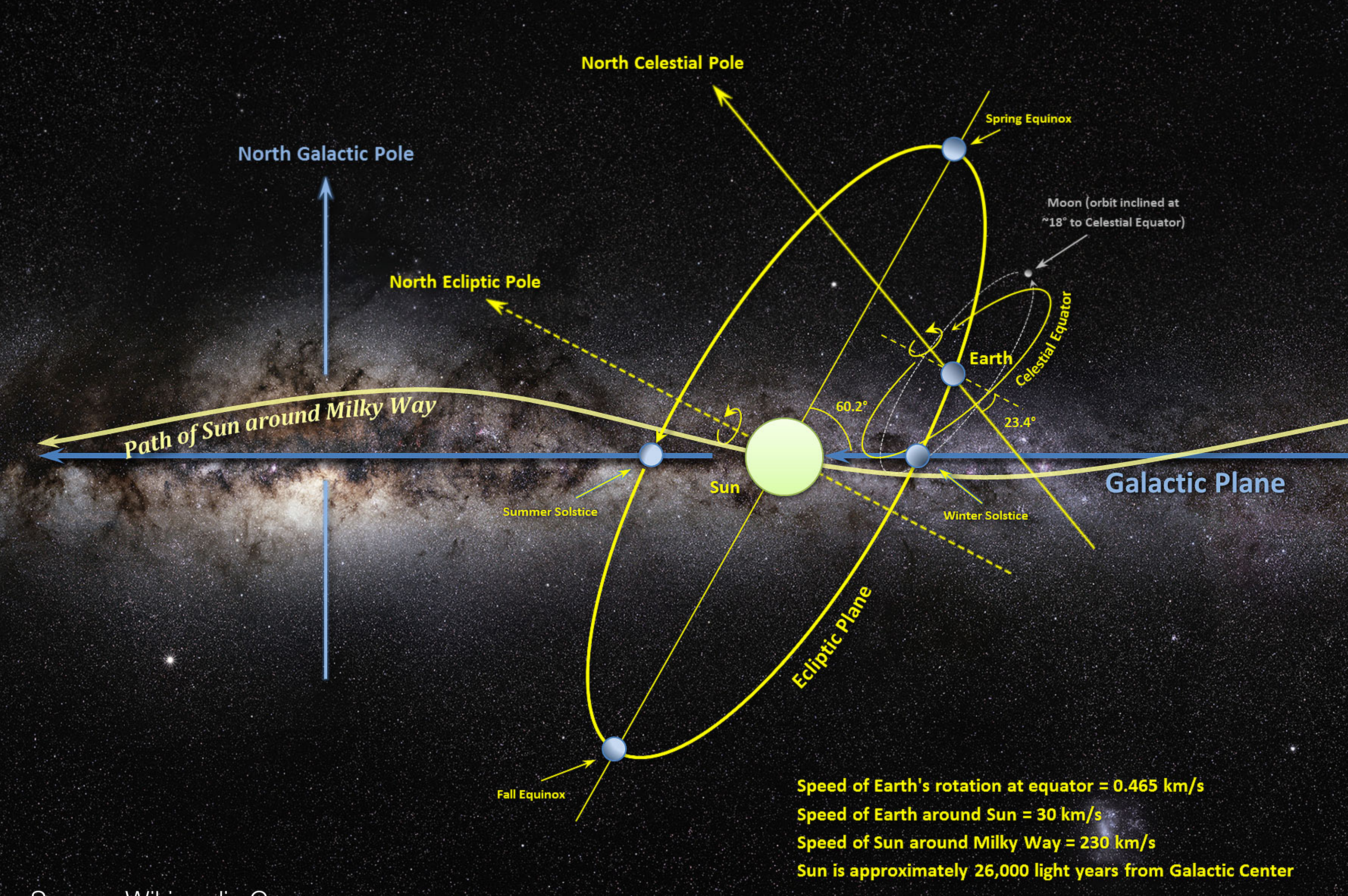
Dienes Kumar Thomas, arXiv:1208.0336

DM Velocity Distribution (Galactic Rest Frame)



Vogelsberger *et al.* arXiv:0812.0362
Strigari arXiv:1211.7090

MOTION OF EARTH AND SUN AROUND THE MILKY WAY

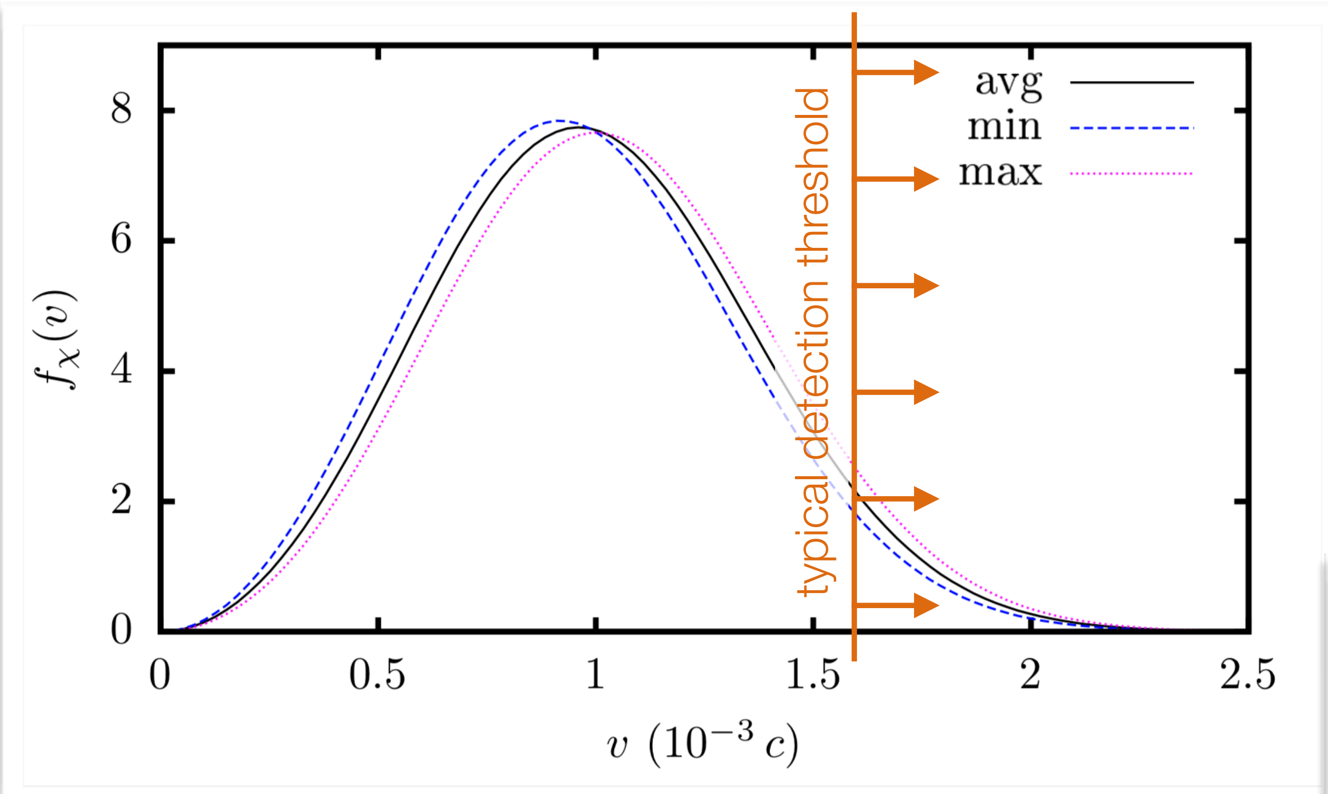


Source: Wikimedia Commons

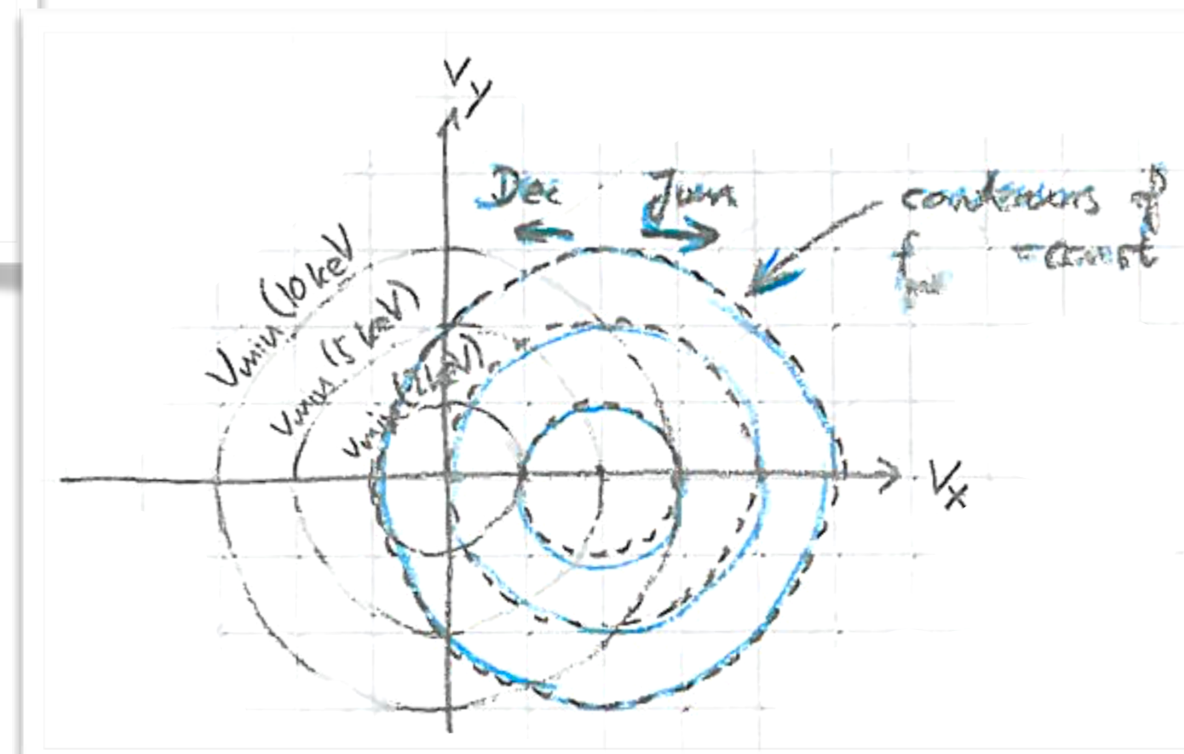
Diagram not to scale

Background Image Credit: ESO/S. Brunier

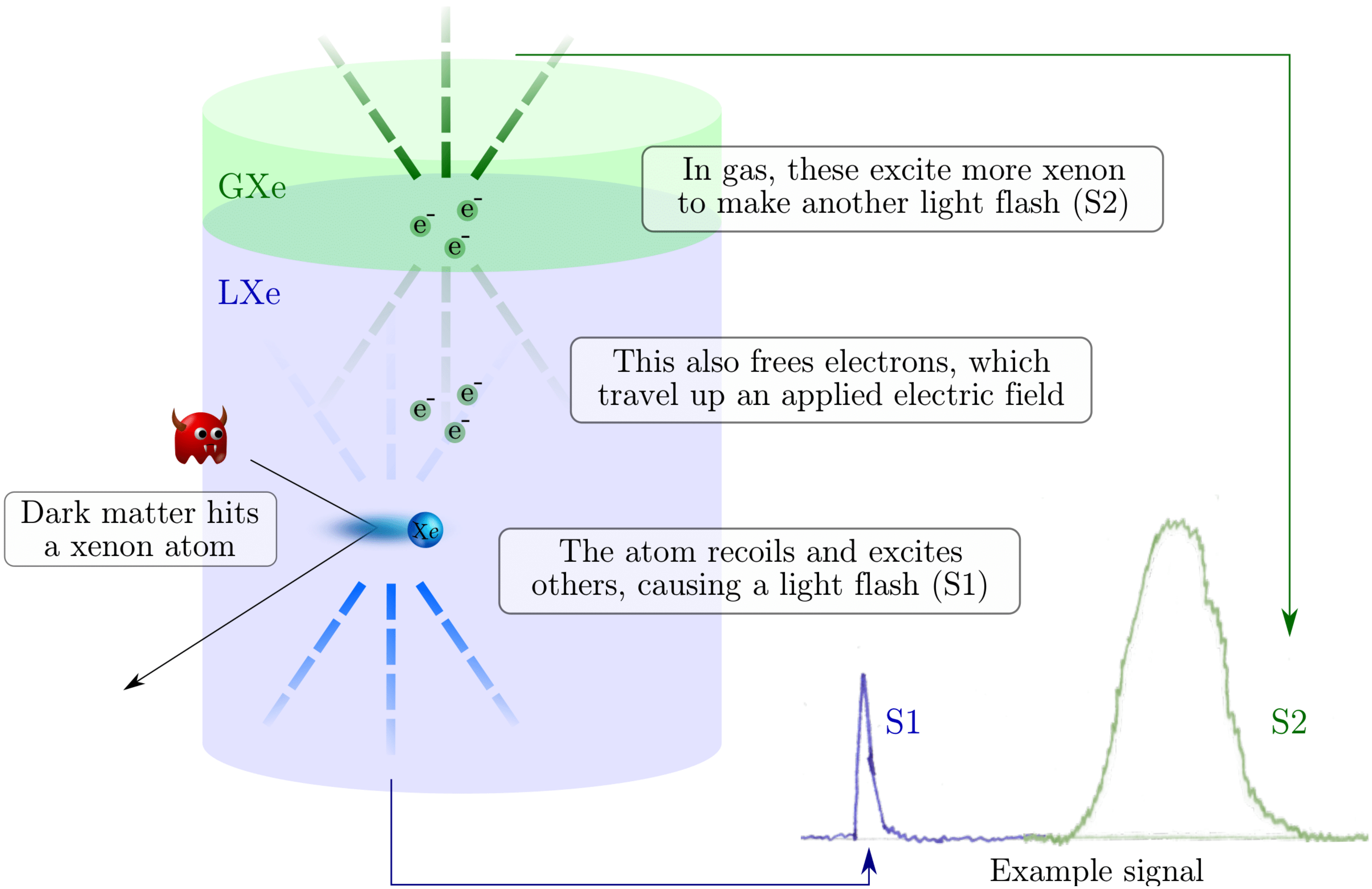
DM Velocity Distribution: Annual Modulation



Roberts *et al.* arXiv:1604.04559



Direct Detection Experiments



XENON collaboration

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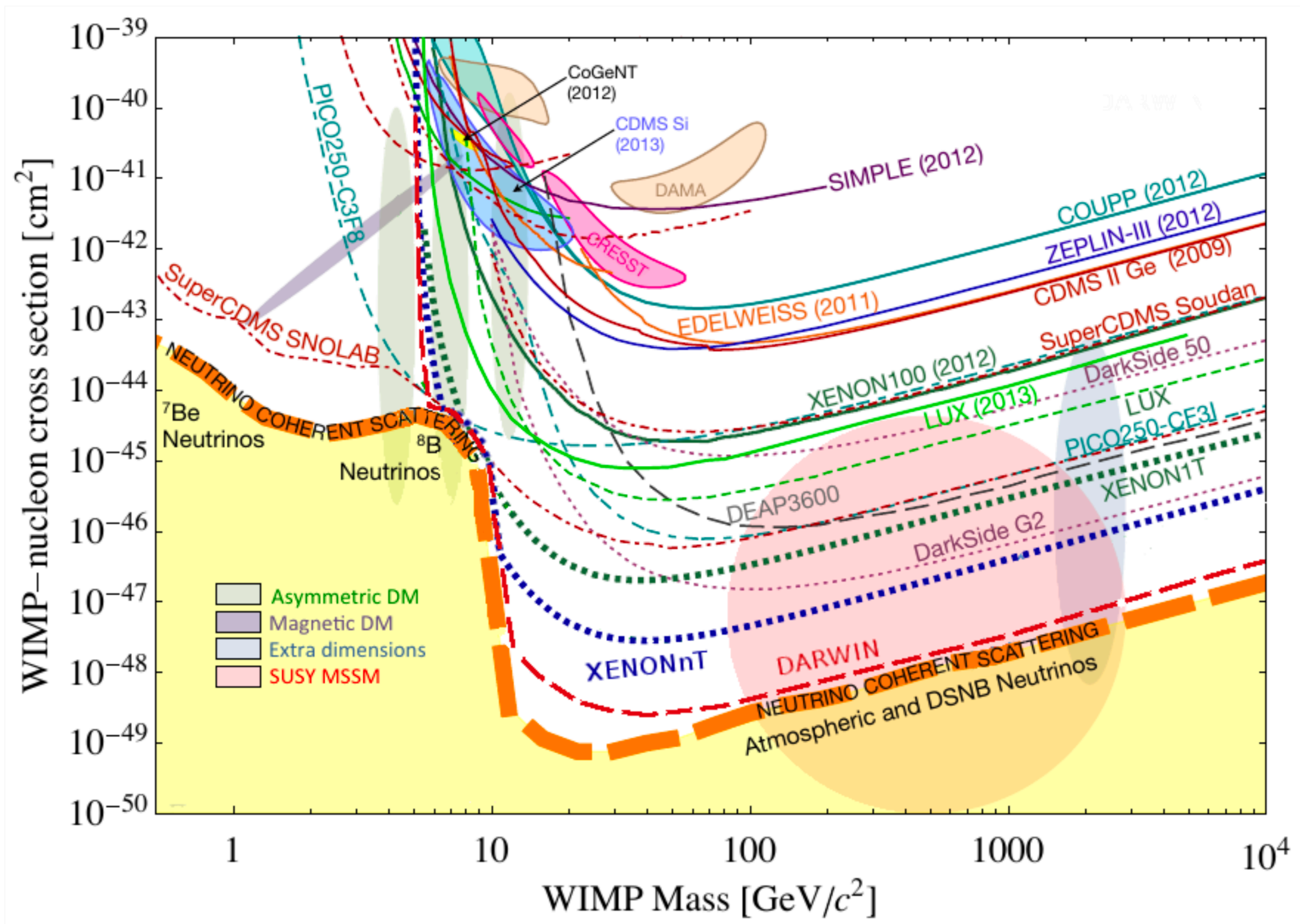
Direct Detection Results



Klasen Pohl Sigl arXiv:1507.03800

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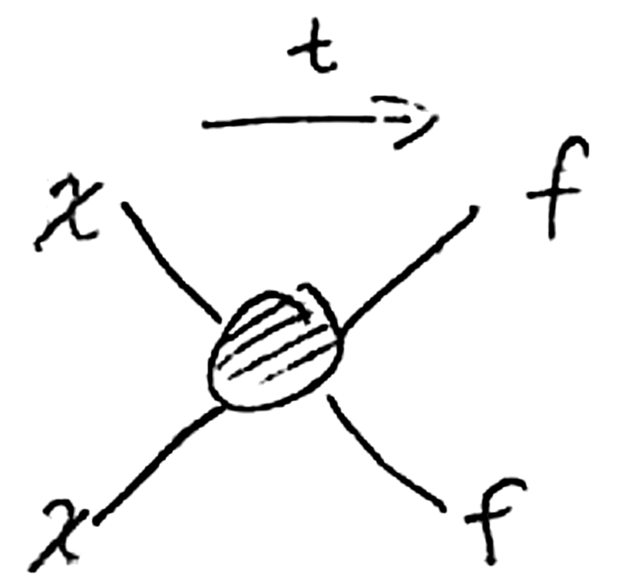
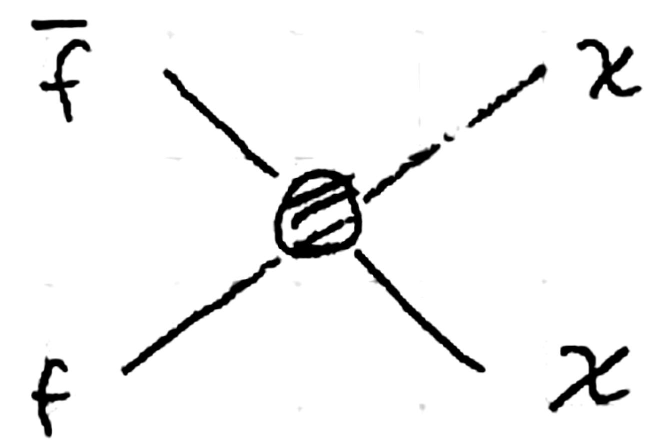
WIMP Dark Matter: Collider Searches

WIMP Production at Colliders

- ☑ Annihilation:



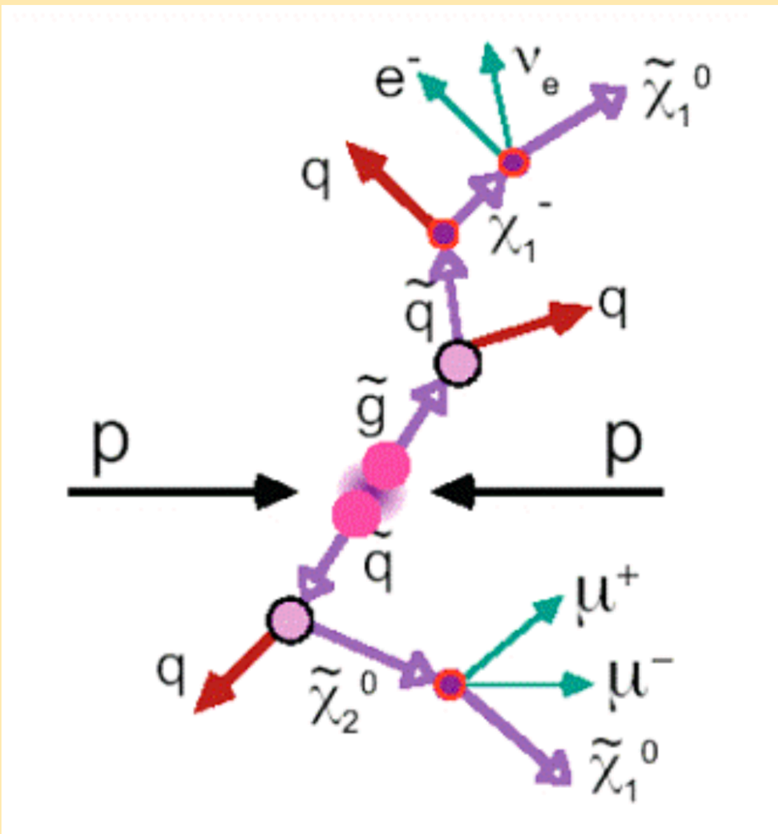
- ☑ Rotate diagram by 180°
  ➠ DM production



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

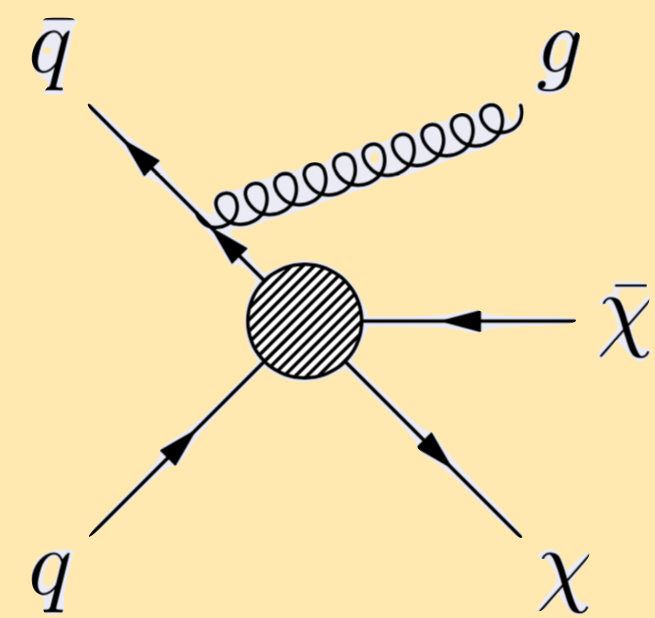
WIMP Detection at Colliders

Cascade Decays



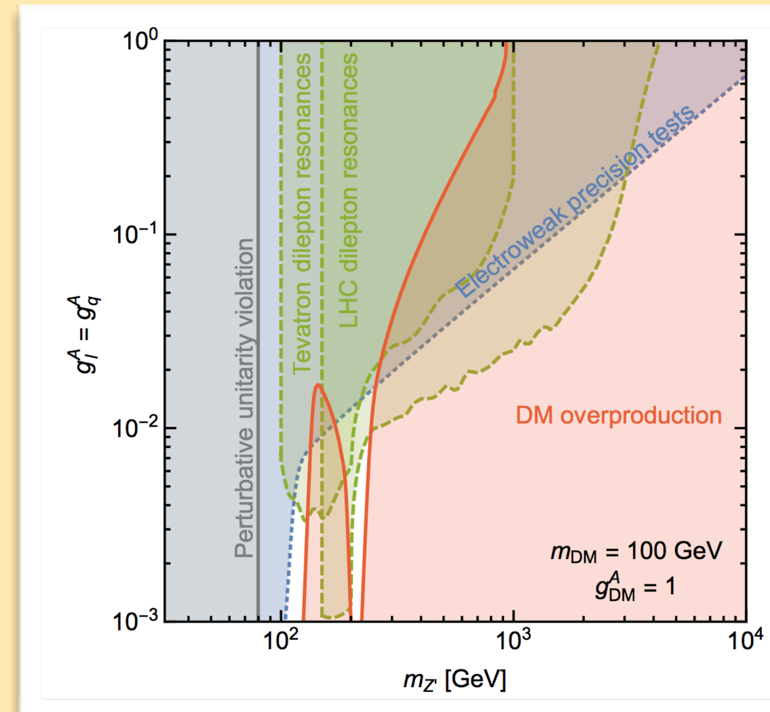
- ☑ missing p_T signatures
- ☑ in UV-complete models
- ☑ highly model-dependent

mono-X signatures

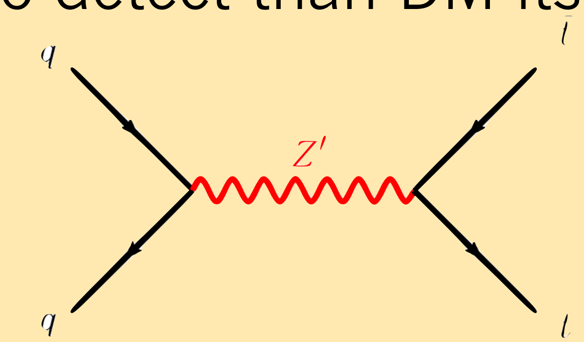


- ☑ X = gluon, photon, ...
- ☑ more model-independent
- ☑ large background

mediator searches



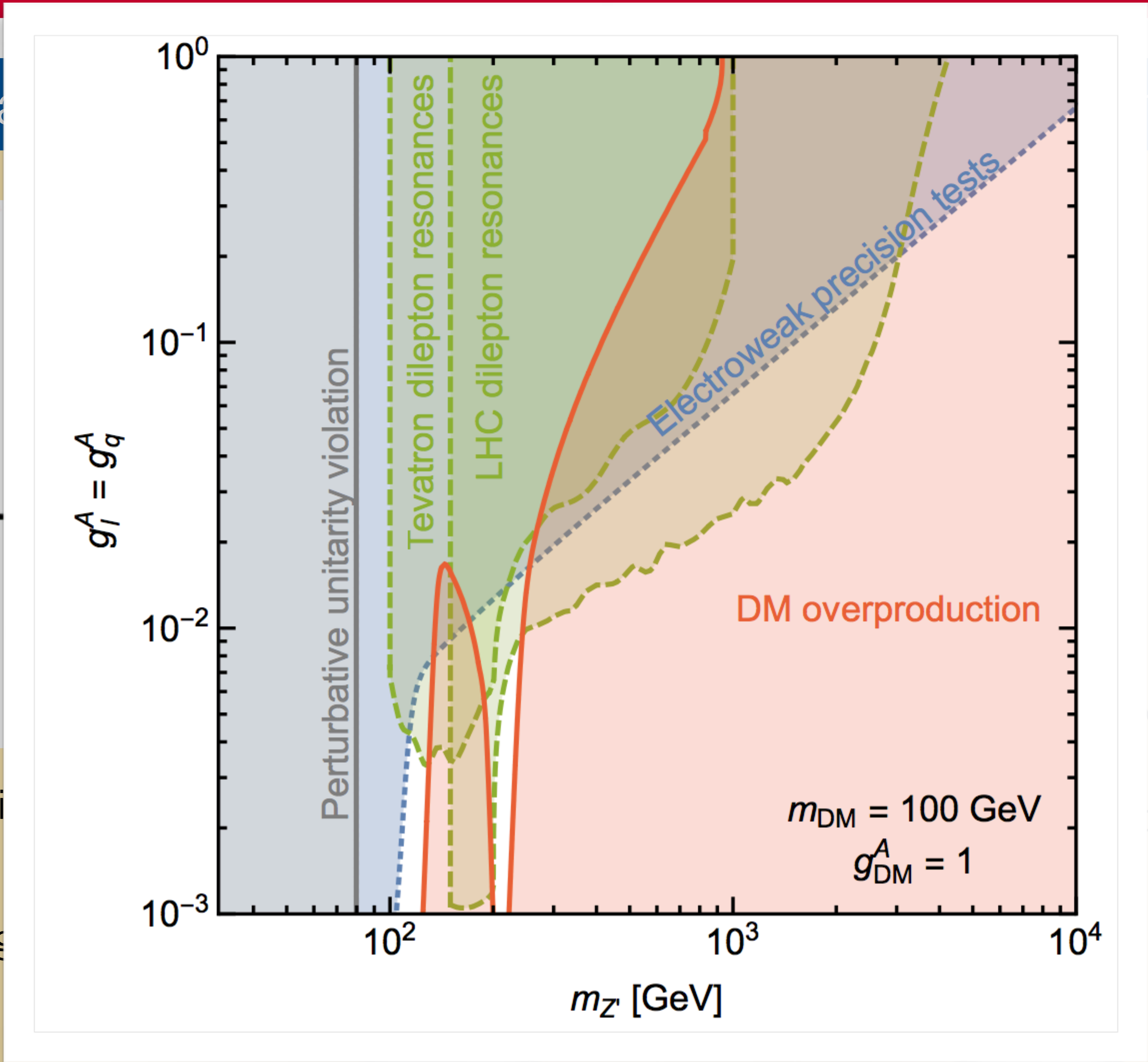
- ☑ Mediators of DM–SM interactions often easier to detect than DM itself



WIMP Detection at Colliders

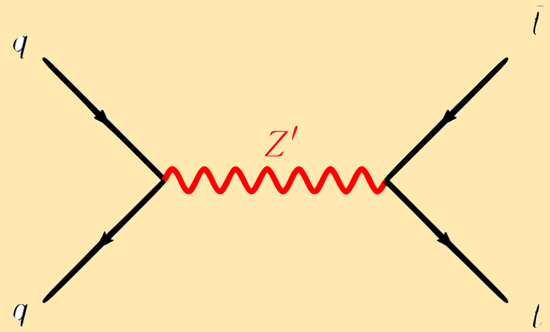
Ca… …ediator searches

p



- ☑ mi…
- ☑ in…
- ☑ hi…

…Mediators of DM–SM …nteractions often easier …o detect than DM itself



WIMP Production at Colliders

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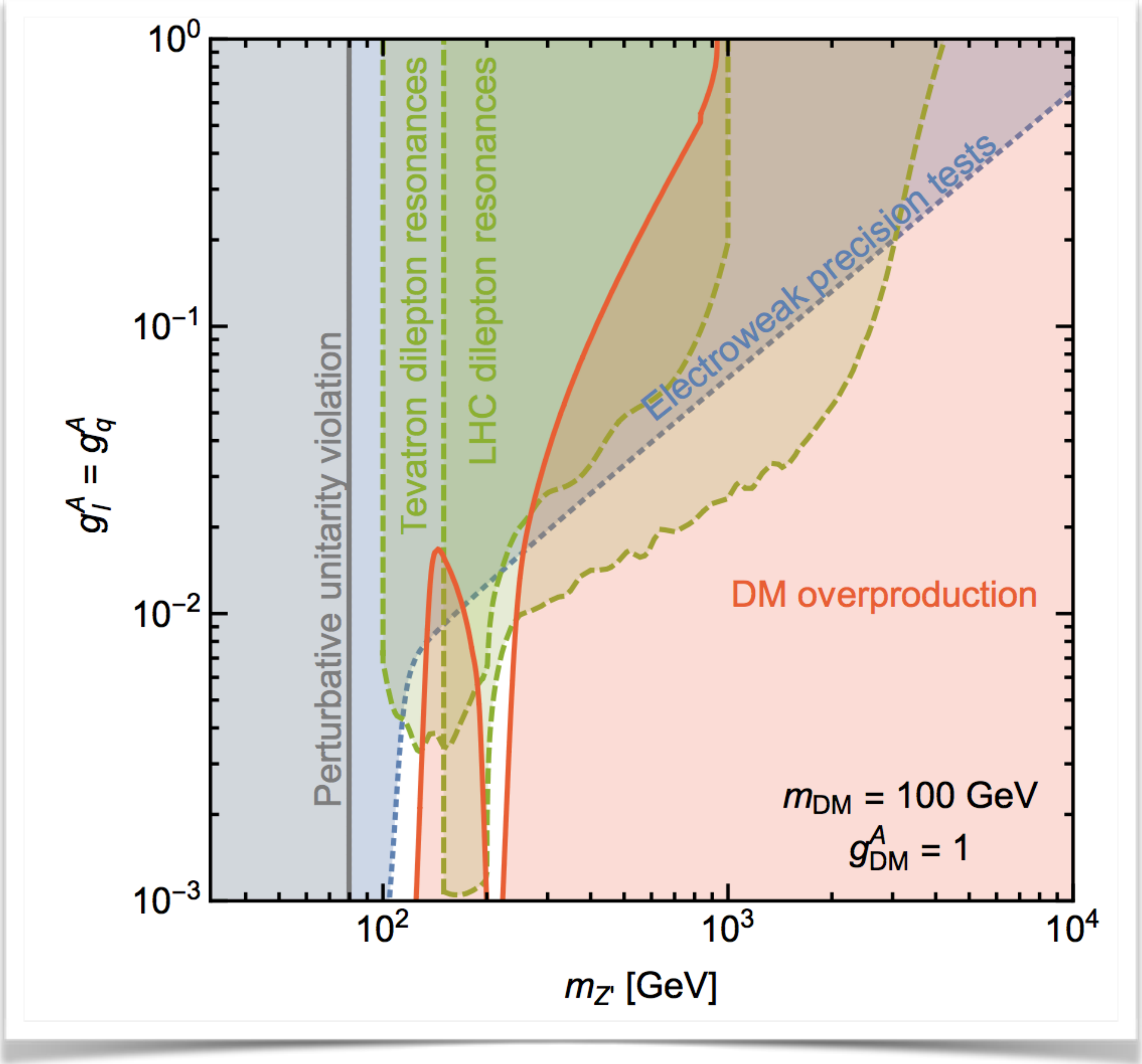

Kahlhoefer Schmidt-Hoberg Schwetz Vogel, 2015

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

Dark Photons

Motivation (1)

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☑ Failure to find traditional electroweak-scale DM models motivates re-examination of low-mass region

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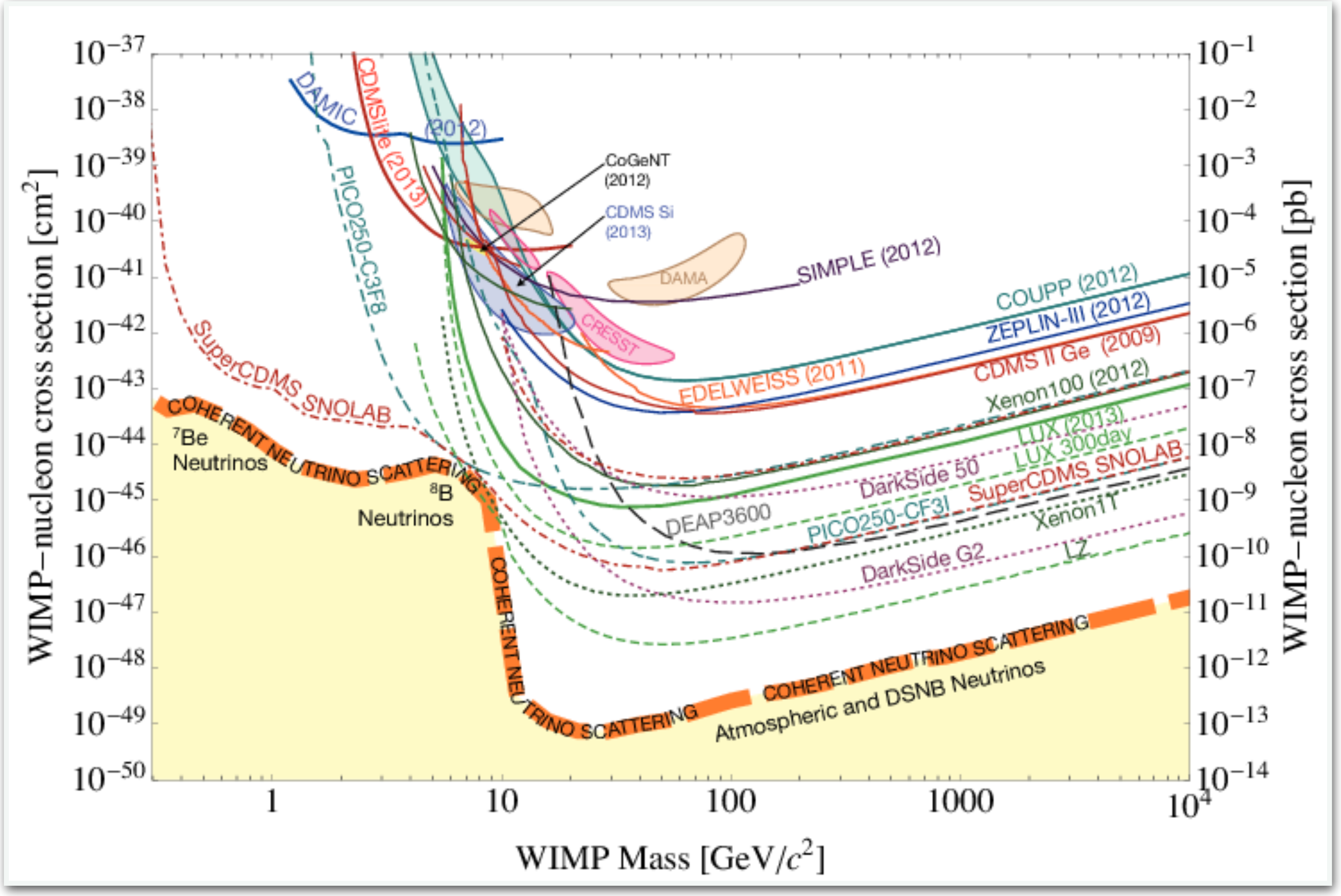
☑ Not probed efficiently by direct detection
nuclear recoil energies too low



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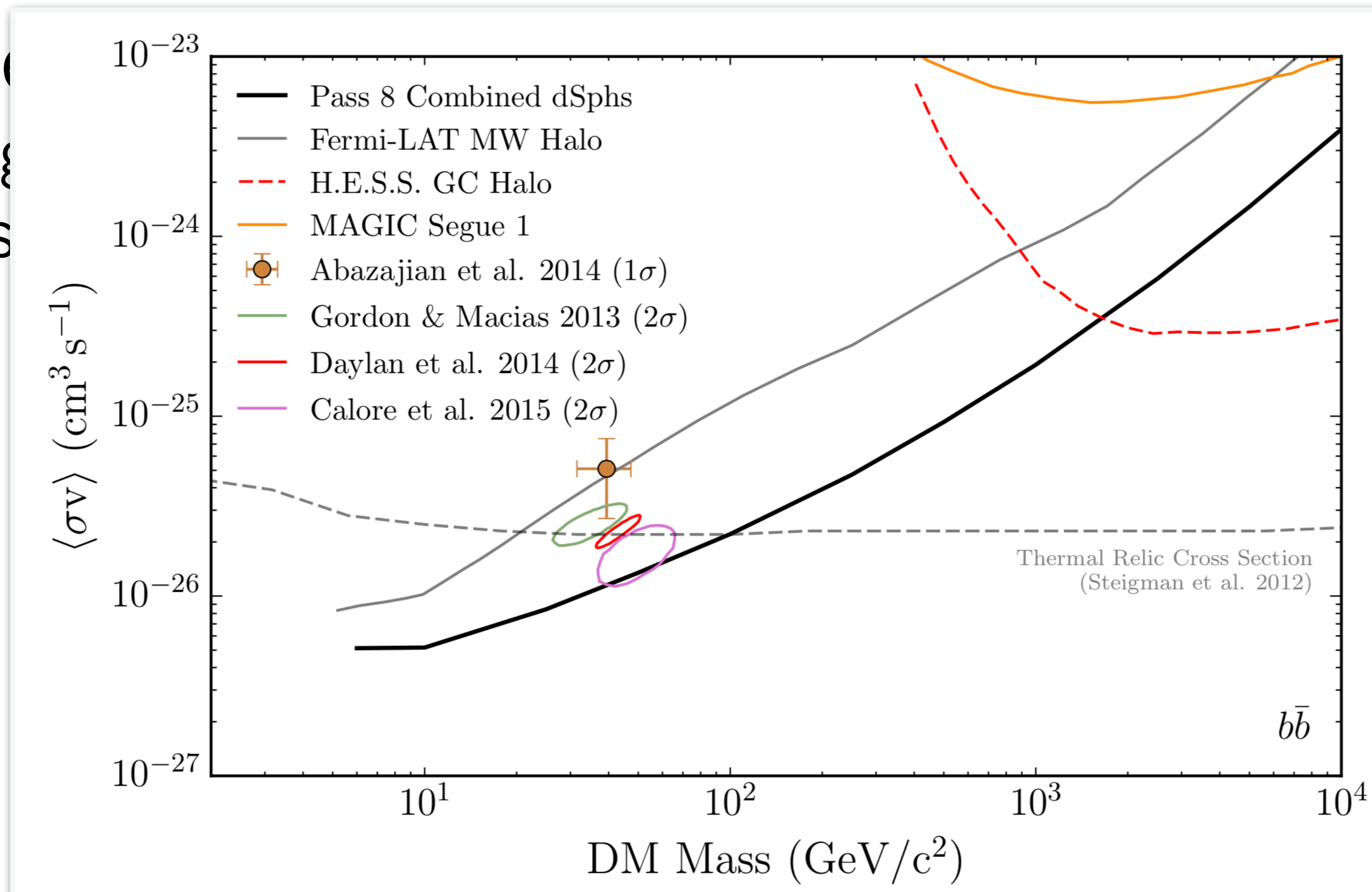

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  below energy threshold of Fermi-LAT (γ), AMS-02 (e^+e^-), ...
  below threshold for annihilation into γ-rich final states ($\bar{b}b$, $\tau^+\tau^-$, ...)
- For light mediator particles, colliders are at relative disadvantage (cross section $\sigma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

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 ➟ Christoph Weniger's lectures)
  - Singlet gauge boson *B'*: kinetic mixing $\mathcal{L} \supset -\frac{1}{2} \sin\chi F_Y^{\mu\nu} F'_{\mu\nu}$

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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 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

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

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- ☑ θ_w is defined such that $\tilde{A}$ is massless.
- ☑ $\tilde{Z}$ and $\tilde{Z}'$ 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

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

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Dark Photons: Formalism

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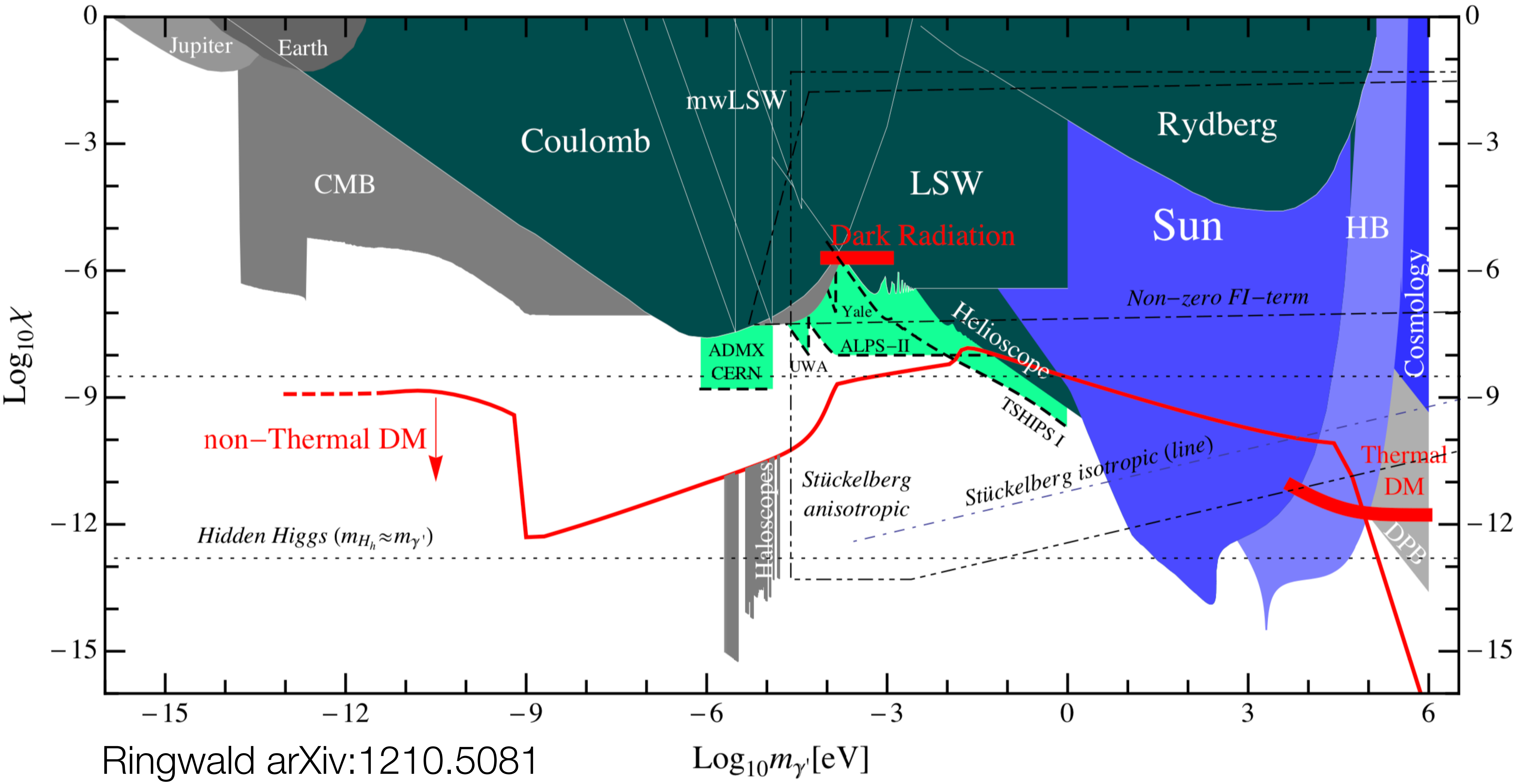
- ☑ Couplings to SM currents in the new basis:

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

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

Dark Photon Constraints



Ringwald arXiv:1210.5081

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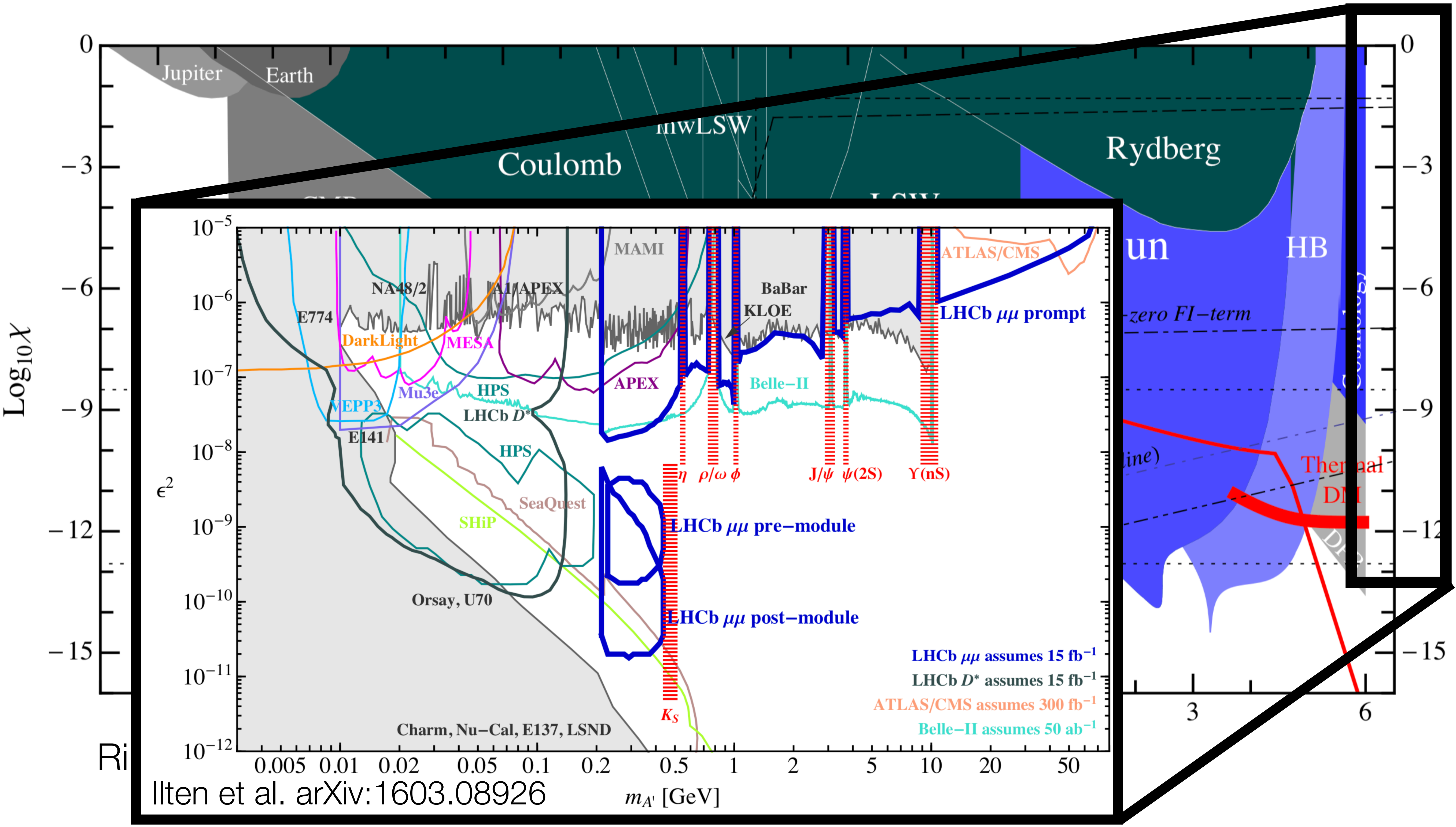
Dark Photon Constraints



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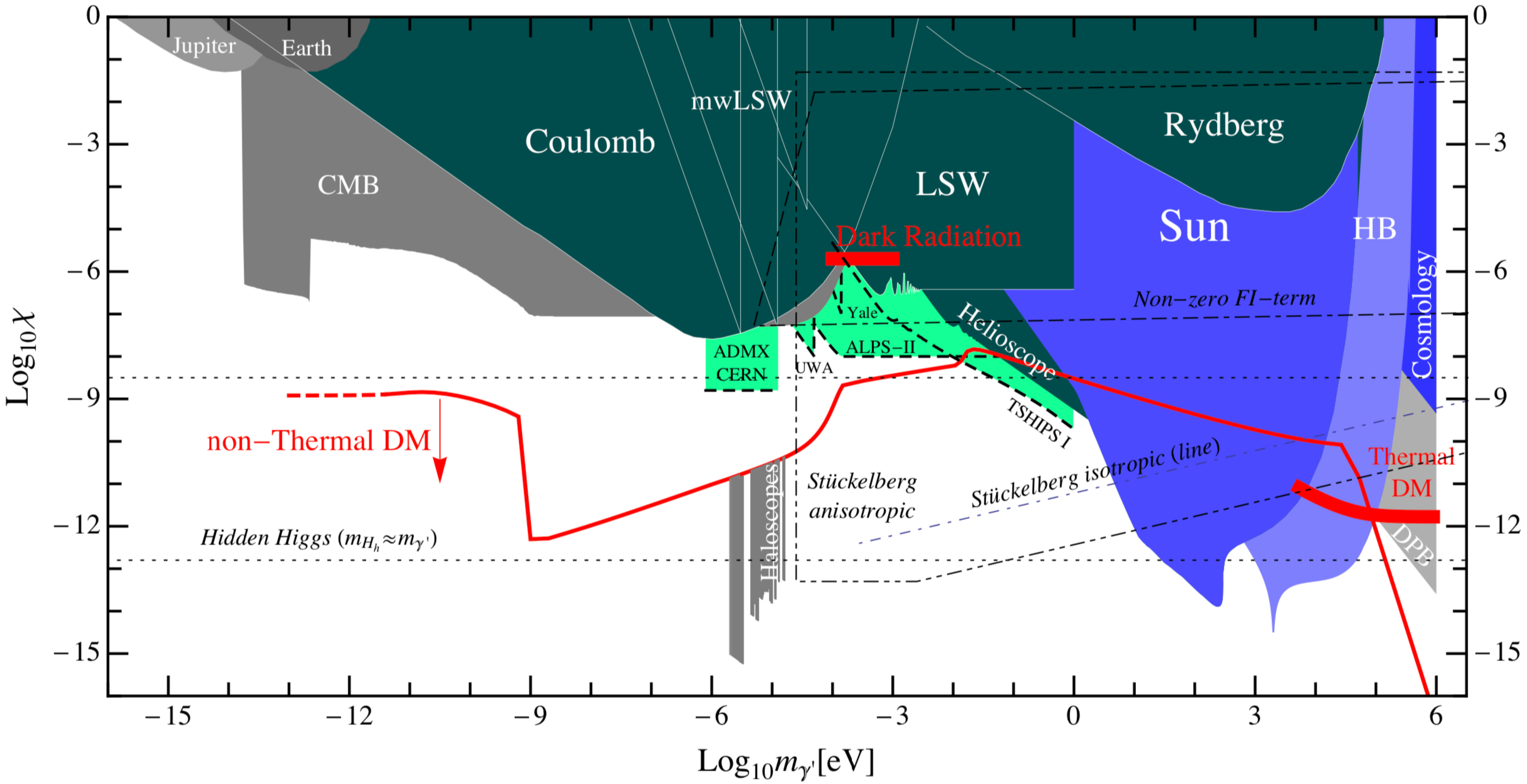
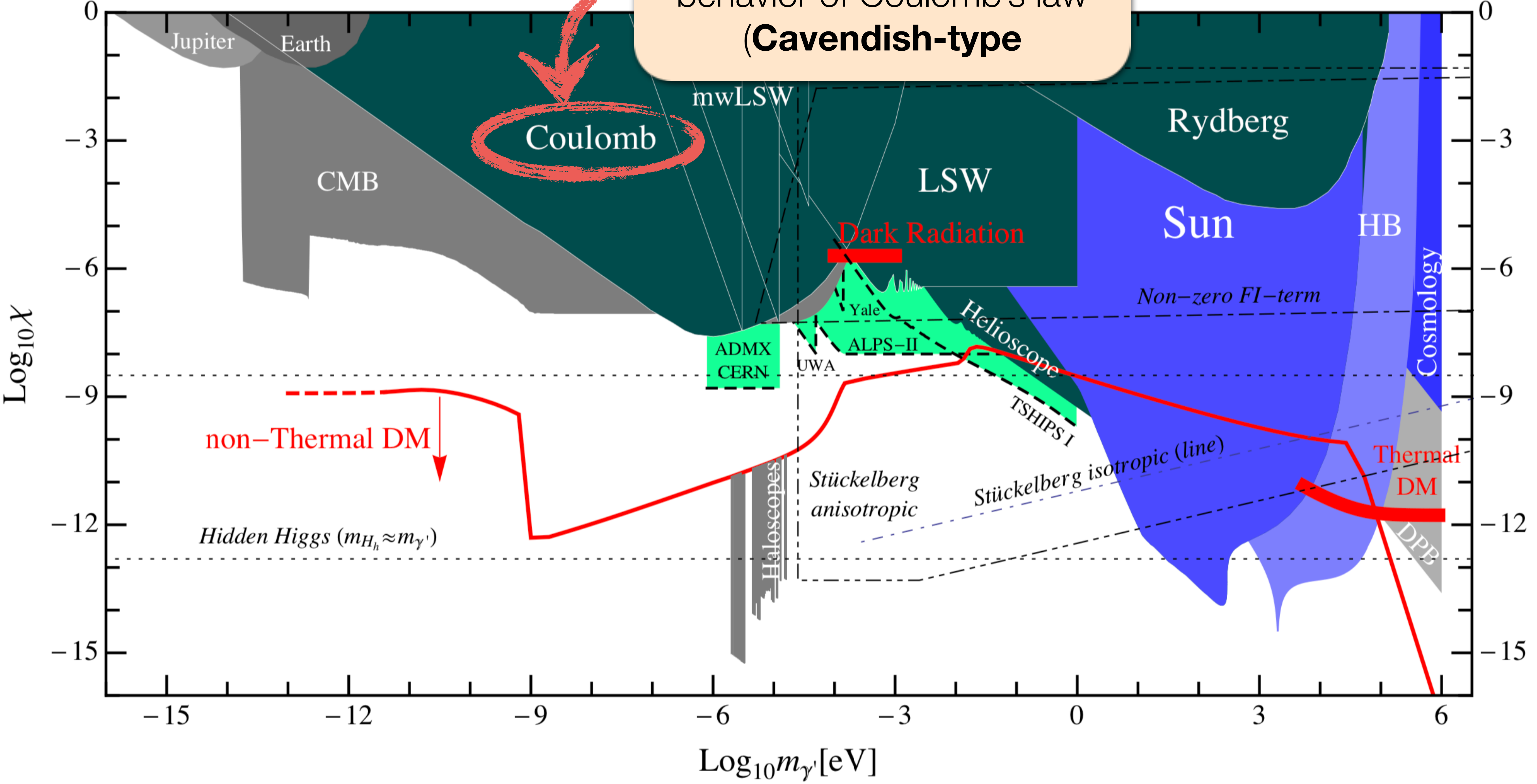


Dark Photon Constraints

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



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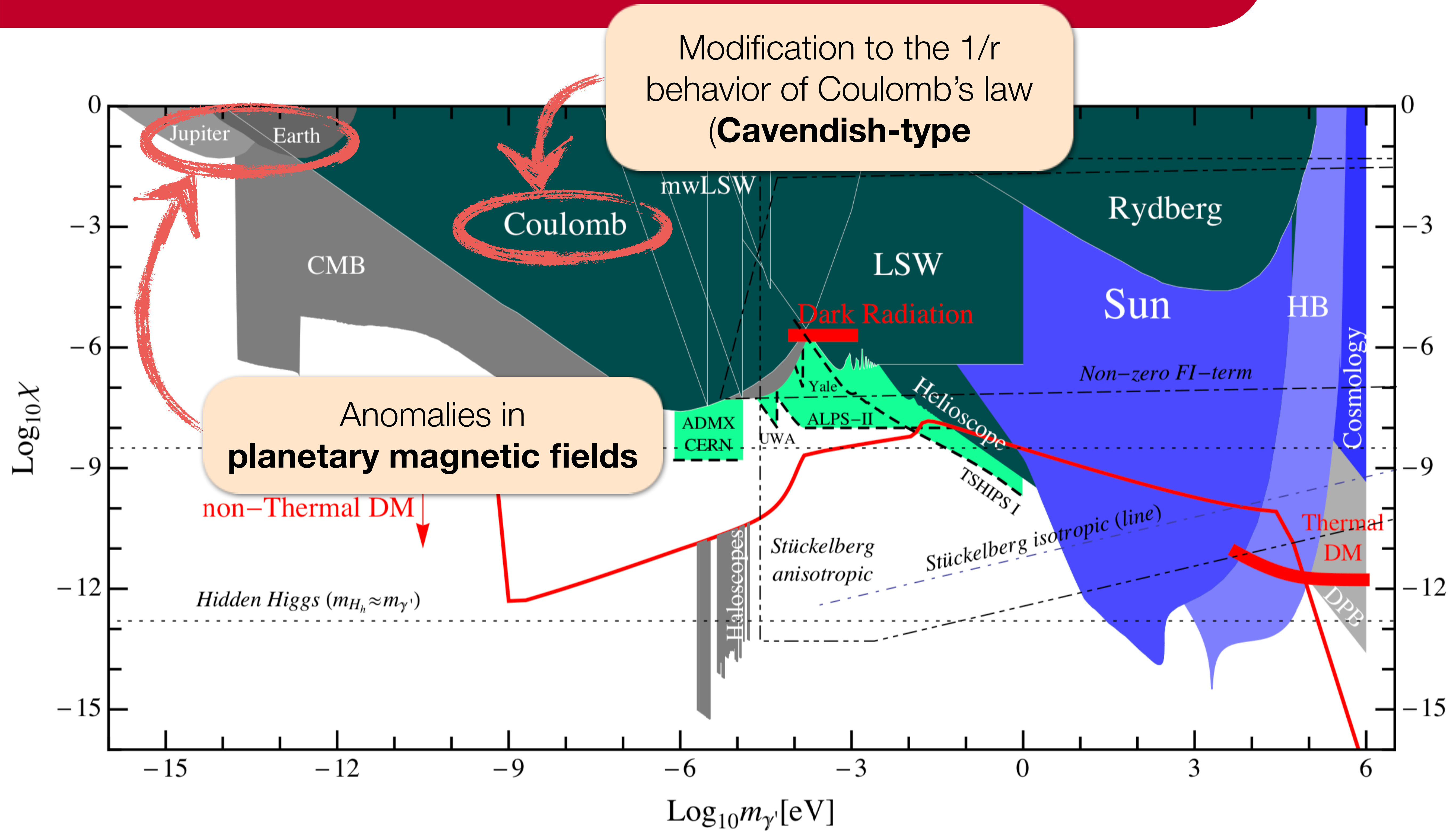
Dark Photon Constraints



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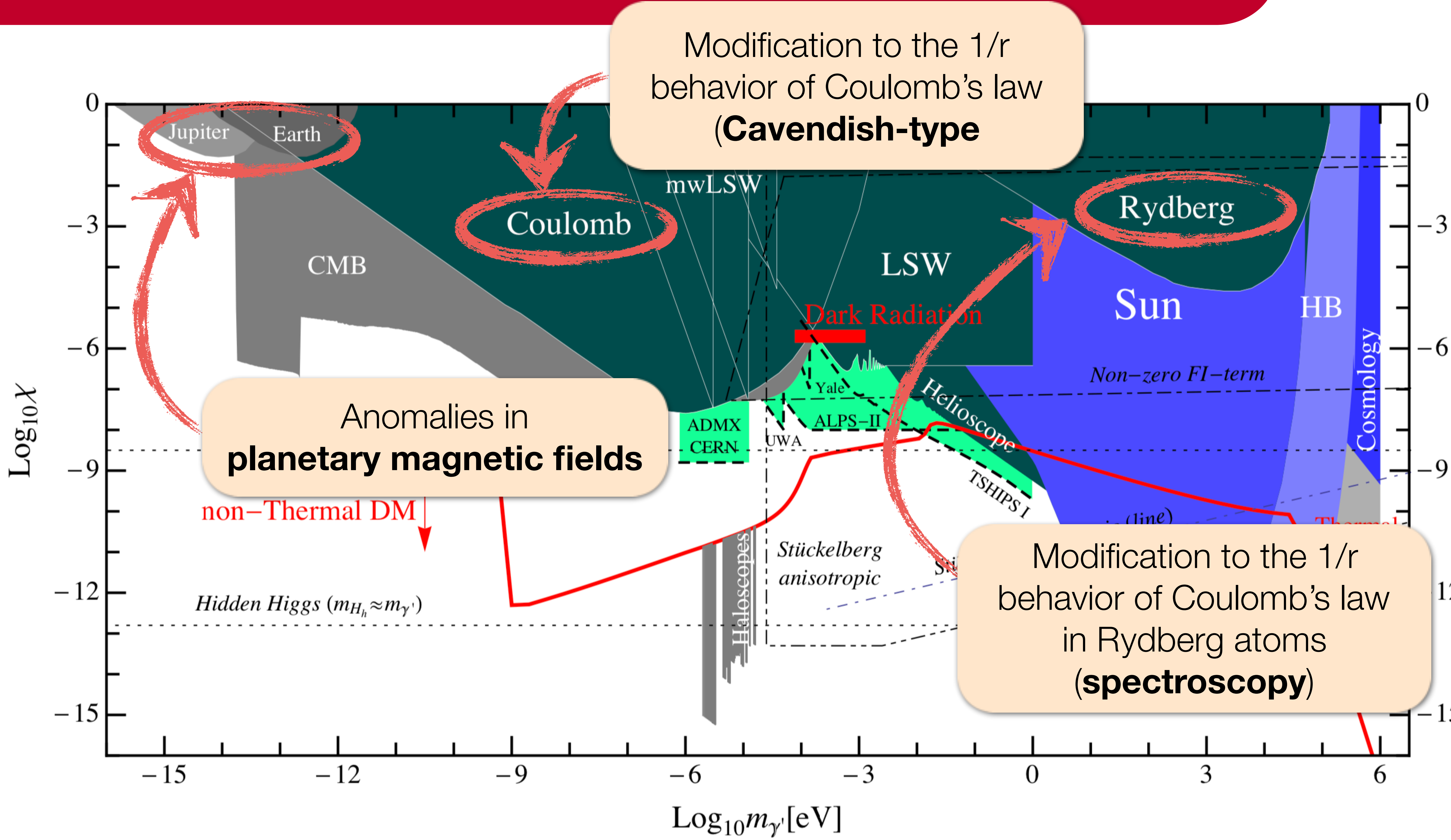

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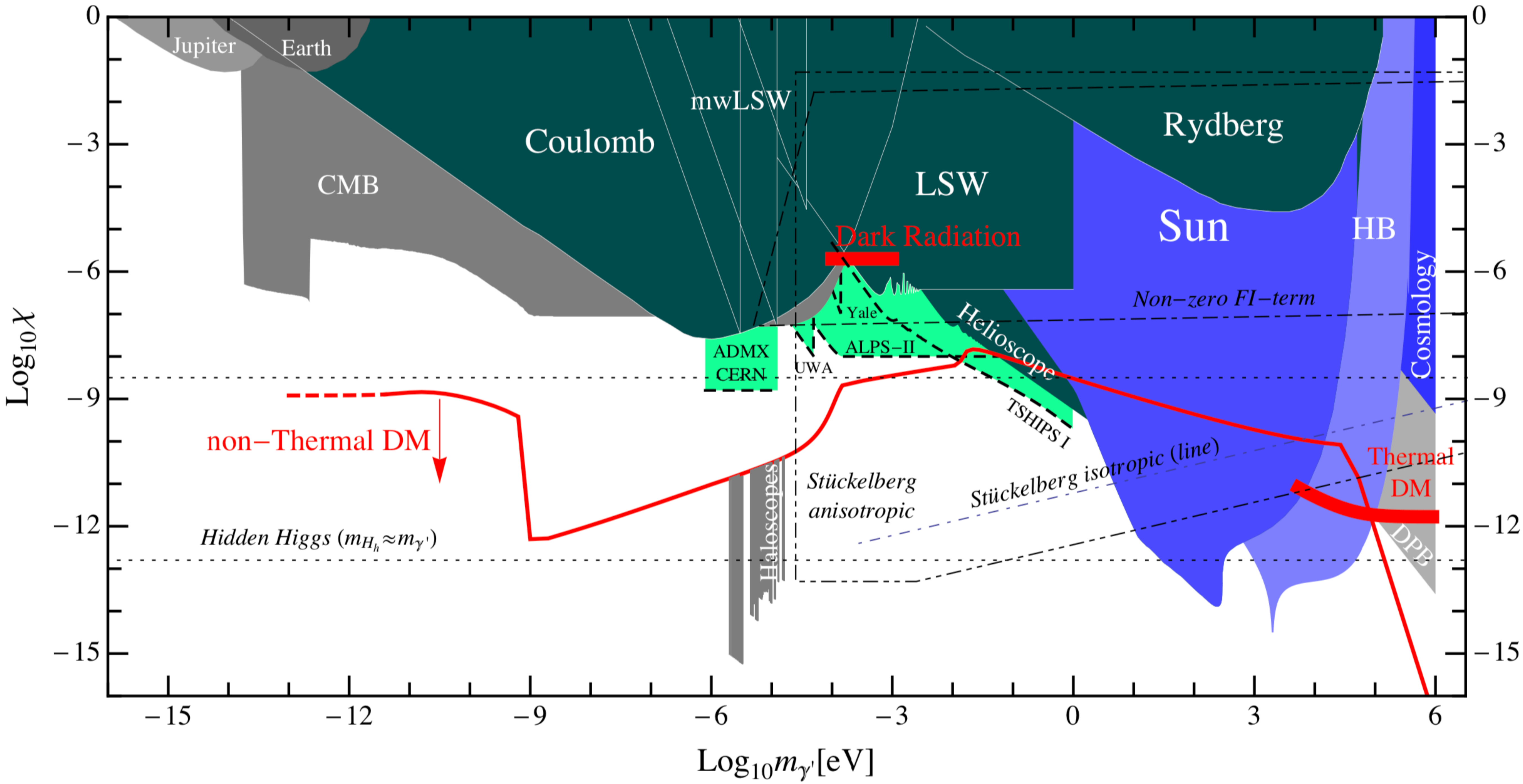

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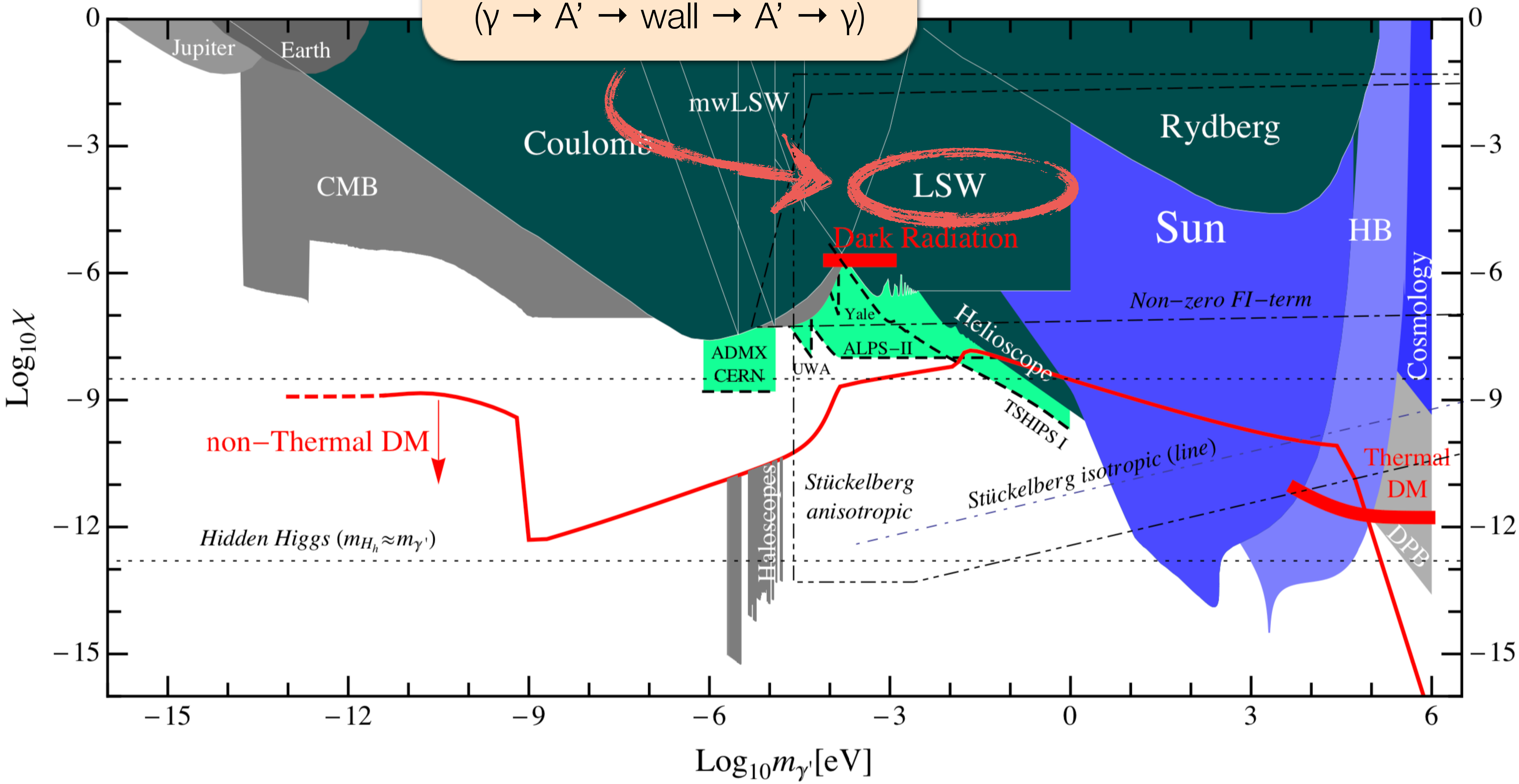
Dark Photon Constraints

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



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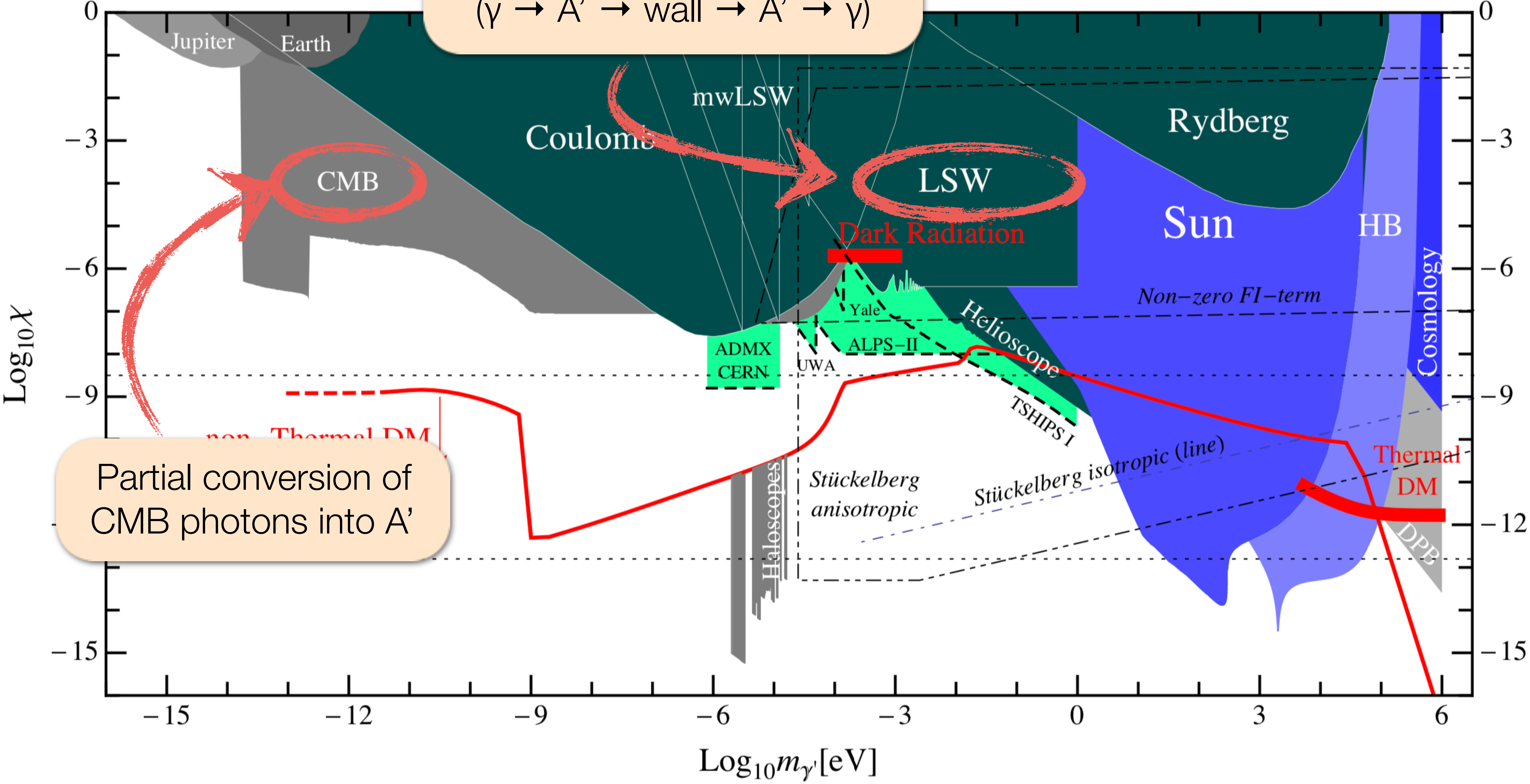

Partial conversion of CMB photons into A'

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Dark Photon Constraints

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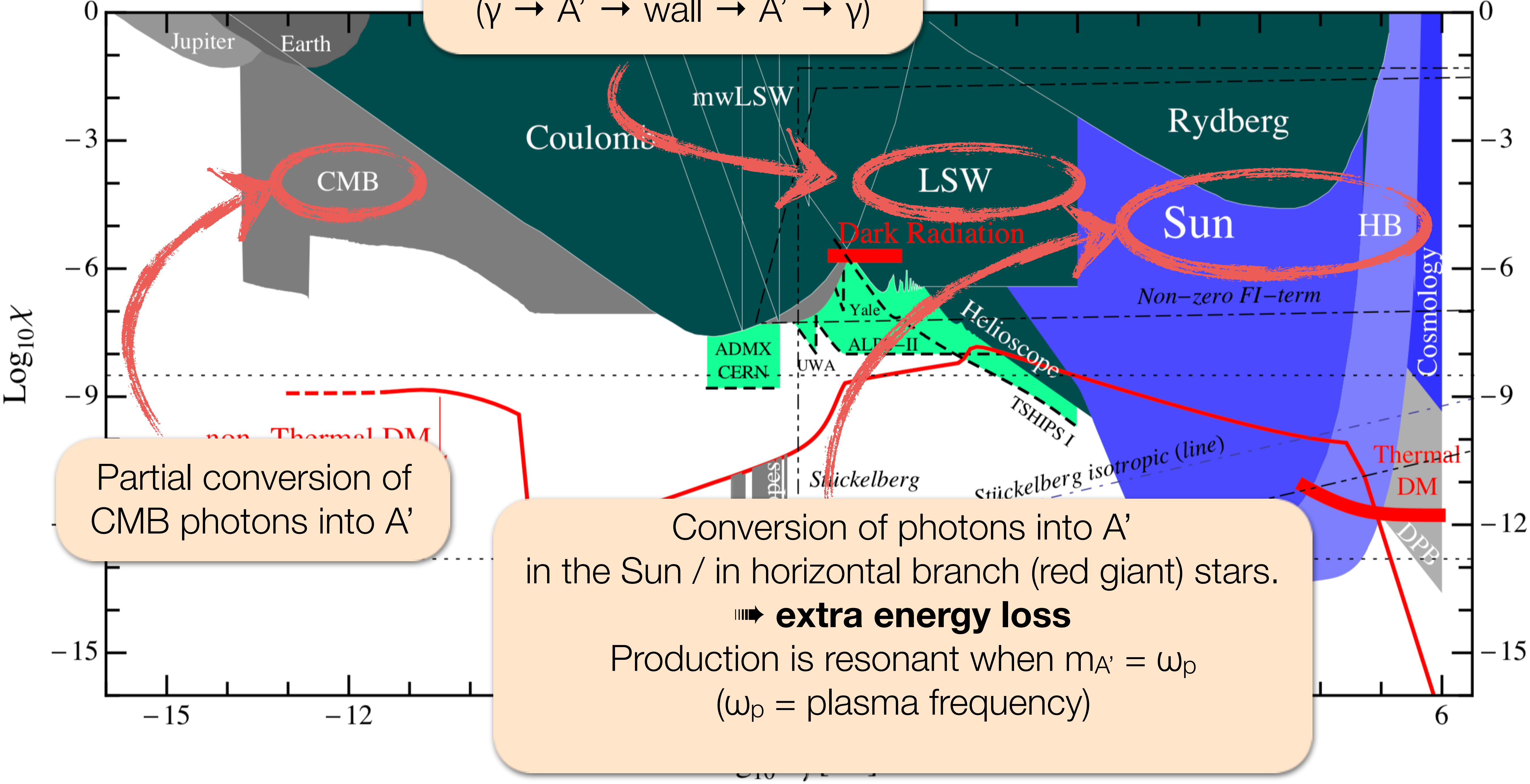

Partial conversion of CMB photons into A'

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)

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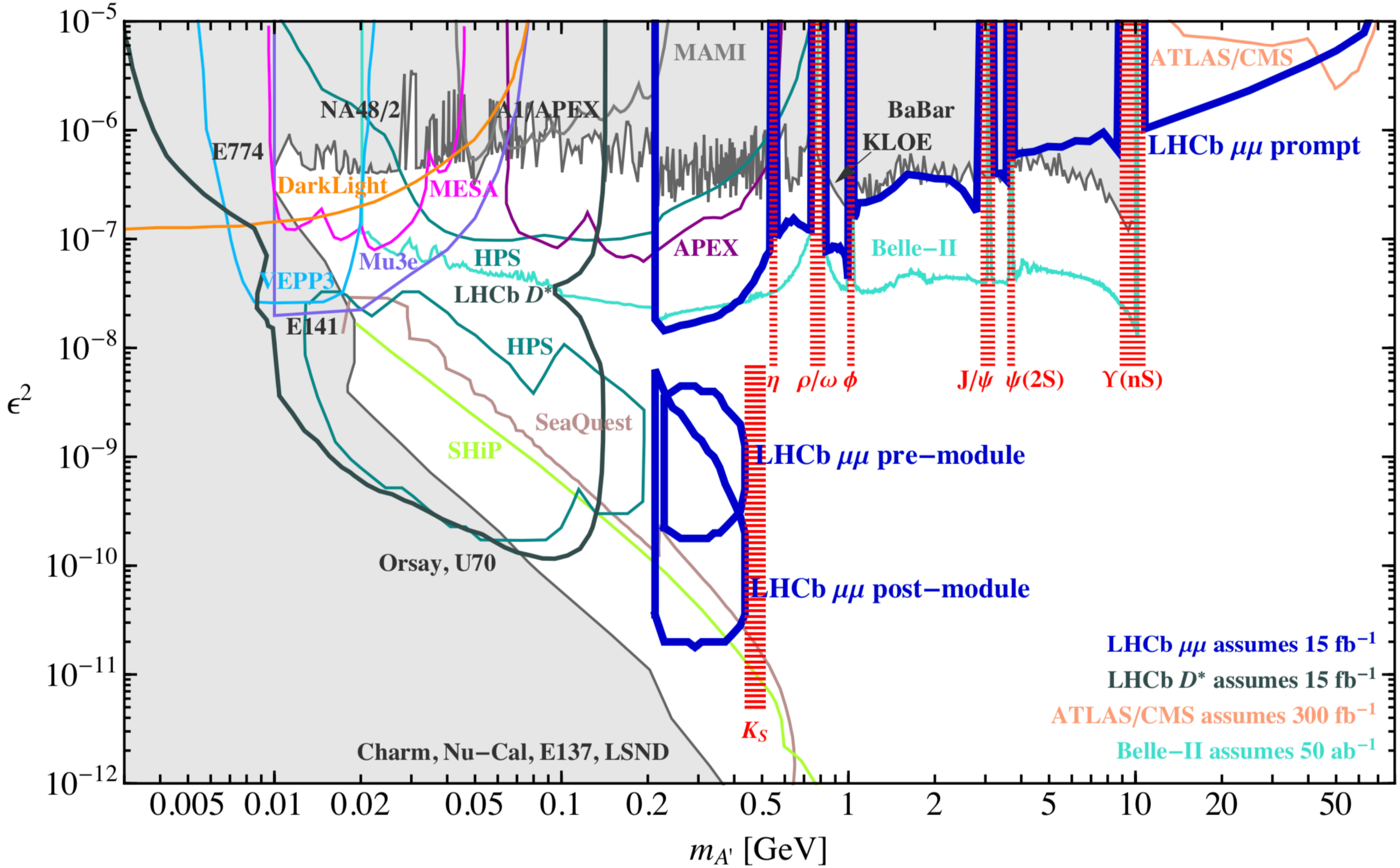
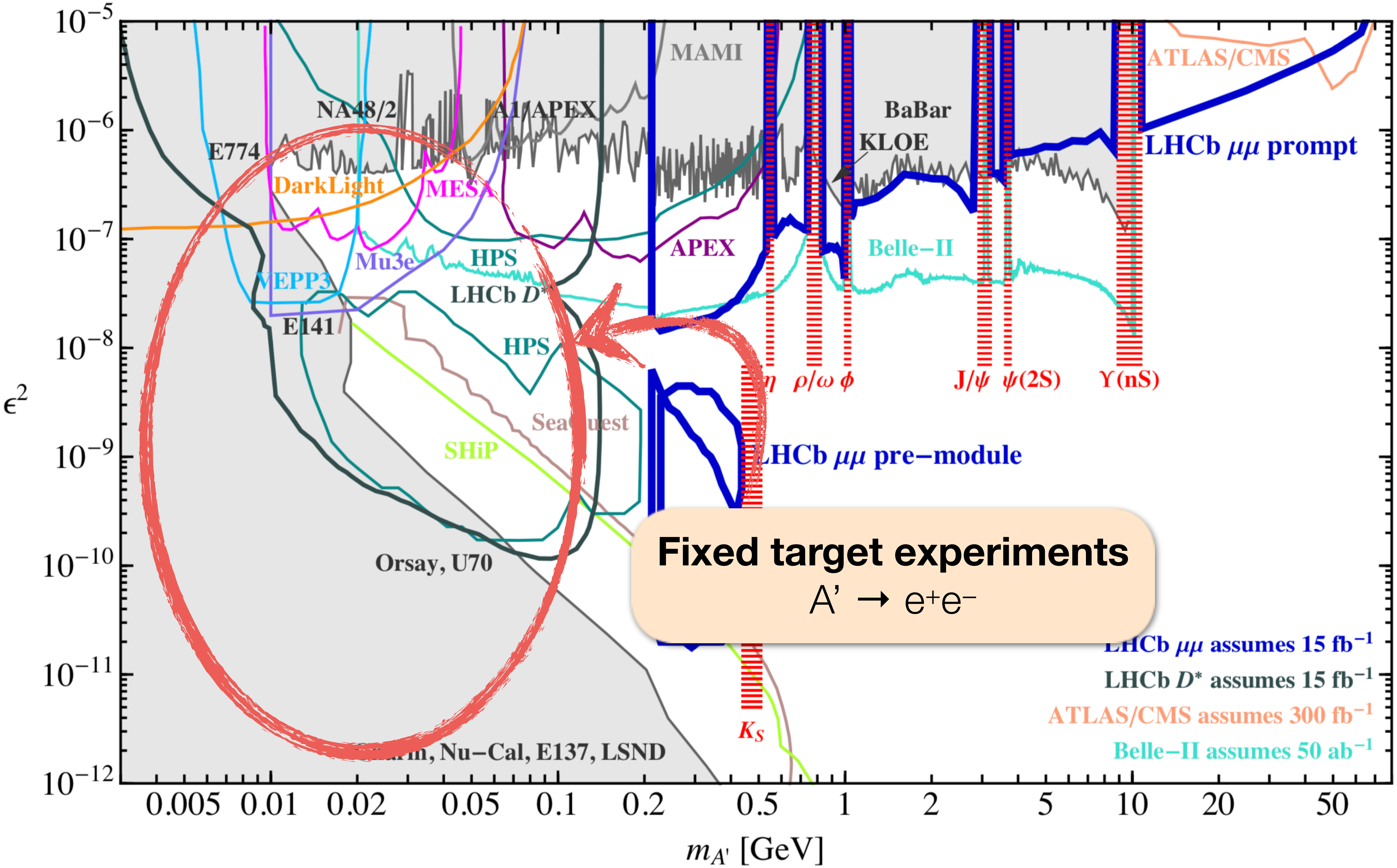
Dark Photon Constraints



Dark Photon Constraints



Fixed target experiments

$A' \to e^+e^-$

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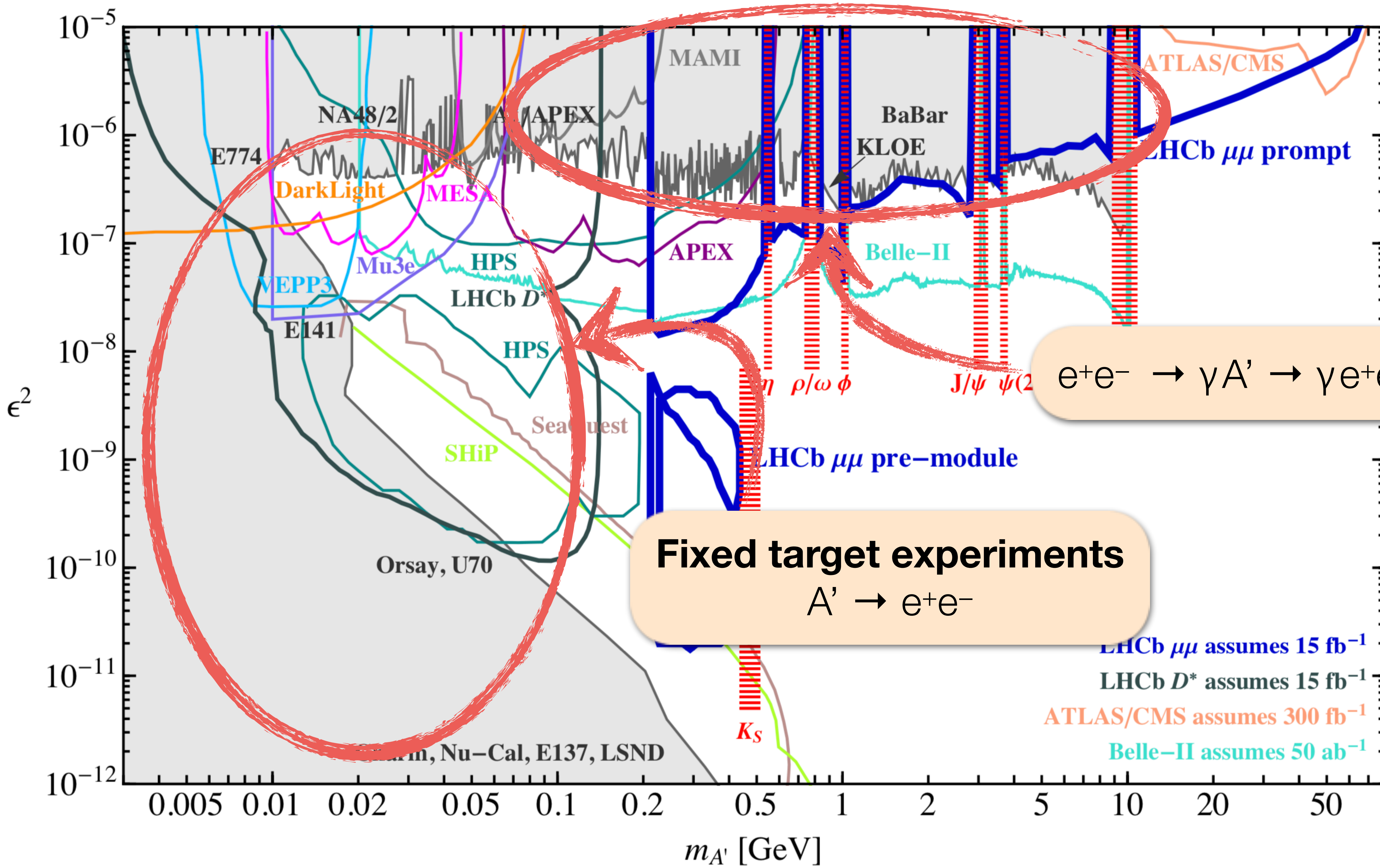
Dark Photon Constraints



$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-$

Fixed target experiments

$A' \rightarrow e^+e^-$

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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

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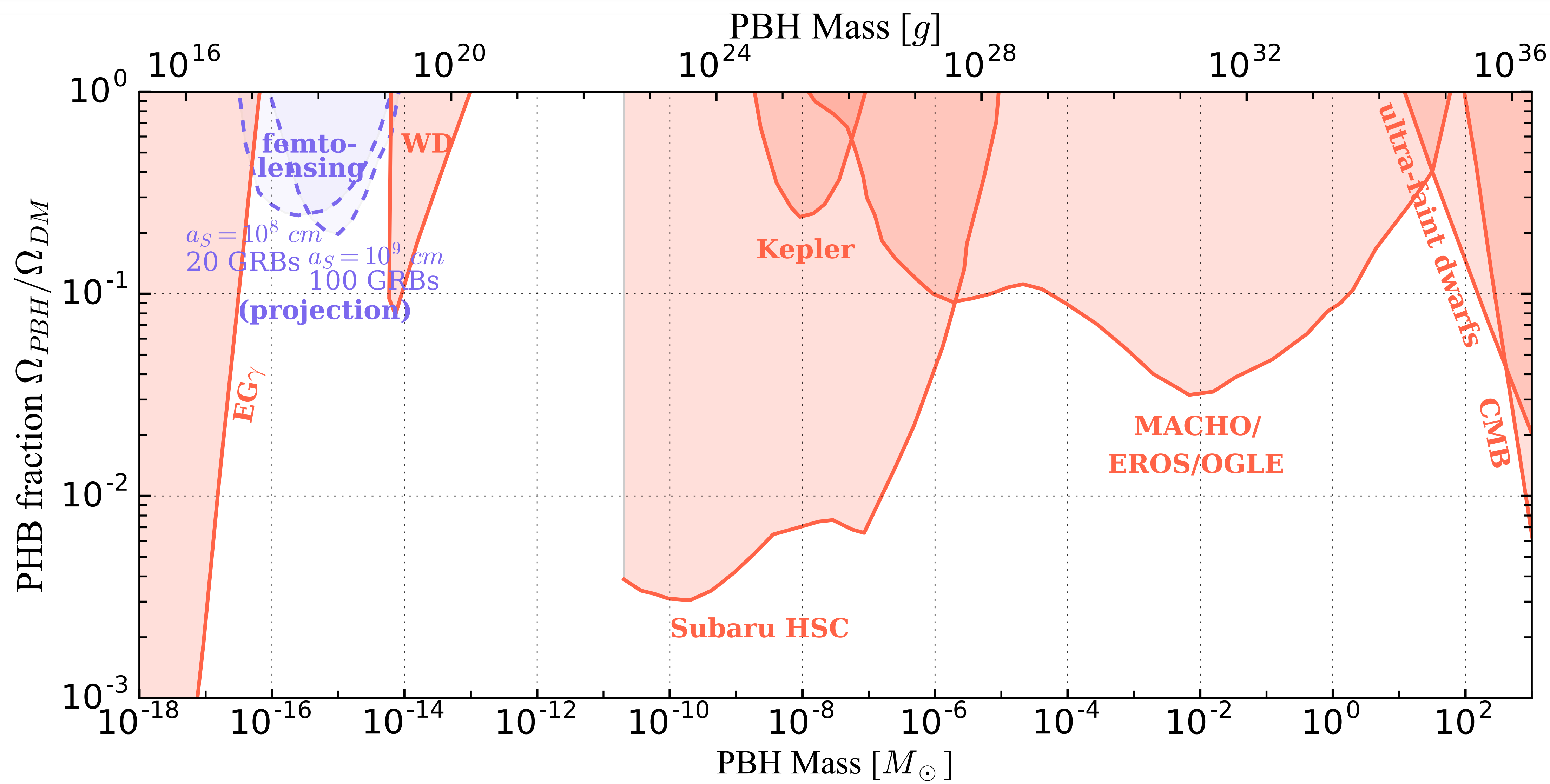
PBH Parameter Space



Katz JK Sibiryakov Xue
arXiv:1807.11495

PBH Evaporation

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

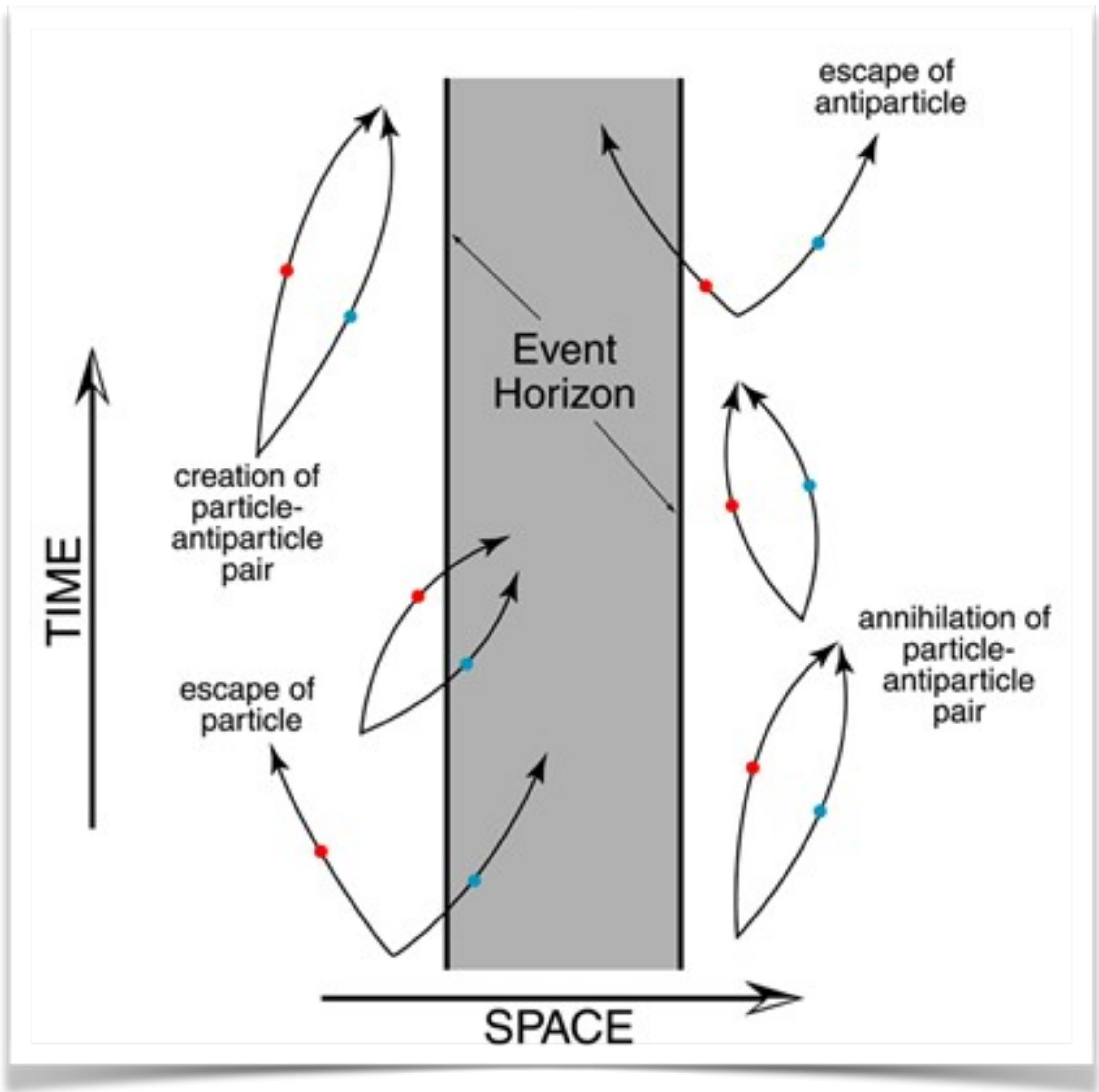


image by Stephen Dilorio

PBH Evaporation

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

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

- Consequently, they eventually evaporate.

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

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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

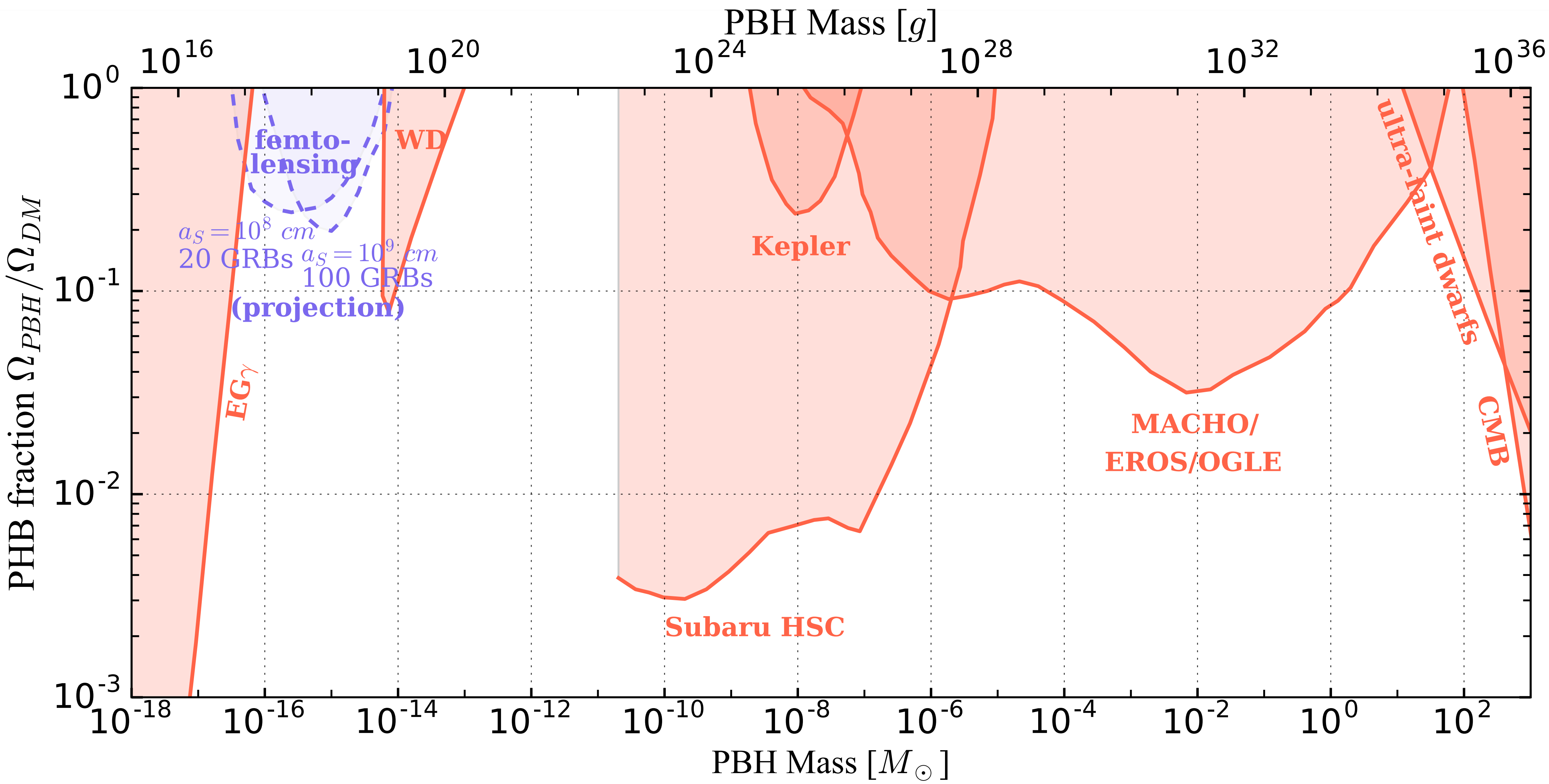
$$\frac{dM_{\rm BH}}{dt} = \sigma T_{\rm BH}^4 \cdot 4\pi R^2 = \frac{1}{2^{10}\pi \cdot 15} \frac{1}{G_N^2 M^2}$$

- ☑ 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

PBH Parameter Space



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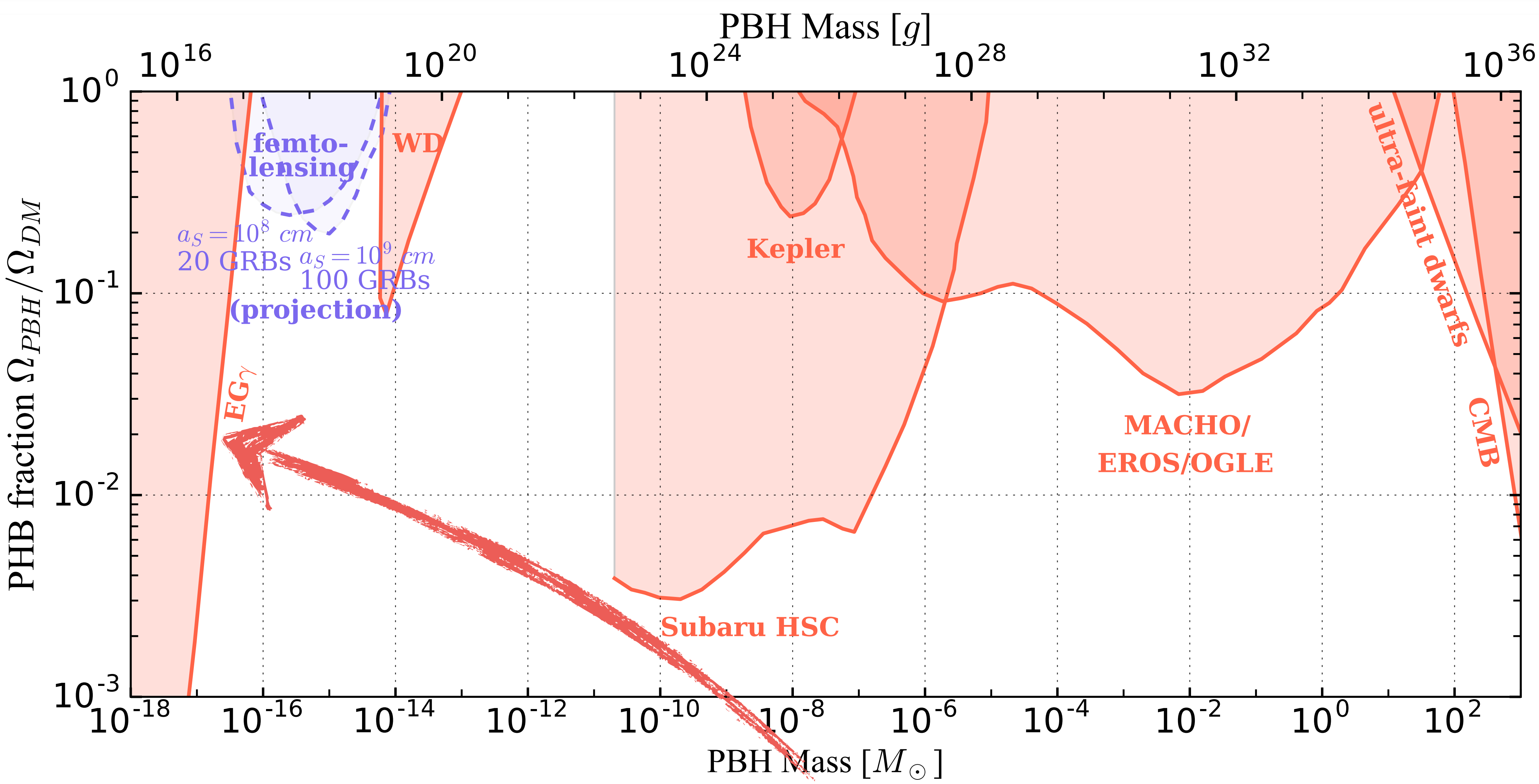

Extragalactic background light
constraint on Hawking radiation
from PBH evaporation

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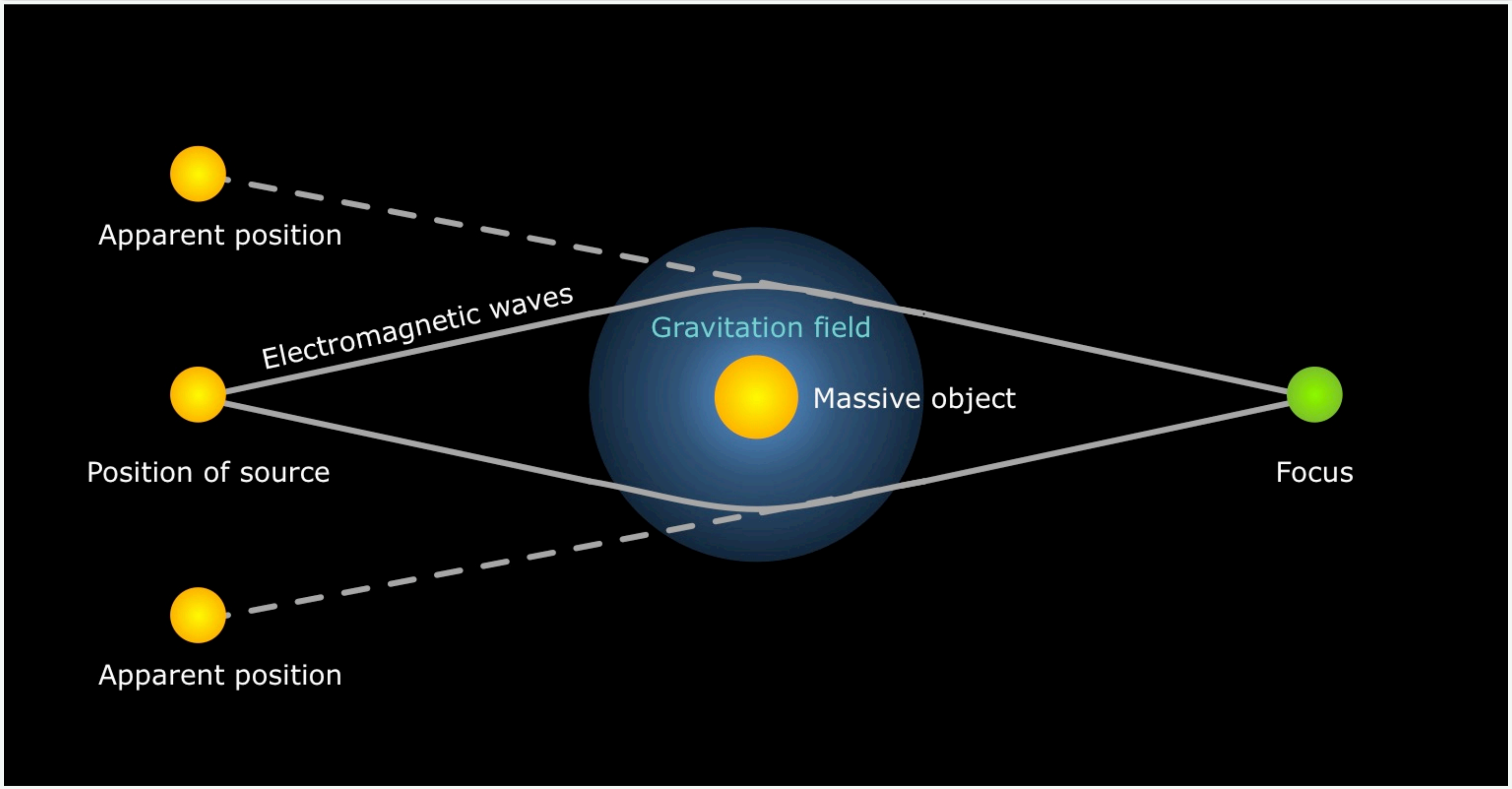
Gravitational Lensing

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

www.spacetelescope.org

www.spacetelescope.org

Gravitational Lensing



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

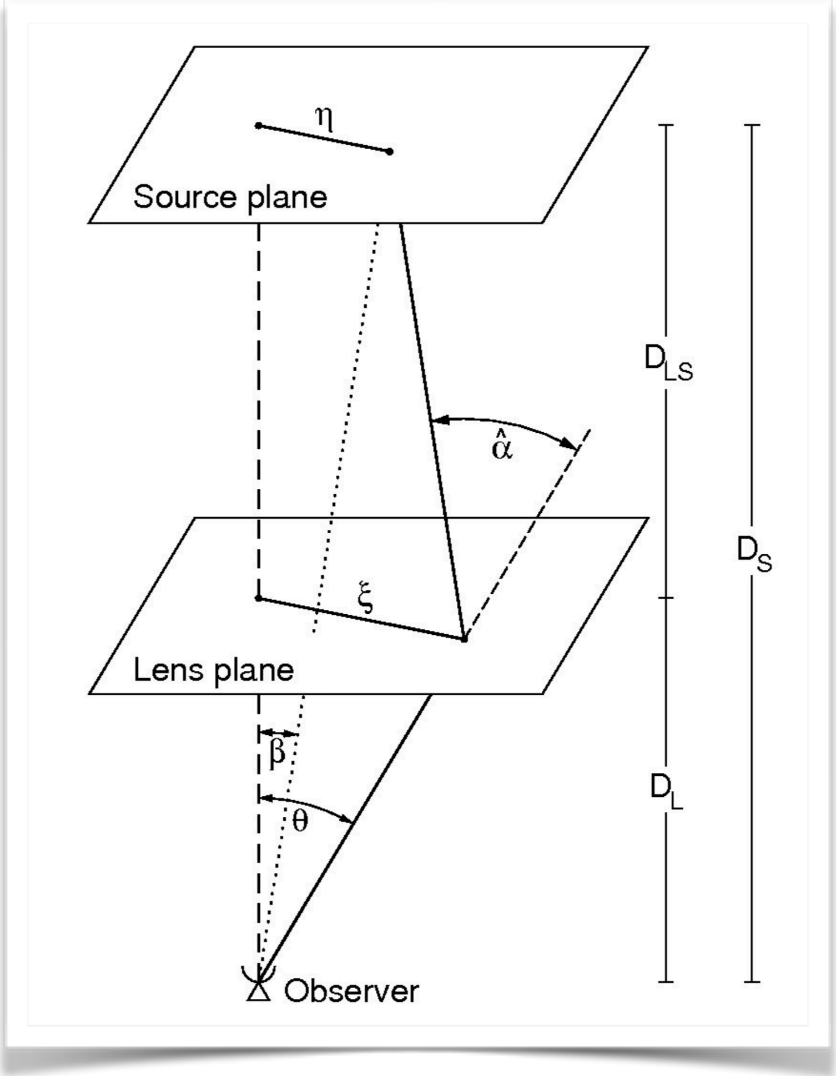
$$c'=\frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t}=c\sqrt{\frac{1+\frac{2\Phi}{c^2}}{1-\frac{2\Phi}{c^2}}}\approx c\left(1+\frac{2\Phi}{c^2}\right)$$

- 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

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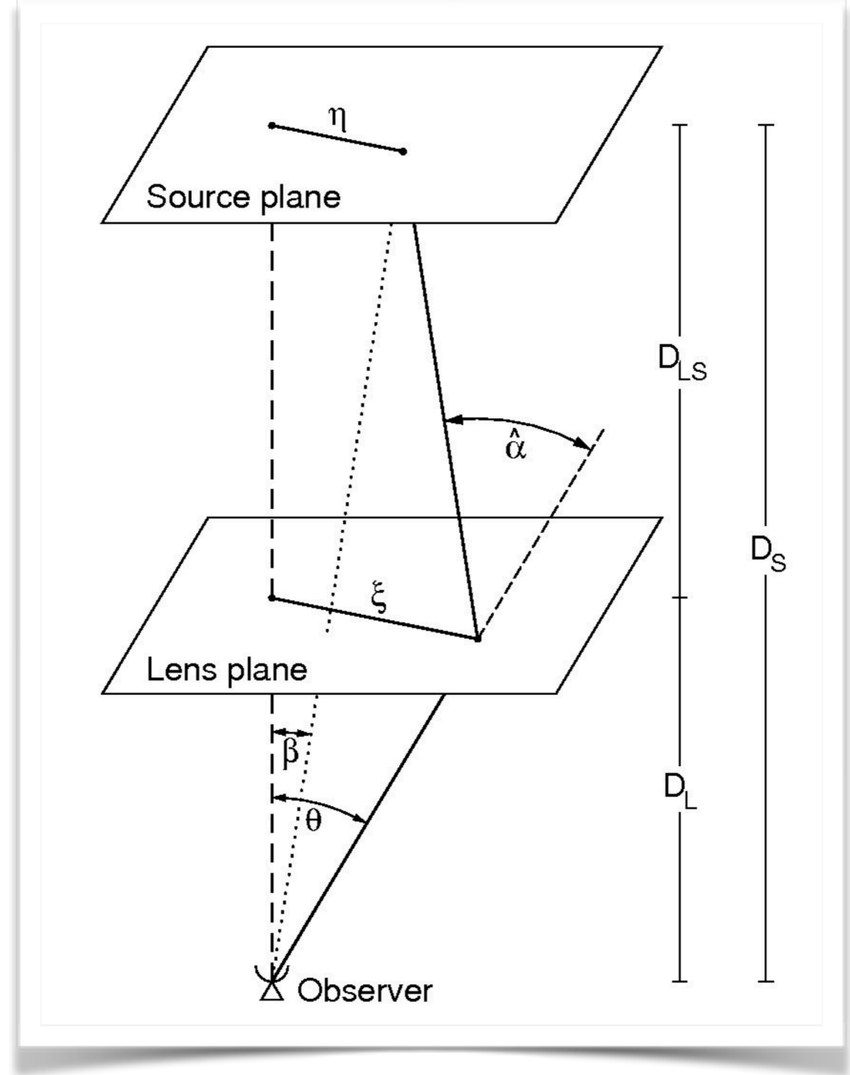

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Integral from source to observer

based on lecture notes by Massimo Meneghetti

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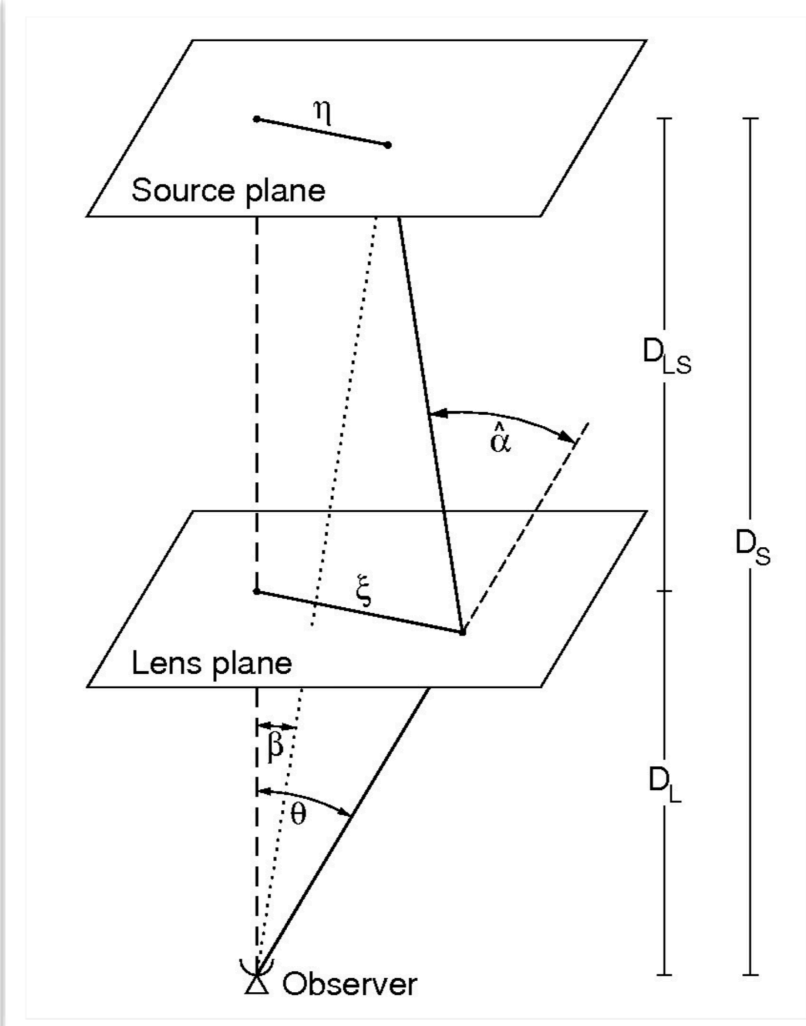

Integral from source to observer

Impact parameter (min. distance to lens)

based on lecture notes by Massimo Meneghetti

Gravitational Lensing: Formalism

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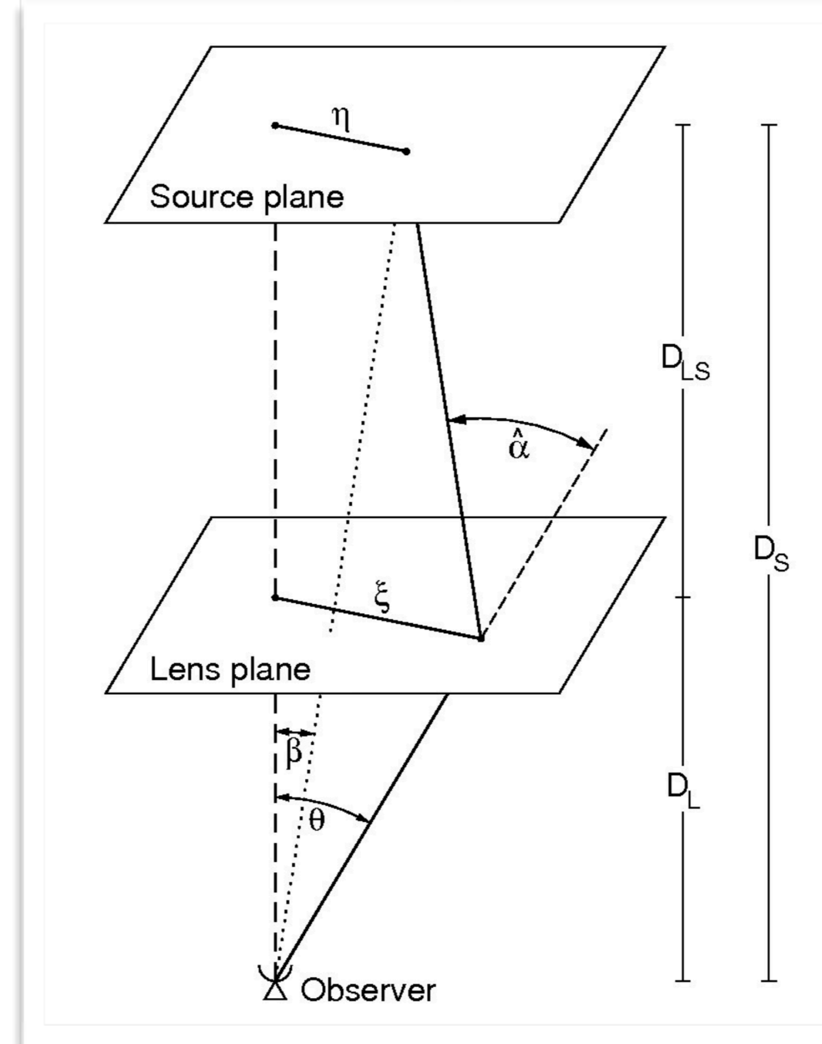


Integral from source to observer

Impact parameter (min. distance to lens)

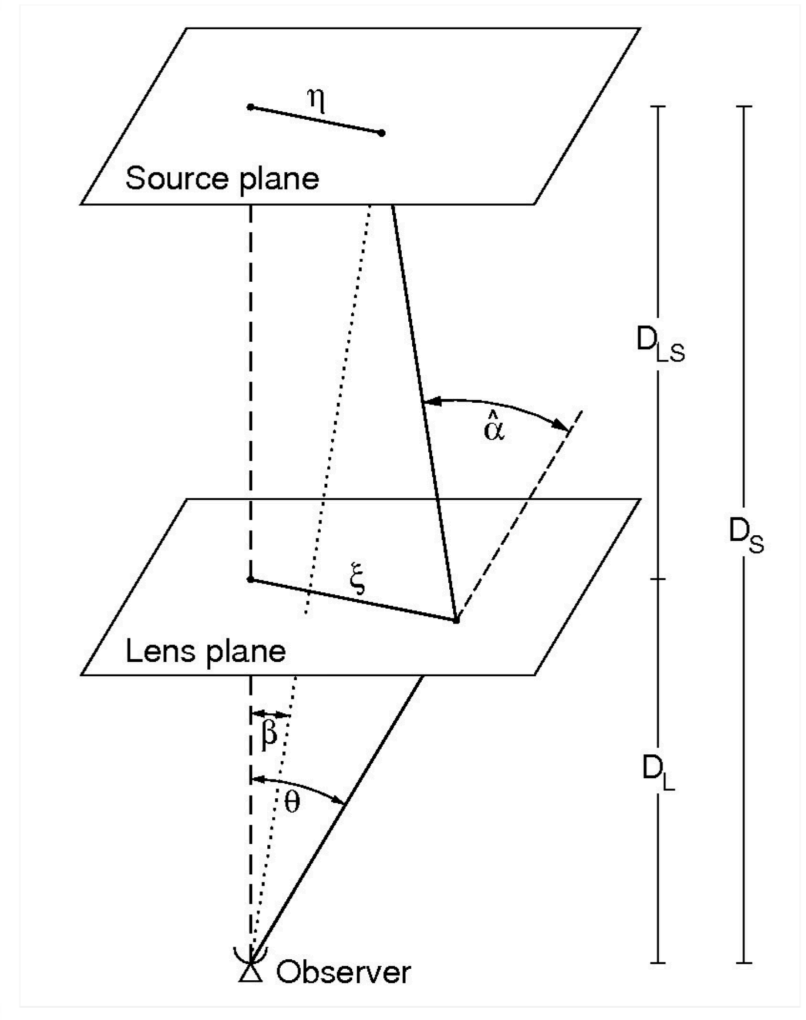
lensing angle
$\theta = \xi/D_S$

based on lecture notes by Massimo Meneghetti

Gravitational Lensing: Formalism

- In addition: geometric time delay

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



- Overall:

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

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Gravitational Lensing: Formalism

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$$\Delta t_{\rm geom} = \left[\frac{D_L}{c\,\cos(\theta-\beta)} - D_L\right] + \left[\frac{D_{LS}}{c\,\cos[(\theta-\beta)D_L/D_{LS}]} - D_{LS}\right]$$
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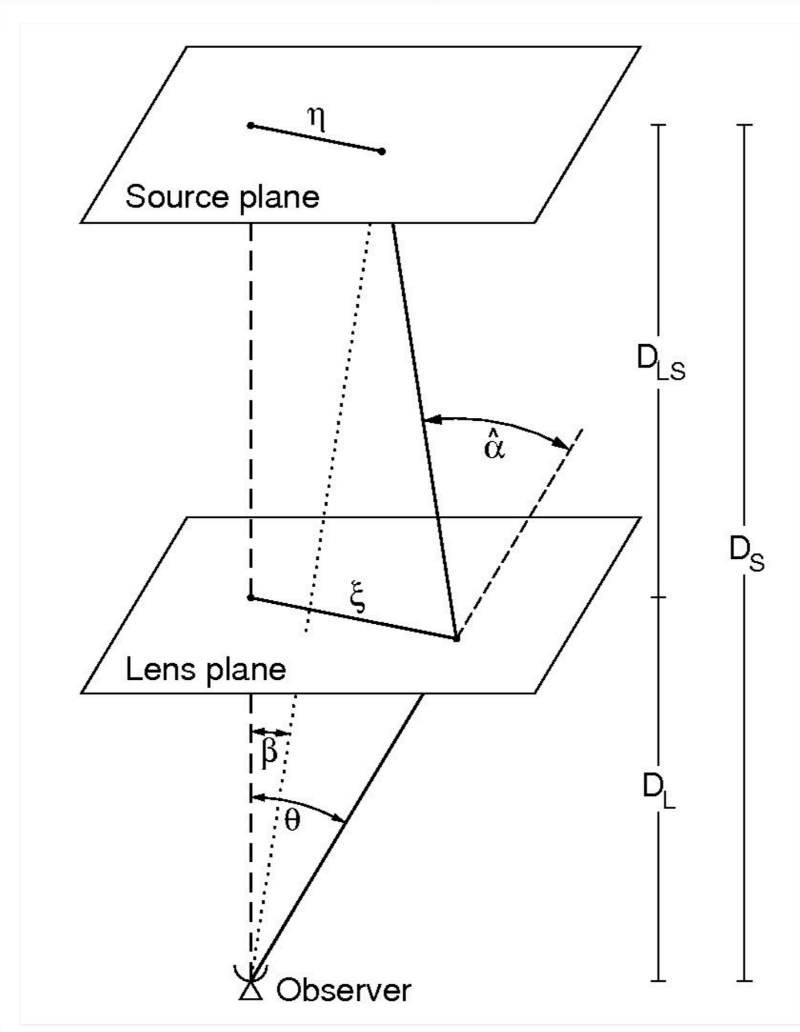

- Overall:

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

Square of the **Einstein angle**:

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

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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:

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

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 $\beta = 0$ (lens along the line of sight).

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

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

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

$$\mu_\pm = \frac{y^2+2}{2y\sqrt{y^2+4}} \pm \frac{1}{2}$$

➟ total magnification: $$\mu = \frac{y^2+2}{y\sqrt{y^2+4}}$$

- 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.

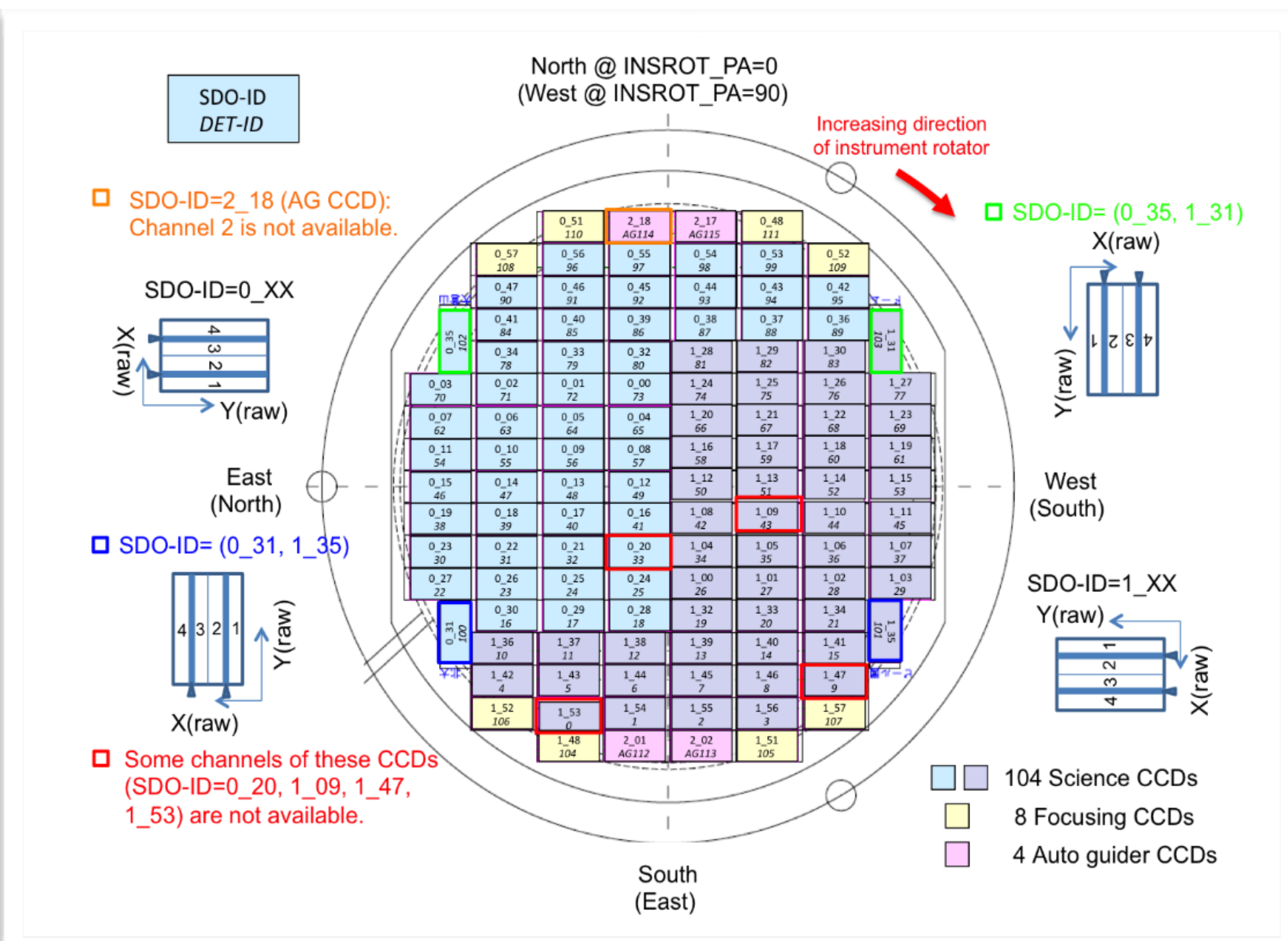
Microlensing

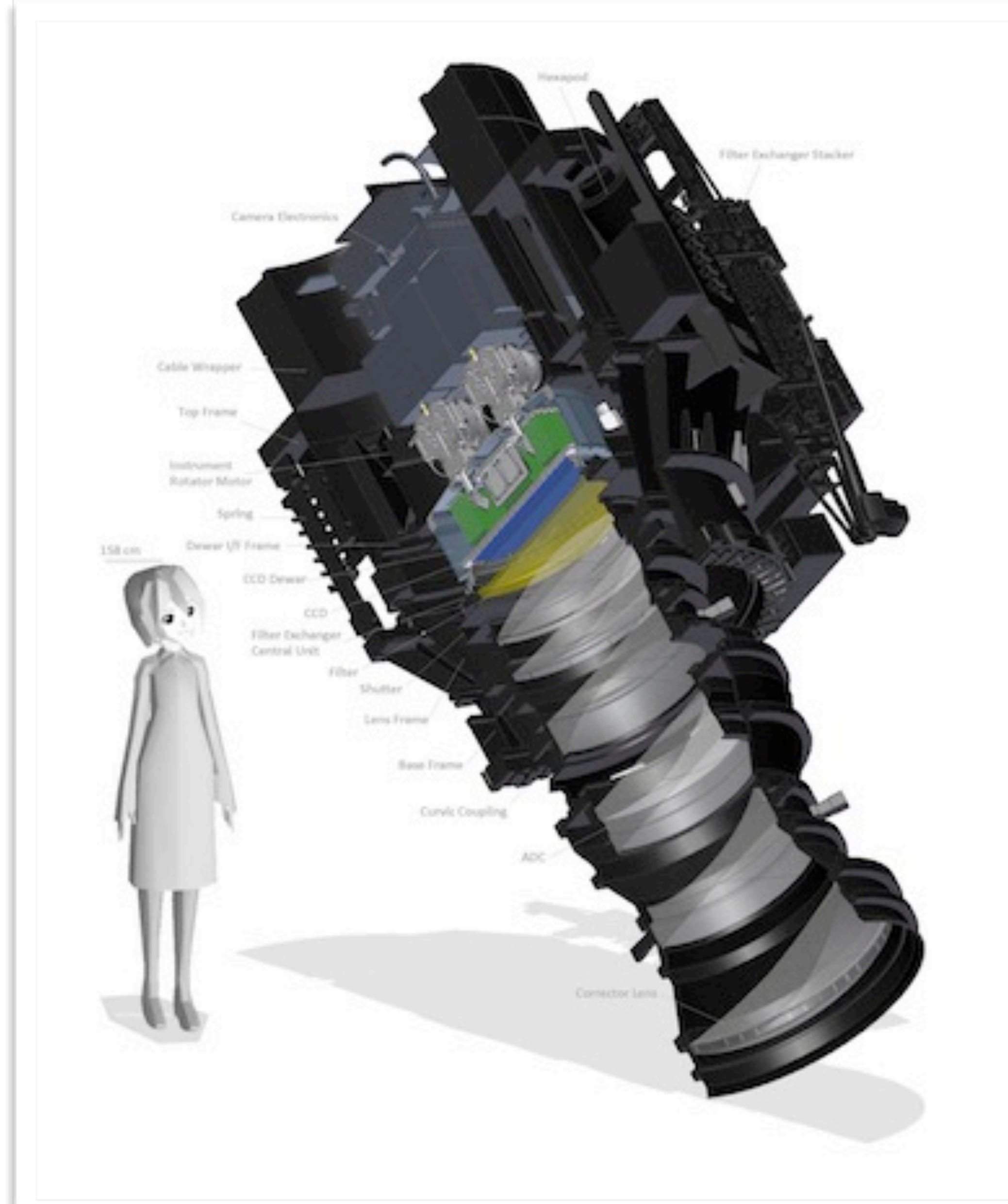
☑ Observations at the 8.2 m Subaru Telescope (Hawaii)

Niikura et al. arXiv:1701.02151

Microlensing

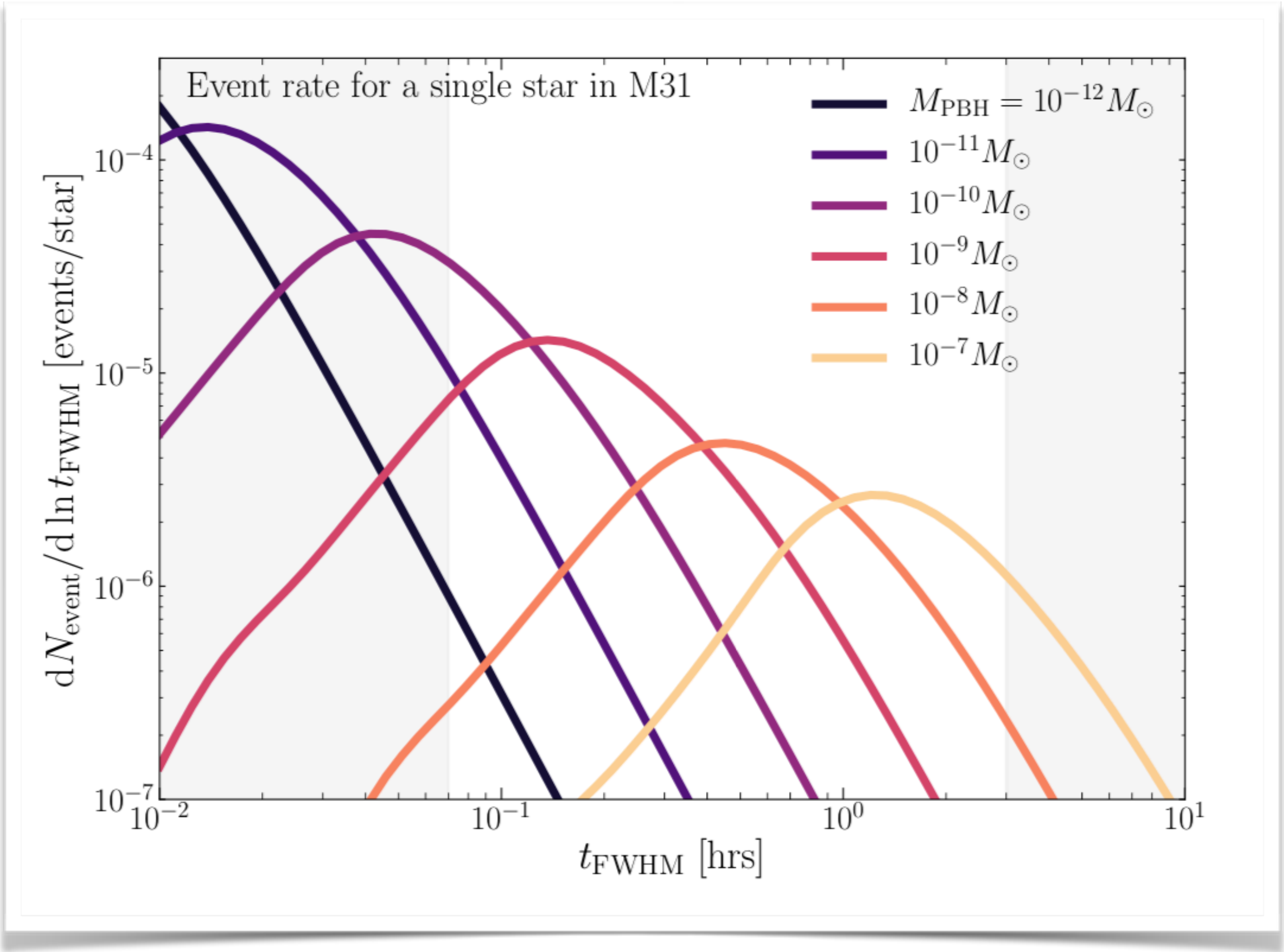
- In particular: Hyper Suprime-Cam
- 1.5 degree field of view (huge!)
- 900 Megapixels





Niikura et al. arXiv:1701.02151

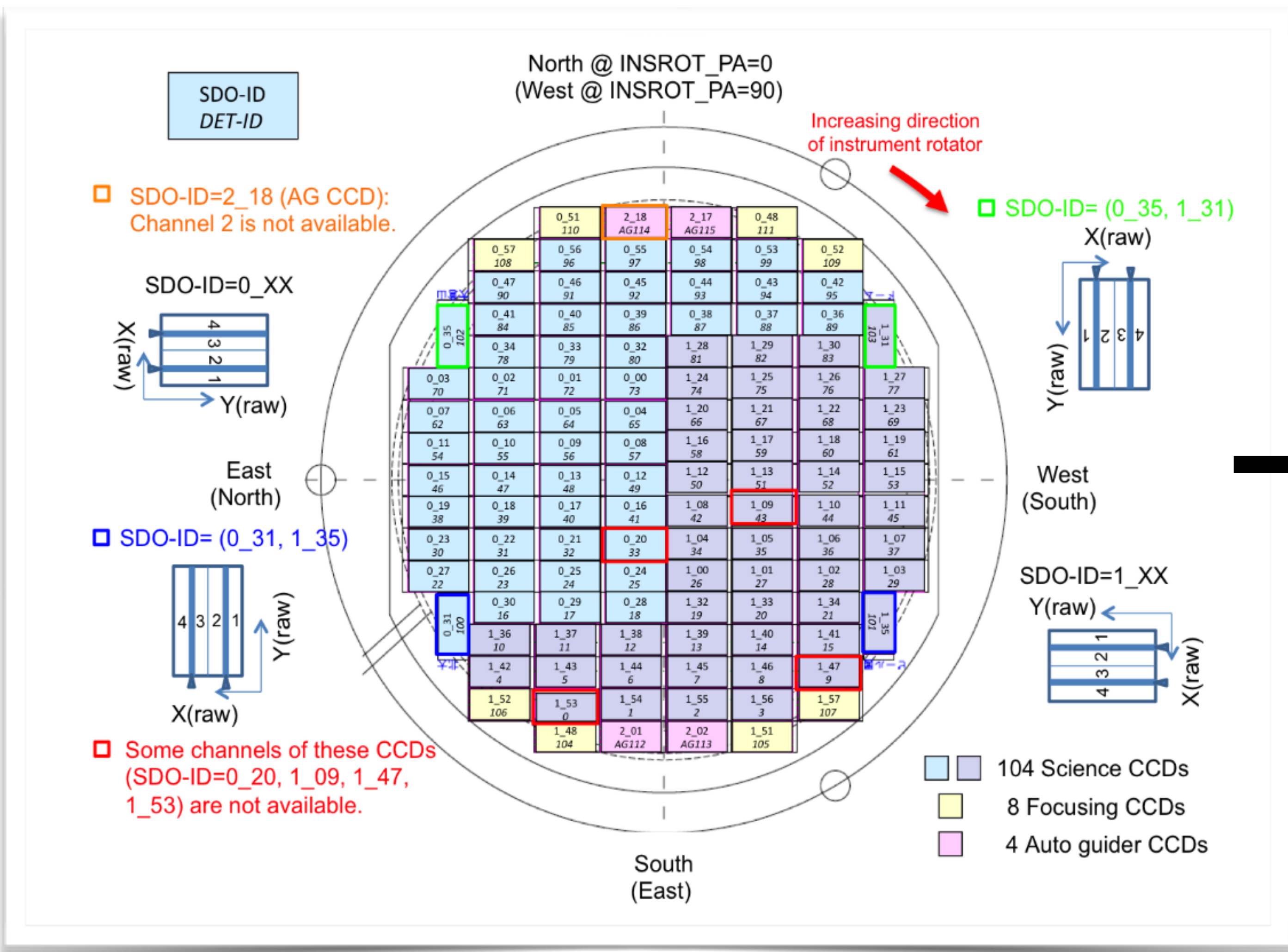
Lensing Probability

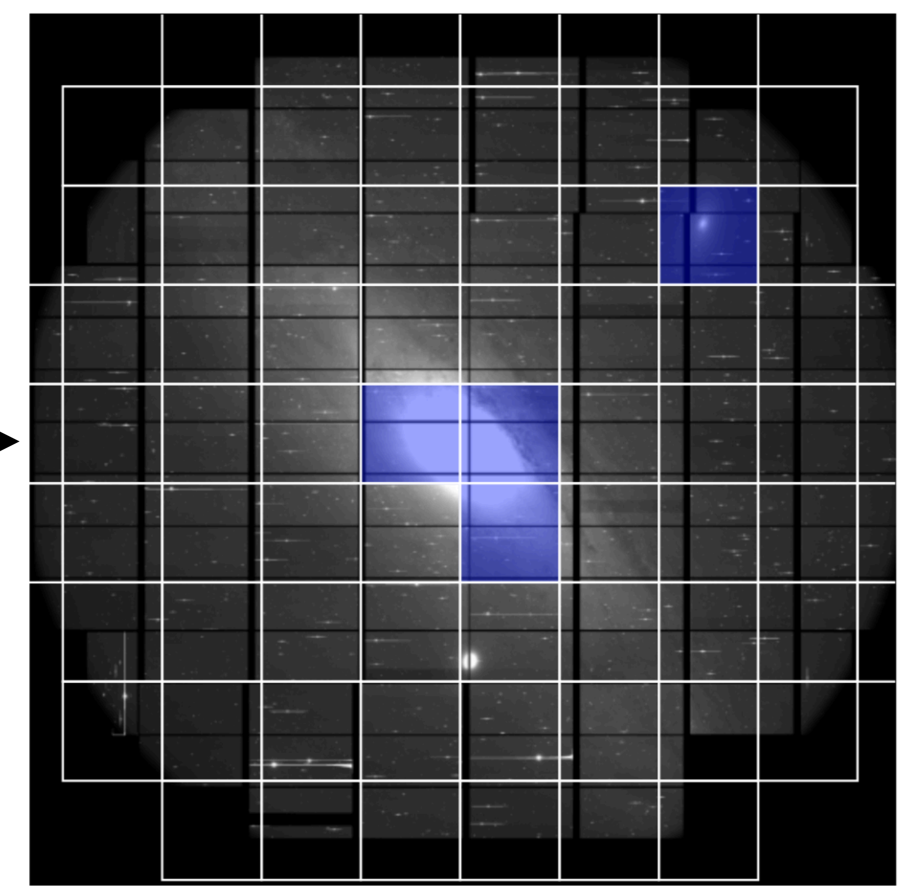


Niikura et al. arXiv:1701.02151

Observation Strategy

- ☑ Single night (7 hours of observations) sufficient
- ☑ Large field of view
  ➠ observe the whole M31 (Andromeda) galaxy at once





Niikura et al. arXiv:1701.02151

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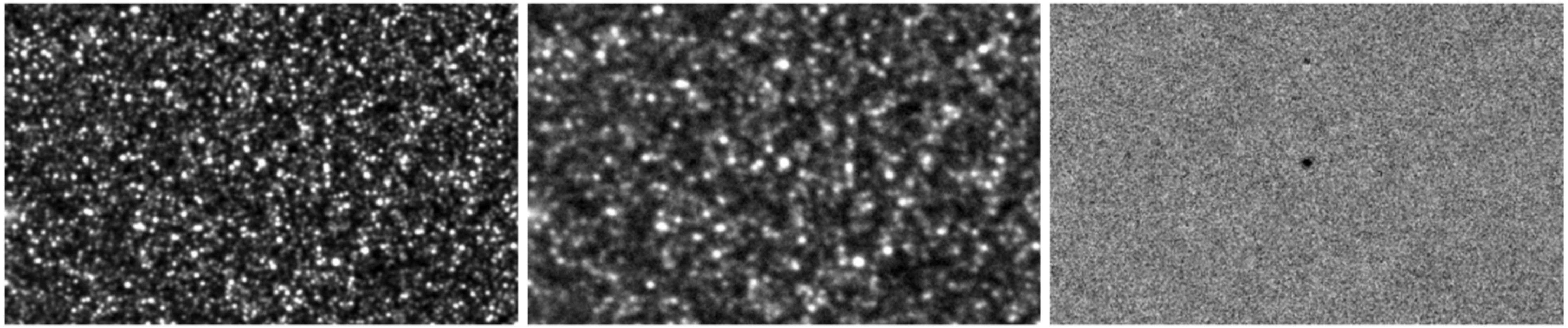
Observation Strategy

- ☑ Single night (7 hours of observations) sufficient
- ☑ Repeated observations of the same patch on the sky (90 sec observation time, 35 sec readout time)
- ☑ Subtract reference image to detect transients



Observation #1 Observation #2 Difference (including transient)

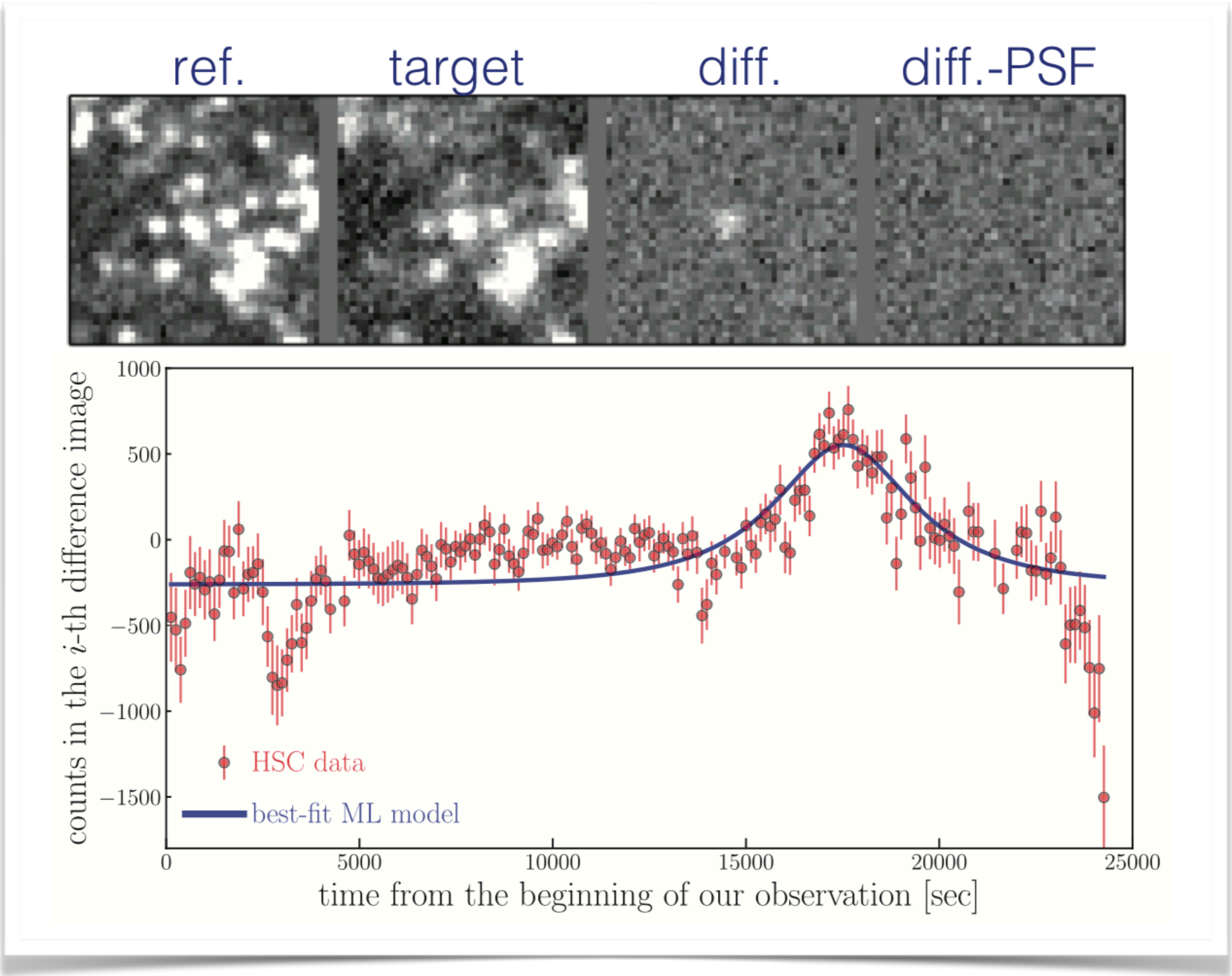
Niikura et al. arXiv:1701.02151

Data Analysis

- Analysis challenges
  - each CCD pixel contains many stars
  - central region of M31 too bright (CCDs saturated ➠ discard)
- Selection criteria for microlensing candidates
  - At least 5σ detection in any of the 188 difference images
  - difference image consistent with point spread function
- Result: 15 571 candidates
- Construct light curve for each of them

Niikura et al. arXiv:1701.02151

Data Analysis



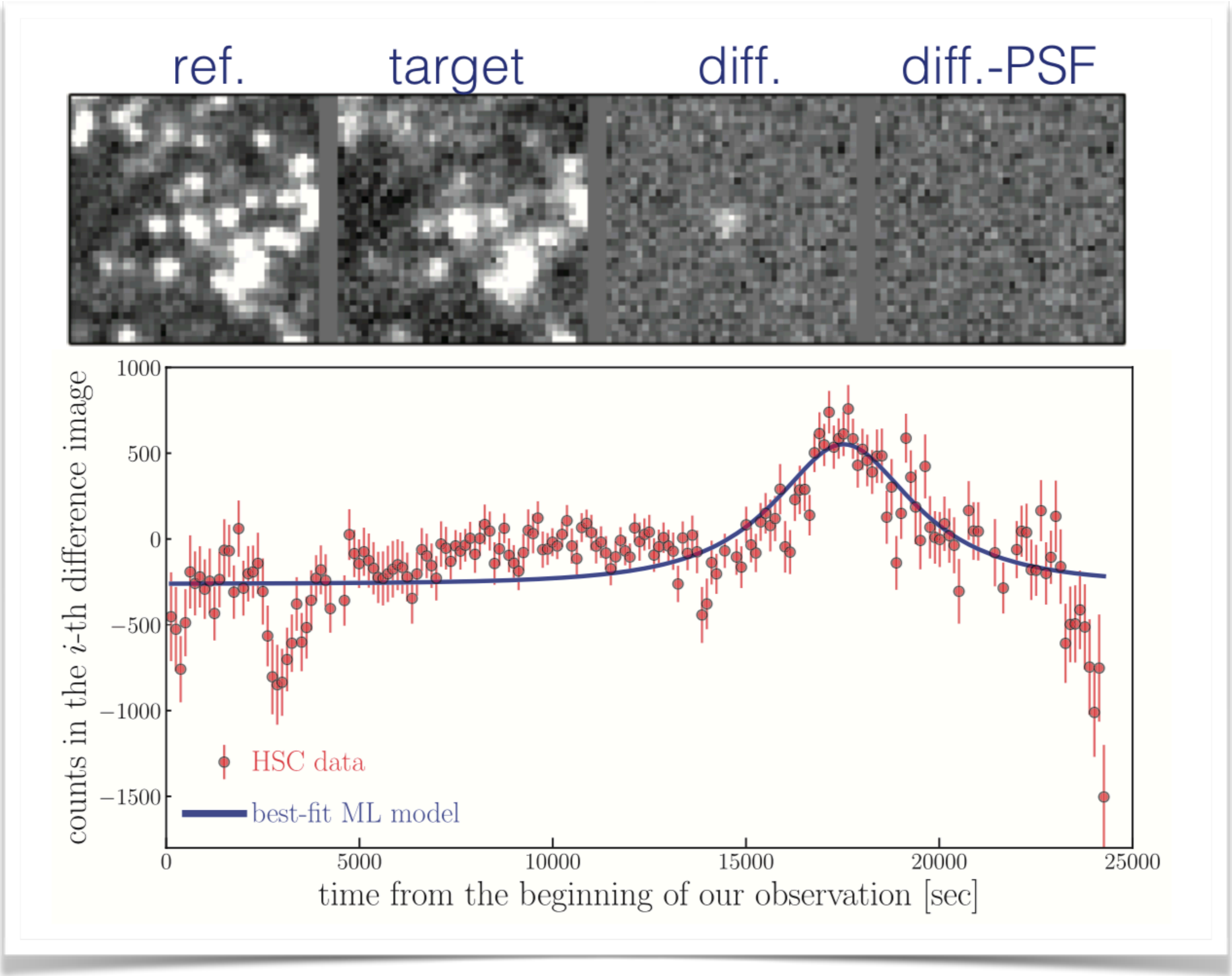
Niikura et al. arXiv:1701.02151

Further Selection Criteria

- Subject the 15 571 candidates to the following cuts
  - Require single bump to exclude periodic stars (➠ 11 703 candidates left)
  - Fit predicted microlensing light curve, require decent goodness-of-fit (➠ 66 candidates left)
- Visual inspection
  - reject 44 candidates due to cross-talk from nearby bright star
  - reject 20 additional candidates at the edges of CCDs
  - reject 1 candidate due to passing asteroid
- 1 candidate left

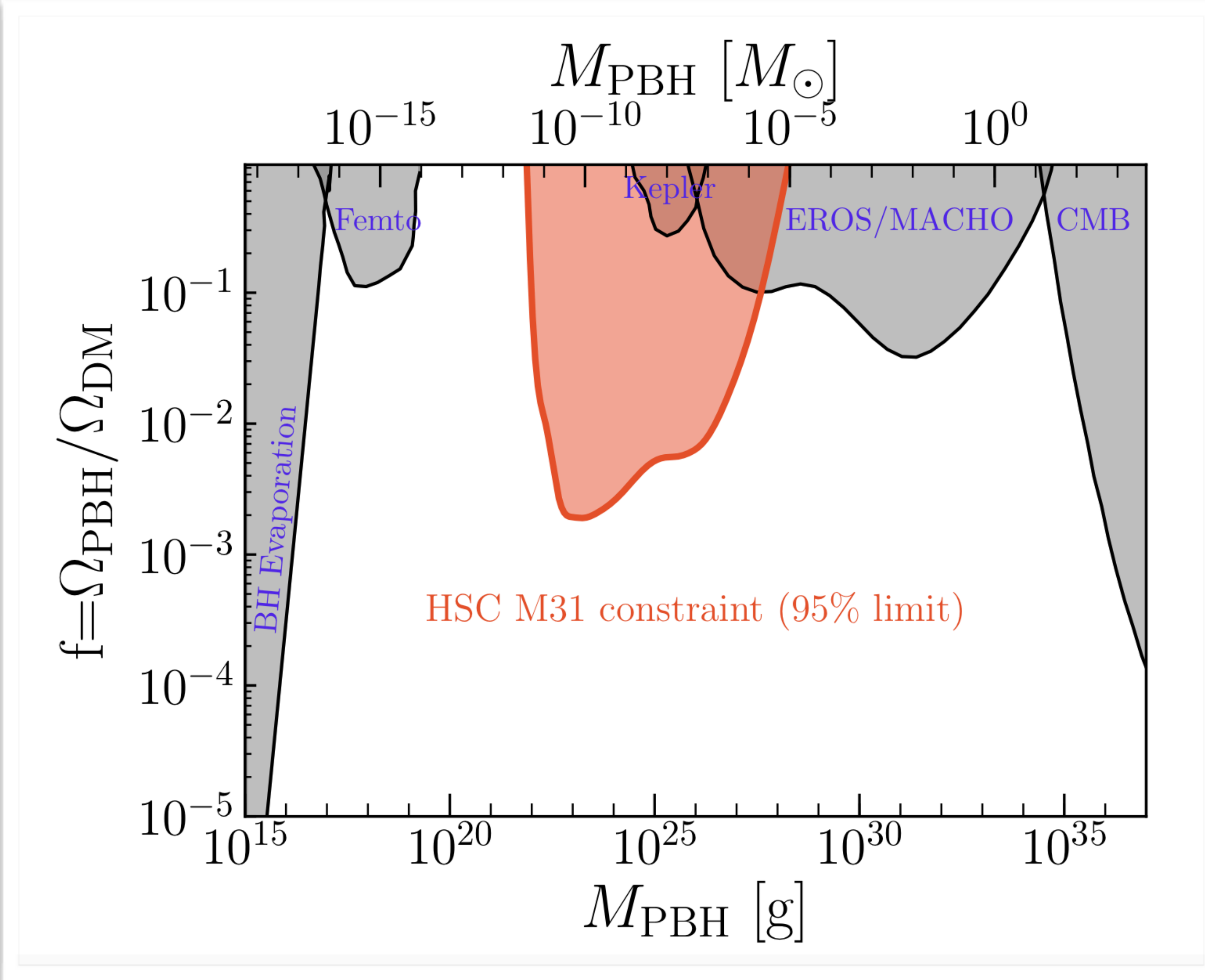
Niikura et al. arXiv:1701.02151

Data Analysis



Niikura et al. arXiv:1701.02151

Resulting Limits



Niikura et al. arXiv:1701.02151

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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)

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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:

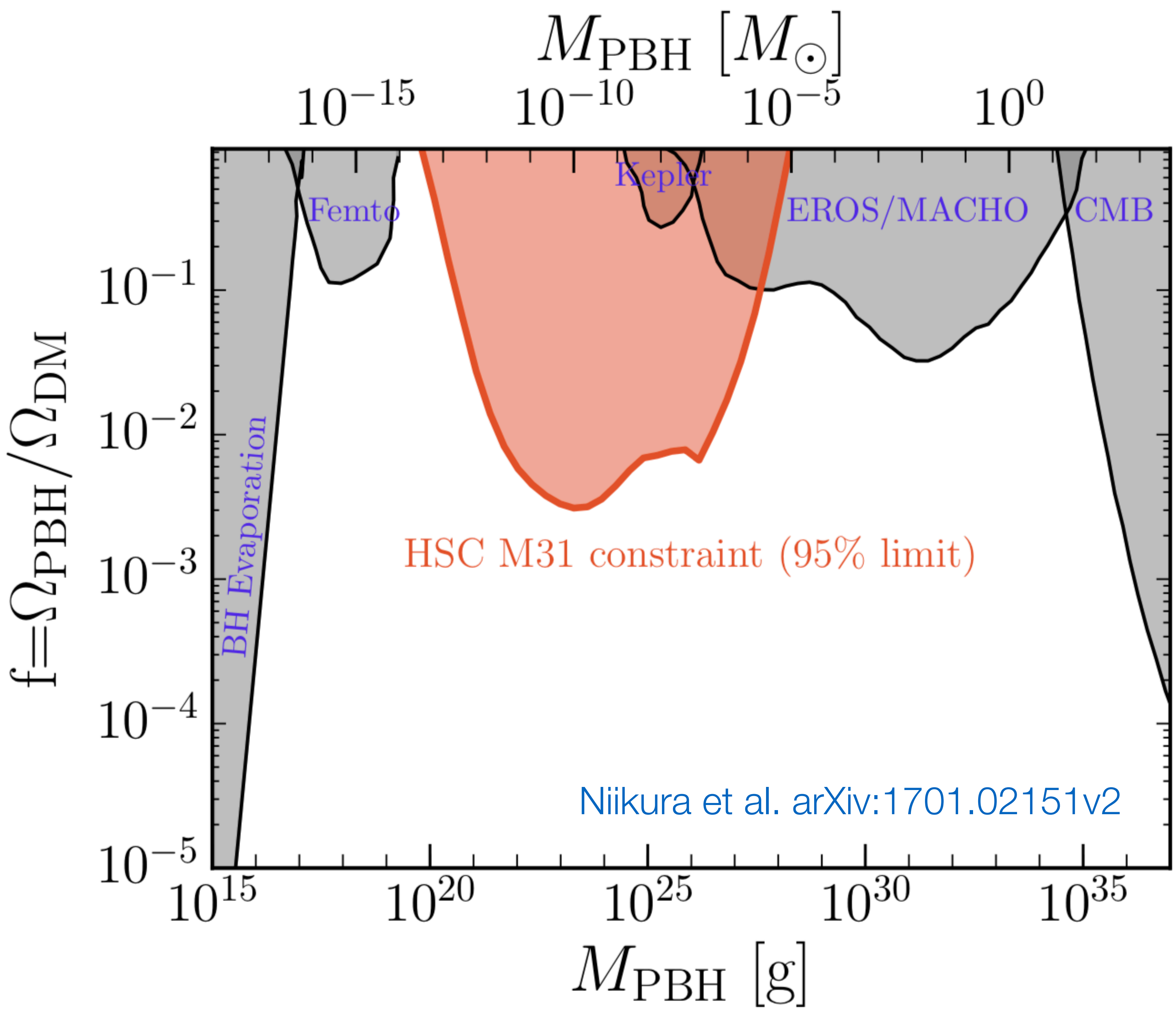
$$\mu = \frac{y^2 + 2}{y\sqrt{y^2 + 4}} \,.$$

- 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

Effect of Wave Optics + Finite Source Size



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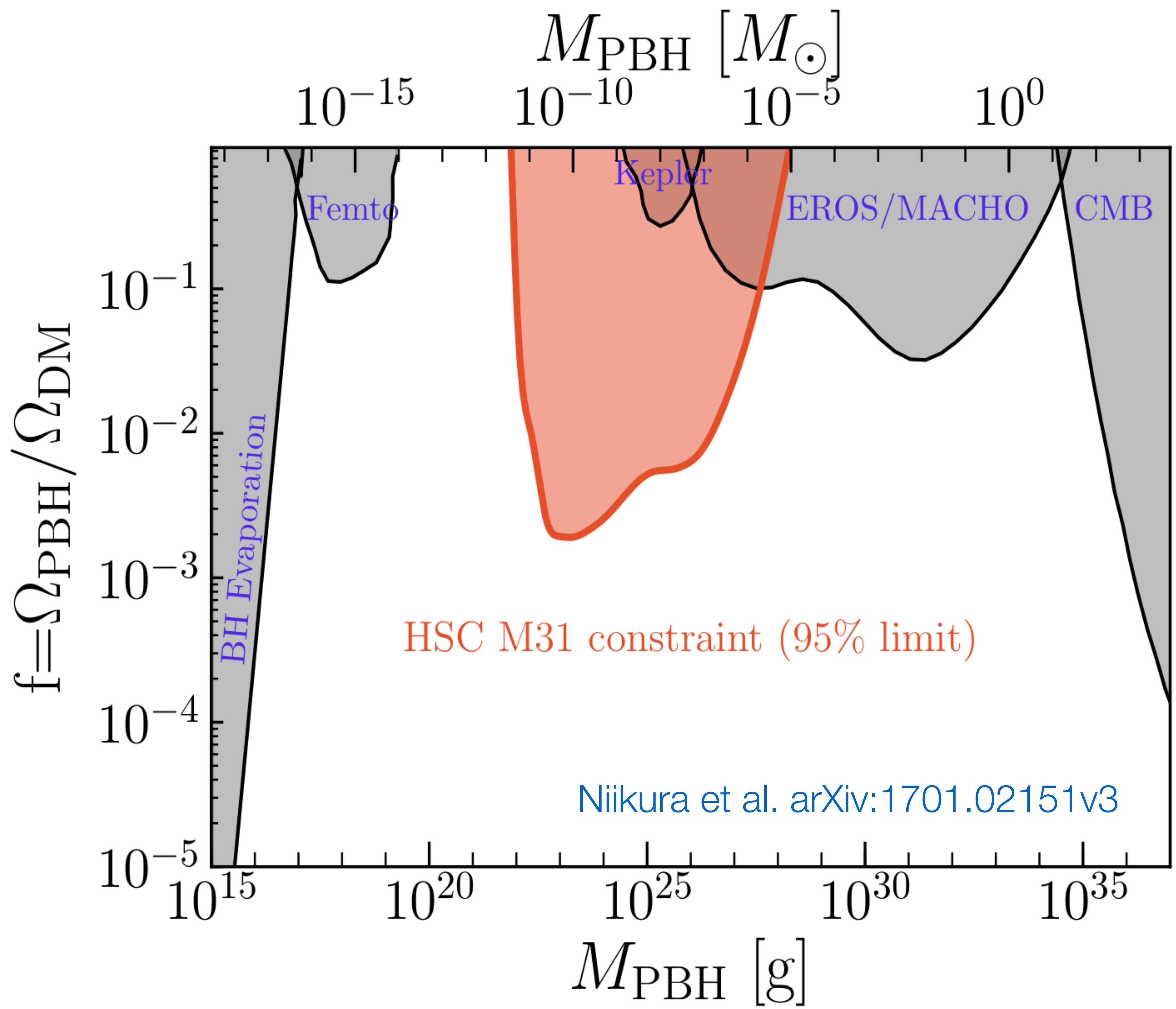
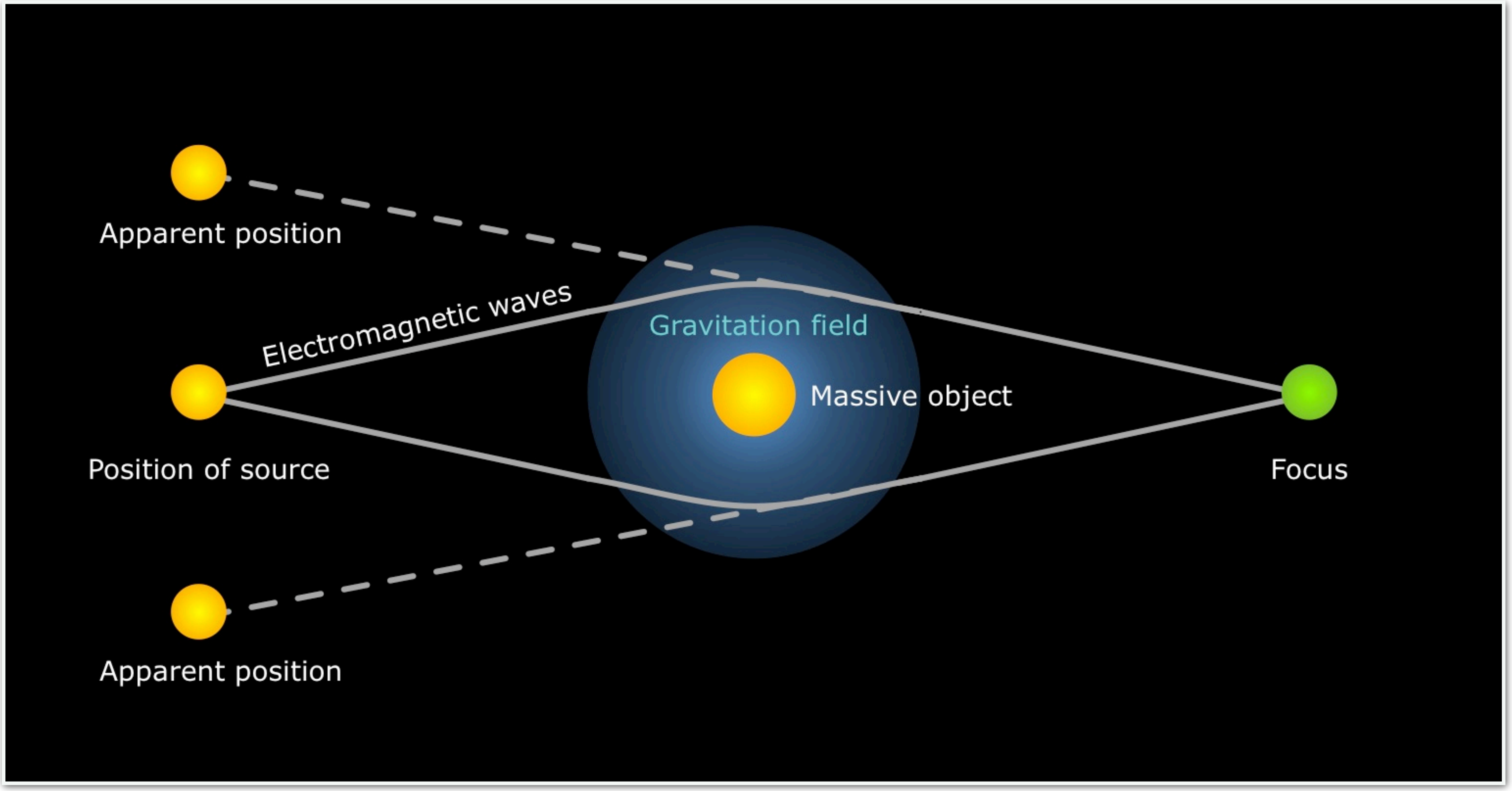
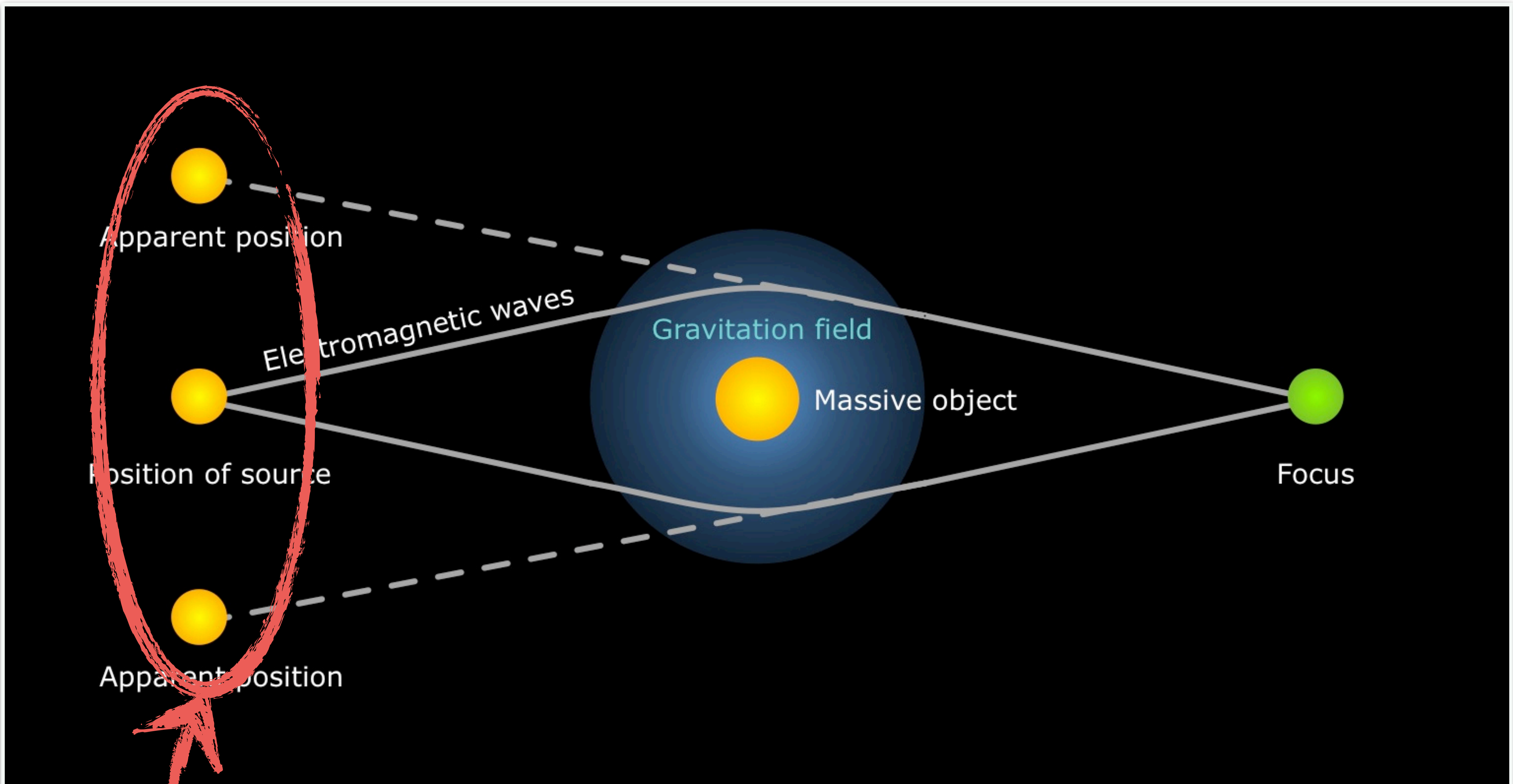
Effect of Wave Optics + Finite Source Size



Femtolensing

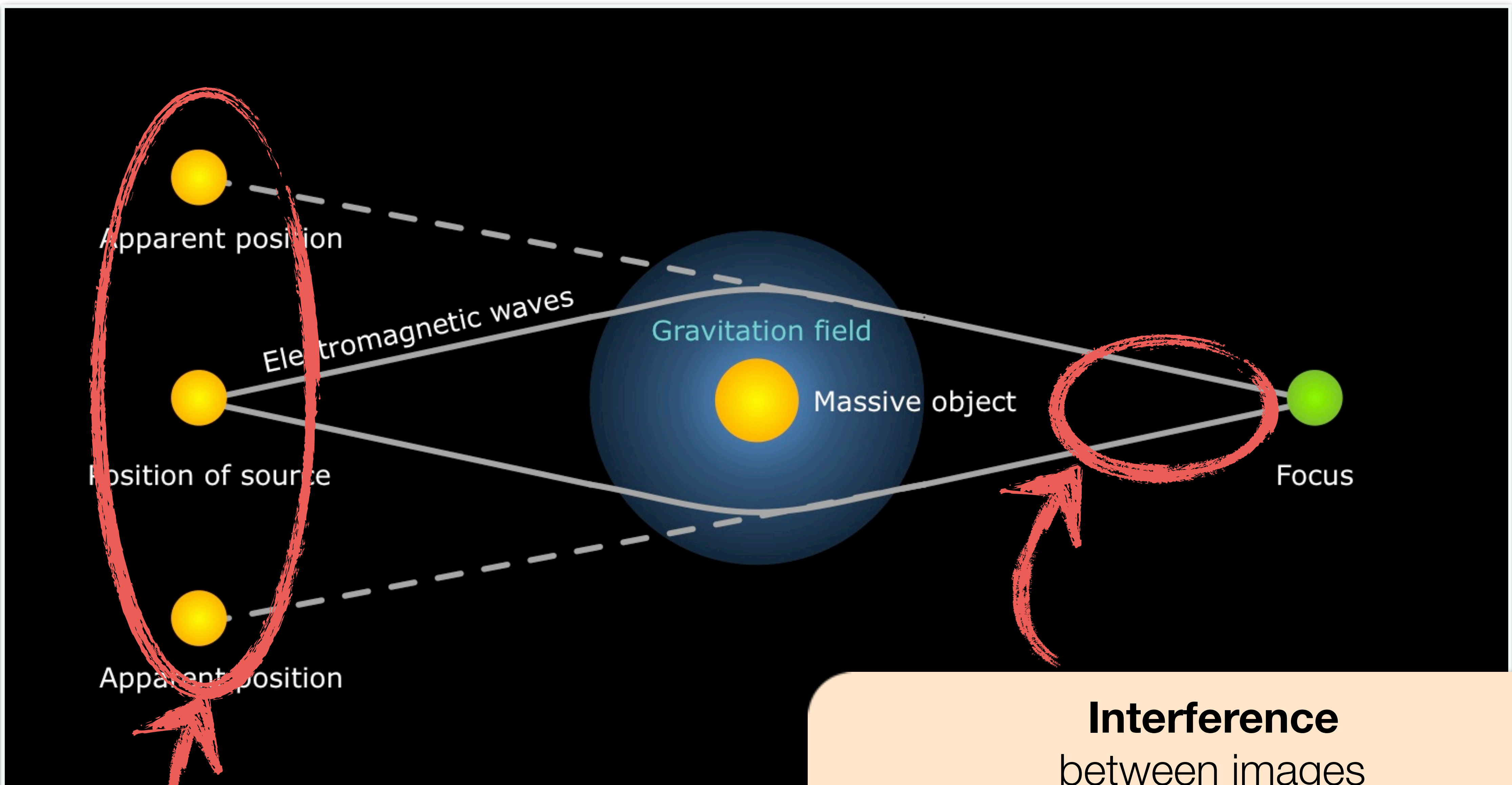


Femtolensing



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

Time Delay (Geometric Optics)

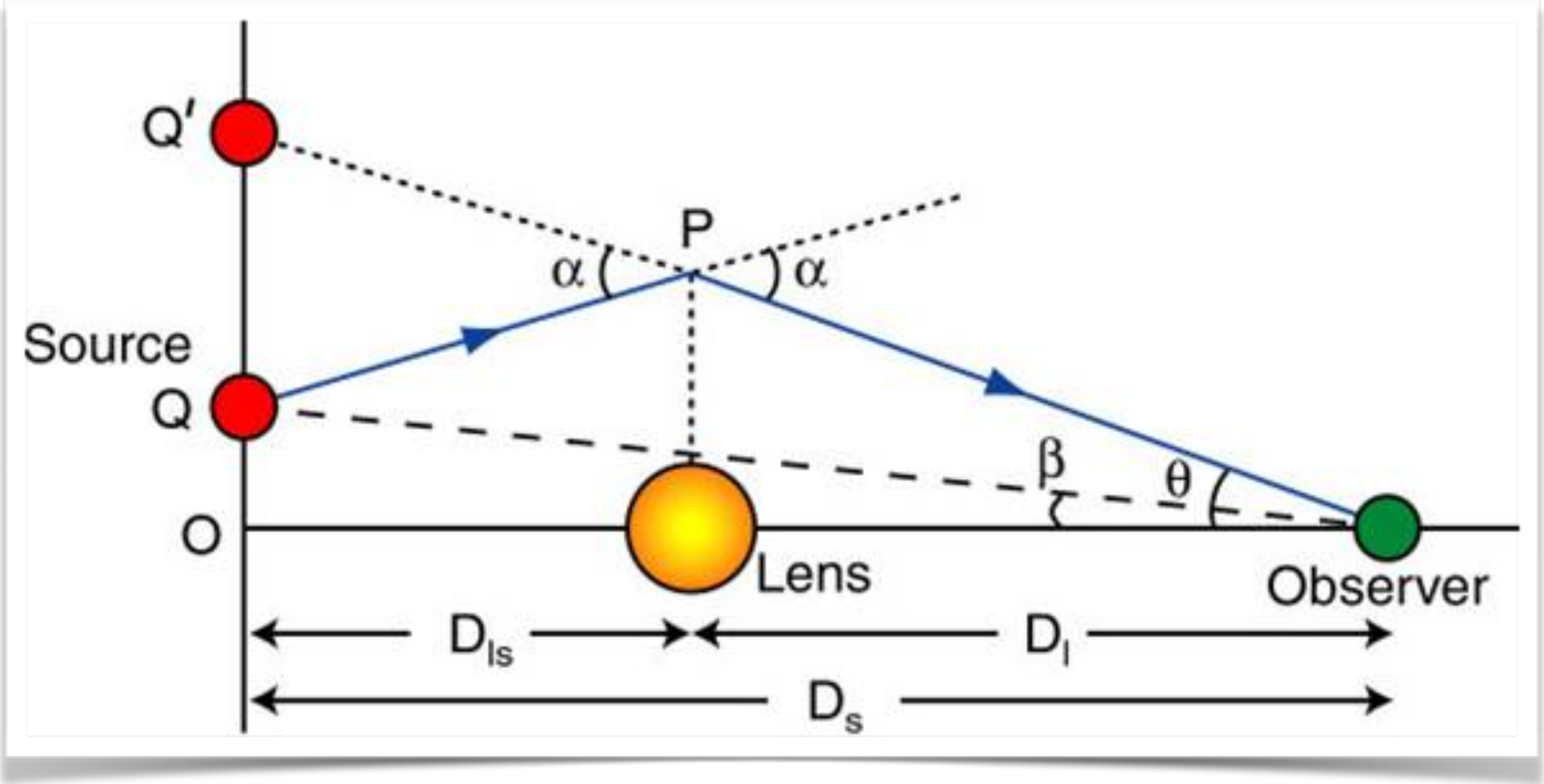
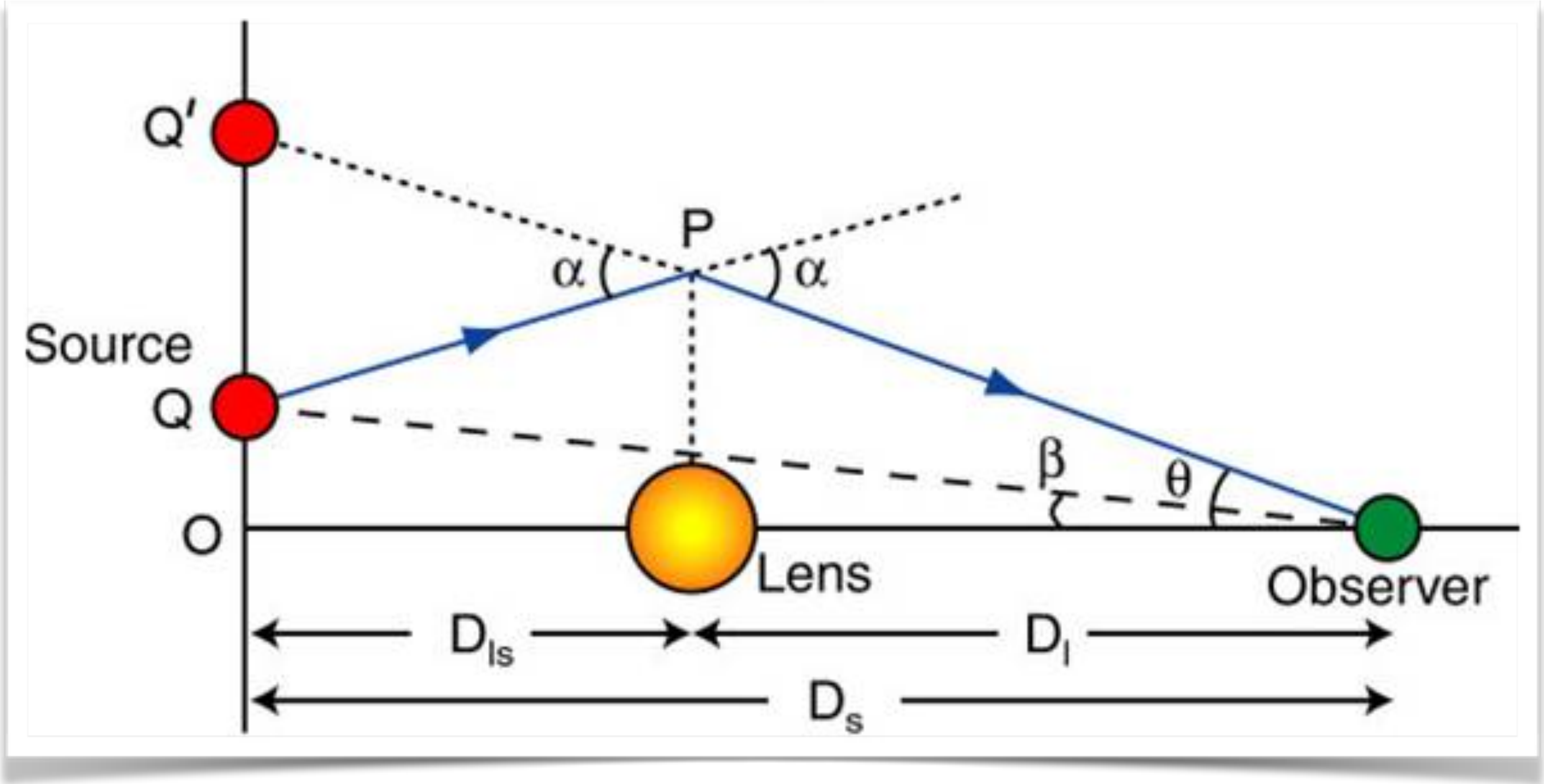


Image: University of Manchester

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)



University of Manchester

Geometric Time Delay

Time Delay:

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

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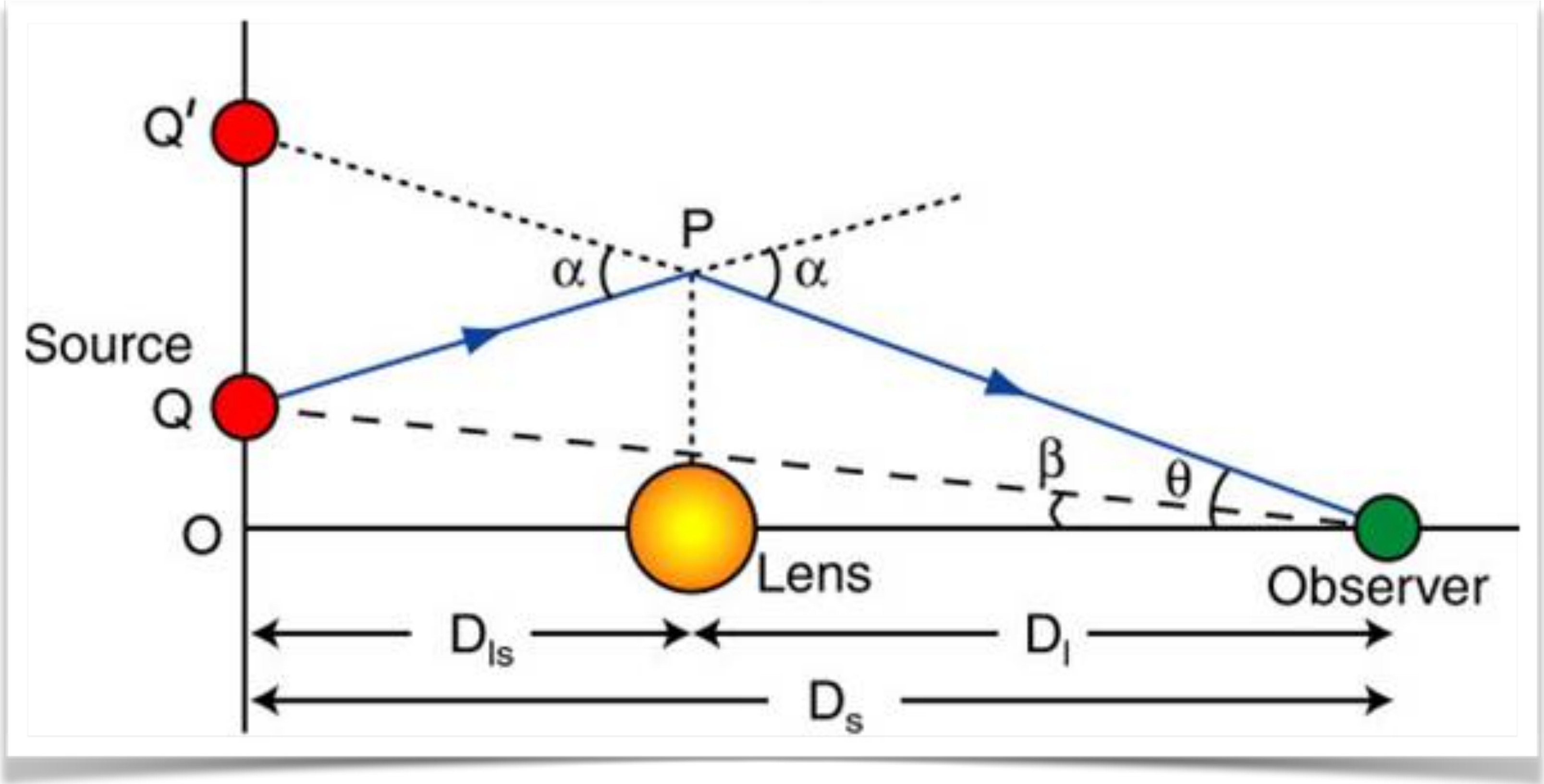

University of Manchester

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: $\psi(\theta) = \theta_E^2 \log\theta$

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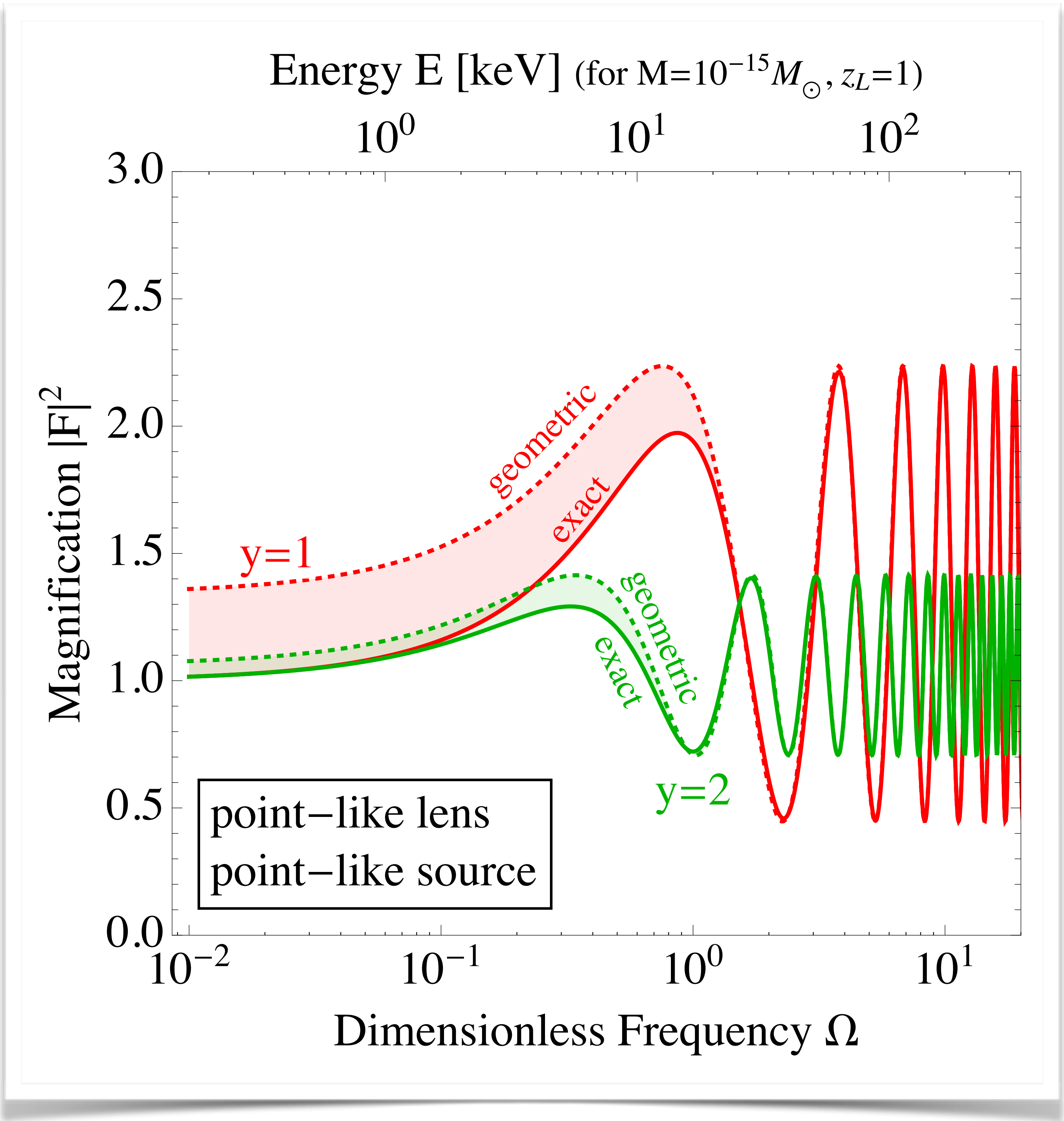
Time Delay (Geometric Optics)

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

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

Magnification Function



Katz JK Sibiryakov Xue
arXiv:1807.11495

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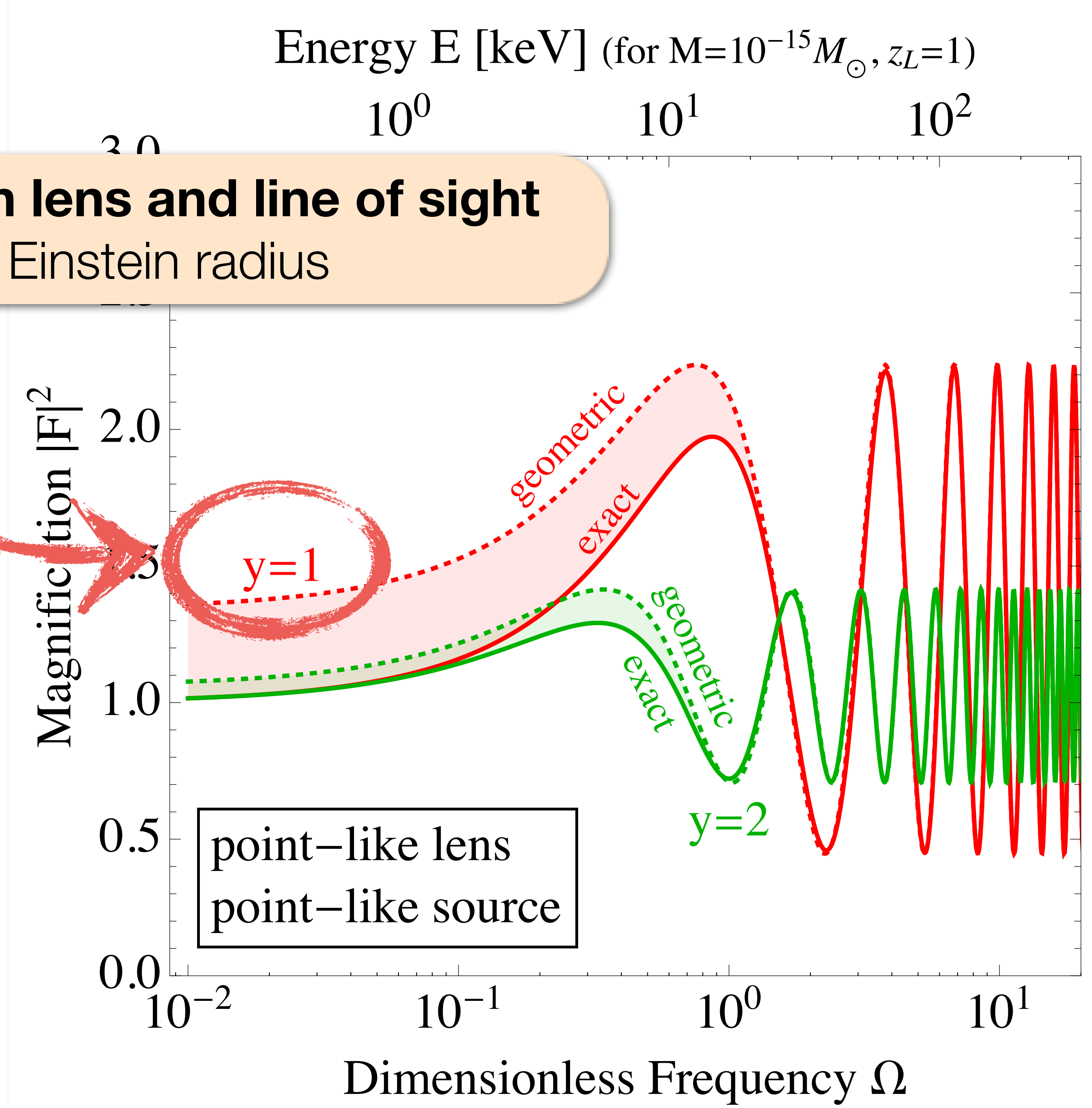
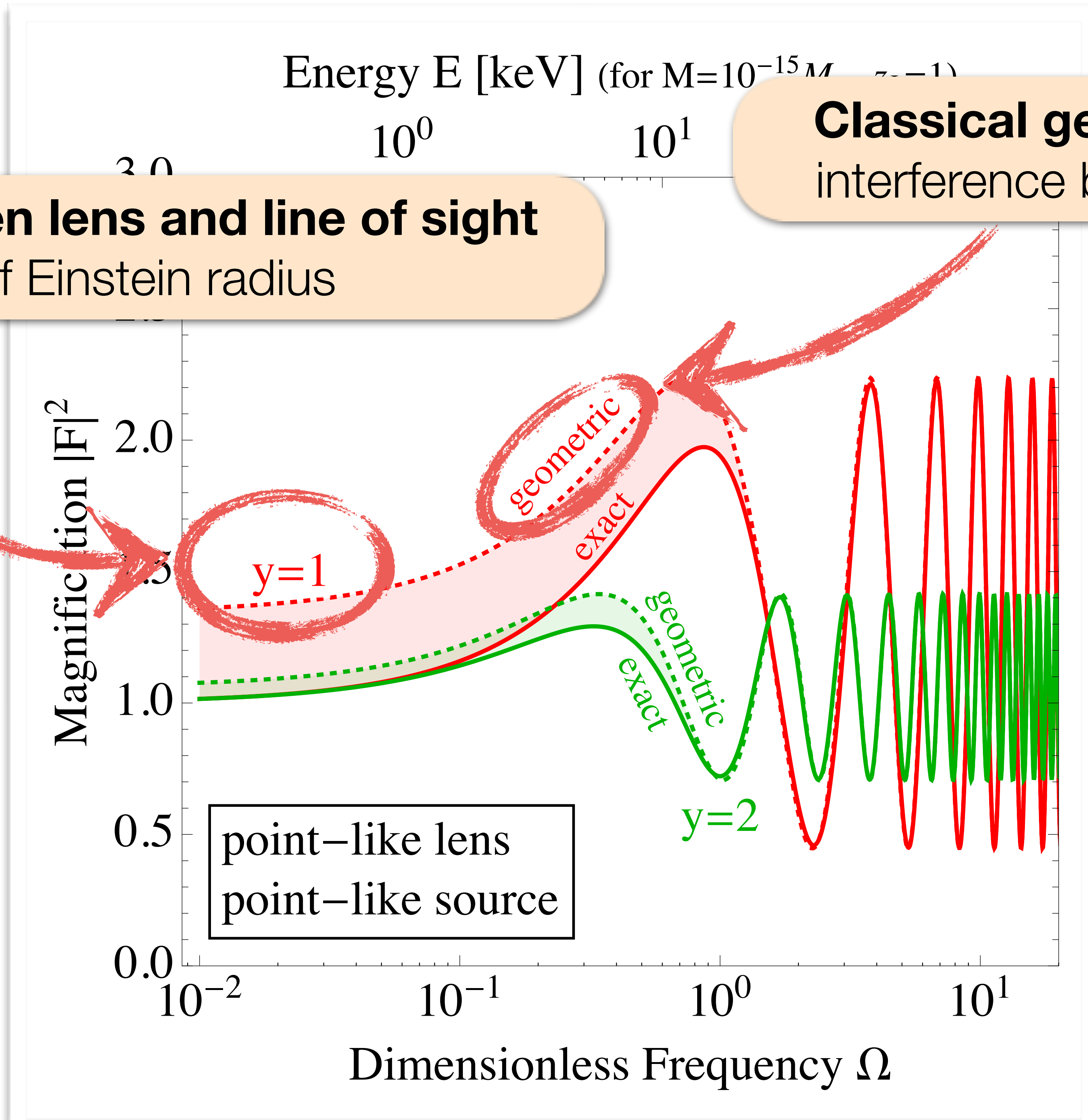
Magnification Function



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
in units of Einstein radius

Classical geometric picture
interference between two rays

Katz JK Sibiryakov Xue
arXiv:1807.11495

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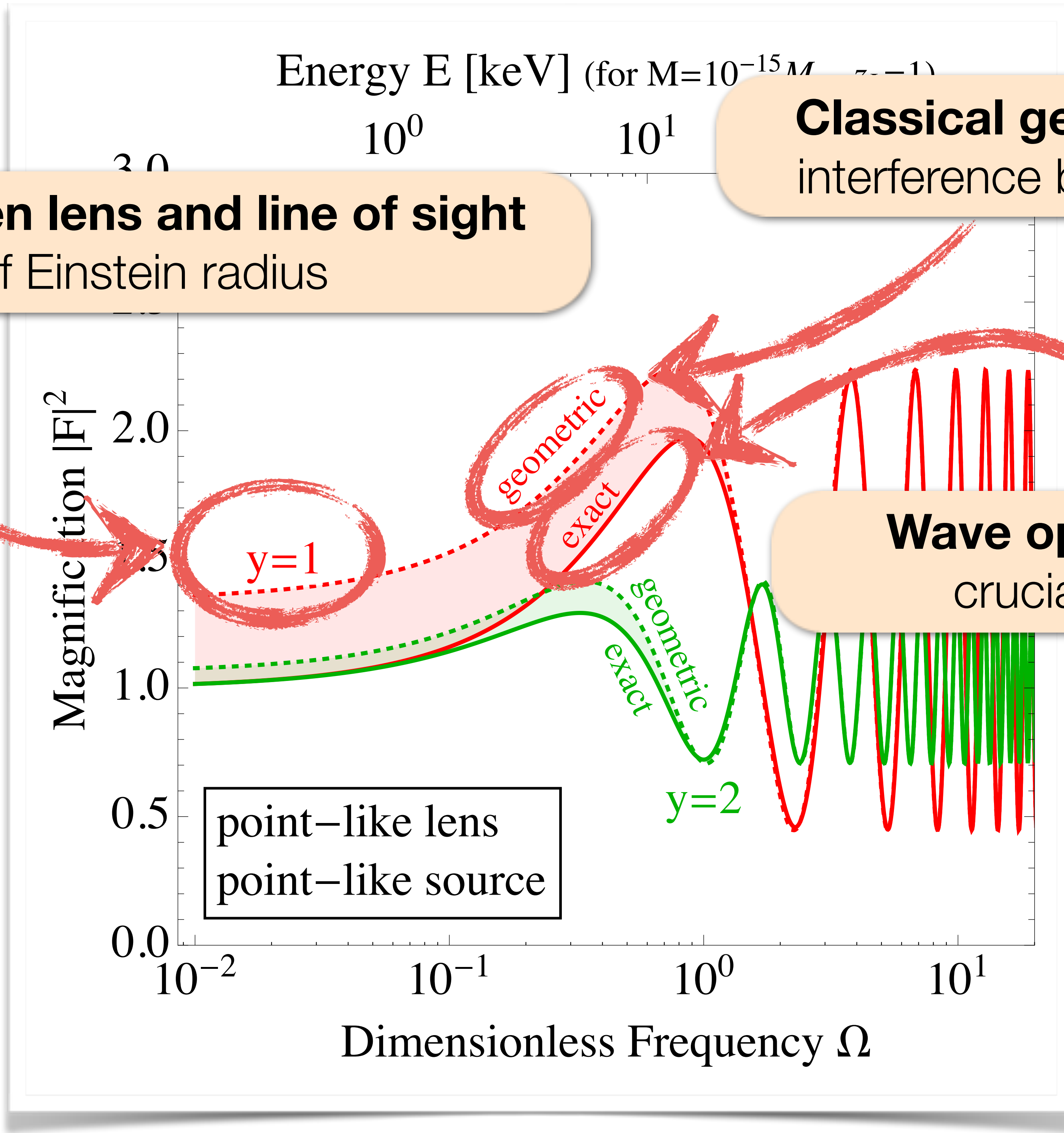
Magnification Function



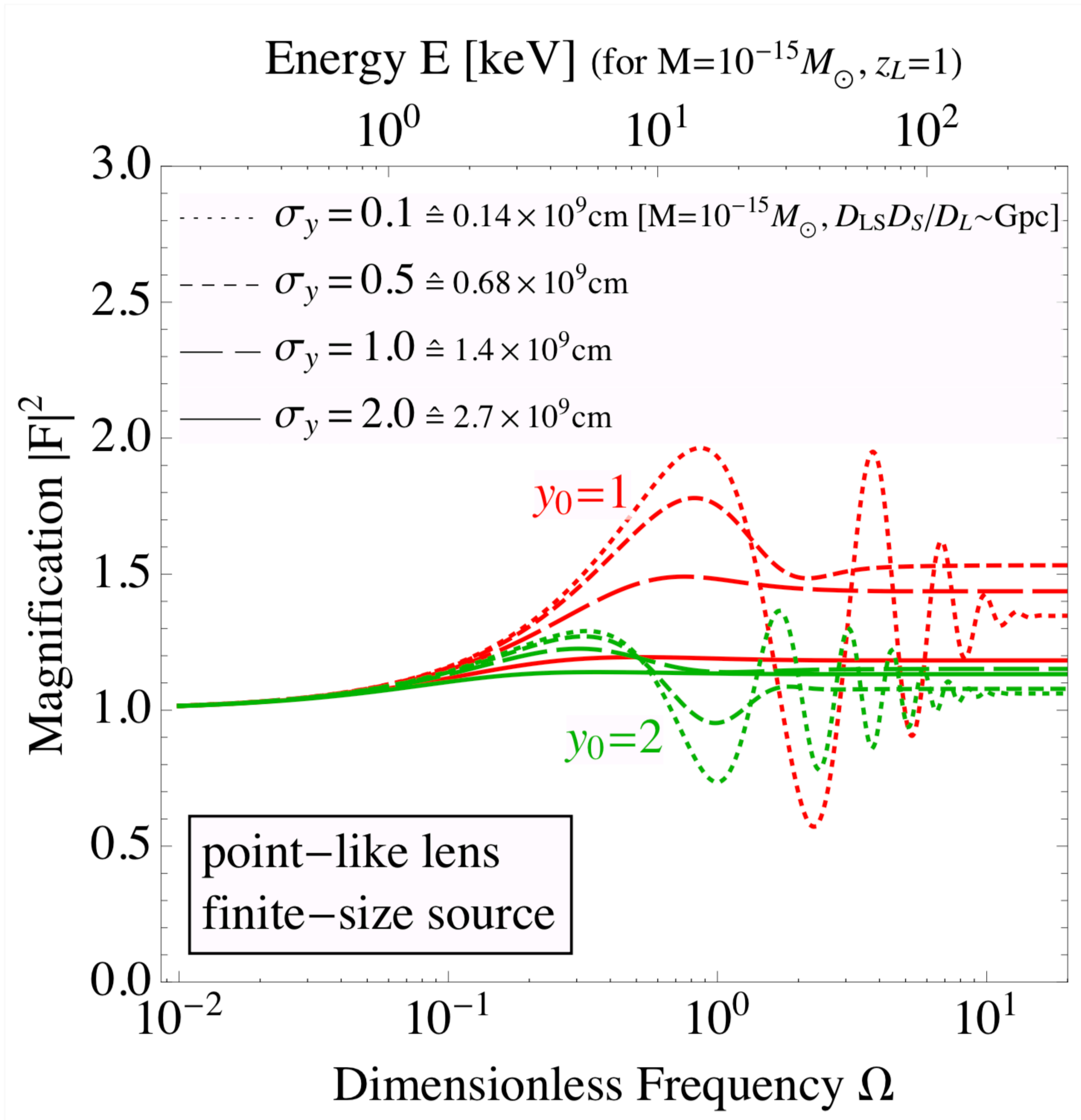
Distance between lens and line of sight
in units of Einstein radius

Classical geometric picture
interference between two rays

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

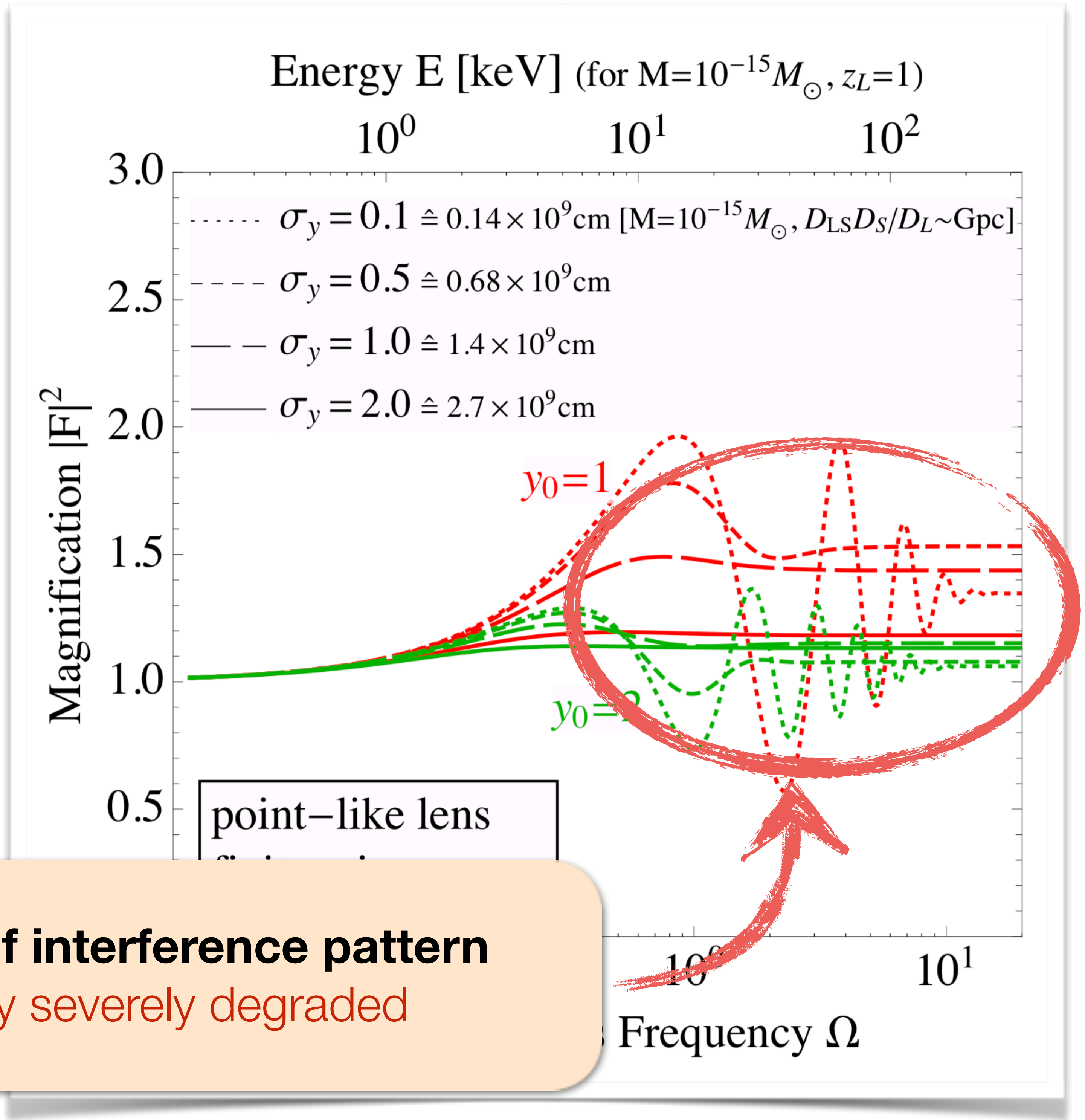
Katz JK Sibiryakov Xue
arXiv:1807.11495

Including Finite Source Size



Katz JK Sibiryakov Xue
arXiv:1807.11495

Including Finite Source Size



Katz
arXiv

Wash-out of interference pattern

sensitivity severely degraded

Requires Source Properties

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

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

$$\sim \frac{4 G_N M}{c^2} = 2 \times 10^{-5} \sec \left(\frac{M}{M_\odot} \right)$$

or, equivalently

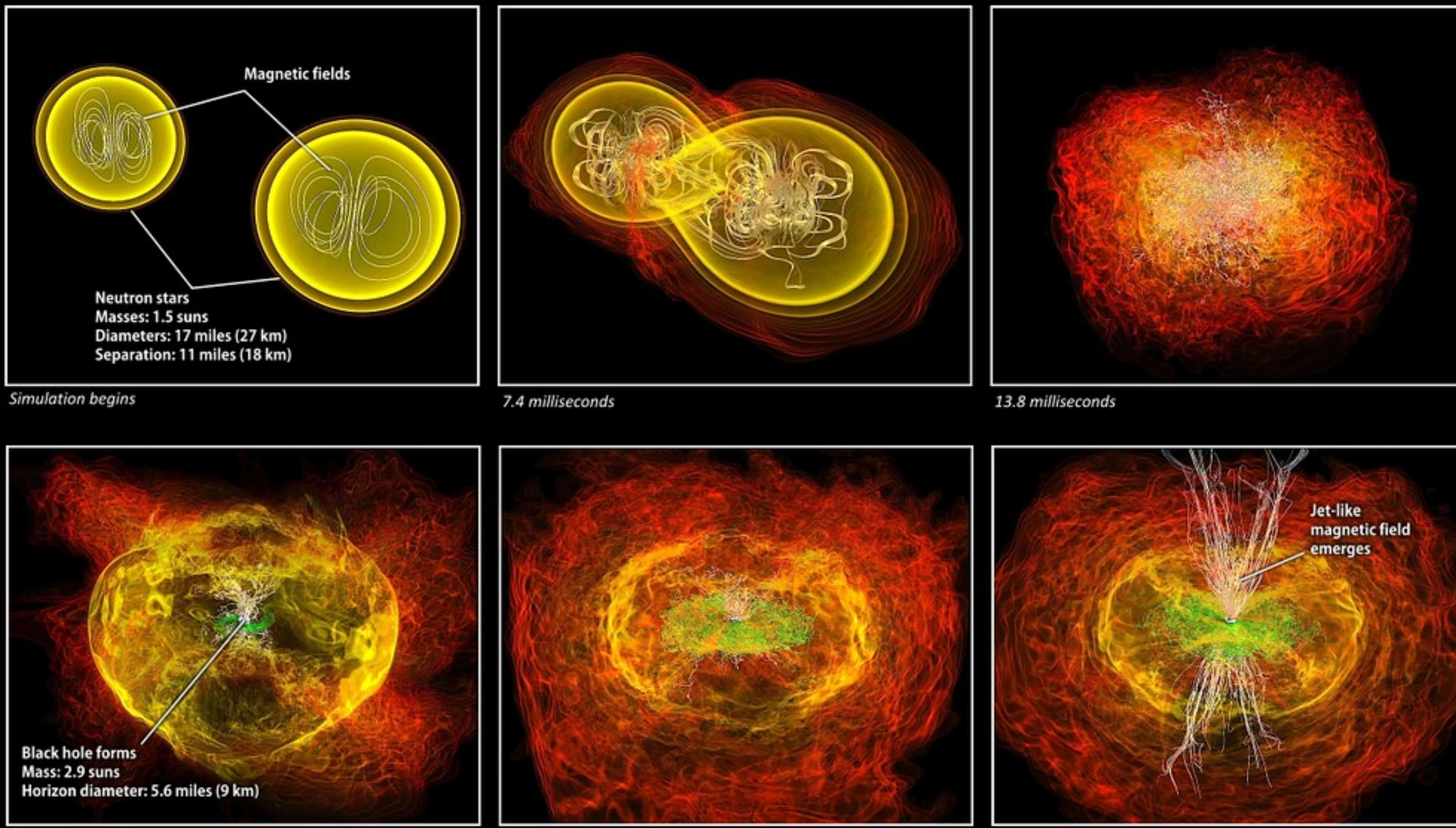
$$\frac{1}{\Delta t} \sim 0.3\, \mathrm{MeV} \left(\frac{10^{-16} M_\odot}{M} \right)$$

- 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 $\gtrsim$ 2 sec)
  - Binary neutron star merger (short GRB, duration $\lesssim$ 2 sec)

Crashing neutron stars can make gamma-ray burst jets



Simulation begins — *7.4 milliseconds* — *13.8 milliseconds*

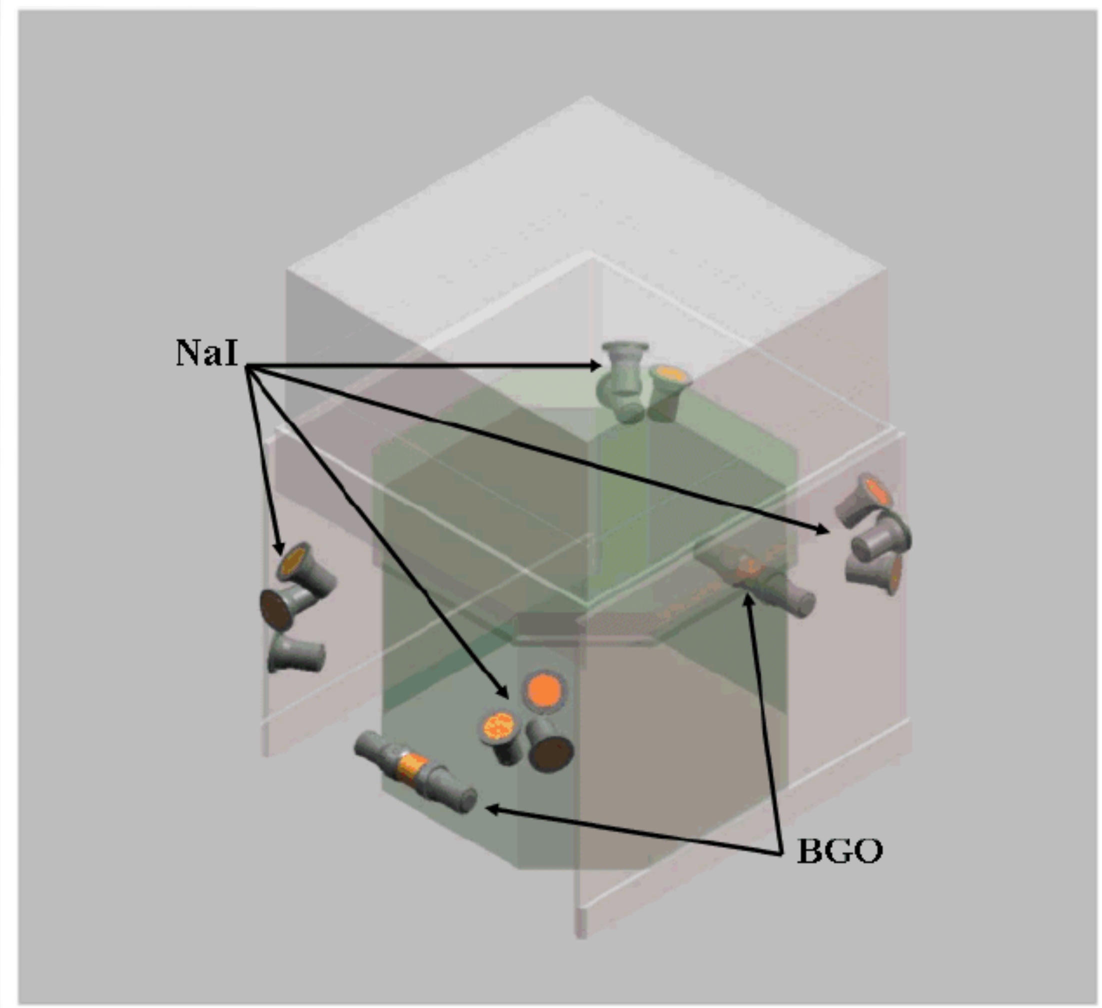
15.3 milliseconds — *21.2 milliseconds* — *26.5 milliseconds*

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

GRB Observations

Fermi Satellite

Fermi Gamma Ray Burst Monitor



GRB Observations

GBM Specifications & Performance

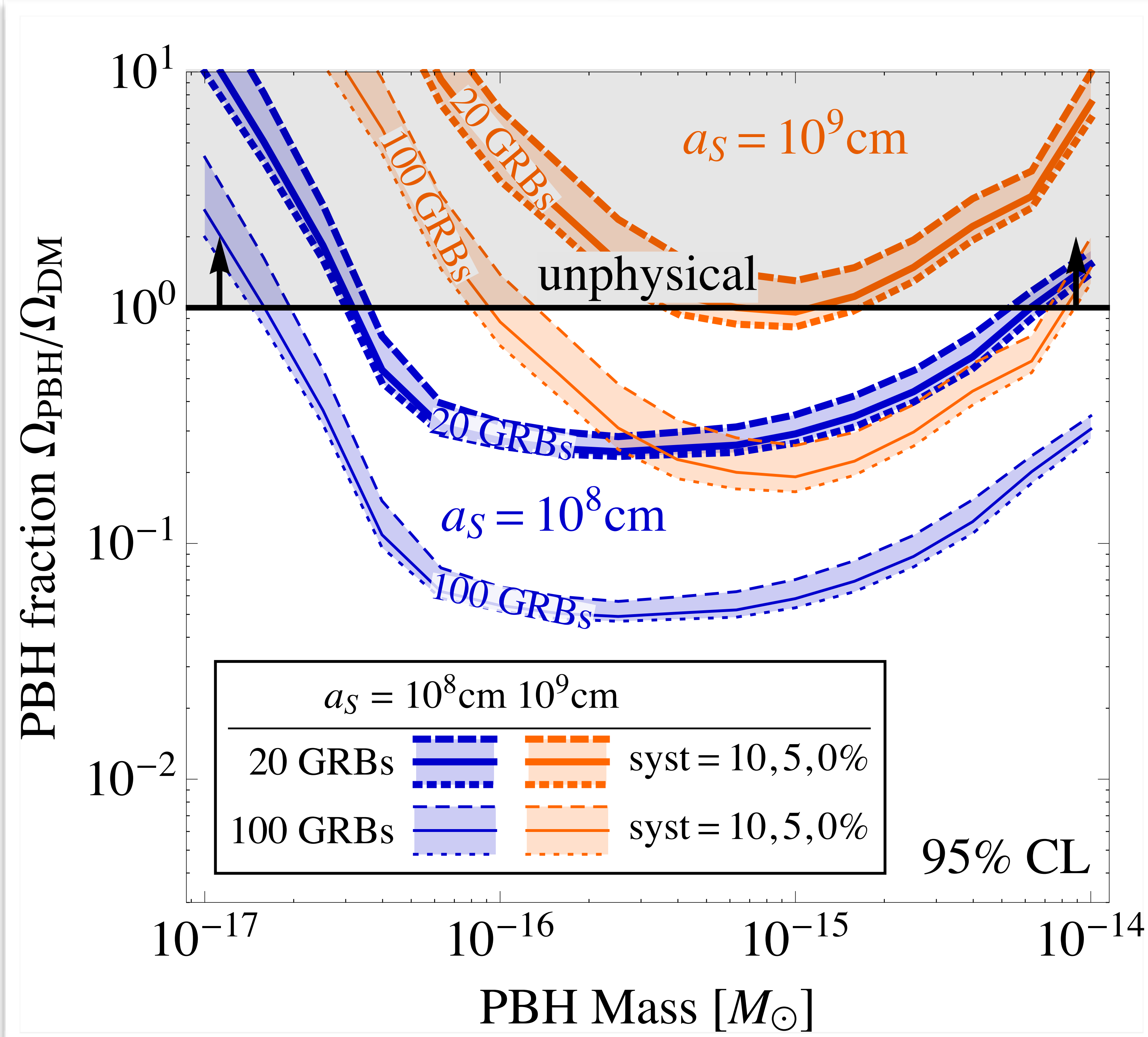
Quantity	GBM (Minimum Spec.)
Energy Range	< 10 keV - > 25 MeV
Field of View	all sky not occulted by the Earth
Energy Resolution [1]	< 10%
Deadtime per Event	< 15 μs
Burst Sensitivity [2]	$< 0.5\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Alert GRB Location [3]	~ 15°
Final GRB Location [4]	~ 3°

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

GRB Caveats

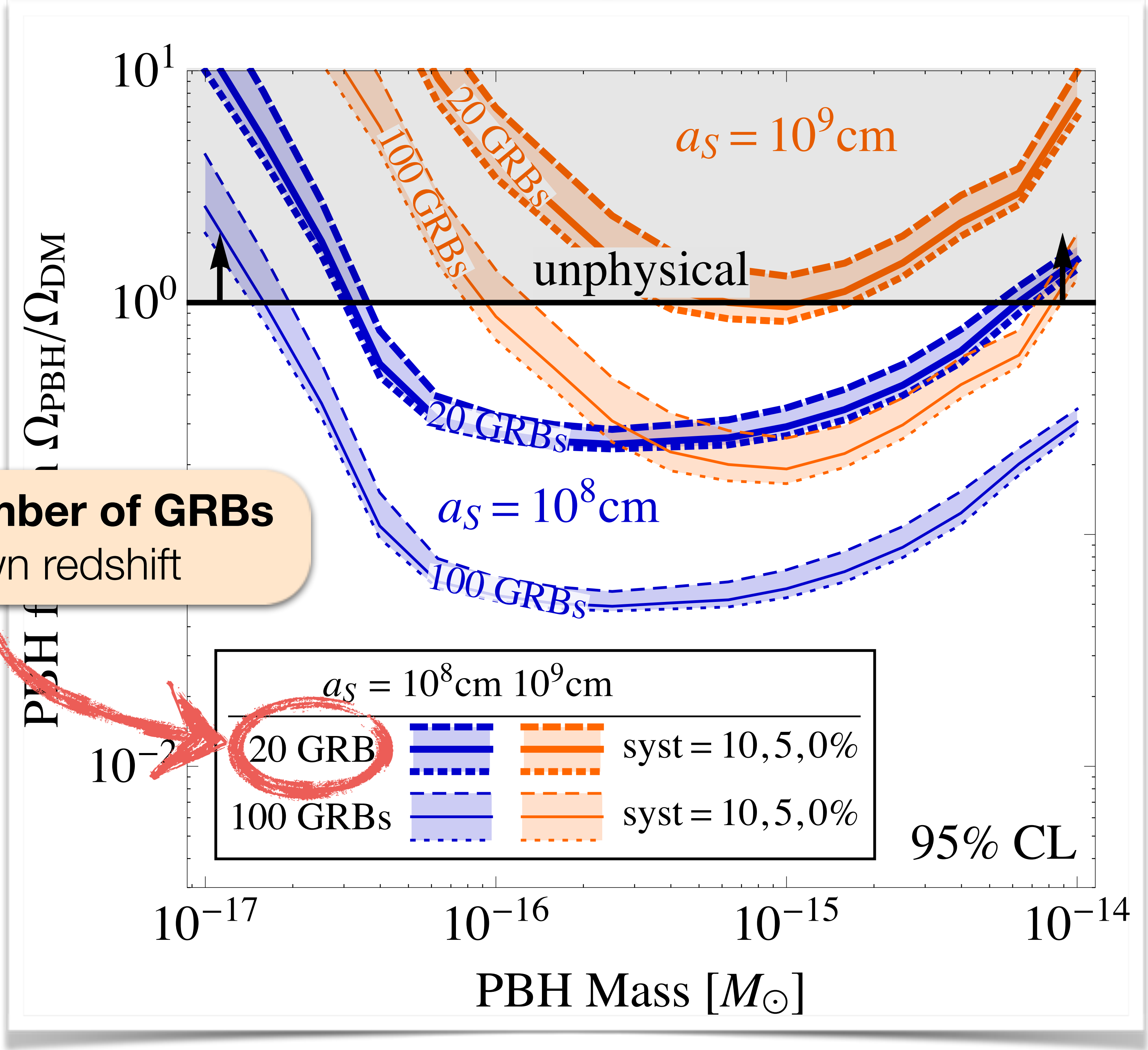
- ☑ To constrain the PBH density using (non-)observation of femtolensing, we need to know the distance to the GRB
  - Requires optical counterpart
  - Only ~20 GRBs with known distance so far
- ☑ Wave optics effects
- ☑ Finite size of GRB source

Sensitivity Estimates



Katz JK Sibiryakov Xue
arXiv:1807.11495

Sensitivity Estimates



~ current number of GRBs with known redshift

Katz JK Sibiryakov Xue
arXiv:1807.11495

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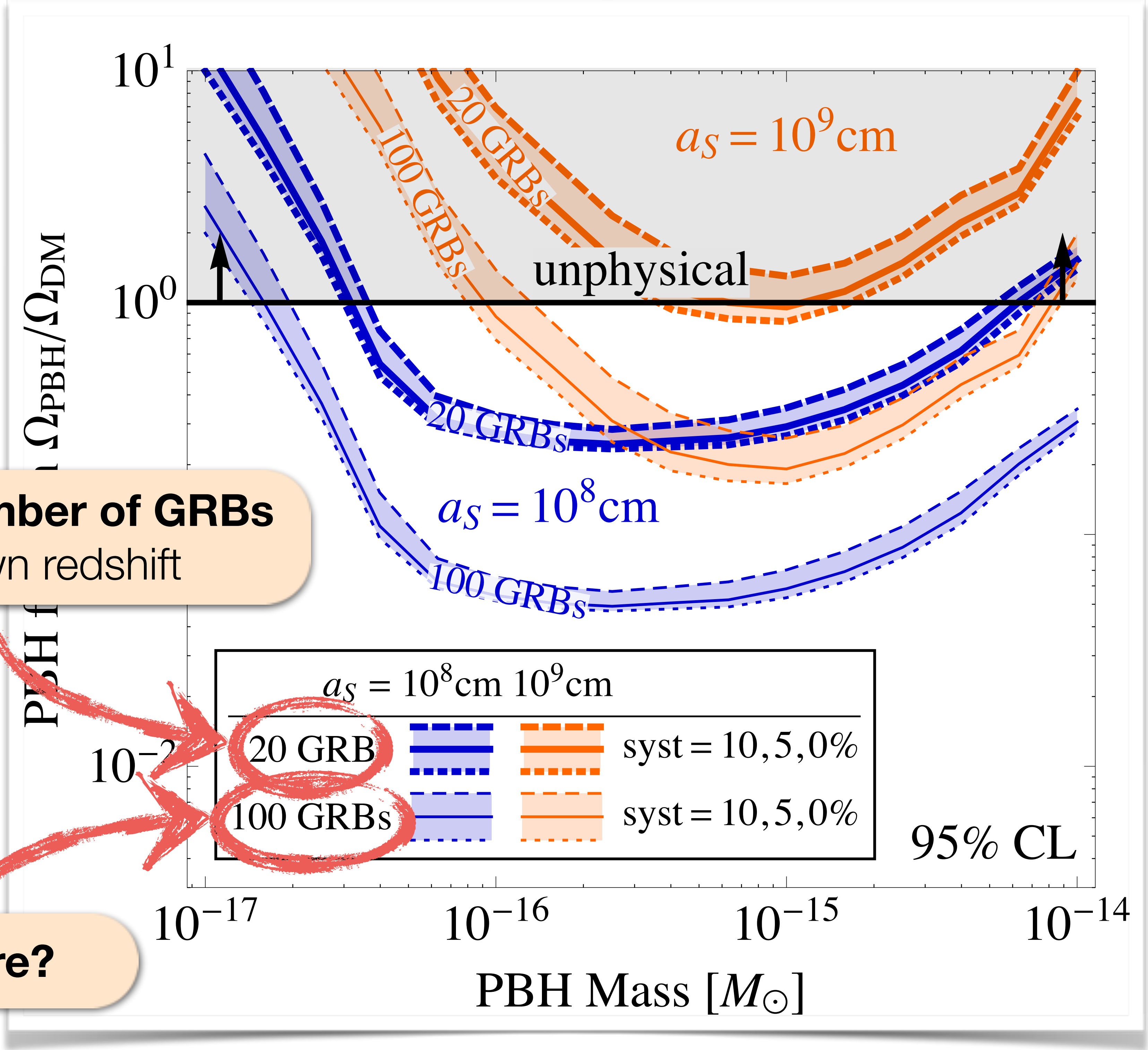
Sensitivity Estimates



~ current number of GRBs
with known redshift

Future?

Katz JK Sibir...
arXiv:1807.11495

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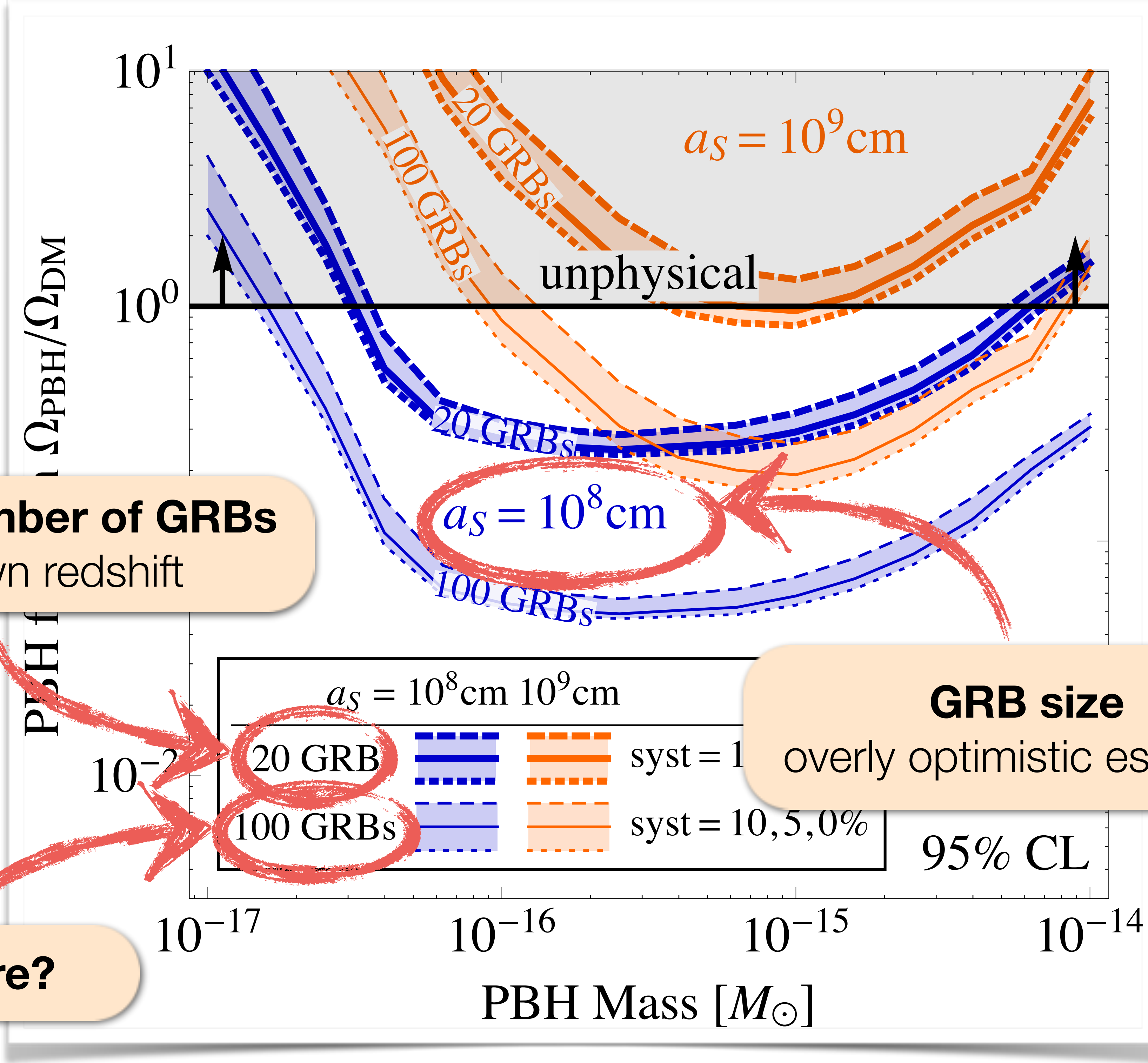
Sensitivity Estimates



~ current number of GRBs
with known redshift

GRB size
overly optimistic estimate

Future?

Katz JK Sibir...
arXiv:1807.11495

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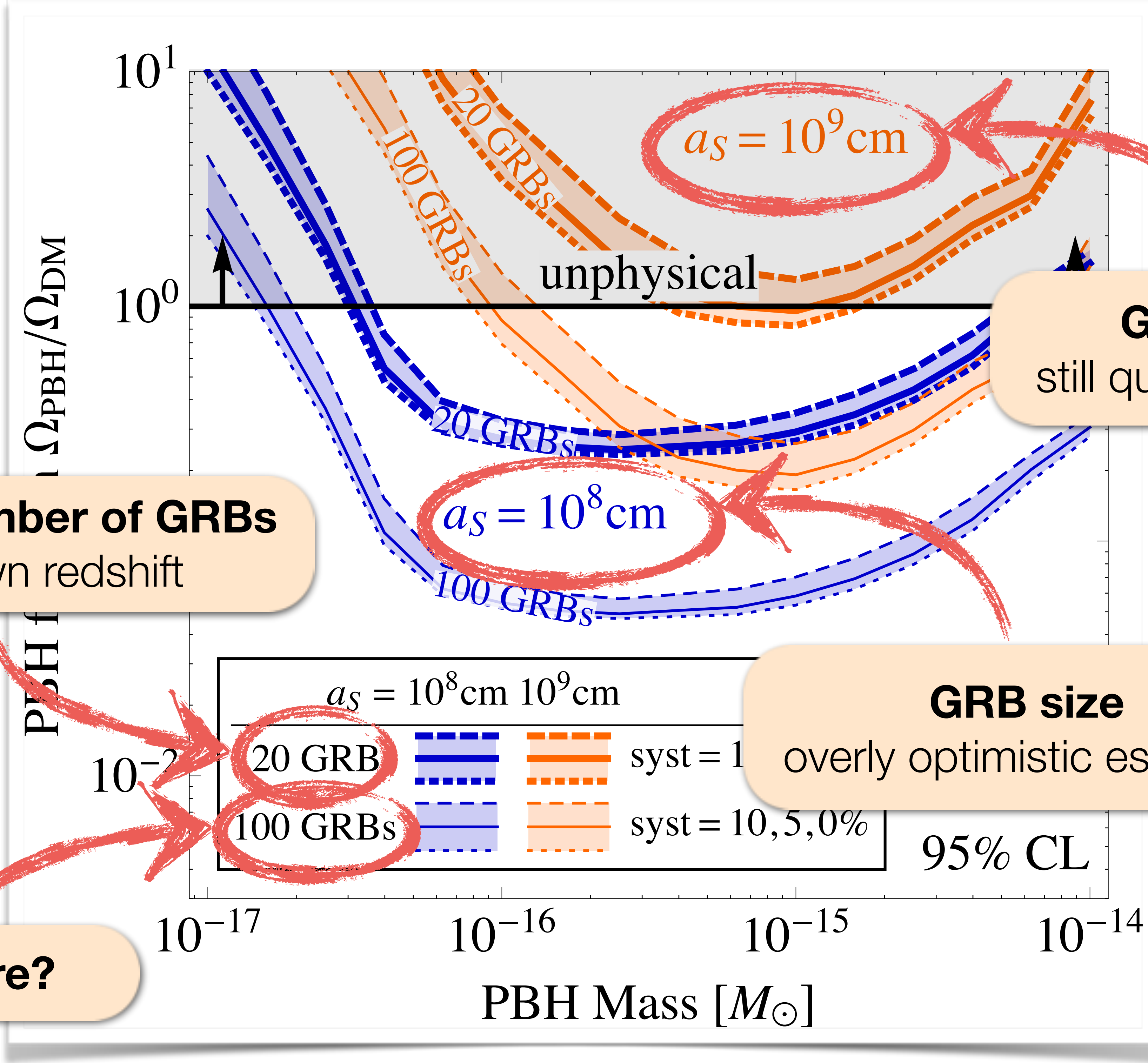
Sensitivity Estimates



~ current number of GRBs
with known redshift

GRB size
still quite optimistic

GRB size
overly optimistic estimate

Future?

Katz JK Sibir...
arXiv:1807.11495

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:

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

- Relativistic boost γ:

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

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

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

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Finite Size of GRB Sources: Caveats

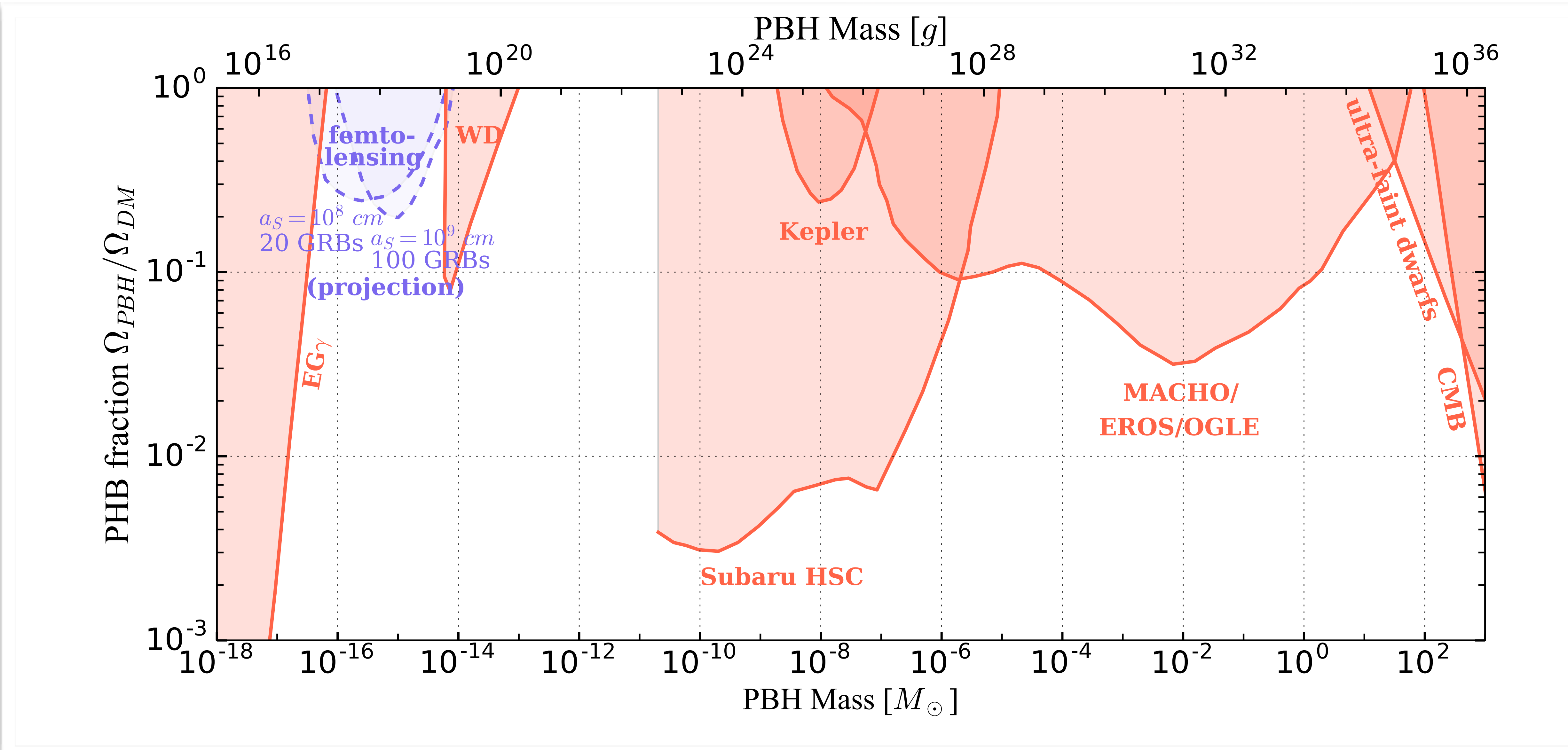
- Some GRBs with shorter variability time scale $t_{var} \lesssim 10^{-3}$ sec
  - t_{var} distribution could have a long tail → use tail for femtolensing
- Intrinsic variability might be too fast to be resolved
- Conservative estimate: require optical depth $\tau < 1$:

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

- 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

PBH Parameter Space



Katz JK Sibiryakov Xue
arXiv:1807.11495

Assuming δ-like PBH mass distribution

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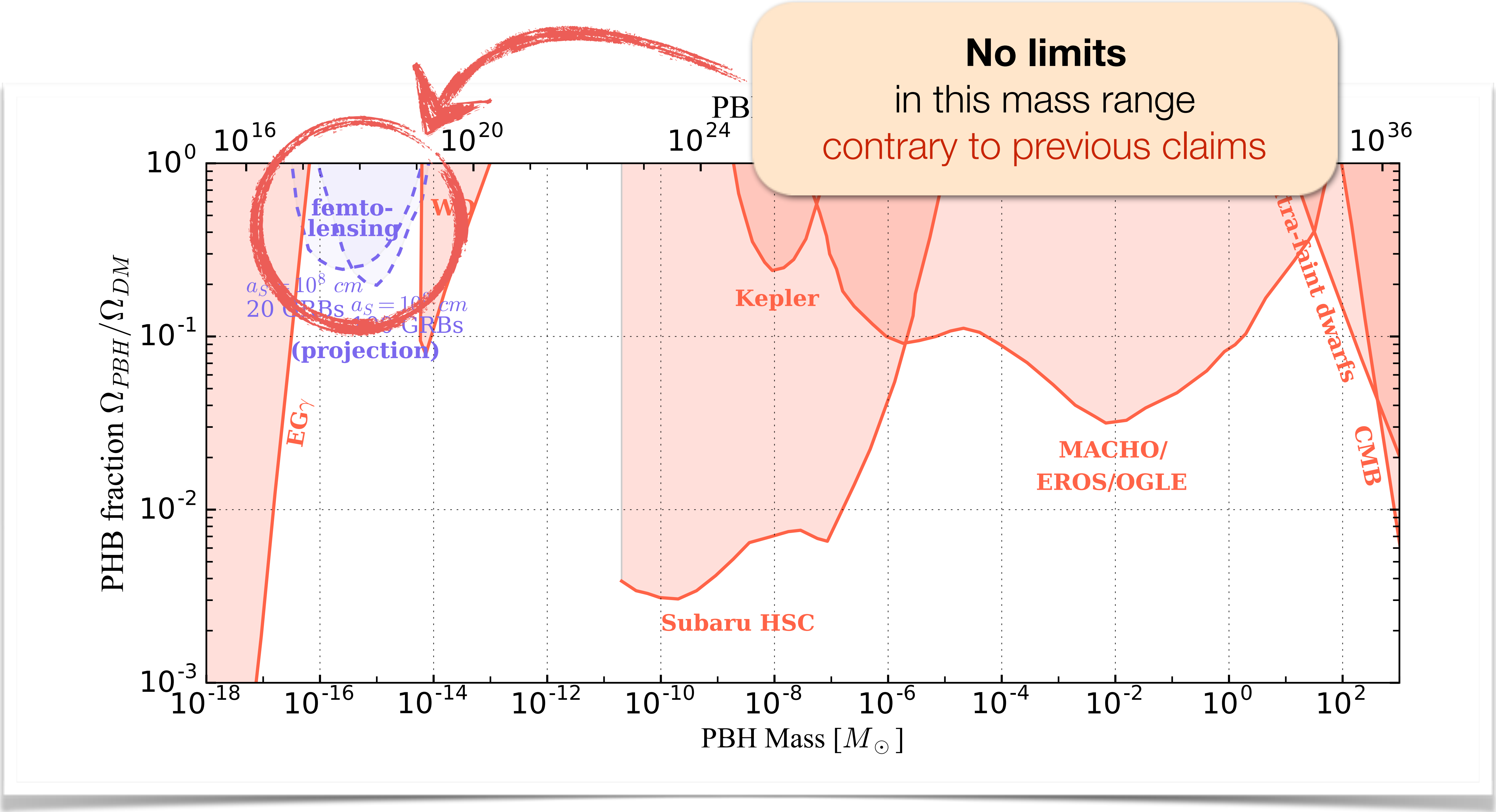
PBH Parameter Space



Katz JK Sibiryakov Xue
arXiv:1807.11495

Assuming δ-like PBH mass distribution

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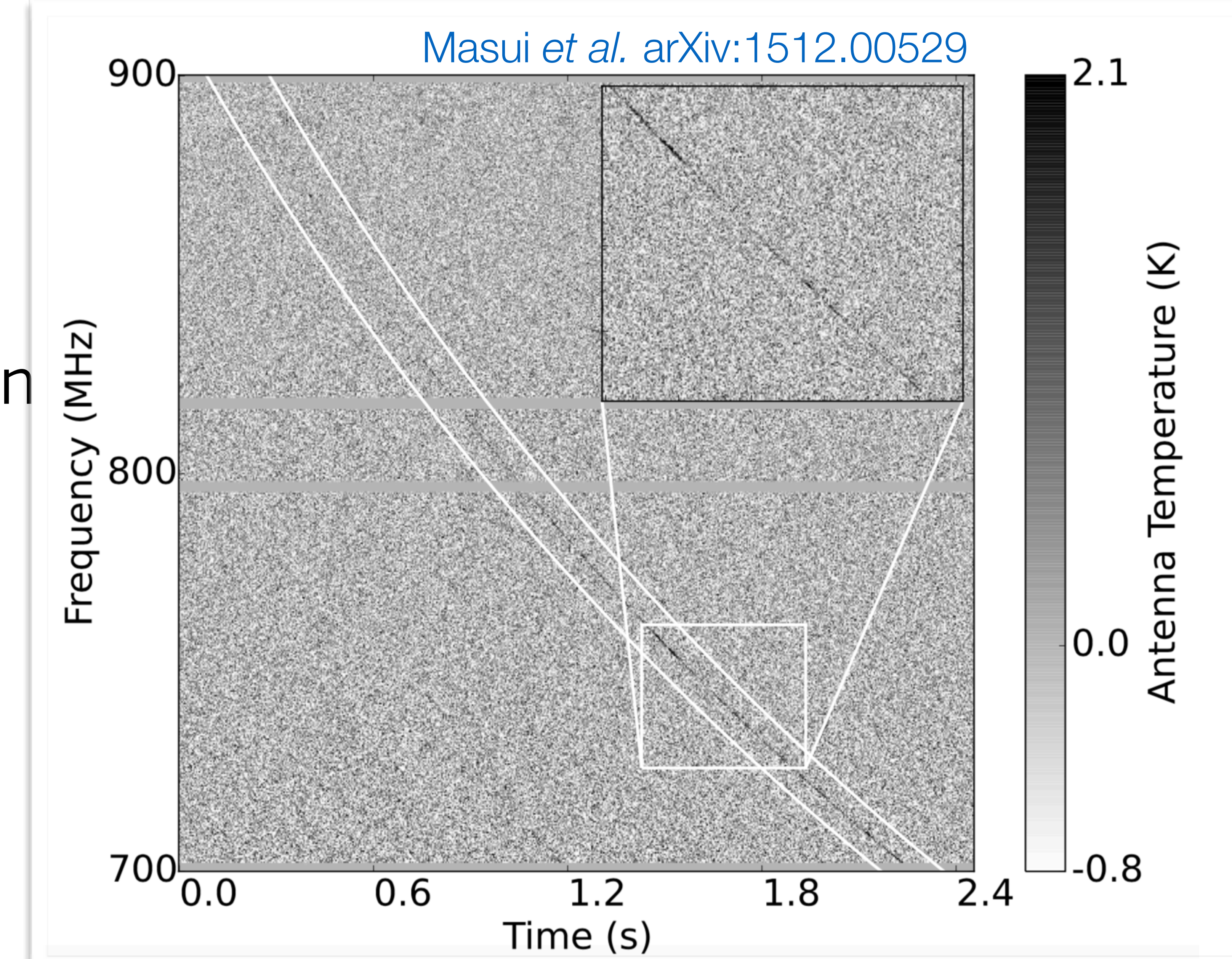
Fast Radio Bursts

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



Fast Radio Bursts

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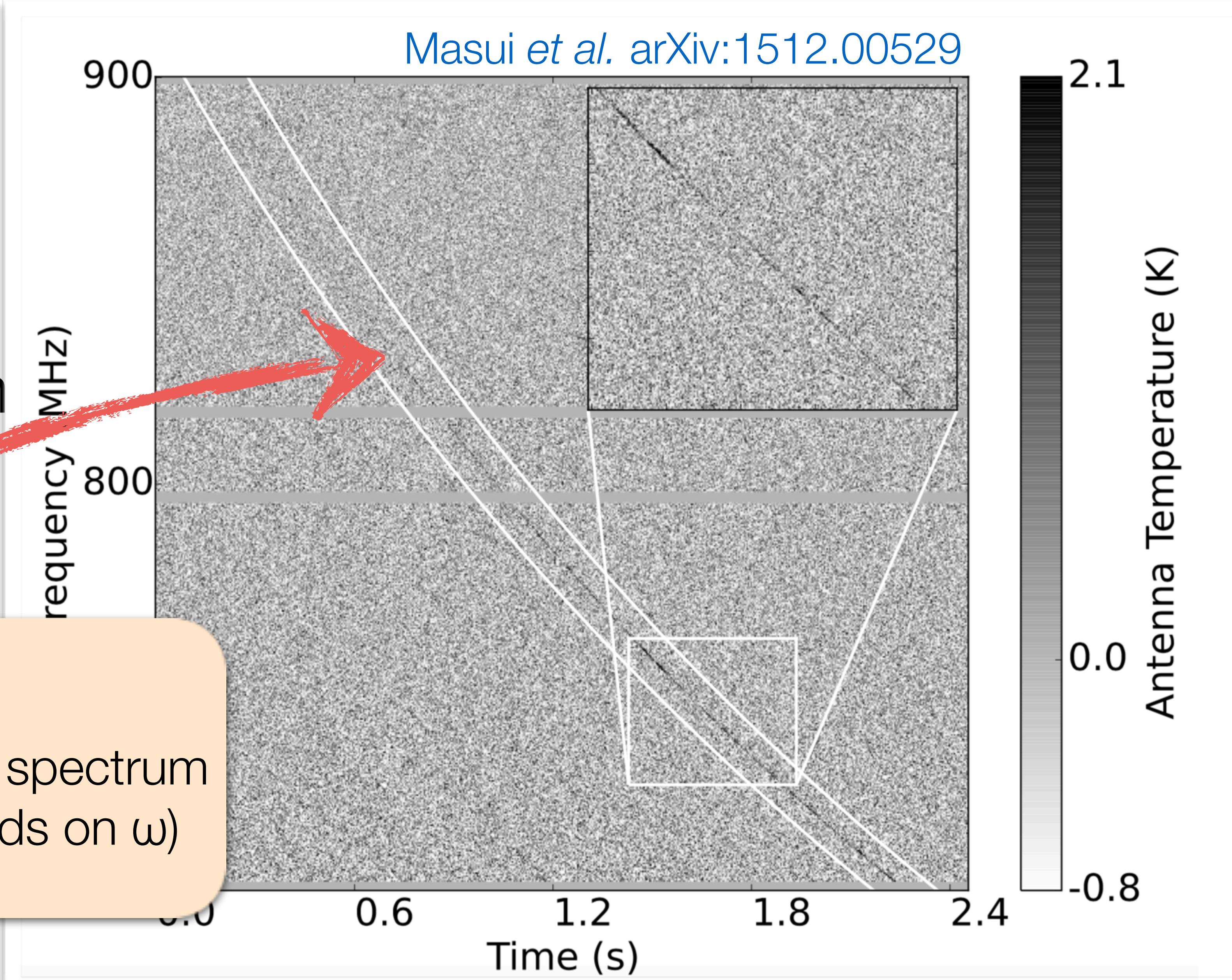
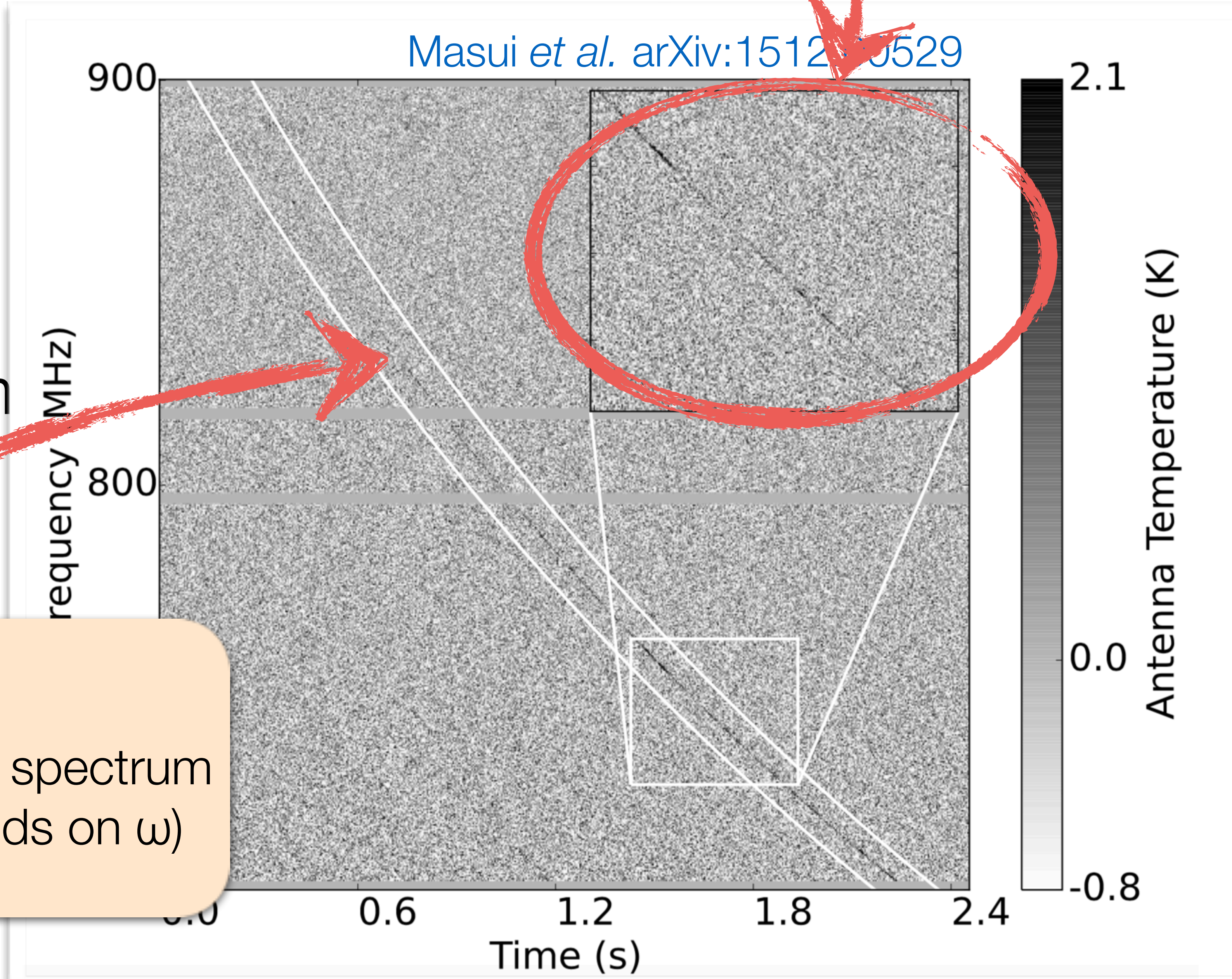


Dispersion
Burst moves through the frequency spectrum
(speed of light in ISM / IGM depends on ω)

Fast Radio Bursts

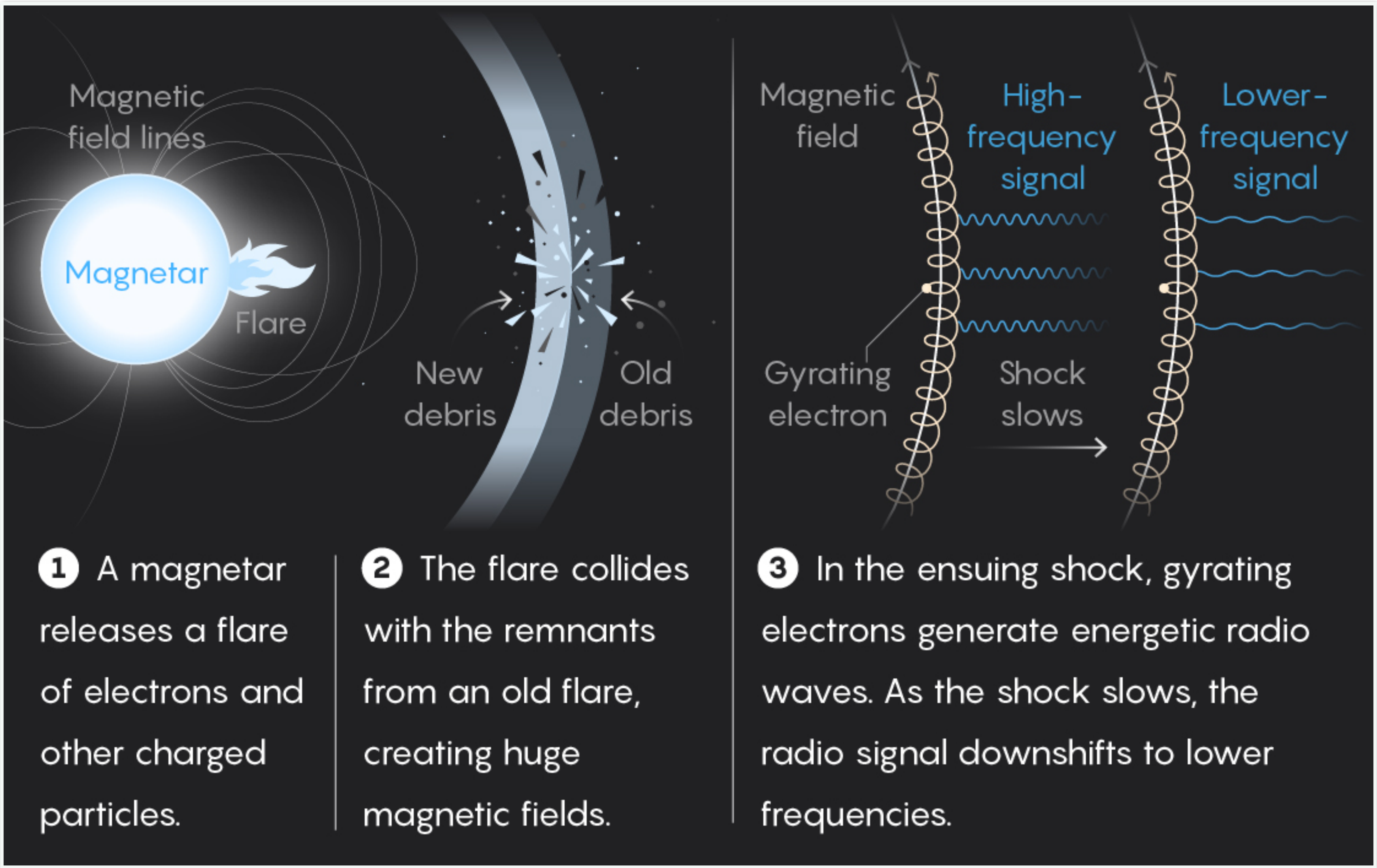
Scintillation
interference between waves traveling along different paths through turbulent ISM / IGM.

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



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

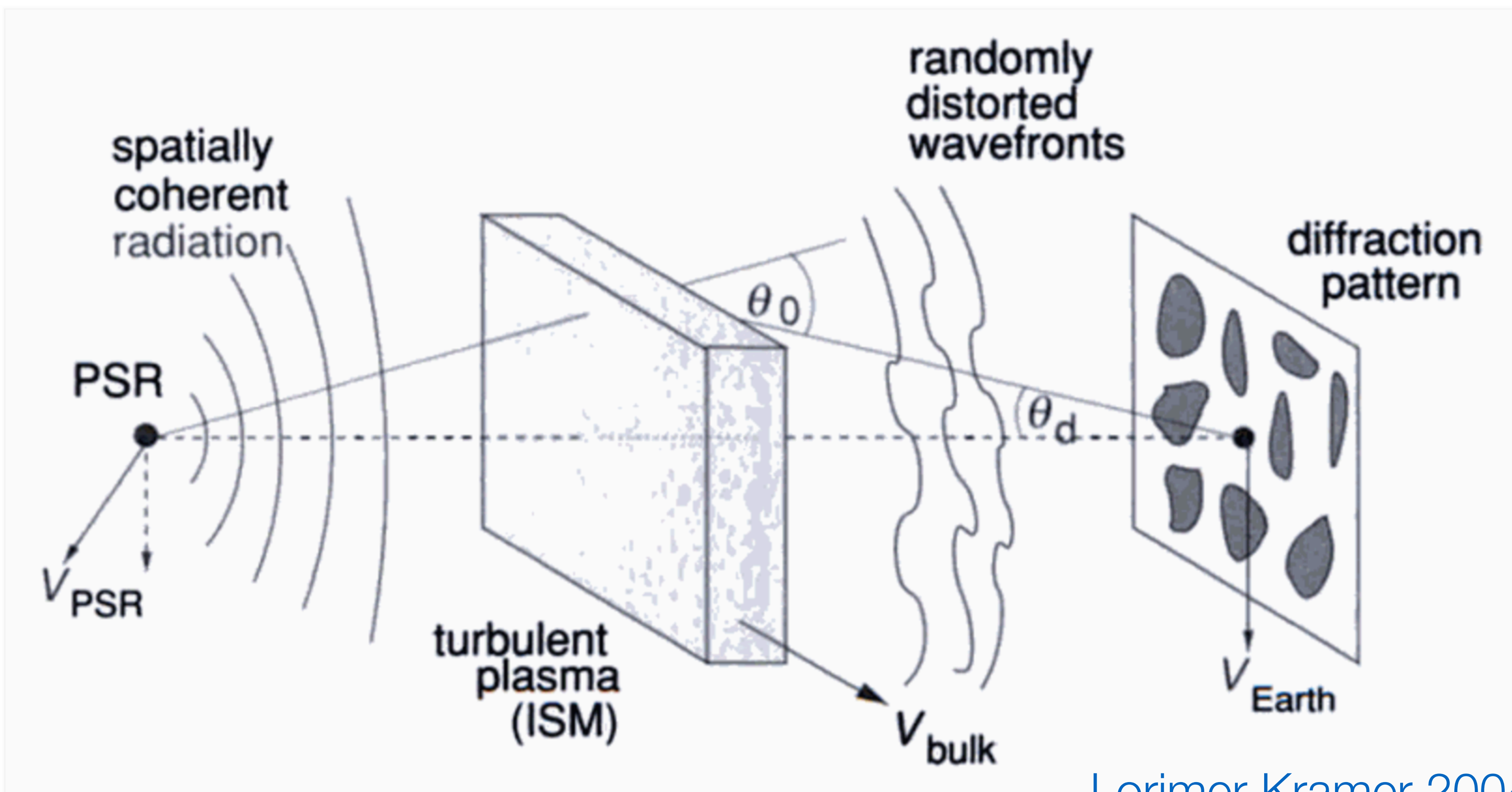
- Remember:

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

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

Scintillation

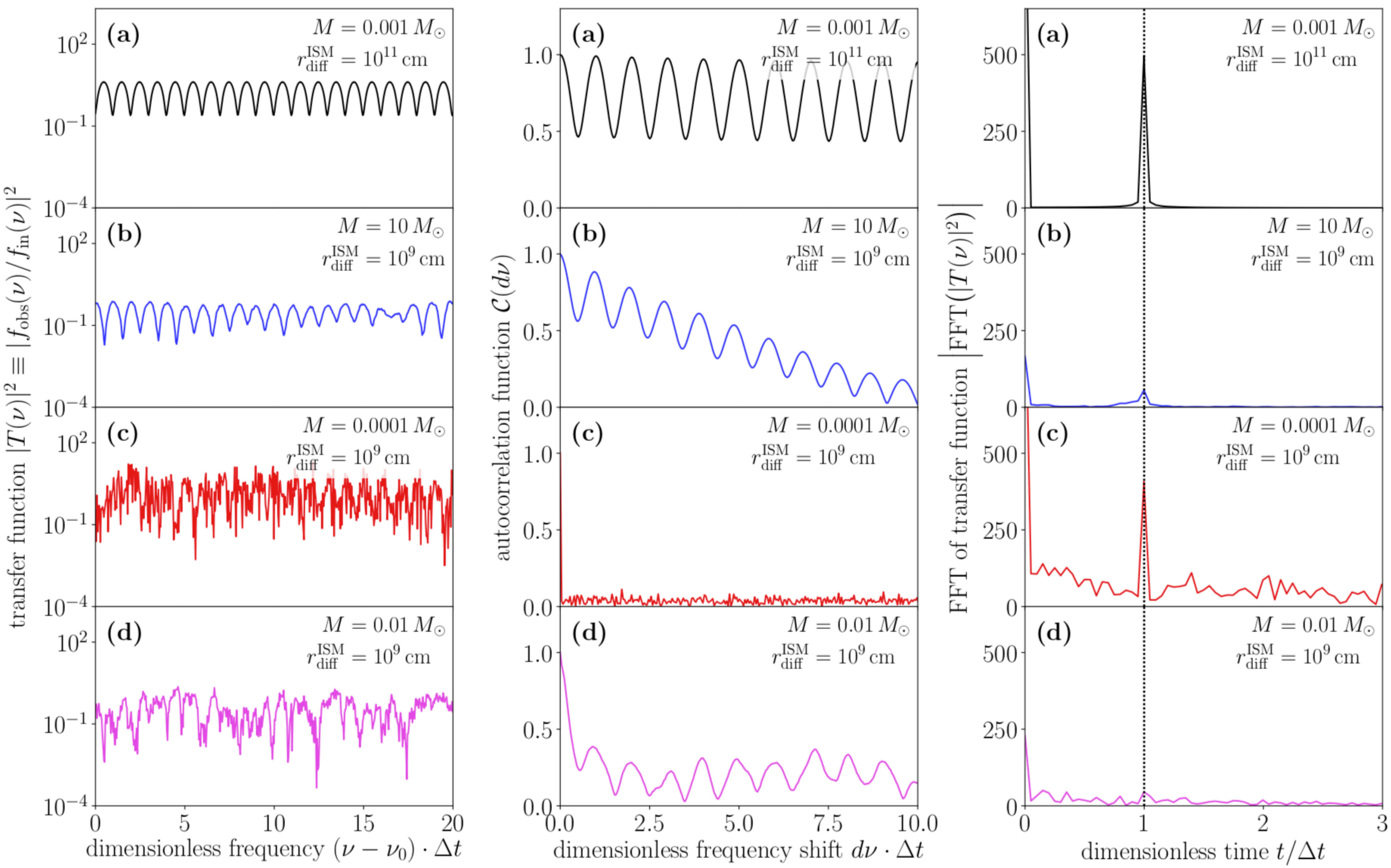
- many different lines of sight to the source because of refraction / diffraction in turbulent ISM / IGM
- leads to random interference patterns



Lorimer Kramer 2004

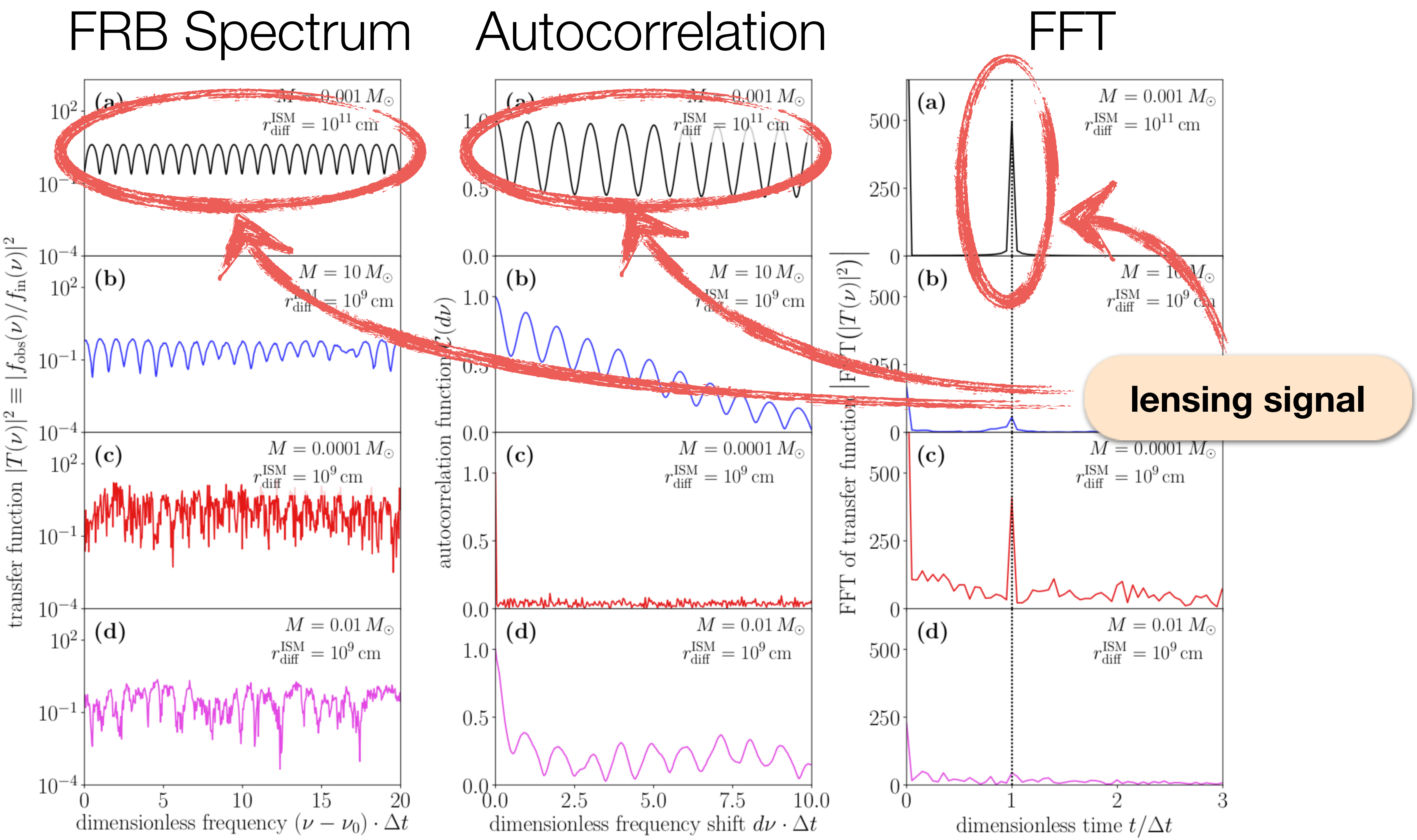
Scintillation

FRB Spectrum | Autocorrelation | FFT



Katz JK Sibiryakov Xue, arXiv:1912.07620

Scintillation



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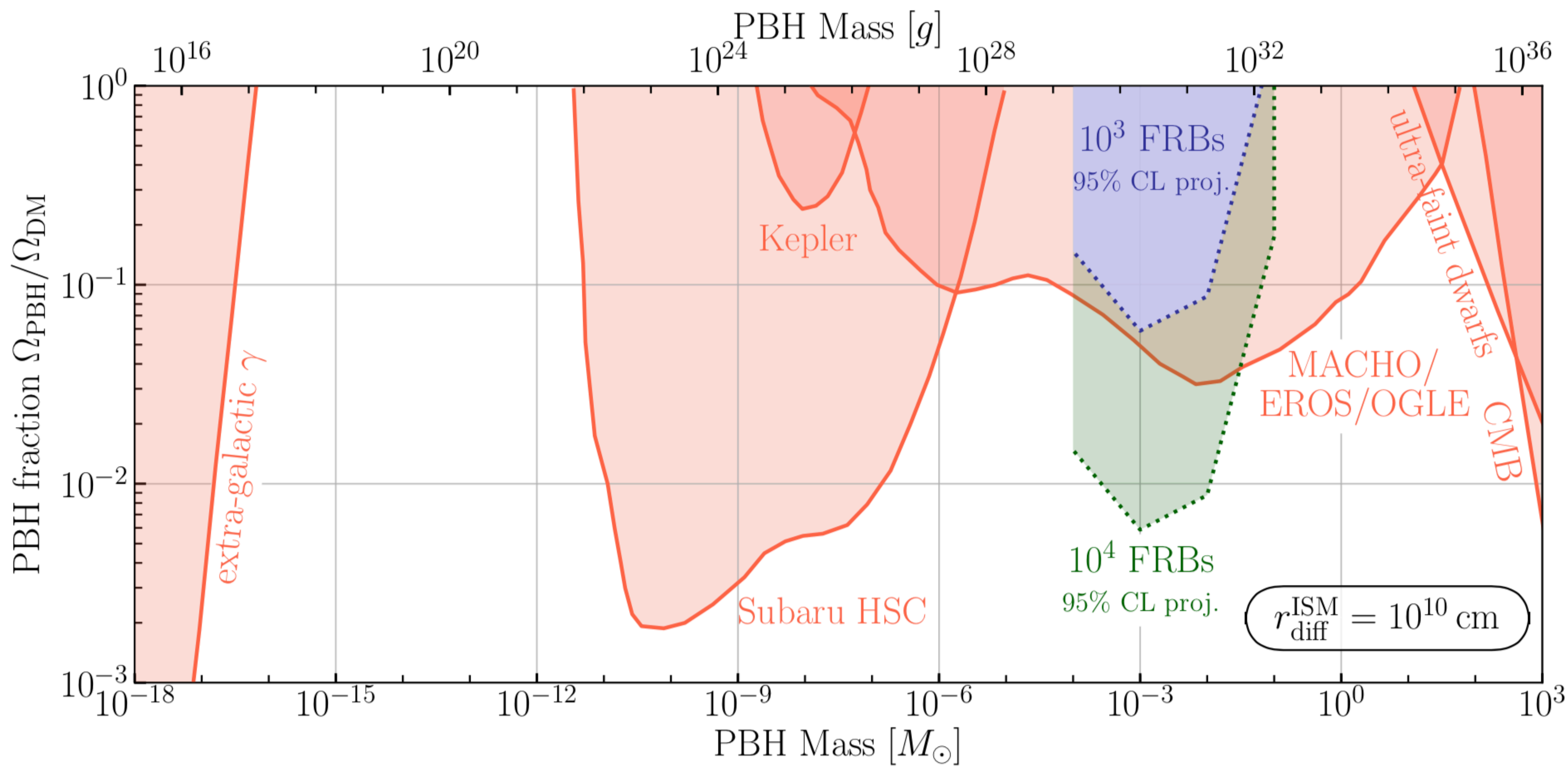
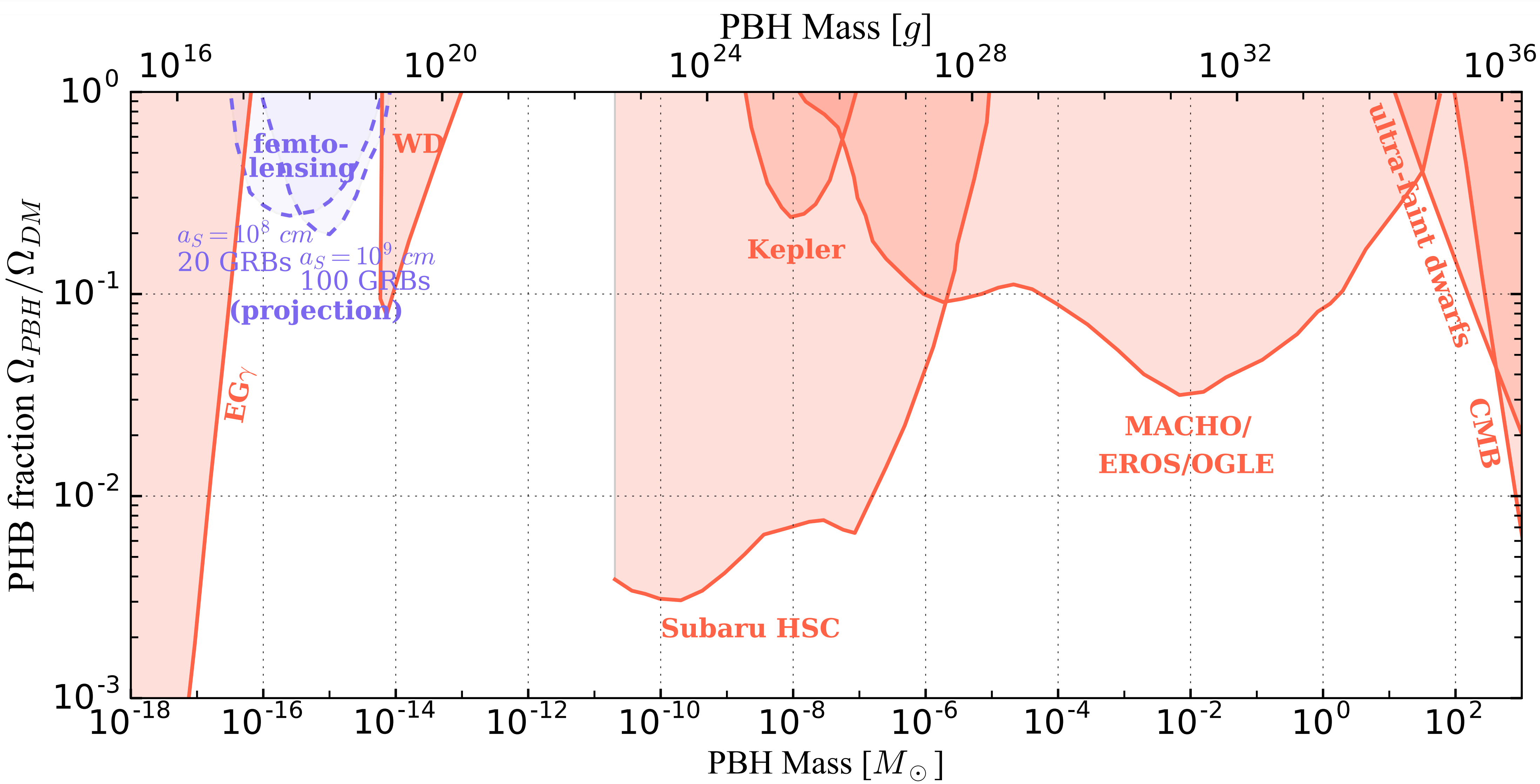
PBH Parameter Space



Katz JK Sibiryakov Xue, arXiv:1912.07620

Assuming δ-like PBH mass distribution

PBH Parameter Space



Assuming δ-like PBH mass distribution

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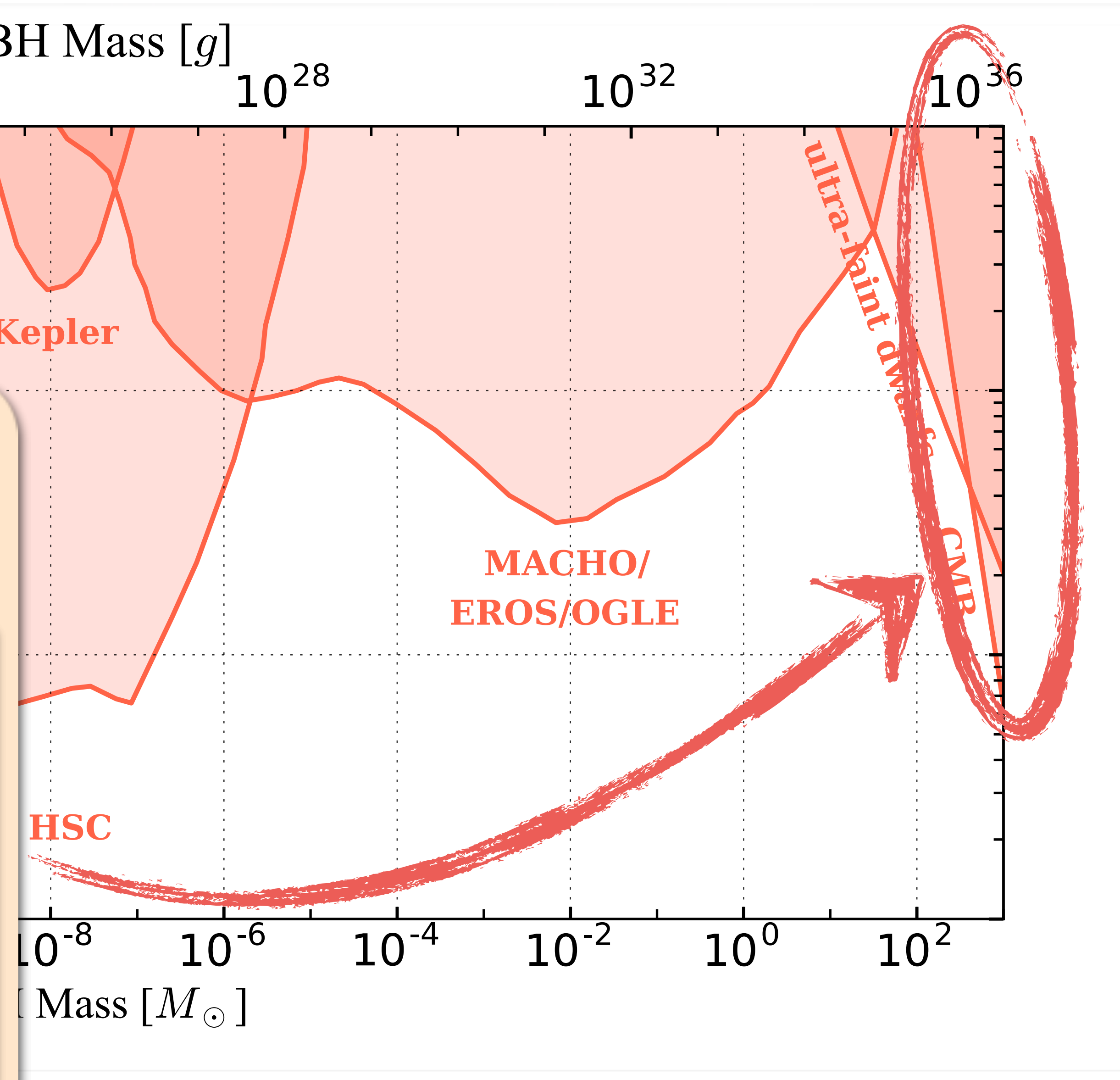
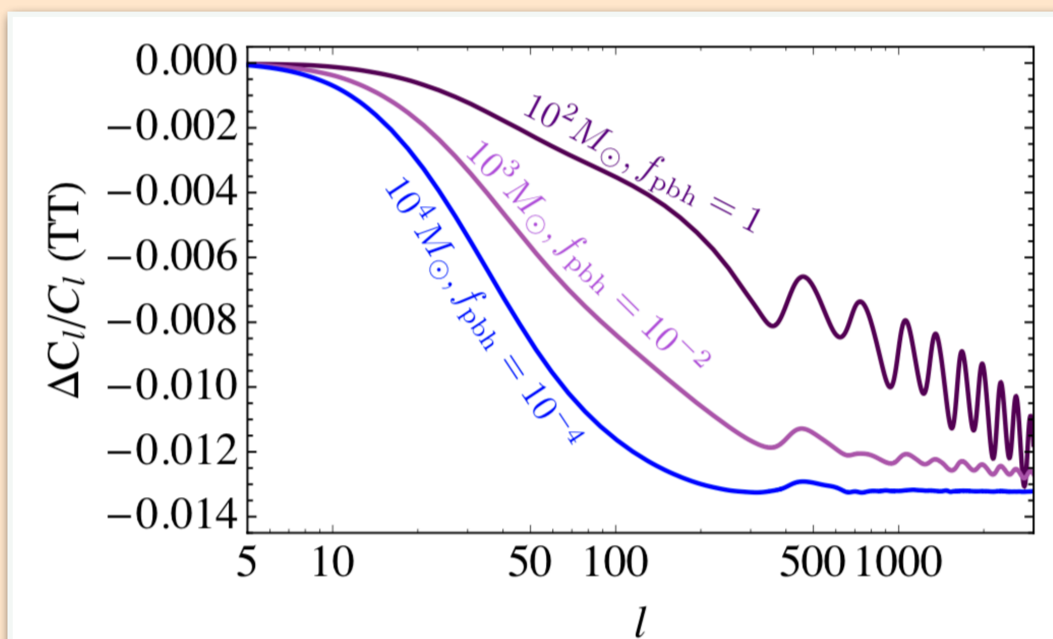
PBH Parameter Space

Ali-Haïmoud Kamionkowski arXiv:1612.05644



CMB Distortions

from accretion onto PBHs



Assuming δ-like PBH mass distribution

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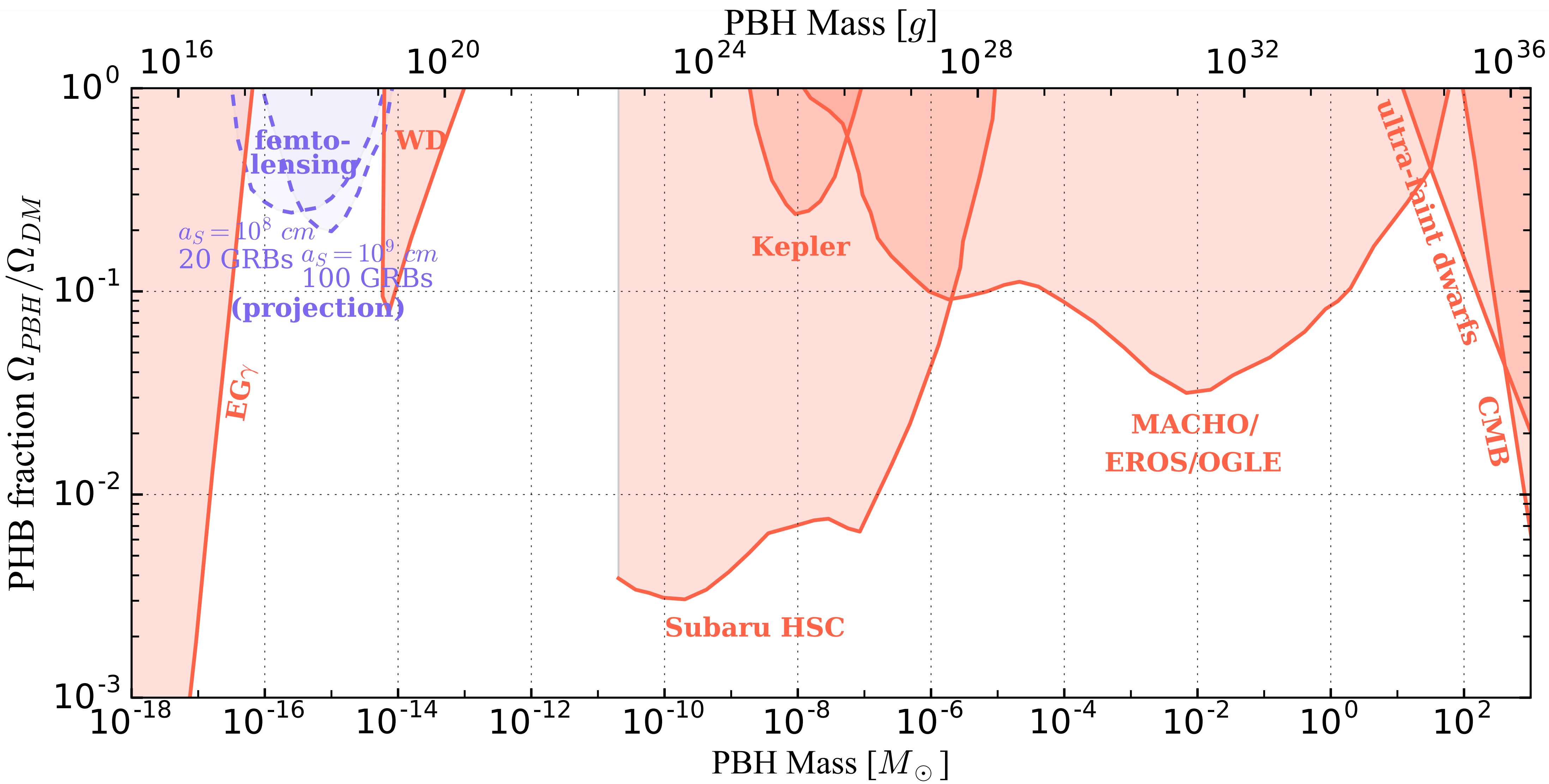
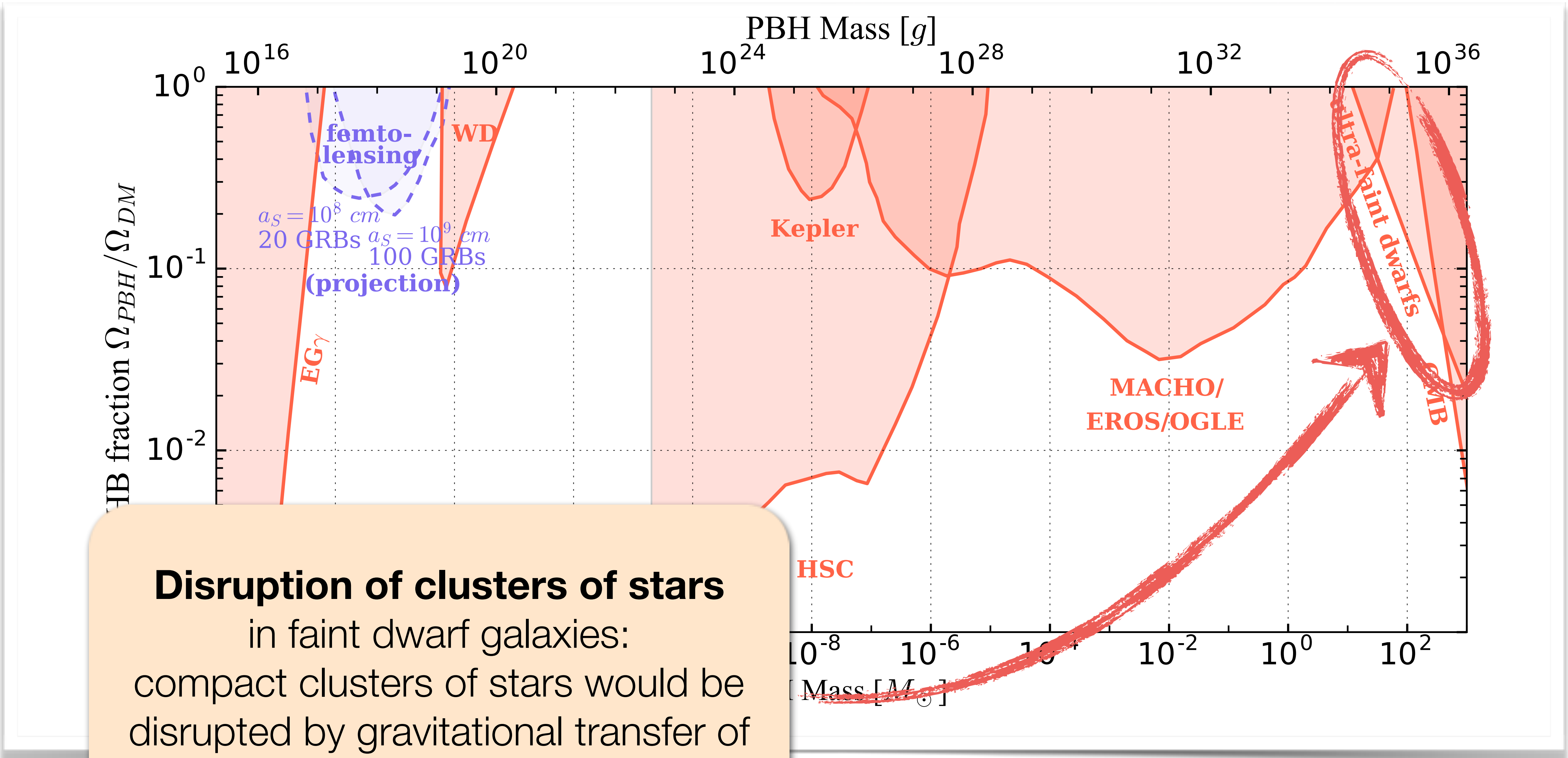
PBH Parameter Space



Assuming δ-like PBH mass distribution

PBH Parameter Space

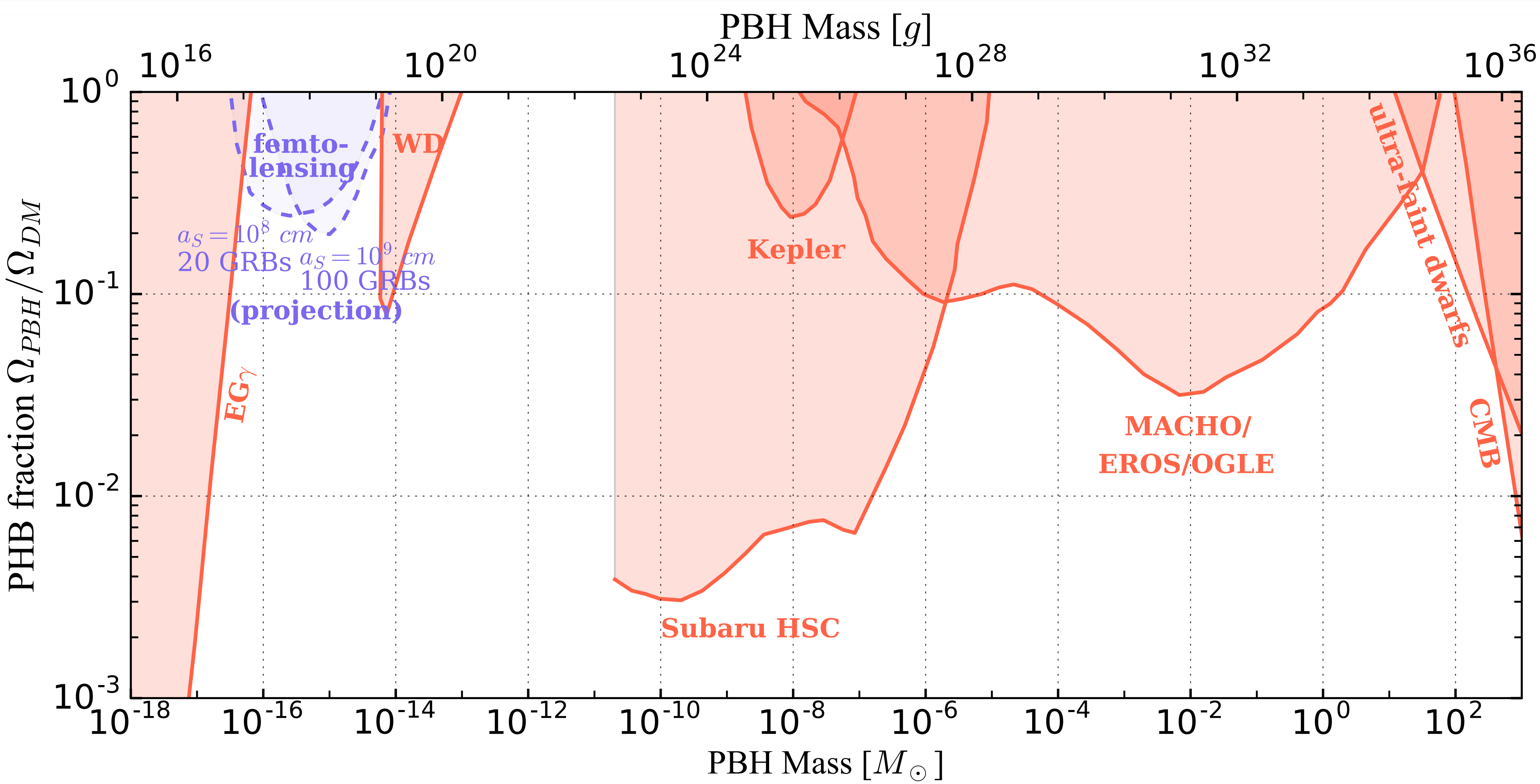
Brandt arXiv:1605.03665



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

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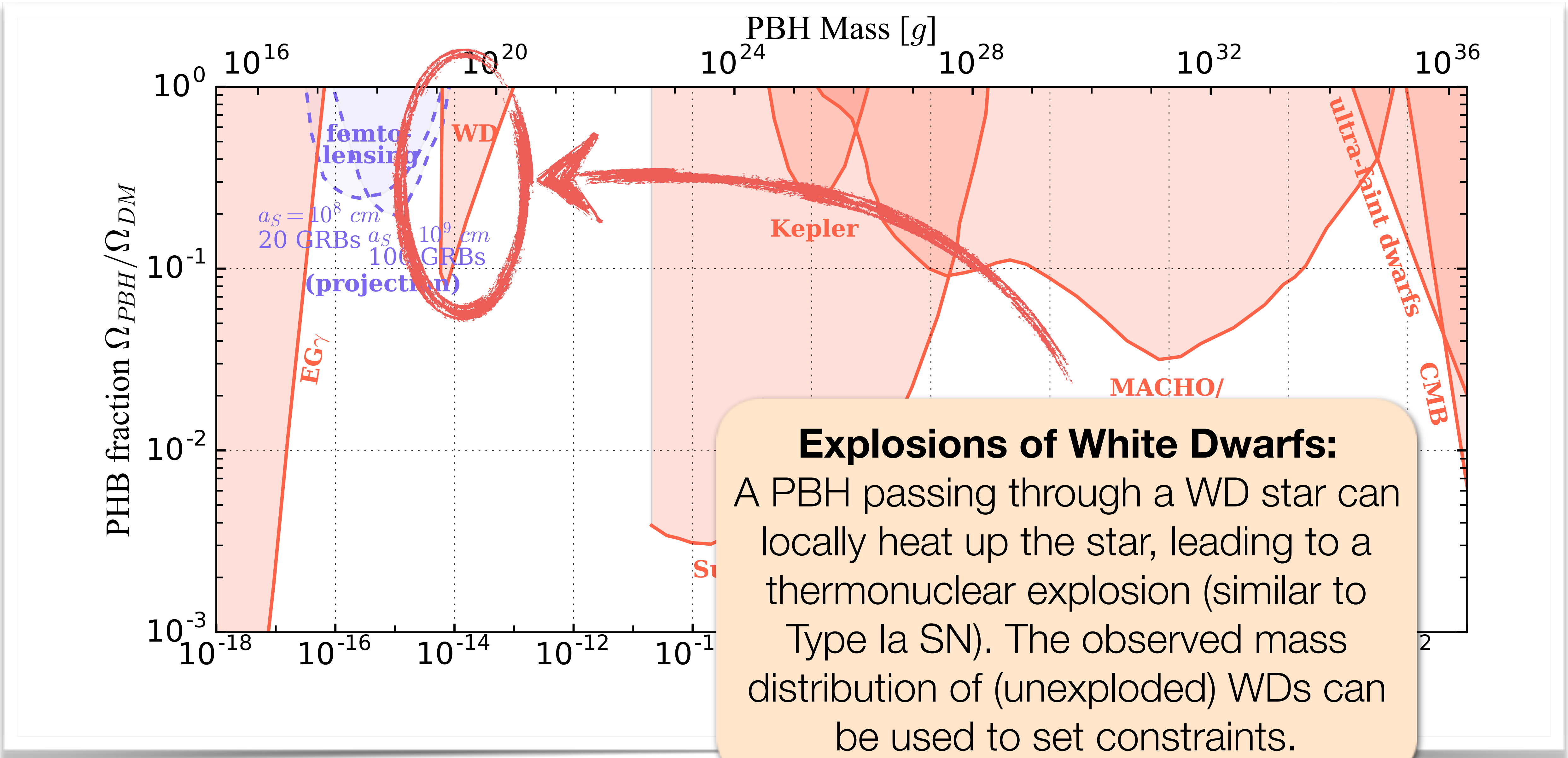
PBH Parameter Space

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

Summary

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WIMP Dark Matter

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

Dark Photons

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

Primordial Black Holes

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

Thank You !