A Bouquet of Dark Matter Candidates

Joachim Kopp (CERN & JGU Mainz)
PSI Colloquium | 22 April 2021

Outline

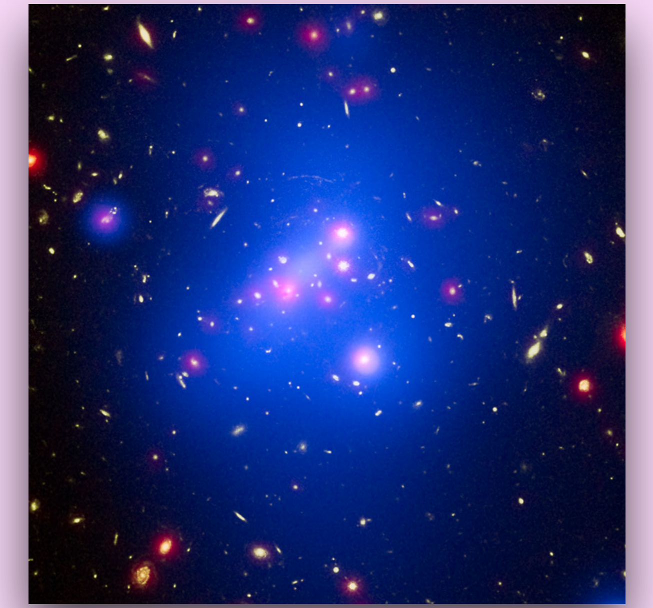
- ☑ Why Dark Matter?
- ☑ Weakly Interacting Massive Particles
- ☑ Sterile Neutrinos
- ☑ Primordial Black Holes

Why Dark Matter?

Evidence for Dark Matter

Evidence for Dark Matter

Galaxy Clusters



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

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

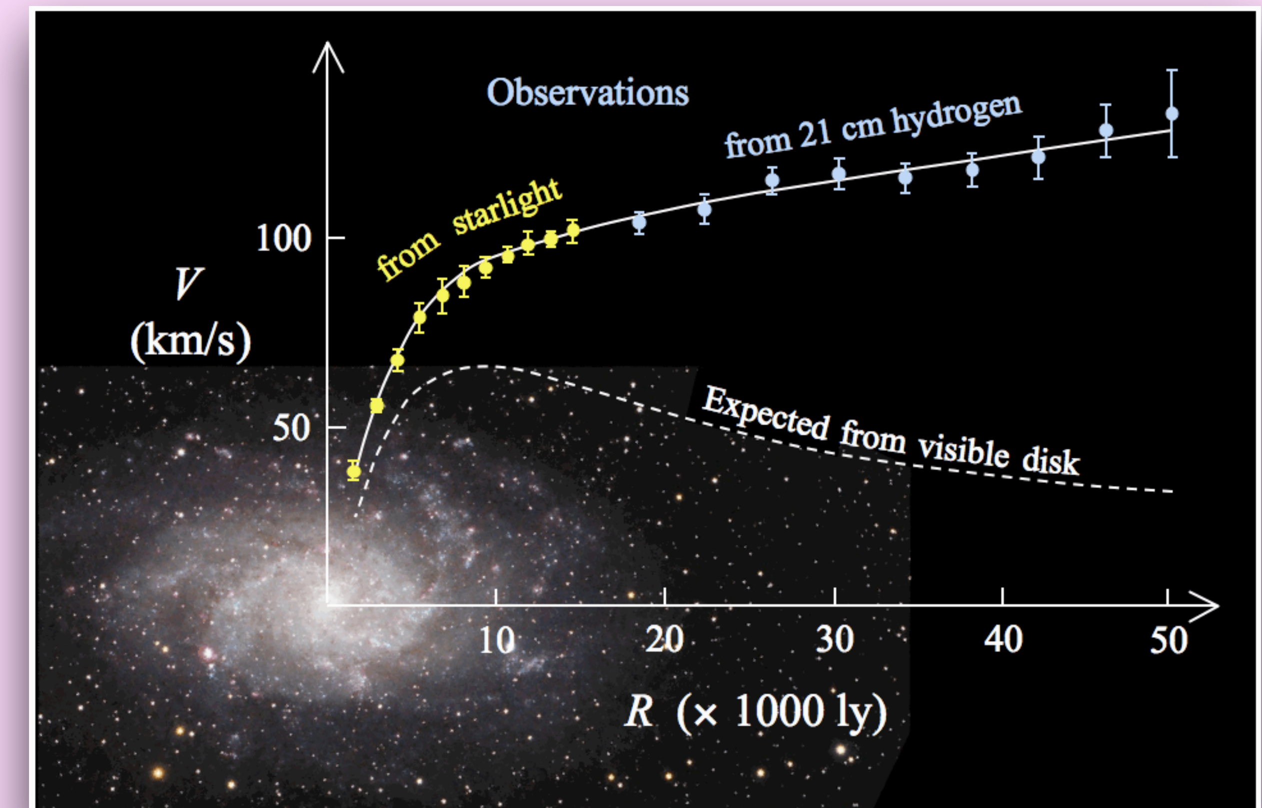
Evidence for Dark Matter

Galaxy Clusters

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

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

Galaxy Rotation Curves



Evidence for Dark Matter

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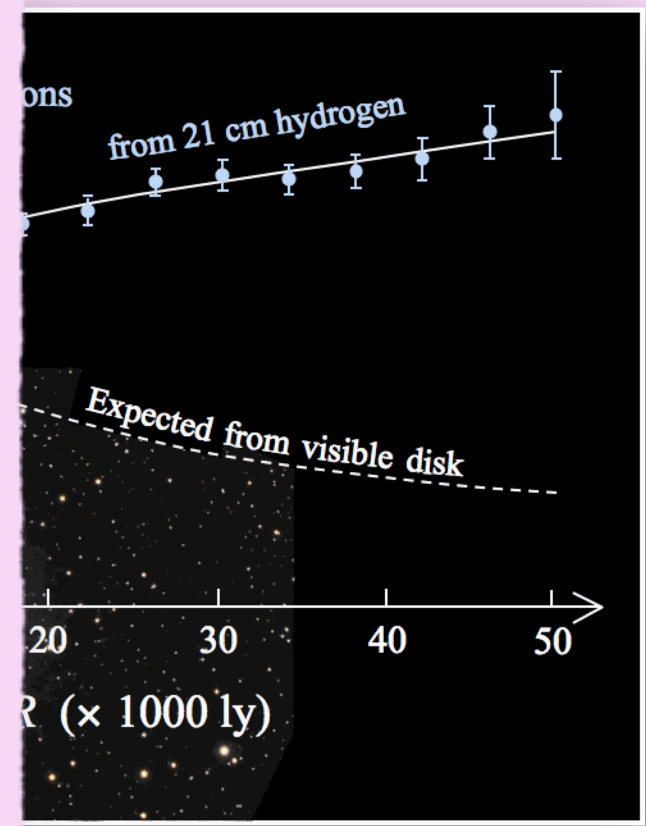
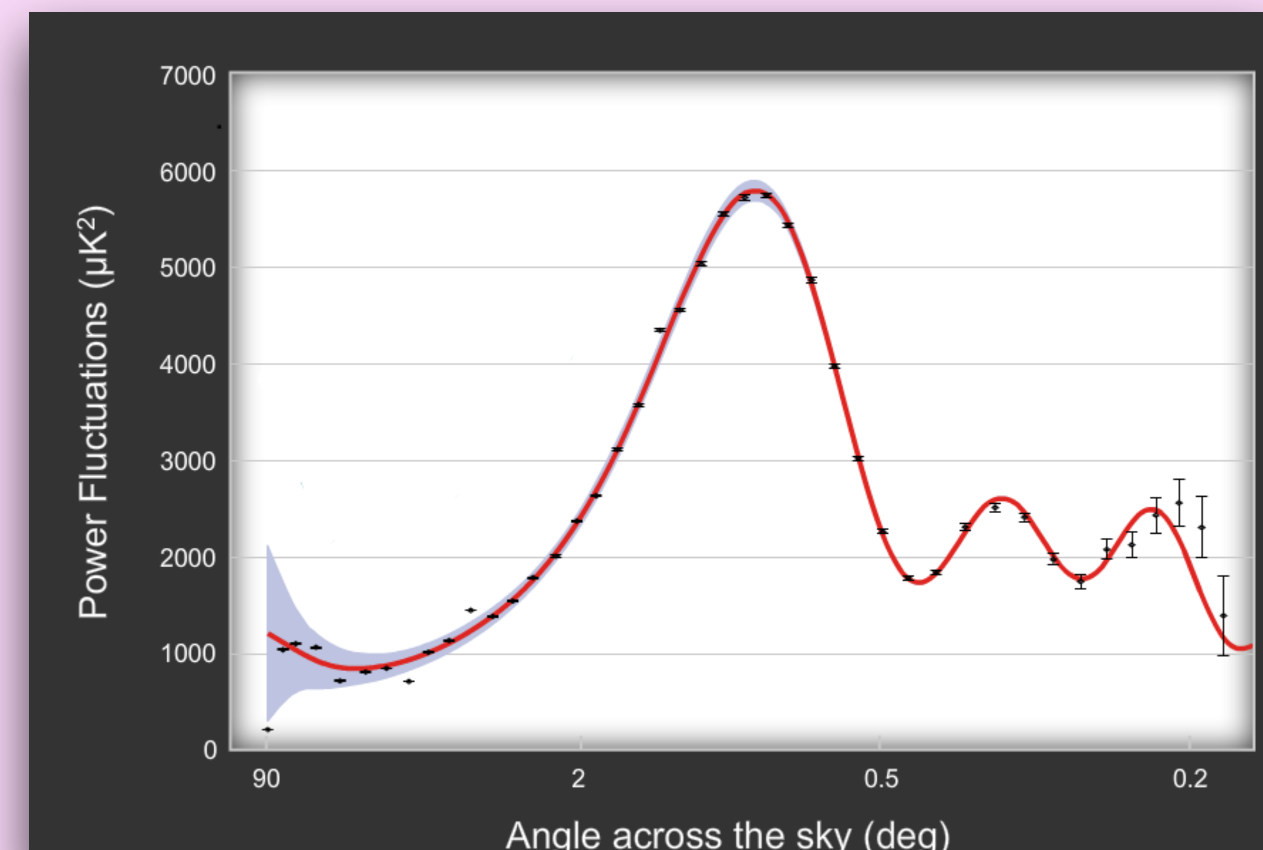


Cosmic Microwave Background



Evidence for Dark Matter

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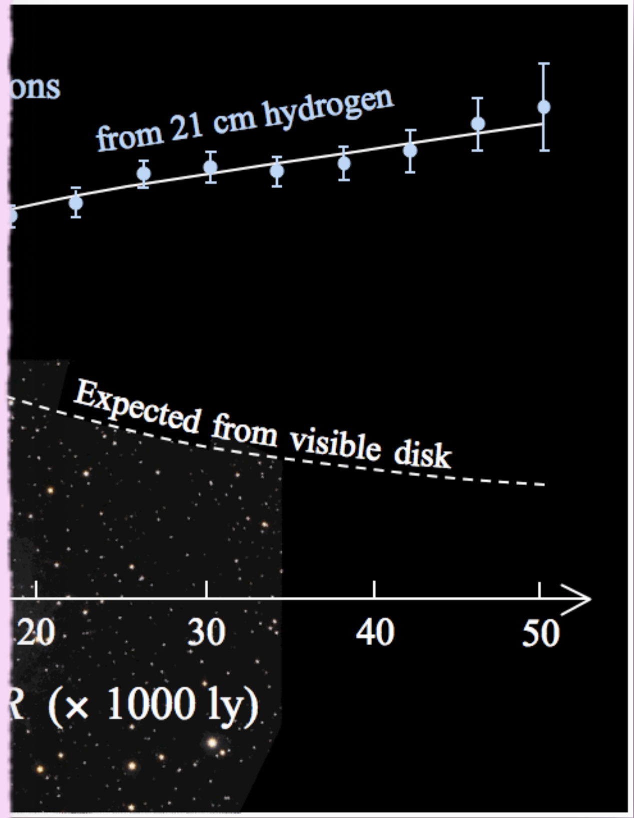

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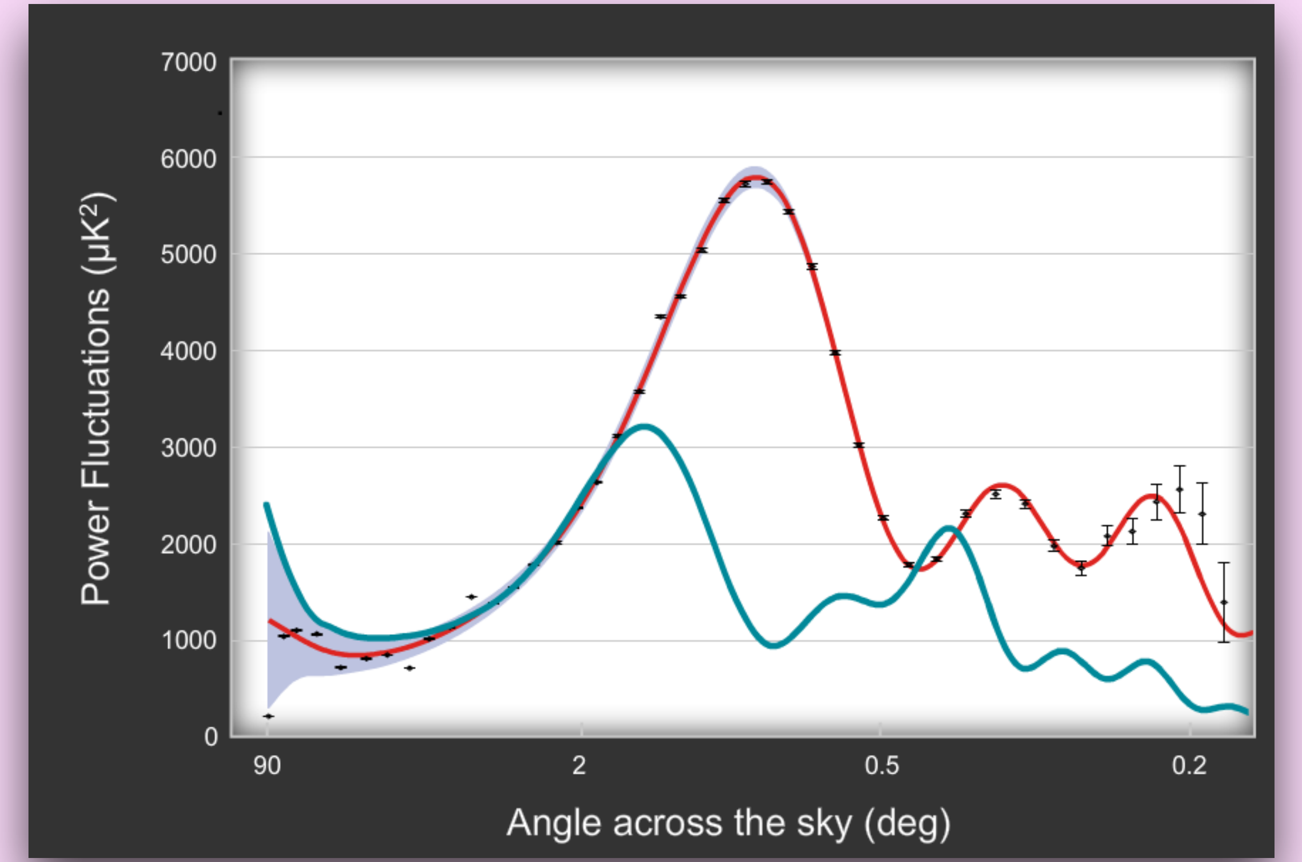

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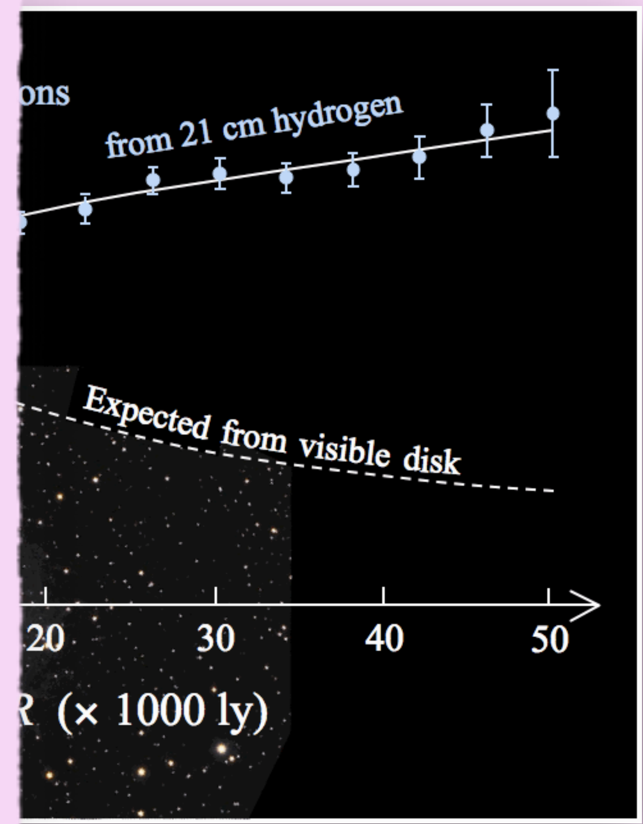

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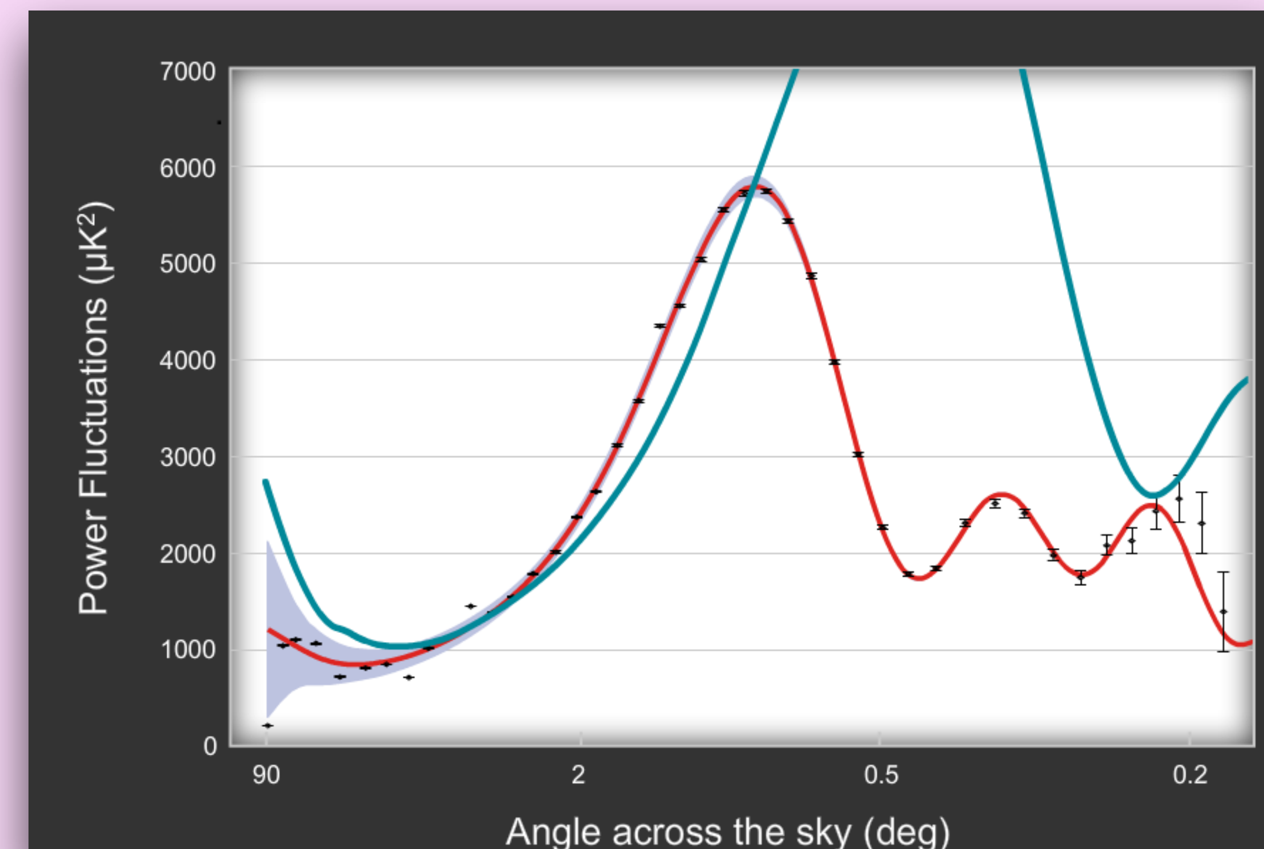
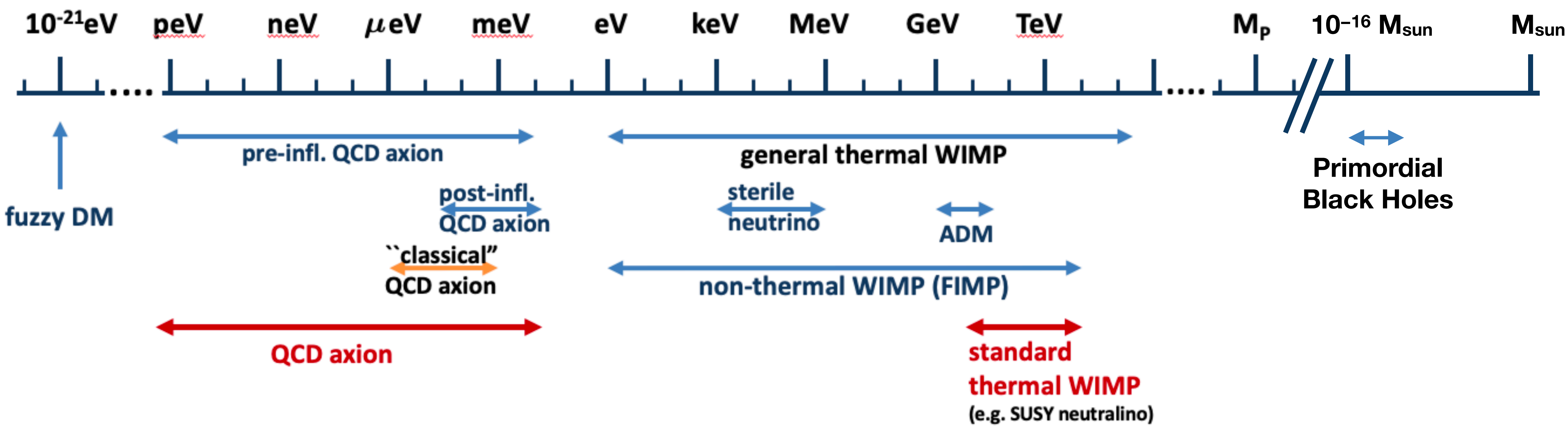


Dark Matter Mass



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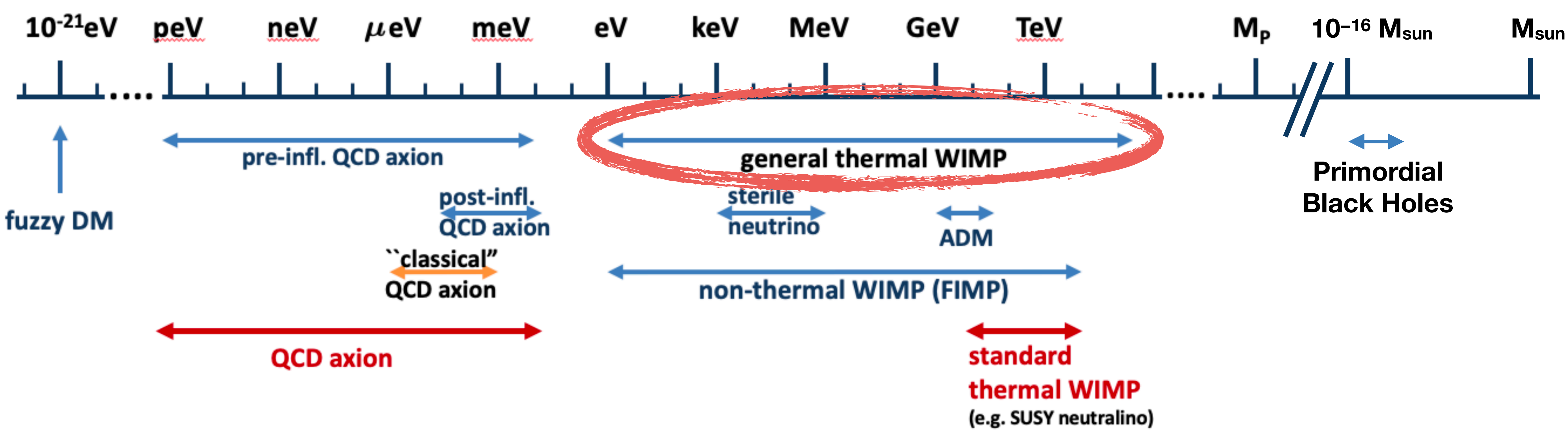

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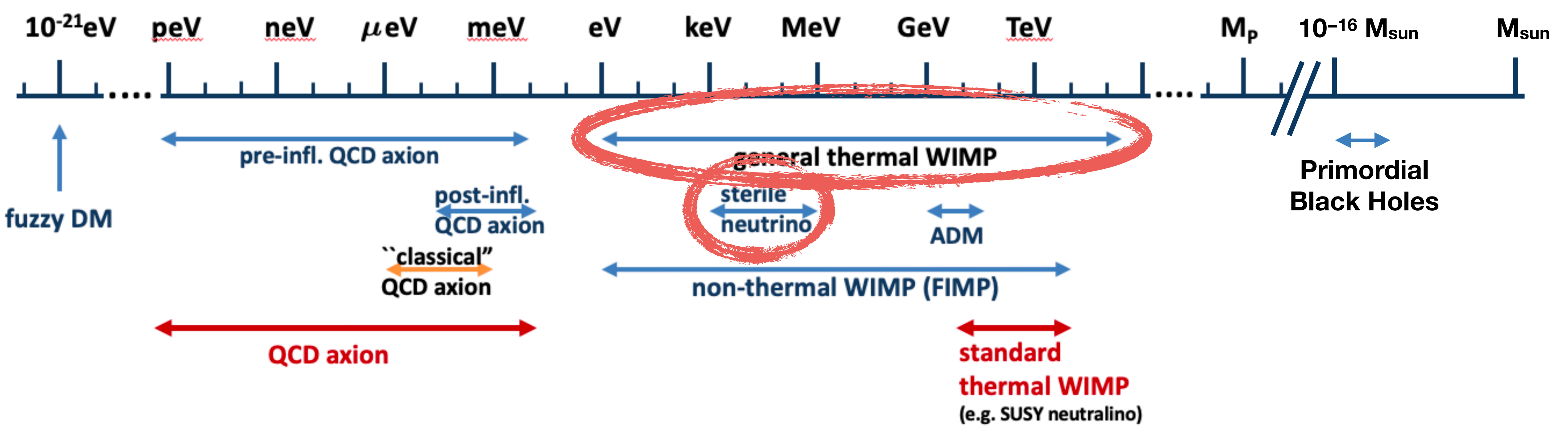

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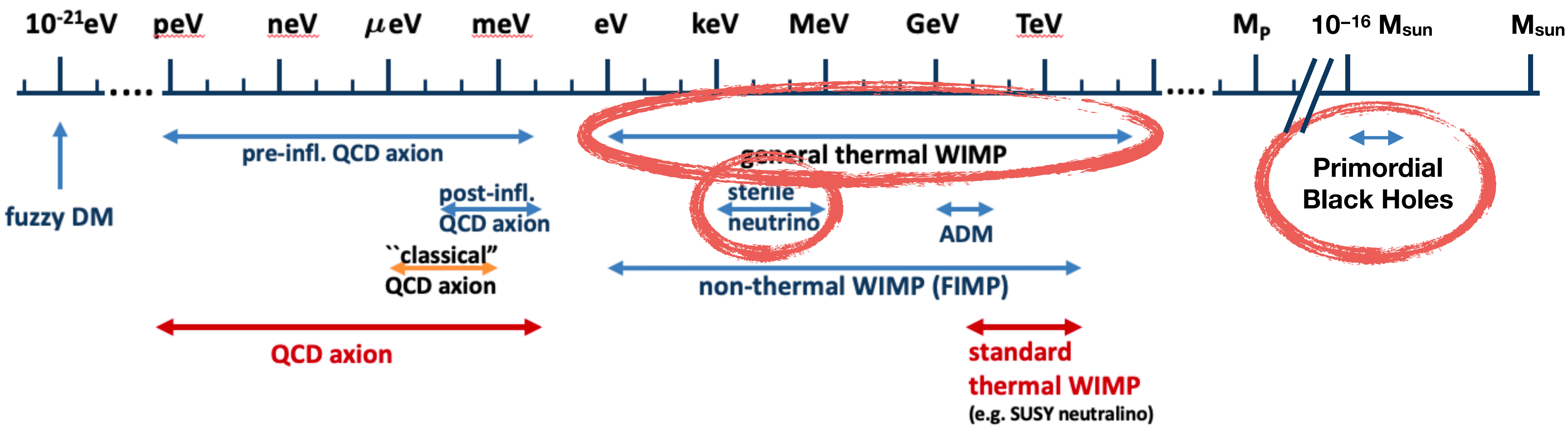
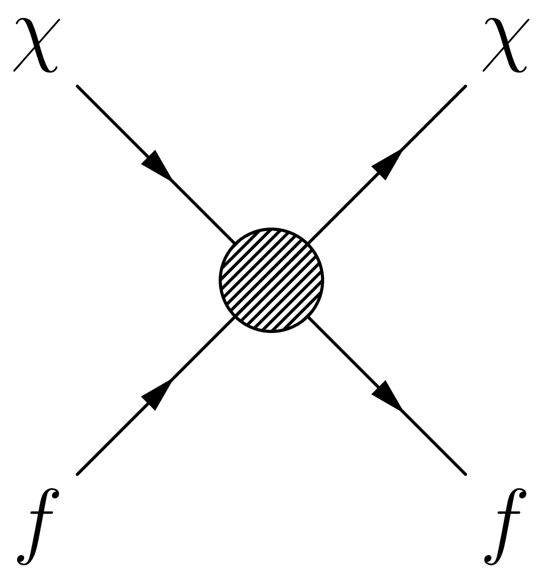


Weakly Interacting Massive Particles

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

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

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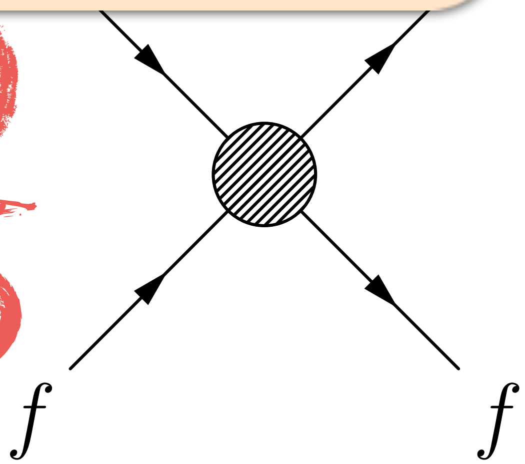

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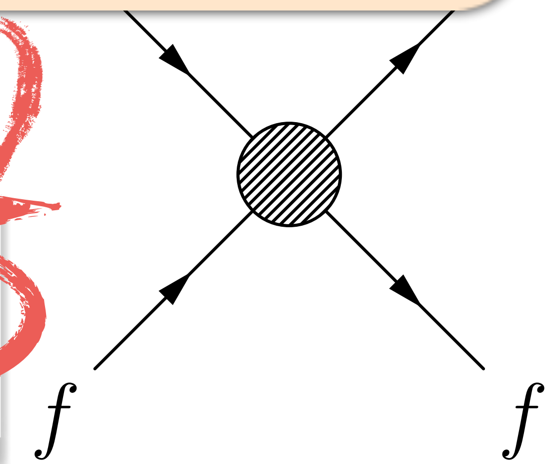

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rate of change of
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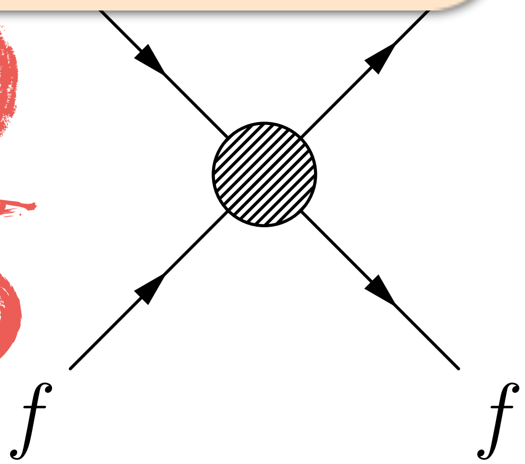

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Expansion of the Universe

Thermal Freeze-Out

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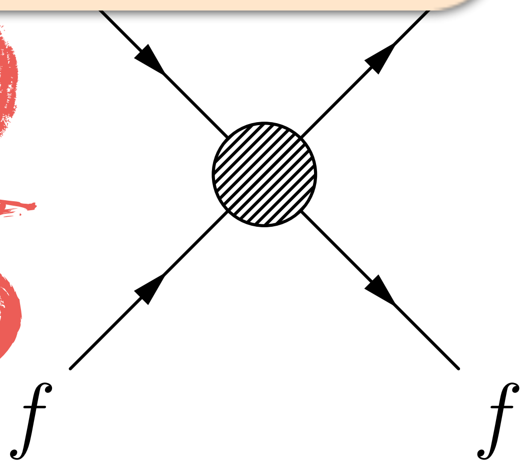

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- s f

rate of change of **DM number density**

DM **Annihilation**

- Described by Boltzmann equation

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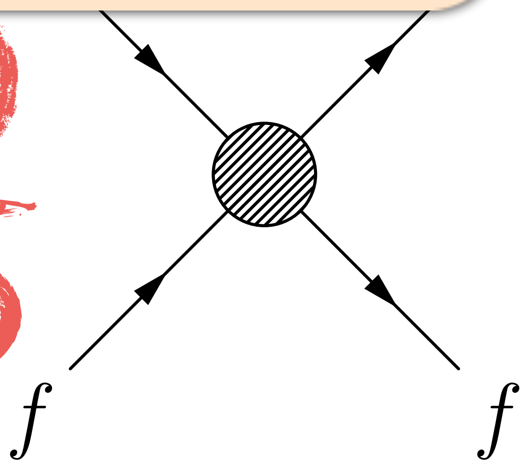

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- s f

rate of change of **DM number density**

DM **Annihilation**

DM **Production**

- Described by Boltzmann equation

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

Expansion of the Universe

Thermal Freeze-Out

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

- ☑ 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

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

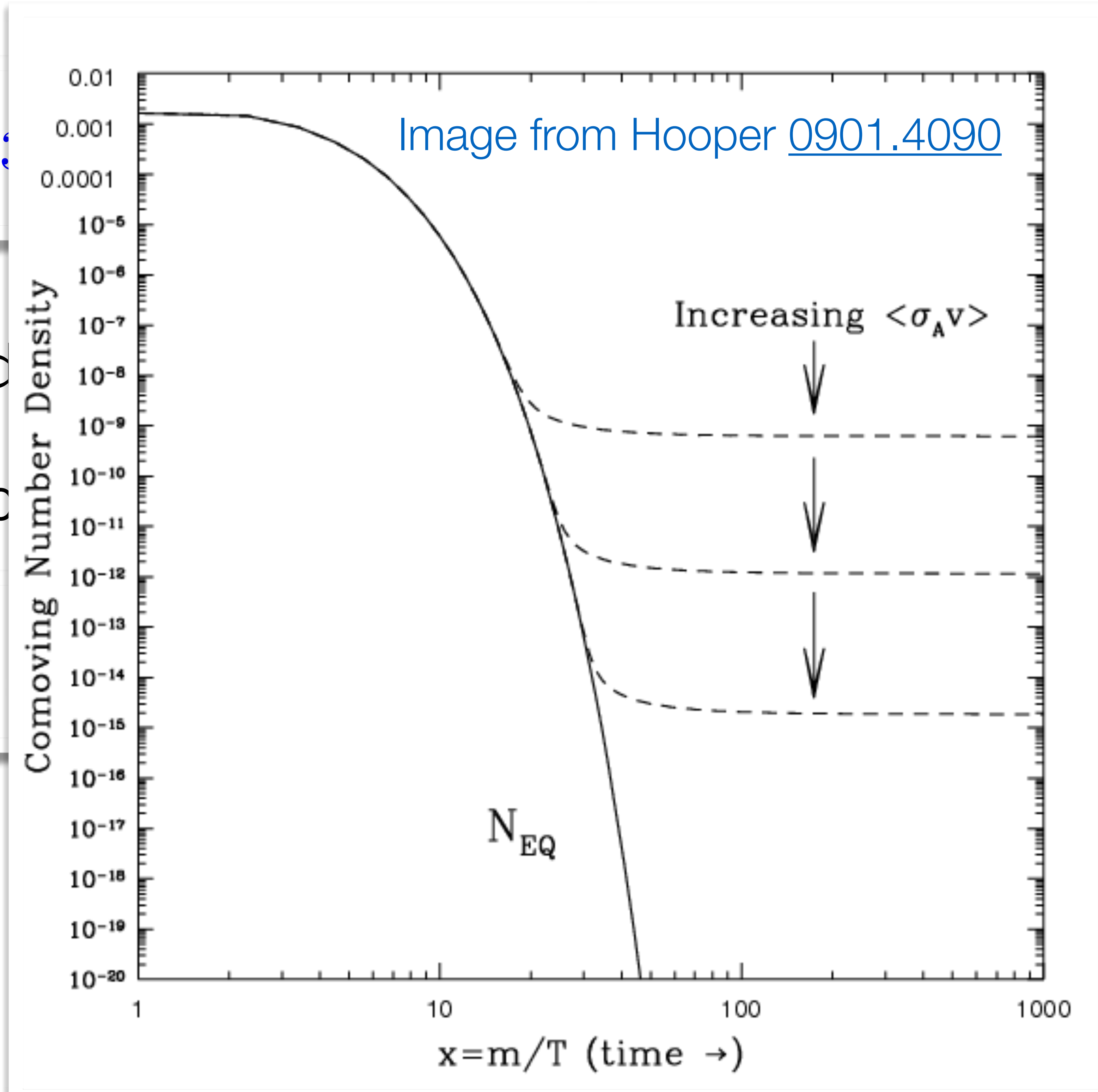
Thermal Freeze-Out

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

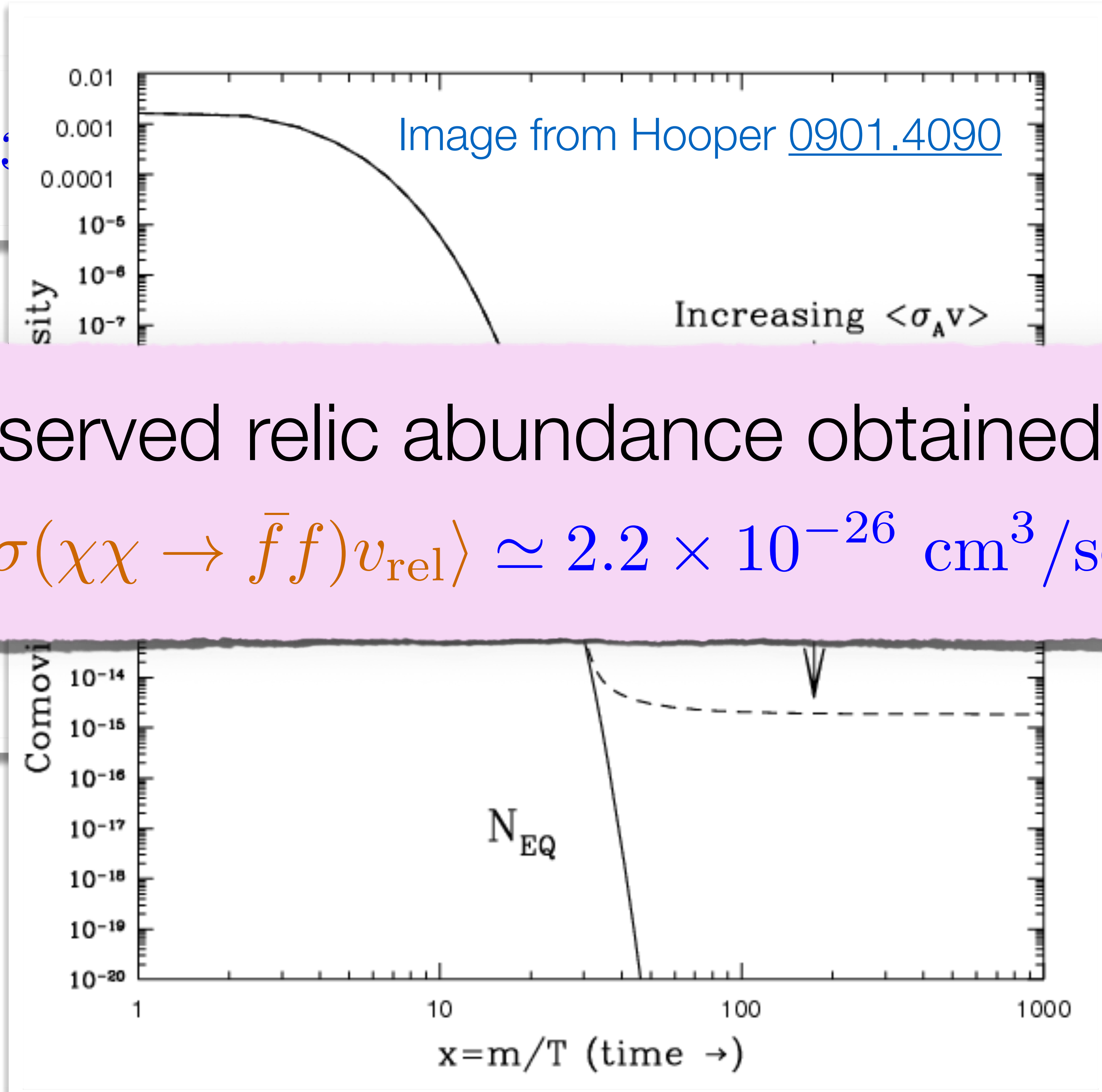
☑ Detailed … $\langle\sigma(\chi\chi \to \bar{f} f) v_{\rm rel}\rangle$

☑ Final Bo…

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



Thermal Freeze-Out



observed relic abundance obtained for

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

Thermal Freeze-Out

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

Thermal Freeze-Out

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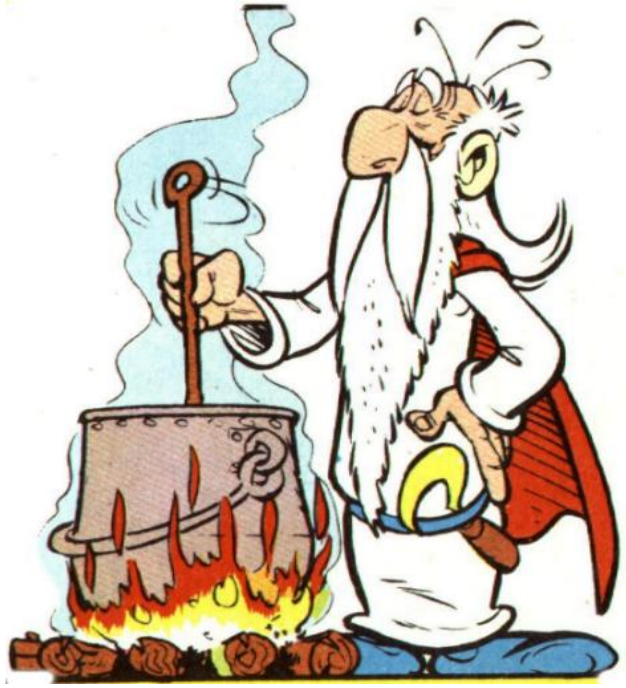
WIMP Miracle



DM Annihilation Today

observed relic abundance obtained for

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

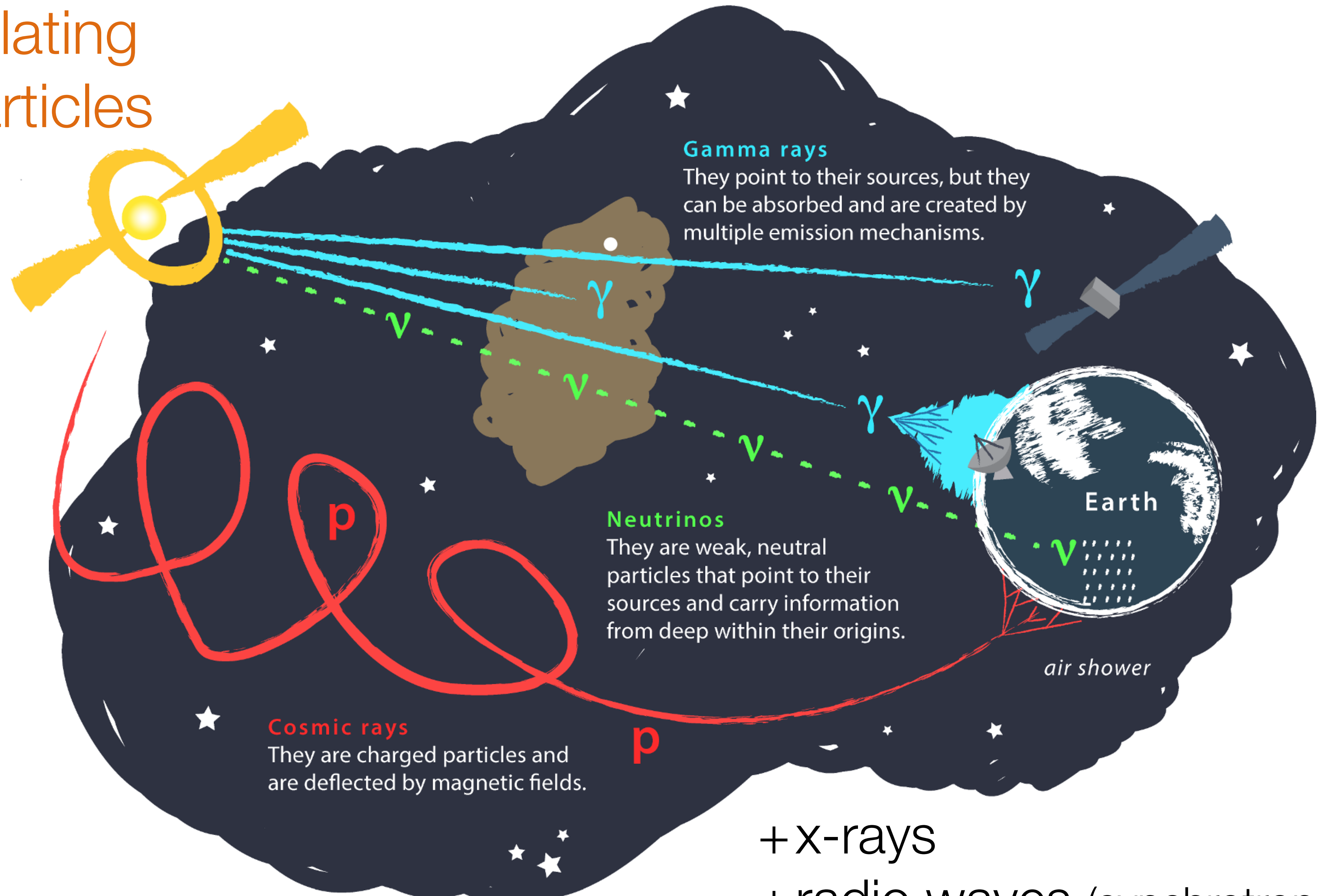
If this is mechanism is responsible for setting the DM abundance in the early Universe,

annihilations should still be happening today

in regions of high DM density

Messengers of DM Annihilation

Annihilating DM particles



+x-rays

+radio waves (synchrotron emission)

+…

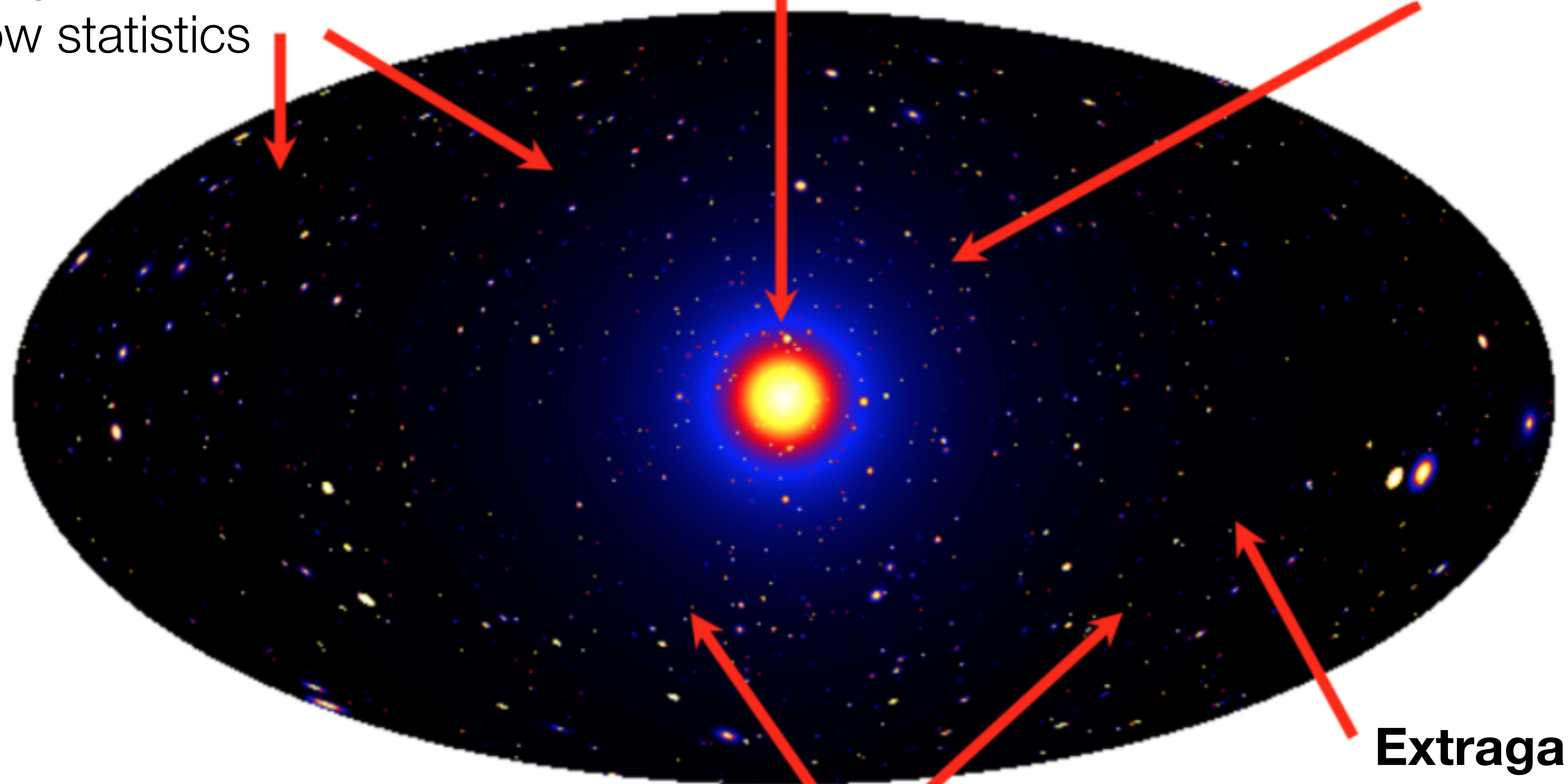
Image: J.A. Aguilar and J. Yang, IceCube/WIPAC

Where to Look for DM Annihilation

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

Galactic Center
good statistics, but source confusion
and diffuse background

Milky Way Halo
good statistics,
but diffuse background

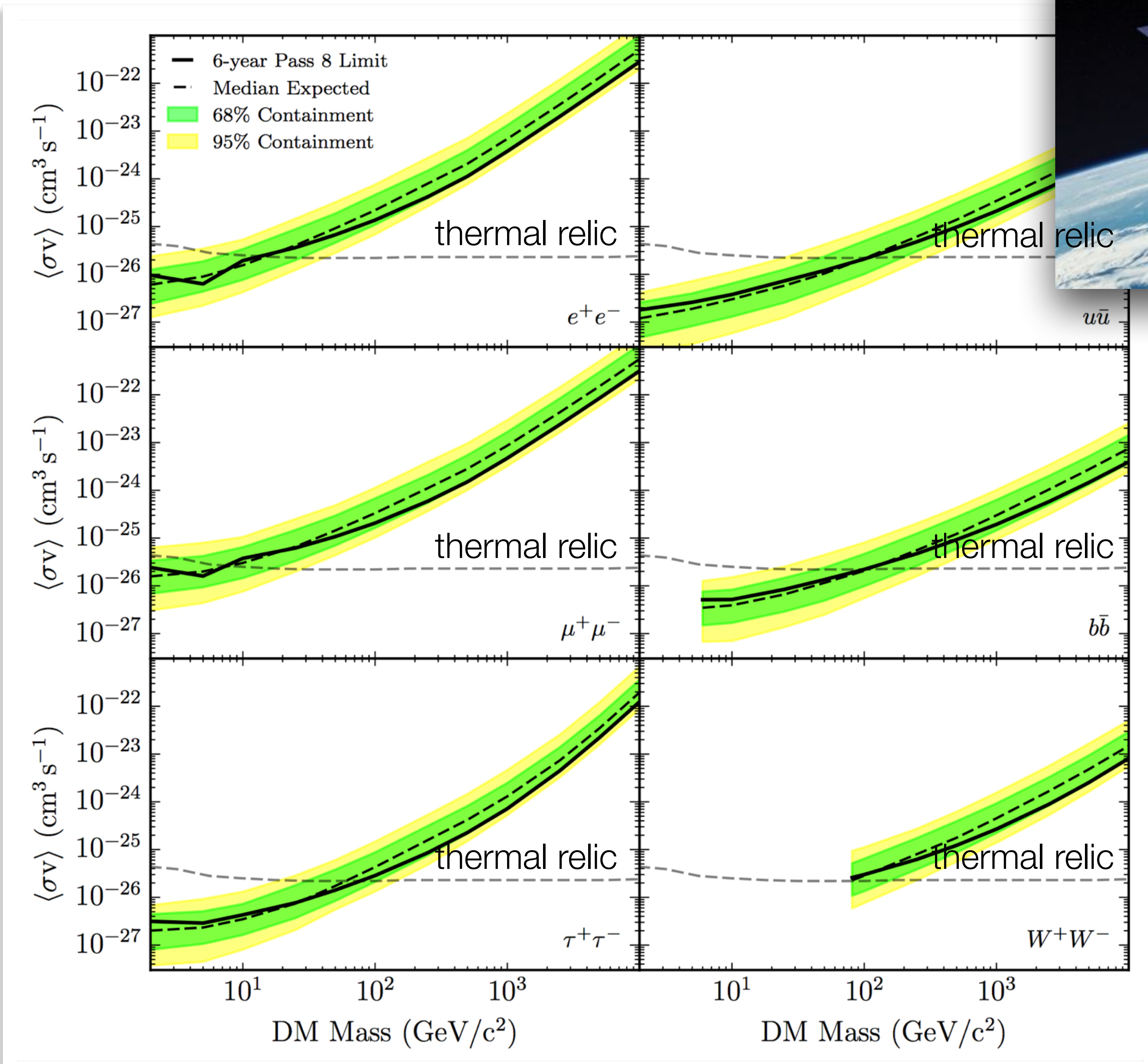


Extragalactic
large statistics, but
astrophysical foregrounds and
Galactic diffuse background

Galaxy Clusters
low background,
but low statistics

arXiv:0908.0195,
Fermi-LAT,
KIPAC/Stanford

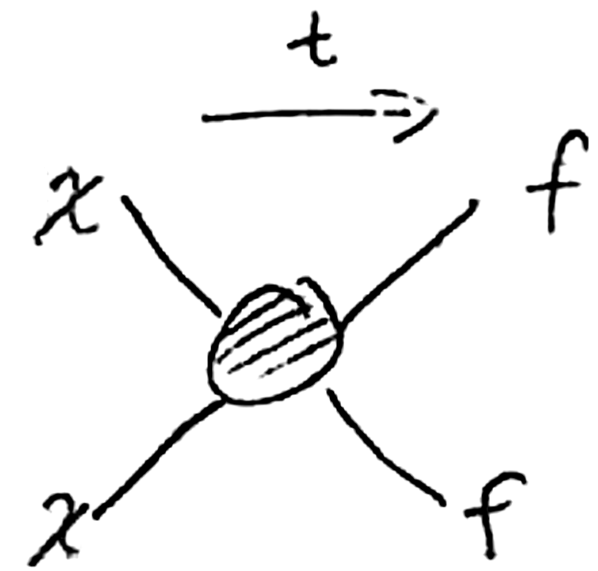
Fermi-LAT Limits from Dwarf Galaxies



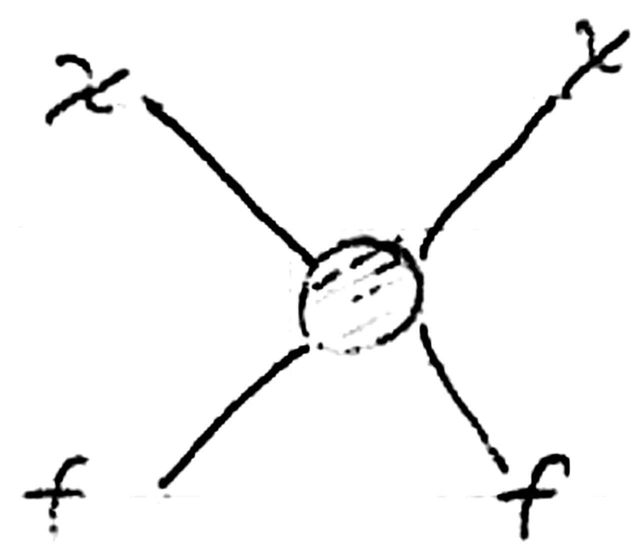
Credit: Fermi-LAT

Direct Detection of WIMP Dark Matter

- Annihilation:

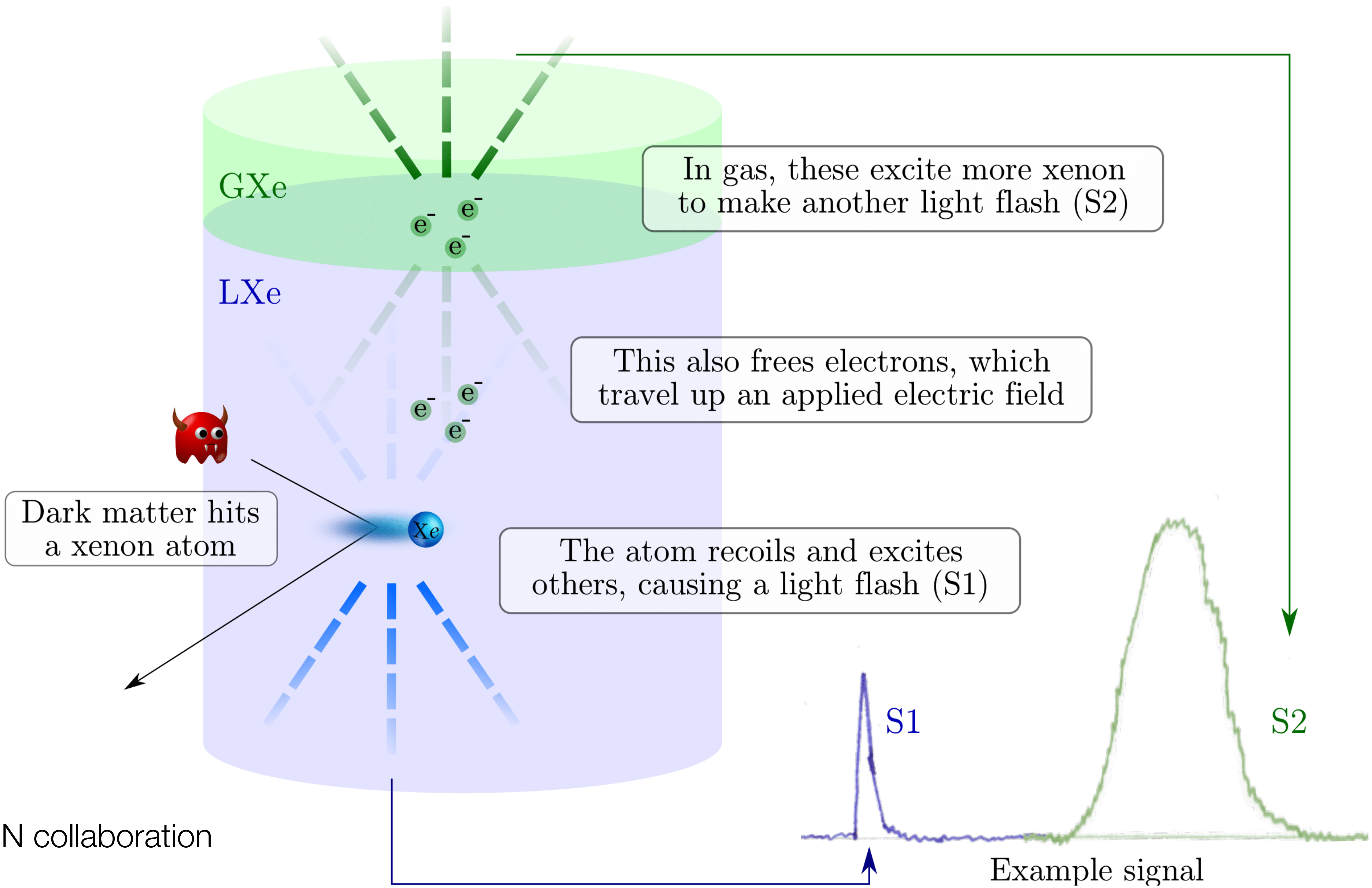


- Turn diagram around
  ➠ DM scattering



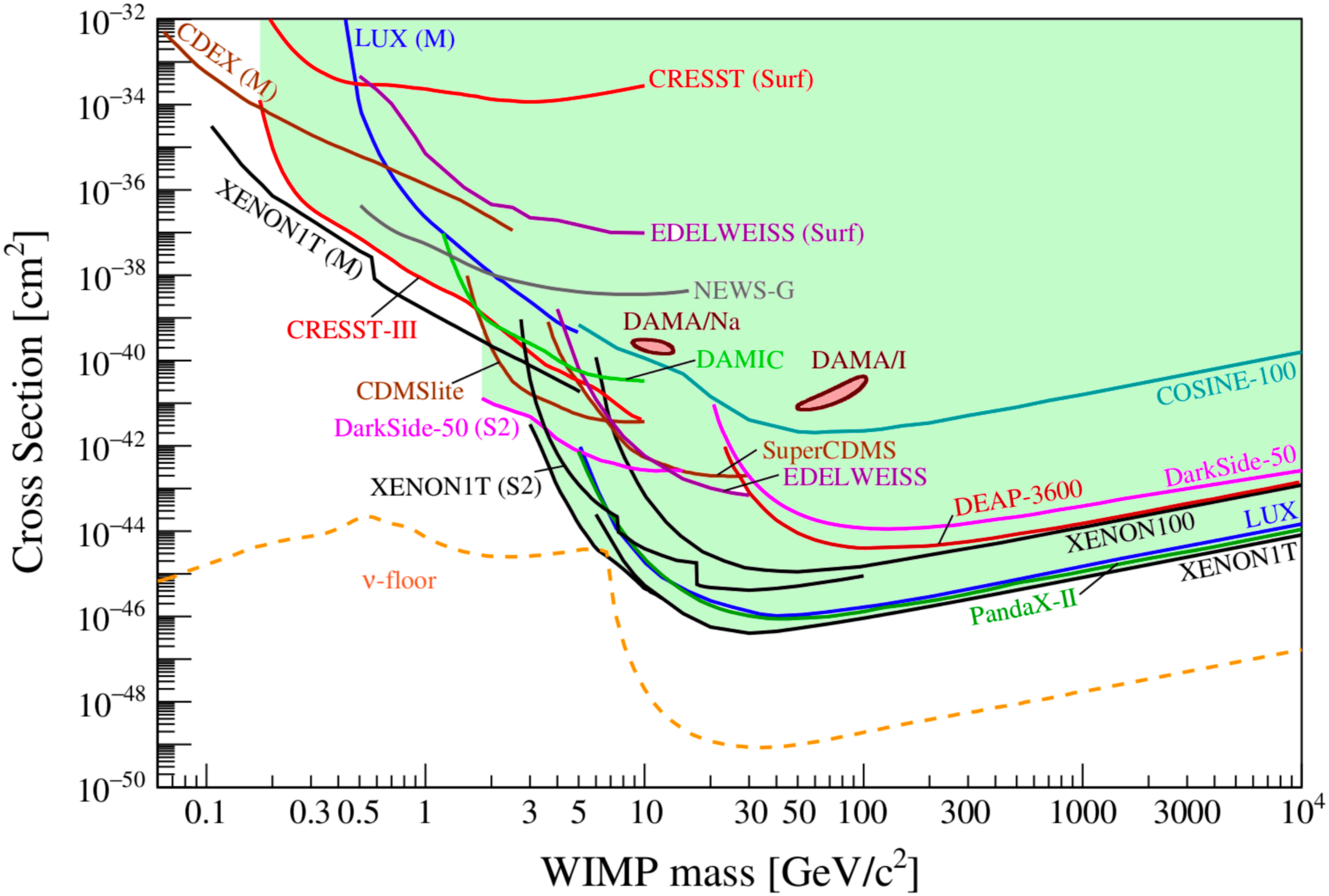
- Galactic WIMPs detectable by scattering
  (preferentially on nuclei for kinematic reasons)

Direct Detection Experiments



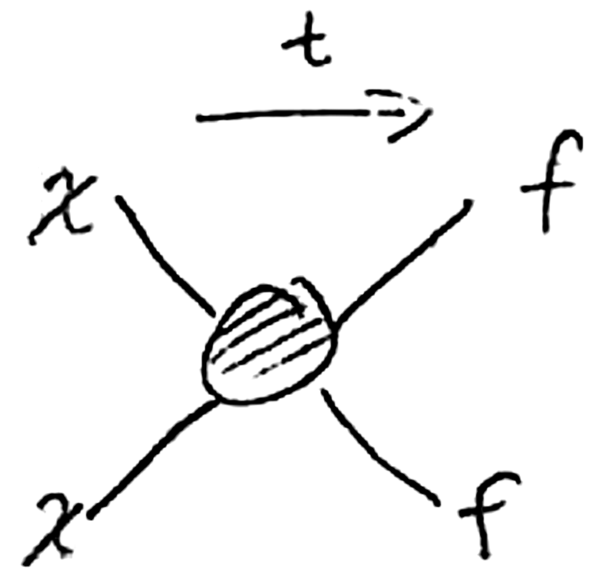
XENON collaboration

Direct Detection Results

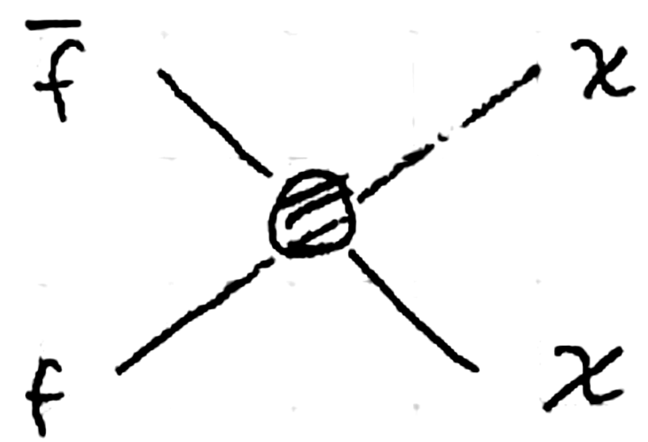


Dark Matter Production at Colliders

- ☑ Annihilation:



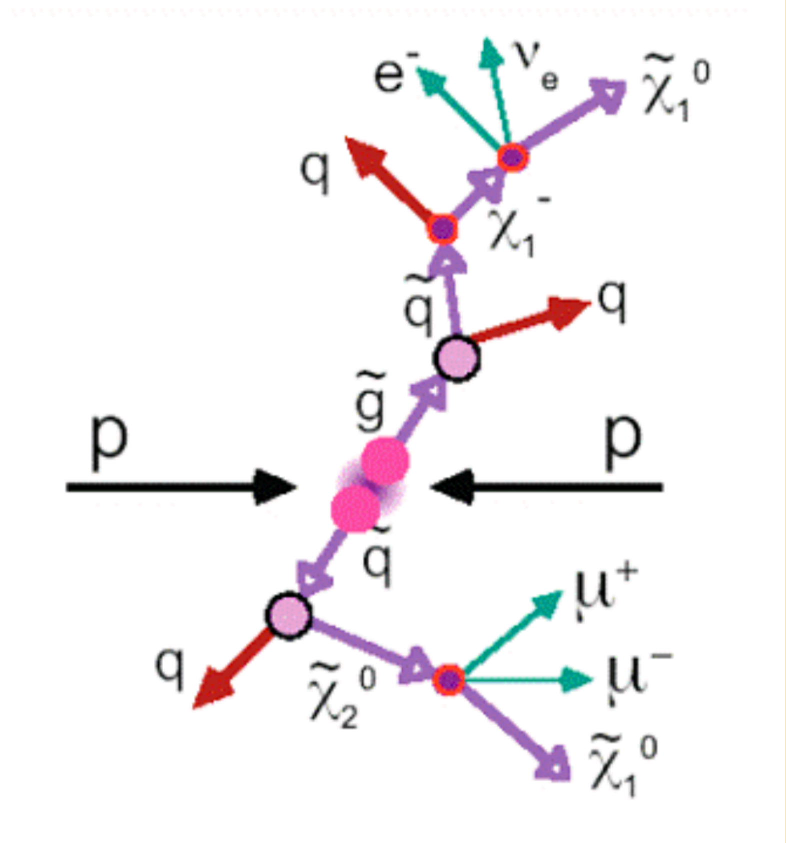
- ☑ Rotate diagram by 180°
  ➠ DM production



- ☑ 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

WIMP Detection at Colliders

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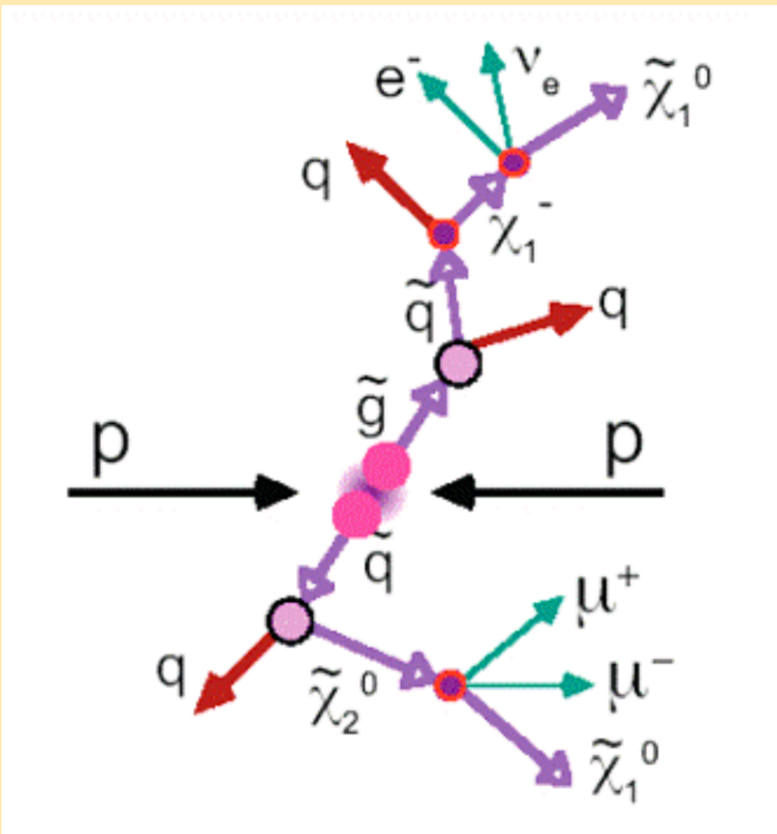

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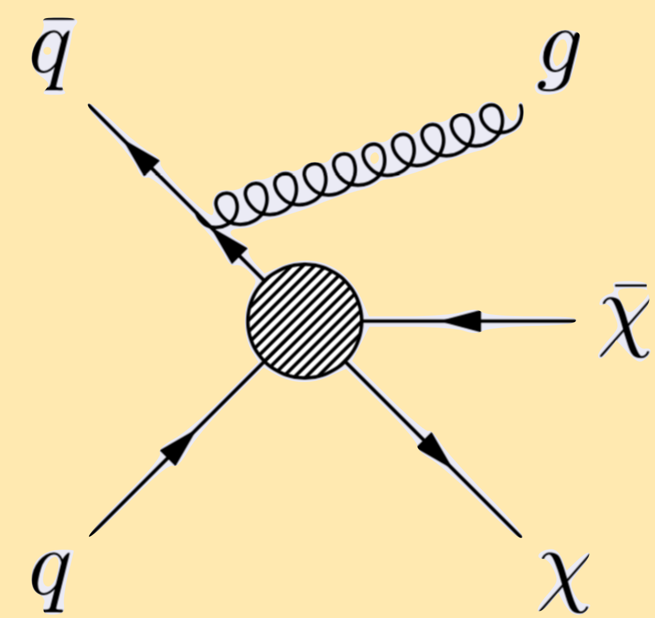
mono-X signatures



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

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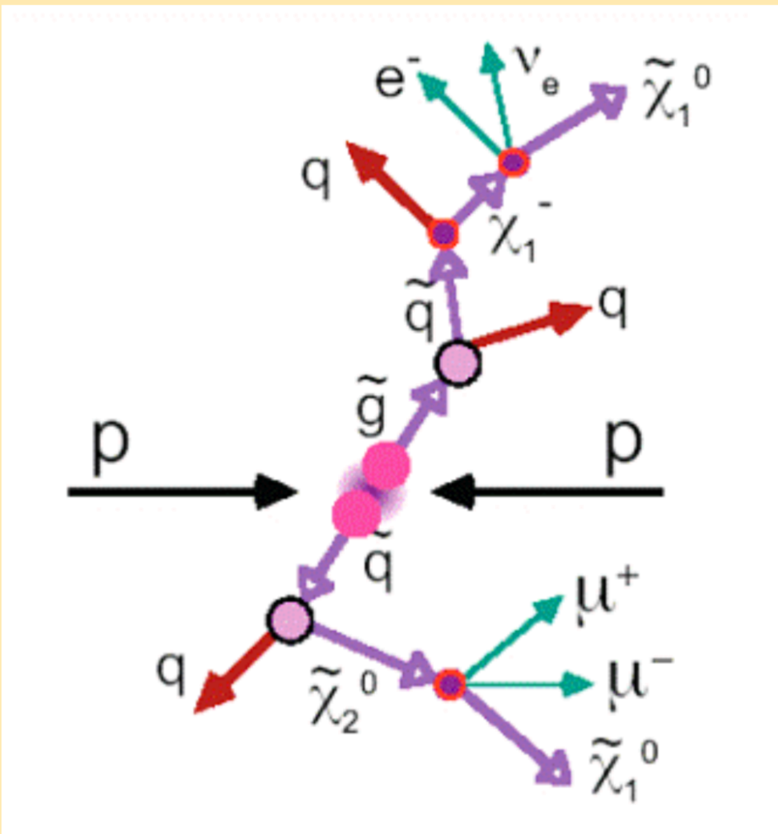

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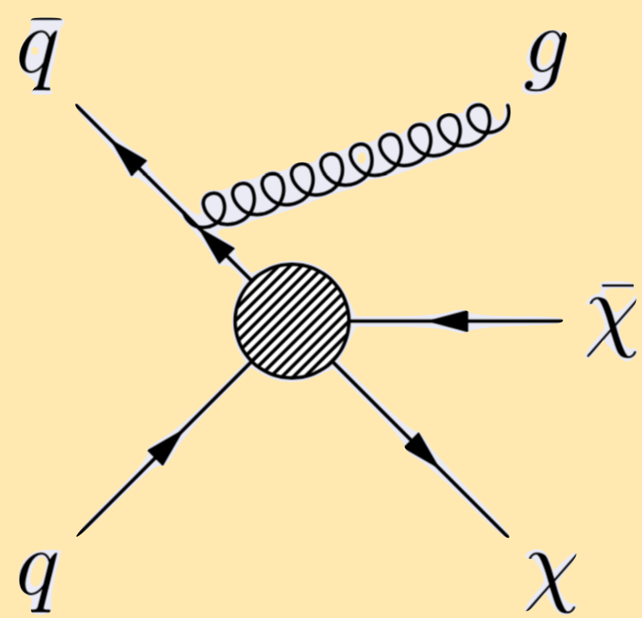

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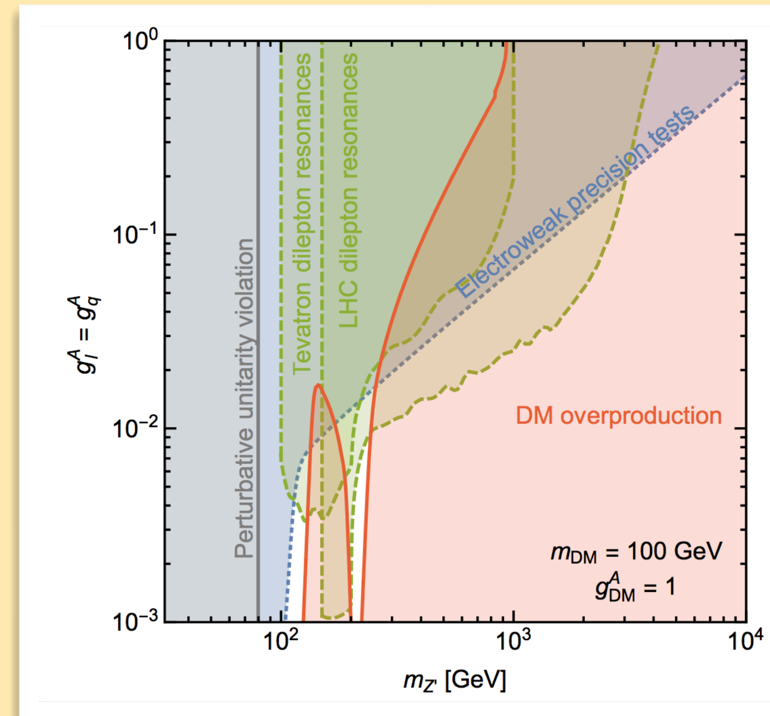
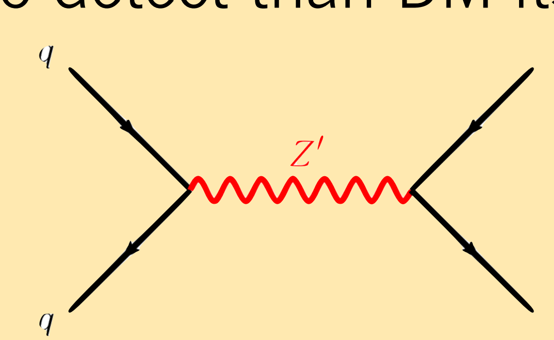
mediator searches



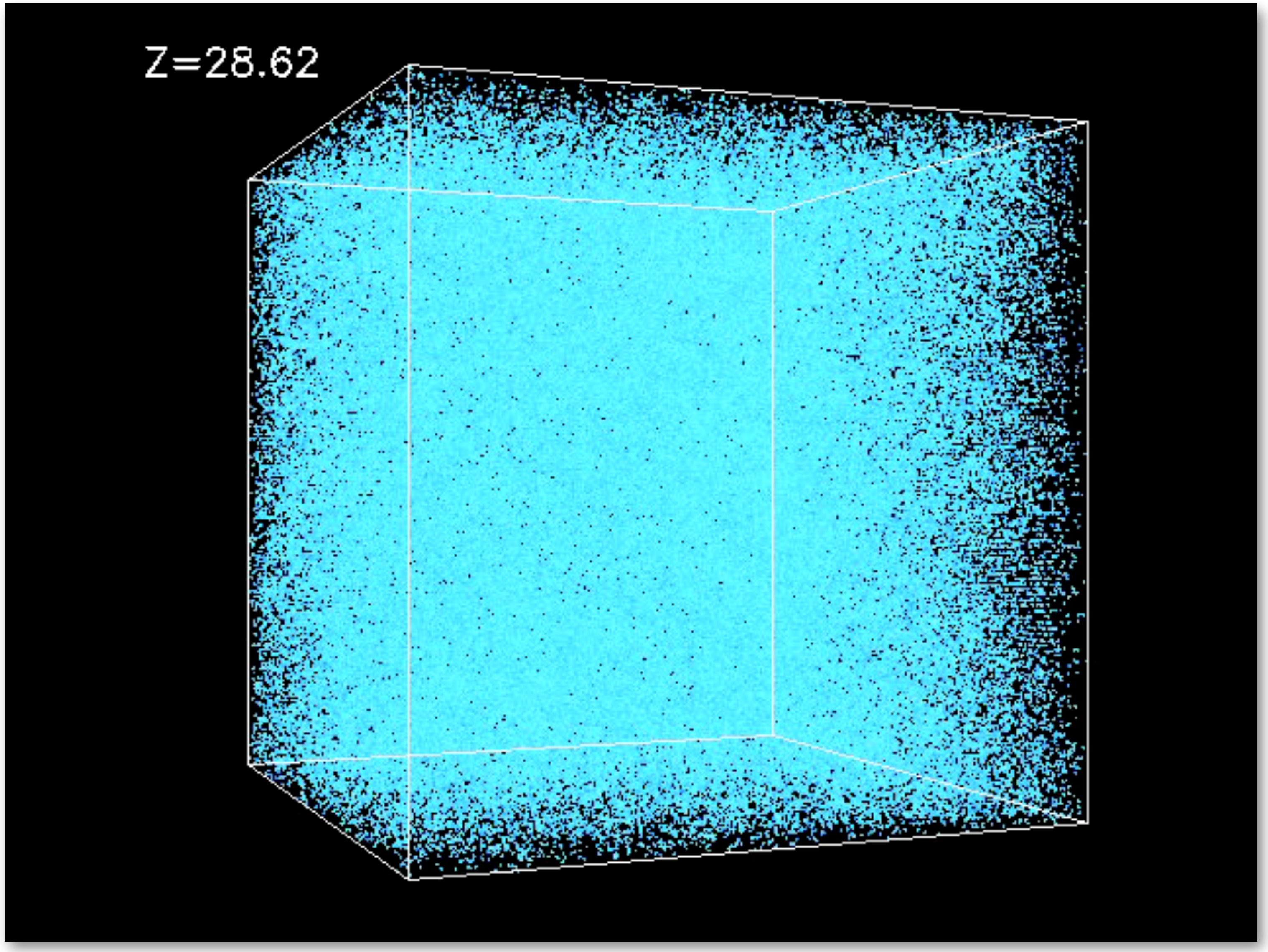
- ☑ Mediators of DM–SM interactions often easier to detect than DM itself



Sterile Neutrinos

Cosmic Structure Formation

☑ Tiny density fluctuations grow thanks to gravity



http://cosmicweb.uchicago.edu/filaments.html

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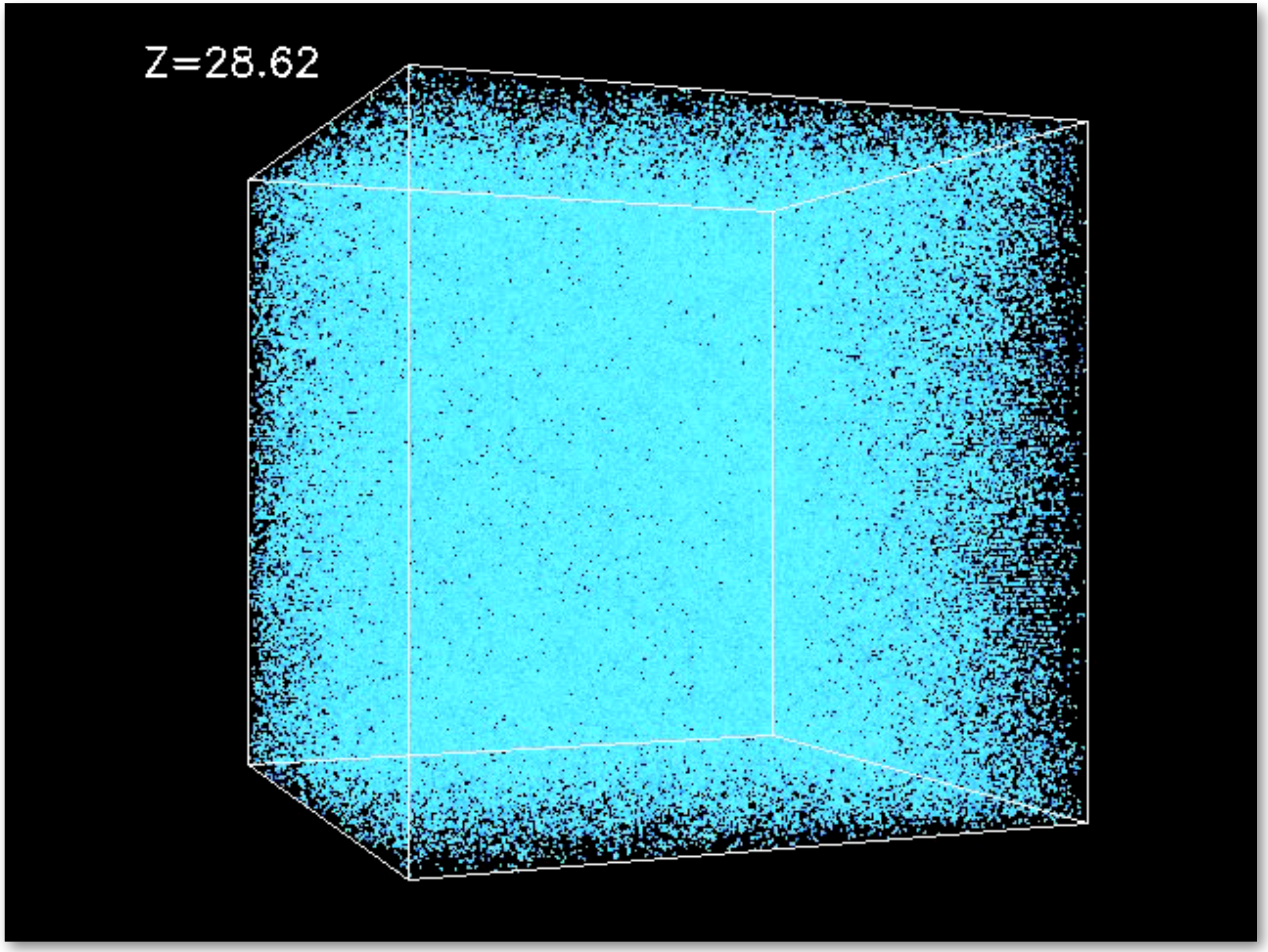

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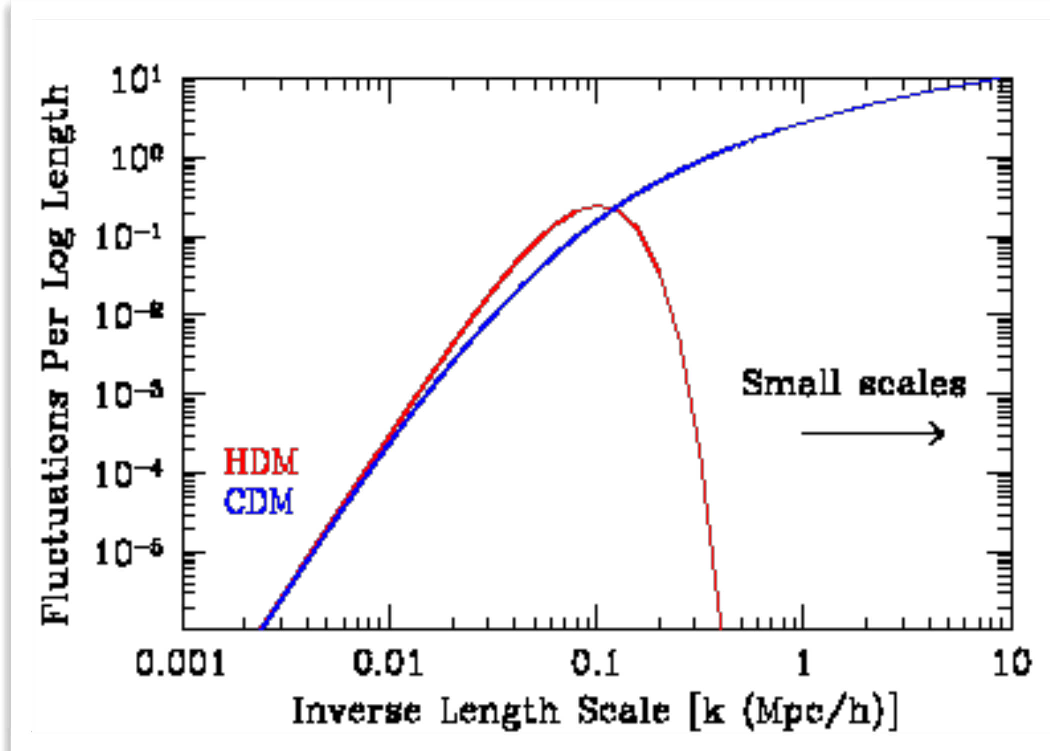
Motivation for the keV Scale

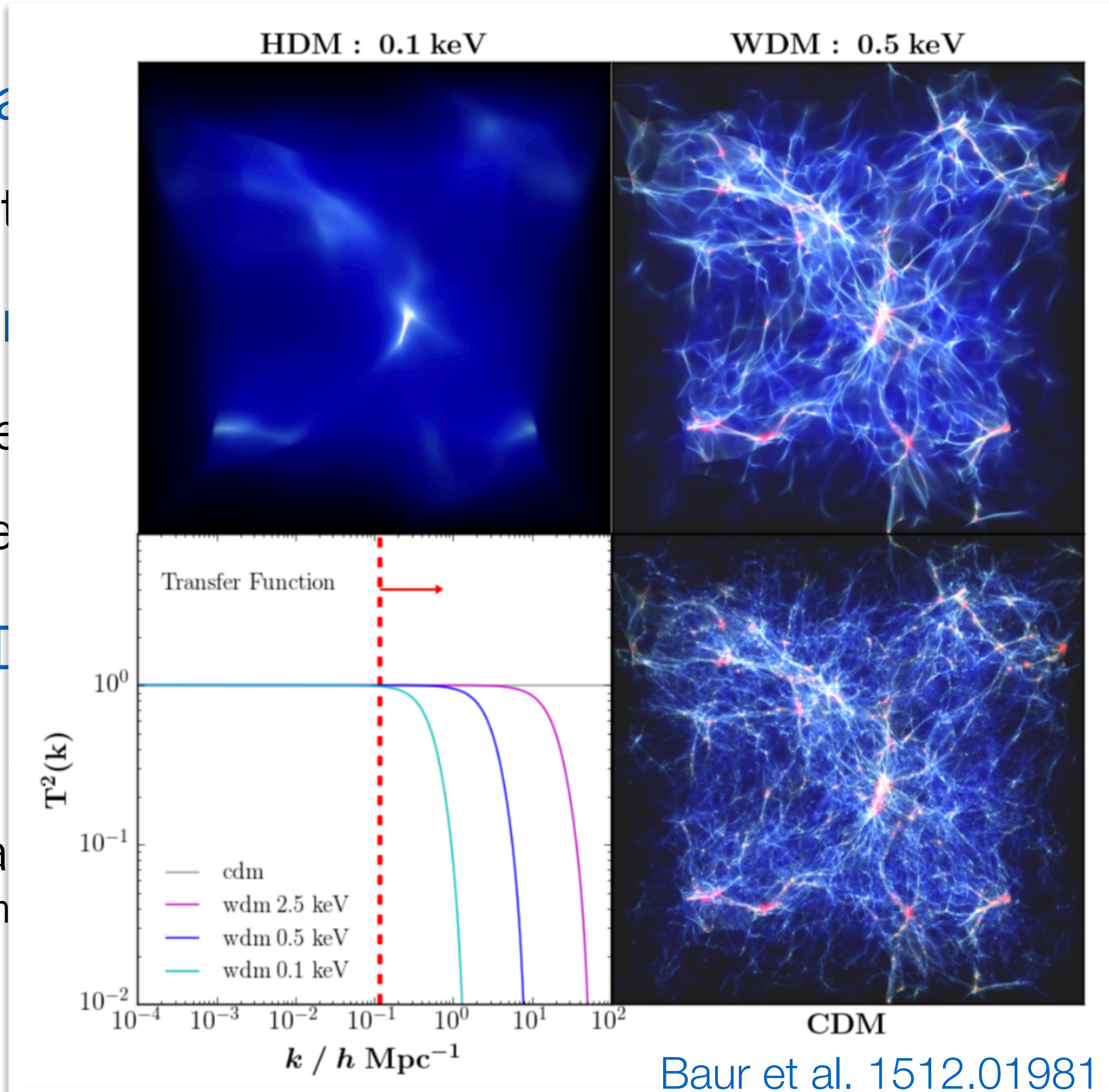
- Cold Dark Matter (≫ keV)
  - the standard scenario
- Hot Dark Matter (≪ keV)
  - carries energy over large distances
  - prevents collapse at scales ≪ Mpc



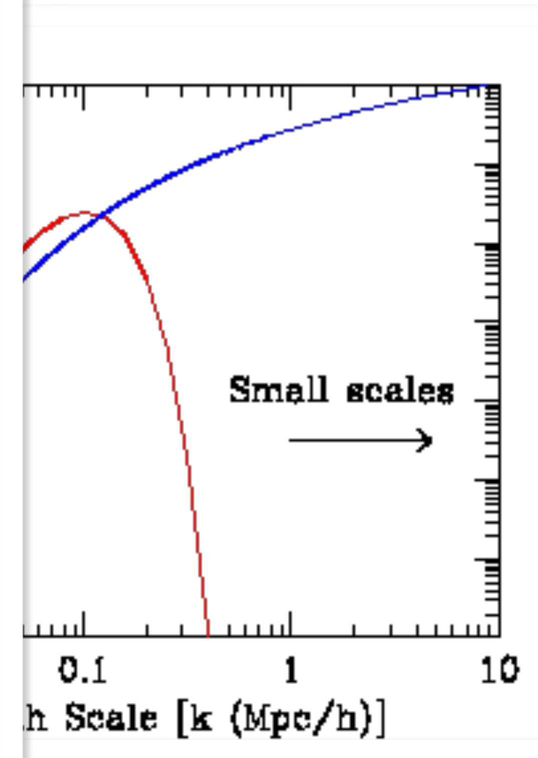
- Warm Dark Matter (~ keV)
  - mild suppression of structure on small scales
  - explain absence of DM “cusps” and other small-scale problems
    (whether or not these are indeed “problems” depends on whom you ask)

Motivation for the keV Scale

- ☑ Cold Da
  - the st
- ☑ Hot Dar
  - carrie
  - preve
- ☑ Warm D
  - mild
  - expla … le problems
    (wheth … ou ask)



Baur et al. 1512.01981



Sterile Neutrinos

- ☑ sterile neutrino = gauge singlet fermion
- ☑ generic extension of the SM
  - e.g. leftovers from extended gauge multiplets (Grand Unification?)
- ☑ Useful in phenomenology
  - neutrino masses via seesaw mechanism ($m \sim$ TeV … M_{Pl})
  - baryogenesis via leptogenesis ($m > 10^9$ GeV)
  - dark matter ($m \sim$ keV) ➠ this talk
  - neutrino oscillation anomalies ($m \sim$ eV)

Production via Neutrino Oscillations

- zero initial abundance of ν_s
- active neutrinos oscillate
  - are in coherent superposition of ν_a and ν_s:

$$\psi = \cos\theta\,|\nu_a\rangle + \sin\theta\,|\nu_s\rangle$$

- scattering interrupts coherent evolution
  - wave function collapses to either ν_a or ν_s
  - ν_s produced with probability $\frac{1}{2}\sin^2 2\theta$
  - after many scatterings: sizeable ν_s abundance

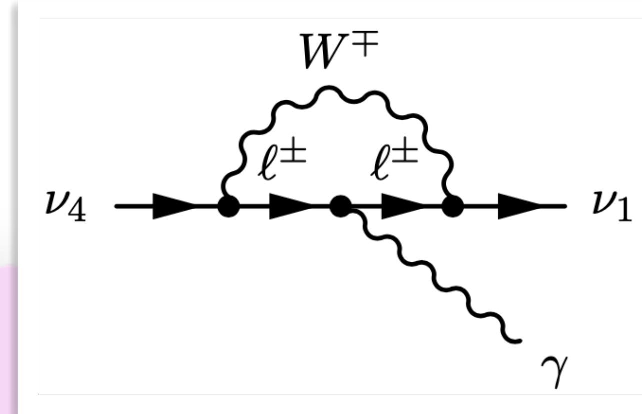
Variation: the Shi–Fuller Mechanism

- ☑ assume non-zero lepton–antilepton asymmetry
- ☑ oscillations resonantly enhanced (MSW effect)

Shi Fuller astro-ph/9810076

X-Ray Constraints on Sterile Neutrino DM

- x-ray lines from ν_s decay



$$\Gamma(\nu_s \to \nu_a \gamma) = \frac{9}{256\pi^4} \alpha_{\rm em} G_F^2 \sin^2\theta m_4^5$$

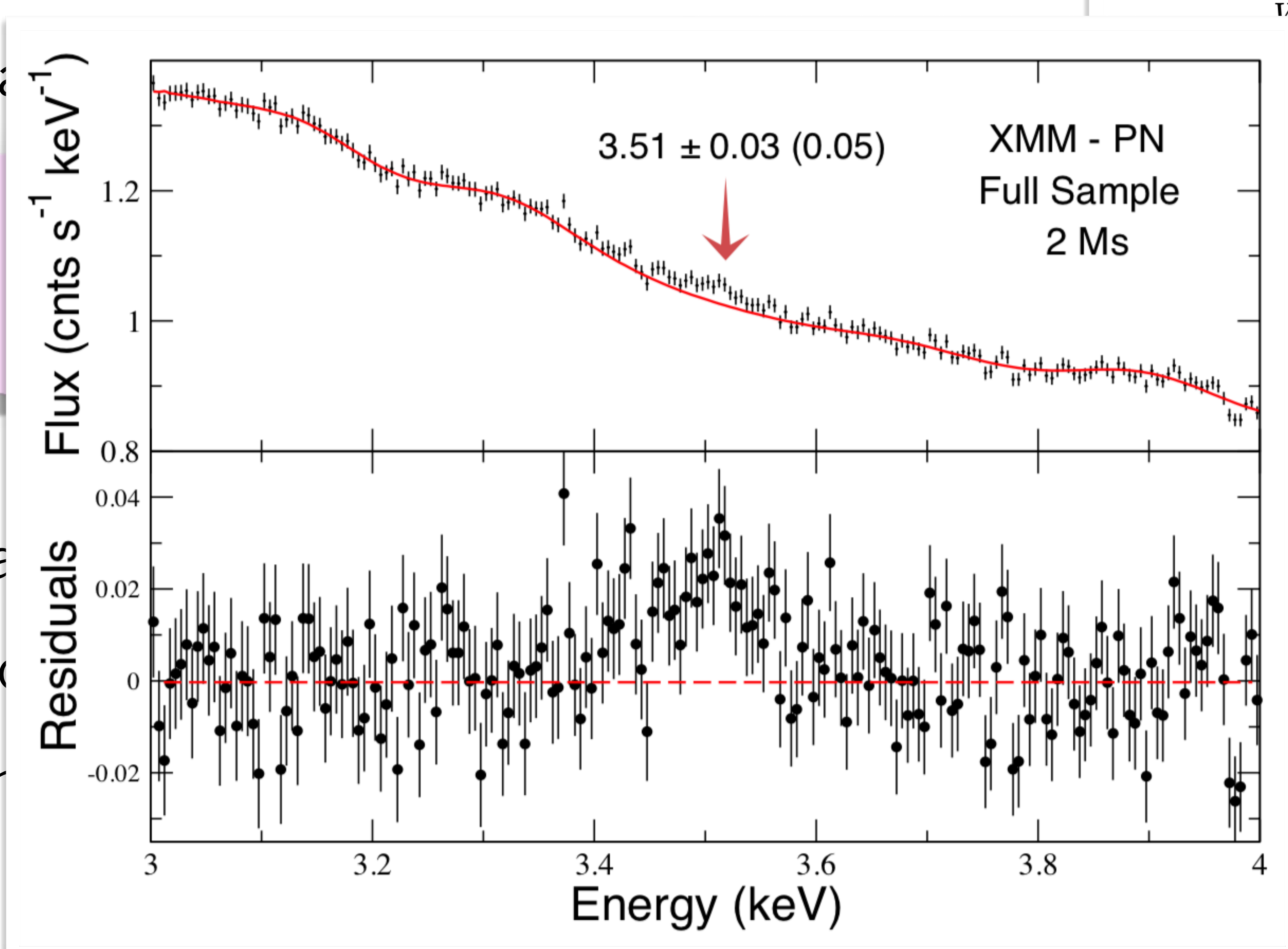
see e.g. Kusenko 0906.2968

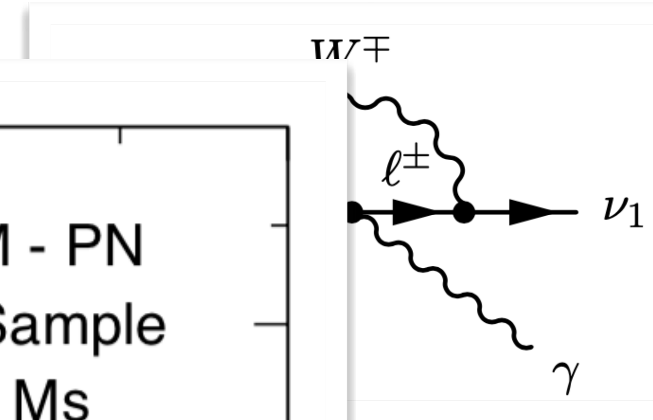
- searches in galaxies, clusters, diffuse x-ray background
- strong constraints
- controversial signal at 3.5 keV

Bulbul et al. 1402.2301, Boyarsky et al. 1402.4119

X-Ray Constraints on Sterile Neutrino DM

- ☑ x-ra





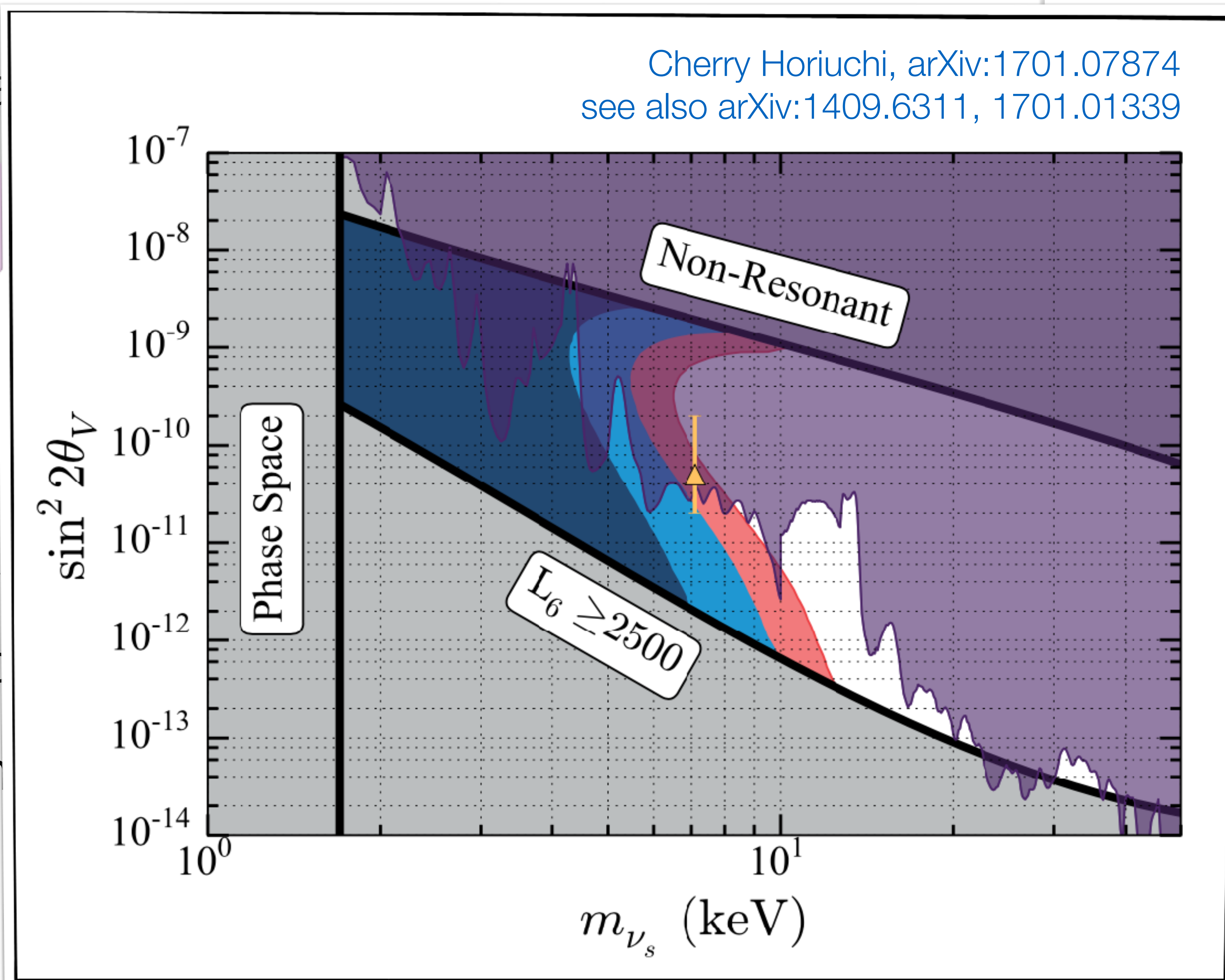
906.2968

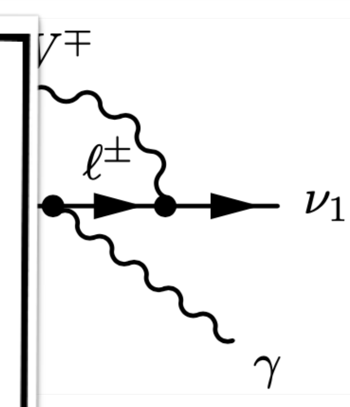
- ☑ sea nd
- ☑ stro
- ☑ con

402.4119

X-Ray Constraints on Sterile Neutrino DM

- x-ra





0906.2968

- sea ... ınd
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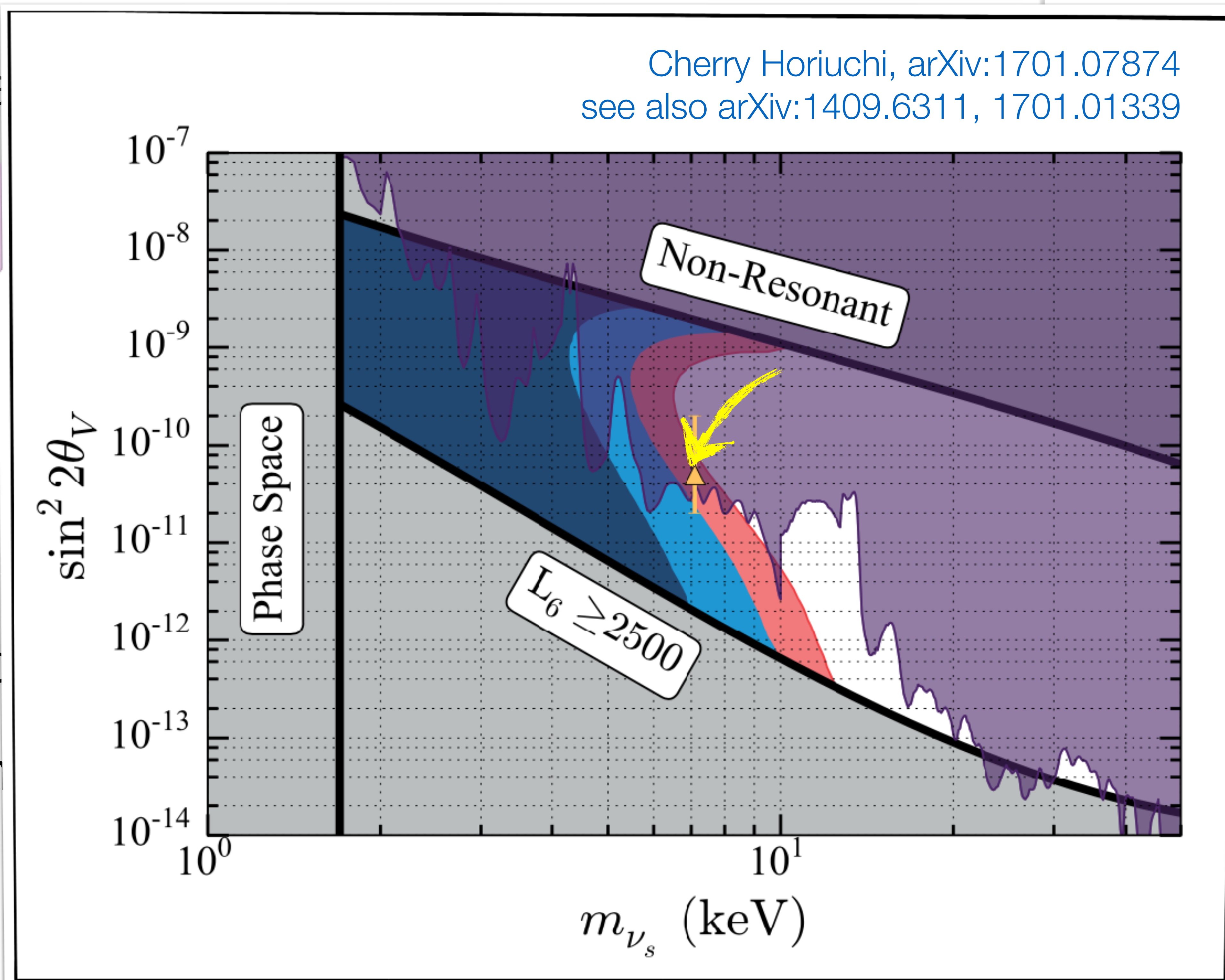
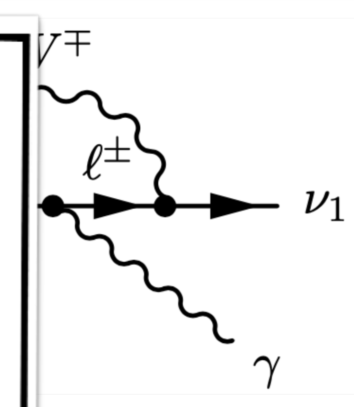
X-Ray Constraints on Sterile Neutrino DM

- ☑ x-ra





0906.2968

- ☑ sea ... und
- ☑ strc
- ☑ con

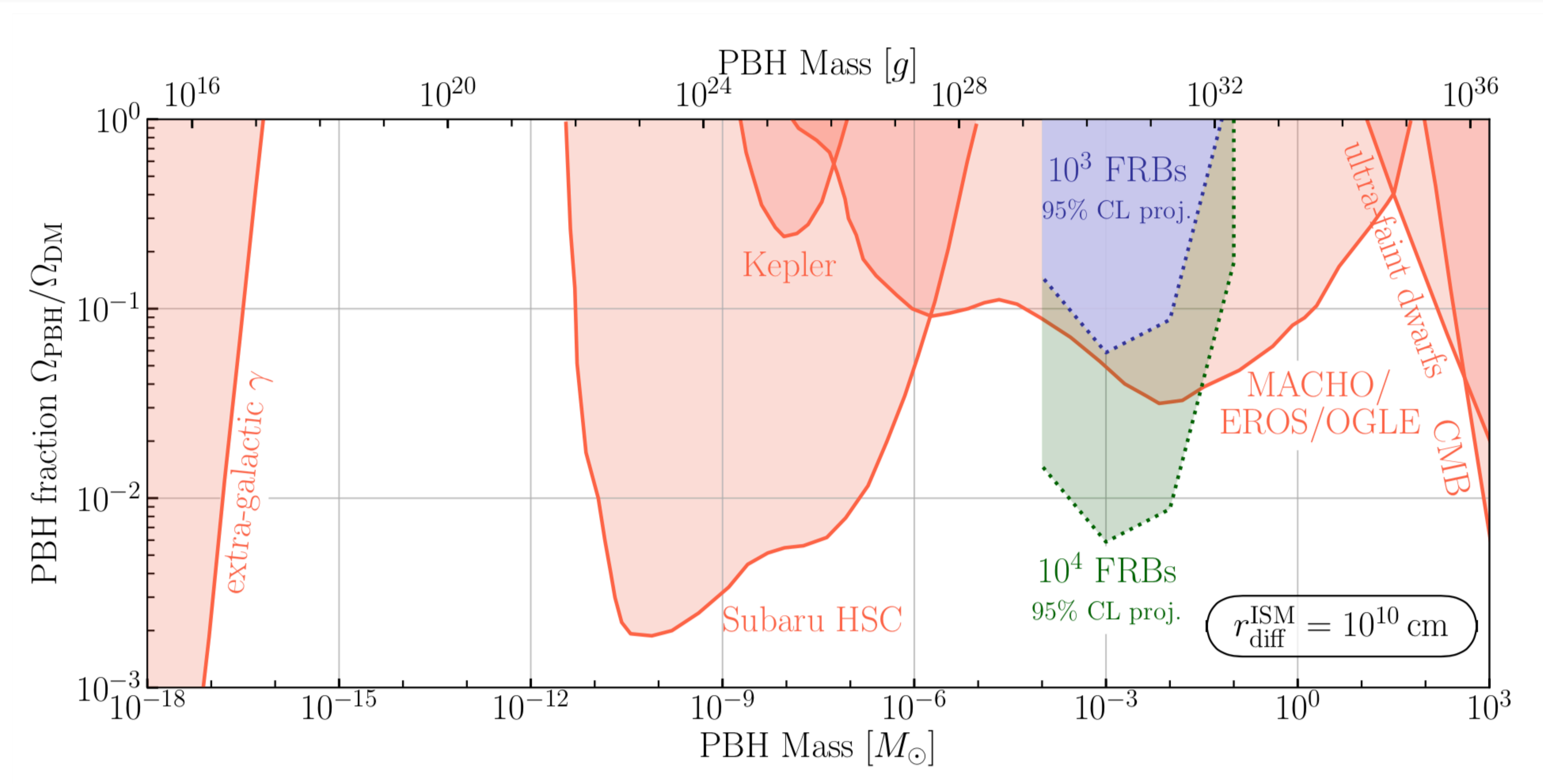
402.4119

Primordial Black Holes

Basic Idea

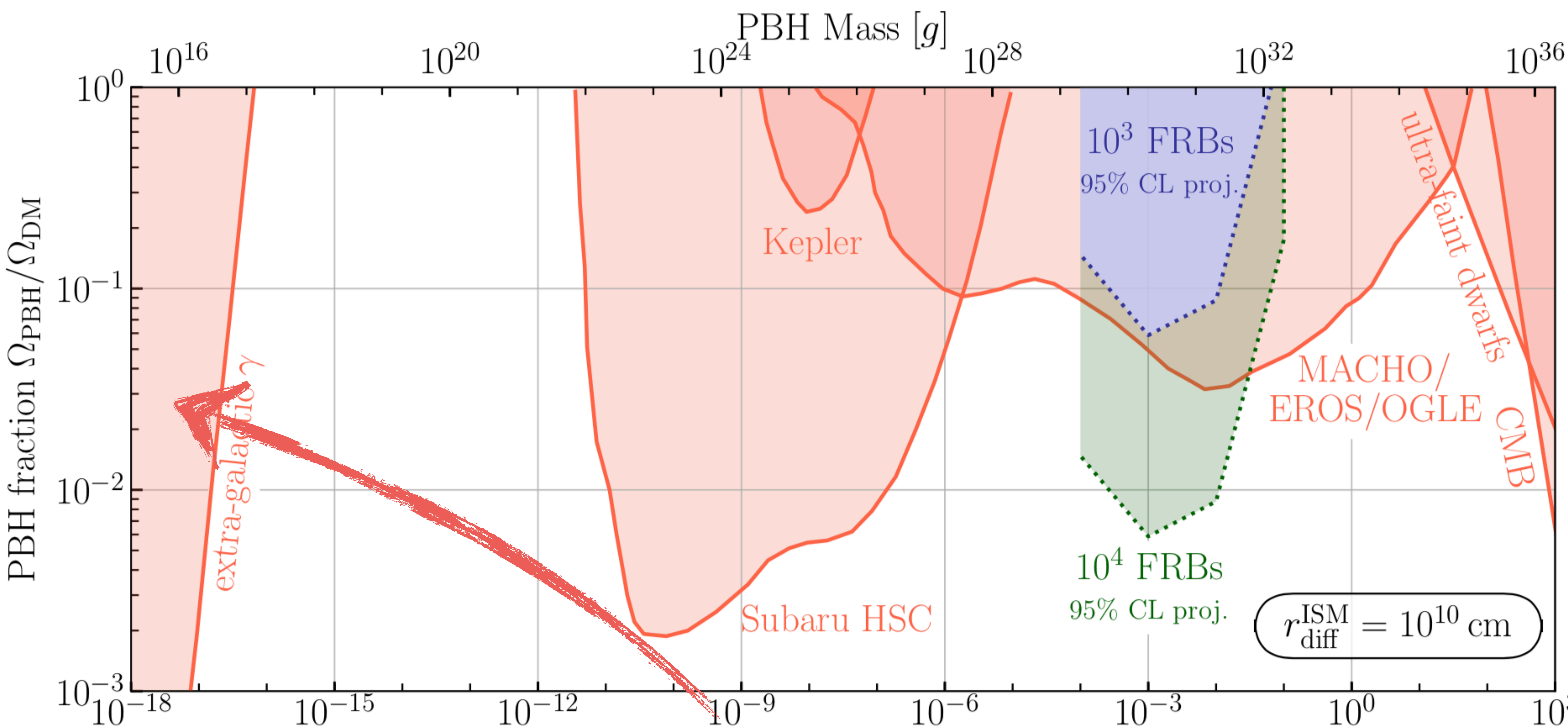
- ☑ Upward fluctuations of the plasma density in the early Universe may gravitationally collapse into black holes.
- ☑ Criterion:
  "collapse should happen faster than rebound"
  - requires $\mathcal{O}(1)$ overdensity

PBH Parameter Space



Greene Kavanagh 2007.10722
Katz JK Sibiryakov Xue 1807.11495

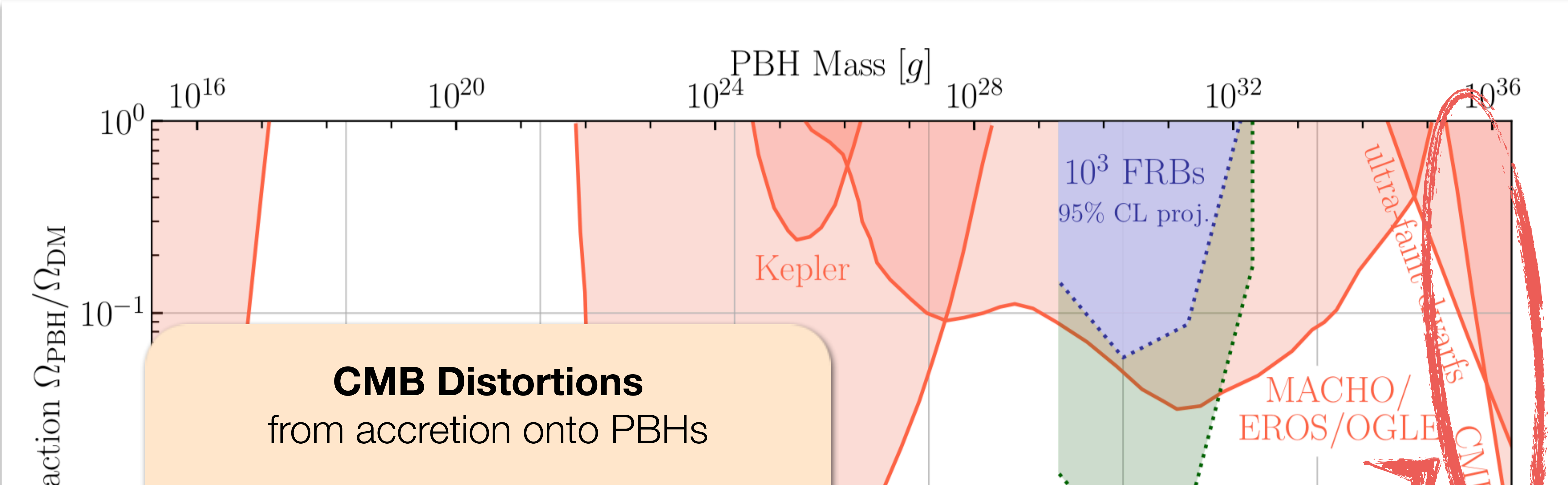
PBH Parameter Space



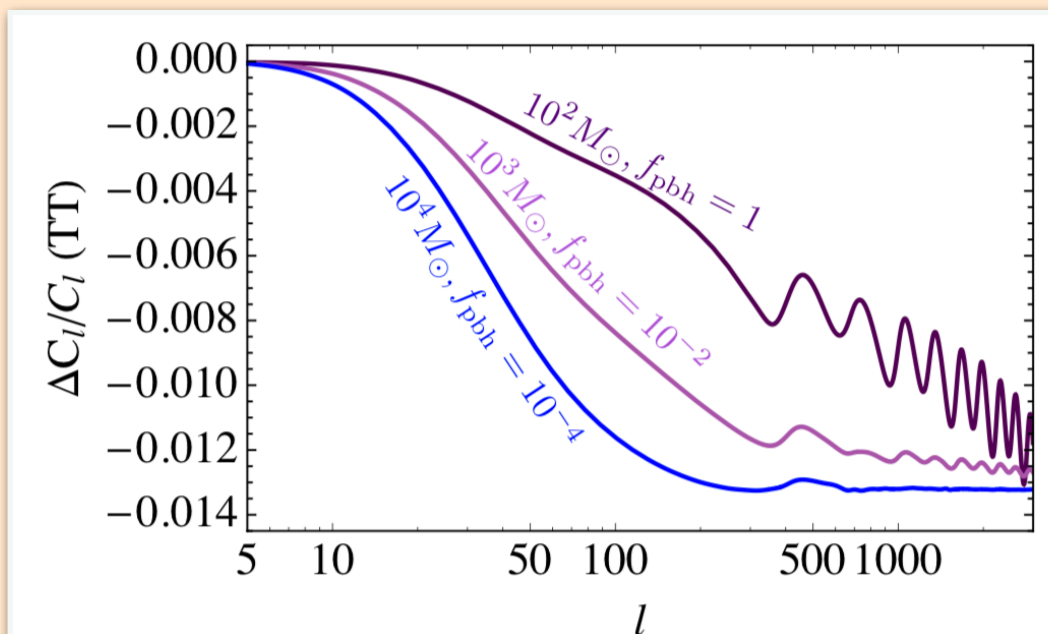
Greene Kavanagh 2007.1072
Katz JK Sibiryakov Xue 1807

Extragalactic background light constraint on Hawking radiation from PBH evaporation

PBH Parameter Space

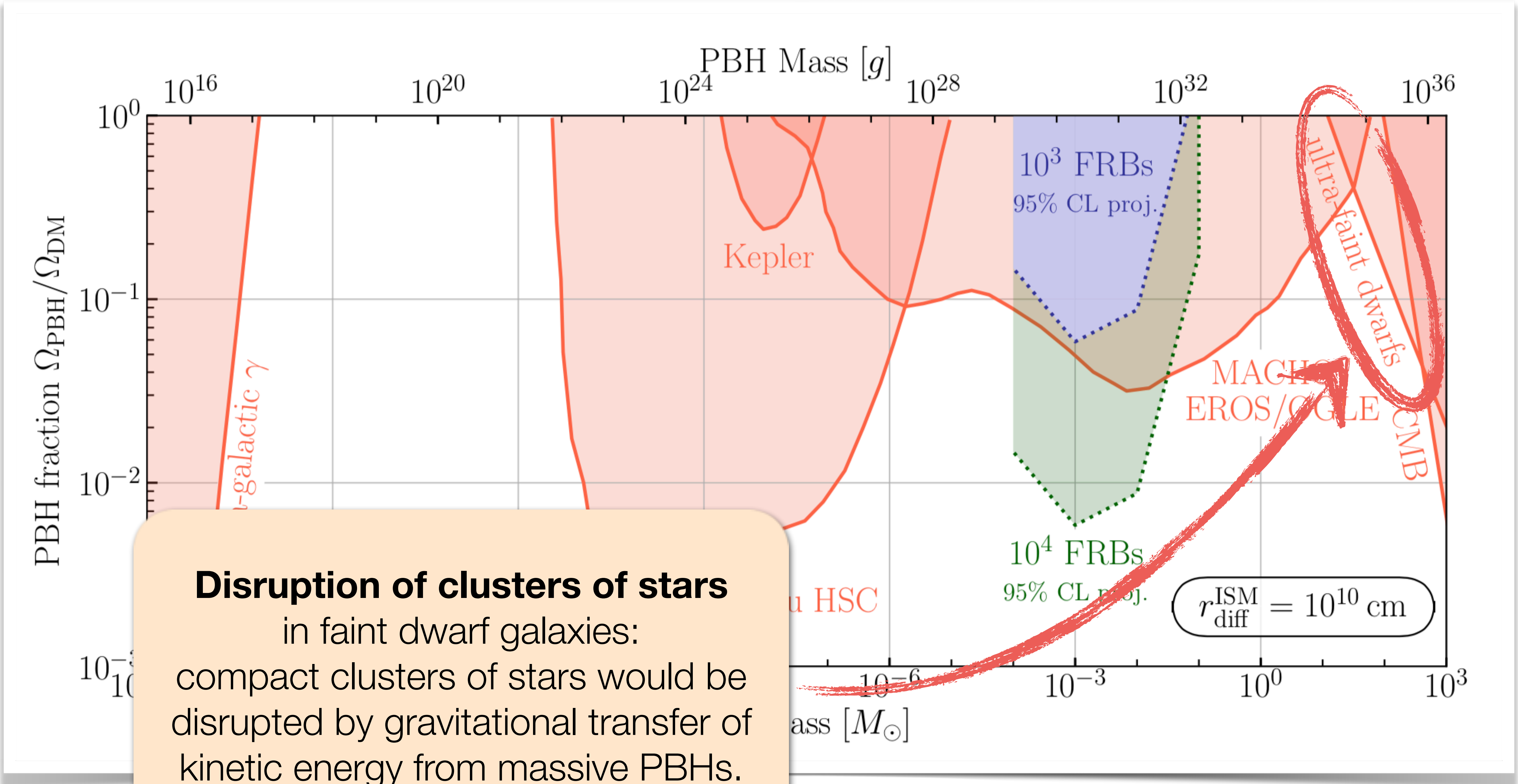


CMB Distortions
from accretion onto PBHs



Greene
Katz JK

PBH Parameter Space



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.

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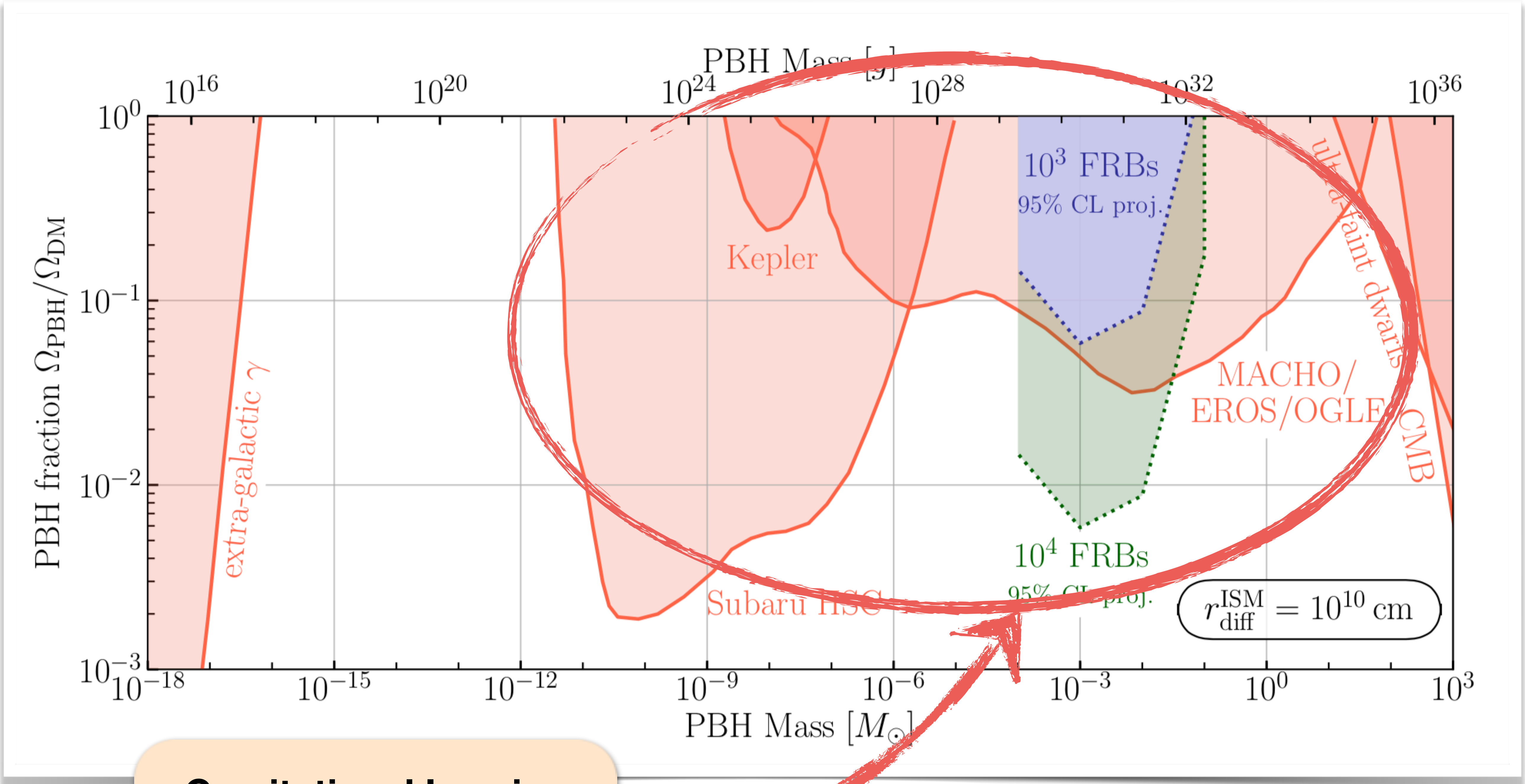
Katz JK Sibiryakov Xue 1807.11495

PBH Parameter Space



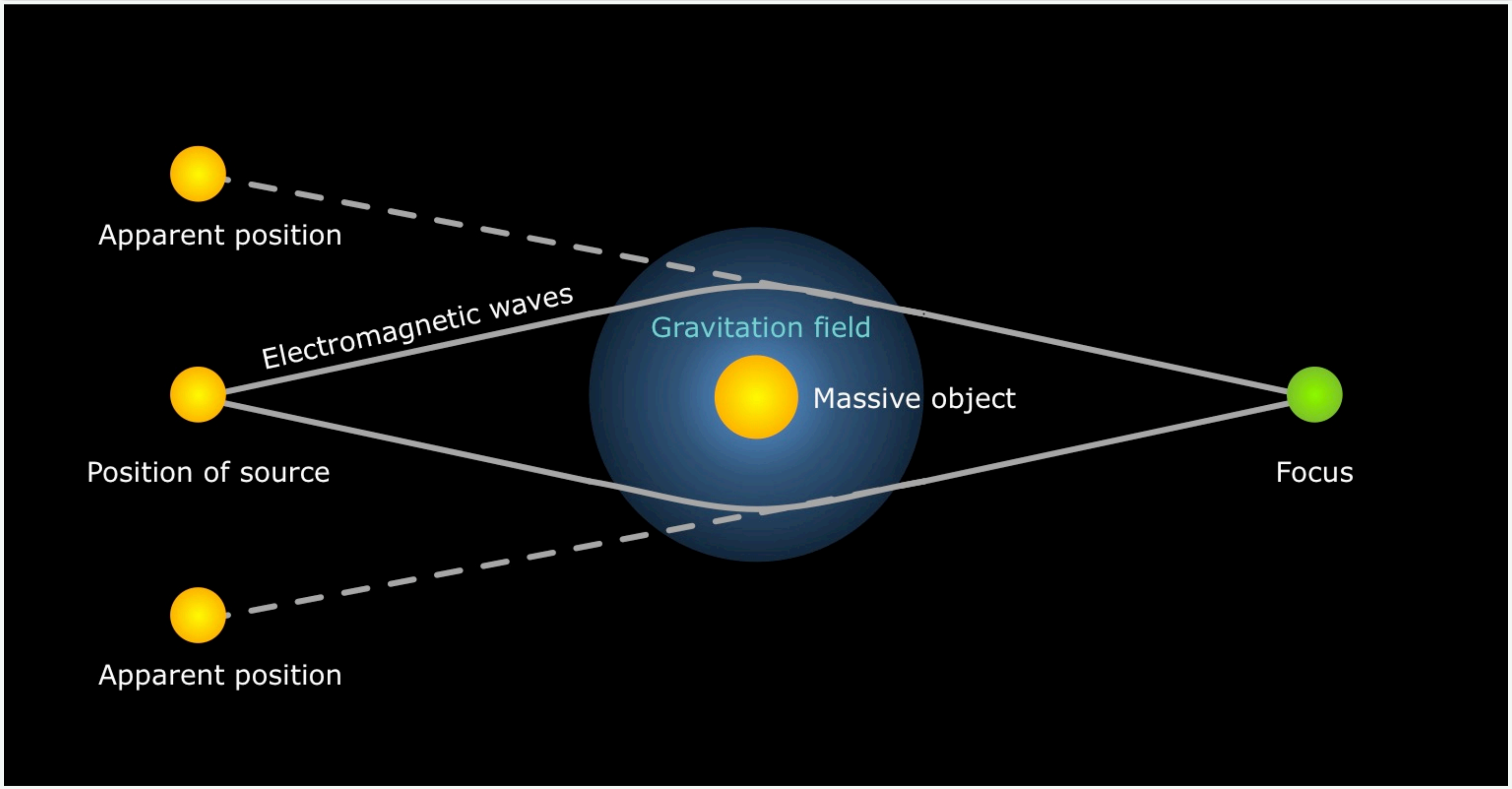
Gravitational Lensing

Greene …
Katz JK Sibiryakov Xue 1807.11495

www.spacetelescope.org

www.spacetelescope.org

Gravitational Lensing



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
- 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.

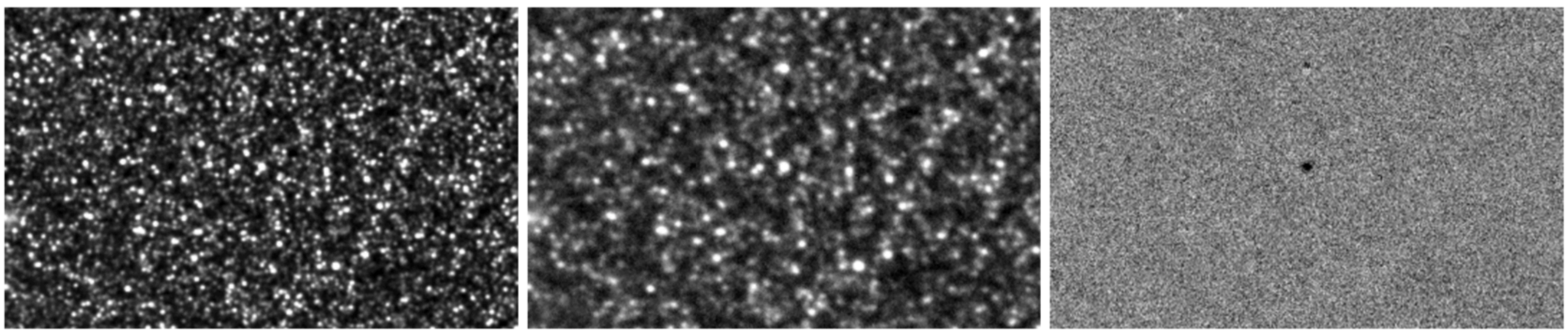
Microlensing

☑ Observations at the 8.2 m Subaru Telescope (Hawaii)

Niikura et al. arXiv:1701.02151

Microlensing

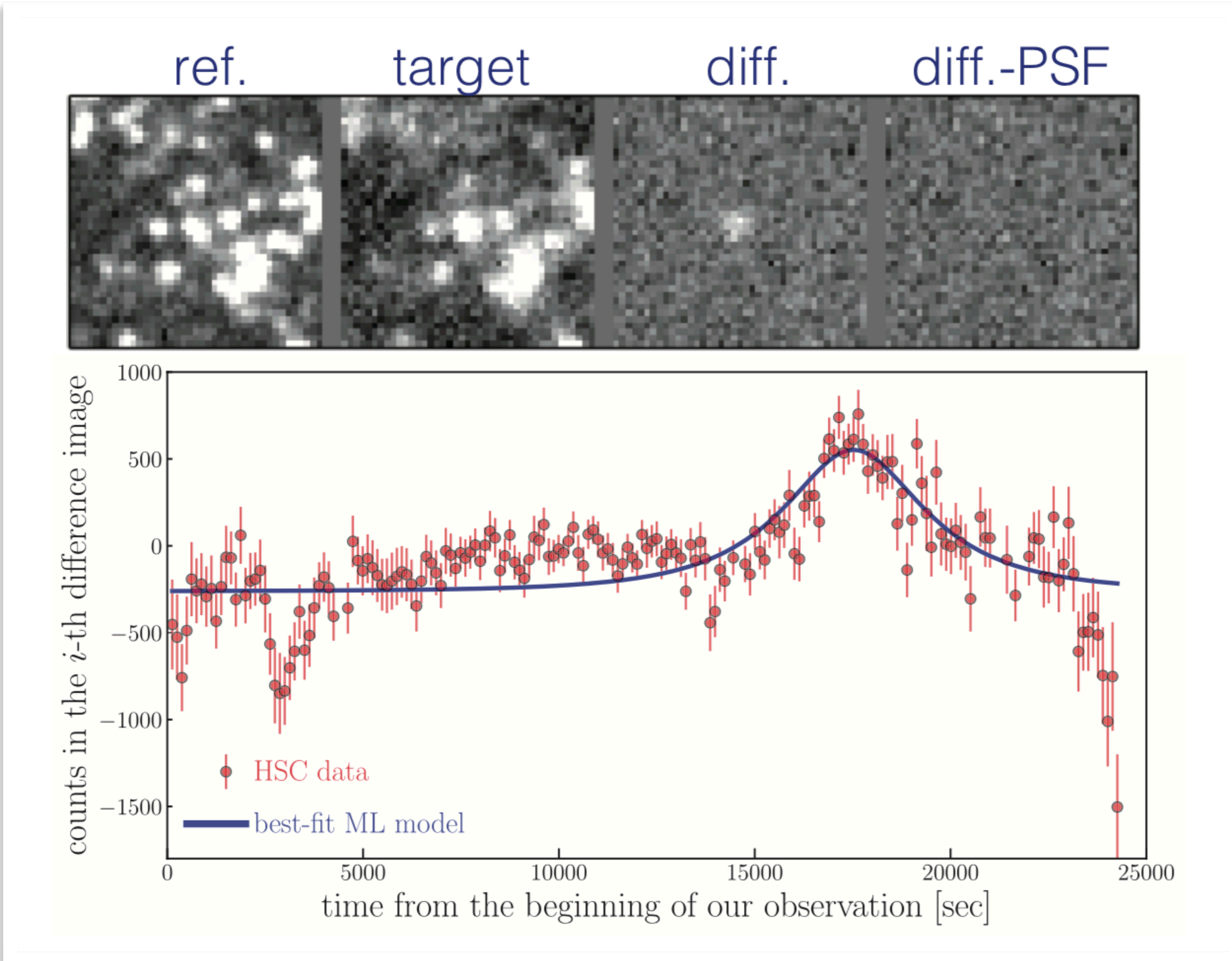
- ☑ Single night (7 hours of observations) sufficient
- ☑ Repeated observations of the same patch on the sky (90 sec observation time, 35 sec readout time)
- ☑ Subtract reference image to detect transients



Observation #1 | Observation #2 | Difference (including transient)

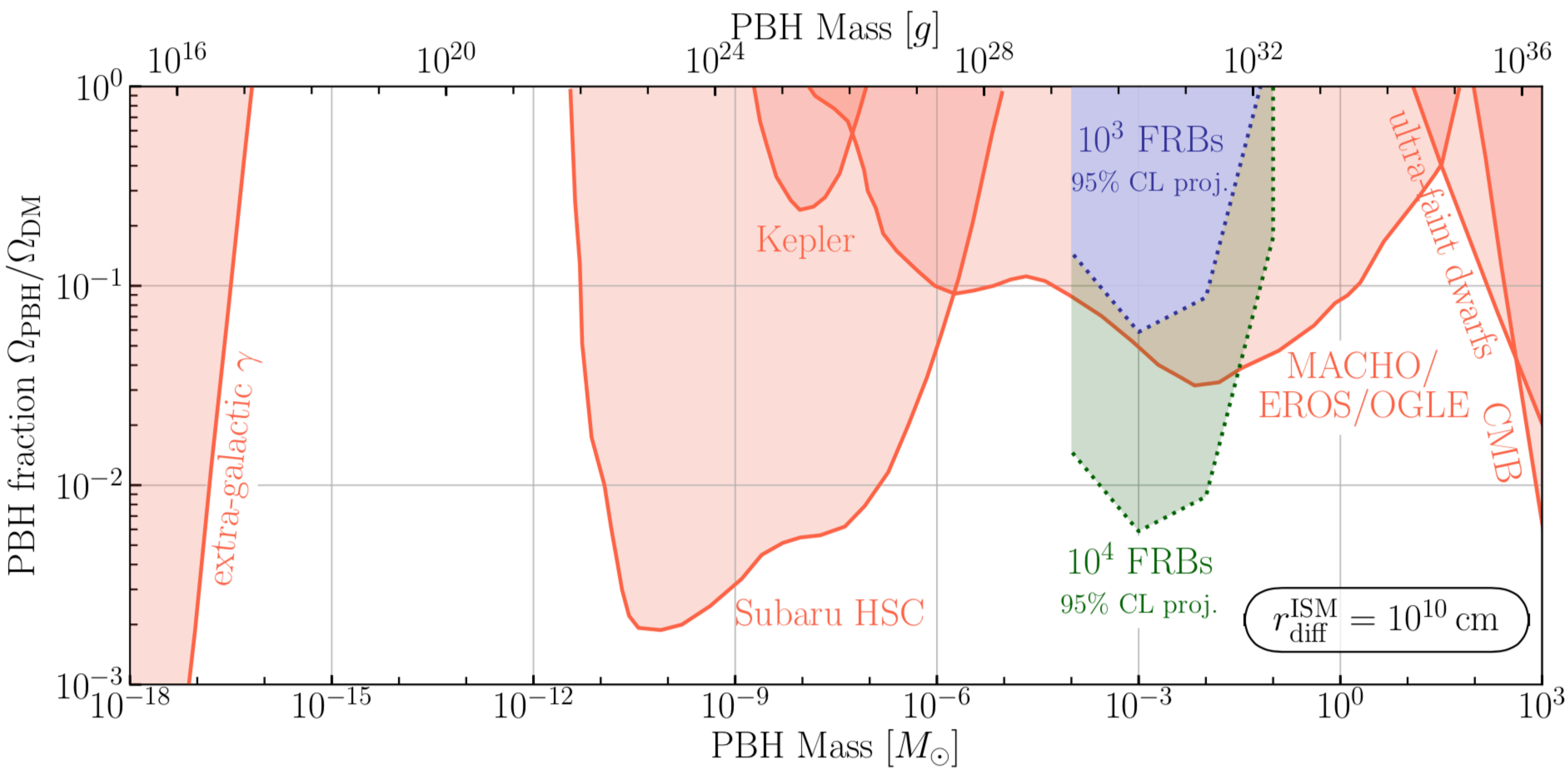
Niikura et al. arXiv:1701.02151

Microlensing



Niikura et al. arXiv:1701.02151

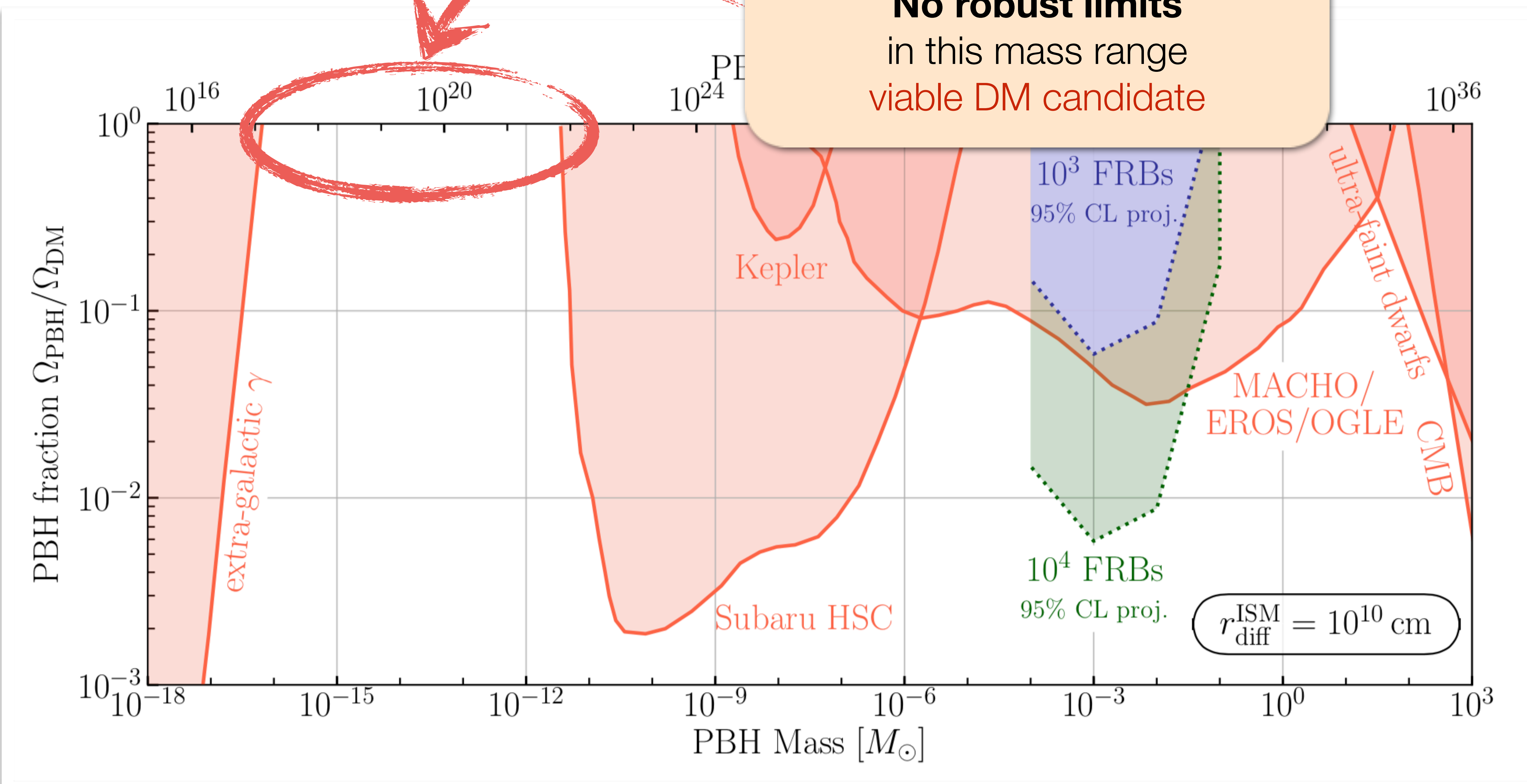
PBH Parameter Space



Greene Kavanagh 2007.10722
Katz JK Sibiryakov Xue 1807.11495

PBH Parameter Space

No robust limits
in this mass range
viable DM candidate



Greene Kavanagh 2007.10722
Katz JK Sibiryakov Xue 1807.11495

Summary

Summary

- WIMPs
  - still the “standard lore”, but not discovery yet
- Sterile Neutrinos
  - Interesting for small scale structure
  - Production via oscillations under pressure
- Primordial Black Holes
  - possibly viable at masses $\sim 10^{-17}$ and $\sim 10^{-12}$ solar masses
  - interesting production and detection mechanisms