21cm probes on dark matter beyond WIMP (weakly interacting massive particles)

Kenji Kadota (HIAS-UCAS, ICTP-AP)

Hangzhou Institute for Advance Study @ Univ. of Chinese Academy of Sciences (HIAS-UCAS)
International Center for Theoretical Physics Asia-Pacific (ICTP-AP Hangzhou (杭州) branch)

Based on the works:

(1) K. Murakami(Nagoya Univ), **KK**, A. Nishizawa (Gifu Univ.), K. Nagamine(Osaka Univ), I. Shimizu (Fukui)

Differentiating Warm Dark Matter Models through 21cm Line Intensity Mapping: A Convolutional Neural Network approach (2024)

(2) C. Sabiu(Seoul U.), **KK**, J. Asorey(Madrid Univ), Inkyu Park(Seoul Univ) (2022)

Probing ultra-light axion dark matter from 21 cm tomography using Convolutional Neural Networks

(3) **KK** and Shota Kisaka (Hiroshima Univ) (2024)

SKA Sensitivity to Sub-GeV Dark Matter Decay: Synchrotron Radio Emissions in White Dwarf Magnetospheres

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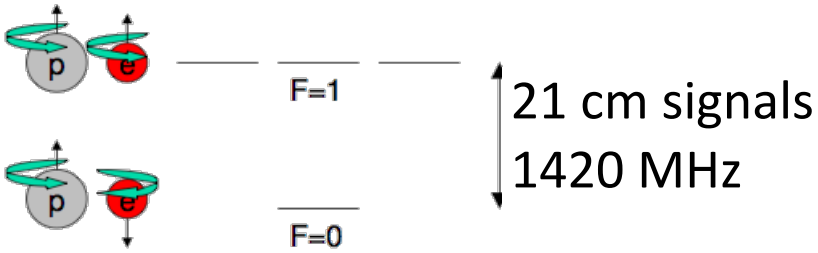
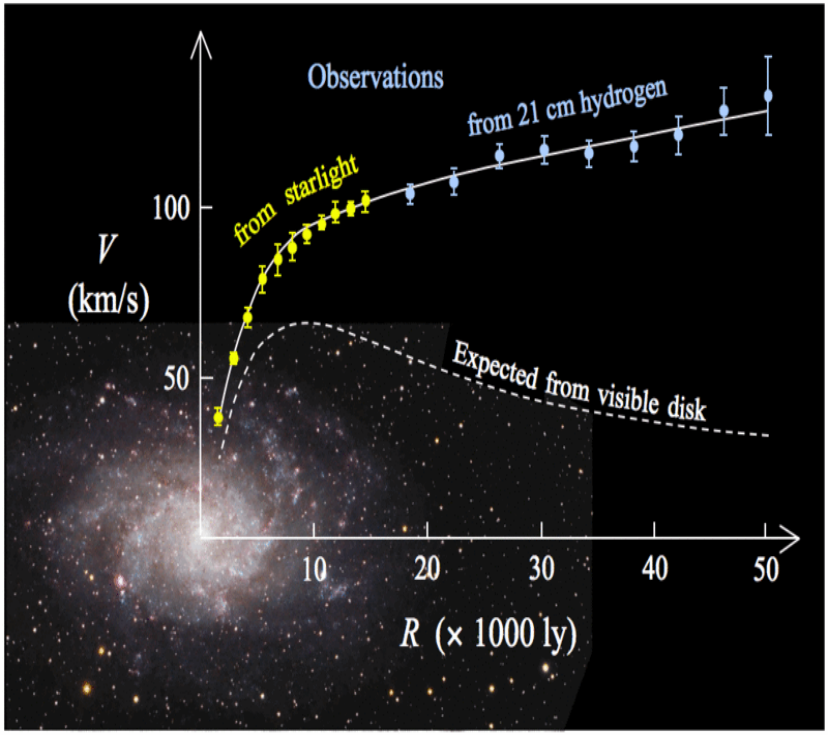
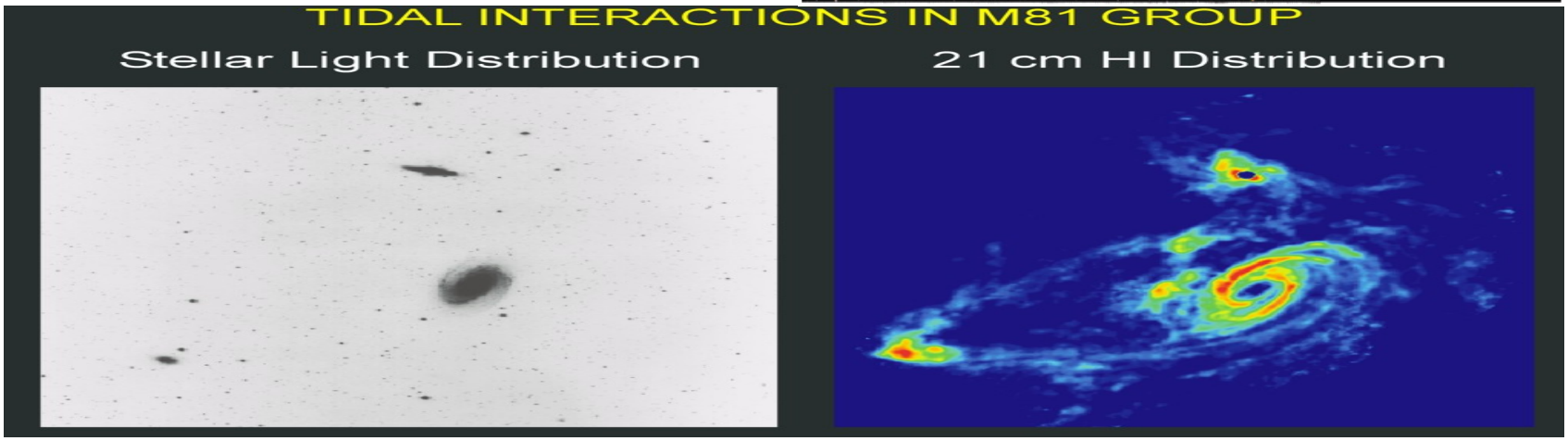
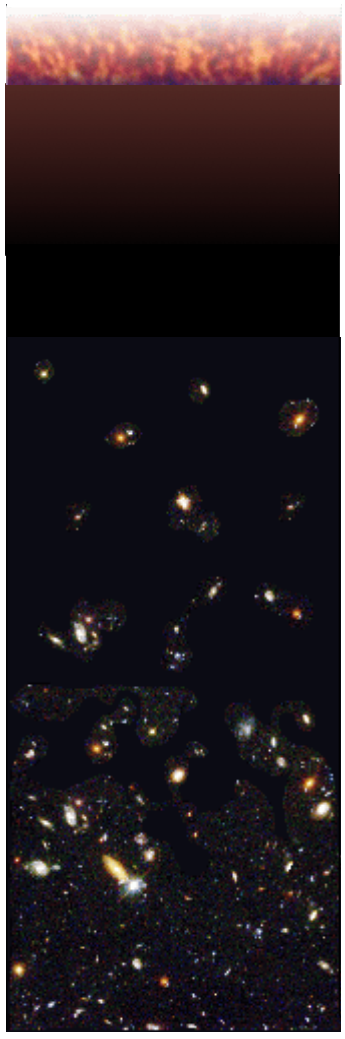

p
e
F=1
p
e
F=0
21 cm signals
1420 MHz


Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)


TIDAL INTERACTIONS IN M81 GROUP
Stellar Light Distribution
21 cm HI Distribution

Brief History of Universe

Years since the Big Bang



~300000 (z~1000)

← Big Bang: the Universe is filled with ionized gas

← Recombination: The gas cools and becomes neutral

Dark Ages

~100 million (z~20-40)

← The first structures begin to form.

Cosmic Dawn

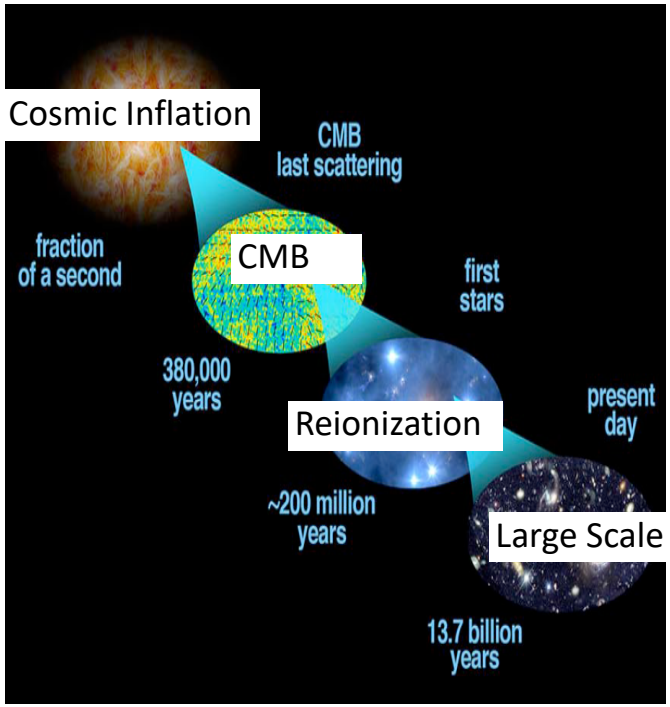
Reionization starts (z ~12)

Reionization

← Reionization is complete

~1 billion (z~6)

← Today's structures



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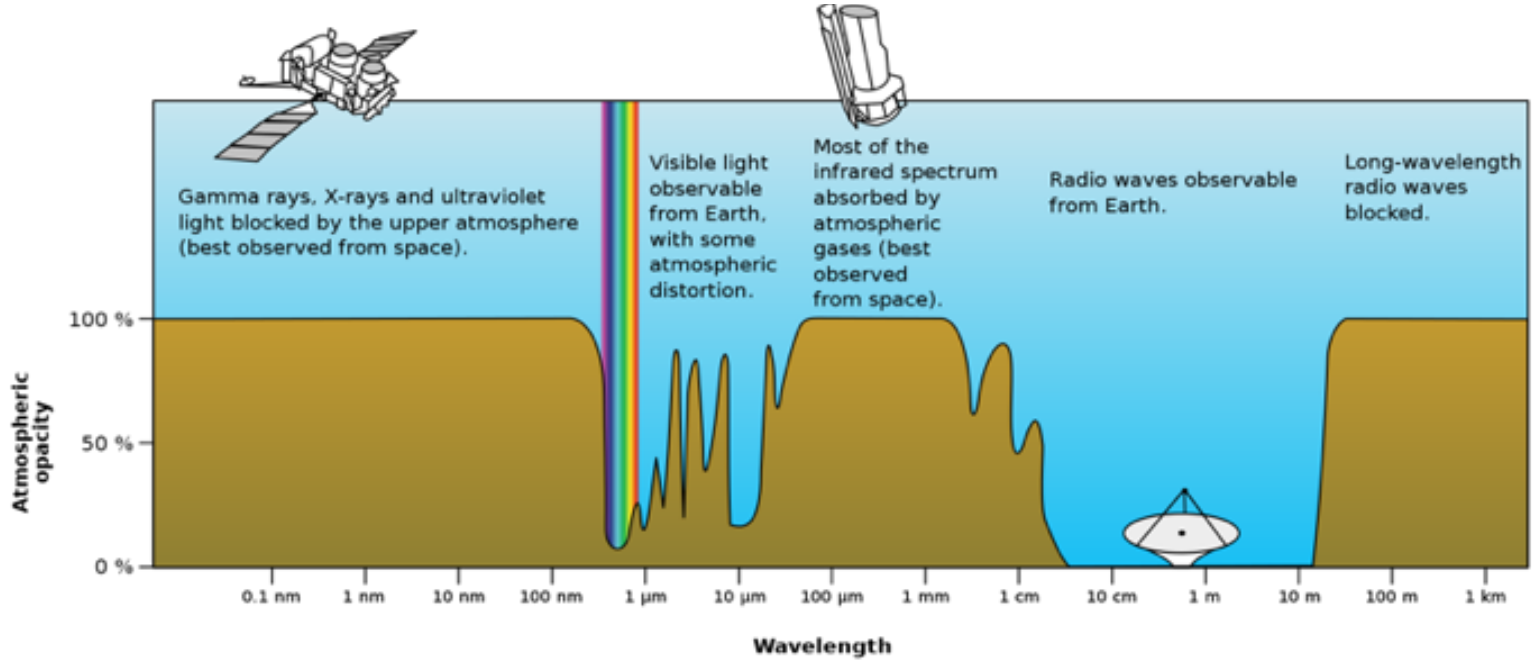

Construction started in 2021

Australia: SKA low: 50-350 MHz

S. Africa: SKA mid: 350 MHz-14GHz

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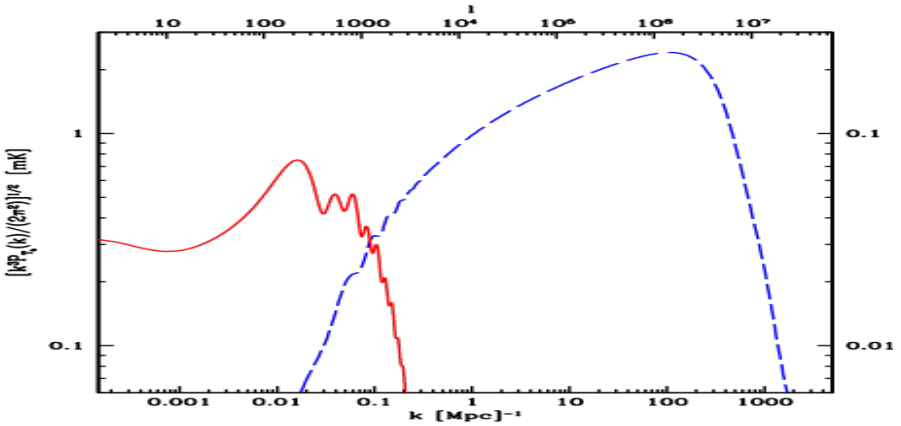
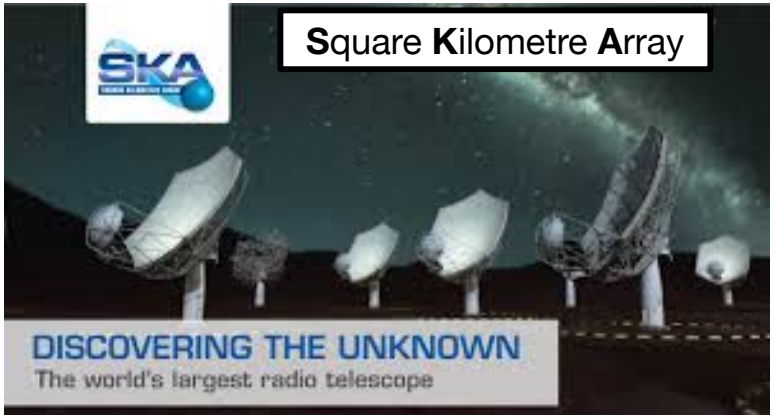
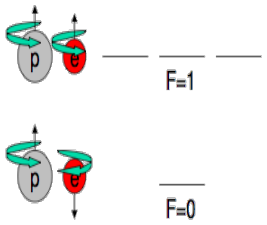
The next cosmic frontier: 21cm

What can we do with 21cm?

High precision on small-scale $\Delta P/P \sim 1/\sqrt{N}$

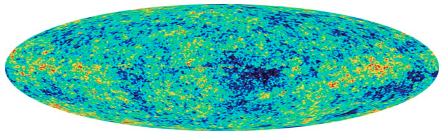




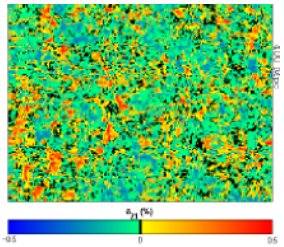


21 cm signals
1420 MHz

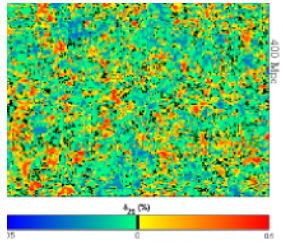
z=1100



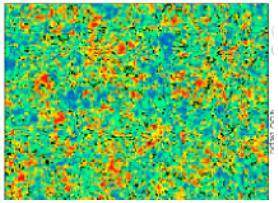
z=30



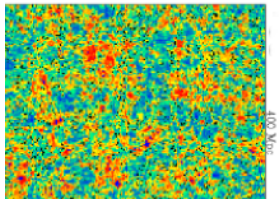
z=25



z=20



z=15



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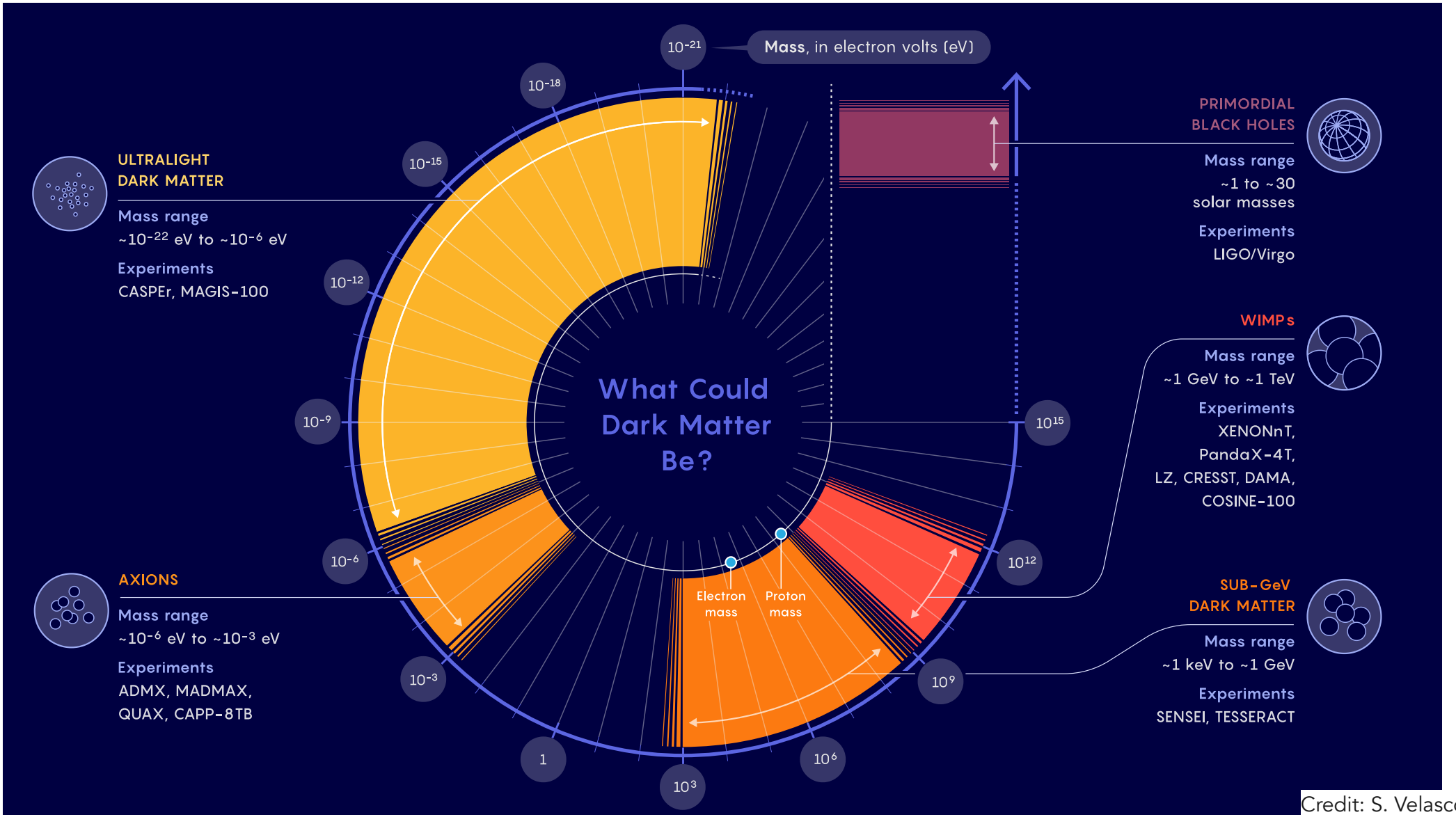
Let us be open-minded about dark matter (DM) mass



Credit: S. Velasco

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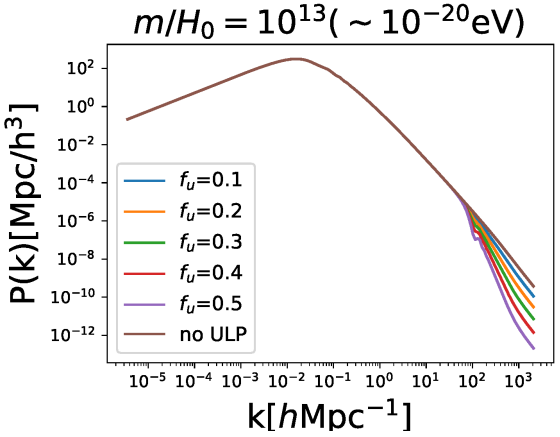
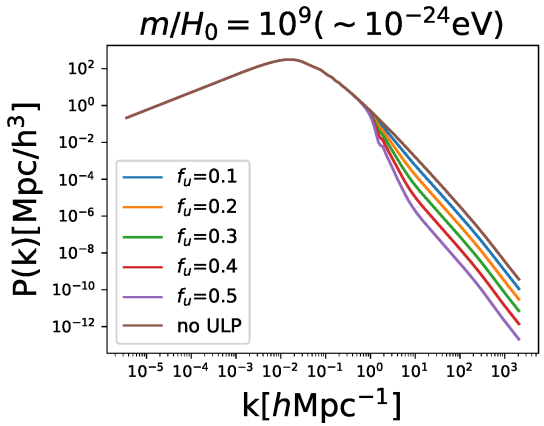
$$\lambda = \frac{2\pi}{mv} \sim 0.5kpc \left(\frac{10^{-22}eV}{m}\right)\left(\frac{250km/s}{v}\right)$$

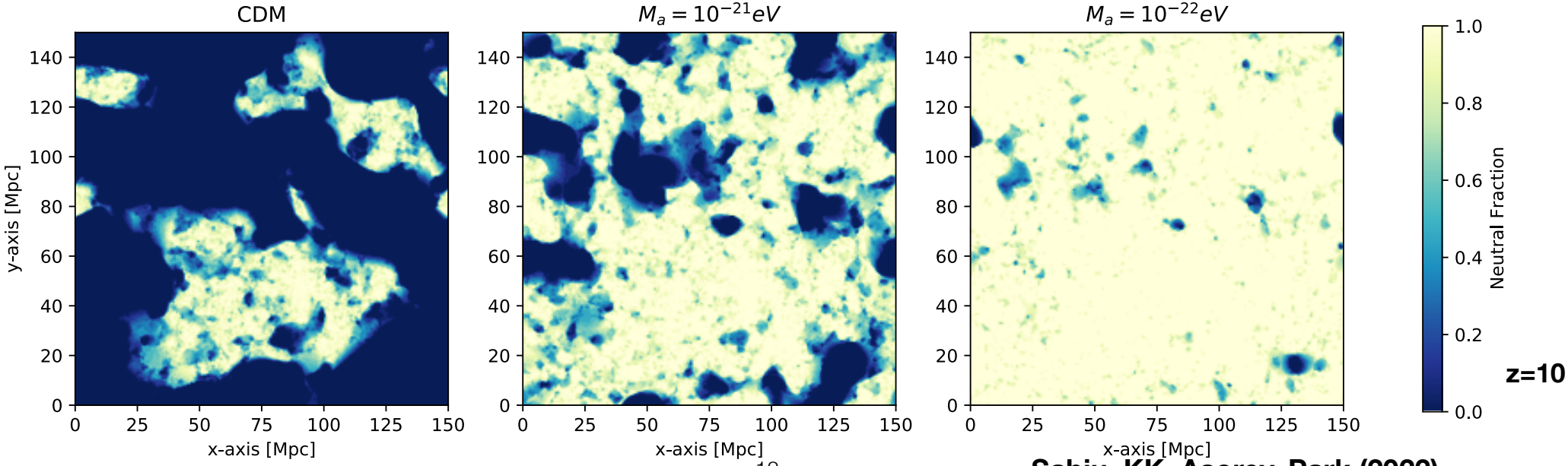
'Probing Ultra-light Dark Matter from 21cm Tomography using Convolutional Neural Networks', Sabiu, KK, Asorey, Park (2022)





$$m_{ALP} > 10^{-20}eV$$

$$\left(\begin{array}{c} Ly-\alpha : m_{ALP} > 10^{-21}eV \\ CMB : m_{ALP} > 10^{-24}eV \end{array} \right)$$



Sabiu, KK, Asorey, Park (2022)

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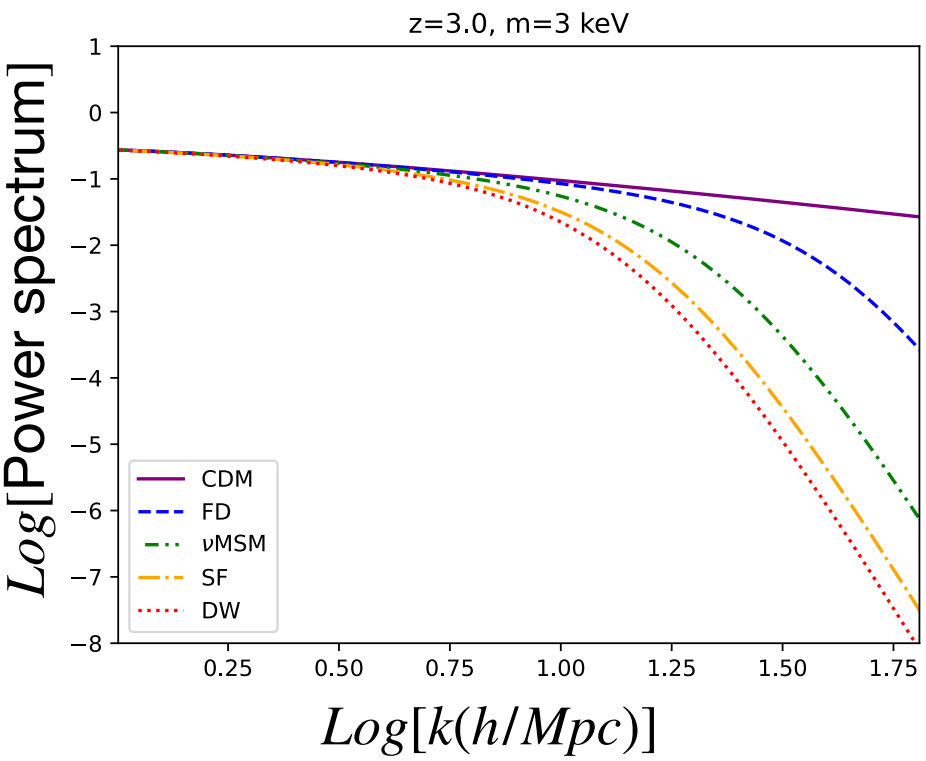
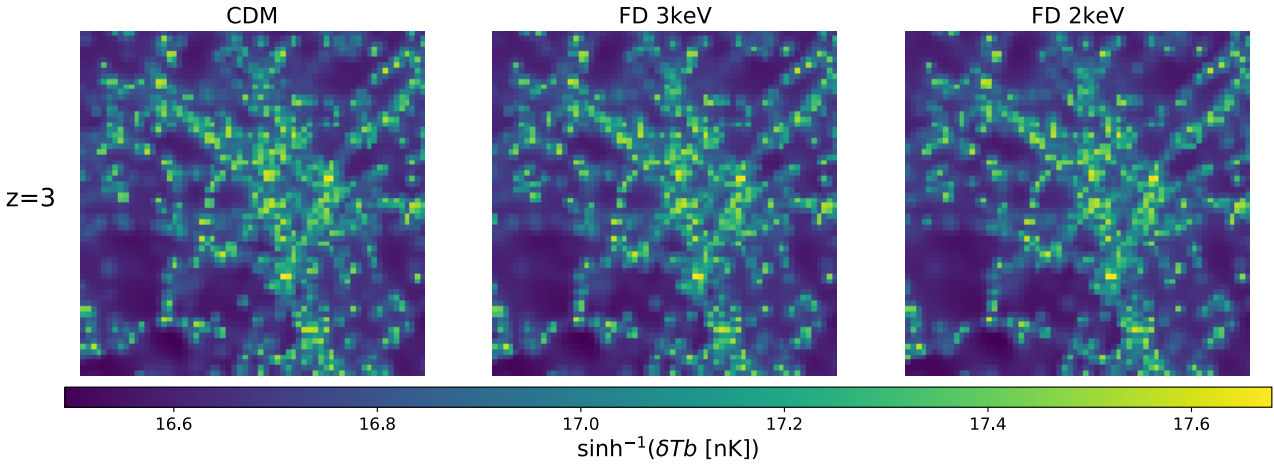
“ **Differentiating Warm Dark Matter Models** through 21cm Line Intensity Mapping: A Convolutional Neural Network Approach”

(Murakami, **KK**, Nishizawa, Nagamine, Shimizu (2024))

Same dark matter mass with different production mechanisms





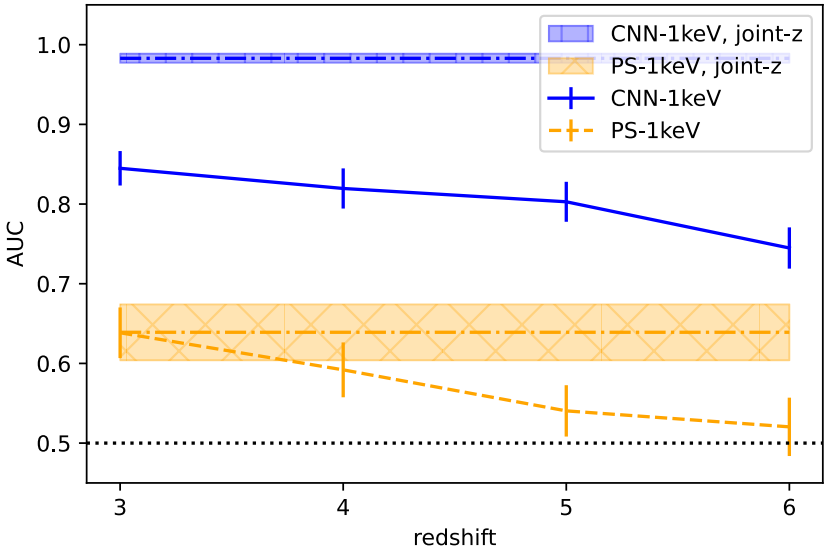
$$m_{DW} \sim 2.85keV \left(\frac{m_{FD}}{keV}\right)^{4/3}$$

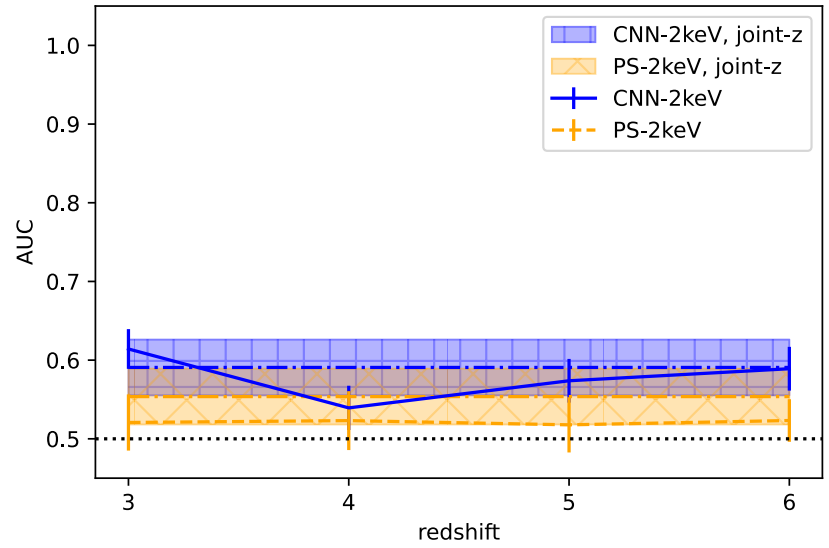
$$m_{\nu MSM} \sim 1.9 m_{FD}$$

$$m_{SF} \sim 2.55 m_{FD}$$

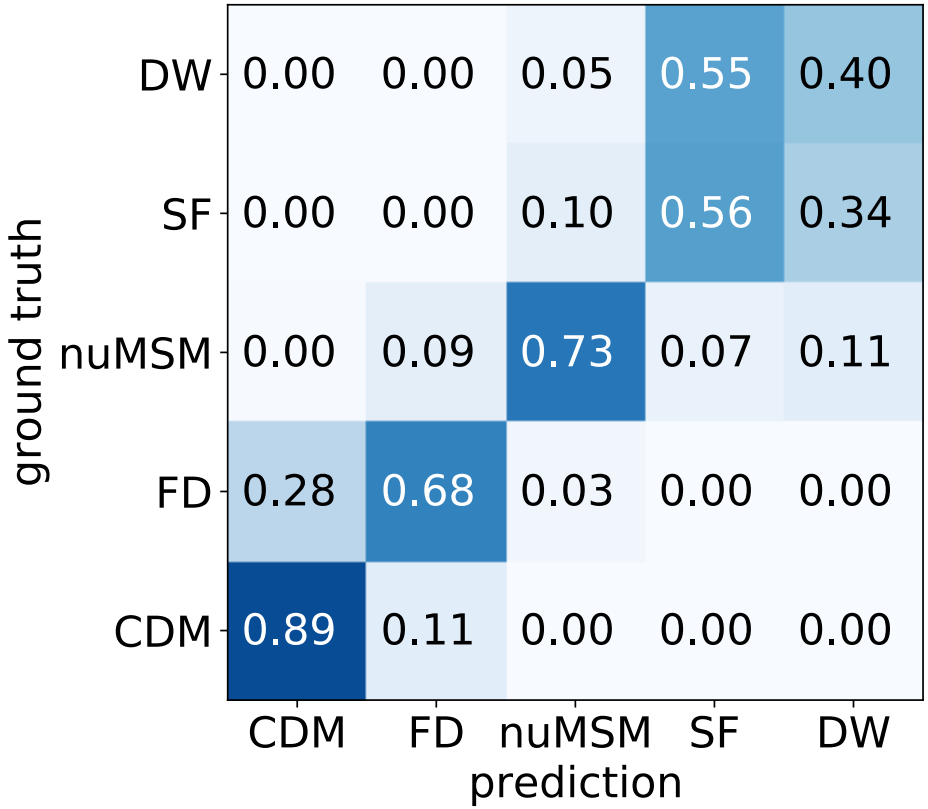
Murakami, **KK**, Nishizawa, Nagamine, Shimizu (2024)

Classification Performance Ability





Performance of Classification



DW and SF indistinguishable for $m = 2keV$

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White dwarf-Black hole system: Multi-messenger sources

White dwarf: 0.1 Msun, 10**4 km, B up to 10**9 G
Neutron Star: Msun, 10km, B up to 10**15 G

WD less compact than NS

EMN singles from tidal disruption, GW early warning of tidal disruption, accretion

WD more abundant than NS

Estimated compact binaries in the Milky Way Galaxy

Source	N	$N^{\rm detected}$
WD+WD	$\sim 10^8$	6,000−10,000
NS+WD	$\sim 10^7$	100−300
BH+WD	$\sim 10^6$	0−3
NS+NS	$\sim 10^5$	2−100
BH+NS	$\sim 10^4 - 10^5$	0−20
BH+BH	$\sim 10^6$	0−70

archive: 2203.06016

New thing in our scenario:

Radio signals, without tidal disruption, from DM decay products and WD magnetosphere

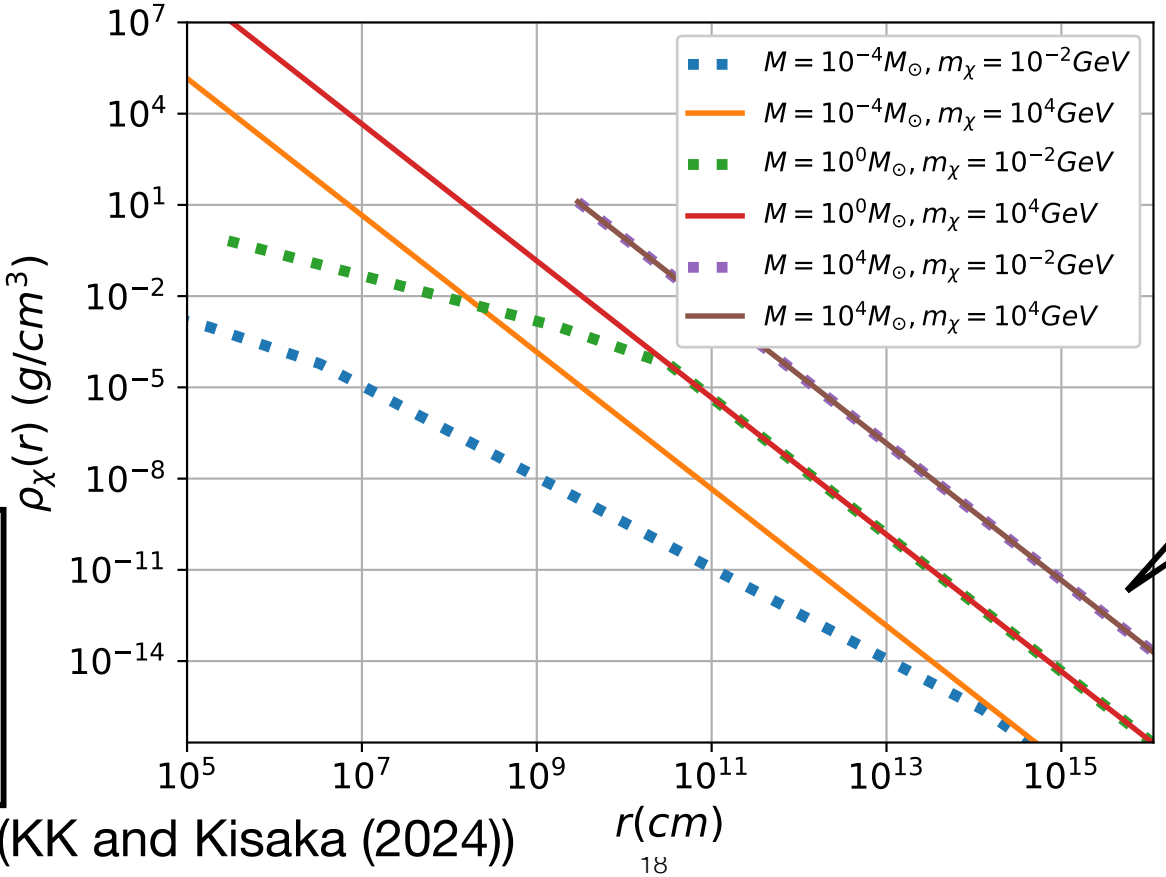
DM accretes onto BH

↓

dressed BH, Ultracompact minihalo (UCMH)

(Gondolo&Silk(99), Eroshenko(2016), Adamek+ (2019) Boucenna+(2017), Serpico+(2020), Carr+(2021),..

UCMH profile around BH



(KK and Kisaka (2024))

Spike

$\rho(r) \propto r^{-\frac{9}{4}}$

Solar system:

$0.3GeV/cm^3 \sim 10^{-25}g/cm^3$

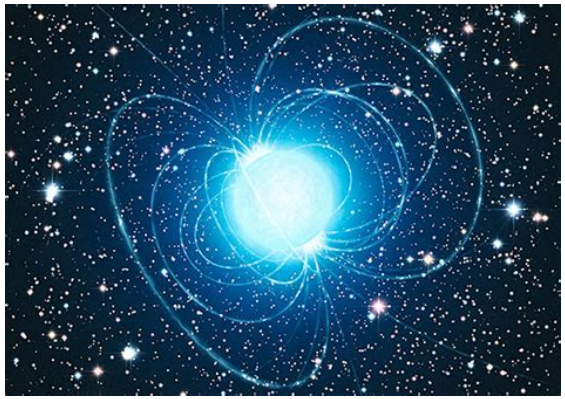
Average in the Universe:

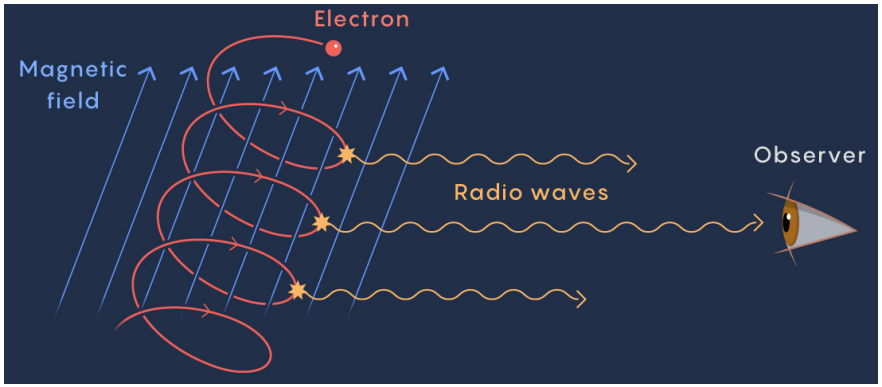
$10^{-6}GeV/cm^3 \sim 10^{-30}g/cm^3$

c.f. NFW cusp:

$$\rho(r) \propto \frac{1}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

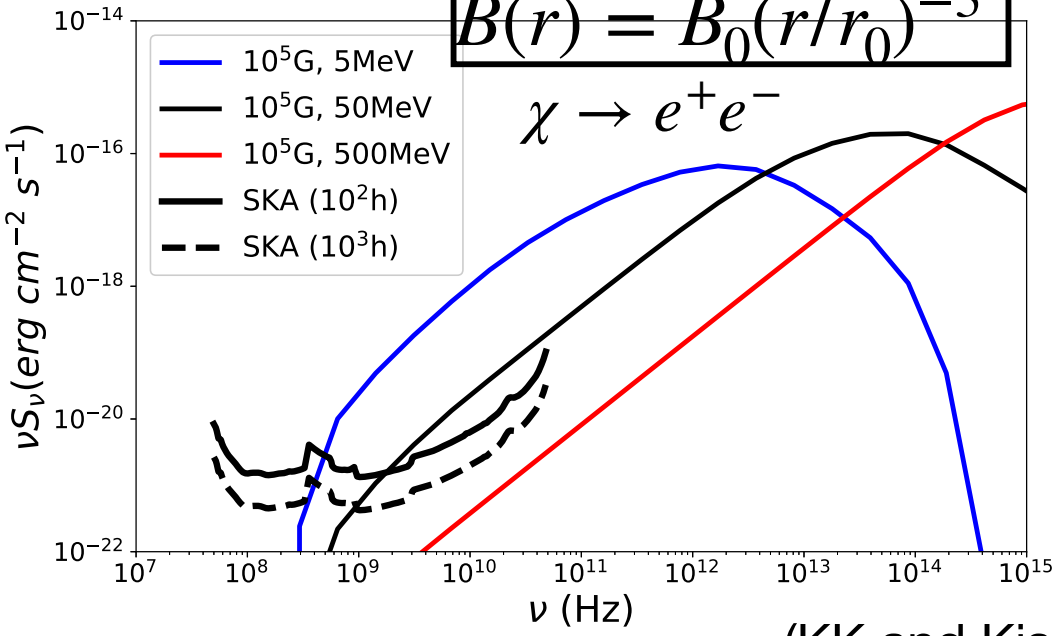
SKA Sensitivity to Sub-GeV Dark Matter Decay: Synchrotron Radio Emissions in White Dwarf Magnetospheres (KK and Kisaka (2024))

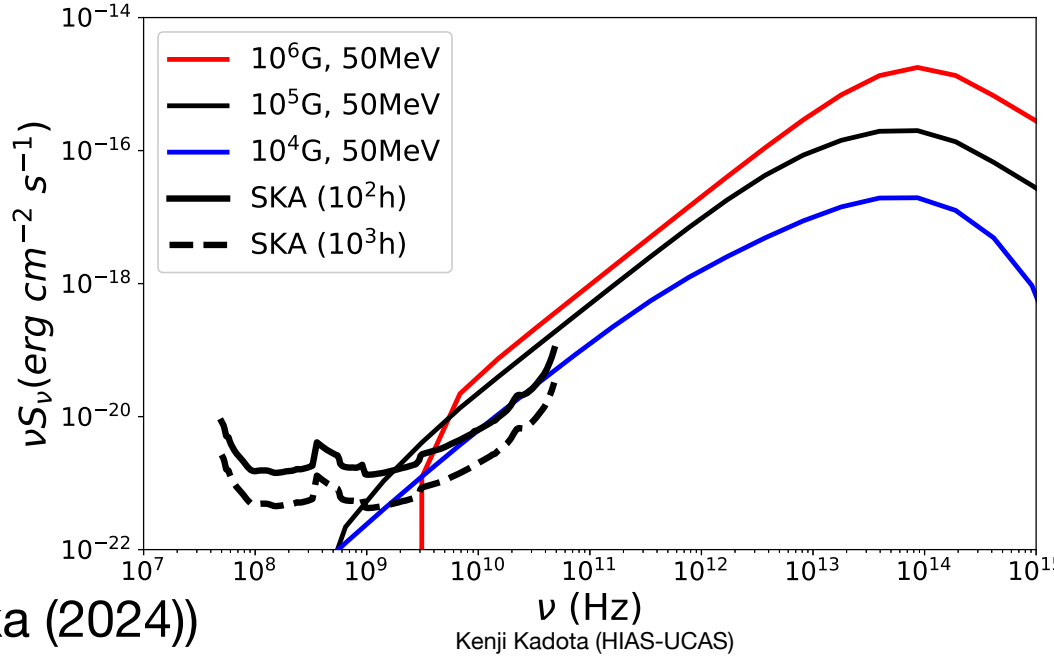




$$B(r) = B_0 (r/r_0)^{-3}$$

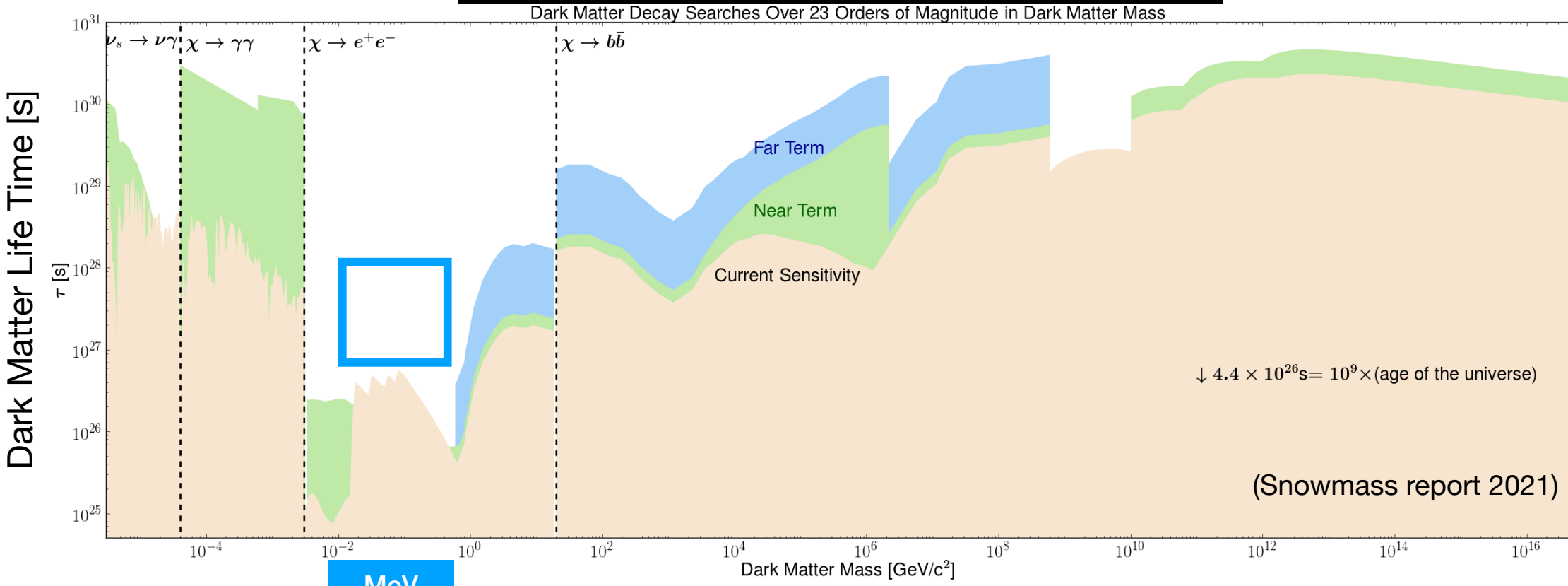
$$\chi \to e^+ e^-$$





(KK and Kisaka (2024))

Dark matter indirect search experiments



MeV Gap

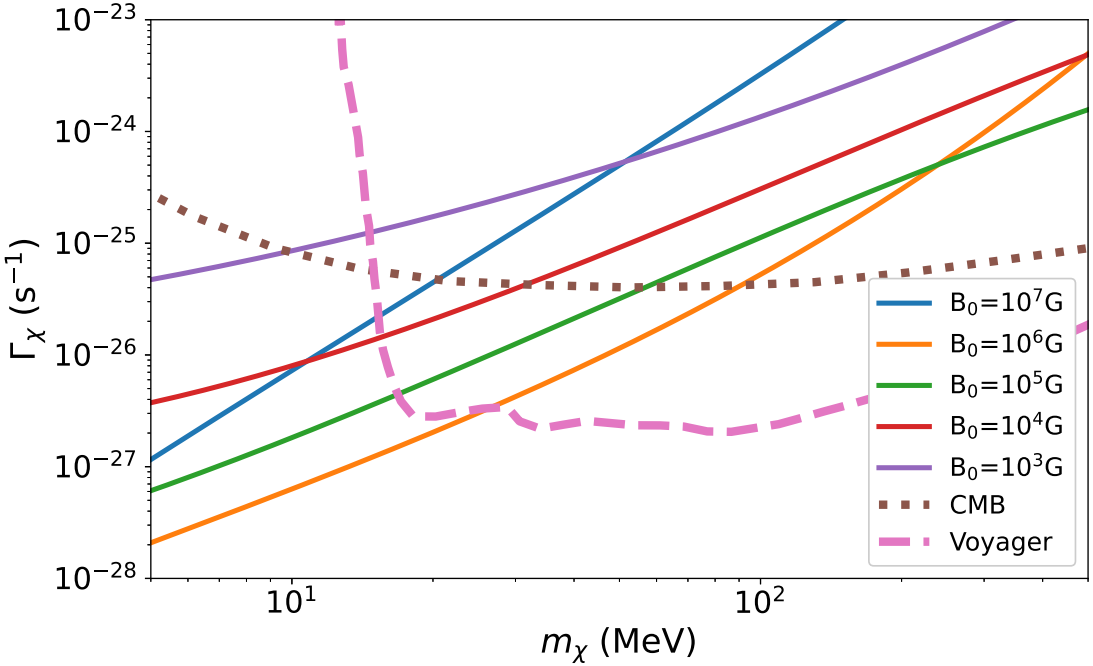
(COMPTEL)
(1991-2000)

sub-MeV
(X-ray and
soft gamma-ray telescopes
e.g. Chandra, NuSTAR)

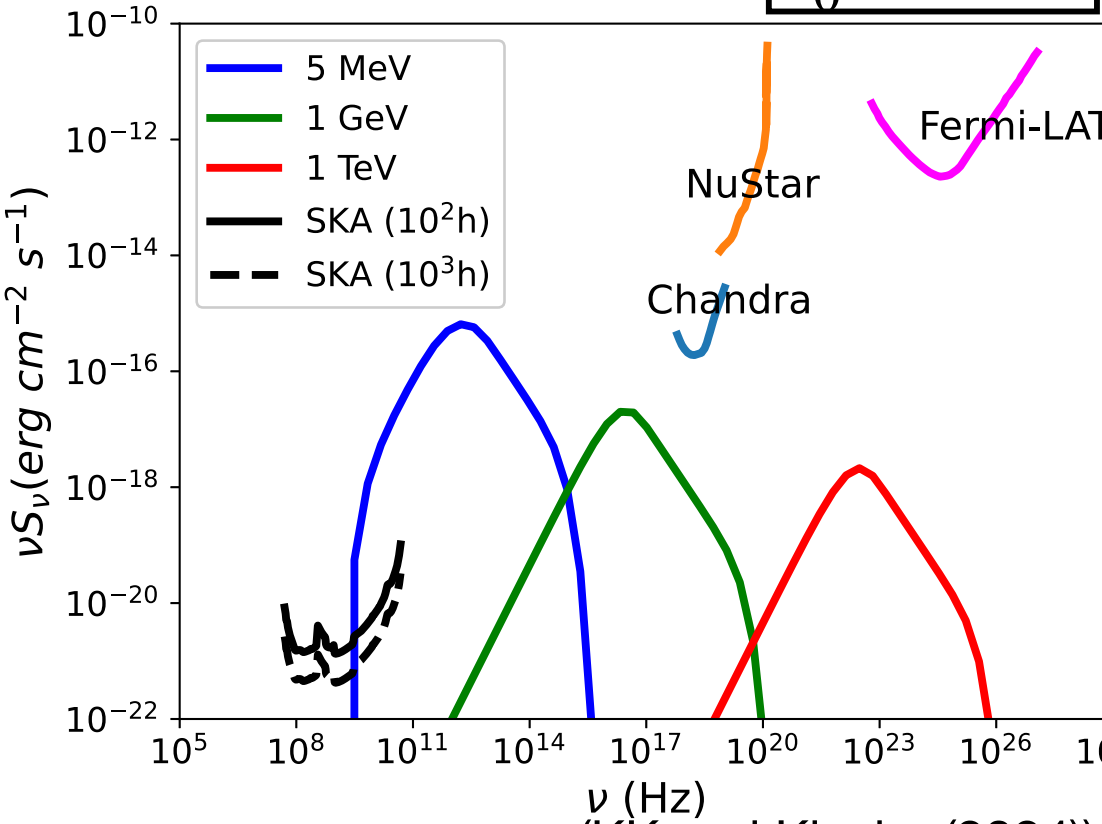
Above 1 GeV
(gamma-ray telescopes
e.g. Fermi-LAT)

SKA Sensitivity to Sub-GeV Dark Matter Decay:
Synchrotron Radio Emissions in White Dwarf Magnetospheres (KK and Kisaka (2024))

$$B(r) = B_0(r/r_0)^{-3} \qquad \chi \to e^+e^-$$



$B_0 = 10^6 G$



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Conclusion: Let us keep open-minded for the properties of dark matter
Analogously to CMB, the 21cm can potentially revolutionize the precision cosmology