What is dark matter?

Comprehensive study of the huge discovery space in dark matter

PI: Hitoshi Murayama（Kavli IPMU、Berkeley）

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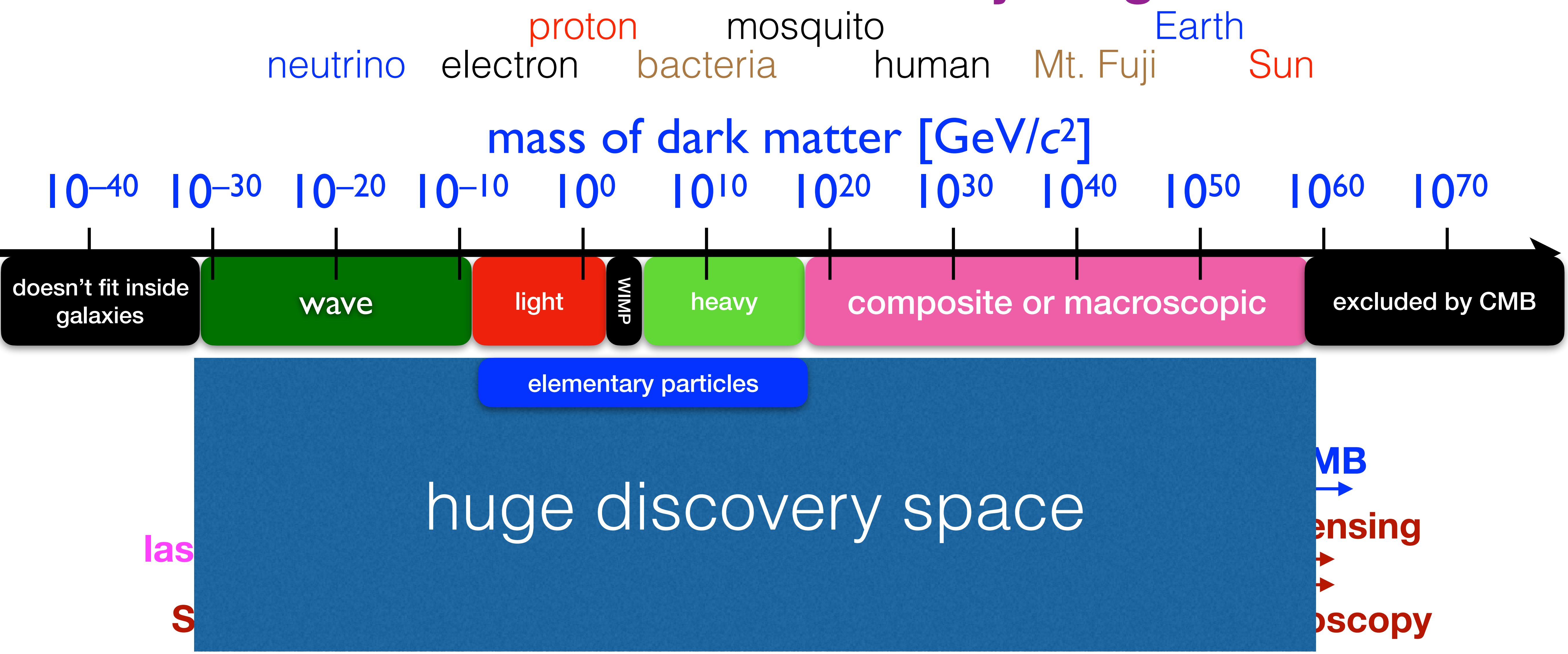
東京大学 THE UNIVERSITY OF TOKYO

BERKELEY LAB

KAVLI IPMU

Main point: **Dark Matter exists**, but **unknown type of matter**

Search so far has been limited to **tiny range of masses**



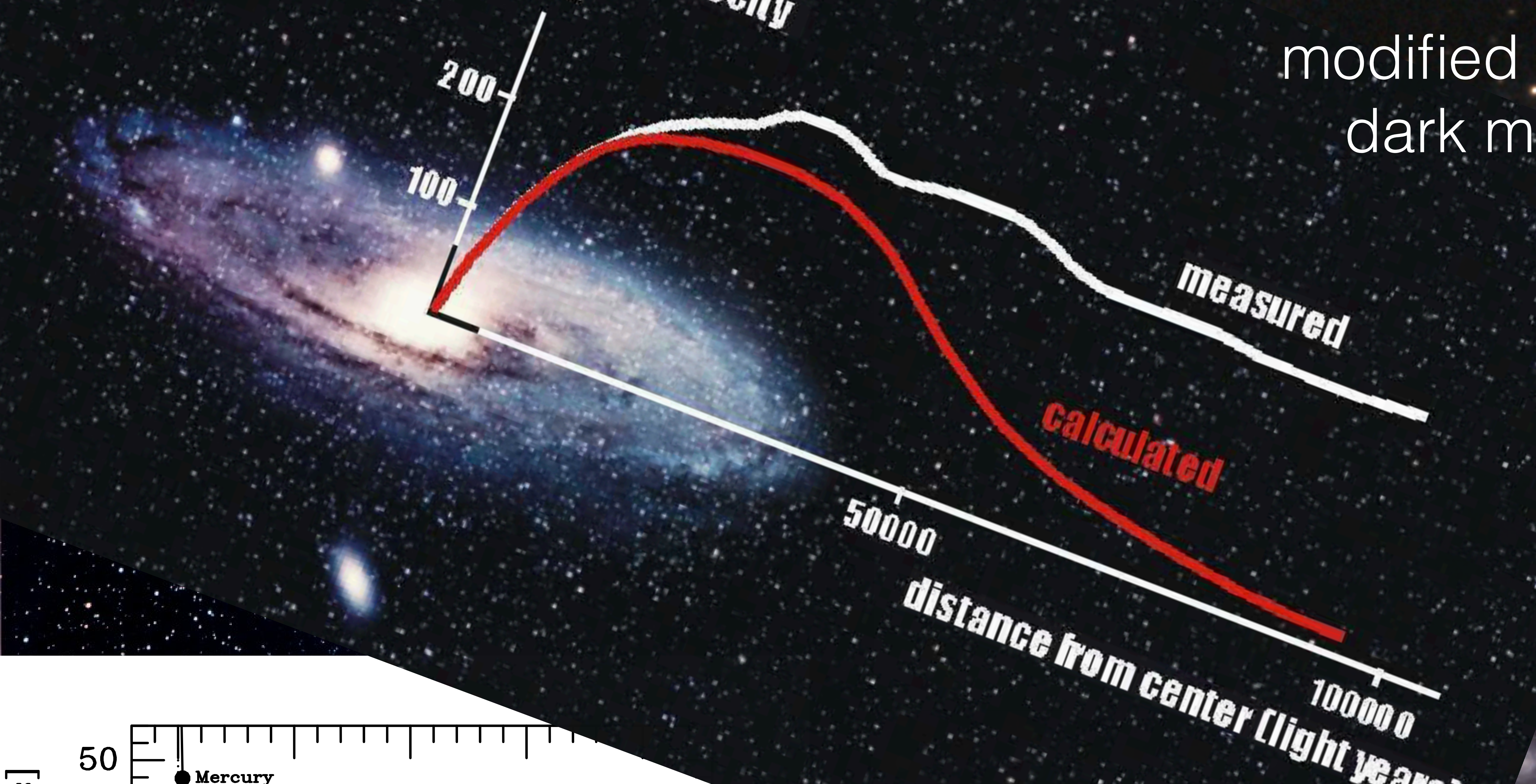
we challenge **discovery space** not studied so far due to theoretical prejudices

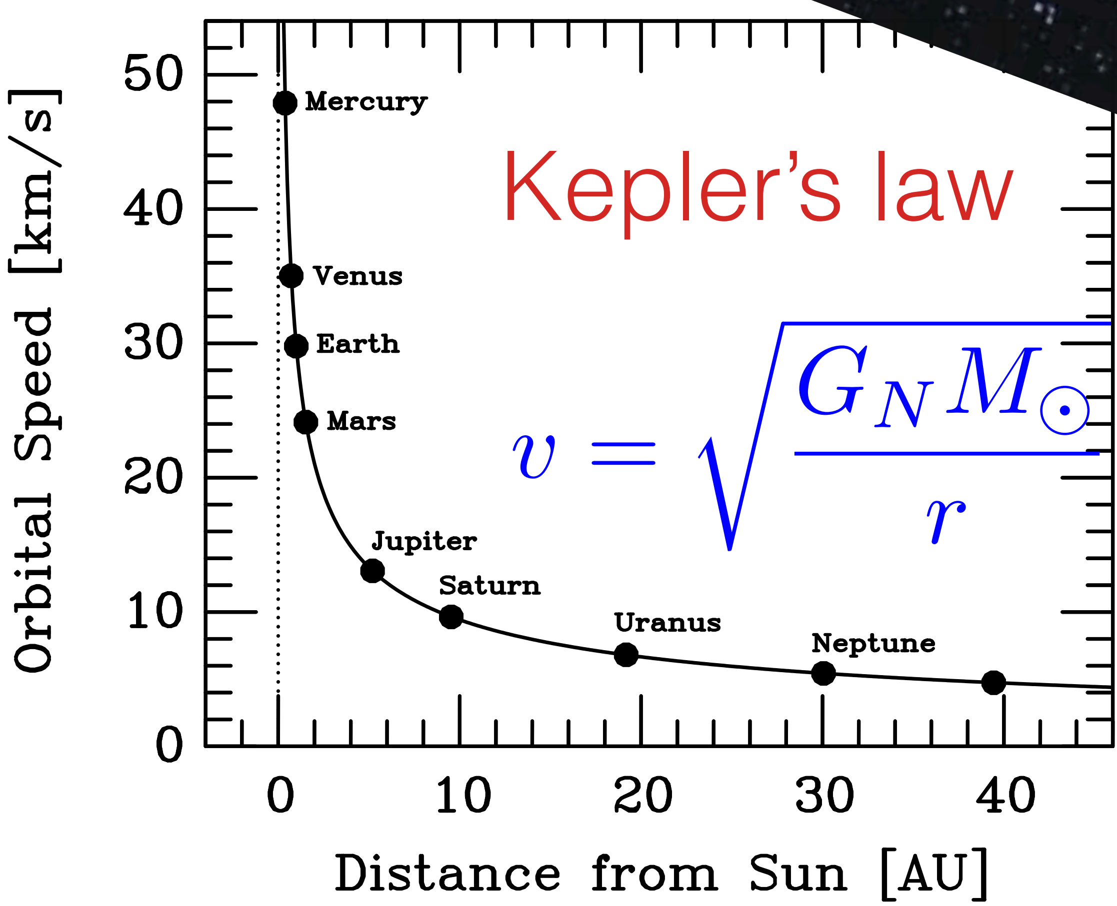
revolutionize dark matter research in Japan

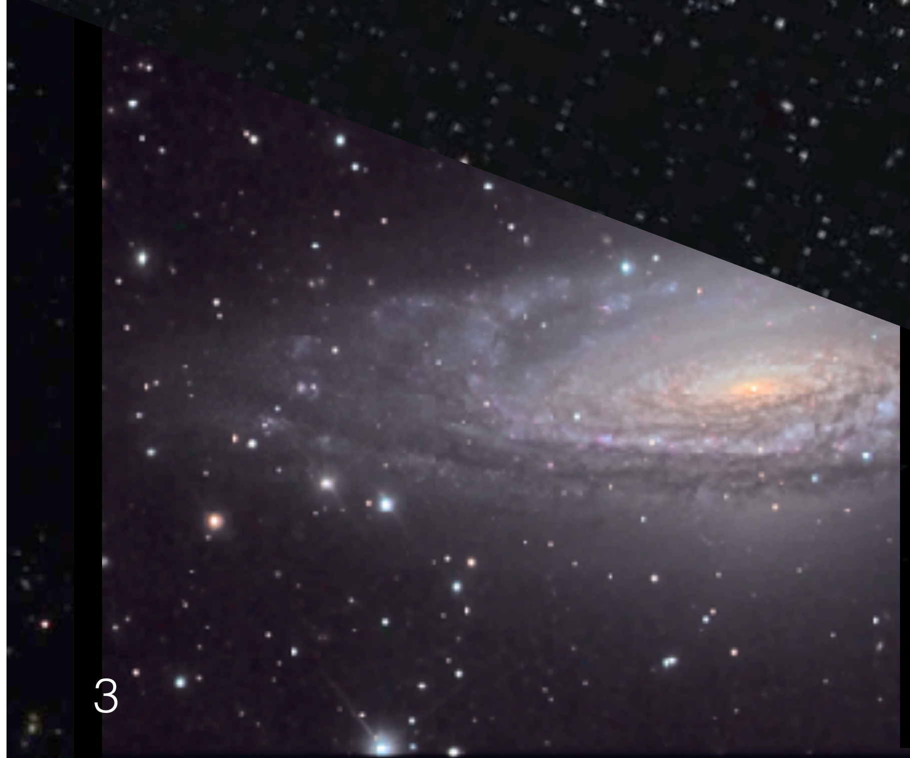
cross-field research beyond traditional barriers

exploit existing facilities in unanticipated fashion

modified gravity?
dark matter?

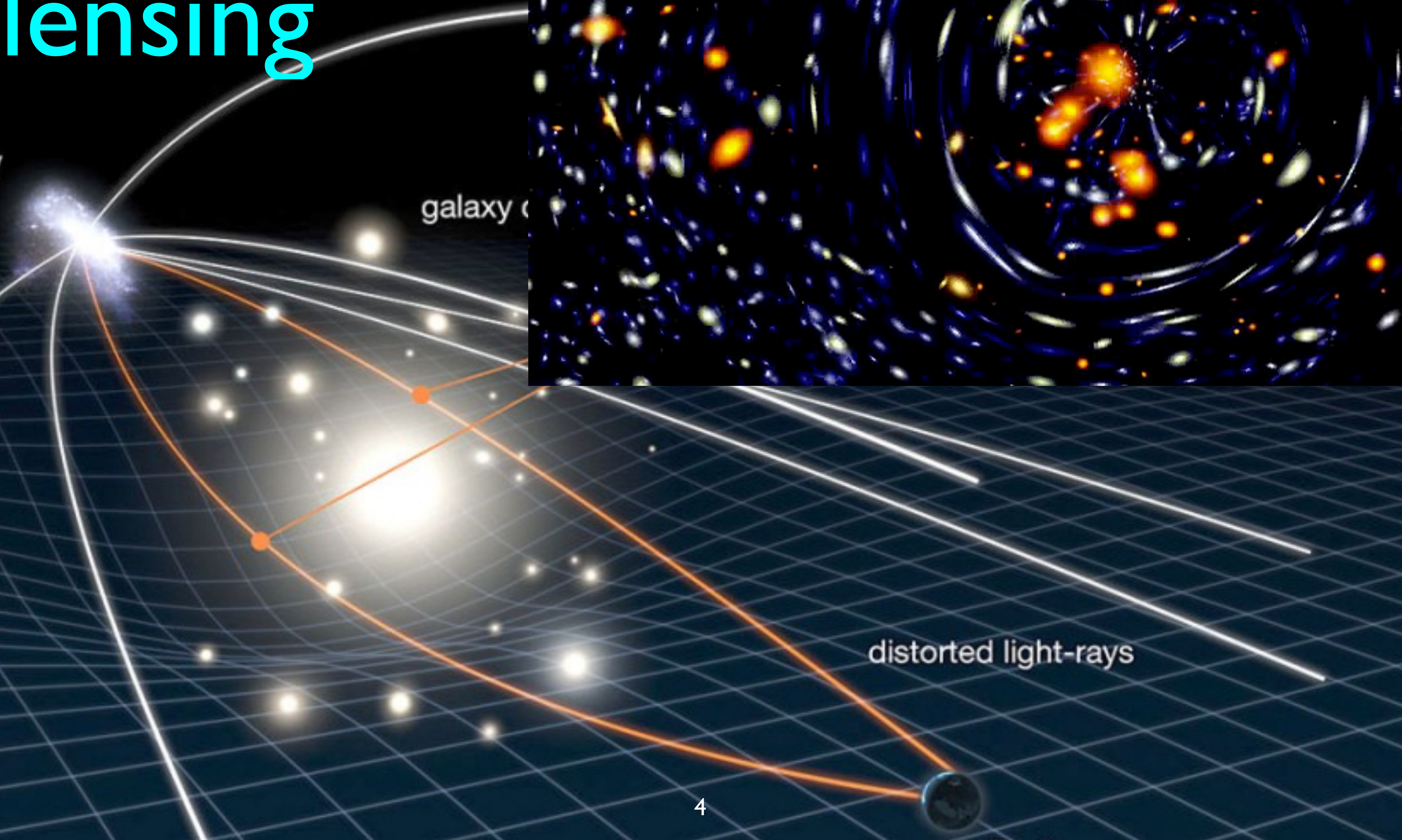






ra Rubin

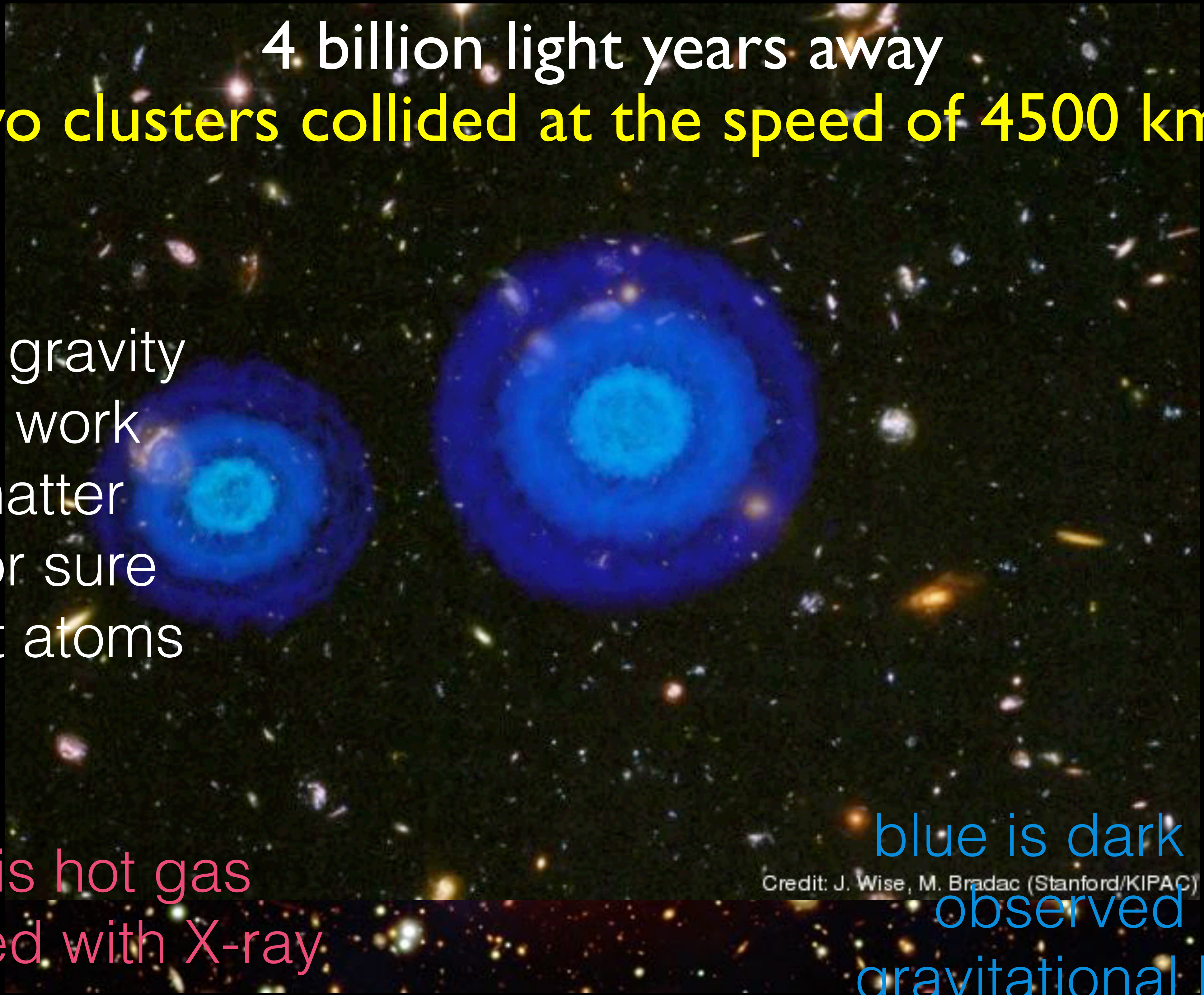
gravitationa lensing



Bullet Cluster

4 billion light years away

two clusters collided at the speed of 4500 km/s



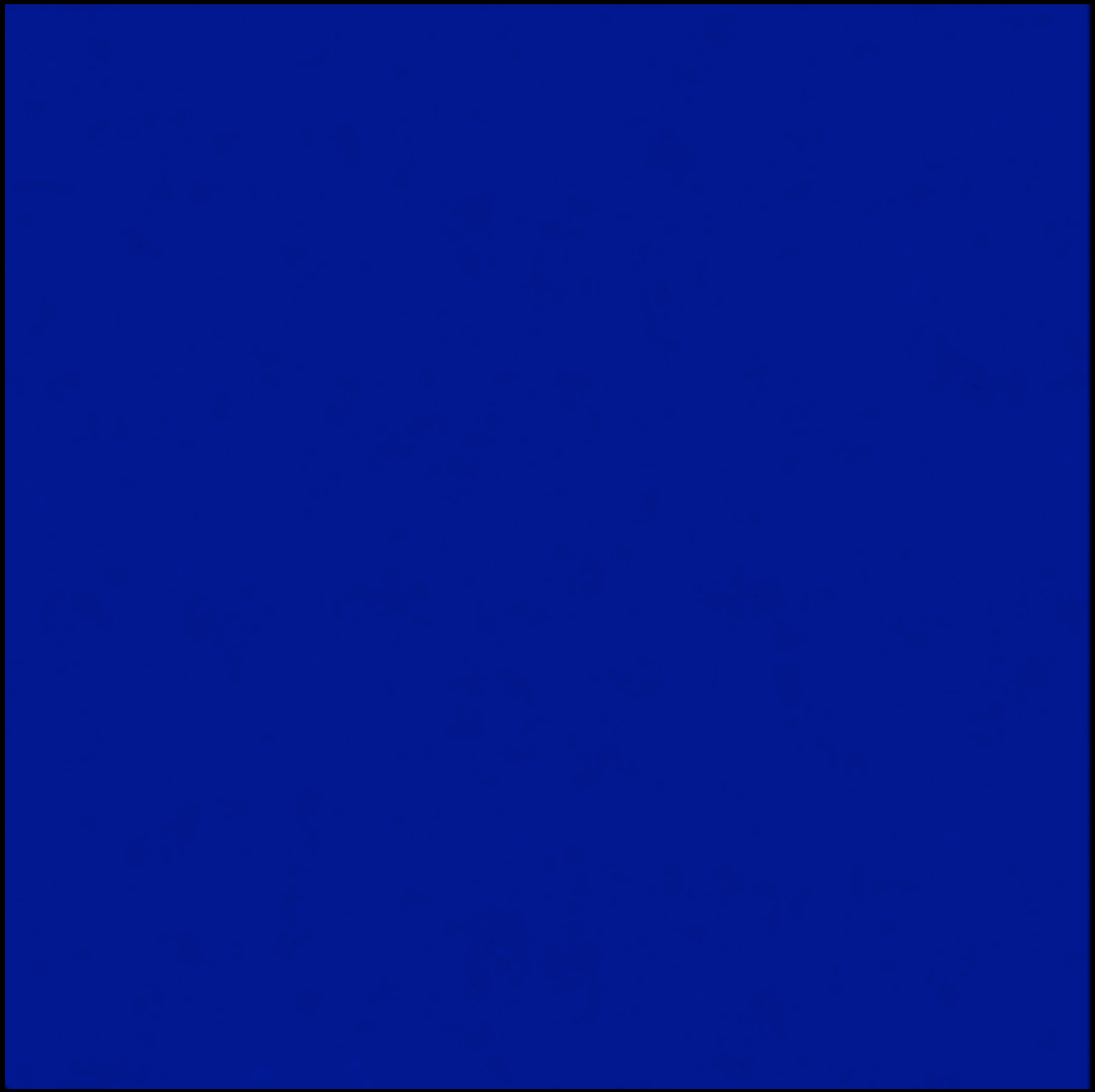
modified gravity
doesn’t work
dark matter
exists for sure
but is not atoms

pink is hot gas
observed with X-ray

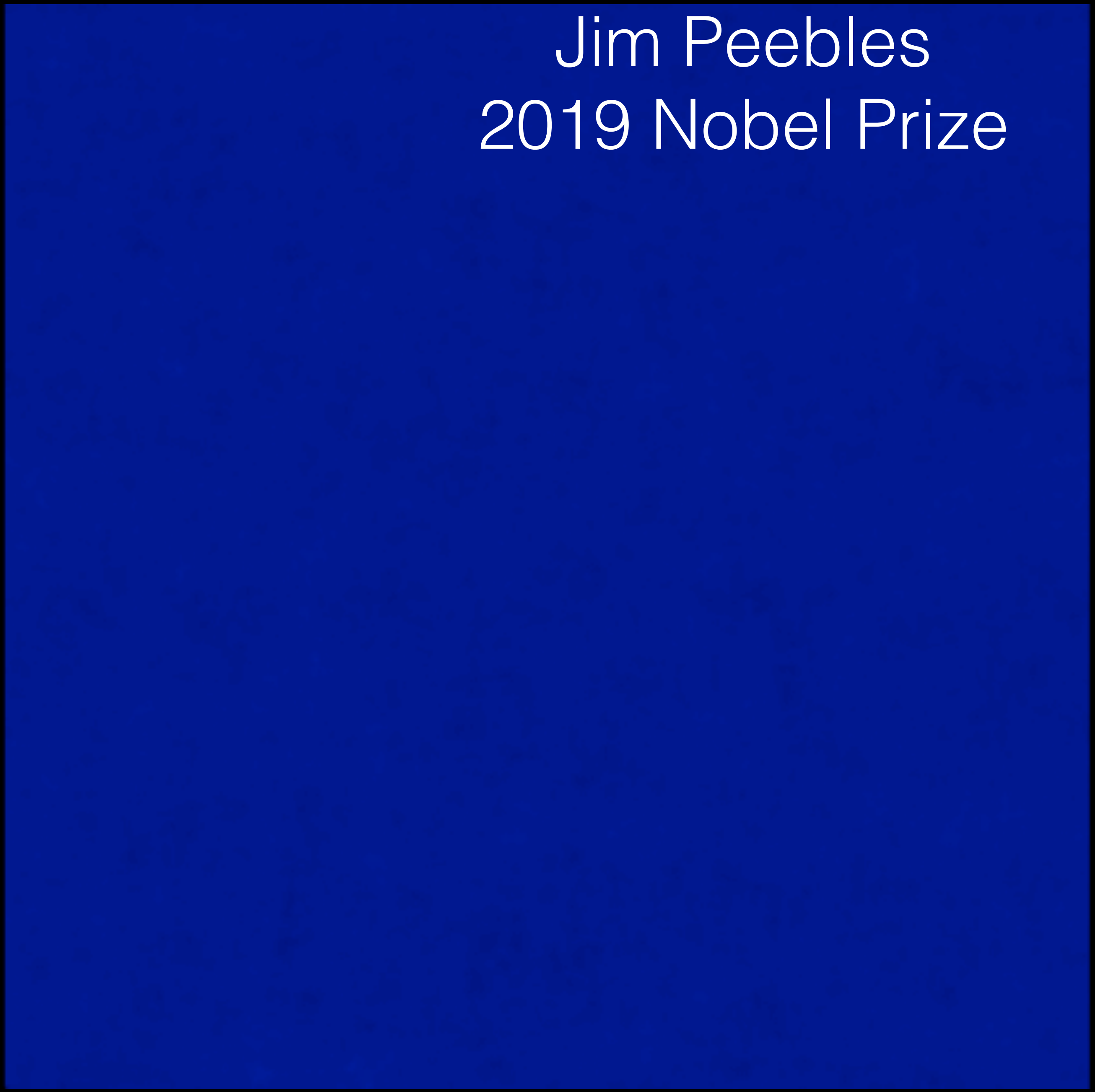
blue is dark matter
observed with
gravitational lensing

dark matter is our Mom

Jim Peebles
2019 Nobel Prize

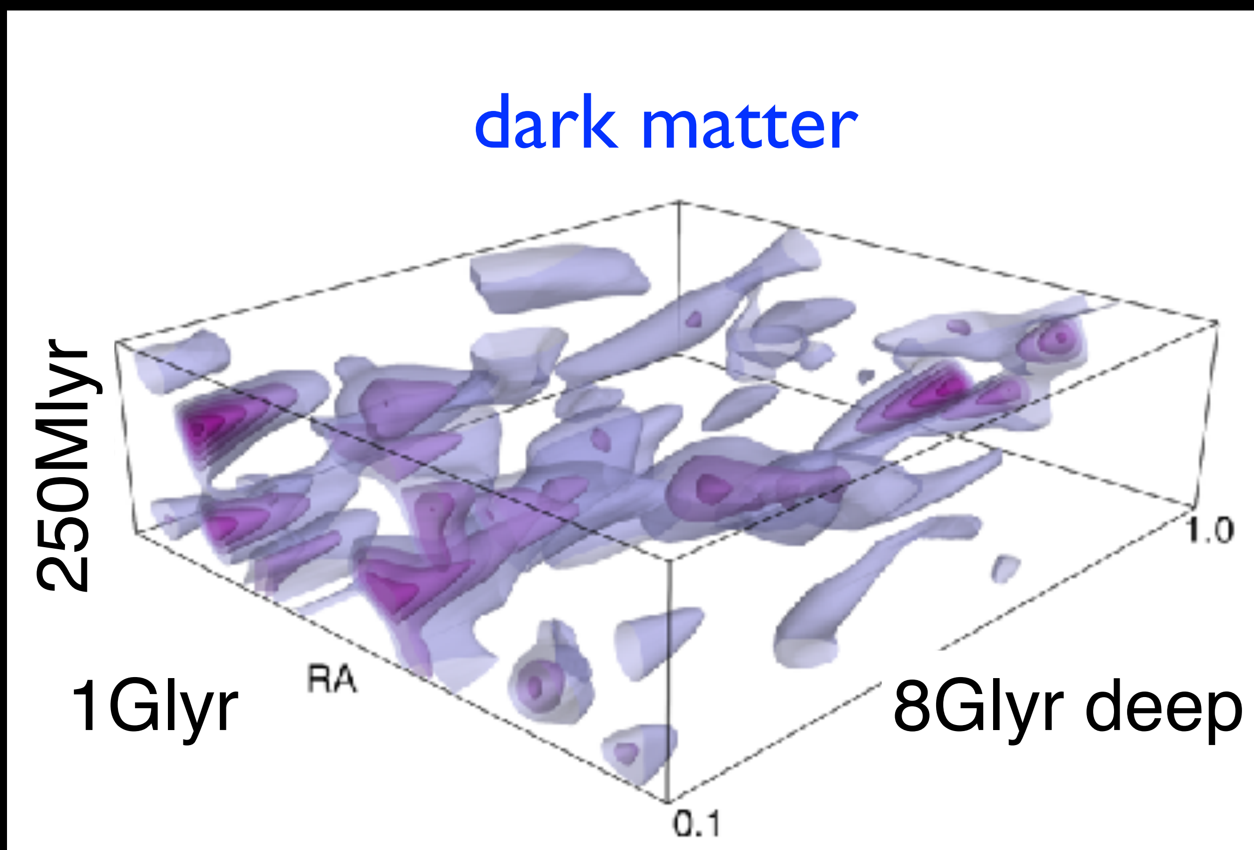


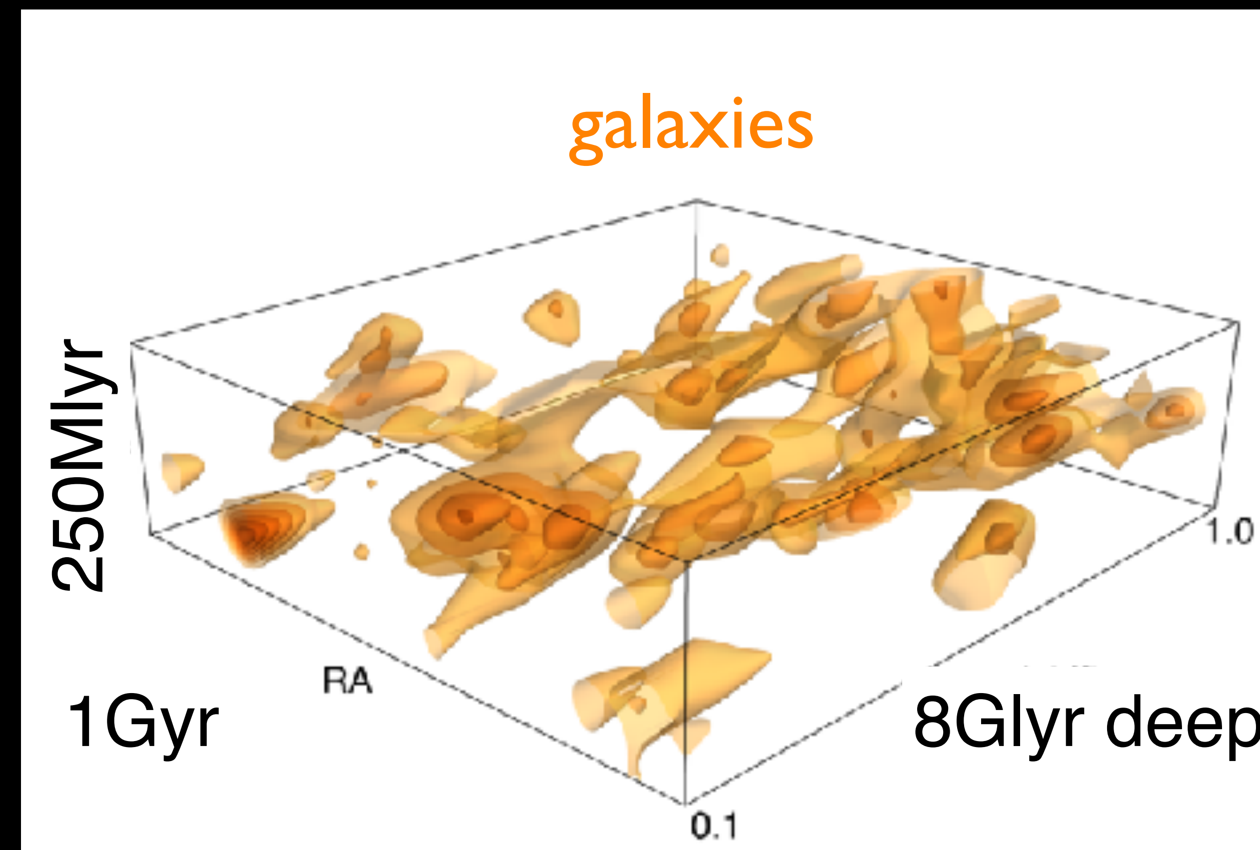
without dark matter



with dark matter

indeed our Mom!



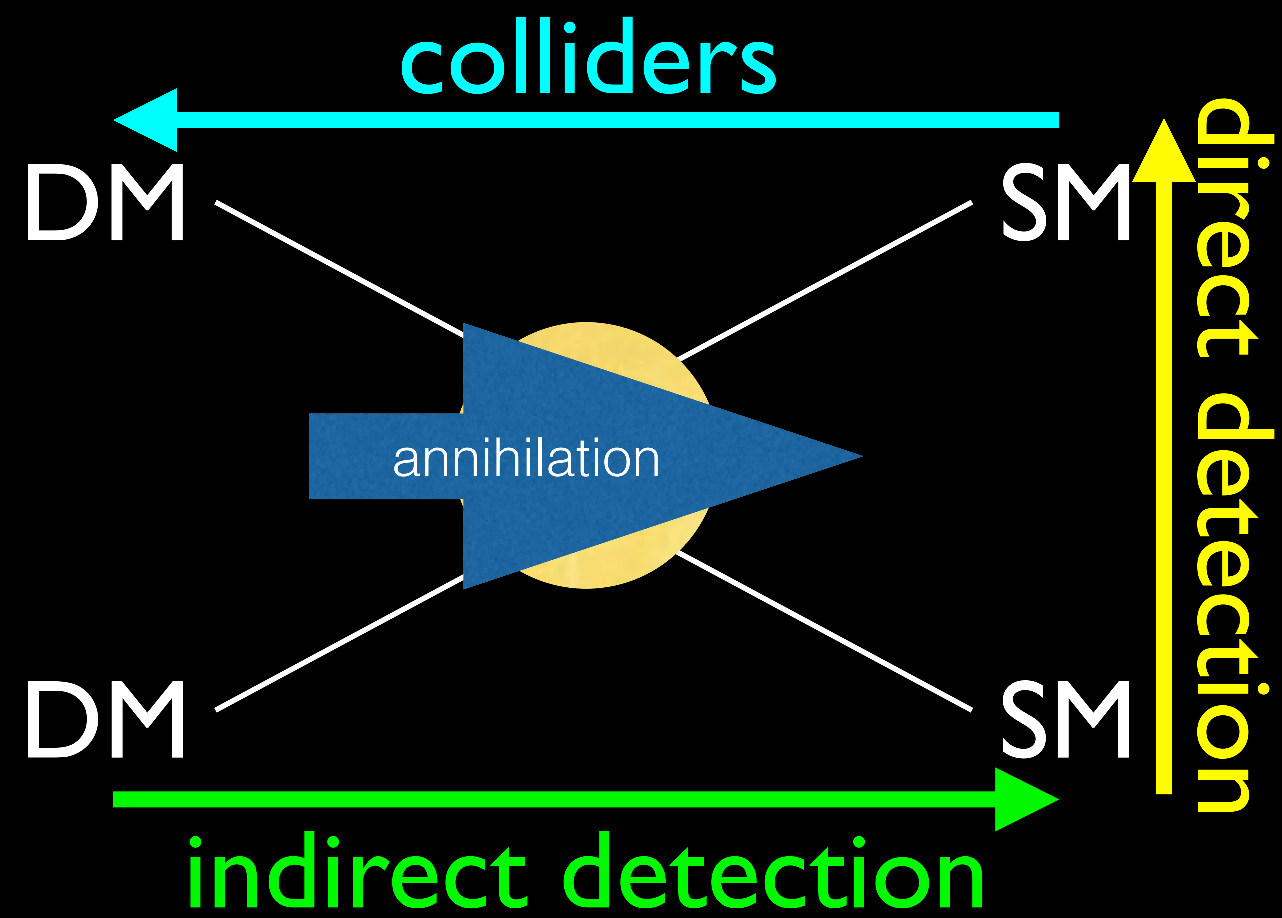


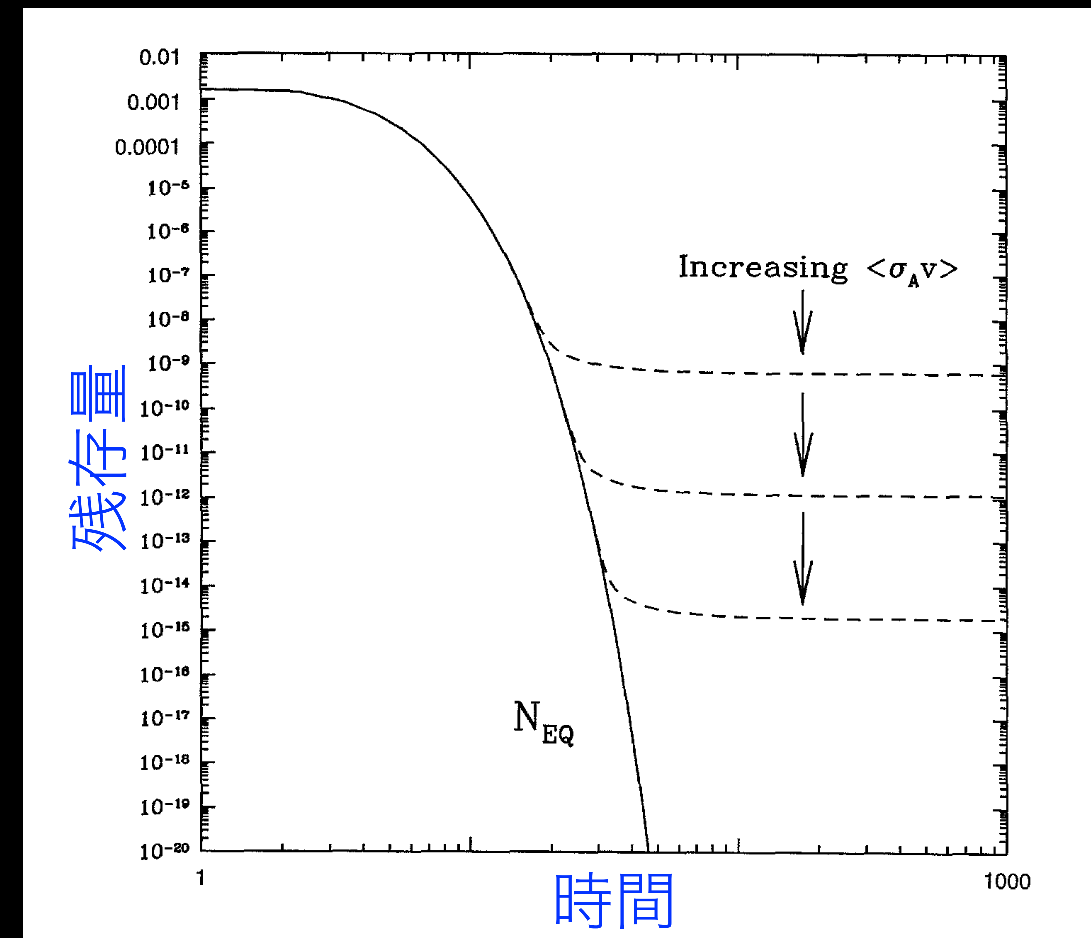
world's largest 3D map
of dark matter

Subaru telescope

current paradigm: WIMP

Weakly Interacting Massive Particle

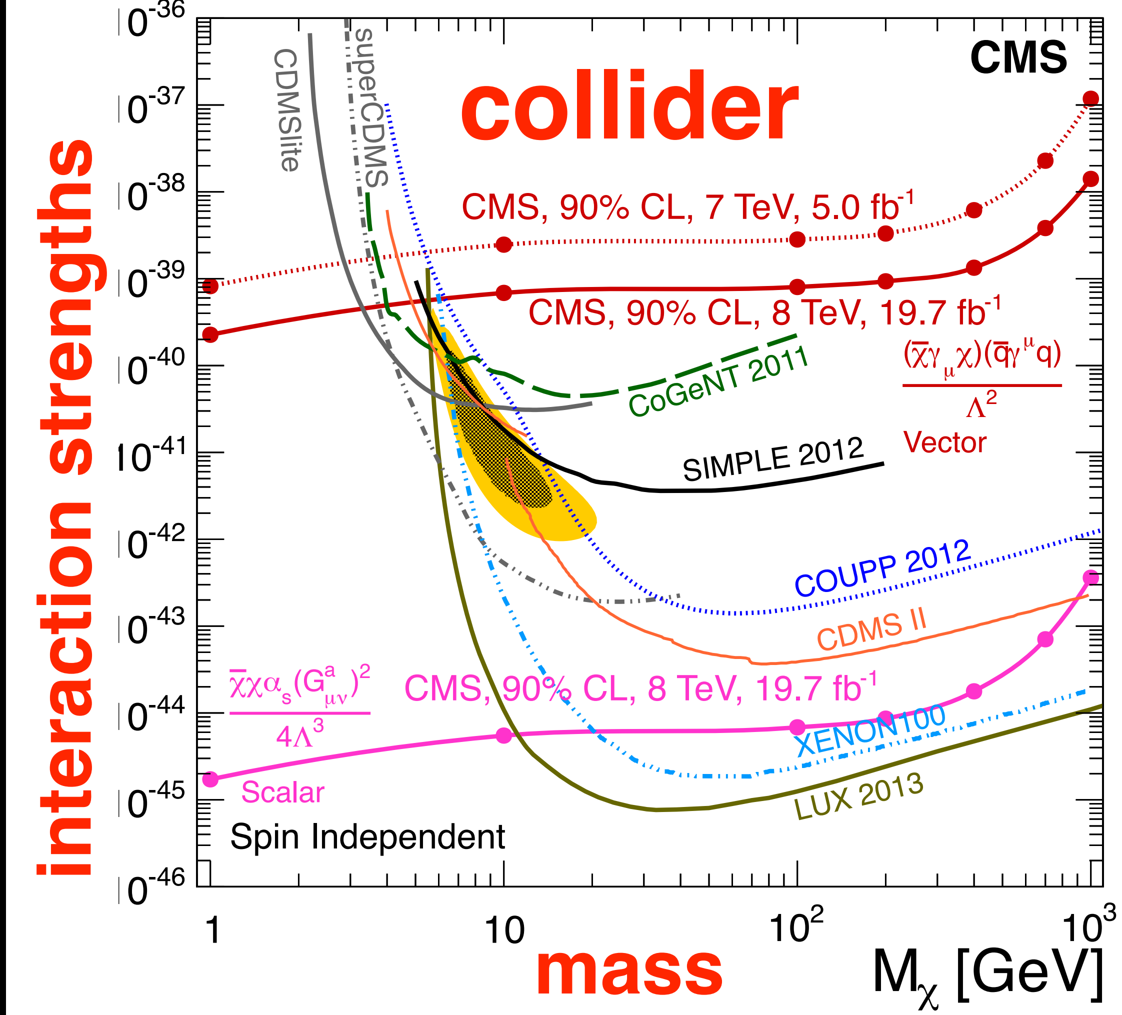


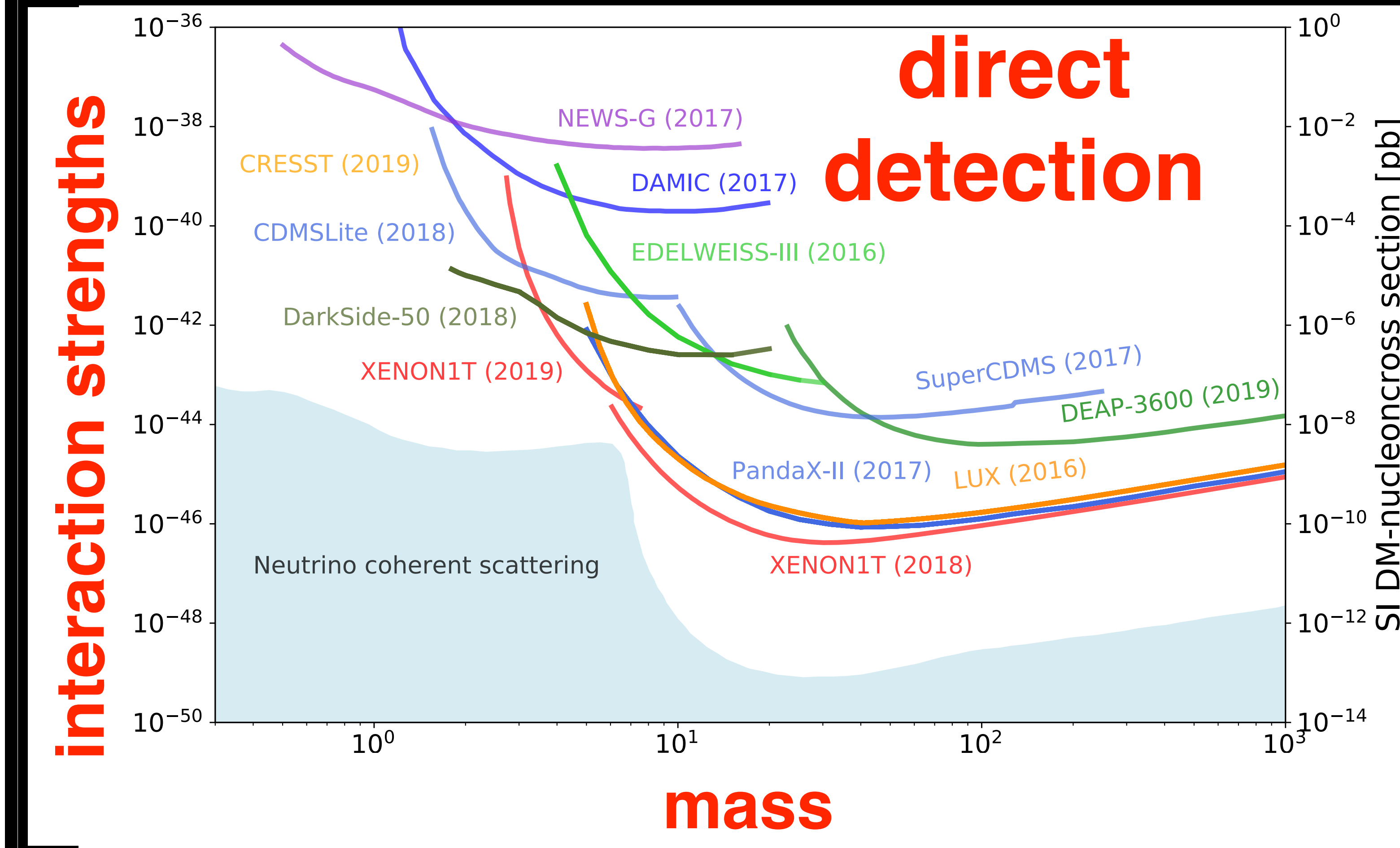


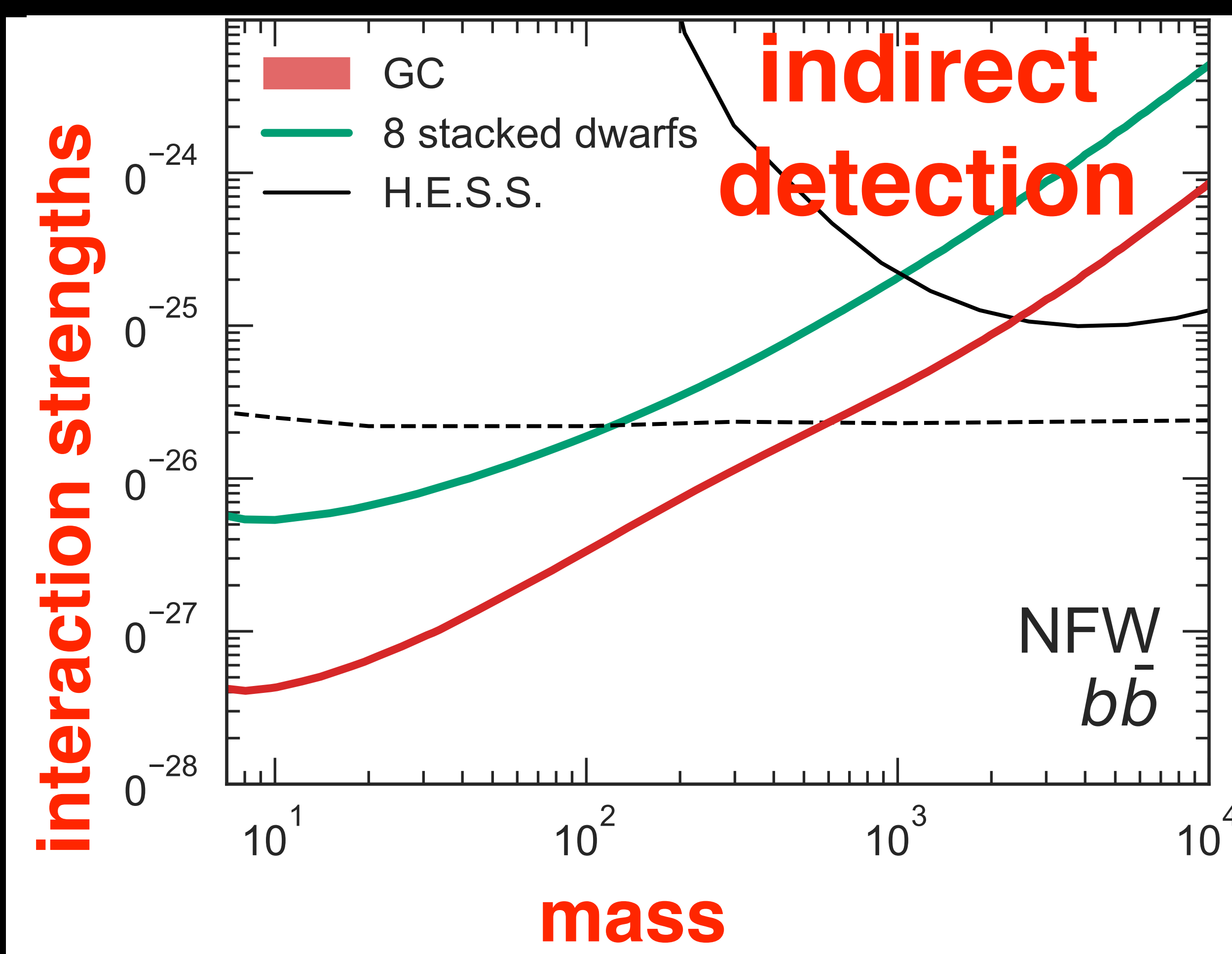
interaction strengths
energy scales

right abundance with
“weak interaction”

theoretical appealing, predicts 10~1000GeV mass
furthermore good mass range for LHC and UG expts

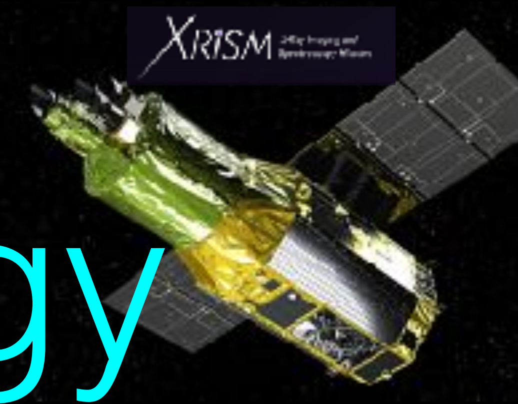






WIMP: theoretically appealing
predicts 10~1000 GeV mass
searches exclusively in this range
most stringent limits today
reflection: need broader search





strategy

- world competitive experiments > $100M
- use excellent existing facilities in Japan
  - exploitation for unforeseen purposes
  - B01：KAGRA（UTokyo）black hole mergers
  - B02, B03：Subaru（NAOJ）galaxy evolution
  - B04：XRISM（JAXA）supernova remnants
  - B05：Belle II（KEK）CP violation
  - B06：Simons Array（intl team incl KEK, IPMU etc）verify inflation theory

[X00] 総括班 村山（KIPMU）	[A01]軽いDM 高橋（東北大）	[A02]重いDM 村瀬（PSU）	[A03]マクロDM 柳（名古屋大）
[B01] レーザー干渉計 道村（東大）	axion, dilaton （円偏光）	背景重力波 （相転移など）	背景重力波 （inflationなど）
[B02] すばる分光 高田（KIPMU）	fuzzy DM, SIDM 3D DM地図	矮小銀河内の対消滅 3D DM地図	PBH, UCMH, DM subhalo, 3D DM地図
[B03] イメージング 宮崎（NAOJ）	DM subhalo DM地図	DM subhalo DM地図	PBH, UCMH （重力マイクロレンズ）
[B04] X線 山崎(典)（ISAS）	sterile neutrino moduli （輝線、連続光）	ダークマター崩壊 （輝線、連続光）	PBH蒸発 （X線背景放射）
[B05] e^+e^-加速器 西田（KEK）	dark photon SIMP	高エネルギーの間接検証 （余剰次元、Higgs）	高エネルギーの間接検証 （余剰次元、Higgs）
[B06] CMB 小松（MPA）	axion （CMB偏光）	宇宙初期の対消滅 $N_{\rm eff}$	PBH（τ）

[C02]宇宙構造形成理論 安藤（アムステルダム大）

[C01]量子重力理論 山崎（雅）（KIPMU）

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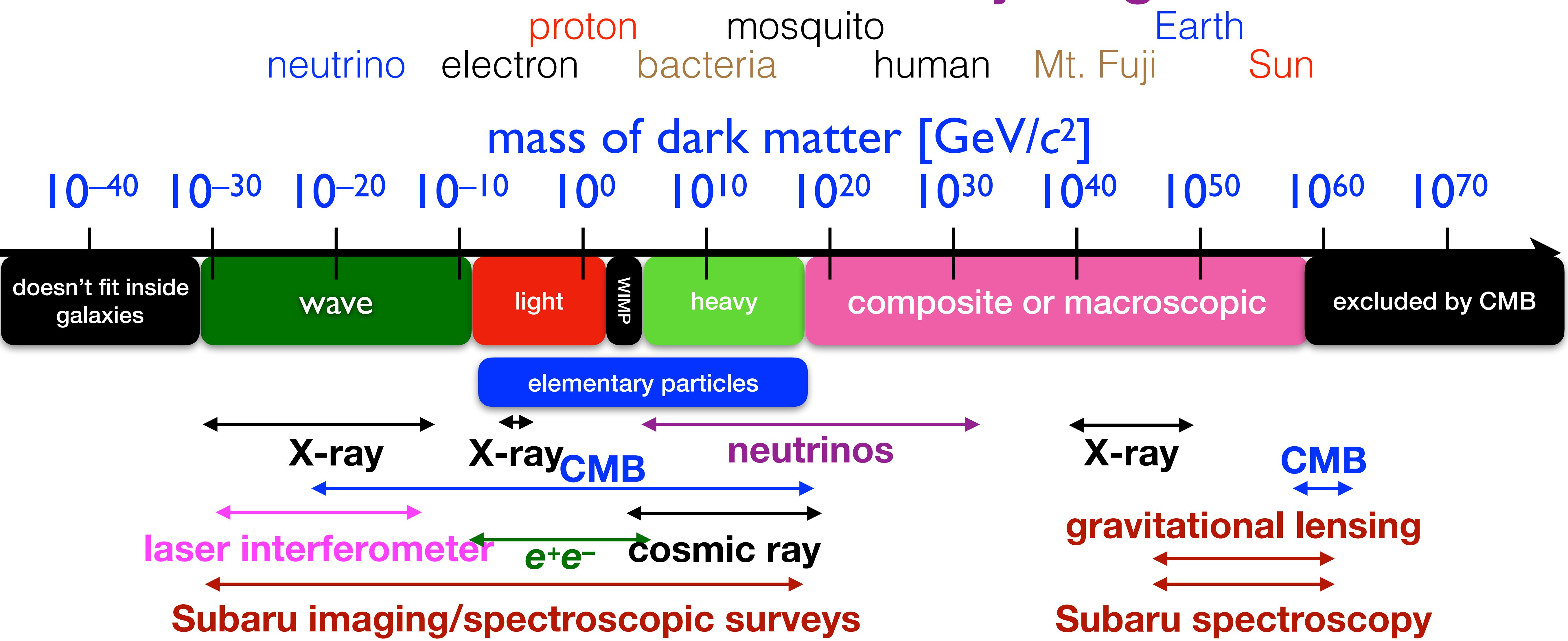

we challenge **discovery space** not studied
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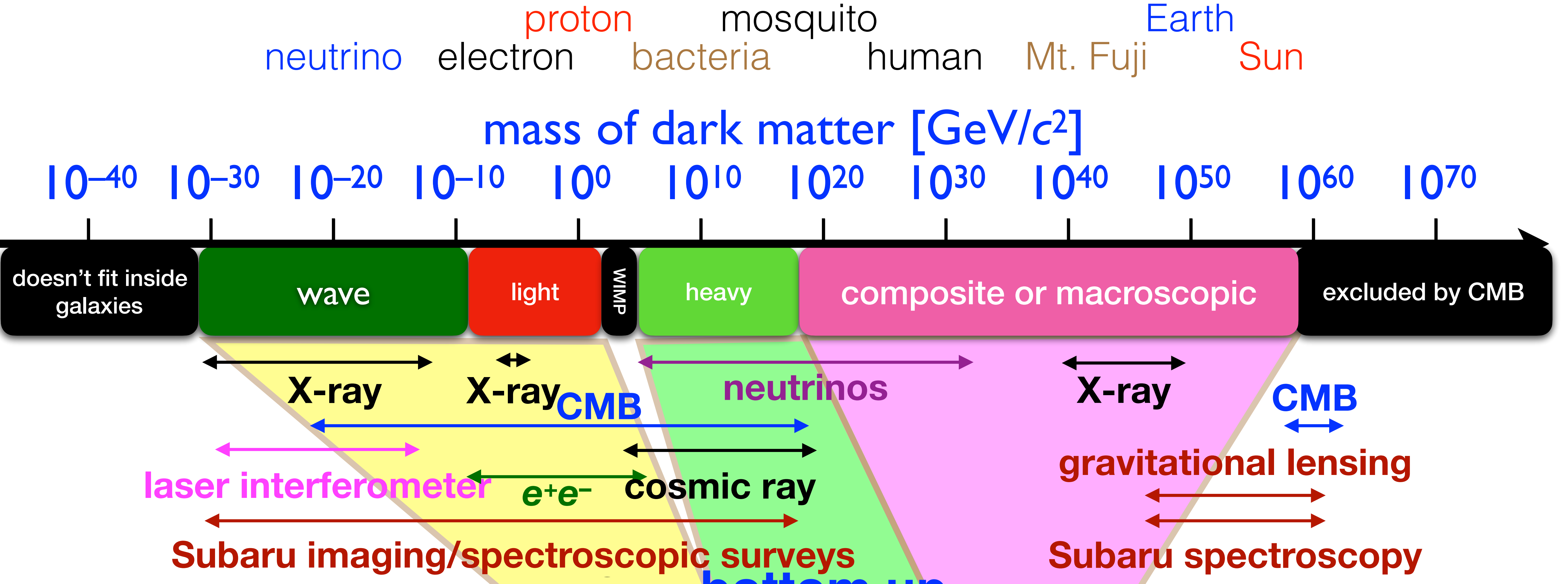
revolutionize dark matter research in Japan

cross-field research beyond traditional barriers

exploit existing facilities in unanticipated fashion



bottom up

	[X00] 総括班 村山 (KIPMU)	[A01]軽いDM 高橋 (東北大)	[A02]重いDM 村瀬 (PSU)	[A03]マクロDM 柳 (名古屋大)
laser interferometer	[B01] レーザー干渉計 道村 (東大)	axion, dilaton (円偏光)	背景重力波 (相転移など)	背景重力波 (inflationなど)
Subaru spectroscopy	[B02] すばる分光 高田 (KIPMU)	fuzzy DM, SIDM 3D DM地図	矮小銀河内の対消滅 3D DM地図	PBH, UCMH, DM subhalo, 3D DM地図
Subaru imaging	[B03] イメージング 宮崎 (NAOJ)	DM subhalo DM地図	DM subhalo DM地図	PBH, UCMH (重力マイクロレンズ)
X-ray satellite	[B04] X線 山崎(典) (ISAS)	sterile neutrino moduli (輝線、連続光)	ダークマター崩壊 (輝線、連続光)	PBH蒸発 (X線背景放射)
e^+e^- collider	[B05] e^+e^-加速器 西田 (KEK)	dark photon SIMP	高エネルギーの間接検証 (余剰次元、Higgs)	高エネルギーの間接検証 (余剰次元、Higgs)
CMB	[B06] CMB 小松 (MPA)	axion (CMB偏光)	宇宙初期の対消滅 $N_{\rm eff}$	PBH (τ)

[C02]宇宙構造形成理論 安藤 (アムステルダム大)

top down

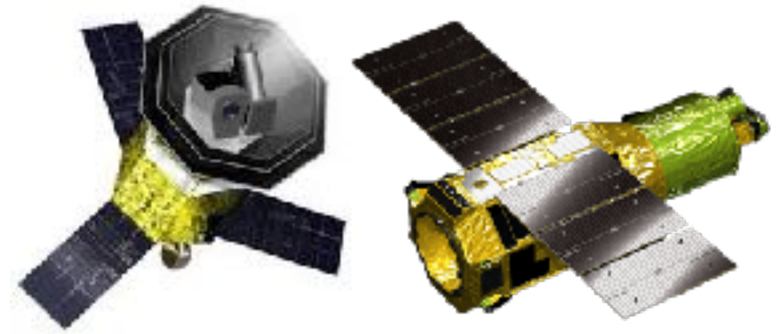
structure formation theory

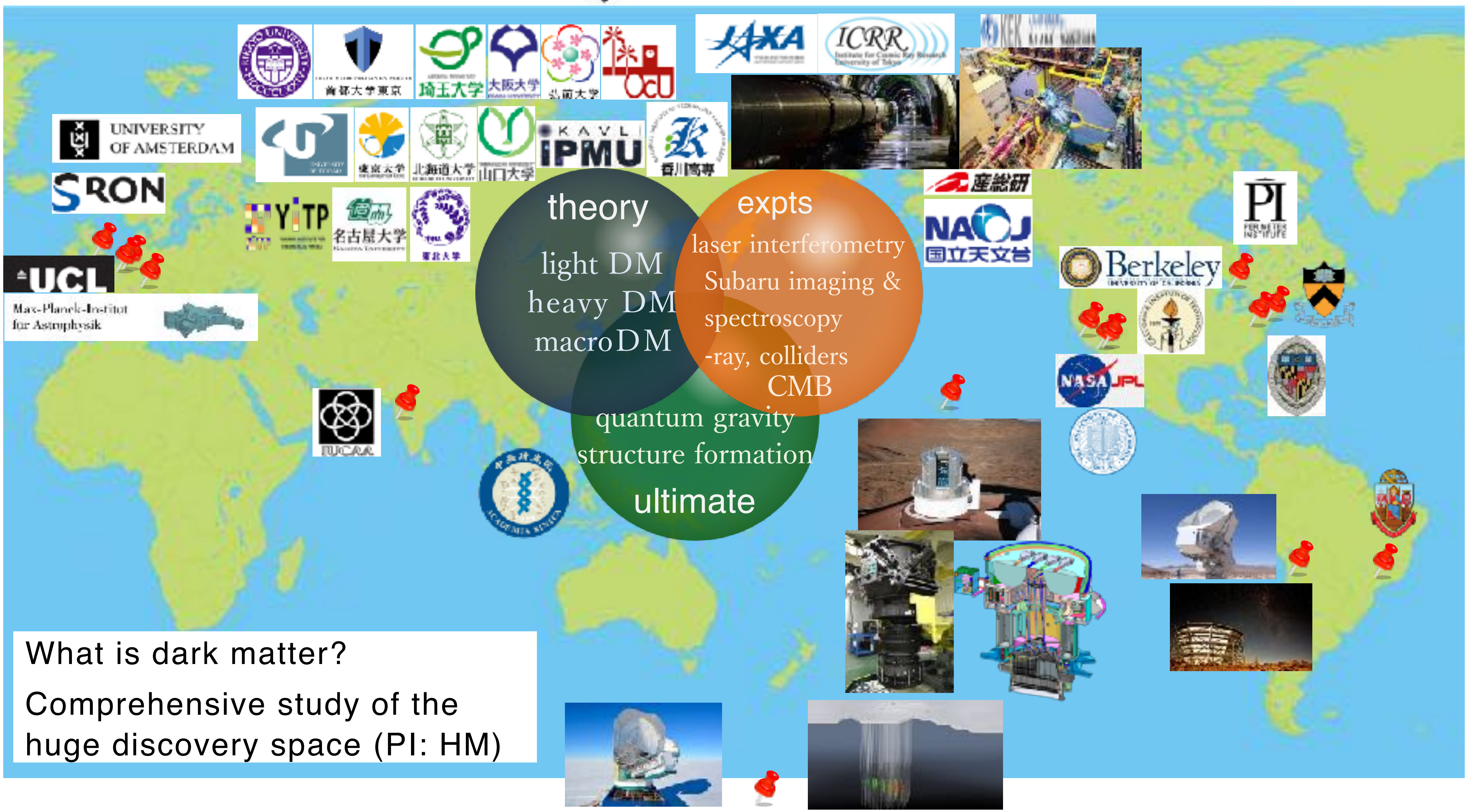
[C01]量子重力理論 山崎 (雅) (KIPMU)

quantum gravity

manage	Murayama	Kavli IPMU / UC Berkeley	particle/cosmology
A01	Takahashi	Tohoku	particle
A02	Murase	Penn State / Kyoto	astrophysics
A03	Yoo	Nagoya	relativity cosmology
B01	Michimura	UTokyo Physics	experiment
B02	Takada	Kavli IPMU	cosmology/astro
B03	Miyazaki	NAOJ	obs. cosmology
B04	Yamasaki	JAXA/ISAS	experiments
B05	Nishida	KEK	experiments
B06	Komatsu	Max Planck / Kavli IPMU	cosmology
C01	Yamazaki	Kavli IPMU	string theory
C02	Ando	Amsterdam / Kavli IPMU	particle astrophysics

space





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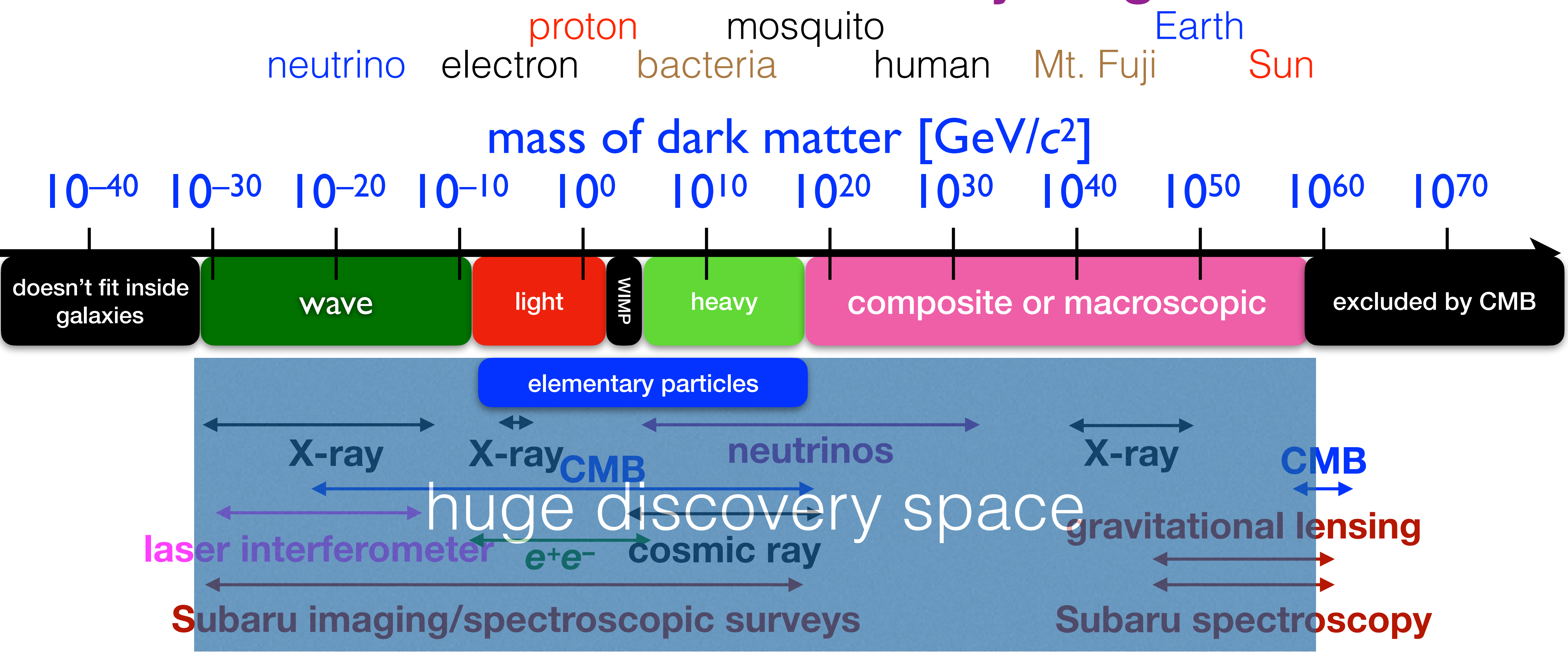

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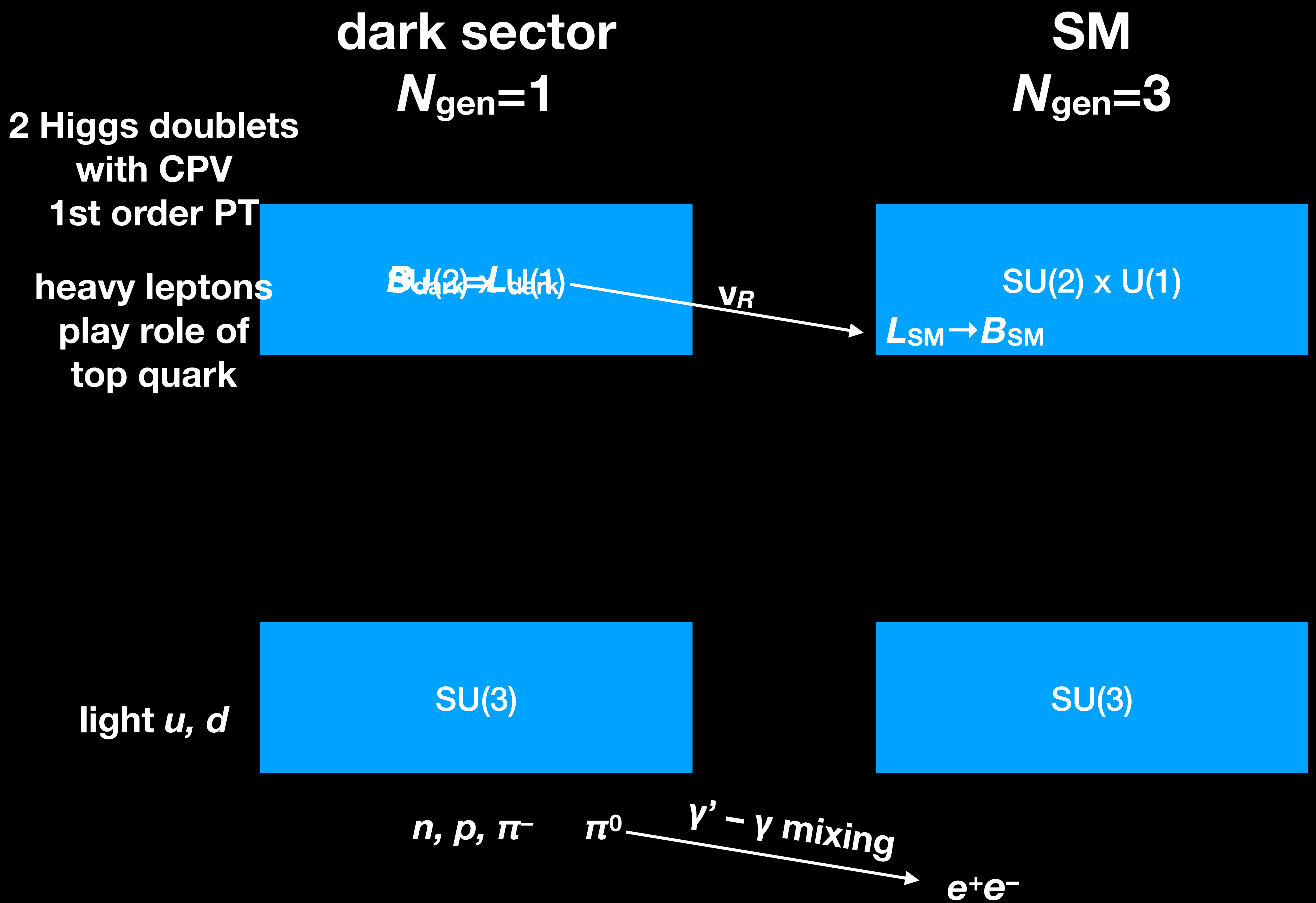
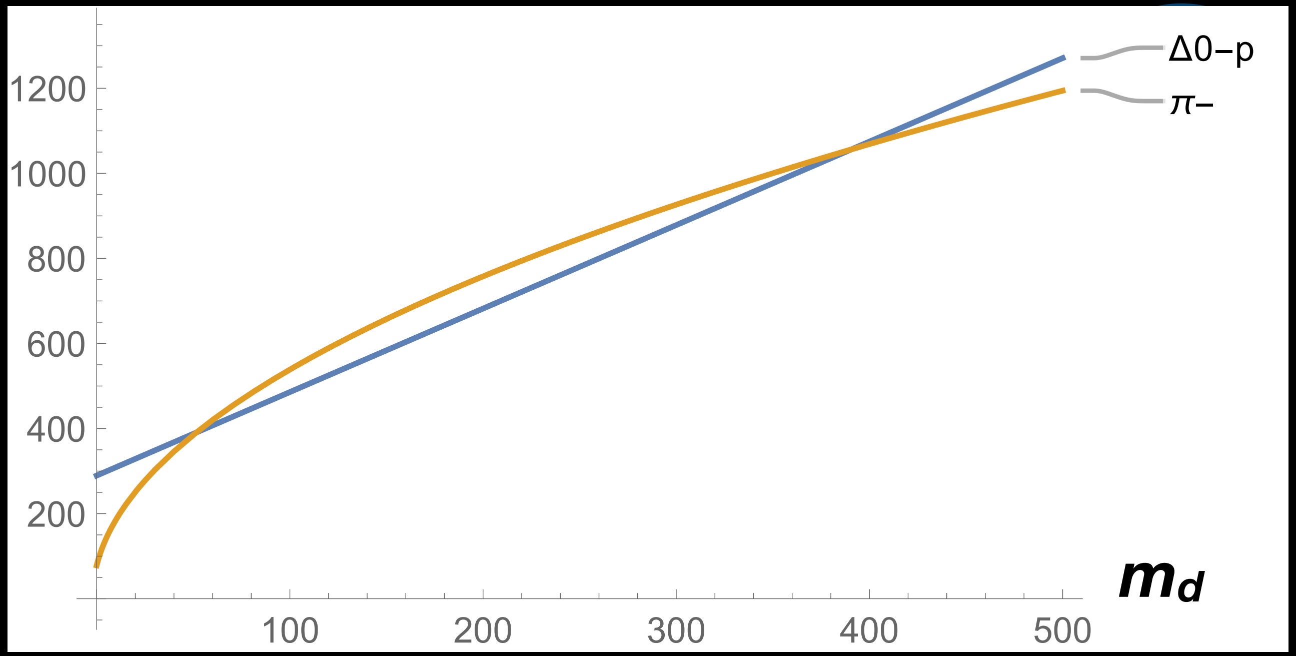
asymmetric dark matter

- Explains both baryon asymmetry and dark matter
- dark neutron, or multi-component dark $p+\pi^-$
- amazingly wide array of experimental signatures
  - dark proton good target for direct detection
  - exotic Z-decay, h-decay (HL-LHC, ILC, CEPC, FCC-ee)
  - dark photon search at Belle II, LHC-b, beam dump
  - gravitational wave at LIGO, LISA, Einstein Telescope, etc
  - self-interacting composite dark matter
  - mass ~ 1GeV
- explain coincidence $\Omega_{\mathrm{DM}} \sim \Omega_b$ if $N_{\mathrm{gen}}=3$ and unification

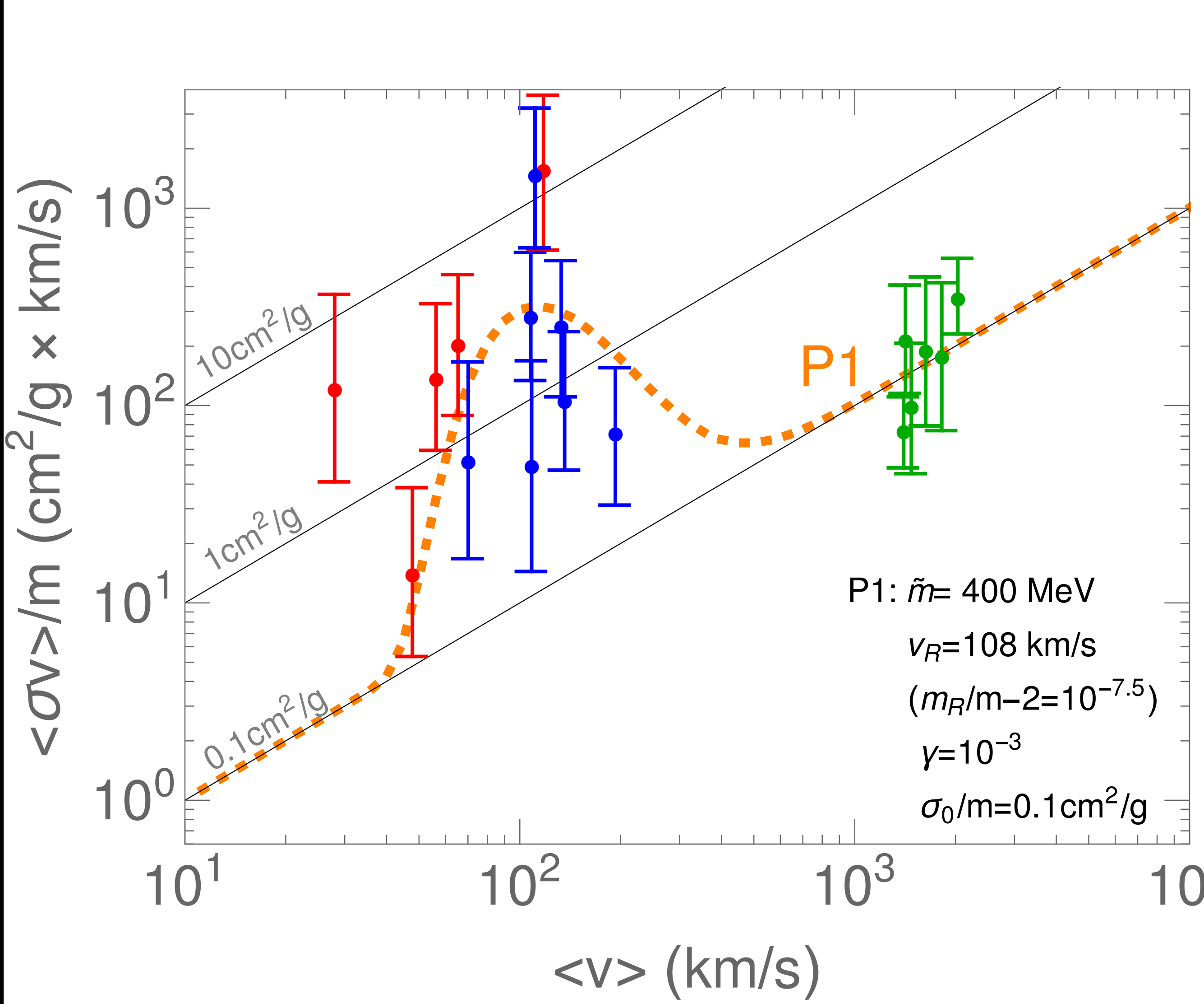

dark sector
$N_{\mathrm{gen}}=1$
SM
$N_{\mathrm{gen}}=3$
2 Higgs doublets
with CPV
1st order PT
heavy leptons
play role of
top quark
SU(2) x U(1)
$B_{\mathrm{dark}} \to L_{\mathrm{dark}}$
ν_R
SU(2) x U(1)
$L_{\mathrm{SM}} \to B_{\mathrm{SM}}$
light u, d
SU(3)
SU(3)
n, p, π^-
π^0
$\gamma' - \gamma$ mixing
e^+e^-

baryon spectrum

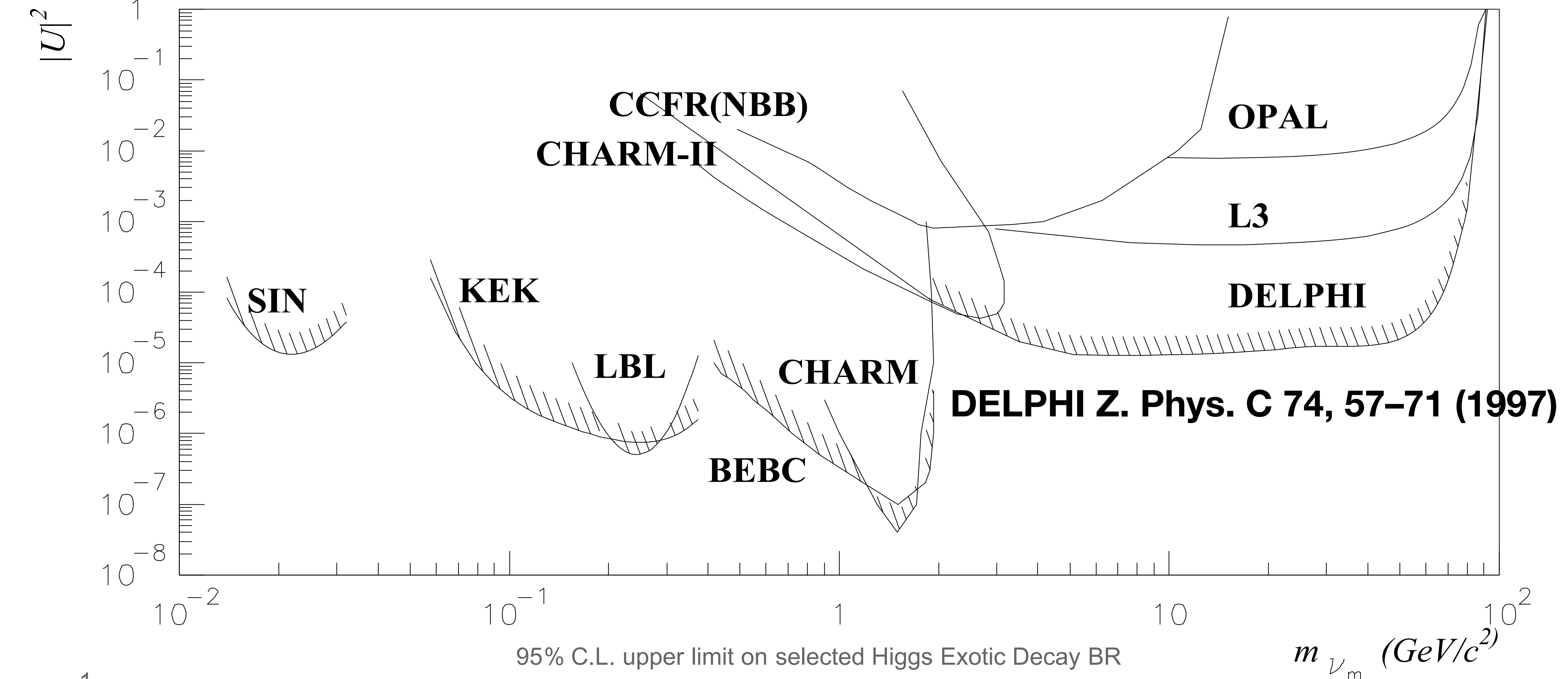
- m_u and m_d free parameters
- If $m_d \ll m_u \ll \Lambda_{\mathrm{QCD}}$, n' dominates
- If $m_u \ll m_d \ll \Lambda_{\mathrm{QCD}}$, p' dominates, together with π'^- for charge neutrality
  - possibly a resonant interaction $\pi'^- p' \to \Delta^0 \to \pi'^- p'$
  - may solve core/cusp problem

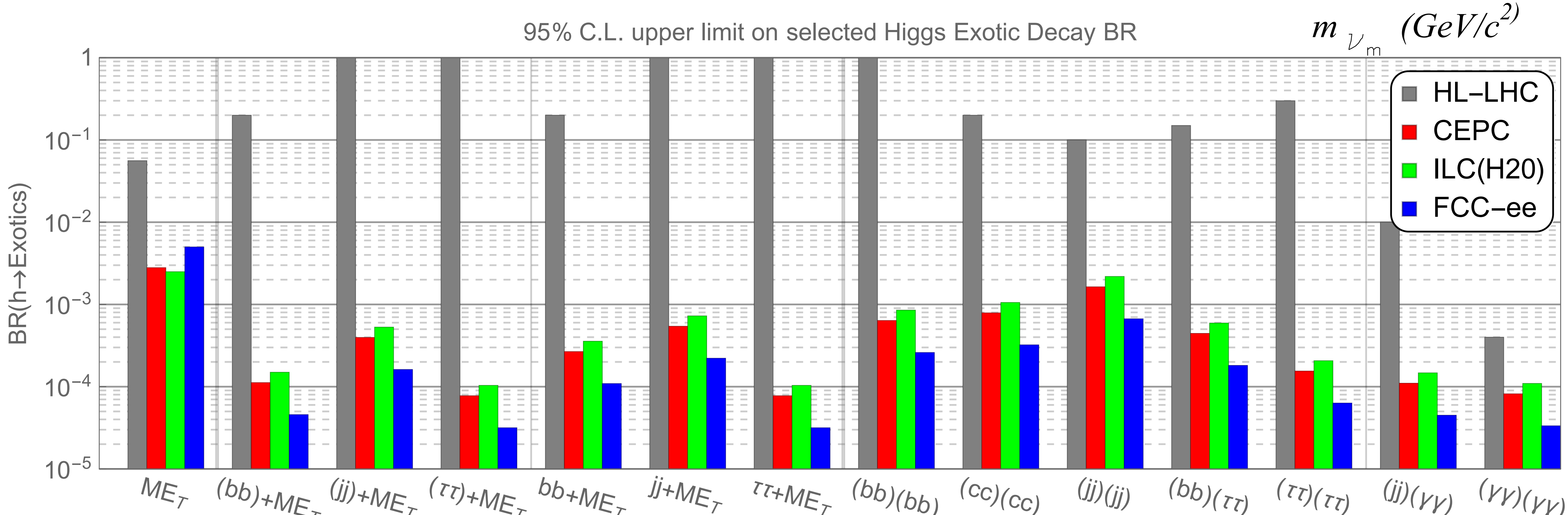


Robert McGehee, HM, Yu-Dai Tsai, in prep

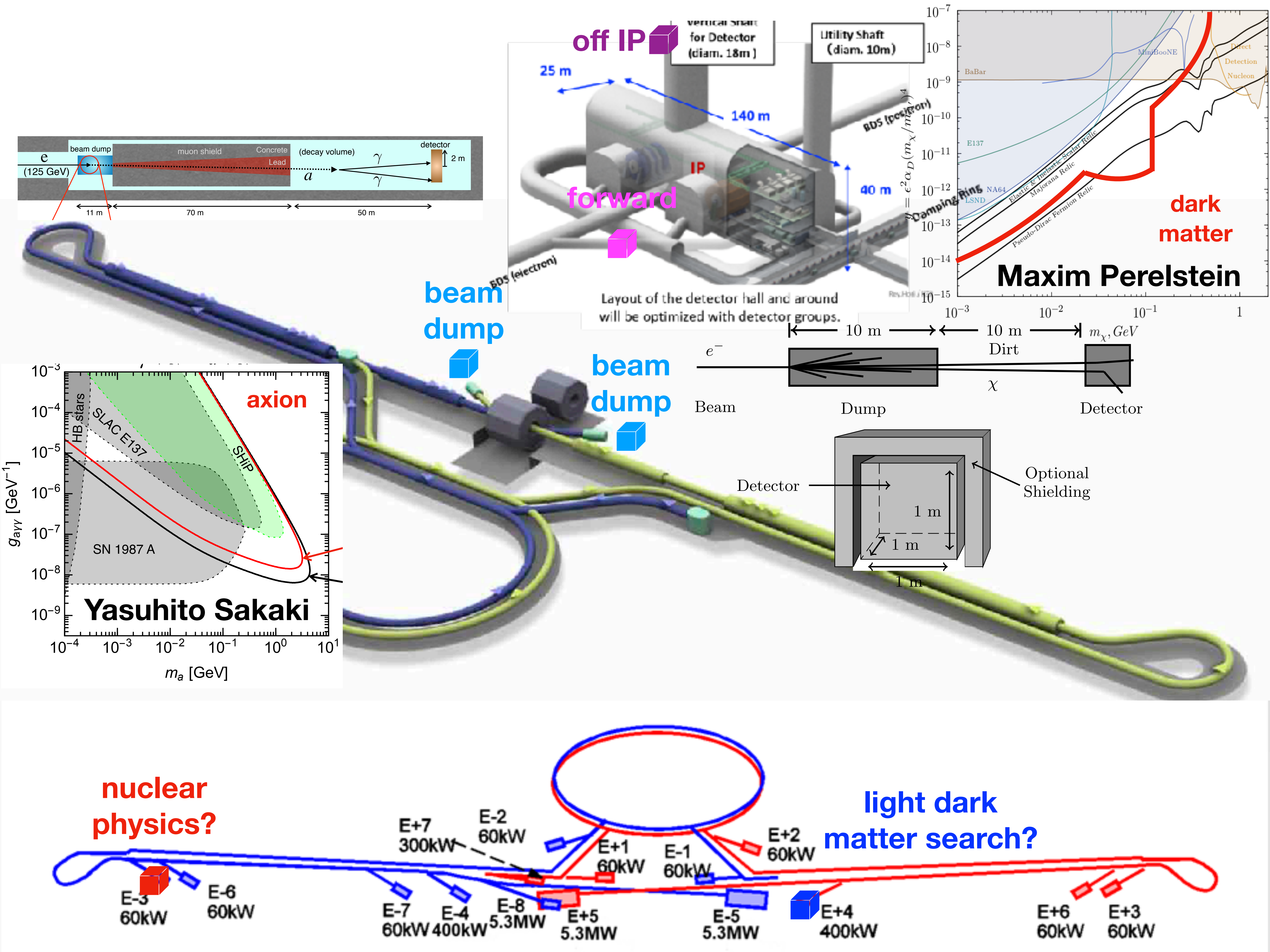


Xiaoyong Chu, Camilo Carcia-Cely, HM, Phys.Rev.Lett. 122 (2019) no.7, 071103

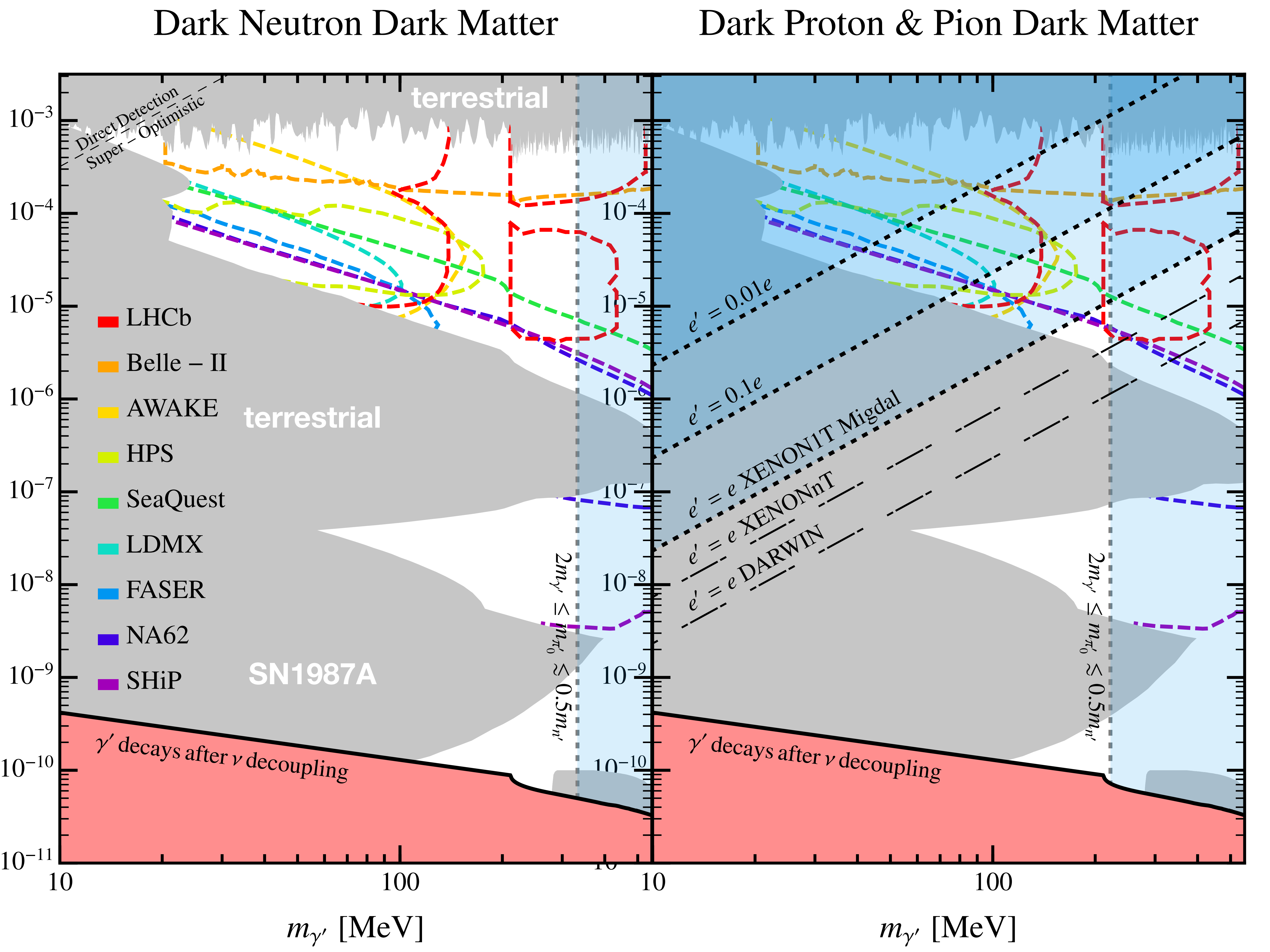




Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

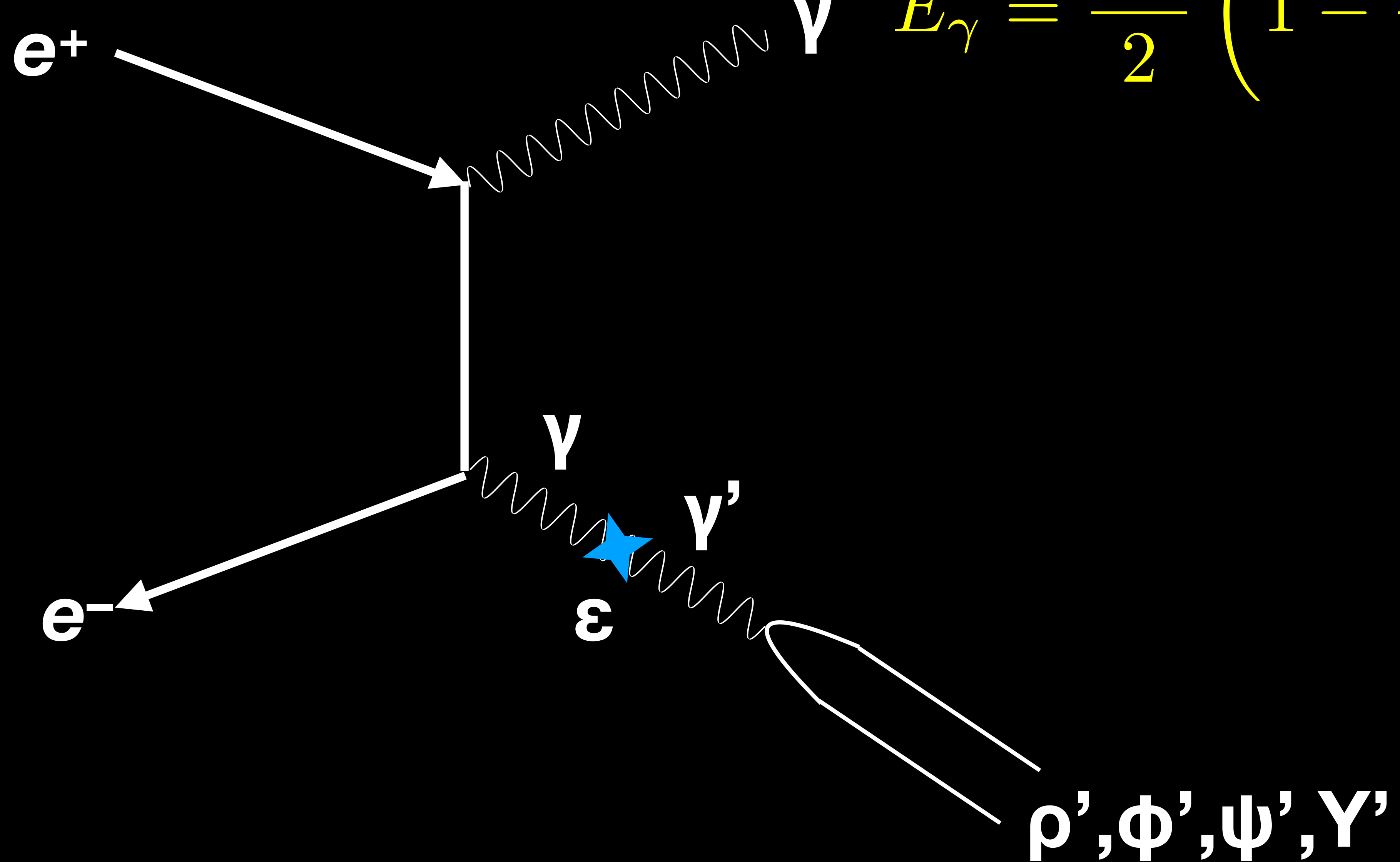


off IP
Vertical Shaft for Detector (diam. 18m)
Utility Shaft (diam. 10m)
25 m
140 m
40 m
IP
forward
BDS (positron)
BDS (electron)
Damping Ring
Layout of the detector hall and around will be optimized with detector groups.
beam dump
beam dump
e
(125 GeV)
beam dump
muon shield
Concrete
Lead
(decay volume)
detector
2 m
11 m
70 m
50 m
dark matter
Maxim Perelstein
BaBar
E137
NA64
LSND
MiniBooNE
Direct Detection Nucleon
Elastic & Inelastic Scalar Relic
Majorana Relic
Pseudo-Dirac Fermion Relic
m_χ, GeV
10 m
10 m
Dirt
Beam
Dump
Detector
Detector
Optional Shielding
1 m
1 m
1 m
axion
HB stars
SLAC E137
SHiP
SN 1987 A
Yasuhito Sakaki
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [GeV]
nuclear physics?
light dark matter search?
E+7 300kW
E-2 60kW
E+1 60kW
E-1 60kW
E+2 60kW
E-3 60kW
E-6 60kW
E-7 60kW
E-4 400kW
E-8 5.3MW
E+5 5.3MW
E-5 5.3MW
E+4 400kW
E+6 60kW
E+3 60kW



Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
Direct Detection
Super – Optimistic
LHCb
Belle – II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ' decays after ν decoupling
$2m_{\gamma'} \leq m_{\pi'_0} \lesssim 0.5 m_{n'}$
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
$m_{\gamma'}$ [MeV]

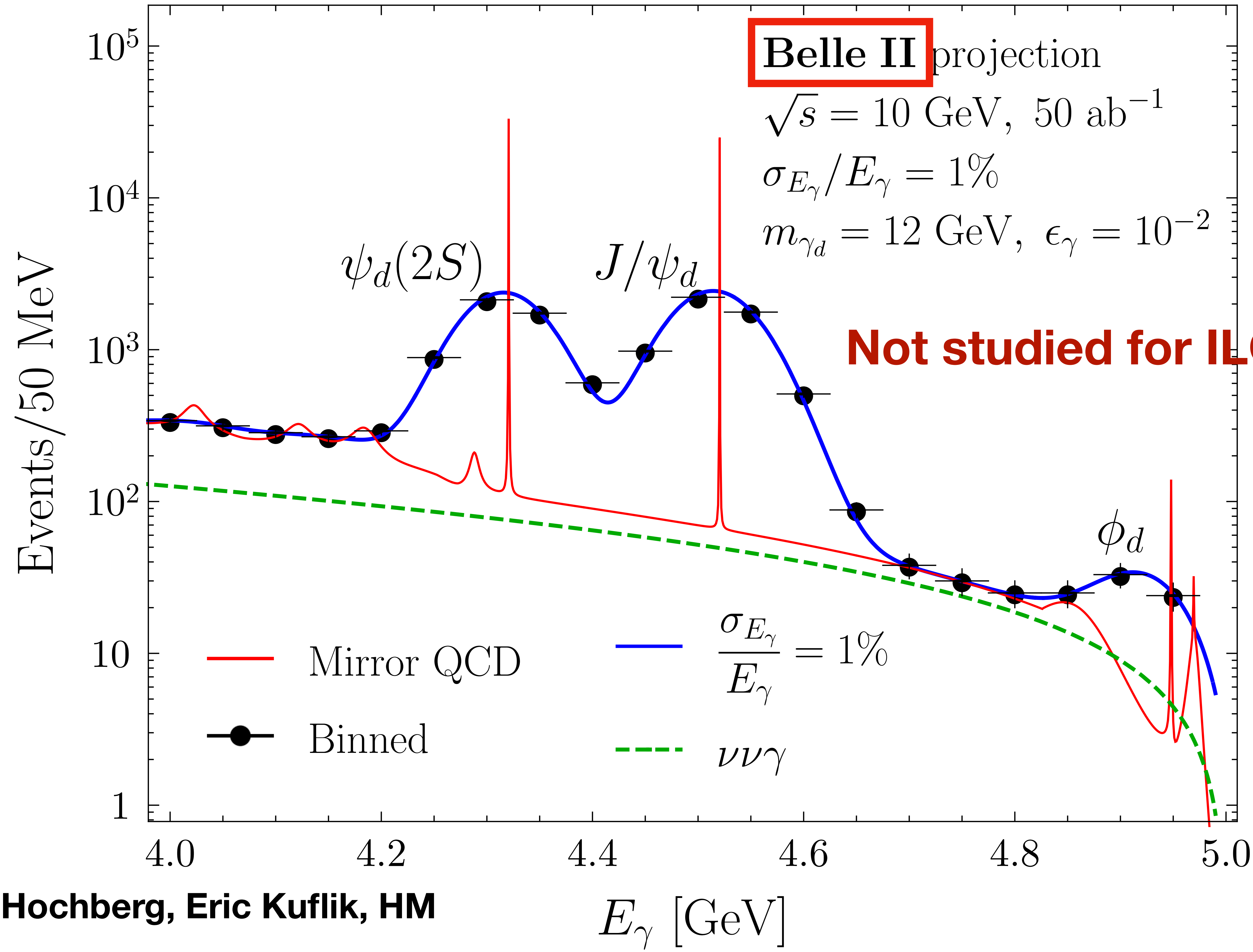
Dark Spectroscopy



$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$

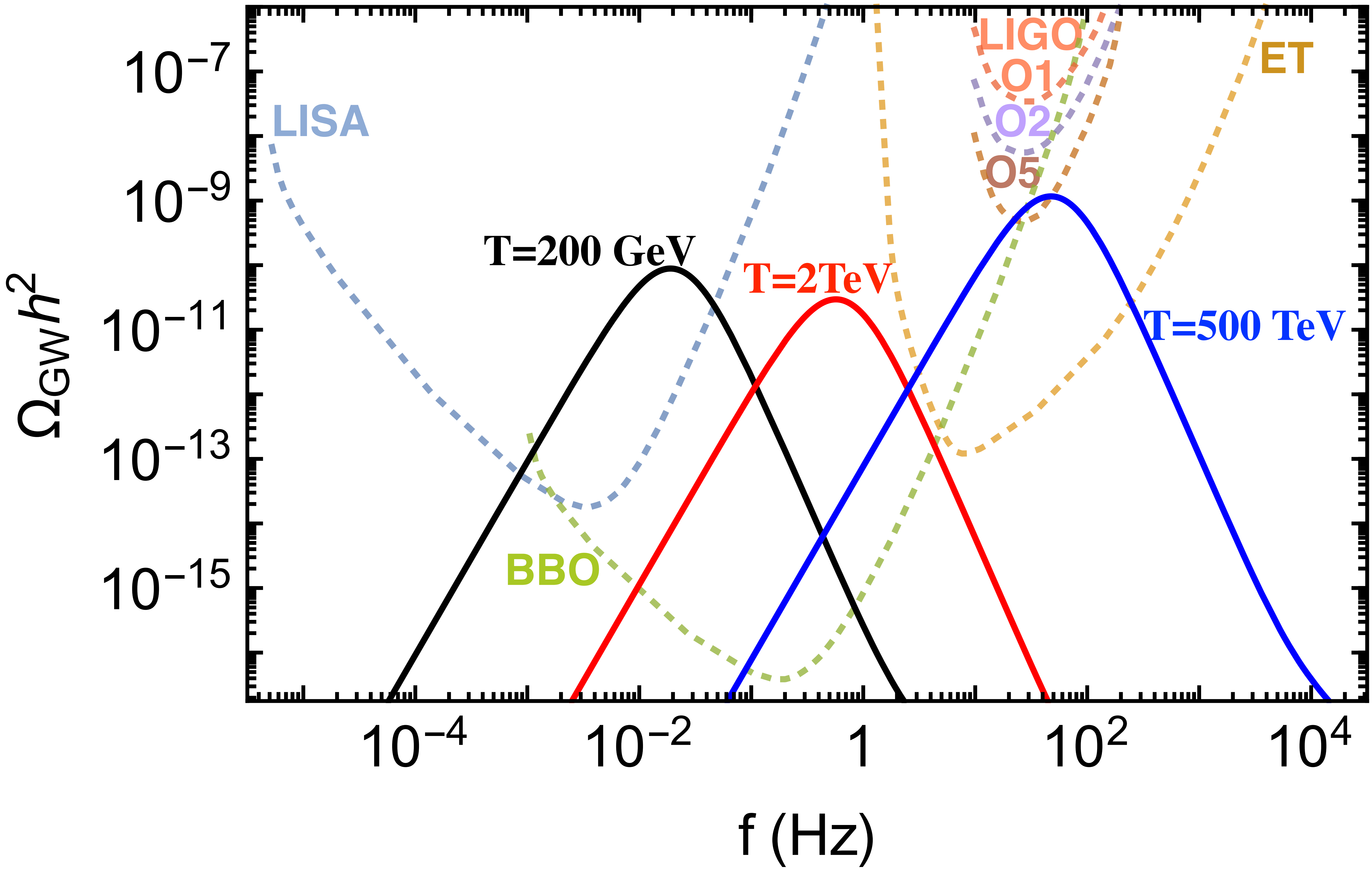
Yonit Hochberg, Eric Kuflik, HM, arXiv:1512.07917, 1706.05008

Dark Spectroscopy



Not studied for ILC yet!

Yonit Hochberg, Eric Kuflik, HM



LISA
LIGO
O1
O2
O5
ET
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)

Today & Tomorrow

- review progress since the launch
- solicited proposals
- seek reinforcements, new directions
- Looking forward to exciting two days!