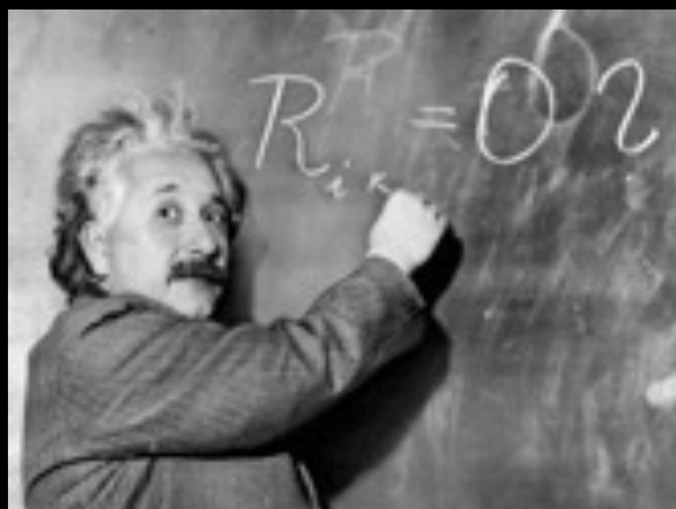
Cosmic Acceleration Overview

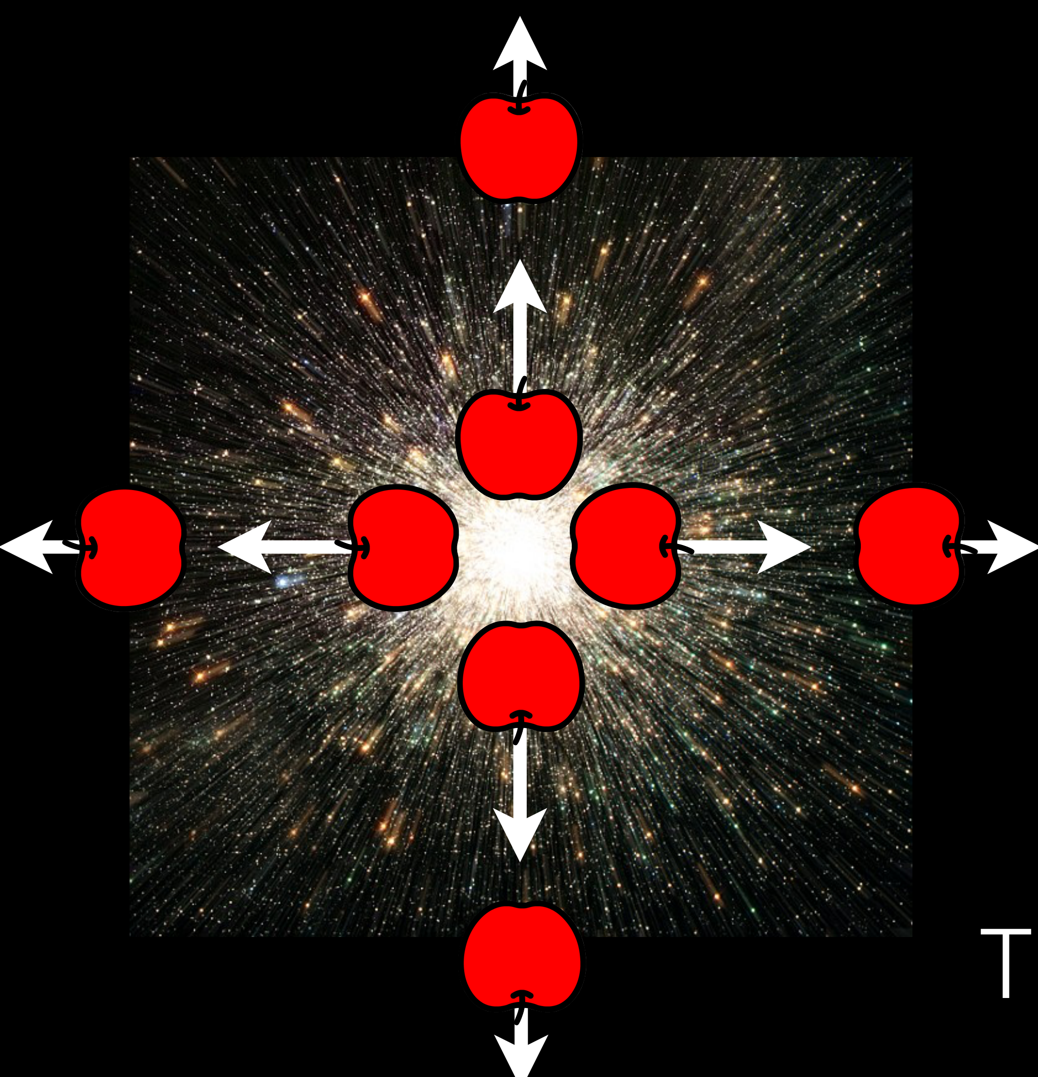
Hitoshi Murayama (Berkeley, Kavli IPMU)

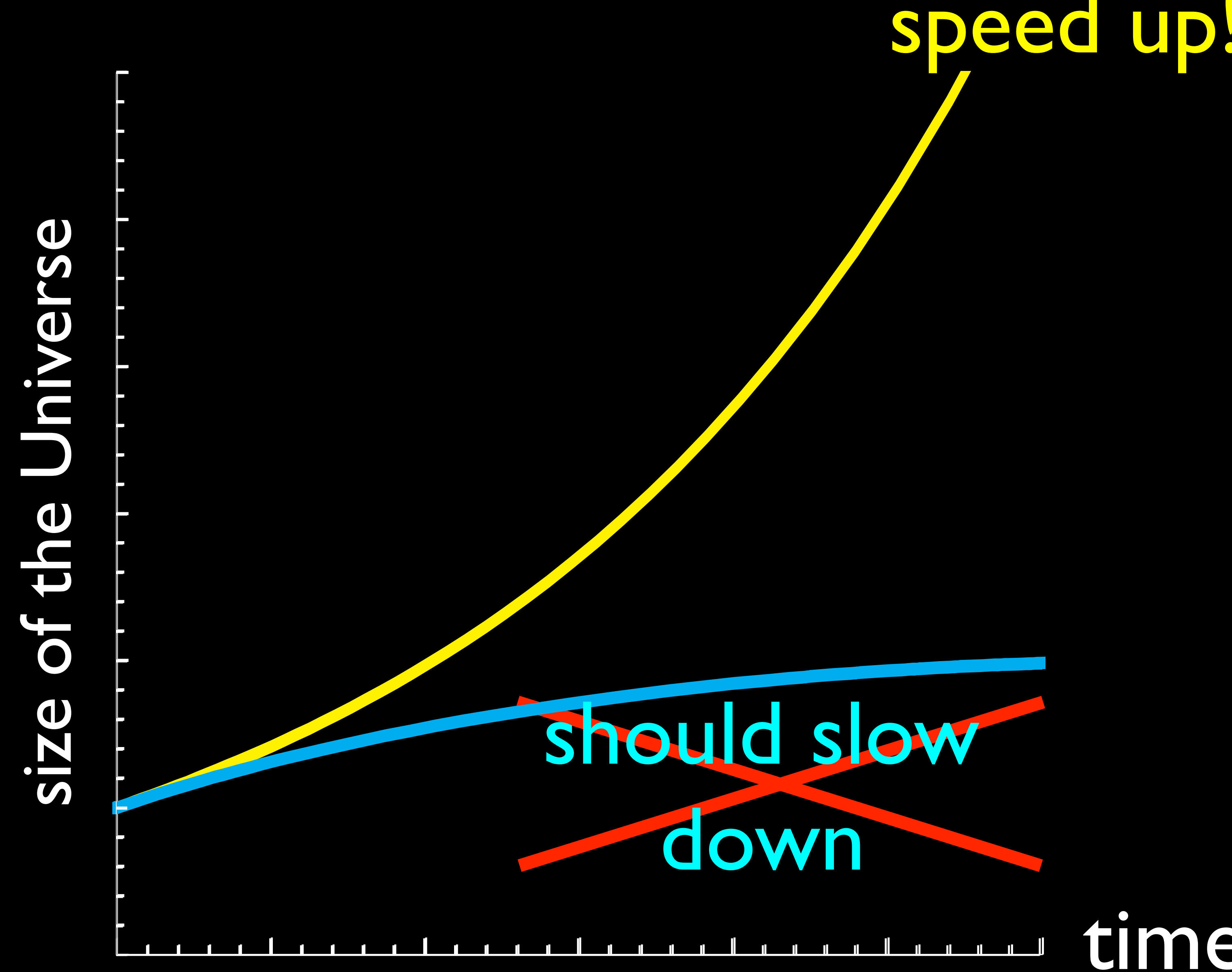
February 17, 2020 Kavli IPMU

NASA/WMAP Science Team

Cosmic Expansion



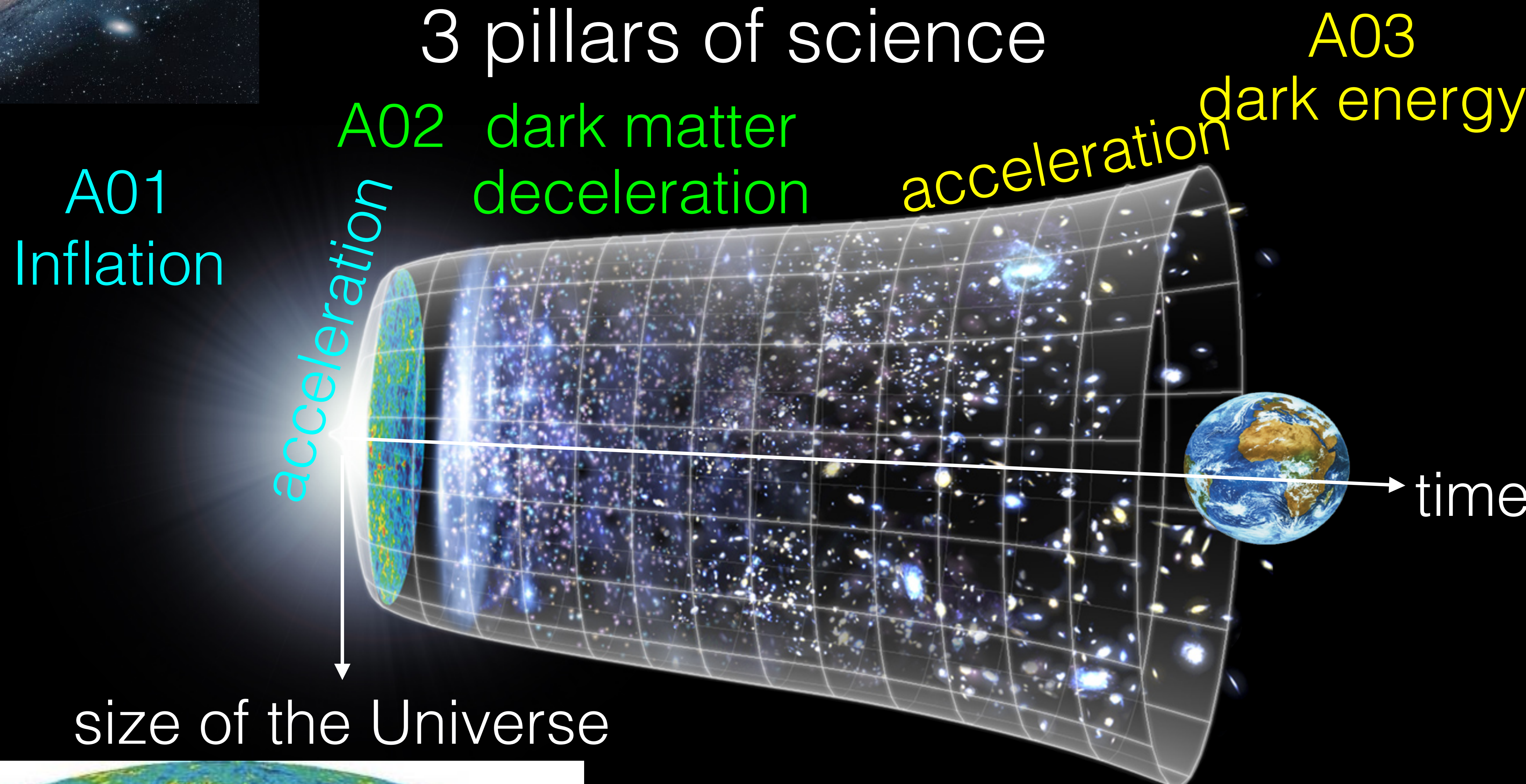


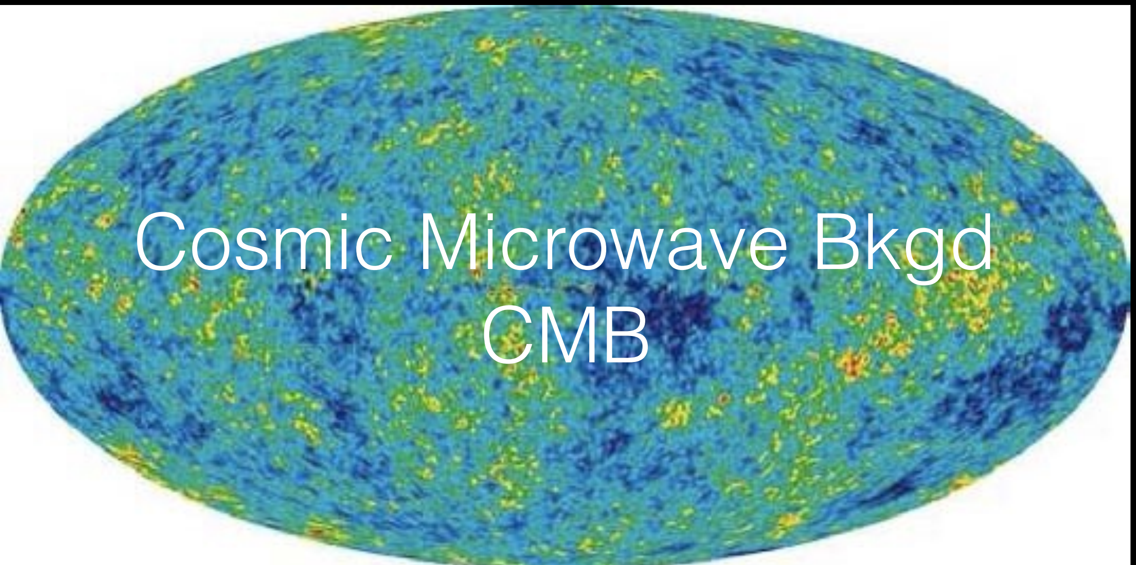


Gravity only pulls
Something is pushing the expansion
The biggest mystery in modern physics!

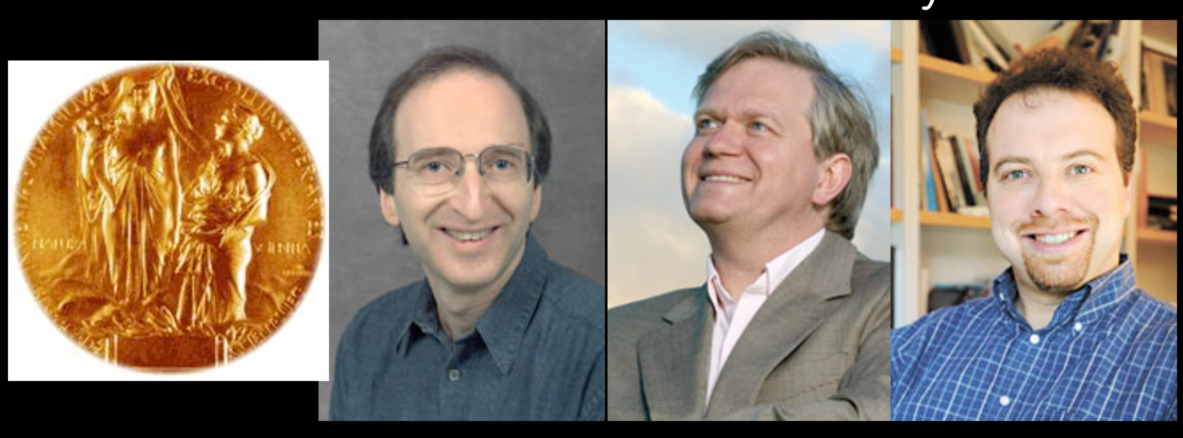
Phases of cosmic expansion

3 pillars of science





2011 Nobel Prize in Physics



3 pillars of science (theory)

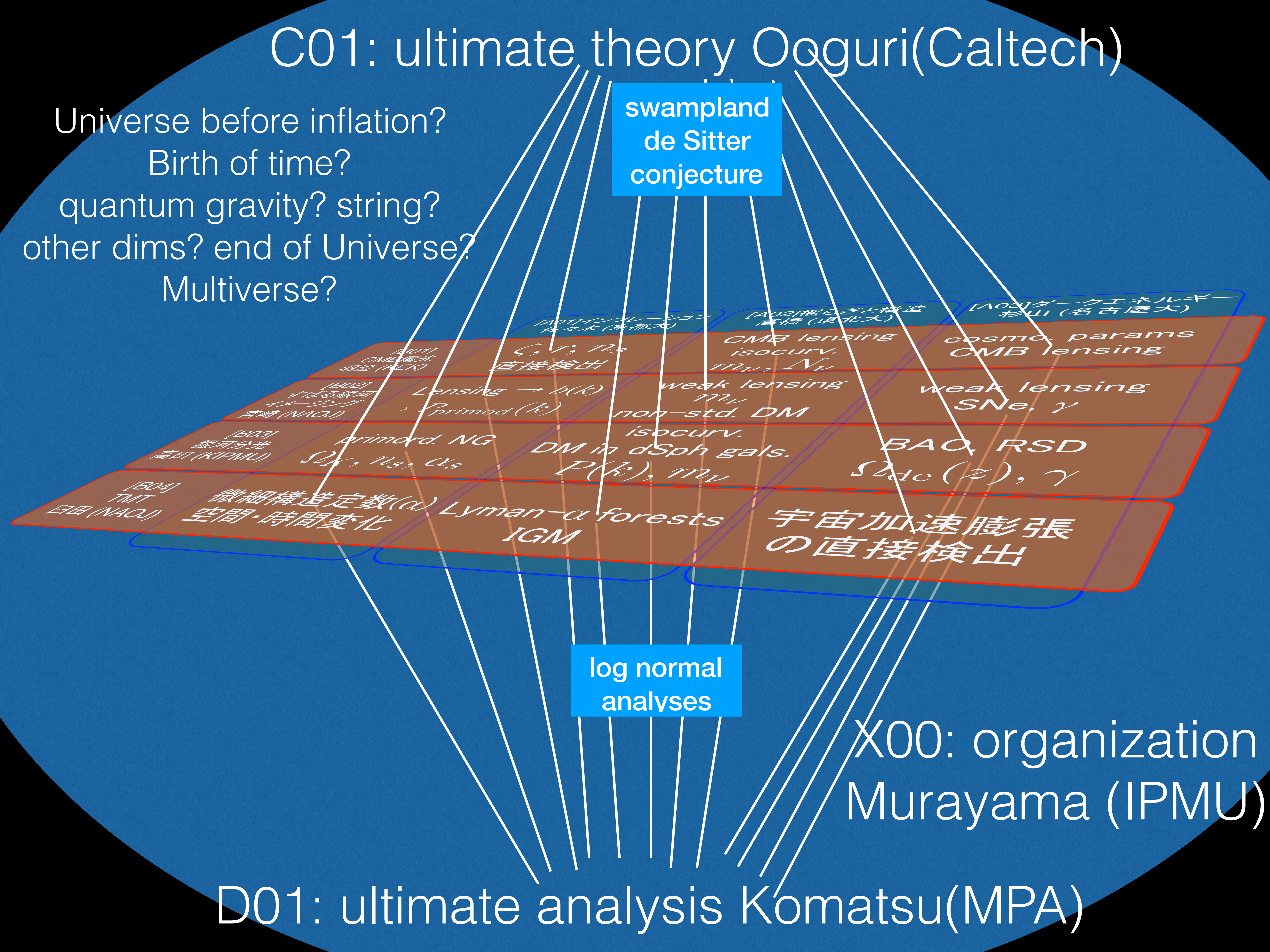
4 approaches (expt, obs)

	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n direct **Simons Array completed**	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
[B02] Subaru galaxy imaging Miyazaki(NAOJ)	Lensing → $b(k)$ $\rightarrow P_{\rm primod}(k)$	weak lensing l. DM **PBH limits on Subaru**	γ **HSC cosmic shear**
[B03] galaxy spectroscopy Takada(KIPMU)	primord. NG Ω_K, n_s, α_s	isocurv. DM in d $P($ **PFS galactic archaeology**	BAO, RSD $\Omega_{\rm de}$ **PFS construction**
[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman-α forests IGM	direct detection of acce **frequency comb R&D**

PFS construction at full steam with 2022 start!

LiteBIRD approved by JAX for 2027 launch!

important observables at each intersection

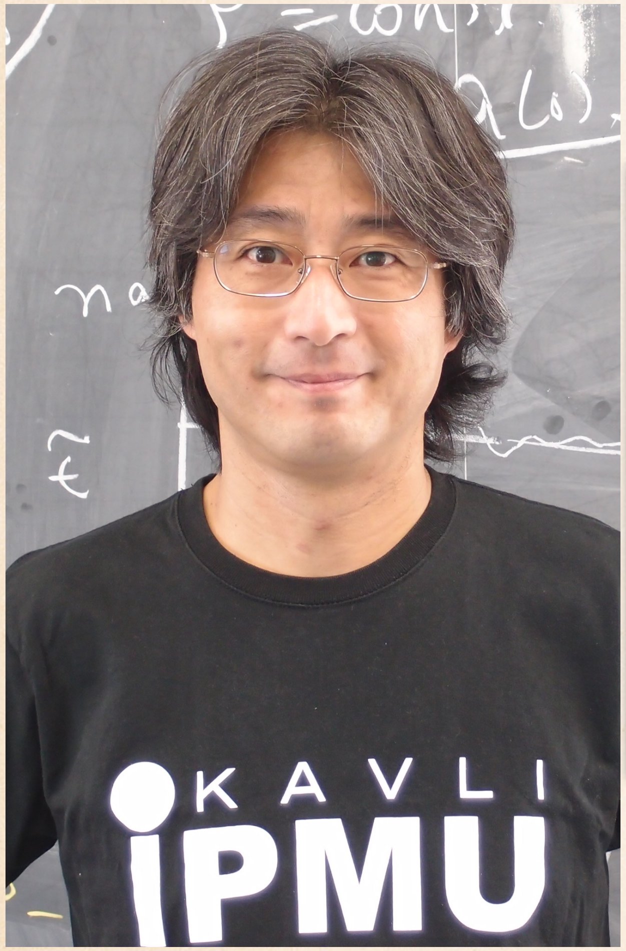

C01: ultimate theory Ooguri(Caltech)
Universe before inflation?
Birth of time?
quantum gravity? string?
other dims? end of Universe?
Multiverse?
swampland
de Sitter
conjecture
[A01]インフレーション
佐々木(京都大)
[A02]揺らぎと構造
高橋(東北大)
[A03]ダークエネルギー
杉山(名古屋大)
[B01]
CMB偏光
羽澄(KEK)
ζ, r, n_s
直接検出
CMB lensing
isocurv.
m_ν, N_ν
cosmo. params
CMB lensing
[B02]
すばる銀河
イメージング
宮崎(NAOJ)
Lensing $\rightarrow b(k)$
$\rightarrow P_{\rm primod}(k)$
weak lensing
m_ν
non-std. DM
weak lensing
SNe, γ
[B03]
銀河分光
高田(KIPMU)
primord. NG
Ω_K, n_s, α_s
isocurv.
DM in dSph gals.
$P(k), m_\nu$
BAO, RSD
$\Omega_{\rm de}(z), \gamma$
[B04]
TMT
臼田(NAOJ)
微細構造定数(α)
空間・時間変化
Lyman$-\alpha$ forests
IGM
宇宙加速膨張
の直接検出
log normal
analyses
X00: organization
Murayama (IPMU)
D01: ultimate analysis Komatsu(MPA)

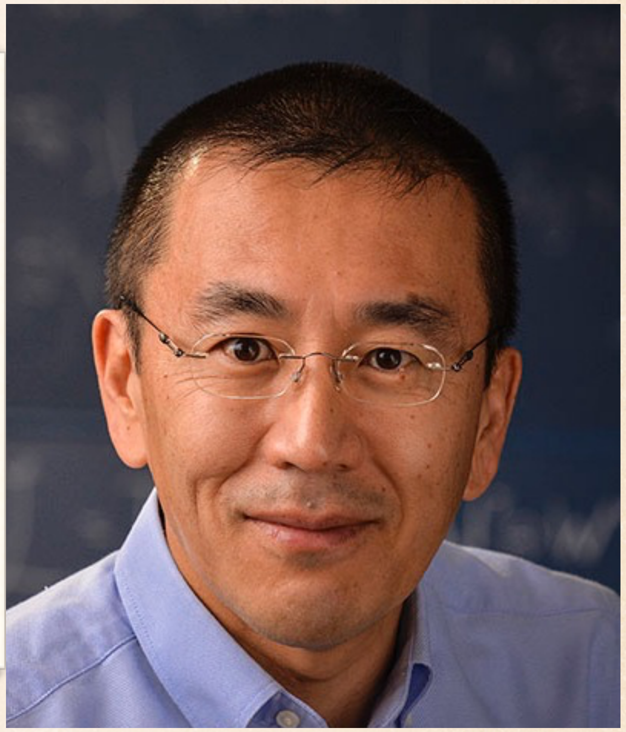
How far have we come?
What lies ahead?

Oct 15, 2018

Kavli IPMU became officially a permanent institute on April 1, 2018

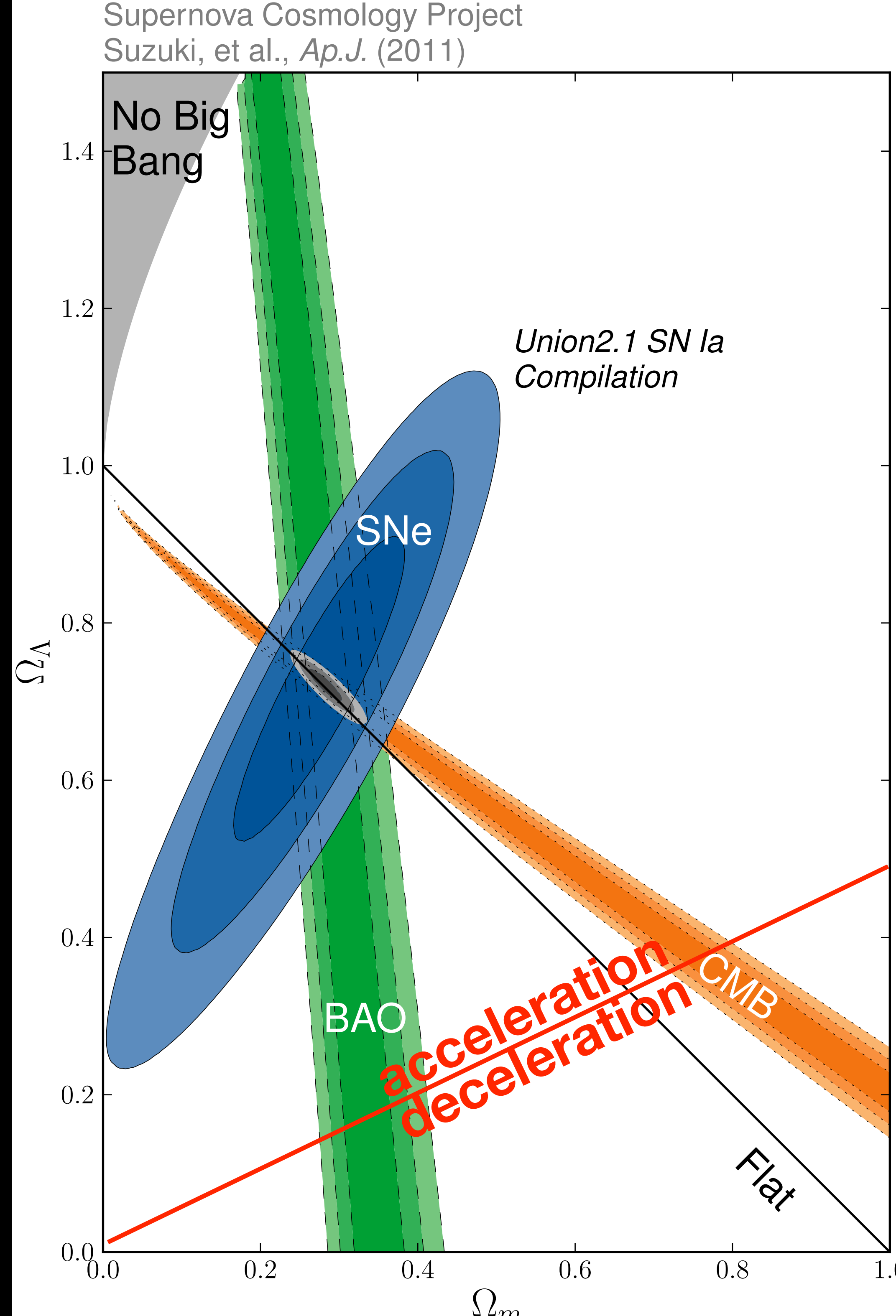
PASSING THE TORCH



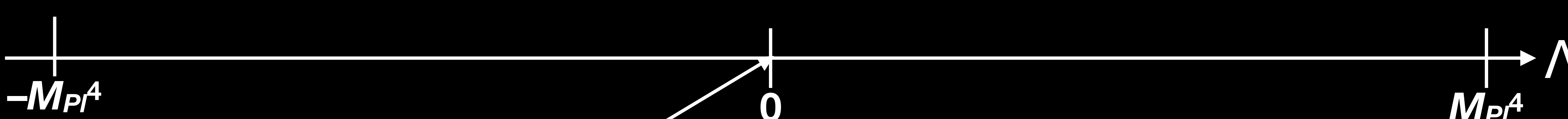


Oct 15, 2018


KAVLI
東京大学



$\Lambda \approx 10^{-120}\, M_{Pl}^4 > 0$



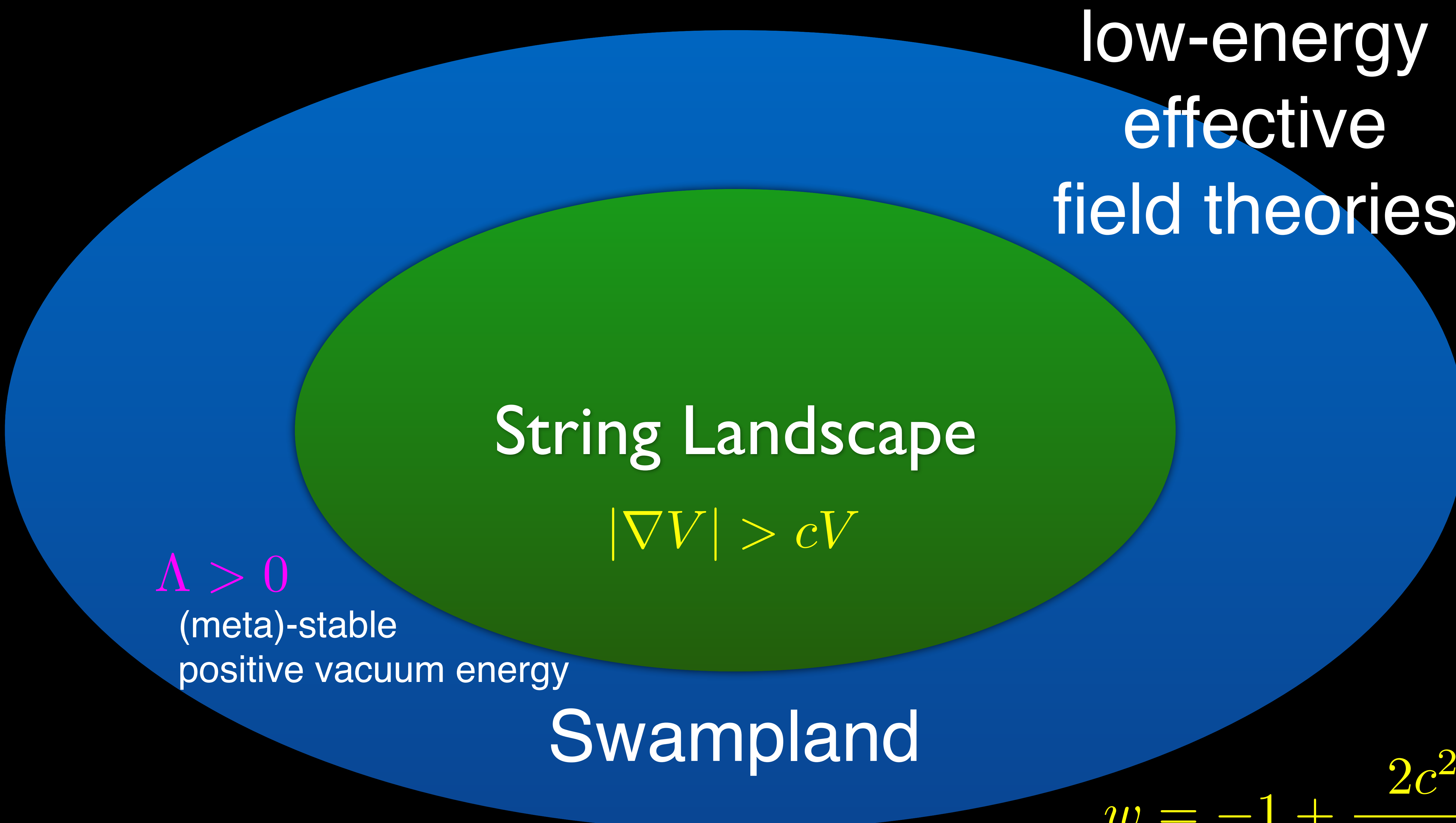
You are here

Anthropic Principle? Multiverse?


Beautiful Landscape
only Λ and w=−1
nothing interesting with measuring w!

C01

Most cited elementary particle theory paper in 2018

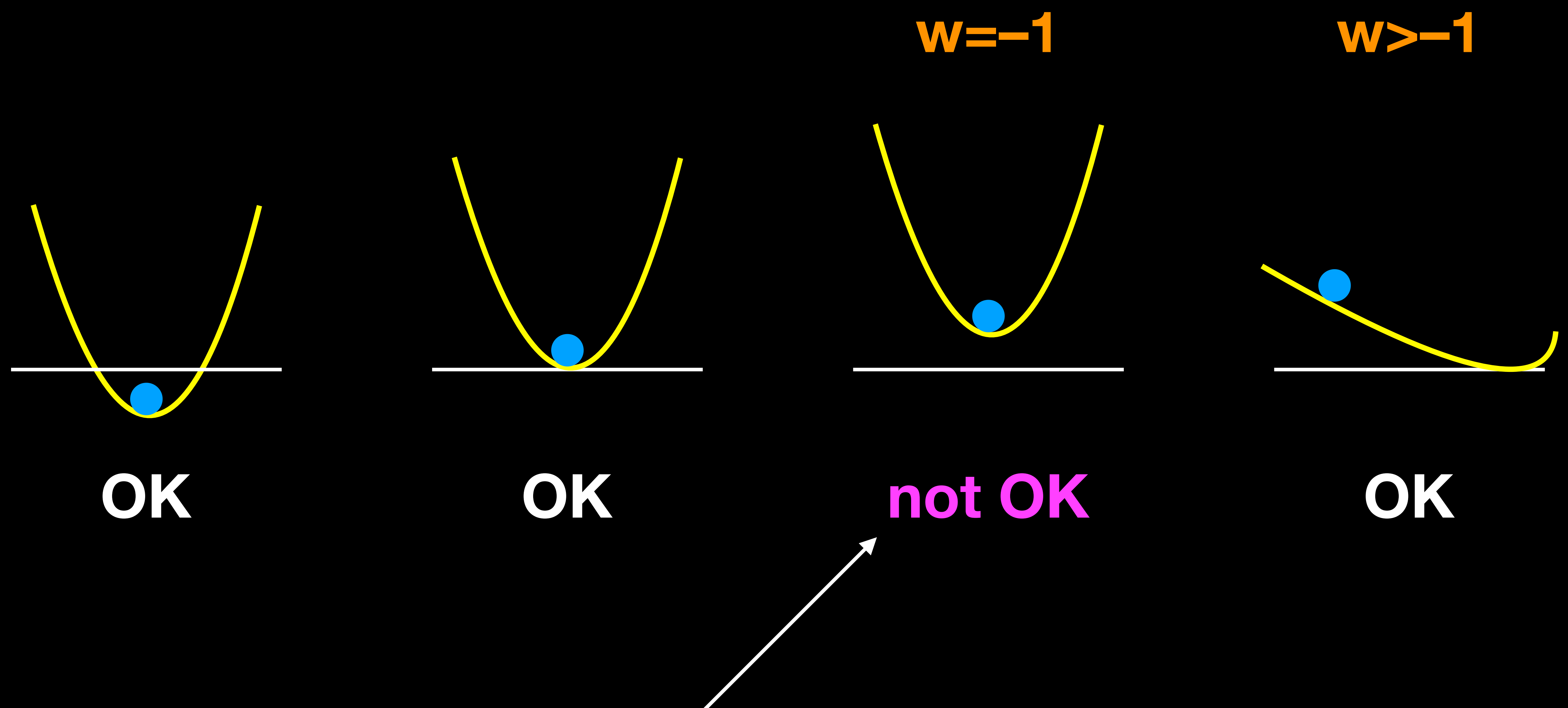


$$w = -1 + \frac{2c^2}{6+c^2}$$

Obied, Ooguri, Spodyneiko, Vafa, arXiv:1806.08362

the conjecture

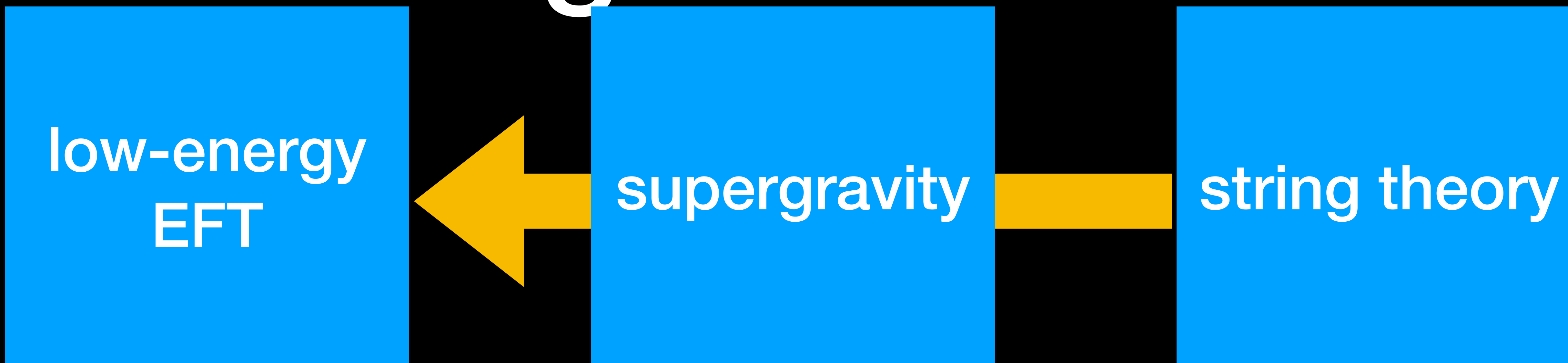
$$|\nabla V| > cV$$



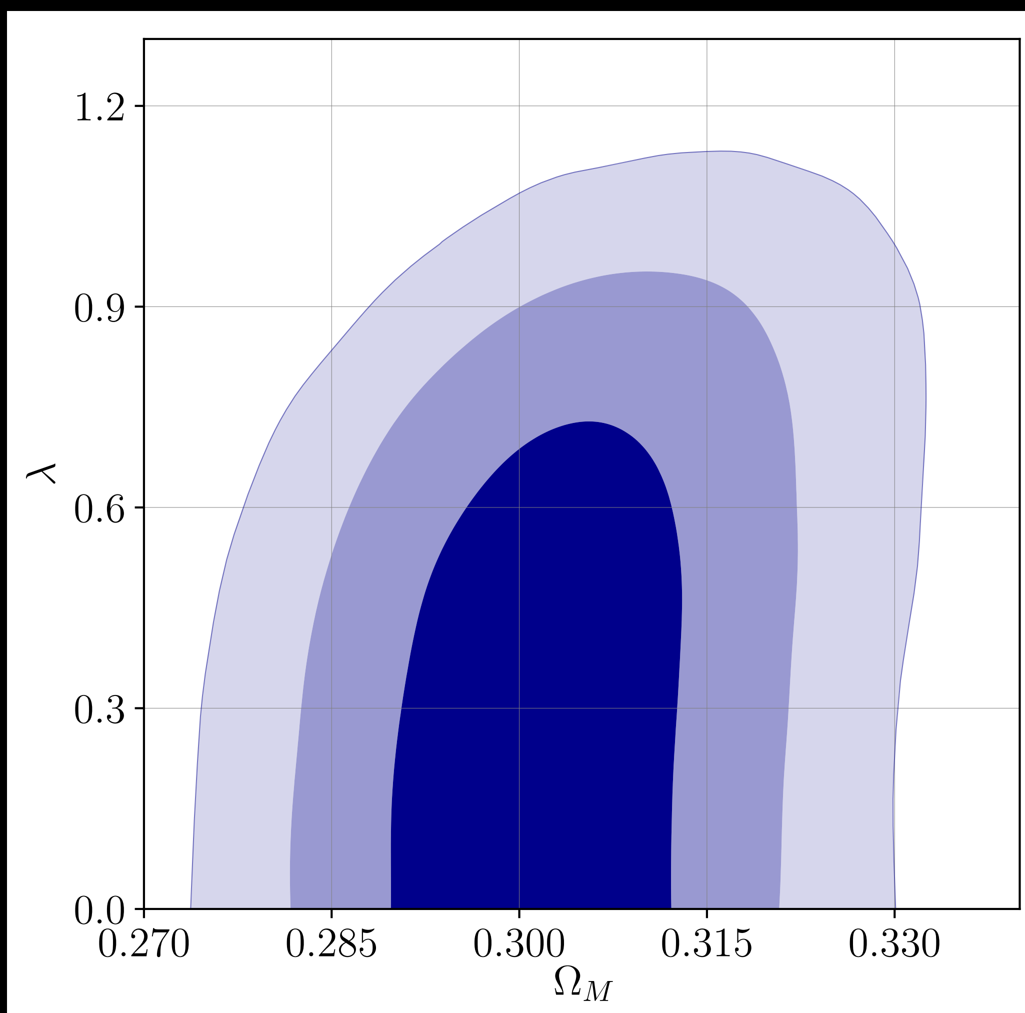
“It is thus fair to say that these scenarios have not yet been rigorously shown to be realized in string theory.”

$|\nabla V| > cV$

rolling scalar field



- very difficult to keep flat potential for Q
- difficult for inflation $m_\varphi \sim H_I \sim 10^{21}$ eV
- we need $m_Q \sim H_0 \sim 10^{-33}$ eV
- SUSY broken, $m_{3/2} > (\mathrm{TeV}^2/M_{Pl}) \sim$ eV
- often a long-range fifth force
- *found a general prescription to promote any potential to supergravity without a fifth force*
- e.g., $V=\Lambda^4 e^{-\lambda\varphi}$

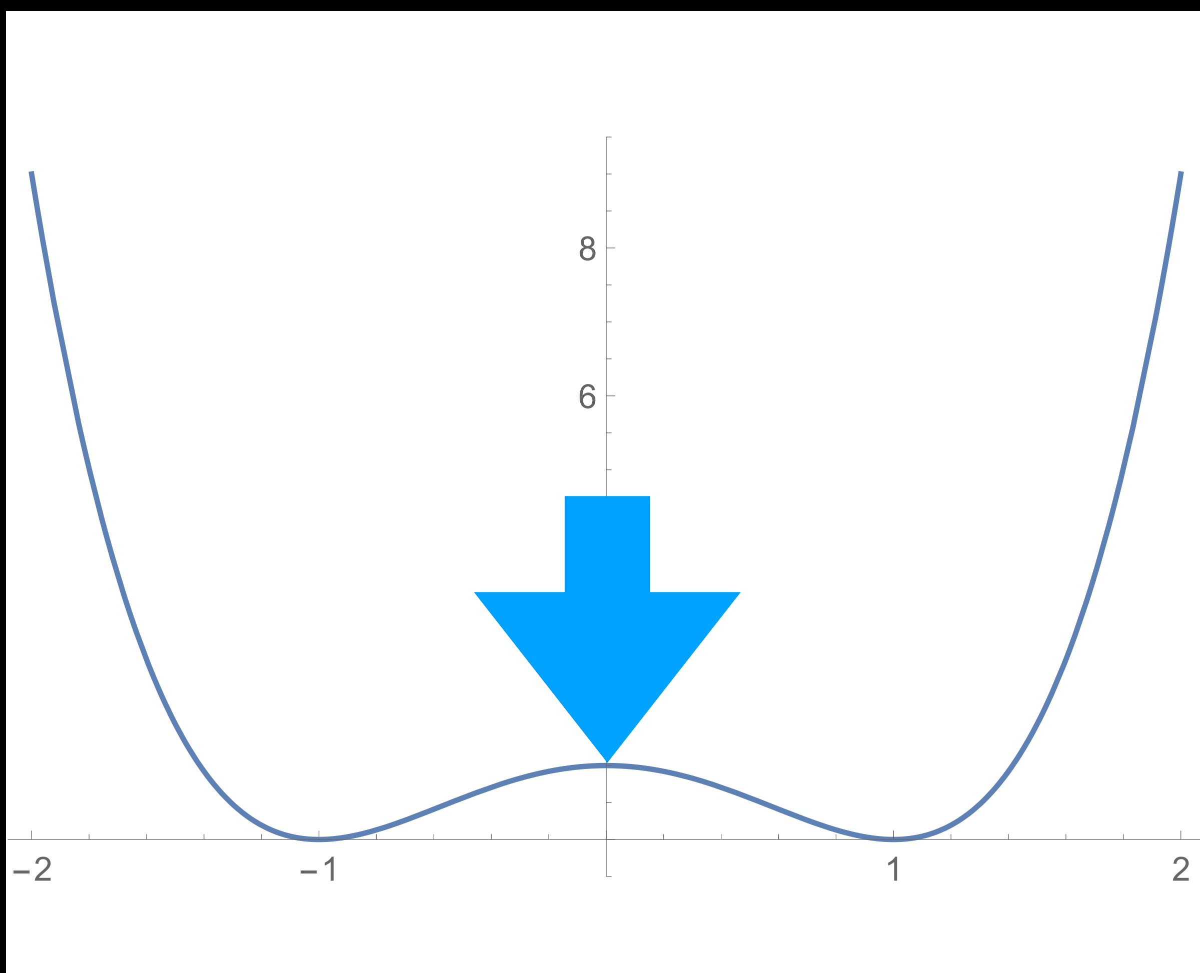


Akrami, Kallosh, Linde, Vardanyan, arXiv:1808.09440

Chien-I Chiang, HM, arXiv:1808.02279

SM is in swampland

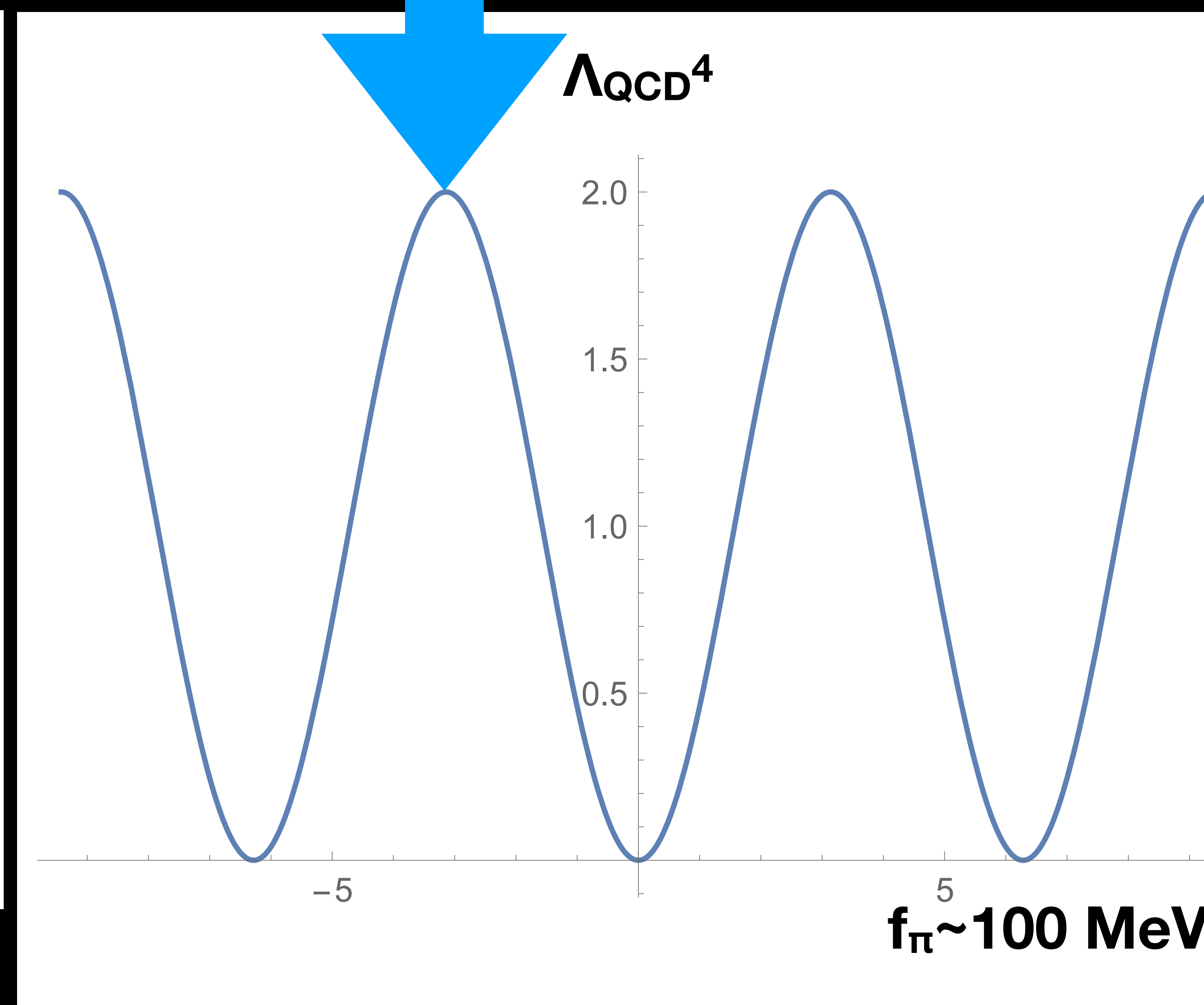
Standard Model Higgs potential has a local maximum ∇V=0



$$V = e^{-\lambda' Q}\lambda(H^\dagger H - v^2)^2$$

Exactly the same issue with GUTs!

So has QCD in chiral Lagrangian

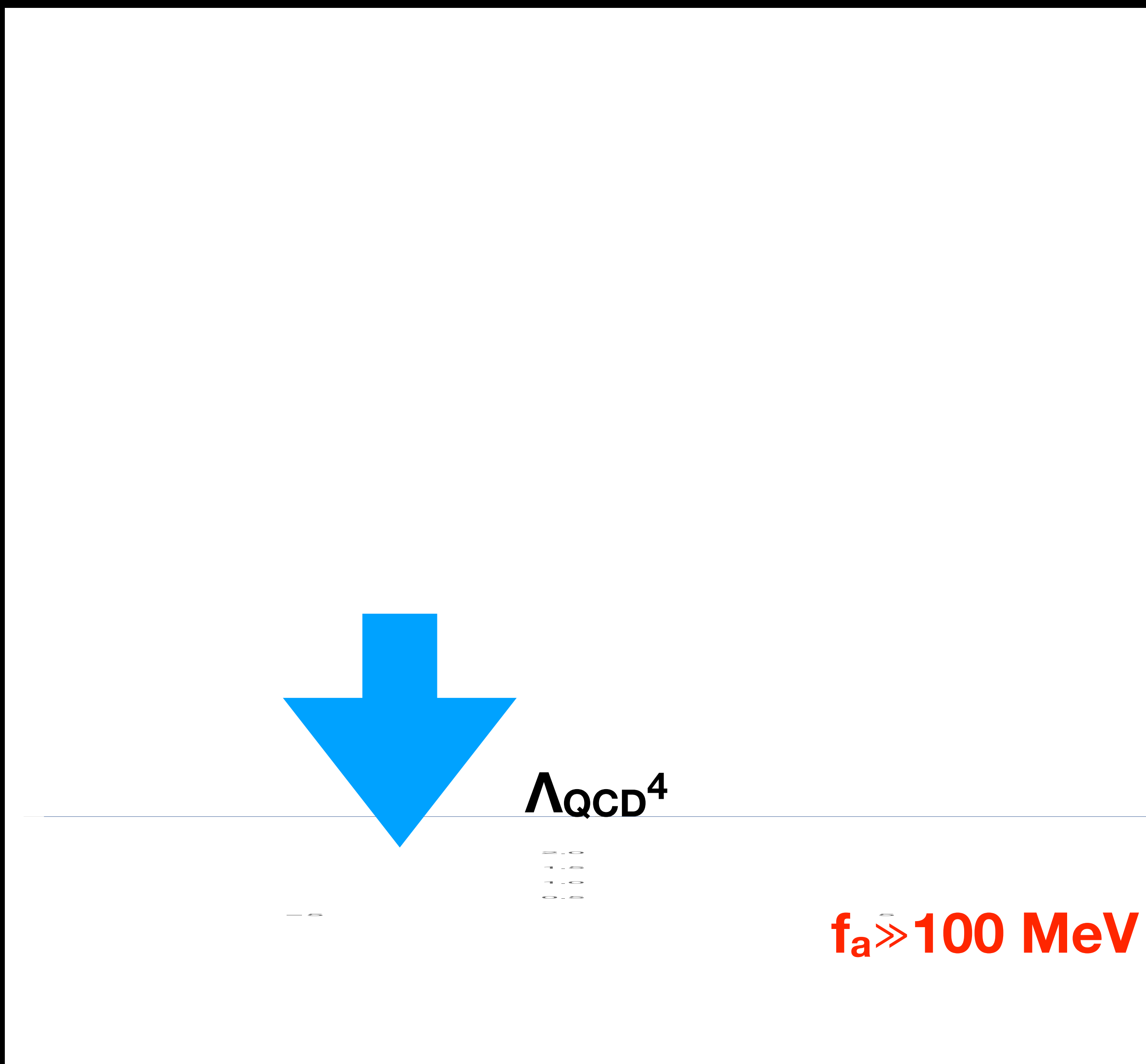


Frederik Denef, Arthur Hebecker, and Timm Wrase, arXiv:1807.06581

HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478

Beyond Standard Model

QCD axion



Supersymmetry Breaking

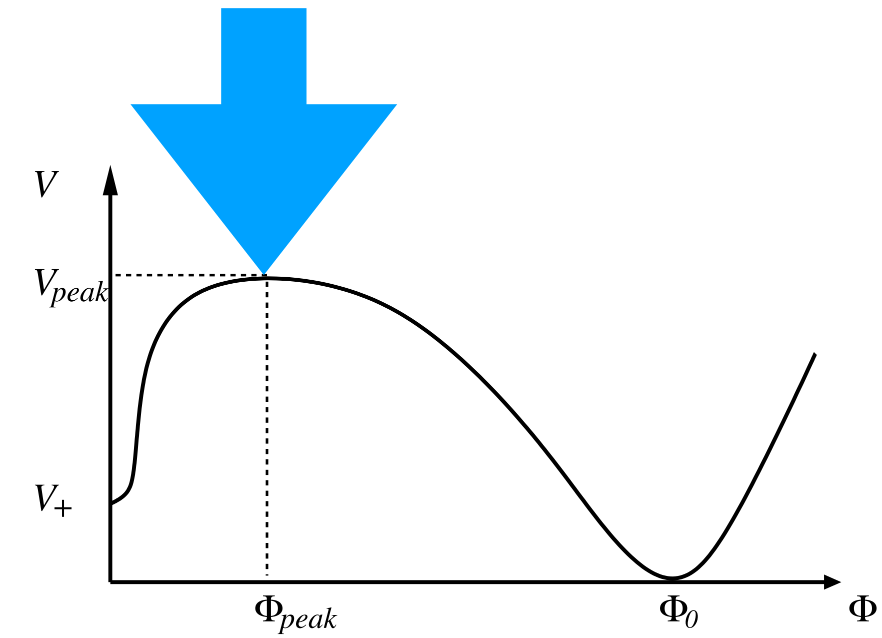


Figure 1: *The potential along the bounce trajectory. The peak is at $\Phi_{peak} \sim \mu$ and the supersymmetric minimum with vanishing potential is at large field $\Phi_0 \sim \mu/\epsilon^{(N_f-3N)/(N_f-N)} \gg \mu$. The values of the potential at the local minimum V_+ and at the peak V_{peak} are of order μ^4.*

HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478

Inflation is in swampland

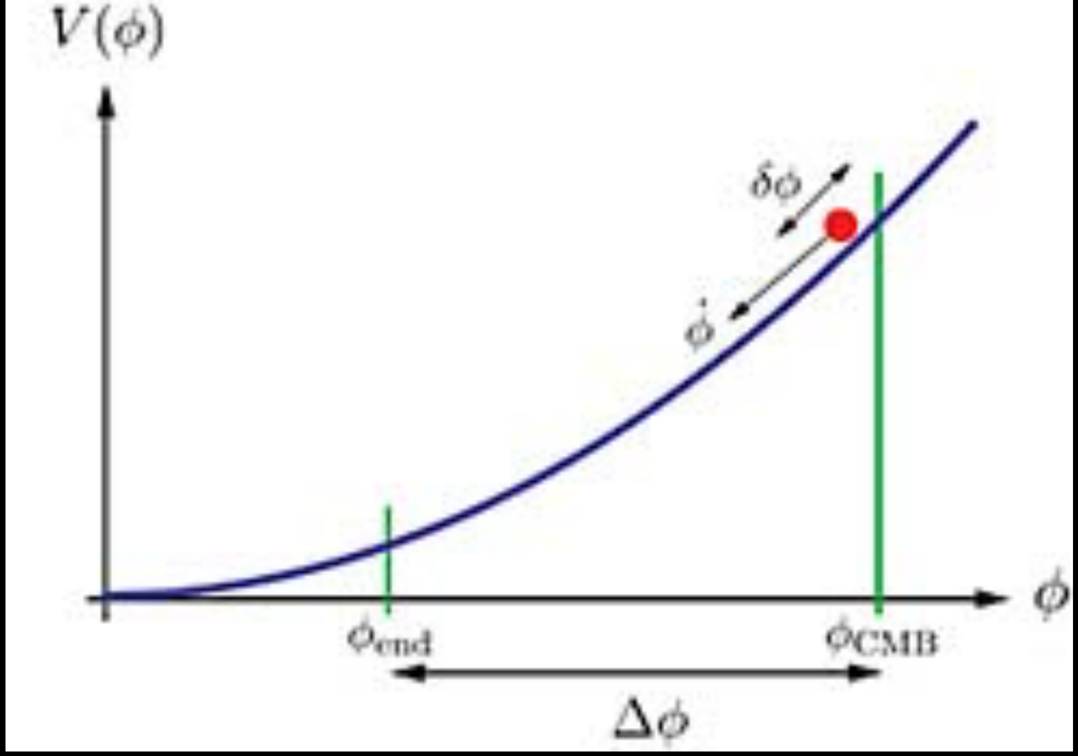
X00/A01/C01

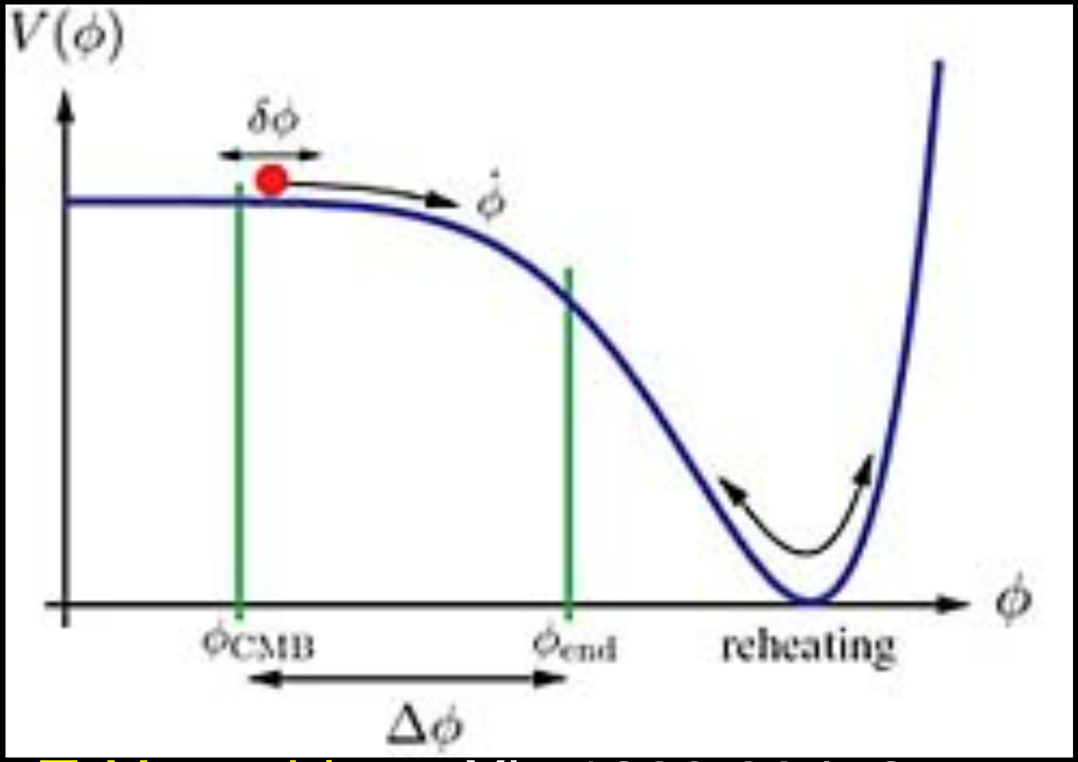
$$|\nabla V| > cV$$

- seems to be inconsistent with the slow-roll condition

$$V' \ll \sqrt{3}V$$

  - one possible attitude: *c*=0.01~O(1)
  - can't expect $w \neq -1$
- "large field inflation" is in swampland?
  - can't expect large tensor component $$r \approx 8 \left(\frac{d\phi}{dN}\right)^2 \lesssim 10^{-3}$$
  - bad news for CMB S4, LiteBIRD





HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478

too strong?

X00/A01/C01

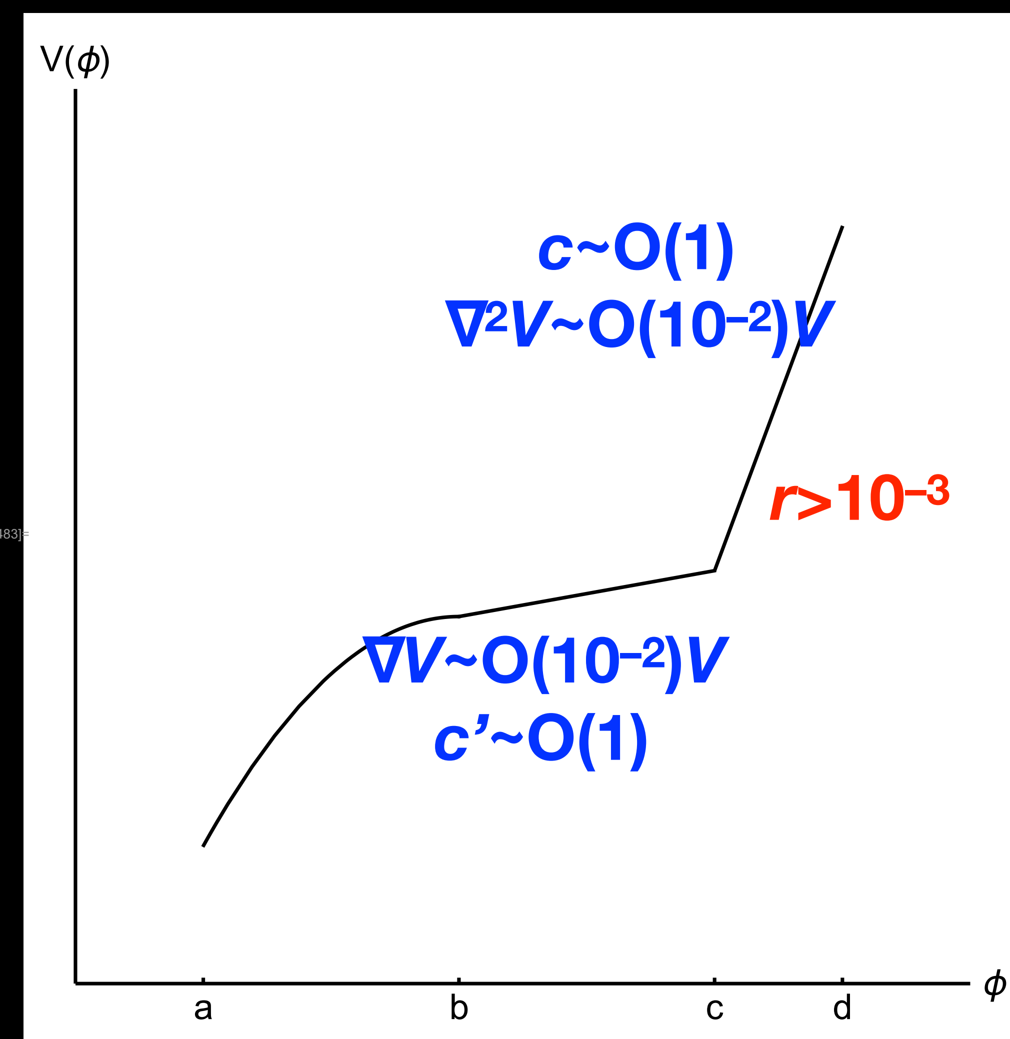
$$|\nabla V| > cV$$

- perhaps, the constraint is too strong?
- would local maxima be ok?
- Our suggestion:
  - $|\nabla V| > cV$ or $\nabla^2 V < 0$
  - $|\nabla V| > cV$ or $\nabla^2 V < -c'V$

Ooguri, Palti, Shiu, Vafa, arXiv:1810.05506

Hope for w≠−1?

Out[483]=

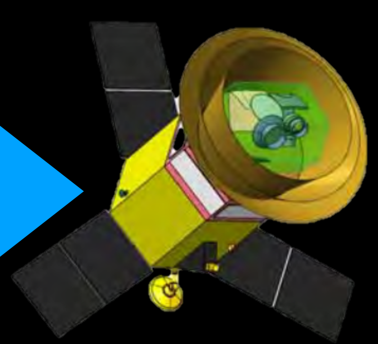


HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478

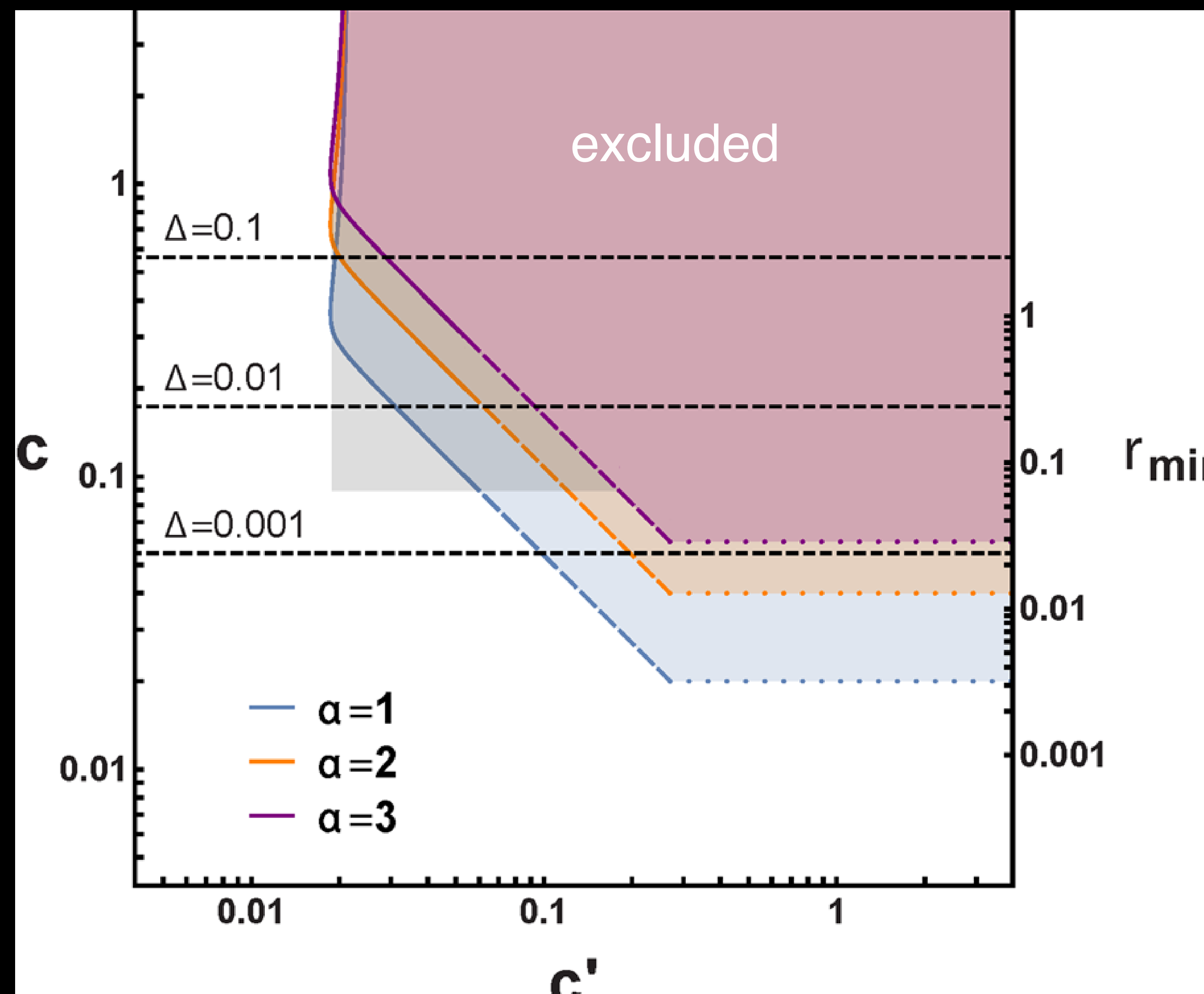
Is Inflation OK?

X00/A01/C01/B01

- Single-field inflation:
  - c or c' ~ 0.1 OK
  - *r* can be detectable
- Multi-field even better!



LiteBIRD
Tomo Matsumura

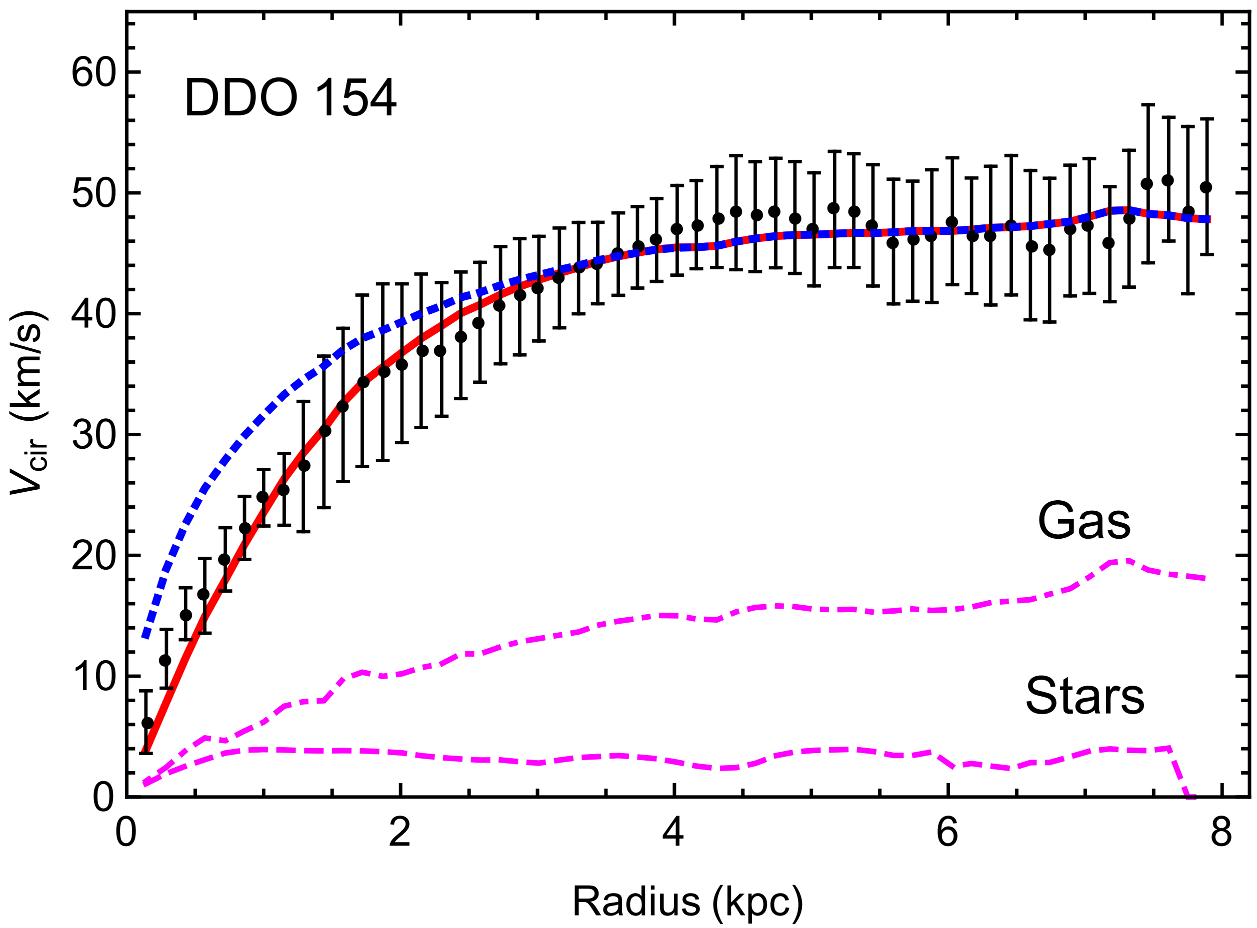


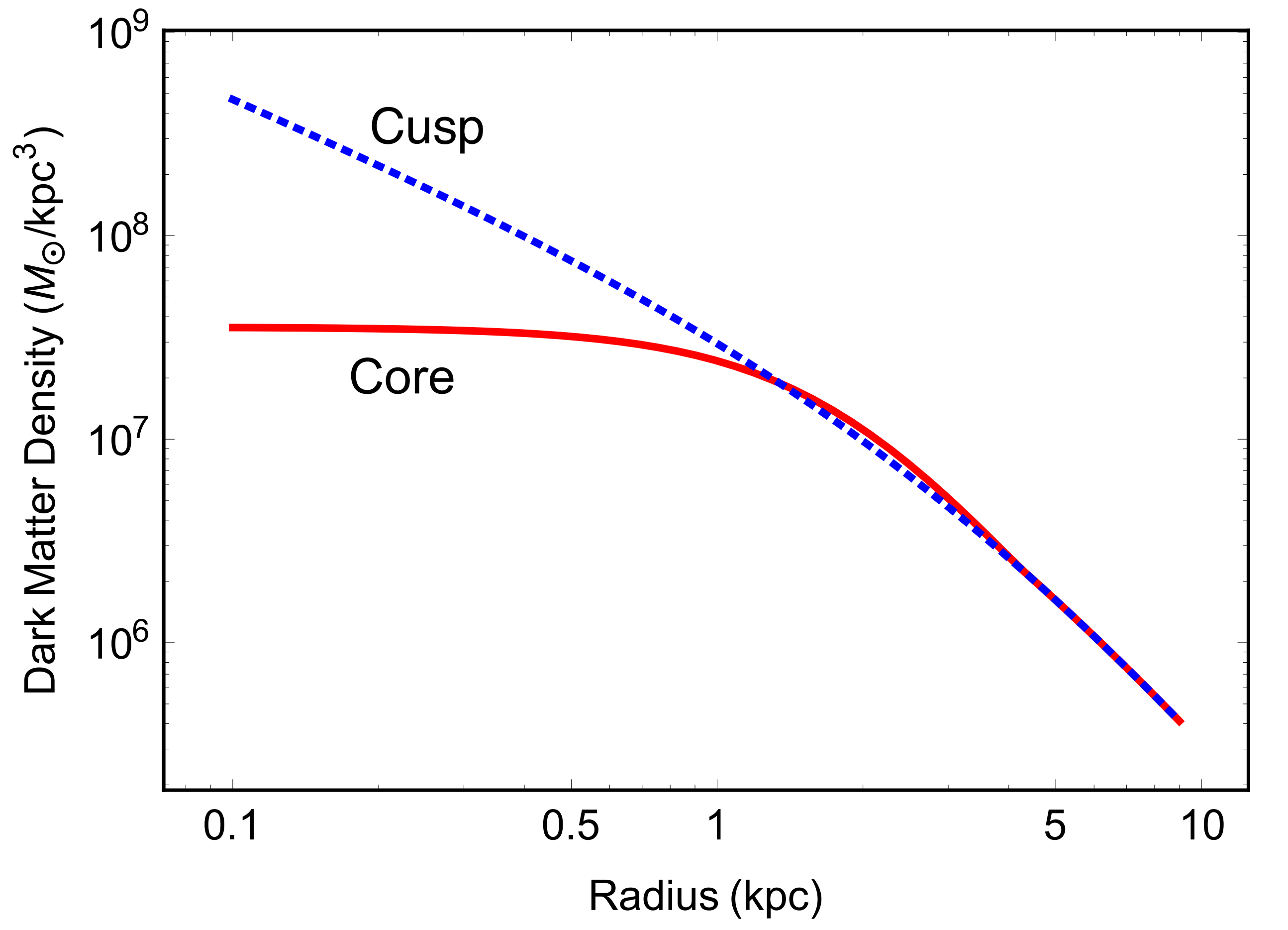
Chien-I Chiang, Jacob Leedom, HM, arXiv:1811.01987

DDO 154 dwarf galaxy

B02/A02

DDO 154 dwarf galaxy





can be explained if dark matter scatters against itself

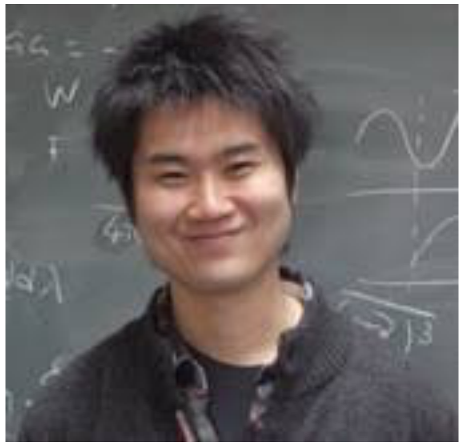
Need $\sigma/m \sim$ 1b / GeV

only astrophysical information beyond gravity

Diversity in stellar distribution

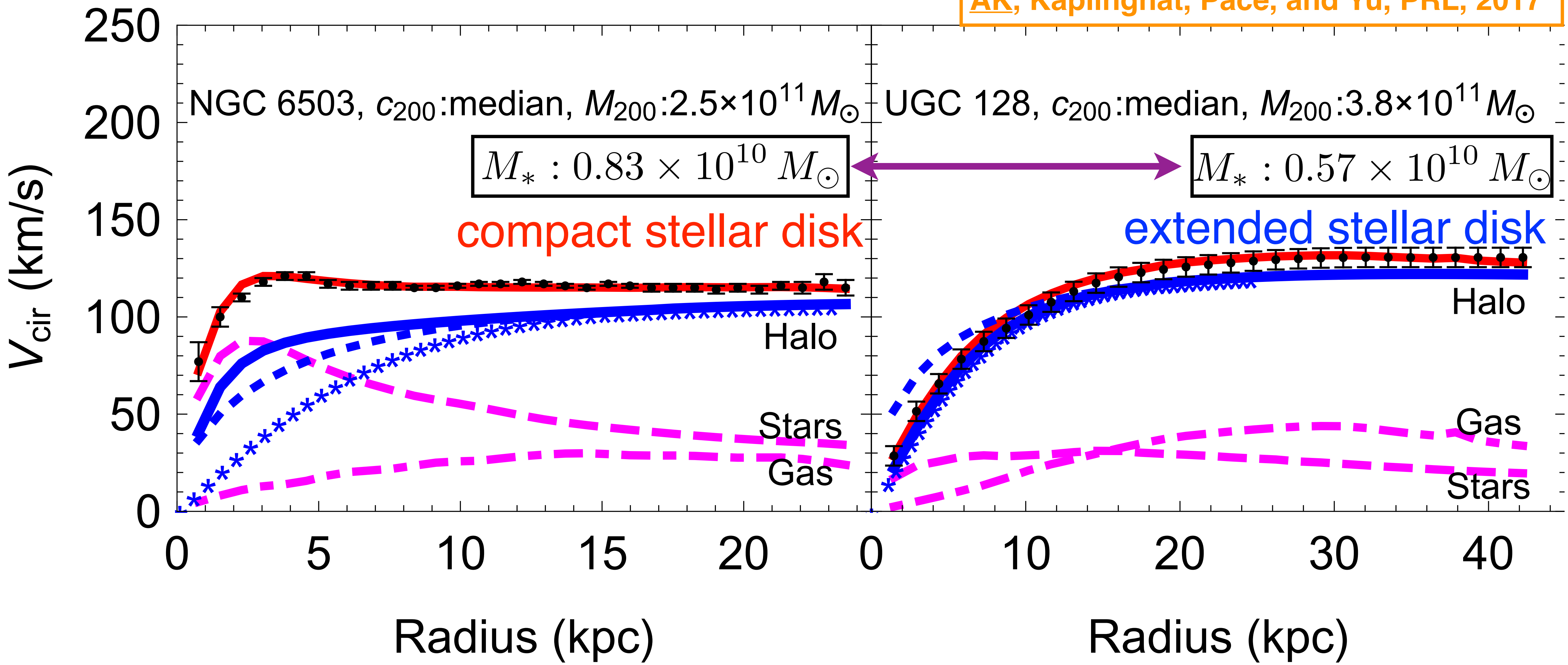
Similar outer circular velocity and stellar mass, but different stellar distribution

- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution



Ayuki Kamada
first student from Kavli IPMU
long term position in Korea

AK, Kaplinghat, Pace, and Yu, PRL, 2017

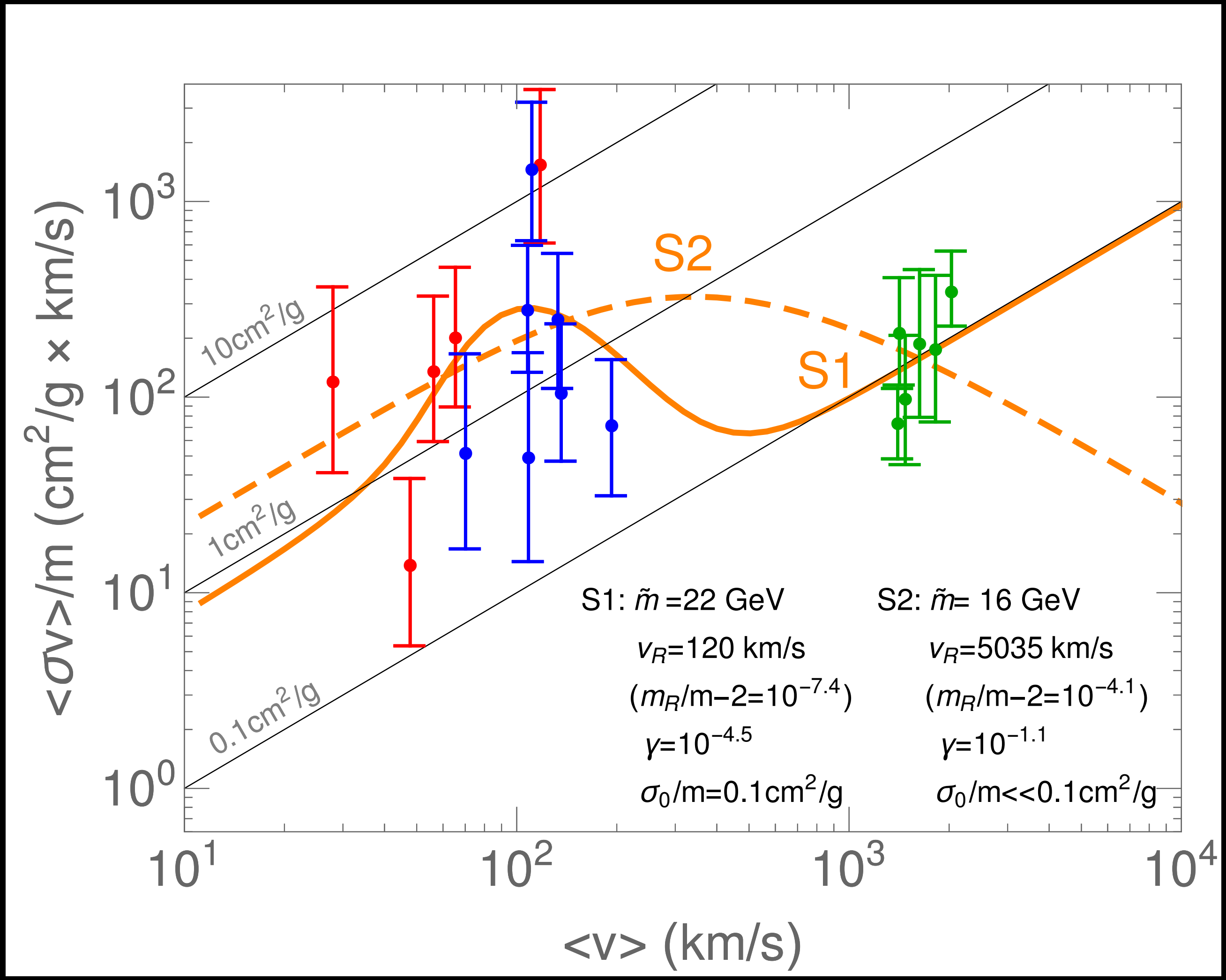


X00/A02

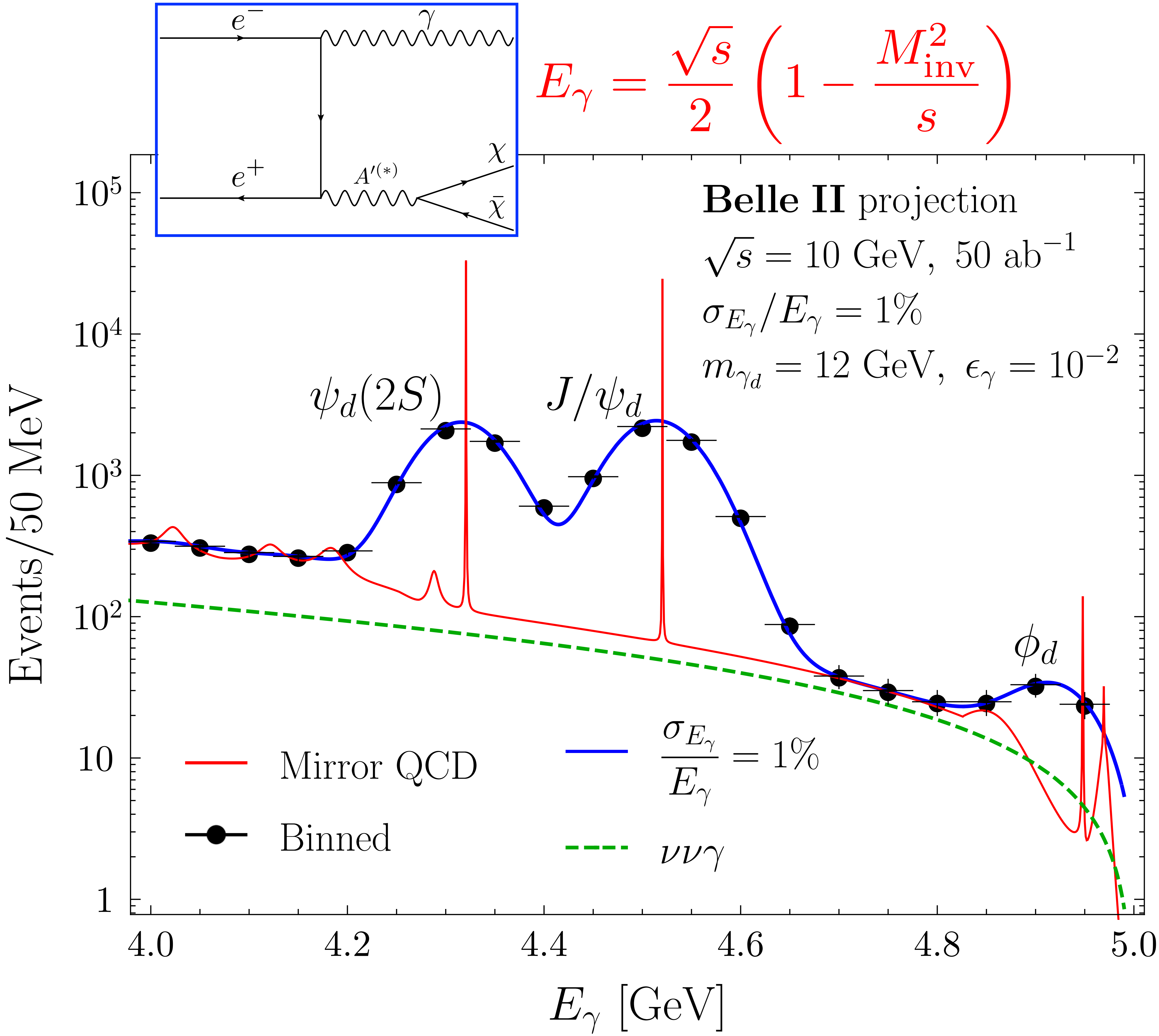
SIMP

- SIMP (Strongly Interacting Massive Particle)
  - Hochberg, Kuflik, HM (Top 1% paper in physics)
- dark matter = dark hadron
- near-threshold resonance can "fit" the data
- *i.e.*, $\pi\pi \to \sigma \to \pi\pi$
  - (Xiaoyong Chu, Camilo Garcia-Cely, HM)

Search @ Belle-2!

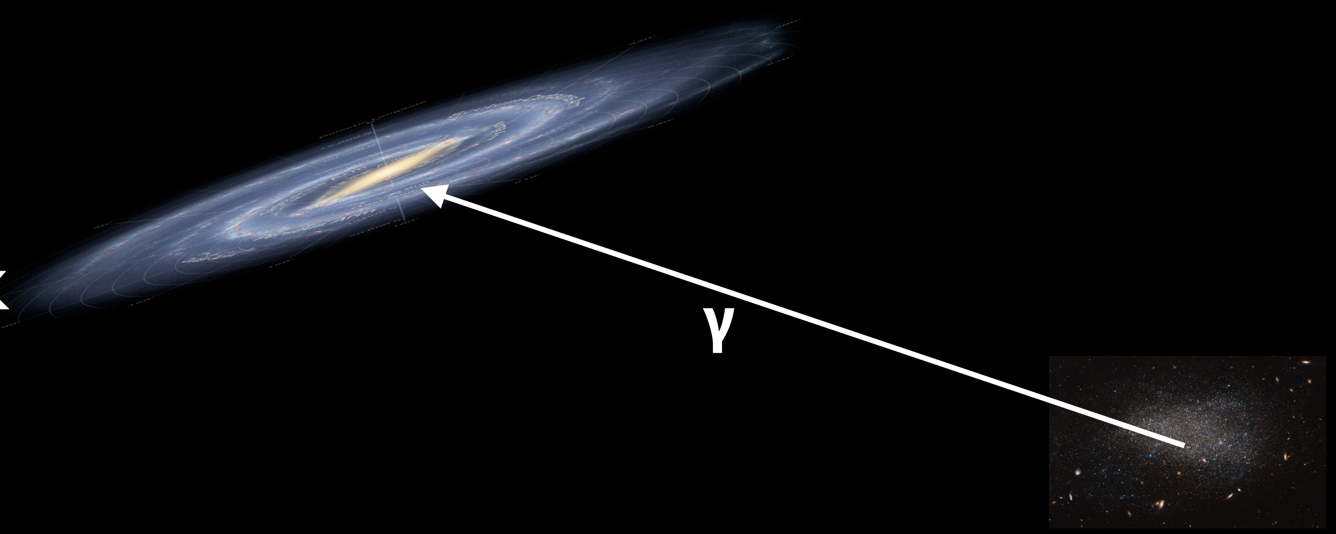


M. Kaplinghat, S. Tulin, and H.-B. Yu, arXiv:1508.03339.
Xiaoyong Chu, Camilo Garcia-Cely, HM, Phys.Rev.Lett. 122 (2019) 071103

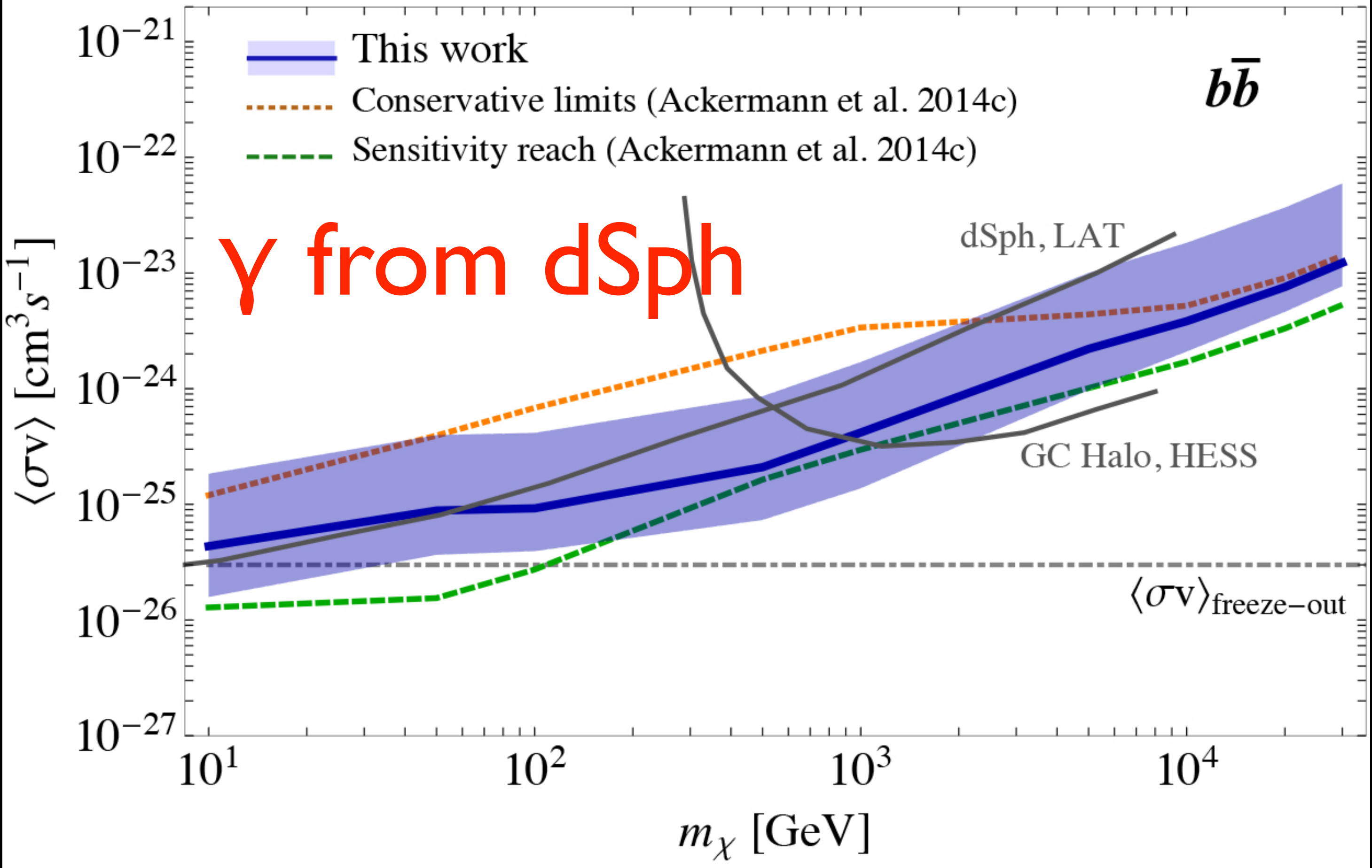


e^-
γ
e^+
$A'^{(*)}$
χ
$\bar{\chi}$
$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$
Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$
$\psi_d(2S)$
J/ψ_d
ϕ_d
Mirror QCD
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
Events/50 MeV
E_γ [GeV]

indirect detection



- powerful probe to dark matter
- annihilation in star-poor dwarf galaxies
- biggest uncertainties:
  - foreground stars
  - density profile



B03/A02

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **479**, 64–74 (2018) doi:10.1093/mnras/sty1387
Advance Access publication 2018 May 29

particle physics

Foreground effect on the *J*-factor estimation of ultrafaint dwarf spheroidal galaxies

string

Koji Ichikawa,[1] Shun-ichi Horigome,[1★] Miho N. Ishigaki,[1] Shigeki Matsumoto,[1] Masahiro Ibe,[1,2] Hajime Sugai[1] and Kohei Hayashi[2]

[1]*Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa 277-8583, Japan*
[2]*ICRR, The University of Tokyo, Kashiwa 277-8582, Japan*

instrumentation

astronomy (galactic archaeology)

Accepted 2018 May 21. Received 2018 May 16; in original form 2017 June 17

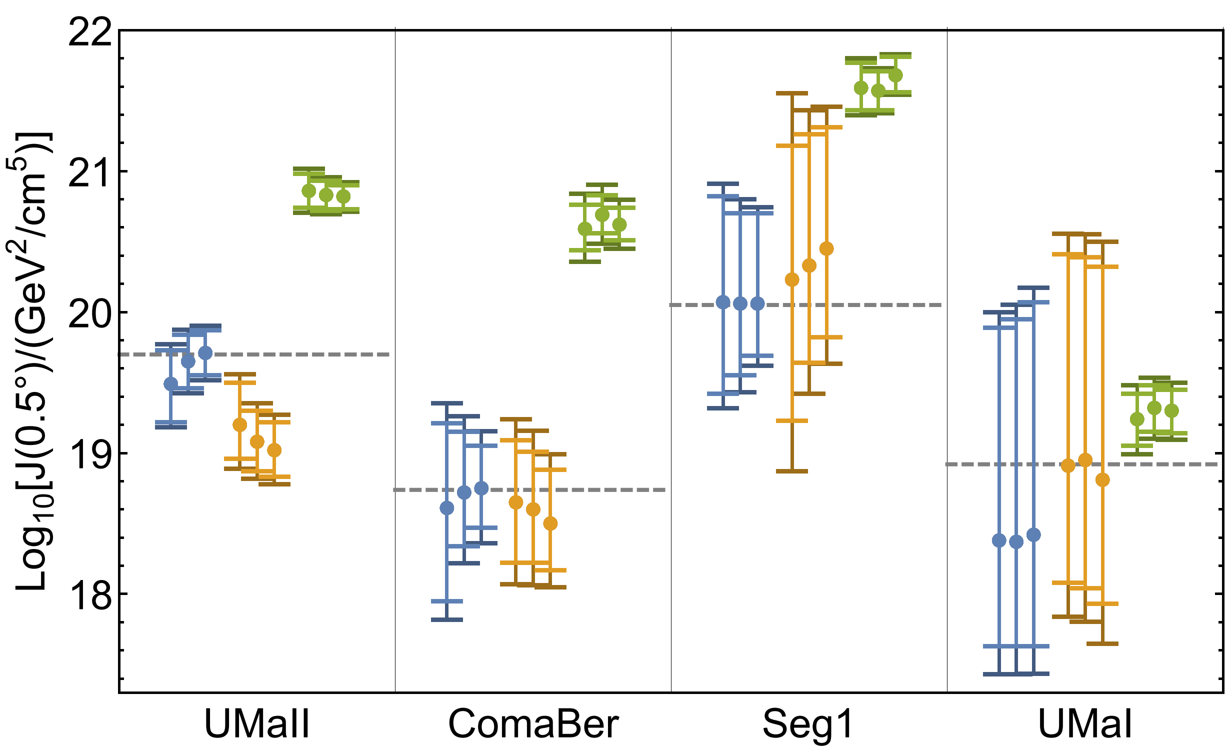
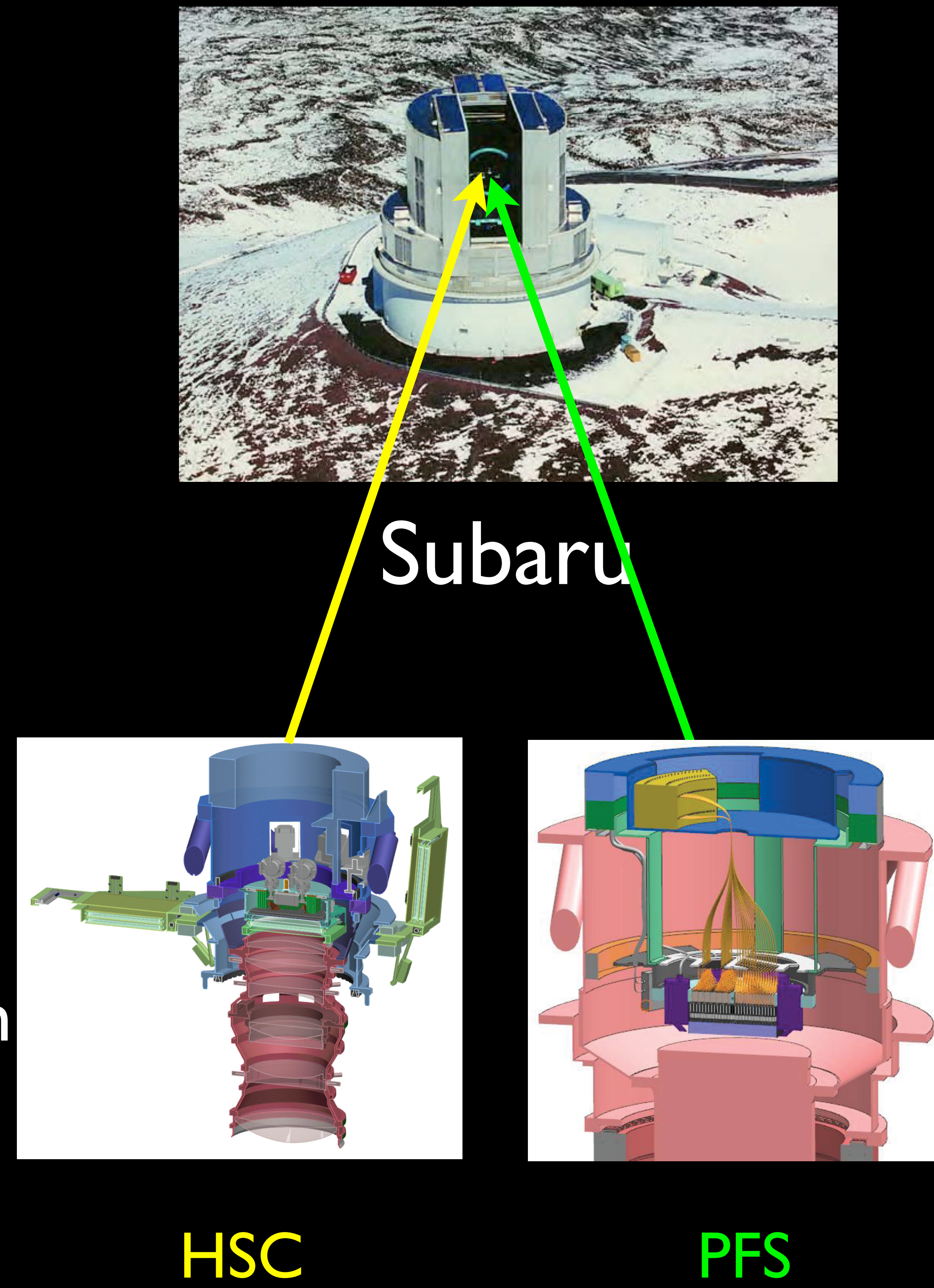


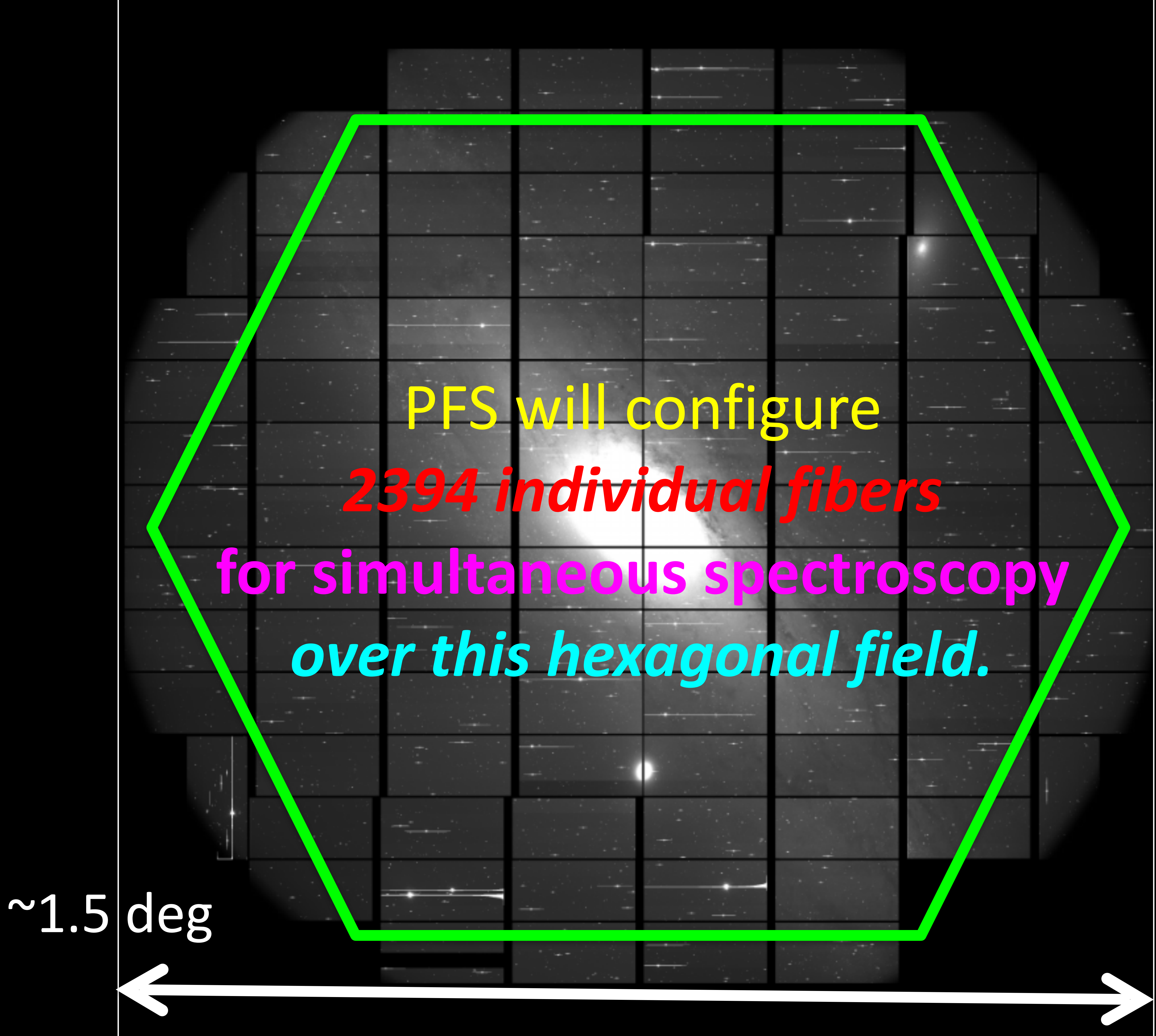
Figure 3. The *J*-factors obtained by the fits are plotted. The blue, orange, and green dots show the *J*-factor estimations of the KI17, *Conventional,* and *Contaminated* analysis. The lighter error bars of each point show the average of the 68 per cent quantile, while the darker ones show the square root of the 68 per cent quantiles and the standard deviation of the median values. The grey dashed lines show the input values. For each dSph, three bars with the same colours correspond to the case of $i_{\max} = 21,\ 21.5$, and 22 with $\theta_{\mathrm{ROI}} = 0.65$ respectively, from the left. See Table A1 and Fig. C1 for the numerical values and their dependence on the $r_{\max}$, respectively.

SuMIRe
Prime Focus Spectrograph

Subaru Measurement of Images and Redshifts

- one of the largest telescopes: 8.2m
- big field of view ~1.5°
- Imaging with Hyper Suprime-Cam (HSC)
  - 870M pixels
  - ~300M galaxy images
  - 2014–2019, 330 nights
- spectroscopy with PrimeFocusSpectrograph (PFS)
  - 2394 optical fibers, 280–1260nm
  - >1M redshifts
  - 2022–2026 360 nights





Naoyuki Tamura

Comprehensive Challenge on the Standard Model of the Universe and Beyond

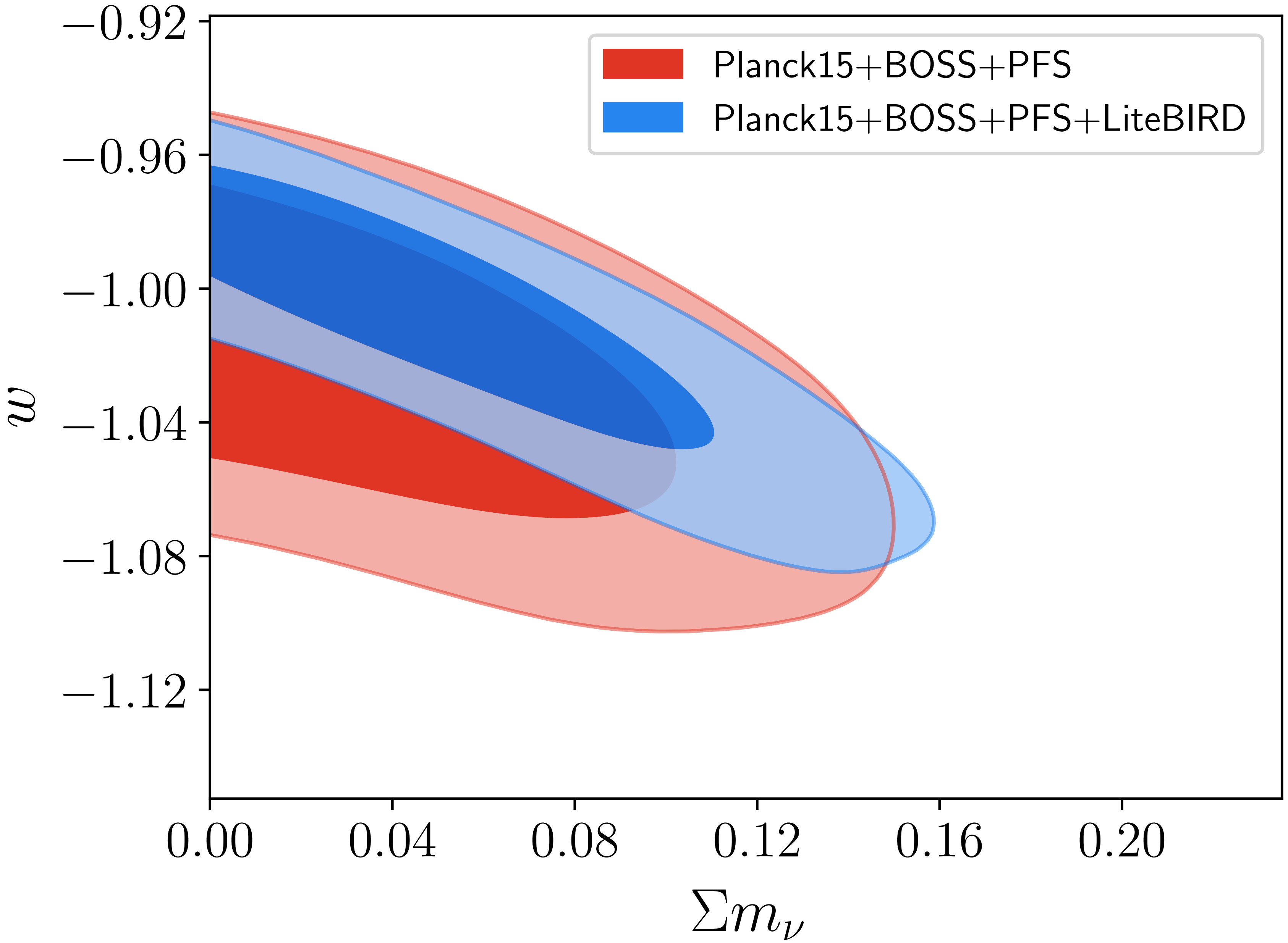
ΛCDM	Galactic Archaeology	Galaxy Evolution	Cosmology
General Relativity		✓	✓
Flat FRW metric			✓
Collisionless Dark Matter	✓		
Nearly Scale-invariant Adiabatic Gauissian Spectrum	✓	✓	✓
Hierarchical Structure Formation	✓	✓	✓
Cosmological Constant			✓
Massless Neutrinos	✓ (warm DM)		✓
Reionization from stellar formation		✓	

B03/D01

Can measure *w*

If *w*>–1, supports swampland conjecture

If *w*=–1, puts string theory in tight corner?



$$w = -1 + \frac{2c^2}{6 + c^2}$$

Now that *c* can be O(1), *w* may deviate from –1

further improvements with τ from LiteBIRD

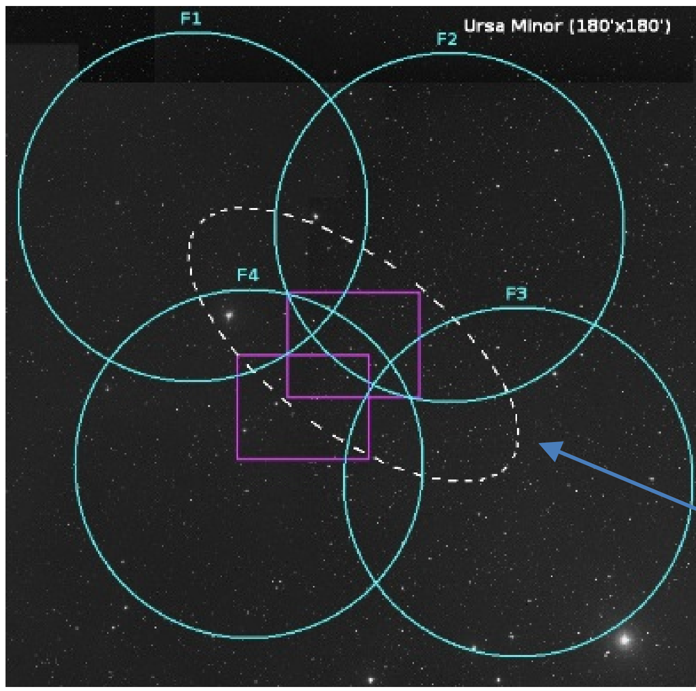
R. Makiya

B02/A02

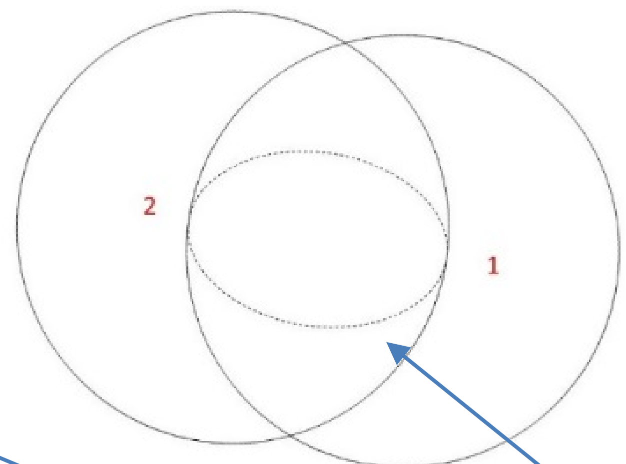
PFS pointings for MW satellites

~ HSC imaging data are available for all samples ~

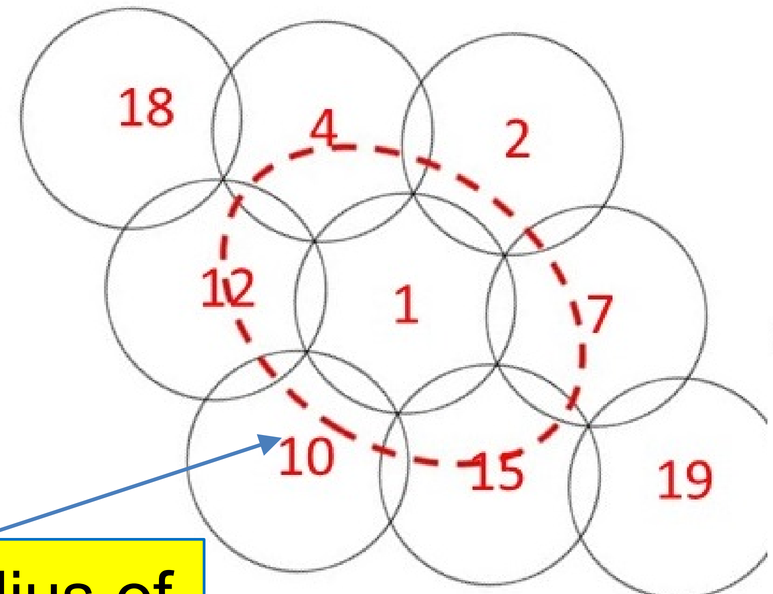
Ursa Minor



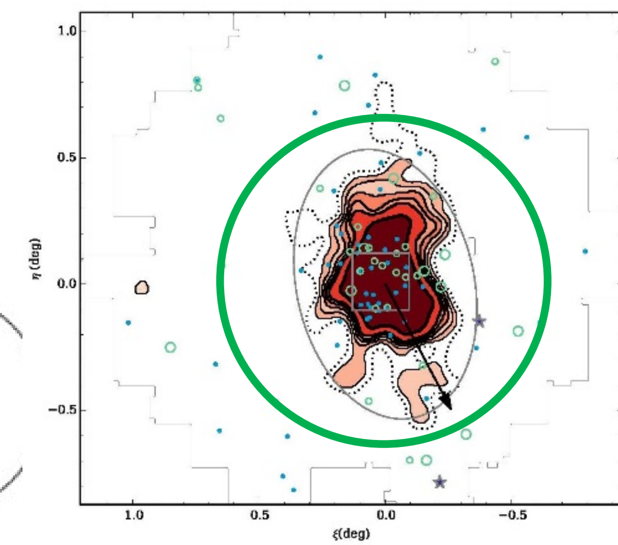
Draco



Sextans

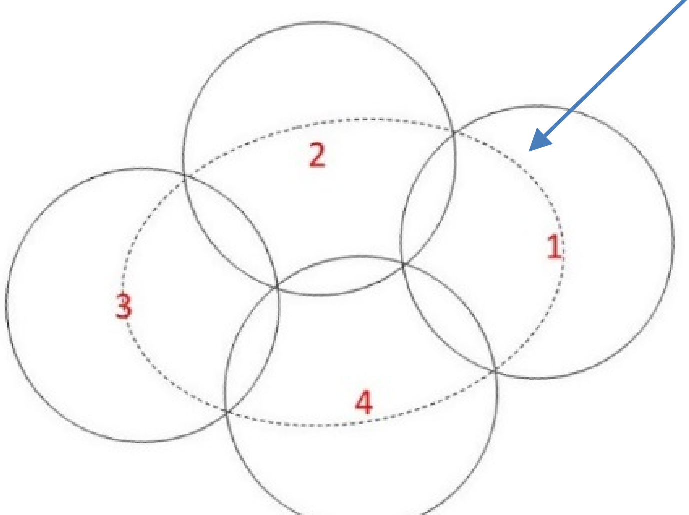


Bootes I

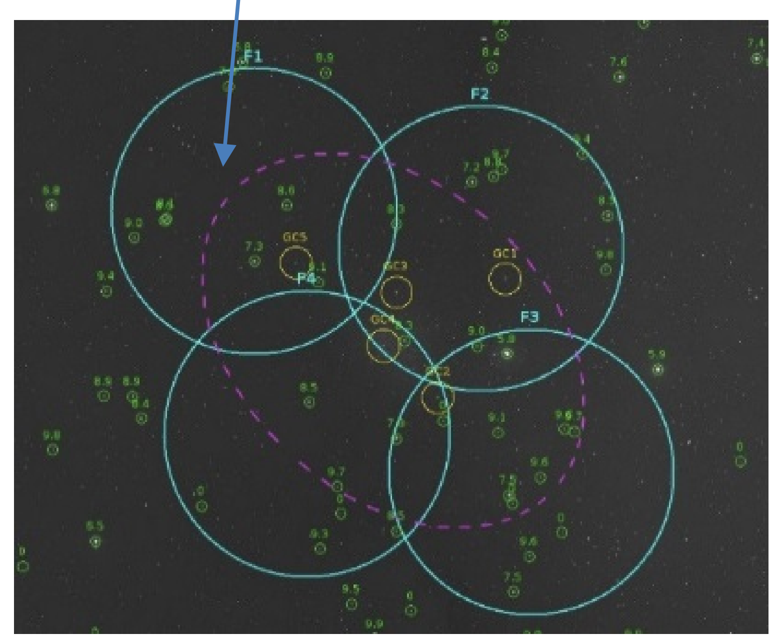


tidal radius of stellar comp.

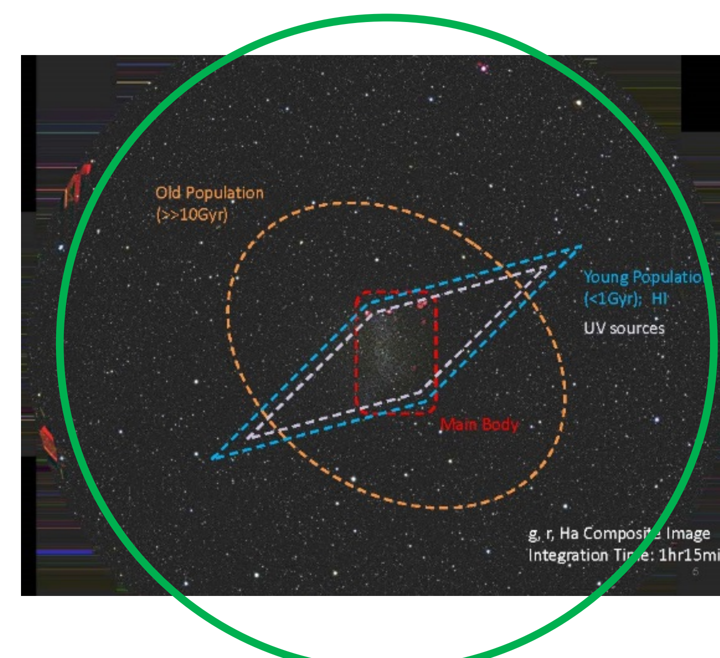
Sculptor



Fornax



NGC6822



X00

C01: Ultimate Theory

	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n_s direct evidence	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
[B02] Subaru galaxy imaging Miyazaki(NAOJ)	Lensing → $b(k)$ $\rightarrow P_{\rm primod}(k)$	weak lensing m_ν non-std. DM	weak lensing SNe, γ
[B03] galaxy spectroscopy Takada(KIPMU)	primord. NG Ω_K, n_s, α_s	isocurv. DM in dSph gals. $P(k), m_\nu$	BAO, RSD $\Omega_{\rm de}(z), \gamma$
[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman-α forests IGM	direct detection of acceleration

D01: Ultimate Analysis

Finale

But there is exciting science ahead!