Au Genesis From Co Genesis: Heavy Asymmetric Dark Matter Makes Gold

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JB, Linden '16
JB, Linden Tsai '17
JB, Unwin '17
Baryakhtar, JB, Li, Linden, Raj '17

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Yu-Dai Tsai
Cornell, PI

Tim Linden
OSU

Masha Baryakhtar
Perimeter

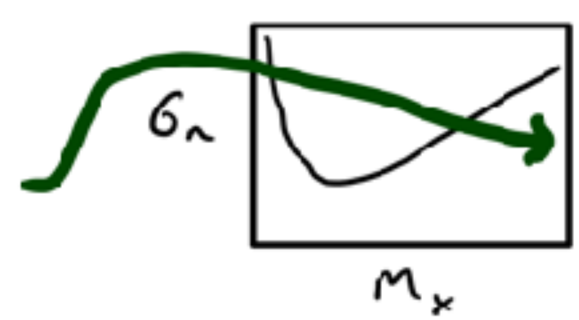
1. Simple WIMP Cosmology

+

2. Baryogenesis

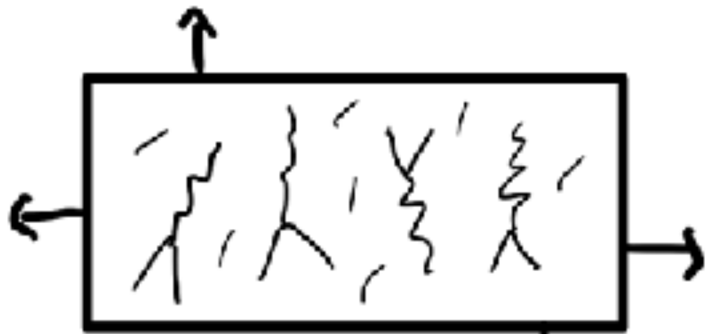
↓

3. Dilute WIMPS

are over here 

GOLD!

The WIMP "Miracle"



Thermal Freeze-out

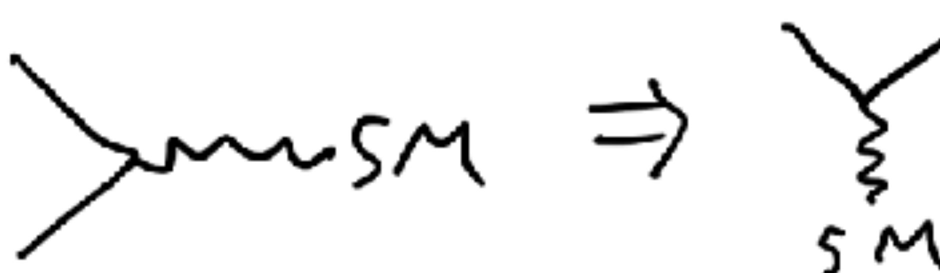
- As universe cools, DM falls out of thermal equilibrium, annihilates to SM particles

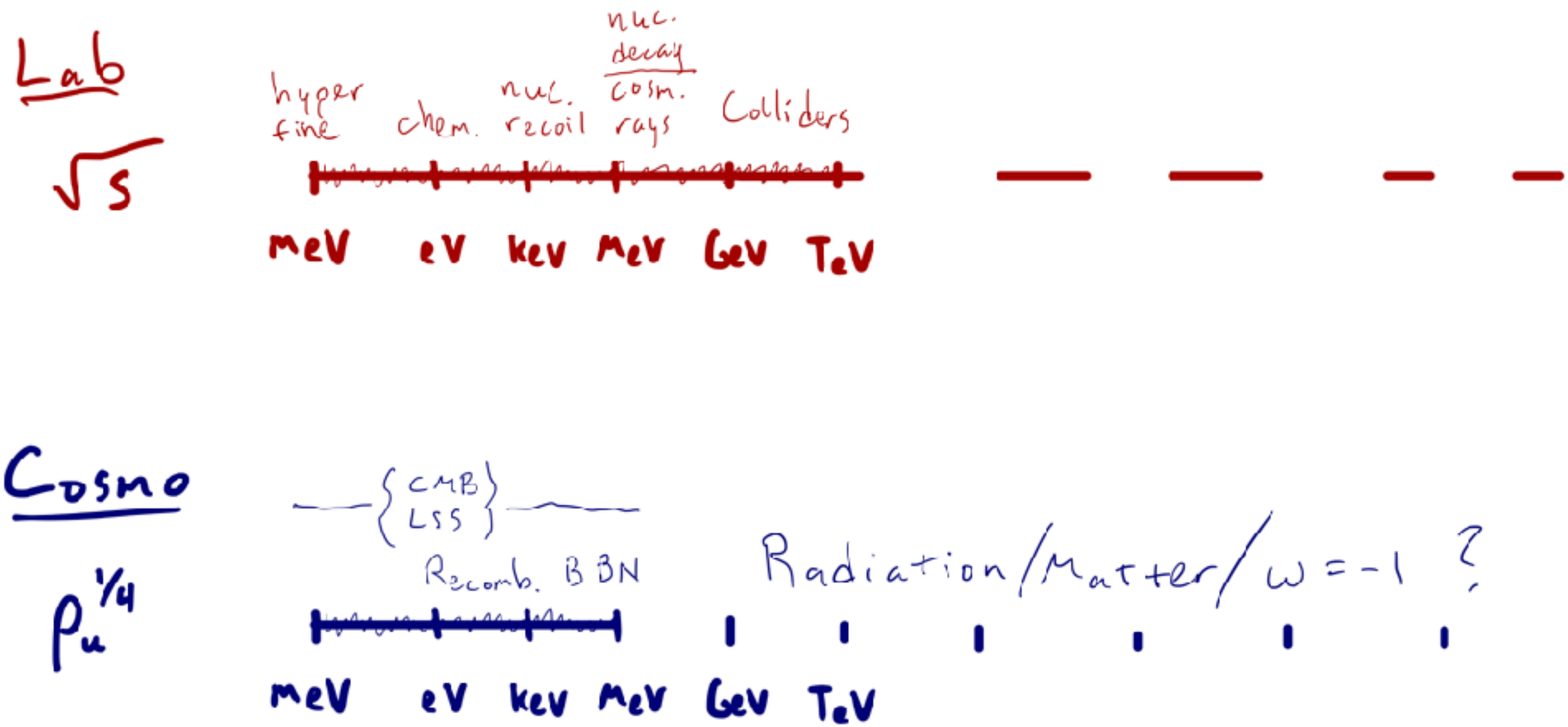
Final Abundance

$$\Omega_{DM} h^2 \propto \frac{x_{FO}}{\sigma_a} \quad \Big| \quad x_{FO}\left[\ln(m_\chi)\right] \sim 10$$

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_V}{100\ \text{GeV}}\right)^2 \left(\frac{0.03}{\alpha_W}\right)^2$$

This implies weak mass scale coupling to SM





Lab
$\sqrt{s}$
hyper fine
chem.
nuc. recoil
nuc. decay
cosm. rays
Colliders
meV
eV
keV
MeV
GeV
TeV
Cosmo
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Radiation/Matter/$w=-1$?
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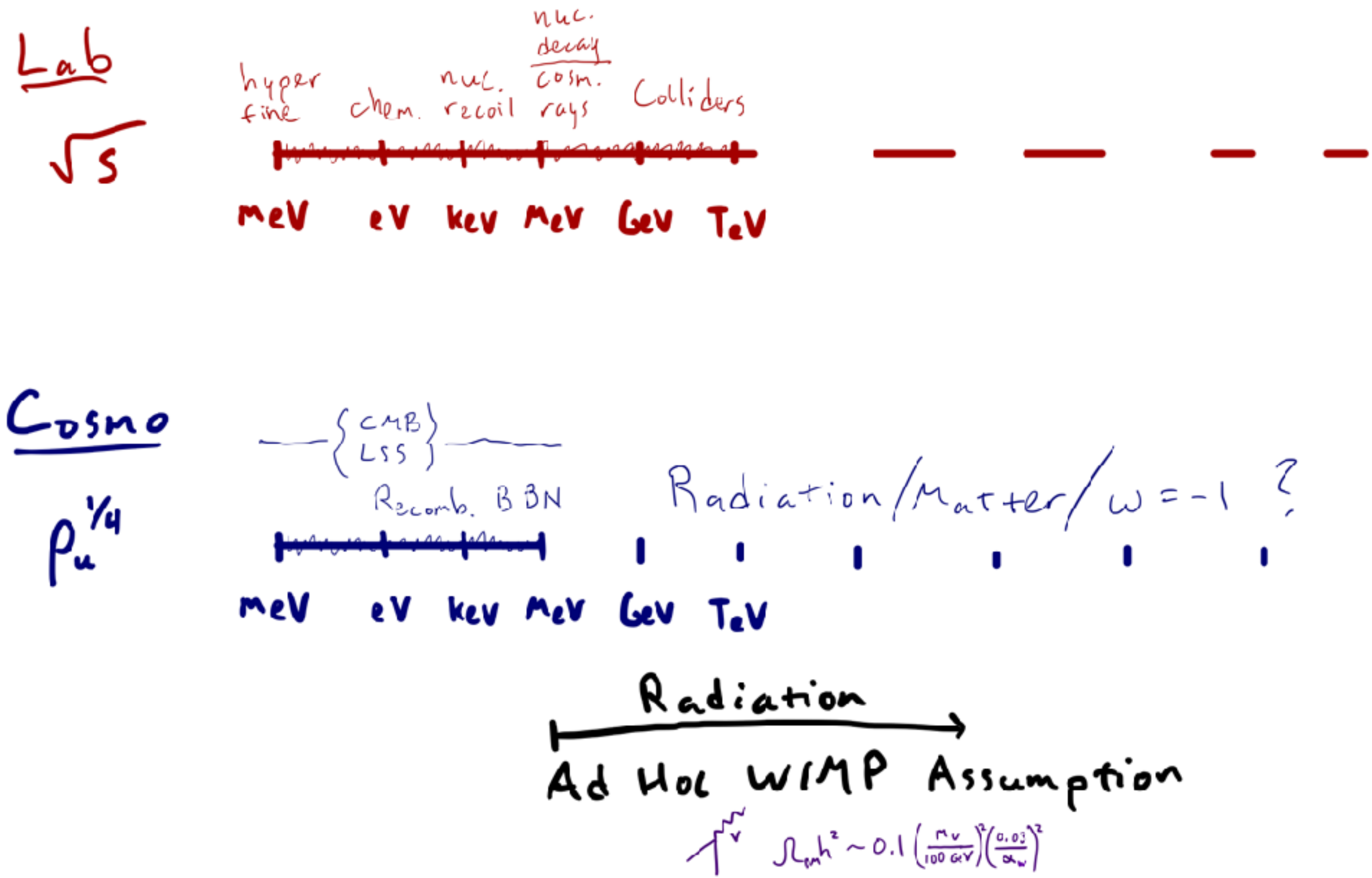
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Radiation/Matter/w=-1 ?
meV eV keV MeV GeV TeV
Radiation
Ad Hoc WIMP Assumption
Ω_DM h² ~ 0.1 (m_χ / 100 GeV)² (0.03 / α_w)²

One Simple Trick For Shifting Abundances

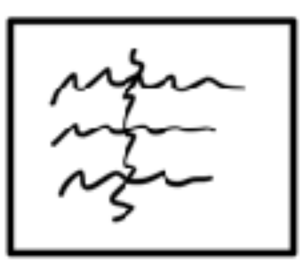
1. Stat. field

2. matt. field

 or 

$\Gamma < H$

3. rad. field



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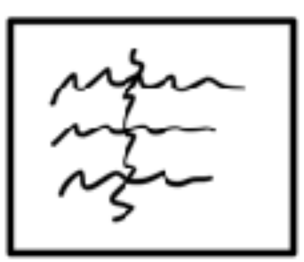

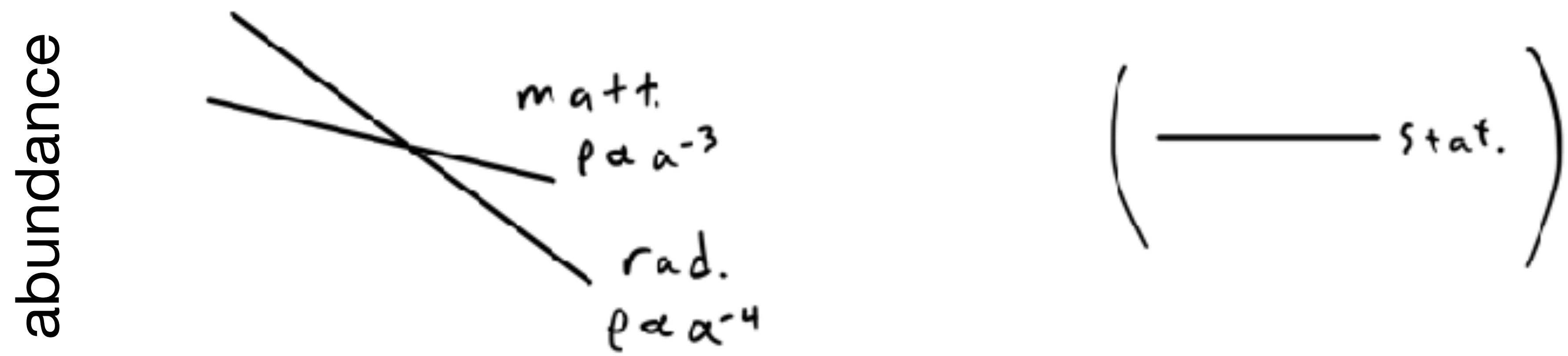

a increases, $\rho_u^{1/4}$ depletes →

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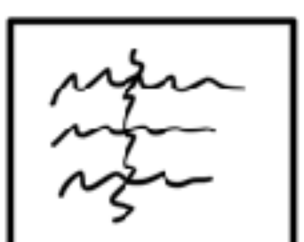

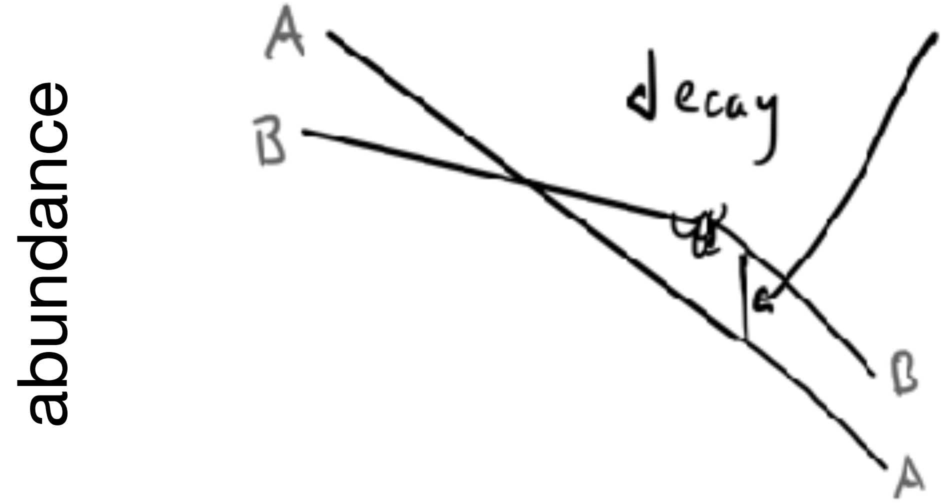

$$\xi \equiv \frac{\rho_A^{3/4}}{\rho_B^{3/4}}$$

$$\Omega h^2 \rightarrow \Omega h^2 \xi$$

dilation

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One Simple Trick For Shifting Abundances

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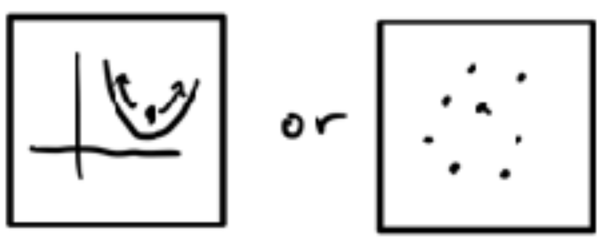

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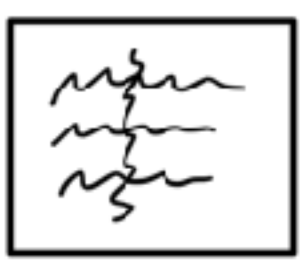
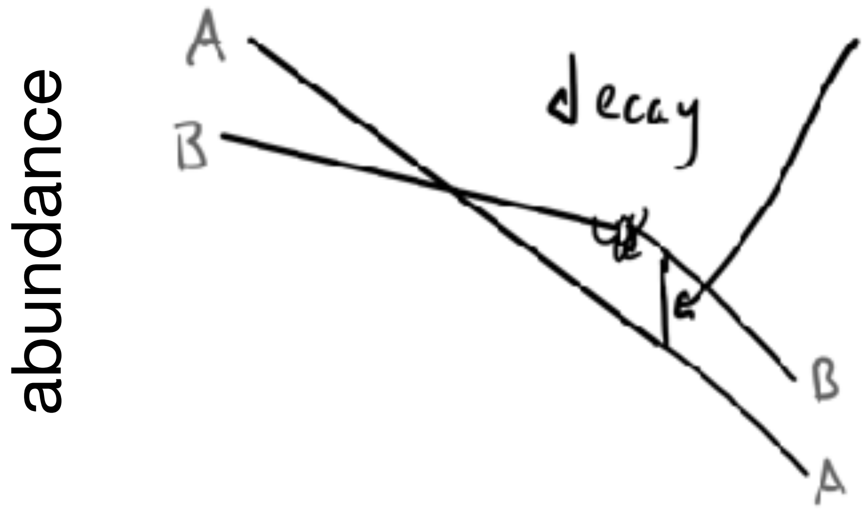




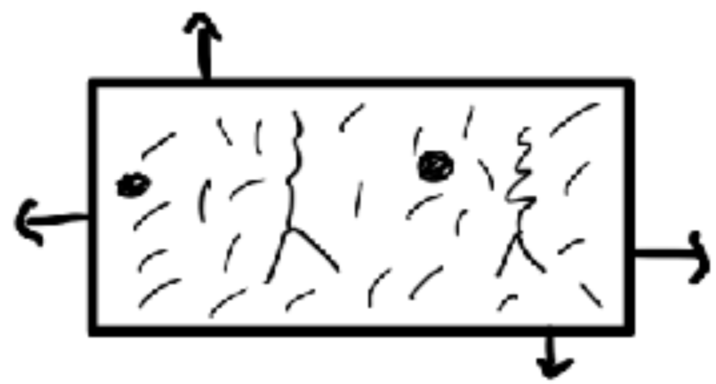
$$\zeta \equiv \frac{\rho_A^{3/4}}{\rho_B^{3/4}}$$

$$\Omega h^2 \rightarrow \Omega h^2 \zeta$$

<u>dilation</u>

- **B** : slow decaying inflatons, moduli, GUT mass states, AD fields...
- **A** : Typically SM w/DM, baryons

Dilute WIMPS



Overabundant Freeze-out

DILUTE

Abundance Later

Late time dilution from decaying states

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_v}{PeV}\right)^2 \left(\frac{0.03}{\alpha}\right)^2 \left(\frac{\zeta}{10^{-8}}\right)$$

DILUTION FACTOR ζ

$$\zeta \equiv \frac{S_{initial}}{S_{final}}$$ { Δ entropy density from decays

See also
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

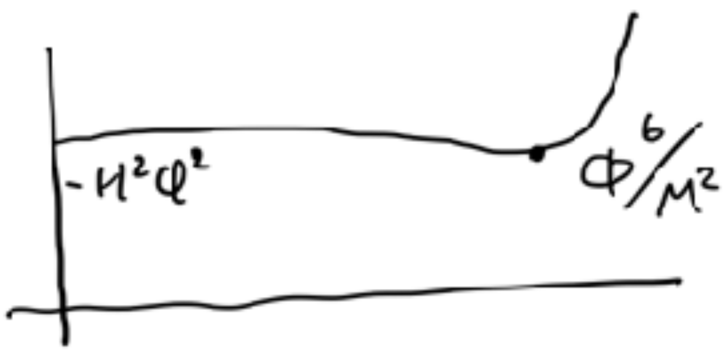
JB, Unwin '17

AD Baryogenesis

Afleck, Dine '85
Linde '85
Dine, Randall, Thomas '95

1. Baryo-charged scalar gets vev during inflation

$$V_{AD} = m_\phi^2 |\phi|^2 - H^2 |\phi|^2 + \frac{\phi^6}{M^2} + \not{CP}$$



2. Baryo-charged scalar decays (CP violating)

after inflation
$H \lesssim m_\phi$

$$(aH + b m_\phi)\phi^4/M + h.c.$$

AD Baryogenesis

Afleck, Dine '85
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1. Baryo-charged scalar gets vev during inflation

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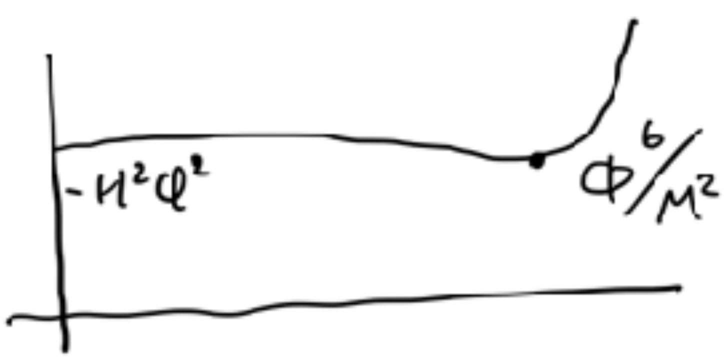

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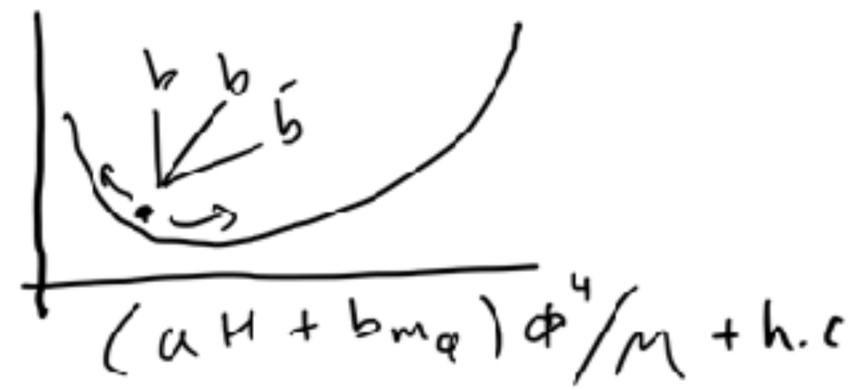
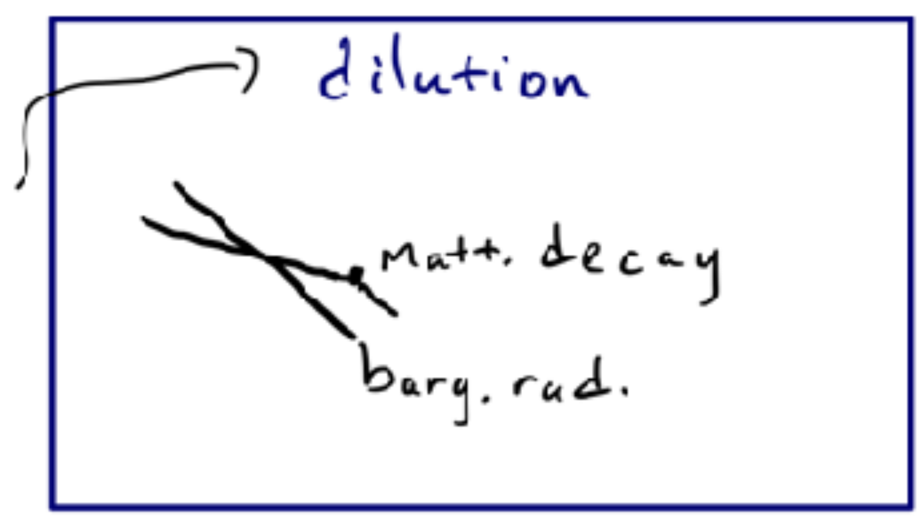


3. Oops! too many baryons, need



Main point: $\eta_b \sim 1 - 10^{-8}$ for a simple baryo-charged scalar

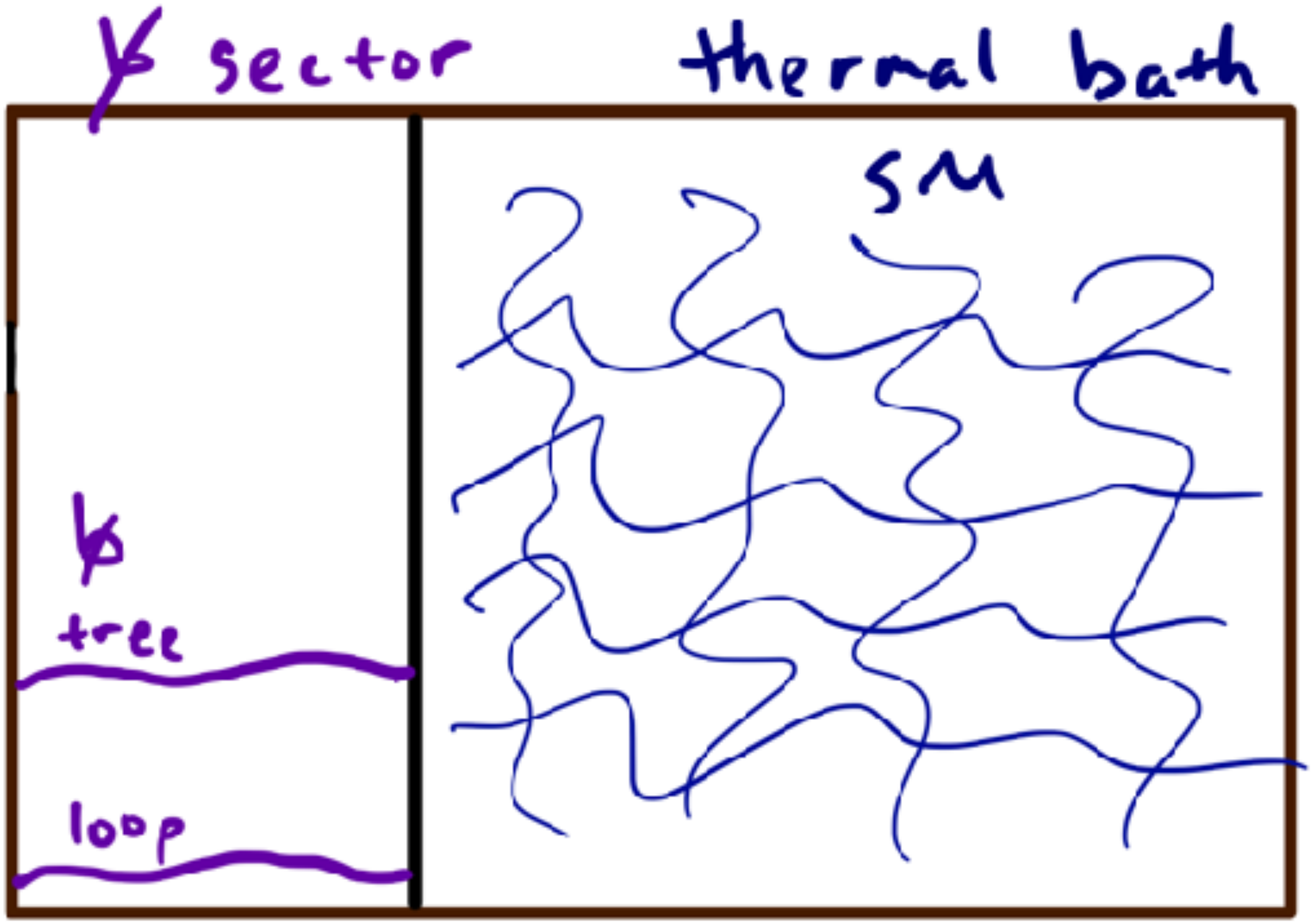
$\eta_b = 10^{-10}$ observed, need dilution.

Why too many baryons?

If: $\mathcal{O}(1)$ CP violating decays

And: $\rho_\phi \sim \rho_u$

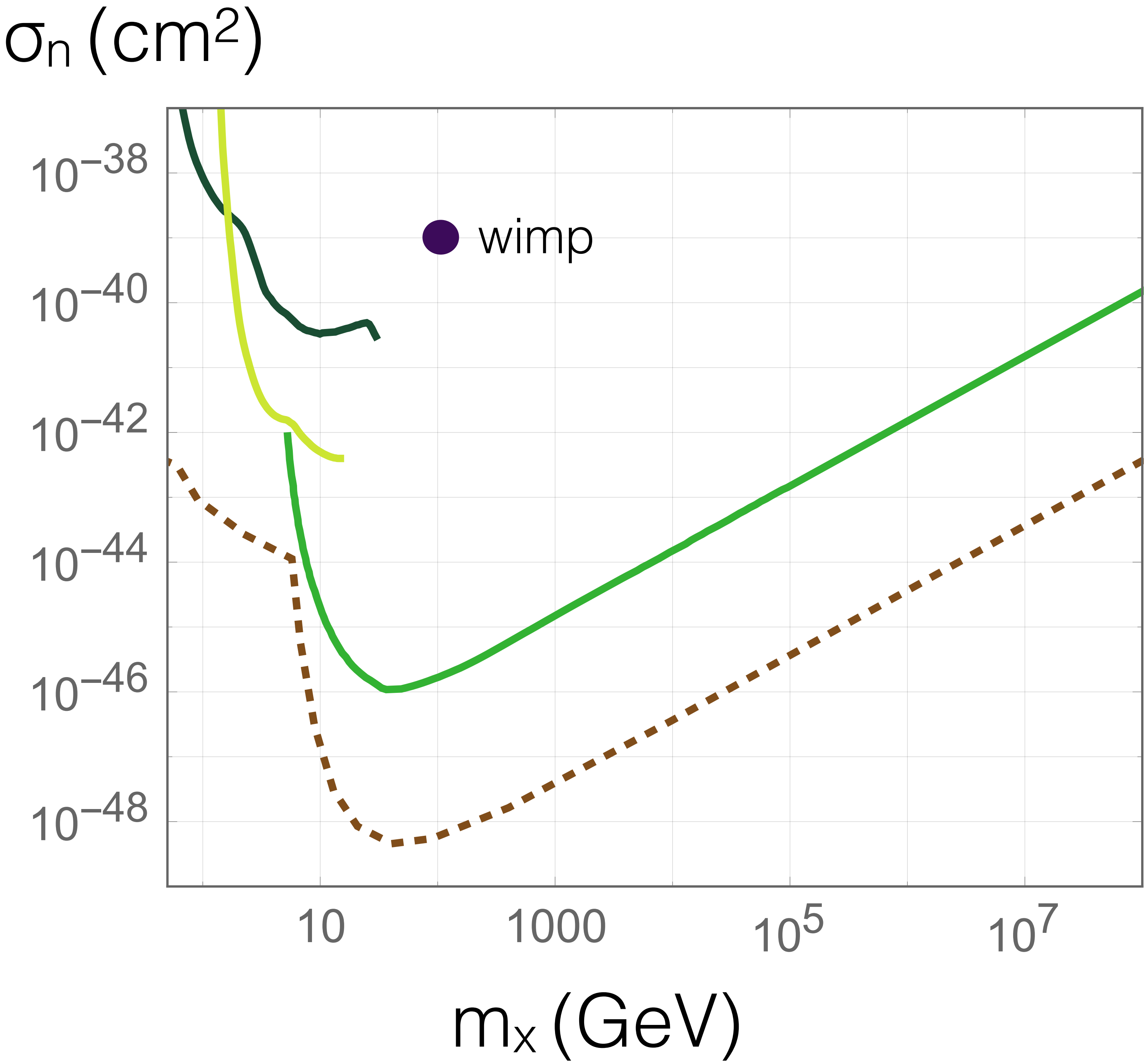
(ρ_ϕ ← $\not{B}$ sector)

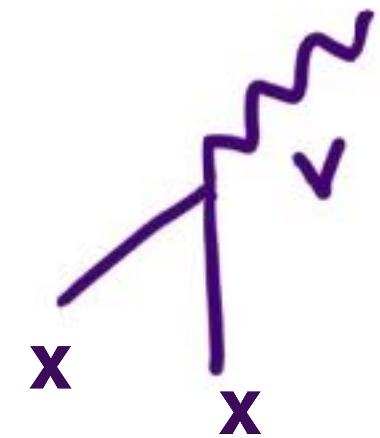


$$\eta_B \simeq \frac{n_b}{\rho_u^{3/4}} \left(\zeta \right)$$

$n_b \sim [10^{-5} - 1]$ for any $\not{B}$ sectors with $\mathcal{O}(1)$ couplings

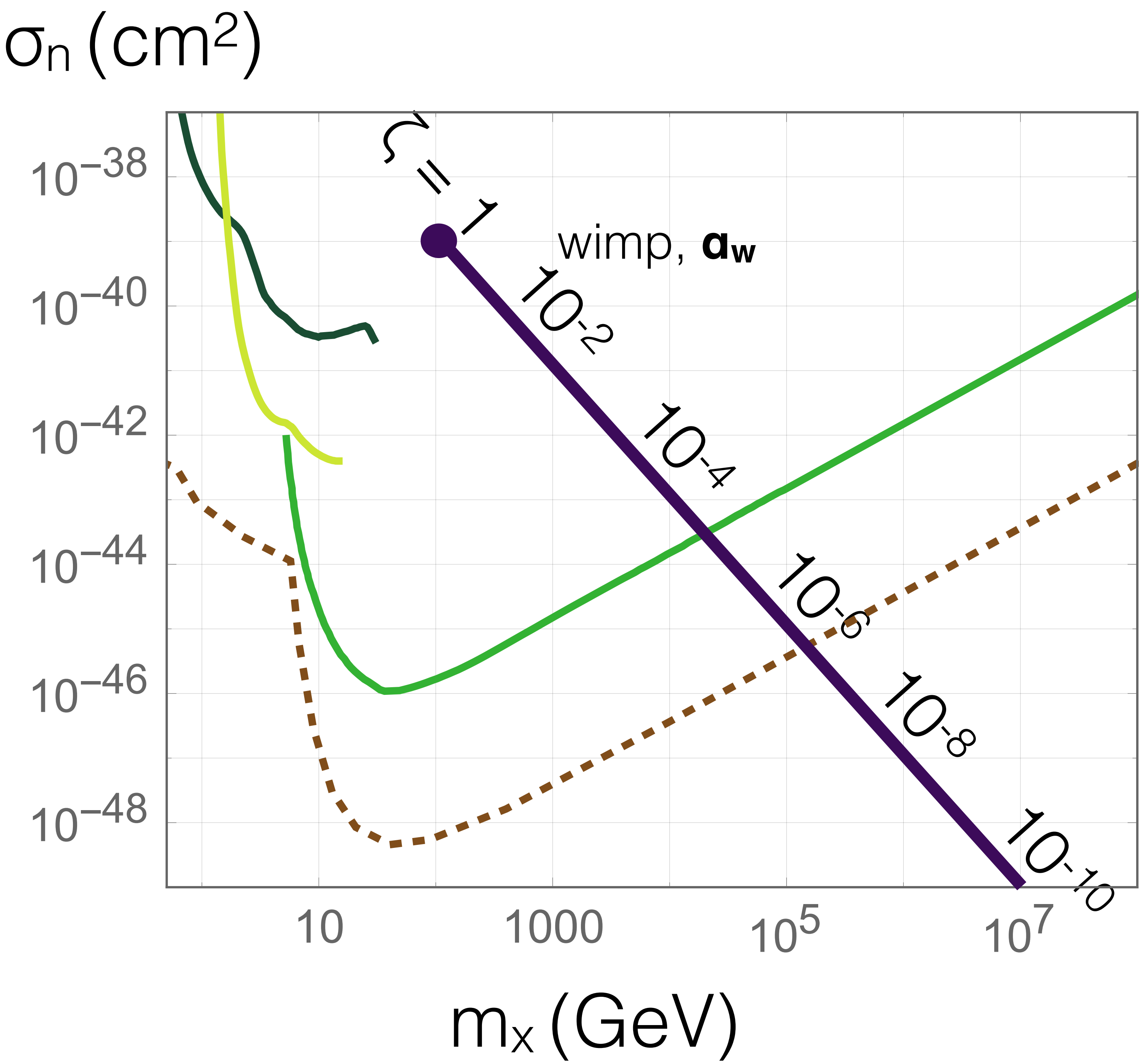
Dilute WIMPS

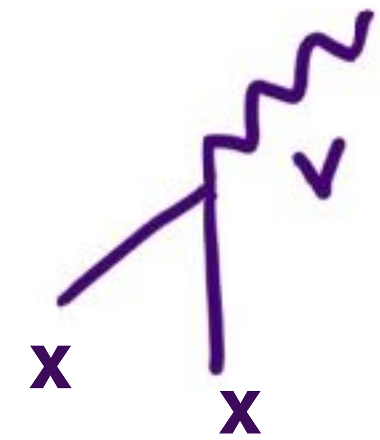




simplest case: let $m_X = m_V$

Dilute WIMPS

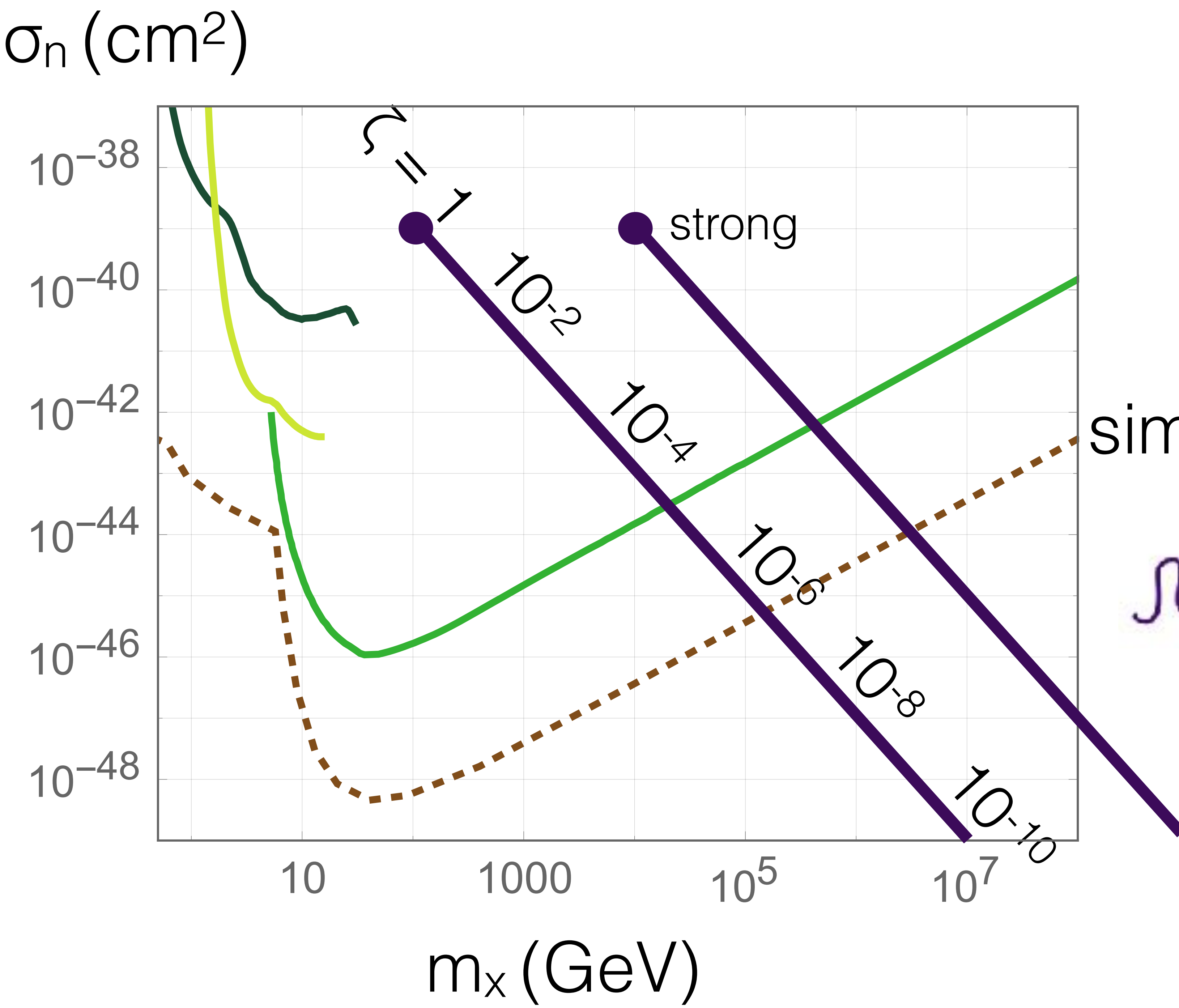


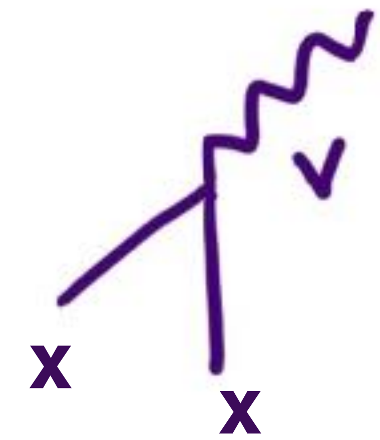


simplest case: let $m_X = m_V$

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_V}{PeV}\right)^2 \left(\frac{0.03}{\alpha}\right)^2 \left(\frac{\zeta}{10^{-8}}\right)$$

Dilute WIMPS





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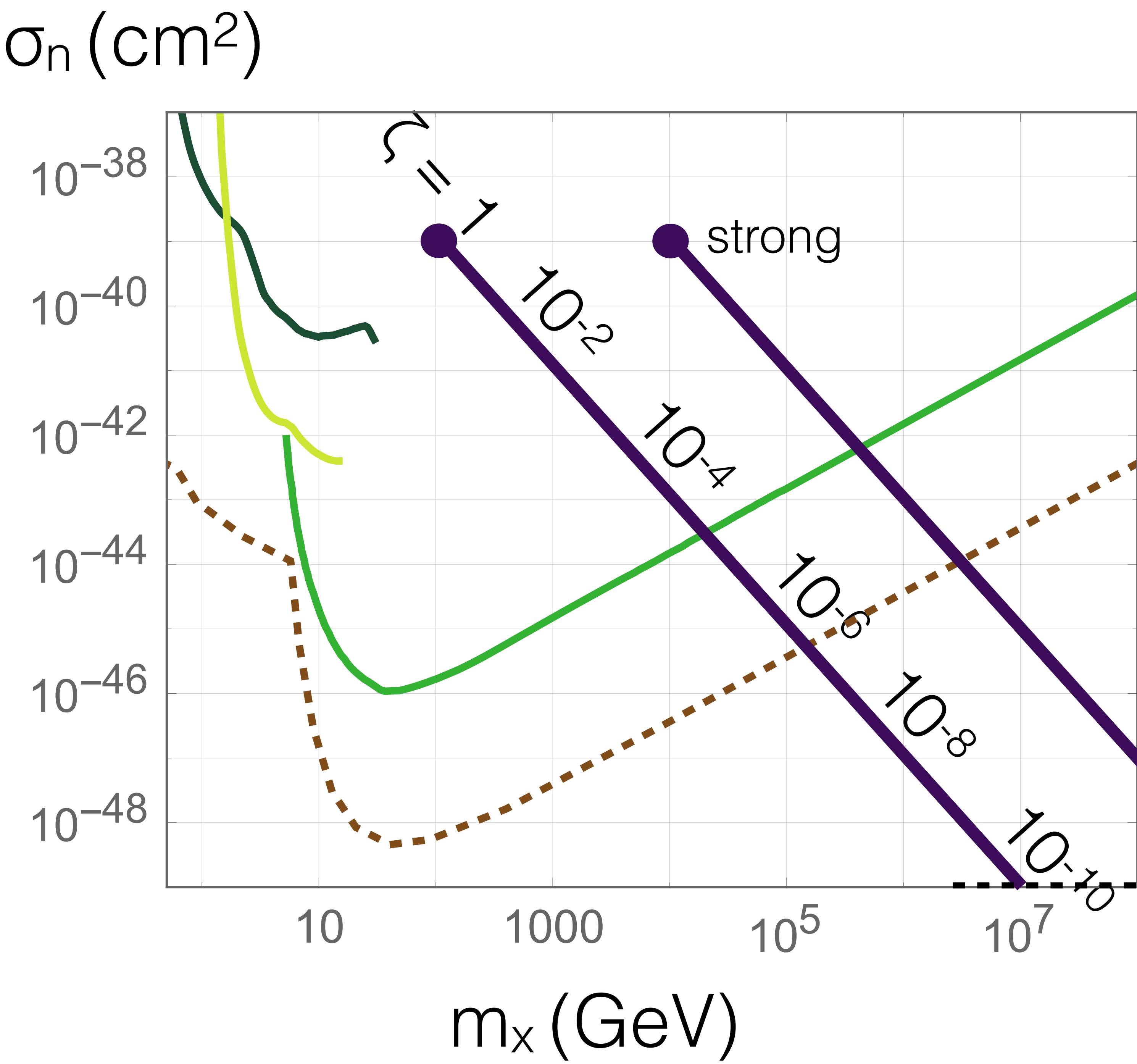

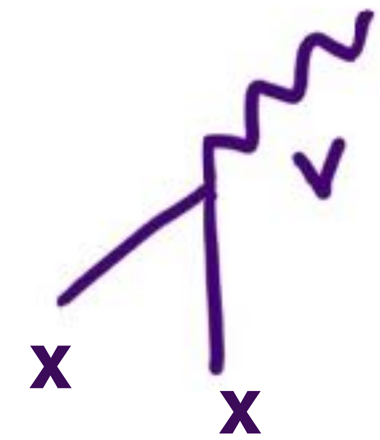

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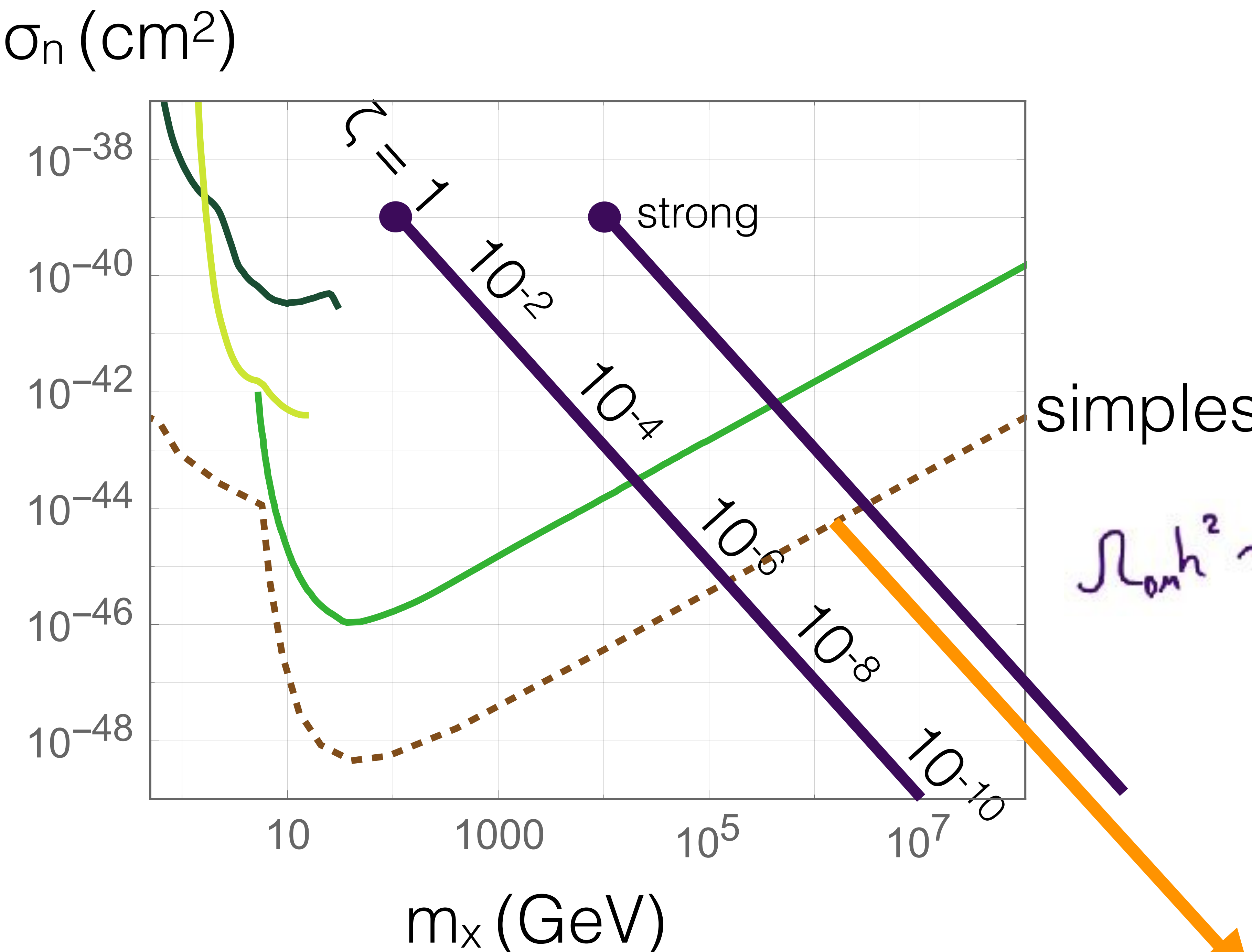
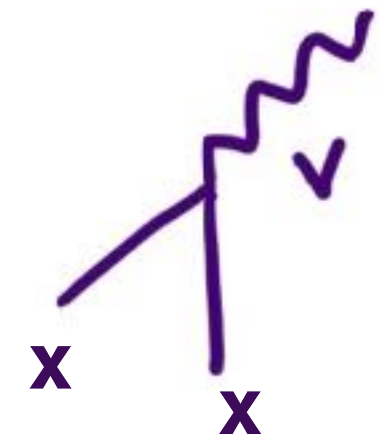
dilution bound for high scale baryogenesis, $\zeta > 10^{-10}$

Dilute WIMPS



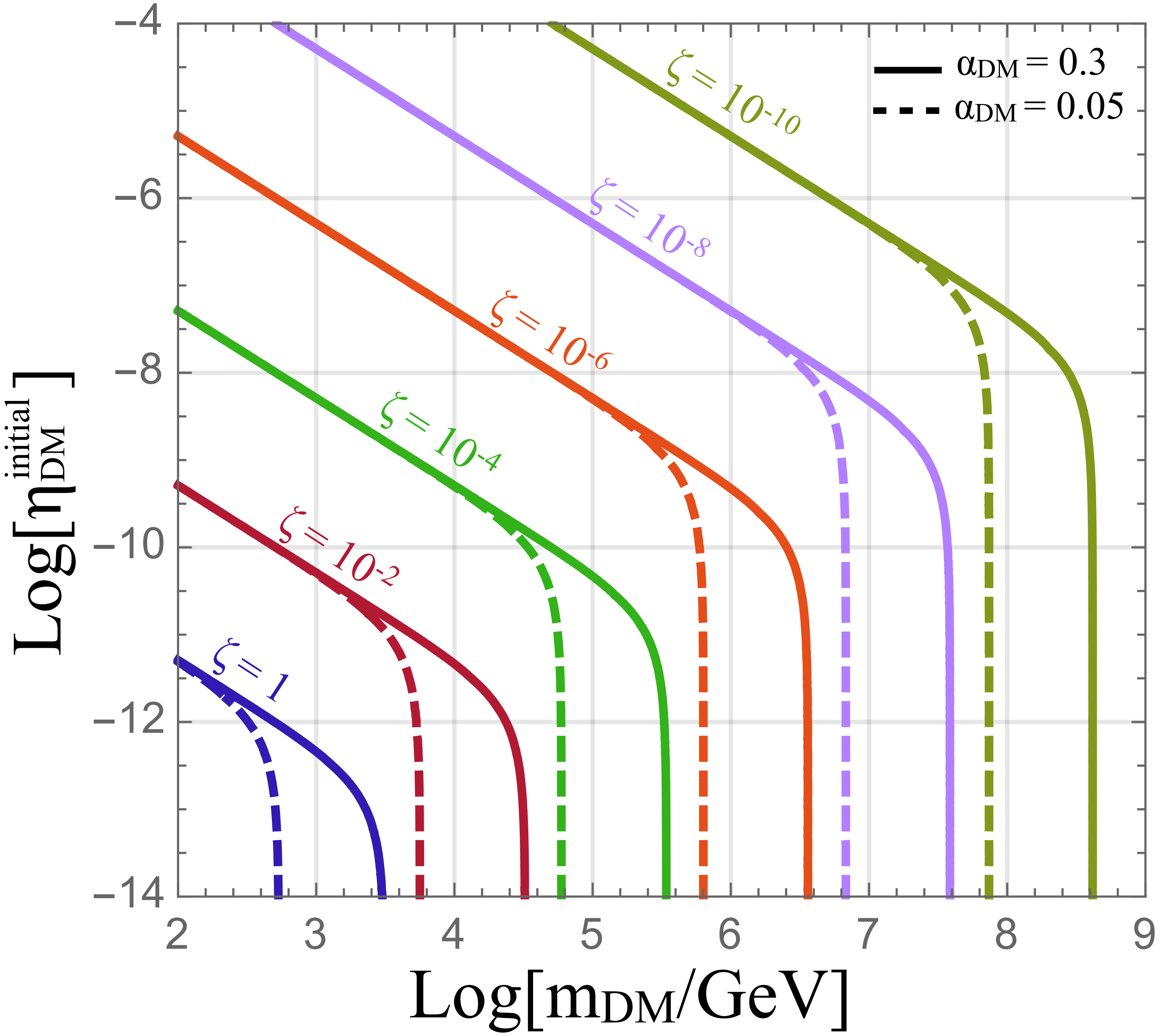


simplest case: let $m_\chi = m_V$

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{m_V}{PeV}\right)^2 \left(\frac{0.03}{\alpha}\right)^2 \left(\frac{\xi}{10^{-8}}\right)$$

see **Nirmal Raj** tomorrow 3pm
to find dilute w**imps** with neutron stars

Heavy Asymmetric Dilute WIMPS



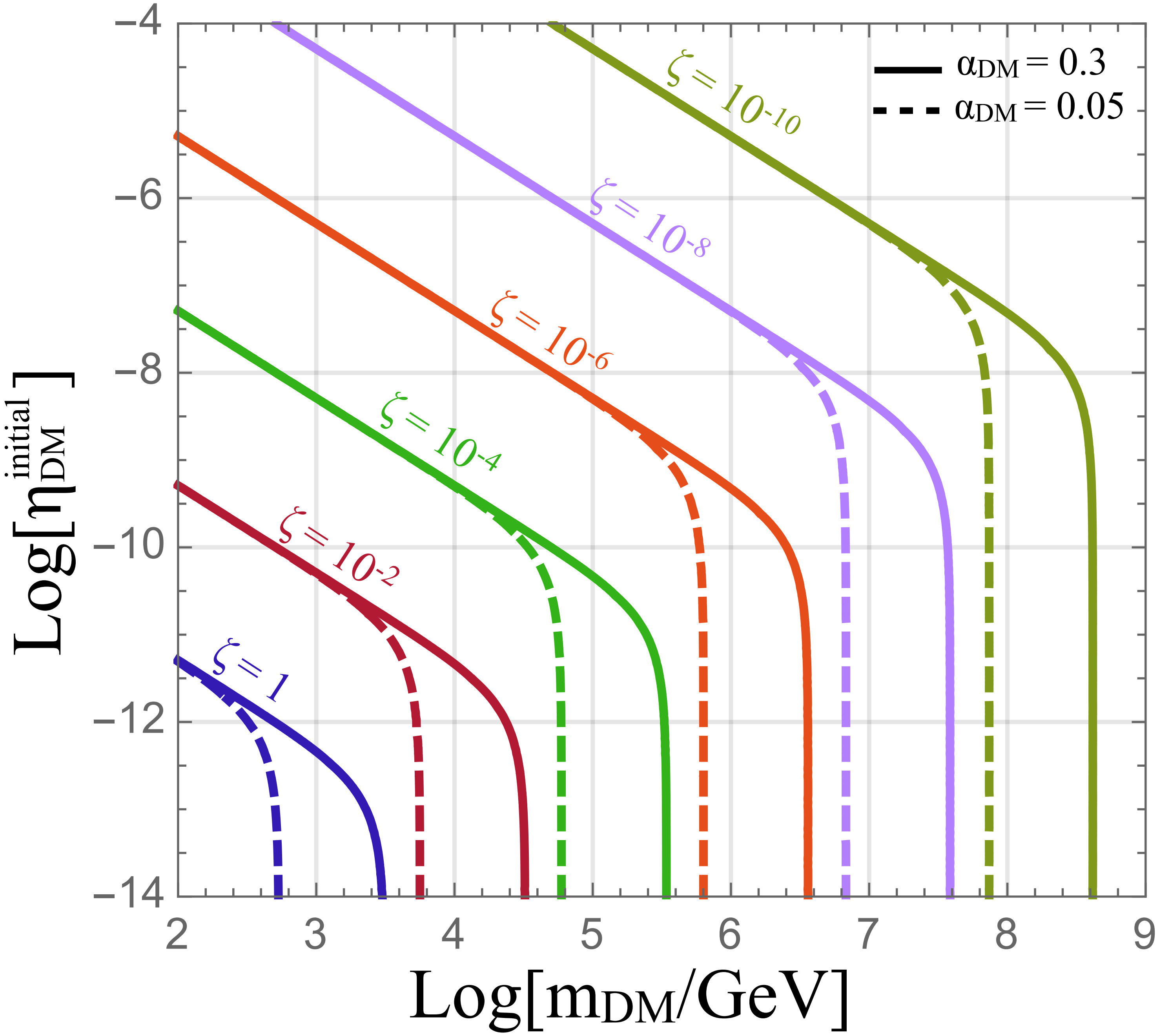
$n_D \to n_D \zeta$

$n_B \to n_B \zeta$

$\Omega h^2 \sim 0.1 \, \frac{n_D}{n_B} \frac{m_{DM}}{m_p}$

HADWIMPS $10^5 - 10^9$ GeV in mass

Heavy Asymmetric Dilute WIMPS



$$n_D \to n_D \zeta$$

$$n_B \to n_B \zeta$$

$$\Omega h^2 \sim 0.1 \frac{n_D}{n_B} \frac{m_{DM}}{m_p}$$

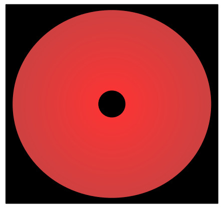
Example: PeV sector

$$\frac{\eta_B^{(1)}}{\eta_{DM}^{(2)}} \simeq \left(\frac{M}{m_{\phi_B}}\right)^{\frac{1}{3}} \simeq 10^4 \left(\frac{M}{M_{Pl}}\right)^{\frac{1}{3}} \left(\frac{1\ \mathrm{PeV}}{m_{\phi_B}}\right)^{\frac{1}{3}}$$

HADWIMPS $10^5 - 10^9$ GeV in mass

Gold from Heavy Asymmetric DM and Neutron Star Implosions

1. Heavy asymmetric dark matter implodes neutron stars by collecting inside, and forming black holes at their cores.



JB Linden 2016

JB Linden Tsai 2017

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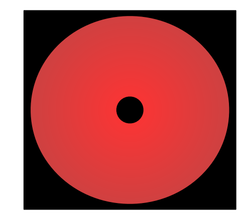

see **Yu-Dai Tsai** tomorrow 245pm
to find HADW**IMPS** with neutron stars, gravity waves, kilonovae, and frbs

JB Linden 2016

JB Linden Tsai 2017

Gold from Heavy Asymmetric DM and Neutron Star Implosions

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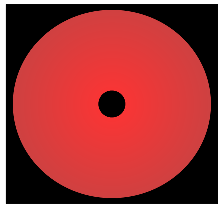
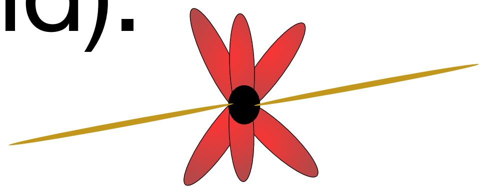


2. Imploding neutron stars eject neutron star fluid that forms heavy r-process elements (gold).



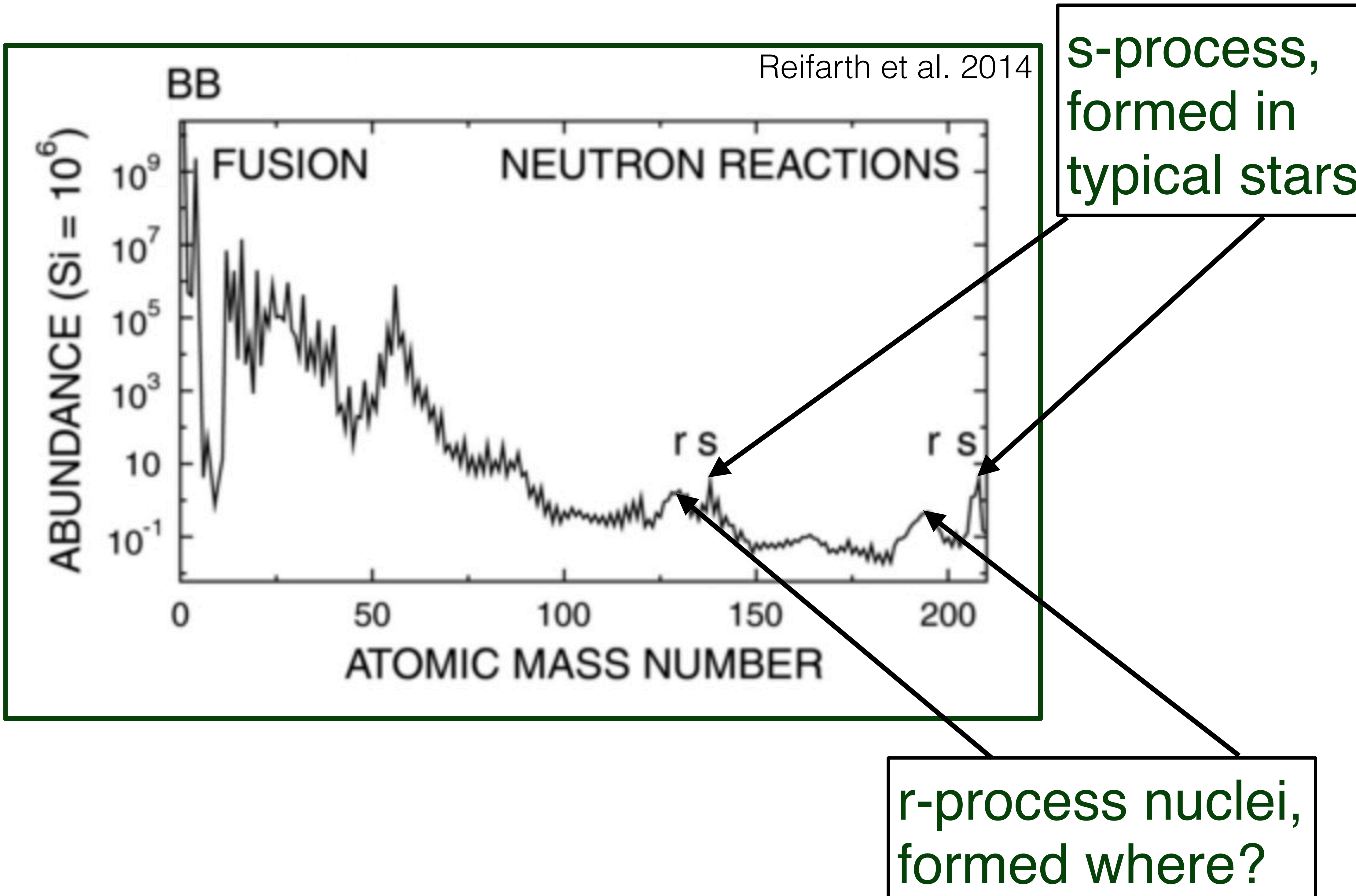
3. DM-induced neutron star implosions can explain why r-process elements are in just one of ten dwarf galaxies.

JB Linden 2016

JB Linden Tsai 2017

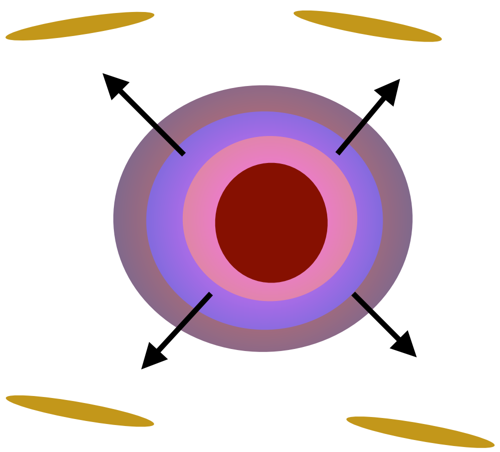
-R-process elements: heavy elements with atomic masses around ~80, ~130, ~195

-Formed in an as-yet-undetermined astrophysical sites rich in neutrons

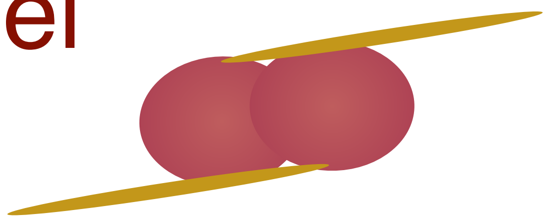


Possible r-process sites — total $10^4\ M_\odot$ produced in Milky Way

-Neutrons ejected by neutrino wind during core collapse supernovae (frequent, ~1/100 years)



-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)



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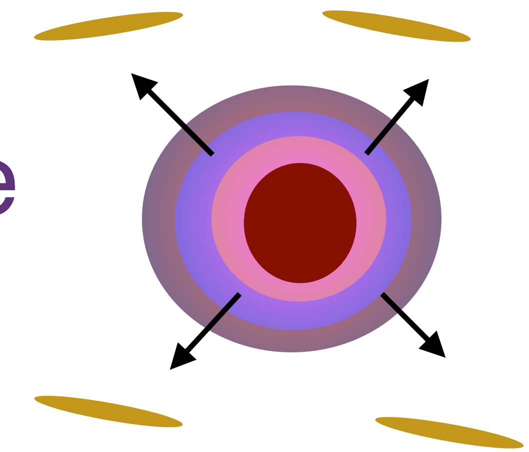

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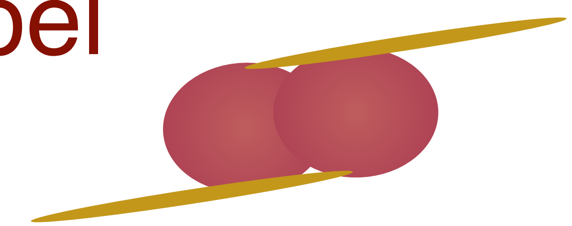
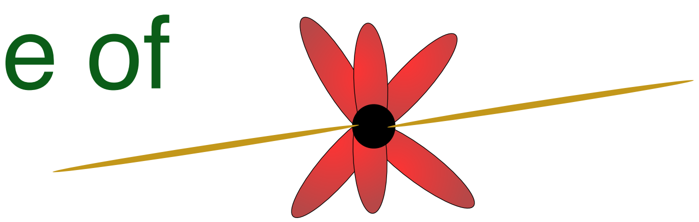
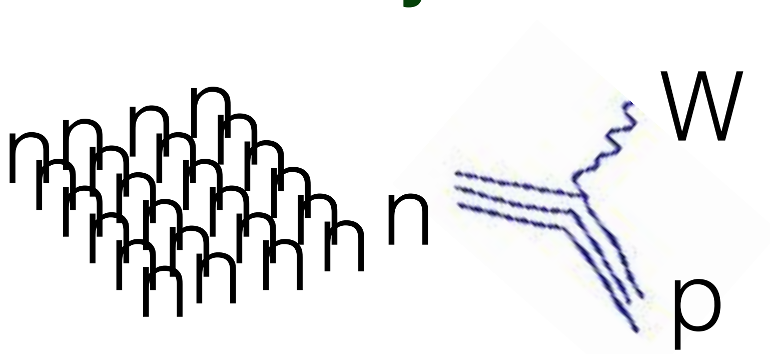


-Neutron star slurped into a black hole made of heavy asymmetric dark matter at its core.



implosion tidally expels some neutron fluid

In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.



… Gold, Uranium, Europium, Barium…

R-process in Ultra Faint Dwarf Galaxies

-Alexander Ji, grad student — "go look for r-process elements in ultra-faint dwarfs"

-Ultra faint dwarfs are star-poor dwarf galaxies formed in a billion year burst ~10 billion years ago

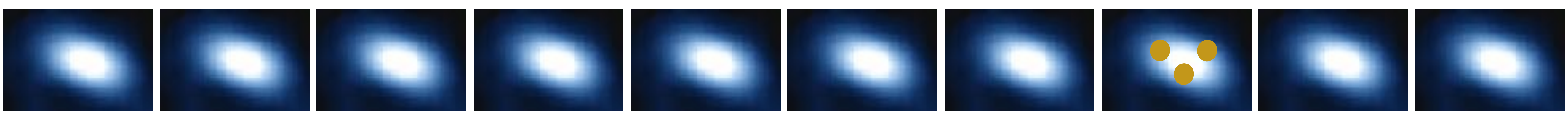
Ji et al. 2016

R-process in Ultra Faint Dwarf Galaxies

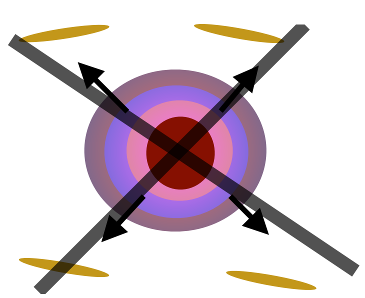
-Alexander Ji, grad student — "go look for r-process elements in ultra-faint dwarfs"

-Ultra faint dwarfs are star-poor dwarf galaxies formed in a billion year burst ~10 billion years ago

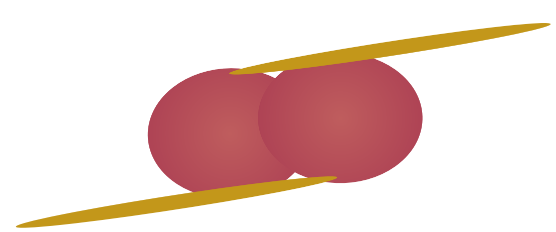
-Found just one with high r-process abundance — low r-process abundance expected in all ultra faint dwarfs



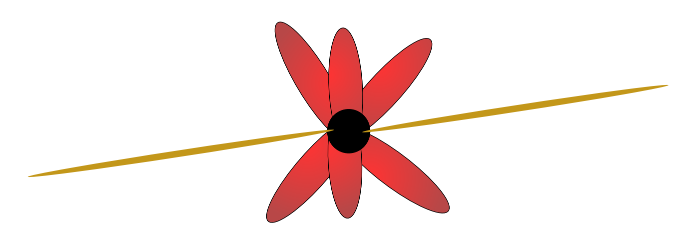
One UFD with r-process, and 9 without, implies rare r-process events.



many CCSN

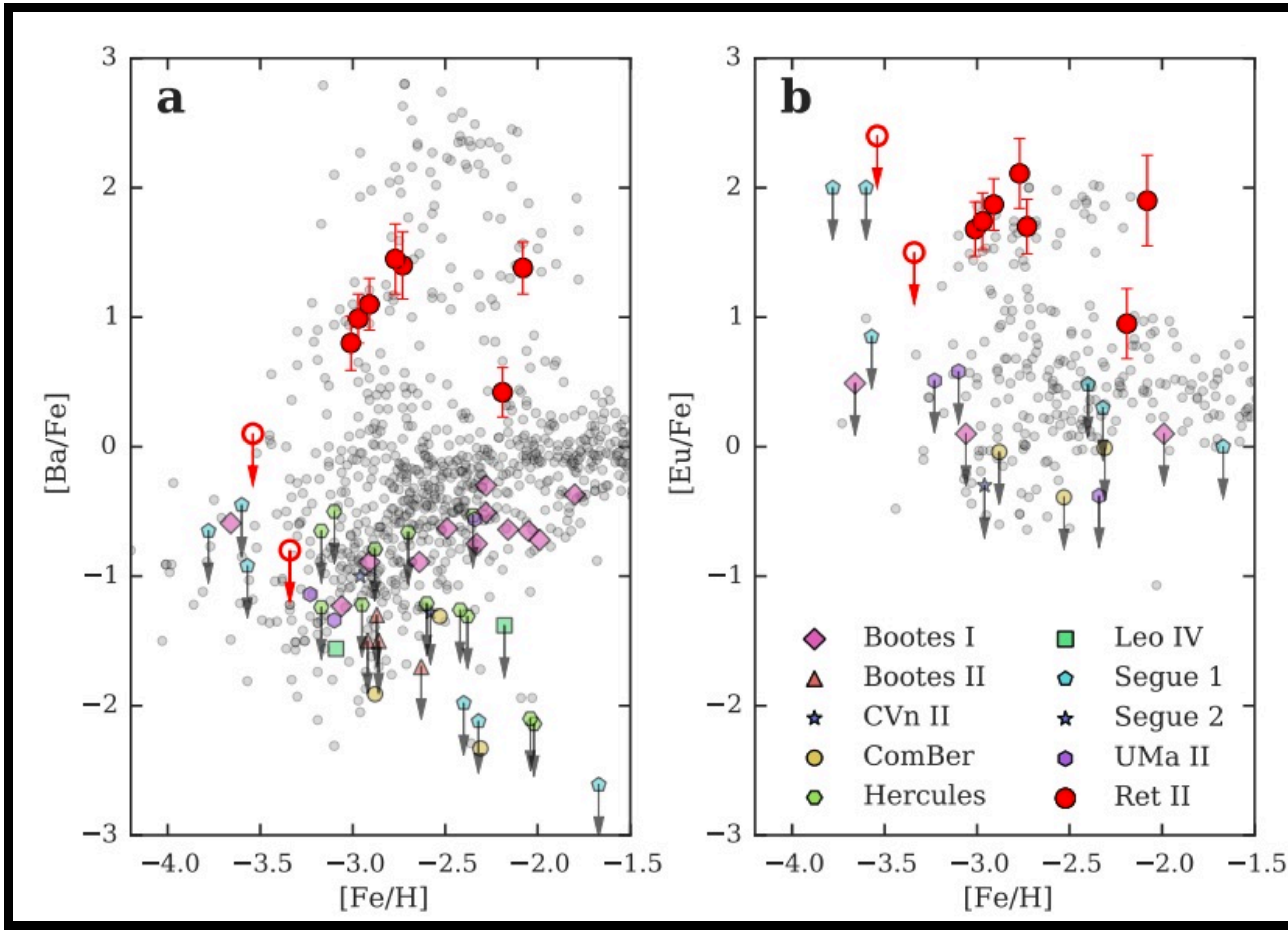


few NS mergers



few implosions

Plot of r-process in dwarfs — grey points are MW stars
➔ [X/Y] is log(X/Y) abundance.
➔ Ba, Eu are r-process elements, [Fe/H] grows with age



Plot of r-process in dwarfs — grey points are MW stars
➔ [X/Y] is log(X/Y) abundance.
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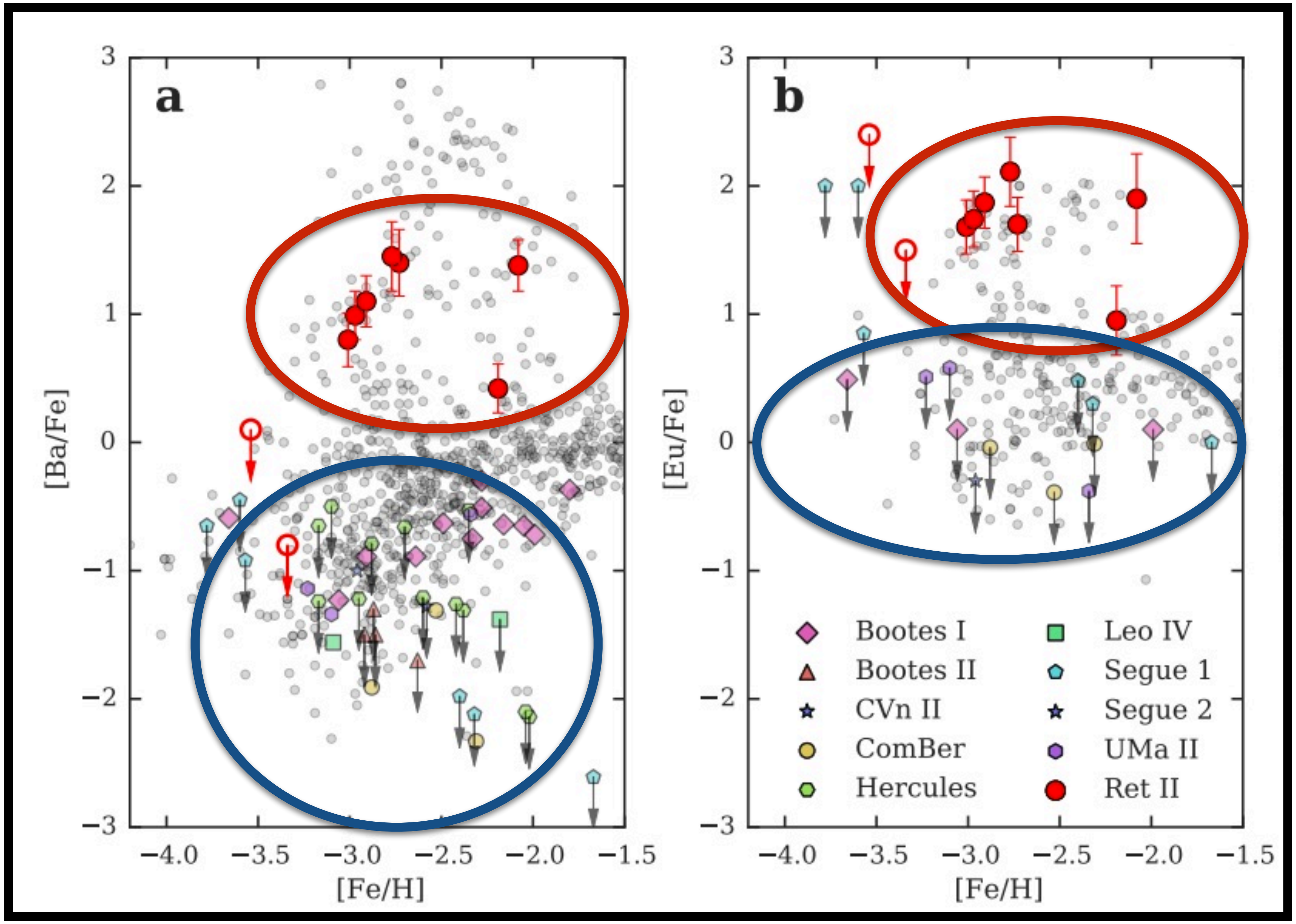
Reticulum II high r-process abundance

Other dwarfs, low r-process abundance



Unexpectedly high r-process abundance in Reticulum II
-indicates r-process from rare event

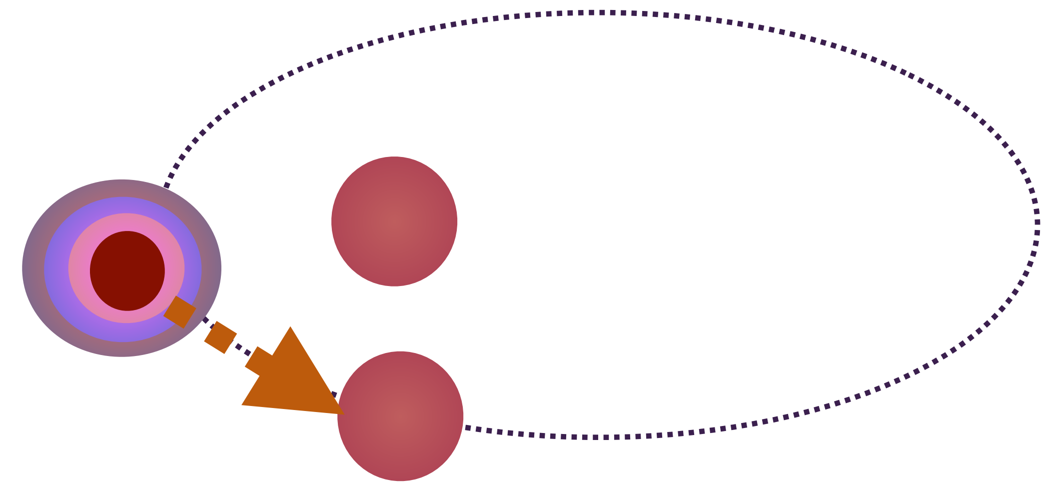
NS mergers kicked out of Reticulum II

**Neutron stars kicked at birth ~100 km/s.

**This kicks NS binary system to ~50 km/s.

**Merging neutron stars are ejected from dwarf spheroidals

—Reticulum II escape velocity <10 km/s.



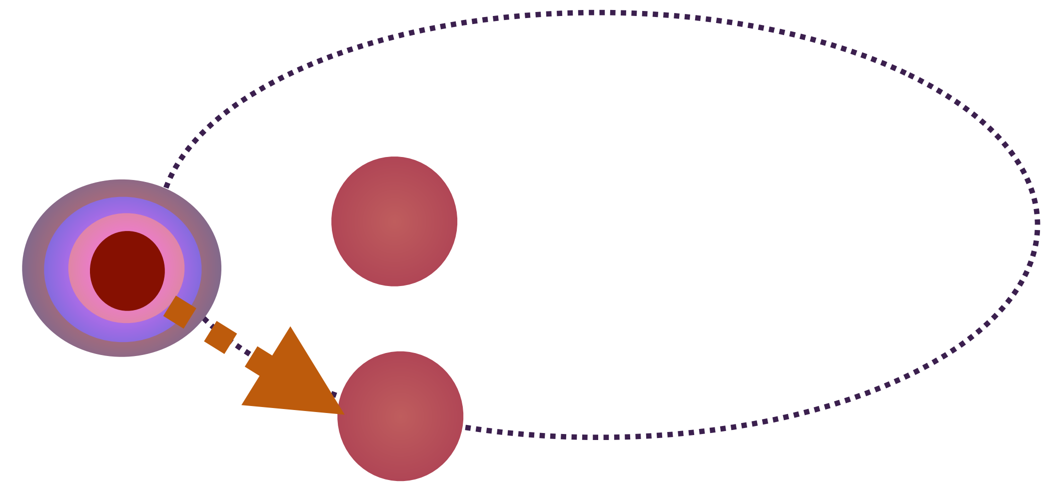
NS mergers kicked out of Reticulum II

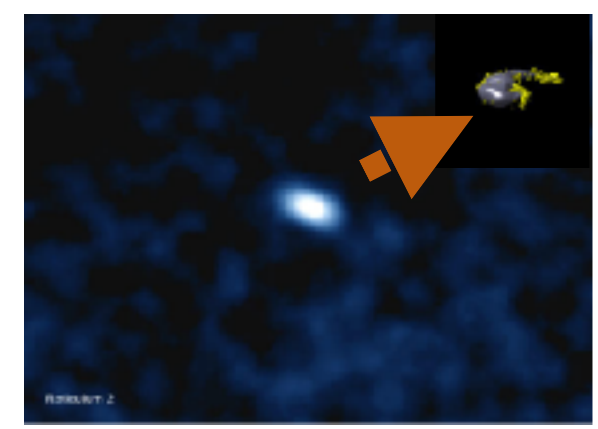
**Neutron stars kicked at birth ~100 km/s.

**This kicks NS binary system to ~50 km/s.

**Merging neutron stars are ejected from dwarf spheroidals

—Reticulum II escape velocity <10 km/s.



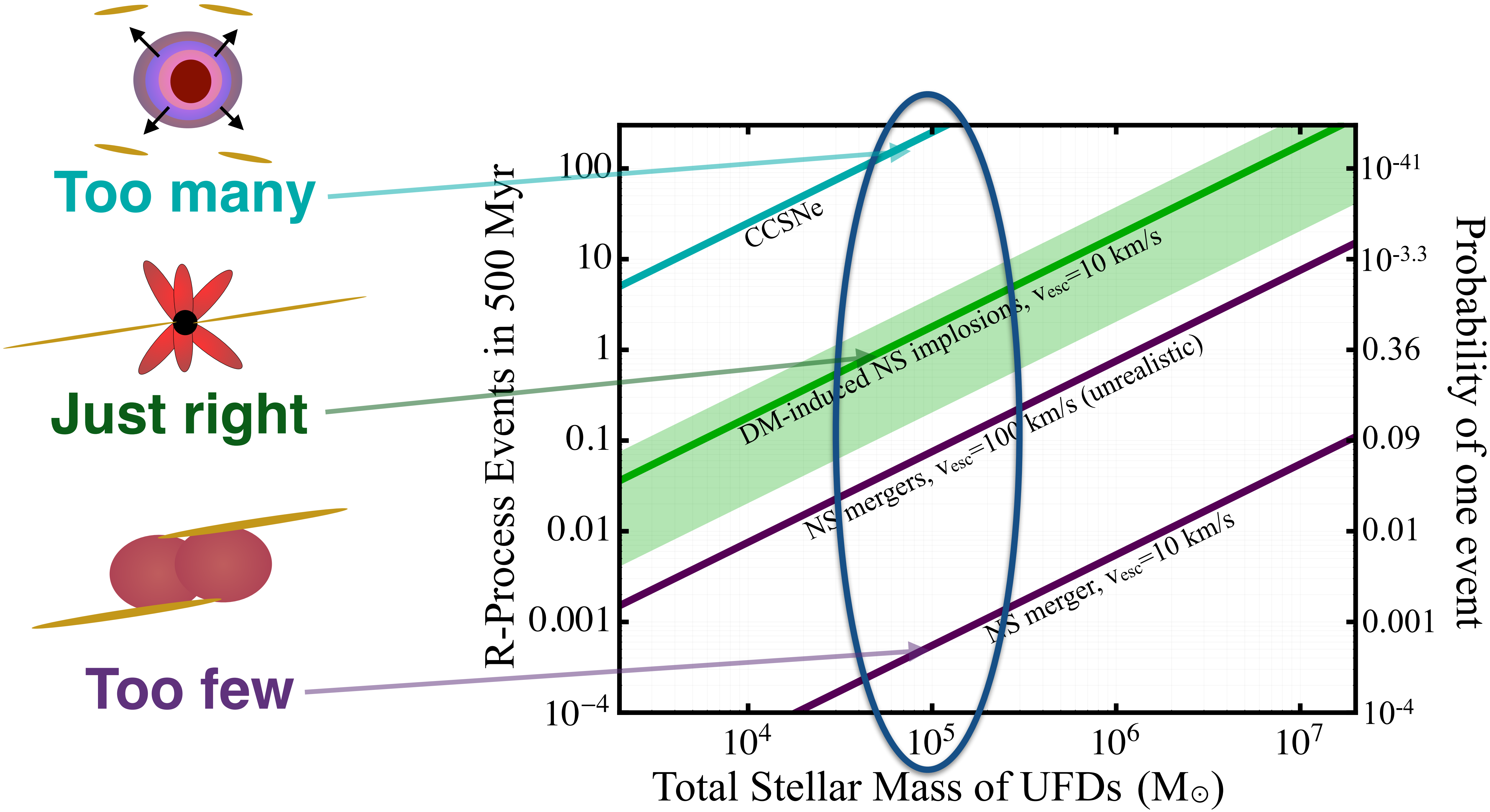


Probability of one merger for 10 UFDs

UFD escape velocity	10 Myr	50 Myr	100 Myr	500 Myr	1 Gyr	10 Gyr
10 km/s	<0.0001	<0.0001	<0.0001	0.0011	0.0016	0.0023
20 km/s	<0.0001	0.0004	0.0008	0.0085	0.0125	0.0183

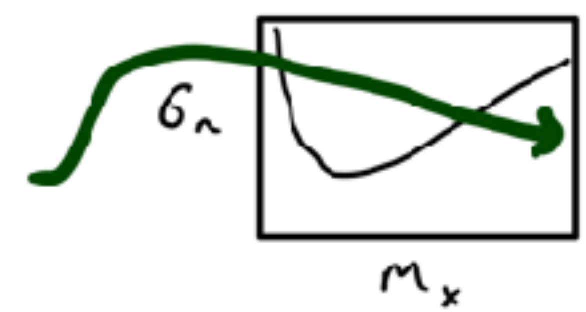
JB, Linden '16

UFD r-process rates

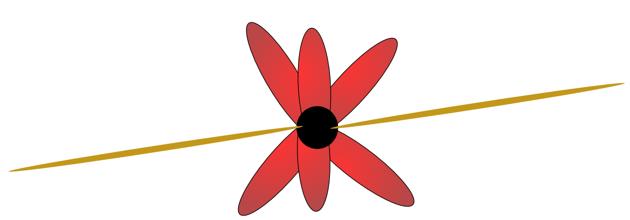


- Dilute WIMPs natural in cosmologies with baryogenesis $\{\eta_b\}$ implies $\{\eta_d\}$

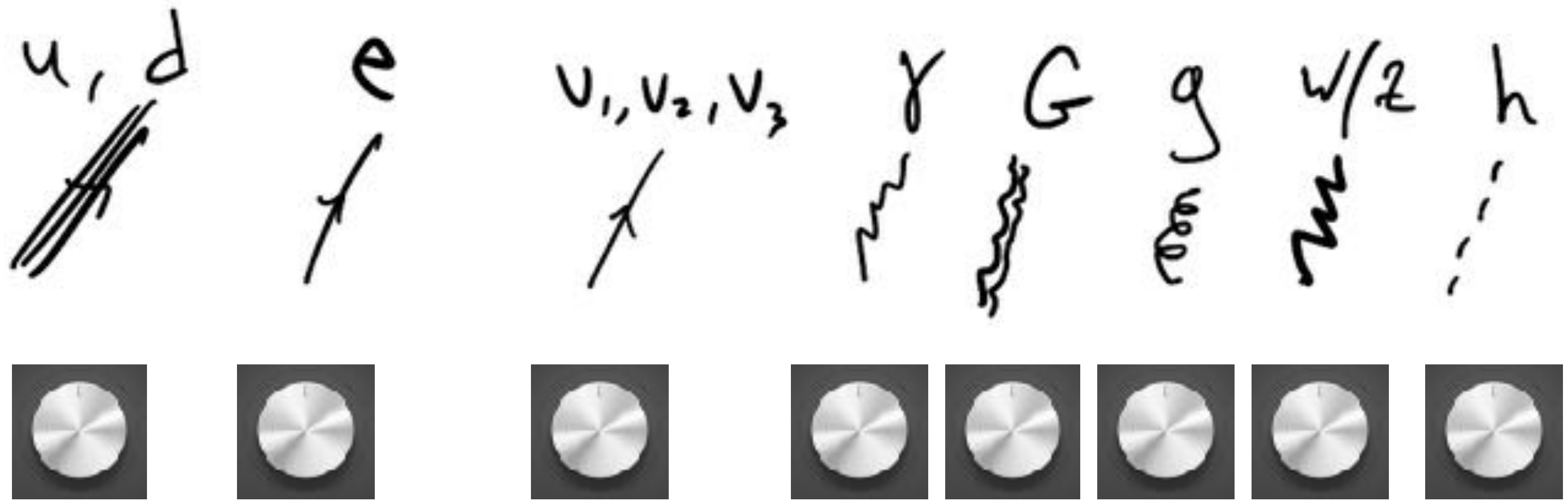
- Exciting time to be a bright young researcher!

(Queen's, SNOLAB, Nirmal Raj) 

- Heavy Asymmetric DM makes Gold!
(and gravity waves, kilonovae, frbs – see Yu-Dai Tsai)



Cosmologically Stable Particles + Bosons

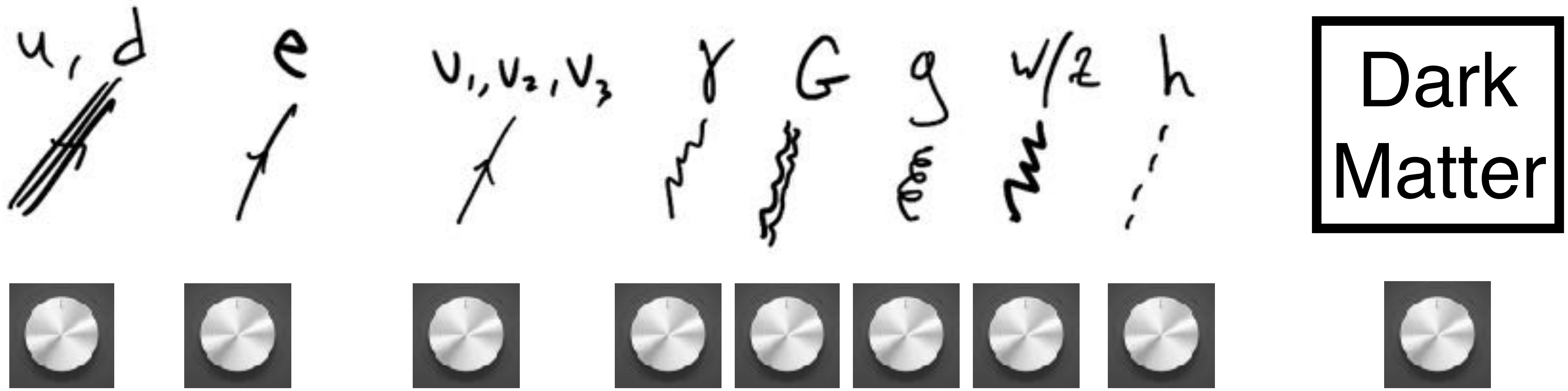


-Tuned towards atomic stability & production in supernovae

-Shift mass or couplings ⇒ supernovae disrupted

⇒ destabilize nuclei

Cosmologically Stable Particles + Bosons



-Tuned towards atomic stability & production in supernovae
-Shift mass or couplings ⇒ supernovae disrupted

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Variation on Atomic Principle

All cosmologically stable matter tuned
for heavy element production.