Co-Decaying Dark Matter and Early Universe Signatures

Dror, Kuflik, BSM, Watson arXiv:1711.04773
Georg, BSM, Watson arXiv:1902.04082

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KITP
Inflationary Reheating Meets Particle Physics Frontier
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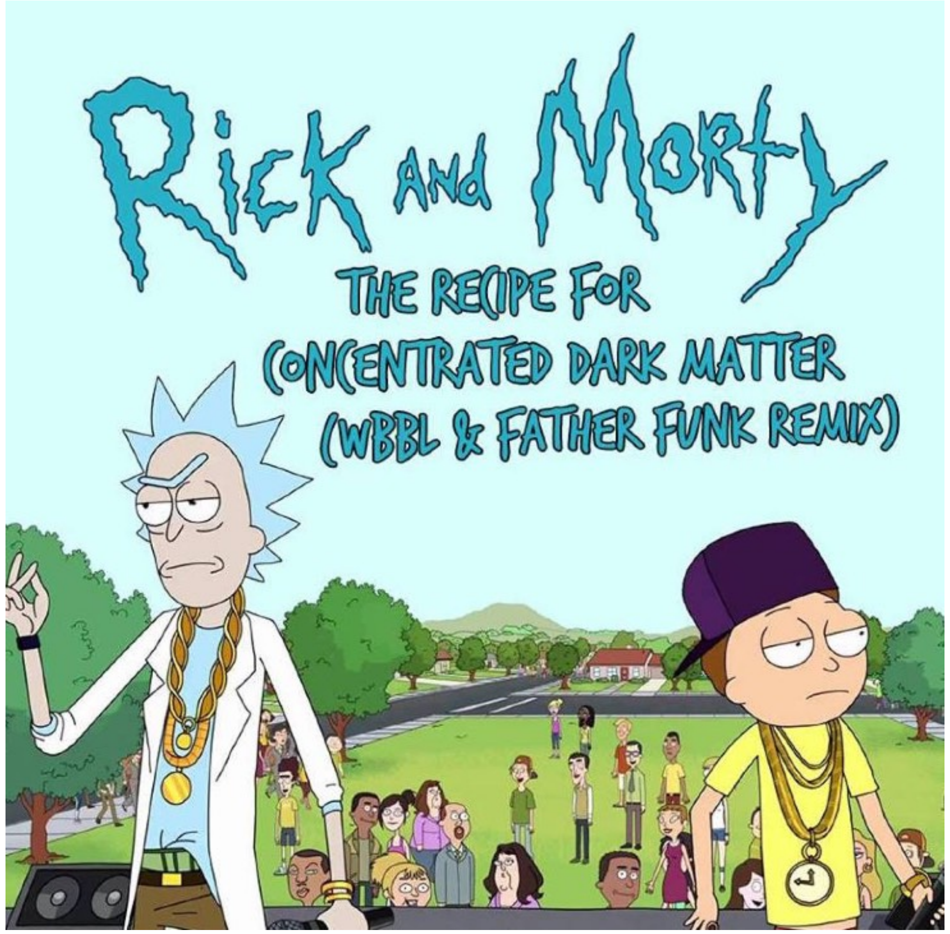
Outline

1. Motivation
2. Co-Decay Basics
3. Early Universe Signatures
    1. Small-scale structure
    2. Primordial Black Holes
4. Future Work and Conclusions



Motivation

WIMP-like Dark Matter

- The typical WIMP scenario assumes new, heavy particles, X, that annihilate to lighter particles in order to maintain thermal and chemical equilibrium with the cosmic plasma

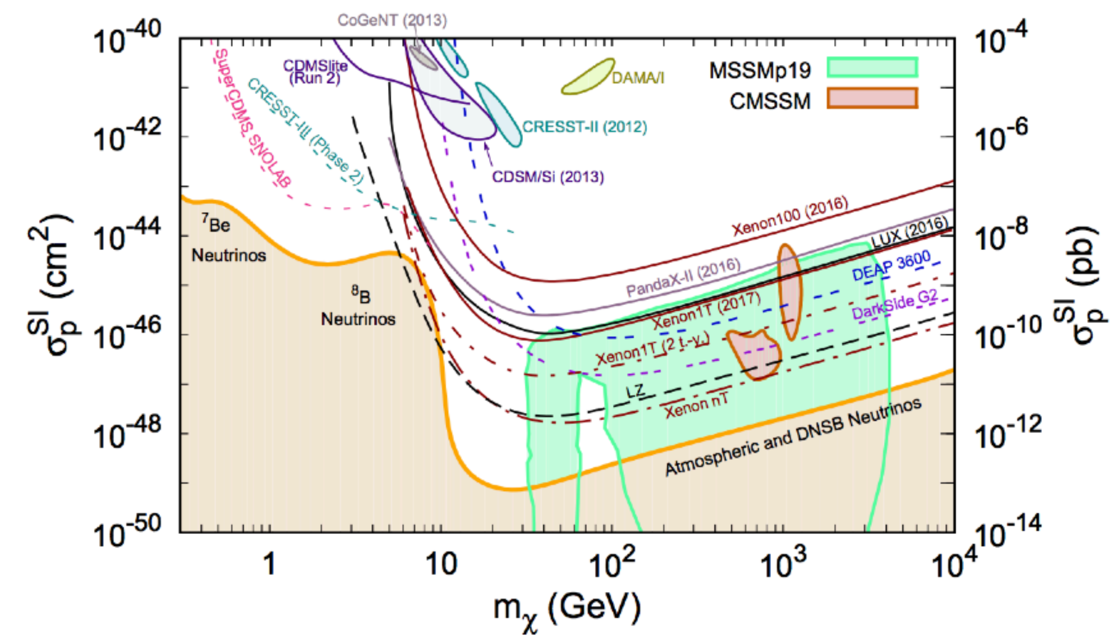
- Eventually, Hubble expansion overcomes the annihilation processes (i.e. $n_X\langle\sigma v\rangle \simeq H$) and the heavy particles freeze-out as relics

- Relic Abundance: $\Omega_X \sim \frac{1}{\langle\sigma v\rangle}$

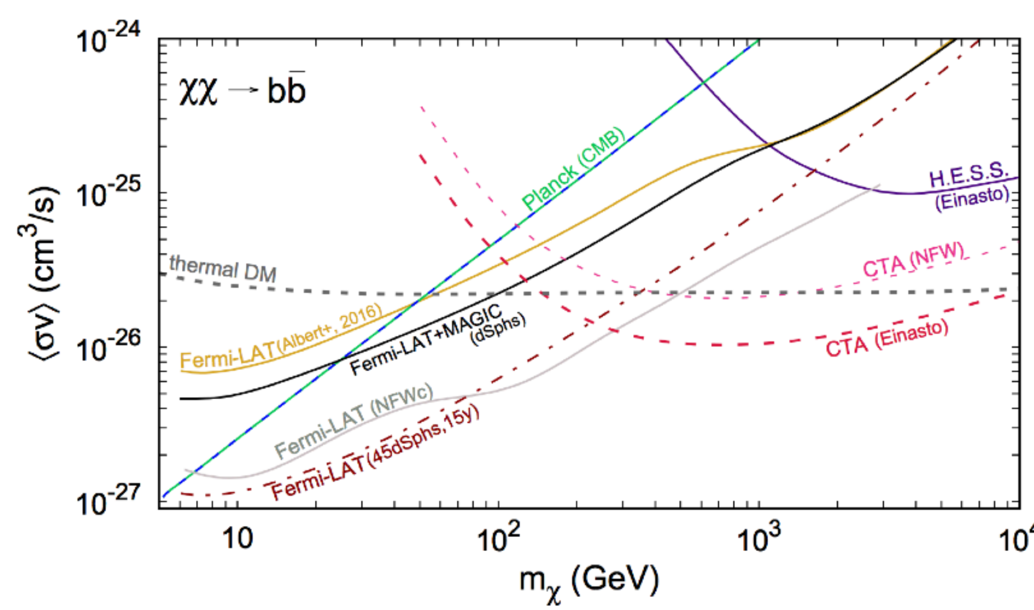
- WIMP Miracle and SUSY candidates?

Where are the WIMPs??

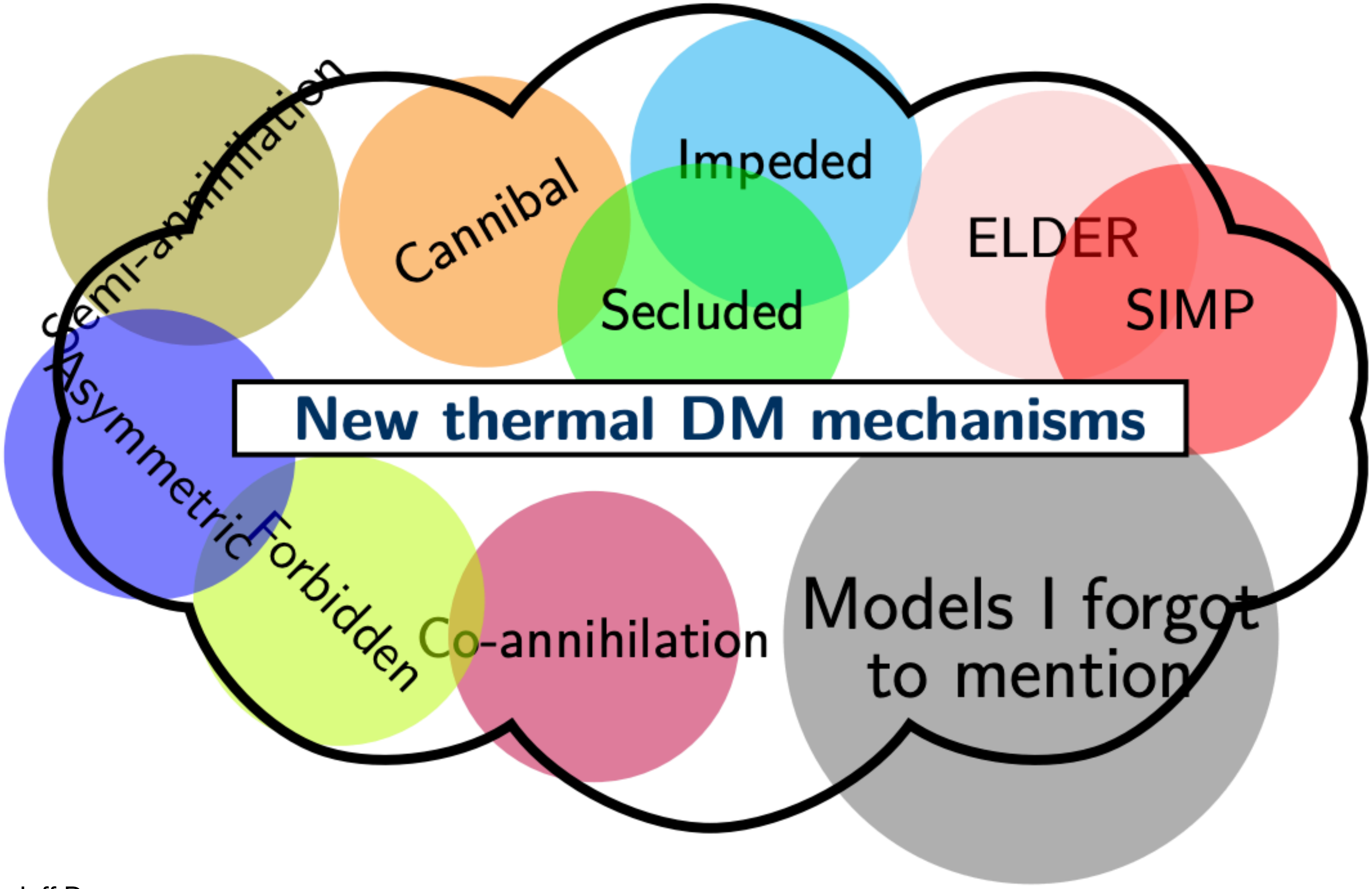
- Dark Matter with WIMP-like dynamics is under increasing pressure from both direct and indirect detection experiments
- Direct detection limits are stronger and approaching neutrino floors
- Indirect detection limits offer more leeway



Roszkowski, Sessolo, Trojanowski Rept.Prog.Phys. 81 (2018)



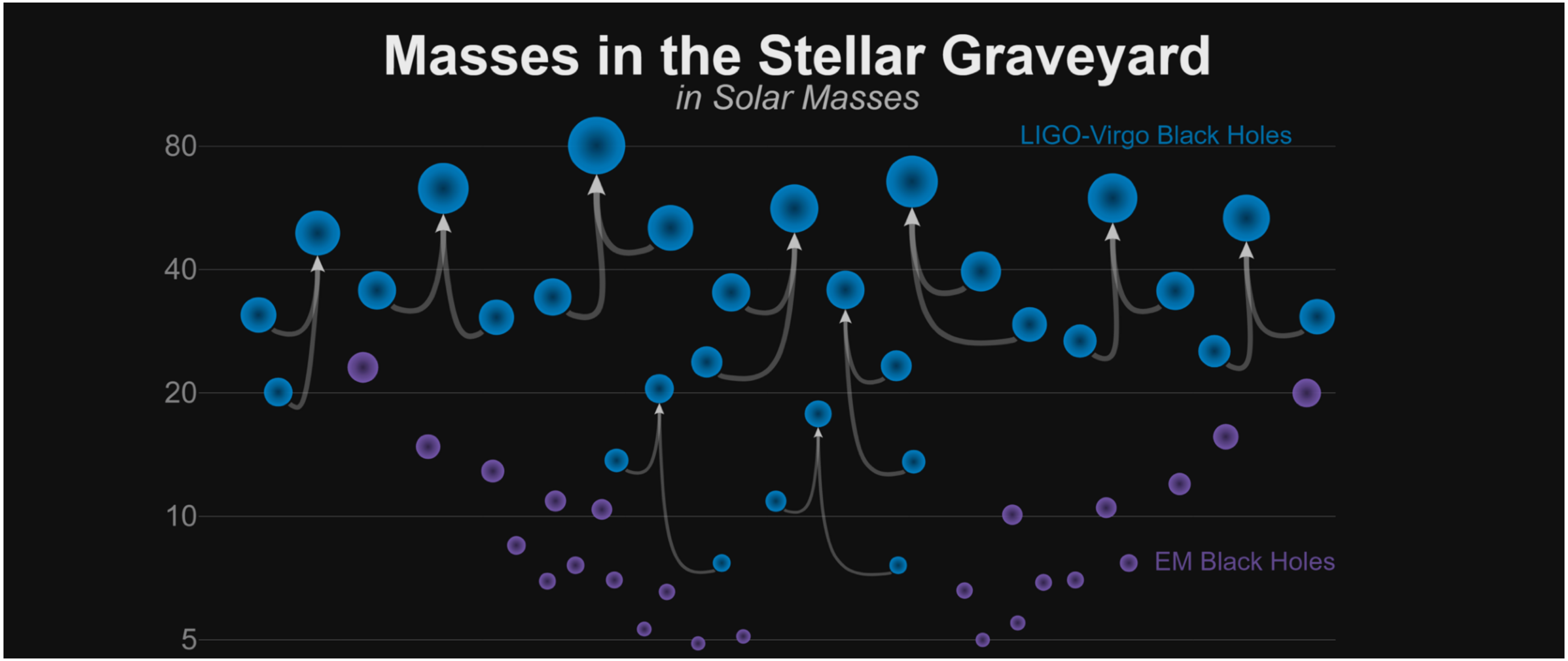
Non-WIMPs



Courtesy Jeff Dror

Black Hole Detections

LIGO detections of black hole mergers reinvigorated the possibility that DM could be partially composed of primordial black holes.



https://www.ligo.org/detections/O1O2catalog.php

PBH Forming Difficulties...

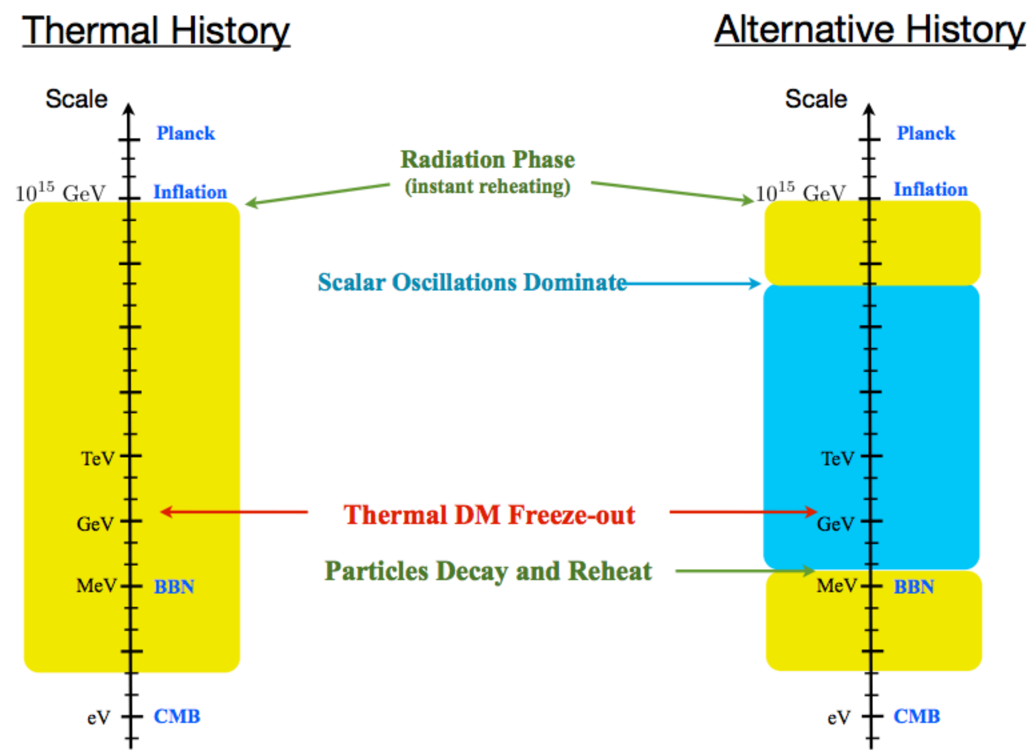
- The probability for forming PBHs from primordial perturbations in a radiation dominated universe is:

$$P_{PBH} \simeq \delta_m \exp\left(-\frac{w^2}{2\delta_m^2}\right)$$

- Jean's pressure of radiation fluid suppresses inhomogeneity collapse that could otherwise form PBHs
- To overcome this suppression, we would need something special to happen in the early universe to enhance power spectrum at some scales:
    - Power spectrum features
    - Monotonic power spectrum
- Other formation possibilities involve collisions of strings and bubbles...

Early Matter Domination

- Many BSM models predict the existence of extra fields
- Early universe dynamics will generically induce oscillations of these fields causing an Early Matter Dominated Era (EMDE)
- Matter Domination $\Rightarrow \delta\rho/\rho \sim a$
- At some point, the field will decay to SM particles and reheat the universe



Kane, Sinha, and Watson Int.J.Mod.Phys. D24 (2015)

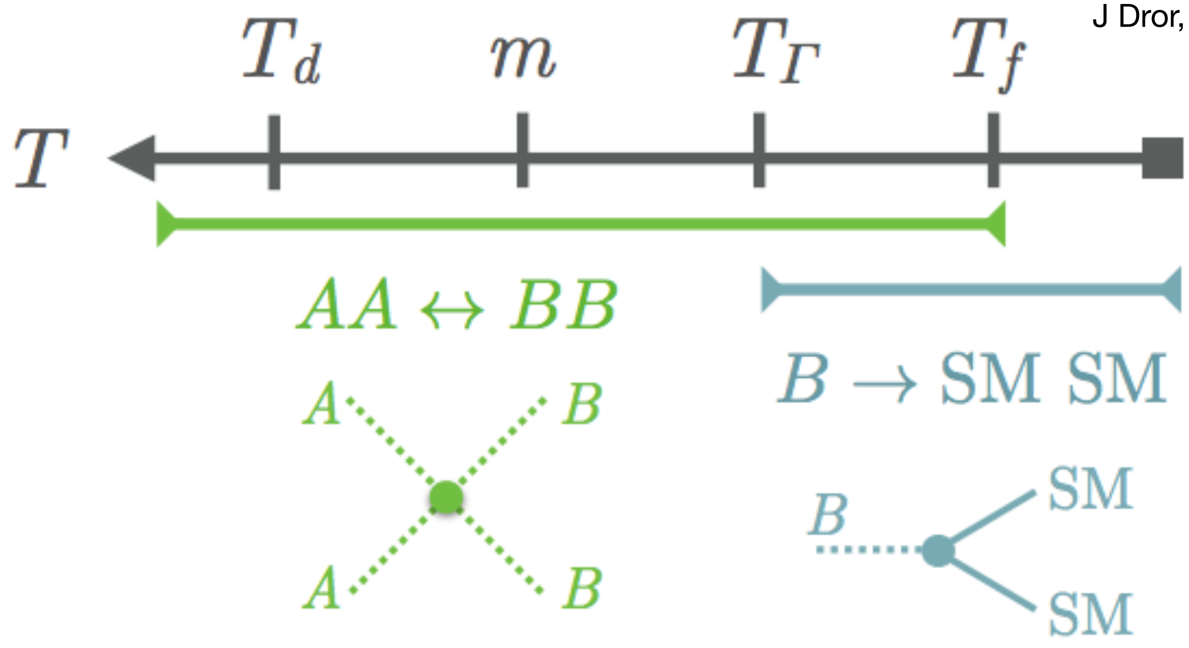
Co-Decay Primer

For more details, see: Dror, Kuflik, Hao Ng; Phys.Rev.Lett. 117 (2016)

Co-Decaying Dark Matter

J Dror, E Kuflik, and W Hao Ng, PRL '16

Basic Idea



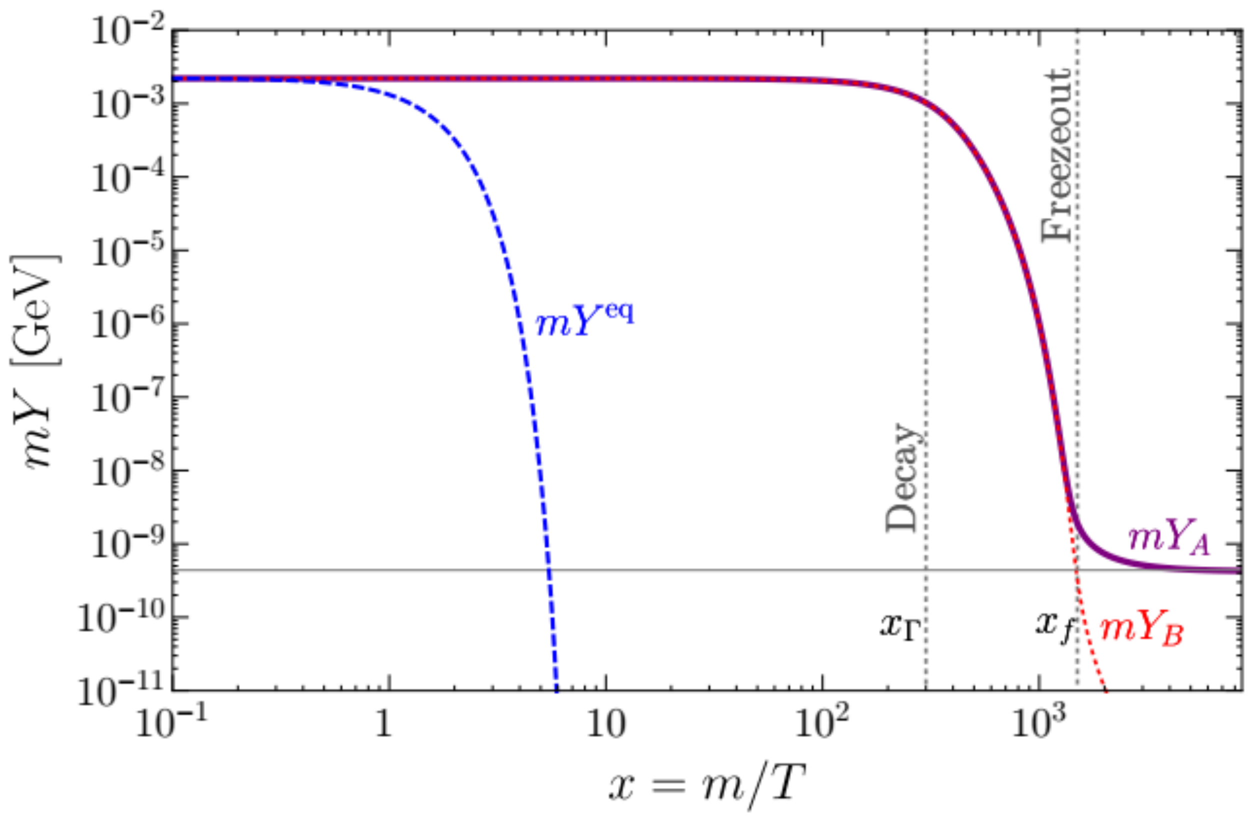
- There is a dark sector (DS) that decoupled from the visible sector prior to becoming non-relativistic
- The lightest DS particle (LDSP) decays to the SM out of equilibrium
- There is at least one additional particle in the dark sector that is degenerate and in equilibrium with the LDSP
- The additional particles will play the role of dark matter
- Similar scenarios in: Berlin, Hooper, Krnjaic; Phys.Lett. B760 (2016), Phys.Rev. D94 (2016)

Co-Decaying Dark Matter

- $A \leftrightarrow B$ interactions are temperature suppressed, but maintain chemical equilibrium and number density equality

- Eventually, $n_f \langle \sigma v \rangle \simeq H_f$, and the A particles freeze out.

- The predicted relic density is then: $\frac{\Omega_A}{\Omega_{DM}} = \left(\frac{10^{-36}}{\sigma/\text{cm}^2}\right)\left(\frac{m}{1\text{GeV}}\right)\left(\frac{10^{-18}}{\Gamma/m}\right)$



m = 1 GeV
$\sigma = 1 \times 10^{-30}\text{cm}^2$
$\Gamma = 6 \times 10^{-23}$ GeV

J Dror, E Kuflik, and W Hao Ng, PRL '16

Example Model

- Consider dark $SU(2)_D$ with a dark Higgs Φ_D that breaks the symmetry and generates mass m_D for the dark gauge bosons

- Introduce a six-dimensional operator that mixes Z_D and the Z of the Standard Model

$$\mathscr{L} \supset \frac{(\Phi_D^\dagger D^\mu \Phi_D)(\Phi^\dagger D^\mu \Phi)}{\Lambda}$$

- W_D bosons are stable and play role of A particle (the DM), Z_D decays and plays role of B particle

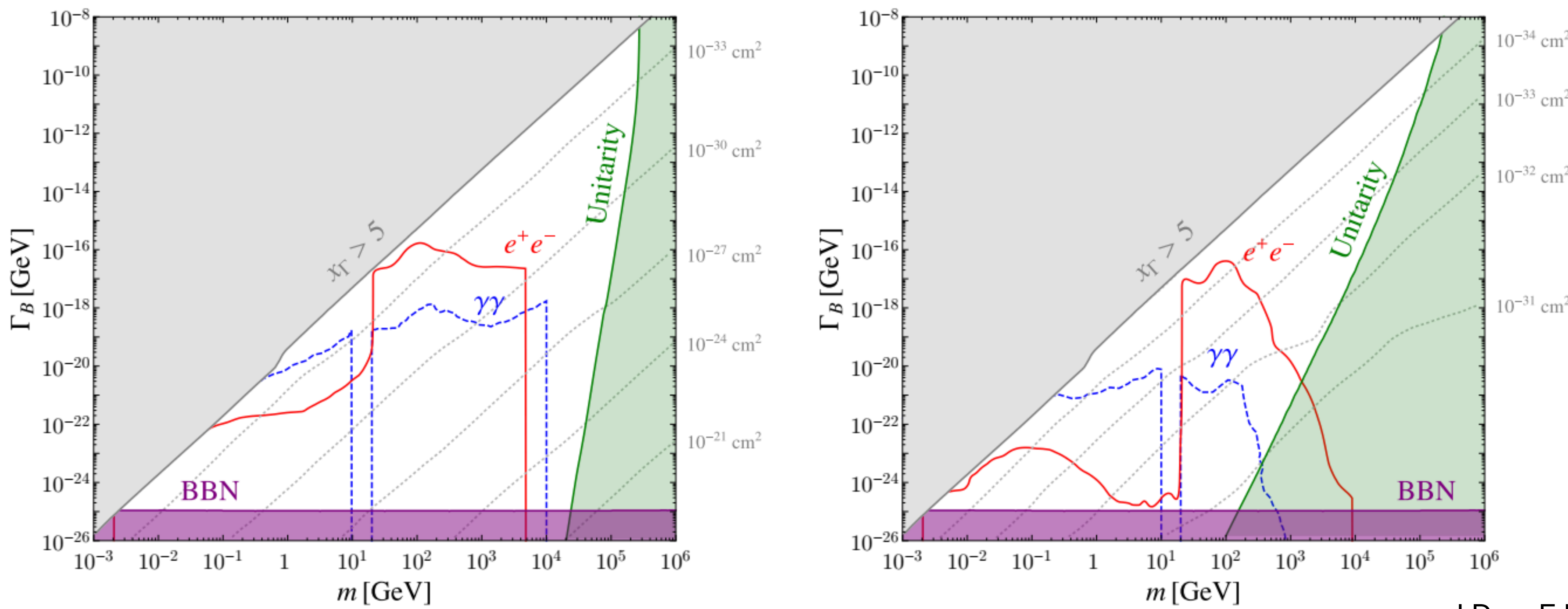
$$Z_D Z_D \leftrightarrow W_D^+ W_D^- : \sigma = \frac{688}{3} \frac{\alpha_D^2}{m_D} \qquad Z_D \to f_{SM} : \Gamma_{Z_D} = \frac{1}{48\pi^2 \alpha_D^2} \frac{m_D^5}{\Lambda^4} |g|^2$$

- An example involving SUSY was explored in Dery, Dror, Haskins, Hochberg, and Kuflik; Phys.Rev. D99 (2019)

Co-Decaying Dark Matter

Non-Cannibalizing

Cannibalizing



J Dror, E Kuflik, and W Hao Ng, PRL '16

- Cannibalization (number changing interactions) does not affect the conceptual picture, but does modify some of the constraints of the system

- If there is a split between A and B masses, there are two options:

  - $m_A > m_B$, the model is essentially unchanged, but the annihilation cross-section is no longer temperature suppressed

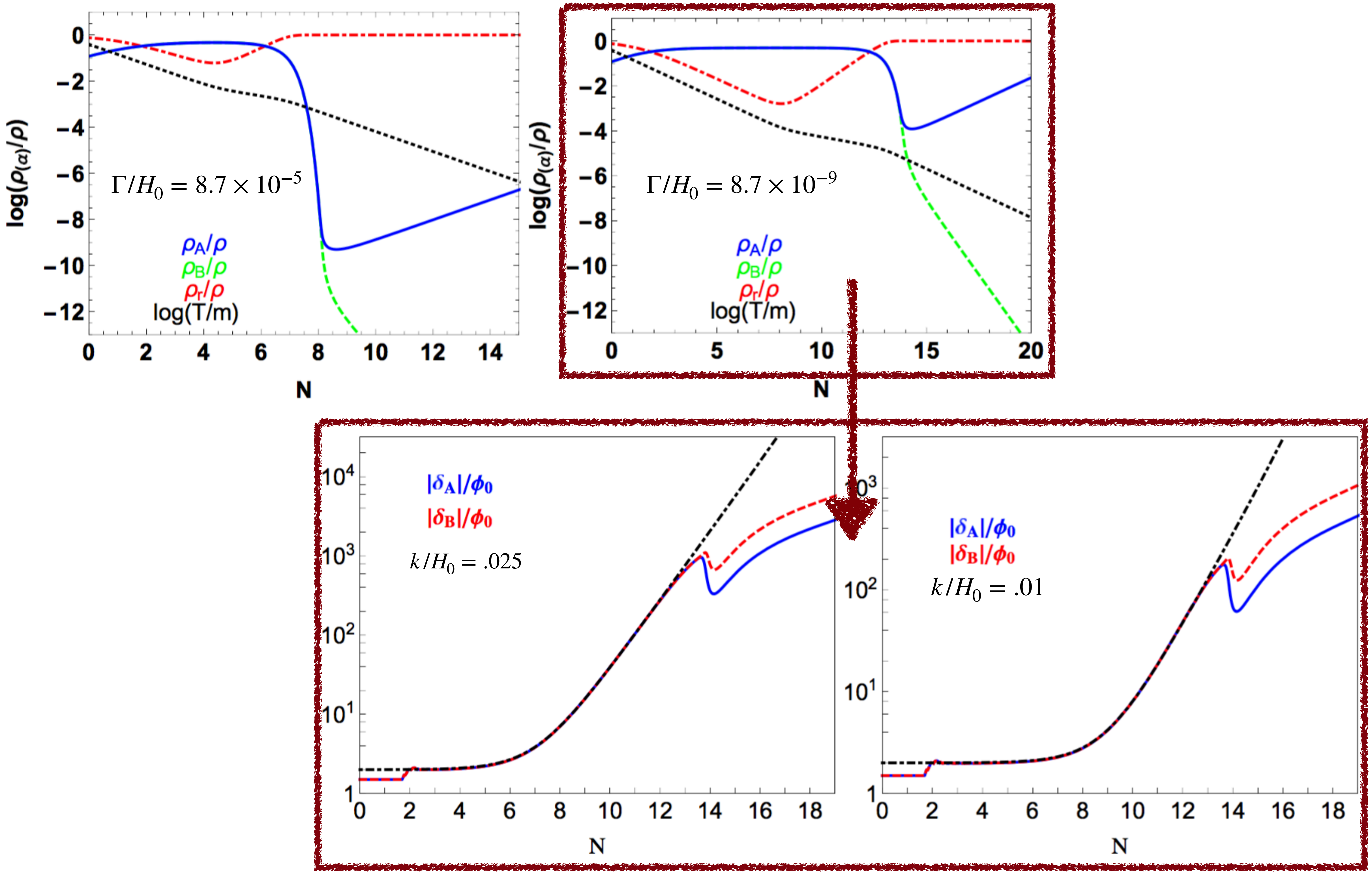
  - $m_A < m_B$, cross-section experiences exponential suppression with temperature

Early Universe Signatures

Dror, Kuflik, BSM, Watson arXiv:1711.04773
Georg, BSM, Watson arXiv:1902.04082

MD and Structure Growth

$m = 10.5$ TeV $\sigma = 10^{-30}$ cm²



Structure Considerations

Largest objects formed during the EMDE is determined by the reheating scale

$$k_{RH} \equiv a_{RH} H_{RH} = .1\mathrm{pc}^{-1} \times \left(\frac{T_{RH}}{3\mathrm{MeV}}\right)\left(\frac{g_\star(T_{RH})}{10.75}\right)^{1/6}$$

Particle streaming and kinetic equilibrium effects would tend to wash out structures

$$\frac{k_{kd}}{k_{RH}} \simeq \left(\frac{g_{kd}}{g_{RH}}\right)^{1/3}\left(\frac{T_{kd}}{T_{RH}}\right)^{8/3}$$

$\frac{1}{k_{fs}} = \int_{a_{kd}}^{a_{eq}} \frac{\langle v \rangle}{Ha^2} da \Rightarrow$ Dominated by non-relativistic streaming $\Rightarrow \frac{k_{fs}}{k_{RH}} \simeq \frac{k_{MD}}{k_{RH}} \simeq \left(\frac{g_{MD}}{g_{RH}}\right)^{1/6}\left(\frac{m\xi}{T_{RH}}\right)^{2/3}$

Rule of thumb: $k_{cut} > 10 k_{RH} \Rightarrow$ **Structures more likely to survive**

We assume $T_{KD} \gg T_{RH}$

Longer EMDE $\Rightarrow m\xi > T_{RH}$

Expect enhancement micro-halos with masses

$$M_{RH} \equiv \frac{4}{3}\pi\rho_A^0 k_{RH}^{-3} = 10^3 M_\oplus \left(\frac{3\mathrm{MeV}}{T_{RH}}\right)^3\left(\frac{10.75}{g_*(T_{RH})}\right)^{1/2}$$

Black Hole Formation

- Two factors determine the likelihood of black hole formation, for a given inhomogeneity in the energy density:

  - Inhomogeneity does not form caustics, β_{inhom}

  - Inhomogeneity will collapse, β_{coll}

No Caustics

- Need two definitions:

$$u \equiv \frac{\rho_0 - \rho_1}{\rho_1} \qquad\qquad x \equiv \frac{r_g}{r_1} \ll 1$$

- Polnarev and Khlopov ('81) showed that caustics don't form as long as the singularity forms after the apparent horizon which implies $u \leq x^{3/2}$.

- Assuming u is Gaussian and Random, $\beta_{inhom} \simeq x^{3/2}$.

- Kokubu et. al. (1810.03490) include time it would take for “outside” spacetime to become aware of singularity

$$\Rightarrow \beta_{inhom} \simeq 3.7 x^{3/2}$$

Deformation Tensor Basics

- We can characterize the inhomogeneities by their deformation tensor: deviation of particle trajectories from Zeldovich approximation

$$\vec{r} = a(t)\left[\overrightarrow{q} + b(t)\,\nabla_q \Phi(\overrightarrow{q}\,)\right]$$

- Eigenvalues of this tensor, α, β, γ, determine how the clump's principal axes deform over time

$$\rho(t, \vec{r}\,) = \frac{\langle \rho \rangle}{(1 + b(t)\alpha)(1 + b(t)\beta)(1 + b(t)\gamma)}$$

- Treat as Gaussian and Random, then can get probability distribution

$$P(\alpha, \beta, \gamma) = \tilde{C} \exp\left(N_{\alpha,\beta,\gamma}\right)(\alpha - \beta)(\alpha - \gamma)(\beta - \gamma)$$

- If $\alpha \sim \beta \sim \gamma$, $N_{\alpha,\beta,\gamma} \to -9/2\alpha^2$.

Collapse Conditions

- The probability of collapse becomes

$$\beta_{coll} = \int_{-\infty}^{0} d\alpha \int_{\alpha}^{\infty} d\beta \int_{\beta}^{\infty} d\gamma \Theta[S(\alpha, \beta, \gamma)] P(\alpha, \beta, \gamma)$$

- S captures condition which causes clump to collapse

- Originally, it was assumed clump had to be almost spherical for collapse

$$\beta_{coll} \simeq .02x^5$$

- More general collapse condition: Hoop Conjecture (see Malec, Xie; Phys.Rev. D91 (2015), and Harada et. al. Astrophys.J. 833 (2016))

$$\beta_{coll} \simeq .06x^5$$

Mass Distribution Function

- Simple scaling arguments for matter dominated universes give

$$\delta_M(t_H) = \delta_C \left(M_H/M_C\right)^{\frac{1-n}{6}}$$

- The total mass fraction at the time of formation is given by

$$\beta(t_f) = \frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}} \simeq \beta_{\rm inhom}\beta_{\rm col} \simeq 0.2\delta_m^{13/2}$$

- Due to entropy transfer at end of EMDE, this dilutes

- To determine total mass fraction, we need (see Carr, Tenkanen, and Vaskonen; Phys.Rev. D96 (2017))

$$\psi(M) = \frac{a_{eq}}{a_r}\frac{\beta_r(M)}{M}$$

Mass Bounds

- Minimum mass: horizon mass at matter domination

$$M_{\rm min} = 7.36 \times 10^{-5} M_\odot \left(\frac{106.75}{g_*}\right)^{1/2} \left(\frac{100\text{GeV}}{m_{\rm DM}}\right)^2 \left(\frac{.1}{\xi}\right)^2$$

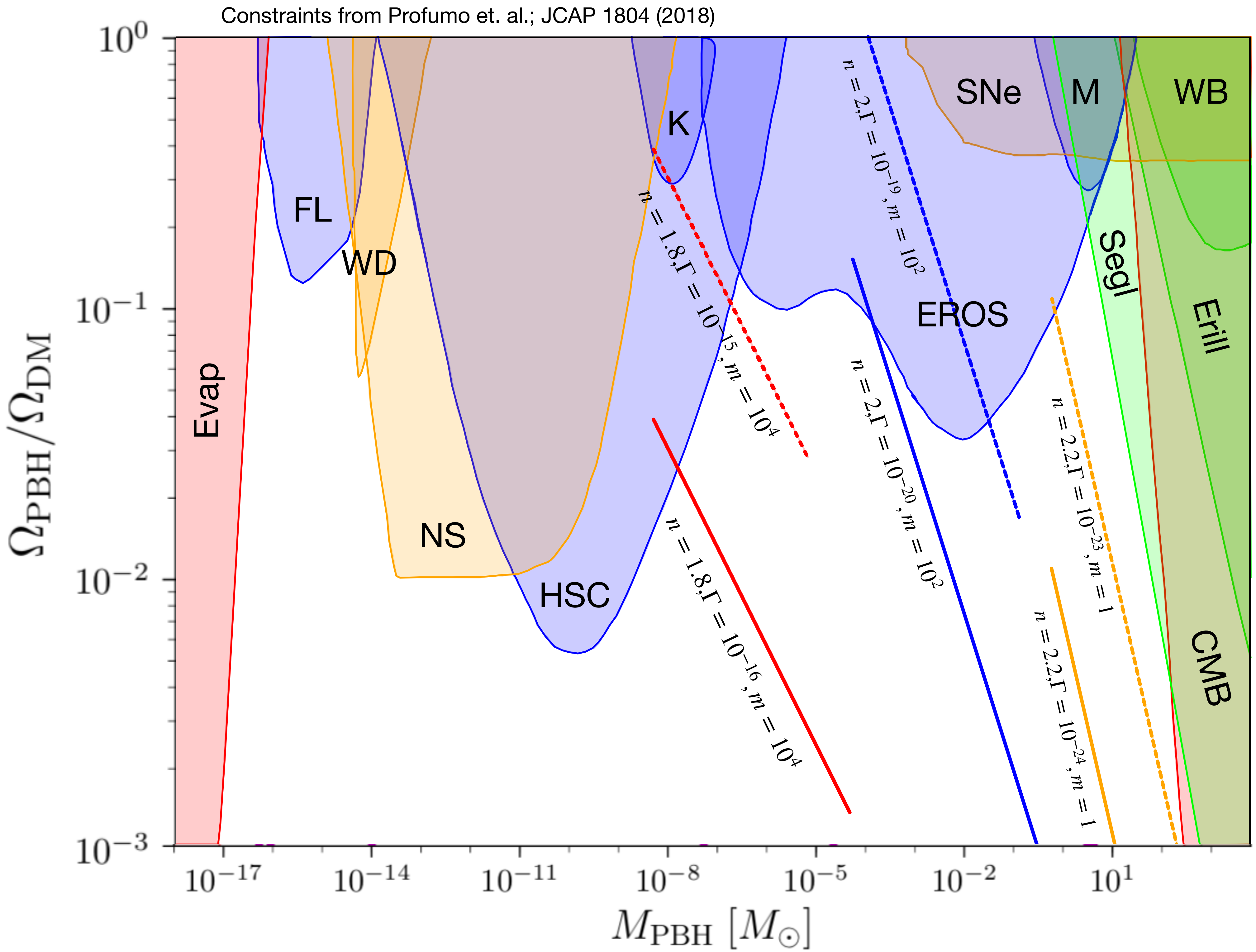
- Maximum mass: mass of perturbation that grows to unity by ``reheating'' time

$$M_{\rm max} = 6.3 M_\odot \left(\frac{10^{-22}\text{GeV}}{\Gamma_{\rm B}}\right)^{\frac{4}{n+3}} \qquad n = 1.8$$

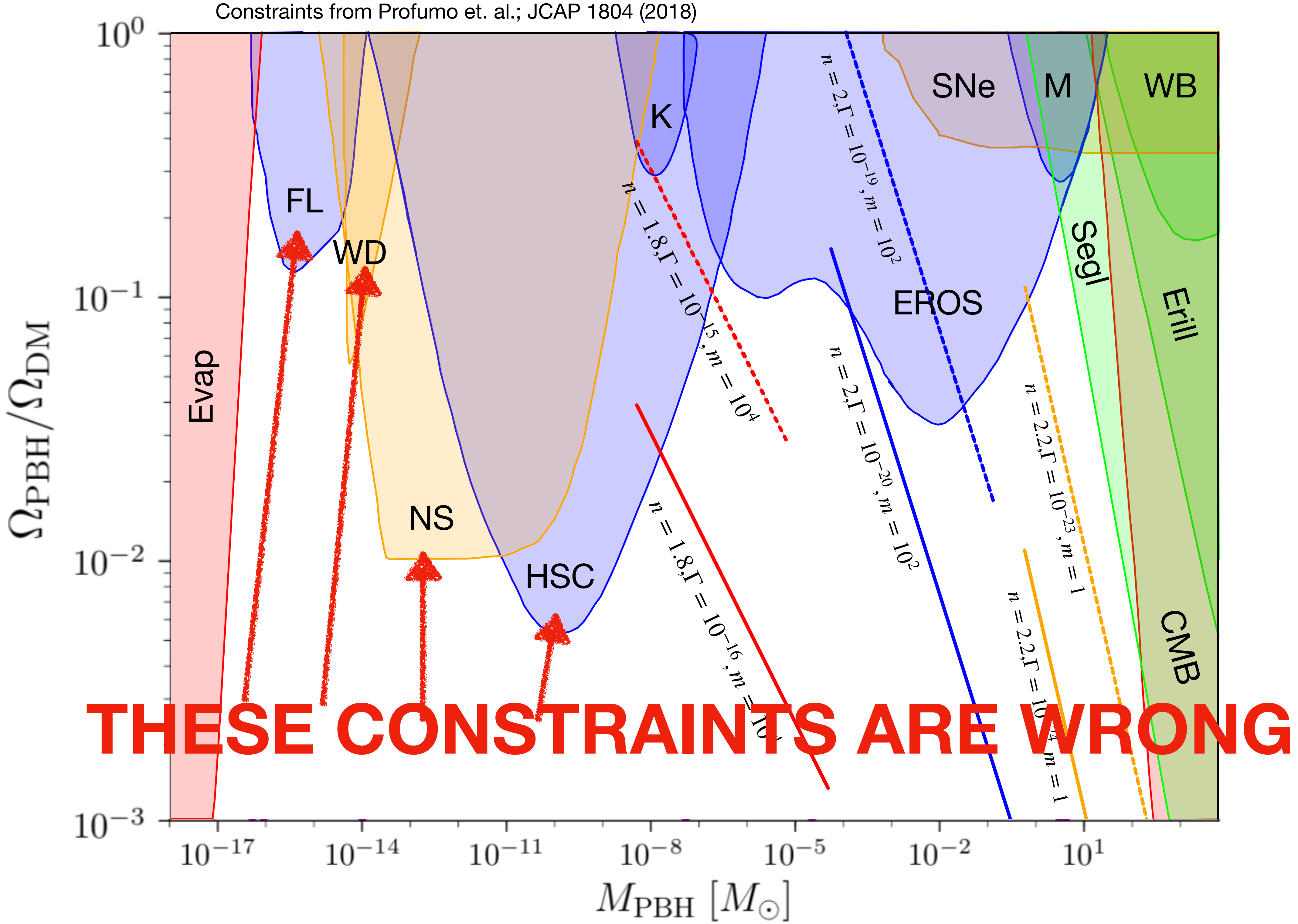
- Comparison of these gives indication of when no black holes form

Georg, BSM, Watson; 1902.04082

Constraints on PBHs, I

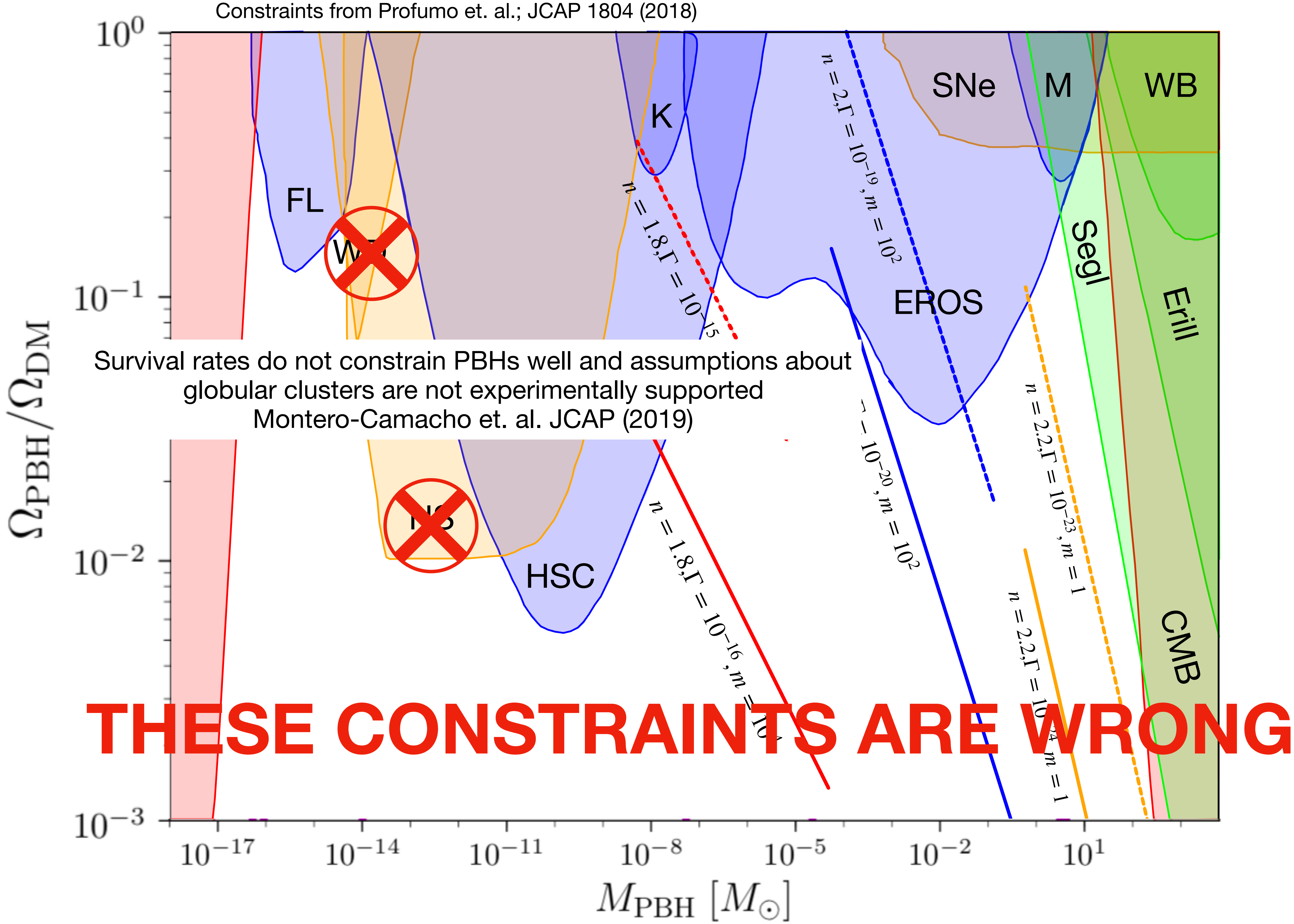


Constraints on PBHs, I



Constraints on PBHs, I

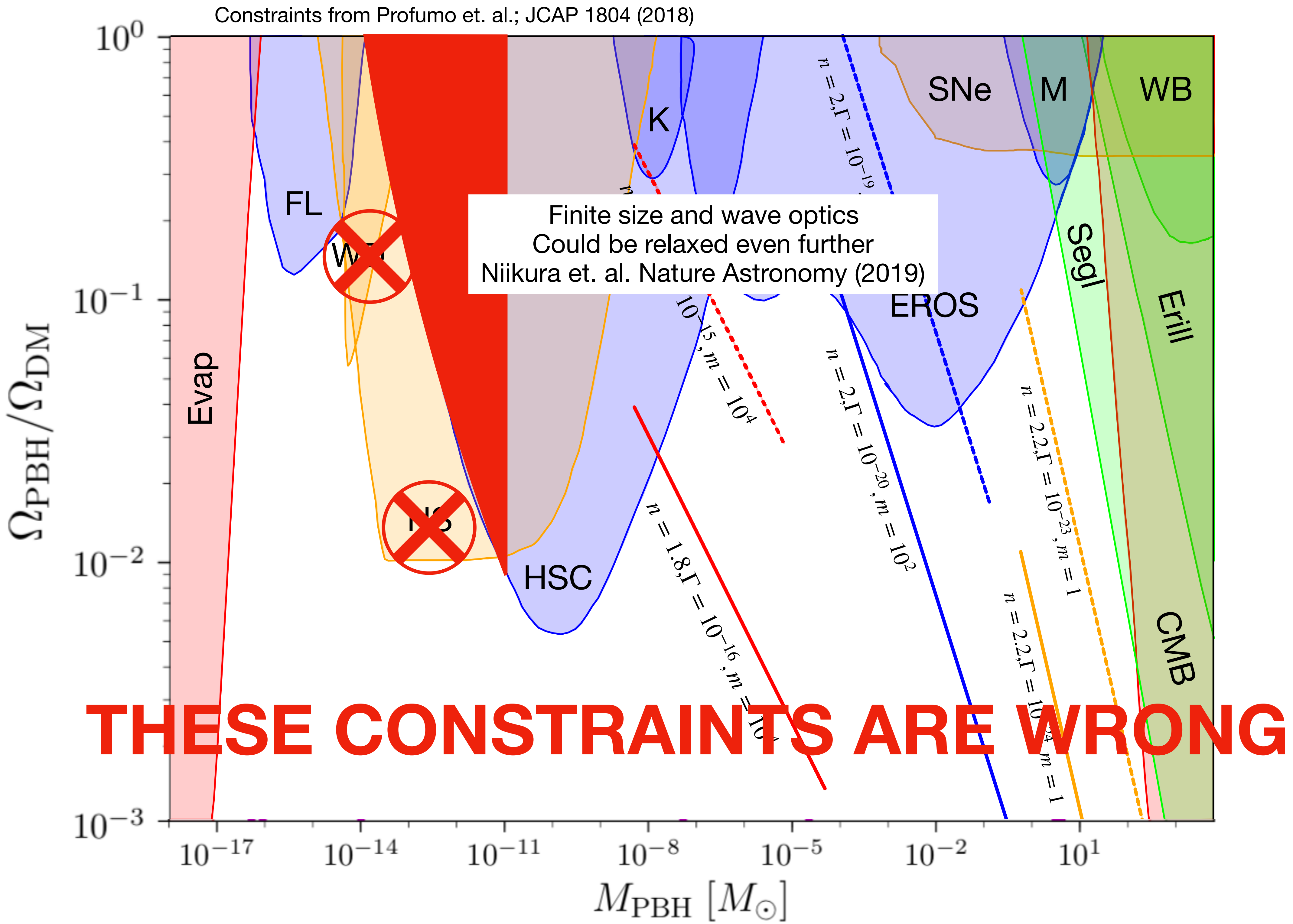
Constraints from Profumo et. al.; JCAP 1804 (2018)



Survival rates do not constrain PBHs well and assumptions about globular clusters are not experimentally supported
Montero-Camacho et. al. JCAP (2019)

THESE CONSTRAINTS ARE WRONG

Constraints on PBHs, I



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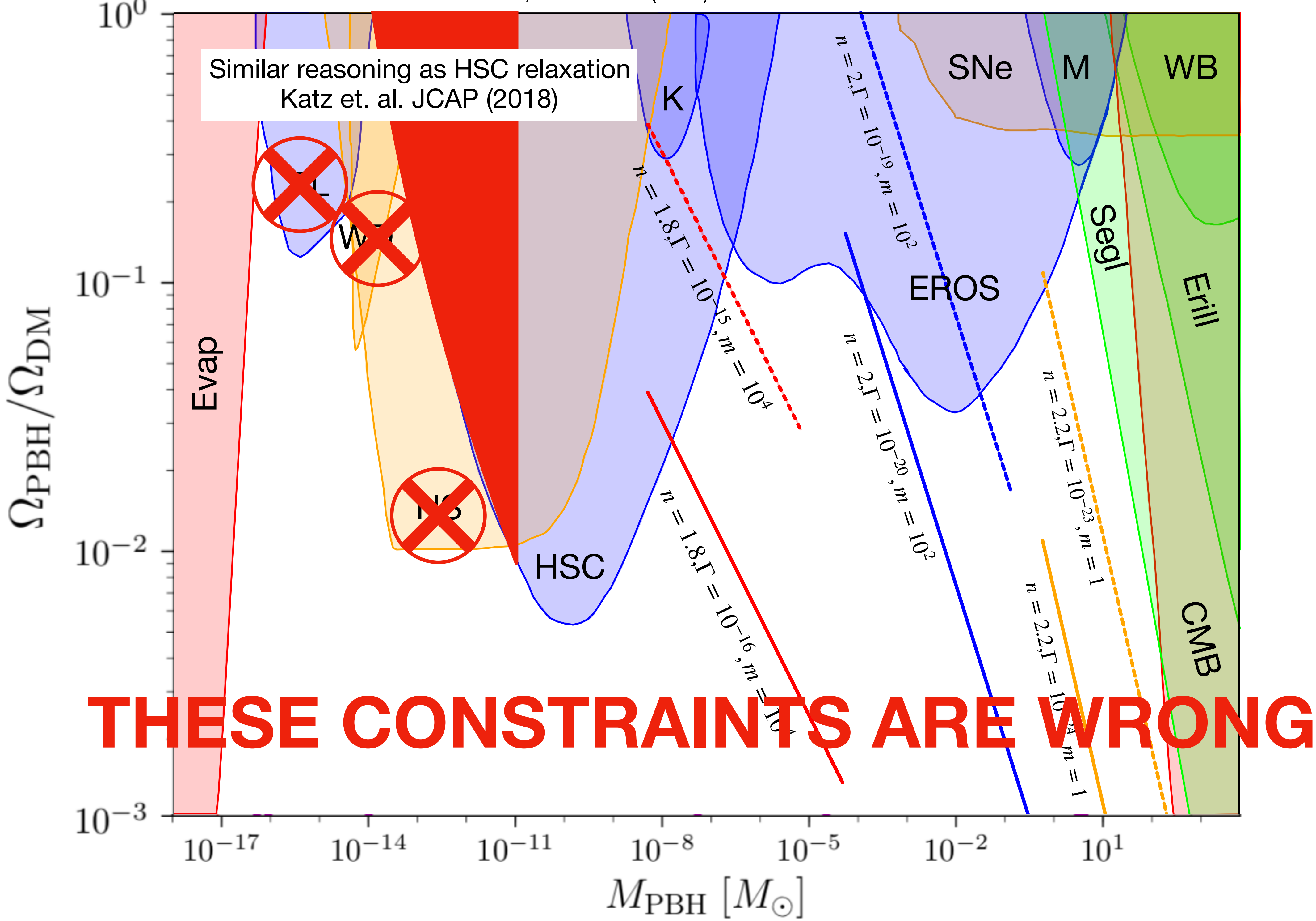
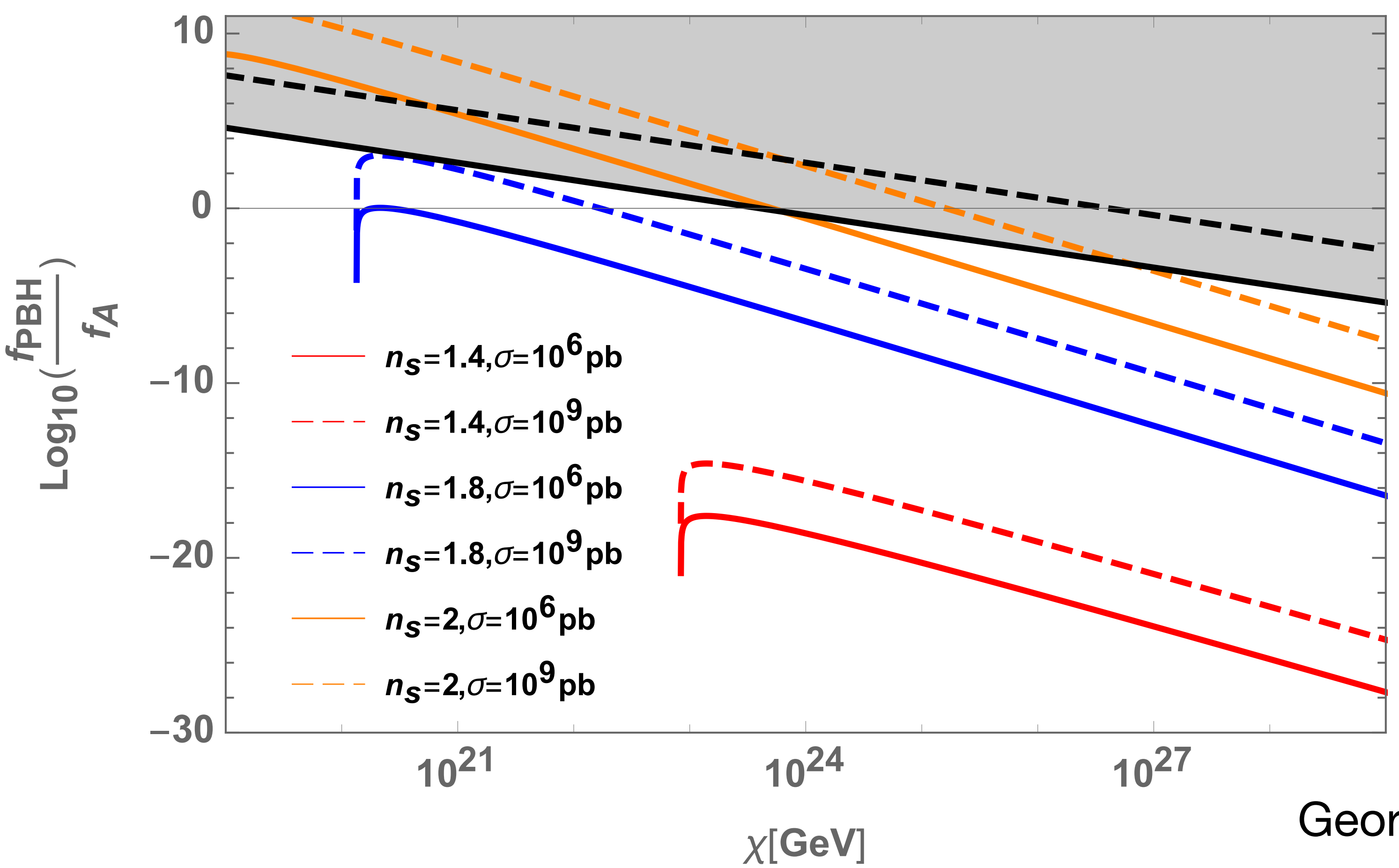


Contraints on PBHs, II

- Profumo et. al.; JCAP 1804 (2018) shows that, irrespective of mass distribution, one can place limits on maximum fraction of DM in PBHs ($\sim .42$)
- Depends on data set, but we use most restrictive combination
- This will also change based on relaxation of PBH constraints



$$\chi \equiv \frac{m_A^2}{\Gamma}$$

Georg, BSM, Watson; 1902.04082

Ongoing/Future Work

Future Work Overview

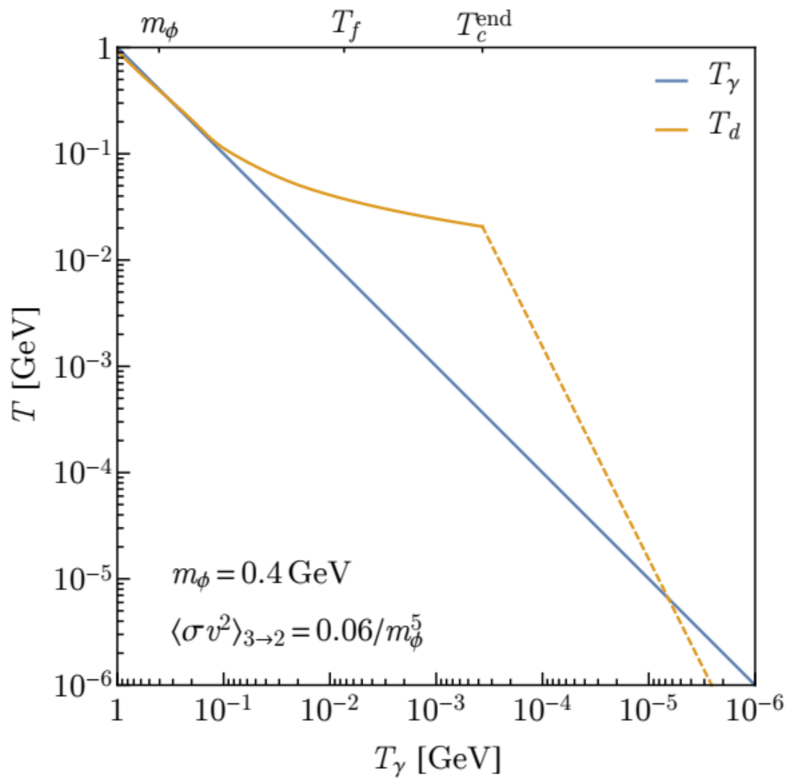
- Include cannibalization in analysis
- Carry out Press-Schechter with gravitational heating analysis to determine halo statistics and more in-depth indirect detection signal
- Calculate PBH merger rates
- Determine affects of Co-Decay on Gravitational Wave Background

Cannibals!

- In CDDM models, cannibalism typically plays some role
- Depending on parameters in the $SU(2)_D$ model, $Z_D Z_D Z_D \to W_D^+ W_D^-$ processes can be important
- Cannibal DM leads to slower temperature decreases, which changes the resulting relic abundance to

$$\frac{\Omega_A}{\Omega_{DM}} = \left(\frac{10^{-36}}{\sigma/\mathrm{cm}^2}\right)\left(\frac{m}{\mathrm{GeV}}\right)^{1/2}\left(\frac{10^{-17}}{\Gamma/m}\right)^{1/2}$$

- Need to check whether the EMDE still occurs under the influence of these processes



Pappadopulo, Ruderman, Trevisan; Phys.Rev. D94 (2016)

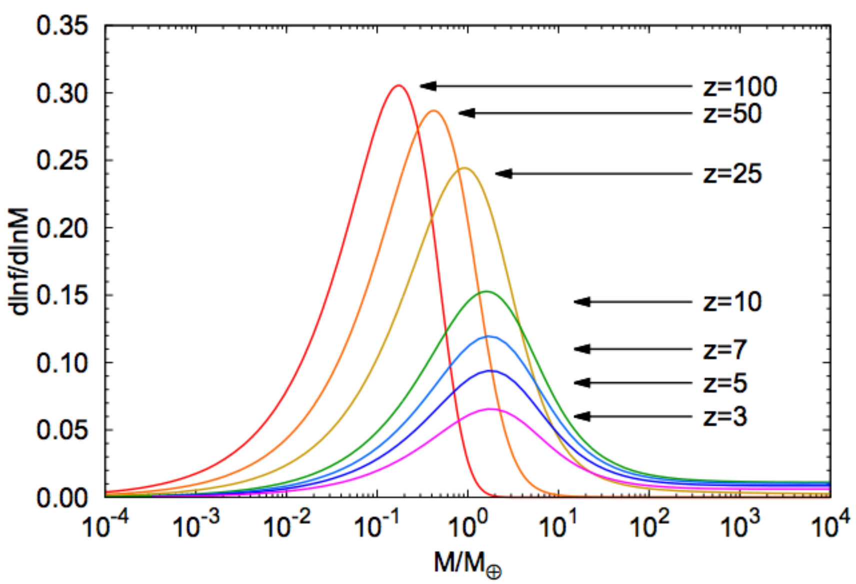
Micro-halo analyses

- Due to perturbation growth in the EMDE, one can follow the perturbations to late time:

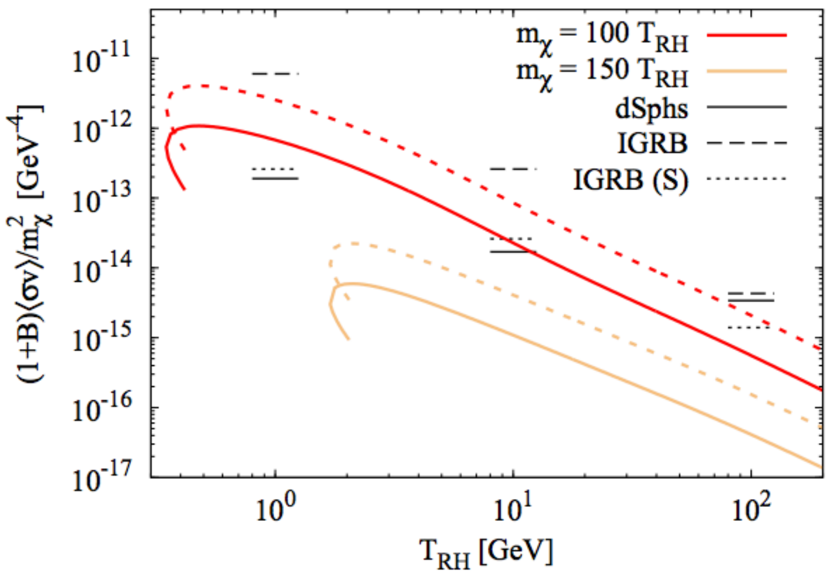
$$T(k) \rightarrow \sigma(M, z) \rightarrow \frac{dn}{d \ln M} \rightarrow \frac{df}{d \ln M}$$

- It is worth determining within CDDM whether we can expect an enhancement in the mass range (M_{cut}, M_{RH})

- If so, we would expect an additional enhancement in the indirect detection channel



Erickcek and Sigurdson; Phys.Rev. D84 (2011)



Erickcek Phys.Rev. D92 (2015)

Gravitational Heating

- We need to be careful with halos that form during the EMDE itself; they consist of particles that decay at the end of the phase!

- If the remaining DM particles cannot "relax" adiabatically after the mass loss, another free streaming scale has to be introduced.

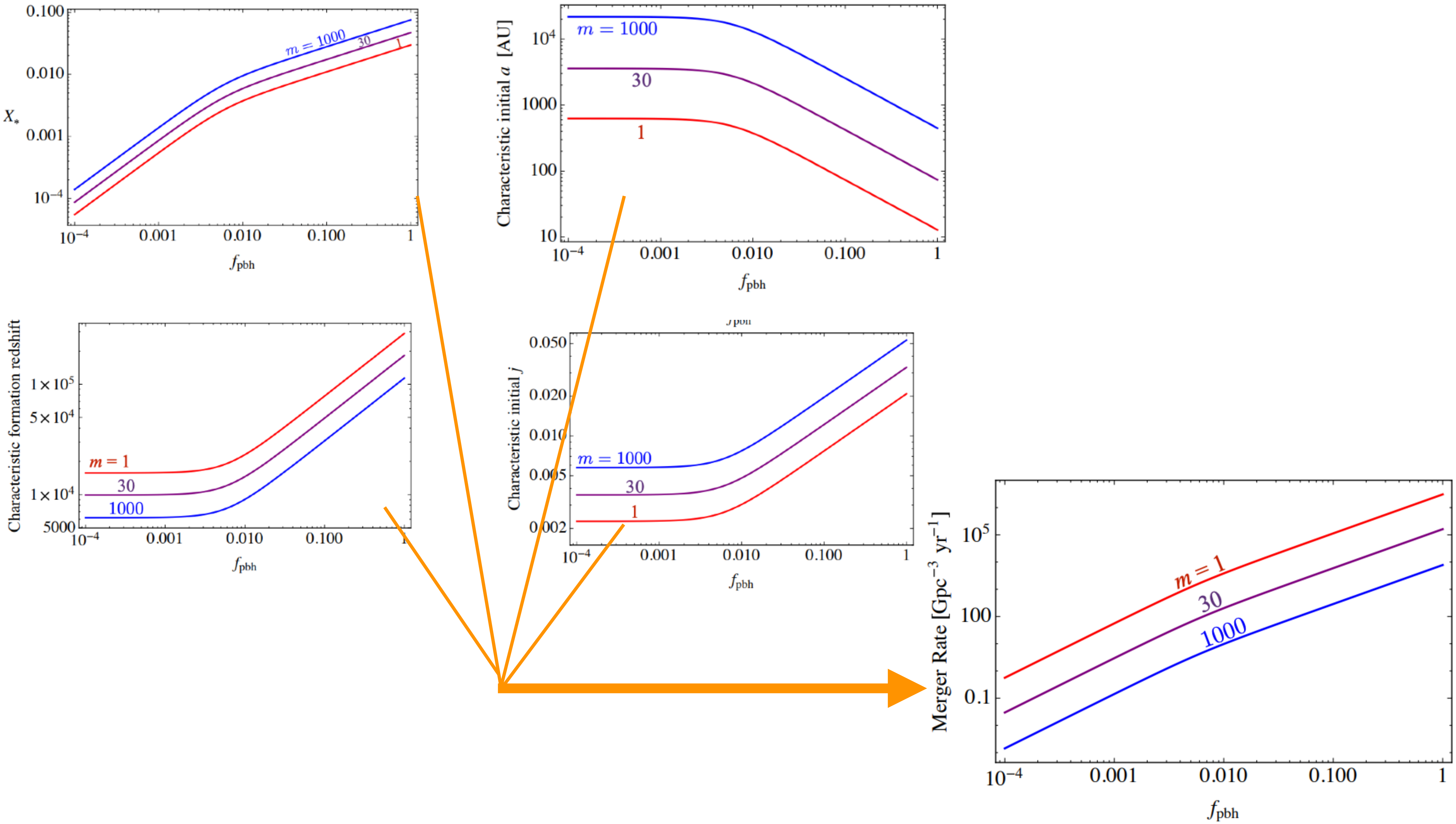
$$\frac{t_{\Delta M}}{t_{dyn}} < 1 \rightarrow \lambda_{fs} \propto \sigma_v$$

- We must then apply an additional cutoff in our mass power spectrum

$$e^{-k^2 \lambda_{fs}^2}$$

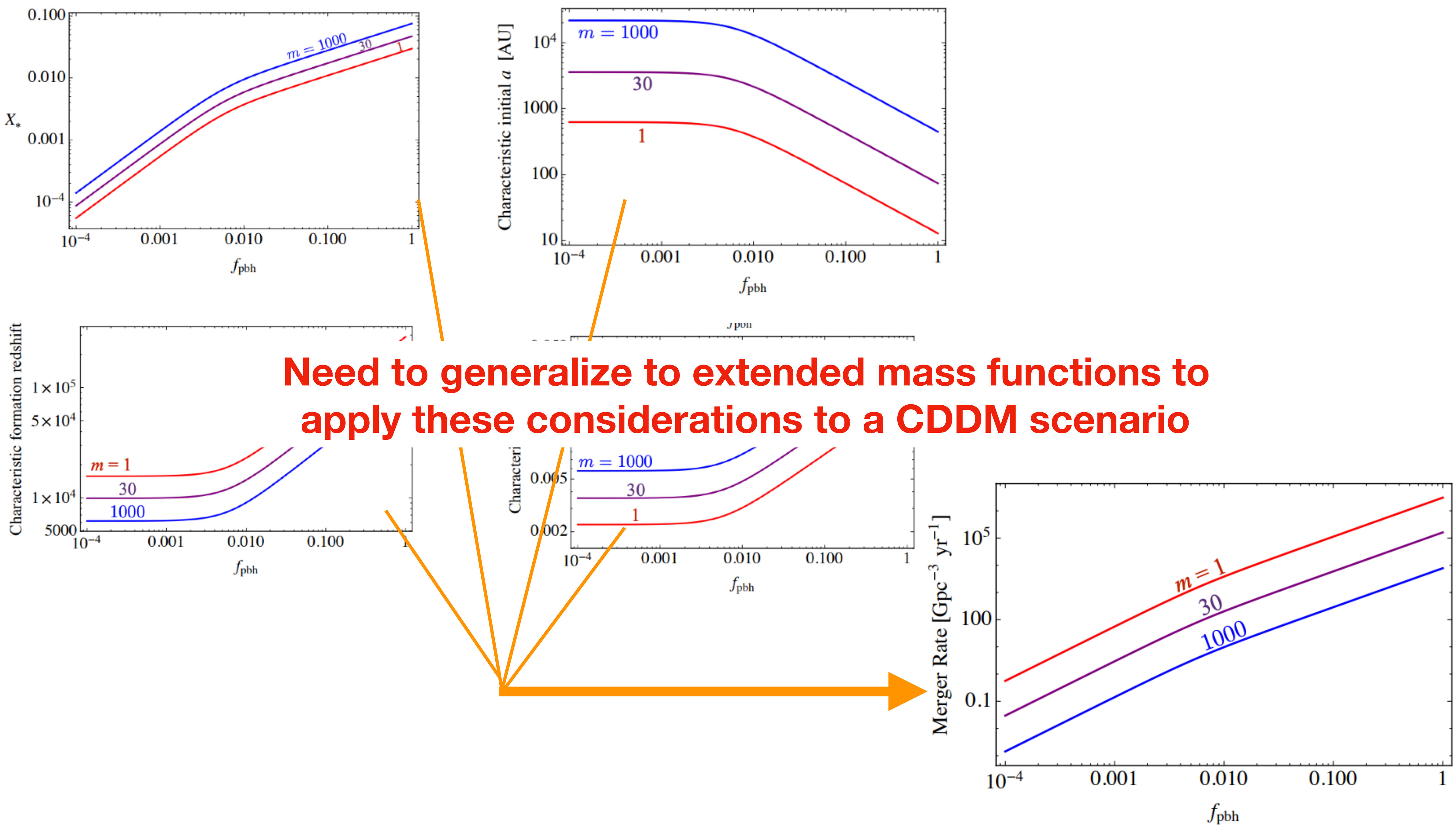
Blanco et. al. arXiv 1906.00010

Black Hole Merger Rates



Ali-Haimoud et. al.; Phys.Rev. D96 (2017)

Black Hole Merger Rates



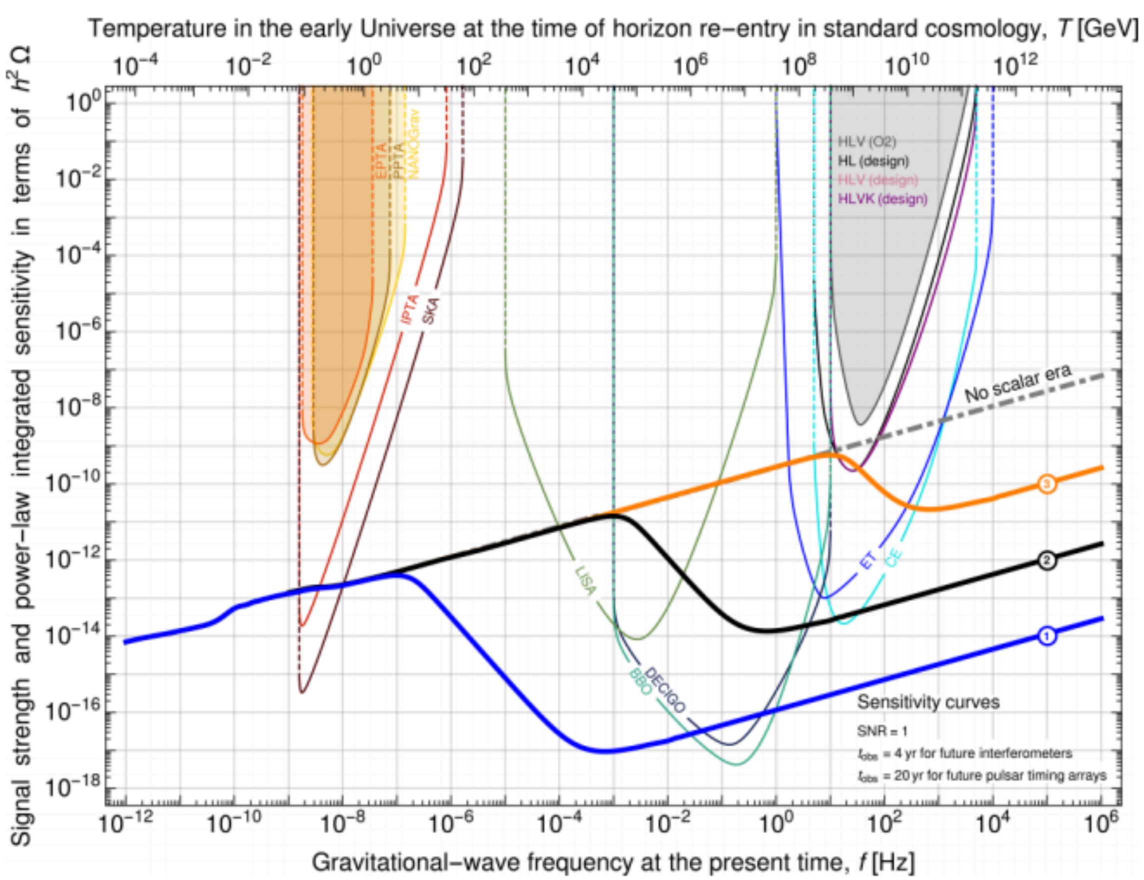
Need to generalize to extended mass functions to apply these considerations to a CDDM scenario

Ali-Haimoud et. al.; Phys.Rev. D96 (2017)

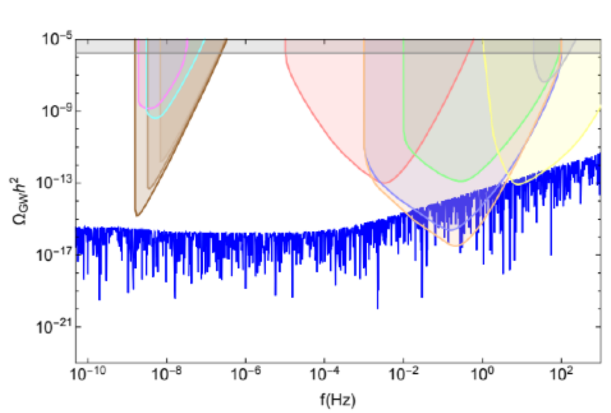
Gravitational Waves-“$\mathcal{O}(1)$” Modifications

- Gravitational waves scale as radiation ($\rho_{GW} \propto a^{-4}$)
- Deviations from the standard thermal history can appear in the gravitational wave background

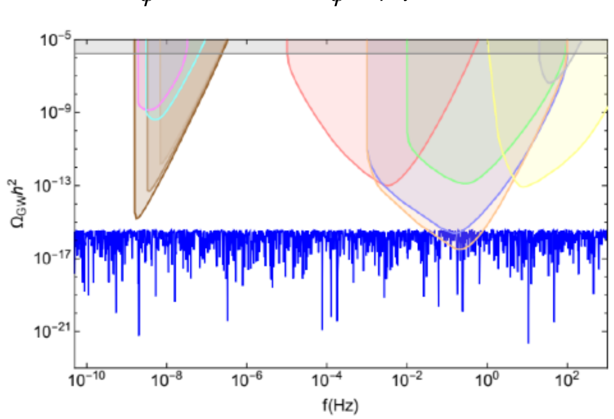
D’Eramo, Schmitz; Phys.Rev.Research. 1 (2019)



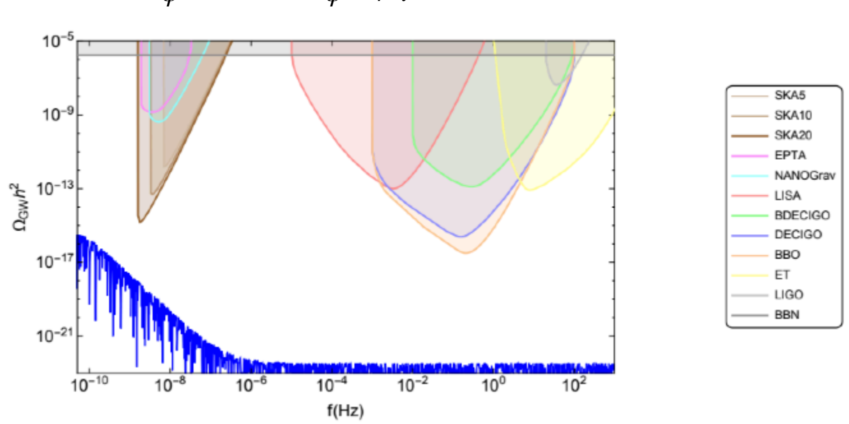
$\omega_\phi = 2/3, \quad (\rho_\phi/\rho_r)_i = 10^{10}$



$\omega_\phi = 1/3, \quad (\rho_\phi/\rho_r)_i = 10^{25}$



$\omega_\phi = 0, \quad (\rho_\phi/\rho_r)_i = 10^{-11}$



Bernal, Hajkarim; Phys.Rev. D100 (2019)

Conclusions

- CDDM offers a novel method of generating the DM relic abundance in our universe that motivates the absence of direct and indirect detection signals to date

- It also generically predicts a EMDE in which small-scale structure can grow and survive

- In addition to small-scale structure, CDDM can produce appreciable amounts of PBHs in interesting mass ranges

- CDDM offers an interesting scenario in which a variety of particle and gravitational detections could be used to validate various models

Thank you!

Background Energy Density Evolution

For the purposes of perturbation evolution, it is more convenient to solve the equations of motion for the energy densities of each fluid. We solve for the dynamics of the fluids only after they become non-relativistic ($T \cong m$) so that we can ignore any ``equilibrium" values. It will also be more convenient to use e-folds, $N = \ln a$, as our time variable so that the background equations take the form:

$$\frac{d\rho_A}{dN} = -3\rho_A - \frac{\langle \sigma v \rangle}{mH}\left[\rho_A^2 - \rho_B^2\right]$$

$$\frac{d\rho_B}{dN} = -3\rho_B - \frac{\Gamma}{H}\rho_B + \frac{\langle \sigma v \rangle}{mH}\left[\rho_A^2 - \rho_B^2\right]$$

$$\frac{d\rho_r}{dN} = -4\rho_r + \frac{\Gamma}{H}\rho_B$$

$$\frac{dH}{dN} = -\frac{1}{2HM_p^2}\left(\rho_A + \rho_B + \frac{4}{3}\rho_r\right)$$

Perturbation Evolution Equations

After Fourier transforming and defining $\delta_\alpha \equiv \delta\rho_\alpha/\rho_\alpha$ and $\theta_\alpha \equiv a^{-1}\nabla^2 v_\alpha$, the perturbation evolution equations are:

$$\delta_A' + \frac{\theta_A}{aH} - 3\Phi' = -\frac{\langle\sigma v\rangle}{mH\rho_A}\left[\rho_A^2\left(\Phi + \delta_A\right) - \rho_B^2\left(\Phi + 2\delta_B - \delta_A\right)\right]$$

$$\delta_B' + \frac{\theta_B}{aH} - 3\Phi' = -\frac{\Gamma}{H}\Phi + \frac{\langle\sigma v\rangle}{mH\rho_B}\left[\rho_A^2\left(\Phi + 2\delta_A - \delta_B\right) - \rho_B^2\left(\Phi + \delta_B\right)\right]$$

$$\delta_r' + \frac{4}{3}\frac{\theta_r}{aH} - 4\Phi' = \frac{\Gamma}{H}\frac{\rho_B}{\rho_r}\left[\Phi + \delta_B - \delta_r\right]$$

$$\theta_A' + \theta_A - \frac{k^2}{aH}\Phi = \frac{\langle\sigma v\rangle}{mH\rho_A}\left[\rho_B^2\left(\theta_B - \theta_A\right)\right]$$

$$\theta_B' + \theta_B - \frac{k^2}{aH}\Phi = \frac{\langle\sigma v\rangle}{mH\rho_B}\left[\rho_A^2\left(\theta_A - \theta_B\right)\right]$$

$$\theta_r' - \frac{k^2}{aH}\left(\frac{\delta_r}{4} + \Phi\right) = \frac{\Gamma}{H}\frac{\rho_B}{\rho_r}\left[\frac{3}{4}\theta_B - \theta_r\right]$$

Perturbation Analytics, I

- In longitudinal gauge, the metric takes the form:

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)\delta_{ij}dx^i dx^j$$

- The perturbed 00 Einstein Equation closes the system of equations

$$\left(\frac{k^2}{3a^2H^2}+1\right)\Phi + \Phi' = -\frac{1}{6H^2m_p^2}\sum_\alpha \delta\rho_\alpha$$

- Adiabatic initial conditions $\frac{\delta\rho_\alpha^0}{\rho'_\alpha} = \frac{\delta\rho_\beta^0}{\rho'_\beta}$

Perturbation Analytics, II

- Before freeze-out, $\delta_A = \delta_B$ and before decay, $\Gamma/H \ll 1$. We solve for the perturbation $\delta_D = \delta_A + \delta_B$.

- Can solve for perturbation evolution in the initial RD phase, but only gives standard results of oscillating δ_r and logarithmic growth in δ_A, δ_B.

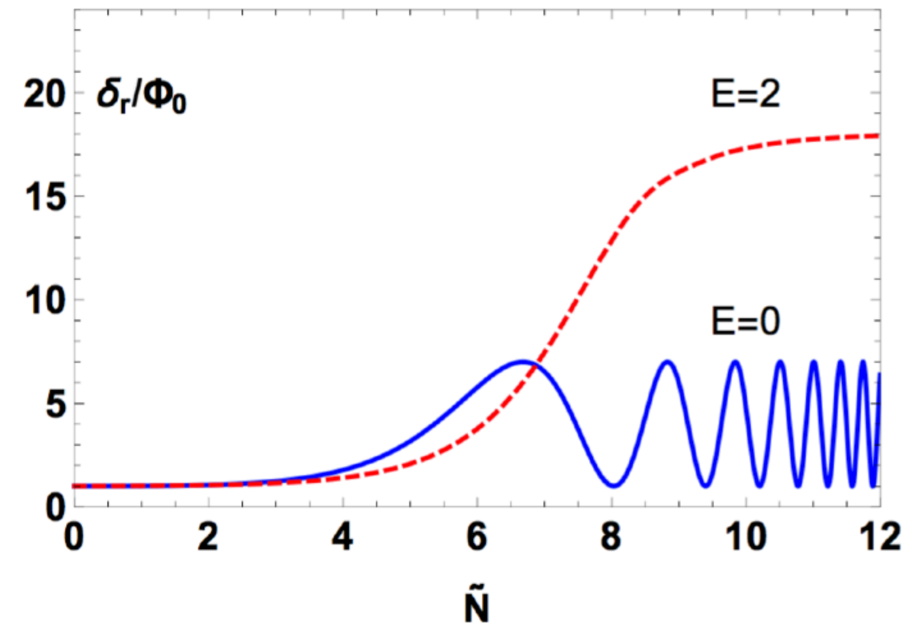
- MD phase $\Rightarrow (\Gamma\rho_B^m)/(H_m\rho_A^m) \equiv E = const$. DM perturbations have the following solution:

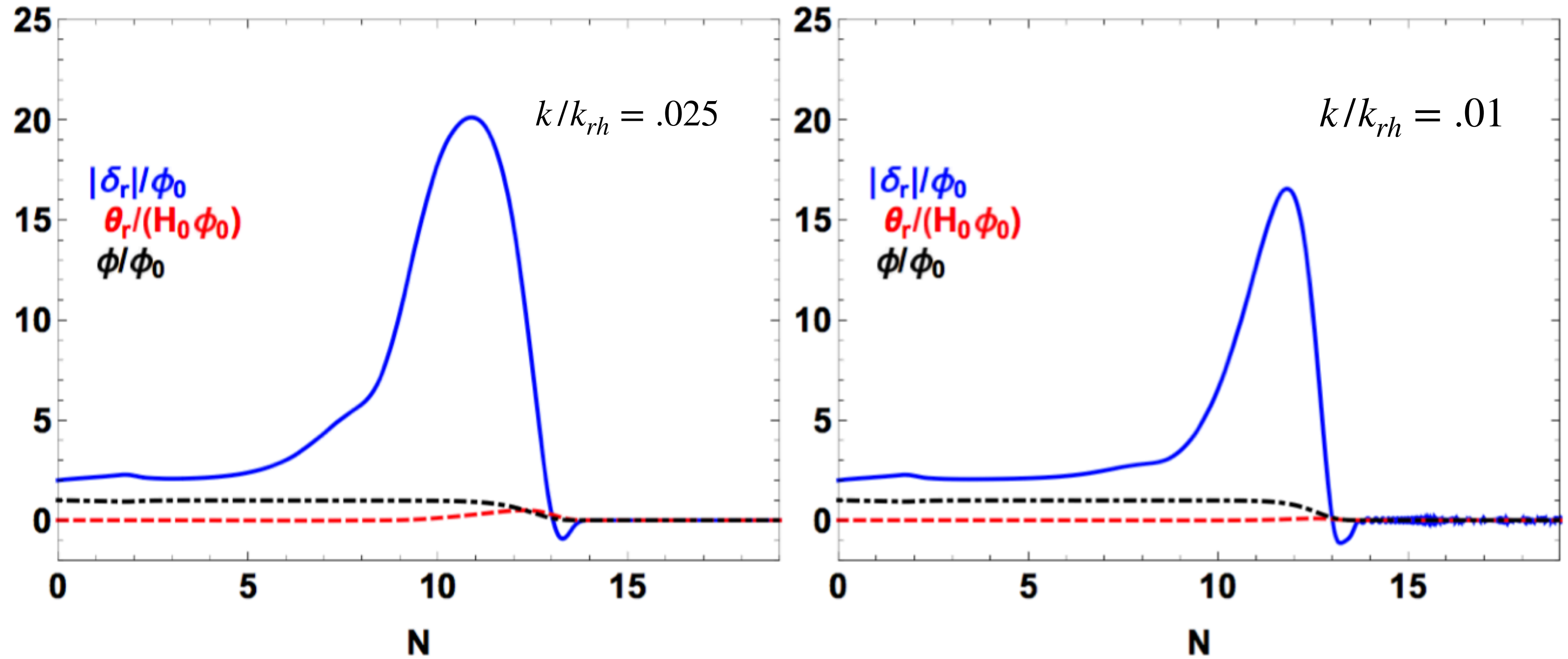
$$\delta_D = -\Phi_m\left(4 + \frac{4}{3}\frac{k^2}{H_m^2}(e^{\tilde{N}} - 1) + \frac{2}{3}\frac{\Gamma}{H_m}(e^{3\tilde{N}/2} - 1)\right)$$

- The decay of the B fluid will act as a source for the radiation perturbations and we can find solutions in closed form, albeit messy

Radiation Perturbations

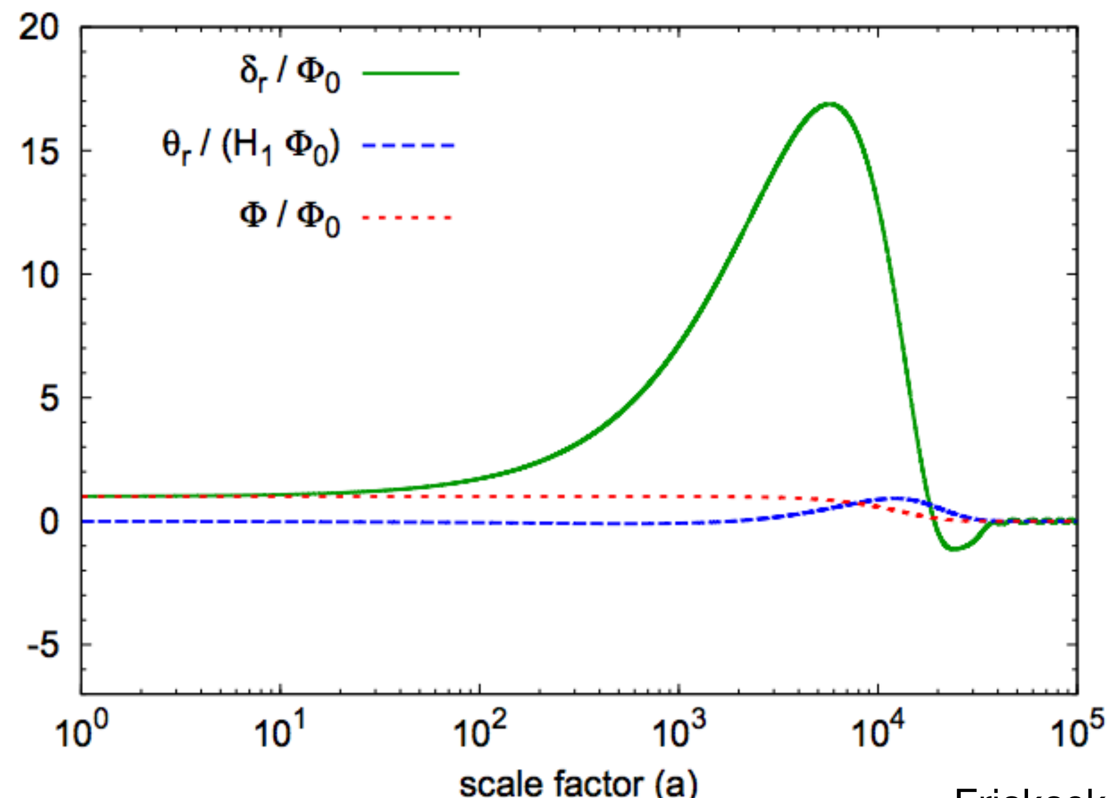
- Analytic solutions show that with decays, we get an enhancement in radiation perturbations
- Numerically solving through the time of decay and freeze-out shows a wash-out of the formed radiation perturbations





Kinetic Decoupling

- Field decays to SM radiation causes a wash-out of radiation perturbation enhancement
- Any DM coupled to this radiation also experience a wash-out
- Any WIMP-like model of DM suffers this effect due to the assumption of thermal equilibrium with SM



Erickcek and Sigurdson; Phys.Rev. D84 (2011)