
# *Gravitational waves as a probe of new physics*

*Ryusuke Jinno (DESY)*

*2021.4.19 @ TDLI*

[ Jinno, Konstandin, Rubira '20 (JCAP 04 (2021) 014) ] [ Domcke, Jinno, Rubira '20 (JCAP 06 (2020) 046) ]
[ Hashino, Jinno, Kakizaki, Kanemura, Takahashi, Takimoto '18 (PRD 99 (2019) 7, 075011) ]
[ Jinno, Takimoto '16, '17 (PRD 95 (2017) 2, 024009, JCAP 01 (2019) 060) ] [ Jinno, Moroi, Nakayama '12 (PRD 86 (2012) 123502) ]

# *Self introduction*

*Ryusuke Jinno / 神野 隆介*

*2016.3 : Ph.D. in physics at the University of Tokyo*

*2016.4 - 2016.8 : Postdoc at KEK (Japan)*

*2016.9 - 2019.3 : Postdoc at Institute for Basic Science (Korea)*

*2019.4 - present : Postdoc at DESY (Germany)*

*Self Introduction*

*Research Overview*

*New physics & GWs*

*Summary*

# Research overview

*Machine learning & neural networks*

*soft & collinear effect in FOPT*

*Neutrinos*

*Higgs dynamics*

***New physics & Gravitational waves***

*Inflation*

*CMB physics*

*Gravitational DM production*

*Tunneling & gravity*

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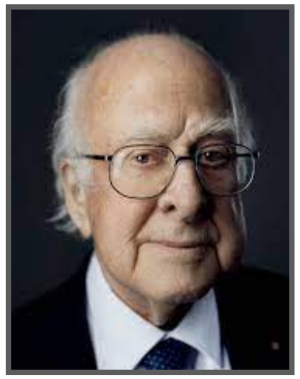
# HIGGS INFLATION & UNITARITY VIOLATION

- Higgs inflation: Our Standard-Model Higgs = inflaton

  [ Salopek, Bond, Bardeen '89 ] [ Futamase, Maeda '89 ] [ Cervantes-Cota, Dehnen '95 ] [ Bezrukov, Shaposhnikov '08 ]

  - Provides an interesting connection between EW physics & inflation



[ Peter Higgs ]

- Question: Can it really describe from inflation to EW?

  - Until 2016, the answer was 'Yes' [ Bezrukov, Shaposhnikov '10 ]

- In 2016, we overturned this common understanding

  [ Jinno '16 (Ph.D. Thesis) ] [ Ema, Jinno, Mukaida, Nakayama '16 ]

  - Unitarity is badly violated during preheating in W and Z production channels

  - Meaning that no consistent description is possible within the theory

- What is possible preheating in Higgs inflation?

  - We analyzed R2-type UV completion of Higgs inflation

  [ He, Jinno, Kamada, Starobinsky, Yokoyama '19, '20 ]

[ Alexei Starobinsky ]

# NEUTRINOS

➤ IceCube neutrino observatory

- Neutrino detector at the South Pole

- $>5000$ optical sensors deployed in $\mathcal{O}(\mathrm{km}^3)$ ice

➤ Reported two PeV neutrino events in 2013

- Many possible DM explanations were on the market

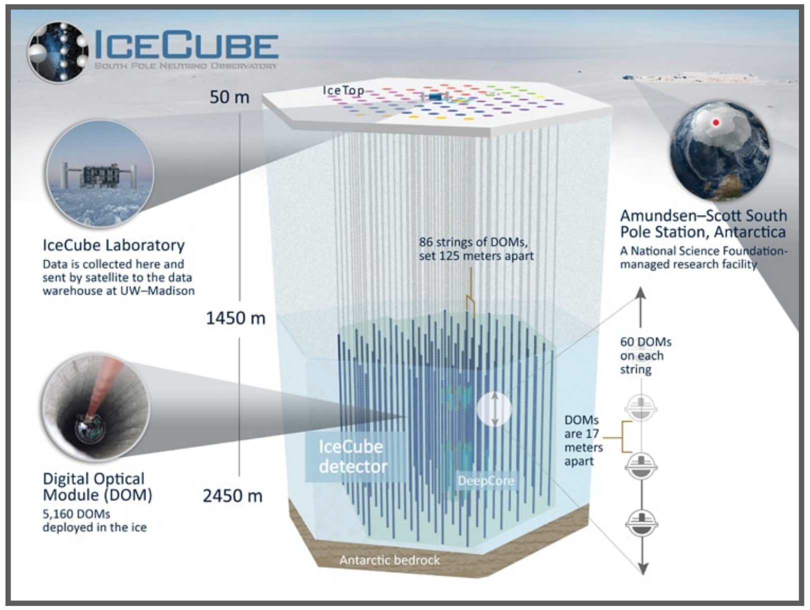
➤ We pointed out another possibility

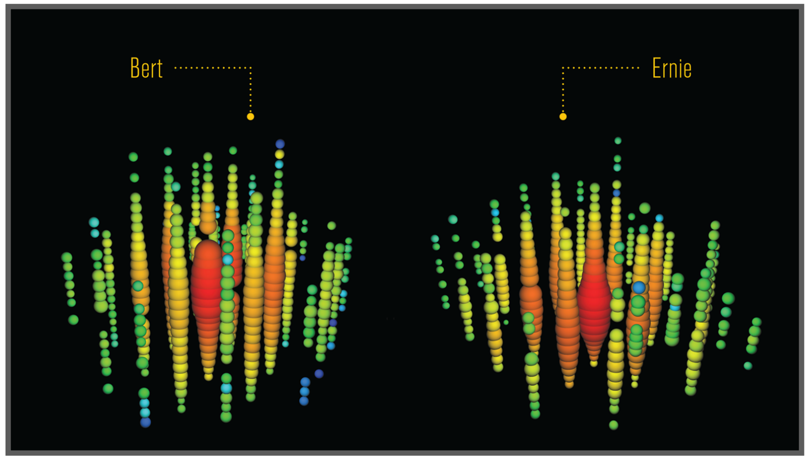
- Mother particle decaying into neutrinos much before the present: "Early Decay" scenario

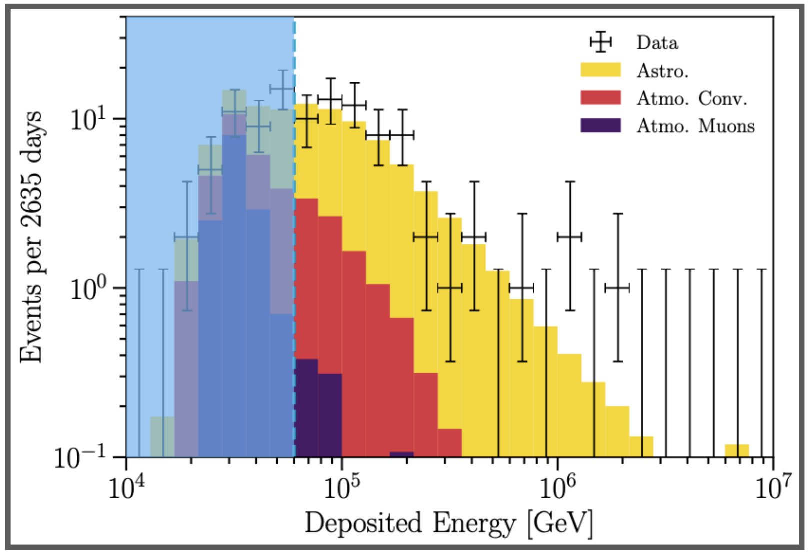
[ Ema, Jinno, Moroi '14 ]

- Makes a good contrast with DM-type scenarios:

  - Mother particle can have mass $\sim \mathcal{O}(1 - 10^4)$ PeV
  - Isotropic signal is predicted

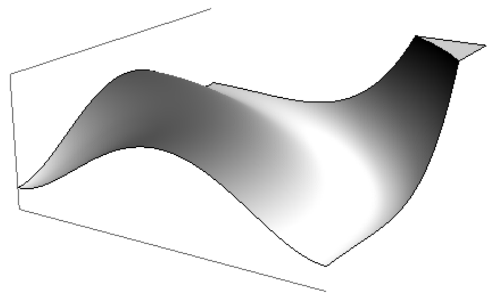
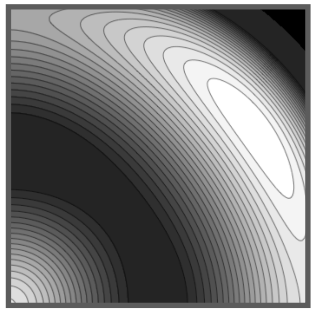


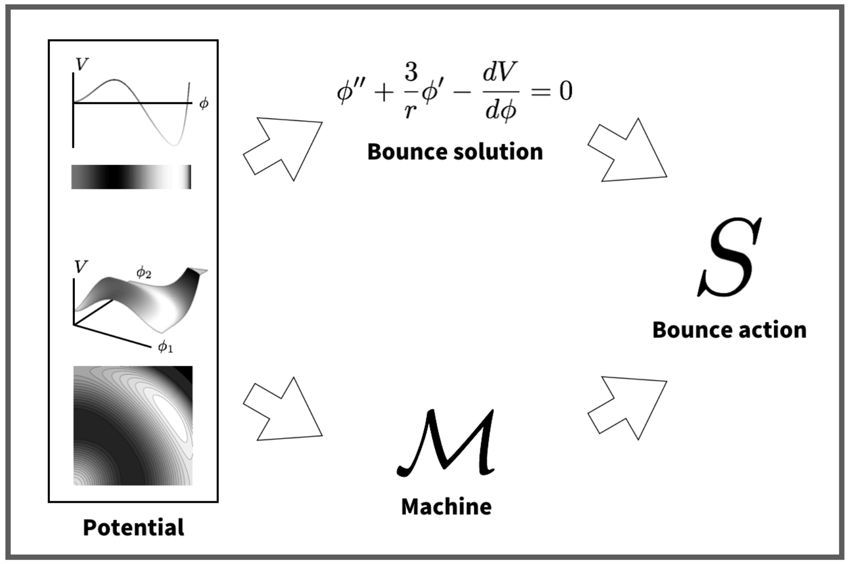



# MACHINE LEARNING & NEURAL NETWORKS

- ➤ Neural networks: powerful technology for image recognition
- ➤ Main idea: Re-interpretation of scalar potentials as images [ Jinno '18 ]

Potential  =  Image

- This idea makes it possible to construct a neural network that calculates tunneling rate (i.e. bounce action) directly from the potential shape



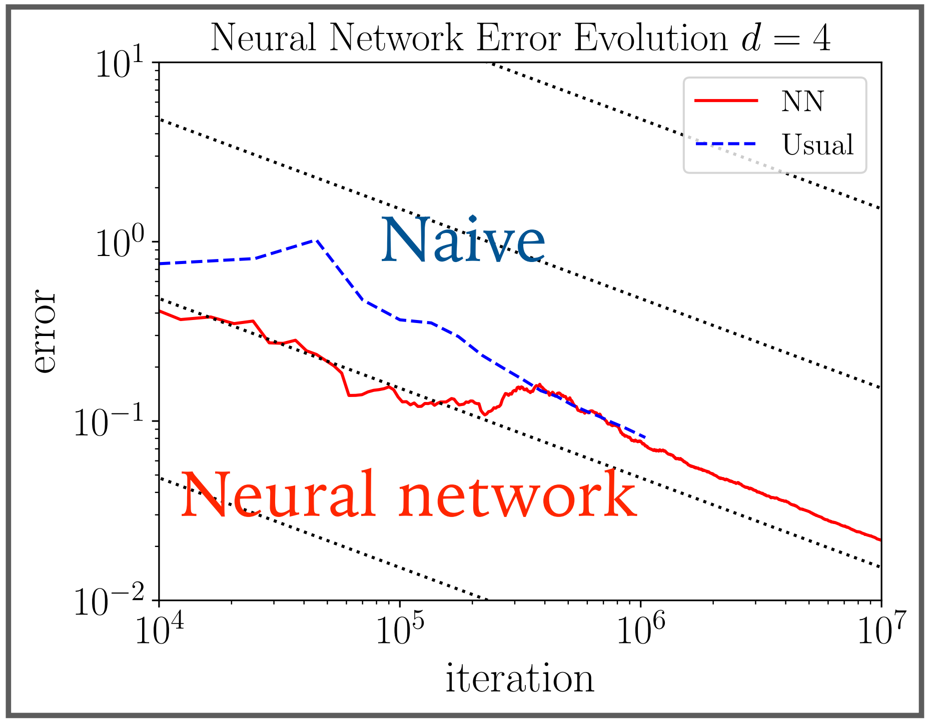

- Later the idea was pursued further by other groups as well [ Piscolo, Spanowsky, Waite '19 ] [ Chala, Khoze, Waite '19 ]

# MACHINE LEARNING & NEURAL NETWORKS

- Gravitational waves from binary systems
  - For new physics searches, it is important to improve the standard prediction first
  - EFT approach in post-Minkowskian approximations is being developed [ Kälin, Porto '20 ] [ Kälin, Liu, Porto '20 ]
- One bottleneck: higher-loop Feynman integals

e.g. $$\mathbf{K}^{(\pm\pm)}_{i_1,i_2;i_3,i_4,i_5,i_6,i_7} \equiv \int d^d l_1 \int d^d l_2 \frac{1}{(\pm l_1 \cdot u_a)^{i_1} (\pm l_2 \cdot u_b)^{i_2} (l_1^2)^{i_3} (l_2^2)^{i_4} ((l_1 + l_2 - q)^2)^{i_5} ((l_1 - q)^2)^{i_6} ((l_2 - q)^2)^{i_7}}$$

  - No general analytic solution is known
- Neural networks will help numerical evaluation




[ Jinno, Kälin, Rubira: in progress ]

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**New physics**
**&**
**Gravitational waves**

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*Summary*

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# GRAVITATIONAL WAVES: A NEW PROBE TO THE UNIVERSE

- Gravitational waves:

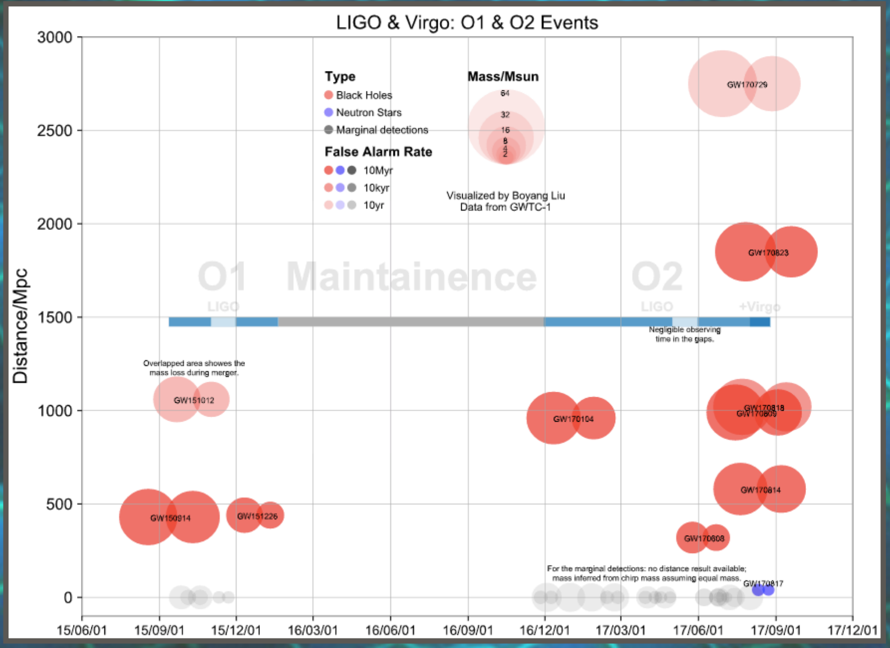
  Transverse-traceless part of the metric

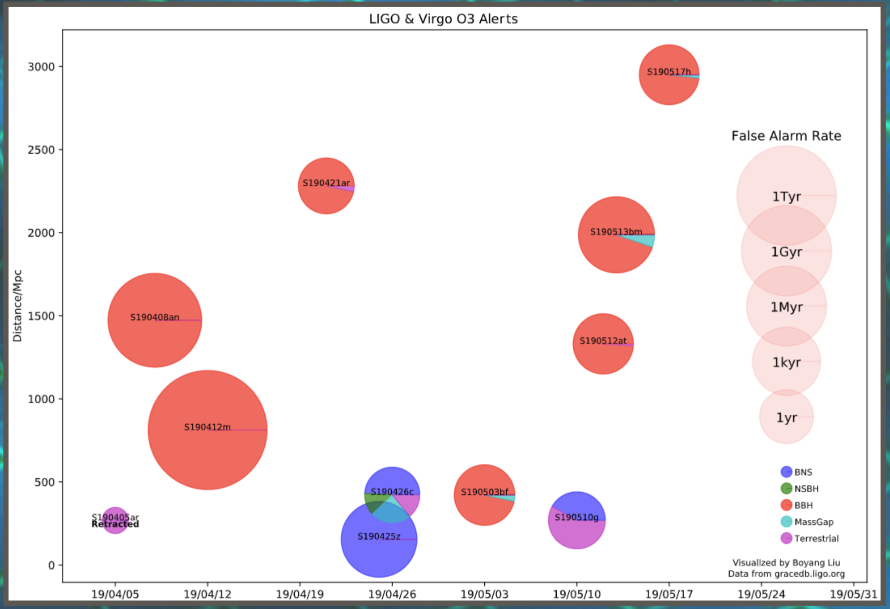
$$ds^2 = -dt^2 + a^2(\delta_{ij} + h_{ij})dx^i dx^j$$

  Obeys an equation of motion sourced by the energy-momentum tensor of the system

$$\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$$

- Detections by LIGO & Virgo have been exciting us



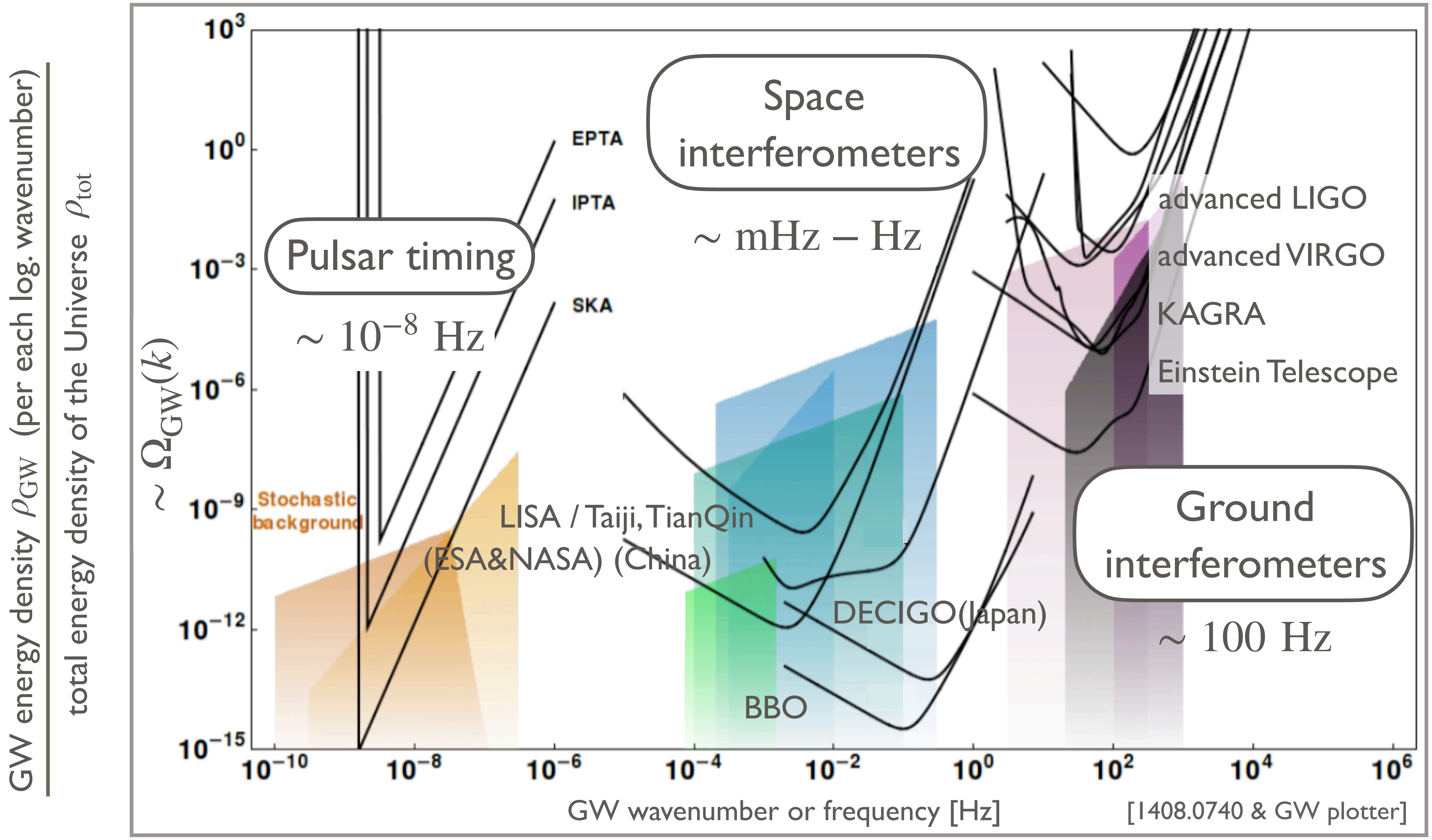




[Wikipedia "List of gravitational wave observations"]

[see also https://gracedb.ligo.org/superevents/public/O3/]

# PRESENT & FUTURE OBSERVATIONS

➤ Summary of ongoing & future experiments



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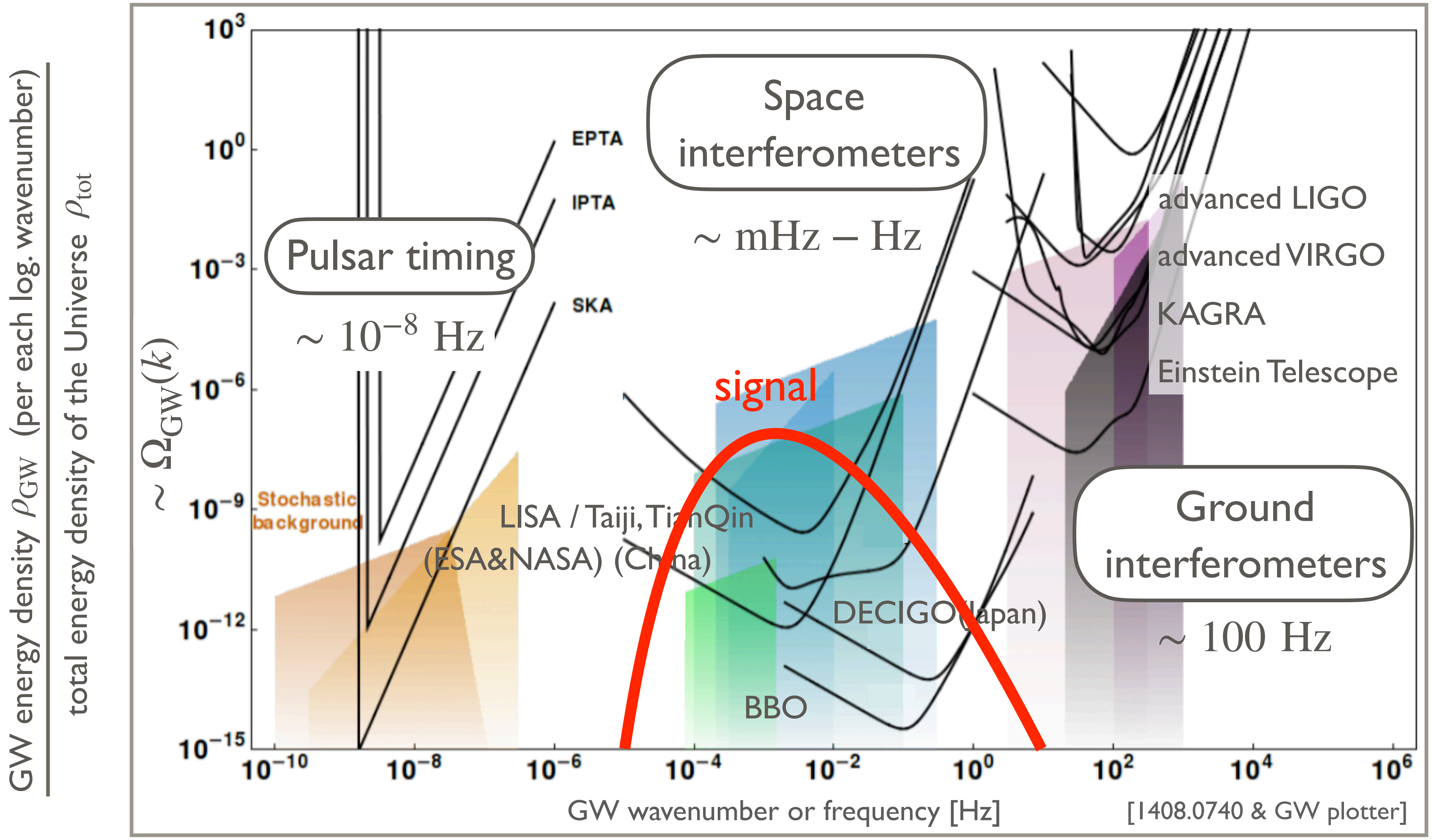
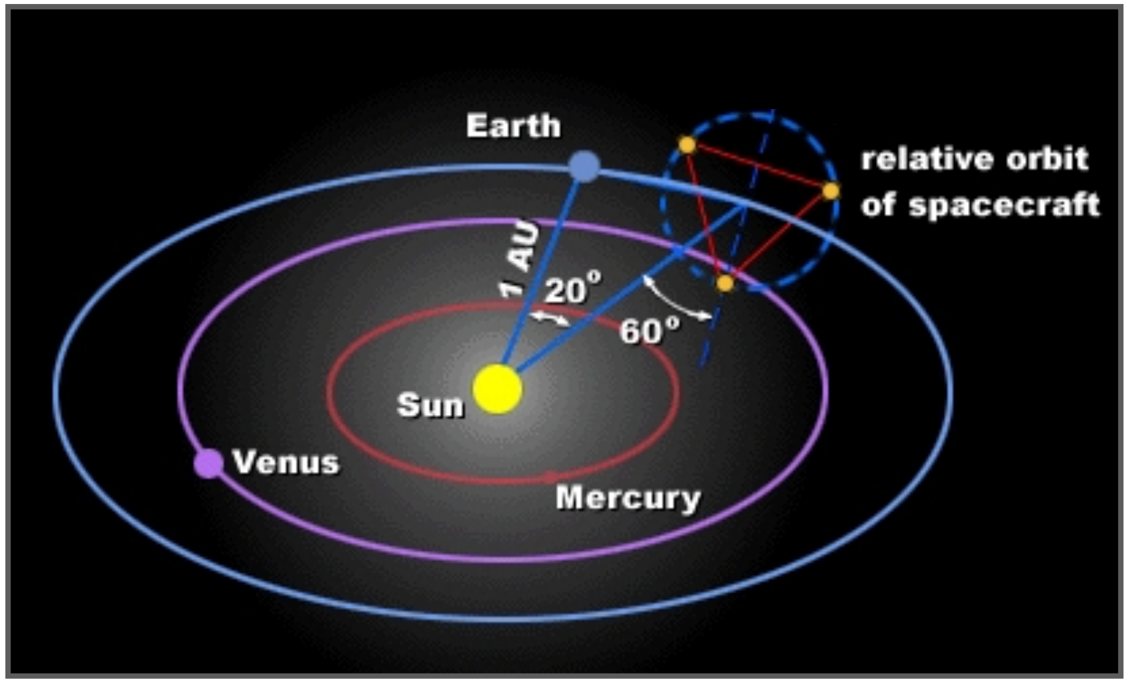
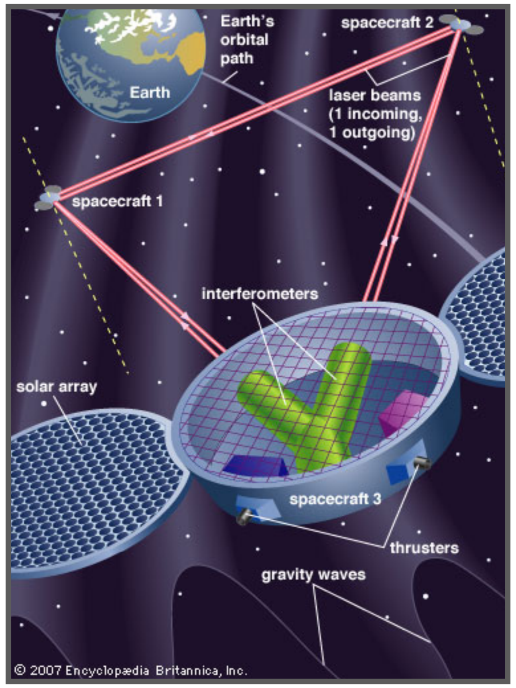


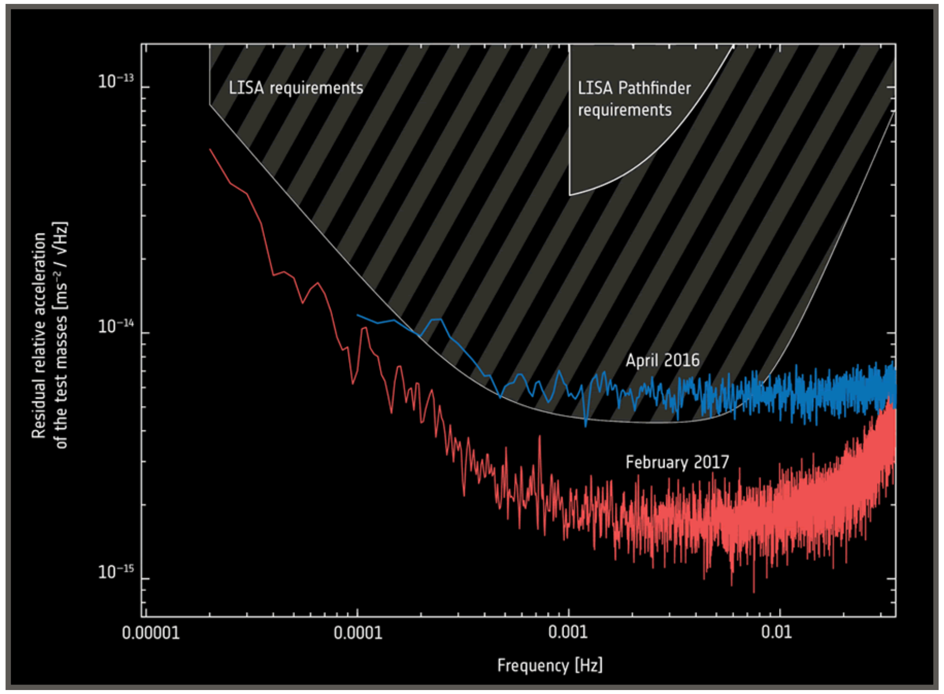
# PRESENT & FUTURE OBSERVATIONS

## LISA (Laser Interferometer Space Antenna)

- Space interferometer project led by ESA & NASA
- Selected as third-large class mission(L3) in 2017. Decided to be launched in 2034.
- 3 spacecrafts orbitting around the Sun. Distance btwn spacecrafts $= 2.5 \times 10^6$ km.
- Testing necessary technologies with LISA pathfinder since 2015. Results successful.



# GWS AS A PROBE OF NEW PHYSICS

- First-order phase transitions [ Witten '84 ] [ Hogan '86 ] [ Kosowsky, Turner, Watkins '92 ] ...
  - as the origin of Baryon Asymmetry of the Universe [ Kuzmin, Rubakov, Shaposhnikov '85 ] [ Morrissey, Ramsey-Musolf '12 ]
- Domain walls [ Zeldovich, Kobzarev, Okun '74 ] [ Kibble '76 ] [ Gleiser, Roberts '98 ]
  - as a probe of SUSY [ Takahashi, Yanagida, Yonekura '08 ] [ Dine, Takahashi, Yanagida '10 ] [ Kamada, Yamada '14 ] ...
- Cosmic Strings [ Kibble '76] [ Vilenkin '81 ]
  - as a probe of local U(1)
  - as a probe of global U(1) [ Battye, Shellard '93 & '96 ] [ Figueroa, Hindmarsh, Urrestilla '13 ] [ Ramberg, Visinelli '19 ] [ Chang, Cui '20 ] ...
- Chiral gauge field
  - from axion during or at the end of inflation [ Cook, Sorbo '11 ] [ Sorbo '11 ] ...
  - from rolling ALP at late times: "audible axion" [ Machado, Ratzinger, Schwaller, Stefanek '19 ]
- PBH & Bosonic stars [ Zel'dovich, Novikov '67 ] [ Hawking '71 ] ... [ Palenzuela, Olabarrieta, Lehner, Liebling '06 ] ...
- Inflation & Preheating [ Starobinsky '79 ] [ Klebnikov, Tkachev '97 ] ...

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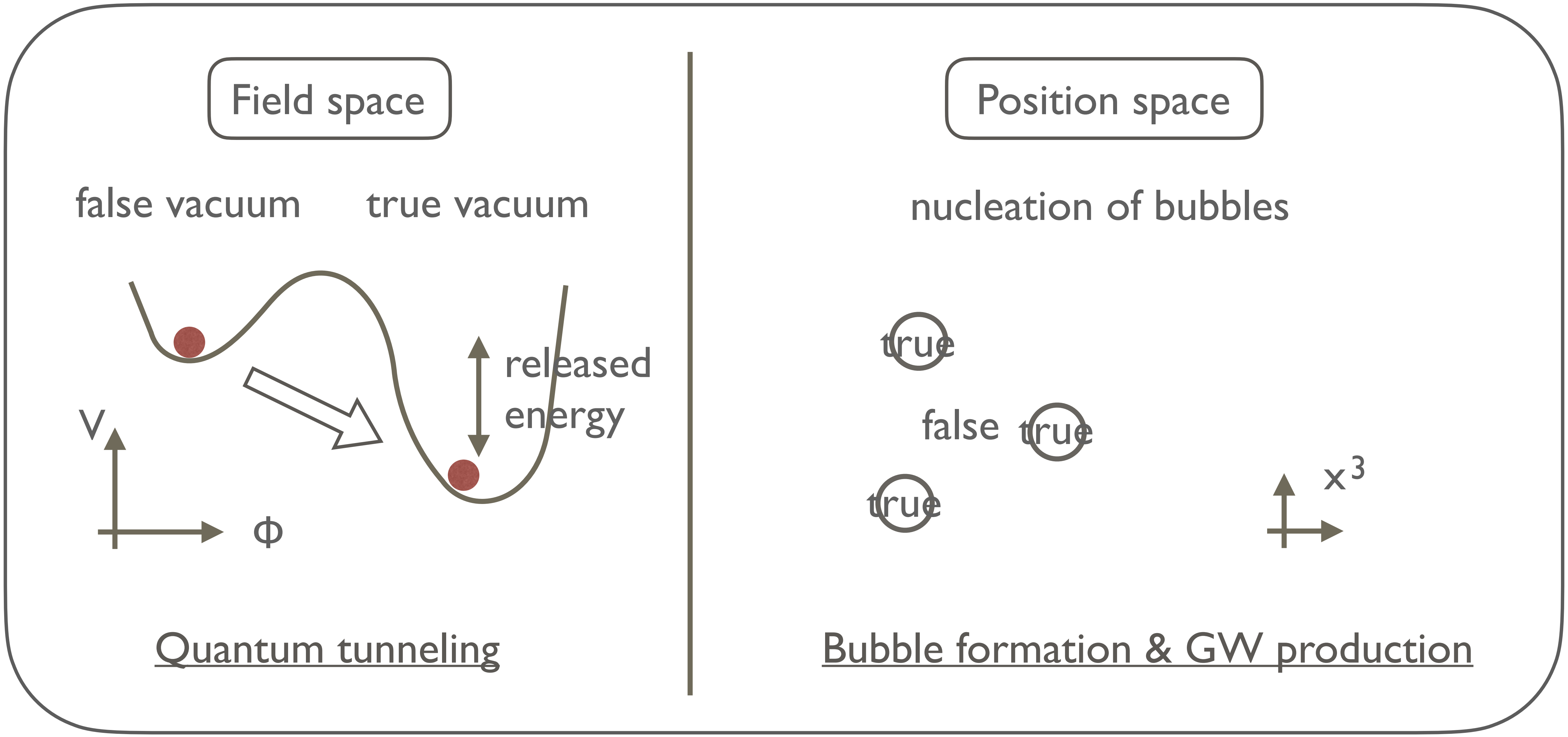
# FIRST-ORDER PHASE TRANSITIONS: A BRIEF PICTURE

- Bubbles nucleate, expand, collide and disappear, involving fluid dynamics



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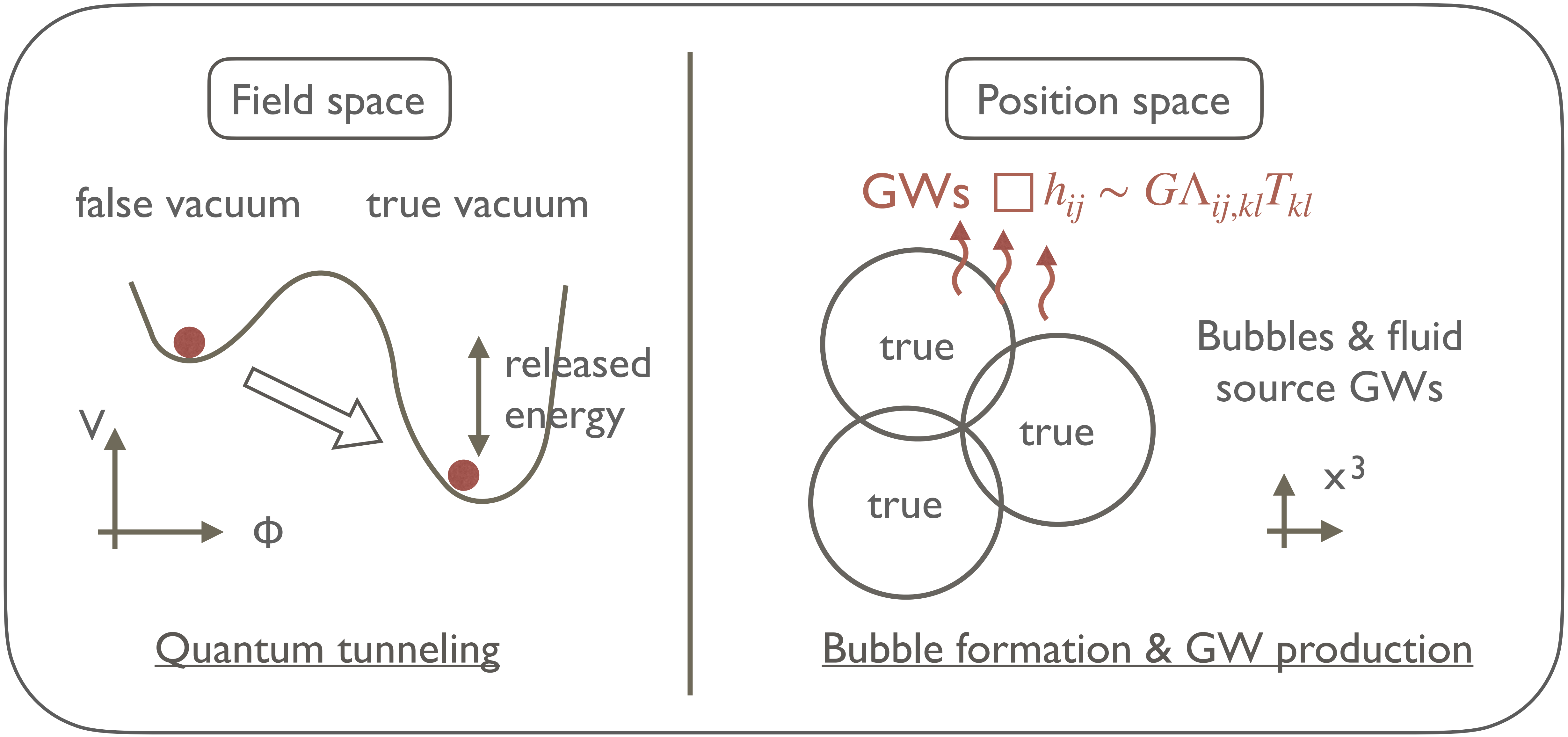


# FIRST-ORDER PHASE TRANSITIONS IN THE SM AND BEYOND

- Within the standard model, the electroweak phase transition is a crossover

  [ Kajantie, Laine, Rummukainen, Shaposhnikov '96 ] [ Gurtler, Ilgenfritz, Schiller '97 ] [ Csikor, Fodor, Heitger '98 ] ...

- However, first-order phase transitions occur in many extensions of the SM

  SUSY [ Giudice '92 ] [ Espinosa, Quiros, Zwirner '93 ] …

  Extra dimensions [ Randall, Servant '06 ] …

  Singlet extensions [ Profumo, Ramsey-Musolf, Shaughnessy '07 ] …

  Confining transitions [ Filippo, Gouttenoire, Baldes '19 ] …

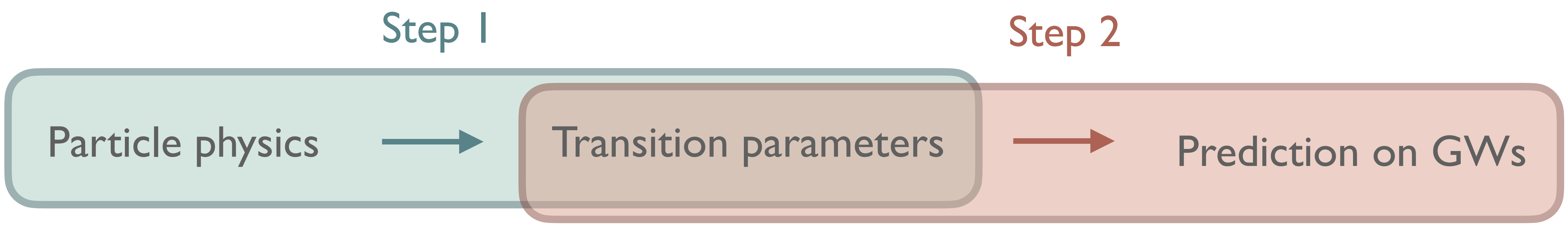
- First-order phase transitions provide a possible explanation for the origin of baryon asymmetry of the Universe [ Kuzmin, Rubakov, Shaposhnikov '85 ]

- In the coming decades, we have chances to observe GW signals from this process with space interferometeres such as LISA, Taiji, TianQin

# PHILOSOPHY OF MY PROJECTS

- What we need before the launch of space interferometers:

<u>To establish a reliable connection from particle physics to GWs</u>




Lagrangian $\mathscr{L}$

$\alpha$ : transition strength
$\beta$ : nucleation speed (~inverse bubble size)
$v_w$ : wall velocity
$T_*$ : transition temperature

GW spectrum $\Omega_{\rm GW}$

- In the following I introduce my works contributing to { Step2 / Step1&2 combined }

- Before moving on, let me stress the importance of Step 1:

[ Parwani '92 ] [ Arnold, Espinosa '93 ]…
[ Wainwright, Profumo, Ramsey-Musolf '11 ]
[ Laine, Meyer, Nardini '17 ]

[ Dine, Leigh, Huet, Linde, Linde '96 ]… [ John, Schmidt '01 ]…
[ Konstandin, Nardini, Rues '14 ]
[ Bodeker, Moore '09 ] [ Bodeker, Moore '17 ] [ Höcke, Kozaczuk, Long, Turner, Wang '20 ]
[ Gouttenoire, <u>Jinno</u>, Sala: to appear ]…

# TALK PLAN

- Intro
- First-order phase transitions & GWs: more on bubble dynamics
- Establishing the connection between particle physics & GWs
  - weak∼moderate transitions
  - extremely strong transitions
- (Optional) "Imprint" of new physics on GWs
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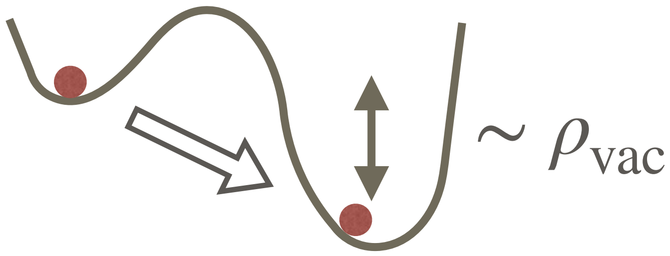
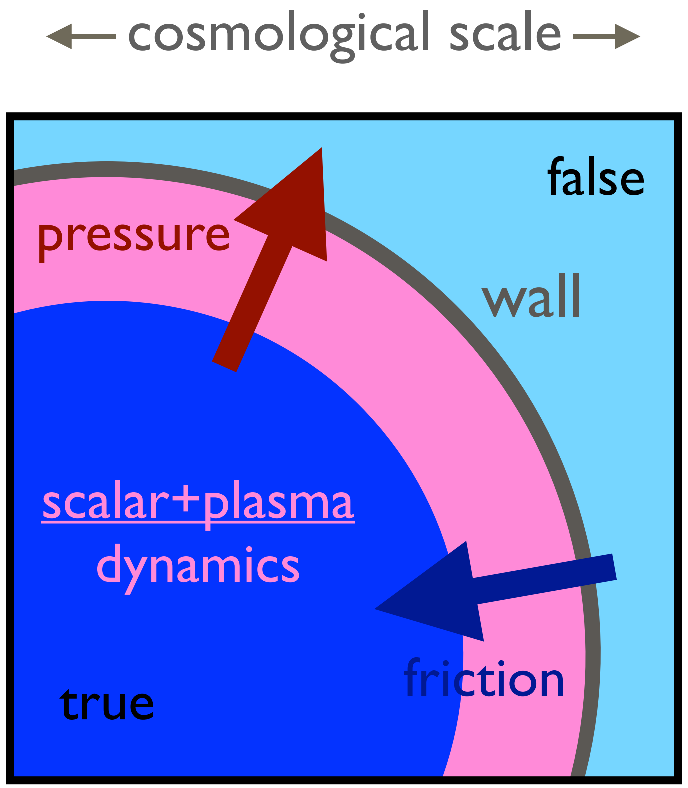
# MORE ON BUBBLE DYNAMICS



➤ "Pressure vs. Friction" determines the behavior of bubble walls




Pressure: released energy pushes the wall outwards

Parametrized by $\alpha \equiv \dfrac{\rho_{\rm vac}}{\rho_{\rm plasma}}$

[ see e.g.
Espinosa et al. '10
Hindmarsh et al. '15
Giese et al. '20
for various definitions ]

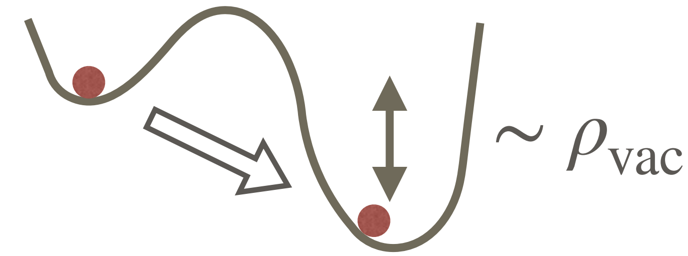
Friction: plasma particles push back the wall

Parametrized by coupling $\eta$ btwn. scalar & plasma

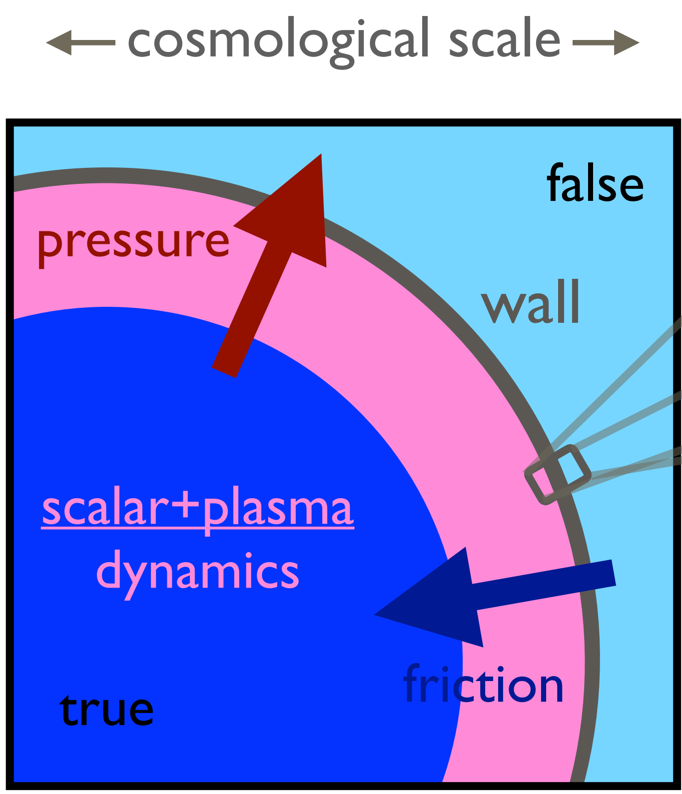
(note: plasma particles exist everywhere)

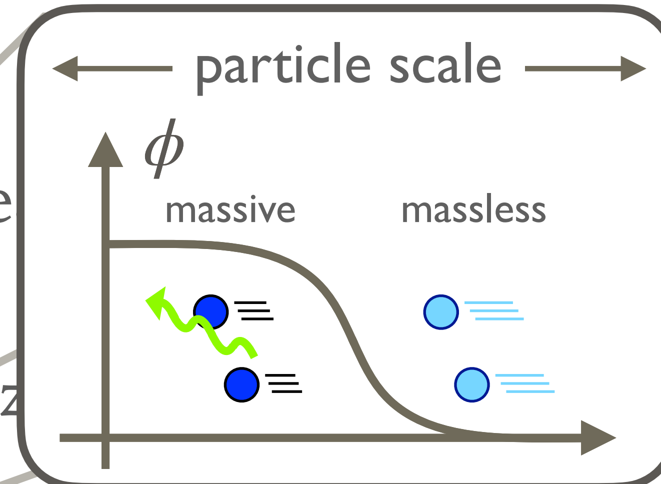
In the next slide I show how bubbles behave for different $\alpha$ (with fixed coupling $\eta$ )

# MORE ON BUBBLE DYNAMICS




➤ "Pressure vs. Friction" determines the behavior of bubble walls

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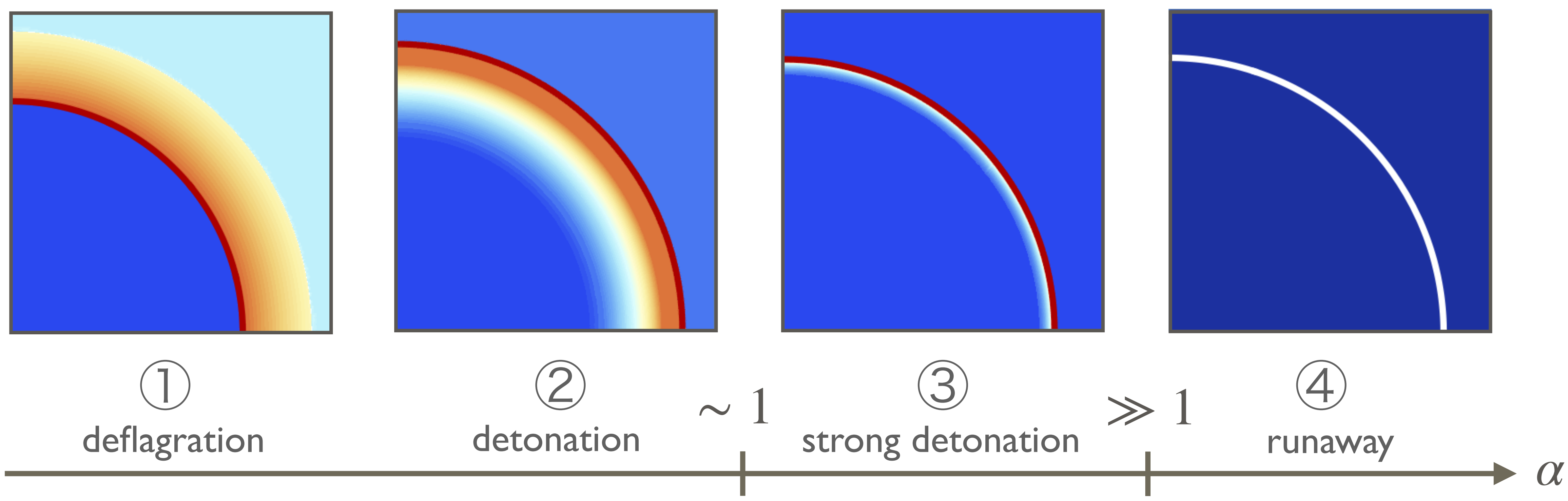
# HOW BUBBLES BEHAVE IN REALITY

➤ Classification of bubble expansion

Walls reach terminal velocity
because of the balance btwn. pressure & friction
Main energy carrier: fluid

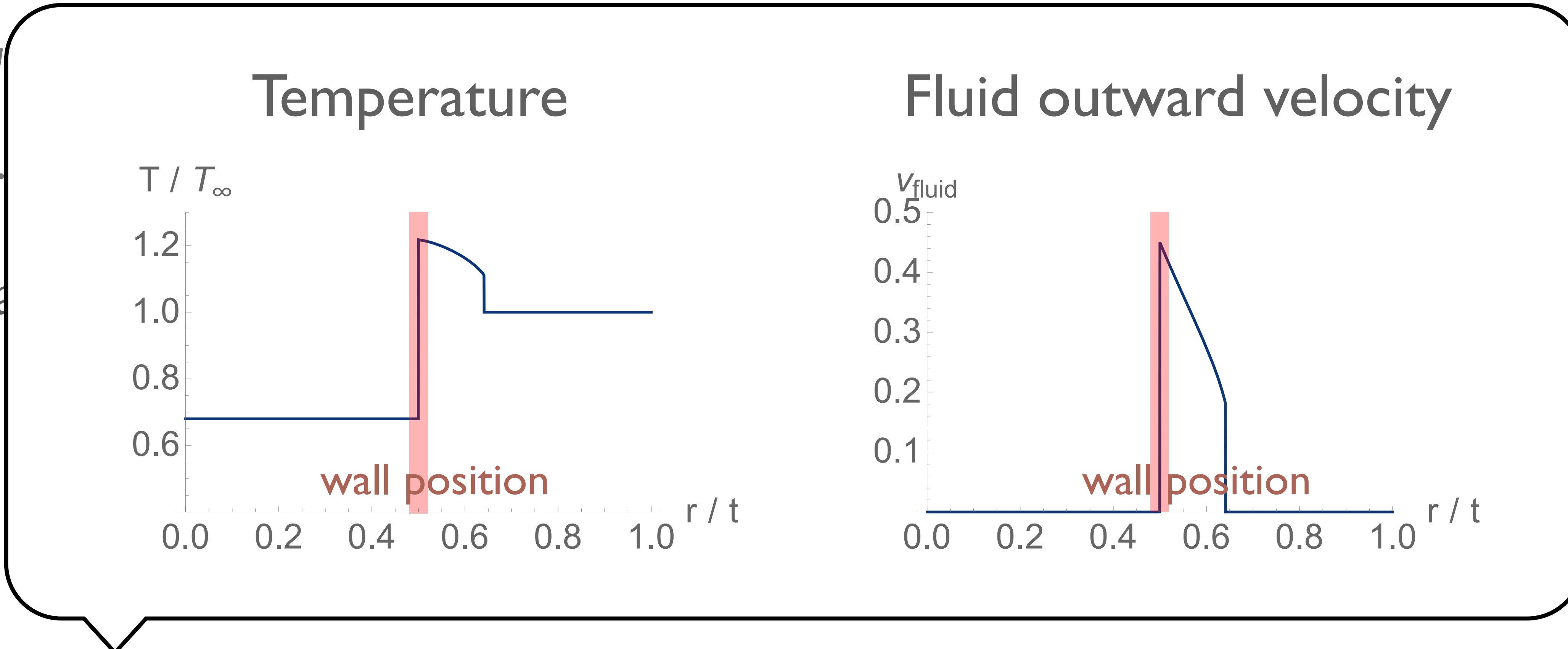
Walls runaway
without caring about the plasma
Main energy carrier: wall (scalar field)




Every detail of these bubbles contain the information on particle physics

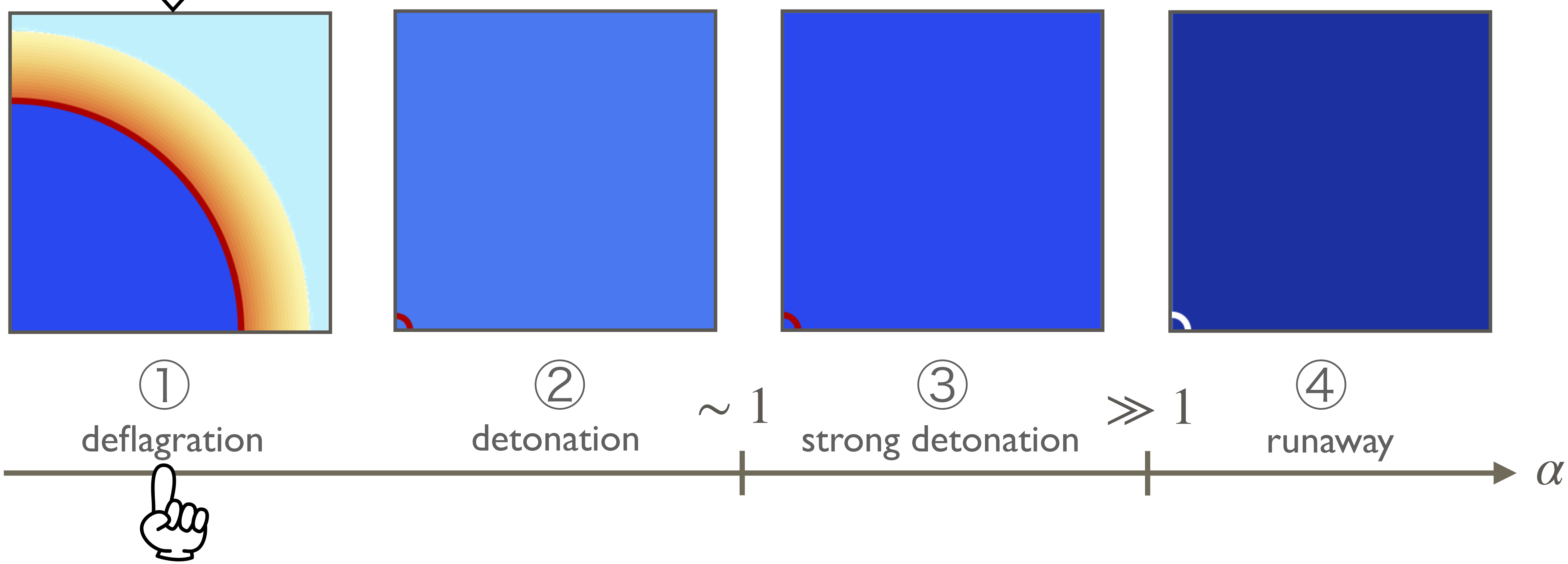
# HOW

➤ Cl




e plasma

(scalar field)

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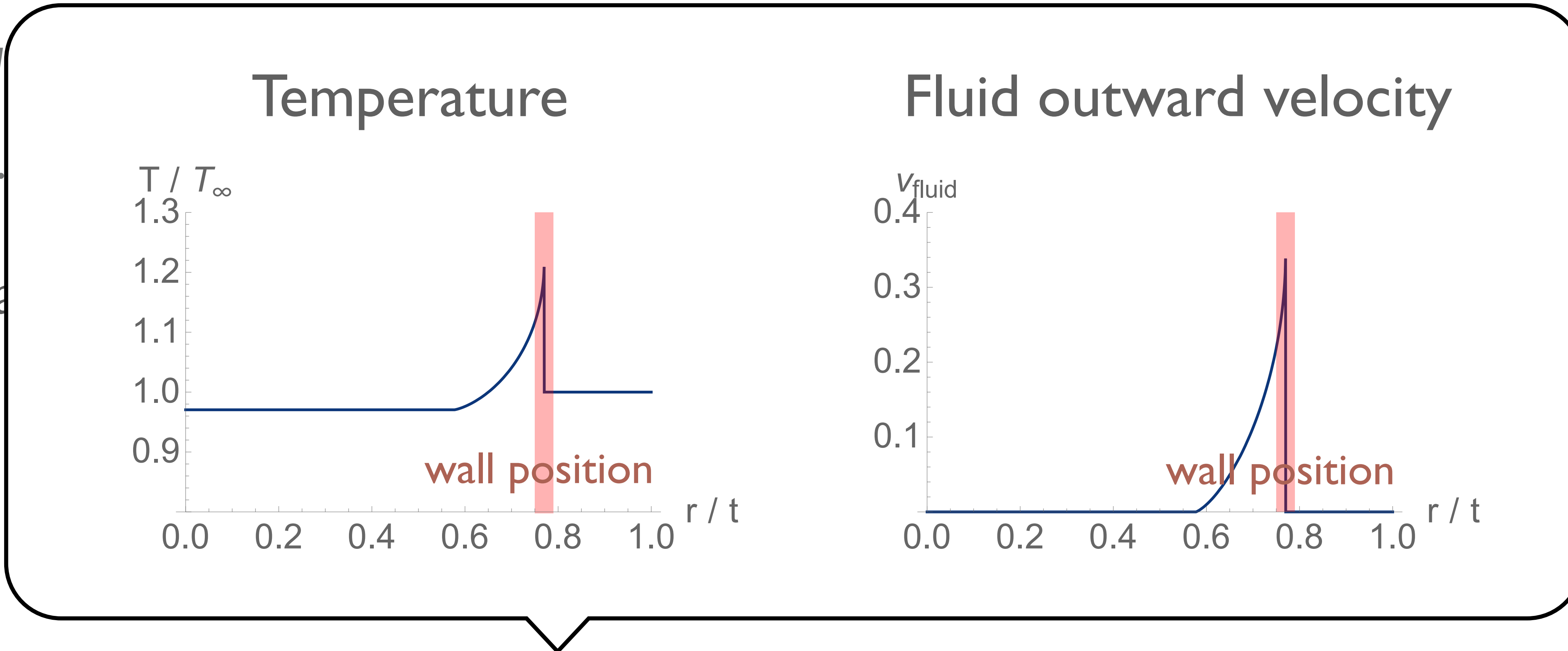


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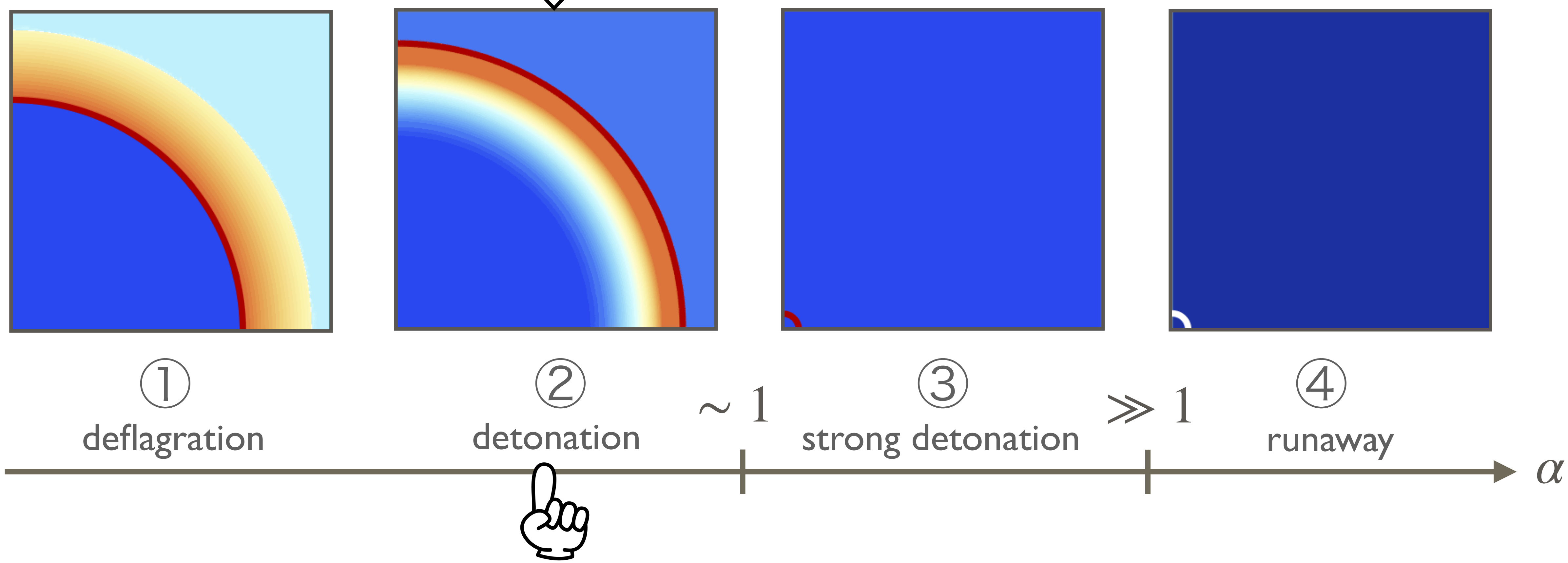


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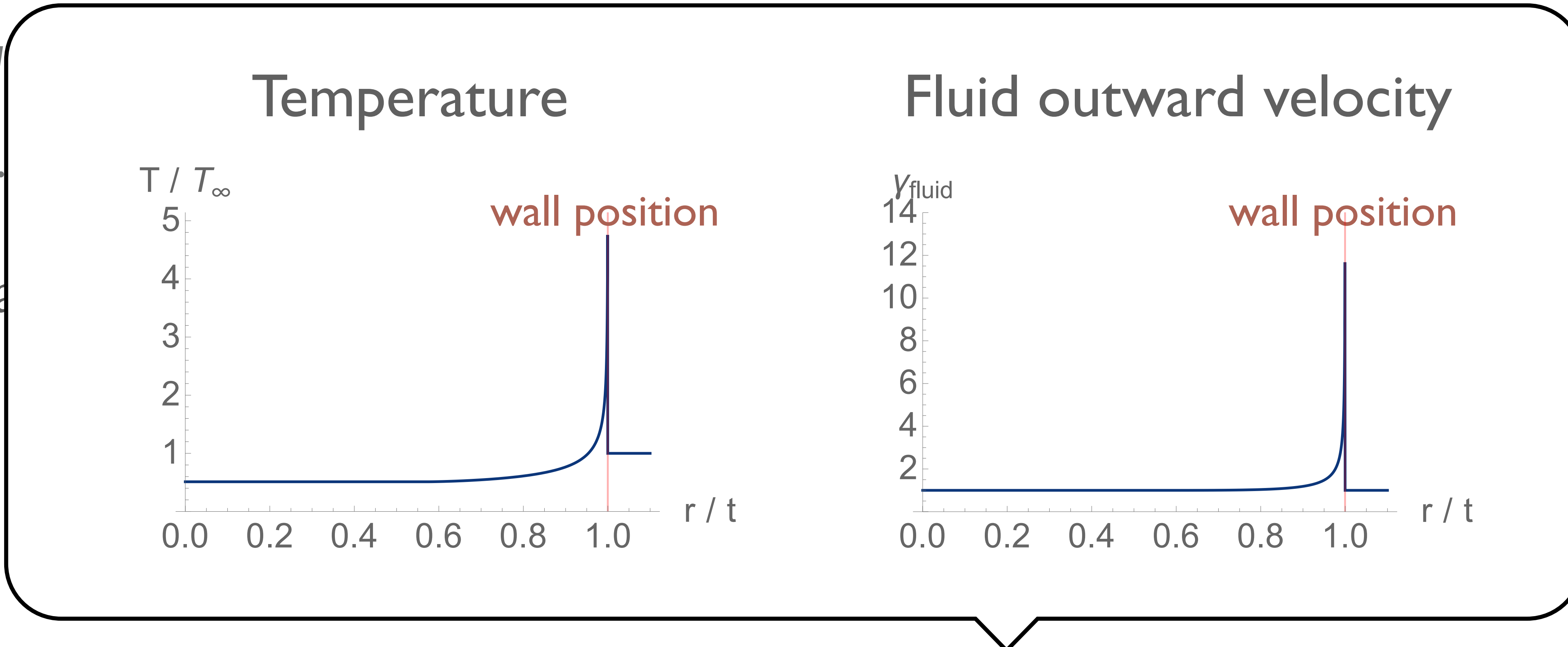
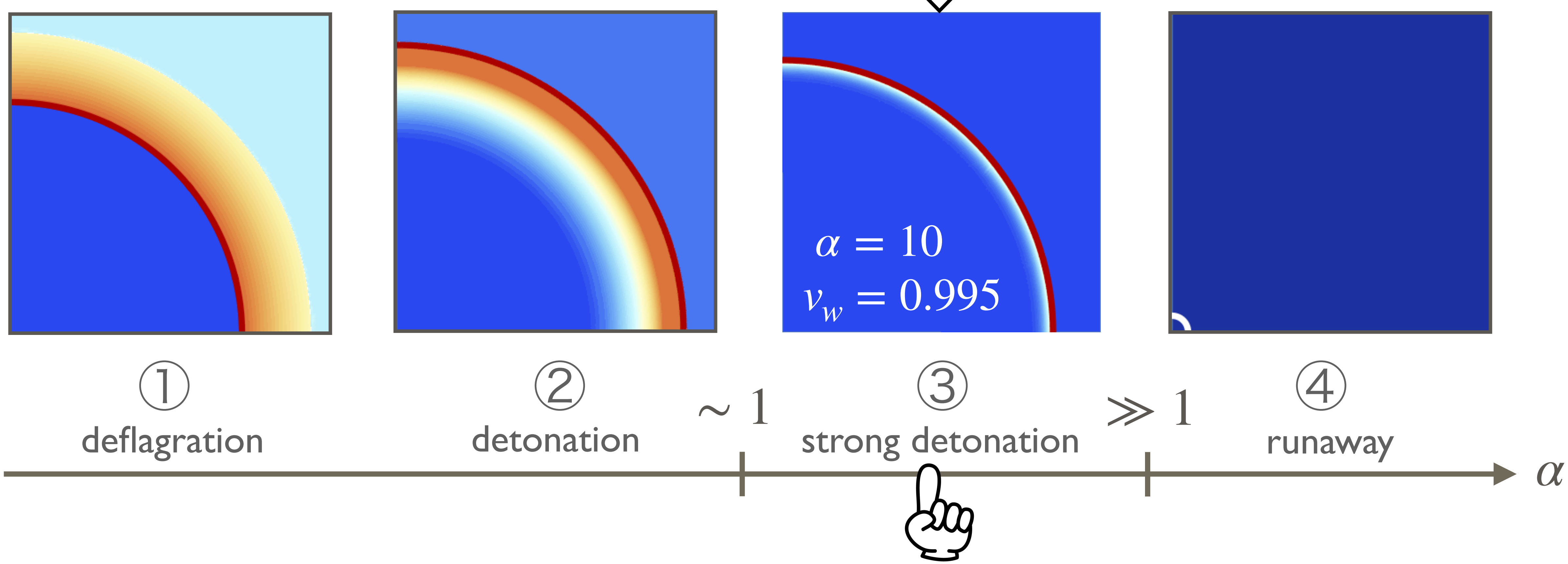



Every detail of these bubbles contain the information on particle physics

# HOW

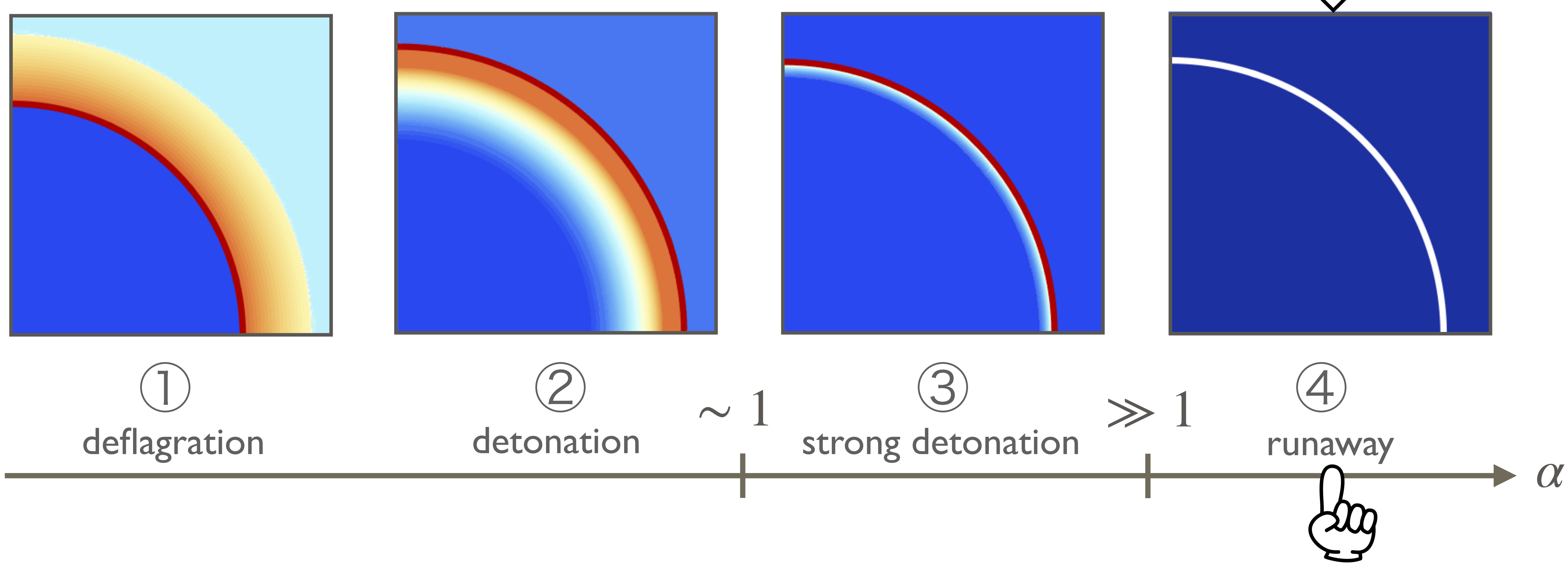
➤ Cla

Plasma particles cannot stop the acceleration of the walls:

walls continue to get accelerated until they collide with others

e plasma

(scalar field)




Every detail of these bubbles contain the information on particle physics

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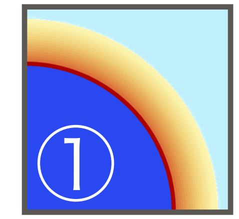
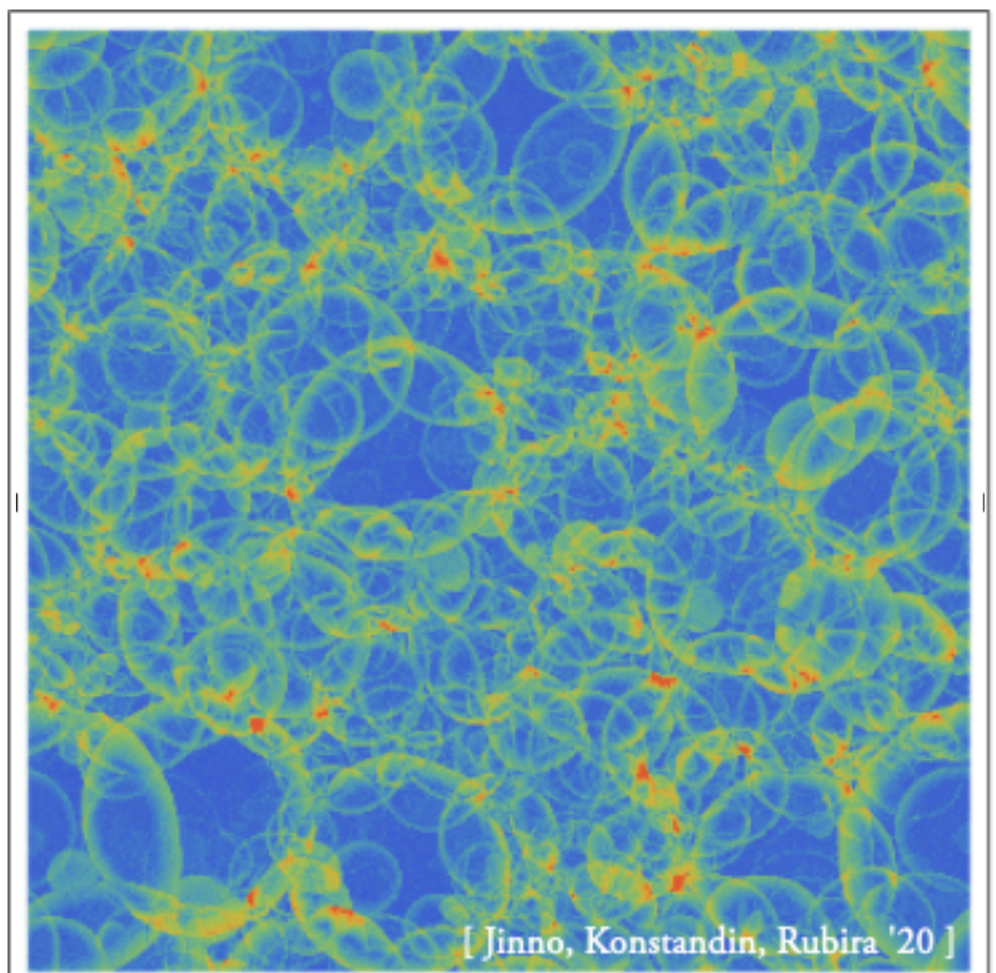
# GW PRODUCTION IN WEAK~MODERATE TRANSITIONS





- ➤ In weak~moderate transitions ( $\alpha \lesssim 1$ ), sound waves (SWs) are an important source of GWs
- ➤ We proposed an efficient scheme for 3d simulation (→ next slide)
  - The simulation uses DESY cluster; As a result, we are now the second group in the world performing a 3d box simulation for GW production from fluid

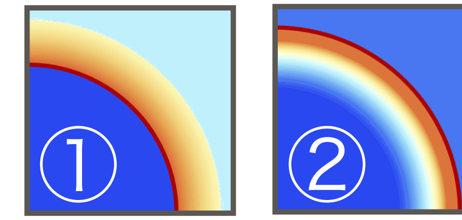
[ T. Konstandin ]



[ Jinno, Konstandin, Rubira '20 ]

[ H. Rubira ]

# OUR SCHEME IN A NUTSHELL

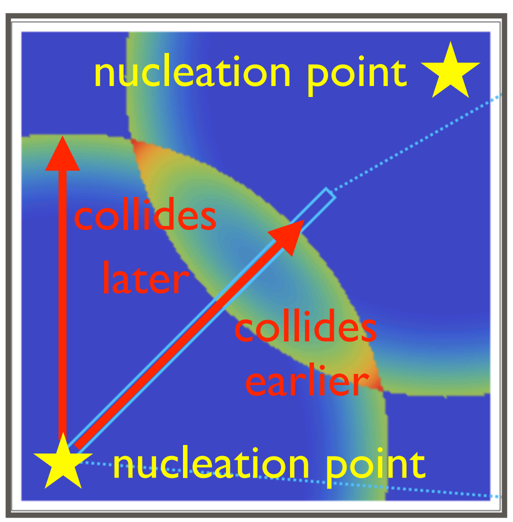


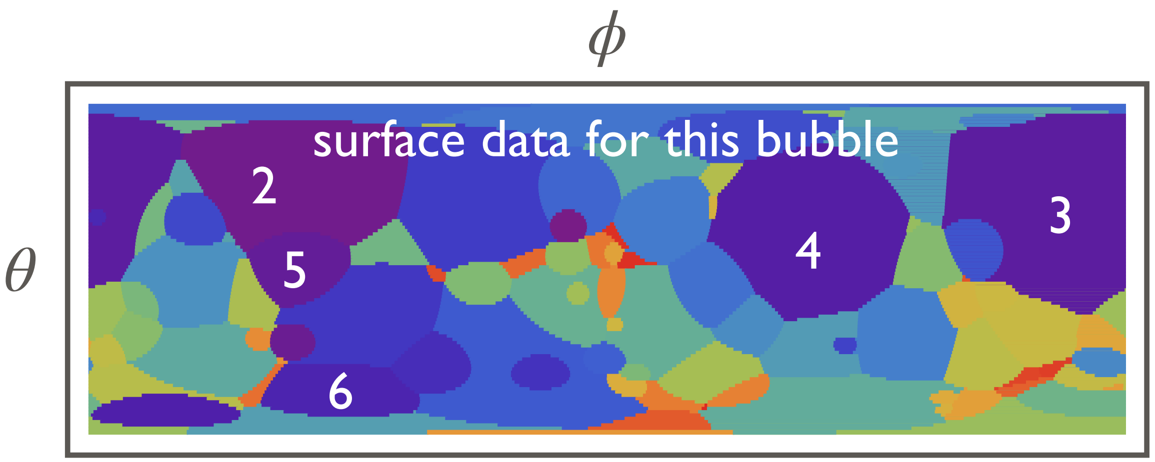

➤ Our approach: Embedding 1d into 3d

<u>Step1</u>: surface data for collision time

Bubble profile before collision is already known (they just expand in a self-similar way).

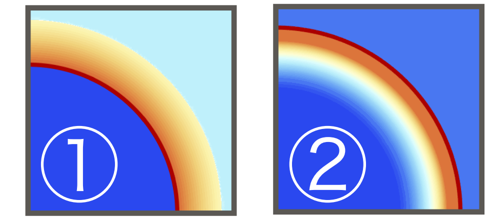
The only difference is the collision time for different directions.




The surface data can be obtained <u>without simulation</u> from the distribution of nucleation points (★)

# OUR SCHEME IN A NUTSHELL

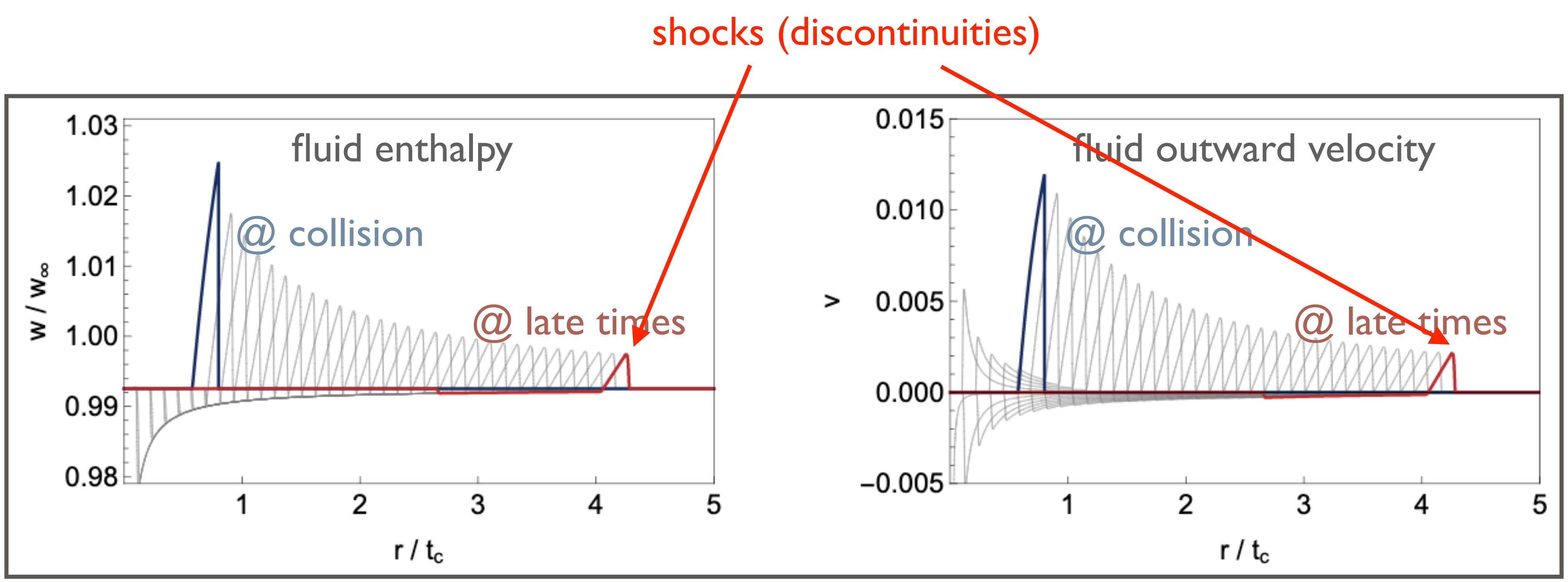



➤ Our approach: Embedding 1d into 3d

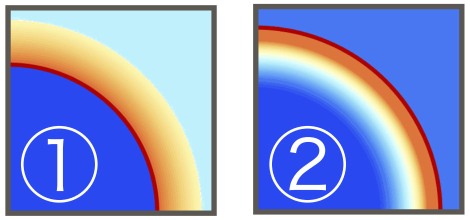
Step2: 1d evolution after collision

After the bubble collision, the fluid is launched into free propagation.

We solve the radial evolution of the fluid, utilizing a shock-conserving scheme (Kurganov-Tadmor)



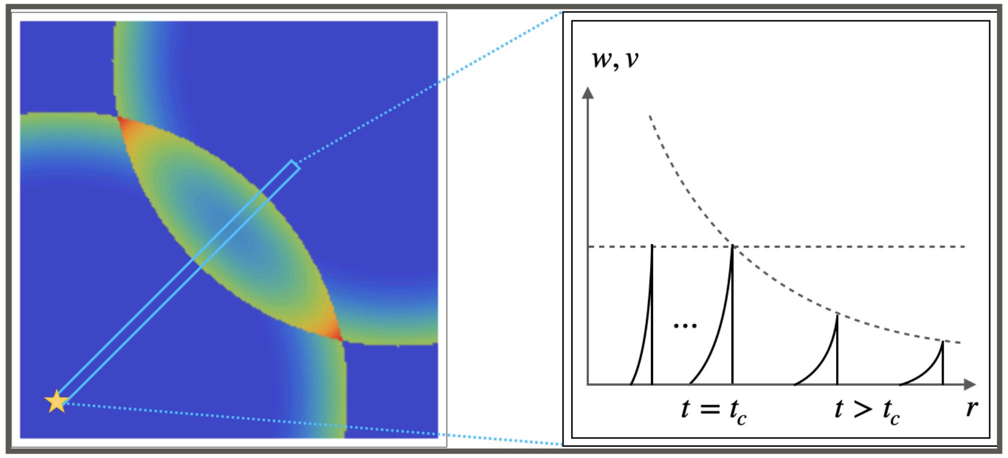
# OUR SCHEME IN A NUTSHELL



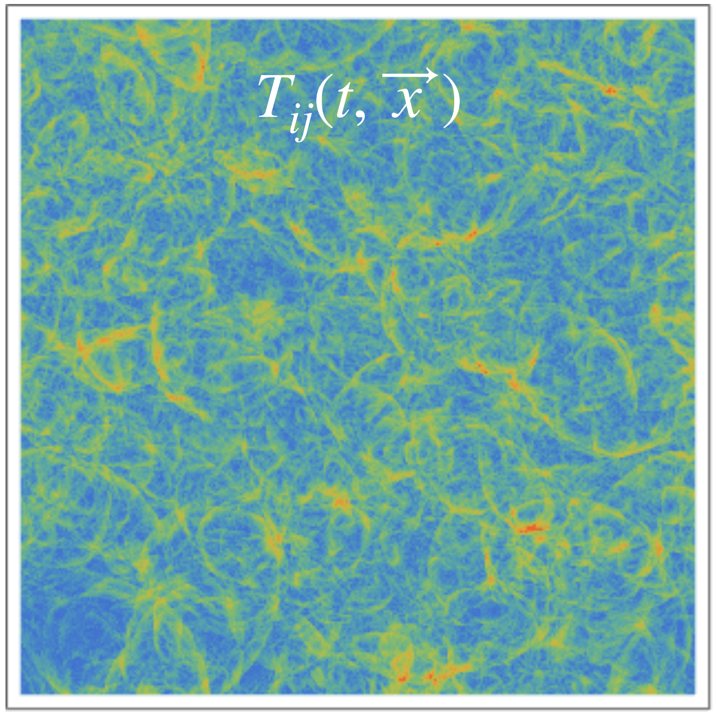

➤ Our approach: Embedding 1d into 3d

Step3: embed 1d back into 3d and calculate GWs

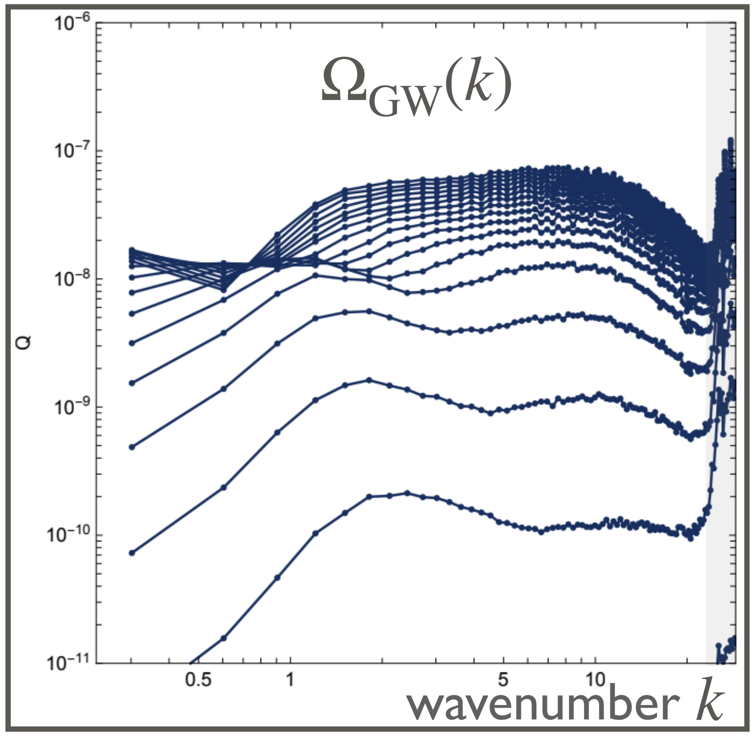
3d



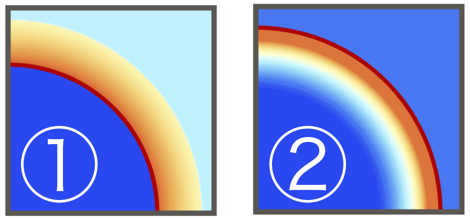

1d




$\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$



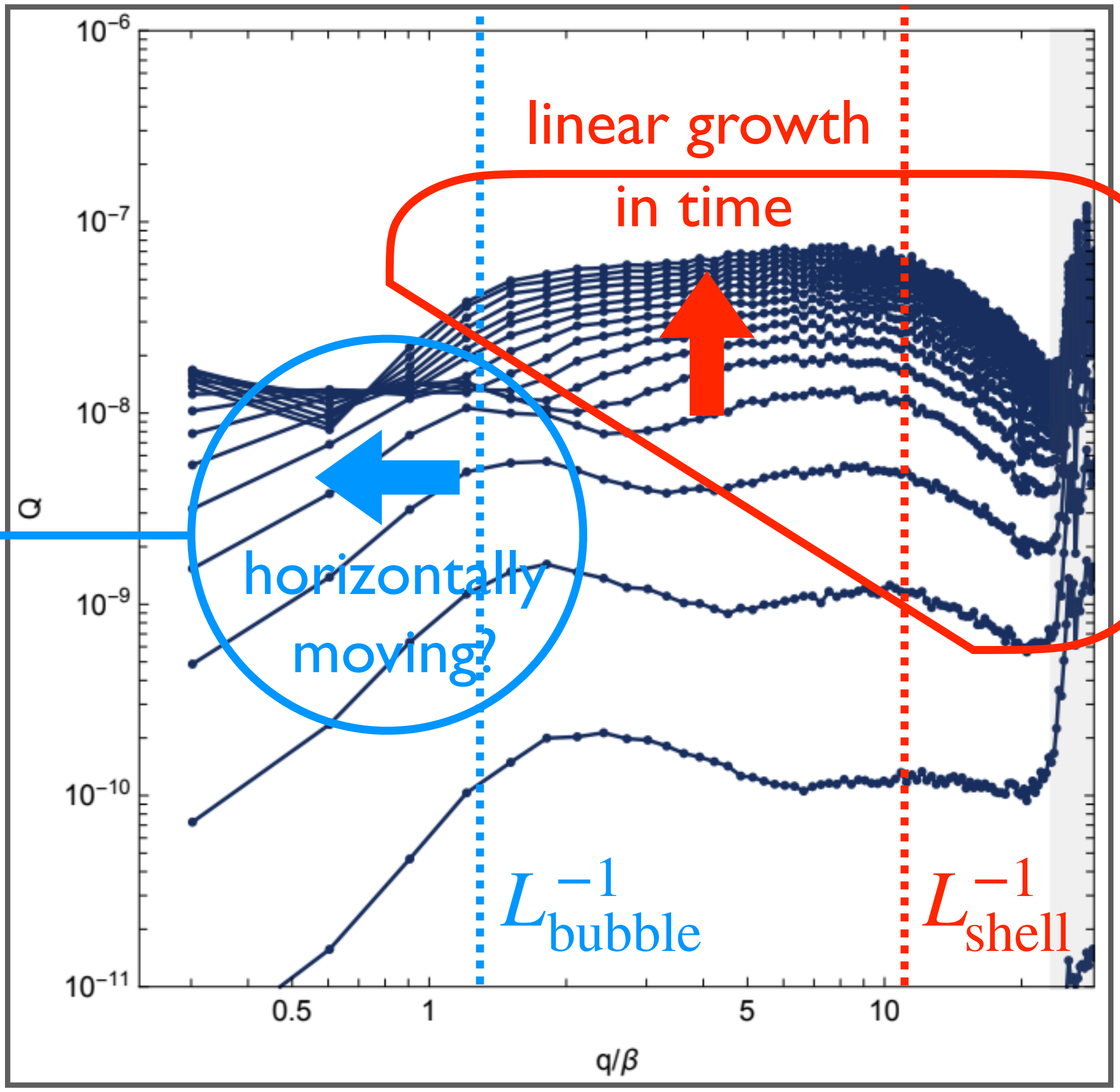
# GW PREDICTION



- Our approach: Embedding 1d into 3d

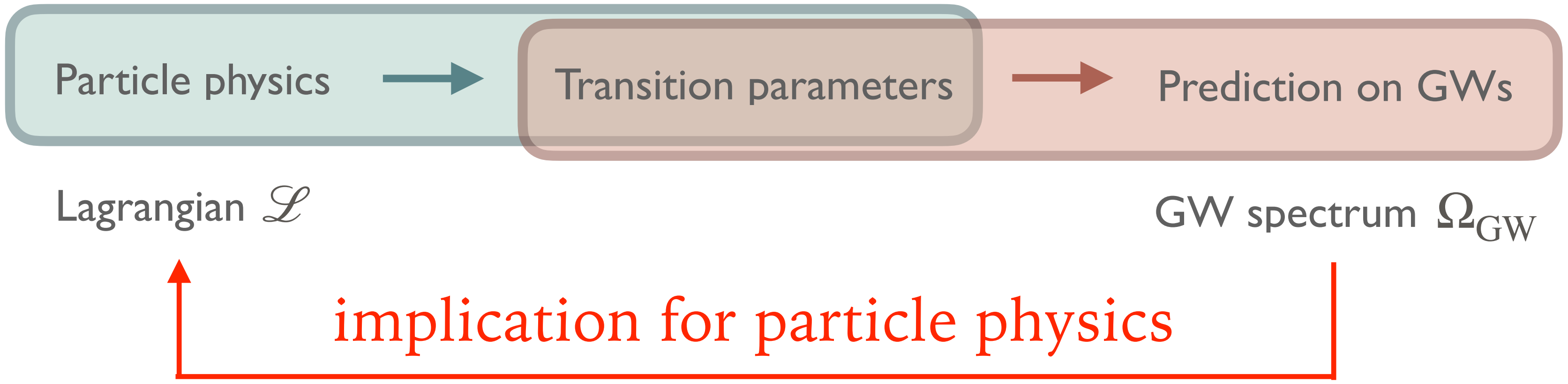
Every structure reflects the fundamental Lagrangian of your model

→ Important for model selection



# COMBINING THE PIPELINE

➤ What can we do after combining the pipeline?

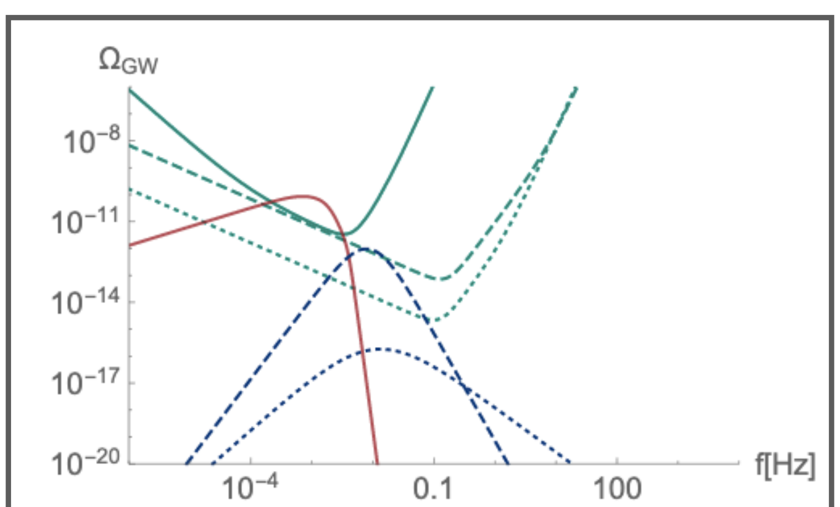



[ S. Kanemura ]

➤ Example 1: Higgs-Singlet Model

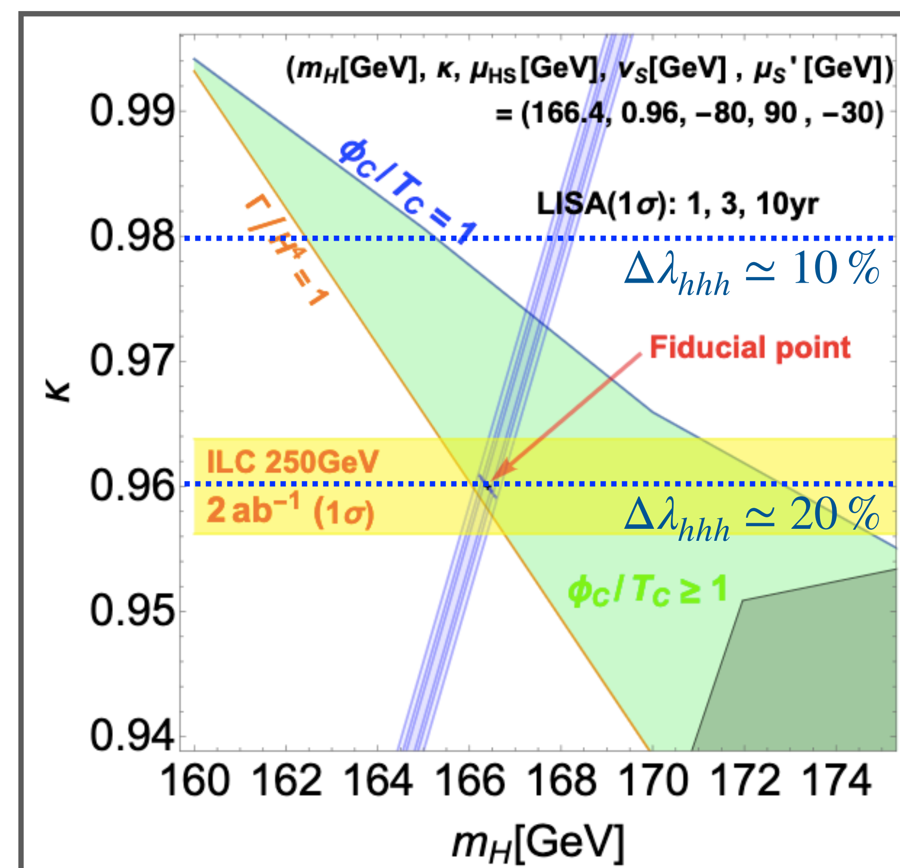
[ Hashino, Jinno, Kakizaki, Kanemura, Takahashi, Takimoto '18 ]

$$V = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 S^2$$
$$+\mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu_S'}{3} S^3 + \frac{\lambda_S}{4} S^4$$




Likelihood analysis

combined with ILC prospect



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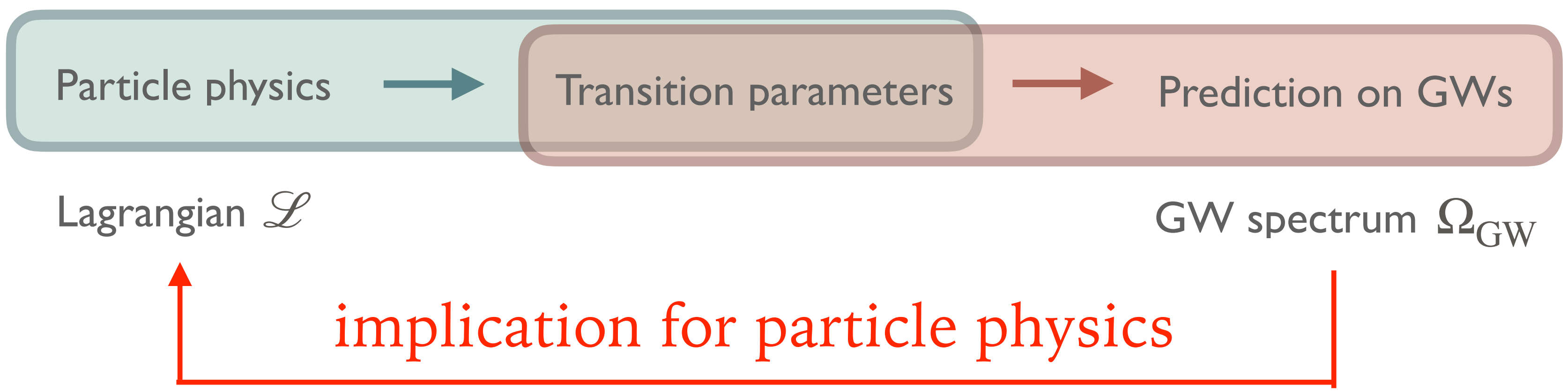


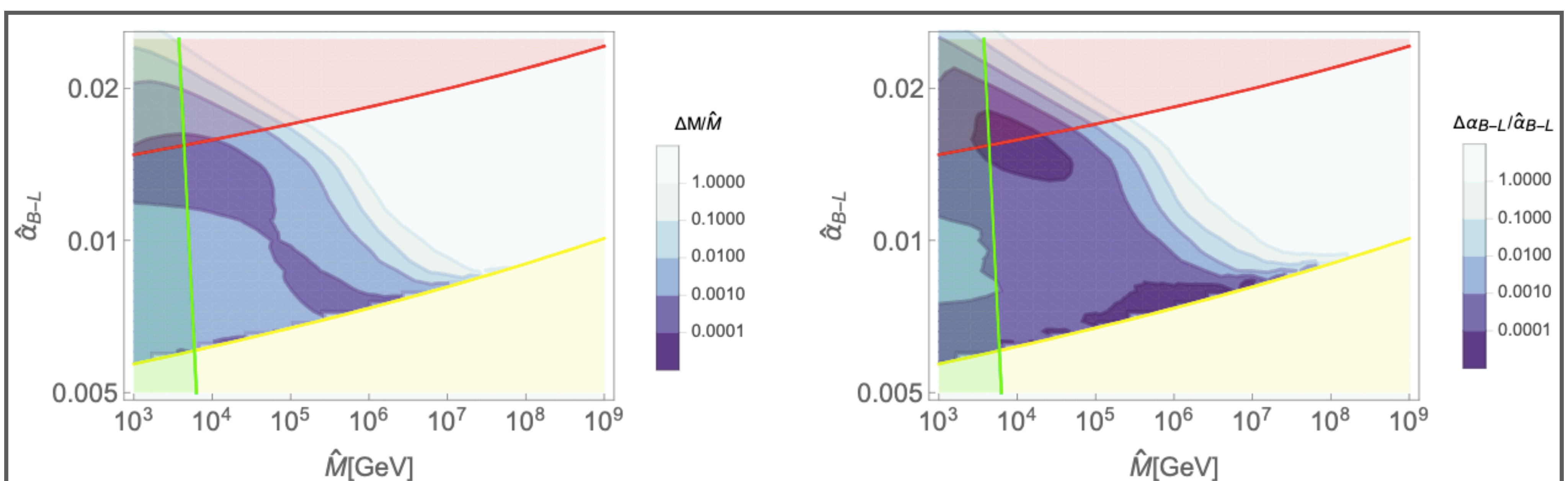

[ S. Kanemura ]

➤ Example 2: Classically conformal B-L model [ Iso, Okada, Orikasa '09 ]

$$V = \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4 - \lambda_{\Phi X} |\Phi|^2 |X|^2$$

Free parameters: $\alpha_{B-L}$ & $M \equiv \sqrt{2}\,\langle X \rangle$

[ Hashino, Jinno, Kakizaki, Kanemura, Takahashi, Takimoto '18 ]



# COMBINING THE PIPELINE

- What can we do after combining the pipeline?

Particle physics → Transition parameters → Prediction on GWs

Lagrangian $\mathscr{L}$ GW spectrum $\Omega_{\rm GW}$

implication for particle physics

[ S. Kanemura ]

- Example 2: Classically conformal B-L model [ Iso, Okada, Orikasa '09 ]

$$V = \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4 - \lambda_{\Phi X} |\Phi|^2 |X|^2$$

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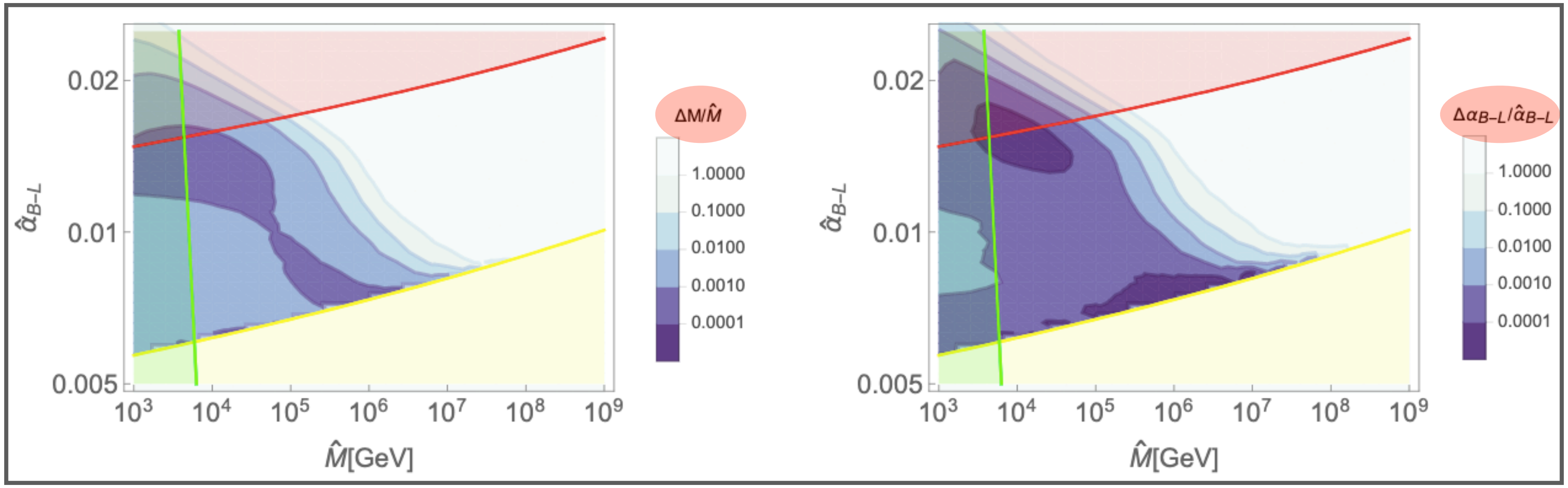
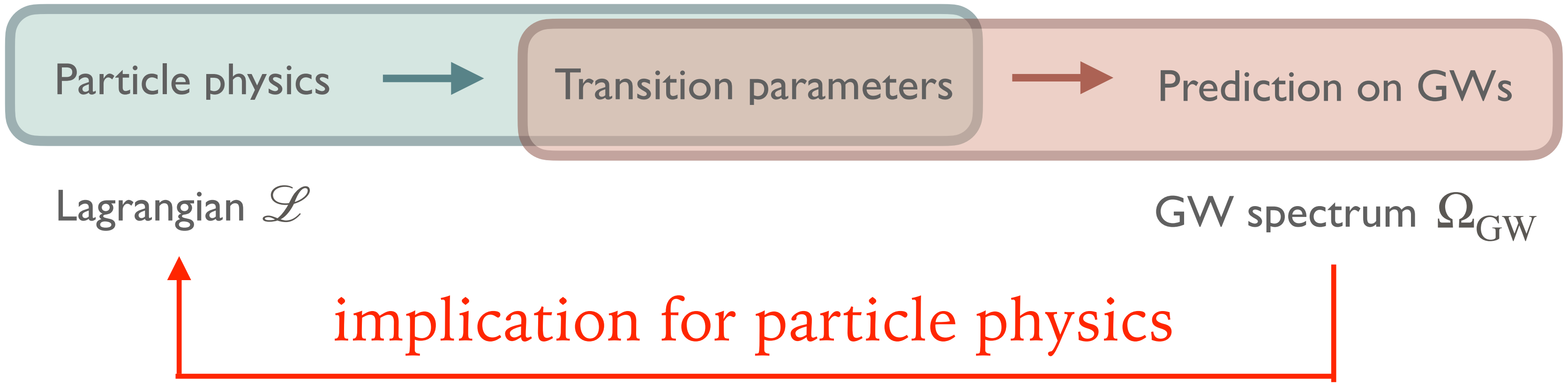


# COMBINING THE PIPELINE

- What can we do after combining the pipeline?




[ S. Kanemura ]

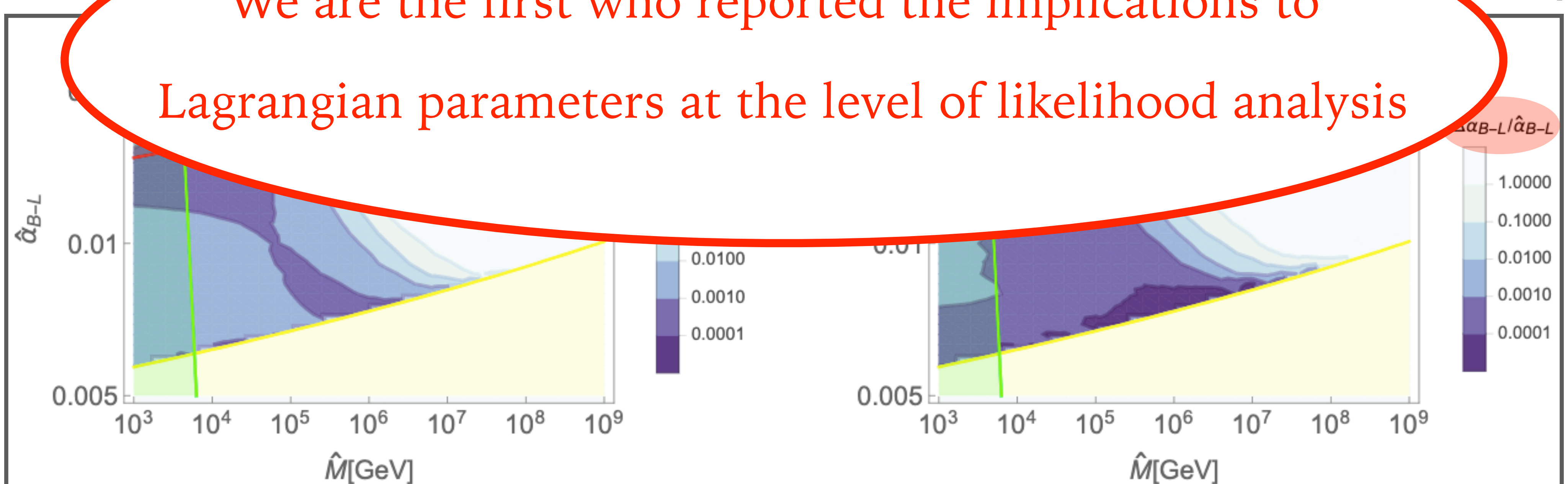
- Example 2: Classically conformal B-L model [ Iso, Okada, Orikasa '09 ]

$V = \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4$ … & $M \equiv \sqrt{2}\,\langle X \rangle$

[ …moto '18 ]

We are the first who reported the implications to

Lagrangian parameters at the level of likelihood analysis



# COMBINING THE PIPELINE

➤ What can we do after combining the pipeline?

Particle physics → Transiti… → …diction on GWs

Lagran…

S. Kanemura ]

What about other models and/or

about HL-LHC, CEPC, FCC-ee,-hh, etc.?

→ I'm ready to collaborate with you

➤ Example 2: Classic… …kada, Orikasa '09 ]

$V = \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4$ … & $M \equiv \sqrt{2}\,\langle X \rangle$

…moto '18 ]

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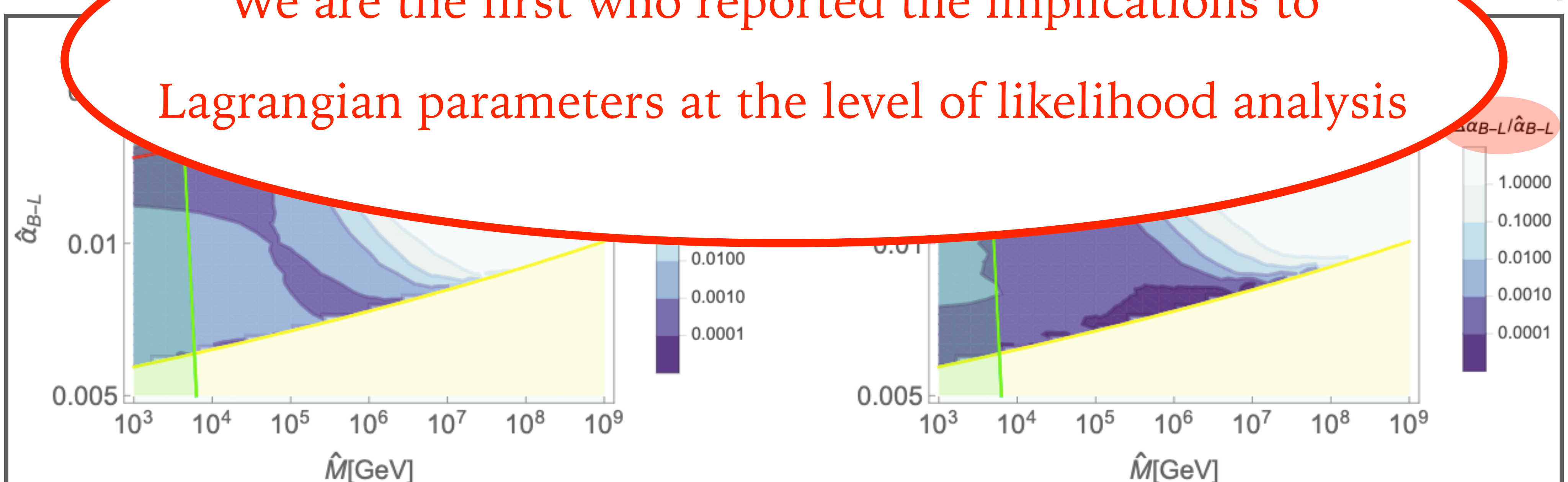


# TALK PLAN

- Intro
- First-order phase transitions & GWs: more on bubble dynamics
- Establishing the connection between particle physics & GWs
  - weak~moderate transitions
  - extremely strong transitions
- (Optional) "Imprint" of new physics on GWs
- Summary

# EXTREMELY STRONG TRANSITIONS



- In some particle models, the transition is extreme strong ( $\alpha \gg 1$ )

  e.g. when the model is approximately conformal around the transition scale

  [ Randall, Servant '06 ] [ Espinosa, Konstandin, No, Quiros '08 ] [ Konstandin, Servant '11 ]
  [ Jinno, Takimoto '16 ] [ Iso, Serpico, Shimada '17 ] [ von Harling, Servant '17 ] [ Baldes, Garcia-Cely '18 ]
  [ Hambye, Strumia '13, '18 ] [ Prokopek, Rezacek, Swiezewska '18 ] [ Baldes, Gouttenoire, Sala '20 ]
  (and many many others; only partially cited)

  why?: The system changes only logarithmically in temperature

  → only gradual bubble nucleation → big bubbles & large supercooling

- Naively: strong transitions → large GWs expected.

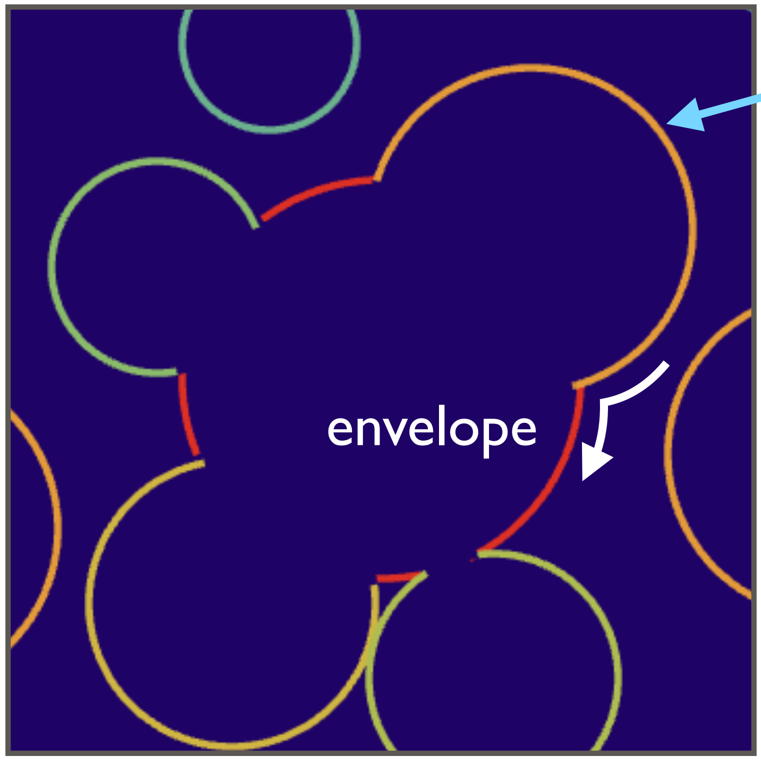
  However, the GW signal from these transitions is still unclear.

  why?: { Extreme energy localization / Shock waves } make simulation difficult

# EXTREMELY STRONG TRANSITIONS



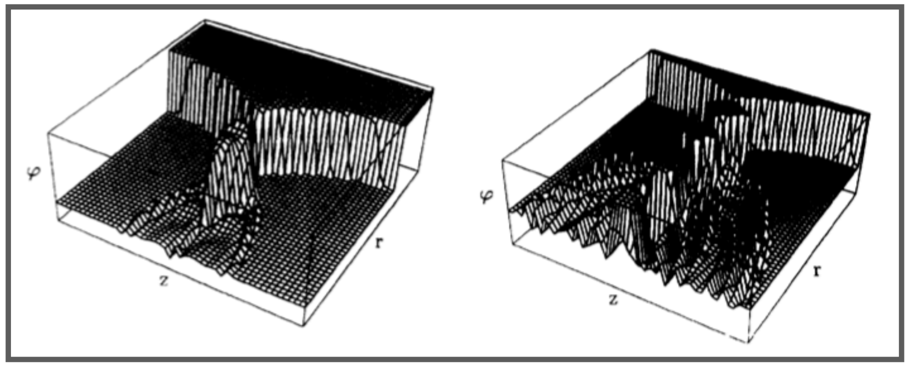
- We tackled this problem [ Jinno, Takimoto '16, '17 ] [ Jinno, Seong, Takimoto, Um '18 ] [ Jinno, Konstandin, Takimoto '19 ]
- The energy shaply localizes around the surface before collision.
  Suppose it's also true after collision. Then how does the system look?
- Traditional modeling: envelope approx. [ Kosowsky, Turner, Watkins '92 ]




$$T_{ij} \text{ grows like } \propto \frac{\text{(released energy)}}{\text{(surface area)}} \propto \text{(radius)}$$

- The surface disappears as soon as it collides ("envelope")

- Proposed in [ Kosowsky, Turner, Watkins '92 ] based on a scalar bubble simulation



# EXTREMELY STRONG TRANSITIONS



- We solved this system <u>analytically</u>, after 24 years since the first proposal
  - Assumptions: linearized gravity $\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$ & negligible cosmic expansion
  - Numerical simulations have been performed before our work [ Huber, Konstandin '08 ]

- The calculation needs just consideration on causality

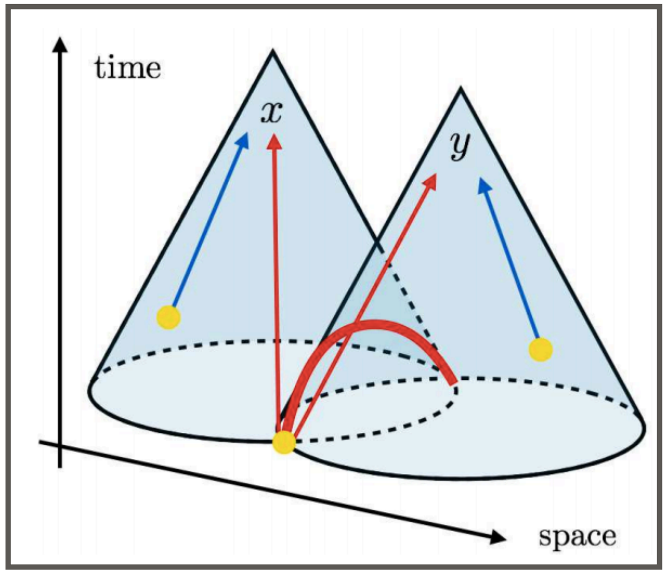
[ <u>Jinno</u>, Takimoto '16 ]

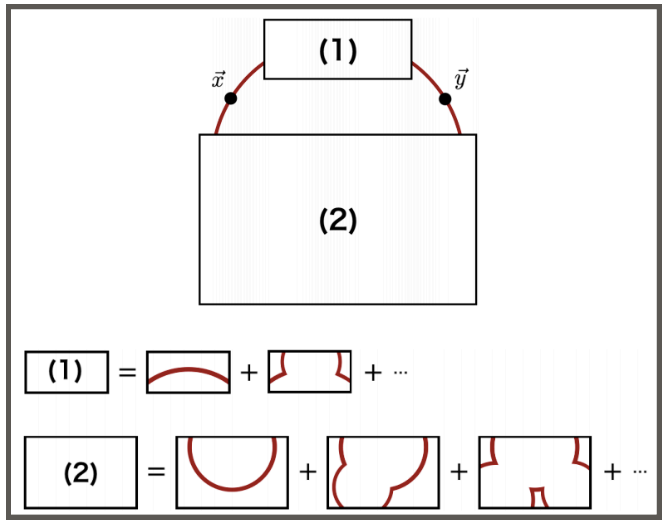
  - In a nutshell:

① GW spectrum $\sim$ 2 point ensemble average of $h_{ij}$

$\sim$ 2 point ensemble average of the source $\left\langle T_{ij}T_{kl} \right\rangle_{\rm ens}$

② $\left\langle T_{ij}(t_x, \vec{x})T_{kl}(t_y, \vec{y}) \right\rangle_{\rm ens}$ is calculable from consideration on the light cones (i.e. bubbles)



# EXTREMELY STRONG TRANSITIONS



- Result (just for completeness)

GW energy fraction
per each log. wavenumber

$$\Omega_{\rm GW}(k) = \Omega_{\rm GW}^{(s)}(k) + \Omega_{\rm GW}^{(d)}(k)$$

spherical Bessel of order 0 — of order 1 — of order 2

$$\Omega_{\rm GW}^{(s)} \propto k^3 \int_{-\infty}^{\infty} dt \int_{|t|}^{\infty} dr \; \frac{e^{-\beta r/2}}{e^{\beta t/2} + e^{-\beta t/2} + \frac{\beta^2 t^2 - (\beta^2 r^2 + 4\beta r)}{4\beta r} e^{-\beta r/2}} \times \left[ j_0(kr) S_0(t,r) + \frac{j_1(kr)}{kr} S_1(t,r) + \frac{j_2(kr)}{k^2 r^2} S_2(t,r) \right] \cos(kt)$$

$$\Omega_{\rm GW}^{(d)} \propto k^3 \int_{-\infty}^{\infty} dt \int_{|t|}^{\infty} dr \; \frac{e^{-\beta r/2}}{\left[ e^{\beta t/2} + e^{-\beta t/2} + \frac{\beta^2 t^2 - (\beta^2 r^2 + 4\beta r)}{4\beta r} e^{-\beta r/2} \right]^2} \times \left[ \frac{j_2(kr)}{k^2 r^2} D(t,r) D(-t,r) \right] \cos(kt)$$

$$S_0(t,r) = \frac{2}{3} \frac{(\beta^2 t^2 - \beta^2 r^2)^2}{\beta^3 r^3} (\beta^2 r^2 + 6\beta r + 12) \qquad S_1(t,r) = \frac{2}{3} \frac{\beta^2 t^2 - \beta^2 r^2}{\beta^3 r^3} \left[ -\beta^2 t^2 (\beta^3 r^3 + 12\beta^2 r^2 + 60\beta r + 120) + \beta^2 r^2 (\beta^3 r^3 + 4\beta^2 r^2 + 12\beta r + 24) \right]$$

$$S_2(t,r) = \frac{1}{6} \frac{1}{\beta^3 r^3} \left[ \beta^4 t^4 (\beta^4 r^4 + 20\beta^3 r^3 + 180\beta^2 r^2 + 840\beta r + 1680) - 2\beta^4 t^2 r^2 (\beta^4 r^4 + 12\beta^3 r^3 + 84\beta^2 r^2 + 360\beta r + 720) + \beta^4 r^4 (\beta^4 r^4 + 4\beta^3 r^3 + 20\beta^2 r^2 + 12\beta r + 24) \right]$$

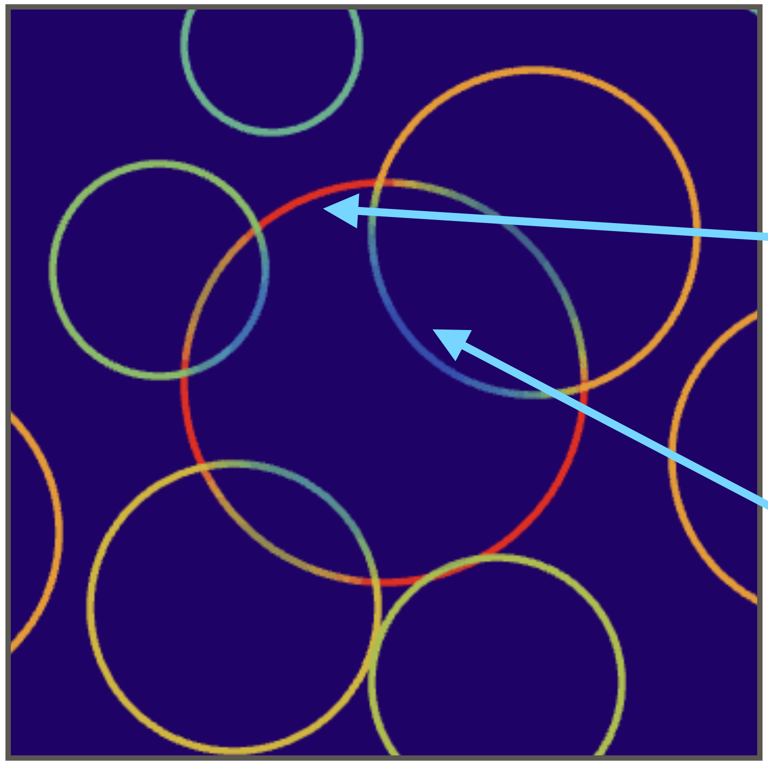
$$D(t,r) = \sqrt{\frac{\pi}{3}} \frac{\beta^2 t^2 - \beta^2 r^2}{\beta^2 r^2} \left[ \beta t (\beta^2 r^2 + 6\beta r + 12) + (\beta^3 r^3 + 2\beta^2 r^2) \right]$$

# EXTREMELY STRONG TRANSITIONS



- We further improved the modelling to better describe the system

[ Jinno, Takimoto '17 ]



Before collision

$$T_{ij} \text{ grows like } \propto \frac{\text{(released energy)}}{\text{(surface area)}} \propto \text{(radius)}$$

After collision [ Jinno, Konstandin, Takimoto '18 ]

$$T_{ij} \text{ decreases like } \propto \frac{1}{\text{(surface area)}} \propto \text{(radius)}^{-2}$$

- ... and solved it

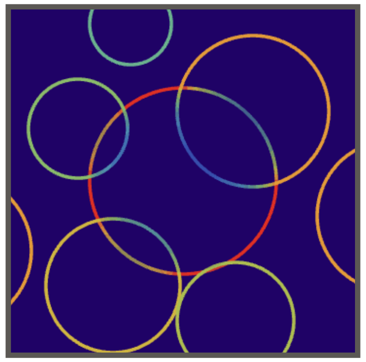
$$\Omega_{\rm GW}(k) = \Omega_{\rm GW}^{(s)}(k) + \Omega_{\rm GW}^{(d)}(k)$$

$$\Delta^{(s)} = \int_{-\infty}^{\infty} dt_x \int_{-\infty}^{\infty} dt_y \int_{v|t_{x,y}|}^{\infty} dr \int_{-\infty}^{t_{\rm max}} dt_n \int_{t_n}^{t_x} dt_{xi} \int_{t_n}^{t_y} dt_{yi}$$
$$\frac{k^3}{3} \left[ \begin{array}{l} e^{-I(x_i,y_i)}\, \Gamma(t_n)\, \dfrac{r}{r_{xn}^{(s)} r_{yn}^{(s)}} \\ \times \left[ j_0(kr)\mathcal{K}_0(n_{xn\times}, n_{yn\times}) + \dfrac{j_1(kr)}{kr}\mathcal{K}_1(n_{xn\times}, n_{yn\times}) + \dfrac{j_2(kr)}{(kr)^2}\mathcal{K}_2(n_{xn\times}, n_{yn\times}) \right] \\ \times\, \partial_{txi} \left[ r_B(t_{xi}, t_n)^3 D(t_x, t_{xi}) \right] \partial_{tyi} \left[ r_B(t_{yi}, t_n)^3 D(t_y, t_{yi}) \right] \cos(k t_{x,y}) \end{array} \right]$$

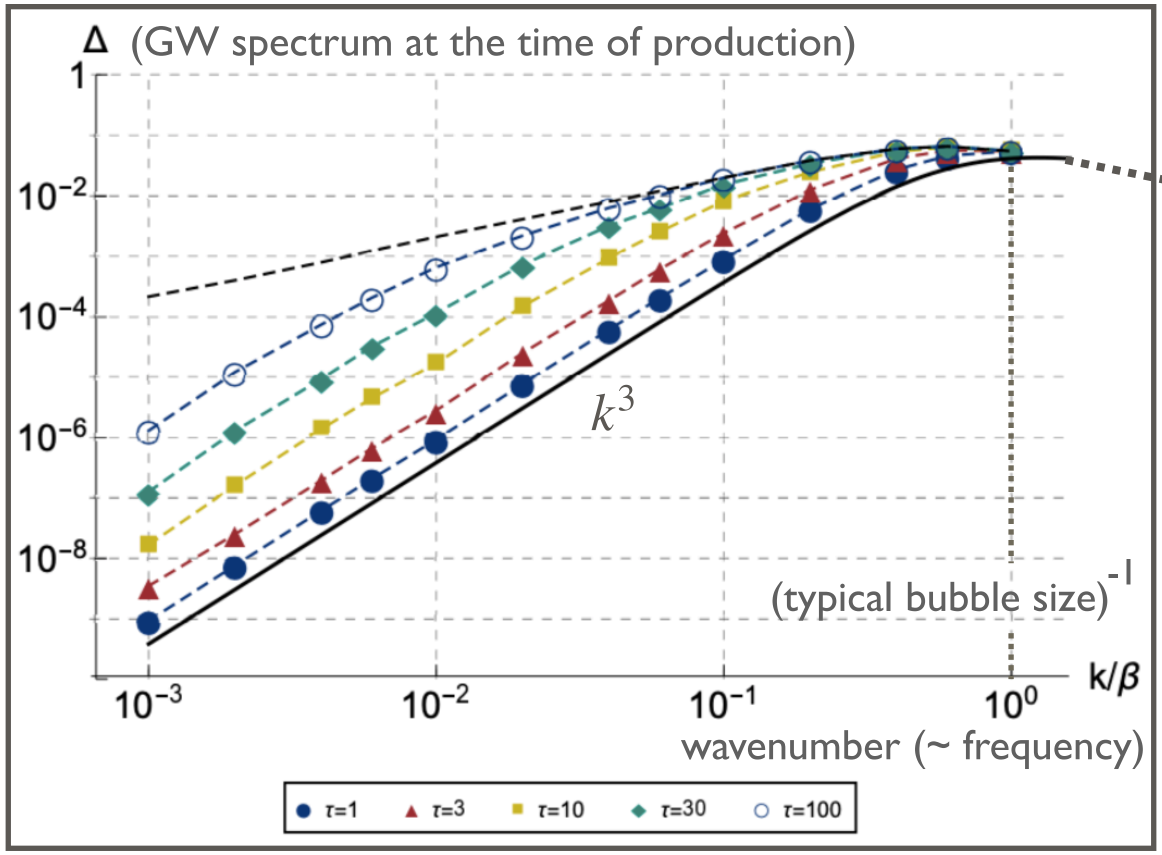
$$\Delta^{(d)} = \int_{-\infty}^{\infty} dt_x \int_{-\infty}^{\infty} dt_y$$
$$\int_0^{\infty} dr \int_{-\infty}^{t_x} dt_{xn} \int_{-\infty}^{t_y} dt_{yn} \int_{t_{xn}}^{t_x} dt_{xi} \int_{t_{yn}}^{t_y} dt_{yi} \int_{-1}^{1} dc_{xn} \int_{-1}^{1} dc_{yn} \int_0^{2\pi} d\phi_{xn,yn}$$
$$\frac{k^3}{3} \left[ \begin{array}{l} \Theta_{\rm sp}(x_i, y_n)\Theta_{\rm sp}(x_n, y_i) e^{-I(x_i,y_i)} \Gamma(t_{xn})\Gamma(t_{yn}) \\ \times\, r^2 \left[ j_0(kr)\mathcal{K}_0(n_{xn}, n_{yn}) + \dfrac{j_1(kr)}{kr}\mathcal{K}_1(n_{xn}, n_{yn}) + \dfrac{j_2(kr)}{(kr)^2}\mathcal{K}_2(n_{xn}, n_{yn}) \right] \\ \times\, \partial_{txi} \left[ r_B(t_{xi}, t_{xn})^3 D(t_x, t_{xi}) \right] \partial_{tyi} \left[ r_B(t_{yi}, t_{yn})^3 D(t_y, t_{yi}) \right] \cos(k t_{x,y}) \end{array} \right]$$

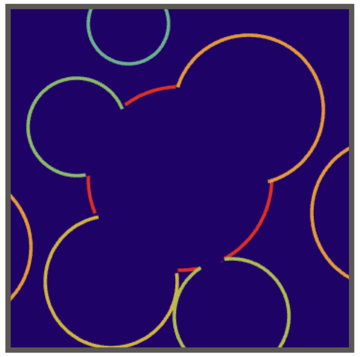
# EXTREMELY STRONG TRANSITIONS


- We pointed out a possible IR enhancement of the GW spectrum



Beyond Envelope



Envelope

→ More chance to detect the signal

More chance to distinguish between particle models

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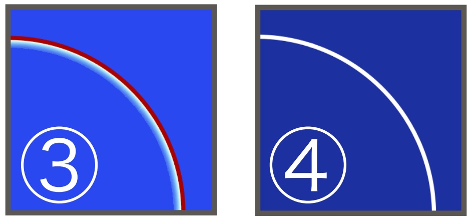
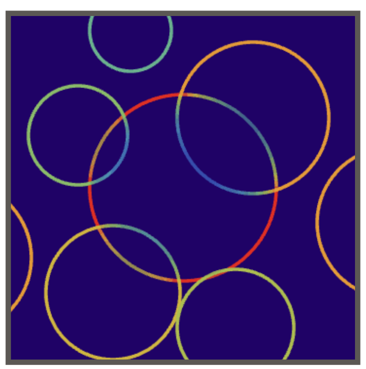



- We pointed out a possible IR enhancement of the GW spectrum



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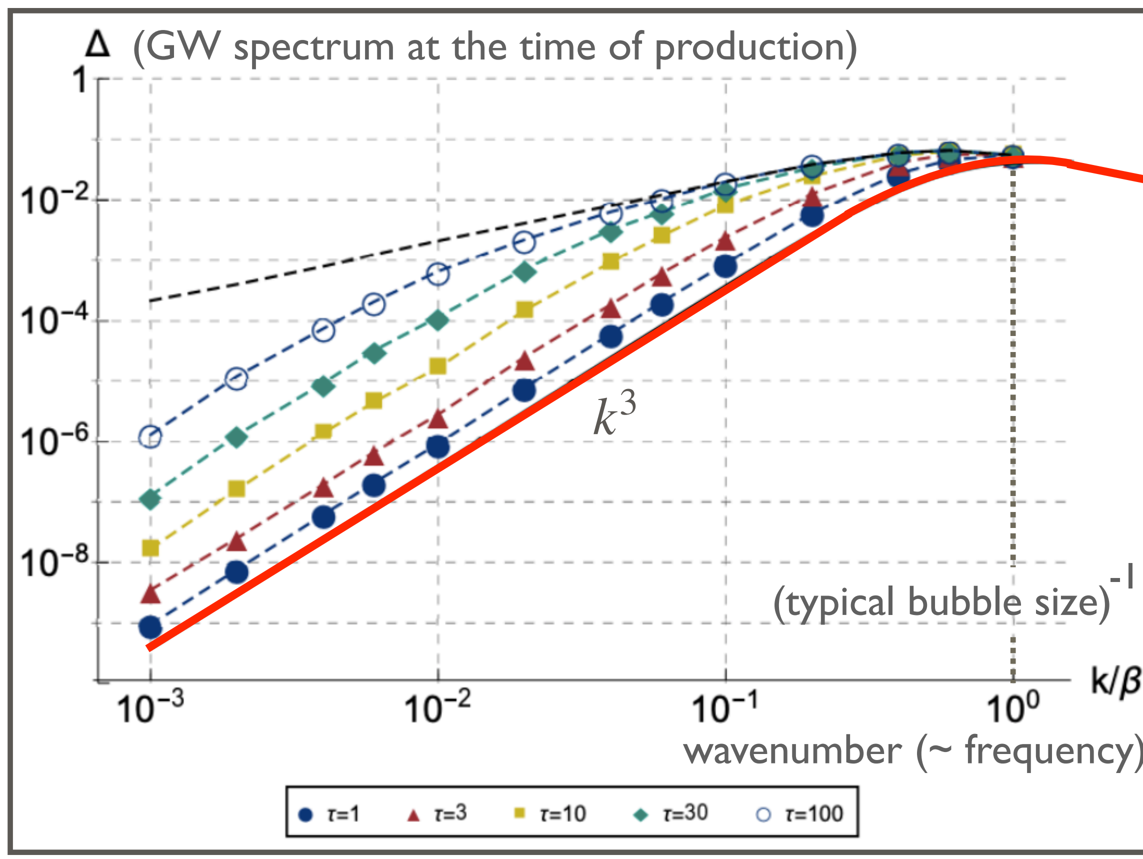
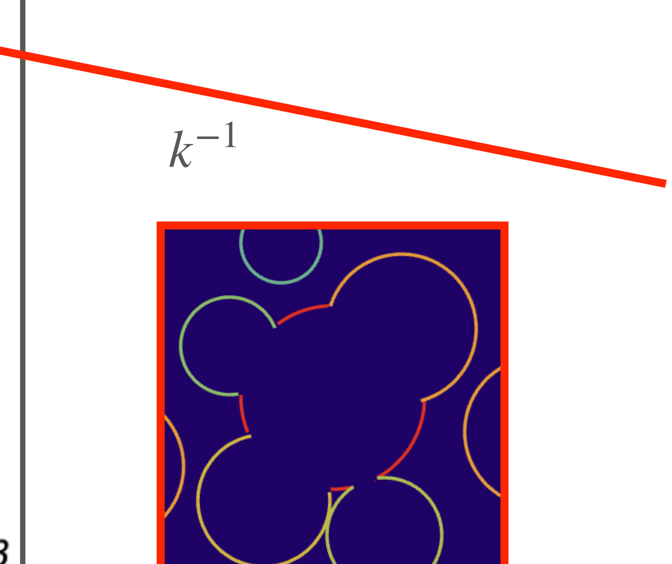


Envelope

More chance to detect the signal

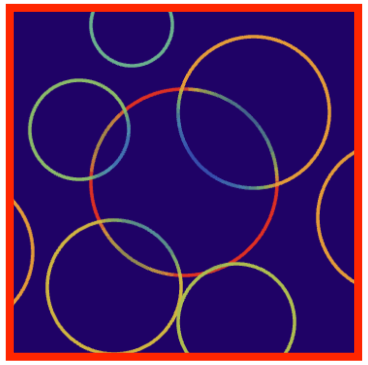
→

More chance to distinguish between particle models

# EXTREMELY STRONG TRANSITIONS



- We pointed out a possible IR enhancement of the GW spectrum



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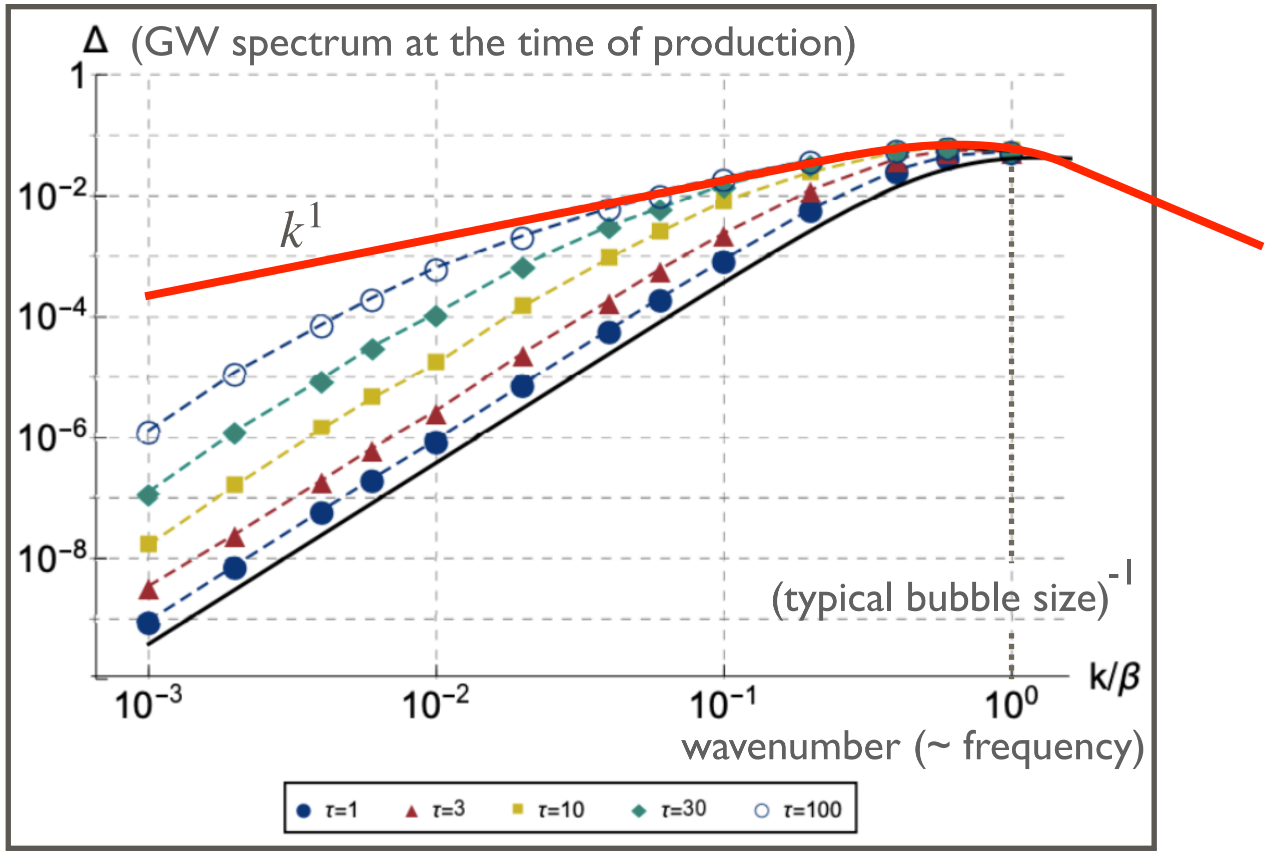


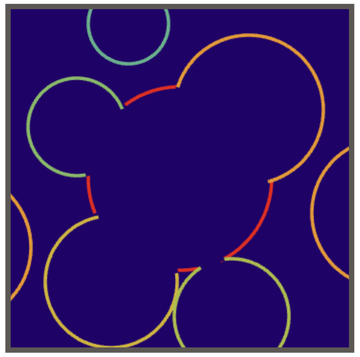

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- Intro
- First-order phase transitions & GWs: more on bubble dynamics
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  - extremely strong transitions
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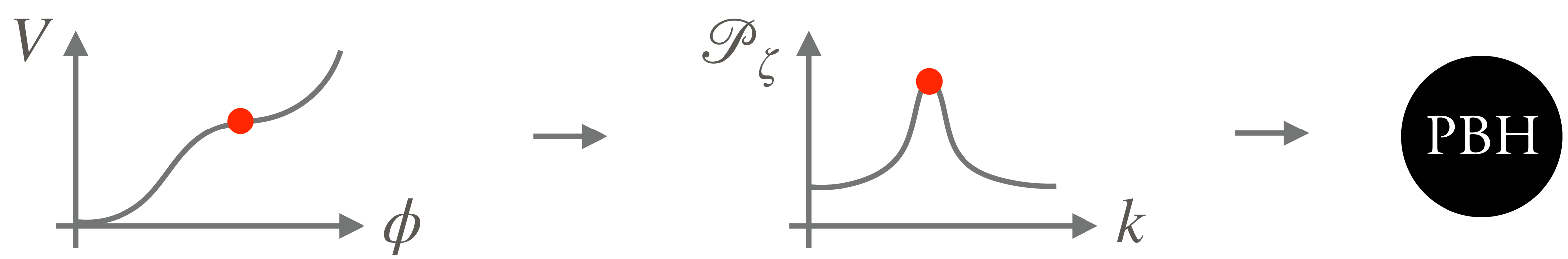
# IMPRINT OF NEW PHYSICS ON GWS

- PBH scenario: Dark matter = Primordial black holes (PBHs)?
- PBHs are produced from an enhanced curvature perturbation from inflation




If confirmed, it would be a breakthrough,
telling us about the structure of the inflaton potential

- Even if DM≠PBH, the curvature pert'n might be enhanced at some scales

Our question: how can we detect large curvature perturbation?

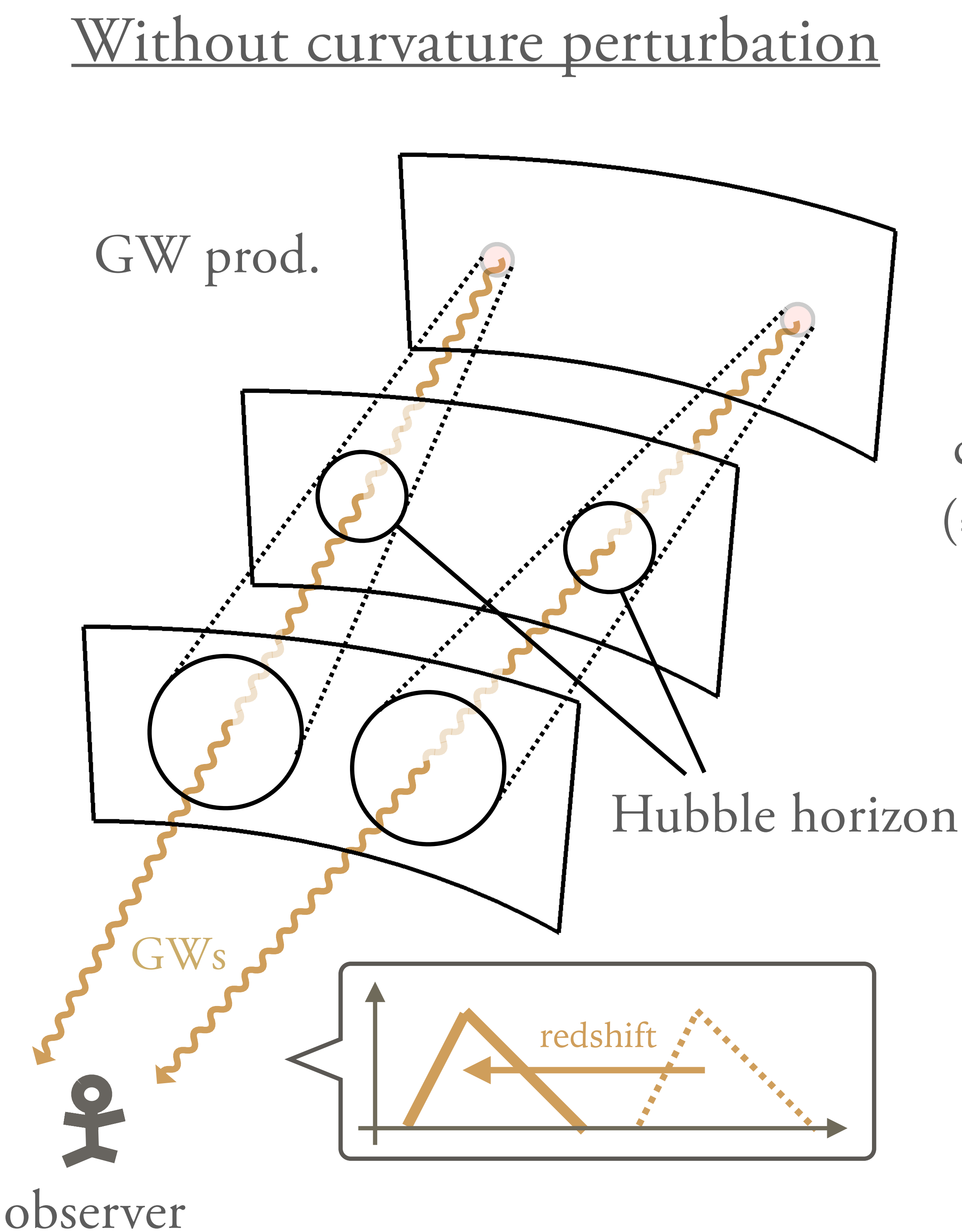
We can use CMB-like effect on GWs

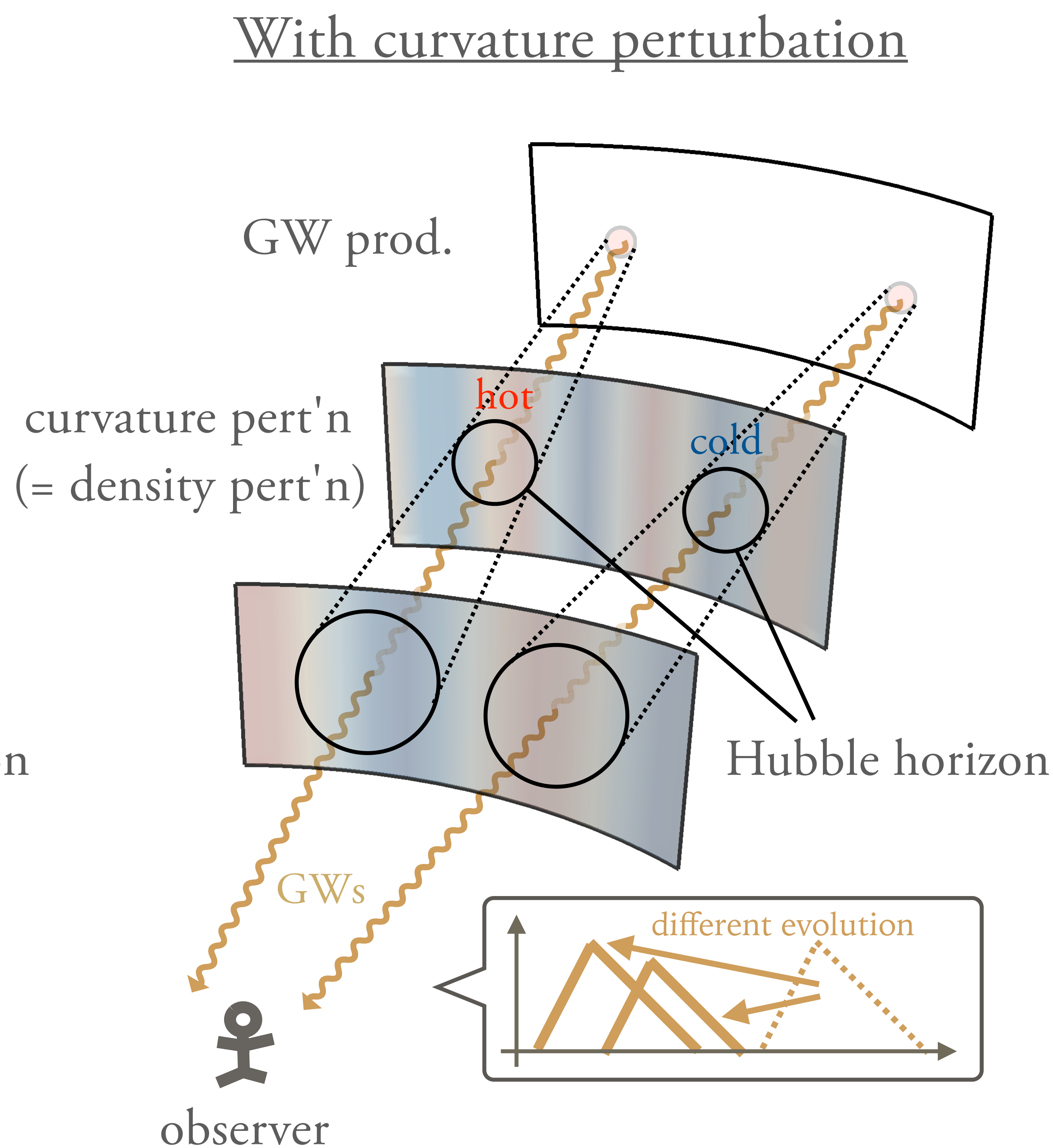
[ Domcke, <u>Jinno</u>, Rubira '20 ]

[ V. Domcke ]

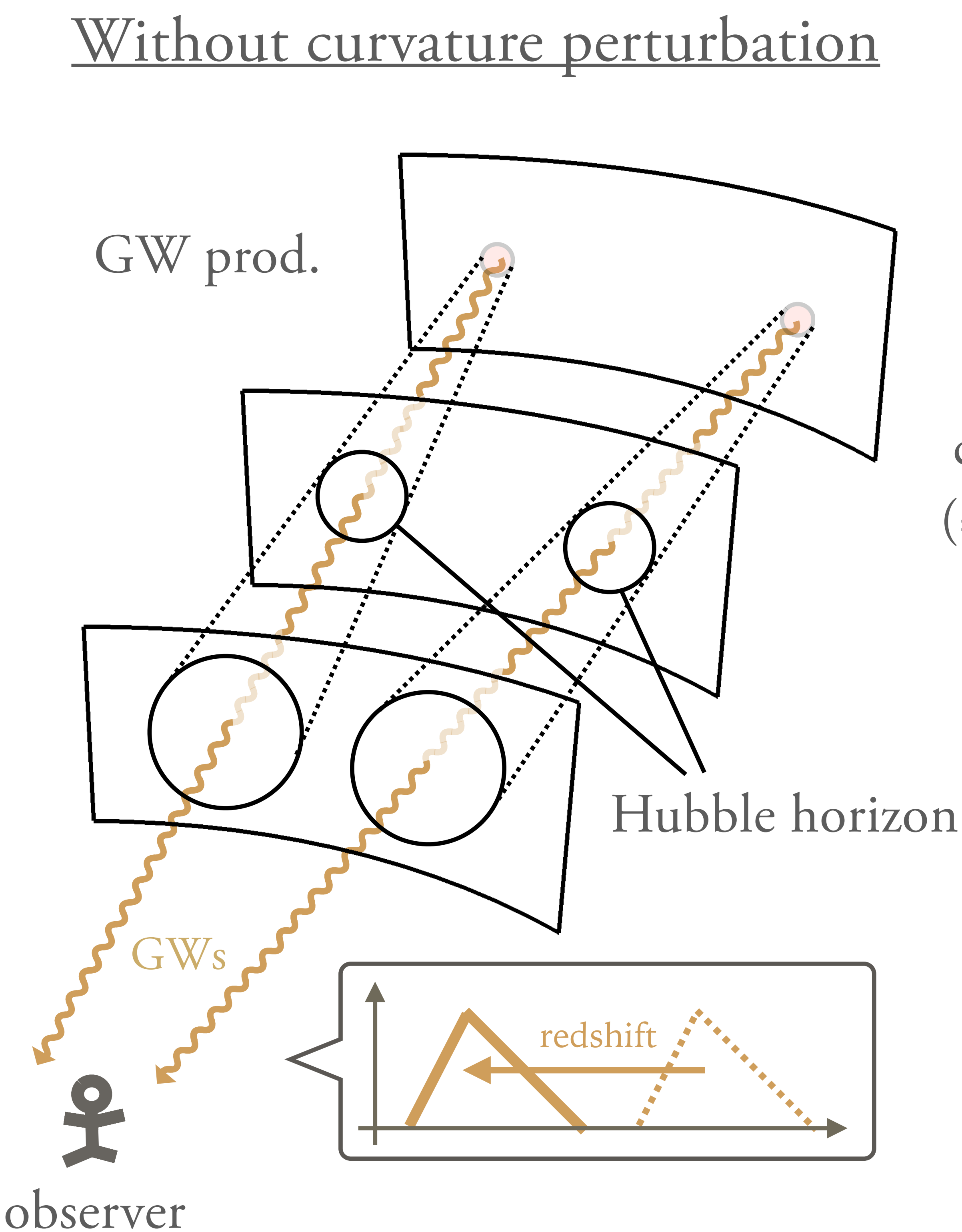
[ H. Rubira ]

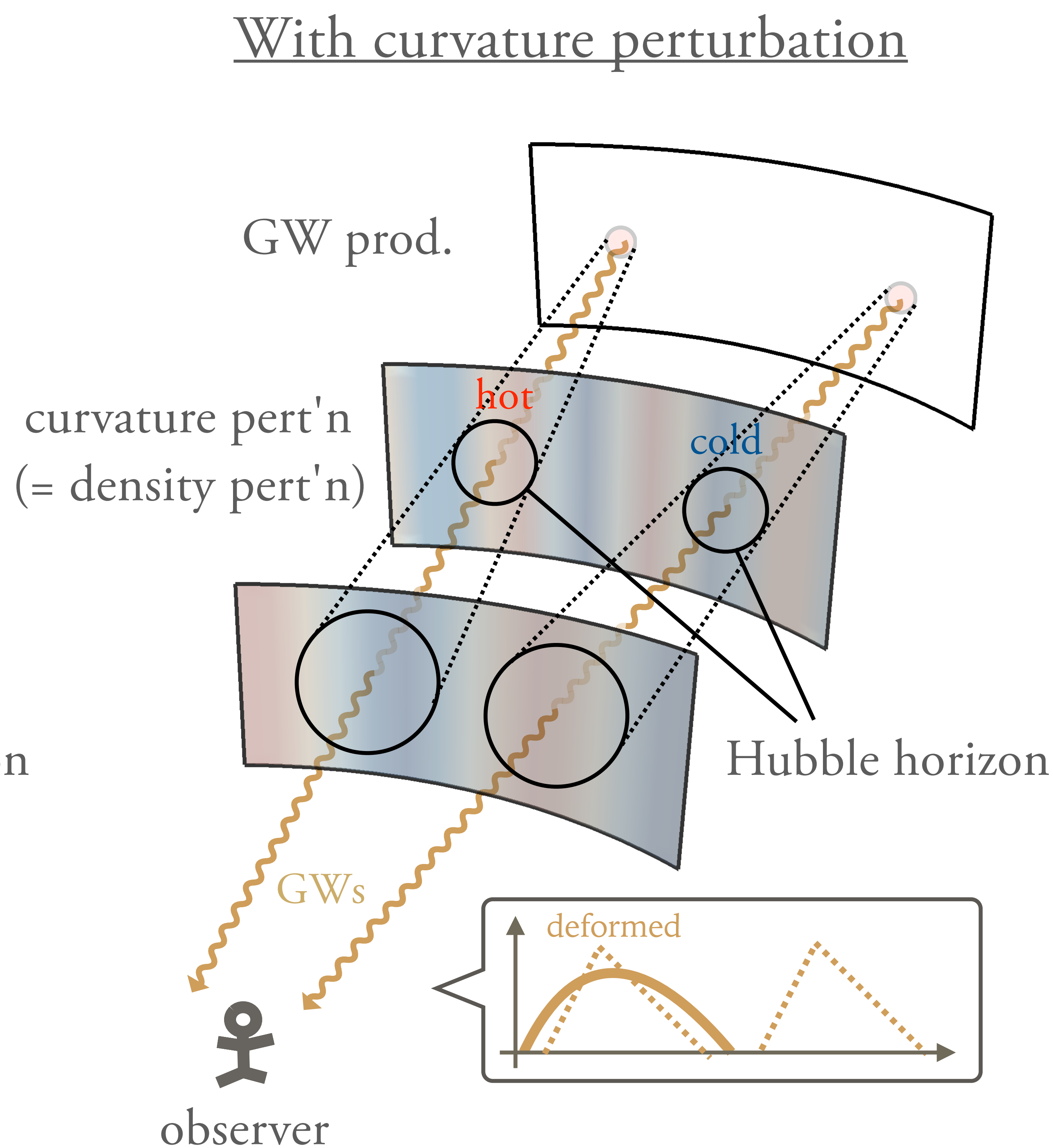
# CMB-LIKE EFFECTS IN A NUTSHELL



# CMB-LIKE EFFECTS IN A NUTSHELL



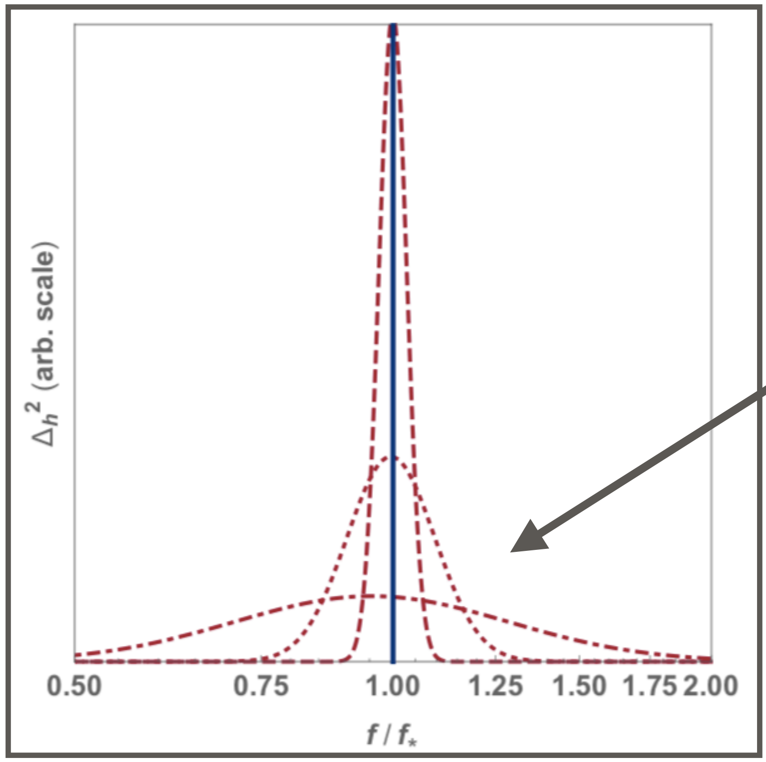
# DEFORMATION OF THE GW SPECTRUM

- We proposed a 'kernel-convolution' method and reported numerical results

$$\Delta_h^{2,(\mathrm{o})}(\ln f) \simeq \int d\ln f' \; \Delta_h^{2,(\mathrm{s})}(\ln f')\, K(f, f')$$

GW spectrum @ observer — GW spectrum @ sourcing — Kernel

- Result (blue = @sourcing, red = @observer)

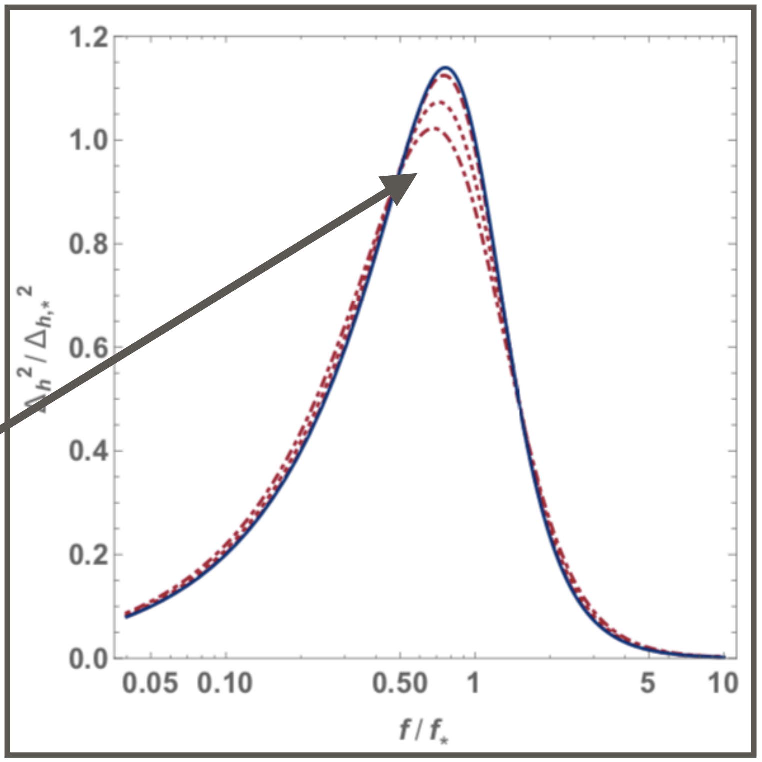



curvature pert'n

$$\int d\ln k\, \Delta^2_{\mathcal{R}}$$

$10^{-3}, 10^{-2}, 10^{-1}$

$0.01, 0.05, 0.1$



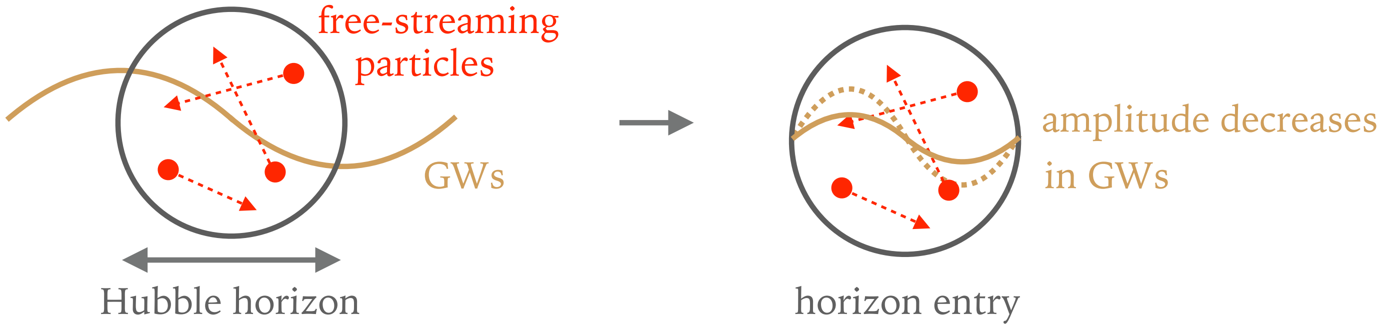
# IMPRINT OF NEW PHYSICS ON GWS (CONT'D)

➤ Free-streaming species contribute to the anisotropic stress in $T_{ij}$

e.g. SM neutrinos

➤ The anisotropic stress affects the evolution of pre-existing GWs [ Weinberg '03 ]

sketch:




[ T. Moroi ]

➤ Our idea: saxion (SUSY partner of axion) decaying into axion in the early Universe should have a similar effect on GWs

- We generalized [ Weinberg '03 ] to the cases in which free-streaming particles are produced at an intermediate stage of the cosmic history [ Jinno, Moroi, Nakayama '12 ]

- Evolution equation derived:

K : spherical Bessels

$$\ddot{h}_{ij}(t) + 3H\dot{h}_{ij}(t) + \frac{k^2}{a^2}h_{ij}(t) = -\frac{24H^2}{a^4\rho_{\rm tot}}\int_0^t dt'\ a(t')^4\rho_X(t')\ K\left(k\int_{t'}^t \frac{dt''}{a(t'')}\right)\ \dot{h}_{ij}(t')$$

X : free-streaming particle

# IMPRINT OF NEW PHYSICS ON GWS (CONT'D)

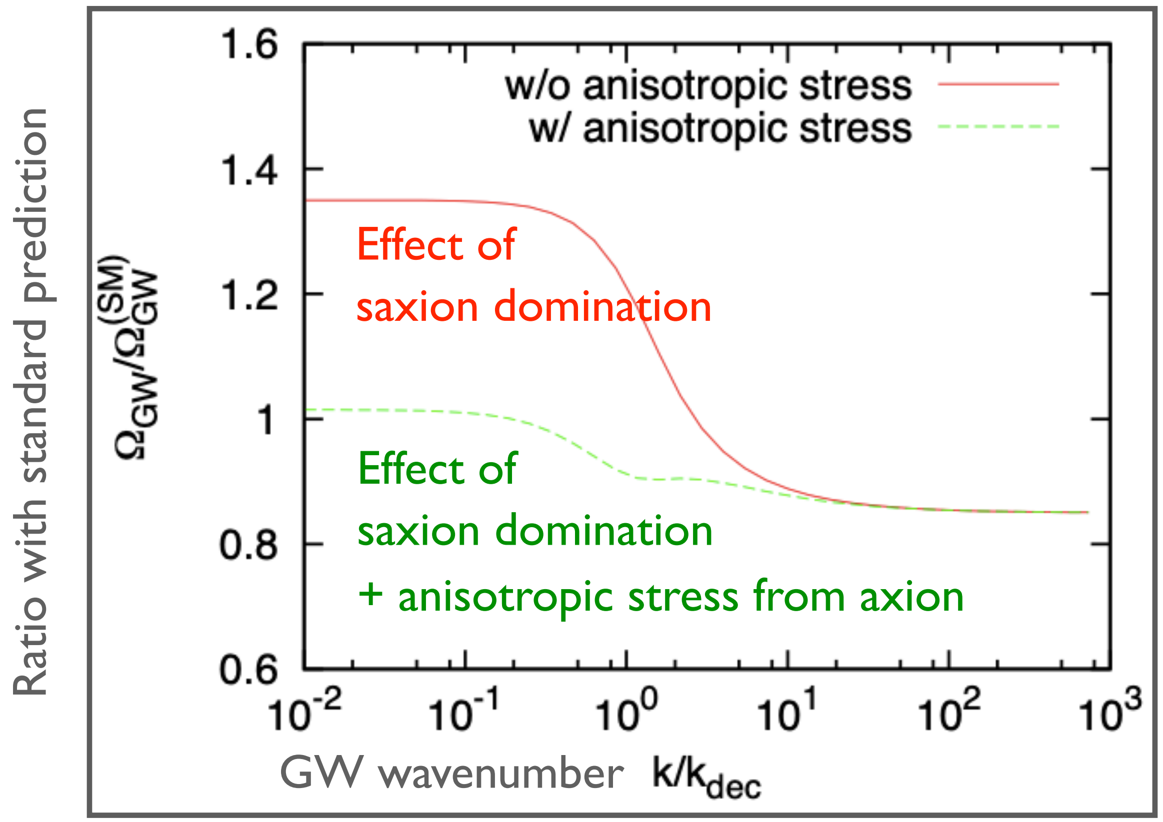
- Setup $\phi$ : saxion (mother particle) $\longrightarrow$ $X$ : axion (free-streaming particle)

  branching ratio $B_X$

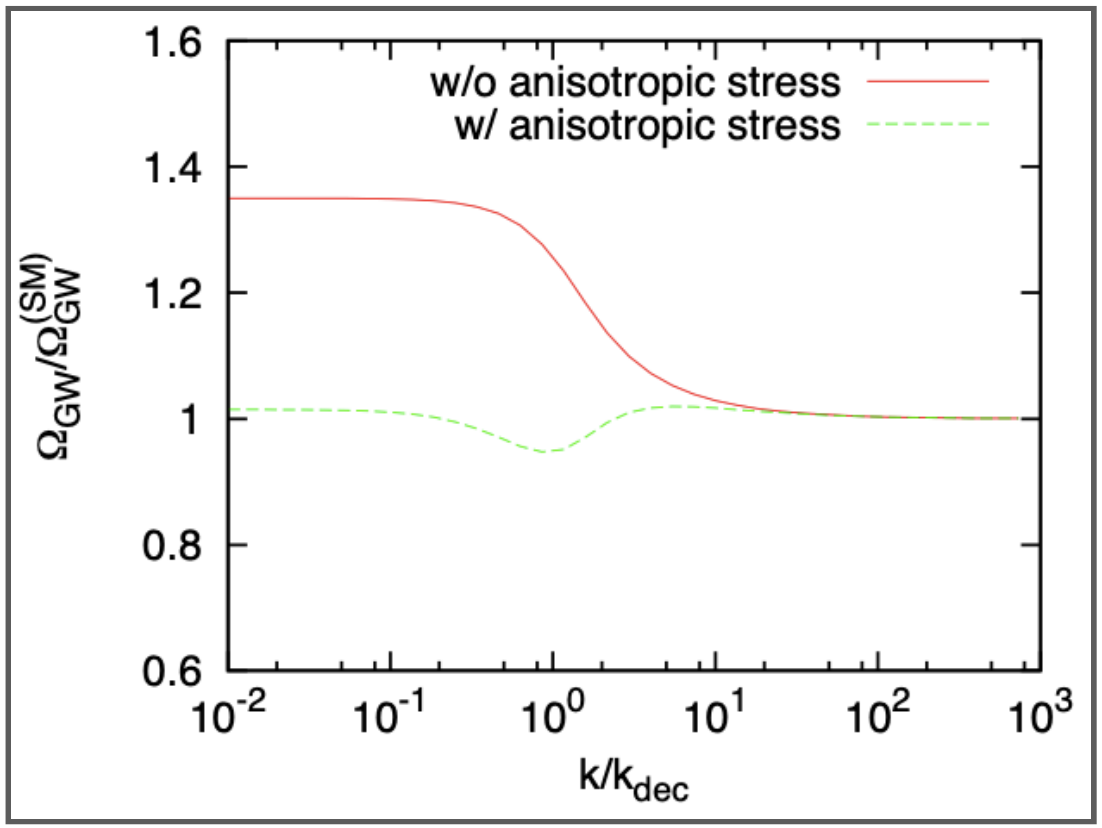
  We set $\Delta N_{\rm eff} = 1$, motivated from CMB observations at that time

- Result

[ Jinno, Moroi, Nakayama '12 ]




Branching ratio $B_X = 0.7$




Branching ratio $B_X = 1.0$

*Summary*

*New physics & GWs*

*Research Overview*

*Self Introduction*

# SUMMARY

- New physics searches will become more and more interesting with the synergy between high-energy experiments and GWs

- I'm ready to collaborate with you

# Backup

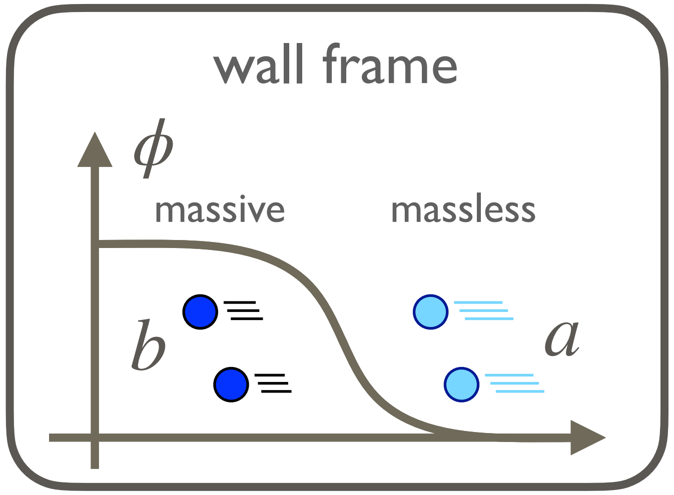
# SOFT&COLLINEAR EFFECT IN FOPT

- How the friction depends on the wall velocity? (i.e. wall relativistic factor $\gamma_w$ )

  This changes phenomenology a lot!

Traditional result

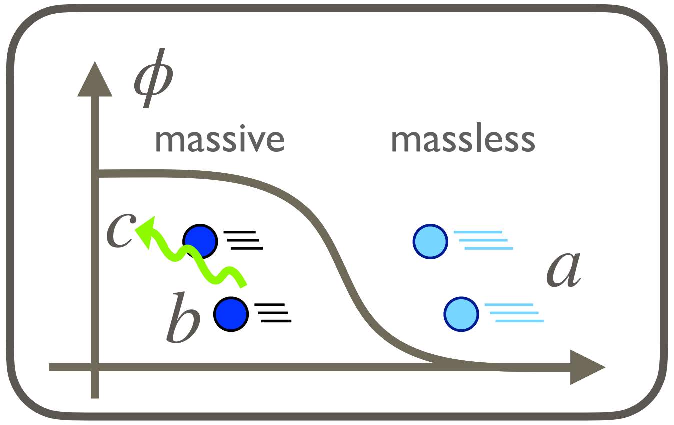
[ Bodeker & Moore '09 ] $\propto \gamma_w^0$




[ Bodeker & Moore '17 ] $\propto \gamma_w^1 m_c T^3$

with c being semi-soft emission

$m_c \ll k_{c,z} \ll \gamma_w T$




[ Höche, Long, Turner, Wang '20 ] $\propto \gamma_w^2 T^4$

after resumming the IR log to all orders

(comment by RJ: their main contribution does not seem to come from far IR)

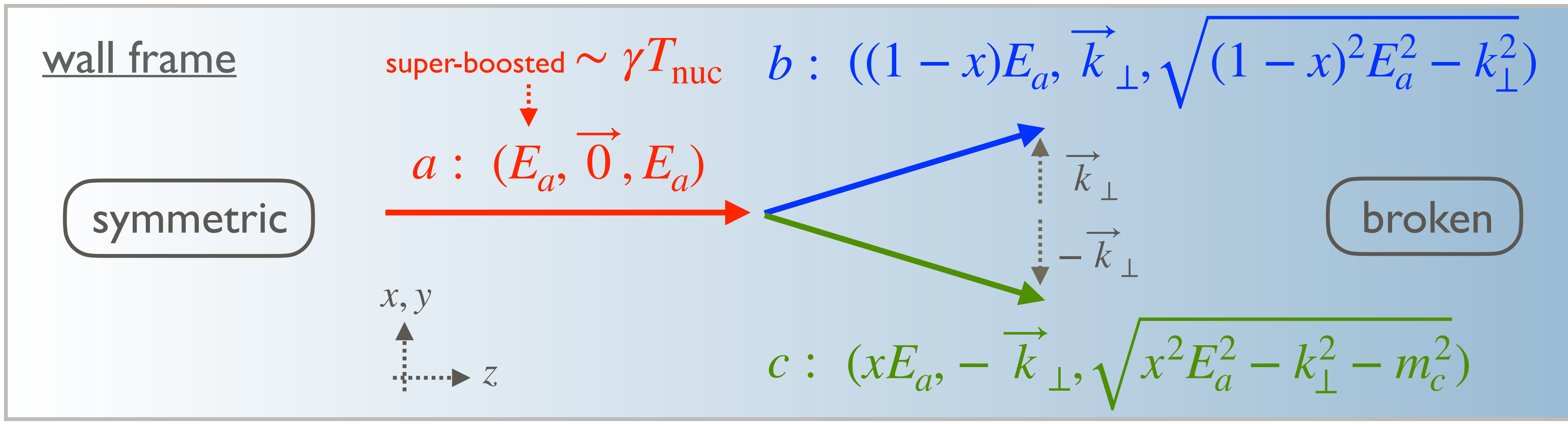
[ Azatov, Vanvlasselaer '20 ] criticizing [ HLTW '20 ]

Main point: it's weird that the friction does not vanish in $m_c \to 0$ limit

since this is the limit where c does not feel the effect of the scalar field

# SOFT&COLLINEAR EFFECT IN FOPT

- The relevant process: Particle $a$ hits the wall → splits into $b$ and $c$




- Assumptions
  - $a$ & $b$ : same species, massless in both phases
  - $c$ (gauge boson) : gets a mass $m_c$ across the wall

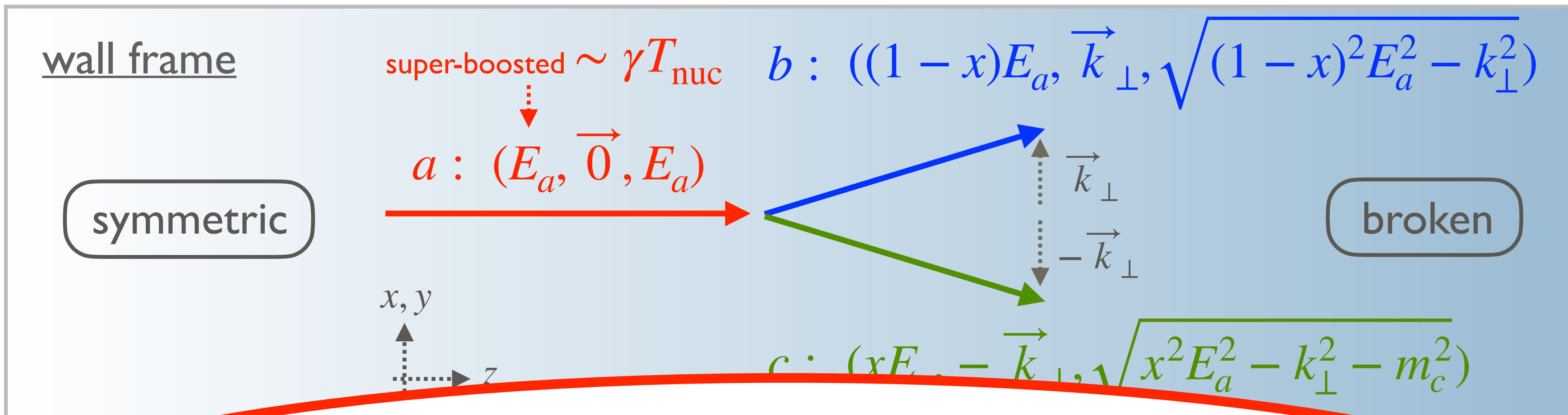
- The differential splitting probability can be calcualted from the matrix element

$$dP_{a\to bc} = \frac{d^2k_\perp}{(2\pi)^2}\frac{dE_c}{2\pi}\frac{1}{2p_{a,z}}\frac{1}{2p_{b,z}}\frac{1}{2p_{c,z}}|\mathcal{M}|^2 \quad \text{with} \quad \mathcal{M} = \int dz\ \text{vertex}(z) \times \chi_a(z)\,\chi_b^*(z)\,\chi_c^*(z)$$

mode functions of a,b,c

# SOFT&COLLINEAR EFFECT IN FOPT

➤ The relevant process: Particle $a$ hits the wall → splits into $b$ and $c$




Note: This is the part which gives $\delta\left(\Sigma p_z\right)$ in 'usual' QFT calculations.

In the present case $z$-translation is broken, which results in the emission.

- The differential splitting probability can be calcualted from the matrix element

$$dP_{a\to bc} = \frac{d^2k_\perp}{(2\pi)^2}\frac{dE_c}{2\pi}\frac{1}{2p_{a,z}}\frac{1}{2p_{b,z}}\frac{1}{2p_{c,z}}|\mathcal{M}|^2 \quad \text{with} \quad \mathcal{M} = \int dz \; \text{vertex}(z) \times \chi_a(z)\,\chi_b^*(z)\,\chi_c^*(z)$$

mode functions of a,b,c

# SOFT&COLLINEAR EFFECT IN FOPT

- The soft & collinear divergence

  - The splitting prob. has soft & collinear divergence, as known in collider physics

$$|\,\text{vertex}\,|^2 = 4g^2 C_{abc} \frac{k_\perp^2}{x^2} \qquad \rightarrow \qquad dP_{a\to bc} \simeq \frac{g^2}{4\pi^2} \frac{dk_\perp^2}{k_\perp^2} \frac{dx}{x} \frac{k_\perp^4}{(k_\perp^2 + m_c^2)^2} \frac{m_c^4}{(k_\perp^2 + m_c^2)^2}$$

[ Altarelli & Parisi '77 ]

integration range $x \geq \sqrt{k_\perp^2 + \mu^2}$ & $k_\perp \geq \mu$

- IR cutoff $\mu$ ?

  - Practically, at least one IR cutoff from the thermal mass of the inpinging particles

$$\mu \sim g T_{\text{nuc}}$$

which we take to be the lower limit of the integration

# SOFT&COLLINEAR EFFECT IN FOPT

➤ Perturbativity breakdown

- As the transition gets stronger and as the gauge coupling gets larger, the (seeming) emission probability exceeds unity:

$$P_{a\to bc} \simeq \frac{g^2}{2\pi^2} C_{abc} \ln \frac{m_c}{\mu} \ln \frac{E_a}{m_c}$$

$\to$ signals the necessity of resummation

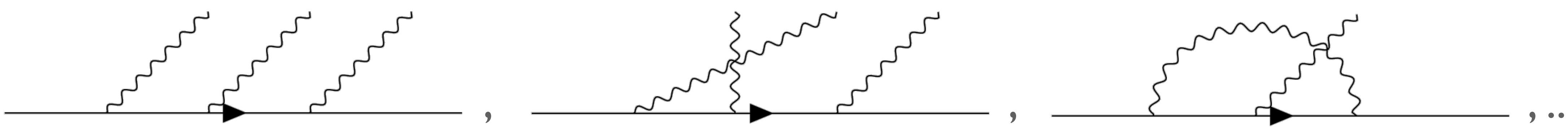
➤ Numerically...

| Emission probability $P_{a\to bc}$ at 1st order in $\alpha$ | $T_{\rm nuc} \sim 0.1\,\Phi$ | $T_{\rm nuc} \sim 10^{-3}\,\Phi$ | $T_{\rm nuc} \sim \Phi^{-6} f$ |
|---|---|---|---|
| $\alpha = 0.003$ | 0.01 | 0.2 | 0.8 |
| $\alpha = 0.03$ | 0.2 | $1.9 \gtrsim 1$ | $7.5 \gg 1$ |
| $\alpha = 0.3$ | $1.5 \gtrsim 1$ | $17 \gg 1$ | $70 \gg 1$ |

# SOFT&COLLINEAR EFFECT IN FOPT

- Sudakov resummation

  - Summation over processes with the largest logarithm at each order in pert'n theory



  - As a result, many-boson emission takes the form of Poisson distribution $P(n) = \frac{1}{n!}\lambda^n e^{-\lambda}$

$$\langle \mathcal{O} \rangle = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int dP_{a_i \to b_i c_i} \right] \mathcal{O} \, \exp\left[ - \int dP_{a \to bc} \right]$$

  - Interpretation: $\begin{cases} \frac{1}{n!}\prod dP & \text{comes from the leading-log real emissions} \\ \exp[\cdots] & \text{resums the leading-log virtual corrections} \end{cases}$

  - This splitting probability should and does satisfy unitarity: $\sum_n \frac{1}{n!}\lambda^n e^{-\lambda} = 1$

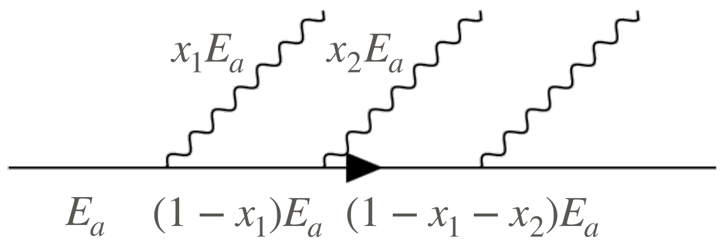
# SOFT&COLLINEAR EFFECT IN FOPT

➤ Monte-Carlo simulations

- We proceed both semi-analytically and numerically (Monte-Carlo)

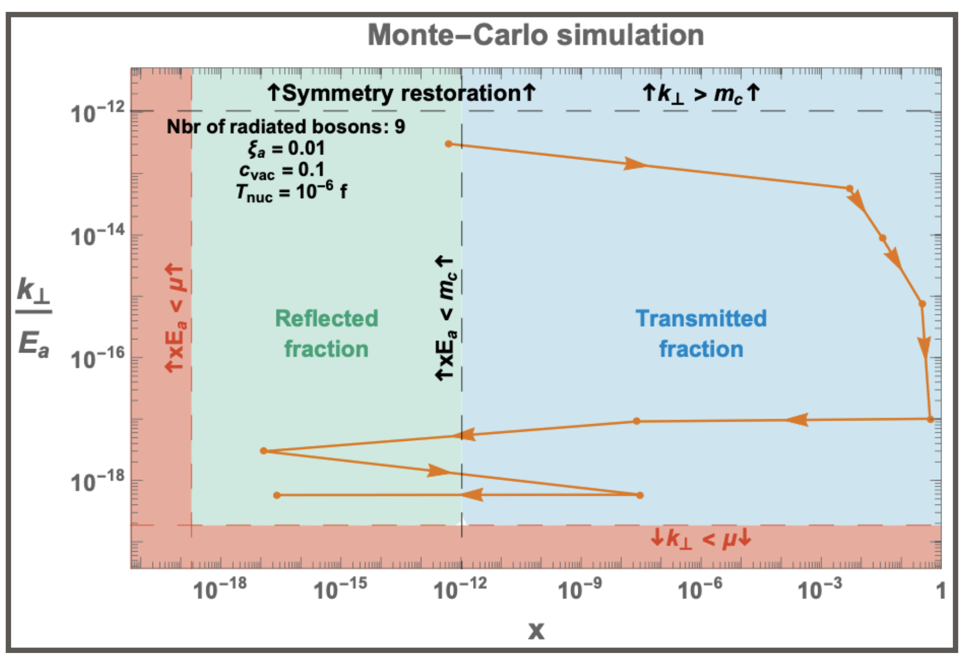
- Numerical evaluation is in order to take into account backreaction:

① $\sum_i x_i < 1$




② $k_{\perp,i} > \mu$

- Typical cascade:




$g \sim 0.6$

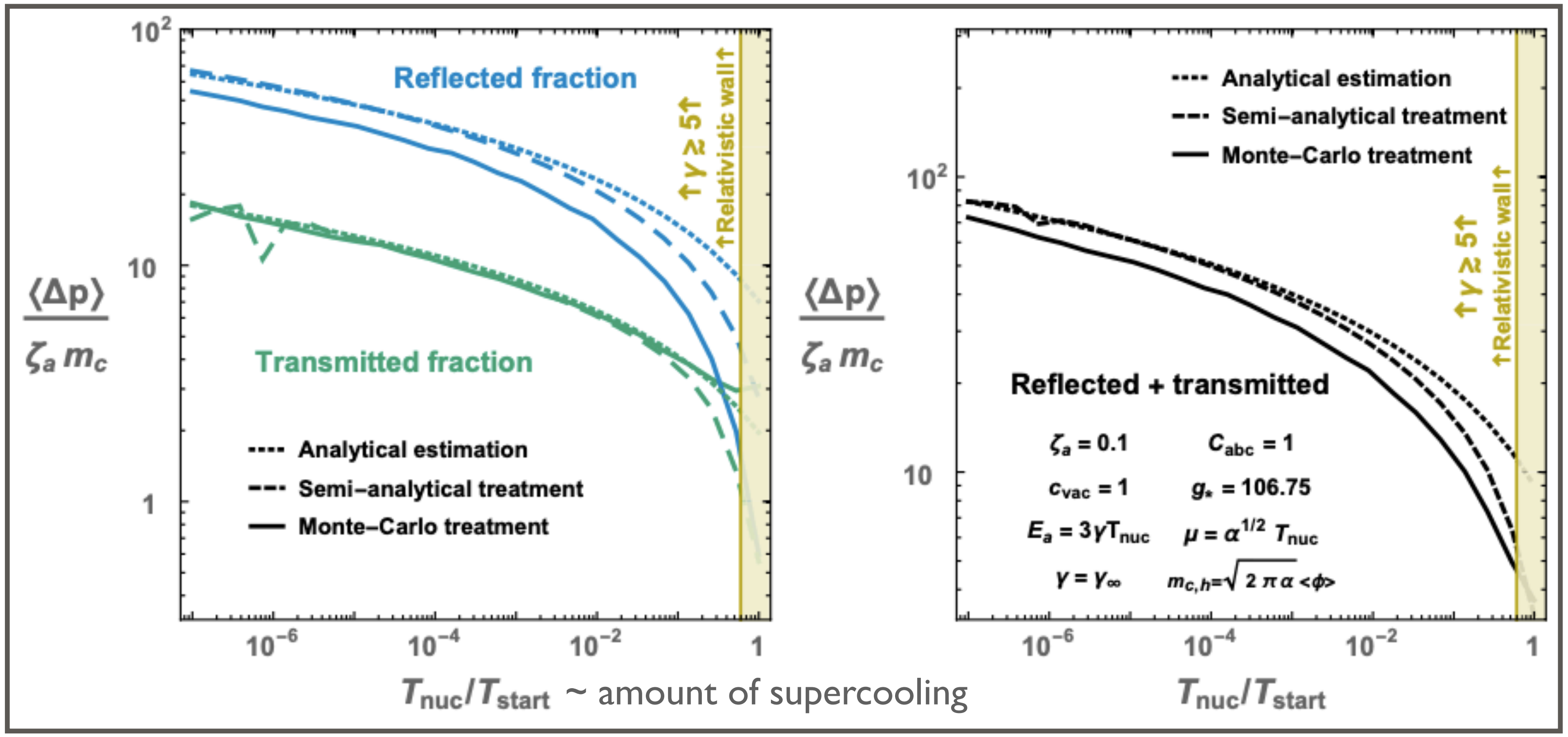
$m_c \sim g\Phi$

$m_c / E_a \sim 10^{-12}$

$T_{\text{nuc}} / \Phi \sim 10^{-6}$

# SOFT&COLLINEAR EFFECT IN FOPT

➤ Friction




$\langle \Delta p \rangle$ : average momentum transfer to the wall (in the wall frame)

$\mathscr{F} \sim \gamma T_{\rm nuc}^3 \times \langle \Delta p \rangle$ : friction to the wall

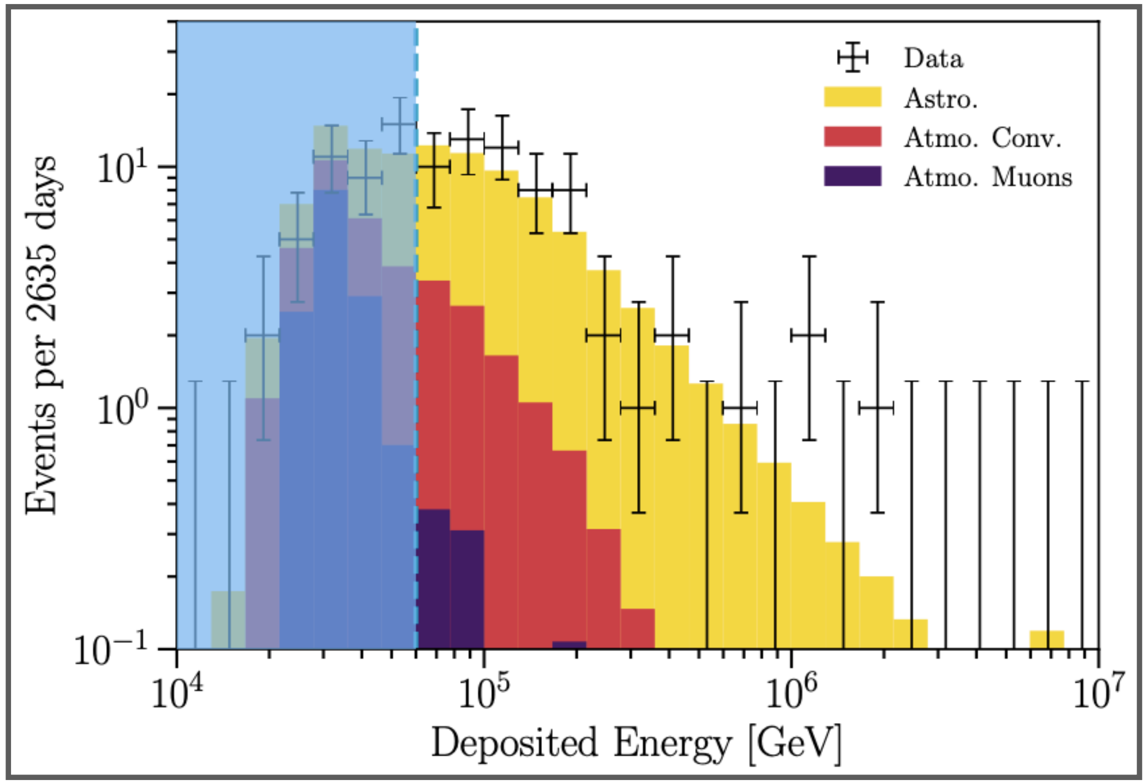
- $\langle \Delta p \rangle$ has no enhancement from the wall $\gamma$ factor $\rightarrow$ Friction is $\propto \gamma$

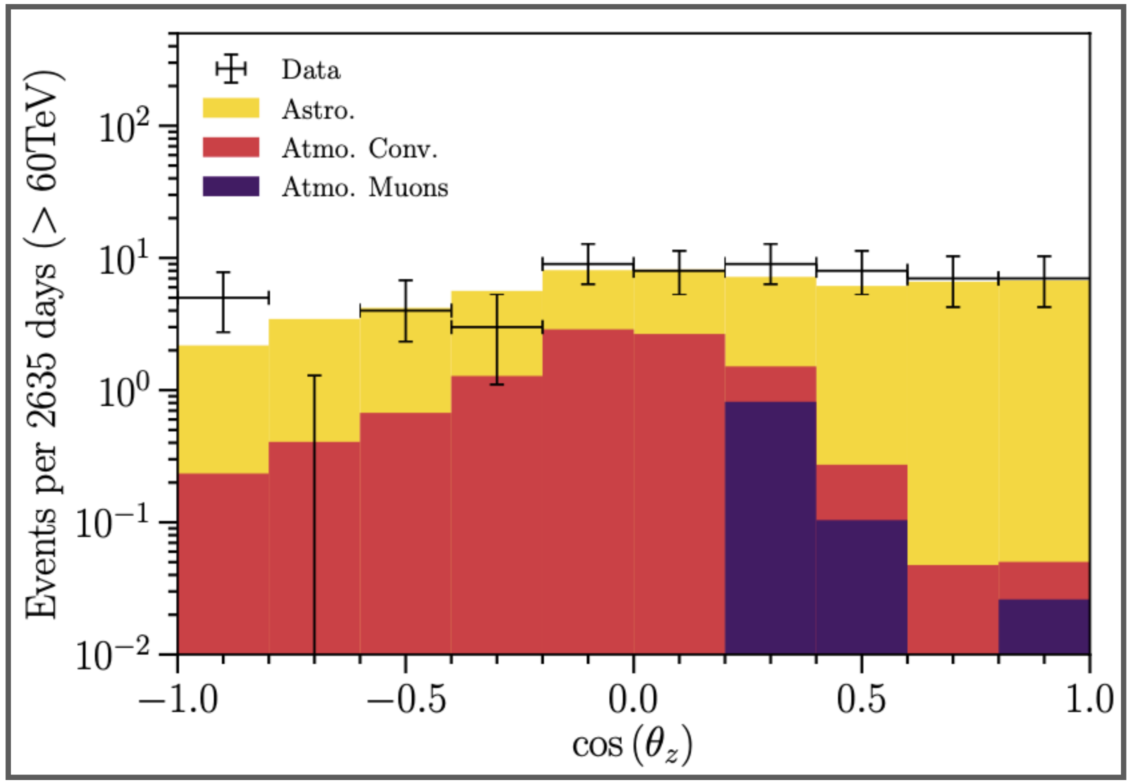
- Consideration on phase-space saturation may suppress the exponent of $\gamma$

[ Bodeker & Moore '17 ]

# ICECUBE NEUTRINOS & EARLY DECAY SCENARIO

➤ IceCube data (7.5yrs)

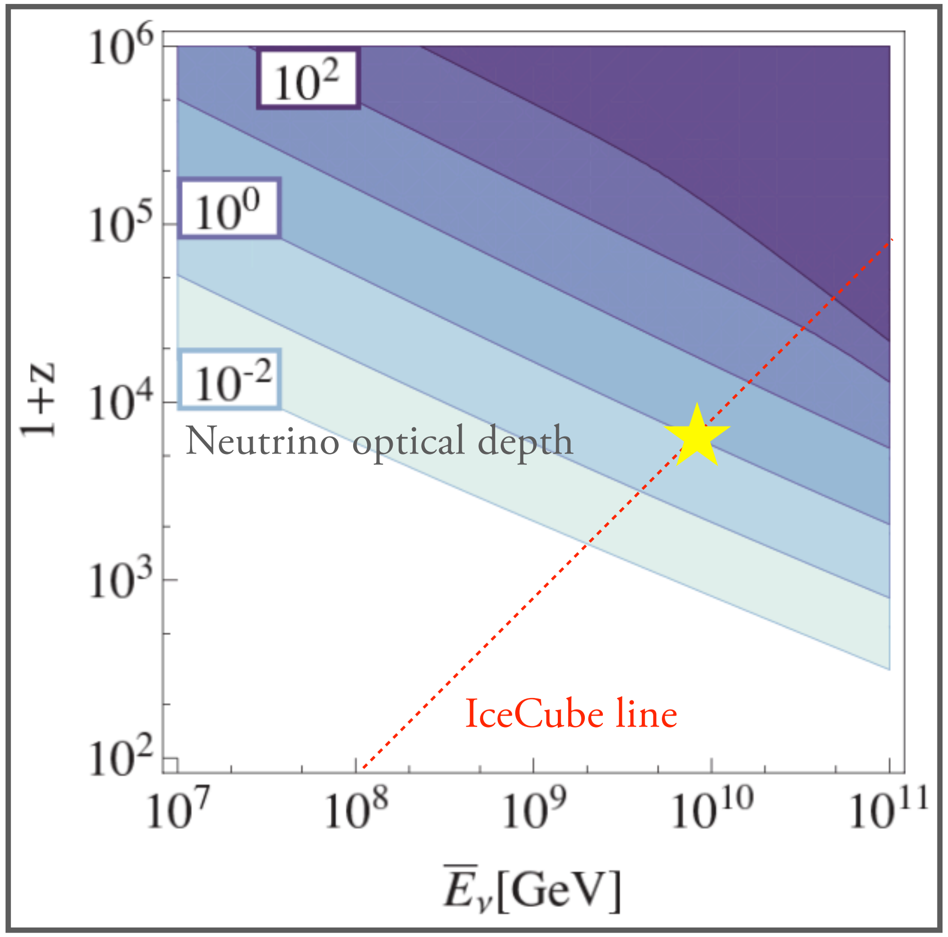


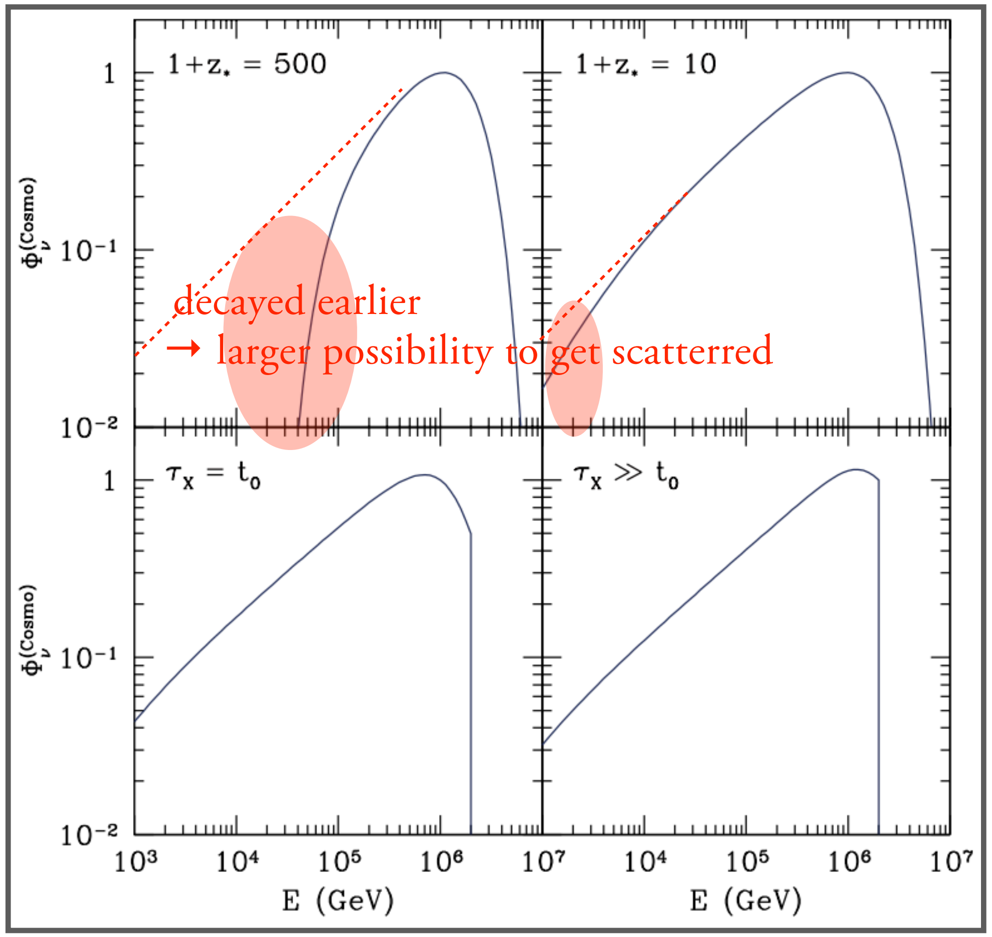




[ IceCube ]

# ICECUBE NEUTRINOS & EARLY DECAY SCENARIO

- Early decay scenario [ Ema, Jinno, Moroi '14 ]
  - Free parameters: $m_X, \quad \tau_X, \quad Y_X$
  - Monochromatic decay: $\delta(E - \bar{E}_\nu)$
  - Cosmological flux >> Galactic flux: $\Phi_\nu(t,E) = \Phi_\nu^{(\mathrm{Cosmo})}(t,E) + \Phi_\nu^{(\mathrm{Galaxy})}(t,E)$
  - Typical yield: $Y_X \simeq 1 \times 10^{-26} \times \bar{N}_\nu^{-1}$ to realize $\bar{\Phi}_{\nu,\mathrm{PeV}}^{(\mathrm{IceCube})} \simeq 3 \times 10^{-16}\ \mathrm{m}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{str}^{-1}\ \mathrm{GeV}^{-1}$



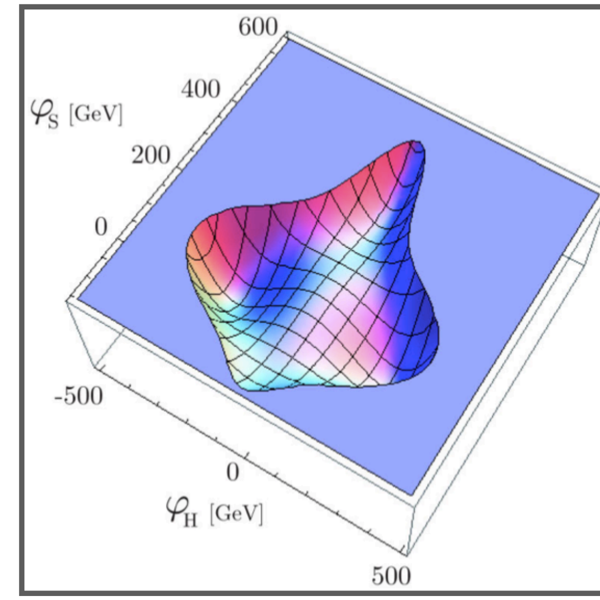



# FIRST-ORDER PHASE TRANSITION & LIKELIHOOD ANALYSIS

➤ Higgs-Singlet Model

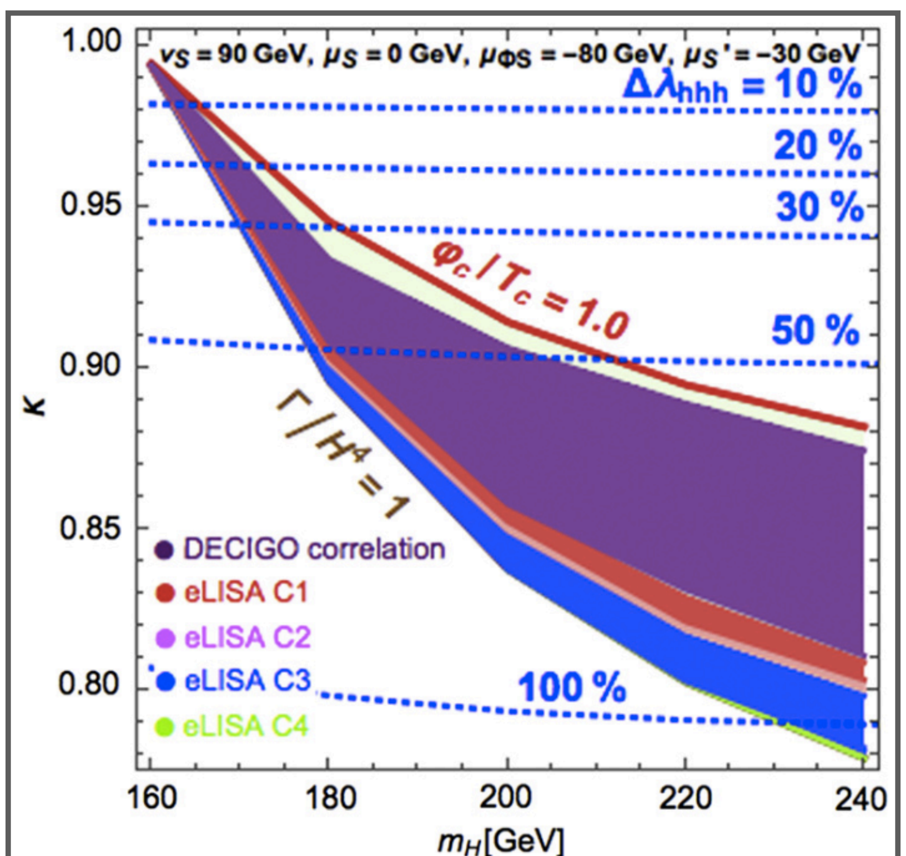
- Potential

$$V = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2$$
$$+\mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

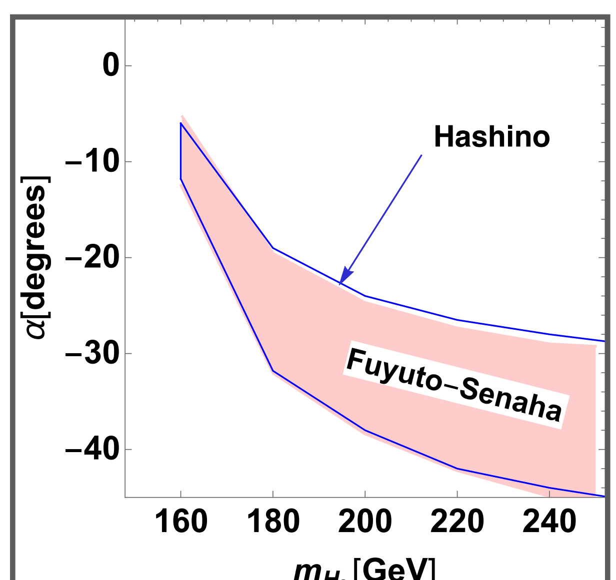



[ Fuyuto-Senaha '14 ]

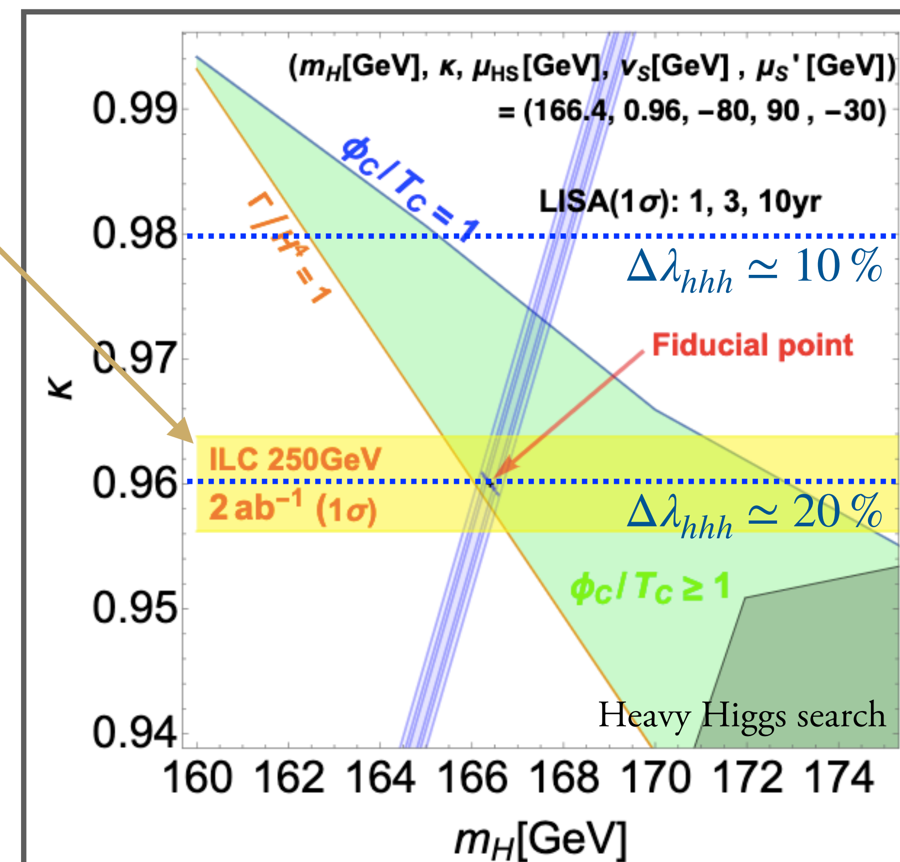
[ Hashino, Kakizaki, Kanemura, Ko, Matsui '16 ]



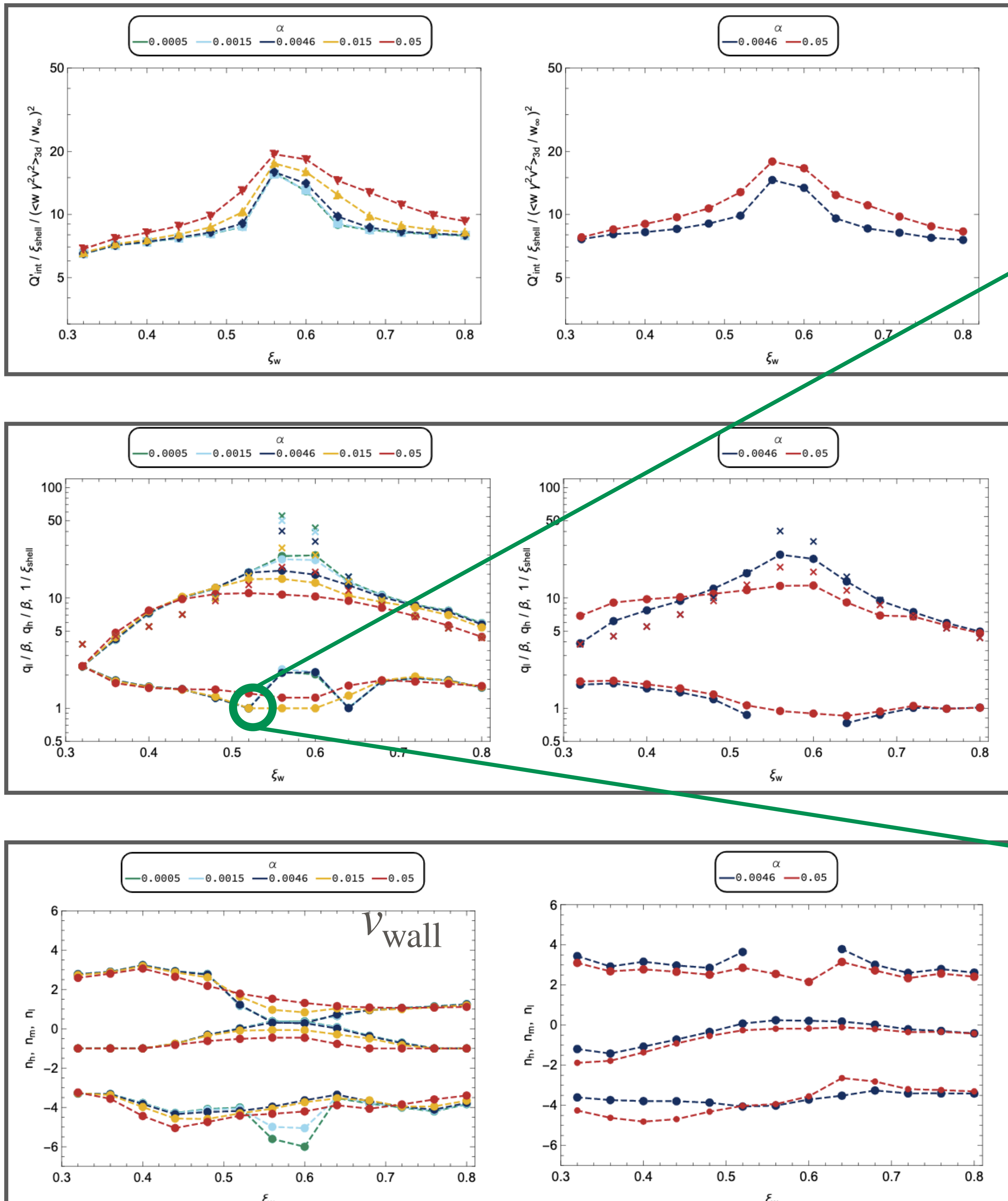

"Physics Case for the 250 GeV Stage of the International Linear Collider "
(~2% for HL-LHC [ 1307.7135 ])



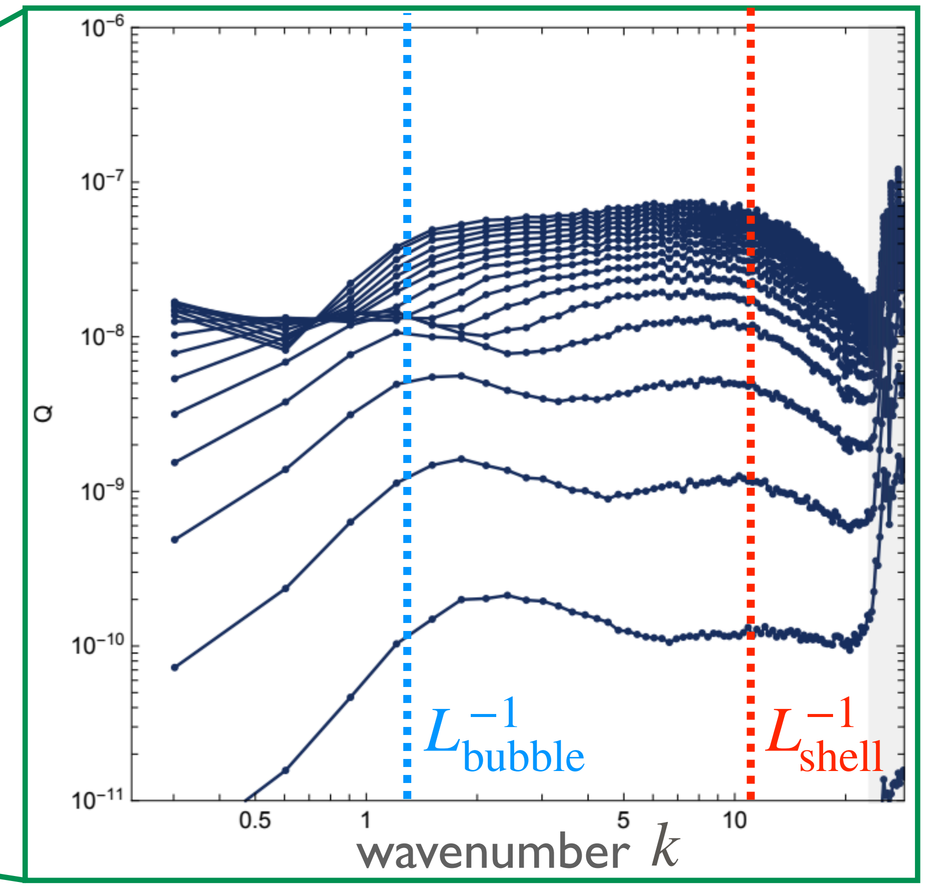

[ Hashino, Jinno, Kakizaki, Kanemura, Takahashi, Takimoto '18 ]



# MORE ON 3D SIMULATION

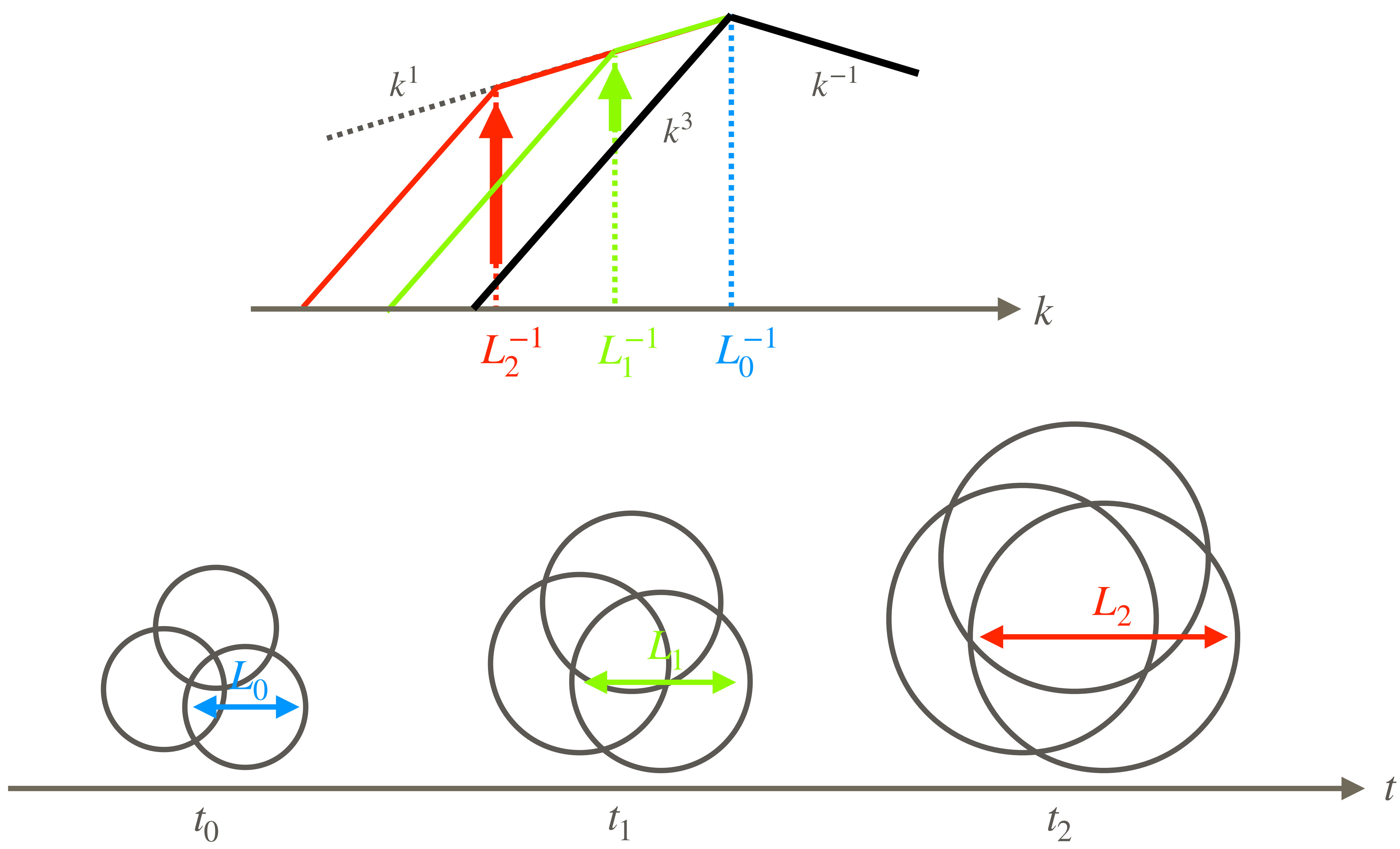



Each point corresponds to a big box simulation




[ Jinno, Konstandin, Rubira ’20 ]

# PHYSICAL INTERPRETATION OF THE SPECTRUM GROWTH

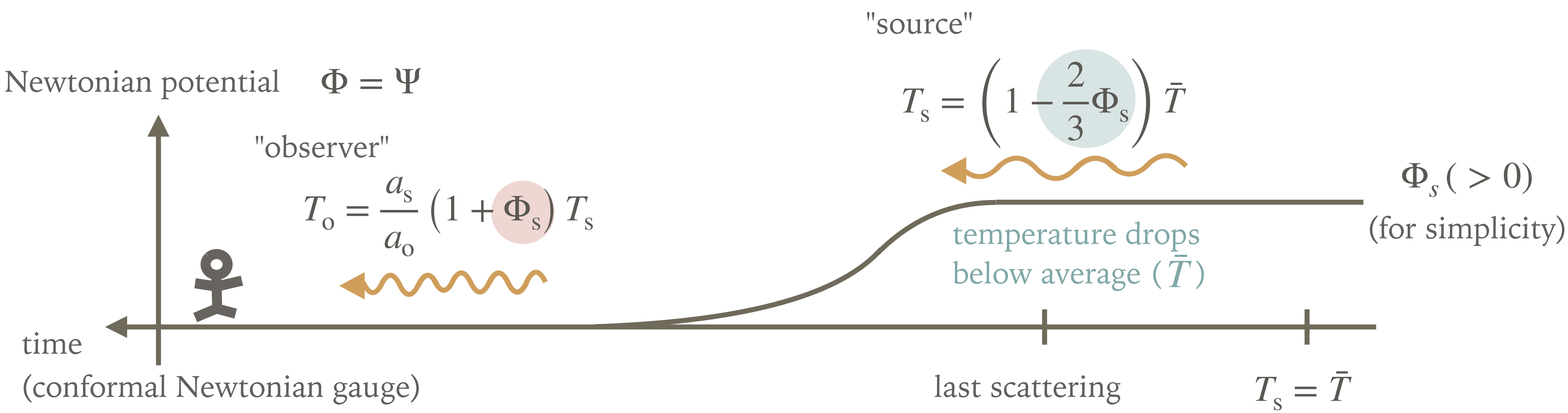


# SACHS–WOLFE & REES–SCIAMA EFFECTS

➤ Sachs-Wolfe effect [ Sachs & Wolfe '67 / Hu & White '97 ]

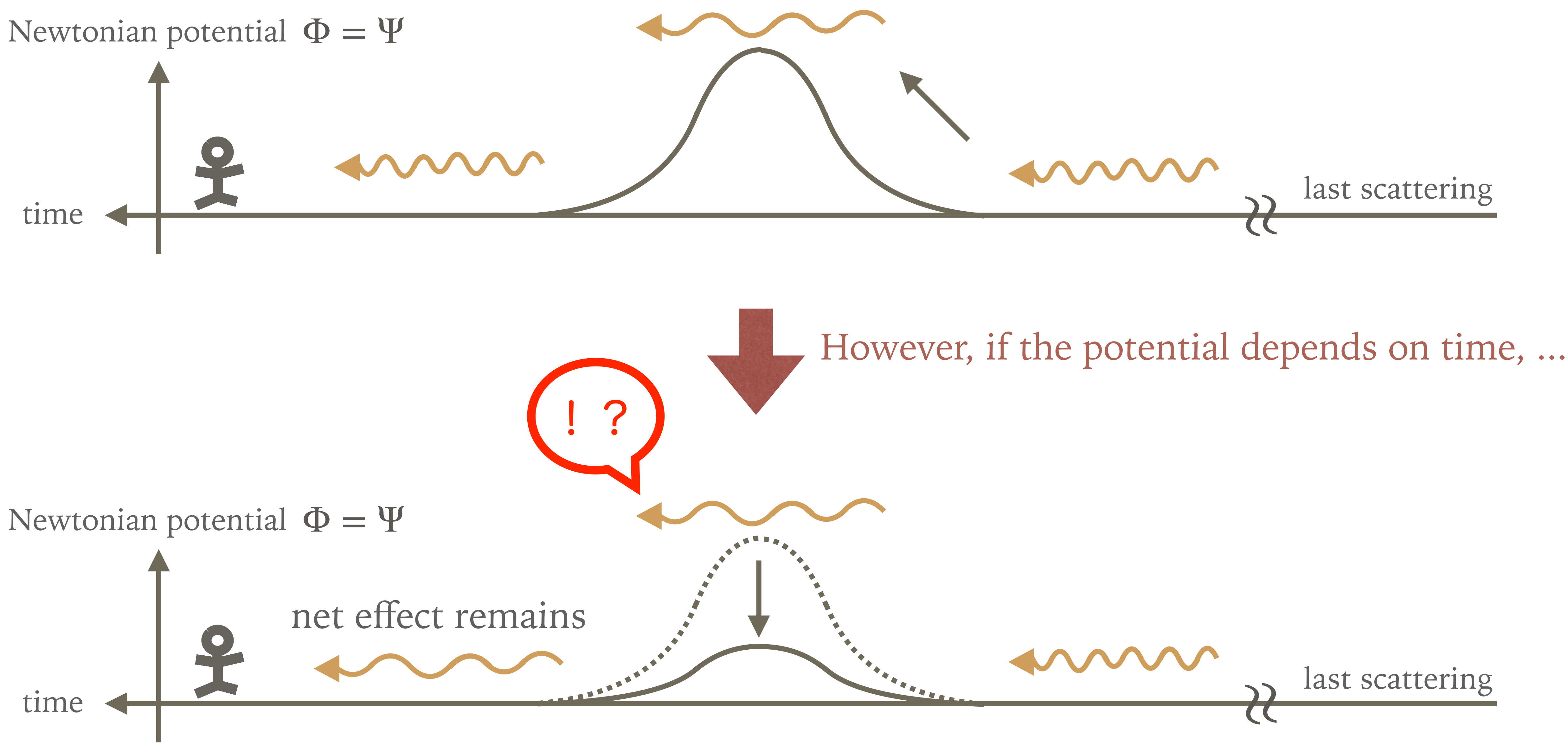
$$\frac{\Delta T}{T} = \Phi_s - \frac{2}{3}\Phi_s$$

Here
$$\begin{cases} ds^2 = -a^2(1+2\Phi)\,d\tau^2 + a^2\delta_{ij}(1-2\Psi)\,dx^i dx^j \\ \Phi = \Psi \end{cases}$$



# SACHS-WOLFE & REES-SCIAMA EFFECTS

➤ Rees-Sciama (integrated Sachs-Wolfe) effect [ Rees-Sciama '67 ]



# GW DEFORMATION KERNEL

$$\Delta_h^{2,(\mathrm{o})}(\ln f) \simeq \int d\ln f' \ \Delta_h^{2,(\mathrm{s})}(\ln f')\, K(f, f')$$

GW spectrum @ observer — GW spectrum @ production — Kernel

kernel $$K(f, f') = \frac{1}{\sqrt{2\pi\sigma^2}}[1 + b(\ln f - \ln f')]e^{-\frac{(\ln f - \ln f')^2}{2\sigma^2}}$$

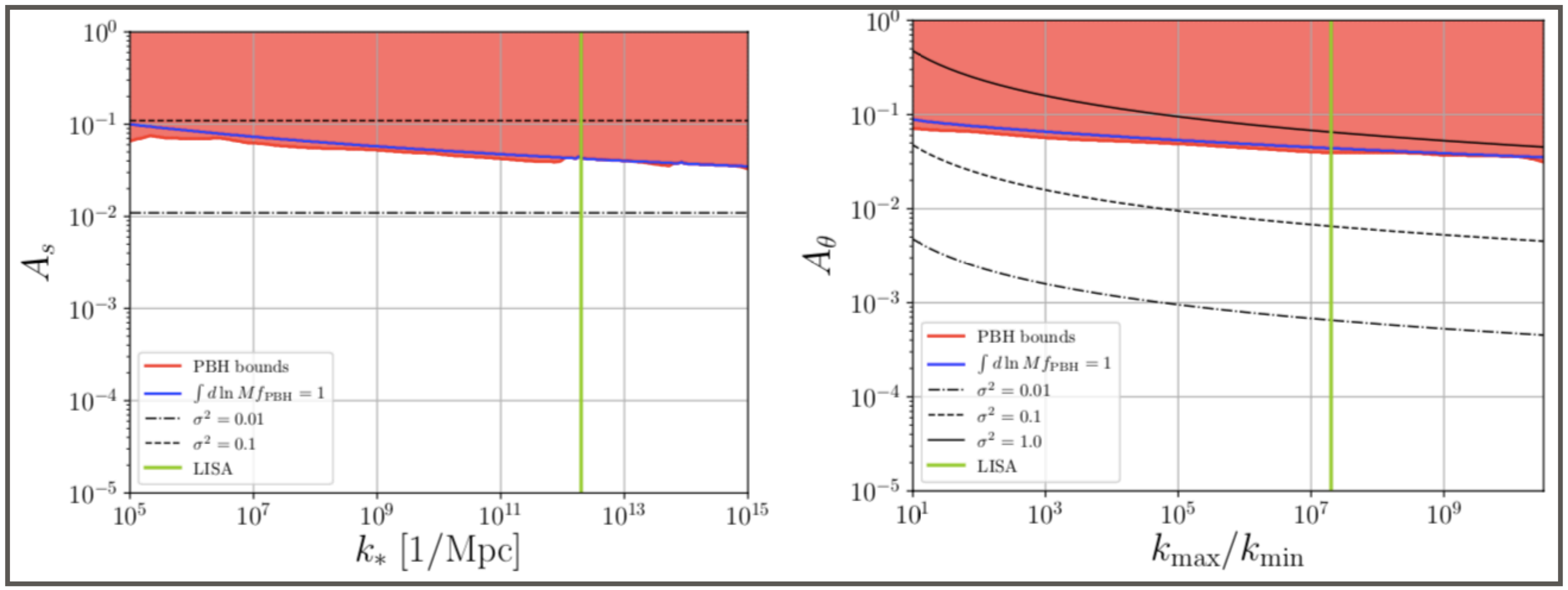
variance $$\sigma^2 \simeq 0.91 \times \int d\ln k\, \Delta^2_{\mathscr{R}}$$ ← inflationary curvature perturbation

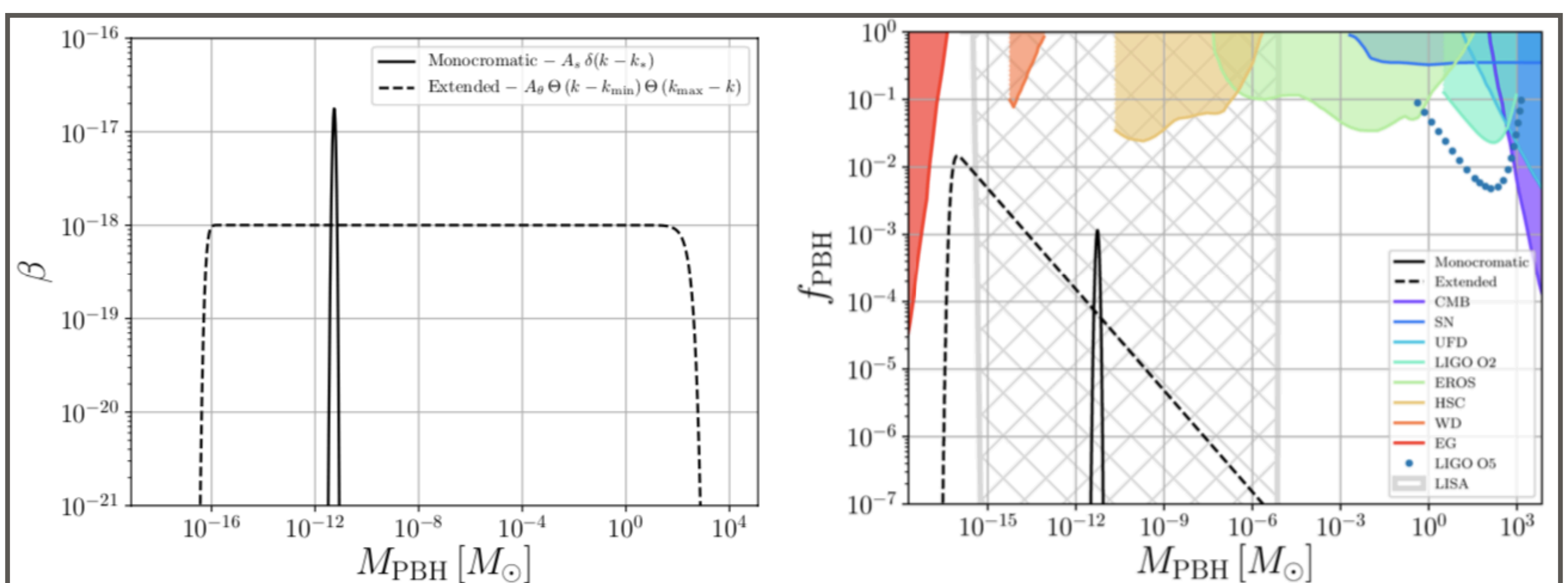
linear bias $$b \simeq -0.52$$

# PBH CONSTRAINTS

$$\Delta^2_{\mathcal{R}}(k) = A_s\, k_*\, \delta(k - k_*) \qquad \Delta^2_{\mathcal{R}}(k) = A_\theta\, \Theta(k - k_{\rm min})\, \Theta(k_{\rm max} - k)$$

$$k_{\rm min} = 10^5\,{\rm Mpc}^{-1}$$



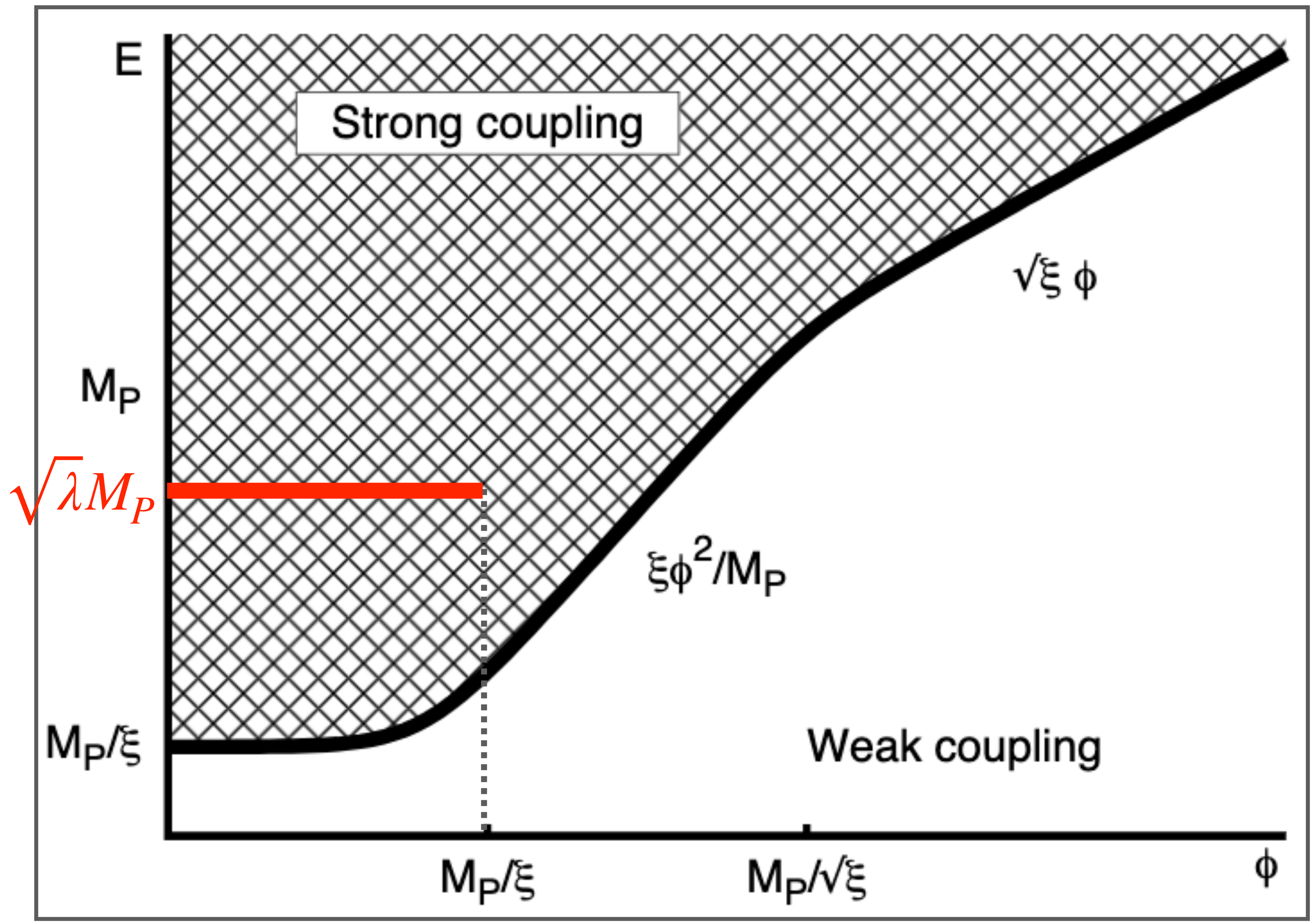



# CUTOFF IN HIGGS INFLATION

- Background-dependent cutoff of the theory

Energy scale of longitudinal W and Z production

[ Jinno '16 (Ph.D. Thesis) ]
[ Ema, Jinno, Mukaida, Nakayama '16 ]




[ Bezrukov, Shaposhnikov '10 ]