COHERENT COLLIDERS AND OTHER THOUGHT EXPERIMENTS

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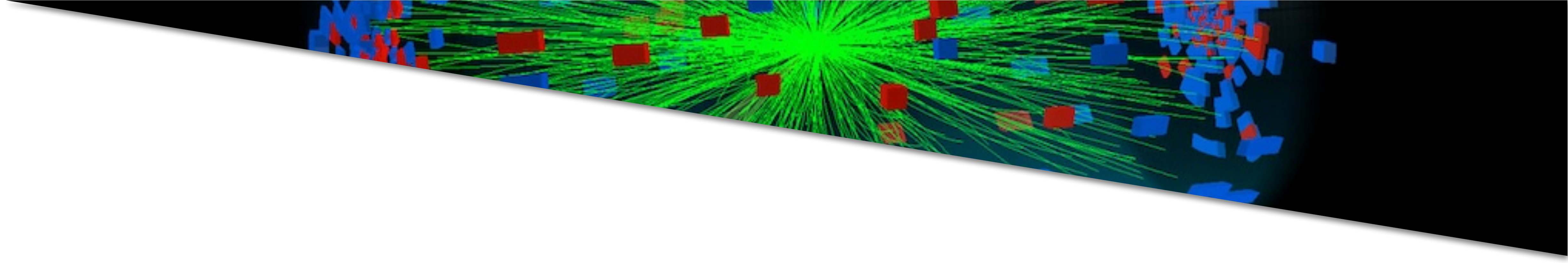


- Coherent Colliders
- Is it easier to detect GUT-scale GWs or to build a GUT-scale collider?
- A new use of existing colliders (if time permits)

COHERENT "COLLIDERS"

Conceptually, colliders are a terrible way to explore high energies

LHC

$$N_p \simeq 10^{11}$$

$$E_p \simeq 7 \text{ TeV}$$

$$E_{\text{tot}} \simeq 10^{15} \text{ GeV}$$

In each collision we use less than 10^{-11} of the total energy

TOY MODEL

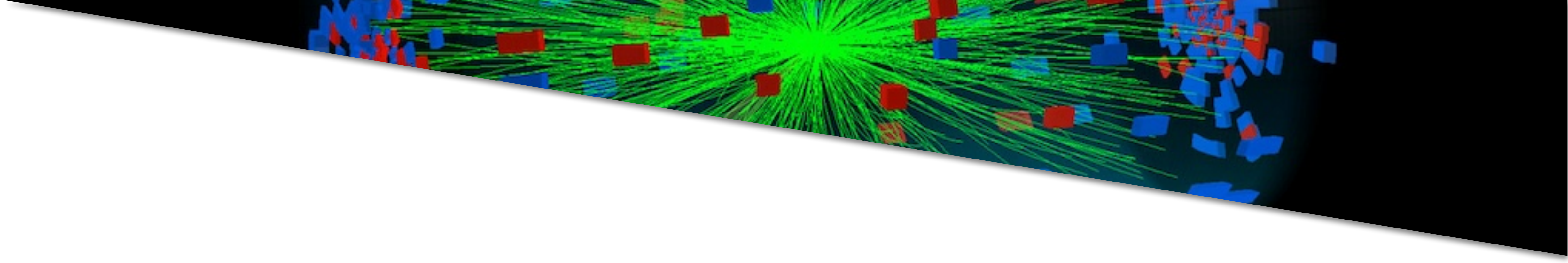
ϕ Colliding Particles

χ Heavy Particles
that we want to produce

TOY MODEL

$$V = \frac{m_\phi^2}{2}\phi^2 + \frac{M^2}{2}\chi^2 + \frac{g^2}{2}\chi^2\phi^2$$

EXPERIMENT



We prepare our thought experiment in a coherent state

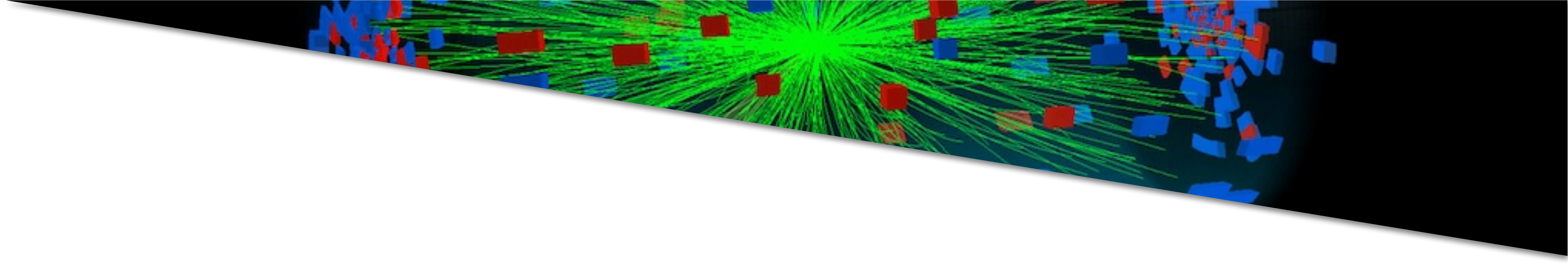
$$\hat{\phi}|\phi_*\rangle = \phi_*|\phi_*\rangle$$

EXPERIMENT

For simplicity I imagine that

$$\frac{\phi_*^2}{m_\phi^2 v_\phi^3} \gg 1$$

EXPERIMENT



So that a classical description holds

$$\phi(t) = \phi_* \cos(m_\phi t)$$

(Assuming spatial isotropy for simplicity)

EXPERIMENT

$$\frac{d^2}{dz^2}\chi_{\mathbf{k}}(z) + \left[A_{\mathbf{k}} + 2q\cos(2z)\right]\chi_{\mathbf{k}}(z) = 0$$

$$z \equiv m_\phi t\,, \quad A_{\mathbf{k}} \equiv \frac{k^2 + M^2}{m_\phi^2}\,, \quad q \equiv \frac{g^2\phi_*}{4m_\phi^2}$$

EXPERIMENT

$$\frac{d^2}{dz^2}\chi_{\mathbf{k}}(z) + \left[A_{\mathbf{k}} + 2q\cos(2z)\right]\chi_{\mathbf{k}}(z) = 0$$

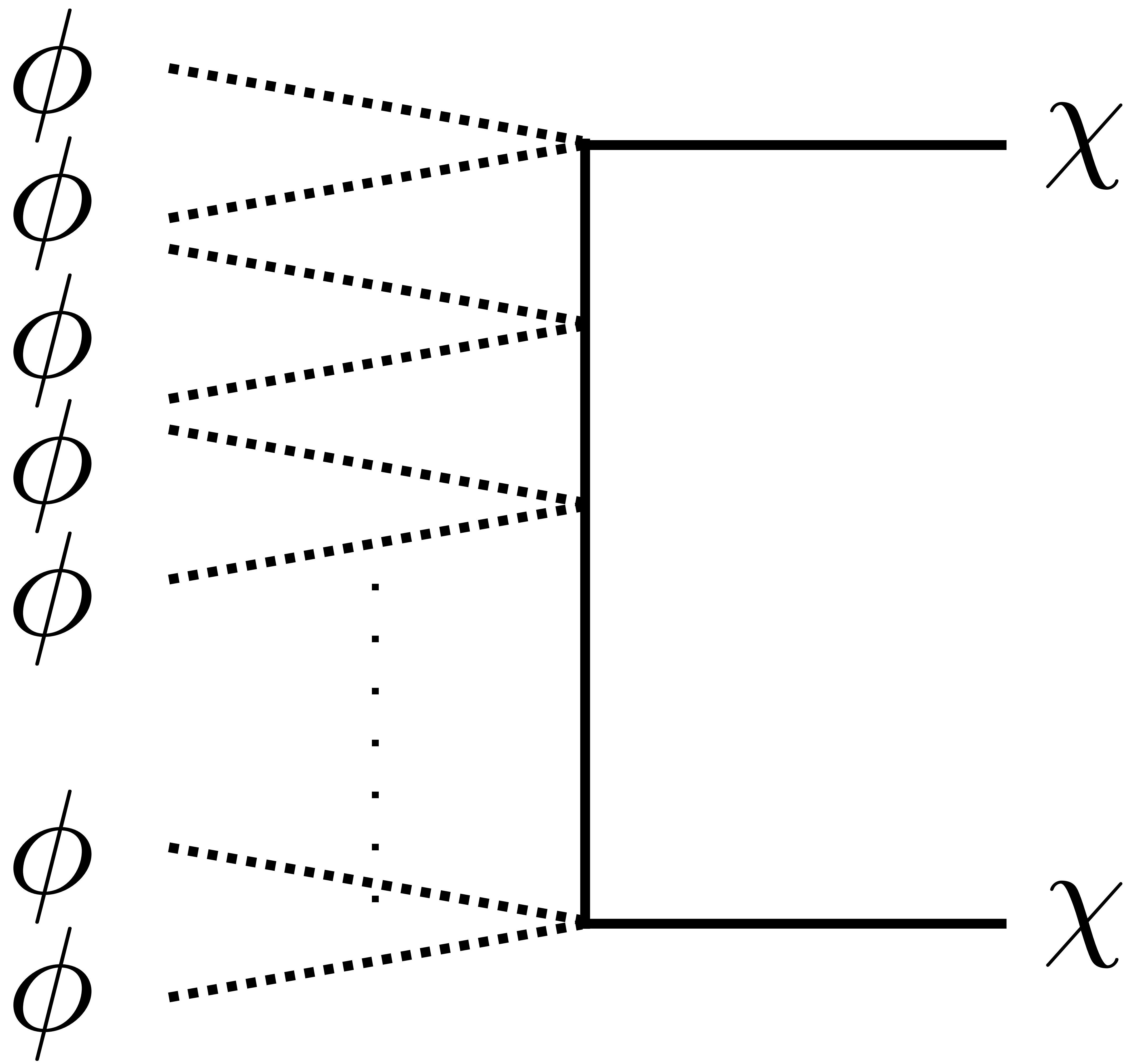
Mathieu Equation

(standard in many fields, for us important for preheating after inflation)

EXPERIMENT

You produce an exponentially large number of particles up to

$$M^2 \lesssim g\phi_* m_\phi \gg \frac{m_\phi^2}{4}$$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This is well-known for photons (Schwinger effect)

$$\Gamma \sim e^{-\frac{m_e^2}{eE}}$$

This is well-known for photons (Schwinger effect)

$$\Gamma \sim e^{-\frac{m_e^2}{eE}}$$

10^{10} photons to make an electron-positron pair

How do we do it in practice?

Not with colliders

$$\Gamma(\text{collision} \to \phi_*) \simeq e^{-B}$$

$$B \simeq M^4 V \Delta t \simeq 10^{87} \left(\frac{M}{10^{15}\ \text{GeV}} \right)^4 \frac{V}{(\mu\text{m})^3} \frac{\Delta t}{(100\ \text{GeV})^{-1}}$$

GRAVITATIONAL WAVES VS COLLIDERS

[Based on RTD, S. Ellis, arXiv:2412.17897, *JHEP* 04 (2025) 164]

$$\omega_g$$

$$\lambda(T_*) < \frac{1}{H(T_*)}$$ Causality

$$\omega_g$$

$$\lambda(T_*) < \frac{1}{H(T_*)}$$ Causality

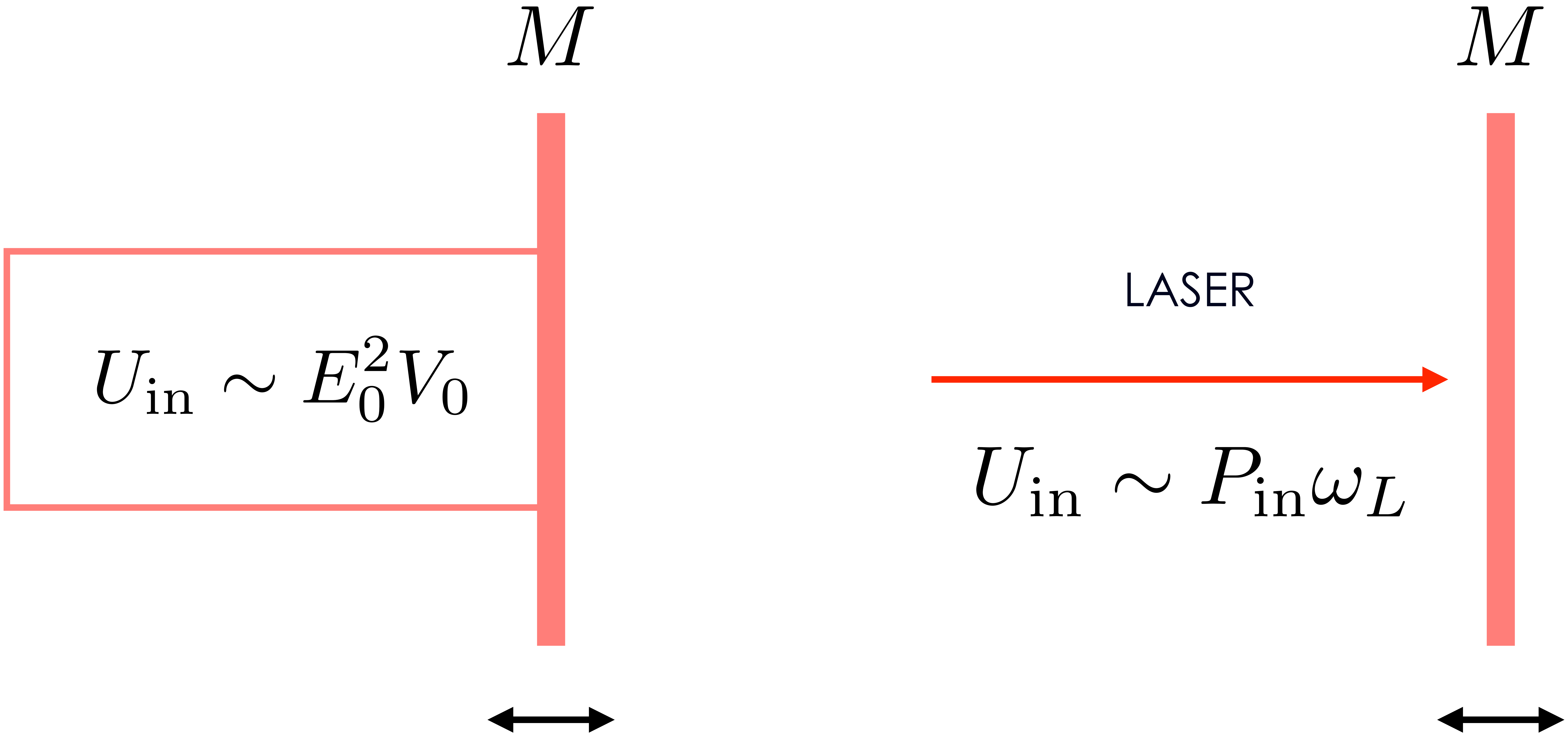
$$\omega_0(T_*) = \omega(T_*)\frac{a(T_*)}{a_0} \gtrsim \boxed{100\ \mathrm{MHz}} \left(\frac{T_*}{10^{15}\mathrm{GeV}}\right)\left(\frac{g_*(T_*)}{100}\right)^{1/6}$$


DETECTORS

DETECTOR I

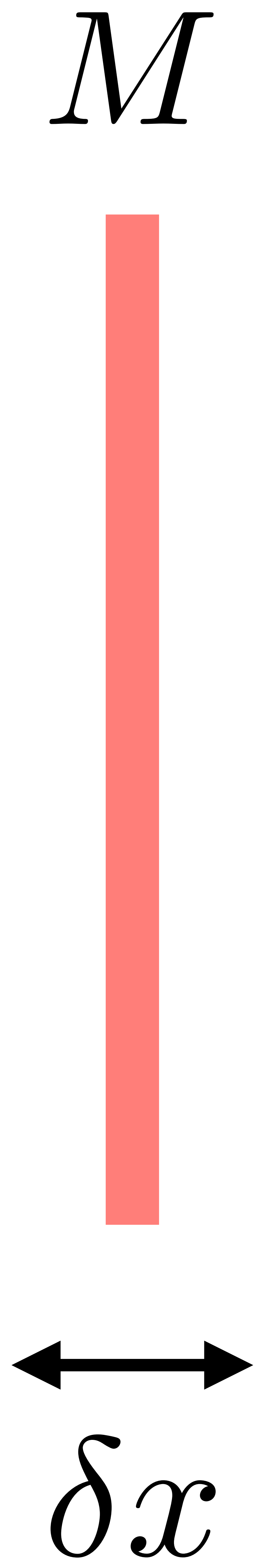
$$U_{\text{in}} \sim E_0^2 V_0$$

DETECTOR II



DETECTOR II

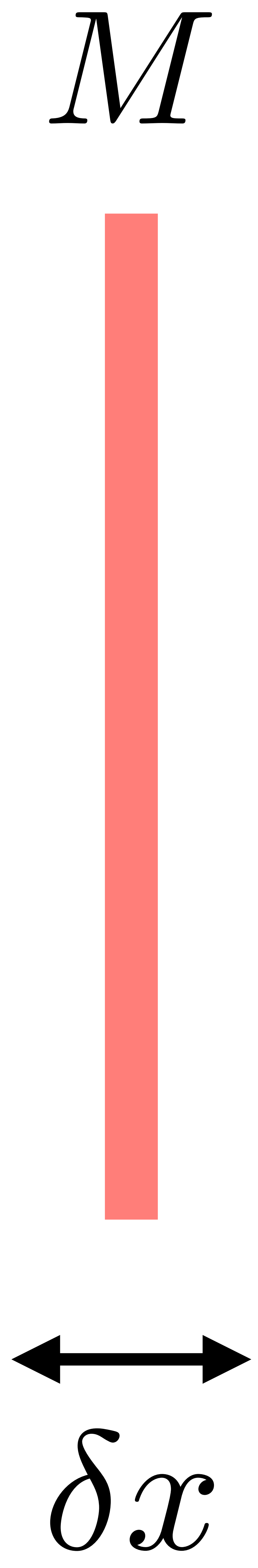
$$M\ddot{\delta x} = M\ddot{h}x + F_{\text{ext}}$$



DETECTOR II

$$M \to \infty$$

$$M\ddot{\delta x} = M\ddot{h}x + F_{\text{ext}}$$



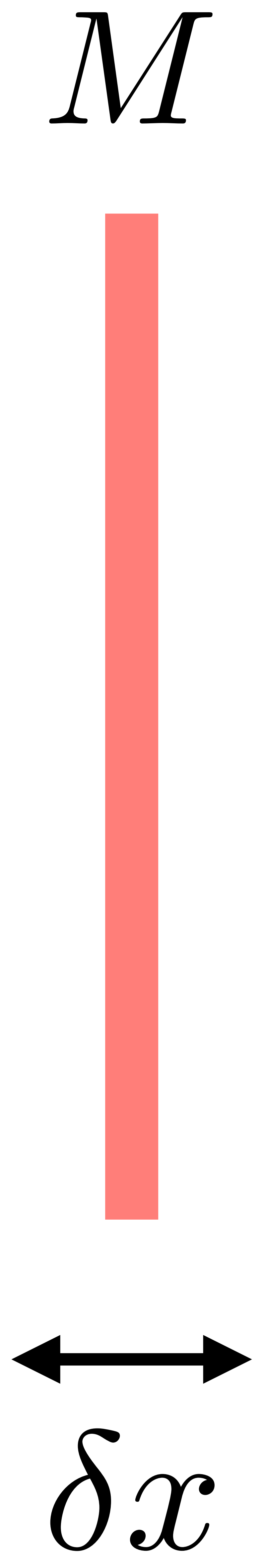
DETECTOR II

$$M \to \infty$$

$$M\ddot{\delta x} = M\ddot{h}x + F_{\text{ext}}$$

$$\ddot{\delta x}_{\text{sig}} \sim \ddot{h}x \sim \text{const}$$

$$\ddot{\delta x}_{\text{noise}} \sim \frac{F_{\text{ext}}}{M} \to 0$$



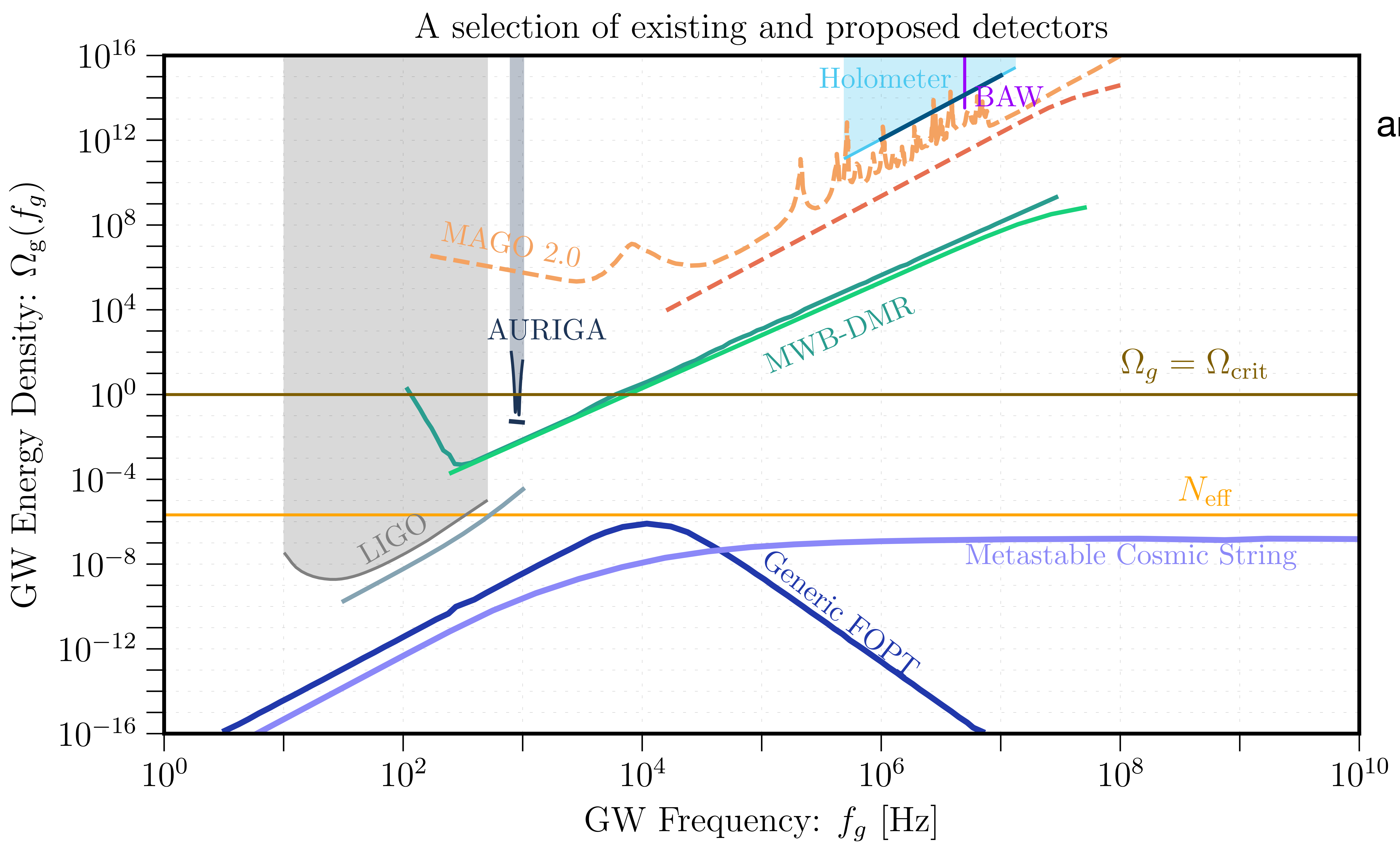
THE BEST POSSIBLE SENSITIVITY

In this limit I can ignore noise from the test mass and focus on the signal (and noise) photons that I can detect

DETECTOR I → $$U_{\text{in}} \sim E_0^2 V_0$$ ← DETECTOR II

$$U_{\text{in}} \sim E_0^2 V_0$$

$$\text{———}\ \mathcal{T}(\omega)\ \text{———}$$



RTD, S. Ellis, arXiv:2412.17897


SIGNALS

$$U_{\text{sig}} \sim U_{\text{in}} \times \begin{cases} (h\mathcal{T})^2 \\ h\mathcal{T} \end{cases}$$

$$\boxed{U_{\text{in}} \sim E_0^2 V_0}$$

CASE I: QUADRATIC SIGNALS

$$\langle E_h(t) E_0(t) \rangle \propto \langle \tilde{E}_h(\omega) \tilde{E}_0(\omega) \rangle = 0$$

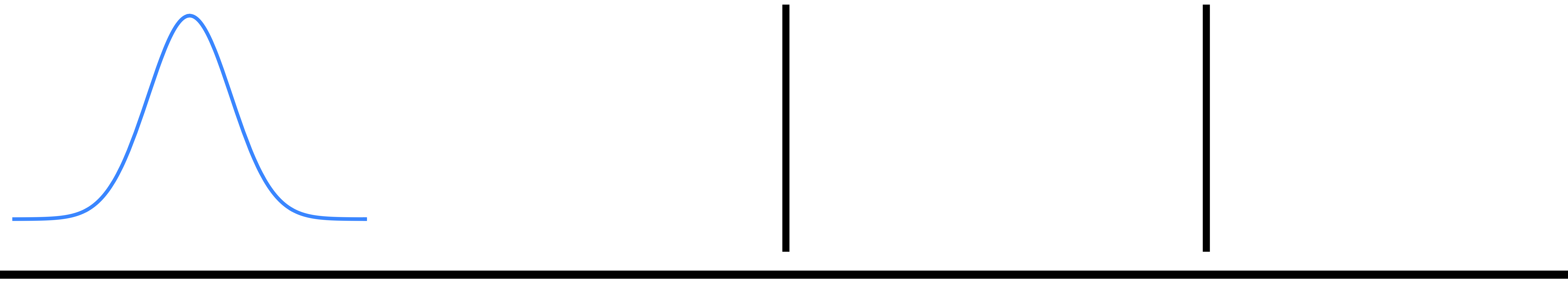
$$\langle E_h(t) E_0(t) \rangle \propto \langle \tilde{E}_h(\omega) \tilde{E}_0(\omega) \rangle = 0$$

$\Delta\omega_d$

Detector Bandwidth

$\tilde{E}_0(\omega)$ $\tilde{E}_h(\omega)$

In absence of a signal,
the detector is empty (classically)



In absence of a signal,
the detector is empty (classically)

$$P_{\rm min} \simeq \frac{2\pi\omega}{t_{\rm int}}$$

But we have one quantum of noise
from vacuum fluctuations

QUADRATIC SIGNAL

$$P_{\text{sig}} \lesssim \underline{h^2 U_{\text{in}}} \omega_s \mathcal{T}^2(\omega_s)$$

Signal Energy

QUADRATIC SIGNAL

$$P_{\mathrm{sig}} \lesssim h^2 U_{\mathrm{in}} \underline{\omega_s} \mathcal{T}^2(\omega_s)$$

Maximum power
from Poynting's theorem

QUADRATIC SIGNAL

$$\frac{P_{\rm sig}}{P_{\rm noise}} \simeq 1 \quad \longrightarrow \quad h_{\rm min} \gtrsim \sqrt{\frac{2\pi}{U_{\rm in} t_{\rm int}} \frac{1}{\mathcal{T}}}$$

CASE II: LINEAR SIGNALS

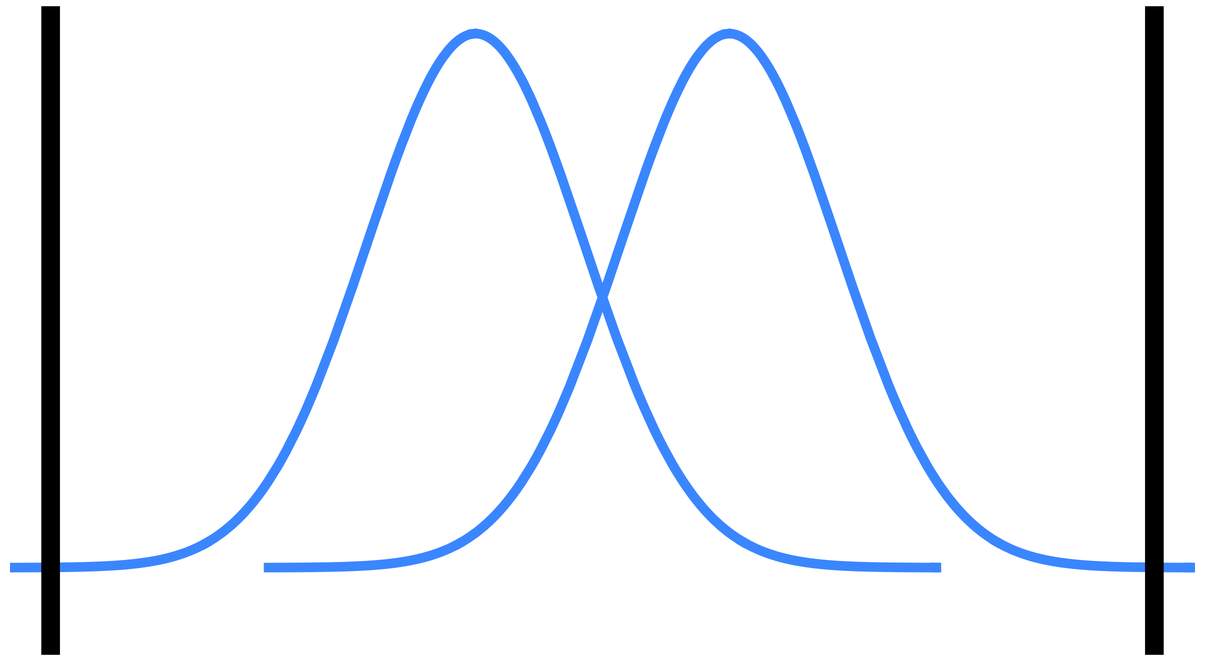
$$\langle E_h(t)E_0(t)\rangle \propto \langle \tilde{E}_h(\omega)\tilde{E}_0\omega)\rangle \neq 0$$

$\tilde{E}_0(\omega)$ $\tilde{E}_h(\omega)$

CASE II: LINEAR SIGNALS

$$\Delta\omega_d$$

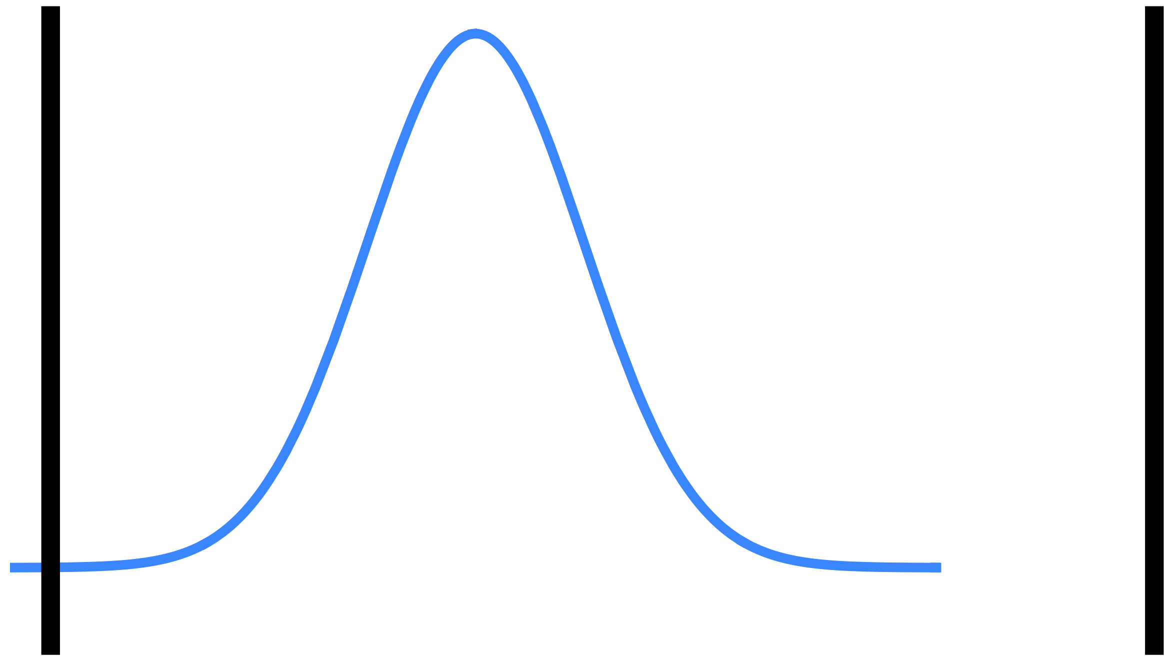
Detector Bandwidth



$$\tilde{E}_0(\omega) \qquad \tilde{E}_h(\omega)$$

CASE II: LINEAR SIGNALS

In absence of a signal,
the detector is not empty



$$P_{\text{noise}}^{\min} \simeq \frac{2\pi\omega}{t_{\text{int}}}\left(1+\sqrt{\frac{P_{\text{in}}t_{\text{int}}}{2\pi\omega}}\right)$$

NARROW LINEAR SIGNAL

$$\frac{P_{\text{sig}}}{P_{\text{noise}}} \simeq 1 \longrightarrow h_{\text{min}} \gtrsim \sqrt{\frac{2\pi}{U_{\text{in}} t_{\text{int}}}} \frac{1}{\tau}$$

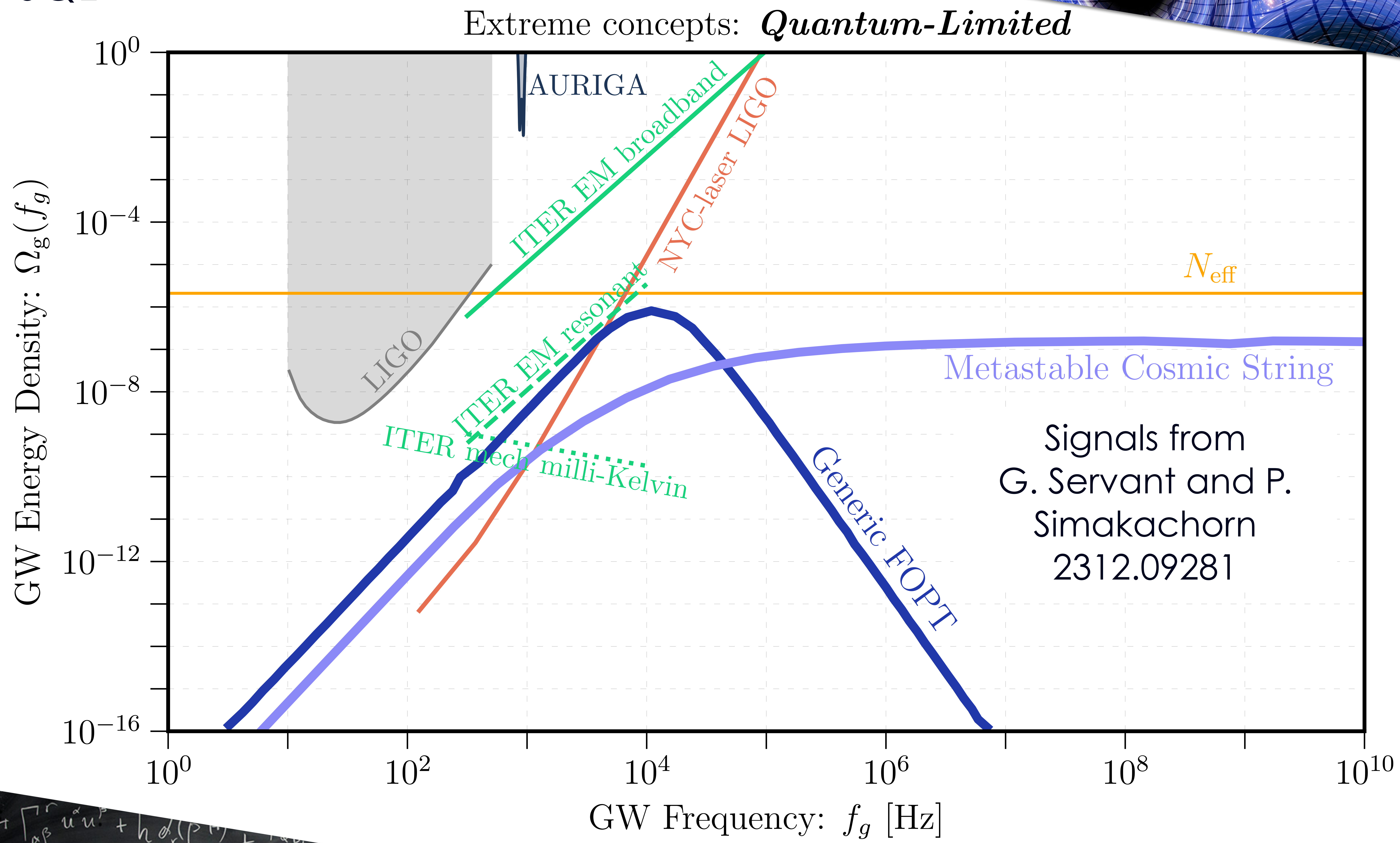
Same as quadratic!


WHAT DID WE LEARN?

QUADRATIC vs LINEAR

$$h_{\mathrm{min}} \gtrsim \sqrt{\frac{2\pi}{U_{\mathrm{in}}\, t_{\mathrm{int}}}}\, \frac{1}{\mathcal{T}}$$

CRAZY SQL



Signals from G. Servant and P. Simakachorn 2312.09281

QUADRATIC vs LINEAR

QUADRATIC

$$P_{\text{noise}}^{\text{min}} \simeq \frac{2\pi\omega}{t_{\text{int}}}$$

LINEAR

$$P_{\text{noise}}^{\text{min}} \simeq \frac{2\pi\omega}{t_{\text{int}}} \left(1 + \sqrt{\frac{P_{\text{in}} t_{\text{int}}}{2\pi\omega}}\right)$$

$$\sqrt{N_\gamma}$$

We can gain a lot from quantum techniques

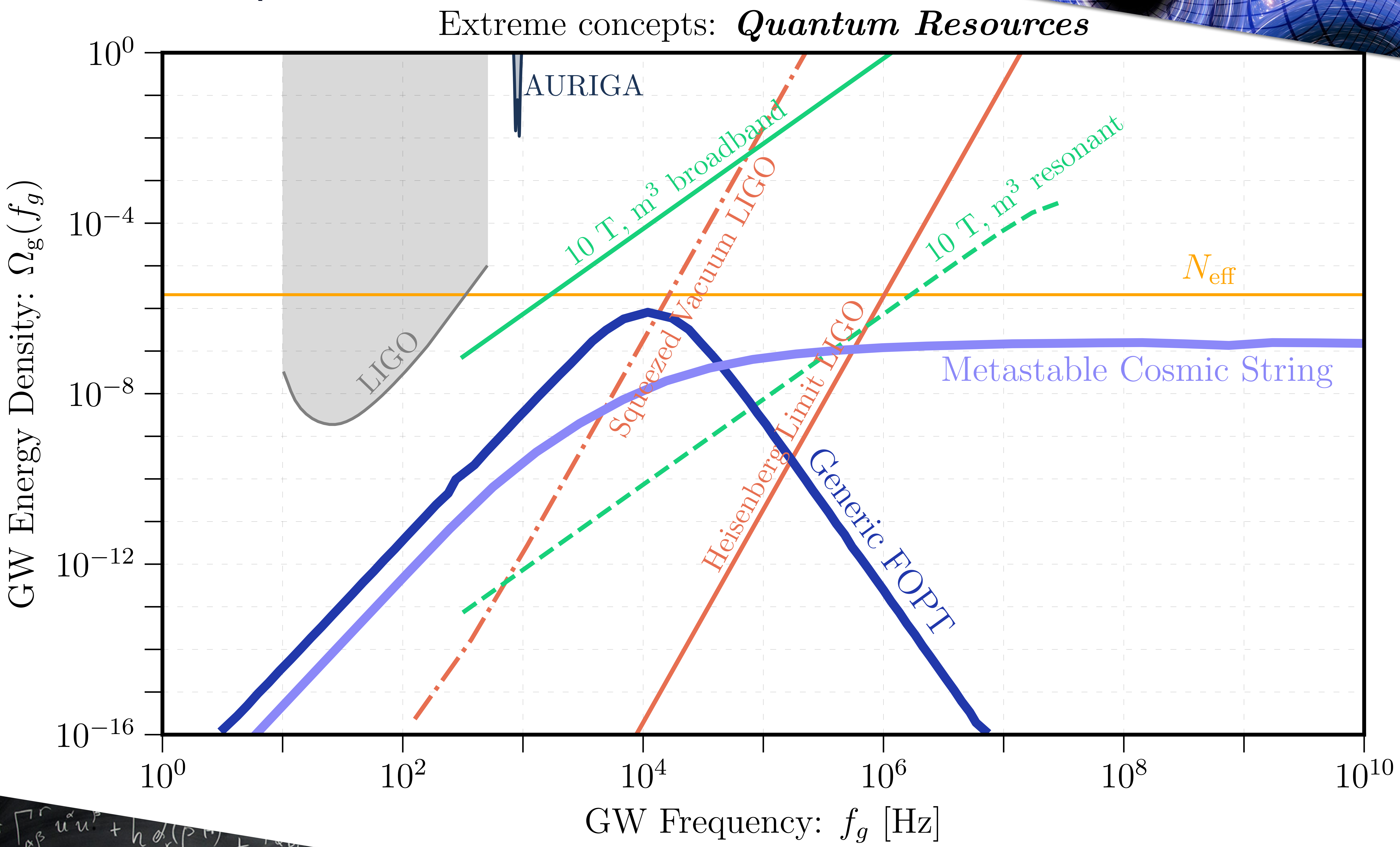
LINEAR

In principle

$$P_{\text{noise}}^{\text{min}} \to \frac{2\pi\omega}{t_{\text{int}}}$$

Heisenberg Limit

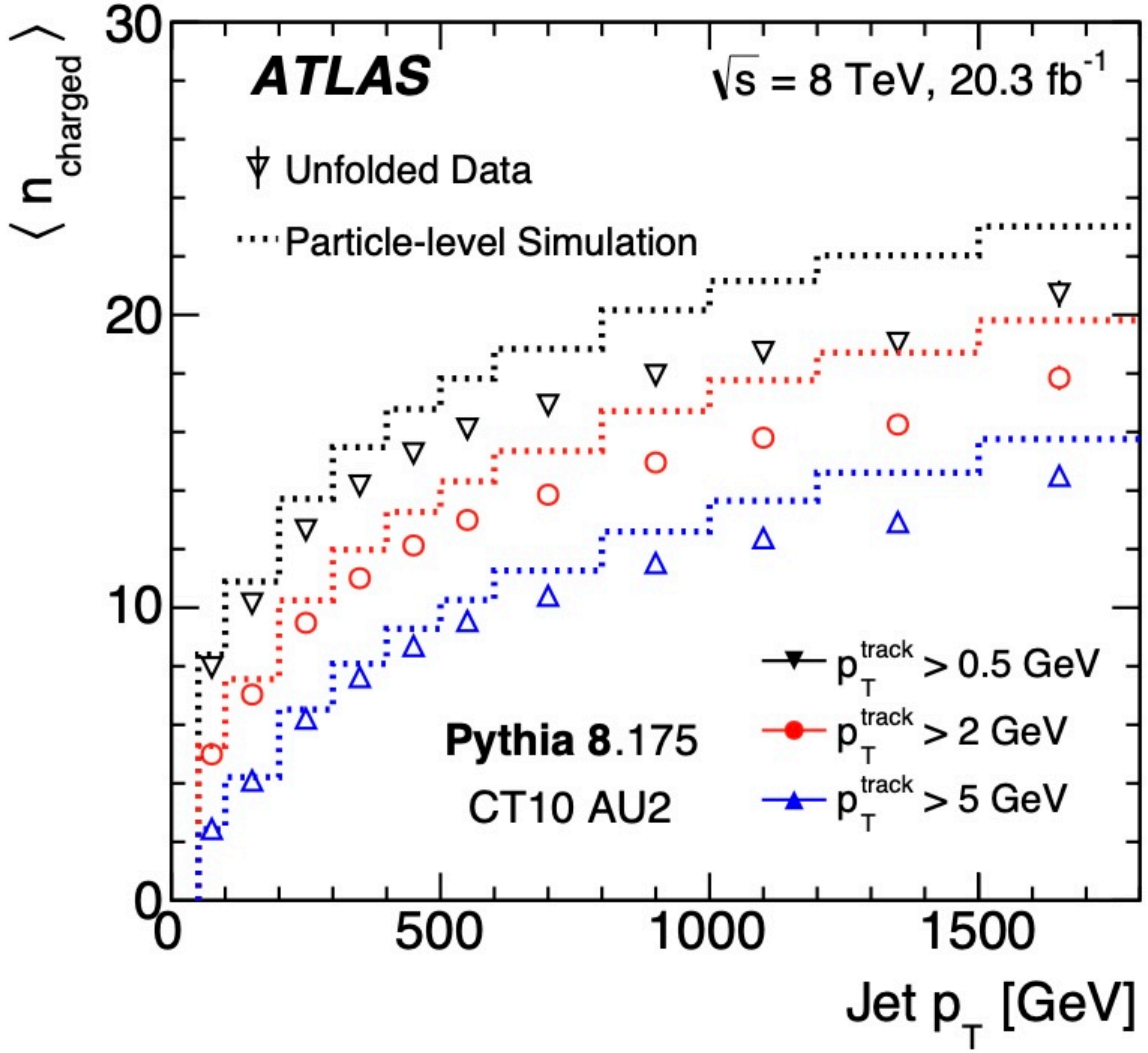
CRAZY BEYOND SQL



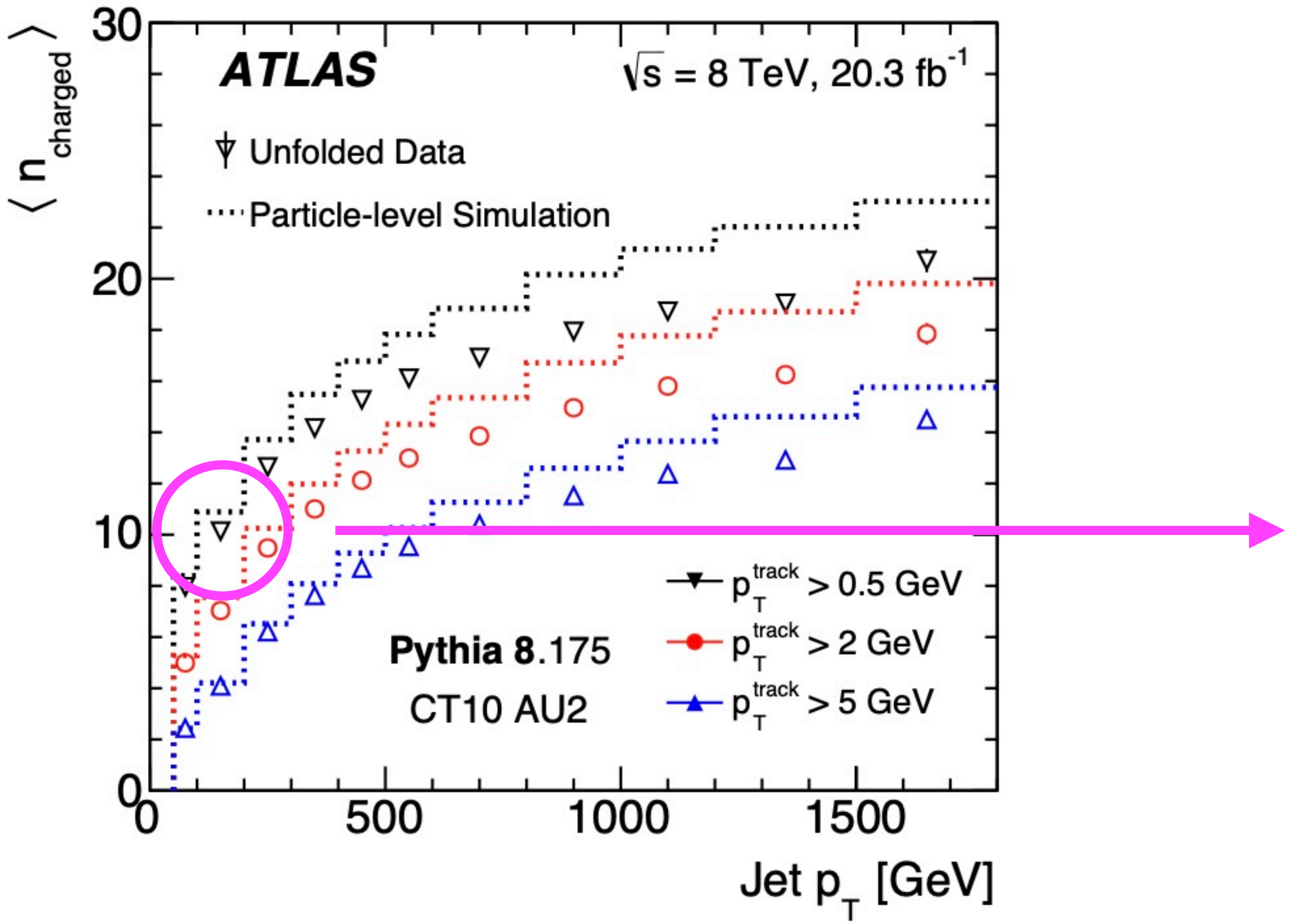
CONCLUSION

	Classical	Quantum
100 MHz GW Laser Power LIGO-sized interferometer	10^{36} W	$10^{9}\ \mathrm{W}\sqrt{\frac{s}{t_{\mathrm{int}}}}$
GUT-scale Collider Energy in the magnets	10^{26} J $R \simeq R_{\oplus}$	? $(E_{\mathrm{magnets}} \simeq 8\,\mathrm{kJ})$

40 SIGMA SIGNALS AND WHERE TO FIND THEM



ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Unfolded Data
Particle-level Simulation
p_T^{track} > 0.5 GeV
p_T^{track} > 2 GeV
p_T^{track} > 5 GeV
Pythia 8.175
CT10 AU2
$\langle n_{charged} \rangle$
Jet p_T [GeV]
0
10
20
30
0
500
1000
1500



Roughly ~ 10 charged tracks in a 100 GeV jet

Dijet event

~ 20 x 3 = **60**

kinematical variables

$$\sim N^{60}$$

Possible signals

$$N > 1$$

But unknown

$$\sim N^{60}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

$$\sim N^{60}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

$$\sim N^{10^4}$$

And this does not even include:

1) All particles from Pile Up

2) The growth at 13 TeV

3) All the hits in the tracker from tracks that don't look "normal"

THE DREAM

Raw data → Dr. Black Box → New Physics?

THE PROBLEMS

Raw data →

Old Physics →

Dr. Black Box → New Physics?

THE PROBLEMS

Raw data →

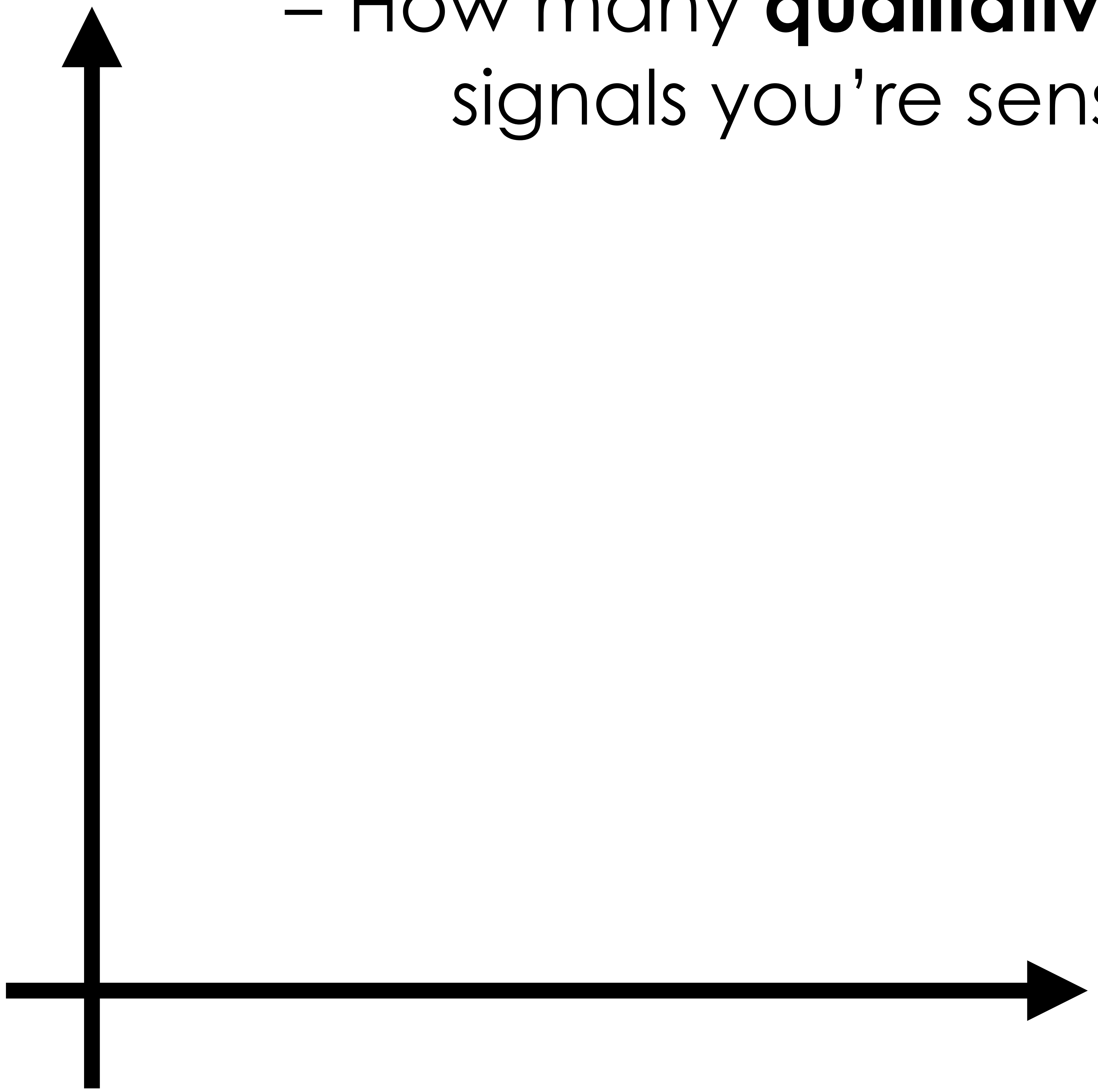
Old Physics →

Look-elsewhere effect

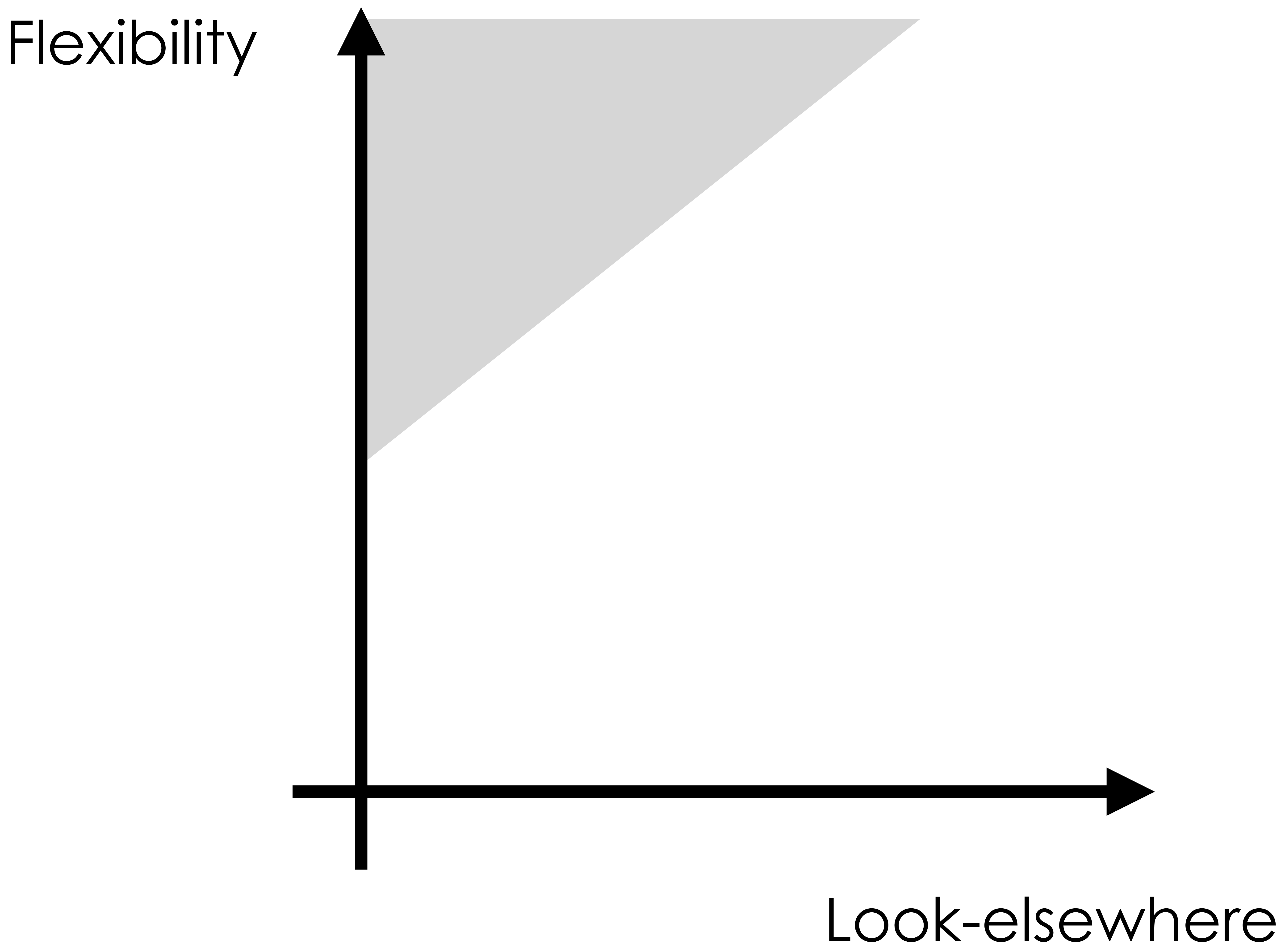
→ New Physics?

= How many **qualitatively different** signals you're sensitive to

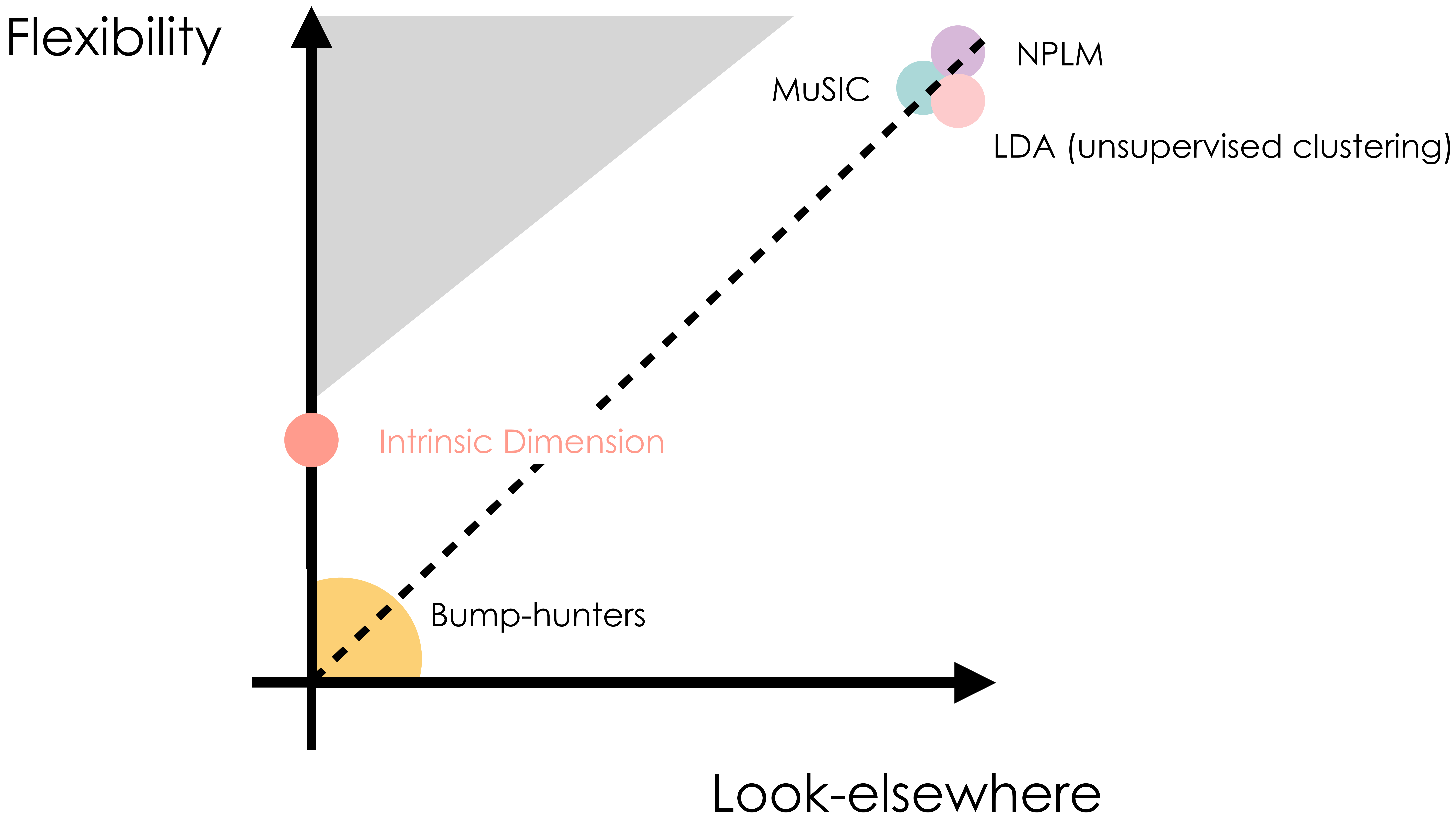
Flexibility



LOOK-ELSEWHERE EFFECT

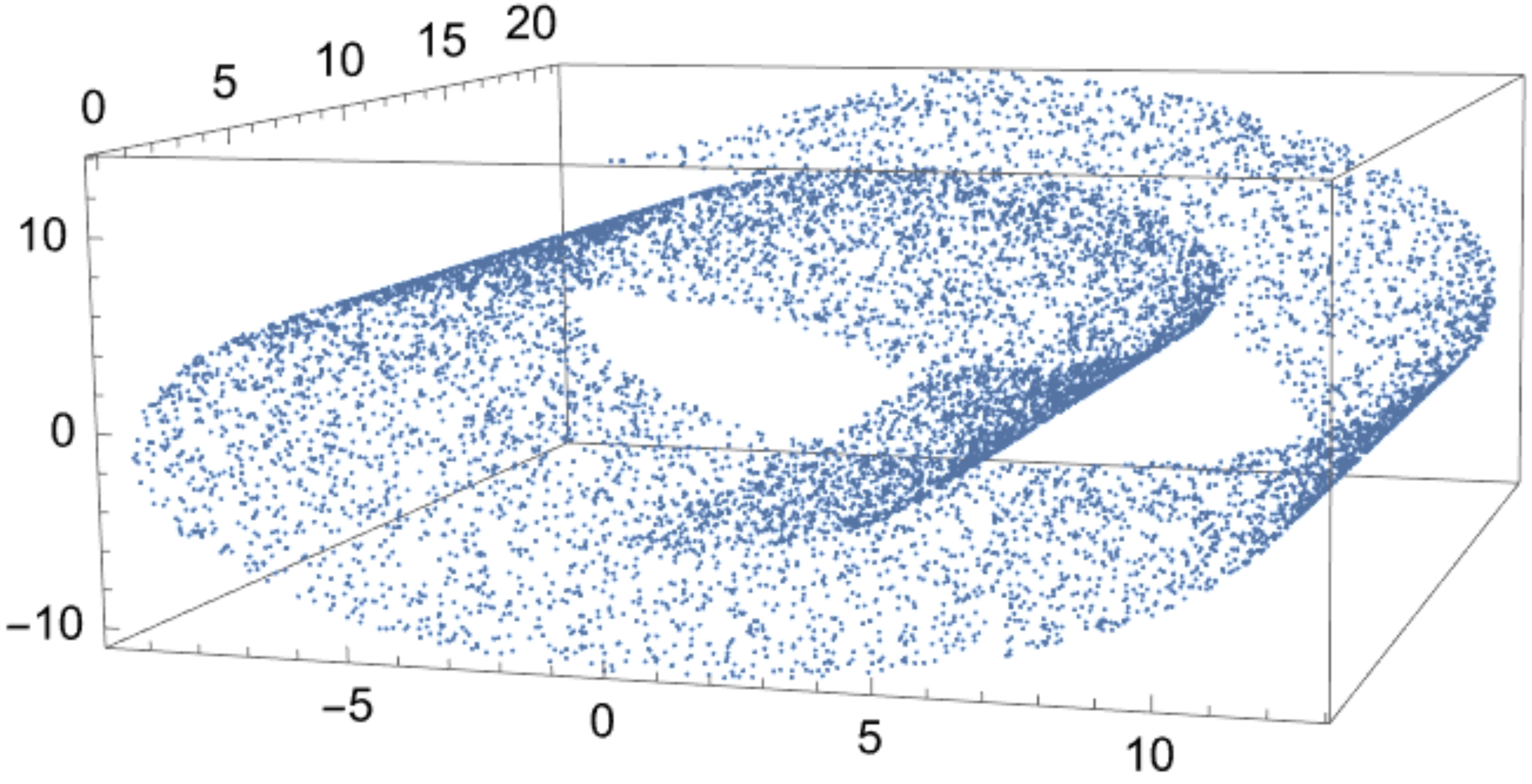


LOOK-ELSEWHERE EFFECT



THE INTRINSIC DIMENSION OF COLLIDER EVENTS

INTRINSIC DIMENSION



Can you tell that D=2 just from the data?

INTRINSIC DIMENSION

$r_i =$ Distance between reference point and its i-th nearest neighbor

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i}$$

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i} \longrightarrow$$

Under mild assumptions

the PDF can be derived analytically

INTRINSIC DIMENSION

$$\mu_{ij} \equiv \frac{r_j}{r_i} \longrightarrow f(\mu_{ij}) = \frac{D(\mu_{ij}^D - 1)^{j-i-1} \mu_{ij}^{-D(j-1)-1}}{B(j-i, i)}$$

WHY?

$$r_i =$$ Earth Mover's Distance

[Komiske, Metodiev, Thaler '19]

As you vary i and j you are exploring non-trivial features of the kinematics

THE INTRINSIC DIMENSION AND NEW PHYSICS

[RTD, A. GLIOTI, G. RIGO, A. VALENTI, In preparation]

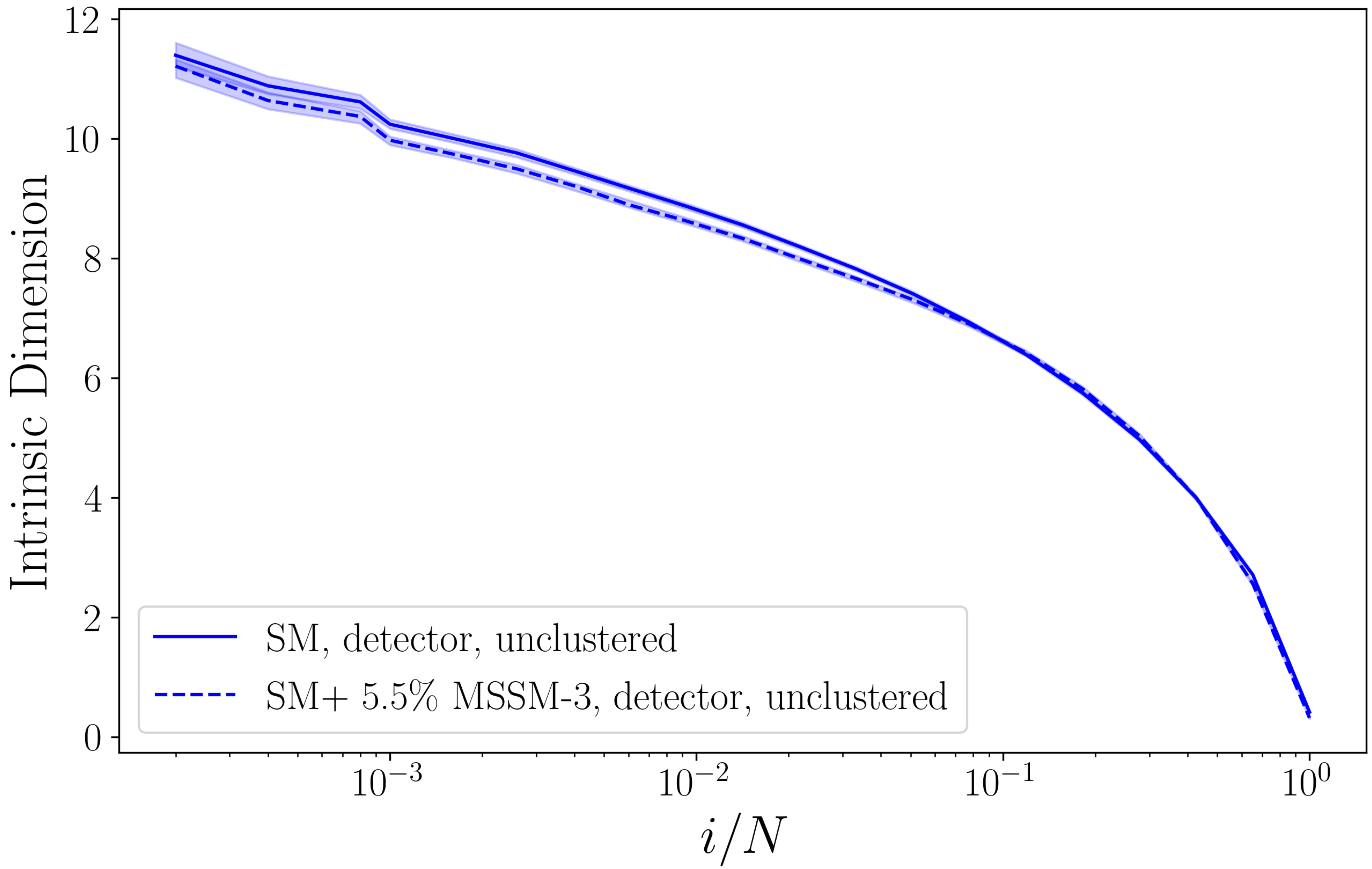
ONE EXAMPLE

SM: $$pp \to WZ \to \mu^+\mu^- jj$$

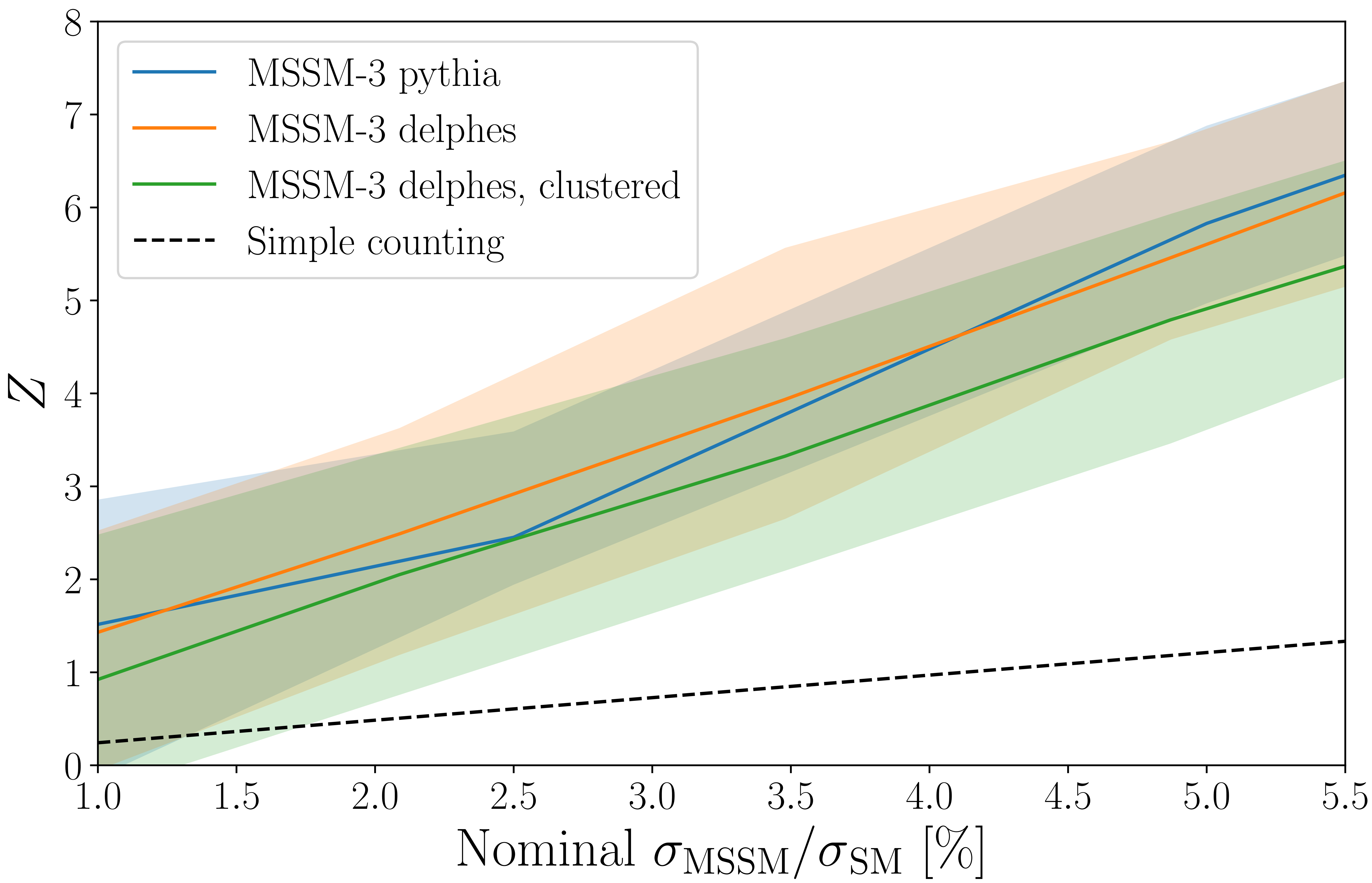
SIGNAL: $$pp \to \chi^\pm \chi_2^0 \to W^\pm Z \chi^0 \chi^0 \to \mu^+\mu^- jj \chi^0 \chi^0$$

But we do not cluster jets !

PRELIMINARY RESULTS



PRELIMINARY RESULTS

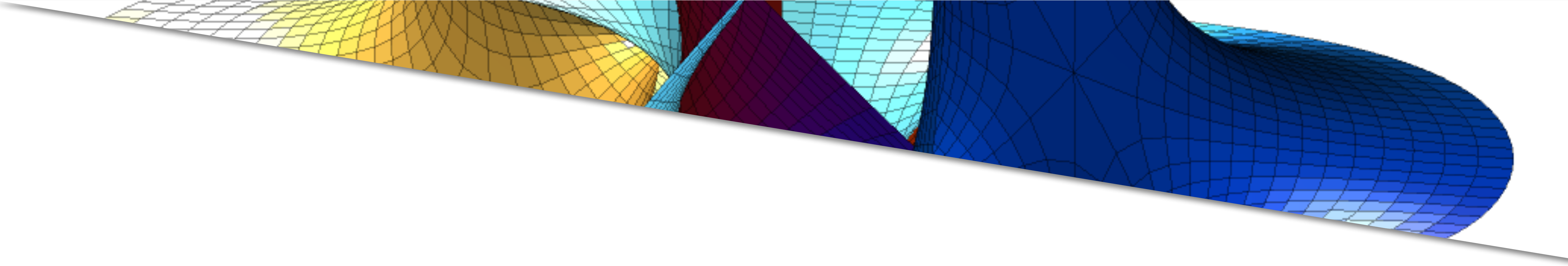


OLD PHYSICS

1. Use it on final states where the MC has been tested to death

2. Test for time variations in LHC data (DQM)

3. Test the exact and approximate symmetries of the Standard Model (CP, Lepton flavor, Lorentz, …)



This search takes single particles as input and not jets!

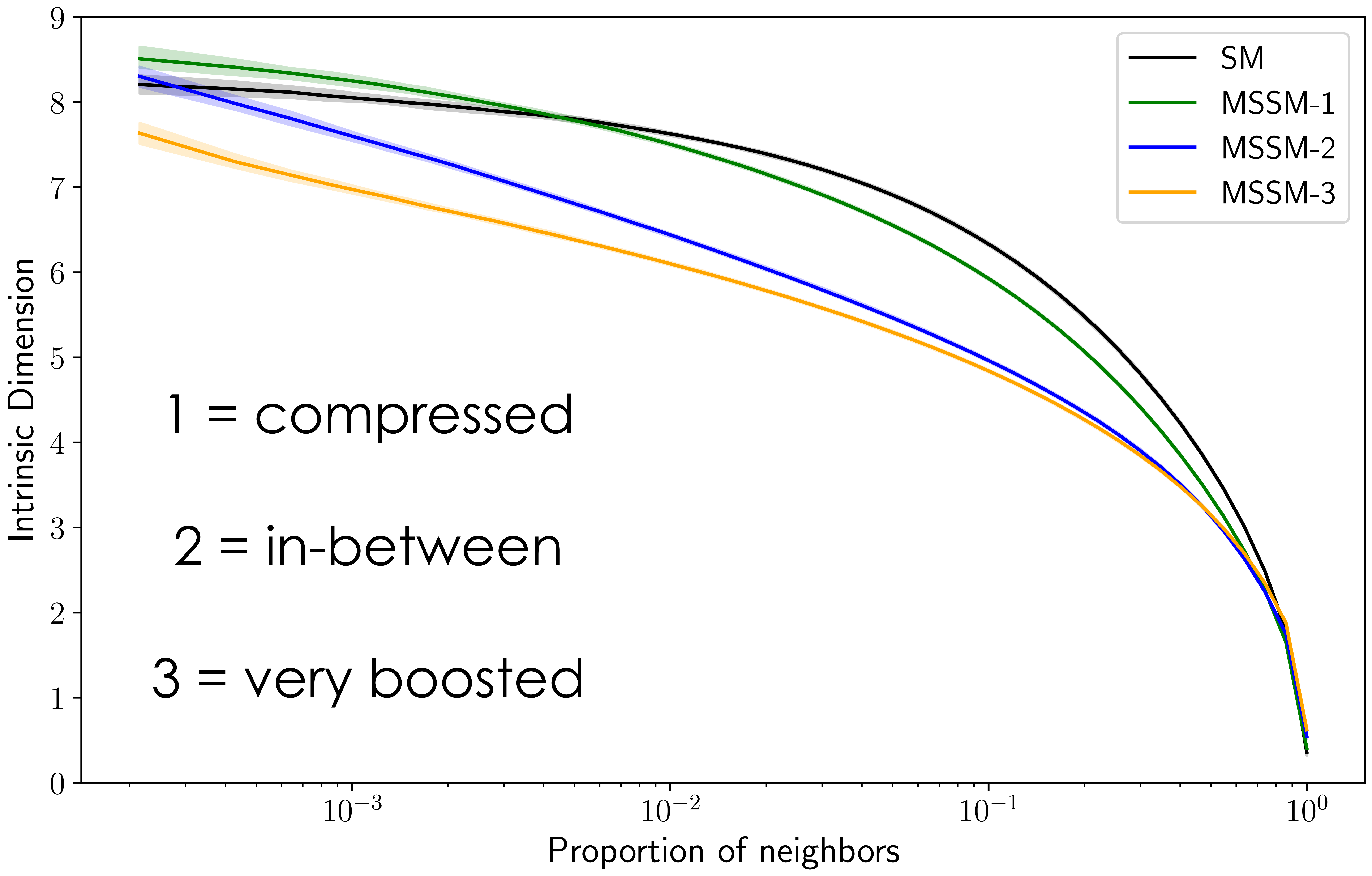
BACKUP

SIGNAL 1

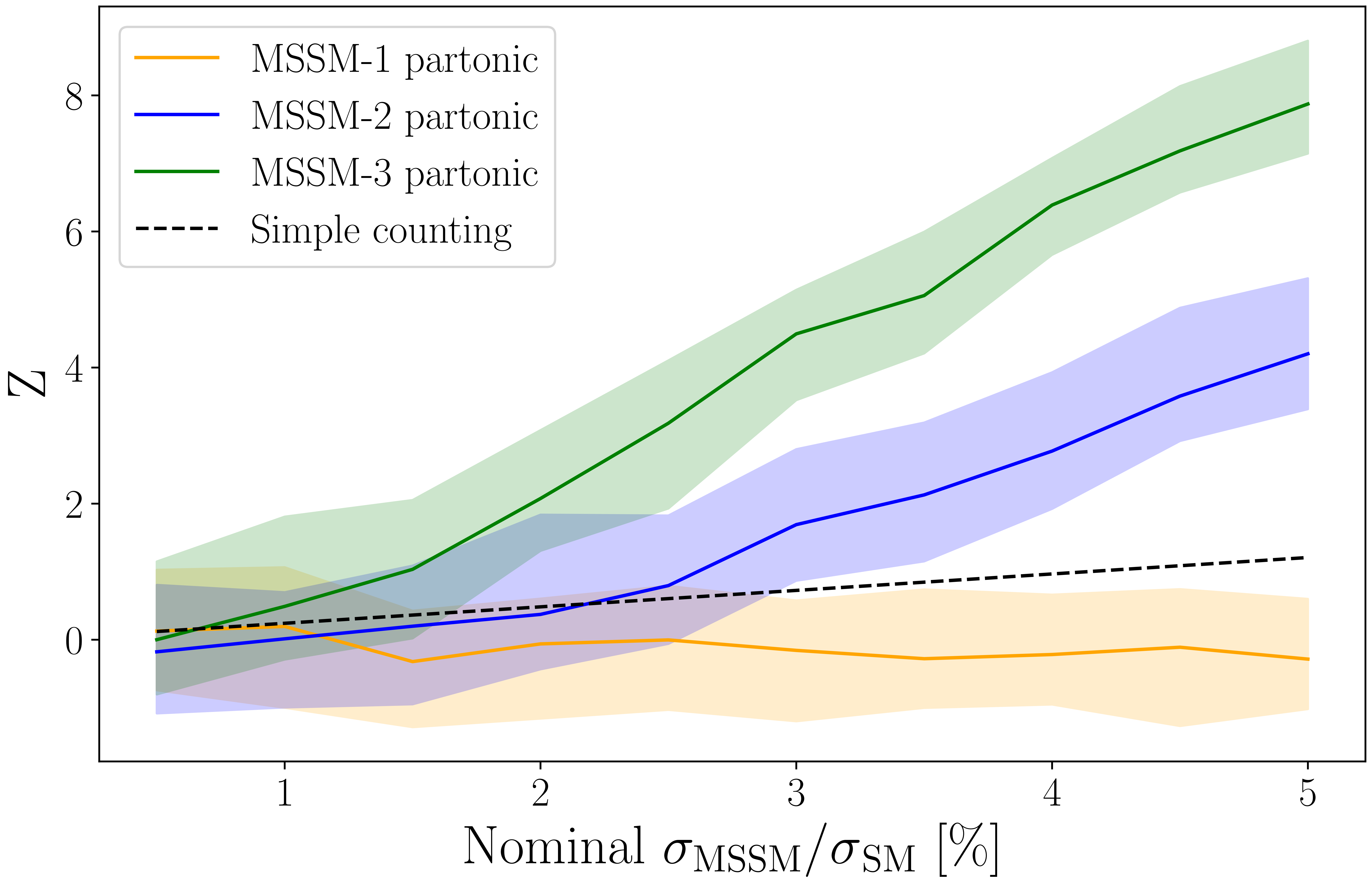
SM: $$pp \rightarrow W^+ Z \rightarrow \mu^+ \mu^- e^+ \nu_e$$

SIGNAL: $$pp \rightarrow \chi^+ \chi_2^0 \rightarrow W^+ Z \chi^0 \chi^0 \rightarrow \mu^+ \mu^- e^+ \nu_e \chi^0 \chi^0$$

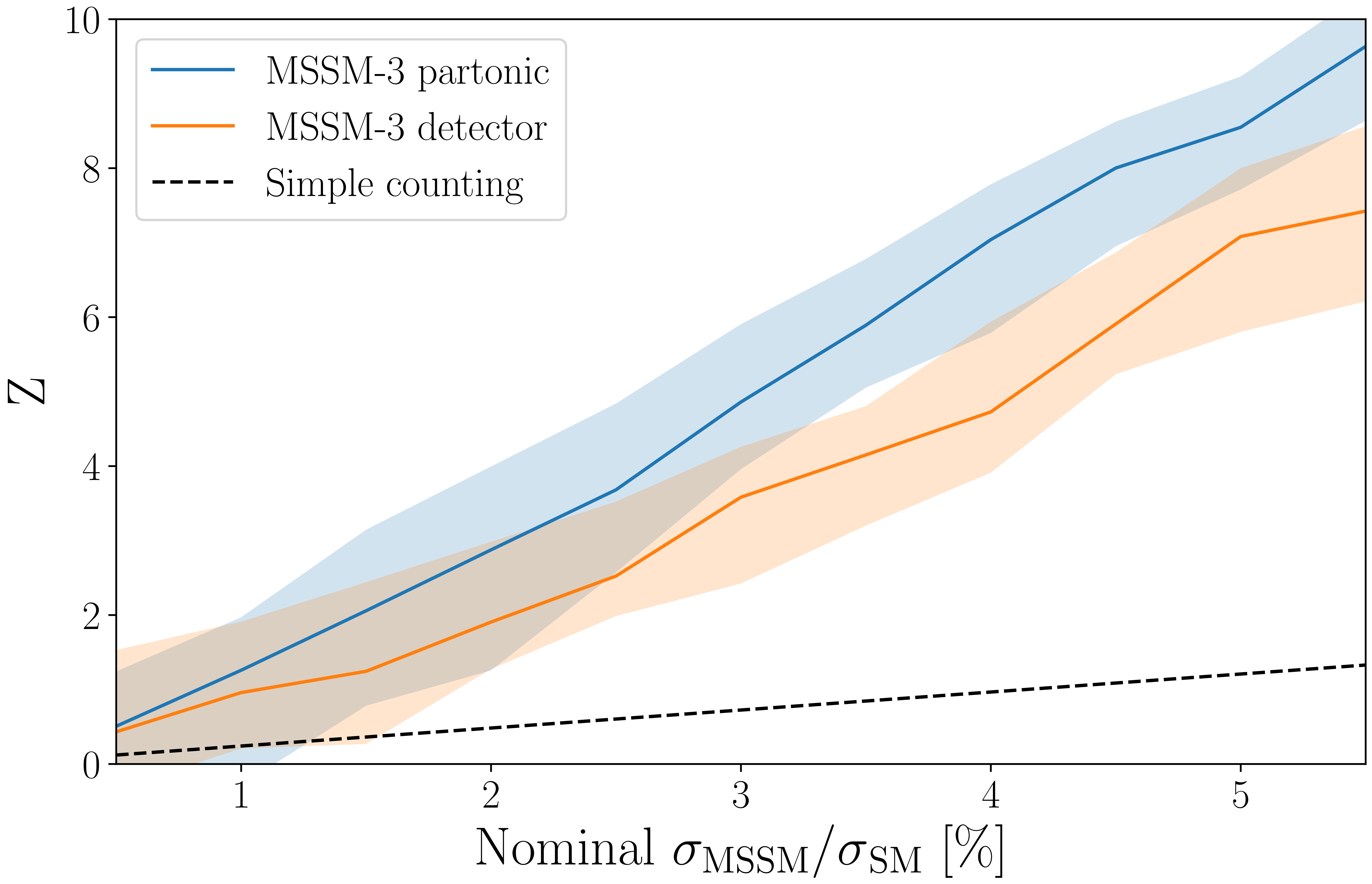
PRELIMINARY RESULTS, SIGNAL 1



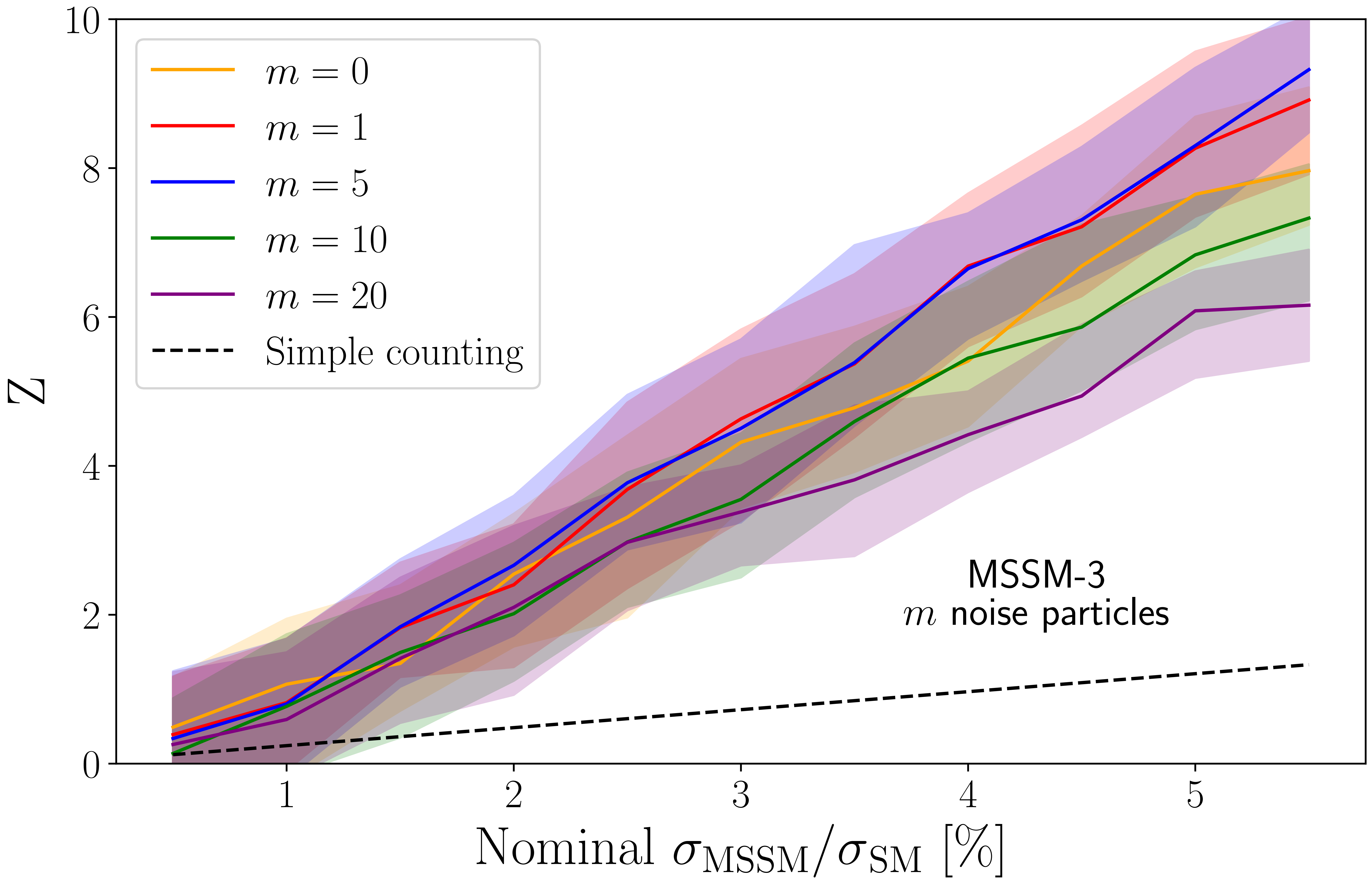
PRELIMINARY RESULTS, SIGNAL 1



PRELIMINARY RESULTS, SIGNAL 1



PRELIMINARY RESULTS, SIGNAL 1

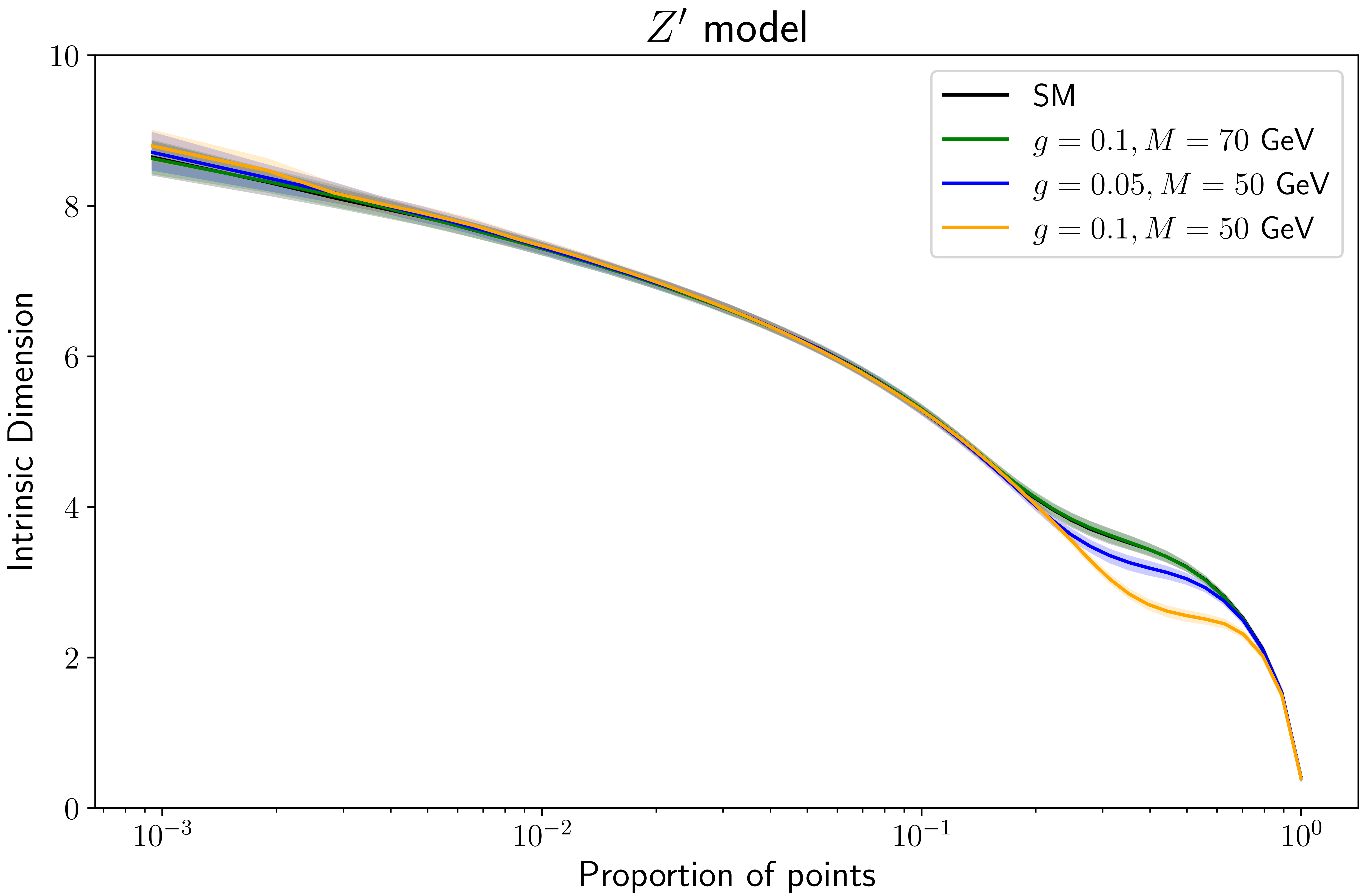


SIGNAL 2

SM: $$pp \to ZZ \to 4\mu$$

SIGNAL: $$pp \to Z \to \mu^+\mu^- Z_{L_\mu - L_\tau} \to 4\mu$$

PRELIMINARY RESULTS, SIGNAL 2



PRELIMINARY RESULTS, SIGNAL 1